23rd International Conference on General Relativity and Gravitation

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Contents

Plenary Session

Falling through masses in superposition: quantum reference frames for indefinite metrics

Caslav Brukner
University of Vienna, Austria

The current theories of quantum physics and general relativity alone do not allow us to study situations where the gravitational source is quantum. In my talk, I will propose a strategy to determine the dynamics of probe quantum systems in the presence of mass configurations in superposition, and thus an indefinite spacetime metric, using quantum reference frame (QRF) transformations. In particular, I will show that one can use an extension of the current QRF formalism to move to a reference frame in which the metric becomes definite even if the initial spacetime metrics in the superposition are not connected by diffeomorphism. Assuming the covariance of the dynamical laws under the QRF transformation, this will transform the problem of the dynamics of probe quantum systems in indefinite metrics into a physically equivalent problem of the dynamics in a definite metric.

Recent advances in mathematical relativity

Mihalis Dafermos
Univ. of Cambridge, UK / Princeton Univ., USA

I will survey some recent advances on our current rigorous mathematical understanding of fundamental questions in general relativity, including the stability of black holes and the structure of generic spacetime singularities.

Testing fundamental physics through observations

Amanda Weltman
Univ. of Cape Town, South Africa

In this talk, we will turn to the astrophysics playground as a laboratory for Cosmology, with a focus on Fast Radio Bursts. After their discovery in 2007, Fast Radio Bursts are fast developing into a rich area for discovery. We will consider the known properties of these bright, rapid bursts of radio light and their environments and explore together the possibilities for using their features as probes of cosmology and fundamental physics. More broadly, we will explore the potential for physics discovery using forthcoming radio telescope array experiments and intensity mapping.

The advances and prospects of gravitational-wave astronomy

Ilya Mandel
Monash Univ., Australia

In just a few years since the first direction gravitational-wave detection of a binary black hole merger on 14 September, 2015, almost a hundred sources have now been observed. Among other advances, these observations of compact binary mergers are teaching us about stellar and binary evolution and dynamics in dense stellar environments. This is an opportune moment to appreciate the fantastic growth of the field, reflect on what we learned so far, consider the near-term prospects, and make some educated guesses for the long-term future.

Recent progresses of the Dark Matter Particle Explorer

Jin Chang
National Astronomical Observatories, Chinese Academy of Sciences, China

The DArk Matter Particle Explorer (DAMPE) is a satellite-borne, calorimetric type, high-energy-resolution space cosmic ray and gamma-ray detector. It was launched in December 2015 and has been stably operating for 6.5 years. Its three major scientific objectives are dark matter indirect detection, cosmic ray physics and gamma-ray astronomy. Precise measurements of the all-electron, proton, and Helium spectra in wide energy ranges and sensitive searches of monochromatic gamma rays have been obtained, shedding new light on the research of cosmic ray physics and constraining the properties of particle dark matter. The operation status of the mission and recent physical results will be introduced.

Experimental dark matter search at China Jinping underground laboratory

Jiang-Lai Liu
Shanghai Jiao Tong University, China

The nature of dark matter is one of the greatest mysteries in modern physics and astronomy. A wide variety of experiments have been carried out worldwide to search for the evidence of dark matter particles. The China Jinping Underground Laboratory (CJPL), with a 2400-m rock overburden, is the deepest underground laboratory in the world, an ideal location to carry out dark matter direct detection experiments. In this talk, I will present an overview of the CDEX and PandaX experiments in CJPL, and discuss their recent results as well as future plans.

Gravitational Surprises at Long Distances

Cliff Burgess
McMaster University / PI, Canada

This talk explores some low-energy surprises that can emerge as consequences of accidental approximate symmetries in the gravity sector that are arguably robust consequences of UV physics (like string theory). Among the surprises are things usually believed to be uncommon in particle physics: naturally light scalars and vacuum energies, together with new screening mechanisms that help these to evade constraints from solar-system tests of gravity.

Gravity insights from replica wormholes

Henry Maxfield
Stanford University, USA

Black holes have long been a source of theoretical tension between general relativity and quantum mechanics. Recent light has been shed on these problems by a new gravitational formula for entropy, and its application to compute the information content of a black hole and its Hawking radiation. This formula is underpinned by “replica wormholes”, a non-perturbative effect in the low-energy effective theory of quantum general relativity. The insights from this and similar results suggest a new paradigm for interpreting the effective theory of quantum gravity.

The Nature of Gravity & Spacetime in HUFT and Taiji Program for GWD in China

Yue-Liang Wu
ICTP-AP/ITP-CAS, China

I am going to talk about the recent progresses on the hyperunified field theory (HUFT) and Taiji program for the space-based gravitation wave detections in China. The focus is paid to the foundation of the HUFT based on the maximum entangled-qubits motion principle and gauge invariance principle, which enables us to understand the nature of gravity and spacetime, and meanwhile make issues on the long-standing open questions: what is made to be the fundamental building block of nature? What is acted as the fundamental interaction of nature? what brings about the fundamental symmetry of nature? how does Einstein’s general relativity arise from unified gauge field theory? what is the basic structure of spacetime? how many dimensions does spacetime have? what makes time difference from space? why is there only a single temporal dimension? why do we live in a universe with only 4D spacetime? Why are there leptons and quarks beyond one family? how does the fundamental symmetry govern basic forces? how does early universe get inflationary expansion? what is a dark matter candidate? what is the nature of dark energy? The space-based gravitational wave detections are expected to provide a new window in probing the gravitational universe and exploring the nature of gravity and spacetime.

Progress of the TianQin Project

Jun Luo
Sun Yat-Sen University, China

The TianQin Project plans to deploy around 2035 three satellites to form an equilateral triangle constellation, TianQin, in an orbit centered on the Earth with an altitude of about 10^5 kilometers, to detect gravitational waves in space. TianQin is expected to open the gravitational wave detection window in the frequency band of 10^{-4} Hz ~ 1 Hz, opening our eyes towards the nature of gravity, the origin of black holes and the history of the universe. The ultimate scientific detection capability of TianQin depends on the level of breakthroughs that can be achieved with various key technologies, including high-precision space inertial refence, long baseline laser interferometry, ultra-quiet and ultra-stable spacecraft, gravitational wave data analysis, etc., which are all being intensely researched. In this talk, I will make a brief introduction to the progress made by TianQin along these directions.

(In)stability of Cauchy horizons

Jorge Santos
Univ. of Cambridge, UK

In recent years we have witnessed tremendous advances in our understanding of the (in)stability properties of Cauchy horizons that are cloaked by black hole horizons. Indeed, not only we have gained new insights into the classical properties of such Cauchy horizons but also on some of their quantum properties. The structure of the black hole interior turns out to be remarkably sensitive on the asymptotics of the domain of outer communications. I will survey some of these results in the talk. In particular, I will explain why a large class of charged black holes with de-Sitter asymptotics violate (classically) Christodoulou’s version of the strong cosmic censorship conjecture, only to have predictability restored by quantum effects. Rotating black holes with de-Sitter asymptotics, however, appear to preserve Christodoulou’s strong cosmic censorship.

Is There a Crisis in Cosmology?

Wendy Freedman
Univ. of Chicago, USA

An important and unresolved question in cosmology today is whether there is new physics that is missing from our current standard Lambda Cold Dark Matter (LCDM) model. Recent measurements of the Hubble constant (H_0), which are based on Cepheids and Type Ia supernovae (SNe), appear to be discrepant at the 5-sigma level with values of H_0 inferred from measurements of fluctuations in the cosmic microwave background (CMB). If real, the current discrepancy could be signaling a new physical property of the universe. I will present results based on Hubble Space Telescope Advanced Camera for Surveys data resulting in an independent calibration of SNe H_0 based on measurements of the Tip of the Red Giant

Branch (TRGB). The TRGB marks the luminosity at which the core helium flash in low-mass stars occurs, and provides a high-precision and accuracy standard candle. Moreover, the TRGB method is less susceptible to extinction by dust, to metallicity effects, and to crowding/blending effects than Cepheid variable stars. I will address the current uncertainties in both the TRGB and Cepheid distance scales, as well as discuss the current tension in Ho and the evidence for additional physics beyond the standard LCDM model.

Infrared interferometry of the galactic center black hole

Frank Eisenhauer
MPI, Germany

The Galactic Center harbors the nearest massive black hole. With a distance of only 8 kpc, it is the closest laboratory to study the astrophysical processes at work in these extreme objects, and to probe Einstein's general theory of relativity in the regime of strong gravity. Our presentation gives an overview of the GRAVITY infrared interferometry observations leading to the detection of the gravitational redshift and the Schwarzschild precession in the orbit of a star orbiting the black hole in a 16 yr orbit, and the observations of orbital motion of hot gas close to the innermost stable orbit. So far all observations are fully described by the laws of general relativity and the motion around a single black hole. We give upper limits on the deviation from general relativity, the extended mass, and the mass of potential intermediate mass black holes. We also present tests of the weak equivalence principle. We end our presentation with an outlook on future measurements of the spin and quadrupole of the black hole by combining infrared interferometry and spectroscopy form extremely large telescopes, which will then also test the cosmic censorship and no hair theorem of black holes.

Behavior of matter in strong field regime

Tanja Hinderer
Utrecht Univ., Netherlands

The gravitational waves from merging binary systems carry unique information about the internal structure of neutron stars, where material is compressed by tremendous gravity to supra-nuclear densities. Under such extreme conditions, novel and largely unexplored phases of matter emerge. I will discuss features of the interplay of matter with strong-field gravity and resulting characteristic signatures in the gravitational waves during a binary inspiral. I will also highlight new insights gained from recent gravitational-wave discoveries, and conclude with an outlook onto the remaining challenges and exciting prospects for the next years, as gravitational-wave science continues to move towards an era of precision physics.

Science with future gravitational-wave detectors

Alberto Sesana
Univ. di Milano Bicocca, Italy

Recent gravitational wave (GW) detections with LIGO/Virgo opened a new window on the Universe, unveiling the most violent catastrophic events in the cosmos. GW astronomy is just in its infancy, the Laser Interferometer Space Antenna (LISA) and Pulsar Timing Arrays (PTAs) will offer a complementary view of the GW universe in a much more extended range of frequencies, from mHz down to nHz, this will be complemented by 3G detectors on the ground and possibly other Interferometers in space such as Tian-Qin, Taiji and Decigo. I will discuss the status and science objectives of those detectors, their targeted sources and the science they will enable in the future decades.

Progress in numerical relativity

William East
Perimeter Institute, Canada

Complementing the spectacular breakthroughs in gravitational wave astronomy, advancements in our theoretical understanding and modeling of the strong field regime of gravity are essential to unlocking the full potential of the observations. I will survey some of the recent developments in using tools from numerical relativity to explore and make detailed predictions in this regime, and match the scope of new physics that might be uncovered. This expanding purview includes not only the mergers of black holes and neutron stars, but also the dynamics of more exotic compact objects, modifications of general relativity, and strong gravity signatures of new particles.

Advances in the 2-body problem

Justin Vines
AEI, Germany

The identification and characterization of gravitational-wave signals from compact binary coalescences relies on (among other things) various perturbative approximations to the two-body problem in general relativity, importantly including the post-Newtonian expansion, the closely related post-Minkowskian expansion, and the extreme-mass-ratio (or "self-force") expansion. This talk will review recently elucidated nontrivial interplays between these complementary approximations, which have led to new state-of-the-art results, and how these advances (and others) have developed in concert with increasing applications, to classical gravitational dynamics, of powerful techniques from quantum scattering amplitude theory.

Parallel Sessions

A1: Classical GR: Theoretical developments (Chair: Robert Wald, Coordinator: Hong Lu)

The second law of black hole mechanics in effective field theory

Harvey Reall
University of Cambridge

We investigate the second law of black hole mechanics in gravitational theories with higher derivative terms in the action. Wall has described a method for defining an entropy that satisfies the second law to linear order in perturbations around a stationary black hole. We show that this can be extended to define an entropy that satisfies the second law to quadratic order in perturbations. We address some outstanding issues with Wall's method, in particular its gauge invariance.

Hamiltonian energy of weak gravitational fields with a cosmological constant Λ

Tomasz Smołka
Department of Mathematical Methods in Physics, Faculty of Physics, University of Warsaw, Warszawa, Poland

We analyse the canonical energy of vacuum linearised gravitational fields on light cones on de Sitter, Minkowski, and anti-de Sitter backgrounds in Bondi gauge. For nonvanishing Λ the energy diverges, but a renormalised formula with well defined flux is obtained when asymptotic conditions on the linearized metric are modeled on the asymptotic behavior of the full solutions of the Einstein equations with a cosmological constant. The renormalised energy coincides with the quadratisation of the generalisation of the Trautman-Bondi mass. The same behaviour is observed for scalar fields but, perhaps surprisingly, for Maxwell fields all Noether charges including the energy are finite. The talk is based on Chruściel, P.T., Hoque, Sk J., Maliborski, M., Smołka, T., "On the canonical energy of weak gravitational fields with a cosmological constant $\Lambda \in \mathbb{R}$" Eur. Phys. J. C (2021) 81: 696

Charges, conserved quantities and fluxes in de Sitter spacetime

Aaron Poole
University of Southampton

In this talk I will discuss conserved quantities in asymptotically locally de Sitter (dS) spacetimes, motivated by the broader aim of a developing a fully nonlinear understanding of the nature of gravitational waves in dS. I will begin with a review of the asymptotics of dS spacetimes, before showing that one can use the tools of the covariant phase space formalism (together with analytic continuation of analogous results in anti-de Sitter spacetime) in order to derive expressions for spatially conserved charges and temporally conserved quantities. I will present flux formulae which capture the effects of outgoing gravitational radiation and illustrate these via application to exact solutions, with particular emphasis on the Robinson-Trautman dS class. This talk is based on work in collaboration with Kostas Skenderis and Marika Taylor.

Glimpses of Strong Cosmic Censorship Violation in Kerr-Newman-de Sitter Spacetimes

Cássio I. S. Marinho
Centro Brasileiro de Pesquisas Físicas (CBPF)

It is well-known that black hole spacetime solutions that have angular momentum and/or charge possess a Cauchy horizon, beyond which the Cauchy value problem is not well-posed: Einstein’s equations cease to be deterministic. This was one of the reasons that led to the formulation of the Strong Cosmic Censorship (SCC) conjecture by Penrose in 1978: Cauchy horizons should not form from generic asymptotically flat initial data. In fact, asymptotically flat black holes with angular momentum and/or charge do not violate SCC since an infinite blueshift mechanism turns the Cauchy horizon into a singularity. However, in a Universe with positive cosmological constant, the exponential decay of field perturbations of the black hole spacetime can be large enough to counter balance this blueshift. Recent investigations on the SCC subject have shown that SCC may be violated for Reissner-Nordström-de Sitter (with charge but non-rotating) black holes, but not for near-extremal Kerr-de Sitter (rotating but neutral) black holes. Here, we consider linear field perturbations of rotating and electrically-charged (Kerr-Newman-de Sitter) black holes. By calculating the quasinormal modes for massless scalar and Dirac fields, we provide evidence for the existence of weak solutions to Einstein’s equations across the Cauchy horizon in the nearly-extremal regime. We thus provide, for the first time, evidence for violation of Strong Cosmic Censorship in (4-dimensional) rotating black hole spacetimes.

Frame-dragging: meaning, myths, and misconceptions

Luis Filipe Costa
CAMGSD - Instituto Superior Tecnico, Universidade de Lisboa

The term frame-dragging is associated today with a plethora of effects related to the off-diagonal element of the metric tensor. It is also frequently the subject of misconceptions leading to incorrect predictions, even of nonexistent effects. In this talk we shall will see that there are three different levels of frame-dragging corresponding to distinct gravitomagnetic objects: gravitomagnetic potential, field, and tidal tensor, whose effects are independent, and sometimes opposing. It is seen that, from the two analogies commonly employed in the literature, the one with magnetism holds strong, whereas the fluid-dragging analogy is, in general, misleading. The associated (all too common) "body-dragging" misconception is debunked; as sharp counter-examples, we consider equilibrium positions for test bodies in the Kerr-dS and Kerr-Newman spacetimes, and the notable "bobbings" in binary systems, where it predicts the exact opposite of the actual effect. The actual origin of such bobbings is also

briefly dissected. Other applications briefly considered include rotating cylinders (Lewis-Weyl metrics) and black holes surrounded by disks/rings.

Scalar lumps with one and two horizons

George Lavrelashvili
A.Razmadze Mathematical Institute at I.Javakhishvili Tbilisi State University

First we investigate a self-interacting scalar field theory coupled to gravity and are interested in spherically symmetric solutions with a regular origin surrounded by a horizon. For a scalar potential containing a barrier, and using the most general spherically symmetric ansatz, we show that in addition to the known static, oscillating solutions discussed earlier in the literature there exist new classes of solutions which appear in the strong field case. For these solutions the spatial sphere shrinks either beyond the horizon, implying a collapsing universe outside of the cosmological horizon, or it shrinks already inside of the horizon, implying the existence of a black hole surrounding the scalar lump in all directions.
Next we study generalizations of the Schwarzschild-de Sitter solution in the presence of a scalar field with a potential barrier. These static, spherically symmetric solutions have two horizons, in between which the scalar interpolates at least once across the potential barrier, thus developing a lump. In part, were cover solutions discussed earlier in the literature and for those we clarify their properties. But we also find a new class of solutions in which the scalar lump curves the spacetime sufficiently strongly so as to change the nature of the erstwhile cosmological horizon into an additional trapped horizon, resulting in a scalar lump surrounded by two black holes. These new solutions appear in a wide range of the parameter space of the potential. We also discuss(challenges for) the application of all of these solutions to black hole seeded vacuum decay.

Asymptotic behavior of null geodesics near future null infinity

Masaya Amo
Kyoto University

We investigate the behavior of null geodesics near future null infinity in asymptotically flat spacetimes. In particular, we focus on null geodesics that correspond to worldlines of photons which are emitted (i) in outward directions, (ii) in the directions tangential to the constant radial surfaces in the Bondi coordinates, and (iii) small inward directions. In four dimensions, some assumptions are required to guarantee the photon to reach future null infinity. In higher dimensions, asymptotic behavior of null geodesics is approximated by that in Minkowski spacetime, and assumptions needed in four dimensions are not necessary. In addition, in the sense of asymptotics, the condition for the constant radial surfaces to be a photon surface is shown to be controlled by a key quantity for asymptotic behavior of null geodesics. As a consequence, in four dimensions, such a non-expanding photon surface can be realized even near future null infinity for a short period of time in the presence of enormous energy flux. By contrast, in higher-dimensional cases, no such a photon surface can exist.

Critical collapse of an axisymmetric ultrarelativistic fluid in 2+1 spacetime dimensions

Patrick Bourg
University of Southampton

Critical collapse is concerned with the threshold of black-hole formation in the space of initial data.
Many rich phenomena occur at this threshold. First, there exists a critical solution, an attractor of codimension one, which has the general characteristics of being self-similar and universal. Second, in certain types of phenomena labelled as "type II", one can obtain black holes with arbitrarily small masses, or spacetimes with arbitrarily large curvature visible from null infinity, through the fine-tuning of a one-parameter family of initial data. The study of critical collapse is therefore of importance to the cosmic censorship conjectures and quantum gravity.
The vast majority of research studies dedicated to critical collapse focuses on spherically symmetric initial data. The generalization beyond spherically symmetric brings about many numerical and theoretical complications, in part due to the existence of gravitational waves. One way to work around those problems is to consider, as a toy model, the situation in 2+1 spacetime dimensions.
In this presentation, I will show that the critical phenomena that occur for an ultrarelativistic fluid in 2+1 dimensions are very different from what is typically expected. First, the critical solution is not self-similar but quasi-static, contracting adiabatically. Second, the spin-to-mass ratio of the critical solution increases as it contracts, and hence, so does that of the black hole created at the end as we fine-tune to the black-hole threshold. Forming extremal black holes is avoided because the contraction of the critical solution smoothly ends as extremality is approached, in support of the weak cosmic censorship conjecture.

A generalization of Einstein's quadruple formula for the energy of gravitational radiation in de Sitter spacetime

Denis Dobkowski-Ryłko
Faculty of Physics, University of Warsaw

We investigate gravitational radiation coming from the compact source in spacetime with positive cosmological constant. It requires developing an adequate generalization of the boundary of asymptotically flat spacetime valid in case of non-vanishing cosmological constant. A possible generalization is the system consisting of two transversal null surfaces; the radiating region is bounded from the past by a weakly isolated horizon, whereas the radiation itself is encoded in the future part of the generalized boundary - which is also a null surface. We consider a first order time-changing source on de Sitter background, where the null boundaries are Killing horizons. Studying such system, we calculate the energy carried by gravitational radiation and passing through the future boundary using definitions formulated in [1] and [2]. As a result, we derived the generalized quadruple formula using the mass and pressure quadruple moments introduced in [3] and show that its limit recovers the famous Einstein quadruple formula [4] obtained for the perturbed Minkowski spacetime [5].

[1] R. M. Wald, A. Zoupas, A general definition of ‘conserved quantities’ in general relativity and other theories of gravity, Phys. Rev. D61 (2000) 084027.

[2] V. Chandrasekaran, E. E. Flanagan and K. Prabhu, Symmetries and charges of the general relativity ar null boundaries, J. High Energy. Physi. 2018, 125 (2018).
[3] A. Ashtekar, B. Bonga and A. Kesavan, Asymptotics with a positive cosmological constant: III. The quadruple formula, Phys. Rev. D 92 (2015), 104032
[4] R. M. Wald, A. Zoupas, A general definition of 'conserved quantities' in general relativity and other theories of gravity, Phys. Rev. D61 (2000) 084027.
[4] R. M. Wald, General Relativity, University of Chicago Press, 2010.
[5] D. Dobkowski-Ryłko, J. Lewandowski, A generalization of the quadruple formula for the energy of gravitational radiation in de Sitter spacetime - to be published

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Charges and fluxes on (perturbed) non-expanding horizons

Jerzy Lewandowski
University of Warsaw, Faculty of Physics

The symmetry group of NEHs is a 1 dimensional extension G of the Bondi-Metzner-Sachs group. For each infinitesimal generator, we now define a charge and a flux on NEHs as well as perturbed NEHs [1]. The procedure uses the covariant phase space framework in presence of internal null boundaries N along the lines of [2,3]. Consequently, charges and fluxes associated with generators of G are free of physically unsatisfactory features that can arise if N is allowed to be a general null boundary. In particular, all fluxes vanish if N is an NEH, just as one would hope; and fluxes associated with symmetries representing 'time-translations' are positive definite on perturbed NEHs. These results hold for zero as well as non-zero cosmological constant. The resulting framework can be used to define and calculate the energy, momentum, angular momentum and other characteristics of gravitational radiation falling in black holes or radiated away by asymptotically de Sitter spacetimes.

[1] A. Ashtekar, N. Khera, M. Kolanowski and J. Lewandowski, Charges and fluxes on (perturbed) non-expanding horizons, JHEP 02 (2022) 066
[2] R.M. Wald and A. Zoupas, Phys. Rev. D 61, 084027 (2000)
[3] V. Chandrasekaran, E.E. Flanagan and K. Prabhu, JHEP 11, 125 (2018)

Non-Expanding horizons: Multipoles and the Symmetry Group

Neev Khera
Penn State

It is well-known that blackhole and cosmological horizons in equilibrium situations are well-modeled by non expanding horizons (NEHs). In the first part of the part of the talk we introduce multipole moments to characterize their geometry covariantly, removing the restriction to axisymmetric situations made in the existing literature. We then show that the symmetry group of NEHs is a 1-dimensional extension of the BMS group.

On the reconciliation between the black hole tidal response problem and the naturalness of General Relativity

Panagiotis Charalambous
Center for Cosmology and Particle Physics, New York University

The tidal deformation problem has been an insightful setup for studying the nature of celestial bodies. On the one hand, it probes the internal structure of a compact body through the tidal response coefficients which are measurable quantities encoded in gravitational wave signals emitted during the inspiraling phase of a binary system. On the other hand, it poses an exceptional challenge to the naturalness of General Relativity, arising from the fact that the conservative parts of the static tidal response coefficients (also referred to as static Love numbers) for general relativistic black holes in four spacetime dimensions are zero at all scales. I will discuss recent progress towards a triumph of naturalness regarding the tidal response problem for black holes, coming from the emergence of an enhanced SL(2,R) ("Love") symmetry that explains these otherwise fine-tuned properties and furthermore hints a connection to the well-known enhanced isometries of the near-horizon geometry of extremal black holes.

Symmetries of Black Hole Perturbation Theory

Adam Solomon
McMaster University

I discuss novel symmetries of perturbation theory around rotating and non-rotating black holes in general relativity, and discuss their origins and implications for gravitational-wave astronomy. This is motivated by two special aspects of black hole perturbations in four dimensions: isospectrality of quasinormal modes and the vanishing of tidal Love numbers. There turn out to be off-shell symmetries underlying both of these phenomena. One is a duality, which on shell reproduces the famous Chandrasekhar duality and therefore underlies isospectrality, and can be thought of as an extension of electric-magnetic duality to black hole backgrounds. The other is an infinite set of "ladder symmetries" relating modes of different angular momentum or spin, which imply the vanishing of Love numbers. This has a geometric origin in the conformal symmetry of low-frequency modes.

Twistors and angular momentum

Adam Helfer
University of Missouri

Twistors give an attractive definition of angular momentum at null infinity: it is manifestly BMS covariant, and there is no supertranslation ambiguity [1]. This approach compares favorably with the more common, BMS-charge, definition: twistors provide more detailed physical descriptions and interpretations of the spin and center of mass, and they give a change-of-origin formula which is much closer to the Poincare one and does not require the

introduction of supermomenta. There is a natural way to compare angular momenta at past and future null infinity. In the twistor picture, general-relativistic angular momentum can be viewed as a unification of two structures, the special-relativistic Poincare angular momentum and the Bondi shear.

[1] Helfer, A. D. PRD 104, 104053 (2021), arxiv:2110.00140

On the Bondi-Sachs mass-loss formula in non-Bondi systems

Joerg Frauendiener
University of Otago

How does one compute the Bondi mass on an arbitrary cut of null infinity $\mathcal{I}$ when it is not presented in a Bondi system? What then is the correct definition of the mass aspect? How does one normalise an asymptotic translation computed on a cut which is not equipped with the unit-sphere metric? These are questions which need to be answered if one wants to calculate the Bondi-Sachs energy-momentum for a space-time which has been determined numerically. Under such conditions there is not much control over the presentation of $\mathcal{I}$ so that most of the available formulations of the Bondi energy-momentum simply do not apply. In this talk we provide the necessary background for a manifestly conformally invariant and gauge independent formulation of the Bondi energy-momentum. We introduce a conformally invariant version of the GHP formalism to rephrase all the well-known formulae. This leads us to natural definitions for the space of asymptotic translations with its Lorentzian metric, for the Bondi news and the mass-aspect. A major role in these developments is played by the ``co-curvature'', a naturally appearing quantity closely related to the Gauß curvature on a cut of ~ $\mathcal{I}$.

Causality at Infinity and Positivity of Mass

Peter Cameron
University of Cambridge

Motivated by a "Lorentz covariant" construction of quantum gravity, Penrose has shown that, despite being asymptotically flat, there is an inconsistency between the causal structure at infinity in Schwarzschild and Minkowski spacetimes. However, the proof of this inconsistency is specific to 4 spacetime dimensions and positive mass Schwarzschild. In this talk I will discuss how this result extends to higher (and lower) dimensions. More generally, I will consider examples of how the causal structure near spatial infinity in asymptotically flat spacetimes is affected by dimension and by the presence of mass (both positive and negative). I will then discuss how these ideas can be used to prove a version of the positive mass theorem in higher dimensions using arguments inspired by those of Penrose, Sorkin and Woolgar.

Gravitational multipole moments for asymptotically de Sitter spacetimes

Sumanta Chakraborty
Indian Association for the Cultivation of Science

We provide a prescription to compute the gravitational multipole moments of compact objects for asymptotically de Sitter spacetimes. Our prescription builds upon a recent definition of the gravitational multipole moments in terms of Noether charges associated to specific vector fields, within the residual harmonic gauge, dubbed multipole symmetries. We first derive the multipole symmetries for spacetimes which are asymptotically de Sitter; we also show that these symmetry vector fields eliminate the nonpropagating degrees of freedom from the linearized gravitational wave equation in a suitable gauge. We then apply our prescription to the Kerr-de Sitter black hole and compute its multipole structure. Our result recovers the Geroch-Hansen moments of the Kerr black hole in the limit of the vanishing cosmological constant.

Significance of Black Hole Quasinormal Modes: A Closer Look

Ramin Daghigh
Metropolitan State University

It is known that approximating the Regge-Wheeler Potential with step functions significantly modifies the Schwarzschild black hole quasinormal mode spectrum. Surprisingly, this change in the spectrum has little impact on the ringdown waveform. We examine whether this issue is caused by the jump discontinuities and/or the piecewise constant nature of step functions. We show that replacing the step functions with a continuous piecewise linear function does not qualitatively change the results. However, in contrast to previously published results, we discover that the ringdown waveform can be approximated to arbitrary precision using either step functions or a piecewise linear function. Thus, this approximation process provides a new mathematical tool to calculate the ringdown waveform. In addition, similar to normal modes, the quasinormal modes of the approximate potentials seem to form a complete set that describes the entire time evolution of the ringdown waveform. We also examine smoother approximations to the Regge-Wheeler potential, where the quasinormal modes can be computed exactly, to better understand how different portions of the potential impact various regions of the quasinormal mode spectrum.

Additively separable family of solutions for the null-surface formulation of general relativity in 2+1 dimensions

Tina Harriott
Mount Saint Vincent

This talk presents a family of exact solutions for the (2+1)-dimensional null-surface formulation (NSF) of general relativity—which is equivalent to standard general relativity but uses null surfaces as basic variables, instead of using the metric or a connection. The field equations of the NSF form a coupled system of highly nonlinear partial differential equations

and are extremely challenging to solve exactly. There are only three previously known exact solutions for the NSF in 2+1 dimensions, and none at all are known in 3+1 dimensions. In this talk, the assumption that the solution be additively separable (as opposed to the more usual multiplicatively separable) is shown to be naturally adapted to the structure of the NSF and, more importantly, opens up the prospect of generalization to 3+1 and higher dimensions. This possibility will be discussed in the talk. The eigenvalues of the Cotton-York tensor will be presented and it will be shown how the spacetimes specified by the family of solutions cover a range of Petrov types: I, II, and D. Two of the previously known solutions are included as special cases. The physical interpretation is discussed in detail and possible sources, notably fluids and scalar fields, are examined.

Refined inequalities for a loosely trapped surface and attractive gravity probe surface

Kangjae Lee
Department of Mathematics, Nagoya University

A trapped surface describes the strong gravity and its existence is crucial in Penrose's singularity theorem for gravitational collapse. If the cosmic censorship conjecture holds, the trapped surface is inside black holes and then it cannot be observed from distant observers. Therefore, it is nice to have another indicator for strong gravity outside black holes. Recently a loosely trapped surface (LTS) has been proposed as a such candidate. Moreover, it has been extended to a surface, called attractive gravity probe surface (AGPS), which may be indicator even for weak gravity. For these surfaces, is has been shown that, under certain conditions, the Penrose-like inequalities hold. In this presentation, taking account of angular momentum, gravitational waves and matters for the LTS and AGPS, I will refine the Penrose-like inequalities for them.

A New Look at the C^0-formulation of the Strong Cosmic Censorship Conjecture

Alexander Yosifov
Bulgarian Academy of Sciences/Huawei Central Research Institute, 2012 Labs

We examine the C^0-formulation of the strong cosmic censorship conjecture (SCC) from a quantum complexity-theoretic perspective and argue that for vacuum initial conditions, defined on a spacelike codimension-one submanifold within the black hole interior, the metric is C^0-extendable to a larger Lorentzian manifold across the Cauchy horizon. To demonstrate the pathologies associated with a hypothetical validity of the C^0 SCC, we prove it violates the "complexity=volume" conjecture for a low-temperature hyperbolic AdS_{d-1} black hole dual to a CFT living on a (d-1)-dimensional hyperboloid H_{d-1}, where in order to save the gauge/gravity duality we impose a lower bound on the interior metric extendability of order the classical recurrence time.

The Weyl double copy in maximally symmetric spacetimes

Shanzhong Han
Niels Bohr Institute, University of Copenhagen

We study the Weyl double copy for vacuum gravity solutions with a cosmological constant. By making use of the method we proposed previously, in which the spin-1/2 massless spinors (Dirac-Weyl fields) are regarded as basic units, we explicitly demonstrate that the single and zeroth copy satisfy conformally invariant field equations on conformally flat spacetime, based on the exact non-twisting vacuum type N and vacuum type D solutions with a cosmological constant. Furthermore, we show that the zeroth copy not only connects gravity fields with the single copy but also connects degenerate electromagnetic fields with Dirac-Weyl fields in the curved spacetime irrespective of the presence of a cosmological constant. Moreover, the study shows that the zeroth copy plays an important role for time-dependent radiation solutions. In particular, for Robinson-Trautman (Λ) gravitational waves solutions, as opposed to the single copy, the zeroth copy carries extra information to indicate whether the sources of associated gravitational waves are time-like, null, or space-like.

A2: Classical GR: Mathematical developments (Chair: Stefanos Aretakis, Coordinator: Song He)

Anisotropic Dynamical Horizons Arising in Gravitational Collapse

Xinliang An
National University of Singapore

Black holes are predicted by Einstein's theory of general relativity, and now we have ample observational evidence for their existence. However theoretically there are many unanswered questions about how black holes come into being and about the structures of their inner spacetime singularities. In this talk, we will present several new results in these directions.

Scattering on black hole interiors and its consequences for Strong Cosmic Censorship

Christoph Kehle
IAS Princeton

I will describe a physical-space and fixed-frequency scattering theory for linear waves on Reissner-Nordström-(A/dS) or Kerr-(A/dS) black hole interiors. It turns out that a crucial aspect of the scattering theory is the presence of certain scattering poles associated with the Killing generator of the Cauchy horizon. I will also discuss the consequences of the distribution of these poles for Strong Cosmic Censorship. This is based on joint work with Y. Shlapentokh-Rothman and M. Van de Moortel.

Self-Similarity and Naked Singularities for the Einstein Vacuum Equations

Yakov Shlapentokh-Rothman
University of Toronto

We will start with an introduction to the problem of constructing naked singularities for the Einstein vacuum equations, and then explain our discovery of a fundamentally new type of self-similarity and show how this allows us to construct solutions corresponding to a naked singularity. Some of this is joint work with Igor Rodnianski.

Hidden symmetries in the geodesic motion from disformal transformations: the pp-wave case in Lorentz and Finsler geometries

Nikolaos Dimakis
Sichuan University

As it is known in the study of geodesic motion, the introduction of mass, breaks the symmetries generated by proper conformal Killing vectors, which generate integrals of motion only for null geodesics. We show that for pp-wave spacetimes, the broken symmetries of the conformal transformations, are substituted by generators of disformal transformations. We demonstrate the connection that the latter have to Noether symmetries of higher order. This property still persists and expands if we further break the symmetries by considering the Bogoslovsky-Finsler line element, which introduces a Lorentz violating parameter.

Triangular decoupling of harmonic gauge linearized gravity around a Schwarzschild black hole

Igor Khavkine
Institute of Mathematics of the Czech Academy of Sciences

I will review the motivations (from classical as well as quantum field theory) for studying electromagnetism and linearized gravity in harmonic gauge (locality and regularity, simplicity of residual gauge freedom, renormalization of interactions). Unfortunately, even after successful separation of variables, this choice of gauge leads to technical difficulties on non-flat backgrounds, like the Schwarzschild black hole, due to rather complicated radial mode equations. I will then describe a recent series of works, in which I have taken steps to overcome these difficulties by explicitly decoupling the radial mode equations into sparse triangular form. This simplification opens the door to immediate applications: solving the equations of motion with sources, proving the absence of exponentially growing modes, constructing Green functions, explicit formulas for Debye potentials, all directly in harmonic gauge.

Extremal, axisymmetric horizons in the presence of a cosmological constant

Eryk Buk
University of Warsaw, Faculty of Physics

All solutions to the near-horizon geometry equations were derived for an axisymmetric, compact, 2-dimensional manifold, in the presence of a cosmological constant. During the calculations the regularity conditions preventing conical singularities were taken into account. Moreover the one-to-one correspondence of the solutions with the extremal horizonsin the Kerr-(anti-)de Sitter spacetimes was established, and in particularthe triply degenerate horizon was identified and characterized. The solutions were also identified among the solutions to the Petrov type D equation.

Decoupling of Maxwell equations in the case of null field

Yurii Taistra
Pidstryhach Institute for Applied Problems of Mechanics and Mathematics NAS of Ukraine

Maxwell equations in the curved space-time are coupled system of first-order PDE. Teukolsky provided decoupling in 1973 by using the Newman-Penrose formalism, and the second-order PDEs for extremal components φ_2 and φ were obtained. Equations decouple in the Petrov type D space-times [1].

Decoupling of the system was also provided by Cohen and Kegeles in 1974, 1979 in Herz potential formulation. The system decouples in generalized Goldberg-Sachs space-times [2], and the Herz field is assumed to be algebraically special $P_{AB}=\psi o_A o_B$.

A similar assumption on the Maxwell field $\varphi_{AB}=\varphi_2 o_A o_B$ implies that only one function describes the field, and the first-order system of Maxwell equations decouples. This case was investigated in our previous works and was called "one-way null" fields [3]. A more general case, where the Maxwell field is assumed to be only null, was not considered. We present an approach for decoupling the Maxwell equations in the case of a null field, where the obtained decoupled equations are the first-order PDEs.

The work was supported by a grant from the NAS of Ukraine for research laboratories/groups of young scientists of the NAS of Ukraine for conducting research on priority areas of science and technology, contract number 02/01-2022(3).

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2. J. M. Cohen, L. S. Kegeles Phys. Rev. D., **10**, No. 4., 1070–1084 (1974).
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Uniqueness of supersymmetric black holes in AdS5

Sergei Ovchinnikov
University of Edinburgh

The classification of anti de Sitter black holes is an open problem of central importance in holography. In this talk, I will present new advances in classification of solutions to five-dimensional minimal gauged supergravity. In particular, we prove a black hole uniqueness theorem for supersymmetric solutions within a class of solutions with SU(2) symmetry and an analytic horizon. As part of the proof, we provide a local classification of Kahler spaces admitting SU(2) isometry. Finally, we discuss future generalizations of this result.

Non-singular spacetimes with NUT parameter

Maciej Ossowski
University of Warsaw

The spacetimes with the NUT parameter are Petrov type D spacetimes commonly associated with a problematic singularity of their axis of symmetry.One of the possible solutions is to compactify the orbits of the symmetries, which imposes the Hopf fibration structure onto the

spacetime. In the simplest case of the Taub-NUT solution this has been done already by Misner, via a so called Misner's interpretation.We provide a recipe for extension of this method to the general type D spacetimes (including mass, rotation, acceleration, NUT parameter and the cosmological constant) - it is achieved by imposing the U(1)-principle bundle structure onto the space of the orbits of suitably chosen Killing vector fields, from which the non-singular spacetime can be constructed.I will discuss the relation to the local theory of horizons, as well as possible applications to the cosmology and regularising the curvature singularities of more widely studied black-hole spacetimes.

Based on:
J. Lewandowski and M. Ossowski, Class. Quantum Grav. 37 205007,
J. Lewandowski and M. Ossowski, Phys. Rev. D 104, 024022,
J. Lewandowski and M. Ossowski, Phys. Rev. D 102, 124055

Semi-global and global constructions of impulsive gravitational wave spacetimes

Yannis Angelopoulos
California Institute of Technology

I will talk about some recent results on constructions of semi-global and global spacetimes within the context of the Einstein equations that contain curvature singularities.

Finsler pp-waves and the Penrose limit

Marcus Werner
Duke Kunshan University

Penrose's plane wave limit of Lorentzian spacetimes is a remarkable result in classical GR. In this poster, we consider its extension to Finsler spacetimes with Lorentzian fundamental tensor, by constructing suitable null coordinates from a null gradient vector field and adapting the definition of Lorentzian pp-waves in GR. We also present a new family of Finsler pp-waves. This is joint work with Amir Babak Aazami (Clark) and Miguel Angel Javaloyes (Murcia).

On the construction of Riemannian three-spaces with smooth inverse mean curvature foliation

István Rácz
Wigner RCP

Consider a one-parameter family of smooth Riemannian metrics on a two-sphere $\mathcal{S}$. By choosing a one-parameter family of smooth lapse and shift, these Riemannian two-spheres can always be assembled into smooth Riemannian three-space, with metric h_{ij} on a three-manifold Σ foliated by a one-parameter family of two-spheres $\mathcal{S}_\rho$. It is shown first that we can always choose the shift such that the $\mathcal{S}_\rho$ surfaces form a smooth inverse meancurvature foliation of Σ. An integrodifferential expression, referring only to thearea of the leaves and the lapse function, is also derived that can be used to quantifythe Geroch mass. If the constructed Riemannian three-space happens to be asymptotically flat and the ρ-integral of the integrodifferential expression is non-negative, then not only thepositive mass theorem but, if one of the $\mathcal{S}_\rho$ leaves is a minimalsurface, the Penrose inequality also holds. Notably, neither of the above resultsrequires the scalar curvature of the constructed three-metric to be non-negative.

Symmetry operators for the conformal wave equation in rotating black hole spacetimes

Finnian Gray
Perimeter Institute/University of Waterloo

We present covariant symmetry operators for the conformal wave equation in the (off-shell) Kerr–NUT–AdS spacetimes. These operators, that are constructed from the principal Killing–Yano tensor, its ‘symmetry descendants’, and the curvature tensor, guarantee separability of the conformal wave equation in these spacetimes. We also discuss how these operators give rise to a full set of conformally invariant mutually commuting operators for the conformally rescaled spacetimes and underlie the R-separability of the conformal wave equation therein.

The Cauchy problem of pp-waves

Ángel Murcia
Instituto de Física Teórica UAM/CSIC

In this talk I will show that the Cauchy problem of pp-waves can be expressed in terms of a very special system of first-order time evolution equations in a three-dimensional Cauchy hypersurface. We do this by the equivalent characterization of pp-waves in terms of the existence of a parallel spinor, whose associated Cauchy problem we find to be given by a system of first-order PDEs on the Cauchy hypersurface. In particular, this provides an initial data characterization of Ricci-flat pp-waves. Next, we find explicit solutions to these first-order equations in simply-connected Lie groups, obtaining along the way necessary and sufficient conditions for the evolution to be defined for all times. This suggests the intriguing possibility of using first-order hyperbolic flows to construct special solutions of second-order curvature flows.

Gyroscopic Precession in the Vicinity of Event-Horizon and Naked Singularity for Spherically Symmetric Spacetime

Paulami Majumder
Indian Institute of Science Education and Research, Kolkata

In this work, we employ Frenet-Serret formalism of gyroscopic precession to compute the precession frequency close to event-horizon and naked singularity (NS). Our goal is to determine the possibility of using the Gyroscopic precession to distinguish a blackhole event-horizon from a naked singularity. We show that it is possible to have a timelike trajectory crossing the blackhole along which the precession frequency remains finite at the horizon. We demonstrate these using spherically symmetric static solutions such as Schwarzschild, Schwarzschild in anti-de-Sitter and Reissner-Norstrom spacetime. We set Q > M in the Reissner-Norstrom solution to investigate the precession around a Naked-singularity.

Cosmological static metrics and Kruskal type coordinates from symmetry transformations

Edgar Leon
Universidad Autonoma de Sinaloa

We derive the static form for the FLRW model from metric transformations, and discuss the way the solutions take a unique form. Then we extend the formalism to obtain a new view of Kruskal coordinates, and in the process we obtain a systematic way to obtain Kruskal for any given spherically symmetric static metric. At the end we obtain explicit Kruskal coordinates for several known metrics. Explicit novel solutions are obtained for the extremal Reissner-Nordström case, where interestingly the golden ratio arises, as well as for the Schwarzschild-de Sitter metric.

Characteristic initial boundary value problem in general relativity

Xiaoning Wu
Academy of Mathematics and Systems Sciences, Chinese Academy of Sciences

Motivated by gravitational radiation and AdS/CFT correspondence, we investigate the mixed boundary problem of field equations. The initial data are imposed on an outgoing null hypersurface and a timelike hypersurface. In this talk, I will briefly review previous results on this topic and introduce our new developments for the scalar and Maxwell fields.

Virial identities in relativistic gravity

Alexandre M. Pombo
Aveiro University

Virial (a.k.a scaling) identities are integral identities that are useful for a variety of purposes in non-linear field theories, including establishing no-go theorems for solitonic and black hole solutions, as well as checking the accuracy of numerical solutions. In this presentation, we provide a pedagogical rationale for the derivation of such integral identities. We propose that a complete treatment of virial identities in relativistic gravity must take into account the appropriate boundary term. For General Relativity this is the Gibbons-Hawking-York boundary term. For both spherical and axial symmetry, there is a particular "gauge" choice, i.e. a choice of coordinates and parameterizing metric functions, that simplifies the

computation of virial identities in General Relativity, making both the Einstein-Hilbert action and the Gibbons-Hawking-York boundary term non-contributing. Under this choice, the virial identity results exclusively from the matter action. For generic "gauge" choices, however, this is not the case.

A Quantum System as The Main Matter of The Universe

Guang Chen
College of Science, Donghua University

The quantized mathematics is based on the set of discrete real numbers and complex numbers formed by the positive and negative signs "＋" and "－", real and imaginary units "1"and "i", and integers 1, 2, 3, ..., C ($C=5\times10^{60}$). It is the discretization of modern mathematics and it has the finiteness of the number set and the finite precision of the operations on the set.
Structural hypothesis: the constituent elements of particles are represented as the generalized sequences of field and space-time or source and space-time. And the constituent elements of an elementary particle are expressed as several generalized sequences with a certain basis.
New equivalence principle: Symmetry is equivalent to uncertainty, specifically, the transformation symmetry of constituent elements is equivalent to the uncertainty of particles.
We consider a quantum system which includes metric tensor $g_{\mu\nu}$ and gravitational tensor $\varphi^{\mu\nu}$ and scalar θ obeying Einstein's equation and linear gravitational field equation and Klein-Gordon equation, respectively. We assume that the linear gravitational field equation is an independent field equation instead of merely the weak field approximation of the Einstein equation. And, based on the quantized mathematics, we can define these equations on the set of discrete numbers. Then, we assume that the quanta of time and space and the quanta of energy have positive and negative signs "＋" and "－" , as well as real and imaginary units "1" and "i". According to the combination of quantum time and quantum space signs and units, we define the corresponding quantum space-times, and stipulate that quantum energy and quantum space-time have the same unit, and quantum energy and quantum space have the same sign. We note that the Einstein equation as well as linear gravitational field equation and Klein-Gordon equation have the symmetry of space-time sign and unit transformations.
We find that there are scalar particles obeying the Klein-Gordon equation, and the symmetry of the Klein-Gordon equation implies the uncertainty of scalar particles. On the one hand, the energy-momentum tensor of scalar particles in flat space-time can be mapped to curved spacetime, and it specifies the source tensor of Einstein's equation, which represents the geometric self-coupling or self-action of the particle system. Since the metric field $g_{\mu\nu}$ has the symmetry of real and imaginary quantum spacetime units as well as positive and negative quantum space signs, the particles have the uncertainty of the corresponding quantum space-times. And, if $g_{\mu\nu}$ has four-dimensional spatial rotational symmetry, the particles also have the uncertainty of the four-dimensional quantum space-times of given signs and unit. On the other hand, the energy-momentum tensor of scalar particles with quantum space-time symmetry can be mapped to a four-dimensional quantum space-time, and it specifies the source tensor of the linear gravitational field equation, which represents the geometric mutual coupling or interaction between particles. Only when the linear gravity breaks the symmetry of spacetime geometry, can the particles have the definite sign and unit of quantum energy as well as a definite four-dimensional quantum spacetime. Correspondingly, in addition to

representing the quantum correlations of scalar particles, the Klein-Gordon equation can be extended to include the effects of gravitational fields on the particles. It is also noted that Einstein's equation has local spacetime transformation symmetry, and the metric field $g_{\mu\nu}$ specifies the curvature of overall spacetime and endows it with local flatness; the linear gravitational field equation has global spacetime transformation symmetry, and the gravitational field $\varphi^{\mu\nu}$ defines the scale of partial space-time and endows it with local inhomogeneity and anisotropy. Moreover, the uncertainty of particles is governed by their quantum correlations. Only the combination of $g_{\mu\nu}$ and $\varphi^{\mu\nu}$ together with θ can give a particle system that constitutes the main matter of the universe.

Based on this theoretical system, the Friedmann universe solutions in two sets of quantum space-times with positive and negative time quanta respectively can be derived. The solutions constitute a periodic Friedmann universe with alternating positive and negative time lapse, and form the cosmic spacetime background of ordinary matter. The ground-state particles with the constituent elements of respective internal parameters can also be obtained, and they constitute the quantum vacuum background of the excited-state particles. Furthermore, the black hole solution is obtained. Its interior is composed of C scalar particles, which are merged into one scalar particle and coupled to the discrete Friedmann spacetime. The mapping of the scalar particle energy on a three-dimensional sphere constitutes the quantum gravitational charge, while its outside is broken into the discrete Schwarzschild spacetime, and forms a gravitational field in local flat spacetime. The dark matter particles with similar spacetime geometry and field structure is also obtained. In particular, the quantum combinations of excited-state particles and ground-state particles make the obtained matter structures constitute finite quantum systems that obey the uncertainty principle. According to this theory, matter particles can exist in different quantum space-times and form a particle system with geometric self-coupling, while only gravitational charges in the same four-dimensional quantum spacetime have gravitational interactions. In addition, the gravitons emitted by the matter particle system with asymmetry are the result of the conversion from internal scalar particles to external tensor particles and the geometric mutual coupling between the tensor particles.

The derived solutions of the universe and black hole, as well as the solutions of ground-state particles and dark matter particles, show that the energy originates from the scalar field. The scalar particles that make up the Friedman universe or ground-state particles have sufficiently large energy densities to form closed spacetime geometries, and the energy densities of the scalar particles that make up black holes or dark matter particles form open spacetime geometries. In addition, the energy-momentum tensor of $g_{\mu\nu}$ has the inverse sign of its source tensor, and the two tensors cancel each other so that the energy-momentum tensor in curved space-time is zero. The gravitational tensor generated by the gravitational charge of a scalar particle has no energy. Only the gravitational tensor of graviton carries energy which is determined by the energy of its corresponding source scalar particle and the geometric self-coupling of the particle system.

Based on the obtained universe solution and introduction of the absorption effect of vacuum on electromagnetic waves caused by electromagnetic interaction, the luminosity distance formula can be derived, and its red-shift curve is consistent with the existing supernovae observations.

The results of this paper show that the quantization of mathematics is the premise and foundation of the establishment of quantum gravity theory. This theory extends the geometry and gravity as well as quantum energy and quantum spacetime, and reveals the different properties of geometry and gravity and their intrinsic connections. It also achieves the compatibility of relativity with quantum mechanics. It encompasses the theoretical results of general relativity that are consistent with experimental observations, whilst providing a possible way to solve a series of important physical problems, including gravitational singularity, vacuum catastrophe, dark energy and dark matter, the uniformity of the universe, the wave-particle duality of elementary particles, and the quantization of energy and spacetime, etc.

The stability of charged black holes

Elena Giorgi
Columbia University

Black hole solutions in General Relativity are parametrized by their mass, spin and charge. In this talk, I will motivate why the charge of black holes adds interesting dynamics to solutions of the Einstein equation thanks to the interaction between gravitational and electromagnetic radiation. Such radiations are solutions of a system of coupled wave equations with a symmetric structure which allows to define a combined energy-momentum tensor for the system. Finally, I will show how this physical-space approach is resolutive in the most general case of Kerr-Newman black hole, where the interaction between the radiations prevents the separability in modes.

Spherically symmetric Einstein-scalar-field equations for wave-like decaying null infinity

Chuxiao Liu
Guangxi University

In this talk, we will discuss the spherically symmetric Einstein-scalar field equations for wave-like decaying initial data at null infinity. We show that there exists a unique global solution in $(0, \infty)$ and unique generalized solution on $[0, \infty)$in the sense of Christodoulou. This is a joint work with my supervisor Xiao Zhang.

Formal Existence of Friedmann-Static Pure Radiation Shock Waves

Christopher Alexander
University of California, Davis

This talk concerns the construction and analysis of a new family of exact general relativistic shock waves. The construction resolves the open problem of determining the expanding waves created behind a shock wave explosion into a static isothermal spacetime with an inverse square density and pressure profile. The construction involves matching two self-similar families of solutions to the perfect fluid Einstein field equations across a spherical shock surface. The matching is accomplished in Schwarzschild coordinates where the shock waves appear one derivative less regular than they actually are. Separately, both families contain singularities, but as matched shock wave solutions, they are singularity free. There was no guarantee ahead of time that the matching of the two families could be achieved

within the regions where both families are non-singular. Indeed, for pure radiation equations of state, the matching occurs very near the singular point of the interior expanding wave, and this makes the analysis quite delicate, both numerically and formally. It is for this reason the construction is accompanied by a novel existence proof in the pure radiation case. The formal analysis is extended to demonstrate Lax stability in the pure radiation case and provide a criterion for stability in all other cases. These shock wave solutions represent an intriguing new mechanism in General Relativity for exhibiting accelerations in perturbed Friedmann spacetimes, analogous to the accelerations modelled by the cosmological constant in the Standard Model of Cosmology. However, unlike in the Standard Model of Cosmology, these shock wave solutions solve the Einstein field equations in the absence of a cosmological constant, opening up the question of whether a purely mathematical mechanism could account for the cosmic acceleration observed today, rather than dark energy.

A new instability for higher dimensional black holes

Gabriele Benomio
Princeton University

In contrast with the classical stability of stationary, asymptotically flat vacuum black holes in four dimensions, some families of higher dimensional black holes suffer from dynamical instabilities. I will discuss a new nonlinear instability which is expected to affect a wide class of higher dimensional black holes. This instability is, in a sense, more fundamental than the other known instability phenomena in higher dimensions and can be related to a precise geometric property of the class of spacetimes considered.

Mode stability for Kerr black holes

Rita Teixeira da Costa
Princeton University

The Teukolsky master equations are a family of PDEs describing the linear behavior of perturbations of the Kerr black hole family, of which the wave equation is a particular case. As a first essential step towards stability, Whiting showed in 1989 that the Teukolsky equation on subextremal Kerr admits no exponentially growing modes. In this talk, we review Whiting’s classical proof and a recent adaptation thereof to the extremal Kerr case. We also present a new approach to mode stability, based on uncovering hidden spectral symmetries in the Teukolsky equations. Part of this talk is based on joint work with Marc Casals (CBPF/UCD).

Killing-Hopf horizons of the Petrov type D

Jerzy Lewandowski
University of Warsaw

Killing horizons (to the second order) whose null generators have the structure of a non-trivial U(1) bundle over a 2 dimensional compact Riemann space are investigated. Their geometries are constrained by vacuum Einstein's equations with arbitrary cosmological constant and by the Petrov type D of the Weyl tensor, both conditions being assumed at the horizons only. For higher genus of the 2 manifold, all the smooth solutions are derived. For the 0 genus, all the axisymmetric solutions are found and all the non rotating ones. A comparizon with horizons contained in the Kerr-NUT-(Anti)-de-Sitter spacetimes [2] leads to relaxation of the regularity conditions and intriguing special cases. This work is a continuation of the research on the Petrov type D horizons [1,3,4,5]. In the trivial bundle case, horizons defined quasilocally satisfy theorems similar to those of the global black hole theory: topological censorship, the rigidity and no-hair property.

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Black holes: the inside story of the gravitational collapse

Maxime C. Van De Moortel
Princeton University

What does the interior of a dynamical black hole look like? While the exterior relaxes to a Kerr spacetime, the interior has a qualitatively different geometry typically featuring a singularity.
I will discuss the known mathematical results in the interior of dynamical black holes and their deep connections to the issue of determinism in classical General Relativity and Penrose's Strong Cosmic Censorship Conjecture.
The main highlight is the surprising result that the dynamical interior exhibits both a null Cauchy horizon and a crushing singularity. This is due to a new phenomenon: "the breakdown of weak null singularities" -- which I proved in spherical gravitational collapse -- that conjecturally also holds without the symmetry restriction.

The interaction of gravitational waves from several localized sources

Federico Pasqualotto
Duke University

In this talk I will describe a research program aimed at understanding the interaction of gravitational waves originating from multiple localized and distant sources. This draws motivation from the problem of interaction of several localized bodies in general relativity.
I will focus on the simplified interaction problem of multiple nonlinear waves, restricting attention to a model problem. I will show how one can take advantage of the specific geometric configuration to control the interaction. I will then describe the relevant directions in the context of general relativity.

Double Null Data and the Characteristic Problem in General Relativity

Gabriel Sánchez Pérez
University of Salamanca

General hypersurfaces of any causal character can be studied abstractly within the hypersurface data formalism. In the null case we write down all tangential components of the ambient Ricci tensor in terms of the abstract data generalizing the null structure equations (which can be recovered in the appropriate gauge). The formalism allows to identify in a completely abstract way the characteristic initial value problem of the Einstein vacuum field equations. The boundary data is fully detached from the spacetime and it is fully diffeomorphism and gauge covariant. Our result puts the characteristic initial value problem on a similar footing as the standard Cauchy initial value problem for the Einstein field equations.

Fefferman-Graham obstruction tensor and Einstein's equations

Wojciech Kaminski
University of Warsaw

Vanishing of the Fefferman-Graham obstruction tensor was proposed by Anderson and Chrusciel as a tool for studying asymptotically simple solutions to Einstein’s equations. The equation is an alternative for a known Friedrich’s construction of conformal version of Einstein’s equations. However, proving well-posedness of this equation is nontrivial due to multiple characteristics of the gauge fixed principal symbol. It turns out that there is a special structure due to the ambient metric behind the equation, which improves its property. This structures is shared by other tensors obtained by the ambient metric constructions like GJMS operators etc. (arxiv: 2108.08085)

Testing the Geometric Surface Conjecture for Rotating Traversable Wormholes

John Joseph Marchetta
Baylor University

Geometric horizons provide a way to identify physically significant quasi-local surfaces, such as a dynamical wormhole throats or black hole horizons, in a foliation independent way. This

is done by determining where a set of scalar polynomial curvature invariants or Cartan invariants vanishes. Geometric horizons, however, do not, at the level of vanishing invariants, distinguish between black hole boundaries and wormhole throats. The recent geometric surface conjecture distinguished the two surfaces by imposing an additional set of inequalities on the curvature invariants. Despite success for Petrov type II/D spacetimes, the known inequalities are insufficient to fully identify and classify the throat in the case of the rotating traversable wormhole discovered by Edward Teo. In this talk we will describe potential methods to identify and classify this surface.

Stable Big Bang formation

Grigorios Fournodavlos
Department of Mathematics, Princeton University

In this talk we will investigate the past dynamics of cosmological solutions to Einstein's equations, containing a Big Bang singularity. More precisely, we will focus on the classical generalised Kasner examples. The celebrated ``singularity" theorem of Hawking tells us that the past of sufficiently small perturbations of such solutions are causally geodesically incomplete. However, it is not in general known whether such a degeneracy is related to the formation of a curvature singularity. In many cases, unstable dynamics are predicted, which add to the difficulty of the problem. I will present joint work with I. Rodnianski and J. Speck that classifies the behavior of perturbed solutions in the so-called subcritical regime.

Hyperbolic Energy and Gluings of Initial Data

Raphaela Wutte
TU Wien

The question of boundedness of energy from below in general relativity for negative cosmological constant is wide open. For time-symmetric initial data sets, this is the question of whether the energy of asymptotically locally hyperbolic spaces is bounded from below. After giving a short review of the currently known bounds, I describe the construction of asymptotically locally hyperbolic spaces with constant negative scalar curvature, arbitrary high genus, and negative total mass.

Classification of five-dimensional black holes from integrability

James Lucietti
University of Edinburgh

The classification of stationary black hole spacetimes is a major open problem in higher-dimensional General Relativity. I will report on recent progress in this direction for five-dimensional, asymptotically flat, vacuum black holes with two commuting axial symmetries, which is a symmetry class of solutions that arise as the integrability condition of an auxiliary

linear system. I will show that this linear system can be exploited to determine the moduli space of black hole solutions that are free of conical singularities on the axes. As examples, we obtain constructive uniqueness proofs for the Myers-Perry black holes and the known doubly spinning black rings. We also use this method to demonstrate the nonexistence of the simplest class of black holes with lens space horizon topology.

Instability of gravitational and electromagnetic perturbations of Extremal Reissner-Nordstr"om spacetime

Apetroaie Marios Antonios
University of Toronto

In a series of papers, Elena Giorgi proved linear stability to gravitational and electromagnetic perturbations for the full subextremal range $|Q| < \mathrm{M}$ of Reissner-Nordstr"om spacetimes as solutions to the Einstein-Maxwell equations. In this thesis, we study the aforementioned problem for the extremal $|Q| = \mathrm{M}$ Reissner-Nordstr"om spacetime, and contrary to the subextremal case we prove that instability results hold for a gauge invariant hierarchy along the event horizon H. In particular, depending on the number of translation invariant derivatives of derived gauge-invariant quantities, we prove decay, non-decay and polynomial blow up estimates asymptotically along H. As a consequence, we show that for generic initial data, solutions to the generalized Teukolsky system of spin ± 2 and spin ± 1 satisfy analogous estimates.

Extreme Black Holes: Anabasis and Accidental Symmetry

Achilleas Porfyriadis
Harvard University

The near-horizon region of black holes near extremality is universally AdS_2-like. In this talk I will concentrate on the simplest example of $AdS_2 \times S^2$ as the near-horizon of (near-)extreme Reissner-Nordstrom. I will first explain the SL(2) transformation properties of the spherically symmetric linear perturbations of $AdS_2 \times S^2$ and show how their backreaction leads to the Reissner-Nordstrom black hole. This backreaction with boundary condition change is called an anabasis. I will then show that the linear Einstein equation near $AdS_2 \times S^2$, with or without additional matter, enjoys an accidental symmetry that may be thought of as an on-shell large diffeomorphism of AdS_2.

A3: Alternative and modified theories of gravity (Chair: Shinji Mukohyama, Coordinator: Yu-Xiao Liu)

Well-Posed Formulation of Scalar-Tensor Effective Field Theory

Aron Kovacs
SISSA, Trieste

Effective field theory provides a way of parametrizing strong-field deviations from general relativity that might be observable in the gravitational waves emitted in a black hole merger. To perform numerical simulations of mergers in such theories it is necessary that the equations be written in a form that admits a well-posed initial value formulation. We study gravity coupled to a scalar field including the leading (four-derivative) effective field theory corrections. We introduce a new class of “modified harmonic” gauges and gauge-fixed equations of motion, such that, at weak coupling, the equations are strongly hyperbolic and therefore admit a well-posed initial value formulation.

Constraining fundamental properties of boson stars through their multipole moments

Massimo Vaglio
Sapienza University of Rome

Boson stars stand out as one of the best motivated models of exotic horizonless stellar objects, which could represent a new family of astrophysical compact sources, together with black holes and neutron stars, to be observed by future gravitational waver detectors. During the talk I will present the results of a new study aimed to investigate the equilibrium solutions of a class of fast rotating, self-interacting, boson stars. I will focus on the non-trivial multipolar structure induced by the rotation, discussing the dependence of the multipole moments on the stellar mass and spin. I will show how such relativistic multipole moments, which are a key ingredient to describe the orbital evolution of a binary system, can be used to construct inspiral waveform templates, to perform parameter estimation and to constrain the boson star fundamental properties with future observations by ground and space interferometers.

Extreme Mass Ratio Inspirals as probes of scalar fields

Susanna Barsanti
Sapienza University of Rome

Extreme Mass Ratio Inspirals (EMRIs), binary systems in which a stellar mass compact object inspiral into a massive black hole (MBH), are among the primary targets for LISA, as they harbour the potential for precise gravity test. Although the description of these systems in modified theories of gravity can be dramatically complex, for a vast class of theories with additional scalar fields great simplifications occur. First, the MBH scalar charge is strongly

suppressed, so that the background spacetime is simply described by the Kerr metric. Moreover, all information about the underlying gravity theory turns out to be encoded in the inspiralling body's scalar charge. In this talk I will show how, for these theories, the surviving charge strongly affects the binary dynamics, accelerating its coalescence and leaving an imprint on the emitted gravitational waves. By analyzing such signals, I will finally present the extremely promising results on the LISA's detectability of the scalar charge, which render EMRIs encouraging probes of gravity and of new fundamental fields.

Leakage of gravitational waves into extra dimension in DGP model

Mikhail Khlopunov
Lomonosov MSU & ITMP MSU

In the DGP model, the graviton is unstable, which leads to a modification of gravity at cosmological distances. In particular, this leads to the leakage of gravitational waves from the brane into an extra dimension at large distances from the source. However, the calculation of the gravitational wave leakage intensity is a non-trivial task due to the violation of the Huygens principle in the five-dimensional bulk of the DGP setup. The odd dimension of the bulk makes it difficult to isolate the radiated part of the field. In this paper, we consider a simplified problem of scalar radiation from a point charge localized on a brane in the framework of the scalar analog of the DGP model.

In this model, the scalar field on the brane can be represented as a continuous spectrum of Kaluza-Klein massive modes. To isolate the emitted part of such a field, we generalize the Rohrlich-Teitelboim approach to radiation to the case of a massive four-dimensional field, using its connections to massless fields in four and five dimensions. In the case of a charge moving along a circular trajectory, we obtain the dependence of the radiation energy flux through a 2-sphere localized on the brane on the radius of the sphere, which allows to calculate the intensity of leakage of scalar radiation from the brane. Consistent with the infrared transparency of the brane, the leakage intensity is found to be higher for low frequency signals. We are also analyzing the possibility of detection of this leak by current and future gravitational wave observatories.

Gravitational waves in bimetric gravity

Araceli Soler-Oficial
University of the Basque Country (UPV/EHU)

We study the propagation of gravitational waves in bimetric gravity in a homogeneous and isotropic cosmological background with non-zero spatial curvature. In particular, we analze in detail the evolution of sub-horizon and super-horizon tensor modes in the limit of small interactions and for a background with a general equation of state. To keep our analysis as general as possible, we do not assume any specific values for the parameters of the theory in the derivation of approximate analytical solutions.

Scalar Perturbations and Stability of a Loop Quantum Corrected Kruskal Black Hole

Ramin Daghigh
Metropolitan State University

We investigate the massless scalar field perturbations of a new loop quantum gravity motivated regular black hole proposed by Ashtekar et al. in [Phys. Rev. Lett. 121, 241301 (2018), Phys. Rev. D 98, 126003 (2018)]. The spacetime of this black hole is distinguished by its asymptotic properties: in Schwarzschild coordinates one of the metric functions diverges as $r \to \infty$ even though the spacetime is asymptotically flat. We show that despite this unusual asymptotic behavior, the quasinormal mode potential is well defined everywhere when Schwarzschild coordinates are used. We propose a useful approximate form of the metric, which allows us to produce quasinormal mode frequencies and ringdown waveforms to high accuracy with manageable computation times. Our results indicate that this black hole model is stable against massless scalar field perturbations. We show that, compared to the Schwarzschild black hole, this black hole oscillates with higher frequency and less damping. We also observe a qualitative difference in the power-law tail of the ringdown waveform between this black hole model and the Schwarzschild black hole. This suggests the quantum corrections affect the behavior of the waves at large distances from the black hole.

Enlightening Cold Dark Matter's darkest side

Giovanni Gandolfi
SISSA

The cold dark matter (CDM) paradigm has proven to be relatively successful on cosmological scales, but struggles in fully describing the observed phenomenology on (sub)galactic scales. In this picture, two long-standing issues are the well-known cusp-core controversy and the existence of several tight scaling laws between dark and baryonic quantities, whose explanation is not trivial in the CDM framework. In this talk, I will entail the possibility that CDM could be dynamically non-minimally coupled to gravity, and how such effect has the potential to solve these issues in a single shot. After outlining the theoretical foundations of the model, I will proceed in discussing quantitative astrophysical results achieved in Gandolfi et al. 2021 and Gandolfi et al. 2022 exploiting this non-minimally coupled DM model. The key findings of our analysis are that a) this model can develop cored dark matter profiles whit a shape closely following out to several core scale radii the phenomenological Burkert profile, b) it can accurately fit the rotation curves of different kinds of local spiral galaxies and c) it can consistently reproduce the Radial Acceleration Relation, one of the most general relations characterizing the dark-baryonic interplay.

Perturbations of spinning black holes beyond General Relativity: Modified Teukolsky equation I

Pratik Wagle
University of Illinois at Urbana Champaign

The detection of gravitational waves from compact binary mergers by the LIGO/Virgo collaboration has, for the first time, allowed us to test relativistic gravity in its strong, dynamical and nonlinear regime, thus opening a new arena to confront general relativity (and modifications thereof) against observations. However, when considering modifications to General Relativity, spinning black holes may be different from their general relativistic counterparts, and can thus serve as probes of these theories. To study perturbations of these black holes, we modify the Teukolsky formalism to obtain a set of linear decoupled differential equations that describe dynamical perturbations of black holes. In this talk, I will first present the modified Teukolsky formalism and the equations of the dynamical perturbations for Petrov type D spacetimes in modified gravity theories. One can then extend this to any spacetime which is a linear perturbation of a Petrov type D spacetime, including the algebraically general Petrov type I spacetimes, in theories beyond general relativity. Such a formalism paves the way for calculation of quasinormal modes of black holes beyond General Relativity.

Perturbations of spinning black holes beyond General Relativity: Modified Teukolsky equation II

Dongjun Li
Caltech

Linear gravitational perturbations of Kerr black holes in general relativity are most efficiently treated by the Teukolsky formalism, which leads to single decoupled equations for Weyl scalars psi0 and psi4. These equations are further separable into radial and angular equations. The standard derivation of the Teukolsky equation in general relativity required the background spacetime to be algebraically special (Petrov type D). In beyond-General-Relativity (bGR) theories, for example, dynamical Chern-Simons (dCS) and Einstein-dilaton Gauss-Bonnet (EdGB) theories, spacetimes of rotating black holes are not type-D, but type-I instead. This lack of symmetry creates potential difficulties in computing gravitational waveforms in bGR theories. In this work, for any stationary background spacetime with an order epsilon deviation from a Petrov type-D spacetime, we obtain a single decoupled modified Teukolsky equation for the perturbative psi0 (and psi4) of that spacetime --- accurate up to linear order in epsilon. This equation may also have a source term on the right-hand side due to matter (including, e.g., dCS and EdGB scalar-field) perturbations. Our derivation is an extension of Chandrasekhar's alternative derivation of the Teukolsky equation and his metric reconstruction procedure (both originally formulated for the Kerr spacetime). For demonstration, we apply our formalism to perturbations of slowly-rotating black holes in dCS gravity. In this case, psi0 (and psi4) are decoupled from all other space-time degrees of freedom, and only couple to the dCS scalar field, which arises due to the source term of the modified Teukolsky equation.

Gravitational-wave polarizations in generic higher-curvature gravity

Tomoya Tachinami
Hirosaki University

We study the polarizations of gravitational waves (GWs) in generic higher-curvature gravity (HCG) whose Lagrangian is an arbitrary polynomial of the Riemann tensor. On a flat background, the linear dynamical degrees of freedom in this theory are identified as massless spin-2, massive spin-2, and massive spin-0 fields. Employing a fully gauge-invariant formalism, we demonstrate that (i) the massless spin-2 is the ordinary graviton with 2 tensor-type (helicity-2) polarizations, (ii) the massive spin-2 breaks down into 2 tensor-type (helicity-2), 2 vector-type (helicity-1) and 1 scalar-type (helicity-0) polarizations, and (iii) the massive spin-0 provides 1 scalar-type (helicity-0) polarization. Therefore, GWs in generic HCG exhibit 6 massive polarizations on top of the ordinary 2 massless ones. In particular, we find convenient representations of the scalar-polarization modes connected directly to the theory parameters of HCG. They are utilized to discuss methods to determine the theory parameters by GW-polarization observations.

Massive tensor modes carry more energy than scalar modes in quadratic gravity

Avijit Chowdhury
Indian Institute of Technology Bombay

Over the last two decades, motivations for modified gravity have emerged from both theoretical and observational levels. Because f(R) gravity is the most straightforward generalization, it has received more attention. However, f(R) gravity contains only the scalar degree of freedom and hence does not contains other modifications of a modified gravity theory. On the other hand, quadratic gravity (also referred to as Stelle gravity) is the most general second-order modification to general relativity and contains massive tensors that are not present in f(R) gravity. We explicitly show that massive tensor modes carry more energy than scalar modes using two different physical settings by evaluating the energy flux of the gravitational waves as measured by an asymptotic observer and the backreaction of the gravitational waves on a Schwarzschild black hole. Thus, we show that the leading order gravitational radiation correction in Stelle gravity is linear in the coupling constant compared to f(R), where the corrections are quadratic in flat space-time.

Memory effects in radiative spacetimes: A study in Eddington-inspired Born-Infeld gravity

Indranil Chakraborty
Indian Institute of Technology Kharagpur

A permanent offset caused by the passage of a gravitational wave pulse, known as the memory effect, is under active research in both theoretical and observational aspects of gravitational physics. Understanding this effect for exact radiative solutions in General Relativity (GR) have received considerable attention lately. Generally, one can arrive at these effects by studying the separation of pairs of geodesics in such spacetimes. Radiative geometries such as Kundt waves have been shown to possess distinct memory behavior. In this talk, we discuss our recent work in the newly proposed determinantal theory of gravity known as Eddington-inspired Born-Infeld (EiBI) gravity. Constructing exact solutions of

Kundt waves for two different matter sources in this theory, we investigate memory by analysing both geodesics and geodesic deviation. Our study reveals significant differences in memory effects obtained for different kinds of matter sources, thereby bringing out some of the characteristic features of EiBI theory.

Gravitational waveforms from the inspiral of compact binaries in scalar-tensor theory

Tan Liu
HUST

Scalar-tensor theory is an extension of general relativity with a scalar field. In addition to the two tensor polarizations, plus polarization and cross-polarization, which already exist in general relativity, the scalar field can introduce extra polarization(s). I will briefly review the development of the calculation of the gravitational waveforms emitted by an inspiralling binary system in scalar-tensor theory and introduce our contribution.

Constraints on the multipole structure of compact binaries using GW190412 and GW190814

Parthapratim Mahapatra
Chennai Mathematical Institute

Nonlinear interactions between multipole moments of a compact binary leads to several intriguing physical effects which are encoded in the gravitational waveform. Strong evidence of non-quadrupolar multipoles are seen only in GW190412 and GW190814, two binary black holes observed during the first half of the third observing run. These two events, therefore, provide a unique opportunity to test the consistency of non-quadrupolar modes with the predictions of general relativity. We present an analysis which shows consistency of mass octupole, first subdominant multipole, with the predictions of general relativity for GW190412 and GW190814. The joint bound on the mass type octupole moment parameter $\delta\mu_3$, which characterizes its deviation from GR, at 90% credibility to $\delta\mu_3=-0.06_{-0.13}^{+0.11}$. With enhanced sensitivity of gravitational wave observatories in the future observing runs, detection of binaries whose orbits are not aligned with the line of sight could facilitate further tests of general relativity with higher multipoles.

Shadow of a nonsingular black hole

Wen-Di Guo
Lanzhou University

Seeking singularity free solutions are important for further understanding black holes in quantum level. Recently, a five-dimensional singularity free topology star/black hole was constructed [Phys. Rev. Lett. 126, 151101 (2021)]. Through the Kaluza-Klein reduction, an effective four-dimensional static spherically symmetric nonsingular black hole can be obtained. In this paper, we study shadow of this nonsingular black hole using three kinds of observers, i.e. static observers, surrounding observers, and freely falling observers, in four-dimensional spacetime. For a spherically symmetric black hole, the shadow is circular for any observer, but the shadow size depends on the motion status of the observer. The shadow size observed by a moving observer will tend to be shrunk. On the other hand, the effect of plasma is also investigated by a simple model. The radius of the photon sphere depends on the plasma model. Most importantly, we find that the shadow sizes do not monotonically decrease with r in some cases. This is a typical phenomenon for this nonsingular black hole.

Multiparameter tests of general relativity using compact binary coalescences

Sayantani Datta
Chennai Mathematical Institute

The inspiral phase of the gravitational wave (GW) signal from a binary black hole is well described by the post-Newtonian (PN) theory of general relativity. The PN coefficients in the inspiral phase encapsulate various nonlinear interactions and physical effects in GR. One can measure these PN coefficients to check for their consistency with GR. However, to get meaningful bounds and map them onto some modified theories of gravity, one needs to perform multiparameter tests of GR, where parametrized deviations from GR at multiple PN orders are simultaneously measured. We show that the multi-band observations of GWs from stellar-mass and intermediate-mass binary black holes by third-generation (3G) ground-based detectors such as Cosmic Explorer (CE) and a space-based detector such as LISA is the only way to constrain PN deviations from GR at all PN orders, simultaneously. However, this test will only be possible around the mid-2030s, when ground-based and space-based detectors are both functional. We propose an alternative way where we use the method of principal component analysis (PCA) to optimize multiparameter tests of GR, by constructing best-measured, linear combinations of multiple PN deviations. Using some events detected during the first and second observing run of Advanced LIGO and Virgo, we show that the most dominant PCA parameter is well consistent with GR. It can recover simulated beyond-GR values with good precision and exclude GR with high confidence. We also find that CE can constrain the two most dominant PCA parameters (out of eight) with a 1σ bound of $\sim O(10^{-3})$. We get the best results from LISA, which can constrain the five most dominant PCA parameters to ≤ 0.1, with the leading one to $\sim O(10^{-5})$. Such precise measurement of the PCA parameters makes it an excellent probe to test the entire PN structure of the GW phasing. This PCA-assisted test of GR also significantly reduces the computational cost compared to the standard method where one carries out eight independent tests of GR, varying only one of the PN deviation parameters at a time.

Statistically separating the modified effects of gravitational-wave generation and propagation

Atsushi Nishizawa
The University of Tokyo

When a gravity theory is modified, the properties of gravitational waves (GWs) are also modified. So far many tests of GW generation and propagation have been performed and given the constraints on the possible deviations from general relativity. However, those tests have been performed separately under the assumption that one of them is modified. In this talk, we take into account both modifications of GWs at the same time and show that the degeneracy can be broken by analyzing multiple sources at the same time because the generation effect is independent of propagation distance but the propagation effect is proportional to source distance. Generating a mock catalog of compact binaries distributed randomly in redshifts (with constant merger rate), we for the first time estimate the number of sources necessary to break the degeneracy and the resultant measurement errors of the model parameters.

Observational constraint on axion dark matter with propagating gravitational waves

Takuya Tsutsui
University of Tokyo

Although we have understood matters around us, most of matters in the Universe is unknown, which is called dark matter. Many candidates have been considered. A candidate of dark matter is axion which is a very interesting theoretically-motivated particle: Axions form clouds and amplify and delay a part of gravitational waves propagating in the clouds. Fortunately the Milky Way is surrounded with the dark matter halo which should be composed of axion patches. Thus, the characteristic secondary gravitational waves can be expected right after the reported gravitational waves from binary mergers. In this talk, we searched the characteristic gravitational waves with a method optimized for the time delay and the signal duration around GW170814, GW170817, GW190728, GW200202 and GW200316. Then, we constrained the axion coupling to the parity violating sector of gravity, which is at most ∼10 times stronger for [1.65 × 10^−13 , 8.47 × 10^−12] eV than that obtained from Gravity Probe B.

Search for mixture of scalar-tensor polarizations of gravitational waves

Hiroki Takeda
Kyoto University

An additional scalar degree of freedom for a gravitational wave is often predicted in theories of gravity beyond general relativity and can be utilized for a model-agnostic test of gravity. We report the direct search for the scalar-tensor mixed polarization modes of gravitational waves from compact binaries in a strong regime of gravity by analyzing the data of GW170814 and GW170817, which are the merger events of binary black holes and binary neutron stars, respectively. Consequently, we obtain the constraints on the ratio of scalar-mode amplitude to tensor-mode amplitude, which are the tightest constraints on the scalar amplitude in a strong regime of gravity before merger.

Gravitational Wave constraints on Gravitational Effective Field Theories

Haoyang Liu
University of Chinese Academy of Sciences

Gravitational waves provide a powerful tool to probe the strong gravity regime, allowing us to test general relativity (GR) and to search for new physics in the fundamental UV complete theory of gravity. In this work, we employ the effective field theory framework, under which all potential UV effects on the low energy gravity are systematically described by the high dimension operators, and perform tests of GR using the gravitational wave signals observed by LIGO and Virgo. Specifically, we construct the inspiral waveform template in a general effective field theory of gravity, in which case the leading corrections to the GR waveform come from the dimension-6 operators. By analyzing the binary black hole merger events GW151226 and GW170608, as well as the binary neutron star merger event GW170817, we impose the first constraints on the dimension-6 operators and the cut-off scale of the gravitational effective field theory. Our results indicate that new physics on energy scales around 10^{-12} eV is disfavored by the current gravitational wave observations.

Horndeski theory in Palatini formalism: polarizations of gravitational waves

Yu-Qi Dong
Lanzhou University

This presentation will report the polarization modes of gravitational waves in Palatini-Horndeski theory. After obtaining the linearized equation of perturbations in Minkowski background, we find that the polarization modes of gravitational waves depend on the selection of the theoretical parameters. The polarization modes can be divided into quite rich cases by parameters. In all cases of parameter selection, there are + and × modes propagating at the speed of light but no vector modes. The only difference from general relativity is scalar modes, especially the scalar degrees of freedom can be 0, 1 or 2 in different cases. The appropriate parameter cases can be expected to be selected in the detection of gravitational wave polarization modes by Lisa, Taiji and TianQin in the future.

Affine Connections, Quantum Gravity and Modified Theories of Gravity

Kaushik Ghosh
Vivekananda College, University of Calcutta

In this manuscript, we will discuss the construction of covariant derivative operator in quantum gravity. We will find it is more perceptive alternative to use affine connections more general than metric compatible connections in quantum gravity. We will demonstrate this using the canonical quantization procedure. This is valid irrespective of the presence and nature of sources. The conventional Palatini and metric-affine formalisms, where the actions are linear in the scalar curvature with metric and affine connections being the independent variables, are not much suitable to construct a source-free theory of gravity with general affine connections. This is also valid for many minimally coupled interacting theories where

sources only couple with metric by using the Levi-Civita connections exclusively. We will discuss potential formalism of affine connections to introduce affine connections more general than metric compatible connections in gravity. We will also discuss possible extensions of the actions for this purpose. General affine connections introduce new fields in gravity besides metric. In this article, we will consider a simple potential formalism with symmetric affine connections and symmetric Ricci tensor. Corresponding affine connections introduce only two massless scalar fields. One of these fields contributes a stress-tensor with opposite sign to the sources of Einstein's equation when we state the equation using the Levi-Civita connections. This means we have a massless scalar field with negative stress-tensor in Einstein's equation. These scalar fields can be useful to explain dark energy and inflation. These fields bring us beyond strict local Minkowski geometries.

Parity Violation in Spin-Precessing Binaries: Gravitational Waves from the Inspiral of Black Holes in Dynamical Chern-Simons Gravity

Nicholas Loutrel
Sapienza University of Rome

Spin precession is intricately tuned to the multipole structure of the underlying bodies. Violations of the no-hair theorems due to modifications of general relativity will modify the precession dynamics of black hole binaries, which is imprinted in the amplitude and phase modulation of the emitted gravitational waves. Using techniques developed to analytically study spin precessing binaries in general relativity, we construct analytic solutions to the spin precession equations in dynamical Chern-Simons (dCS) gravity, a parity violating modified theory of gravity. We further compute the analytic Fourier domain waveform for the inspiral phase of the binary coalescence, and discuss the possibility of inspiral-merger-ringdown tests of general relativity with spin precessing binaries.

Gravitational memory effects in modified theories of gravity: the case study in Chern-Simons gravity

Shaoqi Hou
Wuhan University

We study the gravitational memory effects in Chern-Simons modified gravity. After solving for the asymptotically flat spacetime, we determine that there are also displacement, spin, and center-of-mass memory effects as in general relativity, given that the Chern-Simons scalar does interact with matter directly. This is because the term of the action that violates the parity invariance is linear in the scalar field but quadratic in the curvature tensor. This results in the parity violation occurring at the higher orders in the inverse luminosity radius. Although there exists the Chern-Simons scalar field, interferometers, pulsar timing arrays, and the Gaia mission are incapable of detecting its memory effects. Using the Wald-Zoupas formalism, the conserved charges for the Bondi-Metzner-Sachs algebra are constructed, and the constraints on memory effects are deduced. These results would be used to predict the waveform of the memory effect.

Testing gravity on all scales

Johannes Noller
University of Portsmouth

Recent years have seen great progress in probing gravitational physics on a vast range of scales, from the very largest cosmological scales to those associated with high energy particle physics. In this talk I will focus on an example of how we can use these different systems synoptically to learn more about dark energy. Specifically, I will discuss the interplay of dark energy constraints from cosmological large scale structure and novel theoretical bounds related to the high energy behavior of gravity.

Modified gravity: a unified approach

Christian Boehmer
University College London

Starting from the original Einstein action, sometimes called the Gamma squared action, we propose a new setup to formulate modified theories of gravity. This can yield a theory with second order field equations similar to those found in other popular modified gravity models. Using a more general setting the theory gives fourth order equations. This model is based on the metric alone and does not require more general geometries. It is possible to show that our new theory and the recently proposed f(Q) gravity models are equivalent at the level of the action and at the level of the field equations, provided that appropriate boundary terms are taken into account. Our theory can also reproduce f(R) gravity, which is an expected result. Perhaps more surprisingly, we show that this equivalence extends to f(T) gravity at the level of the action and its field equations, provided that appropriate boundary terms are taken in account. While these three theories are conceptually different and are based on different geometrical settings, we can establish the necessary conditions under which their field equations are the same. The final part requires matter to couple minimally to gravity. Through this work we emphasize the importance played by boundary terms which are at the heart of our approach.

From Amplitudes to Gravitational Waves: Beyond GR

Mariana Carrillo Gonzalez
Imperial College London

Since the first observation of gravitational waves by LIGO, a large theoretical effort has been made to reach the required precision in waveforms used for detection. Scattering amplitudes techniques have shown to be a promising tool towards reaching this goal. In my talk, I will explain how to obtain classical observables, which can be useful for gravitational wave calculations, from scattering amplitudes. This is done by performing loop calculations that can help us describe physics beyond General Relativity in the inspiral phase of a black hole

binary. More specifically, I will focus on understanding the subtleties of non-minimal couplings and the modifications to the binding energy and periastron advance arising from extra graviton polarizations.

Tidal Deformability of Neutron Stars in Scalar Tensor Theories of Gravity

Stephanie Brown
The Max Planck Institute for Gravitational Physics

Gravitational waves from compact binary coalescence are valuable for testing theories of gravity in the strong-field regime, and binary neutron star mergers are one of the three detected sources of gravitational waves. In this work, we explicitly calculate the fully relativistic $l \geq 2$ magnetic-type and electric-type tidal love numbers for neutron stars in scalar-tensor theories of gravitation. Then we explore how the mass, radius, and tidal deformability relations differ from those of general relativity for multiple equations of state including a family of equations based on Chiral effective field theory. As tidal deformability affects gravitational waveforms and can be measured with gravitational wave detectors, having a precise definition for the tidal deformability is important for parameter estimation of gravitational waves in modified theories of gravity. Gravitational waves from compact binary coalescence are valuable for testing theories of gravity in the strong-field regime. Gravitational waves from binary neutron stars also lead to stringent constraints on the equation of state of matter at extreme densities. In this work, we explicitly calculate the fully relativistic $l \geq 2$ tidal love numbers for neutron stars in scalar-tensor theories of gravitation. Combined with a family of nuclear equations of state based on chiral effective field theory, we explore how the mass, radius, and tidal deformability relations differ from those of general relativity. We aim to apply this to the binary neutron star merger event GW170817 in order to obtain observational constraints on neutron star radius in these modified theories of gravity.

Evolution of binary scalar-hairy black holes

Justin Ripley
University of Cambridge/University of Illinois

Characterizing GW signals requires accurate template waveforms for the inspiral, merger, and ringdown of binary black hole systems. In this talk we will discuss recent work on numerically solving for the dynamics of binary black hole systems in Einstein scalar Gauss-Bonnet (ESGB) gravity. This modified gravity theory can be motivated by effective field theory reasoning, and admits scalar "hairy" black hole solutions. These two facts make it a promising theory to perform model-dependent tests of General Relativity with gravitational wave observations of binary black hole merger. We will discuss how recent advances in mathematical relativity--in particular, the development of the "modified harmonic formulation"--have opened up the possibility of constructing fully nonlinear solutions to the equations of motion of ESGB gravity (in addition to a wider class of scalar-tensor modified theories known as "Horndeski" theories) in numerical relativity. We will discuss recent

progress in numerically solving for the dynamics of binary black hole dynamics in this theory, including the merger phase of binary evolution.

This is the first of two talks; the second will be given by Maxence Corman.

Evolution of binary scalar-hairy black holes II

Maxence Corman
Perimeter Institute

Characterizing GW signals requires accurate template waveforms for the inspiral, merger, and ringdown of binary black hole systems. In this talk we will discuss recent work on numerically solving for the dynamics of binary black hole systems in Einstein scalar Gauss-Bonnet (ESGB) gravity. This modified gravity theory can be motivated by effective field theory reasoning, and admits scalar "hairy" black hole solutions. These two facts make it a promising theory to perform model-dependent tests of General Relativity with gravitational wave observations of binary black hole merger. We will discuss how recent advances in mathematical relativity--in particular, the development of the "modified harmonic formulation"--have opened up the possibility of constructing fully nonlinear solutions to the equations of motion of ESGB gravity (in addition to a wider class of scalar-tensor modified theories known as "Horndeski" theories) in numerical relativity. We will discuss recent progress in numerically solving for the dynamics of binary black hole dynamics in this theory, including the merger phase of binary evolution. This is the second of two talks; the first given by Justin Ripley.

Well-posed formulation of Einstein-Maxwell effective field theory

Iain Davies
University of Cambridge

We consider the well-posedness of the initial value problem for Einstein-Maxwell theory modified by higher derivative effective field theory corrections. Field redefinitions can be used to bring the leading parity-symmetric 4-derivative corrections to a form which gives second order equations of motion. We show that a recently introduced "modified harmonic" gauge condition can be used to obtain a formulation of these theories which admits a well-posed initial value problem when the higher derivative corrections to the equations of motion are small.

Noether charge formalism for Weyl transverse gravity

Marek Liška
Institute of Theoretical Physics, Charles University, Prague

The gravitational Noether charge (Iyer-Wald) formalism has been shown to provide a systematic way to calculate conserved quantities in theories of gravity. The original version applies to local, fully diffeomorphism invariant theories obtaining, as its most known outcome, the Wald entropy formula. In my talk, I introduce an extension of the gravitational Noether charge formalism to local theories of gravity invariant under transverse diffeomorphisms and Weyl transformations. Among these theories, Weyl transverse gravity is of particular interest. It has the same classical solutions as general relativity, but the behavior of the cosmological constant differs. Most notably, its value turns out to be unrelated to the vacuum energy density and radiatively stable. Given these attractive features of Weyl transverse gravity, I discuss the application of our formalism to deriving the first law of black hole mechanics in this theory. Especially, I focus on the contributions coming from the cosmological constant and from possible violations of local energy conservation, which are in principle allowed in Weyl transverse gravity.

New effective temperature of scalar-tensor gravity and its dissipation to general relativity

Valerio Faraoni
Bishop's University

A new approach to modified gravity describes general relativity as its zero-temperature state, while scalar-tensor (including Horndeski) gravity is an out-of-equilibrium state. The ‘temperature of gravity’ and its ‘diffusion’ toward the GR equilibrium are described using Eckart’s thermodynamics for the effective imperfect fluid obtained by rewriting the scalar-tensor field equations as effective Einstein equations. Non-GR equilibrium states are in principle possible. The new formalism has been applied to Horndeski gravity, FLRW cosmology, non-GR (trivial) equilibrium states, and black holes, and shown to remain consistent. These aspects will be briefly reviewed.

[Based on V. Faraoni & A. Giusti 2021, Phys. Rev. D 103, L121501;
V. Faraoni, A. Giusti & A. Mentrelli 2021, Phys. Rev. D 104, 12401;
S. Giardino, V. Faraoni & A. Giusti 20JCAP 04, 053;
V. Faraoni & T.B. Franconnet 2022, Phys. Rev. D 105, 104006]

Thermodynamics of Exotic Black Holes

Brayden Hull
University of Waterloo

We examine the thermodynamics of a new class of asymptotically AdS black holes with non-constant curvature event horizons in Gauss-Bonnet & third order Lovelock gravity, with the cosmological constant acting as thermodynamic pressure. We find that non-trivial curvature on the horizon can significantly affect their thermodynamic behavior. For Gauss-Bonnet gravity we observe novel triple points in 6 dimensions between large and small uncharged black holes and thermal AdS. For charged black holes we find a continuous set of triple points whose range depends on the parameters in the horizon geometry. We also find new generalizations of massless and negative mass solutions previously observed in Einstein gravity. For third order gravity no new thermodynamic phenomena is observed. However, all previously observed phenomena witnessed in the Gauss-Bonnet case will be present.

Charged black holes in Einsteinian cubic gravity and nonuniqueness

Jorge Rocha
Iscte - Instituto Universitario de Lisboa

A well-appreciated perk of general relativity is that its vacuum black hole solutions are uniquely determined by their mass and angular momentum. Upon the inclusion of a minimally coupled Maxwell field, this uniqueness theorem extends to electrovacuum black holes, in which case one more parameter is needed to specify the solution: charge. The proof of the theorem relies heavily on the structure of the Einstein equations and therefore it is expected to be evaded in modified gravity. This is shown to be the case for Einsteinian cubic gravity, a modification of general relativity that includes up to third-order curvature corrections determined by low-energy effective theory expectations. Specifically, and restricting to spherically symmetric four-dimensional geometries, we find that there exist two black holes with the same mass and charge in a certain overextremal regime (i.e., charge greater than the mass). Both solutions are pathology-free, asymptotically flat, and none of them features a Cauchy horizon, in contrast with the usual Reissner-Nordstrom spacetime. A brief discussion of these solutions' thermodynamic properties is also presented. Finally, it is pointed out that neutral black holes in Einsteinian cubic gravity coexist with a one-parameter family of naked singularity spacetimes carrying the same mass.

Open thermodynamic systems and particle production processes in scalar-tensor f(R,T) gravity

Miguel Pinto
Institute of Astrophysics and Space Sciences, University of Lisbon

We investigate the possibility of gravitationally generated particle production via the mechanism of non-minimal curvature-matter coupling. An intriguing feature of this theory is that the divergence of the matter energy-momentum tensor does not vanish identically. We explore the physical and cosmological implications of the non-conservation of the energy-momentum tensor by using the formalism of irreversible thermodynamics of open systems in the presence of matter creation/annihilation. The particle creation rates, pressure, temperature evolution and the expression of the comoving entropy are obtained in a covariant formulation and discussed in detail. Applied together with the gravitational field equations, the thermodynamics of open systems lead to a generalization of the standard ΛCDM cosmological paradigm, in which the particle creation rates and pressures are effectively considered as components of the cosmological fluid energy-momentum tensor. We also consider specific models, and we compare the cosmology with a curvature-matter coupling with the ΛCDM scenario, and if it additionally gives rise to particle creation rates, creation pressures, and entropy generation through gravitational matter production in both low and high redshift limits.

The analogy between the LV fermion-gravity and LV fermion-photon couplings

Zhi Xiao
North China Electric Power University

By adopting a methodology proposed by R.J. Adler et.al. We calculate the non-relativistic (NR) Lorentz-violating (LV) matter-gravity couplings in a simple Lense-Thirring (LT) metric. In this NR scheme, we find the interesting analogy between the fermion-gravity and the fermion-electromagnetic couplings persists even in the presence of LV, at least for a bunch of terms. Quite distinct from the extensively studied linear gravitational potential, the LT metric is an essentially curved metric, and thus reveals several interesting matter-gravity couplings as a manifestation of the so-called gravito-magnetic effects, which go beyond the equivalence principle (EP) predictions. Though these LV fermion-gravity couplings are supposed to be extremely small than previous studied ones, such as the $\tilde{b}$ terms, they merit of extensive studies as the tiny spin-gravity couplings may be testable in the future ultraprecision microscopic test of WEP, or high precision test of LT effects.

When can a teleparallel geometry be classified by its scalar polynomial torsion invariants

David Mcnutt
University of Stavanger

General Relativity (GR) is formulated using Lorentzian manifolds with a connection which is required to be metric-compatible and the resulting torsion tensor vanishes. Interestingly, GR can be reformulated on Lorentzian manifolds with a different connection which is still metric-compatible but now the curvature tensor must vanish. This alternative gravity theory is known as the teleparallel equivalent of general relativity (TEGR) and any geometry with this choice of connection will be called a teleparallel geometry.

For a given solution of GR, it is possible to generate a corresponding solution of TEGR, however, this approach is not one-to-one, and we can generate many inequivalent solutions of TEGR. To determine if two solutions of TEGR are equivalent, we could compare their respective scalar polynomial torsion invariants. However, it is expected that the set of all scalar polynomial torsion invariants will not uniquely characterize all teleparallel geometries, so it would be helpful to know when we can use these torsion invariants. In this talk I will discuss the problem in four dimensions and introduce the class of teleparallel geometries which are not characterized by their scalar polynomial torsion invariants.

Conformal Invariance and Warped 5-Dimensional Spacetimes

Reinoud Slagter
University of Amsterdam and ASFYON

My presentation will treat an exact time-dependent solution of a black hole in a conformally invariant gravity model on a warped 5D spacetime, by writing the metric $g_{\mu\nu} = \omega^{\frac{4}{n-2}}\tilde{g}_{\mu\nu}$. Here $\tilde{g}_{\mu\nu}$ represents the "un-physical" spacetime and ω the dilaton field, which will be treated on equal footing as any renormalizable scalar field. This presentation rely on recent work. In the case of a five-dimensional warped spacetime, we thereafter write ${}^{(4)}\tilde{g}_{\mu\nu} = \omega^2\, {}^{(4)}\bar{g}_{\mu\nu}$. The dilaton field ω can be used to describe the different notion the in-going and outside observers have of the Hawking radiation by using different conformal gauge freedom. The disagreement about the interior of the black hole is explained by the antipodal map of points on the horizon. The zero's of the model are described by a quintic polynomial and has no essential singularities. These zeros can also be analyzed by the icosahedral equation. The free parameters of the solution can be chosen in such a way that $g_{\mu\nu}$ is singular-free and topologically regular, even for $\omega \to 0$. It is remarkable that the 5D and 4D effective field equations for the metric components and dilaton fields can be written in general dimension n=4,5. From the exact energy-momentum tensor in Eddington-Finkelstein coordinates, we are able to determine the gravitational wave contribution in the process of evaporation of the black hole. It is conjectured that, in context of quantization procedures in the vicinity of the horizon, unitarity problems only occur in the bulk at large extra-dimension scale. The subtraction point in an effective theory will be in the UV only in the bulk, because the use of a large extra dimension results in a fundamental Planck scale comparable with the electroweak scale. This presentation relies on recent work \cite {Slagter:2019, Slagter: JMP,2022}.
Note: see extended pdf.

Possible quantization of stress-energy tensor on Finsler manifold

Abdel Nasser Tawfik
Future University in Egypt (FUE)

With generalized noncommutative algebra imposing minimal length uncertainty and gravitational interaction to quantum theory (QT), the possible quantization of the field equations could be suggested as additional curvature in relativistic eight-dimensional spacetime tangent bundle, Finsler manifold. The complementary term reconciling principles of quantum theory (QT) and general relativity (GR) and comprising generalized noncommutative algebra with maximal spacelike four--acceleration, the possible quantization of the torsion-free metric tensor is constructed. Accordingly, the possible quantization of the symmetric stress-energy tensor, the source of spacetime curvature and the current density associated with the gauge transformations of gravity, with matter (electromagnetic and scalar) Lagrangian is suggested. Besides the unquantized stress--energy tensor, the quantization introduces additional Lagrangian densities and potentials and coefficients depending on metric tensor, universal constants, and maximal spacelike four-acceleration and four-jerk. The vanishing covariant derivative of the quantized stress-energy tensor suggests that the corresponding continuity equation implies that the gravitational fields do work on matter and vice versa and the non-gravitational energy and momentum are no longer entirely conserved. For vanishing maximal four-acceleration and/or vanishing minimal length uncertainty, classical GR and non-gravitational QT are retrained, and accordingly, Einstein stress-energy

tensor is also obtained. Thus, we conclude that the quantized stress-energy tensor is suitable in quantum and classical field equations.

Slowly Rotating Black Holes in 4D Gauss-Bonnet Gravity

Michael Gammon
University of Waterloo

Since the recent derivation of a well-defined D->4 limit for 4D Gauss-Bonnet (4DGB) gravity, there has been considerable interest in testing it as an alternative to Einstein's general theory of relativity. In this paper, we construct slowly rotating black hole solutions of 4DGB gravity in asymptotically flat, de Sitter, and anti-de Sitter spacetimes. At leading order in the rotation parameter, exact solutions of the metric functions are derived and studied for all three of these cases. We compare how physical properties (innermost stable circular orbits, photon rings, black hole shadow, etc.) of the solutions are modified by varying coupling strengths of the 4DGB theory relative to standard Einstein gravity results. We find that a negative cosmological constant enforces a minimum mass on the black hole solutions, whereas a positive cosmological constant enforces both a minimum and maximum mass with a horizon root structure directly analogous to the Reissner-Nordström de Sitter spacetime. Besides this, many of the physical properties are similar to General Relativity, with the greatest deviations being found in the low mass regime.

Thermodynamics on generalized quasi-topological quartic gravity

Mengqi Lu
Dept. of Physics & Astronomy, University of Waterloo

Generalized quasi-topological gravity (GQG) theories are higher-curvature extensions of Einstein gravity in D-dimensions. Their defining properties include possessing second-order linearized equations of motion around maximally symmetric backgrounds as well as non-hairy generalizations of Schwarzschild's black hole characterized by a single metric function. Here we investigate the thermodynamics of asymptotically anti de Sitter black holes without electric charge in GQG, focusing on theories with two inequivalent genuine quartic Lagrangian densities that exist in $D \geq 5$. We study the temperature-horizon relations of these new black holes. In some coupling regimes there exist four distinct black hole phases: small cold hole (SCH), small hot hole (SHH), large cold hole (LCH), and large hot hole (LHH). We describe the various possible phase transitions, amongst which we observe not only Hawking-Page transitions but also transitions between other states that occur due to inclusion of these quartic curvature terms.

Wormholes in modified gravity with non-commutative background

Anshuman Baruah
Assam University

Wormhole solutions to gravitational field equations serve as an important tool to probe general relativity and its modifications. Moreover, it is deemed plausible that space-time at the smallest length scales is discretized by distributions described via non-commutative operators. In this study, we leverage these two concepts to investigate wormhole solutions in modified gravity, especially focusing on the energy conditions. It is well-known that stable wormholes violate the null energy condition, and we validate this proposition for well constrained modified gravity models, while demonstrating some exceptions with suitable parameterizations. Our comprehensive analyses using both constant and variable wormhole redshift functions should serve as an important contribution to the study of wormholes in modified gravity.

Causality Constraints on Gravitational Effective Field Theories

Jun Zhang
International Centre for Theoretical Physics, Asia-Pacific

We consider the effective field theory of gravity around black holes, and show that the coefficients of the dimension-8 operators are tightly constrained by causality considerations. Those constraints are consistent with -- but tighter than -- previously derived causality and positivity bounds and imply that the effects of one of the dimension-8 operators by itself cannot be observable while remaining consistent with causality. We then establish in which regime one can expect the generic dimension-8 and lower order operators to be potentially observable while preserving causality, providing a theoretical prior for future observations. We highlight the importance of ``infrared causality'' and show that the requirement of ``asymptotic causality'' or net (sub)luminality would fail to properly diagnose violations of causality.

Hawking-Page transition with reentrance and triple point in Gauss-Bonnet gravity

YuanZhang Cui
China University of Geoscience

In this paper, a new family of Hawking-Page (HP) transition, the HP transition with reentrance and triple point is introduced for the first time, by investigating HP transition of hyperbolic AdS black hole in extended thermodynamics of general dimensional Gauss-Bonnet gravity. The Reentrant HP transition is composed of two HP transitions with a large and a small HP temperature, and the triple point corresponds to small black holes/massless black holes/large black holes (SBHs/MBHs/LBHs) phases all coexisting. We present the two branches of HP transition temperatures, which both depend on the pressure (i.e. the cosmological constant) and the Gauss-Bonnet constant. Besides, the pressure and the Gauss-Bonnet constant both enlarge the large HP temperature and diminish the small HP temperature. We also show the coexistence lines in the P−T phase diagrams. The triple point and an up critical point in phase diagrams for arbitrary dimensional Gauss-Bonnet AdS black hole systems are given, together with some interesting universal relations which only depend on the dimensions of spacetime. We can explain the reentrant HP transition and triple point of

SBHs/MBHs/LBHs as the phase transition and triple point of Hadronic matter/Quark-Gluon/Plasma/Quarkyonic matter in the QCD phase diagram. These results may improve the comprehension of the black hole thermodynamics in the quantum gravity framework and shed some light on the AdS/CFT correspondence beyond the classical gravity limit.

Gravitational waves in theories of gravity with broken Lorentz symmetry

Chao Zhang
Zhejiang University of Technology

100 years after Einstein's prediction, gravitational waves (GWs) were finally detected by the Laser Interferometer Gravitational-wave Observatory (LIGO) on September 14, 2015. After that, about 90 GW events were identified by LIGO/Virgo/KAGRA scientific collaboration. This breakthrough confirms a major prediction of general relativity (GR), proposed by Albert Einstein in 1915. In addition, it opens an unprecedented new window onto the cosmos and testing modified theories of gravity.

Currently, GR has passed all the experimental tests carried out so far with flying colors. However, it should not be the final story due to some open questions, including the quantization of gravity. So, various modified theories of gravity have been proposed since the early of 1920s, which need to be filtered by observations, including those of GWs. Among these modified theories, Einstein-æther (æ-) theory is quite a unique one, since it breaks the Lorentz symmetry, a pillar of modern physics, while is still self-consistent and consistent with all observations. Its Cauchy problem is also well-posted. Due to these remarkable properties, it has attracted a lot of attentions in recent years, and investigations to æ-theory will provide important guidelines to the construction of quantum gravity, understanding the nature of the Lorentz symmetry, etc.

In this talk, I shall first give a very brief review on GWs, and then focus mainly on æ-theory. In addition, I shall show the differences between æ-theory and GR, and demonstrate how to test æ-theory by GW observations. These differences could be seen from the two distinct stages of compact multi-body systems during their coalescences. Some essences of æ-theory as well as compact bodies are encoded in and revealed by the exhibited results. For instance, recently we found some observable deviations between æ-theory and GR on certain physical quantities from the so-called ringdown stage, which reflect the influence of Lorentz symmetry broken effects. The detail will be given in the talk.

Testing F(Q) gravity with redshift space distortions

Tiago Barreiro
Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa

A cosmological model with Symmetric Teleparallel Gravity where gravity is non-metrical is constrained with redshift space distortions data. The cosmological background for the model mimics a ΛCDM evolution but differences arise in the perturbations. The linear matter fluctuations are numerically evolved and the study of the growth rate of structures is analyzed in this cosmological setting. The best fit parameters reveal that the σ8 tension between Planck and Large Scale Structure data can be alleviated within this framework.

2-D Gravity with null extra dimension

SUVIKRANTH GERA
IIT KHARAGPUR

Gravity in two dimensions is rather simple as Einstein-Hilbert action leads to trivial equations of motion. To change the scenario in two dimensions, we attempt to obtain a dynamical gravity theory by using the idea of dynamical reduction via vanishing metric null directions. This novel emergent theory is characterized by a dynamical gravity sector along with non-dynamical constraints on the torsion. The framework so developed through our work is more general than the celebrated JT gravity and is inequivalent to the MR dimensional reduction technique. As an implementation of the newly- developed gravity formalism, we study the cases of static and FRW cosmology solutions in this theory. Interestingly, the effective equations of motion remain invariant under appropriate identifications under the addition of extra null dimensions and higher order Lovelock terms.

Talk based on the work: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.124050

Linear stability of black holes with static scalar hair in full Horndeski theories: generic instabilities and surviving models

Shinji Tsujikawa
Waseda University

In full Horndeski theories, we show that the static and spherically symmetric black hole (BH) solutions with a static scalar field ϕ whose kinetic term X is nonvanishing on the BH horizon are generically prone to ghost/Laplacian instabilities. We then search for asymptotically flat hairy BH solutions with a vanishing X on the horizon free from ghost/Laplacian instabilities. We show that models with regular coupling functions of ϕ and X result in no-hair Schwarzschild BHs in general. On the other hand, the presence of a coupling between the scalar field and the Gauss-Bonnet (GB) term G, even with the coexistence of other regular coupling functions, leads to the realization of asymptotically flat hairy BH solutions without ghost/Laplacian instabilities. Finally, we find that hairy BH solutions in power-law F(G) gravity are plagued by ghost instabilities. These results imply that the GB coupling of the form ξ(ϕ)G plays a prominent role for the existence of asymptotically flat hairy BH solutions free from ghost/Laplacian instabilities.

Compact Star in General F(R) Gravity

Taishi Katsuragawa
Central China Normal University

We investigate a compact star in the general F(R) gravity and prove that adjusting the functional form of F(R) can realize an arbitrary Mass-Radius relation of the compact star. Furthermore, we demonstrate that the boundary condition demands a weak curvature correction to the Einstein gravity could be non-integer power of the scalar curvature, which gives a stringent constraint on the functional form of F(R).

Stable bound orbits around static Einstein-Gauss-Bonnet black holes

Ryotaku Suzuki
Toyota Technological Institute

As is well-known, asymptotically flat, static and spherically symmetric black holes do not admit stable bound orbits of massive/massless particles outside the horizon in higher-dimensional Einstein gravity. However, for massive particles, this dramatically changes in higher curvature theories. In this talk, I will clarify the parameter range such that there exist stable bound orbits in d-dimensional Einstein-Gauss-Bonnet theories for 6<=d<=9. In particular, I show the existence of the lower bound of the Gauss-Bonnet coupling constant below which stable bound orbits cease to exist. We also find that for AdS-black holes in the theories, there can exist two stable circular orbits outside the horizon.

Physical black holes in modified theories of gravity

Sebastian Murk
Department of Physics and Astronomy, Macquarie University

The existence of black holes is a central prediction of general relativity and thus serves as a basic consistency test for modified theories of gravity. In spherical symmetry, only two classes of dynamic solutions to the semiclassical Einstein equations are compatible with the formation of an apparent horizon in finite time of a distant observer. Moreover, the formation of black holes follows a unique scenario involving both types of solutions. To be compatible with their existence, any self-consistent theory of modified gravity must satisfy several constraints. We find that modified gravity theories involving up to fourth-order derivatives in the metric generically satisfy all constraints and thus naturally accommodate both classes of solutions, which can be regarded as zeroth-order terms in perturbative solutions of these models. In addition, we explicitly identify a class of non-perturbative solutions. Consequently, the observation of an apparent horizon by itself may not suffice to distinguish between the predictions of general relativity and fourth-order gravity theories.

Spherical black holes in bumblebee gravity

Rui Xu
Kavli Institute of Astronomy and Astrophysics

Bumblebee gravity models are vector-tensor theories of gravity where the vector field couples with the Ricci tensor. Inspired by the special Schwarzschild-like solution in the literature, we search for spherical black-hole solutions numerically assuming a general spherical bumblebee vector field. Two families of spherical black-hole solutions are found: one has three parameters, and the other has five parameters. By setting one of the parameters to a certain value, the existing analytic Schwarzschild-like solution can be recovered and generalized. To put the theories into tests, we consider the consequences to black-hole shadow, advance of perihelion, and deflection of light. Constraints on the black-hole parameters are obtained by comparing the predictions to observational data.

Systematic bias on the inspiral-merger-ringdown (IMR) consistency test of general relativity due to neglect of orbital eccentricity

Sajad A. Bhat
Chennai Mathematical Institute

The inspiral-merger-ringdown (IMR) consistency test checks the consistency of the final mass and final spin of the remnant black hole, independently inferred using the inspiral and merger-ringdown parts of the waveform. Current tests of general relativity (GR) employ quasi-circular waveforms, since binary eccentricity is expected to be damped in the frequency band of ground-based detectors. Here, we quantify the effect of residual orbital eccentricity on the IMR consistency test. We find that the systematic bias in the final mass and final spin of the remnant black hole in the LIGO band becomes significant at an orbital eccentricity ~0.05 (at 10 Hz), for total mass in the range 65-200 Msun . For Cosmic Explorer (CE), these errors start dominating at an eccentricity ~0.01 (at 10 Hz), for 200-600 Msun systems. These biases on the final mass and final spin of the merger remnant may lead to inconsistency between the inspiral and merger-ringdown parts of the signal, manifesting as a false violation of GR.

Fate of radiating black holes with minimum mass in Einstein-dilaton-Gauss-Bonnet theory of gravity

Fabrizio Corelli
Sapienza University of Rome

Einstein-dilaton-Gauss-Bonnet is a theory of modified gravity in which a scalar field, called dilaton, is nonminimally coupled to the metric via an exponential function. Black holes (BHs) in this theory are particularly interesting since they possess a critical configuration with minimum mass and finite Hawking temperature. This means that a critical BH loses mass due to Hawking's radiation, but it is not clear what is its fate after this process, since it cannot reach a final configuration with lower mass. In a recent work we studied this problem by means of fully nonlinear numerical evolutions of spherically symmetric BH spacetimes (Corelli, De Amicis, Ikeda, and Pani, to appear in May 2022). Specifically, by simulating the collapse of wave packets of a phantom scalar field we have been able to dynamically reduce the BH mass, reproducing the effect of the Hawking's evaporation process. In this talk I will present our results focusing on the case in which the BH mass falls below the critical value.

In particular I will show that in the formalism we used an elliptic region with high curvature appears outside the apparent horizon, and I will discuss how this could possibly hint to a violation of the weak cosmic censorship conjecture.

Sharp density gradients in generalized coupling theories

Justin Feng
CENTRA, Instituto Superior Tecnico, University of Lisbon

It has been argued that sharp matter density gradients, such as those which may be present at the boundary of compact objects (neutron stars for instance), produce pathologies in gravity theories containing auxiliary fields. In this talk, I discuss recent work which shows that this is not necessarily the case in generalized coupling theories (GCTs). For the Minimal Exponential Measure model, a simple example of a GCT, we find that while discontinuities in matter density profiles generically produce discontinuities in the effective metric minimally coupled to matter, the physical consequences of sharp density gradients are minimal.

Evolution of the Cluster of Stars in f(R) Gravity

Rubab Manzoor
University of Management and Technology

This article explores the dynamics of evolving cluster of stars in the presences of exotic matter. The f(R) theory is used to presume exotic terms for evolution scenario. We use structure scalars as evolution parameters to explore dynamics of spherically symmetric distribution of evolving cluster of stars. We consider Starobinsky model, f(R)=R+ϵ R^2 and study different evolution modes having features like isotropic pressure, density homogeneity, homologous and geodesic behavior. It is concluded that dynamics of these modes of evolution depends upon the behavior of dark matter. The presences of dark matter directly affects the features of cluster like anisotropic pressure, dissipation, expansion, shear as well as density homogeneity.

Constraining effective equation of state in f (Q, T) gravity

Simran Arora
BITS-Pilani, Hyderabad Campus, Hyderabad, India

New high-precision observations are now possible to constrain different gravity theories. To examine the accelerated expansion of the Universe, we used the newly proposed f (Q, T) gravity, where Q is the non-metricity, and T is the trace of the energy-momentum tensor. The investigation is carried out using a parameterized effective equation of state with two parameters, m and n. We have also considered the linear form of f (Q, T) = Q + bT, where b is constant. By constraining the model with the recently published 1048 Pantheon sample, we

were able to find the best fitting values for the parameters b, m, and n. The model appears to be in good agreement with the observations. Finally, we analyzed the behavior of the deceleration parameter and equation of state parameter. The results support the feasibility of f (Q, T) as a promising theory of gravity, illuminating a new direction towards explaining the Universe's dark sector.

Echoes from braneworld black holes

Sumanta Chakraborty
Indian Association for the Cultivation of Sceince

The holographic interpretation of the Randall-Sundrum model based on the adaptation of the AdS/CFT correspondence to the braneworld scenario states that the black holes localized on the brane are quantum corrected. This can be better understood from the fact that the classical AdS5 bulk dynamics is dual to gravity coupled with conformal field theory (CFT) on the four-dimensional brane. Based on the backreaction of the CFT on the classical black hole geometry, localized on the brane, it is expected that there exist possible near-horizon modifications. This may result in the black hole horizon becoming partially reflective, thus giving rise to echoes in the ringdown signal in gravitational wave observations. In this paper, we investigate the existence of such echoes in the ringdown phase of a black hole localized on the brane, carrying a negative tidal charge, and establish the layout for future investigation of higher-dimensional effects in the ringdown signal. Confirmed detections of echoes at the current levels of instrumental sensitivity can constrain the dimensionless value of tidal charge to |Q|≲M2.

Dynamical features of f(T,B) cosmology

Siddheshwar Kadam
BITS-Pilani, Hyderabad Campus

In this paper, we have explored the field equations of f(T, B) gravity and determined the dynamical parameters with the hyperbolic function of the Hubble parameter. The accelerating behavior has been observed and the behavior of the equation of state parameter indicates the Lambda CDM model at a late time. The role of model parameters in assessing accelerating behavior has been emphasized. Interestingly the term containing η, the coefficient of boundary term, in the model parameter vanishes during the simplification.

Constraining logarithmic f(R,T) model using Dark Energy density parameter

BISWAJIT DEB
Assam University

Of many extended theories of gravity, f(R,T) gravity, a straightforward generalization of f(R) gravity has gained reasonable interest in recent times as it provides interesting results in

cosmology. Logarithmic corrections in modified theories of gravity has been studied extensively, however in f(R,T) gravity it is not studied yet. In this work, we propose a f(R,T) model with logarithmic correction to the trace term T and take the functional form as f (R, T) = R + 16πGα ln T where α is a free parameter. The free parameter is constrained using dark energy density parameter and the lower bound is found to be $\alpha \geq -9.93 \times 10^{-29}$. The cosmological implications are also studied.

Cosmological model with time varying deceleration parameter in F(R,G) gravity

Santosh Lohakare
BITS Pilani, Hyderabad Campus, India

In this work, we investigate dynamical behavior of the Universe dynamical behavior in the theory of gravity, where R and G indicate the Ricci scalar and Gauss-Bonnet invariant, respectively. The energy conditions, cosmographic parameters, stability, and viability of reconstructing the mentioned model using a scalar field formalism are all part of our comprehensive research. At late periods, the model obtained here exhibits quintessence-like behavior.

Matter Bounce Scenario in Extended Symmetric Teleparallel Gravity

Bivudutta Mishra
BITS-Pilani, Hyderabad Campus

In the context of the late time cosmic acceleration phenomenon, many geometrically modified theories of gravity have been proposed in recent times. In this paper, we have investigated the role of a recently proposed extension of symmetric teleparallel gravity dubbed as f(Q,T) gravity in getting viable cosmological models, where Q and T respectively denote the non-metricity and the trace of energy momentum tensor. We stress upon the mathematical simplification of the formalism in the f(Q,T) gravity and derived the dynamical parameters in more general form in terms of the Hubble parameter. We considered two different cosmological models mimicking non-singular matter bounce scenario. Since energy conditions play a vital role in providing bouncing scenario, we have analyzed different possible energy conditions to show that strong energy condition and null energy condition be violated in this theory. The models considered in the work are validated through certain cosmographic tests and stability analysis.

Bouncing universe dual to the concordance model: Scalar-tensor theories in the Jordan frame

Dipayan Mukherjee
Indian Institute of Science Education and Research, Mohali, India

Scalar-tensor theories of gravity can provide a mathematically equivalent description of Einstein's gravity with a scalar field, in a conformally connected spacetime. In this work we use the Jordan frame-Einstein frame correspondence to explore dual universes with contrasting cosmological evolutions. We study the mapping between Einstein and Jordan frames where the Einstein frame universe effectively describes the late-time evolution of the physical universe, driven by dark energy and non-relativistic matter. The Brans-Dicke theory of gravity is taken as an example of scalar-tensor theories in the Jordan frame. We show that the standard Einstein frame universe, with dark energy and non-relativistic matter, always corresponds to a bouncing Jordan frame universe, governed by a Brans-Dicke model. This essentially leads to an alternative description of the late-time evolution of the physical universe, in terms of a bouncing Brans-Dicke universe in the Jordan frame. Previous studies have shown that for a bouncing Jordan frame, particularly for an early-time accelerating phase of the universe, the map between Einstein and Jordan frames may become singular in the perturbative regime, causing the conformal correspondence to break down. In order to check whether the present bouncing model for late-time acceleration is free of such singularities, we study the evolution of scalar metric perturbations. The Jordan frame metric perturbations are numerically solved, first via Einstein frame using the conformal correspondence, then directly in the Jordan frame. The evolutions of perturbations obtained in these two cases are in agreement within small numerical error. Thus, the duality between the Einstein frame, mimicking the physical universe, and the bouncing Brans-Dicke Jordan frame, is shown to be stable against linear perturbations.

Linear growth of structure in projected massive gravity

Yusuke Manita
Kyoto University

In the present study, we investigate the linear growth of matter fluctuations based on a concrete model of the projected massive gravity, which is free of the Boulware-Deser ghost and preserves the global Lorentz symmetry. We found that at subhorizon scales, the modification to the linear growth is strongly suppressed even without nonlinear screening of an additional force. In addition, we obtain observational constraints from distance and redshift space distortion measurements and find that there is a parameter region that is consistent both observationally and theoretically.

Quantum correction to the Newtonian potential in Higher-derivative gravity

Nicolò Burzillà
Southern University of Science and Technology

We present the Newtonian potential and the metric in the weak field limit in fourth-derivative gravity including the one-loop logarithm quantum corrections. At linear level, the behavior of the modified Newtonian potential near the origin is improved compared to the classical one. However, this is not enough to regularize the curvature invariants of the metric. We also discuss the effect of quantum corrections in theories with 6 or more derivatives, that have the property of being super-renormalizable. In this case the regularity of the classical Newtonian potential remains unchanged because the logarithmic corrections are sub-leading with respect

to the analytic part of the form factor. This qualitative behavior is not affected by the specific form of the classical action. In general, the logarithmic quantum corrections have a more prominent role in the far-IR regime, where they generate the leading correction to the Newtonian potential, proportional to r^(-3), supporting the hypothesis of universality of the effective approach to quantum gravity in the IR.

Sign Switching Dark Energy from a Running Barrow Entropy

Sofia Di Gennaro
Yangzhou University

Barrow proposed that the area law of the entropy associated with a horizon might receive a "fractal correction" due to quantum gravitational effects – in place of $S \propto A$, we have instead $S \propto A^{(1+\delta/2)}$,where $0 < \delta < 1$ measures the deviation from the standard area law ($\delta = 0$). Based on black hole thermodynamics, we argue that the Barrow entropy should run (i.e., energy scale dependent), which is reasonable given that quantum gravitational corrections are expected to be important only in high energy regime. When applied to the Friedmann equation, we demonstrate the possibility that such a running Barrow entropy index could give rise to a dynamical effective dark energy, which is asymptotically positive and vanishing, but negative at the Big Bang. Such a sign switching dark energy could help to alleviate the Hubble tension. Other cosmological implications are discussed.

Main Results and Current Progress within the Scale Invariant Vacuum Paradigm

Vesselin Gueorguiev
Institute for Advanced Physical Studies

The talk will review the Scale Invariant Vacuum (SIV) idea as related to Weyl Integrable Geometry [0]. Main results related to SIV and inflation [1], the growth of the density fluctuations [2], and application of the SIV to scale-invariant dynamics of Galaxies, MOND, Dark Matter, and the Dwarf Spheroidals [3] will be summarized. If time permits, a potential connection of the weak field SIV results to the un-proper time parametrization within the reparametrization paradigm, will be discussed as well [4].

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[1] Maeder, A., Gueorguiev, V. G., Scale invariance, horizons, and inflation. MNRAS 504, 4005 (2021). arXiv: 2104.09314 [gr-qc].
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[3] Maeder, A.; Gueorguiev, V.G. Scale-invariant dynamics of galaxies, MOND, dark matter, and the dwarf spheroidals, MNRAS 492, 2698 (2019). arXiv: 2001.04978 [gr-qc]

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Fermi Bubbles in Scalar Field Dark Matter halos

Tonatiuh Matos
Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN

In recent times, the Scalar Field Dark Matter (SFDM) model (also called Fuzzy, Wave, Ultralight dark matter model) has received much attention due to its success in describing dark matter on both cosmological and galactic scales. Several challenges of the Cold Dark Matter (CDM) model can be explained very easily and naturally by the SFDM model. Two of these challenges are to describe the anomalous trajectories of satellite galaxies called the Vast Polar Structure (VPOS) and to explain the Fermi Bubbles (FB) observed in our galaxy. In Phys. Rev. D103 (2021)083535 an alternative explanation for VPOS was shown using the SFDM excited states, explaining the anomalous trajectories in a natural and simple way. In this talk we use the same dark matter structure to show that these excited states of the SFDM can provide a very simple and natural explanation for the FB, assuming that the SFDM is a kind of dark boson. If this assumption is correct, we should see FB in several more galaxies and continue to see gamma-ray events at higher energies, these observations would take place in the near future and could be crucial to the ultimate answer to the nature of dark matter.

Cosmology in $f(R, L_m)$ gravity

Pradyumn Sahoo
BITS-Pilani, Hyderabad Campus

In this talk, we discuss the cosmic expansion scenario of the universe in the framework of $f(R, L_m)$ gravity theory. We consider a non-linear $f(R, L_m)$ model, specifically, $f(R, L_m) = \frac{R}{2} + L_m^n + \eta$, where n and η are free model parameters. Then we derive the motion equations for flat FLRW universe and obtain the exact solution of corresponding field equations. Then we estimate the best fit ranges of model parameters by using updated H(z) datasets consisting of 57 points and the Pantheon datasets consisting of 1048 points. Further we investigate the physical behavior of density and the deceleration parameter. The evolution of deceleration parameter depicts a transition from deceleration to acceleration phases of the universe. Moreover, we analyze the stability of the solution of our cosmological model under the observational constraint by considering a linear perturbation. Lastly, we investigate the behavior of Om diagnostic parameter and we observe that our model shows quintessence type behavior. We conclude that our $f(R, L_m)$ cosmological model agrees with the recent observational studies and can efficiently describe the late time cosmic acceleration.

Sudden singularities in f(R,T) gravity

Tiago Gonçalves
Instituto de Astrofísica e Ciências do Espaço Faculdade de Ciências da Universidade de Lisboa

Might the universe, one day, undergo a Big Crunch, Big Freeze, Big Rip, or some other singularity? A "sudden singularity" occurs if the energy density, the scale factor and the Hubble function remain finite while there is a divergence in higher derivatives of the scale factor which could be accompanied by a pressure divergence. We investigate whether sudden singularities could arise in the f(R, T) theory of modified gravity. We find that the conservation of matter can prevent sudden singularities in this theory. However, due to matter-geometry couplings, f(R, T) gravity does not require matter conservation. Thus, we investigate a particular model where there is a sudden singularity in the third time derivative of the scale factor.

MOND and RMOND from a left-right symmetric extension of the standard model of particle physics

TEJINDER PAL SINGH
TATA INSTITUTE OF FUNDAMENTAL RESEARCH, MUMBAI

We have recently argued that there must exist a formulation of quantum theory which does not depend on classical time, even at low energies. Such a formulation has been developed on a higher dimensional octonionic spacetime, and shows evidence for predicting the standard model and its free parameters. Furthermore, the symmetry group E_6 on which the theory is based, admits a left-right symmetric extension of the standard model, with the right-handed part being a pre-gravitational theory with the symmetry $SU(3)_{grav} \times SU(2)_R \times U(1)$. Of these, $SU(2)_R$ coincides with general relativity, whereas the other two symmetries suggest a scale-invariant modification of GR sourced by square root of mass, rather than by mass. We present evidence that these new gravitational symmetries could be the theoretical origin of MOND and RMOND.

Reference: https://arxiv.org/abs/2110.02062v1

B1: Relativistic astrophysics (Chair: Daniel Siegel, Coordinator: You-Jun Lu)

How do black holes shine? Or: multiwavelength emission in the high-energy Universe

Bart Ripperda
Princeton University/Flatiron Institute

Astrophysical black holes are surrounded by accretion disks, jets, and coronae consisting of magnetized, (near)-collisionless relativistic plasma. They produce observable high-energy radiation and it is currently unclear where and how this emission is exactly produced. The radiation typically has a non-thermal component, implying a power-law distribution of emitting relativistic electrons. Magnetic reconnection and plasma turbulence are viable mechanisms to tap the large reservoir of magnetic energy in these systems and accelerate electrons to extreme energies. The accelerated electrons can then emit high-energy photons that themselves may strongly interact with the plasma, rendering a highly nonlinear system. Modeling these systems necessitates a combination of magnetohydrodynamic models to capture the global dynamics of the formation of dissipation regions, and a kinetic treatment of plasma processes that are responsible for particle acceleration, pair creation and annihilation, and radiation. I will present novel studies of accreting black holes and how they radiate in regions close to black hole event horizon, using both first-principles general relativistic kinetic particle-in-cell simulations and global large-scale three-dimensional magnetohydrodynamics models. I will answer the question of how well fluid-type models like magnetohydrodynamics can capture collisionless plasma physics. With a combination of models, I determine where and how dissipation of magnetic energy occurs, and what kind of emission signatures are typically produced. In the end, I will outline how an approach of global magnetohydrodynamics and kinetic models will enable quantitative comparisons with observations of multiwavelength observations of radio, X-ray, and TeV emission from accreting black holes and potentially study the structure of spacetime.

Neutrino Fast Flavor Conversions in Neutron-star Post-Merger Accretion Disks

Xinyu Li
CITA/Perimeter Institute

A compact accretion disk may be formed in the merger of two neutron stars or of a neutron star and a stellar-mass black hole. Outflows from such accretion disks have been identified as a major site of rapid neutron-capture (r-process) nucleosynthesis and as the source of ‘red’ kilonova emission following the first observed neutron-star merger GW170817. We present long-term general-relativistic radiation magnetohydrodynamic simulations of a typical post-merger accretion disk at initial accretion rates of $\sim$ 1 Msun/s over 400 ms post-merger. We include neutrino radiation transport that accounts for effects of neutrino fast flavor conversions dynamically. We find ubiquitous flavor oscillations that result in a significantly more neutron-rich outflow, providing lanthanide and 3rd-peak r-process abundances similar to solar abundances. This provides strong evidence that post-merger accretion disks are a

major production site of heavy r-process elements. A similar flavor effect may allow for increased lanthanide production in collapsars.

The dark mass signature in the orbit of S2

Gernot Heißel
Observatoire de Paris/LESIA; ESA/Advanced Concepts Team

Background: Infrared observations of the star cluster at the heart of our galaxy revealed the existence of a massive compact object (putative black hole) of 4.2 million solar masses in coincident location with the radio source Sagittarius A*. The enormous efforts to confirm this have been recognised by the 2020 Nobel prize in Physics. The corresponding results demonstrate the utility of the galactic centre as a unique laboratory for relativistic astrophysics and testing relativity. In particular, the precise astrometric and spectroscopic tracking of the orbit of the star S2 allowed the observation of two prominent relativistic effects. The relativistic redshift could be observed during the last pericentre passage in 2018. The relativistic (Schwarzschild) precession of the stellar orbit could be measured in 2020.
Focus: The same study also improved the 1σ upper bound on a possibly present dark continuous extended mass distribution (e.g. faint stars, stellar remnants or Dark Matter) within the orbit of S2 to ~ 4000 solar masses. The secular (i.e. net) effect of an extended mass onto a stellar orbit is known as mass precession, and it runs counter to the Schwarzschild precession. Constraining or detecting an extended mass is not only of interest to study what is hidden in the immediate surroundings of the black hole in its own right, but also as a perturbing effect for the goal of detecting relativistic precessions (Schwarzschild, Lense-Thirring).
Talk: In my talk I will present our recent theoretical and mock-data study on the impact of an extended mass on the orbit of S2 (Heißel et al. 2022, https://doi.org/10.1051/0004-6361/202142114). These results concern general statements on the detectability of an extended mass, statements on the separability between the Schwarzschild and the mass precession, as well as detection threshold estimates for future observations with VLTI/GRAVITY until 2033. I will also highlight these results in the light of the recent observational update on the dark mass bounds in the galactic centre by the GRAVITY Collaboration et al. (2022, https://doi.org/10.1051/0004-6361/202142465).

Photon ring autocorrelations

Shahar Hadar
University of Haifa

In the presence of a black hole, light sources connect to observers along multiple paths. As a result, observed brightness fluctuations must be correlated across different times and positions in black hole images. Photons that execute multiple orbits around the black hole appear near a critical curve in the observer sky, giving rise to the photon ring. In the talk I will briefly review the structure of a Kerr black hole’s photon ring. I will then discuss a novel observable we have recently proposed: the two-point correlation function of intensity fluctuations on the ring. This two-point function exhibits a universal, self-similar pattern

consisting of multiple peaks of identical shape: while the profile of each peak encodes statistical properties of fluctuations in the source, the locations and heights of the peaks are determined purely by the black hole parameters. Measuring these peaks would demonstrate the existence of the photon ring without resolving its thickness, and would provide estimates of black hole mass and spin. With regular monitoring over sufficiently long timescales, this measurement could be possible via interferometric imaging with the next-generation Event Horizon Telescope.
(Based on work with Michael Johnson, Alexandru Lupsasca, and George Wong)

A novel formulation for the evolution of relativistic rotating stars

Hirotada Okawa
Waseda Institute for Advanced Study

We present a new formulation to construct numerically equilibrium configurations of rotating stars in general relativity. Having in mind the application to their quasi static evolutions, we adopt a Lagrangian formulation of our own devising, in which we solve force balance equations to seek for the positions of fluid elements assigned to the grid points, instead of the ordinary Eulerian formulation. Unlike previous works in the literature, we do not employ the first integral of the Euler equation, which is not obtained by an analytic integration in general. We assign a mass, specific angular momentum and entropy to each fluid element in contrast to the previous methods, in which the spatial distribution of the angular velocity or angular momentum is specified. Those distributions are determined after the positions of all fluid elements (or grid points) are derived in our formulation. We solve the large system of algebraic nonlinear equations that are obtained by discretizing the time-independent Euler and Einstein equations in the finite-elements method by using our new multi-dimensional root-finding scheme, named the W4 method. To demonstrate the capability of our new formulation, we construct some rotational configurations both barotropic and baroclinic. We also solve three evolutionary sequences that mimic the cooling, mass-loss, and mass-accretion as simple toy models.

General relativistic study of a misaligned and deformed pulsar

Sagnik Chatterjee
Indian Institute of Science Education and Research Bhopal

Pulsars are neutron stars with very high angular velocity. They rotate about an axis called the rotational axis. The magnetic moment of such a star lies along the magnetic axis. In a realistic scenario, the rotational axis and the magnetic axis form some finite angle between them hence producing pulsed signals, and such stars are said to be misaligned or oblique rotators. The high angular velocity of the star will result in its deformation along the rotational axis. This talk will discuss a general relativistic model of such oblique rotators. Spin down of the rotator will result in the loss of rotational energy through its magnetic pole. A general relativistic study shows some interesting features regarding the magnetic field and the power loss for the star, showing how they differ from the known Newtonian approach. This talk will

also discuss the charge separation occurring near the surface of the pulsar due to rotation and its changes from the Newtonian counterpart considering general relativistic scenario.

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The impact of relativistic corrections on the detectability of dark-matter spikes with gravitational waves

Nicholas Speeney
Johns Hopkins University

Black holes located within a dark matter cloud can create overdensity regions known as dark matter spikes. The presence of spikes modifies the gravitational-wave signals from binary systems through changes in the gravitational potential or dynamical friction effects. We assess the importance of including relativistic effects in both the dark matter distribution and the dynamical friction. As a first step we numerically calculate the particle dark matter spike distribution in full general relativity, using both Hernquist and Navarro-Frenk-White profiles in a Schwarzschild background, and we produce analytical fits to the spike profiles for a large range of scale parameters. Then we use a post-Newtonian prescription for the gravitational-wave dephasing to estimate the effect of relativistic corrections to the spike profile and to the dynamical friction. Finally we include the torques generated by dynamical friction in fast-to-generate relativistic models for circular extreme mass-ratio inspirals around a nonspinning black hole. We find that both types of relativistic corrections positively impact the detectability of dark matter effects, leading to higher dephasings and mismatches between gravitational-wave signals with and without dark matter spikes.

Reconnection-powered radio transients from binary neutron star coalescence

Elias Most
Princeton University

Gravitational wave events of merging neutron stars are exciting laboratories for multi-messenger astronomy, featuring gravitational wave emission as well as electromagnetic counterparts. Apart from the afterglow and short gamma-ray burst observed for GW170817, there is another potential electromagnetic counterpart that has not yet been detected. Because neutron stars are equipped with strong magnetic fields, the non-trivial interaction of two neutron star magnetospheres before the merger might give rise to an electromagnetic precursor emission.

In this talk, I will present relativistic force-free electrodynamics simulations of a novel mechanism that could produce radio transients prior to the merger of two neutron stars.

Stationary black holes and light rings

Pedro Cunha
University of Aveiro

The ringdown and shadow of the astrophysically significant Kerr black hole (BH) are both intimately connected to a special set of bound null orbits known as light rings (LRs). Does it hold that a generic equilibrium BH must possess such orbits? In this Letter we prove the following theorem. A stationary, axisymmetric, asymptotically flat black hole spacetime in 1+3 dimensions, with a nonextremal, topologically spherical, Killing horizon admits, at least, one standard LR outside the horizon for each rotation sense. The proof relies on a topological argument and assumes C2 smoothness and circularity, but makes no use of the field equations. The argument is also adapted to recover a previous theorem establishing that a horizonless ultracompact object must admit an even number of nondegenerate LRs, one of which is stable.

Image variability of black hole photon rings

Alejandro Cardenas-Avendano
Fundacion Universitaria Konrad Lorenz and Princeton University

Horizon-scale observations of astrophysical black holes have initiated another chapter of strong-field studies of general relativity. As technological advances continue to improve our observations, it will become necessary to compare the resulting data against increasingly detailed theoretical predictions. In this talk, I will present an application of a numerical framework that exploits the integrability of the Kerr spacetime to compute black hole high-resolution images of non-stationary and non-axisymmetric stochastic equatorial source profiles and their respective visibility amplitudes at long interferometric baselines. Our framework allows for detailed studies of black hole photon rings (narrow ring-shaped features, predicted by general relativity but not yet observed) and data variability for future tests of general relativity with black hole images.

Strong gravitational lens image of the M87 black hole with a simple accreting matter model

Ezequiel F. Boero
Observatorio Astronomico de Córdoba

We study simulated images generated from an accretion disc surrounding the supermassive black hole hosted in the nearby galaxy M87. We approach the problem employing very simple accreting models inspired from magnetohydrodynamical simulations and introducing a new recipe for dealing with the combined integration of the geodesic and geodesic eviation

equations in Kerr space–time, which allows for a convenient and efficient way to manage the system of equations. The geometry of the basic emission model is given by a two-temperature thin disc in the equatorial plane of the black hole supplemented by an asymmetric bar structure. We show that this configuration permits to generate the most salient features appearing in the EHT Collaboration images of M87 with impressive fidelity.

Making (neutron-star) mountains out of molehills

Fabian Gittins
University of Southampton

Over the past few years, we have enjoyed a wide variety of gravitational-wave detections of compact-binary coalescences. However, the wait continues for the first observation of a rotating neutron star via gravitational waves and, so far, only upper limits on the size of the involved deformations have been obtained. For these reasons, the maximum quadrupole deformation (or mountain) that a neutron star can sustain is of great interest. We outline how neutron-star mountains are calculated, while identifying issues with previous studies relating to boundary conditions. In light of these issues, we present a novel scheme for modelling neutron-star mountains, which requires a description of the fiducial force that takes the star away from sphericity. Finally, we show results computed in full general relativity, exploring the roles of both the deforming force and the equation of state in supporting mountains.

Dynamical quark-hadron phase transition in neutron star cores

Prasad R
Indian Institute of Science Education and Research Bhopal, Bhopal, India

In the dense cores of a neutron star, the nuclear matter is prone to undergo conversion to quark matter (phase-transition), which can result in the formation of quark/hybrid stars. A neutron star's central density is most likely to increase during its lifetime due to spin changes and mass accretion, resulting in the appearance of a small quark phase and a density discontinuity at the center. The discontinuity can lead to a shock wave propagating outward and combusting the hadronic matter to quark matter in the region surpassed by it. Using one-dimensional general relativistic hydrodynamics equations we have performed a simulation of such a dynamical phase transition scenario incorporating combustion equations. The simulation performed reveals the time of conversion to be 30-50 microseconds, which indicates a rapid process. This time scale is different from any other previous studies involving simple analytical estimates. We have also calculated the gravitational wave (GW) emission from this process, the GW from a source at 10 megaparsecs has an amplitude of the order 10^-21 and frequency of 150-300 kHz. The conversion from the neutron star to a hybrid star has a unique signature in the GW signal, which could help in defining and identifying the PT process and the fate of the neutron star. These signals are not in the range of presently operating GW detectors, and may be observed in future high-frequency GW detectors.

A covariant approach to relativistic large-eddy simulations: The fibration picture

Thomas Celora
University of Southampton

Models of turbulent flows require to resolve features all the way down to the dissipation scale. As the required resolution is not within reach of large-scale numerical simulations, standard Newtonian strategies involve either time-averaging or space-filtering of the fluid dynamics. In the talk I will present a new covariant framework for filtering/averaging based on the fibration of spacetime associated with fluid elements and the use of Fermi coordinates to facilitate a meaningful local analysis. I will also touch upon how such smoothing can impact on the physics that is represented, and hence on the thermodynamics inferred from observation/simulations.

Luminosity Selection for Gamma Ray Burst

Shreya Banerjee
Friedrich Alexander University, Germany

There exists an inevitable scatter in intrinsic luminosity of Gamma Ray Bursts(GRBs). If there is relativistic beaming in the source, viewing angle variation necessarily introduces variation in the intrinsic luminosity function (ILF). Scatter in the ILF can cause a selection bias where distant sources that are detected have a larger median luminosity than those detected close by. Median luminosity divides any given population into equal halves. When the functional form of a distribution is unknown, it can be a more robust diagnostic than any that use trial functional forms. In this work we employ a statistical test based on median luminosity and apply it to test a class of models for GRBs. We assume that the GRB jet has a finite opening angle and that the orientation of the GRB jet is random relative to the observer. We calculate Lmedian as a function of redshift by simulating GRBs empirically, theoretically and use the luminosity vs redshift {it Swift} data in order to compare the theoretical results with the observed ones. The method accounts for the fact that at some redshifts there may be some GRBs that go undetected. We find that Lmedian is extremely insensitive to the on-axis (i.e. maximal) luminosity of the jet.

Observing photon rings with future interferometric instruments

Frederic Vincent
Paris Observatory / LESIA

The planet-size network of millimeter antennas Event Horizon Telescope (EHT) has recently delivered images of the surroundings of the supermassive black hole M87* at the center of the galaxy Messier 87. Such images are crucial to better understand the physics at play in a strong gravitational field environment. They might also allow to probe the extreme relativistic effects on the radiation emitted close to the compact object. Images of black holes are known to show thin annular features (« photon rings ») due to the strong lensing of photons, as well as a central flux-depleted region (« shadow »). Photon rings are particularly

interesting features, because they are the direct consequence of the existence of unstable photon orbits, and thus are probes of a crucial property of the spacetime. In this talk, I will first discuss these features, and determine their properties depending on the kind of accretion flow considered (for what kind of flows can we see a clearly distinct photon ring? What kind of shadow depending on the dynamics of the flow?). I will then present a simple accretion model for M87* aimed at studying these features. I will discuss what aspects of the photon rings are (in)dependent of the underlying (typically poorly-constrained) astrophysical assumptions on the accretion flow. I will particularly focus on the effect of realistic radiative transfer on the photon rings, and in particular on the impact of absorption, and discuss the robustness of the photon rings, in the perspective of future missions that would aim at detecting such features.

Extreme astrophysics with GRAVITY: energetic outbursts near the event horizon of the Galactic Centre black hole

Nicolas Aimar
LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. de Paris, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France

For the past two decades, flares (i.e. outbursts of radiation) have been observed from the centre of the Milky Way where a massive compact object of 4.2 millions solar masses resides at only 8.3 kpc. This makes this object called Sgr A* the closest supermassive black hole candidate to Earth and a unique laboratory for relativistic astrophysics. Recent observations have shown that the source of these outbursts is close to the event horizon and has an orbital motion around the black hole. Many scenarios are envisaged to explain this phenomenon without reaching a consensus. Among these scenarios, magnetic reconnection is one of the most promising, supported by many GRMHD and PIC studies. During this presentation I will present two models of flares: a general analytical "hot spot" model taking into account the quiescent state of Sgr A* and a more realistic magnetic reconnection model based on kinetic simulations. I will examine the diversity of observables associated to these models and discuss them in the light of the recent VLTI/GRAVITY observations of Sgr A* flares.

On the Parametrized post-Newtonian Test of GR at Galactic Center Massive Black Hole

Hiromi Saida
Daido University

At the center of our galaxy, the massive BH of 4 million solar mass, named Sgr A*, ought to exist as implied strongly by the monitoring observations of stars orbiting around Sgr A*. A star, named S0-2 or S2, orbiting around Sgr A* has passed the closest point (periapse) to Sgr A* in May 2018. The gravity that S0-2 experienced around the periapse passage, 2018-2019, is two orders of magnitude stronger than the gravity ever observed with photons such as Hulse-Taylor pulsar. Our monitoring observations of S0-2, since 2014 with the Subaru telescope, have contributed to the detection of a significant deviation from the Newtonian gravity in the S0-2 motion. The current aim of our study is to distinguish General Relativity from the other gravity theories, and we have been performing the parametrized post-

Newtonian (PPN) test using the observational data of S0-2 motion. This talk reports the current status on our PPN test.

What lies in the heart of the Milky Way?

Riccardo Della Monica
Universidad de Salamanca

The centre of the Milky Way has been subject of an intense observational program throughout the last thirty years, leading to exhibit the existence of a point source supermassive object named Sagittarius A* (Sgr A*). While stars orbiting around it are accelerated by gravity up to speeds of 10.000 km/s, Sgr A* moves at less than 1 km/s. The kinematic properties of such stars, called S-stars, set up its mass to about 4 million solar masses, concentrated in a region of only six light hours. These observations seem to indicate that Sgr A* is a supermassive black hole as described by General Relativity. However, the intrinsic nature of this object is still a mystery and intense studies have been carried out exploring alternatives to the standard supermassive black hole picture. In this talk I will discuss about a uniparametric class of models (called Black Bounce) - ranging from a Schwarzschild black hole to two-ways transversable wormholes - and to the constraints that we are able to put on this model using current and future observational data of the S-star.

Testing General Relativity with black hole X-ray data

Cosimo Bambi
Fudan University

The theory of General Relativity has successfully passed a large number of observational tests. The theory has been extensively tested in the weak-field regime with experiments in the Solar System and observations of binary pulsars. The past 5-6 years have seen significant advancements in the study of the strong-field regime, which can now be tested with gravitational waves, X-ray data, and mm Very Long Baseline Interferometry observations. In my talk, I will summarize the state-of-the-art of the tests of General Relativity with black hole X-ray data, discussing its recent progress and future developments.

Blazar microvariability and long term variability

Rosa Poggiani
University of Pisa

Blazars exhibit variations over the electromagnetic spectrum at different time scales. Microvariability occurs at time scales ranging from minutes to hours. The photometric search for microvariability in a sample of blazars and the search for possible correlations with the brightness level of the source will be reported. The fast variations can be used to constrain the central black hole mass. The links with gravitational astronomy will be discussed.

Pulsar as a lab for gravitational wave with the FAST telescope

Chengmin Zhang
FAST Lab, National Astronomical Observatories, Chinese Academy of Sciences

FAST Lab, National Astronomical Observatories, Chinese Academy of SciencesFive-hundred-meter Aperture Spherical Radio Telescope (FAST) is the biggest single dish for pulsar survey, with the highest accuracy, situated in the south of China, which has observed over 500 new pulsars. In this talk, we present how to use the FAST data to constrain the gravitational wave and general relativity effects, including the other gravitational theory. The future perspective proposals are discussed.

Superradiance Suppression from a Binary Companion

Xi Tong
The Hong Kong University of Science and Technology

We study the impact of a binary companion on black hole superradiance at orbital frequencies away from the gravitational-collider-physics resonance bands. We find that a superradiant state can couple to a strongly absorptive state via the tidal perturbation of the companion, thereby acquiring a suppressed superradiance rate. Below a critical binary separation, this suppression prevents the boson cloud from growing up. Such a critical distance leads to tight constrains on gravitational collider physics, especially on the binary mass ratio for Bohr and fine transitions. Meanwhile, backreaction manifests itself as a torque acting on the binary, producing floating/sinking orbits that can be verified via pulsar timing. In addition, the possible termination of cloud growth may help to alleviate the current bounds on the ultralight boson mass from various null detections.

B2: Numerical Relativity (Chair: Matt Choptuik, Coordinator: Zhou-Jian Cao)

Direct Evidence of Gravitational Wave Turbulence

Sebastien Galtier
University Paris-Saclay

I will present the first direct numerical simulation of gravitational wave turbulence (Galtier & Nazarenko, PRL, 2021). General relativity equations are solved numerically in a periodic box with a diagonal metric tensor depending on two space coordinates only (Hadad-Zakharov metric), and with an additional small-scale dissipative term to avoid numerical instabilities. We limit ourselves to weak gravitational waves and to a freely decaying turbulence. We find that an initial metric excitation at intermediate wave number leads to a dual cascade of energy and wave action. When the direct energy cascade reaches the dissipative scales, a transition is observed in the temporal evolution of energy from a plateau to a power-law decay, while the inverse cascade front continues to propagate toward low wave numbers. The wave number and frequency-wave-number spectra are found to be compatible with the analytical theory of weak wave turbulence (Galtier & Nazarenko, PRL, 2017) and the characteristic timescale of the dual cascade is that expected for four-wave resonant interactions. The simulation reveals that an initially weak gravitational wave turbulence tends to become strong as the inverse cascade of wave action progresses with a selective amplification of the fluctuations.

Study of the Intermediate Mass Ratio Black Hole Binary Merger up to 1000:1 with Numerical Relativity

Carlos Lousto
Rochester Institute of Technology

We explicitly demonstrate that current numerical relativity technology is able to accurately evolve black hole binaries with mass ratios of the order of 1000:1. This has direct implications for future third generation (3G) gravitational wave detectors and space mission LISA, as by purely numerical methods we are able to accurately compute gravitational waves, as directly predicted by general relativity. We perform a sequence of simulations in the intermediate to small mass ratio regime, $m_1^p/m_2^p = 1/7, 1/16, 1/32, 1/64, 1/128, 1/256, 1/512, 1/1024$, with the small hole starting from rest at a proper distance $D \approx 13M$. We compare this full numerical evolution with the corresponding semianalytic perturbative results finding a striking agreement for the total gravitational radiated energy and linear momentum as well as for the gravitational waveforms. We display numerical convergence of the results and identify the minimal numerical resolutions required to accurately solve these very low amplitude gravitational waves. We conclude that we have the numerical technology to build up template banks in time for 3G detectors and LISA.

Coherent Gravitational Waveforms and Memory from Cosmic String Loops

Thomas Helfer
Johns Hopkins University

We construct, for the first time, the time-domain gravitational wave strain waveform from the collapse of a strongly gravitating Abelian Higgs cosmic string loop in full general relativity. We show that the strain exhibits a large memory effect during merger, ending with a burst and the characteristic ringdown as a black hole is formed. Furthermore, we investigate the waveform and energy emitted as a function of string width, loop radius and string tension Gμ. Conversely, we show that the efficiency is only weakly dependent on the initial string width and initial loop radii.

Detecting the impact of nuclear reactions on neutron-star mergers through gravitational waves

Nils Andersson
University of Southampton

In order to extract the precise physical information encoded in the gravitational and electromagnetic signals from neutron-star mergers, we need to include as much of the relevant physics as possible in our numerical simulations. In particular, nuclear reactions may affect the gravitational-wave signal, but the impact is uncertain. In order to gain insight, we compare two simulations representing intuitive extremes. In one case, reactions happen instantaneously. In the other case, they occur on timescales much slower than the evolutionary timescale. The results show that, while the differences in the two gravitational-wave signals are small, they should be detectable by third-generation observatories.

Merger dynamics of binary boson stars

Nils Siemonsen
Perimeter Institute

Particle physics models of dark matter, and extensions to the Standard Model, predict the existence of a large abundance of light scalar degrees of freedom in the universe. From a diffuse cloud, these can form into clumps of energy - boson stars. Additionally, due to their high compactness, close to that of black holes, these solutions serve as test beds to study the non-linear dynamics of a large class of ultra-compact objects. We outline a method to obtain constraint satisfying binary Boson star initial data, and discuss the dynamics of merging binaries, focussing specifically on the formation of rotating Boson star remnants.

Double null evolution of a scalar field in Kerr spacetime

Marcos A. Argañaraz

Universidad Nacional de Córdoba, Argentina

We have developed and implemented a numerical scheme and code that computes the evolution of the massless scalar field wave equation in Kerr spacetime, using double null coordinates. The results show a smooth behavior across the event horizon, making it possible to give initial data outside the event horizon, evolve the scalar field across the horizon, and keep the evolution even inside the black hole. This is the first time that a double null evolution is performed for a scalar field in Kerr spacetime.
DOI:https://doi.org/10.1103/PhysRevD.105.084012

Some ongoing Efforts for Evolving Einstein Field Equations on Hyperboloidal Slices

Shalabh Gautam
International Centre for Theoretical Sciences (ICTS), Bengaluru, India

One of the challenges in numerical relativity is to include future null infinity in the computational domain with a well-posed formulation. Success will not only enable us to evolve any system of astrophysical interest, e.g. binary black holes and extracting the gravitational wave signal at future null infinity, with any desired accuracy, but also help in studying various phenomena of fundamental interest. One proposal is to use hyperboloidal slices. In this talk, I will present our ongoing efforts for obtaining a well-posed formulation of the Einstein Field Equations on hyperboloidal slices, all in spherical symmetry. The natural extension will be to generalize these methods to full 3d.

Black hole binaries and light fields: Gravitational molecules

Taishi Ikeda
Sapienza University of Rome

We show that light scalars can form quasibound states around binaries. In the nonrelativistic regime, these states are formally described by the quantum-mechanical Schrodinger equation for a one-electron heteronuclear diatomic molecule. We performed extensive numerical simulations of scalar fields around black hole binaries showing that a scalar structure condenses around the binary – we dub these states “gravitational molecules”. We further show that these are well described by the perturbative, nonrelativistic description.

Gauge structure of the Einstein field equations in Bondi-like coordinates

Thanasis Giannakopoulos
CENTRA - Instituto Superior Tecnico, Lisbon

In the growing field of gravitational wave astronomy, the characteristic problem of general relativity (GR) can help provide waveform models with high accuracy. When combined with the standard Cauchy problem, it can eliminate systematic extrapolation errors. GR in the

characteristic setup is typically formulated in a Bondi-like gauge. Recently it was shown that several prototype formulations of this type are only weakly hyperbolic. I will discuss the root cause of this result and its implication for the Cauchy-Characteristic extraction and matching methods.

Gravitational Waves from Fully General Relativistic Oscillon Preheating

Xiao-Xiao Kou
University of Science and Technology of China

Oscillons are dense nonperturbative objects that may be copiously produced in the preheating period after inflation. During this period, stochastic gravitational waves can also be generated. However, non-perturbative effects are ignored when computing the gravitational wave spectra in the conventional FLRW background. Meanwhile, recent research show that full general relativistic backreaction might be very important within this process. I will discuss how full general relativistic simulations can play a role in characterising the contribution of these non-perturbative effects to gravitational waves, and investigating ambiguities in computing the gravitational wave power spectra in different gauges beyond leading order perturbation.

Non-linear gravitational perturbation of a black hole: Curvature oscillations and the Newman-Penrose constants

Chris Stevens
University of Canterbury

In recent years, a (numerically) wellposed initial boundary value problem for the generalized conformal field equations has been put forward. This has been used to successfully evolve, in the fully non-linear regime, the Schwarzschild space-time perturbed with a gravitational wave out to and beyond null infinity. This allows for direct calculations of global quantities, which has recently been exemplified by obtaining the Bondi energy and momentum (see talk by Jörg Frauendiener). After a brief overview of the above framework, further results will be presented for the same case. Curvature oscillations, namely the non-linear version of quasinormal ringing, will be displayed and loosely compared to their linear counterparts. Preliminary calculations of the Newman-Penrose constants and how we have implemented this into our framework will also be discussed.

A global approach to the nonlinear perturbation of a black hole by gravitational waves

Jöerg Frauendiener
University of Otago

The excitation of a black hole by infalling matter or radiation has been studied for a long time, mostly in linear perturbation theory. In this talk we report on our approach to study numerically the response of a Schwarzschild black hole to an incoming gravitational wave pulse. A wave profile for the ingoing wave is specified at an outer time-like boundary which then hits an initially static and spherically symmetric black hole. The non-linear interaction of the black hole with the gravitational wave leads to scattered radiation moving back out. The clean separation between initial state and incoming radiation makes this setup ideal to study scattering problems. The use of the conformal field equations allows us to trace the response of the black hole to null infinity where we can read off the scattered gravitational waves and compute the Bondi-Sachs mass and the gravitational flux through $\mathscr{I}$. In this way we check the Bondi-Sachs mass loss formula directly on null infinity.

Cauchy Characteristic Matching

Sizheng Ma
Caltech

Two major approaches are used when numerically solving the Einstein field equations. The first one is to use spatial Cauchy slices and treat the system as a standard Cauchy initial value problem. Cauchy-characteristic evolution (CCE) serves as the second approach, which evolves spacetime based on null hypersurfaces. The Cauchy formulation is suitable for the strong field region but is computationally expensive to extend to the wave zone, whereas the Characteristic approach is fast in the wave zone but fails near the binary system where the null surfaces are ill-defined. By combining those two techniques — simulating the inner region with Cauchy evolution and the outer region with CCE, Cauchy-Characteristic matching (CCM) enables us to take advantage of both methods. In this talk, I present our recent implementation of CCM based on a numerical relativity code SpECTRE. We also discuss how CCM improves the accuracy of Cauchy boundary conditions — a benefit that allows us to evolve less of the wave zone in the Cauchy code without losing precision.

On the asymptotics of near Kerr initial data by evolutionary solvers

Károly Csukás
University of Mississippi and Wigner RCP

We have studied the asymptotic behavior of perturbed Kerr initial data by solving the evolutionary form of the vacuum Einstein constraint equations. Unlike in the elliptic formulation, solving the constraints in their evolutionary form, we have direct control over the constrained data only on a single 2-surface. This immediately raises the question of whether it can guarantee the asymptotic flatness of initial data yielded by the evolutionary approach.
Previous works based on perturbed Schwarzschild initial data have already demonstrated that it is possible to guarantee the asymptotic flatness of solutions with certain modifications. Integrating the equations numerically, we have found that results on the modified parabolic-hyperbolic system can be generalized toperturbed Kerr initial data. We have also investigated a new method for the algebraic-hyperbolic system that is more robust than the one applied earlier.

Part of this work is funded by NSF CAREER Award PHY2047382 and NKFIH Grant No. K-115434.

Numerical simulation of PBH formation during the QCD phase transition

Albert Escrivà
University of Brussels (ULB)

Primordial Black Holes (PBHs) could have been formed in the very early universe due to the collapse of large curvature fluctuations after inflation. PBHs are nowadays one of the most attractive and fascinating research areas in cosmology for their possible theoretical and observational implications. In this talk, I will review the physical process of PBH formation, and I will give some new results regarding the numerical simulation of PBHs during the QCD phase transition.

The endpoint of the Gregory-Laflamme instability of black strings revisited

Chenxia Gu
Queen Mary University of London

Numerical studies on the Gregory and Laflamme (GL) instability suggest violations to the Weak Cosmic Censorship (WCC) conjecture in higher dimensions. In the first numerical study on the GL instability of the five-dimensional black strings, Lehner and Pretorius found that the development of the instability can be described as a continuously shrinking black string, more and more parts of which become hyper-spherical black holes (BHs) of different sizes. The process is believed to be self-similar, and as a result, the horizon will pinch off in the late stage of the GL instability, yielding a naked singularity. This provides a counterexample to the WCC. In our study, we revisit the simulation of the GL instability of the five-dimensional black strings with higher resolutions and different numerical methods. Our own GRChombo code which employed conformal and covariant Z4 (CCZ4) formulation, together with the modified Cartoon method, allow us to study the subtle dynamics in the late time of the black string evolution accurately and efficiently. We manage to extend the simulation with a more accurate picture of the late-time dynamics. Interestingly, our evolution results are highly symmetric up to the third generation of the satellite BHs, but beyond that the symmetry is broken and the results become more chaotic.

Fully relativistic simulations of fast rotating quark stars and their universal relations

Kenneth Chen
Department of Physics, The Chinese University of Hong Kong

Numerical simulations of a quark star often face the obstacle of a significant surface density discontinuity. We here report successful fully-relativistic simulations of rotating quark stars using a positivity-preserving Riemann solver for cold MIT bag models empowered by the

EinsteinToolkit. Both the fundamental and first overtone quadrupole ($l = 2$) mode frequencies were successfully extracted. Results were compared with universal relations proposed by Kruger and Kokkotas (2020). We find that quark star's co-rotating bar mode frequencies significantly deviate from their universal relation for the constant baryon mass sequences of uniformly rotating neutron stars whose spin parameters $j = J/M\hat{}2$ are commonly bounded by the value of 0.7. In contrast, a quark star can have a greater spin parameter, even larger than the Kerr black hole limit, and reach very close to the triaxial instability onset when rotating near the Keplerian frequency. New universal relations were also presented, and results from some neutron and hybrid star models were also included.

B3: Approximations, perturbation theory, and their applications (Chair: Alexandre Le Tiec, Coordinator: Li-Ming Cao)

Gravitational wave memory and the wave equation

David Garfinkle
Oakland University

Gravitational wave memory and its electromagnetic analog are shown to be straightforward consequences of the wave equation. From Maxwell's eqautions one can derive a wave equation for the electric field, while from the Bianchi identity one can derive a wave equation for the Riemann tensor in linearized gravity. Memory in both cases is derived from the structure of the source of those wave eqautions.

High-order Classical gravitational scattering from quantum scattering amplitudes

Pierre Vanhove
Institut de Physique Théorique - CEA/Saclay

Recent advances in the scattering amplitude-based approach to the Post-Minkowskian expansion of classical general relativity have demonstrated that this new approach holds the promise of significantly changing the efficiency of computations in general relativity. This approach completes the post-Newtonian computations by providing information beyond its regime of validity. This framework leads to surprising results connecting the conservative part and gravitational radiation effects. As well, the scattering amplitude methods apply to a wide range of effective field theories in various dimensions. In this talk, we will present new results for the post-Minkowskian expansion in various dimensions. We will present a new organisation of the scattering amplitudes for an efficient evaluation of the classical post-Minkowskian contributions to high-loop order. We will discuss a reformulation of the effective-one-body formalism for connecting the scattering amplitudes to the effective classical hamiltonian of the two-body systems and gives applications to probe regime results and the high-energy limit in various dimensions.

Pseudospectrum and black hole quasi-normal mode (in)stability

Rodrigo Panosso Macedo
University of Southamptom

Black hole spectroscopy is as a powerful approach to extract spacetime information from gravitational wave observed signals. However, quasinormal mode (QNM) spectral instability under high wave-number perturbations has been recently shown to be a common classical general relativistic phenomenon. I will discuss these recent results on the stability of QNM in asymptotically flat black hole spacetimes by means of a pseudospectrum analysis.

Pseudospectrum of black holes and compact objects

Kyriakos Destounis
Universität Tübingen

Black hole spectroscopy is a powerful tool to probe the Kerr nature of astrophysical compact objects and their environment. The observation of multiple ringdown modes in gravitational waveforms could soon lead to high-precision gravitational spectroscopy, so it is critical to understand if the quasinormal mode spectrum itself is stable against perturbations introduced by environmental media. In this talk, I will review the pseudospectrum, a mathematical tool which can shed light on the spectral stability of quasinormal modes, and discuss its novel applications in black holes physics and horizonless compact objects. Furthermore, I will show that quasinormal spectra generically suffer from spectral instabilities and argue how such behavior may affect black hole spectroscopy.

Axial perturbations and stability of a Lorentzian wormhole family: triple barrier potentials, quasinormal modes and echoes

Poulami Dutta Roy
IIT Kharagpur

In the context of perturbation analysis of spacetimes, triple barrier potentials are rarely observed and hence their physics is not well understood. We encounter such novel potentials along with their well-known counterparts namely, the double and single barrier potential, while analysing stability under axial perturbations of a Lorentzian wormhole family. The metric parameters n (an even number) and b (throat radius) characterize distinct geometries of the member wormholes among which, the Ellis-Bronnikov wormhole is a special case. The quasi-normal modes associated with each wormhole are linked to their stability and also play instrumental role in distinguishing between different members in the family. Depending on the choice of parameters and the value of the angular momentum number, single, double or triple barrier perturbation potentials are found to occur. The multi-peak nature of the potential leads to an intricate time domain profile, which is characterised by repetitive `echoes' for certain geometries. In the full signal, the echoes get suppressed owing to the nature of the potential. In order to extract the echoes, special `cleaning' techniques have been used, which ultimately highlight the impact of the triple peaks on the echo profile. Finally, the ringdown behaviour of different wormholes in the family are compared with those for black holes, in order to suggest their black hole mimicking features.
"Novel triple barrier potential for axial gravitational perturbations of a family of Lorentzian wormholes", P.D.Roy, arXiv: 2110.05019 [gr-qc]

Applications of the close-limit approximation: horizonless compact objects and scalar fields

Lorenzo Annulli
University of Aveiro

The ability to model the evolution of compact binaries from the inspiral to coalescence is central to gravitational wave astronomy. Current waveform catalogues are built from vacuum binary black hole models, by evolving Einstein equations numerically and complementing them with knowledge from slow-motion expansions. Much less is known about the coalescence process in the presence of matter, or in theories other than general relativity. In this talk, I will show how to use the Close Limit Approximation as a powerful tool to understand the head-on collision of two equal-mass, compact but horizonless objects, showing the appearance of "echoes". I will also apply the Close Limit Approximation to investigate the effect of colliding black holes on surrounding scalar fields, showing that observables obtained through perturbation theory may be extended to a significant segment of the merger phase, where in principle only a numerical approach is appropriate.

Superradiant Instabilities triggered by effective masses

Enrico Cannizzaro
Sapienza University of Rome

It is well known that bosonic waves scattering off a spinning BH can extract rotational energy from it via a phenomenon called superradiance. If this process is supported by a confinement mechanism of the modes, the extraction of energy happens at a continuous level, leading to a so-called superradiant instability. Remarkably, a bare mass of the bosonic field can serve for such purpose, as it can naturally confine low-frequency modes in the vicinity of the BH. Hence, this phenomenon can be used to probe ultralight bosons beyond the Standard Model, such as axions or dark photons. Another interesting possibility is that confinement is provided by an effective mass. For example, spin-1 particles propagating in a plasmic medium acquire a space-dependent effective mass, the plasma frequency, and scalar modes in scalar-tensor theories acquire an effective mass proportional to trace of the stress-energy tensor of the surrounding matter. In this talk, I will describe the role of an effective mass in different systems, showing where the latter can (or cannot) lead to an efficient superradiant instability.

Massive vector fields in Kerr-Newman and Kerr-Sen black hole spacetimes

David Kubiznak
Charles University

The superradiant instability modes of ultralight massive vector bosons are studied for weakly charged rotating black holes in Einstein-Maxwell gravity (the Kerr-Newman solution) and low-energy heterotic string theory (the Kerr-Sen black hole). We show that in both these cases, the (appropriately modified) massive vector (Proca) equations can be fully separated, exploiting the hidden symmetry present in these spacetimes. The resultant ordinary differential equations are solved numerically to find the most unstable modes of the Proca field in the two backgrounds and compared to the vacuum (Kerr black hole) case.

Gravitational waveforms for compact binaries from second-order self-force theory

Barry Wardell
University College Dublin

Extreme mass ratio inspirals (EMRIs) are expected to be a key source of gravitational waves for the LISA mission. In order to extract the maximum amount of information from EMRI observations by LISA, it is important to have an accurate prediction of the expected waveforms. In particular, it will be necessary to have waveforms that incorporate effects that appear at second order in the mass ratio. In this talk I will present the latest progress towards this goal, including recent results for the second-order gravitational waveform.

Self-force in hyperbolic black hole encounters

Oliver Long
University of Southampton

Scattering orbits are excellent probes of the strong-field regime around black holes. It has been shown that knowledge of the scattering angle through linear order in the mass ratio can be used to inform high order analytic expressions for scatter and bound orbits. With this motivation in mind, we describe a programme to calculate the self-force correction to the scatter angle. We show a formulation of the conservative self-force correction to the scatter angle in Schwarzschild spacetime, and thus identify the necessary self-force input. We describe a novel time-domain method for setting up such a calculation, and present results for the toy model of a scalar charge on a hyperbolic orbit.

Self-force in hyperbolic scattering: a frequency-domain approach

Christopher Whittall
University of Southampton

Hyperbolic scattering orbits, able to penetrate deep into the sub-ISCO region even at relatively low energies, provide an excellent probe of the strong-field regime outside black holes. Of particular recent interest are self-force calculations of the scatter angle, which can greatly advance the development of post-Minkowskian theory and the effective-one-body model of binary dynamics, at any mass ratio. Frequency-domain codes already exist for calculating self-force along bound orbits, and they are prized for their accuracy and efficiency. However, extending these established techniques to unbound orbits poses certain challenges. We investigated and resolved some of these issues in the context of a scalar charge moving along a hyperbolic geodesic in the Schwarzschild spacetime, and present our findings here. Particular attention will be paid to the numerical challenges involved in calculating slowly-convergent oscillatory integrals which stretch to radial infinity, the status of the EHS method usually used to overcome the Gibbs phenomenon, and a discussion of efficient time-domain

reconstruction with a continuous spectrum. We will end our talk by presenting our most recent results for the self-force, and the next steps towards a calculation of the scatter angle.

Proposal of a gauge-invariant treatment of l=0,1-mode perturbations on the Schwarzschild background spacetime

Kouji Nakamura
National Astronomical Observatory of Japan, Gravitational Wave Science Project

We have been developing a gauge-invariant perturbation theory on a generic background spacetime from 2003 [1]. In 2013, we proposed "zero-mode problem" for linear metric perturbations as the essential problem in this formulation [2]. In the perturbation theory on the Schwarzschild background spacetime, l=0,1 modes of perturbations correspond to the above "zero-mode" and the gauge-invariant treatments of these modes is a famous non-trivial problem in perturbation theories on the Schwarzschild background spacetime.
In this talk, we propose a gauge-invariant treatment of the l=0,1-mode perturbations on the Schwarzschild background spacetime. Through this gauge-invariant treatment, we derive the solutions to the linearized Einstein equation for these modes with a generic matter field. In the vacuum case, these solutions include the Kerr parameter perturbations in the l=1 odd modes and the additional mass parameter perturbations of the Schwarzschild mass in the l=0 even modes. Then, the linearized version of Birkhoff's theorem is confirmed in a gauge-invariant manner. In this sense, our proposal is reasonable.
This talk is based on our recent works [3].

[1] K. Nakamura, Prog. Theor. Phys. 110 (2003), 723;
K. Nakamura, Prog. Theor. Phys., 113 (2005), 413.
[2] K. Nakamura, Prog. Theor. Exp. Phys. 2013 (2013), 043E02.
[3] K. Nakamura, Class. Quantum Grav. 38 (2021), 145010;
K. Nakamura, Letters in High Energy Physics, 2021 (2021), 215;
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K. Nakamura, arXiv:2110.13512v3 [gr-qc];
K. Nakamura, arXiv:2110.13519v3 [gr-qc].

Towards the gravitational wave phase of compact binaries with 4PN precision

François Larrouturou
Deutsches Elektronen-Synchrotron (DESY)

The precise knowledge of the gravitational phase of compact binaries is crucial to the detection methods for gravitational waves. To this days, we know it analytically (for non-spinning systems) up to the 3.5 post-Newtonian (PN) order, ie. up to the (v/c)^7 correction beyond the leading order. If this precision is sufficient for the data analysis of the current generation of detectors, the next ones (notably The Einstein Telescope) will require a better accuracy.An essential ingredient to compute the gravitational wave phase is the mass quadrupole moment, that we are currently computing for compact binaries at 4PN order, using a post-Newtonian-multipolar-post-Minkowskian matching algorithm. This method involves challenging technical issues, due to the appearance of non-physical divergences, that have to be properly regularized, as well as non-linear interaction terms (dubbed "tails"). In this talk, I will present the current status of the computation, and review the steps that are left in order to fully derive the gravitational phase at 4PN order.

Gravitational-wave tails-of-memory

David Trestini
Institut d'Astrophysique de Paris / Laboratoire Univers et Théories

Gravitational-wave tails are linear waves that backscatter on the curvature of space-time generated by the total mass-energy of the source. Conversely, the memory effect is gravitational radiation sourced by the stress-energy distribution of linear waves themselves. These two effects are due to quadratic interactions (mass-quadrupole and quadrupole-quadrupole) and other quadratic, cubic and quartic effects have more recently been investigated. In this work, we focus of the cubic mass-quadrupole-quadrupole interaction, which contributes to the 4PN gravitational waveform. In particular, we compute the contribution to the 4PN radiative quadrupole. We find new non-local terms -- the 'tails-of-memory' -- which can be seen as the gravitational radiation sourced by the stress-energy distribution of tails.

Gravitational wave memory and its tail in cosmology

Miika Sarkkinen
University of Helsinki

We study gravitational wave memory effect in the FRW cosmological model with matter and cosmological constant. Since the background is curved, gravitational radiation develops a tail part arriving after the main signal that travels along the past light cone of the observer. First we discuss first order gravitational wave sourced by a binary system, and find that the tail only gives a negligible memory, in accord with previous results. Then we study the nonlinear memory effect coming from induced gravitational radiation sourced by first order gravitational radiation propagating over cosmological distances. In the light cone part of the induced gravitational wave we find a novel term missed in previous studies of the cosmological memory effect. Furthermore, we show that the induced gravitational wave has a tail part that slowly accumulates after the light cone part has passed and grows to a sizeable magnitude over a cosmological timescale. This tail part of the memory effect will be a new component in the stochastic gravitational wave background.

Effect of a viscous fluid matter shell on gravitational wave propagation

Nigel Bishop
Rhodes University

Previous work [1] used the Bondi-Sachs formalism to consider the problem of a gravitational wave (GW) source surrounded by a spherical dust shell. Using linearized perturbation theory, solutions were found in three regions: in the shell, exterior to the shell, and interior to the shell, and it was shown that the dust shell causes the GW to be modified both in magnitude and phase. These effects are astrophysically significant since there are scenarios for which the modification to the GW signal is large enough to be measurable [2].Here, the above approach is extended to the case that the matter shell comprises a viscous fluid, so that the shear induced in the velocity field by GWs results in an energy transfer to the fluid so reducing the magnitude of the GWs. Previous work has considered the case that GW damping occurs far from the source and is proportional to the distance traversed through the viscous fluid. We obtain a simple formula for GW damping by a viscous fluid, and find the novel result that it can be significant when the shell radius r is much smaller than the GW wavelength λ. The GW damping effect is proportional to the coefficient of shear viscosity times λ8/r7, and so there are scenarios for which it is relevant to GW measurements.

1. N.T. Bishop, M. Naidoo, and P.J. van der Walt (2020), Gen. Rel. Grav. 52:92, https://doi.org/10.1007/s10714-020-02740-92. M. Naidoo, N.T. Bishop, and P.J. van der Walt (2021), Gen. Rel. Grav. 53:97, https://doi.org/10.1007/s10714-021-02841-z

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Fine structure and symmetries of the photon ring

Shahar Hadar
University of Haifa

Light rays that execute multiple orbits around a black hole appear near a critical curve in an observer's sky, and can give rise to a sharp bright ring. This photon ring inherits a universal, intricate structure from the spacetime geometry and displays a self-similarity which controls the black hole's near-critical perturbations. In the talk I will describe this symmetry structure, the corresponding critical exponents, and its consequences for black hole images and eikonal quasinormal modes.

(Work in collaboration with Johnson et al. [Science Advances 6 no. 12, (Mar., 2020) eaaz1310,], and Daniel Kapec, Alexandru Lupsasca, and Andrew Strominger)

Review talk on spin effects in compact binary systems

Michèle Levi
UK

I will present the state of the art in classical gravity for spin effects in gravitational-wave measurements, and the significant advancement therein via the EFT of spinning gravitating objects, and the incorporation of modern QFT advances, which my work pioneered more than a decade ago.Finally, we will present some recent advanced results accomplished within this framework, with modern QFT advances.

Energetics and scattering of compact objects at fourth post-Minkowskian order

Mohammed Khalil
Max Planck Institute for Gravitational Physics

Accurate waveform models are crucial for gravitational-wave data analysis, and since numerical-relativity waveforms are computationally expensive, it is important to improve the analytical description of the binary dynamics. The post-Newtonian (PN) approximation is valid for small velocities and weak gravitational field, while the post-Minkowskian (PM) approximation is valid for arbitrary velocities in the weak field. We assess the accuracy of recent results for the 4PM conservative dynamics through comparisons with the PN approximation and numerical relativity simulations for the circular-orbit binding energy and the scattering angle. We also incorporate the PM results in effective-one-body Hamiltonians, which significantly improves the accuracy over PM-expanded Hamiltonians. We find that while the 4PM approximation gives comparable results to the 3PN approximation for bound orbits, it performs better for scattering encounters.

Gravitational self-force and multiscale expansions at "post-adiabatic +" order

Adam Pound
University of Southampton

As gravitational-wave detectors become more sensitive to lower frequencies, they will increasingly detect binaries with smaller mass ratios, larger spins, and higher eccentricities. Gravitational self-force theory, when combined with a method of multiscale expansions, provides an ideal framework for modelling these systems. The framework proceeds from first principles while simultaneously enabling rapid generation of waveforms on a timescale of milliseconds. While it was originally motivated by extreme-mass-ratio inspirals with mass ratios $\sim 10^4$--10^7, new results show that it can be highly accurate even for mass ratios ~ 10.

In this talk, I present the framework for generic inspirals around spinning, Kerr black holes at second order in the mass ratio ("first post-adiabatic order") and the formalism’s extension to include a spinning secondary and the final merger. This lays the groundwork for companion talks by Wardell, Durkan, Leather, Lewis, Spiers, and Upton.

The Two-Timescale Expansion for Extreme-Mass-Ratio Inspirals.

Jack Lewis
University of Southampton

This talk will provide an overview of the two-timescale expansion of the Einstein field equations in the study of the extreme-mass-ratio inspiral (EMRI) problem. This expansion takes advantage of the natural separation of timescales in an EMRI into the short orbital timescale and the longer radiation-reaction timescale. In this expansion, the perturbation to the metric can be expanded in modes whose amplitudes vary slowly, and whose phases vary

on the orbital timescale. Such an expansion is uniformly accurate over the inspiral until the transition to plunge, and is at the core of current waveform generation schemes for EMRIs.

In this talk I will also detail the scheme for waveform generation using the two-timescale expansion for eccentric equatorial orbits in Schwarzschild spacetime.

Covariant and coordinate punctures for second-order gravitational self-force in a highly regular gauge

Samuel Upton
University of Southampton

Second-order gravitational self-force (2GSF) is the primary way of modelling extreme-mass-ratio inspirals (EMRIs). These are an important class of gravitational wave sources for the future space-based detector the Laser Interferometer Space Antenna (LISA). In an EMRI, a compact object of ~10 solar masses spirals into a supermassive black hole, ~10^6 solar masses, over the course of a year. One difficulty that appears in self-force calculations is dealing with the strong divergence that occurs near the worldline of the small object, causing both numerical and analytical issues. Previous work demonstrated that this could be alleviated within a class of highly regular gauges and also presented the metric perturbation in these gauges in a local coordinate form. We build on this previous work using methods developed for Lorenz gauge 2GSF calculations to derive expressions for the highly regular gauge metric perturbations in both fully covariant form and in a generic coordinate expansion. These results could then be used as input into a puncture scheme or two-timescale expansion in order to solve the field equations.

Post-Newtonian expansions in second-order self-force theory

Adam Pound
University of Southampton

Small-mass-ratio black hole binaries and their gravitational radiation can be described analytically using the gravitational self-force approach in tandem with a post-Newtonian approximation. Post-Newtonian-self-force (PN-SF) results can typically be taken to high PN order and have proven highly fruitful in exchanging information with standard PN theory, informing effective-one-body theory, and providing easy-to-use weak-field benchmarks for numerical self-force calculations. In this talk we describe a methodology for computing post-Newtonian self-force expansions at second order in the mass ratio. The method is naturally compatible with the two-timescale framework used in current numerical 2SF calculations. We discuss the requirements on our method in obtaining an arbitrary PN order, and the associated challenges. Finally we demonstrate results using a representative model.

Evolving black hole with scalar field accretion

Marco de Cesare
University of the Basque Country UPV/EHU

We obtain approximate analytical solutions of the Einstein equations close to the trapping horizon for a dynamical spherically symmetric black hole in the presence of a minimally coupled self-interacting scalar field. This is made possible by a new parametrization of the metric, in which the displacement from the horizon as well as its expansion rate feature explicitly. Our results are valid in a neighbourhood of the horizon and hold for any scalar field potential and spacetime asymptotics. An exact equation for the accretion rate is also obtained, which generalizes the standard Bondi formula. We also develop a dynamical system approach to study near-equilibrium black holes; using this formalism, we focus on a simple model to show that the near-equilibrium dynamics is characterised by scaling relations among dynamical variables. Moreover, we show that solutions with purely ingoing energy-momentum flux never reach equilibrium.

Talk based on arxiv preprint: 2205.01712

Redshift factor and the small mass-ratio limit in binary black hole simulations

Aaron Zimmerman
University of Texas at Austin

The redshift factor, a measure of the rate of proper time elapsed along a particle worldline, is a quantity of fundamental interest in analytic approximations to relativistic two-body dynamics. Here I present the extraction of the redshift factor from quasi-circular simulations of nonspinning binary black holes. By investigating the redshift factor over a range of mass ratios, we are able to fit our results to a small-mass-ratio expansion. We recover the test-particle limit and find agreement with first-order self-force results using numerical simulations alone. We find accelerated convergence of this expansion for a symmetric combination of the redshift factors on both black holes, when using the symmetric mass ratio as our small parameter. Our work provides further evidence of the surprising effectiveness of the small-mass-ratio approximation in binary systems, even at comparable masses.

Action-angle coordinates for binary inspirals

Vojtěch Witzany
University College Dublin

Action-angle (AA) coordinates are a traditional tool in celestial mechanics with roots already in 1609 in the works of Johannes Kepler. The Actions are gauge-invariant orbital elements, and the Angles decode spectral solution of the equations of motion. As a result, they serve as an extremely convenient basis for further analytical computations. I will show how AA coordinates are constructed in various approximations to the relativistic two-body problem (EOB, large mass ratio,...) and how they allow to efficiently generate binary inspirals.

Transition to Plunge: Modelling IMRIs for ground-based detectors

Leanne Durkan
University College Dublin

The LIGO, Virgo, Kagra Collaboration are already beginning to detect intermediate mass ratio inspirals (IMRIs), driving the need for improved IMRI models. In recent work (arXiv: 2112.12265) we have shown that waveforms modelled using the second-order gravitational self-force approach, intended for modelling extreme mass ratio inspirals (EMRIs), match exceedingly well to waveforms produced by NR simulations at intermediate mass ratios, at least during the inspiral. However, missing from current self-force waveforms are the transition to plunge, the plunge itself, the merger and of course the ringdown. In this talk I will discuss progress on modelling the transition to plunge for both IMRIs and EMRIs, with the aim of using our model to assist signal extraction of IMRI data from the next gravitational wave observation run, especially for mass ratios beyond the reach of NR. In particular I will discuss how we match the amplitudes of the waveform in the inspiral to the transition regime. This work is in collaboration with Lorenzo Kuchler, Geoffrey Compere, Adam Pound, Niels Warburton, Barry Wardell, Alexandre Le Tiec and Jeremy Miller.

Calculating the second-order self-force for a Teukolsky formalism

Benjamin Leather
University College Dublin

Second-order self-force calculations are key to modelling extreme mass-ratio inspirals (EMRIs) and recently have been shown to also model intermediate mass-ratio binaries (IMRIs). These calculations are carried out in the Lorenz gauge which is not separable for the astrophysically relevant scenario of Kerr spacetime. Hence we are now pursuing a second-order calculation for the Teukolsky equation. In this talk, I present a numerical implementation to compute the second-order Weyl scalar with a new, alternative hyperboloidal method. In this approach the spacetime is foliated by horizon-penetrating hyperboloidal slices. Further compactifying the coordinates along these slices allows for simple treatment of the boundary conditions and to implement this approach with a multi-domain spectral solver. We shall consider preliminary results for the second-order flux from applying this method with an appropriately constructed second-order source for quasi-circular orbits in Schwarzschild spacetime (see Andrew Spiers' talk on the second-order Teukolsky source in Schwarzschild).

Mode decomposing the second-order Teukolky source

Andrew Spiers
University of Southampton

As black hole perturbation theory research begins to tackle second-order applications (see self-force and quasi-normal modes), a barrier to efficient calculations has become apparent: separating the source of the Teukolsky equation. The separability of the Teukolsky equation

has been utilised to solve the homogeneous case for many problems. However, in the non-homogeneous case, one must decompose the source into spin-weighted spheroidal harmonics (the eigenbasis of the angular Teukolsky equation) to solve the separable Teukolsky equation. I present our results for decomposing the second-order source to the Teukolsky equation into spin-weighted spherical harmonics in Schwarzschild (for solving the second-order Teukolsky equation with this source, see Ben Leather's talk). I follow with a description of why the mode decomposition becomes problematic in Kerr, which could block efficient second-order calculations (a necessity for modelling generic EMRIs with second-order self-force). I finish with a discussion on the methods I am developing to overcome this problem.

Simple and efficient, high-order expansion of the Detweiler-Whiting singular field

Patrick Bourg
University of Southampton

In an extreme-mass-ratio inspiral, the smaller-mass object is typically modelled as a point particle. While conceptually elegant, the main drawback of this approach is that the first-order-in-the-mass-ratio metric perturbation is singular at the particle. Current methods of dealing with this consist of splitting the full retarded field into a singular piece, encoding the local multipole moments of the particle, and a regular piece. This last piece is key in computing self-force corrections to geodesic motion in Kerr. While it is not possible to obtain an exact expression of the singular piece, one can find a local one, in powers of the distance to the particle. The current methodology to do this invokes many subtle mathematical constructs. In addition to its technical complexity, it is challenging to obtain the local expression of the singular field beyond a few total orders.
In this presentation, I will show a novel, both simple and efficient, approach in computing this local expression. As a proof of principle, I will show that applying this method to a scalar charge in circular orbit around a Schwarzschild black hole, one can generate a 12th-order puncture. As a result, when used in a puncture scheme it will provide a smoother effective source, improving convergence of Fourier- and spherical-harmonic mode sums and particularly ameliorating the catastrophic mode-coupling problem that arises at second order.

Rotational tidal Love numbers and their impact on neutron star inspirals

Goncalo Castro
Sapienza University of Rome

The coupling between the angular momentum of a compact object and an external tidal field gives rise to the "rotational" tidal Love numbers, which affect the tidal deformability of a spinning self-gravitating body and enter the gravitational waveform of a binary inspiral at high post-Newtonian order. We provide numerical evidence for a surprising "hidden" symmetry among the rotational tidal Love numbers with opposite parities, which are associated to perturbations belonging to separate sectors. We further show that neglecting this and other tidal-rotation couplings in the gravitational waveform may lead to a significant error in the parameter estimation by third-generation gravitational wave detectors, suggesting that current models of tidal deformation in late inspiral should be improved in order to avoid waveform systematics and extract reliable information from gravitational wave signals observed by next generation detectors.

B4: Cosmology: Theory and observations (Chair: Richard Battye, Coordinator: Bin Hu)

The running curvaton and its corresponding formation of primordial blackhole

Lei-Hua Liu
Department of Physics, Jishou University, Jishou, China

In this talk, we first will introduce the running curvaton model, in which the curvaton is explicitly coupled to the inflaton. The production of curvaton contains the cases of narrow resonance and broad resonances whose criteria comes via the spectral index of curvaton. The various inflationary potential can be approximately to be a quadratic term, thus our running curvaton model is almost model independent. Finally, as the decay of inflaton finishes, the relic of curvaton potential will be approaching a constant of order of cosmological constant, which may play a role of dark energy. We investigate the possibility of formation for primordial black-hole during preheating period, in which we have implemented the instability of the Mathieu equation. For generating sufficient enough enhanced power spectrum, we choose some proper parameters belonging to the narrow resonance. To characterize the full power spectrum, the enhanced part of the power spectrum is depicted by the δ function at some specific scales, which is highly relevant with the mass of inflaton due to the explicit coupling between the curvaton and inflaton. One case could account for the dark matter in some sense since the abundance of a primordial black hole is about 75%. Thus, our model could unify dark energy and dark matter from the perspective of phenomenology.

Primordial black hole formation during the QCD phase-transition

Ilia Musco
INFN, Sapienza University of Rome

The formation of Primordial black holes is naturally enhanced during the QCD phase transition, because of the softening of the equation of state: at a scale between 1 and 3 solar masses, the threshold is reduced of about 10% with a corresponding abundance of primordial black holes increased by more than 100 times. Such black holes could be an interesting source of gravitation waves emitted during black hole mergers, detected by LIGO/VIRGO.

Hubble diversity: Chameleon dark energy model for the environmentally-dependent Hubble constant

Shao-Jiang Wang
Institute of Theoretical Physics, Chinese Academy of Sciences

The Hubble tension has become a crisis with a 5-sigma discrepancy between the most recent local distance ladder measurement from Type Ia supernovae calibrated by Cepheids and the global constraint from fitting the cosmic microwave background data to the Lambda-cold-dark-matter model. This Hubble tension, if not caused by any known systematics, could be relieved by modifying either the early-time or late-time Universe. However, the early-time modifications are usually in tension with either galaxy clustering or galaxy lensing constraints, and the late-time homogeneous modifications are also in tension with the inverse-distance-ladder constraints. We therefore propose a late-time inhomogeneous resolution with a chameleon field coupled to the local matter density, which behaves as a local effective cosmological constant proportional to the local matter density. Therefore, the regions with a higher matter density would expand locally faster than the regions with a lower matter density. We further report our recent finding of an observational hint from the large-scale-structure data for the environmentally-dependent Hubble constant.

Searching for primordial black holes at current and future gravitational wave detectors

Gabriele Franciolini
La Sapienza University of Rome

Primordial Black Holes might comprise a significant fraction of dark matter in the Universe and can give rise to observable signatures at current and future gravitational wave experiments. First, we review the PBH model and discuss how accretion and clustering may affect the properties of PBH binaries. Second, we confront the PBH model with LIGO/Virgo/KAGRA data showing its upsides and shortcomings, by also including state-of-the-art astrophysical models in a multi-population inference. Finally, we discuss how future generation detectors may be able to discover a PBH population by searching for high redshift merger events.

Cosmological Standard Timers in Primordial Black Hole Scenarios

Qianhang Ding
The Hong Kong University of Science and Technology

We propose a formalism of standard timers in tracking the evolution of the Universe. By studying the evolution of the dynamic systems in the Universe, their physical evolution time can be extracted. Meanwhile, their observational signals encode the cosmological redshift. Accordingly the redshift-time calibration can be obtained from the observable of the cosmological dynamic systems, which helps the understanding the evolution of the Universe. In a practical description of the cosmological standard timer, we use the Hawking radiation from the Primordial Black Holes (PBHs) clustering and the gravitational waves from PBH binaries as the examples to show how to extract the redshift-time calibration from the observables, which also shows the great potential of standard timers in understanding the Universe.

Analytical model for black hole evaporation in cosmological space-time

Semin Xavier
Indian Institute of Technology Bombay, India

Astronomical and cosmological evidence suggests that cold, non-baryonic dark matter dominates the universe. The Primordial Black Holes (PBHs) have been presented as a possible dark matter contender. PBHs that characterize dark matter should be entrenched in the cosmological background, surrounded by mass distributions, in a realistic scenario. As a result, studying the exact solutions of the Einstein equations, which could represent things with strong gravitational fields contained in an expanding universe, would be extremely beneficial.This talk discusses an exact time-dependent solution for evaporating black holes with a matter content represented by a two-fluid source. As a result, the solution considers all three aspects of PBHs: Hawking radiation, black hole mass distribution, and cosmological backdrop. Furthermore, unlike black holes in asymptotically flat space-times, our model predicts that the decay rate of PBHs is faster for greater masses. In addition, we discuss invariant quantities such as Misner-Sharp-Hernandez energy, the dynamical horizon, and the Kodama vector. Finally, we analyze how theoretical restrictions affect PBHs as dark matter (Based on arXiv:2110.14379)

Coupled quintessence with a generalized interaction term

Paulo M. Sá
Universidade do Algarve and IA-U.Lisboa

We describe a cosmological model in which dark energy, represented by a quintessential scalar field, is directly coupled to a dark-matter perfect fluid. A generalized class of couplings between these two dark components of the Universe is considered. Resorting to methods of qualitative analysis of dynamical systems, solutions of cosmological relevance are identified and analyzed.

Small-scale fluctuations in alpha-attractor inflation

David Wands
University of Portsmouth

Alpha-attractor models of inflation in the very early universe naturally meet the increasingly tight observational bounds coming from cosmic microwave background (CMB) anisotropies on large scales. We study the dynamics in alpha-attractors driven by scalar fields in a hyperbolic field space including the effect of geometrical destabilisation and non-geodesic motion in field space which can lead to a large enhancement of the scalar power spectrum on small scales, and potentially primordial black hole production and second-order gravitational waves. Consistency with current CMB constraints on the spectral tilt on large-scales suggests that PBHs can only be produced with masses smaller than 10^8g and are accompanied by ultra-high frequency GWs, with a peak expected to be at frequencies of order 10kHz or above.

Warm inflation as a way out of the swampland

Meysam Motaharfar
Department of Physics and Astronomy, Louisiana State University

We discuss how warm inflation, an alternative dynamical realization of conventional inflation, during which dissipative particle production effects sustain thermal bath, can evade swampland conjectures. We realize that warm inflation resides in the landscape of string theory provided it occurs with sufficiently large dissipation factor. However, most michrophysical quantum field theory models result in temperature dependent dissipation coefficients, leading to a growing mode in power spectrum, due to back-reaction of coupling of inflaton and radiation field perturbations, and rendering the power spectrum blue for large dissipation factor. To remove this difficulty, we propose two phenomenological models inspired from string theory to realize such large dissipation factor. First, we study a warm inflation model, with exponential potential and cubic temperature dependent dissipation coefficient, embedded in the Randall-Sundrum braneworld scenario. We find that the presence of extra dimension effect together with exponential potential, not only bring inflation to an end but also the growing mode becomes decreasing mode, then allows the model to achieve large enough dissipation factor to overcome all swampland conjectures. Second, we consider warm inflation with Dirac-Born-Infeld kinetic term in which both the dissipative effect and small sound speed slow the motion of inflaton. Then, computing the power spectrum for both linear and cubic temperature dependent dissipative coefficients, we find that growing mode is strongly suppressed or completely disappear for small enough sound speed, allowing the model to be realized with strong enough dissipation factor. These findings give a strong hint that warm inflation may consistently be embedded into string theory as an UV-complete model.

Refs:

[1] M. Motaharfar, V. Kamali and R. O. Ramos, Phys. Rev. D 99, no.6, 063513 (2019) doi:10.1103/PhysRevD.99.063513[arXiv:1810.02816 [astro-ph.CO]].
[2] V. Kamali, M. Motaharfar and R. O. Ramos, Phys. Rev. D 101, no.2, 023535 (2020) doi:10.1103/PhysRevD.101.023535[arXiv:1910.06796 [gr-qc]].
[3] M. Motaharfar and R. O. Ramos, Phys. Rev. D 104, no.4, 043522 (2021) doi:10.1103/PhysRevD.104.043522[arXiv:2105.01131 [hep-th]].

Particle production from oscillating scalar backgrounds in an FLRW universe

Wen-Yuan Ai
King's College London

We study perturbative particle production from oscillating scalar backgrounds in a spatially flat Friedmann–Lemaître–Robertson–Walker universe using non-equilibrium quantum field theory. The latter naturally captures the thermal effects and backreaction effects. For quasi-harmonic oscillations, we obtain analytical approximate expressions for the self-consistent evolution of the scalar background and the energy density of the produced particles in terms of the retarded self-energy and retarded proper four-vertex function, whose imaginary parts characterize different condensate decay channels and lead to dissipation. At finite temperature, there are new condensate decay channels that would be absent at zero

temperature. These new channels could play an important role in ensuring a complete reheating.

Non-Gaussianities in the Hubble-Lemaître diagram

Giuseppe Fanizza
Instituto de Astrofísica e Ciência do Espaço - Lisbon

I will present the theoretical framework to understand the non-Gaussianities in the Hubble-Lemaître diagram emerging from relativistic simulations. With these analytic results, I will quantify which kind of non-Gaussianity can be addressed to intrinsic non-linear effects, such as post-Born corrections and higher-order statistic, against spurious effects introduced by the binning in redshift along the data analysis.

Gowdy models as physically viable inflationary early spacetimes

Javier Olmedo
Universidad de Granada

In this talk we will show that polarized Gowdy cosmologies on the three torus coupled to a massive scalar field are relevant as physical cosmological models displaying nonperturbative inhomogeneities and anisotropies at early times. Concretely, we identify sectors in phase space of physical interest where nonperturbative inhomogeneities have linear dynamics, despite the metric being fully inhomogeneous. Inhomogeneities can be expressed in Fourier modes and written as linear combinations of a basis of orthonormal complex solutions to the equations of motion, with complex amplitudes that turn out to be an infinite collection of constants of motion: annihilation and creation variables. We will argue that this model can help us to understand the role played by nonperturbative inhomogeneities and anisotropies in the dynamics of an early universe dominated by the kinetic energy of an inflaton at early times and reaching a slow-roll regime where the mean scale factor expands nearly exponentially at late times. Despite this expansion rapidly dilutes inhomogeneities and anisotropies, they can leave (dipolar, quadrupolar, ...) anomalies in the CMB.

Gravitational wave anisotropies as a probe of the inflationary particle content

Ameek Malhotra
University of New South Wales Sydney

Stochastic gravitational wave backgrounds (SGWB) can be generated by a variety of processes in the early universe, most notably inflation. These backgrounds are characterised in terms of their spectral shape, polarization, (non-)Gaussianity and anisotropies. In this talk I will show how the anisotropies of the inflationary SGWB could be used to constrain primordial ultra-squeezed non-Gaussianity in the tensor sector and potentially probe the inflationary particle content. I will present projected constraints on the corresponding non linearity parameter F_NL for several upcoming GW detectors and also highlight how the angular dependence of the primordial bispectrum affects these constraints. The angular dependence may be a signature of additional spinning fields present during inflation. This talk will be based on arxiv:2012.03498 and arxiv:2109.03077.

2nd-order cosmological perturbations during the inflation stage

Bo Wang
USTC

We study the 2nd-order scalar, vector and tensor metric perturbations in Robertson-Walker (RW) spacetime in synchronous coordinates during the inflation which is driven by the inflaton scalar. We analyze the solutions of 1st-order perturbations, upon which the solutions of 2nd-order perturbation are based. We show that the 1st-order tensor modes propagate at the speed of light and are truly radiative, but the scalar and vector modes do not. The 2nd-order perturbed Einstein equation contains various couplings of 1st-order metric perturbations, and the scalar-scalar coupling is considered in this paper. We decompose the 2nd-order Einstein equation into the evolution equations of 2nd-order scalar, vector, and tensor perturbations, and the energy and momentum constraints. By solving this set of equations up to 2nd order analytically, we obtain the 2nd-order integral solutions of all the metric perturbations, and the inflaton perturbations. We perform the residual gauge transformations between synchronous coordinates up to 2nd order, and identify the gauge-invariant modes of 2nd-order solutions.

Magnetogenesis in inflationary models leading to features in the scalar power spectrum: Challenges and possible resolution

Sagarika Tripathy
IIT Madras, Chennai, Tamilnadu

According to the standard paradigm of magnetogenesis, magnetic fields on cosmological scales are generated during inflation by breaking the conformal invariance of the electromagnetic action. This is usually achieved by coupling the electromagnetic field to the inflaton. Also, a parity-violating term is often added to the action to generate helical magnetic fields. We examine the effects of deviations from slow roll inflation on the spectra of non-helical as well as helical electromagnetic fields. We find that, to generate nearly scale invariant spectra of magnetic fields, even in slow roll inflation, one has to construct coupling functions that are dependent on the inflationary model being considered. We show that sharp features in the scalar power spectrum generated due to departures from slow roll inflation inevitably lead to strong features in the power spectra of the electromagnetic fields. Moreover, we find that such effects can also considerably suppress the strengths of the generated electromagnetic fields over the scales of cosmological interest. While it seems possible to undo the strong features that arise in the electromagnetic power spectra in such situations, we point out that it is realized at the cost of severely fine tuned non-minimal coupling functions. We discuss the wider implications of these results for inflationary magnetogenesis.

Large-Field Inflation and the Cosmological Collider

Zhong-Zhi Xianyu
Tsinghua University

Large-field inflation is a major class of inflation models featuring a near- or super-Planckian excursion of the inflaton field. We point out that the large excursion generically introduces significant scale dependence to spectator fields through inflaton couplings, which in turn induces characteristic distortions to the oscillatory shape dependence in the primordial bispectrum mediated by a spectator field. This so-called cosmological collider signal can thus be a useful indicator of large field excursions. We show an explicit example with signals from the "tower states" motivated by the swampland distance conjecture.

Boostless Cosmological Collider Bootstrap

Dong-Gang Wang
DAMTP, University of Cambridge

Cosmological correlation functions contain valuable information about the primordial Universe, with possible signatures of new massive particles at very high energies. Recent advances of the cosmological bootstrap, bring new perspectives and powerful tools to study these observables. In this talk, I will systematically classify inflationary three-point correlators of scalar perturbations using the bootstrap method. For the first time, we derive a complete set of single-exchange cosmological collider bispectra with new shapes and potentially detectable signals. Specifically, our analysis incorporates the exchange of heavy particles with any mass and spin, from all possible boost-breaking interactions during inflation. The resulting correlators are presented in analytic form, for any kinematics. We identify new phenomenology in these shapes. For example, the oscillatory signals around the squeezed limit have different phases. Furthermore, when the massive particle has much lower speed of sound than the inflaton, oscillations appear around the equilateral configuration. As large primordial non-Gaussianities are allowed in boost-breaking theories, these new shapes are of interest for near-future cosmological surveys.

Cutting Rule for Cosmological Collider Signals: A Bulk Evolution Perspective

Yuhang Zhu
The Hong Kong University of Science and Technology

We show that the evolution of interacting massive particles in the de Sitter bulk can be understood at leading order as a series of resonant decay and production events. From this perspective, we classify the cosmological collider signals into local and nonlocal categories with drastically different physical origins. This further allows us to derive a cutting rule for efficiently extracting these cosmological collider signals in an analytical fashion. Our cutting

rule is a practical way for extracting cosmological collider signals in model building, and can be readily implemented as symbolic computational packages in the future.

Resonances in the very early universe

Yi-Fu Cai
USTC

Primordial black holes (PBHs) are widely considered as a hypothetical candidate of dark matter. However, the formation and astrophysical effects of PBHs still remain unclear. To gain the insights from the theoretical perspective, we proposed a novel mechanism of the sound speed resonance (SSR) cosmology that produces PBHs efficiently. I will briefly review the PBHs and the SSR mechanism and summarize what we have learned in this subject so far. I will also introduce the recent work on the application of the SSR mechanism into the stochastic gravitational waves which are expected to be a new probe for new physics in the early universe. Moreover, the resonance effect could have occurred during inflation that may only affect primordial gravitational waves. In this case, the renowned Lyth bound may be violated and thus some interesting observational signatures would be found in the cosmic microwave background experiments.

Gravitational waves from bubble collisions in FLRW spacetime

Taotao Qiu
Huazhong University of Science and Technology

In this talk, I will focus on the gravitational waves produced by bubble collisions, which is a process during first order phase transition. I will discuss about the conditions we should consider, in order to get a analytical formula of gravitational wave energy spectrum in FLRW spacetime, and try to compare our results with previous results in Minkowski spacetime. I also confront our results to the future space-based observational data.

Induced Gravitational Waves as a Probe of the Anisotropy of Small-Scale

Chao Chen
Jockey Club Institute for Advanced Study, The Hong Kong University of Science and Technology

The scalar-induced gravitational waves (SIGWs) are attracting growing attention for probing extremely short-scale scalar perturbations via gravitational wave measurements. While the ensemble average of the SIGW energy spectrum is isotropic for the standard statistically isotropic scalar perturbations, the statistical anisotropy in the source introduces the multipole moments of the differential SIGW energy spectrum. I will talk about the possibility of testing the isotropy of primordial density perturbations at extremely small scales through SIGWs.

Cosmological constraints on a simple model for varying alpha

Nelson Nunes
Institute of Astrophysics and Space Sciences

We use quasars spectra measurements, including the latest ESPRESSO data point, as well as Planck observations of the cosmic microwave background to constrain a simple parametrization of scalar field dark energy also responsible for the possible variation of the fine structure constant . We combine them with local results from atomic clocks and the MICROSCOPE experiment. The constraints placed on the parameters of the model are consistent with a null variation of the field.

Cosmological gravitational wave damping as estimated by linearized perturbations on null cone coordinates

Petrus van der Walt
Rhodes University

We previously [1] used the Bondi-Sachs formalism to consider the problem of a gravitational wave (GW) source surrounded by a thin spherical dust shell. Using linearized perturbation theory, solutions were found in three regions: in the shell, exterior to the shell, and interior to the shell, and it was shown that the dust shell causes the GW to be modified both in magnitude and phase. These effects are astrophysically significant since there are scenarios for which the modification to the GW signal is large enough to be measurable [2]. Recently, the work was extended to include viscous effects in the matter shell. Areas of interest for this model are GWs originating from core-collapse supernovae and primordial GWs (pGWs) propagating through the early universe. Our interest here is the latter case where pGWs originating from cosmic inflation propagate through the photon plasma during the recombination epoch. The approach is to analyse the damping effects on different amplitude-frequency locations in the stochastic pGW background spectrum by representing these as discrete pGW sources where theoretical values for the shear viscosity are introduced into the shell model while the thin shell is extended by integrating over a series of thin shells to represent the cosmic plasma. 1. N.T. Bishop, P.J. van der Walt, and M. Naidoo (2020), Gen. Rel. Grav. 52:92, https://doi.org/10.1007/s10714-020-02740-9 2. M. Naidoo, N.T. Bishop, and P.J. van der Walt (2021), Gen. Rel. Grav. 53:97, https://doi.org/10.1007/s10714-021-02841-z.

HI intensity mapping with MeerKAT

Yichao Li
Northeastern University

Measurements of the cosmic large-scale structure (LSS) play an important role for precision cosmology. HI intensity mapping (IM) has been proposed as an important probe of the

cosmic LSS. Such novel technique has been investigated using existing large single dish radio telescopes, such as the Green Bank Telescope or Parkes Telescope, and proposed as the major cosmological probe with future radio facilities, such as FAST or Square Kilometer Array (SKA). In this talk, I will report the most recent detection of correlated clustering between galaxies from the WiggleZ Dark Energy Survey and the HI intensity maps from MeerKAT radio observations. With 10.5 hours observation, we find a 7.7 sigma detection of cross-correlation power spectrum at z ~ 0.43. This detection is the first practical demonstration of the multi-dish auto-correlation intensity mapping technique for cosmology. This marks an important milestone in the roadmap for the cosmology science case with the full SKAO.

HI intensity mapping: A novel technique to probe the large-scale structure

Andre Costa
Yangzhou University and Nanjing University of Aeronautics and Astronautics

The 21cm line of neutral hydrogen (HI) opens a new avenue in our exploration of the cosmos. It allows us to explore a large fraction of the universe’s evolution, parts unaccessible by other means, and provide complementary data to current constraints with different systematics. This line can also use the intensity mapping (IM) technique to probe large fractions of the sky in a more efficient way, which is especially suitable to detect baryon acoustic oscillations (BAO). BAO provides a standard ruler to probe the late-time cosmic acceleration, and although it has already been observed using optical surveys, several instruments are being designed to detect it in the radio band of 21cm for the first time. In this talk, I will present our current status and future developments on this field, with special emphasis on the BINGO radio telescope.

Exploring the Universe with Fast Radio Bursts

Zhengxiang Li
Beijing Normal University

There are several serious challenges in the cosmological standard concordance model, such as the Hubble constant tension or the nature of dark energy, the dark matter candidates, and the missing baryon. Fast radio bursts (FRBs) are mysterious transients with short durations (~a few milliseconds) and cosmological origins. Their some key properties enable them as one of the most promising probes for measuring some fundamental cosmological parameters, constraining the abundance of compact dark matter objects, locating missing baryons, etc. In this talk, I will discuss the possibility of using FRBs to explore the Universe from these aspects.

Probing cosmic structures with gravitational wave lensing

Miguel Zumalacarregui

Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

Just like light, gravitational waves (GWs) are deflected and magnified by the large-scale structure of the Universe. Their low frequency, phase coherence and capacity to propagate with no absorption make GW lensing highly complementary to gravitational lensing of electromagnetic radiation. I will discuss the framework of lensing in the wave optics regime and describe some of the opportunities that strong lensing of GWs will open to probe the matter distribution, including novel tests for dark matter scenarios. The rich phenomenology of GW lensing will greatly benefit with the rapidly increasing rate of GW detections.

Gravitational Wave Cosmology: Propagation in an Inhomogeneous Universe

Jared Fier
Baylor University

In this talk, we shall present our recent studies on gravitational waves (GWs) produced by remote compact astrophysical sources. To describe such GWs properly, we introduce three scales, the typical wavelength of GWs, the scale of the cosmological perturbations, and the size of the observable universe. For GWs to be detected by the current and foreseeable detectors, we show that such GWs can be well approximated as high-frequency GWs. To simplify the field equations, we show that the spatial, traceless, and Lorentz gauge conditions can be imposed simultaneously, even when the background is not vacuum, as long as the high-frequency GW approximation is valid. Applying the general formulas, along with the geometrical optics approximation, we calculate the gravitational integrated Sachs-Wolfe effects due to the presence of the cosmological scalar and tensor perturbations, whereby the dependences of the amplitude, phase and luminosity distance of the GWs on these two kinds of perturbations are given explicitly.

Influence of cosmological expansion in local experiments

Alessio Belenchia
University of Tübingen

Whether the cosmological expansion can influence the local dynamics, below the galaxy clusters scale, has been the subject of intense investigations since the ’40s. In this talk, I will consider the effect of the global cosmological expansion on local experiments in an idealized setting by employing McVittie and Kottler spacetimes, embedding a spherical object in a FLRW spacetime, as approximate, idealized models of a local gravitational environment. In particular, I will discuss the influence of the cosmological expansion on the frequency shift of an optical resonator and estimate its effect on the exchange of light signals between local observers, clarifying some of the statements present in the literature.

References
[1] F. Spengler, A. Belenchia, D. Rätzel, and D. Braun, Influence of cosmological expansion in local experiments, Class. Quantum Grav. 39 055005 (2022).

No-go guide for the Hubble tension

Wang-Wei Yu
Institute of Theoretical Physics, Chinese Academy of Sciences

The Hubble tension seems to be a crisis with $\sim 5\sigma$ discrepancy between the most recent local distance ladder measurement from Type Ia supernovae calibrated by Cepheids and the global fitting constraint from the cosmic microwave background data. To narrow down the possible late-time solutions to the Hubble tension, we have used in a recent study [Phys. Rev. D 105 (2022) L021301] an improved inverse distance ladder method calibrated by the absolute measurements of the Hubble expansion rate at high redshifts from the cosmic chronometer data, and found no appealing evidence for new physics at the late time beyond the ΛCDM model characterized by a parametrization based on the cosmic age. We further investigate the perspective of this improved inverse distance ladder method by including the late-time matter perturbation growth data. Independent of the dataset choices, model parametrizations, and diagnostic quantities (S8 and S12), the new physics at the late time beyond the ΛCDM model is strongly disfavoured so that the previous late-time no-go guide for the Hubble tension is further strengthened.

Accurate relativistic observables from post-processing light cone catalogues

Chi Tian
Anhui University

In this talk, we will introduce a new scheme to construct relativistic observables from post-processing light cone data. This construction is based on a novel approach, LC-Metric, which takes general light cone or snapshot output generated by arbitrary N-body simulations or emulations and solves the linearized Einstein equations to determine the spacetime metric on the light cone. We find that this scheme is able to determine the metric to high precision, and subsequently generate accurate mock cosmological observations sensitive to effects such as post-Born lensing and nonlinear ISW contributions. By comparing to conventional methods in quantifying those general relativistic effects, we show that this scheme is able to accurately construct the lensing convergence signal, and the accuracy of this method in quantifying the ISW effects in the highly nonlinear regime outperforms conventional methods by an order of magnitude. This scheme opens a new path for exploring and modeling higher-order and nonlinear general relativistic contributions to cosmological observables, including mock observations of gravitational lensing and the moving lens and Rees-Sciama effects

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C1: Pulsar Timing Arrays (Chair: Ingrid Stairs, Coordinator: Xing-Jiang Zhu)

Recent results from Pulsar Timing Arrays

Siyuan Chen
KIAA, Peking University

Pulsar Timing Arrays (PTAs) search for nHz gravitational waves by timing the radio signals from a network of stable millisecond pulsars and looking for a spatially correlated common signal in the data set. We expect to find a gravitational wave background (GWB) first, followed by possible individual sources. PTAs have reported the finding of a spectrally similar but spatially uncorrelated signal in various data sets, namely North American Nanohertz Observatory for Gravitational waves (NANOGrav), Australian Parkes PTA, European PTA, together with the Indian PTA they form the International PTA. We hope to deepen collaboration with Chinese and South African PTA colleagues.
I will present the recent results from the different PTAs on the search for a GWB. All PTAs report consistent results of a common signal with a nominal amplitude of 2-3e-15, but no characteristic spatial correlation required for a GWB. This putative signal has been tested against both cosmological and astrophysical sources for a GWB and helped to put constraints for various theories. We are working in the four PTA collaborations to collect and analyze the most recent data sets in a coordinated process, including the supervision of an external Detection Committee under the guidance of the IPTA. We hope to have exciting results to present by the end of this year. These new data sets will form the basis for the next IPTA DR3 combination in the coming year.

Using low frequency scatter broadening measurements for precision estimates of DM and its implications on GW detection using PTAs

Jaikhomba Singha
Indian Institute of Technology Roorkee

As the pulsar signal passes through the interstellar medium (ISM), it gets smeared due to the variation of the group velocity of the radiation with wavelength caused by the electrons in the line of sight. This smearing can be due to dispersion by the integrated column density of electrons or multipath propagation due to inhomogeneities in the electron distribution across the line of sight. The dynamic nature of the ISM makes both these effects vary with observation epochs. This variation can mimic a slowly varying noise in ToA covariant with GW signature of an isotropic stochastic gravitational wave background (SGWB). We present a new method to estimate the DM accurately in presence of scatter broadening in the pulse profile by compensating for variable scatter broadening, estimated using 300-500 MHz wide-band uGMRT measurements. We evaluate this method in comparison with traditional DM estimation methods, ignoring such effects, using simulated data. We also present results from this method using InPTA year data set on PSR J1643-1224 and discuss implications of our results.

The gravitational wave signal from primordial magnetic fields in the Pulsar Timing Array frequency band

Alberto Roper Pol
APC/Université de Paris/CNRS

The NANOGrav, Parkes, and European pulsar timing array (PTA) collaborations have reported evidence for a common-spectrum process that can potentially correspond to a stochastic gravitational wave background (SGWB) in the 1–100 nHz frequency range. I will present the scenario in which this signal is produced by magnetohydrodynamic (MHD) turbulence in the early universe, induced by a non-helical primordial magnetic field at the energy scale corresponding to the quark confinement phase transition. I will present the results of MHD simulations studying the dynamical evolution of the magnetic field and the resulting SGWB. The SGWB output from the simulations can be very well approximated by assuming that the magnetic anisotropic stress is constant in time, over a time interval related to the eddy turnover time. The analytical spectrum derived under this assumption features a change of slope at a frequency corresponding to the GW source duration that is confirmed with the numerical simulations. The SGWB signal can be compared with the PTA data to constrain the temperature scale at which the SGWB is sourced, as well as the amplitude and characteristic scale of the initial magnetic field. The generation temperature is constrained by PTA to be in the 2-200 MeV range, the magnetic field amplitude must be > 1% of the radiation energy density at that time, and the magnetic field characteristic scale is constrained to be > 10% of the horizon scale. The turbulent decay of this magnetic field will lead to a field at recombination that can help to alleviate the Hubble tension and can be tested by measurements in the voids of the Large Scale Structure with gamma-ray telescopes like the Cherenkov Telescope Array.

Pulsar Timing Residuals induced by Wideband Ultralight Dark Matter

Yun-Long Zhang
National Astronomical Observatories, Chinese Academy of Sciences

The coherent oscillation of ultralight dark matter induces changes in gravitational potential with the frequency in nanohertz range. This effect is known to produce a monochromatic signal in the pulsar timing residual. Here we discuss the multi fields scenario that produces a wide spectrum of frequencies, such that the ultralight particle oscillation can mimic the pulsar timing signal of stochastic gravitational wave background. We discuss how ultralight dark matter with various spins produces such a wideband spectrum on pulsar timing residuals and perform the Bayesian analysis to constrain the parameters.

Vela pulsar: single pulses analysis with machine learning techniques

Carlos Lousto

Rochester Institute of Technology

We study individual pulses of Vela (PSR B0833−45/J0835−4510) from daily observations of over 3 h (around 120 000 pulses per observation), performed simultaneously with the two radio telescopes at the Argentine Institute of Radioastronomy. We select four days of observations in 2021 January to March and study their statistical properties with machine learning techniques. We first use Density-Based Spatial Clustering of Applications with Noise clustering techniques, associating pulses mainly by amplitudes, and find a correlation between higher amplitudes and earlier arrival times. We also find a weaker (polarization dependent) correlation with the mean width of the pulses. We identify clusters of the so-called mini-giant pulses, with ∼10 times the average pulse amplitude. We then perform an independent study, with Self-Organizing Maps (SOM) clustering techniques. We use Variational AutoEncoder (VAE) reconstruction of the pulses to separate them clearly from the noise and select one of the days of observation to train VAE and apply it to the rest of the observations. We use SOM to determine four clusters of pulses per day per radio telescope and conclude that our main results are robust and self-consistent. These results support models for emitting regions at different heights (separated each by roughly a hundred km) in the pulsar magnetosphere. We also model the pulses amplitude distribution with interstellar scintillation patterns at the inter-pulses time-scale finding a characterizing exponent n_ISS ∼ 7–10. In the appendices, we discuss independent checks of hardware systematics with the simultaneous use of the two radio telescopes in different one-polarization/two-polarizations configurations. We also provide a detailed analysis of the processes of radio-interferences cleaning and individual pulse folding.

Observation of Gravitational Waves by Invariants for Electromagnetic Waves

Chan Park
IBS

All detectors have motions with velocities and accelerations that affect measurements. Because electric and magnetic fields rely on 4-velocities of observers, their measurements also depends on the motions. Moreover, when we detect a gravitational wave (GW), the motions of detectors are under the influence of GW. Even if we set a stationary observer that does not oscillating along GW, the spatial direction in which the measurement is performed has an unpredictable rotational mode. To avoid these complexities, we propose a gauge-invariant quantity of electromagnetic waves to detect GWs without acceleration noise. We discuss a thought experiment to measure the quantity.

C2: Gravitational wave astronomy: searches, data analysis, parameter estimation (Chair: Barak Zackay, Coordinator: Wen Zhao)

Distortion of Gravitational Wave Signals by Astrophysical Environments

Xian Chen
Peking University

Measuring the mass and distance of a gravitational wave (GW) source is a fundamental problem in GW astronomy. The issue is becoming even more pressing since LIGO and Virgo have detected massive black holes that in the past were thought to be rare, if not entirely impossible. The waveform templates used in the detection are developed under the assumption that the sources are residing in a vacuum, but astrophysical models predict that the sources could form in gaseous environments, move with relatively large velocity, or reside in the vicinity of supermassive black holes. In this talk, I will demonstrate how the above environmental factors could distort the GW signals and lead to a biased estimation of the physical parameters. In particular, I will highlight the ubiquity of such a bias among the GW sources produced in a major formation channel, i.e., in active galactic nuclei. If not appropriately accounted for, the above bias may alter our understanding of the formation, evolution, and detection of GW sources.

Black Hole Ringdown: Beyond the Fundamental Quasinormal Mode

Christopher Moore
University of Birmingham

The ringdown is associated with a black hole settling down into its final, stationary state. The ringdown is expected to consist of a superposition of damped oscillations, known as quasinormal modes QNMs, the frequencies of which give us insight into the strong field spacetime near the event horizon. The LIGO and Virgo detectors have now detected almost 100 binary black holes and identified the ringdown in a few tens of high mass systems. Usually, only the fundamental QNM is detected. However, in a few cases several authors have claimed evidence for additional QNMs, opening up new exciting opportunities for tests of general relativity and fundamental physics. These claims are still controversial and are being actively debated in the literature and there are differences in the data analysis which requires a great deal care. In this talk I will describe the different analysis methods that are used to model the ringdown and review the observational evidence for additional QNMs, beyond the fundamental mode.

On the identification of strongly-lensed gravitational wave events

Justin Janquart
Nikhef / Utrecht University

Like light, gravitational waves can be deflected by massive objects present on their travel path from source to observer. Depending on the mass of the lens, the wave can get distorted, magnified, or split into multiple potentially detectable images. The latter case is called strong lensing and happens in the so-called geometrical optics limit when the characteristic size of the lens is much larger than the gravitational-wave wavelength. In this case, one would observe several images with the same frequency evolution but magnified, time-shifted, and with a possible overall phase shift. This phenomenon is expected to be observed in the coming years and could lead to new tests of general relativity, the identification of the host galaxy for binary black hole mergers, and tests of cosmology. However, because of the growing number of events over the year, the detection of strongly-lensed images represents a major challenge. Indeed, for O(1000) unlensed events, one has to analyze all the possible pairs, making for $O(5x10^5)$ pairs to analyze. This requires the development of both fast and precise tools for their identification. In addition, the presence of the extended unlensed background leads to a high probability of false alarms, making it difficult to identify genuinely lensed events. Here, we present GOLUM, a framework able to do fast and precise parameter estimation for lensed events, reducing significantly the background compared to other fast methods. We also show how the inclusion of lensed models can help in the identification of lensed events in an unlensed background for a realistic observation scenario.

Interplay of spin-precession and higher harmonics in the parameter estimation of binary black holes

Krishnendu Naderi Varium
Albert Einstein Institute, Hannover

Gravitational-wave signals from coalescing compact binaries carry an enormous amount of information about the source dynamics and are an excellent tool to probe unknown astrophysics and fundamental physics. Though the updated catalog of compact binary signals reports evidence for slowly-spinning systems and unequal mass binaries, the data so far cannot provide convincing proof of strongly precessing binaries. Here, we use the gravitational-wave inference library parallel Bilby to compare the performance of two waveform models for understanding the spin-induced orbital precession effects in simulated binary black hole signals. One of the waveform models incorporates both spin-precession effects and subdominant harmonics. The other model accounts for precession but only includes the leading harmonic at quadrupolar order. By simulating signals with varying mass ratios and spins, we find that the waveform model with subdominant harmonics enables us to infer the presence of precession in most cases accurately. On the other hand, the dominant harmonic model often fails to extract enough information to measure precession. In particular, it cannot distinguish a face-on highly-precessing binary from a slowly-precessing binary system irrespective of the binary’s mass ratio. As expected, we see a significant improvement in characterizing precession for edge-on binaries. Other intrinsic parameters also become better constrained, indicating that precession effects help break the correlations between mass and spin parameters. In contrast, spin-precession measurements are prior dominated for equal-mass binaries with face-on orientation, even if we employ a waveform model including subdominant harmonics. In this case, doubling the signal-to-noise ratio does not help to reduce these prior induced biases. As we expect detections of highly-spinning binary signals

with misaligned spin orientations in the future, simulation studies like ours are crucial for understanding the prospects and limitations of gravitational-wave parameter inferences.
Based on https://journals.aps.org/prd/abstract/10.1103/PhysRevD.105.064012

Constraining spin precession and nutation in current gravitational wave events

Daria Gangardt
University of Birmingham

Unlike in Newtonian dynamics, if two gravitationally bound objects are individually spinning in general relativity, their spins will interact and the orbital plane will precess. This spin precession can be detected from its effect on the gravitational wave signal. The catalogue of gravitational wave events has already been investigated for spin precession, described using the two effective parameters $\chi_{m_{eff}}$ and χ_P. Here, we repeat the investigation, looking at the mergers of black hole binaries, but with a new characterisation - the precession and nutation of the orbital angular momentum. Instead of effective parameters, we choose a geometrical approach to describe spin precession, where the precession of the orbital plane is split into its azimuthal motion (its precession) and its polar motion (its nutation). Looking for these effects, and understanding what binary parameters influence them, is non-trivial. We use sequential prior conditioning to resolve this. Prior conditioning is performed by combining prior distributions with posterior distributions of the parameters we're conditioning our priors on. We find that nutation, given its small expected amplitudes, is difficult to constrain. Precession, on the other hand, is clearly constrained, especially for events with highly unequal masses and relatively high signal to noise ratios. We also construct a synthetic binary that we would expect to have a high nutational amplitude, and show that with the future detector sensitivities of LIGO-Virgo-KAGRA, these events are detectable and their nutation can be constrained to be non-zero.

Hunting for Gravitational Waves with Higher-Order Modes from Asymmetric Intermediate Mass Black Hole Binaries with THAMES

Kritti Sharma
Indian Institute of Technology Bombay

Hierarchical black hole mergers are expected to be one of the most significant contributors to Intermediate Mass Black Hole (IMBH) binary mergers. This formation channel can produce binaries with a large amount of mass asymmetry, and therefore, their mergers can produce gravitational waves with a measurable amount of higher-order mode content. The search for IMBH binaries poses a unique challenge. These signals are expected to be highly short-lived (often lasting less than one-tenth of a second) within the current detector bandwidth. Therefore, they can be confused with the frequently occurring noisy glitches whose morphology they often resemble. Moreover, in highly asymmetric systems, significant waveform modulations due to higher-order modes make it difficult to model and detect these signals buried in the detector noise. The time-frequency representation of these signals has distinctive features owing to these waveform modulations. We have developed a Deep Transfer Learning algorithm, THAMES, which extracts such characteristic features from the

spectrograms to distinguish between IMBH binary signals and several classes of glitches. This algorithm looks for time coincident triggers in two detectors and ranks the coincident events using a novel detection statistic. We have evaluated the sensitivity of our algorithm with asymmetric, nearly edge-on IMBH binary injections in Gravitational Wave open data. Our algorithm notably outperforms the optimized template-based PyCBC search for signals with higher-order mode content. This talk presents the detailed model development, analysis framework and results from our work.

Systematic bias on parameterized tests of general relativity due to neglect of orbital eccentricity

Pankaj Saini
Chennai Mathematical Institute, Siruseri

Gravitational-wave observations provide a unique opportunity to test General Relativity (GR) in the strong-field and highly-dynamical regime of the theory. Parameterized tests of GR are a well-known approach for searching for GR violations. This approach constrains deviations in the coefficients of the post-Newtonian phasing formula, which describes the gravitational-wave phase evolution of an inspiralling compact binary. Current bounds from this test using LIGO/Virgo observations assume that binaries are circularized by the time they enter the detector frequency band. Here, we investigate the systematic biases in the testing GR parameter bounds when a phasing based on the circular orbit assumption is employed for a system that has some small residual eccentricity. We find that a systematic bias (for example, on the leading Newtonian deformation parameter) becomes comparable to the statistical errors for even moderate eccentricities of ~ 0.04 at 10 Hz in the LIGO/Virgo band. This happens at a lower value of orbital eccentricity (~ 0.005 at 10 Hz) in the frequency band of third-generation detectors like Cosmic Explorer. These results demonstrate that incorporating physical effects like eccentricity in waveform models is important for accurately extracting science results from future detectors.

On the validity of linear perturbation theory in the ringdown from binary mergers

Mark Ho-Yeuk Cheung
Johns Hopkins University

According to linear black hole perturbation theory, the remnant of a black hole binary merger emits gravitational waves given by a combination of quasinormal modes. Measuring multiple mode frequencies may allow us to test the Kerr nature of the remnant and to test general relativity. Linear perturbation theory is expected to be valid only when the spacetime perturbation is small in magnitude. However, there have been claims that merger waveforms can be accurately modeled by a combination of linear modes already at the peak of the waveform amplitude. These linearity arguments were used to claim detection of an overtone in the GW150914 merger event. We show that models with more than 2 or 3 overtones overfit the signal. We argue that including spherical-spheroidal mixing in the fit is important to accurately recover the mode frequencies, and we propose methods to quantify the time at which a linear ringdown fitting model is robust.

Constraining two-spin effects in gravitational-wave data with an augmented definition of the precessing spin parameter χp

Viola De Renzis
University of Milano-Bicocca

Spin precession is a key feature in the dynamics of black-hole binaries predicted by General Relativity. Misalignments between the black-hole spins and the binary's orbital momentum induce characteristic modulations to the emitted gravitational waves which are intrinsically hard to estimate because they provides a highly subdominant contribution. The most commonly used quantity to track the amount of relativistic precession in current LIGO/Virgo observations is the so-called effective precession parameter χp. Here we exploit a recently developed re-definition of χp that considers all the variations occurring on the precession timescale, allowing to capture two-spin effects in a consistent fashion. In particular, sources with two precessing spins populate a dedicated region of the parameter space where χp>1. Using a large number of software injections in synthetic data, we recover the posterior distribution of such augmented χp parameter and identify the regions of the parameter space where present and future gravitational-wave interferometers could detect two-spin effects in black-hole binary data.

4-OGC: Catalog of gravitational waves from compact-binary mergers

Yi-Fan Wang
Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

We present the fourth Open Gravitational-wave Catalog (4-OGC) of binary neutron star (BNS), binary black hole (BBH) and neutron star-black hole (NSBH) mergers. The catalog includes observations from 2015-2020 covering the first through third observing runs (O1, O2, O3a, O3b) of Advanced LIGO and Advanced Virgo. The updated catalog includes 7 BBH mergers which were not previously reported with high significance during O3b for a total of 94 observations: 90 BBHs, 2 NSBHs, and 2 BNSs. The most confident new detection, GW200318_191337, has component masses 49.1+16.4-12.0 msun and 31.6+12.0-11.6 msun; its redshift of 0.84+0.4-0.35 (90% credible interval) may make it the most distant merger so far. For BNS and NSBH sources, we estimate a merger rate of 200+309-148 Gpc^{-3} yr^{-1} and 19+30-14 Gpc^{-3} yr^{-1}, respectively, assuming the known sources are representative of the total population. We provide reference parameter estimates for each of these sources using an up-to-date model accounting for instrumental calibration uncertainty. The corresponding data release also includes our full set of sub-threshold candidates.

Searching for gravitational-wave higher-order modes from asymmetric intermediate-massblack hole binary

Koustav Chandra

Indian Institute of Technology Bombay

Most current gravitational-wave searches for compact binary mergers rely on matched-filtering the calibrated gravitational-wave detector data with a set of model waveforms that omit the higher-order mode content of a gravitational-wave signal. The effects of these higher-order modes become important in systems with asymmetric masses having an orbital geometry that is nearly edge-on with respect to the observer. Therefore their omission reduces the sensitivity of the searches. Here, we present a new gravitational-wave search on real data collected during the third observing run of Advanced LIGO and Advanced Virgo using waveforms that includes higher-order modes. Our algorithm benefits from searching with a generic matched-filter statistic over a restricted parameter space of quasi-circular mergers of binary black holes with a total mass between $100-500\,\mathrm{M}_{\odot}$ and mass-ratio between $1-10$, stricter signal-noise discriminators and improved ranking statistics. In particular, while evaluating the sensitivity of our search, in terms of sensitive volume-time, we find that our search is up to 450% more sensitive than previous searches with overlapping target space.

Searching for boson-star mergers in LIGO-Virgo data

Juan Calderon Bustillo
University of Santiago de Compostela

The Advanced LIGO and Virgo detectors have delivered several compact mergers with individual masses populating the pair-instability supernova gap and whose remnants are consistent with intermediate-mass black-holes. The interpretation of these events, however, is challenging as barely any information about the merging objects is actually present in the signals. This makes such events merit further investigation on their nature. We compare events, including GW190521 to ~800 numerical simulations of vector boson-star mergers, which are Bose-Einstein condensates of ultralight (vector) boson fields, widely considered as excellent candidates to form Dark Matter. We show that for GW190521, such scenario is preferred to that of a black-hole merger and that all events return consistent masses for the (vector) boson forming the stars of ~9x10^-13 eV. We perform the first compact-merger population studies considering sub-populations of boson-star and black-hole mergers.

Identifying non-linear phase couplings in gravitational wave data

Sudhagar Suyamprakasam
Inter-University Centre for Astronomy and Astrophysics, Pune, India

Some of the non-astrophysical noise that appeared in the gravitational Wave (GW) strain data originated from various interferometer systems through non-linear couplings. It degrades the quality of the GW strain data and adversely impacts the signal search sensitivity in various frequency bands. Third-order statistics, such as bicoherence analysis, aid in identifying the existence and origin of non-linear noise couplings. The conventional bicoherence analysis has a demerit of identifying the non-phase coupled (NPC) bifrequency as phase coupled (PC) bifrequency, and it leads to false detection of phase coupled bifrequency. The false detection can be reduced by introducing artificial phase randomization in the bicoherence analysis (i.e., phase randomized bicoherence). Moreover, the artificial randomization does not affect the actual phase-coupled disturbances. We demonstrate the merit of the phase-randomized short-duration (lasting up to a few seconds) bicoherence analysis with the simulated phase-coupled and non-phase-coupled disturbances. We carry out statistical hypothesis testing to distinguish between them. In this work, the advantage of the phase-randomized short-duration bicoherence analysis in GW time-series data is presented in two contexts: (1) If non-astrophysical short-duration noise, such as blips and koi fish, have a common source of origin, their bifrequencies show the third-order similarities in bicohgrams, which can be found with the bicoherence analysis. (2) Identifying repeated phase coupled bifrequencies in the background noise from the O2 and O3 observation runs and vetoing these bifrequencies will improve the search sensitivity.

Surppresing GRS disturbances with TDI combinations

Pengzhan Wu
Lanzhou university

For LISA-like space-borne GW antennas, the key noise cause by laser frequency instability in the inter-satellite interfrometer measurements is supposed to be 6-8 orders of magnitude larger than the expected readout noise, which could be resolved by a pre-data process method called time-delayed interferometry (TDI). Therefore, TDI is the basic framework of the data pre-processings for LISA and Taiji missions. According to the baseline designs of the LISA and Taiji missions, the foreseeable disruptions or data gaps in science measurements may come from scheduled maintenance and unexpected instrument anomalies. The scheduled maintenance may include regular re-pointing of the telecommunication antennas, orbital maneuvers, re-locking in interferometers due to laser frequency plans etc. The first two operations could cause large disturbances of satellite platforms and affect heavily the performances of the key payloads, such as lasers, interferometers and GRS. GRS disruptions in data processing must be removed and suppressed. Our team suggest a novel approach, by means of specific TDI combinations, to suppress the GRS anomalies produced by satellite platform disturbances and scheduled continuous maintenances. This talk will give a quick overview of time-delay interferometry and the TAIIJI simulator, as well as new breakthroughs in using time-delay interference technology to reduce inertial sensor noise.

A comparison of GstLAL performance in gaussian data and LIGO detectors data

Andre Guimaraes
Louisiana State University
LIGO Scientific Collaboration

In this study we explore the differences of results of GW searches with the GstLAL pipeline applied to real LIGO data and simulated Colored-Gaussian data. This difference is quantified with a measure derived from the Kolmogorov–Smirnov test, and is used to find out significant differences depending on template bank parameters. We find that regions

representative of high chirp mass are roughly 6 times more well behaved than those of low chirp mass according to the chosen measure.

Tests of General Relativity with Gravitational-Wave Observations using a Flexible–Theory-Independent Method

Ajit Kumar Mehta
AEI, Potsdam

We perform tests of General Relativity (GR) with gravitational waves (GWs) from the inspiral stage of compact binaries using a theory-independent framework, which adds generic phase corrections to each multipole of a GR waveform model in frequency domain. This method has been demonstrated on LIGO-Virgo observations to provide stringent constraints on post-Newtonian predictions of the inspiral and to assess systematic biases that may arise in such parameterized tests. Here, we detail the anatomy of our framework for aligned-spin waveform models. We explore the effects of higher modes in the underlying signal on tests of GR through analyses of two unequalmass, simulated binary signals similar to GW190412 and GW190814. We show that the inclusion of higher modes improves both the precision and the accuracy of the measurement of the deviation parameters. Our testing framework also allows us to vary the underlying baseline GR waveform model and the frequency at which the non-GR inspiral corrections are tapered off. We find that to optimize the GR test of high-mass binaries, comprehensive studies would need to be done to determine the best choice of the tapering frequency as a function of the binary's properties. We also carry out an analysis on the binary neutron-star event GW170817 to set bounds on the coupling constant α0 of Jordan-Fierz-Brans-Dicke gravity. We take two plausible approaches; the first approach involves translating directly the theory-agnostic bound on dipole-radiation into a bound on α0 for different neutron-star equations of state (EOS). The second theory-specific approach involves reparameterizing the test such that the deviation parameter is α0 itself. The two approaches provide slightly different bounds, namely, $\alpha 0 \leq 2 \times 10{-}1$ and $\alpha 0 \leq 4 \times 10{-}1$, respectively, at 68% credible level. These differences arise mainly since in the theory-specific approach the tidal and scalar-charge parameters are fixed coherently for each neutron-star EOS and mass.

C3: Astrophysics and multi-messenger astronomy with gravitational waves (Chair: Daniel Holz, Coordinator: Xian Chen)

Triples in the sky with LISA: Gravitational waveform modeling and data analysis implications

Rohit Subbarayan Chandramouli
University of Illinois at Urbana-Champaign

Gravitational waves emitted by inner binaries in hierarchical triple systems are interesting astrophysical candidates for space-based detectors such as the Laser Interferometer Space Antenna, LISA. In the presence of a third body, such as a supermassive black hole, an inner binary consisting of intermediate mass black holes can undergo oscillations in eccentricity and inclination angle because of the Kozai-Lidov mechanism. We construct ready-to-use gravitational waveforms in the Fourier domain, taking into account the Kozai-Lidov effect within the framework of post-Newtonian (PN) theory. The separation of timescales in the system allows us to use multiple-scale analysis to combine the effects of both Kozai-Lidov oscillations and PN effects. To leading order in conservative and dissipative dynamics, we constructed a preliminary model by assuming small eccentricity and obtained analytic solutions describing the evolution of the orbital elements. We used the stationary phase approximation and computed the resulting imprint on the gravitational waveform in the Fourier domain. We found that the oscillations have a clear signature on the Fourier amplitude of the waveform while leaving a measurable imprint on the gravitational wave phase. We also found that our analytic results are consistent with numerics. Further, we identified potential source candidates in the LISA band for which the KL effect could be significant. As part of our ongoing work, we extend our preliminary model to larger eccentricities and to next-to-leading order in PN theory. In this talk, I will highlight our published results and outline our ongoing work.

The Bardeen-Petterson effect and its consequences for LISA observations of supermassive black-hole binary spin orientations

Nathan Steinle
University of Birmingham

Supermassive black-hole binaries are driven to merger by many processes, such as dynamical friction, loss-cone scattering of individual stars, disk migration, and gravitational-wave emission. Two main astrophysical formation channels are expected. Binaries that form in gas-poor galactic environments do not experience disk migration and accretion, and likely enter the gravitational wave dominated phase with roughly isotropic spin orientations. Comparatively, binaries that evolve in gas rich galactic environments experience disk migration and accretion prior to the gravitational-wave phase, where the Bardeen-Petterson effect aligns the spins of the binary with the orbital angular momentum of the disk or aligns them to a critical angle where alignment ceases. We find that these possibilities for binary black-hole spin orientations produce subpopulations of binaries that evolve in gas-rich hosts,

which depend on the parameters governing disk migration and accretion. For example, in a distribution of binaries with initially isotropic spin directions, moderately viscous accretion disks result in a large fraction of binaries with at least one aligned black hole spin, depending on the total mass of the binary. Consequently, the subpopulations can provide different predictions for the relativistic spin precession that occurs during the gravitational-wave dominated inspiral and merger. Observations of gravitational waves from supermassive binary black-hole mergers by LISA may constrain the binary spin orientations and the corresponding subpopulations, offering a chance to probe the complicated physics of disk migration and accretion.

Hunting for intermediate-mass black holes with LISA binary radial velocity measurements

Vladimir Strokov
Johns Hopkins University

Despite their potential role as massive seeds for quasars, in dwarf galaxy feedback, and in tidal disruption events, the observational evidence for intermediate-mass black holes (IMBHs) is scarce. LISA may observe stellar-mass black hole binaries orbiting Galactic IMBHs, and reveal the presence of the IMBH by measuring the Doppler shift in the gravitational waveform induced by the binary's radial velocity. We estimate the number of detectable Doppler shift events from the Milky Way globular clusters (assuming they host IMBHs) and we find that it decreases with the IMBH mass. A few Galactic globular clusters (including M22 and ω Centauri) may produce at least one event detectable by LISA. Even in more pessimistic scenarios, one could still expect ∼1 event overall in the Milky Way. We also estimate the number of Doppler shift events for IMBHs wandering in the Milky Way as a result of the disruption of their parent clusters. If there is at least one binary black hole orbiting around each wandering IMBH, LISA may detect up to a few tens of Doppler shift events from this elusive IMBH population. Under more pessimistic assumptions, LISA may still detect ∼1 wandering IMBH that would hardly be observable otherwise.

Constraining deviations from general relativity using quadruply lensed gravitational waves from coalescing compact objects

Harsh Narola
Universiteit Utrecht

Gravitational waves (GWs), just like light waves, undergo gravitational lensing when they encounter a massive object in their path. When the massive object is at a galaxy scale, typically one has strong lensing, which produces multiple images of the same gravitational wave source. When the gravitational wave signal from a coalescing binary is quadruply lensed, we can localize its source to sub-arcsecond precision by using simultaneous constraints from gravitational wave and electromagnetic observations. In this work, we show that the improved localisation could help us constrain cosmological parameters and theories of gravity beyond general relativity. In particular, we consider models with time-varying Planck mass, large extra-dimensions, and a phenomenological parameterization that can be

mapped to several other beyond-GR theories. We analyse a simulated catalogue of quadruply lensed GWss that are detectable by a network of LIGO/Virgo/KAGRA/LIGO-India detectors to find out what kind of bounds can be placed on the parameters governing these models.

Constraints on compact dark matter from gravitational wave microlensing

Soummyadip Basak
ICTS-TIFR, Bangalore, India

If a significant fraction of dark matter is in the form of compact objects, they will cause microlensing effects in the gravitational wave (GW) signals observable by LIGO and Virgo. From the non-observation of microlensing signatures in the binary black hole events from the first two observing runs and the first half of the third observing run, we constrain the fraction of compact dark matter in the mass range 10^2 − 10^5 to be less than ~ 50 − 80% (details depend on the assumed source population properties and the Bayesian priors). These modest constraints will be significantly improved in the next few years with the expected detection of thousands of binary black hole events, providing a new avenue to probe the nature of dark matter.

Fake massive gravitational wave sources from AGN accretion disks

Xian Chen
Peking University

Measuring the mass and distance of a gravitational wave (GW) source is a fundamental problem in GW astronomy. The issue is becoming even more pressing since LIGO and Virgo have detected massive black holes that in the past were thought to be rare, if not entirely impossible. The waveform templates used in the detection are developed under the assumption that the sources are residing in a vacuum, but astrophysical models predict that the sources could form in gaseous environments, move with relatively large velocity, or reside in the vicinity of supermassive black holes. In this talk, I will demonstrate how the above environmental factors could distort the GW signals and lead to a biased estimation of the physical parameters. In particular, I will highlight the ubiquity of such a bias among the GW sources produced in a major formation channel, i.e., in active galactic nuclei. If not appropriately accounted for, the above bias may alter our understanding of the formation, evolution, and detection of GW sources.

Can Thorne-Zytkow objects source GW190814 type events?

David Garfinkle
Oakland University

The LIGO-Virgo collaboration reported in their third run the coalescence event GW190814 involving a 2.6 $M_\odot$ object with a 23 $M_\odot$ black hole. In this letter we study the conditions under which Thorne-Z˙ytkow objects (TZ˙Os) can be connected to that type of events. We evaluate first the rate of appearance of TZ˙Os in the local Universe. Under the assumption that TZ˙Os eventually become low mass gap black holes we evaluate how those black holes end up in binaries with other stellar mass black holes and compare to the reported rate for GW190814-type of events (1-23 Gpc−3yr−1). We find that TZ˙Os in dense stellar clusters can not explain the LIGO-Virgo rate without a TZ˙Os population in the field providing a dominant contribution. We also find that TZ˙Os formed within hierarchical triple systems in the field with the third more distant star being the progenitor of a stellar mass black hole, may be able to give a rate comparable to that of GW190814-type events. In that case, future observations should discover mergers between stellar mass and low mass gap black holes, with the lower mass spanning the entire low mass gap range.

Illuminating the pair-instability supernova mass gap with collapsars

Aman Agarwal
Perimeter Institute and University of Guelph

The core collapse of rapidly rotating massive ~10 Msun stars ("collapsars"), and resulting formation of hyper-accreting black holes, are a leading model for the central engines of long-duration gamma-ray bursts (GRB) and promising sources of r-process nucleosynthesis. We explore the signatures of collapsars from progenitors with extremely massive helium cores >130 Msun above the pair-instability mass gap. While rapid collapse to a black hole likely precludes a prompt explosion in these systems, we demonstrate that disk outflows can generate a large quantity (up to >50 Msun) of ejecta, comprised of >5-10 Msun in r-process elements and ~0.1-1 Msun of Ni(A=56), expanding at velocities ~0.1c. Radioactive heating of the disk-wind ejecta powers an optical/infrared transient, with a characteristic luminosity ∼1e42 erg s−1 and spectral peak in the near-infrared (due to the high optical/UV opacities of lanthanide elements) similar to kilonovae from neutron star mergers, but with longer durations ≳ 1 month. These "super-kilonovae" (superKNe) herald the birth of massive black holes >60 Msun, which, as a result of disk wind mass-loss, can populate the pair-instability mass gap ‘from above’ and could potentially create the binary components of GW190521. SuperKNe could be discovered via wide-field surveys such as those planned with the Roman Space Telescope or via late-time infrared follow-up observations of extremely energetic GRBs. Gravitational waves of frequency ~0.1-50 Hz from non-axisymmetric instabilities in self-gravitating massive collapsar disks are potentially detectable by proposed third-generation intermediate and high-frequency observatories at distances up to hundreds of Mpc; in contrast to the "chirp" from binary mergers, the collapsar gravitational-wave signal decreases in frequency as the disk radius grows ("sad trombone").

Black hole mergers in compact star clusters and massive black hole formation beyond the mass gap

Francesco Paolo Rizzuto
Helsinki University

We present direct N-body simulations, carried out with NBODY6++GPU, of young and compact low-metallicity (Z = 0.0002) star clusters with >100k stars (10% of which in binaries), a half-mass radius Rh = 0.6 pc, including updated evolution models for stellar winds and (pulsation) pair-instability supernovae (PSNe). Within the first tens of megayears, each cluster hosts several black hole (BH) merger events which nearly cover the complete mass range of primary and secondary BH masses for current LIGO-Virgo-KAGRA gravitational wave detections. The importance of gravitational recoil is estimated statistically during post-processing analysis. We present possible formation paths of massive BHs above the assumed lower PSN mass-gap limit (45 Msun) into the intermediate-mass black hole (IMBH) regime (> 100 Msun) which include collisions of stars, BHs, and the direct collapse of stellar merger remnants with low core masses. The stellar evolution updates result in the early formation of heavier stellar BHs compared to the previous model. The resulting higher collision rates with massive stars support the rapid formation of massive BHs. For models assuming a high accretion efficiency for star–BH mergers, we present a first-generation formation scenario for GW190521-like events: a merger of two BHs which reached the PSN mass-gap merging with massive stars. This event is independent of gravitational recoil and therefore conceivable in dense stellar systems with low escape velocities. One simulated cluster even forms an IMBH binary (153, 173 Msun) which is expected to merge within a Hubble time.

Population synthesis of BBH mergers with B-POP

Manuel Arca Sedda
Dep. of Physics and Astronomy, University of Padova (Italy)

In this talk I will present B-POP, a tool enabling population synthesis of BBH mergers originating either via isolated binary stellar evolution or dynamical interactions in young, globular, and nuclear clusters. We used B-POP to explore the role of dynamics, natal spin and kicks, and IMBH seeds in determining the detectable population of BBH mergers. Our results show that the observed population of BBHs detected via GW emission can be explained by a population composed of 34%(66%) of isolated(dynamical) binaries. The modelled primary mass distribution nicely overlaps with the one inferred from observations but exhibits an unseen tail extending beyond 200 Msun. In our fiducial model, hierarchical mergers represent 4.6-7.9% of mock mergers and dominate the primary mass distribution beyond 65Msun, whilst around 2.7-7.5% of mergers might involve IMBH-sized objects. Finally, we explore the impact of various natal spin distributions on our results, suggesting that current detections might hint at different natal spins for single and binary BHs.

Merging binary black holes formed through isolated binary stars with all the metallicities

Ataru Tanikawa
The University of Tokyo

Many black hole mergers have been discovered by gravitational wave observations, however their origins have been under debate. We investigate the formation of merging binary black holes through isolated binary evolution by means of binary population synthesis technique. We find that isolated binary stars can form merging binary black holes consistent with gravitational wave observations. Especially, we show that extremely metal poor stars including Pop III stars have dominant contribution to the formation of GW190521 which contains at least one black hole within the so-called pair instability mass gap. In this talk, we will discuss about how to verify our scenario by future gravitational wave and electromagnetic observations.

Black Hole Coalescences in Star Clusters - observed in the supercomputer

Rainer Spurzem
ARI/ZAH Univ. of Heidelberg and KIAA Peking Uni

Direct N-body simulations of star clusters (globular and nuclear) with NBODY6++GPU on massively parallel GPU-accelerated supercomputers are presented. We now use updated stellar evolution models for massive stars - as a consequence many stellar and intermediate mass black holes are produced. Many of them form tight binaries, but they are also kicked out by Newtonian three-body interactions and recoil kicks after relativistic mergers. We use the Post-Newtonian approximation up to order PN3.5 for the relative motion of compact binaries, as well as spin-spin and spin-orbit interactions up to that order (though not yet implemented for all published results which will be presented here). With a sample of models we find both very good agreement of the distribution of black hole mergers with current ground based gravitational wave observations; also we get good cases of high mass mergers in the so-called pair instability mass gap for black holes, as they are also observed. Direct N-body models are very costly, so to reach a good coverage of parameter space we collaborate with the Monte Carlo (MOCCA) Survey Database teams. In the future parameters obtained from our model mergers may be useful to distinguish the astrophysical origin of observed sources. This is work of the Silk Road team, an international research team, with main bases in Beijing, China, and Heidelberg, Germany.

Formation of intermediate mass black holes and black hole mergers in young massive clusters with up to 1 million stars

Manuel Arca Sedda
Dep. of Physics and Astronomy, University of Padova (Italy)

The coalescence of black holes (BHs) with masses in the range of 5-200 Msun represents a pivotal class of gravitational wave sources that can be recorded across a wide range of frequencies, being potential targets for multiband detection with future space-borne and ground-based observatories like LISA, DECIGO, and the Einstein Telescope.
One possible formation channel for these sources is via dynamical interactions in dense clusters. However, the large computational time demanded to simulate such environments generally limits the size of the simulated clusters or leads to the choice of faster, but less accurate, methods than direct N-body simulations. Here, we present a suite of first-of-their-kind young massive cluster simulations with 0.1-1 million stars that include self-consistently

stellar evolution for single and binary stars, a treatment for close encounters, and relativistic corrections to model compact object binary mergers.
In the talk, I will use the results of these simulations to discuss the mechanisms that drive the formation of intermediate-mass black holes (IMBH) with masses up to 250 Msun, the properties of the population of BH mergers formed in these clusters, and the implications for current and future GW detectors.

Direct N-body simulations of extremely massive, rotating Population-III star clusters

Albrecht Kamlah
Max-Planck Institute for Astronomy (MPIA) and Astronomical Computation Institute at Heidelberg University (ARI-ZAH)

Population-III (Pop-III) star clusters with extremely low metallicity and very top-heavy initial mass function are possible birthplaces of seed black holes for galactic nuclei. Moreover, multi-generation mergers of black holes and other compact objects originating from these will be relevant gravitational wave (GW) detection events. In this talk, I present the results from a suite of eight direct N-body simulations with 1.01x10^5 particles using Nbody6++GPU of extremely massive Pop-III star clusters (log10(Z/Z*) = -8) that are initialised with rotating King model distributions. Our models feature primordial (hard) binaries, a continuous mass spectrum, and tidal mass loss induced by the overall gravitational field of the host galaxy. We include highly innovative stellar evolution fitting formulae for Pop-III stars in combination with state-of-the-art stellar evolution that affect all stars. Furthermore, in half of the simulations we include GW merger recoil kicks for the black holes. With our experimental setup we are in a unique position to disentangle the dependence of the formation of massive stars and (intermediate-mass) black holes on several processes: initial star cluster bulk rotation, the presence of gravitational wave merger recoil kicks and the impact of the new stellar evolution fitting formulae. I will also discuss the impact of all the above on the global, dynamical evolution of the star cluster and focus on the development and evolution the gravothermal-gravogyro catastrophe.
In the talk, I will use the results of these simulations to discuss the mechanisms that drive the formation of intermediate-mass black holes (IMBH) with masses up to 250 Msun, the properties of the population of BH mergers formed in these clusters, and the implications for current and future GW detectors.

Where is the love? The dynamical tides of rotating stars

Fabian Gittins
University of Southampton

Ground-based gravitational-wave instruments have witnessed several binary coalescences that comprise at least one neutron star. In these binaries, tidal interactions deform the star and imprint finite-size corrections on the associated gravitational waveform. These finite-size effects depend on the interior stellar composition and present a promising opportunity to constrain the elusive nuclear-matter equation of state. With current-generation detectors improving in sensitivity and future observatories planned, it proves timely to consider the weaker dynamical effects on the gravitational-wave signal. We study the dynamical tides of spinning stars. Stars possess a spectrum of normal vibrational modes, which become excited by the presence of an exterior gravitational field. We calculate the stellar response to a tidal field and present an expression for the effective Love numbers in terms of the natural modes. We find that rotation introduces a coupling between the prograde and retrograde modes that was not present in the non-rotating case. Considering the static tide, we show that rotation modifies the deformability at second order.

Damping of gravitational waves originating from core-collapse supernovae

Monos Naidoo
Rhodes University

Core-collapse supernovae (CCSNe) are promising sources of detectable gravitational waves (GWs). Yet, with three observation runs complete to date, of the 90 GW signals detected, none are from CCSNe. The delay in detection, though, may suggest the influence of the astrophysical environment of these anticipated sources. In CCSNe, GWs are generated in the inner core precipitated by the bounce of this core. A substantial outer core exists surrounding this GW source. In previous work [1], using the Bondi-Sachs formalism, together with linearised perturbation theory, we considered the problem of a gravitational wave (GW) source surrounded by a spherical dust shell. We found that the effect of a thin shell of matter surrounding a GW source, is to modify the GW signal in both magnitude and phase. These effects are astrophysically significant since there are scenarios for which the modification to the GW signal is large enough to be measurable [2]. We also indicated that the thin shell analysis may be extrapolated to that of a thick shell by considering a series of consecutive thin shells and integrating. We have extended our analysis to the case of the matter shell comprised of a viscous fluid, so that the shear induced in the velocity field by GWs results in an energy transfer to the fluid, thus reducing the magnitude of the GWs. Using our result that GW damping can be significant when the shell radius r_i is much smaller than the GW wavelength lambda, we apply our formula obtained, to CCSNe and find upper and lower bounds for the damping for various parameter values. These results may have implications for current calculated detection rates of CCSNe.

1.N.T. Bishop, M. Naidoo, and P.J. van der Walt (2020), Gen. Rel. Grav. 52:92, https://doi.org/10.1007/s10714-020-02740-9
2. M. Naidoo, N.T. Bishop, and P.J. van der Walt (2021), Gen. Rel. Grav. 53:97, https://doi.org/10.1007/s10714-021-02841-z

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Gravitational waves from small spin-up and spin-down events of neutron stars

Garvin Yim
University of Southampton, KIAA (Peking University)

In this talk, I will outline a novel model that can account for small positive and negative changes in the spin of a neutron star, which collectively may contribute to the uncertain phenomenon of "timing noise". In brief, the model posits that changes in spin are caused by the excitation and decay of non-axisymmetric f-modes. A consequence of this is that gravitational waves are emitted, and hence, there is an independent test for our model using gravitational waves. We comment on the potential detectability of the corresponding gravitational waves using recent data from the Crab and Vela pulsars. Our results form the basis for a new multi-messenger study of pulsars. (Based on Yim & Jones, arXiv:2204.12869)

A phenomenological inspiral-merger-postmerger gravitational waveform model for binary neutron star coalescence

Anna Puecher
Nikhef - Utrecht University

Gravitational waves provide us with an extraordinary tool to study the matter of neutron stars. In particular, the postmerger signal will reveal a lot of information about matter at such high densities. Although current detectors are mainly sensitive to the signal emitted by binary neutron stars during the inspiral and merger phase, the detectors' improvements planned for the next observing runs and future generation detectors, like Einstein Telescope and Cosmic Explorer, will allow us to detect postmerger signals too. We present a new model for the inspiral-merger-postmerger signal emitted by binary neutron stars systems. The inspiral part of the model is described by one of the state-of-the-art waveform models employing a closed-form expression for the tidal contribution, while the postmerger is modeled with a three-parameters Lorentzian, with two different approaches: in one case the Lorentzian parameters are kept as free parameters, in the other one we model them via quasi-universal relations. We test the performance of both versions of our model in parameter estimation analysis, employing a set of signals obtained from hybrid waveforms, and simulated at different distances. We compare the results for the LIGO-Virgo network with aLIGO+ sensitivity to a network including also LIGO-India and KAGRA. We also study the possible improvement given by the high-frequency detector NEMO, and we finally compare results to what we will obtain for the same sources with third-generation detectors.

Inferring the dense nuclear matter equation of state with neutron star tides

Pantelis Pnigouras
Sapienza University of Rome

During the late stages of a neutron star binary inspiral finite-size effects come into play, with the tidal deformability of the supranuclear density matter leaving an imprint on the gravitational-wave signal. As demonstrated in the case of GW170817—the first direct detection of gravitational waves from a neutron star binary—this can lead to strong constraints on the neutron star equation of state. As detectors become more sensitive, effects which may have a smaller influence on the neutron star tidal deformability need to be taken into consideration. Dynamical effects, such as oscillation mode resonances triggered by the orbital motion, have been shown to contribute to the tidal deformability, especially close to the neutron star coalesence, where current detectors are most sensitive. We calculate the contribution of the various stellar oscillation modes to the tidal deformability and demonstrate the (anticipated) dominance of the fundamental mode. We show what the impact of the matter composition is on the tidal deformability, as well as the changes induced by

more realistic additions to the problem, e.g. the presence of an elastic crust and superfluidity. Finally, based on this formulation, we develop a simple phenomenological model describing the effective tidal deformability of neutron stars and show that it provides a surprisingly accurate representation of the dynamical tide close to merger.

Constraining the equation of state of neutron stars using multimessenger observations

Bhaskar Biswas
Oskar Klein Centre, Stockholm University

We are now in a golden era of neutron star (NS) physics. Not only gravitational wave observation by LIGO/Virgo, recently NICER collaboration has also provided a very accurate measurement of mass and radius of PSR J0030+0451 and PSR J0740+6620 by observing X-ray emission from several hot spots of NS surface. In recent times, laboratory experiments such as PREX-II has also shown us a promise to put further constraint on the NS equation of state (EoS). By combining these observations coming from multiple messengers we could provide a stringent constraint on NS properties. In this talk, I will discuss the present status of NS EoS by combining this information using a comprehensive Bayesian statistics. We use a hybrid EoS formulation that employs a parabolic expansion-based nuclear empirical parameterization around the nuclear saturation density augmented by a generic 3-segment piecewise polytrope model at higher densities.

Simultaneous inference of Neutron Star Equation of State and Hubble Constant with a Population of Merging Neutron Stars

Tathagata Ghosh
Inter-University Centre for Astronomy and Astrophysics

Gravitational wave (GW) from compact binary coalescence (CBC) directly provides luminosity distance measurement but no redshift information. If their redshifts were available by alternative means, such as via electromagnetic counterparts, the Hubble constant could be estimated from the distance-redshift relation. However, while binary neutron star (BNS) mergers are expected to be accompanied by electromagnetic counterparts, like GW170817, a redshift measurement may not always be available. Here, we have extended a past proposal for utilizing prior knowledge of neutron star (NS) equation of state (EoS) instead to infer the Hubble constant. Unlike in the past, we employ a realistic EoS parameterization in a Bayesian framework to simultaneously measure the Hubble constant and refine the constraints on EoS parameters.
The phase of the frequency domain GW waveform consists of two components: the standard post-Newtonian (PN) point-particle frequency domain phase and the tidal phase component arising due to the tidal deformation of neutron stars. The PN point-particle piece depends on the redshifted chirp-mass and luminosity distance – in contrast to the tidal phase term, which depends on source-frame component masses. The degeneracy between mass parameters and the redshift is thus broken with the knowledge of EoS. Since GW observation also provides the luminosity distance, the Hubble constant can therefore be inferred.

We demonstrate the performance of our methodology with a mock GW catalog of sources, simulated for Cosmic Explorer – a proposed third-generation GW detector. We consider three sets of priors over EoS parameters and deduce how precisely the Hubble constant can be measured and the EoS parameters constrained in that era.
[More details are reported in https://arxiv.org/abs/2203.11756 .]

Probing ultralight dark matter with gravitational-waves

Chen Yuan
Institute of Theoretical Physics, Chinese Academy of Sciences

Ultralight bosons are one of the promising dark matter candidates and can condensate around black holes, resulting in a long-lived gravitational-wave signal. Detecting such a gravitational-wave signal provides a universal way to probe the ultralight boson in the Universe. We extend the former investigations by including all unstable modes and the latest released LIGO-Virgo data, and finally obtain the widest excluded boson mass range which is several times better than the former results from LIGO O1 data by considering only the unstable dipolar and quadrupolar modes.

Gravitational waves from axion and related searches

Sichun Sun
Beijing Institute of Technology

We discuss the axion objects such as axion mini-clusters and axion clouds around spinning black holes, which induce parametric resonances of electromagnetic waves through the axion-photon interaction, as well as high frequency gravitational waves through gravitational Chern-Simons (CS) coupling. We also present some new detection schemes for axions and high frequency waves.

Gravitational wave echoes from interacting quark stars

Chen Zhang
Hong Kong University of Science and Technology

We show that interacting quark stars (IQSs) composed of interacting quark matter (IQM), including the strong interaction effects such as perturbative QCD corrections and color superconductivity, can be compact enough to feature a photon sphere that is essential to the signature of gravitational wave echoes. We utilize an IQM equation of state unifying all interacting phases by a simple reparametrization and rescaling, through which we manage to maximally reduce the number of degrees of freedom into one dimensionless parameter $\bar{\lambda}$ that characterizes the relative size of strong interaction effects. It turns out that gravitational wave echoes are possible for IQSs with h $\bar{\lambda} \gtrsim 10$ at large center pressure. Rescaling the dimension back, we illustrate its implication on the dimensional parameter space of the effective bag

constant B_{eff} and the superconducting gap Δ with variations of the perturbative QCD parameter a_4 and the strange quark mass m_s in their empirical range. We calculate the rescaled GW echo frequencies $\bar{f}_{echo}$ associated with IQSs, from which we obtain a simple scaling relation for the minimal echo frequency $f_{echo}^{min} \approx 5.67\sqrt{B_{eff}/(100MeV)^4}$kHz at the large $\bar{\lambda}$ limit. (Based on Phys. Rev. D 104 (2021) no.8, 083032)

Scalar Gravitational Waves from Core-Collapse in Self-Interacting Massive Scalar-Tensor Gravity

Da Huang
National Astronomical Observatories, Chinese Academy of Sciences

The spontaneous scalarization during the stellar core collapse in the massive scalar-tensor theories of gravity introduces extra polarizations (on top of the plus and cross modes) in gravitational waves, whose amplitudes are determined by several model parameters. Observations of such scalarization-induced gravitational waveforms therefore offer valuable probes into these theories of gravity. Considering a triple-scalar interactions in such theories, we find that the self-coupling effects suppress the magnitude of the scalarization and thus reduce the amplitude of the associated gravitational wave signals. In addition, the self-interacting effects in the gravitational waveform are shown to be negligible due to the dispersion throughout the astrophysical distant propagation. As a consequence, the gravitational waves observed on the Earth feature the characteristic inverse-chirp pattern. Although not with the on-going ground-based detectors, we illustrate that the scalarization-induced gravitational waves may be detectable at a signal-to-noise ratio level of O(100) with future detectors, such as Einstein Telescope and Cosmic Explorer.

Implications of the quantum nature of the black hole horizon on the gravitational-wave ringdown

Sumanta Chakraborty
Indian Association for the Cultivation of Sceince

Motivated by capturing putative quantum effects at the horizon scale, we model the black hole horizon as a membrane with fluctuations following a Gaussian profile. By extending the membrane paradigm at the semiclassical level, we show that the quantum nature of the black hole horizon implies partially reflective boundary conditions and a frequency-dependent reflectivity. This generically results into a modified quasi-normal mode spectrum and the existence of echoes in the postmerger signal. On a similar note, we derive the horizon boundary condition for a braneworld black hole that could originate from quantum corrections on the brane. This scenario also leads to a modified gravitational-wave ringdown. We discuss general implications of these findings for scenarios predicting quantum corrections at the horizon scale.

A viable model to explain the Fast radio burst using the Gertsenshtein-Zel'dovich effect

Ashu Kushwaha
Indian Institute of Technology Bombay

Fast Radio Bursts (FRBs) are one of the super-energetic radio pulsed signals with a short (< 1 sec) time duration. In recent years, numerous theoretical explanations for the origin of FRBs have been proposed. However, even with exotic physics, models have been unable to universally explain the properties of these events, such as peak flux and pulse width. In this study, we present a novel model that explains the origin of FRBs of GHz frequency radio waves. The model has three ingredients: compact object, progenitor with very strong effective magnetic field strength, and GHz frequency gravitational waves (GWs). Due to the Gertsenshtein-Zel'dovich effect, when GWs pass through the magnetosphere of such compact objects, their energy is converted into electromagnetic waves. This conversion produces bursts of electromagnetic waves in the GHz range, leading to FRBs. Therefore, we infer that millisecond pulsars may be the origin of FRBs. Further, our model offers a novel perspective on the indirect detection of GWs at high-frequency beyond detection capabilities. (Based on arxiv:2202.00032)

Tidal Stripping of a White Dwarf by an Intermediate-Mass Black Hole

Jin-Hong Chen
Sun Yat-sen University

White dwarf (WD) inspiralling into an intermediate-mass black hole (IMBH, $M_h \sim 102 - 5\ M_\odot$) in an eccentric orbit (e ~ 0.7 - 0.9) can be observed by both of the gravitational waves (GWs) and electromagnetic (EM) radiation. When the pericenter radius is slightly larger than the tidal radius, the WD would be tidally stripped during each pericenter passage, and the accretion of these stripped mass would produce EM radiation. It is suspected that the quasi-periodic eruptions (QPEs) and the fast ultraluminous X-ray bursts (ULXBs), which are discovered by the X-ray telescopes in recent years, might originate from such system. Modeling these flares requires an prediction of the stripped mass of the WD and how these masses supply to the accretion disk. The goal of this work is studying the orbital parameter dependencies of the stripped mass and the corresponding mass fallback rate through hydrodynamical simulation. Based on these results, we further calculate the mass-loss evolution of the WD during its inspiral and investigate the detectability of the GW and EM signals. We find that the EM signal from the mass-loss stage can be easily detected: the limiting distance is ~ $323(M_h/10^4\ M_\odot)$ Mpc for the Einstein Probe, which is scheduled to be launched by the end of 2022. And the GW detectable horizon distance is much smaller, which is ~ $14(M_h/10^4\ M_\odot)^{7/15}$ Mpc for the next-generation GW detectors, e.g., Laser Interferometer Space Antenna (LISA) and TianQin. Those WD-IMBH inspirals with large WDs (~ 1 $M_\odot$) will be the ideal targets for the GW detection.

Multi-messenger prospects with massive black hole binaries: counterparts prediction and cosmological applications

Alberto Mangiagli
APC (Paris)

In ~2034 the Laser Interferometer Space Antenna (LISA) will detect the coalescence of massive black hole binaries (MBHBs) from 105 to 107 solar mass up to z~10. The gravitational wave (GWs) signal is expected to be accompanied by an electromagnetic (EM) counterpart, from radio to X-ray, generated by the gas accreting on the binary.
In this talk, I present some recent results on the standard sirens rates detectable jointly by LISA and EM telescopes. We combine state-of-the-art models for the galaxy formation and evolution with Bayesian tools to perform the parameter estimation of the GW event and estimate the cosmological parameters.
We explore three different astrophysical scenarios employing different seed formation (light or heavy seeds) and delay-time models, in order to have realistic predictions on the expected number of events. We estimate the detectability of the sources in terms of its signal-to-noise ratio in LISA and perform parameter estimation, focusing especially on the sky localization of the source. Exploiting the additional information from the astrophysical models, such as the amount of accreted gas and BH spins, we model the expected EM counterpart to the GW signal in soft X-ray, optical and radio.
Overall, we predict ~ 14 standard sirens (stsi) with detectable counterparts over 4 yr of LISA time mission and ~6 (~20) in the pessimistic (optimistic) scenario.
We also explore the impact of absorption from the surrounding gas both for optical and X-ray emission: assuming typical hydrogen and metal column density distribution, we estimate only ~3 stsi in 4 yr.
Finally we combined the redshift and luminosity distance information to estimate cosmological parameters: we find that H can be constrained to ~few percent precision thanks to few sources whose redshift is measured spectroscopically.

Measuring the Hubble constant with dark sirens: inputs from the large scale structure clustering

Sayantani Bera
Universitat de les Illes Balears, Spain

The standard sirens in the gravitational wave (GW) astronomy provide us with a direct measure of the cosmological distances independent of the cosmic distance ladder. When accompanied by an optical counterpart, it can also provide a redshift measurement, thus constraining the Hubble parameter H, like in the case of the event GW170817. But, for majority of the detected GW events, it is not possible to obtain an electromagnetic counterpart. Such sources with unknown redshifts, known as the ‘dark sirens’, can also be used to infer H, by making use of the clustering properties of the galaxies and other large scale structures. In this talk, I will show how the angular clustering between gravitational-wave standard sirens and galaxies with known redshifts allows an inference of H, regardless of whether the host galaxies of any of these sirens are present in the galaxy catalog. With a realistic simulation of the GW events detected with a three-detector network, it is shown that the cross-correlation technique infers the Hubble parameter with a precision of less than 10% (2%) at 90% confidence with 50 (500) sources, even with a 100% incomplete catalog. I will point out the important difference between this method and the current state-of-the-art technique adopted within the LVK collaboration.

GRMHD simulations of neutron star mergers with weak interactions: dynamical ejecta signatures and post-merger evolution

Luciano Combii
Instituto Argentino de Radioastronomía

In this talk, I will present new GRMHD simulations of NS mergers which include neutrino transport and nuclear equations of state. I will first show a detailed analysis of the dynamical ejecta and its r-process nucleosynthesis obtained from these simulations. Based on these results and using new semi-analytical models, I will give a comprehensive picture of the electromagnetic signatures associated with the dynamical phase, namely, the free neutron precursor and the kilonova afterglow. Finally, I will show preliminary results on post-merger physics, where both magnetic fields and neutrinos become crucial to understanding the evolution and outflows from the system.

Studying Magnetically-driven Outflows from Magnetized Neutrino-cooled Accretion Disks

Fatemeh Hossein Nouri
Center for Theoretical Physics of the Polish Academy of Science

Neutrino-cooled accretion flow around a spinning black hole, produced by a compact binary merger is a promising scenario for jet formation and launching magnetically-driven outflows. Based on GW170817 gravitational wave detection by LIGO and Virgo observatories followed by electromagnetic counterparts, this model can explain the central engine of the short duration gamma ray bursts (GRB) and kilonova radiations. Using the open-source GRMHD HARM_COOL code, we evolved several 2D magnetized accretion disk-black hole models with realistic equation of state in the fixed curved space-time background. The disk and black hole's initial parameters are chosen in a way to represent different possible post-merger scenarios of the merging compact objects. Our simulations show a strong correlation between black hole's spin and ejected mass. Generally, mergers producing massive disks and rapidly spinning black holes launch more wind outflows. We applied particle tracer technique to measure the properties of the outflows. We observed our models generate winds with moderate velocity (v/c ~ 0.1-2.0), and broad range of electron fraction. We use these results to estimate the luminosity and light curves of possible radioactively powered transients emitted by such systems. We found the luminosity peaks within the range of $10^{40} - 10^{41}$ erg/s which agrees with previous studies for disk wind outflows.

C4: Gravitational waves: Present and future of ground-based and space-based detectors (Chair: Gabriela Gonzalez, Coordinator: Ze-Bing Zhou)

Progress on Tian Qin Mission Concept Studies

Xuefeng Zhang
Sun Yat-sen University

The Tian Qin mission plans to deploy three drag-free controlled satellites in circular high Earth orbits with a 10^5 km radius, which form a nearly equilateral-triangle constellation set almost vertical to the ecliptic. Tian Qin features a geocentric concept. A critical question is how to detect gravitational waves in a high Earth orbit? To answer it, mission studies need to identify unique challenges, technical solutions, and pros/cons. In this talk, we briefly summarize recent progress on Tian Qin mission concept studies. These include constellation stability optimization, orbital orientation and radius selection, the Earth-Moon's gravity disturbance, and eclipse avoidance, thermal environment, and solar-wind plasma disturbance (Ye et al, IJMPD 1950121(2019), Zhou et al, PRD 103026(2021), Tan et al, IJMPD 2050056(2020), Zhang et al, PRD 062001(2021), Luo et al, PRD accepted (2022), Ye et al, PRD 042007(2021), Chen et al, CQG 155015(2021), Lu et al, JGR: Space Physics e2020JA028579(2021), Su et al, APJ, 139(2021)).

Astronomy with the Tian Qin Observatory

Yi-Ming Hu
Sun Yat-sen University

In this talk, I intend to briefly introduce the concept of the Tian Qin project, and examine its potential in gravitational wave astronomy. As a space-borne GW mission, Tian Qin has the ability to detect GW signals in milli-Hertz range, and sources like stellar-mass black hole binary inspirals, extreme mass-ratio inspirals, massive black hole mergers, Galactic compact binaries, and stochastic gravitational wave backgrounds are all expected to be detectable by Tian Qin. The operation of Tian Qin will open an exciting window for studying the evolution of stars and galaxies. The future detections can also be used to measure the expansion rate of the Universe. We also discussed the scientific potential of the collaboration of Tian Qin and other GW missions like LISA.

The landscape of massive black-hole spectroscopy with LISA and the Einstein Telescope

Costantino Pacilio
Sapienza University of Rome

Measuring the quasi-normal mode (QNM) spectrum emitted by a perturbed black hole (BH) provides an excellent opportunity to test the predictions of general relativity in the strong-gravity regime. We investigate the prospects and precision of BH spectroscopy in massive binary black hole ringdowns, one of the primary science objectives of the future Laser Interferometric Space Antenna (LISA) mission. We simulate various massive binary BH population models and we find that, for any heavy seed scenario, LISA will measure the dominant mode frequency within 0.1 % relative uncertainty and will estimate at least 3 independent QNM parameters within 1 % error. On the other hand, light seed scenarios produce lighter merger remnants, which ring at frequencies higher than LISA's sensitivity. Interestingly, the light seed models give rise to a fraction of mergers in the band of Einstein Telescope, allowing for the measurement of 3 QNM parameters within 10 % relative error in approximately O(10) events/yr.

Gravitational-wave imprints of non-integrable extreme-mass-ratio inspirals

Kyriakos Destounis
Universität Tübingen

The detection of gravitational waves from extreme-mass-ratio inspirals (EMRIs) with upcoming space-borne detectors will allow for unprecedented tests of general relativity in the strong-field regime. Aside from assessing whether black holes are unequivocally described by the Kerr metric, they may place constraints on the degree of spacetime symmetry. Depending on exactly how a hypothetical departure from the Kerr metric manifests, the Carter symmetry, which implies the integrability of the geodesic equations, may be broken. In this talk, I will discuss the impact of non-integrability in EMRIs which involve a supermassive compact object with anomalous multipolar structure. After reviewing the features of chaotic phenomena in EMRIs, I will argue that non-integrability is precisely imprinted in the gravitational waveform. Explicit examples of non-integrable EMRIs will be discussed, as well as their role in LISA data analysis.

Intracavity parametric amplification system to enhance the gravitational-wave signal at high frequencies

Kentaro Somiya
Tokyo Institute of Technology

An intracavity parametric amplification system is one of the most advanced techniques to be implemented in the next generation gravitational wave telescopes. A non-linear crystal is inserted in the detuned signal-recycling cavity to increase the rigidity of the optomechanical spring. With the optomechanical spring frequency at a few kHz, we expect to observe a clear signal of gravitational waves from a neutron star binary coalescence.
We have built a prototype signal-recycled interferometer with an intracavity parametric amplifier to demonstrate the state-of-the-art technique and succeeded in operating the entire system with 5 degrees of freedom, namely the second harmonics generation, the subcarrier PLL, the signal recycling cavity, the dark fringe control, and the relative phase of the amplifier. Most of the degrees of freedom are controlled via a commercial digital controller. We then measured the transfer function from the motion of the end mirror to the dark fringe

photo detector in order to observe the optomechanical spring resonance. The final goal is to examine the shift of the resonance with changing the parametric gain.
In this presentation, we will introduce the theoretical background of the technique and report the current status of the prototype experiment performed at Tokyo Institute of Technology.

Development of a control scheme of a signal recycling interferometer with a nonlinear optical effect

KAIDO SUZUKI
Tokyo Institute of Technology

Gravitational waves are space-time distortions generated by accelerated masses, and gravitational wave detectors are based on the Michelson interferometer. Since the sensitivity of a simple Michelson interferometer cannot be high enough to observe gravitational waves, currently operated detectors, namely LIGO, Virgo, and KAGRA, use two arm cavities and recycling cavities to increase the sensitivity.

A new method to further improve the sensitivity has been proposed. It is a technique that combines an optical parametric amplification and an optomechanically coupled oscillator. In the proposed setup, the optical spring that amplifies the gravitational wave signal at its resonance can be stiffened to improve the sensitivity at a few kHz band.

We built a prototype experiment with a Michelson interferometer and a signal recycling cavity to verify the theory of the parametric optomechanical amplification. Since our experimental setup requires a simultaneous control of many degrees of freedom control, we established a digital control system using on-market devices. By now, we have succeeded in the simultaneous control of 5 degrees of freedom including a state-of-the-art coherent control of the intracavity amplifier in the signal recycling cavity. In this presentation, I will report the current status of our prototype experiments.

The Impact of Solar-Terrestrial Plamsa and Magnetic Field on the Space-Borne Detection of Gravitational Waves

Wei Su
Sun Yat-sen University

Space gravitational wave detection raises a new question for heliospheric physics: how does the solar terrestrial space environment affect gravitational wave detection and how much does it affect? The space-borne gravitational wave detection project uses laser interferometry to measure the distance between two free-floating test masses changes caused by gravitational waves (GWs). The accuracy of laser ranging is required to be on the order of pm (10^{-12} m), and the accuracy of acceleration measurements, which is used to describe whether the mass is "free", is required to be 10-15 m/s^2. The influence of space plasma and magnetic field on GWs detection needs to be fully considered. The propagation of laser in space plasma leads to time delay, optical path difference noise, polarization angle change, wavefront distortion and so on, which affect the ranging accuracy of GWs detection. The interaction between

space magnetic field and free test mass produces non-conservative force, which leads to acceleration noise. Here, we use MHD simulations and satellite in-situ observations to study the influence of the range finding and acceleration noise caused by solar and space physical processes on space GWs detection in MHD scales.
The Space Weather Modeling Framework is used to simulate the interaction between the Earth magnetosphere and solar wind. From the simulations, we extract the magnetic field and plasma parameters on the orbits of Tian Qin at four relative positions of the satellite constellation in the Earth magnetosphere. We calculate the OPD noise for single link, Michelson combination, and Time-Delay Interferometry (TDI) combinations ($\alpha$and X). For single link and Michelson interferometer, the maxima of $|\Delta l|$ are on the order of 1 pm. For the TDI combinations, these can be suppressed to about 0.004 and 0.008 pm for $\alpha$and X. The OPD noise of the Michelson combination is colored in the concerned frequency range; while the ones for the TDI combinations are approximately white. Furthermore, we calculate the ratio of the equivalent strain of the OPD noise to that of TQ, and find that the OPD noises for the TDI combinations can be neglected in the most sensitive frequency range of TQ.

Stimulative detection of high frequency gravitational waves

Lianfu Wei
Southwest Jiaotong University

An experimental system to detect the electromagnetic responses of high frequency gravitational wavs (HFGWs) passing through a rf-modulated high magnetic field is proposed. The sensitivity of the system is calibrated by numerically simulating the thermal and shot noises. It is shown that the proposed system could be utilized to implement the relic GWs in the microwave band. A deep learning method is also developed to process the big simulated detection data. By using the coidence detection, it is argued that the stochastic GWs could be detected.

Prospects for third generation gravitational wave interferometers

Rosa Poggiani
University of Pisa

The third generation of gravitational wave interferometer will adopt cryogenic test masses, as in the KAGRA interferometer, to reduce thermal noise and improve the sensitivity. The test mass suspension systems or part of them will operate at low or cryogenic temperatures. The scientific and technical issues of suspensions operating at low temperatures in the low contamination environment of the interferometers will be discussed.

Constraining ΛCDM cosmological parameters with Einstein Telescope mock data

Matteo Califano

Scuola Superiore Meridionale ,University of Naples "Federico II"

Abstract: We investigate the capability of Einstein Telescope to constrain the cosmological parameters of the non-flat ΛCDM cosmological model. Two types of mock datasets are considered depending on whether or not a short Gamma-Ray Burst is detected and associated with the gravitational wave event using the THESEUS satellite. Depending on the mock dataset, different statistical estimators are applied: one assumes that the redshift is known, and another one marginalizes over it, assuming a specific prior distribution. We demonstrate that (i) using mock catalogs collecting gravitational wave events to which a short Gamma-Ray Burst has been associated, Einstein Telescope may achieve accuracy on the cosmological parameters of $\sigma_{H0}\approx 0.40 km \cdot s^{-1} \cdot Mpc^{-1}$, $\sigma_{\Omega,k} \approx 0.09$ and $\sigma_{\Omega,\Lambda} \approx 0.07$; while (ii) using mock catalogs collecting also gravitational wave events without a detected electromagnetic counterpart, Einstein Telescope may achieve an accuracy on the cosmological parameters of $\sigma_{H0} \approx 0.04\ km \cdot s^{-1} \cdot Mpc^{-1}$, $\sigma_{\Omega,k} \approx 0.01$ and $\sigma_{\Omega,\Lambda} \approx 0.01$. These results show an improvement of a factor 2-75 with respect to earlier results using complementary datasets.

LISA-Taiji Sensitivity to an Anisotropic Stochastic Gravitational-Wave Background

Zehua Song
Dartmouth College, Hanover, NH, USA, 03755

Space-based gravitational wave detectors LISA and Taiji are both scheduled to be in operation in the 2030s and a joint analysis would increase the sensitivity to a primordial stochastic gravitational-wave background. In this talk, we present results for intensity, circular polarization, and anisotropies in the presence of detector and astrophysical sources of noise, for various orbital configurations.

C5: Experimental gravitation (Chair: Yoshio Kamiya, Coordinator: Shan-Qing Yang)

Mechanical sensors for exploring the dark sector

Swati Singh
University of Delaware

When properly engineered, simple quantum systems such as harmonic oscillators or spins can be excellent detectors of feeble forces and fields. Following a general introduction to this fast growing area of research, I will focus on using optomechanical systems as sensors of weak acceleration and strain fields. I will discuss the feasibility of searching for ultralight dark matter using various optomechanical systems. I will also show that current mechanical systems have the sensitivity to set new constraints on screened scalar field candidates for dark energy, such as the chameleon. Finally, I will briefly discuss the promise of quantum noise limited detectors in the search for beyond the standard model physics.

Gravity tests with the Double Pulsar - from MeerKAT to the SKA

Huanchen Hu
Max Planck Institute for Radio Astronomy, Bonn, Germany

The Double Pulsar, PSR J0737-3039A/B, has offered a wealth of gravitational experiments, for which GR has passed all with flying colors. One of the most significant results is that it provides currently the most accurate test of GR’s quadrupole gravitational wave prediction. Observations with MeerKAT and the SKA can greatly improve the accuracy of these tests and facilitate the tests of next-to-leading order contributions in the orbital motion and the signal propagation. Moreover, measurement of neutron star moment-of-inertia via relativistic spin-orbit coupling will be possible and provide important additional constraints on the dense matter equation-of-state. In this talk, I will summarize the current tests with the Double Pulsar, and present new MeerKAT observations which already improve on Shapiro delay and next-to-leading order signal propagation effects. In particular, I will focus on testing the retardation effect due to the movement of the companion and the deflection of the signal by the gravitational field of the companion. Furthermore, I will discuss future prospects with MeerKAT and the SKA, such as potential measurements of lensing, moment-of-inertia, frame-dragging, and next-to-leading order gravitational wave damping.

A new timing model for testing scalar-tensor gravity

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Scalar-tensor gravity (STG) theories are well-motivated alternatives to general relativity (GR). We are particularly interested in Damour-Esposito-Farese (DEF) gravity because it is rich in different observable phenomena, such as dipolar GW emission and spontaneous scalarization of neutron stars.
In this talk we present a new timing model called DDSTG for testing DEF gravity with binary radio pulsars. This novel approach avoids correlations between PK parameters and extracts information from weakly measured relativistic effects.
We apply the DDSTG model to the up-to-date timing data for PSR J2222-0137 and PSR J1141-6545. The limits obtained by the DDSTG model are more restrictive and more reliable compared to the PK method. DDSTG is highly beneficial for PSR J1141-6545, where the Shapiro delay is present at a low significance, and where, in addition, there are correlations between PK parameters and the unconstrained effects arising from spin-orbit coupling. Moreover, we argue what limits we can obtain from a hypothetical pulsar-black hole system.

Gravitational and whispering-gallery states of light neutral particles

V.V. Nesvizhevsky
Institut Max von Laue – Paul Langevin

In the last decades, massive quantum particle bouncing off a surface under the influence of gravity [1] turned from being an issue of textbooks and pedagogical essays into a subject of precision experiments on atom-optics gravitational cavities and physics of ultracold neutrons (UCNs). The observation of gravitational quantum states (GQSs) [2] and whispering gallery states (WGSs) [3] of neutrons (n) fueled a vast research in this area, which, among other goals, aims to the search for new fundamental short-range interactions and physics beyond the standard model of particle physics, as well as verification of weak equivalence principle in the quantum regime.
The accuracy of measurements of n GQSs and WGSs is improving due to the efforts of qBounce, Tokyo and GRANIT collaborations [8-10]. Cold atoms and antiatoms can also bounce on surfaces and form GQSs [4] due to the quantum reflection from a rapidly changing attractive van der Waals/Casimir-Polder (vdW/CP) surface potential [5]. GRASIAN collaboration aims at precision gravitational, optical and hyperfine spectroscopy of ultracold hydrogen (H) [11-12]. The GQSs method promises a high accuracy for the direct measurement of the gravitational acceleration of antimatter (ultracold antihydrogen, $\bar{H}$) [6] in the framework of GBAR collaboration [7]. Feasibility and motivations of measurement of GQSs and WGSs of other light neutral particles is under discussion.
We present the current status of this research, discuss its prospects and underline the importance of providing long times of observation of the particles in quantum states [11] and the flexibility of methods of their analysis, which facilitate the optimization of measuring methods for particular tasks [13].

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Experimental progress towards measuring antimatter gravity using positronium

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Positronium (Ps), the bound state of an electron and its antiparticle positron, is a unique system suitable for precise tests of fundamental physics. It’s purely leptonic and simple structure allows us to search for even small signs of new physics beyond the Standard Model through comparisons between precise theoretical calculations and experimental measurements. Another interesting feature of Ps is that it consists of antimatter, while the asymmetry between matter and antimatter is searched in various aspects. Measurements of a gravity effect on antimatter is one of the intriguing topics in antimatter physics. Because Ps is easy to produce compared with other antimatter atomic systems, precise spectroscopy and Ps atomic interferometer combined with large statistics can be powerful methods to a measure gravity effect on Ps, and then on antimatter.

Even Ps is potentially useful for measuring a gravity effect on antimatter, it requires an order of magnitude colder Ps cloud than currently available one to improve the sensitivity to measure the gravity effect which is expected to be small. In precise spectroscopy, it has been proposed [1] to measure an annual shift of an atomic transition frequency by different gravitational potential from the sun, which can be observed if the precision of 0.1 ppb is achieved through reducing systematic uncertainties arising from its high temperature as around hundreds of Kelvins. Also, in Ps atomic interferometer, translational motion of Ps should be reduced by cooling to realize enough visibility to observe possibly small deflection by the gravity [2]. In order to cool Ps down to the required low temperature, we are currently proceeding laser cooling experiment of Ps by developing an optimized laser [3]. In this contribution, we will introduce basic physics and the current status in the experimental attempt to measure antimatter gravity using cold Ps.

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Quantum gravity experimental initiative at the LANSCE UCN facility

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We propose to initiate new quantum gravity experiments at the LANSCE UCN facility in Los Alamos. After successful creation of quantized UCN states, one of the first sets of experiment is to measure in real-time the quantum states of ultracold neutrons (UCN) and their behavior in the Earth's gravitational field. Another experiment to test weak equivalence principle (WEP) will be led by the University of Tokyo. First real-time measurement of UCN quantum states will be the critical next step for the new quantum gravity experiment initiative. CCD detector technology has recently been demonstrated through a multi-institutional collaboration led by LANL and Fermilab [K. Kuk et al, https://arxiv.org/ abs/1903.01335; NIMA 1003 (2021) 165306]. Other new detectors are being developed in parallel by the University of Tokyo, LANL and will be tested in the upcoming beam cycle. Initial WEP-UCN experimental design is also underway. We welcome new theoretical and experimental contributions to this budding collaboration. This work is made possible in part by the LANL LDRD program.

The Search for Deviations from Newton's Gravity at Micrometer Scales

Simon Zeidler
Rikkyo University

Newton’s inverse square law is one of the most successful theories in physics. At the same time, we still have insufficient information about its validity range, particularly at small distances between attracting bodies. That is due to the very nature of gravity and its particular weakness compared to the other three fundamental forces in our universe. A characteristic that sets gravity apart. Theories exist to explain the special role of gravity and how gravity eventually can be unified with the other forces, which, however, means that Newton’s law may not be valid at small distances. In the past, a number of experiments have been performed to verify those theories, mostly in terms of Yukawa approximations using strength and distance parameters α and λ.

At Rikkyo University, we perform the "Newton" measurement campaign to measure gravity at distances down to 10 μm. Currently, the experiment is in its fifth version and is further being developed to increase precision. In my presentation, I will give an overview of the "Newton" experiments and the future upgrade plans, as well as α-λ constraints calculated from the measurement results we got this far.

Present status of the LAG experiment

Luciano Di Fiore
INFN - Napoli

LAG (Liquid Actuated Gravity) is an experiment, funded by the INFN (National Institute of Nuclear Physics), for the development and testing of a new actuation technique for gravity experiments based on a liquid field mass. The basic idea of the experiment is to modulate the gravitational force acting on a test mass by controlling the level of a liquid in a suitable container, thereby producing a periodically varying gravitational force without moving parts (apart from the liquid level) close to the test mass. The scientific goal is to improve upon present limits that test the gravitational inverse-square law in the mm to cm distance region. The experiment is now in the R&D phase and a prototype has been assembled for testing with a torsion pendulum facility in Napoli. We will describe the apparatus, report on preliminary results and describe next steps, and scientific perspectives for the LAG experiment.

Using varying-frequency time-of-flight experiments to test the trapped quintessence model

Hai-Chao Zhang
Key Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences

The varying-frequency TOF (VFTOF) experiments demonstrated that the fall acceleration of test atoms is dependent on the detuning of the probe light frequency with respect to the atomic transition frequency. We use a trapped quintessence model to explain the experimental results. The quintessence field in the model is required to account for the accelerated expansion of the Universe entirely, then the field results in a short-range fifth force. The interaction range of the scalar is inversely proportional to the square root of the microscopic nonrelativistic matter density. The interaction range has been estimated to be several μm in the current cosmic density $\sim 10^{-27}$ kg/m^3. The Universe is assumed to be permeated with fuzzy dark matter, which means that the microscopic nonrelativistic matter density defined through the quantum wavefunctions of the ultralight particles can be used on the cosmic scale.

The experiments were performed in an ultrahigh vacuum chamber. In an almost completely empty space between atoms of a dilute atomic gas in the chamber, the interaction range of the scalar field may approach to the order of $\sim$1 μm in the presence of dark matter and then the scalar field might be detected in laboratories. Since the trapped quintessence model hypothesizes that the scalar strongly couples to nonrelativistic matter but do not couple to radiation, the source for generating the fifth force was experimentally set up by the laser-irradiated background atoms in the ultrahigh vacuum chamber. The mass density of the source was altered by detuning the frequency of the probe laser light from the atomic resonance transition. The test atoms were prepared by the laser cooling technique and located initially above the probe light. When the test atoms were released from their initial positions, they were able to pass through the region of the source that generated the fifth force to be measured. Thus, if the scalar field existed, the corresponding fifth force might be sensed by the test atoms even if the interaction range was extremely short. By measuring the fall acceleration of the test atoms with the TOF method step-by-step in the detuning frequency domain of the probe light, we derived the dispersion curves of the measured acceleration versus the frequency detuning of the probe light. When the nonrelativistic matter density of the source increased due to the energy gained from the laser light, the test atoms were pulled to the center of the source, and vice versa. If the trapped quintessence model is correct, the observed detuning-dependent acceleration in the VFTOF scheme suggests a closed Universe.

Interferometry of Entangled Quantum States of Light in Curved Space-Time

Thomas Mieling
University of Vienna

Precision quantum interferometry provides a viable way to probe the behavior of single photons and entangled photon pairs in gravitational fields: a domain that defies a purely Newtonian description. While currently planned experiments aiming to detect such effects at the laboratory-scale are explicable using the weak equivalence principle, larger-scale experiments have the potential to detect gravitationally induced quantum interference in which space-time curvature matters. In this talk, I present the basic mechanisms underlying such experiments and explain how maximally path-entangled NOON states could be used to demonstrate Riemann curvature, thereby propping the interplay of quantum field theory and general relativity beyond the weak equivalence principle. This talk is based on joint work with C. Hilweg and P. Walther (arXiv:2202.12562)

Signal do Noise Ratio Analysis of a Proposed Experiment to Measure the Speed of Gravity in Short Distances

Carlos Frajuca
Universidade Federal do Rio Grande: FURG

In order to investigate the speed of gravitational signals travelling in air or through a different medium two experiments were designed. One of the experiments contains 2 masses rotating at very high speed and in the other experiment a sapphire bar will vibrate, in both cases they will emit a periodic tidal gravitational signal and one sapphire device that behaves as a detector, which are suspended in vacuum and cooled down to 4.2 K will act as a detector. The vibrational amplitude of the sapphire detector device is measured by a microwave signal with ultralow phase-noise that uses resonance in the whispering gallery modes inside the detector device. Sapphire has a quite high mechanical Q and electrical Q which implies a very narrow detection band thus reducing the detection sensitivity. A new detector shape for the detector device is presented in this work, yielding a detection band of about half of the device vibrational frequency. With the aid of a Finite Element Program the normal mode frequencies of the detector can be calculated with high precision. The results show a similar expected sensitivity between the two experimental set up, but the experiment with the vibration masses is more stable in frequency then it is chosen for the experimental setup to measure the speed of gravity in short distances. Then a more precise analysis is made with this experiment reaching a signal-noise ratio of 10 at a frequency of 5000 Hz.

The Electromagnetic Field in Gravitational Wave Interferometers

Thomas Mieling
University of Vienna

The response of laser-interferometric detectors to gravitational waves is commonly modelled using approximation schemes such as the geodesic deviation equation or geometric optics, lacking a thorough justification. In this talk, I will present a refined model of such detectors, avoiding such approximation schemes, based on Maxwell's equations in curved space-time. This analysis allows to estimate the errors of previous approximations and also resolves ambiguities in some previous calculations for the limiting case of co-propagating electromagnetic and gravitational waves. This talk is based on joint work with P. Chruściel and S. Palenta (arXiv:2107.07727 and arXiv:2112.05784).

Perspectives of measuring gravitational effects of laser light and particle beams

Dennis Raetzel
Universität Bremen: Bremen, Bremen, DE

We study possibilities of creation and detection of oscillating gravitational fields from lab-scale high energy, relativistic sources. The sources considered are high energy laser beams in an optical cavity and the ultra-relativistic proton bunches circulating in the beam of the large hadron collider (LHC) at CERN. These sources allow for signal frequencies much higher and far narrower in bandwidth than what most celestial sources produce. In addition, by modulating the beams, one can adjust the source frequency over a very broad range, from Hz to GHz. The gravitational field of these sources and responses of a variety of detectors are analyzed. We optimize a mechanical oscillator such as a pendulum or torsion balance as detector and find parameter regimes such that—combined with the planned high-luminosity upgrade of the LHC as a source—a signal-to-noise ratio substantially larger than 1 should be achievable at least in principle, neglecting all sources of technical noise. This opens new perspectives of studying general relativistic effects and possibly quantum-gravitational effects with ultra-relativistic, well-controlled terrestrial sources.

D1: Loop quantum gravity and spin foams (Chair: Alejandro Perez, Coordinator: Yong-Ge Ma)

Dynamics of Loop Quantum Cosmology

Yongge Ma
Beijing Normal University

This talk is contributed to review the dynamics of loop quantum cosmology. Much attention will be paid on the construction of the Hamiltonian which is closely related to that in the full theory of loop quantum gravity. Some applications of this dynamics in cosmology will also be introduced.

A scheme to quantize Poincare gauge gravity: Kinematics

Hongchao Zhang
Zhejiang University of Technology

A scheme to quantize Poincare gauge gravity in the manner of Loop Quantum General Relativity is studied.

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r-Fock representations and loop quantum gravity

Mehdi Assanioussi
Faculty of Physics, University of Warsaw

The subject of the talk concerns the r-Fock representations and their relation to the standard loop representations, in light of the recent generalization of the construction of r-Fock measures for SU(N) gauge theories. The presentation will focus on the technical aspects of the construction of r-Fock measures, and the role that r-Fock representations could play in bridging the gap between quantum field theory on Minkowski spacetime and the background independent framework of loop quantum gravity.

Quantum speed limit and stability of coherent states in quantum gravity

Klaus Liegener
Walther-Meißner-Institut

Utilizing the program of expectation values in coherent states and its recently developed algorithmic tools, this talk investigates the dynamical properties of cosmological coherent states for Loop Quantum Gravity. To this end, the Quantum Speed Limit is adapted to

Quantum Gravity, yielding necessary consistency checks for any proposal of stable families of states. To showcase the strength of the developed tools, they are applied to a prominent model: the Euclidean part of the quantum scalar constraint. We report the variance of this constraint evaluated on a family of coherent states showing that, for short times, this family passes the Quantum Speed Limit test, allowing the transition from one coherent state to another one.

Coherent states and simplicity constraint in all dimensional loop quantum gravity

Gaoping Long
South China University of Technology

In this talk, I will introduce the generalized twisted geometry parametrization of the SO(D+1) phase space for all dimensional loop quantum gravity, and a new family of coherent states based on the twisted geometry parametrization. I will show that the generalized twisted geometry parametrization of the SO(D+1) phase space clarifies the geometric information encoded in the SO(D+1) spin-network states for all dimensional loop quantum gravity, and identifies proper gauge degrees of freedom associated with the anomalous discretized simplicity constraint. Also, I will introduce our studies on the new family of coherent states, including the works on the over-completeness property, the peakedness property, and the Ehrenfest Property. Especially, I will emphasize that the new family of coherent states based on the twisted geometry parametrization reduces the quantum gauge degrees of freedom associated with the anomalous quantum simplicity constraint properly.

Does Loop Quantum Gravity restrict a cyclic evolution

Parampreet Singh
Louisiana State University

It is generally expected that in a non-singular cosmological model a cyclic evolution is straightforward to obtain on introduction of a suitable choice of a scalar field with a negative potential or a negative cosmological constant which causes a recollapse at some time in the evolution. We present a counter example to this conventional wisdom. Working in the realm of loop cosmological models with non-perturbative quantum gravity modifications we show that a modified version of standard loop quantum cosmology based on Thiemann's regularization of the Hamiltonian constraint while generically non-singular does not allow a cyclic evolution unless some highly restrictive conditions hold. Irrespective of the energy density of other matter fields, a recollapse and hence a cyclic evolution is only possible if one chooses an almost Planck sized negative potential of the scalar field or a negative cosmological constant. Further, cycles when present do not occur in the classical regime. Surprisingly, a necessary condition for a cyclic evolution, not singularity resolution, turns out to be a violation of the weak energy condition. These results are in a striking contrast to standard loop quantum cosmology where obtaining a recollapse at large volumes and a cyclic evolution is straightforward, and, there is no violation of weak energy condition. On one hand our work shows that some quantum cosmological models even though non-singular and bouncing are incompatible with a cyclic evolution, and on the other hand demonstrates that

differences in various quantization prescriptions in loop cosmology need not be faint and buried in the pre-bounce regime, but can be striking and profound even in the post-bounce regime.

Role of dissipative effects in the Loop quantum gravitational onset of warm Starobinsky inflation in a closed universe

Meysam Motaharfar
Department of Physics and Astronomy, Louisiana State University

We discuss an alternative solution for initial condition problem of low energy scale inflationary model, such as Starobinsky potential, in spatially closed universe based on non-singular cyclic universe and hysteresis-like phenomena in Loop Quantum Cosmology. However, we find that although inflation can set in for large part of phase space of initial conditions, the onset of inflation for certain highly unfavorable initial condition is difficult to obtain. Motivated by this fact, we study how dissipative particle production effect, inherent characteristic of warm inflation, during pre-inflationary phase leads into entropy production making the hysteresis-like phenomena stronger, as a result of which even highly unfavorable initial conditions lead to inflationary period quickly. Finally, we phenomenologically consider three warm inflation scenarios with distinct forms of dissipation coefficient, Warm Little Inflation, Variant of Warm Little Inflation and Minimal Warm Inflation, and from dynamical solutions and phase space portraits find that the phase space of favorable initial conditions turns out to be much larger than in cold inflation.

Ref:

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The primordial power spectrum in modified loop quantum cosmology

Baofei Li
Zhejiang University of technology, Louisiana State University

In this talk, I will focus on the background dynamics and the primordial power spectra in two modified models of loop cosmology which arise from loop quantization of a spatially flat Friedmann-Lemaitre-Robertson-Walker (FLRW) universe with a separate treatment of the Lorentzian term in the classical Hamiltonian constraint. The qualitative dynamics of the background evolution of the universe in these two models will be compared. To numerically compute the primordial power spectra in two models, we have extended both the dressed metric and the hybrid approaches developed in loop quantum cosmology to the new models. We find although both models yield scale-invariant power spectra in the ultraviolet regime, appreciable deviations between these two models can become manifest in the intermediate and infrared regimes. Therefore, our results serve as a concrete example which explicitly shows how the quantization ambiguities can lead to different phenomenological implications of the quantum theories.

Properties of the spherically symmetric polymer black holes

Wencong Gan
Baylor University

In this paper we systematically study a recently proposed model of spherically symmetric polymer black/white holes by Bodendorfer, Mele, and Münch (BMM), which generically possesses five free parameters. However, we find that, out of these five parameters, only three independent combinations of them are physical and uniquely determine the local and global properties of the spacetimes. After exploring the whole 3-dimensional (3D) parameter space, we show that the model has very rich physics, and depending on the choice of these parameters, various possibilities exist, including: (i) spacetimes that have the standard black/white hole structures, that is, spacetimes that are free of spacetime curvature singularities and possess two asymptotically flat regions, which are connected by a transition surface (throat) with a finite and nonzero geometric radius. The black/white hole masses measured by observers in the two asymptotically flat regions are all positive, and the surface gravity of the black (white) hole is positive (negative). In this case, there also exist possibilities in which the two horizons coincide, and the corresponding surface gravity vanishes identically. (ii) Spacetimes that have wormhole like structures, in which the two masses measured in the two asymptotically flat regions are all positive, but no horizons exist, neither a trapped (black hole) horizon nor an anti-trapped (white hole) horizon. (iii) Spacetimes that still possess curvature singularities, which can be either hidden inside trapped regions or naked. However, such spacetimes correspond to only some limit cases. In particular, the necessary (but not sufficient) condition is that at least one of the two "polymerization" parameters vanishes. These results are not in conflict to the Hawking-Penrose singularity theorems, as the effective energy-momentum tensor, purely geometric and resulted from the "polymerization" quantization, satisfies none of the three (weak, strong or dominant) energy conditions in any of the two asymptotically flat regions for any choice of the three independent free parameters, although they can hold at the throat and/or at the two horizons for some particular choices of them. In addition, it is true that quantum gravitational effects are mainly concentrated in the region near the throat, however, in this model even for solar mass black/white holes, such effects can be still very large at the black/white hole horizons, again depending on the choice of the parameters. Moreover, in principle the ratio of the two masses (for both of the black/white hole and wormhole spacetimes) can be arbitrarily large.

Topspin Networks: Cylindrical Functionsand Coherent States

Christopher Duston
Merrimack College

The topspin network formalism is a concrete approach that allows topological analysis of the spatial sections in which spin networks live. By adding "topological labels" to the network (along with the standard spin labels), it becomes possible to represent non-trivial topologies without significantly changing the underlying theory. In this poster we give up an update of this approach, including an alternative perspective that comes from looking at the these spin

networks in non-topologically trivial spatial sections as covering graphs. We will also discuss the possible options for defining coherent states of topspin networks, based on ideas about coherent states from standard LQG.

Analytic studies of power spectra of cosmological perturbations in loop quantum cosmology

Rui Pan
Baylor University

In general, the equations of motion of primordial cosmological perturbations belong to a specific type of the second-order Schrödinger differential equation with a particular effective potential, which can be studied analytically by the uniform asymptotic approximate (UAA) method. In particular, depending on the behaviors of the given potential around their poles and turning points, the analytical approximate solutions will take different forms. Previously, the case with poles and various turning points were studied in quantum cosmology, including loop quantum cosmology (LQC). In this talk, I shall present our recent investigations of the problem in LQC in the dressed metric and hybrid approaches, in which the effective potentials are free of poles (singularities), but multiple turning points generically appear. In this case, to minimize the errors, different analyses about the error control functions must be carried out. To show explicitly how to apply the UAA method to this case, we first model the effective potentials (in both of the approaches) by a Pöschl-Teller (PT) potential, as analytical solutions of the Schrödinger differential equation for the PT potential exist. This provides an excellent model to test the analytical approximate solutions obtained by the UAA method. We find that the upper bounds of the errors are quite small even only up to the first-order approximation, and the method is well suitable to the studies of quantum gravitational effects of the power spectra of CMB and their possible observational signals for the current and forthcoming cosmological experiments.

Dirac observables and loop quantum black holes

Geeth Chandra Ongole
Baylor University

Ideas from Loop quantum gravity and Loop quantum cosmology are borrowed in an effort to resolve the classical singularity of a Schwarzschild black hole. Following these ideas, an effective Hamiltonian of the polymerized black hole can be constructed. Singularity resolution is a common feature of the phase space generated by this Hamiltonian. A few issues that remain in the literature were resolved by Ashtekar, Olmedo and Singh (AOS) in a series of papers. One of them is treating the polymerization parameters as Dirac observables by extending the phase space and fixing them at the transition surface by minimum area conditions.

Bodendorfer, Mele and Münch (BMM) first pointed out that they can be directly considered as Dirac observables without extending the phase space. This idea was further consolidated by García-Quismondo and Marugán. As expected, this modifies the equations of motion and the metric components. Deviations and similarities that arise from this prescription in comparison to the AOS model are presented here. Ascribing the deviations to the polymerization parameters, we leave them undetermined and let properties such as asymptotic flatness guide us in fixing them. In the black hole exterior, curvature invariants indicate that the metric is asymptotically flat but is independent of the mass parameter to the first order. Calculation of the Hawking temperature of the horizon indicate the quantum corrections are negligible for macroscopic black holes.

Covariant Loop Quantum Gravity

Muxin Han
Florida Atlantic University

This talk discusses the recent advances in the covariant formulation of Loop Quantum Gravity (LQG), and in particular, the spinfoam theory. The discussions include the analytic and numerical studies of the spinfoam amplitudes, the large-j semiclassical analysis, and the spinfoam model with cosmological constant. If time permits, this talk will also mention the recent path integral formulation of LQG relating to the reduced phase quantization.

Improved effective dynamics of loop-quantum-gravity black hole and gravitational collapse

Hongguang Liu
FAU Erlangen-Nuernberg

We propose a new model of the spherical symmetric quantum black hole in the reduced phase space formulation. We deparametrize gravity by coupling to the Gaussian dust which provides the material coordinates. After the spherical symmetry reduction, our model is a 1 + 1 dimensional field theory containing infinitely many degrees of freedom. We then treat both the black hole interior and exterior in a unified manner. The effective dynamics of the quantum black hole is generated by the improved physical Hamiltonian with mu-bar regularization. We studied the stationary solution of the effective dynamics, as well as the effective dust collapse. The effective dynamics of the interior of the dust shell with a homogeneous dust density coincides with the effective Friedmann equations given in LQC with K-quantization.

The thermodynamics of isolated horizon in higher dimensional loop quantum gravity

Xiangdong Zhang
South China University of Technology

The statistical mechanical calculation of the thermodynamical properties of higher-dimensional non-rotating isolated horizons is studied in loop quantum gravity framework. By introducing an universal horizon temperature and a well-defined Komar mass in Planck units.

The microcanonical and canonical ensembles associated with the system are well established. As a result, the black hole entropy and other thermodynamical quantities can be computed and consistent with well-known Hawking's semiclassical analysis.

Entropy of black holes with arbitrary shapes in loop quantum gravity

Shupeng Song
School of Physics, Beijing Institute of Technology, Department of Physics, Beijing Normal University

Although the entropy of the spherically symmetric and axisymmetric isolated horizon in loop quantum gravity has been deeply investigated, the entropy of a generic isolated horizon is an open issue. In this talk, I will introduce the idea of characterizing the shape of a horizon by a sequence of local areas, and apply this idea to calculate the entropy of isolated horizons with arbitrary shapes by SO(1,1) BF boundary theory matching loop quantum gravity in the bulk. I will give the generating function for calculating the microscopical degrees of freedom of a given isolated horizon and use a new numerical method to calculate the entropy. Numerical computations of small black holes indicate a new entropy formula containing the quantum correction related to the partition of the horizon. We derive that the entropy decreases for a given horizon area as a blackhole deviates from the spherically symmetric one. The shape contributes certain higher-order corrections to the entropy which is worth further investigating.

Finiteness of spinfoam vertex amplitude with timelike polyhedra, and the full amplitude

Wojciech Kaminski
Florida Atlantic University

This work focuses on Conrady-Hnybida's 4-dimensional extended spinfoam model with timelike polyhedra, while we restrict all faces to be spacelike. Firstly, we prove the absolute convergence of the vertex amplitude with timelike polyhedra, when SU(1,1) boundary states are coherent states or the canonical basis, or their finite linear combinations. Secondly, based on the finite vertex amplitude and a proper prescription of the SU(1,1) intertwiner space, we construct the extended spinfoam amplitude on arbitrary cellular complex, taking into account the sum over SU(1,1) intertwiners of internal timelike polyhedra. We observe that the sum over SU(1,1) intertwiners is infinite for the internal timelike polyhedron that has at least 2 future-pointing and 2 past-pointingface-normals. In order to regularize the possible divergence from summing over SU(1,1) intertwiners, we develop a quantum cut-off scheme based on the eigenvalue of the "shadow operator". The spinfoam amplitude with timelike internal polyhedra (and spacelike faces) is finite, when 2 types of cut-offs are imposed: one is imposed on j the eigenvalue of area operator, the other is imposed on the eigenvalue of shadow operator for every internal timelike polyhedron that has at least 2 future-pointing and 2 past-pointing face-normals.

Primordial power spectrum from a matter-Ekpyrotic bounce in loop quantum cosmology

SAHIL SAINI
Guru Jambheshwar University of Science and Technology

A union of matter bounce and ekpyrotic scenarios is often studied in an attempt to combine the most promising features of these two models. Since nonperturbative quantum geometric effects in loop quantum cosmology (LQC) result in natural bouncing scenarios without any violation of energy conditions or fine tuning, an investigation of matter-ekpyrotic bounce scenario is interesting to explore in this quantum gravitational setting. In this work, we explore this unified phenomenological model for a spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) universe in LQC filled with dust and a scalar field in an ekpyrotic scenario like negative potential. Background dynamics and the power spectrum of the comoving curvature perturbations are numerically analyzed with various initial conditions and a suitable choice of the initial states. By varying the initial conditions we consider different cases of dust and ekpyrotic field domination in the contracting phase. We use the dressed metric approach to numerically compute the primordial power spectrum of the comoving curvature perturbations which turns out to be almost scale invariant for the modes which exit the horizon in the matter-dominated phase. But, in contrast with a constant magnitude power spectrum obtained under approximation of a constant ekpyrotic equation of state using deformed algebra approach in an earlier work, we find that the magnitude of power spectrum changes during evolution. Our analysis shows that the bouncing regime only leaves imprints on the modes outside the scale-invariant regime. However, an analysis of the spectral index shows inconsistency with the observational data, thus making further improvements in such a model necessary.

Scalar curvature operator for loop quantum gravity on a cubical graph

Ilkka Mäkinen
Faculty of Physics, University of Warsaw

We introduce a new operator representing the three-dimensional scalar curvature in loop quantum gravity. The starting point of our construction is to express the classical Ricci scalar directly as a function of the Ashtekar variables. The construction does not apply to the entire Hilbert space of loop quantum gravity; instead, the operator is defined on the Hilbert space of a fixed cubical graph. As such, the operator can be applied in approaches such as quantum-reduced loop gravity, algebraic quantum gravity and models of effective dynamics.

Fermion coupling to loop quantum gravity: canonical formulation

Cong Zhang
University of Warsaw

In the model of fermion field coupled to loop quantum gravity, we consider the Gauss and the Hamiltonian constraints. According to the explicit solutions to the Gauss constraint, the

fermion spins and the gravitational spin networks intertwine with each other so that the fermion spins contribute to the volume of the spin network vertices. For the Hamiltonian constraint, the regularization and quantization procedures are presented in detail. By introducing an adapted vertex Hilbert space to remove the regulator, we propose a diffeomorphism covariant graph-changing Hamiltonian constraint operator. This operator shows how fermions move in the loop quantum gravity spacetime and simultaneously influences the background quantum geometry.

An effective model for the quantum Schwarzschild black hole

Asier Alonso-Bardaji
University of the Basque Country

We present a covariant model to describe spherically symmetric vacuum with holonomy corrections inspired by loop quantum gravity. We implement the effective modifications through a canonical transformation and a regularization of the Hamiltonian of general relativity, and construct the corresponding metric in a fully covariant way to ensure that gauge transformations on phase space correspond to coordinate changes. The resulting spacetime is asymptotically flat and contains a globally hyperbolic black-hole/white-hole region with a minimal spacelike hypersurface that replaces the Schwarzschild singularity. The exterior regions are isometric and allow the computation of the ADM mass. We find the global causal structure and its maximal analytical extension. Both Schwarzschild and Minkowski spacetimes are recovered as limiting cases of the model.

Computing cosmological primordial fluctuations from the full covariant quantum theory

Francesca Vidotto
Western U., Canada

One of the major challenges of a quantum theory of gravity would be to be able to predict the amplitude of the fluctuation of the primordial quantum geometry, at the origin of the structure in our universe. I discuss a proposal to concretely compute such fluctuations in Loop Quantum Gravity using the spinfoam formalism. The spinfoam transition amplitudes provide a natural notion of state as a superposition of Lorentzian geometries compatible with a given spatial boundary. It is possible to compute correlations between spatially separated regions and the corresponding entanglement entropy, with the advantage of doing so for a state defined by the well-defined dynamics of the full theory. The computation of observable quantities relies on the recent development of numerical techniques to compute the transition amplitudes. The results obtained so far open new interesting questions regarding the property of the vacuum states and the relation with the inflationary framework in cosmology.

Recent advances in numerical loop quantum gravity

Pietropaolo Frisoni
Western University

The application of numerical techniques in covariant LQG may able to provide answers to many of the current open questions in theory. In this talk, I first present one of the formalism currently used to implement numerical computations. Then I illustrate recent applications of numerical techniques concerning the study of infrared divergences, the primordial fluctuations of the universe and the black hole lifetime.

Black to White Hole Transition

Farshid Soltani
Western University

Black holes formation and evolution have been extensively studied at the classical level. However, little is known about the end of their lives and about the true nature of the spacetime singularity in their interior, the description of which requires to consider the quantum nature of the gravitational field. Recent theoretical evidence suggests a scenario in which the black hole horizon undergoes a quantum transition into a white hole horizon and the classical singularity is replaced by a smooth transition of the interior trapped region into an anti-trapped region. I review the evidence supporting this scenario and I discuss how the spin foam formalism can be used to describe the non-perturbative physics of the horizon.

Towards black hole entropy in chiral loop quantum supergravity

Konstantin Eder
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

Recently, many geometric aspects of N-extended AdS supergravity in chiral variables have been encountered and clarified. In particular, if the theory is supposed to be invariant under SUSY transformations also on boundaries, the boundary term has to be the action of a OSp(N|2) super Chern-Simons theory, and particular boundary conditions must be met.
Based on this, we propose a way to calculate an entropy for surfaces, presumably including black hole horizons, in the supersymmetric version of loop quantum gravity for the minimal case N=1. It proceeds in analogy to the non-supersymmetric theory, by calculating dimensions of quantum state spaces of the super Chern-Simons theory with punctures, for fixed quantum (super) area of the surface. We find $S = A/4$ for large areas A and determine the subleading correction. Due to the non-compactness of OSp(1|2) and the corresponding difficulties with the Chern-Simons quantum theory, we use analytic continuation from the Verlinde formula for a compact real form, UOSp(1|2), in analogy to work by Noui et al. This also entails studying some properties of OSp(1|2) representations that we have not found elsewhere in the literature.

D2: Gravitational aspects of string theory (Chair: Alejandra Castro, Coordinator: Ya-Wen Sun)

Double copy with topological masses

Mariana Carrillo Gonzalez
Imperial College London

The double copy allows us to write gravitational theories as the square of guage theories. In recent years, it has been shown that considering theories with massive mediators can lead to inconsistent gravitational theories on the double copy side. In this talk I will explain explain why this is not the case for topologically massive theories in 2+1 dimensions. I will give a brief summary of the different constructions of topologically massive double copies and conclude higlighting a new promising result dubbed the Cotton Double Copy.

Celestial Holography

Sabrina Pasterski
Perimeter Institute

Celestial holography proposes a duality between the gravitational S-matrix and correlators in a conformal field theory living on the celestial sphere. We review the motivation from asymptotic symmetries, fundamentals of the proposed holographic dictionary, potential applications to experiment and theory, and some important open questions.

Collisions of localized shocks and quantum circuits

Ying Zhao
KITP

We study collisions between localized shockwaves inside a black hole interior. We give a holographic boundary description of this process in terms of the overlap of two growing perturbations in a shared quantum circuit. The perturbations grow both exponentially as well as ballistically. Due to a competition between different physical effects, the circuit analysis shows dependence on the transverse locations and exhibits four regimes of qualitatively different behaviors. On the gravity side we study properties of the post-collision geometry, using exact calculations in simple setups and estimations in more general circumstances. We show that the circuit analysis offers intuitive and surprisingly accurate predictions about gravity computations involving non-linear features of general relativity.

Subleading Corrections to AdS Black Hole Entropy

Marina David
University of Michigan

The success of implementing the near-horizon geometry to extract the entropy leaves room for speculation as to what extent the black hole horizon provides a window into the full understanding of quantum gravity. In this talk, I will discuss current efforts in this direction by investigating where the quantum degrees of freedom live for asymptotically AdS spacetimes. More specifically, I will focus on the logarithmic corrections to the entropy of a class of four dimensional electrically charged and rotating asymptotically AdS black holes. In contrast to flat space, we observe that the logarithmic correction for supersymmetric black holes can be non-topological. I will discuss implications of this result including what this may suggest for the low-energy gravity theory.

Thermodynamics of AdS Black Holes: Central Charge Criticality

Robert Mann
University of Waterloo

We reconsider the thermodynamics of AdS black holes in the context of gauge-gravity duality. In this new setting where both the cosmological constant Λ and the gravitational Newton constant G are varied in the bulk, we rewrite the first law in a new form containing both Λ (associated with thermodynamic pressure) and the central charge C of the dual CFT theory and their conjugate variables. We obtain a novel thermodynamic volume, in turn leading to a new understanding of the Van der Waals behavior of the charged AdS black holes, in which phase changes are governed by the degrees of freedom in the CFT. Compared to the "old" $P-V$criticality, this new criticality is "universal" (independent of the bulk pressure) and directly relates to the thermodynamics of the dual field theory and its central charge.

Cosmological horizon in a dS_2 universe

Beatrix Muehlmann
McGill University

I will discuss the two-dimensional gravitational path integral in the limits when it allows a round two-sphere saddle. Since the two-sphere is the geometry of Euclidean two-dimensional de Sitter space our discussion is tied to the conjecture of Gibbons and Hawking, according to which the entropy associated to the dS cosmological horizon is encoded in the Euclidean gravitational path integral with dominant sphere saddle.

Fluxes and charges in de Sitter

Marika Taylor
University of Southampton

In this talk we will discuss the definition of conserved quantities in asymptotically locally de Sitter spacetimes. One may define an analogue of holographic charges both at future and past infinity and at other Cauchy surfaces, as integrals over the intersection of timelike surfaces C and these Cauchy surfaces. In general these charges depend on the choice of timelike surface C but if gravitational flux is absent the charges are conserved quantities, independent of the choice of timelike surface. If there is net gravitational flux entering or leaving the spacetime region bounded by two timelike surfaces and two Cauchy surfaces, this may be characterised in terms of a corresponding change in charge. We illustrate these discussions using examples such as Kerr de Sitter black holes and Kerr Robinson-Trautmann solutions.

TsT, black holes, and irrelevant deformations

Wei Song
Tsinghua University

I will describe a class of toy models of holographic duality beyond the AdS/CFT correspondence. The starting point is IIB string theory on AdS3 with NS-NS three form flux, which is holographically dual to a two dimensional CFT. Performing TsT transformations(T-duality, shift, and T-duality) in the bulk, we can obtain black hole solutions which interpolate BTZ black holes in the IR and linear dilaton background in the UV. The holographic dual is conjectured to be a single trace TTbar deformed CFT. As supporting evidence, we find a matching of the deformed spectrum, the thermodynamics, and a critical value of the deformation parameter. Similarly, TsT transformations can also be used to generate the holographic dual for the single trace version of JTbar, and TTbar+JTbar+TJbar deformations.

Breakdown of hydrodynamics from holographic pole collision

Yan Liu
Beihang University

We study the breakdown of diffusive hydrodynamics in holographic systems dual to neutral dilatonic black holes with extremal near horizon geometries conformal to AdS2×R2. We find that at low temperatures by tuning the effective gauge coupling constant in the infra-red, the lowest non-hydrodynamic mode, which collides with the charge diffusive mode and sets the scales at which diffusive hydrodynamics break down, could be either an infra-red mode or a slow mode, resulting in different scaling behaviors of the local equilibrium scales. We confirm that the upper bound for the charge diffusion constant is always satisfied using the velocity and timescale of local equilibration from the pole collision. We also examine the breakdown of hydrodynamics at general temperature and find that the convergence radius has nontrivial dependence on temperature, in addition to the effective gauge coupling constant.

Islands at interfaces between conformal field theories

Tarek Anous
University of Amsterdam

Quantum extremal surfaces and islands have led us to rethink the very meaning of microscopic entropy in the presence of dynamical gravity. I will present some work elucidating how the island/QES prescription emerges in a simple doubly holographic setup where we have analytic control. We will consider two holographic 2d CFTs joined at an interface such that the bulk dual is a geometry that interpolates between two locally 3d AdS geometries with different AdS lengths. In particular we will consider systems where the transition region is a thin brane with tension T. In the limit of large tension, the brane gets pushed outward towards the boundary, meaning the effective theory on the brane is conformal and gravity almost decouples. We show precisely how the canonical CFT entropy and the remaining gravity dynamics leads to an island formula in this setup. The location of the island is identified with where the RT surface crosses the brane in the full holographic 3d picture.

Towards a new infinite family of holographic dualities

Alexandre Belin
University of Geneva

I will present evidence for a new infinite family of holographic dualities. On the CFT side, the theories are obtained by deforming symmetric orbifolds of N=2 minimal models by an exactly marginal operator. I will present various evidence that such theories are holographic CFTs and discuss potential gravity duals.

Black Tsunamis and Naked Singularities in AdS

Roberto Emparan
ICREA

The AdS/CFT correspondence still has to throw clearer light on the dual (microscopic and fundamental) meaning of known violations of cosmic censorship: What mechanisms drive them? How do they manifest in the dual large-N field theory? How does the theory deal with them when N is finite and quantum gravitational bulk effects are incorporated? For this purpose, we study the evolution of the Gregory-Laflamme instability for black strings in global AdS spacetime, and investigate the CFT dual of the formation of a bulk naked singularity. We uncover a rich variety of dynamical behaviour -- including tsunami flows of horizon generators from the boundary, and nakedly singular horizon pinch-offs. The holographic dual describes different patterns of heat flow due to the Hawking radiation of two black holes placed at the antipodes of a spherical universe. We also present a model that describes the burst in the holographic stress-energy tensor when the signal from a bulk naked singularity reaches the boundary.

Algebra of diffeomorphism-invariant observables in Jackiw-Teitelboim Gravity

Jie-qiang Wu
UCSB

In this work, we use the covariant Peierls bracket to compute the algebra of a sizable number of diffeomorphism-invariant observables in classical Jackiw-Teitelboim gravity coupled to fairly arbitrary matter. We then show that many recent results, including the construction of traversable wormholes, the existence of a family of SL(2, R) algebras acting on the matter fields, and the calculation of the scrambling time, can be recast as simple consequences of this algebra. We also use it to clarify the question of when the creation of an excitation deep in the bulk increases or decreases the boundary energy, which is of crucial importance for the "typical state" versions of the firewall paradox.
Reference: arXiv: 2108.04841

Quantum Black Holes and Holographic Complexity

Antonia Micol Frassino
ICC, University of Barcelona

In this talk, I will consider quantum effects on some specific black hole solutions and take into account their gravitational backreaction. In particular, I will describe the holographic construction of the quantum BTZ black hole (quBTZ) from an exact four-dimensional bulk solution. I will present some of the thermodynamic properties of these black holes, focus on the generalized first law and analyze the different complexity proposals for the quBTZ. Our results indicate that Action Complexity fails to account for the additional quantum contributions and does not lead to the correct classical limit. On the other hand, the Volume Complexity admits a consistent quantum expansion and agrees with known limits.

Aspects of Wedge Holography

Rong-Xin Miao
School of Physics and Astronomy, Sun Yat-Sen University

In this talk, we discuss the effective action, the mass spectrum and the first law of entanglement entropy for a novel doubly holographic model called wedge holography. First, we work out the effective action of quantum gravity on the branes, which is given by a higher derivative gravity. We provide evidence that the effective higher derivative gravity on the brane is equivalent to a ghost-free multi-gravity. We also prove that the effective action yields the correct Weyl anomaly. Interestingly, although the effective action on the brane is an infinite tower of higher derivative gravity, the holographic Weyl anomaly is the same as that of Einstein gravity. Second, we analyze the mass spectrum of wedge holography. Remarkably, there is a massless mode of gravitons on the end-of-the-world branes with Neumann boundary condition. On the other hand, the massless mode disappears if one imposes Dirichlet boundary condition on one of the branes as in brane world theory and AdS/BCFT. Finally, we verify the first law of entanglement entropy for wedge holography.

Interestingly, the massive fluctuations are irrelevant to the first-order perturbation of the holographic entanglement entropy. Thus, in many aspects, the effective theory on the brane behaves like massless Einstein gravity.

Holographic superconductors at zero density

Jie Ren
Sun Yat-sen University

We construct holographic superconductors at zero density. The model enjoys a luxury property that the background geometry dual to the ground state is analytically available. It has a hyperscaling-violating geometry in the IR and is asymptotically AdS in the UV. We numerically construct the finite temperature solution of hairy black holes and verify the phase transition by tuning a double-trace deformation parameter. For a holographic superconductor from M-theory, we obtain an analytic solution of the AC conductivity, which explicitly shows a superconducting delta function and a hard gap.

Hologhraphic complexity in the presence of defects and boundaries

Stefano Baiguera
Ben Gurion University of the Negev

Complexity is a quantum-information tool which measures the difficulty to build a target state starting from a given reference state. This quantity is conjectured to be dual to either volumes or actions in the dual gravitational system, and it is believed to contain information on the interior structure of black holes.
In this talk, I will compare the structure of UV divergences in the computation of holographic complexity applying the volume and action proposals to three-dimensional geometries containing defects or boundaries.
While the two-sided Randall-Sundrum and the AdS/BCFT models are logarithmically divergent according to the volume conjecture and finite using the action proposal, I will show that the Janus AdS background presents the same structure of divergences and comment on these results.

D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity (Chair: Astrid Eichhorn, Coordinator: Xiao Zhang)

Higher-derivative gravity, regular black holes and the finite action principle

Breno Loureiro Giacchini
Southern University of Science and Technology

In this talk we discuss some interesting applications of invariants containing covariant derivatives of the curvature tensors. In the first part, we show that superrenormalizable higher-derivative gravity models which include this type of scalars in the action have a regular Newtonian limit (without curvature singularities). Moreover, curvature-derivative scalars can also be regular, depending on the number of derivatives in the gravitational action. In some classes of nonlocal gravity models, it can happen that all (linearized) curvature-derivative scalars are regular. In the second part of the talk, we discuss the effect of such higher-derivative terms in the framework of the finite action principle applied to the Lorentzian path integral approach to quantum gravity. In particular, we show that not only singular spacetimes but also some of the regular black holes do not seem to contribute to the path integral if certain higher-derivative terms are present in the action.

Noncommutative differential geometry and quantum effects of gravity

Haoyuan Gao
Guangxi University

We discuss noncommutative analogues of metrics and curvatures in a natural coordinate chart on manifolds via deformation quantization. Based on them, we are able to propose the noncommutative Einstein field equations which provide quantum effects of gravity. We show that the deformation of classical pp-wave is the exact solution of vacuum field equations and the deformation of classical Schwarzschild solution is the unevaporated quantum black hole.

Emergence of smooth Lorentzian spacetimes in stochastic composite gravity

Joshua Erlich
William and Mary

In a composite gravity scenario, gravitation emerges as an artifact of short-distance physics in a vacuum characterized by the expectation value of a composite metric or vielbein operator. We demonstrate the dynamical evolution towards a smooth Lorentzian spacetime, and the emergence of Einstein gravity at long distances, in a composite gravity model described fundamentally in terms of stochastic processes.

The Mixmaster model in quantum geometrodynamics

Sara Fernández Uria
University of the Basque Country (UPV-EHU)

According to the Belinski-Khalatnikov-Lifshitz scenario, close to a spacelike singularity different spatial points decouple and follow a Mixmaster dynamics. In order to understand the role played by quantum effects in this scenario, in this work we consider the semiclassical behavior of the Mixmaster model in the context of quantum geometrodynamics. Classically this system undergoes a series of transitions between Kasner epochs, described by a specific transition law, which is derived based on the conservation of certain physical quantities and the rotational symmetry of the system. In a quantum scenario, however, fluctuations and higher-order moments modify these quantities and consequently also the transition rule. In particular, the corrections of this law are analytically obtained up to second-order in quantum moments, which corresponds to neglecting terms of an order $\hbar^2$.

Quantum Belinski-Khalatnikov-Lifshitz scenario

Włodzimierz Piechocki
Department of Fundamental Research, National Centre for Nuclear Research

We quantize the solution to the Belinski-Khalatnikov-Lifshitz scenario using the affine coherent states quantization method. Quantization smears the gravitational singularity avoiding its localization in the configuration space. Classical chaotic behaviour of the BKL scenario becomes enhanced at the quantum level. Our results strongly suggest that the generic singularity of general relativity can be avoided at quantum level giving support to the expectation that quantum gravity has good chance to be a regular theory.

Talk based on:

[1] P. Goldstein and W. Piechocki, "Generic instability of the dynamics underlying the Belinski-Khalatnikov-Lifshitz scenario", Eur. Phys. J. C (2022) 82:216, arXiv:2103.16145.

[2] A. Gozdz, A. Pedrak, and W. Piechocki, "Quantum dynamics corresponding to the classical BKL scenario", arXiv:2204.11274.

Jordan and Einstein frames form the perspective of Hamiltonian Brans-Dicke theory

Gabriele Gionti, S.J.
Vatican Observatory (Specola Vaticana)

A longstanding issue is the equivalence between the Jordan and the Einstein frames. Our aim is to tackle this problem from the perspective of the Hamiltonian formalism. For this reason, we will perform the Hamiltonian analysis of the Brans-Dicke theory with Gibbons-Hawking-York boundary term both in the Jordan and the Einstein frames. We will analyze the two cases $\omega \neq -3/2$ and $\omega = -3/2$. We will perform Dirac's constraint analysis. The case $\omega\neq$-

3/2 exhibits four secondary first class constraints, in the Jordan frame, which have the same constraint algebra as Einstein's geometro-dynamics. The Weyl (conformal) transformations from the Jordan to the Einstein frame result not to be a (Hamiltonian) canonical transformations. We found a set of canonical transformations which correspond to the strong gravity limit (Carrolian gravity).
Many of these features continue to hold also for the $\omega=-3/2$ case. The main difference, respect to the previous case, is that now the theory has a Weyl (conformal) invariance. This invariance generates a further secondary first class constraint, besides the four secondary first class constraints due to diffeomorphism invariance. The constraint algebra of the secondary five first class constraints is now different in the two frames. This addresses a mathematical inequivalence of the two frames also at classical level. Anyway, the Poisson brackets are defined on the extended phase space where the constraints are not necessarily zero.
We will examine a particular case of a flat FLRW Brans-Dicke mini-superspace model and show that the equations of motions in the Jordan and the Einstein frames are equivalent after the Dirac's constraints are taken in consideration. Once we perform a gauge fixing on the lapse functions both in the Jordan and the corresponding Einstein frame, there exists a canonical transformation between Jordan and Einstein frames on this reduced phase space.

Asymptotically safe gravity and dynamically emergent gravity

Masatoshi Yamada
Heidelberg University

In this talk, we first introduce the basic idea of asymptotic safety and discuss its application to quantum gravity. We compute non-perturbative flow equations for the couplings of quantum gravity in fourth order of a derivative expansion. It is shown that the beta functions admit two possible fixed points: One is the asymptotically safe fixed point, and the other is the asymptotically free one. The corresponding critical exponents to these fixed points are evaluated. Next, we argue that asymptotically safe gravity could be an effective theory emerging from the spontaneous symmetry breaking of SO(4) local Lorentz in an ultraviolet (UV) theory. We will discuss prospects whether or not this UV theory could be a fundamental theory underlying asymptotically safe gravity.

Quantum Ricci curvature in action

Renate Loll
Radboud University, NIjmegen (NL)

Our ability to understand the nonperturbative dynamics of four-dimensional quantum gravity at the Planck scale depends crucially on identifying and measuring observables. A well-known example is the spectral dimension of quantum spacetime, which in Causal Dynamical Triangulations (CDT) was found to exhibit a "Planckian fingerprint" at short distances. Importantly, in a field too often dominated by prima facie arguments, this has stimulated a computational effort across approaches to reproduce this result. While "dimensions" are an important tool, more intrinsically geometric observables are needed to be able to relate the properties of quantum geometry to those of classical spacetimes in general relativity. I will report on promising progress that has been made using the new quantum Ricci curvature, a notion of Ricci curvature applicable on nonsmooth (ensembles of) geometries. It has been extensively tested and explored in (C)DT models of quantum gravity, and opens exciting new opportunities for bridging the gap with "real" early-universe physics. I will describe some intriguing new results, including the finding of "quantum flatness" in 1+1 [1] and new insights into the quantum behaviour of spatial slices in 2+1 nonperturbative quantum gravity [2].

Classical sequential growth dynamics and manifoldlike causal sets

He Liu
University of Mississippi

The classical sequential growth (CSG) dynamics by Rideout and Sorkin is a framework for growing a causal set that fulfils physical conditions. In it, elements are added one at a time, and the new element's past structure is determined by a sequence of parameters. I will talk about the search for parameters that potentially lead to manifoldlike causal sets. I will begin with an evaluation of the transitive percolation, one of the simplest CSG models, with chain statistics of causal intervals generated with various transition probabilities. Next I will show the results of applying transitive percolation to manifoldlike causal sets. I will comment on the limits of the transitive percolation and conclude from chain distributions the selection of parameters in more general CSG models. Finally I will introduce a scheme for searching for CSG parameters and present some preliminary results.

Bulk reconstruction: surface growth approach and tensor networks

Jia-Rui Sun
Sun Yat-Sen University

Bulk reconstruction in the AdS/CFT correspondence is aimed to construct the bulk physics from the information of the boundary CFT. In this talk, we will introduce a novel surface growth approach for building up the bulk spacetime geometry, we will show that this formalism can be explicitly realized with the help of the surface/state correspondence and the one-shot entanglement distillation method, which provides a concrete and intuitive way for the entanglement wedge reconstruction. We also check the validity of the approach by directly analyzing the growth of bulk minimal surfaces in 3d asymptotically AdS spacetimes. Furthermore, we will extend the surface growth approach into the AdS/BCFT correspondence.

D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models (Chair: Stefan Hollands, Coordinator: Xian-Hui Ge)

Infrared finite scattering theory in QFT and quantum gravity

Kartik Prabhu
University of California, Santa Barbara

The "infrared problem" is the generic emission of an infinite number of low-frequency quanta in any scattering process with massless degrees of freedom. That the out state contains an infinite number of such quanta implies that it does not lie in the standard Fock representation. Consequently, the standard S-matrix is undefined as a map between "in" and "out" states in the standard Fock space. This fact is due to the existence of a low-frequency tail of the radiation field (i.e. the memory effect) as well as the existence of an infinite number of conserved charges at spatial infinity. In massive QED, the scattering representations known as "Kulish-Faddeev" representations have been argued to yield an I.R. finite S-matrix. We clarify the "preferred status" of such representations as eigenstates of the conserved "large gauge charge". We prove a "No-Go" theorem for the existence of a suitable Hilbert space analogously constructed scattering states in massless QED, QCD, linearized quantum gravity with massive/massless sources, and in full quantum gravity. We then develop an "infrared-finite" formulation of scattering theory without any a priori choice of "in/out" Hilbert space.

Gravitational memory effect - Can a localised quantum system see soft photons?

Sanved Kolekar
Indian Institute of Astrophysics, Bangalore

The Gravitational memory effect, BMS symmetries at asymptotically flat spacetimes and Weinberg’s soft graviton theorems have a deep connection; the significance of which was recently realised by Hawking, Perry and Strominger who conjectured that applying these relations to an asymptotically flat spacetime with a black hole in the interior would imply the existence of an infinite number of soft hairs for the black hole.

We ask whether soft photons, defined by asymptotic charges, can have consequences for the outcome of localised quantum processes. We consider a spatially localised two-state system, at rest in flat spacetime, coupled to a U(1) gauge invariant charged scalar field. We find that the system’s de-excitation rate does depend on the soft charges that correspond to the radial component of the electric field dressing at the asymptotic infinity; the excitation rate, by contrast, remains zero, regardless of the soft charges. Implications are discussed.

Based on S. Kolekar & J. Louko, arXiv: 2108.04278 [hep-th]

Semiclassical energy fluxes at the inner horizon of a rotating black hole

Noa Zilberman
Technion - Israel Institute of Technology

Astrophysical black holes are known to be rotating. The simplest spacetime solution describing a classical rotating black hole (the analytically extended Kerr solution) reveals a non-trivial spacetime structure, in which the geometry connects through an inner horizon to another external universe. But does such a traversable passage really exist inside a physically-realistic spinning black hole?

Answering this question, along others, requires one to understand the manner in which quantum energy fluxes affect the internal geometry of a black hole. It has been widely anticipated, yet inconclusive (till this work), that semiclassical effects would diverge at the inner horizon of a spinning black hole. Such a divergence, if indeed takes place, may drastically affect the internal black hole geometry, potentially preventing the inner horizon traversability. Clarifying this issue requires the computation of the semiclassical energy fluxes (the $T_{\mu\mu}$ and $T_{\upsilon\upsilon}$ components of the stress-energy tensor, where u and v are the standard Eddington coordinates) in black hole interiors, and particularly at the inner horizon. However, this has been a serious challenge for decades.

Using a new method (a variant of the state-subtraction method), we have recently managed to compute the renormalized flux components at the inner horizon of a spinning black hole, in the Unruh vacuum state (corresponding to an evaporating black hole). We found that these fluxes are either positive or negative, depending on the black hole spin and polar angle theta. The sign of these fluxes may be crucial to the nature of their backreaction on the geometry, as should be dictated by the semiclassical Einstein equation.

In this talk, we shall describe our new regularization procedure, and then present our results for the semiclassical fluxes at the inner horizon of a rotating black hole, briefly mentioning possible implications for the inner horizon traversability.

Quantum effects in black hole interiors

Christiane Klein
Leipzig University

The strong cosmic censorship conjecture states that the inner horizons of black holes should become singular to avoid travel into spacetime regions where determinism breaks down. In this talk I present results on the influence of quantum effects on the strong cosmic censorship conjecture in charged black hole spacetimes. In addition, I discuss the (dis-)charge of charged black hole interiors by quantum effects, and give an outlook how similar results can be obtained for rotating black holes.

Renormalization in quantum field theory in curved space-times via a mode decomposition of the Feynman Green function

Gabriel Freitas
Brazilian Center for Research in Physics (CBPF)

In quantum field theory in curved space-time, an important physical quantity is the renormalized expectation value of the stress-energy tensor, $< T_{\mu\nu} >_{ren}$, and the renormalized expectation value of the square of the field operator, $< \Phi^2 >_{ren}$. However, the renormalization method that is usually implemented in the literature, in principle, only applies to static, spherically-symmetric space-times, and does not readily generalize to other types of space-time. In this project, we present a new implementation of the renormalization procedure, using the Feynman Green Function, which may be used for more general space-times such as Kerr space-time. We then apply this method to the calculation of $< \Phi^2 >_{ren}$ both in Schwarzschild space-time and in Reissner-Nordstrom space-time, finding good agreement with the previous literature.

The two-point function for massive and massless scalar fields in the Unruh state in 1+1 dimensional Schwarzschild-de Sitter spacetime

Paul Anderson
Wake Forest University

The two-point function for a massless minimally coupled scalar field in the Unruh state has been computed in Schwarzschild-de Sitter space in 1+1 dimensions. It was found that for space like separations of the points the two-point function grows linearly in terms of a time coordinate that is well-defined on the future black hole horizon and the future cosmological horizon. The generalization to the massive field will be discussed and comparisons will be made between the modes and the two-point functions in the massless and massive cases.

Gravitationally Mediated Entanglement: Newtonian Field vs. Gravitons

Gautam Satishchandran
University of Chicago

Recently proposed "low-energy" tabletop experiments in quantum gravity aim to experimentally verify quantum entanglement mediated by a Newtonian gravitational field. We argue that if the Newtonian gravitational field of a body can mediate entanglement with another body, then it should also be possible for the body producing the Newtonian field to entangle directly with on-shell gravitons. Our arguments are made by revisiting a gedankenexperiment previously analyzed by Belenchia et al., which showed that a quantum superposition of a massive body requires both quantized gravitational radiation and local vacuum fluctuations of the spacetime metric in order to avoid contradictions with complementarity and causality. We provide a precise and rigorous description of the entanglement and decoherence effects occurring in this gedankenexperiment, thereby significantly improving upon the back-of-the-envelope estimates given in the analysis of Belenchia et al. and also showing that their conclusions are valid in much more general circumstances. As a by-product of our analysis, we show that under the protocols of the gedankenexperiment, there is no clear distinction between entanglement mediated by the

Newtonian gravitational field of a body and entanglement mediated by on-shell gravitons emitted by the body. This suggests that Newtonian entanglement implies the existence of graviton entanglement and supports the view that the experimental discovery of Newtonian entanglement may be viewed as implying the existence of the graviton.

Black holes decohere quantum superpositions

Daine Danielson
The University of Chicago

We show that if a massive body is put in a quantum superposition of spatially separated states, the mere presence of a black hole in the vicinity of the body will eventually destroy the coherence of the superposition. This occurs because, in effect, the gravitational field of the body radiates soft gravitons into the black hole, allowing the black hole to acquire "which path" information about the superposition. A similar effect occurs for quantum superpositions of electrically charged bodies. We provide estimates of the decoherence time for such quantum superpositions. We believe that the fact that a black hole will eventually decohere any quantum superposition may be of fundamental significance for our understanding of the nature of black holes in a quantum theory of gravity.

Quantum signatures of black hole mass superpositions

Cemile Arabaci
University of Waterloo

In his seminal work, Bekenstein conjectured that quantum-gravitational black holes possess a discrete mass spectrum, due to quantum fluctuations of the horizon area. The existence of black holes with quantized mass implies the possibility of considering superposition states of a black hole with different masses. Here we construct a spacetime generated by a BTZ black hole in a superposition of masses, using the notion of nonlocal correlations and automorphic fields in curved spacetime. This allows us to couple a particle detector to the black hole mass superposition. We show that the detector's dynamics exhibits signatures of quantum-gravitational effects arising from the black hole mass superposition in support of and in extension to Bekenstein's original conjecture.

Towards the non-perturbative cosmological bootstrap

Joao Penedones
EPFL

I will discuss the non-perturbative bootstrap approach to Quantum Field Theory (QFT) on Anti-de Sitter, Minkowski and de Sitter spacetimes. I will argue that this approach is not yet fully understood in de Sitter space and present some first steps based on https://arxiv.org/abs/2107.13871.

Singularity theorems in semiclassical gravity

Eleni Alexandra Kontou
University of Amsterdam

The classical singularity theorems predict the existence of singularities, defined using incomplete geodesics, under a set of general assumptions. One of those assumptions, namely the energy condition, is always violated by quantum fields and thus the realm of semiclassical gravity is outside the scope of these theorems. However, quantum fields do obey weaker conditions which can also be used to predict singularities. In this talk, I will present derivations of such semiclassical singularity theorems both in the timelike and the null case and discuss the challenges and open questions for each case.

Semiclassical theories of gravity and their linear stability

Nicola Pinamonti
University of Genova

During this talk we shall discuss new developments in the analysis of semi-classical theories of gravity. First of all, we present some results about existence and uniqueness of solutions of the semiclassical Einstein equation driven by quantum scalar fields with arbitrary mass and with arbitrary coupling to the scalar curvature in the cosmological case. In the second part of the talk, we discuss the linearization of semi-classical theories of gravity in a toy model. The equations governing the dynamics of linear perturbations around simple exact solutions of this toy model are analyzed by constructing the retarded fundamental solutions and by discussing the related initial value problem. If the quantum field which drives the back-reaction to the classical background is massive, there are choices of the renormalization parameters for which the linear perturbations with compact spatial support decay polynomially in time for large times, thus indicating stability of the underlying semiclassical solution.

Gravitational Collapse of Quantum Fields and Choptuik Scaling

Benjamin Berczi
University of Nottingham

The behaviour of quantum fields around black holes has been in the forefront of research for almost half a century, since the discovery of Hawking radiation in 1974. However, we still know remarkably little about the details of the evaporation of black holes beyond first order approximations. In this talk, I will introduce our formalism using which a fully quantum mechanical field can be simulated to collapse into a black hole. Initial results of the quantum

effects around the formed black hole will be presented, in addition to the verification of Choptuik scaling in critical collapse of semiclassical black holes.

Quantum particle creation in gravastar formation

Ken-ichi Nakao
Osaka Metropolitan University

We study the quantum particle creation in a toy model of spherically symmetric gravitational collapse whose final product is not a black hole but a gravastar. Precedent studies revealed that even in the case of the gravitational collapse to form a horizonless ultra-compact object, the thermal radiation named the transient Hawking radiation is generated at the late stage of the gravitational collapse, and a sudden stop of collapsing motion to form a horizonless ultra-compact object causes one or two bursts of quantum particle creation. The very different behavior of the model studied in this paper from the precedent ones is the quantum radiation with the thermal spectrum from the gravastar between two bursts. The temperature of the radiation is not the same as the Hawking one determined by the gravitational mass of the system but the Gibbons-Hawking one of the de Sitter spacetime inside the gravastar.

Quantum Detection of Inertial Frame Dragging

David Kubiznak
Charles University

A relativistic theory of gravity like general relativity produces phenomena differing fundamentally from Newton’s theory. An example, analogous to electromagnetic induction, is gravitomagnetism, or the dragging of inertial frames by mass-energy currents. These effects have recently been confirmed by classical observations. Here we show, for the first time, that they can be observed by a quantum detector. We study the response function of Unruh De-Witt detectors placed in a slowly rotating shell. We show that the response function picks up the presence of rotation even though the spacetime inside the shell is flat and the detector is locally inertial. The detector can distinguish between the static situation when the shell is non-rotating and the stationary case when the shell rotates and the dragging of inertial frames, i.e.gravitomagnetic effects, arise. Moreover, it can do so when the detector is switched on for a finite time interval within which a light signal cannot travel to the shell and back to convey the presence of rotation.

Thermal and Bounded Unruh-DeWitt Detectors in Circular Motion

Cameron Bunney
University of Nottingham

Given the difficulty in experimentally measuring the Unruh effect for a linearly accelerated observer, it has become relevant to probe other Unruh-like regimes which are more experimentally viable. One such approach looks into the experience of an observer in uniform

circular motion. Recently, Biermann et al. (2020) have investigated this circular acceleration version of the Unruh effect by analysing the excitations and de-excitations of a two-level detector in several limiting regimes. In this talk, I will extend the analysis to regimes accessible in analogue spacetime laboratory experiments. In particular, I will consider a non-zero background temperature and a field confined in a cavity.

Dissipative processes at the acoustic horizon

Silvia Trabucco
Gran Sasso Science Institute , Viale Francesco Crispi, 7, 67100 L'Aquila

Our work is set in the context of acoustic analogue gravity theories. A transonic fluid flow creates, under proper conditions, an acoustic hole that is the hydrodynamic analogue of a gravitational black hole. Acoustic holes emit a detectable thermal radiation of phonons at a characteristic Hawking temperature. Within a covariant kinetic theory approach for excitations and fully exploiting the analogy between black and acoustic holes, we rederive the expression of the Hawking temperature by equating the entropy and energy losses of the acoustic hole to the entropy and energy gains of the spontaneously emitted phonons. Differently from previous calculations we do not need a microscopical treatment of normal modes propagation[1,2].Our approach opens to the study of non-stationary horizons beyond thermodynamic equilibrium. We show that viscosity arises from the thermal phonon emission associated to the horizon entropy, shedding light on its geometrical origin and on how viscosity acts as an effective coupling between background (metric) perturbations and the acoustic horizon. The celebrated Kovtun, Son and Starinets (KSS) universal lower bound $\eta/s = 1/4\pi$ of the shear viscosity to entropy density ratio, readily follows, and is extended to the longitudinal bulk viscosity. The underlying key concept is reduced to its essential significance, especially useful to understand the original phenomenon for black holes and to design analogue gravity experiment to test the bound[3].

Based on : [1] M. Mannarelli, D. Grasso, S. Trabucco, and M. L. Chiofalo, "Hawking temperature and phonon emissionin acoustic holes," Phys. Rev. D, vol. 103, no. 7, p. 076001, 2021. [2] M. Mannarelli, D. Grasso, S. Trabucco, and M. L. Chiofalo, "Phonon emission by acoustic black holes,"Contribution to the 2021 Gravitation session of the 55th Rencontres de Moriond, 2021. [3] M. L. Chiofalo, D. Grasso, M. Mannarelli, and S. Trabucco, "Dissipative processes at the acoustichorizon," arXiv:2202.13790v1, 2022.

Can quantum mechanics breed negative masses?

George E. A. Matsas
Institute for Theoretical Physics, Sao Paulo State University

The Casimir effect realizes the existence of static negative energy densities in quantum field theory. We establish physically reasonable conditions for the non-negativity of the total mass of a Casimir apparatus held in equilibrium in the Minkowski background, irrespectively of any condensed matter consideration. Specifically, the dynamical equilibrium requires the presence of additional matter to hold the system apart. As long as this extra matter satisfies

the dominant energy condition, the mass of the combined system is positive. Thus, the very same reason why energy cannot travel backwards in time could be the underlying mechanism behind the positivity of the mass. We discuss the takeaways from the Casimir setting to more general circumstances.

A little excitement across the black hole horizon

Jorma Louko
University of Nottingham

We analyse numerically the transitions in an Unruh-DeWitt detector, coupled linearly to a massless scalar field, in radial infall in (3+1)-dimensional Schwarzschild spacetime. The detector is spatially pointlike and operates for a finite proper time interval with a C^3 switch-on and switch-off. In the Hartle-Hawking and Unruh states, the transition probability attains a small local extremum near the horizon-crossing and is then moderately enhanced on approaching the singularity. The unexpected near-horizon extremum arises numerically from angular momentum superpositions, with a deeper physical explanation to be found. (Based on e-print 2109.13260.)

A first approach to entanglement harvesting in (3+1)D Schwarzschild spacetime

João Caribé
Brazilian Center for Research in Physics

We investigate entanglement harvesting with two static Unruh-DeWitt particle detectors interacting with a free, massless, scalar field on a (3+1)D Schwarzschild background spacetime. To leading order in perturbation theory we managed to study the effect of the spacetime geometry on the entanglement harvesting resulting from the interaction between the detectors and the background field. We see how the change in the singularity structure of the Wightman function manifests itself in the entanglement negativity when one of the detectors is near the caustic and show that in such case the resulting negativity is larger when the field is in the Boulware state than in the Hartle-Hawking state.

Summing Large Logarithms from Loops of Inflationary Gravitons

Richard Woodard
Depatmnt of Physics/University of Florida

Quantum gravitational corrections on flat space background do not affect particle kinematics at all, and only make fractional changes of order G/r^2 to long range forces. The situation during inflation is very different because (1) the Hubble parameter H allows fractional corrections of the form GH^2 and (2) the continuous production of inflationary gravitons introduces a secular element. As a result, corrections to both particle kinematics and long range forces typically grow like logarithms of the scale factor and/or the spatial separation. If

inflation persists long enough, this growth must eventually cause perturbation theory to break down, begging the question of what happens next. I report on recent progress in summing the very similar large logarithms which occur in nonlinear sigma models by combining a variant of Starobinsky's stochastic formalism with a variant of the renormalization group. I discuss how this technique can be generalized to quantum gravity. This talk is based on arXiv:2110.08715.

Fluctuations in the stress-energy tensors of quantum fields in FRW spacetimes

Ankit Dhanuka
IISER Mohali

In this talk, I will discuss the behavior of the fluctuations in the stress-energy tensors of scalar and spinor fields in FRW spacetimes. First, I will discuss the behavior of massive scalar fields in de Sitter spacetime, and then using an equivalence between scalar fields in FRW spacetimes and de Sitter spacetime, I show analogous results for massless scalar fields in power-law FRW spacetimes. After scalar fields, I will talk about spinor fields in de Sitter spacetimes and the corresponding behavior of the fluctuations. Finally, making use of the conformal invariance of massless spinor fields, I will present the results for the fluctuations in these fields in general FRW spacetimes.

Anti-Hawking Effect and Robin Boundary Conditions

Claudio Dappiaggi
University of Pavia

On the class of stationary and asymptotically anti-de Sitter spacetimes and in presence of a Klein-Gordon field it is possible to construct ground and KMS states of Hadamard form, endowed with Robin boundary conditions. In this framework we discuss the transition rate of an Unruh-DeWitt detector coupled to these states and we use the outcome of our analysis to discuss the so-called anti-Hawking effect. We focus our attention to two distinguished scenarios: a massless, conformally coupled scalar field on a static BTZ black hole and a massive Klein-Gordon field an n-dimensional, massless, topological black hole with hyperbolic sections.

Joint work with Lissa de Souza Campos -- ArXiv: 2011.03812 [hep-th] and 2009.07201 [hep-th]

Black hole thermodynamics beyond Lorentz invariance

Stefano Liberati
SISSA, Trieste

A possible signature of the quantum/discrete nature of spacetime at small scales is a breakdown of its local symmetries and in particular of local Lorentz invariance. While a wealth of knowledge has been acquired about departures from such a fundamental symmetry in the matter sector of the Standard Model, not so much is known about the gravitational sector (where it has been suggested that UV Lorentz breaking could be a key ingredient for renormalizability) and current observations leave an interesting parameter space amenable to exploration. In this talk, I will review our knowledge concerning the phenomenological constraints we acquired so far, and then focus on black hole solutions in Lorentz breaking gravity and on the theoretical issue concerning their thermodynamic behaviour. In this sense, I will present a series of recent results pointing to a surprising resilience of Hawking radiation in these settings: a fact that might help expositing what fundamentally lies at the root of black hole radiation and the associated thermodynamic laws.