NEB-19 Recent Developments in Gravity (Online)

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Book of Abstracts

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Model agnostic approaches to cosmology

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In this talk two cosmological studies will be presented and their results discussed. In these studies we have tried to remain model agnostic as much as possible. In particular, our first study (arxiv;1905.08512) performs dynamical analysis of a broad class of non-minimally coupled real scalar fields in spatially curved Friedmann-Robertson-Walker (FRW) spacetimes with unspecified positive scalar potential. While, the second study (arXiv:2001.00825) performs dynamical analysis of a barotropic fluid with positive energy density but otherwise unspecified Equation of State in spatially curved FRW spacetimes.

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Constraints on bimetric gravity

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Bimetric gravity is a ghost-free extension of general relativity, exhibiting both a massless and a massive graviton. We show how the theory can be parameterized with five observables with specific physical interpretations and then constrain the parameter space by requiring: (i) observationally viable cosmology, (ii) a working screening mechanism that restores general relativity locally, and (iii) viable propagation of gravitational waves. Interestingly, the theory provides a good fit to data even away from any general relativity limit.

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Late time tails and thermodynamics of dirty black holes

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In this work we consider black holes surrounded by anisotropic fluids in four dimensions. We first study the causal structure of these solutions showing some similarities and differences with Reissner-Nordström-de Sitter black holes. In addition, we consider scalar perturbations on this background geometry and compute the corresponding quasinormal modes. Moreover, we discuss the late-time behavior of the perturbations finding an interesting new feature, i.e., the presence of a subdominant power law tail term. Likewise, we compute the Bekenstein entropy bound and the first semiclassical correction to the black hole entropy using the brick wall method, showing their universality.

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Impact of Resonances and Chaos on Gravitational Waves from Extreme Mass Ratio Inspirals

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Extreme Mass Ratio Inspirals (EMRIs) are one of the prominent sources for gravitational wave detection by the Laser Interferometer Space Antenna (LISA). EMRIs consist of a stellar compact object ispiralling into a supermassive black hole due to gravitational radiation reaction. During this process the stellar object traces the background and the gravitational waves it emits carry away the information about the central black hole. When an EMRI gravitational signal is detected we will be able to test our understanding of strong gravity to unrivaled precision. However, there are physical factors introducing phenomena that might render EMRIs not detectable. We will discuss this issue by presenting the factors inducing effects like prolonged resonances and chaos. We will show what is the impact of these effects on gravitational waves and how they can be detected.

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Automorphism in Bianchi Type Cosmologies

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The automorphisms of the various Bianchi-type Lie algebras are seen to arise from particular g.c.t.'s of the base manifold. They can be used as Lie-point symmetries of the corresponding Einstein field equations, entailing a reduction of their order and ultimately leading to the entire solution space. The example of the Kasner-like (spatially flat) 4+1 geometry is presented.

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Chiral primordial gravitational waves in extended theories of Scalar-Tensor gravity

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We examine parity violation in gravity during a transitory non-attractor phase of inflation, which amplifies the would be decay tensor mode and enhances tensor fluctuations at super horizon scales.

This is realised in a kinetically driven scenario of inflation which is extended to include higher order corrections to gravity.

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Conserved charges from distorted conformal Killing vectors in pp-waves

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It has been shown that massive geodesics may admit certain nonlocal integrals of motion associated with conformal Killing vectors. In the exceptional case of pp-wave space-times these charges reduce to local expressions generated by a mass dependent distortion of the conformal Killing algebra. We demonstrate under which modification of the Noether symmetry procedure these vectors can be obtained as point symmetries and we discuss their relation to higher order symmetry vectors giving integrals of motion which are rational functions in the momenta.

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Gravitational wave asteroseismology in protoneutron stars

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We examine the eigenfrequencies in gravitational waves from accreting protoneutron stars (PNSs) provided via core-collapse supernova. For this purpose, We adopt profiles of central objects obtained from the numerical simulations. Using a series of snapshots as a static configuration at each time step, we solve the eigenvalue problem to determine the specific frequencies of gravitational waves from the evolving PNSs with accretion by the relativistic Cowling approximation. In this talk, we discuss the protoneutron star properties by identifying the gravitational wave signal obtained by the numerical simulation with the eigenfrequencies of PNSs.

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Logarithmic superfluid vacuum and its manifestations through gravitational and cosmological phenomena

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Recently proposed statistical mechanics arguments 1 and hydrodynamical presentation of quantum wave equations 2 have revealed that the quantum liquids with logarithmic nonlinearity, often referred as “logarithmic fluids”, are very instrumental in describing generic condensate-like matter, including strongly-interacting quantum liquids, one example being He II, a superfluid component of

He-4 [3-6].
A large number of applications of the logarithmic fluids can be also found in a theory of physical vacuum, which is a useful tool for understanding and describing the phenomenon of gravity. Using the logarithmic superfluid model, one can formulate an essentially quantum post-relativistic theory of superfluid vacuum, which successfully recovers special and general relativity in the "phononic" (low-momenta) limit, but otherwise has rather different tenets and foundations. The paradigm of superfluid as a fundamental background opens up an entirely new prospective on the emergence of Lorentz symmetry and induced four-dimensional spacetime, induced gravitational potential, deformed dispersion relations, black holes, cosmological evolution and singularities, and so on [7-13].

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The rise and fall of the black hole chemistry

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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. This has the very interesting consequence that varying bulk pressure (as done in the black hole chemistry literature) no longer qualitatively changes phase diagrams. Their qualitative behavior depends entirely on the value of the central charge – in particular, phase transitions of charged black holes only exist provided the dual CFT has a sufficient number of degrees of freedom. In this sense our work marks "the fall" of black hole chemistry as traditionally understood, but opens up a new frontier for exploring its relationship with the AdS/CFT correspondence.

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Wormhole solutions in beyond Horndeski theories

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A particularly interesting property emerging in Horndeski (and beyond) solutions is the presence of regions with negative effective energy density – this is due to the presence of the higher-curvature gravitational terms in the action and is therefore of purely gravitational nature. This negative effective energy density leads to the violation of both the Weak and the Null Energy Conditions in the near horizon regime. The violation of the energy conditions may allow the emergence of wormhole solutions since it is essential for the creation of the throat. In this work we will present a method to derive analytic traversable wormhole solutions in beyond Horndeski theories. The spacetime of our wormhole solutions is regular over the entire radial regime and does not possess horizons or singularities; thus, our wormholes are traversable. In addition, to construct traversable wormhole solutions with no spacetime singularities beyond the throat, our regular solution over the positive range of the radial coordinate was regularly extended in the negative range in a symmetric way. Finally, for every solution we constructed the isometric embedding diagram and the domain of existence has been studied in detail as well.

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On the stability of rotating spherical fluid shells

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ABSTRACT:

Spherical energy shells in General Relativity tend to collapse due to gravitational effects and/or due to tension effects. Shell stabilization may be achieved by modifying the gravitational properties of the background spacetime. Thus, gravastars consist of stiff matter shells with an interior de Sitter space with repulsive gravitational properties and an exterior Schwarzschild spacetime which balances the interior repulsive gravity leading to a stable stiff matter shell. Similar stabilization effects may be achieved by considering rotation shells. Here we study the stability of slowly rotating fluid shells. We show that the angular velocity of the shell has stabilizing properties analogous to the repulsive de Sitter gravity of the interior of a gravastar. We thus use the Israel junction conditions and the fluid equation of state of the rotating shell to construct the dynamical equations that determine the evolution of the rotating shell radius. These dynamical equations depend on the parameters of the background spacetime and on the angular velocity of the shell. Assuming a rotating interior and a Schwarzschild exterior spacetime we show that the angular velocity of the shell has interesting stabilizing properties on the evolution of its radius R. Thus rotating matter (or vacuum) shells can imitate black holes while avoiding the presence of a singularity and without the presence of an interior de Sitter space.

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Robinson-Trautman Einstein-Maxwell fields of Petrov type D

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In the quest for exact solutions of the Einstein-Maxwell (EM) equations a considerable amount of research has been devoted to the study of aligned EM fields, in which at least one of the principal null directions (PND) of the electromagnetic field **F** is parallel to a PND of the Weyl tensor, a so called Debever-Penrose (DP) direction. One of the main triumphs of this effort - spread out between 1960 and 1980− has been the complete integration of the field equations (with a possible non-0 cosmological constant Λ), for the Petrov type D doubly aligned non-null EM fields, in which \emph{both} real PNDs of **F** are parallel to a corresponding double DP vector, the so called ''class $\mathcal{D}$ metrics". In a recent systematic treatment of the non aligned algebraically special EM fields it was noted that, at least for non-0 Λ, the double alignment condition of the class $\mathcal{D}$ metrics is actually a consequence of their multiple DP vectors being geodesic and shear-free. A natural question therefore arises as to whether EM solutions exist which are of Petrov type D, have $\Lambda = 0$ and in which the two real DP vectors $\mathbf{k}, \ell$ are geodesic and shearfree, but are \emph{both non aligned} with the PND's of **F**. Recently [Class. Quantum Grav. 37, 21, 2020] we have been able to answer this question affirmatively, by completing the full integration of the EM field equations for the double Robinson-Trautman family, under the additional assumption that also the complex eigenvectors of the canonical Weyl-tetrad are hypersurface-orthogonal.

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A new class of massive spin−2 theories with stable cosmologies

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The non-linear and Lorentz invariant theory of a massive spin−2 field, proposed by de Rham, Gabadadze and Tolley (dRGT), has attracted considerable attention in the last decade, thanks to its potential to provide an alternative to dark energy. However, due to the pathologies of the cosmological solutions, the community has moved on to extensions with additional degrees of freedom and broken symmetries.

In this talk, I will show that the dRGT theory is a special case of a larger class of Lorentz invariant massive spin−2 field theories with 5 degrees of freedom. I will then discuss a minimal example, a proof-of-principle model with: i. none of the pathologies of dRGT cosmology; ii. a late time cosmic acceleration; iii. potentially observable (and distinguishable from scalar-tensor theories) deviations from standard cosmological model at linear order; iv. a new, yet successful, screening mechanism.

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

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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. 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.

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Cosmic Acceleration Induced by Friedmann-Static Shock Waves

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In 1970, Taub sought to construct a particular two-parameter family of spherically symmetric self-similar shock-wave solutions to the Einstein field equations with a perfect fluid source. This family would consist of a Friedmann-like interior spacetime expanding into a static exterior spacetime, the physical realisation of which would be a general relativistic explosion. Taub was not successful, but in 2002 Smoller and Temple were able to construct an interior family of Friedmann-like spacetimes local to the centre of expansion. These Friedmann-like spacetimes had the interesting property of inducing an accelerated expansion despite solving the Einstein field equations in the absence of a cosmological constant. This observation led Smoller and Temple to conjecture that a vast primordial shock wave, consisting of a Friedmann-like spacetime on the interior, could account for the cosmic acceleration observed today without the need for dark energy. In this talk I will demonstrate how to construct this family of Friedmann-Static shock waves numerically and then outline the details of a formal existence proof. Furthermore, the predicted rate of expansion induced by these shock waves and their viability as cosmological models will be discussed.

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On the representation theory of the BMS group and its variants in three space-time dimensions

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The original Bondi–Metzner–Sachs (BMS) group B is the common asymptotic symmetry group of all asymptotically flat Lorentzian radiating 4-dim space–times. As such, B is the best candidate for the universal symmetry group of General Relativity (G.R.). In 1973, with this motivation, McCarthy classified all relativistic B-invariant systems in terms of strongly continuous irreducible unitary representations (IRS) of B. Here we introduce the analogue B(2, 1) of the BMS group B in 3 space–time dimensions. B(2, 1) itself admits thirty-four analogues both real in all signatures and in complex space–times. In order to find the IRS of both B(2, 1) and its analogues, we need to extend Wigner–Mackey's theory of induced representations. The necessary extension is described and is reduced to the solution of three problems. These problems are solved in the case where B(2, 1) and its analogues are equipped with the Hilbert topology. The extended theory is necessary in order to construct the

IRS of both B and its analogues in any number d of space−time dimensions, d≥3, and also in order to construct the IRS of their supersymmetric counterparts. We use the extended theory to obtain the necessary data in order to construct the IRS of B(2, 1). Themainresultsoftherepresentationtheoryareasfollows:TheIRSareinducedfrom "little groups" which are compact. The finite "little groups" are cyclic groups of even order. The inducing construction is exhaustive notwithstanding the fact that B(2, 1) is not locally compact in the employed Hilbert topology.

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Localized and analytic braneworld black-hole solutions

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In the context of a five-dimensional braneworld model with a warped extra dimension, we construct novel localized, analytic black-hole solutions. The geometry of the bulk spacetime possesses a higher-dimensional spherical symmetry, while on the brane the geometry is of a Schwarzschild-like form. The singularity of these solutions occupies a single point in the higher-dimensional space, which is located on the 3-brane. In addition, the horizon of these black holes shrinks exponentially as we move away from the brane. No exotic matter is necessary in order to solve the gravitational field equations in the bulk. All these characteristics make these solutions good candidates for solving the black-hole localization problem in braneworld models.

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A singularity theorem for evaporating black holes

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The classical singularity theorems of General Relativity rely on energy conditions that are easily violated by quantum fields. In this talk I will provide motivation for an energy condition obeyed by semiclassical gravity: the smeared null energy condition (SNEC), a proposed bound on the weighted average of the null energy along a finite portion of a null geodesic. I will then then present the proof of a semiclassical singularity theorem using SNEC as an assumption. This theorem extends the Penrose theorem to semiclassical gravity and has interesting applications to evaporating black holes. Based on: arXiv:2012.11569

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Computing EMRI using canonical perturbation theory

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We compute the extreme mass ratio inspiral in a system of a Schwarzschild black hole perturbed by an additional matter located far in the equatorial plane. First the geodesic equation is solved using an approximate transformation of our hamiltonian to the action-angle coordinates. The approximate solution is then expressed as a Fourier-like expansion which is subsequently inserted to the quadrupole formulas for gravitational wave fluxes. This allows us to adiabatically evolve the energy and angular momentum of the smaller body and extract the corresponding gravitational waveform.

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Quantum potentiality in silent universes

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We investigate the modification of the gravitational field equations for the Szekeres spacetimes in the content of de Broglie–Bohm theory for quantum cosmology. We determine a nonzero contribution of quantum potential. Finally, the physical properties provided by the quantum terms in the semiclassical limit are discussed.

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Investigation of binary neutron star merger remnants with equilibrium models

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Transient compact remnants briefly supported by differential rotation and thermal pressure are a possible outcome of binary neutron star (BNS) mergers, with the post-merger phase expected to yield pivotal constraints for the equation of state of high density matter. Modelling remnants as equilibrium configurations can aid in interpreting the post-merger gravitational wave (GW) signal, deducing the threshold mass for prompt collapse to a black hole, constructing universal or empirical relations for remnant properties and understanding processes relevant for multi-messenger follow-up studies of GW observations. Here, we will summarize recent results obtained using equilibrium models to describe merger remnants. Employing a realistic differential rotation law, we construct sequences of remnant-like configurations with rotational profiles resembling those of numerically simulated remnants. Using specific equations of state we infer the threshold mass for prompt collapse and reproduce key predictions of BNS coalescence simulations. Finally, we conjecture a possible correlation between the compactness of quasi-equilibrium remnant models at the threshold mass and the compactness of maximum mass non-rotating models.

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How to do Cosmology with gravitational waves and afterglow observations from neutron star mergers

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A fundamental role in Cosmology is played by the Hubble constant, which measures the current expansion rate of the Universe. A discrepancy exists in the Hubble constant measurements, between the Planck results that use the Cosmic microwave background (CMB) and the supernovae distance ladder. Binary neutron star mergers are promising sources for gravitational waves (GW) accompanied by electromagnetic (EM) counterparts and offer a completely independent Hubble constant estimation. However GW measurements have a degeneracy in the viewing angle determination, which for GW170817 was ~ 0 − 60 degrees. GW170817 was the first ever detection of GW from a neutron star merger, and was followed by a well monitored electromagnetic afterglow, produced by a relativistic jet. The afterglow modeling can break the viewing angle degeneracy. We argue that the choice of jet modeling through either hydrodynamic or magneto-hydrodynamic simulations can have a big impact of the Hubble constant estimation. We present a comprehensive analysis of the viewing angle from different assumptions on the jet model and present a way to distinguish between different jet models that can result to a better estimation of the Hubble constant.

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Tidal deformability of ultracompact Schwarzschild stars in the BH limit

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One of the macroscopically measurable effects of gravity is the tidal deformability of astrophysical objects, which can be quantified by their tidal Love numbers. For compact objects, these numbers measure the resistance of their material against the tidal forces, and the resulting contribution to their gravitational multipole moments. According to GR, the Love numbers for nonrotating black holes are zero. In this talk I will discuss different configurations of nonrotating compact and ultracompact stars to bridge the compactness gap between black holes and neutron stars and calculate their Love number k2. In particular, I will discuss our results for k2, for the first time, for uniform density ultracompact stars, with compactness beyond the Buchdahl limit. We found that k2 approaches smoothly to zero as the compactness approaches the Schwarzschild limit. Our results provide insight on the zero tidal deformability limit and we use current constraints on the binary tidal deformability Λ from GW170817 (and future upper limits from binary black hole mergers) to propose tests of alternative models.

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Acceptable cosmologies with wave maps

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We consider theories of gravity that include many coupled scalar fields with arbitrary couplings, in the geometric framework of wave maps. The possibility of obtaining acceptable cosmological solutions without the inclusion of a potential term to the scalar fields is examined. We also address the issue of the conditions that must be satisfied by the wave maps for an accelerated phase of the Universe.

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Spontaneous scalarization of compact objects with Ricci and Gauss-Bonnet couplings

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Spontaneous scalarization of compact objects provides one of the most interesting manifestations of new strong gravity physics while remaining undetected in the weak field regime. We demonstrate that there are theories that exhibit spontaneous scalarization while having General Relativity as a cosmological attractor. For that to happen, we assume a scalar-Ricci coupling in addition to the scalar-Gauss-Bonnet coupling. We show that the former term contributes non-trivially to the characteristics of the scalarized compact objects, including the scalar charge, and affects the radial stability of the solutions.

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Multi-field cosmology

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Scalar fields in cosmology have been intensively studied during the last decades due to their potential application in the physics of the early and late universe cosmology. In this talk, we will explore the high-energy motivation and the theoretical implications of considering more than one scalar fields in the early universe and then discuss the observational viability of these models. We will focus on the inflationary regime and briefly discuss some of their applications in the late universe.

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Comparing Spin Supplementary Conditions for Circular Equatorial Orbits

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The Mathisson-Papapetrou-Dixon (MPD) equations describe the motion of an extended test body in general relativity. This system of equations, though, is underdetermined and has to be accompanied by constraining supplementary conditions, even in its simplest version, which is the pole-dipole approximation corresponding to a spinning test body. In particular, imposing a spin supplementary condition (SSC) fixes the center of the mass of the spinning body, i.e. the centroid of the body. In the present talk, we examine whether characteristic features of the centroid of a spinning test body, moving in a circular equatorial orbit around a massive black hole, are preserved under the transition to another centroid of the same physical body, governed by a different SSC. For this purpose, we establish an analytical algorithm for deriving the orbital frequency of a spinning body, moving in the background of an arbitrary, stationary, axisymmetric spacetime with reflection symmetry, for the Tulczyjew-Dixon, the Mathisson-Pirani and the Ohashi-Kyrian-Semerak SSCs. Then, we focus on the Schwarzschild as well as Kerr black hole backgrounds and a power series expansion method is developed, in order to investigate the discrepancies in the orbital frequencies expanded in power series of the spin among the different SSCs. Lastly, by employing the fact that the position of the centroid and the measure of the spin alters under the centroid's transition, we impose proper corrections to the power expansion of the orbital frequencies, which allows to improve the convergence between the SSCs. Our concluding argument is that when we shift from one circular equatorial orbit to another in the Schwarzschild/Kerr background, under the change of a SSC, the convergence between the SSCs holds only up to certain powers in the spin expansion, and it cannot be achieved for the whole power series.

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Multi black hole system at equilibrium in an external gravitational field

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Analytical and regular solutions in four-dimensional General Relativity representing multiblack hole systems immersed in external gravitational fields are discussed. The external fields background is composed by an infinite multipolar expansion, which allows to regularise the conical singularities of an array of collinear static black holes. Charged, Rotating, NUT and accelerating generalisations are presented. Limits to the binary Majumdar–Papapetrou, Bonnor–Swaminarayan and the Bičák–Hoenselaers–Schmidt metrics are recovered.

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A Parametrized Equation of State for Neutron Star Matter with Continuous Sound Speed

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We present a generalized piecewise polytropic parametrization for the neutron-star equation of state using an ansatz that imposes continuity in not only pressure and energy density, but also in the

speed of sound. The universe of candidate equations of state is shown to admit preferred dividing densities, determined by minimizing an error norm consisting of integral astrophysical observables. Generalized piecewise polytropes accurately reproduce astrophysical observables, such as mass, radius, tidal deformability and mode frequencies, as well as thermodynamic quantities, such as the adiabatic index. This makes the new equations of state useful for parameter estimation from gravitational waveforms. Since they are differentiable, generalized piecewise polytropes can improve pointwise convergence in numerical relativity simulations of neutron stars. Existing implementations of piecewise polytropes can easily accommodate this generalization with the same number of free parameters. Optionally, generalized piecewise polytropes can also accommodate adjustable jumps in sound speed, which allows them to capture phase transitions in neutron star matter.

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Alleviating H0 tension in generalized Galileon theories

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The Standard Model of Cosmology, namely Λ-Cold Dark Matter (ΛCDM) plus inflation in the framework of general relativity, proves to be very efficient in describing the universe evolution, both at the background and perturbation levels. However, theoretical issues such as the cosmological constant problem and the non-renormalizability of general relativity, as well as the possibility of a dynamical nature for the late-time acceleration, led to the appearance of various extensions and modifications. The last years there have appeared an additional motivation in favour of extensions/modifications of the concordance cosmology, namely the need to incorporate tensions such as the H_0. This tension arises from the fact that the Planck collaboration estimation for the present day cosmic expansion rate is $H_0 = (67.27{\pm}0.60)\, km/s/Mpc$, which is in tension at about 4.4 with the 2019 SH0ES collaboration (R19) direct measurement, i.e $H_0 = (74.03{\pm}1.42)\, km/s/Mpc$, obtained using the Hubble Space Telescope observations of 70 long-period Cepheids in the Large Magellanic Cloud. In this work we are interested in alleviating the H_0 tension in the framework of Horndeski gravity. Horndeski gravity, which is equivalent to Generalized Galileon theory, is the most general four-dimensional scalar-tensor theory that has second-order field equations and thus is free from Ostrogradski instabilities. Hence, by choosing suitable sub-classes of the theory we can obtain a cosmological behavior that is almost identical with that of ΛCDM at early times, but which at intermediate times deviates from it due to the weakening of the gravitational interaction, and thus alleviating the tension.

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Black holes and neutron stars in entangled relativity

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Entangled relativity is a new general theory of relativity that is free of any new parameter at the classical level. It is based on the same principles as general relativity, has the same fields and number of dimensions, but it changes the way spacetime and matter interact with each other, in a way that avoids the possibility of defining the theory of relativity without defining matter and the same time. In other words, unlike in general relativity, gravity and inertia cannot be defined without defining matter in the first place. In this talk, I shall present recent results on spherically charged black holes, as well as neutron stars within this new framework. While astrophysical black holes are argued to be indistinguishable from the ones of general relativity, neutron stars can be slightly more massive than in general relativity. It is noteworthy that these results are parameter free.

86

Positivity bounds with gravity in 4 dimensions

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We formulate Positivity Bounds for scattering amplitudes including exchange of gravitons in four dimensions. We generalize the standard construction through dispersion relations to include the presence of a branch cut along the real axis in the complex plane for the Maldestam variable s. In general, validity of these bounds require the cancellation of divergences in the forward limit of the amplitude. We show that this is possible only if one assumes a Regge behavior of the amplitude at high energies. As a non-trivial fact, a concrete UV behaviour of the amplitude is uniquely determined by the structure of IR divergences. We discuss also possible phenomenological applications of these bounds.

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A new approach to the thermodynamics of scalar-tensor gravity

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We discuss a new approach to the thermodynamics of scalar-tensor gravity and to its possible diffusion" toward general relativity, seen as anequilibrium state" in a space of theories. This new approach echoes ideas from the thermodynamics of spacetime, but it is different. The main idea consists of describing scalar-tensor gravity as an effective dissipative fluid and applying constitutive relations from Eckart's first order thermodynamics to it. This procedure gives explicit effective quantities: heat current density, "temperature of gravity", viscosity coefficients, entropy density, plus an equation describing the "diffusion" to Einstein gravity. These quantities, otherwise missing in spacetime thermodynamics, pop out with minimal assumptions.

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Tests of General Relativity with Black Hole Shadows

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The imaging of black-hole shadows with the Event Horizon Telescope has opened a new window into the strong-field spacetimes of these extreme astrophysical objects. I will first discuss the technological and theoretical advances that led to the first image of the black hole in the M87 galaxy. I will describe how this observation allows us to perform new tests of General Relativity. I will explore the connection of the new results to tests of gravity with other astrophysical and cosmological probes. I will conclude with a prognosis on what ground-based observations of shadows can tell us about black-hole metrics and the underlying theory of gravity.

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Hunting for the gravitational-wave background: implications for astrophysics, high energy physics, and theories of gravity

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I will first define the gravitational-wave background (GWB) and highlight the method we are using to detect it in the presence of correlated magnetic noise. I will then discuss astrophysical (compact binary coalescences) and cosmological (cosmic strings, first-order phase transitions) sources and report on the current constraints imposed from a non-detection during the last observing run of the LIGO/Virgo/KAGRA collaboration. I will also address the question of a simultaneous estimation of astrophysical and cosmological stochastic GWB. Then I will present a search for circularly polarised stochastic GWB and its relation to early universe cosmology. Finally, I will discuss how the GWB can provide tests for gravity theories, including quantum gravity proposals.

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Differential geometry with SageMath and applications to gravity

Author: Eric Gourgoulhon[1]

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The open-source Python-based computer algebra system SageMath [[1]] has some differential geometry and tensor calculus capabilities, which have been implemented through a community effort – the SageManifolds project [[2]]. I shall briefly present the project and illustrate it by various examples relevant to relativistic gravity, among which the demonstration that the Poincaré horizon of AdS spacetime is a degenerate Killing horizon and the dynamics of a Nambu-Goto string in a 5-dimensional Kerr-AdS spacetime for the gauge-gravity duality approach of the quark-gluon plasma.

1. https://www.sagemath.org/
2. https://sagemanifolds.obspm.fr/

99

Black hole hair: from no-hair theorems to scalarization

Author: Thomas Sotiriou[1]

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In general relativity black holes are fully characterised by their mass, spin, and electromagnetic charge. No-hair theorems indicate that scalar fields cannot affect black hole spacetimes. However, the devil is on the details and, in practice, no-hair theorems allow us to identify a list of interesting exceptions in which scalar field leave their imprint on black holes. Such scenarios are of particular

interest to gravitational wave searches for new fundamental physics. I will give an overview of how new fundamental scalars affect black hole spacetimes and of how this can be imprinted on gravitational wave observations.

100

Gravitational-wave astronomy: what's next?

Author: Emanuele Berti[1]

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The observation of compact binary mergers by the LIGO/Virgo collaboration marked the dawn of a new era in astronomy. LISA will expand this vision by opening a new observational window at low frequencies. The gravitational radiation emitted by compact binary systems in these two frequency windows encodes important information on their astrophysical formation mechanism. Furthermore, compact objects - whether in isolation or in binaries - are excellent astrophysical laboratories to probe our understanding of high-energy physics and strong-field gravity. I will highlight the potential of Earth- and space-based detectors to further our understanding of the formation and evolution of compact binaries. I will also discuss potential smoking guns of new physics in gravitational-wave detectors, and the theoretical and observational challenges associated with their search.

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Modified cosmological scenarios through extended horizon entropies

Author: Andreas Lymperis[1]

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We apply the gravity-thermodynamics conjecture, namely the first law of thermodynamics on the Universe horizon, but using the generalized Kaniadakis entropy instead of the standard Bekenstein-Hawking one. The former is a one-parameter generalization of the classical Boltzmann-Gibbs-Shannon entropy, arising from a coherent and self-consistent relativistic statistical theory. We obtain new modified cosmological scenarios, namely modified Friedmann equations, which contain new extra terms that constitute an effective dark energy sector depending on the single model Kaniadakis parameter K. We investigate the cosmological evolution, by extracting analytical expressions for the dark energy density and equation-of-state parameters and we show that the Universe exhibits the usual thermal history, with a transition redshift from deceleration to acceleration at around 0.6. Furthermore, depending on the value of K, the dark energy equation-of-state parameter deviates from ΛCDM cosmology at small redshifts, while lying always in the phantom regime, and at asymptotically large times the Universe always results in a dark-energy dominated, de Sitter phase. Finally, even in the case where we do not consider an explicit cosmological constant the resulting cosmology is very interesting and in agreement with the observed behavior.

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Gravitational Wave Detectors, present and future, an introduction

Author: Stavros Katsanevas[1]

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I will develop briefly the existing plans of ugrade of the current
detectors, their projected physics horizons, as well as the horizons of 3rd generation detectors, on earth (ET and CE) and space (LISA) including new proposals for the Moon. I will also briefly visit, the technological fronts, the multimessenger and more generally the interdisciplinary context, including climate change tasks, and finally the tasks of communication, education and engagement needed to support the ongoing GW scientific revolution.

103

Could the self-force enhance the plateau effect in resonance crossing?

Author: Theocharis Apostolatos[1]

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We have studied a non-ntegrable analogue of a perturbed Kerr metric and found that the passage of an orbit through a resonance is further prolonged when the self-force itself is used to evolve the orbit, instead of the average losses of energy and angular momentum caused by the same self-force. The enhancement is of the order of (but less than) 10. This result renders the revealing of non-Kerrness through EMRIs more plausible.

104

Disformed Kerr metric

Author: Eugeny Babichev[1]

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I will talk about disformal versions of the Kerr spacetime in higher order scalar tensor theories. Properties of the constricted solutions are rather non-trivial and in many aspects differ from those of the Kerr solution. Although the disformed metric has only a ring singularity and asymptotically is quite similar to Kerr, it is found to be neither Ricci flat nor circular. Non-circularity has far reaching consequences on the structure of the solution. The horizon for the disformed metric does not coincide with the stationary limit of infalling observers, unlike the Kerr case. I will also discuss constraints using the recent measurement of the pericenter precession of the star S2 by the GRAVITY Collaboration, and a possibility to probe these Kerr deformations in future experiments.

105

(Absence of) screening in gravitational-wave generation

Author: Enrico Barausse[1]

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I will review how non-linearities can allow for screening solar-system scales from non-tensorial gravitational polarizations, focusing on the case of scalar-tensor theories with derivative self-interactions (K-essence). I will then present fully relativistic simulations in these theories in 1+1 dimensions (stellar oscillations and collapse) and 3+1 dimensions (binary neutron stars), showing how to avoid breakdowns of the Cauchy problem that have affected similar attempts in the past. I will show that screening tends to suppress the (subdominant) dipole scalar emission in binary neutron star systems, but that it fails to quench monopole scalar emission in gravitational collapse, and quadrupole scalar emission in binaries.

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Modified gravity and Cosmology

Author: Spyros Basilakos[1]

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In this review talk we'll discuss the main properties of a large family of modified gravity models, aiming to explain the cosmic acceleration. In the second part of the presentation we'll test their performance against the recent cosmological data.

107

The Nonlinear Stability of Black Holes

Author: Mihalis Dafermos[1]

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I will discuss the mathematical status of the problem of the nonlinear stability of black holes in classical general relativity.

108

Ising Spins and Causal Sets

Author: Lisa Glaser[1]

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Causal sets are a theory that encodes space-time through the causal relations between events. This leads to a fundamentally Lorentzian, discrete, formulation, in which space-time is reduced to partial orders. One possible way to quantize causal sets, is to calculate the path integral over these partial orders. This can either be attempted analytically or explored through Monte Carlo simulations. In

this talk I will first introduce causal sets, and then speak about recent work on matter and the path integral in causal sets.

109

Acceleration in 3 dimensions - a new perspective

Author: Ruth Gregory[1]

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The C-metric in 4D is an interesting exact solution of Einstein's equations, representing a black hole being pulled by a "cosmic string". In 3D, we can construct similar metrics, but these turn out to have sometimes quite different properties. I will give a complete classification of "3DC" metrics, and show how their global structure varies from their 4D cousins, and the BTZ solution.

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Astrophysical tests of hairy black holes

Author: Daniela Doneva[1]

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Testing different beyond-Kerr alternatives has been amongst the major goals of astrophysics and especially gravitational wave physics. In the present talk, we will focus more specifically on black holes endowed with scalar hair. We will discuss the peculiar properties these objects can possess and their astrophysical manifestations both in the electromagnetic and gravitational wave channels. Special attention will be also paid to highly dynamical processes leading to the formation of such hairy black holes.

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Detecting Gravitational Waves with LISA: Searching and extracting signals in the data

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The ESA Laser Interferometer Space Antenna (LISA) is a space born Gravitational-Wave (GW) observatory scheduled to be launched in the early 2030s. LISA will be comprised by a constellation of three satellites forming a triangle with sides of 2.5 million kilometres, following a heliocentric orbit. In this talk I will present the measuring principle of LISA, as well as the different GW sources that are going to be captured by the observatory. I will also discuss the data analysis challenges that we will need to face in order to extract the signals from the data, as well as the key differences with our experience so far with the ground-based detectors.

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Neutron Stars in the Era of Gravitational Wave Astronomy

Author: Kostas Kokkotas[1]

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The detection of gravitational waves 6 years ago and the first detection of binary neutron stars mergers two years later signalled the beginning of a new era for Gravitation and Astrophysics. Neutron stars is a prominent source of gravitational waves and the first observations from them already provided unique information for their structure but also for the associated physics. We will review the results of the last four years and we will discuss the expectations and the challenges from the new observations that will commence in about 10 months.

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Time-symmetric integration and discontinuous collocation methods for self-force applications

Author: Charalampos Markakis[1]

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The scheduled launch of the LISA Mission has called attention to the gravitational self-force problem. Accurate long-time numerical computations of gravitational waves from extreme-mass-ratio-inspirals (EMRI) remain challenging. First, we discuss a class of evolution schemes suitable to this problem based on Hermite integration. Their time-reversal symmetry and unconditional stability allows such methods to accurately track radiative energy loss over long time periods. We apply these methods to the linearized Einstein equations governing black hole perturbation theory. We solve the Bardeen-Press-Teukolsky and Regge-Wheeler-Zerilli equations in the time domain, describing perturbations on a Schwarzschild black hole background, and show that Noether charges and symplectic structure associated with these equations are numerically conserved by time-symmetric methods (but not by explicit methods, such as Runge-Kutta). Second, in a method of lines framework, we combine time-symmetric integration with a discontinuous collocation method, and solve the black hole perturbation equations sourced by a particle inspiralling into a massive black hole. We demonstrate that the symplectic structure of EMRI waveforms extracted at scri+ is preserved by time-symmetric methods.

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Autoencoder-driven Spiral Representation Learning for Gravitational Wave Surrogate Modelling

Author: Paraskevi Nousi[1]

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We investigate the use of neural networks for surrogate modeling of non-spinning EOB BBH waveforms. Specifically, we use autoencoders to first uncover any underlying structure in the empirical interpolation coefficients and discover a spiral pattern wherein the spiral angle is linearly related to

the mass ratio q of the waveforms. We then design a neural spiral module with learnable parameters, which can be added to any fully connected neural network and "informs" the network about the nature of the fitting problem, i.e., about how q is related to the coefficients via a spiral. The proposed spiral module leads to better regression errors as well as to a better mismatch between the surrogate and ground-truth waveforms, compared to baseline models without the addition of this spiral. We finally present a surrogate model for EOBNRv2 waveforms with q ranging from 1 to 8, which can generate millions of coefficients in less than a millisecond on a desktop GPU with median mismatches as low as 10^{-8}.

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Study of the stability of compact objects in scalar-tensor theories of gravity

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We consider compact objects solutions of a Horndeski subclass
which includes a massless scalar field non-minimally coupled to the Einstein tensor. We study the stability of such solutions under scalar and axial perturbations and we find that they are gravitationally stable at the linear level.

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TBA

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TBA

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Solving the dark matter problem with new gravitational degrees of freedom

Author: Constantinos Skordis[1]

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In this talk, I will discuss how a newly proposed gravitational theory (arXiv: 2007:00082, PRL in press) can solve the dark matter problem by reducing to Milgrom's Modified Newtonian Dynamics at the scale of galaxies and to the LambdaCDM model on cosmological scales. I will show that the theory (i) leads to correct gravitational lensing on galactic scales, (ii) propagates tensor modes at the speed of light, and (iii) gives excellent fits to the Cosmic Microwave Background anisotropies and the large-scale structure power spectrum.

120

The mixed R^2 - Higgs model during and after inflation

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The $R + R^2$ (Starobinsky), where R is the Ricci scalar, and the Higgs inflationary models represent the simplest phenomenological inflationary models which are internally
consistent, have only one free dimensionless parameter taken from observations, produce a smooth exit from inflation to the subsequent hot radiation-dominated stage through an intermediate matter-dominated one, and which formally identical prediction for primordial scalar (matter) perturbations is in the excellent agreement with all present observational data. Their target prediction for the tensor-to-scalar ratio is $r = 3(1 - n_s)^2 = 0.004$. Consideration of the mixed R^2 Higgs inflationary model driven both by the modified $R + R^2$ gravity and a strongly non-minimally coupled scalar (possibly, the Higgs) field helps to shift problems with strong coupling at high energies up to the Planck energy scale. The inflationary behavior of this two-field model is effectively one-field-like and depends on one parameter, too 1. The difference between these three models lies in their post-inflationary behaviour which becomes especially interesting and complicated in the mixed R^2 - Higgs case due to its chaotic character [2,3]. The rate of post-inflationary heating though particle creation in the mixed model is intermediate between those in the Higgs and R^2 models. Generically inflaton (scalaron) decay is not instantaneous and occurs after a large number of its oscillations. In some fine-tuned ranges of its parameters, morerapid preheating through tachyonic instability of the Higgs field becomes possible. In other ranges, reheating ends in the perturbative regime. However, even in the latter case, the reheating temperature in the mixed model is typically high due to the large non-minimal Higgs coupling to gravity.

1. M. He, A. A. Starobinsky and J. Yokoyama, JCAP 1805, 064 (2018); arXiv:1804.00409.
2. M. He, R. Jinno, K. Kamada, S. C. Park, A. A. Starobinsky, J. Yokoyama. Phys. Lett. B 791, 36 (2019); arXiv:1812.10099.
3. M. He, R. Jinno, K. Kamada, A. A. Starobinsky, J. Yokoyama. JCAP 2101, 066 (2021); arXiv:2007.10369.

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Out-of-equilibrium hydrodynamic rotating black holes

Author: Silke Weinfurtner[1]

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We will discuss theoretical and experimental results studying the wave-vortex interaction arising from rotating fluid and superfluid flows. The dynamical equation describing the wave-vortex interaction can be mapped to scalar fields exhibiting an effective rotating black hole. This opens the possibility of studying a variety of rotating black hole processes in hydrodynamic systems. The focus of this presentation is to showcase the behaviour of perturbed hydrodynamic fluid and superfluid vortex flows and establishing analogies with out-of-equilibrium black holes.

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New fully nonlinear dynamical mechanism for formation of scalarized black holes

Author: Stoytcho Yazadjiev[1]

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We will discuss the existence of a new fully nonlinear dynamical mechanism for the formation of scalarized black holes which is different from the spontaneous scalarization. We consider a class of scalar-Gauss-Bonnet gravity theories within which no tachyonic instability can occur. Although the Schwarzschild black holes are linearly stable against scalar perturbations, we show dynamically that for certain choices of the coupling function they are unstable against nonlinear scalar perturbations. This nonlinear instability leads to the formation of new black holes with scalar hair.

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Astrophysical constraints on compact objects in 4D Einstein-Gauss-Bonnet gravity

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Recently, the 4D Einstein-Gauss-Bonnet gravity has received a lot of attention. Remarkably, it possesses an exact vacuum solution that deviates from general relativity. I will discuss the important features of black holes and neutron stars in this theory. In particular, for very compact objects, the sequence of neutron stars matches asymptotically to the black hole limit, closing the mass gap between neutron stars and black holes of same radius. Compact objects also offer the best environment to constrain the single parameter that controls the deviations of this theory with respect to general relativity.

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Cosmic String Loop Collapse in full general relativity

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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 $G\mu$. We show that the efficiency is only weakly dependent on the initial string width and initial loop radii.

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Tests of GR with Gravitational Wave Detections

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The first observations of gravitational waves (GWs) from the coalescence of a black-hole binary in 2015 and a neutron-star binary in 2017 inaugurated a new era in experimental gravity. In less than 5 years and with the continuous upgrades of our GW observatories, LIGO, Virgo and now KAGRA, the detection of GWs evolved from non-existent to a weekly business and has led to a plethora of results with implications for fundamental physics, astrophysics, nuclear physics and cosmology. I will give an overview of how the data from detected GW events have been used to probe the true nature of gravity and test general relativity (GR) to unprecedented levels. I will focus on an array of methods developed by the LIGO/Virgo/KAGRA collaboration exactly for this purpose and will give an update on their latest results from the first half of the third observing run, O3a.

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Frequency deviations in neutron star universal relations: Additional equation of state information

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Gravitational wave observations are crucial in the effort to determine the high-density equation of state. Fluid modes in neutron stars can lead to the emission of gravitational waves. Various empirical relations have been proposed between the frequencies of such modes and stellar properties of the system. In this talk we focus on two distinct systems and their oscillation modes. On the one hand the quadrupolar fluid mode in isolated, cold, non-rotating neutron stars and on the other hand the dominant fluid oscillation in binary neutron star merger remnants. We examine empirical relations with respect to the radius and tidal deformability for both systems. We show that there is a striking similarity between the two systems in the way points, i.e. individual stellar models, distribute with respect to the corresponding fits to all data. We quantify these deviations and demonstrate that they encode additional equation of state information. We discuss how these deviations can be employed for improved gravitational wave observations in the future.