Dark Matter and Stars: Multi-Messenger Probes of Dark Matter and Modified Gravity

Wednesday 3 May 2023 - Friday 5 May 2023

Center for Astrophysics and Gravitation, Instituto Superior Técnico, University of Lisbon

Book of Abstracts

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Investigating Sexaquark as a candidate for dark matter constraining the parameters of nlNJL model when Bayesian analysis of neutron stars mass and radius is performed.

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A stable sexaquark state with quark content (uuddss) is investigated as a candidate for dark matter in the core of neutron star. We find that there is a "sexaquark dilemma"
(analogous to the hyperon dilemma) for which the dissociation of the sexaquark in quark matter is a viable solution fulfilling all present constraints from multi-messenger astronomy. Furthermore, the mass of sexaquark is constrained using a gereneralized relativistic mean-field approach called DD2Y for discribing hadronic matter in the core of neutron star. The parameters of the covariant nonlocal Nambu–Jona-Lasinio
(nlNJL) model which describes the color superconducting quark matter phase, are provided by a systematic Bayesian analysis of hybrid neutron star equations of state (EoS). We find the squared speed of sound at high densities to be about 0.5 for the optimized parameters.

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Modified Gravity in Stellar Physics

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We investigate the non-trivial implications of modified gravity theories on stellar observables in the presence of stellar pressure anisotropies originating due to either stellar magnetic fields or stellar rotation. We demonstrate how one can constrain the modified gravity theories from such studies therein. We also develop an analytical formalism for studying slowly rotating stellar objects in any modified gravity theory in general.

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Intermediate mass-ratio inspirals with dark matter minispikes

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The dark matter (DM) distributed around an intermediate massive black hole (IMBH) forms an overdensity region called DM minispike.
We consider the binary system which consists of an IMBH with DM minispike and a small black hole inspiralling around the IMBH in eccentric orbits.
The factors which affect the evolution of the orbit include the gravity of the system, the dynamical

friction and accretion of the small black hole caused by the DM minispike, and the radiation reaction of gravitational waves (GWs).
Using the method of osculating orbit, we find that when the semi-latus rectum $p \ll 10^5 R_s$ (R_s is the Schwarzschild radius of the IMBH) the dominated factors are the dynamical friction and accretion from the DM minispike, and the radiation reaction.
When $p \gg 10^5 R_s$,
the gravity from the DM minispike dominates the orbital evolution.
The existence of DM minispike leads to the deviation from the Keplerian orbit,
such as extra orbital precession,
henceforth extra phase shift in the GW waveform.
By calculating the signal-to-noise ratio for GWs with and without DM minispikes and the mismatch between them,
we show that the effect of the DM minispike in GW waveforms can potentially be detected by future space-based GW detectors such as LISA, Taiji, and Tianqin.

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Tight constraints on Einstein-dilation-Gauss-Bonnet gravity from GW190412 and GW190814

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Gravitational-wave (GW) data can be used to test general relativity in the highly nonlinear and strong field regime. Modified gravity theories such as Einstein-dilation-Gauss-Bonnet and dynamical Chern-Simons can be tested with the additional GW signals detected in the first half of the third observing run of Advanced LIGO/Virgo. Specifically, we analyze gravitational-wave data of GW190412 and GW190814 to place constraints on the parameters of these two theories. Our results indicate that dynamical Chern-Simons gravity remains unconstrained. For Einstein-dilation-Gauss-Bonnet gravity, we find $\sqrt{\alpha_{\mathrm{EdGB}}} \leq 0.40\,\mathrm{km}$ when considering GW190814 data, assuming it is a black hole binary. Such a constraint is improved by a factor of approximately 10 in comparison to that set by the first Gravitational-Wave Transient Catalog events.

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Boson star head-on collisions

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Colliding boson stars (BS) can be regarded as one potential source for astrophysical gravitational wave signals. Templates for the detection of such signals are now being constructed, which makes accurate calculations of such more important. In contrast to fluid matter, BS solutions are smooth, which makes them, in some sense, an optimal domain for the application of pseudospectral numerical methods. Simulations so far have been limited due to the difficulty in building initial data containing two BSs. Most groups undergoing such studies either use a simple superposition of two boosted BSs

or an improved version thereof. In this talk I will present first results of BS head-on collisions that start from constraint solved initial data.

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f(Q) gravity: DGP-like model at background and pertubations levels

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We take a model in f(Q) gravity which has been studied as having a DGP-like behaviour at background level (Q is the non-metricity scalar). We study cosmological perturbations of this model in view of applying an Einstein-Boltzmann solver, thereby comparing cosmological observables with the current paradigm (Cosmological Constant + Cold Dark Matter model).

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Dark matter capture in Celestial objects: Effect of multi-scattering and light mediators

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We revisit dark matter (DM) capture in celestial objects, including the impact of multiple scattering, and obtain updated constraints on the DM-proton cross-section using observations of white dwarfs. Considering a general form for the energy loss distribution in each scattering, we derive an exact formula for the capture probability through multiple scatterings. We employ these results to compute a "dark"luminosity (LDM), arising solely from the thermalized annihilation products of the captured dark matter. Demanding that LDM does not exceed the luminosity of the white dwarfs in the M4 globular cluster, we set a bound on the DM-proton cross-section, almost independent of the dark matter mass between 100 GeV and 1 PeV and mildly weakening beyond. This is a stronger constraint than those obtained by direct detection experiments in both large masses (M>5 TeV) and small mass (M<10 GeV) regimes. For dark matter lighter than 350 MeV, which is beyond the sensitivity of the present direct detection experiments, this is the strongest available constraint. Moving further, we also generalize the formalism for DM capture in celestial bodies to account for arbitrary mediator mass, and update the existing and projected astrophysical constraints on DM-nucleon scattering cross-section from observations of neutron stars. We show that the astrophysical constraints on the DM-nucleon interaction strength, which were thought to be the most stringent, drastically weaken for light mediators and can be completely voided.

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Gamma-ray flux limits from nearby brown dwarfs: Implications for dark matter annihilating into long-lived mediators.

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Brown dwarfs (BDs) are celestial objects representing the link between the least massive main-sequence stars and giant gas planets. I will present a recent analysis (Bhattacharjee et al.,2023) where consider a sample of nine nearby ($<$ 11 pc distance), cold and old BDs and look for gamma-ray signal from the direction of these objects using 13 years of \textit{Fermi}-LAT data. In the absence of any gamma-ray excess, we set 95\% confidence level upper limits on the gamma-ray flux with a binned-likelihood approach.

I will then show how this null result can be used to constrain particle dark matter (DM). If the DM of the universe is constituted of particles with non-negligible couplings to the standard model, BDs may efficiently accumulate them through scatterings. DM particles eventually thermalize and can annihilate into light, long-lived, mediators which later decay into photons outside the BD.

Within this framework, we set a stacked upper limit on the DM-nucleon elastic scattering cross section at the level $\sim 10^{-38}$ cm^2 for DM masses below 10 GeV. Our limits are comparable to similar bounds from the capture of DM particles in celestial objects but have the advantage of covering a larger portion of the parameter space in mediator decay length and DM mass and being less affected by DM modeling uncertainties.

Reference:
Bhattacharjee et al.,2023 - "Gamma-ray flux limits from brown dwarfs: Implications for dark matter annihilating into long-lived mediators" -Pooja Bhattacharjee, Francesca Calore, and Pasquale Dario Serpico - Phys. Rev. D 107, 043012 –Published 10 February 2023

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Quark matter and non-radial oscillations in hybrid stars

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We study the possibility of the existence of a deconfined quark matter in the core of neutron star (NS)s and its relation to non-radial oscillation modes in NSs and hybrid star (HS)s. We use relativistic mean field (RMF) models to describe the nuclear matter at low densities and zero temperature. The Nambu-Jona-Lasinio (NJL) model is used to describe the quark matter at high densities and zero temperature. A Gibbs construct is used to describe the hadron-quark phase transition (HQPT) at large densities. Within the model, as the density increases, a mixed phase (MP) appears at density about 2.5 times the nuclear matter saturation density (ρ_0) and ends at density about $5\rho_0$ beyond which the pure quark matter phase appears. It turns out that a stable HS of maximum mass, M = 2.27M$_\odot$ with radius R = 14 km (for NL3 parameterisation of nuclear RMF model), can exist with the quark matter in the core in a MP only. HQPT in the core of maximum mass HS occurs at radial distance, r$_c$ = 0.27R where the equilibrium speed of sound shows a discontinuity. Existence of quark matter in the core enhances the non-radial oscillation frequencies in HSs compared to NSs of the same mass. This enhancement is significantly large for the g modes. Such an enhancement of the g modes is also seen for a density dependent Bayesian (DDB) parmeterisation of the nucleonic EOS. The non-radial oscillation frequencies depend on the vector coupling in the NJL model. The values of g and f mode frequencies decrease with increase the vector coupling in quark matter.

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Phonon-based quantum detection schemes for dark energy and dark matter exploration

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In this work, we address the problems of dark energy and dark matter from the perspective of relativistic quantum metrology.

We begin by considering confined quantum bosonic fields described using quantum field theory. These fields satisfy relativistic equations and have mode solutions which can be interpreted as phonons in the case of Bose-Einstein condensation. Then, we restrict our studies to Gaussian states, formed with the phonons, to take advantage of the covariance matrix formalism. This formalism lets us apply quantum metrology techniques to the bosonic fields, allowing their use to estimate physical parameters. By studying the interaction between gravity and the phonons in a Bose-Einstein condensate, we aim to design new detector concepts to explore and constrain dark energy and dark matter models.

A first application is done by studying the response of the phonons in a Bose-Einstein condensate under the gravitational influence of a small oscillating mass nearby. To allow the exploration of dark matter, we consider a gravitational potential inspired by the Modified Newtonian dynamics theory.

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Impact of Fermionic Dark matter on Neutron Star Properties: Taking into account of broad spectrum of nuclear EOSs obtained from Bayesian Inference

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This study explores the impact of fermionic dark matter on neutron star properties such as mass, radius, and tidal deformability. A wide range of nuclear matter equations of state (EOSs) are considered, obtained through Bayesian Inference with minimal constraints on nuclear saturation properties, maximum neutron star mass, and pressure of pure neutron matter. The two fluid formalisms are adopted to investigate the effect of dark matter on neutron star properties, where no direct interaction occurs between dark matter and nuclear matter. The study also examines the correlation between dark matter mass, its fraction inside the core, and its properties across the range of nuclear matter EOSs. Additionally, the study provides estimates of statistical uncertainty and identifies potential unknown parameters responsible for dark matter EOS modeling. The results show that low-mass dark matter candidates could potentially form a dark halo around neutron stars, and the study also measures the dispersion of the universal relation between tidal deformability and compactness in the presence of dark matter, using our large ensemble of EOSs.

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Can LIGO Detect Non-Annihilating Dark Matter?

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Dark Matter (DM) is ubiquitous and thus has been proposed to be probed by several terrestrial and celestial detectors. DM particles from the galactic halo can accumulate in Neutron Stars (NS) and transmute them into sub-2.5 solar mass black holes (BH) if the DM particles are heavy, stable, and have interactions with nucleons. These BHs are named as Transmuted Black Holes (TBH). Null detection of these TBH-TBH mergers from LIGO's low mass BH search can exclude an interesting parameter space in the DM particle mass (m_{\chi}) vs. interaction strength with nucleons (\sigma_{\chi n}) plane. These exclusion limits depend on the priors chosen on DM parameters and the currently uncertain Binary Neutron Star (BNS) merger rate density, precisely on merger rate density of the low mass compact object binaries. The prospect of Gravitational Wave (GW) detectors as a non-annihilating DM direct detection experiment is found to be very positive given continued null detection with increased sensitivity (50 times of the current sensitivity) over the next decade.

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Faint light of old neutron stars and detectability at the James Webb Space Telescope

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Isolated ideal neutron stars (NS) of age $> 10^9$ yrs exhaust thermal and rotational energies and cool down to temperatures below $\mathcal{O}(100)$ K. Accretion of particle dark matter (DM) by such NS can heat them up through kinetic and annihilation processes. This increases the NS surface temperature to a maximum of ~ 2550 K in the best case scenario. The maximum accretion rate depends on the DM ambient density and velocity dispersion, and on the NS equation of state and their velocity distributions. Upon scanning over these variables, we find that the effective surface temperature varies at most by $\sim 40\%$. Black body spectrum of such warm NS peak at near infrared wavelengths with magnitudes in the range potentially detectable by the James Webb Space Telescope (JWST). Using the JWST exposure time calculator, we demonstrate that NS with surface temperatures ⊠ 2400 K, located at a distance of 10 pc can be detected through the F150W2 (F322W2) filters of the NIRCAM instrument at SNR ⊠ 10 (5) within 24 hours of exposure time. Independently of DM, an observation of NS with surface temperatures ⊠ 2500 K will be a formative step towards testing the minimal cooling paradigm during late evolutionary stages.

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Gravitational waves to probe Dark Matter in Neutron Stars

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The recent direct detection of Gravitational Waves from mergers of Neutron Stars has opened up the possibility to explore the properties of dense matter in their interior. Isolated neutron stars can also emit gravitational waves when perturbed, and the wave characteristics if detected may contain signatures of their composition. It is conjectured that dark matter may also exist within neutron stars, and their presence could affect their observable properties. We present results from our recent studies on constraining dark matter models using recent astrophysical data and investigation of effects of the presence of dark matter on neutron star mode oscillations and gravitational wave emission.

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Fermion-Boson-Stars - Neutron Stars Admixed with Ultra-Light Dark Matter

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I will give an introduction to Fermion-Boson-Stars, Neutron Stars with an additional massive, self-interacting complex scalar field, which interact only gravitationally. I explore its history, the mass-radius-relations, tidal deformability, and compare to observations from HESS, NICER, and LIGO.

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Constraining the fraction of bosonic dark matter in neutron stars by NICER and LIGO/Virgo measurements

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Multi-messenger observations of neutron stars (NSs) provide a unique opportunity to probe the nature of Dark matter (DM). In this work, we focus on a new type of exotic compact objects composed of asymmetric DM and baryonic matter which are interacting only through gravitational force where the DM component can be introduced by different accumulation scenarios. By considering the maximum mass, radius and tidal deformability of DM admixed NSs, we investigate the parameter space of self-repulsive sub-GeV bosonic DM in a strong coupling regime. It is shown that depending on the DM particle mass and its fraction, a dense core inside NS or an extended halo around it will be formed which alters its observable quantities. We find that the DM core formation might disfavor maximum mass and radius constraints while the DM halo formation may result in tidal deformability

values which are not well consistent with observational bounds. Finally, applying joint astrophysical limits from the NICER X-ray telescope and LIGO/Virgo Gravitational-Wave detectors, a stringent constraint on the possible fraction of bosonic DM in NSs has been obtained.

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Mapping the landscape of gravity theories

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Both Einstein's equations and the field equations of a modified theory of gravity can be derived as equations of state from purely thermodynamical considerations, leading to the identification of GR with an equilibrium state of gravity and modified gravity with a non-equilibrium one. This breakthrough made the relationship between gravity and thermodynamics even more intriguing. I will present a new approach to the thermodynamics of modified gravity which is inspired by these results, but follows a starkly different path. A precise description of the approach to equilibrium naturally emerges from using Eckart's first-order irreversible thermodynamics on the effective imperfect fluid describing scalar-tensor gravity. Applications of this framework to cosmology, extensions to different classes of modified theories, and the formulation of two complementary descriptions based on the notions of temperature and chemical potential all contribute to a new and unifying picture of the landscape of gravity theories GR is embedded in.

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Boson stars in scalar field theory with different potentials

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In this talk different stability mechanisms for dark matter boson stars will be presented. The first mechanism is a mass term in the Lagrangian and the other one is a vacuum term in the potential. They differ in the shapes of the resulting mass radius curves and their compactnesses. The established ϕ^4 potential will be extended to different values of the exponent (ϕ^n). Calculating the equation of state and solving the TOV equations results in high masses and radii, depending on the exponent of the potential. We find extremely large values for the maximum compactness much larger compared to the ones for the standard potentials for bosonic matter.
The calculated compactness exceeds those of neutron stars and goes asymptotically to the limit of causality ($C_{max} = 0.354$). This opens up the possibility of boson stars being potential neutron star or black hole mimicker.

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Scalarized neutron stars in massive scalar-tensor gravity: X-ray pulsars and tidal deformability

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We investigated neutron stars (NSs) in scalar-tensor theories of gravity with spontaneous scalarization, exploring three classes of massive scalar-tensor theories and obtaining numerical solutions for slowly rotating NSs. These solutions were used to construct X-ray pulse profiles of hot spots on the surface of NSs, and we also calculated the tidal deformability for NSs with spontaneous scalarization, which was done for the first time with a massive scalar field. Our findings suggest that the I-Love universal relation between the moment of inertia and the tidal deformability deviates from that in GR, serving as a powerful test of GR. The class of scalar-tensor theories with the scalar field coupling to the Gauss-Bonnet invariant has drawn great interest since solutions of spontaneous scalarization were found for black holes in these theories. We studied rotating and tidally-deformed NSs in the scalar Gauss-Bonnet theory and found that while the mass, radius, and moment of inertia of spontaneously scalarized NSs show very moderate deviations from those of NSs in GR, the tidal deformability exhibits significant differences between the solutions in GR, and the I-Love universal relation breaks down in this theory.

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Testing Λ-Free f(Q) Cosmology

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We study a model of $f(Q)$ gravity that is able to account for the accelerated expansion of the universe at low redshifts without relying on dark energy, without adding extra parameters. We study this model by making use of dynamical system techniques to identify regions in parameter space with viable cosmologies and constrain it using SnIa, CMB data and forecast standard siren events.

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Using compact stars on Globular Clusters to constrain dark matter interactions

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It has been argued that Globular Clusters can be originated as dwarf galaxies whose dark matter is then stripped through tidal interactions with the host galaxy. If that is the case, one can argue that, using compacts stars such as white dwarfs, and assuming that a dark matter component survived the stripping, it is possible to place constrains on dark matter interactions such as annihilation and scattering through observables such as the temperature of the stars. One important ingredient, is the dark matter density present in the GC, so far, only semi-analytical methods have been used to

provide such value. In this work we revisit those limits using the stellar kinematics of the GC to place constraints on the dark matter density.

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The impact of asymmetric dark matter on the thermal evolution of compact stars

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We study the effect of asymmetric fermionic dark matter (DM) on the thermal evolution of neutron stars (NSs). No interaction between DM and baryonic matter was assumed, except the gravitational one. Using the two-fluid formalism, we show that DM accumulated in the core of a star modifies the direct Urca threshold, and, consequently, significantly affects the star's cooling. Thus, due to the gravitational pull of DM, the direct Urca threshold shifts towards the lower star mass. Based on these results, we discuss the importance of NSs observations in the X-ray band at different distances from the Galactic center. Since the DM distribution peaks towards the Galactic center, NSs in this region are expected to contain higher DM fractions, showing a different cooling behavior.

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Anisotropic stars made of exotic matter in light of the complexity factor formalism

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Within Einstein's General Relativity we study exotic stars made of dark energy assuming an extended Chaplygin gas equation-of-state. Taking into account the presence of anisotropies, we employ the formalism based on the complexity factor to solve the structure equations numerically, obtaining thus interior solutions describing hydrostatic equilibrium. Making use of well-established criteria we demonstrate that the solutions are well behaved and realistic. A comparison with another, more conventional approach, is made as well.

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Black hole mergers in cubic gravity

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The merging of two black holes is a notoriously difficult process to describe exactly. Nevertheless, the hindrances posed by gravity's nonlinearity can be avoided by focusing on the strict extreme mass ratio limit, in which one of the black holes is infinitely larger than the other. Such an approach has been developed recently and applied within General Relativity to investigate the time evolution of event horizons melding, using nothing but elementary concepts in gravitational physics and simple integrations of geodesics. We apply this strategy to study black hole mergers in Einsteinian cubic gravity, in order to assess how the defining characteristics of the fusion process change as the gravitational theory is modified. In particular, we determine how the mergers'duration, area increment, and rate of throat swelling change as the theory's single coupling parameter is varied. The modified gravity theory under scrutiny possess long-lived microscopic black holes which might play the role of dark matter.

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Dark matter evaporation from celestial bodies

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Scatterings of galactic dark matter (DM) particles with the constituents of celestial bodies could result in their accumulation within these objects and could give rise to observable effects. Nevertheless, the finite temperature of the medium sets a minimum mass, the evaporation mass, that DM particles must have in order to remain trapped. DM particles below this mass are very likely to scatter to speeds higher than the escape velocity, so they would be kicked out of the capturing object and escape. In this talk, I will obtain the DM evaporation mass for all spherical celestial bodies in hydrostatic equilibrium and I will illustrate the critical importance of the exponential tail of the evaporation rate.

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Stars in modified gravity

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I will briefly present the recent works related to effects of modified gravity on particular matter properties, such as Fermi gas, specific heats and cooling processes.

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Motion of S2 and bounds on scalar clouds around SgrA*

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The motion of S2, one of the stars closest to the Galactic Centre, has been measured accurately and used to study the compact object at the centre of the Milky Way. It is commonly accepted that this object is a supermassive black hole but the nature of its environment is open to discussion. Here, we investigate the possibility that dark matter in the form of an ultralight scalar field "cloud" clusters around SgrA*. We use the available data for S2 to perform a Markov Chain Monte Carlo analysis and find the best-fit estimates for a scalar cloud structure. Our results show no substantial evidence for such structures. When the cloud size is of the order of the size of the orbit of S2, we are able to constrain its mass to be smaller than 0.1% of the central mass, setting a strong bound on the presence of new fields in the galactic centre.

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Non-Linear Dynamics Simulation for LISA

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LISA is a multi-satellite mission led by ESA and designed to measure gravitational waves in space. Its sheer size gives access to the millihertz bandwidth, a whole new range of frequencies for gravitational wave astronomy. It is crucial to understand the expected noise for the complicated detection mechanism. We use the LISANode framework to implement a non-linear dynamical simulation of the spacecrafts motion and attitude from the point of view of the test masses. This enables a detailed analysis of the propagation of dynamics-driven noise and transient disturbances through the complex detection and post-processing chains.

53

Effects of a Dark Matter Halo on X-ray Observations of Neutron Stars

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The high densities of neutron stars (NSs) and resulting strong gravitational potentials could provide astrophysical locations for dark matter (DM) to accumulate. Depending on the DM model, these DM admixed NSs (DANSs) could have significantly different properties than pure baryonic NSs, accessible to probing through X-ray observations of rotationally powered pulsars. We adopt the two-fluid formalism in general relativity to numerically simulate stable configurations of DANSs, assuming a fermionic equation of state (EOS) for the DM with repulsive self-interaction. The distribution of

DM in the DANS as a halo affects the path of X-rays emitted from hot spots on the baryonic surface (R_B) causing notable changes in the pulse-profile observed by telescopes such as NICER, compared to pure baryonic NSs. We find the deviation of the spacetime metric from Schwarzschild at R_B to be an important indicator in characterizing effects of DM halos on the X-ray pulse profiles. Finally, we provide schematic diagrams of how current and future X-ray data from NSs can be analysed in the DANS paradigm, and predict its qualitative effects on NS baryonic EOS constraints.

54

Preheating in Higgs Inflation

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We investigate the post-inflationary dynamics of Higgs-Inflation within the framework of Einstein-Cartan gravity, with a particular emphasis on the scalar sector of the theory. Notably, we find that the inflaton potential is capable of supporting the formation of meta-stable non linear structures, which can generate a significant gravitational wave signal, and significantly modify the standard expansion history of the Universe.

55

Heat transport by asymmetric dark matter in stars: beyond approximations

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Two formalisms have traditionally been used to approximate the energy conducted by asymmetric dark matter that has been captured in stellar objects. These take opposing limits of the Boltzmann equation, and make approximations or extrapolations that are strictly incorrect. Using the first Monte Carlo simulations of heat transport in over 3 decades, we assess the accuracy of these schemes, and provide an updated prescription for self-consistently including such effects in stellar simulations.

56

Multimessenger signals from dark photons around black holes

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I will discuss how rotating black holes source exponentially large numbers of gravitationally-bound ultralight particles, creating nature's laboratories for new physics. These systems emit gravitational

waves, allowing observatories such as LIGO to search for axions and dark photons. If the dark photons interact with the Standard Model, black holes could turn into a new type of bright 'pulsar' in the sky. I will focus on the electrodynamics of a kinetically mixed dark photon cloud that forms through superradiance around a spinning black hole. I will describe the resulting multimessenger signals of these systems which, if they exist, could result in some of the brightest X-ray sources in the universe.

57

Black hole-wormhole collisions and the emergence of islands

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We use ray-tracing techniques to determine the evolution of the event horizon of a large black hole that "gobbles"a tiny, traversable wormhole. The wormhole considered is described by the Ellis-Bronnikov space-time, which is a solution of modified gravity. This calculation has physical meaning in the extreme mass ratio limit. Two setups are considered: a single-mouth wormhole connecting two otherwise independent universes, and a double-mouth zero-length wormhole within the same universe. In the first setting it turns out that, at early times, there exist two disconnected horizons, one in each universe, which then merge as the wormhole falls into the large black hole. In the second setup, we observe the appearance of an 'island', a region of spacetime that is spatially disconnected from the exterior of the black hole, but in causal contact with future null infinity. The island shrinks as time evolves and eventually disappears after sufficient time has elapsed, as compared to the distance between the two mouths. This provides a communication channel with the interior of the large black hole for a certain time interval. We compute numerically the lifetime of the island and verify that it depends linearly on the inter-mouth distance.

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Simulating Binary Neutron Star Mergers: Implications for Multi-messenger Astronomy and Dark Matter Searches

Author: Tim Dietrich[1]

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Throughout the Universe, many high-energy, cataclysmic astrophysical collisions of neutron stars are continuously occurring. These collisions provide an excellent testbed to probe the properties of supranuclear-dense matter, to study the production of heavy elements, to allow for an independent measurement of the expansion rate of our Universe, and to perform an indirect search for dark matter. Essential for such studies are reliable models describing the merger dynamics. Keeping this in mind, numerical-relativity simulations can be seen as a prerequisite for a reliable interpretation of multi-messenger events, and to further develop gravitational-wave and electromagnetic transient models. We show some of our most recent results and identify how simulation can be used for multi-messenger studies and how simulations including dark matter admixed stars will open the door to identify the presence of dark matter in binary neutron star mergers.

59

Nuclear cluster, dark matter or both? Constraints on distributed matter in the innermost galactic centre from stellar orbits

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In the centre of most galaxies there reside(s) (a) massive black hole(s). The one in our own galaxy, Sgr A, *weights roughly four million solar masses. How black holes can become so massive is an open question. Certain theories predict that black holes can grow continuously by accreting dark matter. A star orbiting a black hole through such a distribution would feel a continuously changing gravitational pull, altering its trajectory. Naturally also ordinary matter, such as other members of the nuclear cluster, can have almost the same effect if it is distributed. Small differences arise due the different matter types relaxing in distinct profiles. Inverting the problem we can infer the underlying distribution from precise measurements of stellar orbits. Future infrared observations of the Galactic Centre will thus help not only to further constrain the amount of distributed matter around Sgr A*, but may also allow to infer the nature of that matter. In my talk I will summarise my work with collaborators on this front:

• A theoretical study of the impact of dark matter onto the orbit of S2, focusing on the guiding of observational campaigns w. r. t. key orbital sections, and estimates on future constraints. https://doi.org/10.1051/0004-6361/202142114

• The latest observational constraints on dark matter around Sgr A* of the GRAVITY collaboration. https://doi.org/10.1051/0004-6361/202142465

• A novel shell model for dark matter, and its potential utility for both theoretical investigations and future observational constraints due to its ability to assume a wide range of shapes. https://www.esa.int/gsp/ACT/projects/dark_

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Dark Stars

Author: Chris Kouvaris[None]

Dark matter could possibly form its own compact star-like objects. Although composed of dark matter, there are several ways that these "dark stars" can be observed in the sky, through lensing, gravitational waves from mergers and other exotic astrophysical processes.

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Constraints on the Size of Extra Compactified Dimensions from Compact Star Observations

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Compact stars with Kaluza-Klein excitations are considered and constraints on the size of compactified extra dimensions are given.

The model is a static, spherically symmetric Kaluza-Klein-based theory with one extra compactified dimension. A realistic equation of

state has been introduced and applied in order to reproduce compact star observables. Comparison of the theoretical calculation with available observational data led us to consequences on the size of extra dimensions within the Kaluza-Klein framework.

63

Effective Field Theory Approach to Gravitational Radiation From Binary Systems in Massive Scalar-Tensor Theory

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With the rapid advancements in gravitational wave astronomy, performing precision tests of general relativity in the strong field regime become increasingly viable via e.g. observations of the inspiral waveform of binary systems. A natural modification to general relativity consists of coupling an additional scalar degree of freedom to curvature invariants, which generically leads to a fifth force being mediated by this scalar. I will present how an effective field theory can be constructed in order to systematically calculate corrections to the gravitational and scalar waveform generated by binary systems.

64

Dark Matter admixed Strange Stars

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We investigate the effect of the fermionic nature of dark matter (DM) on the Equation of State (EoS) and macroscopic properties of strange quark matter. We employ the Vector Interaction Enhanced Bag (vBag) model to study the quark matter EoS. For a fixed DM mass, we vary the DM fraction inside the star. It is observed that the macroscopic properties depend upon the DM and are strongly influenced by its fraction inside the star. Varying the DM fraction results in a decrease in the maximum mass and the corresponding radius.
We also investigate the effect of DM on the radial oscillations of strange stars by calculating the fundamental as well as higher excited eigenfrequencies and corresponding oscillation functions of DM admixed strange matter.

65

QCD in the Cores of Neutron Stars

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Rapid advancement in neutron-star observations allows unprecedented empirical access to cold, ultra-dense QCD matter. The combination of these observations with theoretical calculations reveals previously inaccessible features of the equation of state and the phase diagram of QCD. In this talk, I will demonstrate how perturbative-QCD calculations at asymptotically high densities can provide robust constraints on the equation of state at neutron-star densities. This approach offers a way to test the fundamental assumptions that neutron stars are described by the Standard Model (SM) and general relativity, that could allow us to test various dark matter models and beyond GR scenarios.

66

Dirty black hole binaries as probe of dark matter halos

Author: Andrea Maselli[None]

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Coalescing compact binaries provide natural laboratories in which black holes act simultaneously as targets of gravitational wave observations, and moving probes of their medium, where matter fields and particles live in a genuine strong gravity regime.

Within the family-tree of coalescing systems, asymmetric binaries provide a unique phenomenology, which makes them golden sources for next generations of interferometers to investigate the properties of non-vacuum spacetimes.

In this talk I will review some of the possibilities offered by such sources to provide novel insights on the environment in which binaries evolve. I will focus on astrophysical scenarios in which binary black holes orbit embedded by a dark matter halo, showing how the latter affects the propagation and generation of gravitational waves, leaving a detectable imprint on the emitted signals. I will discuss how future observations can exploit such footprints to infer the properties of the dark matter content, possibly allowing to distinguish between different models proposed so far to describe its distribution around massive objects.

67

Constraining f(R) gravity with GW170817

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Modifications of General Relativity may explain some cosmological observations, such as the acceleration of the expansion of the universe or the homogeneity of the CMB radiation.
Interestingly, modified gravities affect the generation of gravitational waves: it is then possible to test these theories with the LIGO/Virgo/KAGRA observations.
In this presentation I will explain how we can use the event GW170817 to constrain modified gravity, and in particular f(R) gravity, that is equivalent to General Relativity plus a scalar field.

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Fermion-Boson Stars with Vector-Boson Dark Matter

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Fermion-boson stars, neutron stars with admixed bosonic dark matter, have increased in popularity as a topic of study lately. The system containing a complex scalar field, minimally coupled to neutron star matter, has already been studied in a variety of cases. In this work I will present the extension from the scalar-field case to a complex vector-field with mass- and self-interaction-term. Describing the dark matter as a vector field has interesting phenomenological properties and also differences to the scalar-field case, which will be highlighted during this talk. The whole investigation is also part of my master thesis.

69

Self-Similar Solutions in Dark-Fluid Cosmology

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The scale-free nature of gravitational interaction in both Newtonian gravity and the general theory of relativity gives rise to the concept of self-similarity, where solutions replicate themselves as the scale varies. As a result of this property, the governing partial differential equations are greatly simplified. Moreover, certain self-similar solutions can describe the asymptotic behaviors of more general solutions. However, there are situations where similarity is partially broken, these are called kinematic self-similar solutions. These kinds of solutions have a wide application in cosmology and mathematical general relativity. We used self-similar solutions to study dark-fluid-based cosmological models.

70

Continuous gravitational-wave probes of dark matter

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The third observing run of advanced LIGO, Virgo and KAGRA brought unprecedented sensitivity towards a variety of quasi-monochromatic, persistent gravitational-wave signals. Continuous waves allow us to probe not just the canonical asymmetrically rotating neutron stars, but also different forms of dark matter, thus showing the wide-ranging astrophysical implications of using a relatively simple signal model. In this talk, I will summarize recent results from searches for dark matter in the form of asteroid-mass primordial black holes, dark matter clouds that could form around rotating black holes, and even dark matter that could interact with the detectors themselves.

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Loop-mediated Dark Matter-neutrino interactions

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The nature of Dark Matter is an ongoing and relevant object of study in astroparticle physics. Despite our best efforts to identify its possible particle properties, the results have been null, which has led to a plethora of models describing viable connections to the Standard Model. In particular, loop models of Dark Matter, like the scotogenic model, have received attention in the last decade but their phenomenology in regard to Dark Matter interactions with neutrinos has not been widely studied in a global analysis. We aim to explore whether parameters of a one-loop model of scalar Dark Matter-neutrino interactions such as the DM mass, the thermally averaged cross-section, and the couplings can be constrained by performing a Bayesian and a frequentist analysis using data on the DM relic abundance, BBN and N_{eff}, the lightest neutrino mass, and meson decays.

72

Uniformly rotating compact stars with a dark matter halo

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In this contribution we consider the uniform rotation of compact stars admixed with dark matter, which forms an extended halo. We use as inputs state of the art equations of state like the hadronic the DD2, IST ones as well a hybrid quark-hadron equation of state based on a recently developed relativistic density functional for quark matter. The resulting configurations contain a typical dark matter to baryonic matter fractions of the order up to 3%.

We report a significant frame dragging effect caused rotation of the dark matter halo and confront this results with the same setup for static compact stars in order to draw conclusions. We discuss astrophysical scenarios like compact stars constrains from the fastest neutron stars observed, mergers of compact stars with halos, and cooling observation of compact stars.

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Accretion of self-interacting dark matter onto neutron stars

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Accumulation of a sizable amount of dark matter in the interiors of neutron stars can significantly modify their observational properties and merger dynamics. If caused by accretion onto a neutron star, rate of such an accumulation is controlled by the strength of non-gravitational interaction of the dark matter particles with the neutron star matter. While the strength of interaction with baryonic matter is strongly constrained by the terestial experiments, self-interaction of dark matter is only limitted by the numerical simulations of the Bullet Cluster combined with the results from X-ray, strong lensing, weak lensing, and optical observations. It is demonsrated that self-inetraction of dark matter crusially impacts its accretion onto neutron stars and is able to provide a sizable amount of dark matter about a few percent of the total mass of a neutron star. More specifically, two models of self-interacting dark matter, which are consistent with the mentioned constraint on the corresponding cross-section, are considered. Modification of the neutron star properties due to the accretion of self-interacting dark matter is also discussed.

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Finding Exotic Particles in Fireballs

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Compact transients such as supernovae and binary neutron star mergers can produce enormous fluxes of exotic particles. One way to look for them is through fireballs, a dense expanding photon electron plasma formed when exotic particles escaping a compact source quickly decay to Standard Model particles. Fireballs produce a unique signal, allowing us to observe new parts of dark photon and axion parameter space. Fireball formation changes previously predicted signals from axions emitted by SN 1987a, and may generate new constraints on axions with masses between 1 MeV and 1 GeV based off of observations of the neutron star merger GW 170817.

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Chameleon Screening and Stars: Newtonian, Post-Newtonian, and Relativistic Analysis

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Dark energy is the name of probably the most relevant problem in cosmology, and there is still no convincing solution to it. However, we can all agree that we need to go beyond Lambda-CDM and the SM to solve it. One of the ways to explain the accelerated expansion of the universe consists of adding a light scalar field that couples to matter. Nevertheless, might this field exist, we would need to explain how come it eluded detection in our planet and solar system. This discrepancy can be resolved by introducing a screening mechanism. From the plethora of theories, we are interested in studying the Chameleon field. The coupling of this field to compact objects, such as neutron stars or white dwarves, affects their structure, stability, and dynamics, providing us with some hints about its detectability. We analyse how the presence of this field affects different kinds of stars, from Newtonian, post-Newtonian, and relativistic perspectives, comparing the advantages and disadvantages of each description.

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Mergers of Dark Matter Admixed Neutron Stars

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We investigate mergers of neutron stars consisting of two non-interacting fluids minimally coupled to the gravitational field using the numerical relativity code BAM. The first fluid represents baryonic matter, whereas the second fluid models dark matter, which we describe using the equation of state of a degenerate Fermi gas.

We consider two different scenarios for the distribution of the dark matter. In the first scenario the dark matter is confined to the core of the star, whereas in the second scenario the dark matter extends beyond the surface of the baryonic matter forming a halo around the baryonic star.

We show how the dark matter impacts the binary dynamics and merger waveforms.

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Dark matter in compact stars and galactic structure

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Dark matter that accumulates in compact stars can have a number of observable effects, including thermal emission from the surface of neutron stars, converting neutron stars into black holes, and causing white dwarfs to explode. After reviewing these compact star dark matter searches I will present some preliminary work on dark matter induced white dwarf explosions, and how these can alter galactic structure through dark matter induced baryonic feedback.

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Primordial Black Holes as laboratories for Physics beyond the standard scenarios

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We use the evaporation of Primordial Black Holes (PBHs) as a laboratory to investigate Physics beyond the Standard Model of particles and to probe the structure of black holes. We show that PBHs develop non-negligible spins through Hawking's emission of a large number of axion-like particles generically present in string theory compactifications, yielding a unique probe of the total number of light scalars in the fundamental theory, independent of how weakly they interact with known matter. We study a regular rotating black hole, described by the Kerr-black-bounce metric, and evaporating under the Hawking emission of a single scalar field. We compared it with a Kerr black hole evaporating under the same conditions and showed how the regularizing parameter affects the evolution of the PBH. We briefly comment on the possibility of investigating the beyond-the-horizon structure of a black hole by exploiting its Hawking emission.

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Smoking gun signals of dark matter in compact stars

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We present here the smoking-gun signals of the presence of dark matter (DM) in compact stars, such as neutron stars (NSs). We demonstrate the conditions under which the DM particles tend to form a compact core or a diluted halo embedding the NS. At the same time, we point out the possible degeneracy between the effect of accumulated DM and the deconfinement phase transition in the core of the star. Both configurations lead to the effective softening of the equation of state and could mimic each other. Moreover, we show the impact of DM on the star thermal evolution and properties, e.g. mass, radius, tidal deformabilities, and its possible detection with the present and future multi-messenger observations.

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Status of dark matter in S_3-symmetric three-Higgs-doublet model

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In scenarios beyond the Standard Model of Particle Physics it is common to invoke models with an extended scalar sector. Such extensions are appealing due to their simplicity from the mathematical point of view and the ability to deal with several shortcomings of the Standard Model, like addressing the origin of dark matter. The most natural way to accommodate a dark matter candidate in the extended scalar models, and to assure stability of dark matter, while controlling the number of free parameters is to assume an underlying symmetry. Governed by this, we consider a three-Higgs-doublet model with an S_3 symmetry. Within this framework there are different implementations which could possibly accommodate a dark matter candidate. The family of S_3-symmetric three-Higgs-doublet implementations arises due to different vacua and, as a result, different minimisation conditions. In this framework the dark matter candidate falls into the class of weakly interacting massive particles. The dark matter candidate is associated with the $\mathbb{Z}_2$ symmetry which survives spontaneous symmetry breaking and is a remnant of the S_3 symmetry. After classifying all possible dark matter candidates within the framework we explore two cases numerically, R-II-1a and C-III-a. The main difference between these two cases is the presence of an irremovable phase, which leads to CP violation in one of the implementations, C-III-a. The two candidate cases differ from other previously studied models with three scalar doublets by the fact that they do not allow for heavy dark matter candidates, $\mathcal{O}(500)$GeV. Valid dark matter regions were identified as $m_{\mathrm{DM}} \in [52.5,\, 89]$ GeV for R-II-1a and $m_{\mathrm{DM}} \in [29,\, 44]$ GeV for C-III-a.

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New fields in the strong gravity regime

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Gravitational wave signals from merging compact objects provide an exciting opportunity to probe fundamental physics beyond General Relativity - this includes the potential for new fields and particles (e.g. dark matter candidates), and for modifications to General Relativity at higher curvature scales. To identify modifications to the standard paradigm we require accurate modelling of the effect of new physics on gravitational wave signals. In this talk I will discuss recent progress in modelling such effects in the strong, dynamical gravity regime of binary black hole mergers, using numerical techniques.

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Dark Matter models and production mechanisms

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We will review different models and production mechanisms for Dark Matter and highlight their different DM properties and signatures.

85

Challenges to the Standard Cosmological Model

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The Lambda Cold Dark Matter (LCDM) model has been widely accepted as the standard cosmological model due to its good agreement with a broad range of cosmological data. However, recent studies have shown discrepancies among the model's key cosmological parameters, which have different levels of statistical significance. While some of these inconsistencies could be due to systematic errors, the persistence of such tensions across various probes suggests a potential failure of the canonical LCDM model. In this seminar, I will review the current tensions, including the Hubble constant disagreement, the S8 tension, and the CMB tension, and explore proposed solutions that could potentially alleviate them. However, I will also discuss the limitations of these proposed solutions and note that none of them have successfully resolved the discrepancies. Nevertheless, there are a few intriguing possibilities that warrant further investigation.

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Neutron Stars as Dark Matter Laboratories in the Multi-messenger Era

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I will describe our current understanding of neutron stars and identify observables that could reveal new physics beyond the standard model. In the next decade, multi-messenger observations of neutron stars, neutron star mergers, and core-collapse supernovae will provide new insights into

neutron stars' structure, dynamics, and thermal evolution. I will outline how this can help discover or constrain the particle nature of dark matter.

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Stars as Axion Laboratories

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It is well-known that light and weakly coupled particles, such as axions, are efficiently produced in hot stellar cores. I will discuss the wide variety of methodologies developed in the community to search for axion emission from stars via their effects on stellar evolution. I will then discuss a related set of work using magnetic stars, in which axion-photon conversion in the magnetosphere can induce a polarization of the thermal emission pointing perpendicular to the direction of the magnetic field. Searches for this polarization result in some of the strongest constraints on the axion to-date.

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Neutron stars in theories beyond GR - from theory to astrophysical constraints

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Even though often underestimated as probes of the strong field regime of gravity because of the matter uncertainties, neutron stars still provide the best up-to-date constraints in a number of GR modifications. In the present talk, we will review the most important models of neutron stars in such theories focusing primarily on the astrophysically viable candidates. Their dynamics and the related astrophysical implications will be also discussed. Special attention will be paid to scenarios that offer clear qualitative different
signatures of beyond GR physics.

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Nonlinear Cosmological probes of gravity theories beyond General Relativity

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Several modifications to general relativity have been proposed with the aim to explain the nature of dark energy and the accelerated expansion of the Universe. In this talk I will review the present status of modified theories of gravity in the light of astrophysical probes of gravity in the weak-field regime, ranging from stars to cosmological scales. I begin by setting the scene for how theories beyond General Relativity are expected to behave in the different astrophysical systems, as well as their cosmological signatures. With these in hand, I present a range of observational tests with an eye to using the current and next generation of observations for tests of gravity. In particular, I will show how physical observables of the non-linear regime of structure formation are promising probes to constraining theoretical models in the nonlinear dynamics of galaxies, clusters and large scale structure.

Invited talks / 90

New fields in the strong gravity regime

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Gravitational wave signals from merging compact objects provide an exciting opportunity to probe fundamental physics beyond General Relativity - this includes the potential for new fields and particles (e.g. dark matter candidates), and for modifications to General Relativity at higher curvature scales. To identify modifications to the standard paradigm we require accurate modelling of the effect of new physics on gravitational wave signals. In this talk I will discuss recent progress in modelling such effects in the strong, dynamical gravity regime of binary black hole mergers, using numerical techniques.

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Observational constraints on f(Q) cosmologies

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Modified gravity theories of the f(Q) theories have aroused some recent interest as candidates to replace Einstein's prescription for gravity. These scenarios present new degrees of freedom in the action due to the free torsionless connection allowed by the nonmetricity tensor Q. In this talk we discuss some specific classes of f(Q) theories. We carry out a Baseyian statistical bunch of tests relying upon background data. These include Type Ia supernovae luminosities and direct Hubble data (from cosmic clocks), along with cosmic microwave background shift and baryon acoustic oscillations data. Our discussion is multifaceted and we focus on comparisons with the (concordance) ΛCDM setup. Our results indicate that at the current precision level the best fits of the f(Q) models explored do not make them really observationally preferred.