Bottom-Up Cross-Cutting Workshop “JENAS Initiative: Gravitational Wave Probes of Fundamental Physics”

Monday, 12 February 2024 - Friday, 16 February 2024

Sapienza University of Rome

Book of Abstracts

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Pions, hyperons and quark matter in neutron star mergers

Corresponding Author: a.bauswein@gsi.de

We discuss recent calculations investigating the detailed impact of various "non-nucleonic" degrees of freedom in neutron star mergers. Pions are neglected in equation of state tables for merger simualtions but might actually occur in neutron star matter. We quantify their potential impact on the obseravbles of neutron star mergers. We describe a weak but potentially measurable signature of hyperons in neutron star mergers. Finally, we discuss the effects of deconfined quark matter.

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The QCD equation of state from Heavy ion collisions and neutron star mergers:

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In this talk I will give a short overview on the current status and challenges in the exploration of dense QCD matter. While in relativistic heavy ion collisions, experiment and theory have been struggling for three decades to get a quantitative understanding of the QCD phase diagram. Only recently, new experimental programs allowed for significant progress. At the same time, the observation of gravitational waves from binary neutron star mergers has opened new venues in the study of dense QCD matter. Based on state-of-the-art models from both communities I intend to show the areas of overlap and opportunities for HIC and BNSM (with a short detour to core-collapse supernovae). In addition I plan to discuss open challenges and give some comments on what we can expect to learn from BNSM and what we should not expect to learn.

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Strong gravity as a probe of physics beyond GR and the Standard Model

I will discuss how GW probes could identify modifications to GR and the presence of new particles

beyond the Standard Model. I will focus on how numerical simulations in strong gravity regimes can help us to understand and identify such signatures.

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Ultralight bosons and gravitational waves: theory and observations

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Quantum spacetime in the sky: from the horizon to the vacuum

I will discuss two aspects of the quantum fluctuations of vacuum spacetime that can be probed in gravitational wave (GW) observatories. The first is the quantum fluctuations near the horizon that lead to (stimulated) Hawking emission (a.k.a. echoes) AND multipolar deformation of Kerr geometry. The second is an irreducible noise in the GW detectors due to the quantum fluctuations of spacetime geometry. These are both (potential) manifestations of a UV/IR coupling that is inevitable in any non-perturbative theory of quantum gravity.

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Searching for Nanohertz Gravitational Waves with Pulsar Timing Arrays

Pulsar timing arrays are sensitive to low-frequency gravitational waves with periods of months to decades. They do so by precisely timing a collection of millisecond pulsars, whose extremely stable rotation makes them ideal for measuring perturbations in spacetime. Gravitational waves induce correlations in the pulse arrival times that follows a characteristic pattern known as the Hellings-Downs curve. Recently, pulsar timing array experiments around the world published the first evidence of nanohertz gravitational waves in the form of a gravitational wave background. In this talk, I will discuss how pulsar timing arrays detect gravitational waves, how we construct pulsar timing arrays, and describe recent results from the NANOGrav collaboration and the International Pulsar Timing Array (IPTA) collaboration.

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The Hubble tension: Status and Perspectives

The success of the LCDM standard model of cosmology has now been established across a wide range of scales. Yet, despite this incredible success the precise nature of its ingredients has so far remained elusive.
To this end, in the past decades a vast experimental effort has been undertaken to measure observables in the local and distant universe to unprecedented precision. These promising measurements have only deepened the mysteries of cosmology, however, as they revealed a growing tension between the current expansion rate of the Universe (specified by the Hubble constant) measured through the local distance ladder and that inferred from the cosmic microwave background. Now that the formal significance of this discrepancy has reached a level of five sigma significance, it is crucial to thoroughly re-examine the astrophysical observations at the heart of this Hubble tension. Similarly important is the role of looking at the future experimental efforts that are certain to bring striking new evidence that will help us to solve this cosmic puzzle.

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Have pulsar timing array methods detected a cosmological phase transition?

Author: Antonino Marciano[1]

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We show [1] that the recent detection of a gravitational wave (GW) background reported by various pulsar timing array (PTA) collaborations including NANOGrav-15yr, PPTA, EPTA, and CPTA can be explained in terms of first order phase transitions (FOPTs) from dark sector models (DSM). Specifically, we explore a model for first order phase transitions that involves the majoron, a Nambu-Goldstone boson that is emerging from the spontaneous symmetry breaking of a U(1)L or U(1)B−L symmetry. We show how the predicted GW power spectrum, with a realistic choice of the FOPT parameters, is consistent with 1-σ deviations from the estimated parameters of the background detected by the PTA collaborations.

[1] A. Addazi, Y.F. Cai, A. Marciano and L. Visinelli, [arXiv:2306.17205 [astro-ph.CO]].

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Nonequilibrium evolution of quarkonium inside the Quark Gluon Plasma

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Using nonrelativistic QCD effective field theories and open quantum system we obtain a master equation to describe the nonequilibrium evolution of bottomonium in the QCD medium. The obtained Linblad equation fully accounts for the quantum and nonabelian nature of the system. The characteristic of the Quark Gluon Plasma are encoded in transport coefficients defined in terms of nonperturbative chromoleectric correlators evaluated on the lattice. We obtain
predictions for the nuclear suppression factor, differential observables and momentum anisotropy and we compare with the data of LHC experiments.
The method can be used to study other similar systems, for example the evolution of dark matter pairs in the early universe.

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Some aspects of the three-body problem in General Relativity

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Relativistic three-body systems could be observed in the future interferometer LISA. In this talk, I will illustrate some striking properties of three-body systems in General Relativity which do not have an equivalent in the simpler two-body problem. While the Kozai-Lidov oscillations typical of the Newtonian three-body problem are suppressed in the relativistic regime, there exists some resonances which could drastically modify gravitational wave emission. Finally, I will show how gravitational waves of two binary systems can interfere, thus modifying the quadrupole energy emission rate.

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Timing the cosmic expansion with populations of gravitational waves dark sirens

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For over 20 years, measurements of the Universe expansion rate from close-by and far sources are in tension hinting at the presence of new physics. Gravitational Waves (GWs) from compact binary coalescences (CBCs) are emergent cosmological probes, potentially observable from close to far scales. GWs are Standard Sirens as they are the only source for which it is possible to measure the distance. In this talk, I will discuss how populations of dark sirens, namely GW sources observed without electromagnetic counterparts, can be exploited to measure cosmic expansion. I will mainly discuss two methodologies that can assign a redshift to GW events either using galaxy surveys or the source mass spectrum of binary black holes. I will show possible pitfalls of the two methodologies that could potentially introduce a systematic bias in the estimation of the Hubble constant. Finally, I

will present the latest results on the measurement of the cosmic expansion rate from the dark sirens reported in the latest Gravitational Wave Transient catalogue.

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A Bayesian investigation of the neutron star equation-of-state vs. gravity degeneracy

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Despite its elegance, the theory of General Relativity is subject to experimental, observational, and theoretical scrutiny to arrive at tighter constraints or an alternative, more preferred theory.
In alternative gravity theories, the macroscopic properties of neutron stars, such as mass, radius, tidal deformability, etc. are modified. This creates a degeneracy between the uncertainties in the equation of state (EoS) and gravity since assuming a different EoS can be mimicked by changing to a different theory of gravity. We formulate a hierarchical Bayesian framework to simultaneously infer the EoS and gravity parameters by combining multiple astrophysical observations. We test this framework for a particular 4D Horndeski scalar-tensor theory originating from higher-dimensional Einstein-Gauss-Bonnet gravity and a set of 20 realistic EoS and place improved constraints on the coupling constant of the theory with current observations. Assuming a large number of observations with upgraded or third-generation detectors, we find that the $A+$ upgrade could place interesting bounds on the coupling constant of the theory, whereas with the LIGO Voyager upgrade or the third-generation detectors (Einstein Telescope and Cosmic Explorer), the degeneracy between EoS and gravity could be resolved with high confidence, even for small deviations from GR.

Reference: arXiv:2309.05420

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Exploring new physics with pulsar timing arrays

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Earlier this year several pulsar timing arrays unveiled the first detection of the stochastic gravitational wave background at nano-Hertz frequencies. The background could potentially arise from myriad merging black holes or –arguably more exciting –an event in the early cosmos. In this talk, I will discuss two recent works on the origin of the new signal: First, I will show under which conditions dark sector phase transitions can serve as an explanation compatible with constraints from precision cosmology. In a second part I will explore how merging clusters of primordial black holes present a promising complementary explanation. I conclude with a comment on the question of the likelihood of a new physics explanation in a Bayesian framework.

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Constraints on Phase Transition in Neutron Stars in a Generalized Setup

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We examine the constraints on a first order phase transition from hadronic matter to deconfined quark matter, based on current astrophysical constraints. In particular we hypothesize the effect a well constrained mass radius data point of a compact star would have on the allowed parameter space. To this end we employ the most likely candidates of the recently updated NICER limits of PSR J0030+0451. A parameterizable relativistic mean field equation of state in compliance with χ_{EFT} results is used, where the stiffness of the equation of state can be varied. The phase transitions is modeled using a Maxwell construction. We find that astrophysical constrains have reduced the parameter space for a phase transition to such an extend that mass and radius measurements may become unreliable in providing indicators for a phase transition in the near future.

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Nuclear physics inputs for neutron stars and nucleosynthesis simulations

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Describing matter at the extreme conditions present in neutron stars (NS) within a unified framework is challenging in view of the wide range of densities encountered. On the other hand, nucleosynthesis simulations of rapid neutron-capture processes (or r-process) require detailed knowledge of nuclear reactions and radioactive decay (hence of the nuclear structure properties, in particular, nuclear masses) for a few thousand exotic neutron-rich nuclei. The challenge for nuclear theory is then the construction of a model that accurately describes (i) masses of neutron-rich nuclei present in the crust of neutron stars and (ii) masses of all the neutron-rich nuclei potentially produced during the r-process nucleosynthesis, together with (iii) a stiff enough neutron matter equation of state to explain the most massive observed pulsars.

We will present the new family of microscopic nuclear energy density functionals (EDFs) [1] developed at IAA, which aims to provide accurate nuclear physics inputs to astrophysical applications, and progress in the above topics. The Brussels-Skyrme-on-a-Grid (BSkG) are parameterizations of the Skyrme EDF with the advantage of being based on the powerful concept of symmetry breaking, allowing for exotic shapes such as triaxial and octupole deformation during the adjustment process. To compensate for the increase in computational cost, machine learning techniques are employed to optimize the parameter adjustment. The latest BSkG3 [2] greatly improves the infinite nuclear matter properties (INM) of BSkG parametrizations. Compared to its predecessors, BSkG3 offers a more realistic description of matter at the extreme densities relevant to NS and is consistent with observations of heavy pulsars, a condition that is not reached in most of the Skyrme forces. Furthermore, we include a pairing treatment designed to match the 1S0 pairing gaps in INM deduced from ab-initio calculations. The latter is particularly important for a reliable description of superfluids in NS. Quantitatively, the model offers lowered root-mean-square deviations on 2457 masses (0.631 MeV), and an unmatched accuracy with respect to 45 primary fission barriers of actinide nuclei (0.33 MeV). Reconciling the complexity of NS with those of atomic nuclei establishes BSkG3 as a tool of choice for applications in nuclear astrophysics.

The next step is to improve the nuclear inputs to NS merger simulations. We will also present our

efforts to add constraints at finite temperature INM properties in the fit protocol. For that we explore an alternative form for the Skyrme EDF that could tackle more INM properties, while keeping a high quality description of nuclear structure properties.

[1] G. Scamps et al., Eur. Phys. J. A 57, 333 (2021); W. Ryssens et al., Eur. Phys. J. A 58, 246 (2022).
[2] G. Grams, et al, Accepted to Eur. Phys. J.. arXiv: 2307.14276 (2023).

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The ringdown of spinning horizonless compact objects

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When formed in a compact binary coalescence, black holes vibrate in a process called ringdown, which leaves the gravitational-wave footprint of the horizon. Some models of quantum gravity that attempt to solve the singularities of general relativity replace black holes with regular and horizonless objects with effective reflectivity. Motivated by these scenarios, we develop a generic framework to study the ringdown of horizonless compact objects. By extending the black-hole membrane paradigm, we describe models of compact objects with different interior solutions in terms of the properties of a fictitious membrane located at the object's radius. In this talk, we derive the quasinormal modes in the ringdown of spinning horizonless compact objects at the linear order in spin. The extension to higher values of the spin would allow us to constrain the properties of the remnants of gravitational-wave events.

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Dynamical friction on compact binary systems

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I will present an approach to calculate the drag force produced by a background of gas or dark matter during a compact binary inspiral. Eccentricity and gravitational wave emission will also be discussed.

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NMMA: A nuclear-physics and multi-messenger astrophysics framework to analyze binary neutron star mergers

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The multi-messenger detection of the gravitational-wave signal GW170817, the corresponding kilonova AT2017gfo and the short gamma-ray burst GRB170817A, as well as the observed afterglow has delivered a scientific breakthrough. For an accurate interpretation of the emitted gravitational-wave and electromagnetic emission, one requires robust theoretical models and efficient computational tools to enable Bayesian inference of observational or synthetic data. For this purpose, we have developed the Nuclear-physics and Multi-Messenger Astrophysics framework, NMMA. We demonstrate that NMMA allows to simultaneously analyze multi-messenger observational data, constrain the equation of state of supranuclear dense matter, classify electromagnetic observations, perform model selection and to measure the Hubble constant.

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A degeneracy between the effect of dark matter and strongly interacting matter at high densities

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We study the impact of asymmetric fermionic and bosonic dark matter on neutron star properties, including tidal deformability, maximum masses, radii, thermal evolution, etc. The conditions at which dark matter particles tend to condense in the core of the star or create an extended halo are presented. We show that dark matter condensed in a core leads to a decrease of the total gravitational mass and tidal deformability compared to a pure baryonic star, which we will perceive as an effective softening of the equation of state. On the other hand, the presence of a dark matter halo increases those observable quantities. Thus, observational data on compact stars could be affected by accumulated dark matter and, consequently, constraints we put on strongly interacting matter at high densities. We will discuss how the ongoing and future X-ray, radio, and GW observations could shed light on dark matter admixed compact stars and put multi-messenger constraints on its effect.

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Title: Black holes as point particles: from amplitudes to self-force

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Abstract: For the inspiral phase of the two-body dynamics, compact objects essentially behave like point particles interacting through the gravitational force. This allows to harness the power of particle physics, like effective field theory techniques and modern scattering amplitude methods, to study analytically the evolution of the binaries in the weak field expansion but with extremely efficient computational tools. A resummation of these perturbative results is possible in the small mass-ratio expansion by making contact with the self-force framework, valid also for strong gravitational fields. We develop this connection further and we propose new analytic continuation methods to compute observables for bound orbits from results valid for scattering orbits.

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A Global Network of Cavities to Search for Gravitational Waves (GravNet): A novel scheme to hunt gravitational waves signatures from the early universe

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The idea of searching for gravitational waves using cavities in strong magnetic fields has recently received significant attention. In particular, cavities with rather small volumes that are currently used to search for axion-like particles are discussed in this context. We propose here a novel experimental scheme enabling the search for gravitational waves with GHz frequencies, which could be caused for example by primodial black hole mergers. The scheme is based on synchronous measurements of cavity signals from several devices operating in magnetic fields at distant locations. Although signatures of gravitational waves may be present as identifiable signal in a single cavity, it is highly challenging to distinguish them from noise. By analyzing the correlation between signals from multiple, geographically separated cavities, it is not only possible to increase substantially the signal over noise ratio, but also to investigate the nature and the source of those gravitational wave signatures. In the context of this talk, a first demonstration experiment with one superconduction cavity has been conducted, which is the basis of the proposed data-analysis approaches. The prospects of GravNet (Global Network of Cavities to Search for Gravitational Waves) are outlined in this talk.

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Tidal heating as a direct probe of Strange matter inside Neutron stars

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The cores of neutron stars (NS) reach densities several times the nuclear saturation density and could contain strangeness containing exotic particles such as hyperons. During the binary inspiral, viscous processes inside the NS matter can damp out the tidal energy induced by the companion and convert this to thermal energy to heat up the star. In this work, we demonstrate that the bulk viscosity originating from the non-leptonic weak interactions involving hyperons is several orders of magnitude higher than the standard neutron matter shear viscosity in the relevant temperature range of $10^6 - 10^9$ K and for heavier mass NSs ($M \geq 1.6 M_{\odot}$) that contain a significant fraction of hyperons in their core, the bulk viscosity can heat up the stars upto $0.1 - 1$ MeV before the final merger. We also show that this "tidal heating" process introduces a net phase shift in the order of $0.1 - 0.5$ rad in the gravitational wave (GW) signal that can potentially be detected using current and future generation GW detectors. Such a detection would be the first direct confirmation of the presence of hyperons inside the NS core, having a great significance for the study of dense matter under extreme condition.

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Gravitational waves from primordial black hole isocurvature: The effect of primordial non-Gaussianity

Author: Theodoros Papanikolaou[None]

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The energy density perturbations of a population of primordial black holes (PBH) forming out of the collapse of enhanced cosmological perturbations are isocurvature in nature. Interestingly enough, they can induce through second order gravitational interactions a stochastic gravitational-wave (GW) background, potentially detectable by current and future gravitational-wave detectors. This GW background can act as a novel method to extract constraints on cosmological models and gravitational theories. In this talk, working within the context of general relativity we will discuss the effect of primordial non-Gaussianity on the clustering properties of PBHs as well as on the spectral shape of the aforementioned induced GW signal.

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Properties of quark matter in extreme conditions

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We briefly review the properties of quark matter at large chemical potentials. In particular, we discuss the properties of the color superconducting phases that can be realized in the interior of compact stars and their impact on astrophysical observables.
Moreover, we show how a sufficiently large isospin asymmetry may drive the system in a meson condensed phases.

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Have pulsar timing array methods detected a cosmological phase transition?

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Exploring new physics with pulsar timing arrays

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New probe for non-Gaussianities with primordial black hole induced gravitational waves

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We propose a new probe of primordial non-Gaussianities through the observational window of gravitational waves (GW) being induced by ultra-light ($M_{\rm PBH} < 10^9$g) primordial black holes (PBHs). An existence of primordial non-Gaussianity can leave imprints on the clustering properties of PBHs and the spectral shape of the induced GW signal. Focusing on local-type non-Gaussianities, we find a distinctive double-peaked GW energy spectrum which, depending on the PBH mass M and the initial PBH abundance at formation time, i.e. $\Omega_{\rm PBH,f}$, can lie within the frequency bands of forthcoming GW detectors, including LISA, ET, SKA and BBO, hence rendering this signal promisingly detectable by GW experiments and promoting it as a novel portal probing non-Gaussianities. Moreover, by accounting on BBN bounds on the non-Gaussian GW amplitude we set model-independent constraints on the effective $\tau_{\rm NL}$, denoted as $\bar{\tau}_{\rm NL}(k)$, on scales $k > 10^5 {\rm Mpc}^{-1}$, which read as $\bar{\tau}_{\rm NL}(k)\mathcal{P}_{calR}(k) < 2\times 10^{-20}\Omega_{\rm PBH,f}^{-17/9}\left(\frac{M_{\rm PBH}}{10^4{\rm g}}\right)^{-17/9}$, where $\mathcal{P}_{calR}(k)$ is the primordial curvature power spectrum.

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Decoding the phase structure of QCD via particle production at high energy

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Rotating metrics from scattering amplitudes in arbitrary dimensions

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