WE Heraeus Physics School und 62. Karpacz Winter School in Theoretical Physics ”Multimessenger Astrophysics and Cosmology”

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Book of Abstracts

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Constraining Nuclear Matter Properties with Gravitational Wave Signals from Core-Collapse Supernovae

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The equation of state (EOS) of high-density matter is a fundame\
ntal concept in astrophysics, describing how matter behaves under extreme conditions. Understanding the EOS is essential for studying compact objects, such as neutron stars and black holes. Although several EOS models have been proposed, only some align with observational data. Core-collapse supernovae (CCSNe) offer a promising opportunity to test the properties of dense matter. In this work, we use a recently proposed parameterized EOS model to simulate a few thousand rotating CCSNe. With this data, we investigate the potential of future gravitational wave (GW) observations of rotating CCSNe to constrain the nuclear matter EOS.

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Two talks on dense matter (Part 1)

Bulk viscosity in nuclear matter. In a neutron star merger, nuclear matter experiences dramatic changes in temperature and density that happen in milliseconds. Mergers therefore probe dynamical properties that may help us uncover the phase structure of ultra-dense matter. I will describe some of the relevant material properties, focusing on flavor equilibration and its consequences such as bulk viscosity and damping of oscillations.

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Two talks on dense matter (Exercise)

Exercises for the talks of Prof. M. Alford.

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Two talks on dense matter (Part 2)

Solid quark matter. I will review three ways in which quark matter can occur in a solid phase, where translational invariance is broken by some sort of crystalline structure. These include a color superconductor of the Fulde-Ferrell-Larkin-Ovchinnikov type, mixed phases that can arise at a nuclear/quark matter interface, and the strangelet crystal crust of a strange star.

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The role of the nuclear symmetry energy on low mass twin compact stars

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In this presentation I briefly discuss the role of the symmetry energy on low mass twin compact stars under the framework of the state-of-the-art compact star measurements. In particular, I review the conjecture of the universal symmetry energy contribution to the compact star equation of state that follows from the direct Urca constraint for the cooling of low mass compact stars. Implications for the onset density of quark deconfiment and quark model EoS are discussed.

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Static structure function of quark-gluon plasma

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The statistical structure factor of the quark-gluon plasma is considered. The screening mass of the low-order perturbative approach is modified by taking into account the Polyakov loop. The effect of modified screening mass on the static structure function of the quark-gluon plasma at temperatures near the critical temperature was shown. At temperatures far from the critical temperature, the effect of the modified screening mass is negligible. In addition, the pair correlation function is calculated.

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Rotochemical heating with NSCool 2D

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A significant fraction of neutron stars (NSs) rotate, and they can rotate very fast (e.g., millisecond pulsar). An isolated rotating NS or an NS that has permanently stopped accreting from its companion gradually loses its rotational energy and spins down. The most common cause for this is magnetic braking. As the star spins down, the centrifugal force decreases, the star shrinks, and its density increases. This drives the matter inside the star out of beta equilibrium. Restoration of equilibrium occurs via nuclear reactions. As weak interactions are relatively slow, the matter can remain in a non-equilibrium state and thus accumulate chemical energy that can be released and heat up the star. This phenomenon is called "rotochemical heating."Most works dedicated to it were performed in the 1D spherical symmetry approximation and assumed isothermal interiors of the NS. We present our preliminary results of the investigation of rotochemical heating employing our advanced NSs thermal evolution code NSCool 2D updated to handle spinning down stars. The calculations were carried out in full general relativity, in 2D axial symmetry, and take into account the full 2D distribution of temperature inside the star. We analyze the impact of the magnetic field strength, the initial

rotation frequency, the equations of state of dense matter, and the mass of the star. While general features coincide with the results of earlier works, we show that some differences exist.

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How effectively can Neural Posterior Estimation infer the Neutron Star Equation of State?

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The equation of state (EoS) of neutron star matter encodes the relationship between pressure and density at supranuclear densities, fundamentally governing the star's structure and observable macroscopic properties, such as mass, radius, and tidal deformability. In this work, we apply Neural Posterior Estimation (NPE) with conditional normalising flows to infer the EoS from synthetic observational data. We consider a model-agnostic EoS family and train our models on mock mass-radius and mass-radius–tidal deformability datasets with varying noise levels. We evaluate reconstruction performance in terms of pressure and squared speed of sound across baryonic densities, and quantify the impact of including tidal deformability information. Our results demonstrate that tidal measurements significantly reduce inference uncertainty, particularly for pressure, and confirm that NPE-based models can accurately capture physical constraints.

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Cooling of neo-neutron stars with temperature dependent inner crusts

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The neo-neutron star (neo-NS) phase directly follows the proto-neutron star (PNS) phase. During the PNS phase, the core of the star forms and acquires its final properties, such as composition and size, whereas the crust forms later during the neo-NS phase. This work is a further development of previous neo-NS studies carried out by one of the authors.
I will present our preliminary results on the cooling of neo-NSs using a fully temperature-dependent equation of state for the entire crust, accounting for the temperature dependence of both pressure and composition in the outer and inner crusts. I will demonstrate the implications of a temperature-dependent composition on the cooling curves and compare various initial luminosity profiles.

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Thermal conduction and thermopower of a warm neutron star crust in magnetic fields

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We compute the thermal conductivity and thermoelectric power (thermopower) of the inner crust of compact stars across a broad temperature–density domain relevant for proto–neutron stars, binary neutron-star mergers, and accreting neutron stars. The analysis covers the transition from a semi-degenerate to a highly degenerate electron gas and assumes temperatures above the melting threshold of the nuclear lattice, such that nuclei form a liquid. The transport coefficients are obtained by solving the Boltzmann kinetic equation in the relaxation-time approximation, fully incorporating the anisotropies generated by non-quantizing magnetic fields. Electron scattering rates include (i) dynamical screening of the electron–ion interaction in the hard-thermal-loop approximation of QED, (ii) ion–ion correlations within a one component plasma, and (iii) finite nuclear-size effects. As an additional refinement, we evaluate electron–neutron scattering induced by the coupling of electrons to the anomalous magnetic moment of free neutrons; this contribution is found to be subdominant throughout the parameter range explored. To assess the sensitivity of transport coefficients to the underlying microphysics, we perform calculations for several inner-crust compositions obtained from different nuclear interactions and many-body methods. Across most of the crust, variations in relaxation times and in the components of the anisotropic thermal-conductivity and thermopower tensors reach up to factors 3 to 4 and 1.5 to 2, respectively, with the exception of the region where pasta phases are expected. These results provide updated, composition-dependent microphysical inputs for dissipative magneto-hydrodynamic simulations of warm neutron stars and post-merger remnants, where anisotropic heat and charge transport are of critical importance.

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Exercises

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Equation of State of Dense Matter in Hot and Cold Neutron Stars (Part 2)

Matter inside neutron stars and their mergers can reach densities of more than 10 times normal nuclear density. In such extreme environments, new particles and phases of matter appear, as well as different interactions become important. In my lectures, I review old and new ways to use neutron star observables to learn about dense matter, comment on what we know and what we expect to discover within the next years concerning dense matter, and provide an overview of modern ways to build and share dense matter descriptions (usually referred to as equations of state).

Modelling dense matter:

1) Speed of sound of dense matter

2) Example of parametric approach

3) RMF models (beyond Walecka covered by Andreas)

4) Chiral models

5) Dense matter EoS repositories

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Equation of State of Dense Matter in Hot and Cold Neutron Stars (Part 1)

Matter inside neutron stars and their mergers can reach densities of more than 10 times normal nuclear density. In such extreme environments, new particles and phases of matter appear, as well as different interactions become important. In my lectures, I review old and new ways to use neutron star observables to learn about dense matter, comment on what we know and what we expect to discover within the next years concerning dense matter, and provide an overview of modern ways to build and share dense matter descriptions (usually referred to as equations of state).

Introduction

1) Introduction to dense matter

2) Phase transitions

3) QCD phase diagram

4) Neutron stars

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Numerical Relativity: Simulating Black Holes and Neutron Stars (Exercises)

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Exercises for the lectures of Prof. T. Dietrich.

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Numerical Relativity: Simulating Black Holes and Neutron Stars (Part 1)

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Describing the most compact objects in the Universe requires the use of Einstein's general relativity and solving its field equations. In the presence of matter, these equations must at least be coupled with the equations of general-relativistic hydrodynamics, and the potential inclusion of magnetic fields or neutrino radiation further increases the complexity.
While analytic solutions exist for simple problems under specific symmetry assumptions (e.g., isolated, spherically symmetric black holes or neutron stars), more complex scenarios—such as the merger of compact binaries—require numerical solutions of the general-relativistic field equations. We will discuss some standard methods and provide simplified examples to test these approaches on your own.

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Numerical Relativity: Simulating Black Holes and Neutron Stars (Part 2)

Describing the most compact objects in the Universe requires the use of Einstein's general relativity and solving its field equations. In the presence of matter, these equations must at least be coupled with the equations of general-relativistic hydrodynamics, and the potential inclusion of magnetic fields or neutrino radiation further increases the complexity.
While analytic solutions exist for simple problems under specific symmetry assumptions (e.g., isolated, spherically symmetric black holes or neutron stars), more complex scenarios—such as the merger of compact binaries—require numerical solutions of the general-relativistic field equations. We will discuss some standard methods and provide simplified examples to test these approaches on your own.

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Neutron-star-crust elastic properties at zero temperature

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The crust of a neutron star is important for many astrophysical phenomena such as the cooling of the star and its transport properties. I will discuss results for neutron-star-crust elastic properties, namely the shear modulus, and their associated uncertainties, obtained within a bayesian analysis.

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AT2025ulz and the Challenge of Optical Contaminants in GW Follow-up

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Identifying electromagnetic counterparts to neutron star mergers (Kilonovae) is crucial for multi-messenger astronomy but is made difficult by the presence of contaminants. In this work, we present an analysis of AT2025ulz: an optical candidate identified within the localization of the gravitational wave event S250818k. Despite initial spatio-temporal consistency, deep Hubble Space Telescope (HST) observations reveal a different nature. We discuss the lines of evidence identifying AT2025ulz as a probable Type IIb Supernova: the transient's evolution on the color-magnitude diagram and the host galaxy analysis, which classifies the host as an edge on star forming spiral, and discussing the offset.

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Thermoelectric coefficients of two-flavor quark matter from the Kubo formalism

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The hot quark matter created in heavy-ion collision experiments can
exhibit strong temperature and chemical-potential gradients, which in turn can generate electric fields through thermoelectric
effects. In this work, we investigate two relevant thermoelectric
coefficients—the thermopower (Seebeck coefficient) and the Thomson

coefficient—of two-flavor quark matter using the Kubo formalism and the Nambu–Jona-Lasinio model as an effective description of dense, finite-temperature QCD. The required two-point equilibrium correlation functions are evaluated using the Matsubara formalism of thermal field theory, applying a $1/N_c$ expansion to the relevant multi-loop Feynman diagrams. We employ previously derived quark spectral functions obtained from one–meson-exchange diagrams above the Mott transition temperature. Our numerical results show that both thermoelectric coefficients increase approximately linearly with temperature and decrease with increasing chemical potential. We also estimate the magnitude of the electric fields that can be generated in heavy-ion collisions by thermal gradients via the Seebeck effect.

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Diquark Properties from First Principles QCD

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Recent observations of neutron stars provide insights into the equation of state of matter at high densities, where exotic phases may emerge. One candidate is color superconductivity, in which quarks form diquark pairs that condense. A first-principles understanding of diquark dynamics is therefore essential for interpreting astrophysical data. In this work, we present a self-consistent, first-principles study of the vacuum properties of scalar diquarks within QCD. Using the functional renormalization group, we demonstrate how high-energy quark and gluon degrees of freedom can be integrated out, yielding an effective low-energy description in terms of mesons and diquarks. Our approach predicts properties of a scalar diquark bound state, consistent with the quark-diquark picture of the nucleon. We further show how these results can be used to constrain low-energy models of color superconductivity, providing new insights into the equation of state of cold and dense quark matter.

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The cosmic equation of state & primordial black holes

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Gravitational wave detection has revived primordial black holes (PBHs) as a compelling dark matter candidate. PBH formation from overdensity collapse during the radiation-dominated era depends sensitively on the cosmic equation of state, particularly across the QCD transition. Following Bödeker et al. 2021, I investigate how lepton flavor asymmetries—poorly constrained prior to neutrino decoupling—impact the cosmic trajectory through the 5+1 dimensional space of chemical potentials (μ_B, μ_Q, μ_Le, μ_Lμ, μ_Lτ) and temperature. High lepton asymmetries could remain hidden in the undetectable cosmic neutrino background, enabling exploration of a large parameter space with significant effects on both the cosmic phase diagram trajectory and the resulting PBH mass distribution. I compute the equation of state for various lepton flavor asymmetry scenarios, extending beyond previous work by incorporating charm quark contributions using the latest lattice QCD and functional QCD data.

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Color-superconducting quarkyonic matter

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We explore the role of color superconductivity in quarkyonic matter under the conditions of color and electric neutrality at β- and strong equilibrium, as relevant for neutron stars. By explicitly incorporating the color-superconducting pairing gap into the phenomenological model of a smooth transition from hadron to quark matter, we extend the known quarkyonic framework to include this essential aspect relevant at high densities. The momentum dependence of the pairing gap, motivated by the running of the QCD coupling and introduced similarly to chiral quark models with nonlocal interaction, is a novel element of the model that is crucial for enabling the simultaneous onset of all color–flavor quark states in the presence of color superconductivity.

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Presentation of WE Hereaus Foundation

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Insights from GRBs for optical follow-up of gravitational-wave counterparts

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Identifying the electromagnetic counterparts to gravitational wave sources is vital to enabling the myriad of investigations possible with multi-messenger astronomy. However, locating faint, fast-varying transients in large sky localisations, given the intrinsic uncertainty in their detailed properties, is challenging. Here we investigate the expected gravitational wave localisations for a sample of merger-induced gamma-ray bursts within the horizon of gravitational-wave detectors during the observing run, O5 (2027+), and determine for which events counterparts could have been detected by various sky searches based only on the gravitational wave localisation (e.g., assuming no additional location constraints from gamma-ray detections). We do this by constructing synthetic skymaps for each event, assuming they arise from either a binary neutron star or a neutron star-black hole merger, and then simulating follow-up searches for these skymaps. Thereafter, by comparing the known counterpart brightness at the time different surveys would have observed, we assess which counterparts would have been detected by searches with the available instrumentation. We further discuss the challenges of correctly identifying these sources as their counterpart and how prospects may improve in observing run O5, thanks to both improved gravitational wave localisations and

follow-up capabilities. We also make recommendations for future follow-up campaigns using the insights gained from this study.

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Proto-Neutron Stars with Color Superconductivity

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At high densities and low temperatures, hadronic matter is expected to undergo a first-order phase transition into a color-superconducting state. While such conditions occur in neutron stars, studies focusing only on cold neutron stars are not fully conclusive because they neglect the evolutionary processes that may influence the appearance of color-superconducting phases. A proto–neutron star, however, describes the earliest evolutionary stages during the first seconds to minutes after core collapse and therefore has different thermodynamic properties compared to a cold neutron star —in particular higher temperatures and trapped neutrinos. To address this, we incorporate proto–neutron star conditions into the equation of state. Tracking stellar configurations from the maximum mass of the hot proto–neutron star to the final cold neutron star allows us to investigate whether color-superconducting phases can form at any point along this trajectory.

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Gravitational Wave Cosmology: From Standard to Biased Sirens

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The measurement of the Hubble constant has became a critical effort given the discrepancy between the early and late universe measurements, dubbed as the Hubble tension. Since the discovery of gravitational waves (GWs) in 2015, compact binary mergers are used as an independent probe to infer cosmological parameters, since they may allow for joint measurements of their luminosity distance and redshift. The most common assumption at the very first step of this process is that the binary merger evolves in vacuum. However, it is widely accepted that a significant fraction of mergers originate in Active Galactic Nucleus (AGN) disks, meaning that there will be a gaseous environment and third body contribution to the binary evolution. We show that neglecting these so-called environmental effects in the waveform, leads to biased cosmological inference, severely limiting the prospects for alleviating the Hubble tension with GWs.

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Impact of nuclear equation of states on the maximum mass of differentially rotating neutron stars

Author: Pratul Manna[1]

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One of the key factors influencing the structure and evolution of neutron stars is differential rotation. It plays a crucial role in understanding the behavior of matter in extreme conditions and affects observable properties like gravitational wave signals from Core-collapse supernovae or binary merger events. However, a major uncertainty exists surrounding the equation of state (EoS)

used for modeling these astrophysical sources. Despite ongoing debates and controversies regarding the correct form of the EoS, much of the existing work have focused on polytropic models, which provide a simplified framework for exploring the stellar properties. In this study, we extend these efforts by investigating the solution space for nuclear EoS models, which serves as a better alternative for the underlying nuclear physics. We show that, despite the complexities introduced by the EoS, the solution space exhibits all four types of equillibrium solutions predicted by polytropic models, allowing for the determination of maximum possible mass. Our results provide a maximum mass limit which is 2-3 times higher than the maximum mass of non-rotating configurations depending on the stiffness of the EoS considered.

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Investigating Possible Signatures of a Supermassive Binary Black Hole in Blazars

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Active galactic nuclei (AGNs) are among the most energetic objects in the Universe, with relativistic jets launched by accreting supermassive black holes. Blazars, a subclass of AGNs with jets aligned close to our line of sight, often exhibit strong variability across the electromagnetic spectrum. Quasi-periodic oscillations (QPOs) in blazar light curves can provide important clues about the central engine, including the possible presence of supermassive binary black holes (SMBBHs) and jet dynamics. Here, we present a preliminary analysis of the gamma-ray emission of the blazars PKS 1824-582 and PKS 2155-83 using Fermi-LAT observations. Our initial results reveal hints of QPOs with a period of ~ 2 years and ~4.5 years respectively, suggesting possible periodic processes in the jet or the presence of a binary supermassive black hole system. I will discuss if it is SMBBHs system then prediction of merger time and modelled characteristic strain of its expected gravitational wave emission.

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Updated constraints on the neutron star equation of state

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The nuclear matter equation of state (EOS) is poorly known at the limit of high density and temperature. While this limit is not currently reached in laboratory settings, it is in neutron star interiors. In this talk, I will discuss an approach to probing the EOS using neutron star measurements. I will describe how neutron star mass and radius inferences from the NICER telescope and tidal deformability measurements, from the LIGO-VIRGO interferometers, constrain the EOS. Furthermore, I will explain how results from ab initio calculations - such as chiral effective field theory (cEFT) and perturbative QCD (pQCD) –can be incorporated to perform EOS inference. I will also discuss how the recent implementation of cEFT calculations including uncertainties obtained with Gaussian processes updated our knowledge of the high-density EOS behavior and enabled the inference of EOS parameters.

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Updated constraints on the neutron star equation of state

Corresponding Author: melissa.mendes@tu-darmstadt.de

The nuclear matter equation of state (EOS) is poorly known at the limit of high density and temperature. While this limit is not currently reached in laboratory settings, it is in neutron star interiors. In this talk, I will discuss an approach to probing the EOS using neutron star measurements. I will describe how neutron star mass and radius inferences from the NICER telescope and tidal deformability measurements, from the LIGO-VIRGO interferometers, constrain the EOS. Furthermore, I will explain how results from ab initio calculations - such as chiral effective field theory (cEFT) and perturbative QCD (pQCD) −can be incorporated to perform EOS inference. I will also discuss how the recent implementation of cEFT calculations including uncertainties obtained with Gaussian processes updated our knowledge of the high-density EOS behavior and enabled the inference of EOS parameters.

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Spin-induced Quadrupole Moment (SIQM) Test for Eccentric Compact Binaries

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Spin-induced deformations of compact binary components can be probed through their gravitational-wave signals and are characterized by a parameter called kappa (κ), which equals 1 for black holes. Measuring its symmetric combination, κs, enables tests of the black hole nature of binary constituents. While previous studies focused on circular binaries, we investigate eccentric systems and forecast the expected measurement precision using a Fisher matrix analysis. For a 10-solar-mass binary with component spins greater than 0.8, we find that the fractional error in κs decreases from about 18% (circular) to about 8% (4%) for initial eccentricities e0 = 0.2 (0.5) at 5 Hz with Cosmic Explorer. Compared to the Advanced LIGO design sensitivity, the combined effects of eccentricity and the improved sensitivity of CE enhance precision by nearly an order of magnitude.

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Classification of Sub-solar mass events: black holes or… something else?

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Compact binary black hole systems are a primary source of gravitational wave detection through LIGO-Virgo-KAGRA detectors. Recent improvements to the detectors have led to improved sensitivity, leading to the detection of more gravitational wave signals. Recent studies have suggested the possibility of observing binary systems in the sub-solar mass range. In third-generation detectors, the possibility of finding a binary in the sub-solar mass range is larger compared to current detectors. We inject different subsolar mass coalescence gravitational wave signals into Gaussian noise and recover it with the assumption of both binary black hole and binary matter star systems. We differentiate them based on the recovered tidal deformability and Bayes factors. These systems can be either a neutron star or an exotic star. We also use symbolic regression models to obtain analytical equations connecting equation of state parameters to observable global parameters.

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Lecture 2

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Exercise

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Role of isospin asymmetry in the onset of quark matter

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Co-authors: Alexander Ayriyan [2]; David Blaschke [3]; Oleksii Ivanytskyi [3]; TIm Dietrich [4]; Violetta Sagun [5]

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In contrast to symmetric nuclear matter, which has been extensively studied in laboratory experiments, the matter inside neutron stars is highly isospin-asymmetric. We investigate the properties of strongly interacting matter under both symmetric and neutron-star-like conditions to determine how electric charge neutrality and beta equilibrium influence the emergence of quark matter. In particular, we establish a relation between the quark onset density in electrically neutral, beta-equilibrated matter and that in symmetric matter. This relation is demonstrated across a broad class of hybrid equations of state and reveals a significant reduction in the quark onset density in highly asymmetric regimes. These findings are further tested through Bayesian analyses of astrophysical measurements, underscoring their relevance for dense matter. A direct consequence of our finding is that a lower-limit constraint on the deconfinement transition in symmetric nuclear matter may imply that this transition could occur in neutron stars at densities even below nuclear saturation density. This study is of significant importance to both the heavy-ion collision and neutron star communities.

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PRIME Telescope Follow-Up of Gravitational Waves related emissions

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The merging of binary black hole (BBH) systems produces gravitational wave (GW) events. We can use their direct measurement of luminosity distance (dL) in combination with the redshift of the merging system to place cosmological constraints. BBH mergers are not expected to produce any electromagnetic counterpart; thus, to obtain the redshift of the source event, we rely on a statistical assignment of the host galaxy, provided by a catalog that covers the localization area. We follow up GW events using the PRIME telescope, a 1.8 m telescope located in Sutherland, South Africa. PRIME is a powerful instrument for GW follow-up, as it can observe large areas with few pointings, thanks

to its wide ≈1.5 deg² field of view. Moreover, PRIME is one of the most sensitive near-infrared telescopes; thus, it is particularly well-suited for studying kilonovae and acquiring crucial photometric data for determining photometric redshifts. As a case study, we present follow-up observations of the BBH.

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Impact of positrons on electrical conductivity of hot and dense astrophysical plasma

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We study the influence of positrons on the outer crusts of neutron stars and the interiors of white dwarfs, introducing them as a novel component in both the composition of matter and in transport processes. We solve a system of coupled Boltzmann kinetic equations for the electron and positron distribution functions in the relaxation-time approximation, taking into account electron–ion, positron–ion, and electron–positron collisions. The relevant scattering matrix elements are calculated from one-plasmon exchange diagrams, with in-medium polarization tensors derived within the hard–thermal–loop effective theory. Numerical results are obtained for matter composed of carbon, iron and helium nuclei. We find that the conductivity rises with temperature, following a power law $\sigma \propto T^4$ in the semi-degenerate regime and $\sigma \propto T$ in the nondegenerate regime, due to the intense creation of thermal electron–positron pairs and the resulting collisions among them. These results highlight the importance of including positrons in the transport properties of heated, dense astrophysical plasmas.

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Generating ultra-compact hybrid stars with bosonic dark matter

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We investigate the impact of a stiff dark matter equation of state (EoS) on the structure and stability of neutron stars. For dark matter, we use bosonic, self-interacting scalar fields that generate ultra-compact boson stars with compactness exceeding 1/3. Varying the dark matter particle mass and stiffness shifts stellar configurations across distinct regions of the mass–radius diagram, including regimes inaccessible to normal hadronic matter. We further examine the impact of a phase transition to quark matter and identify features that distinguish these hybrid configurations from stars without a quark core. In both scenarios, stability is assessed within a two-fluid framework by analyzing the onset of unstable radial modes.

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Dark Matter Heating in Evolving Proto-Neutron Stars: A Two-Fluid Approach

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Neutron stars provide a unique laboratory to probe dark matter (DM) through its gravitational imprint on stellar evolution. We study proto-neutron stars in a two-fluid, quasi-static framework with non-annihilating asymmetric DM (fermionic or bosonic) that interacts with ordinary matter only via gravity, and follow the Kelvin–Helmholtz cooling phase. We find a clear thermal signature: compact DM cores deepen the potential well and heat/compress the baryons, while extended DM halos add external support and cool the stellar matter. Unlike DM cores, hyperons also soften the equation of state but typically lower the temperature, providing a way to distinguish these effects. DM further increases compactness and shifts the hyperon onset, with the strongest impact during deleptonization and the neutrino-transparent stage. These changes in early thermal evolution could be tested with supernova neutrino signals and young neutron-star cooling curves.

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Quasi-Universal Relations for f-Mode Oscillations in Compact Stars

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Gravitational wave astronomy provides a vital tool for probing extreme matter. This study investigates f-mode oscillations of cold, catalyzed Neutron stars as well as protoneutron stars with different evolutionary phases. We analyze the collective impact of nucleons, hyperons, phase transition to the quark matter, and dark matter admixtures on these oscillations employing full General Relativistic formalism.
The primary focus lies on the quasi-universal relations connecting f-modes to bulk stellar properties. Our results demonstrate that these relations remain robust across stars with hyperonic cores, quark matter, and dark matter, as well as in the specific conditions of proto-neutron stars. While the relations exhibit some model dependence, their stability across such diverse physical scenarios

highlights their potential for constraining stellar properties from future gravitational wave detections.

References:

[1] I. A. Rather, K. D. Marquez, P. Thakur, and O. Lourenco, Phys. Rev. D 112, 023013 (2025).
[2] P. Thakur, I. A. Rather, and Y. Lim, Phys. Rev. D 112, 043017 (2025).
[3] P. Thakur, A. Issifu, I. A. Rather, Y. Lim, and T. Frederico, arXiv:2505.24104 (2025).

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Linking microphysics and cosmology through next-generation detections of neutron-star mergers

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Evaluating joint models for the electromagnetic and gravitational signals received from the 2017 neutron-star merger has proven both challenging and insightful. By incorporating further model assumptions or different data sources, we can obtain even tighter constraints on related fields. In particular, such mergers offer a natural connection to both nuclear properties through the dense-matter equation of state and cosmological parameters through independent measurements of distance and redshift. Moreover, next-generation detectors will drastically increase the amount and quality of detected signals. Consequently, statistically robust statements will become computationally more demanding as we expand our modelling and analysis scope. I will discuss how recent extensions to the multimessenger analysis package NMMA allow the incorporation of new data across sectors for tighter multimessenger constraints at acceptable computational cost in a Bayesian framework.

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Estimating the Hubble constant from the mock GW data of Einstein Telescope

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The Hubble constant is a crucial cosmological parameter that is a measure of the rate of change of the cosmic scale factor per unit cosmic scale factor i.e. a_dot / a. There is a considerable discrepancy between the measurements of the Hubble constant from standard candle observations and those from cosmic microwave background (CMB) observations. Data from gravitational wave (GW) events can provide an independent constraint on the Hubble constant. Higher the number of events, the stronger is the constraint. A tight constraint is expected to be achieved in the era of the third generation detectors such as the Einstein Telescope (ET). Without relying on any electromagnetic observation, one can either use the double black hole (BH) merger or the double neutron star (NS) merger detections to break the mass-redshift degeneracy. We present a method of estimating the Hubble parameter using ET mock data for binary BH events and discuss the challenges. We assume flat cosmology in our analysis.

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Phases of dense nuclear and quark matter (Part 2)

Ultra-dense matter in neutron stars is governed by the theory of the strong nuclear force, QCD. After a brief introduction to QCD and its phase diagram I will discuss the basic properties of dense nuclear and quark matter. I will then focus on the color-superconducting phases of quark matter, where quarks form Cooper pairs just like electrons in an ordinary superconductor. The lectures

will be closely connected to the ones by Mark Alford, who will discuss transport properties and crystalline variants of the phases introduced here.

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Phases of dense nuclear and quark matter (Exercises)

Exercises for the Lectures of Prof. A. Schmitt.

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Phases of dense nuclear and quark matter (Part 1)

Ultra-dense matter in neutron stars is governed by the theory of the strong nuclear force, QCD. After a brief introduction to QCD and its phase diagram I will discuss the basic properties of dense nuclear and quark matter. I will then focus on the color-superconducting phases of quark matter, where quarks form Cooper pairs just like electrons in an ordinary superconductor. The lectures will be closely connected to the ones by Mark Alford, who will discuss transport properties and crystalline variants of the phases introduced here.

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Lecture 1

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Lecture 2

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Exercise

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The equation of state of hypernuclear matter within ab initio approach

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We investigate the equation of state (EOS) and macroscopic properties of neutron stars (NSs) and hyperonic stars within an Ab initio approach extended to include interacting Λ hyperons. The ΛN and ΛΛ interactions are described by realistic spin- and parity-dependent potentials fitted to hypernuclear data. Cold, charge-neutral, and β-equilibrated matter composed of neutrons, protons, electrons, muons, and Λ hyperons is considered. We compare our results with recent NICER and gravitational-wave observations. The inclusion of Λ hyperons leads to EOS softening, reducing the maximum NS mass while keeping it consistent with the 2 solar mass constraint. At 1.4 solar mass, the model satisfies observational limits on radius and tidal deformability, with the Λ onset occurring below this mass permitting even canonical-mass NSs to accommodate hyperons. These results suggest that hyperons can appear in NSs across the observed mass range without violating current astrophysical constraints, and that the extended LOCV method provides a consistent, microscopic approach to modeling dense hypernuclear matter.

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Finite-temperature hypernuclear EoS and universal relations of compact stars

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The equation of state (EoS) for dense, strongly interacting matter serves as the central input in astrophysical simulations involving isolated compact objects and binary systems across various scenarios. While numerous models exist to describe the composition of cold neutron stars, the range narrows considerably when considering EoS that encompass varying temperatures, densities, and electron fractions. This talk will discuss the generation of finite temperature EoS of hypernuclear matter in the range of densities, temperatures, and electron fractions required for numerical simulations of SNe, protoneutron stars, and BNS mergers, along with the response of their generic features and composition to varying the baryon-meson couplings. In addition, it will address the properties of hot, isentropic compact stars constructed from those EoS, in the limiting cases of static and maximally rotating configurations, and the validity of universal relations between their global properties.

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Travel to Karpacz

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Travel Karpacz-Wroclaw