External Collaborator Proposal to join the eROSITA Scientific Working Group

Title: Exploring the equation of state of ultra-dense neutron star matter using eROSITA data
Proposer: Fridolin Weber (San Diego State University & University of California at San Diego)

Background: The lack of knowledge of the physical properties of matter at densities that exceed the nuclear saturation density, henceforth referred to as ultra-dense matter, remains one of the principal outstanding problems in nuclear and particle physics. A number of plausible theoretical predictions for the state of such matter exist, which range from normal nucleonic matter to particle exotica such as hyperons and deconfined quarks. If existing in neutron stars, the latter are expected to be in a color superconducting state, with gaps as large as around 100 MeV. Neutrons and protons have been shown to form superfluids respectively superconductors in the cores of neutron stars too, and current research shows that hyperons may form superfluids there as well [1]. All these features manifest themselves in the mass-radius relation and thermal evolution of neutron stars, since they are strongly dependent on the equation of state of ultra-dense matter (Fig.1). The photons and thermal surface radiation from

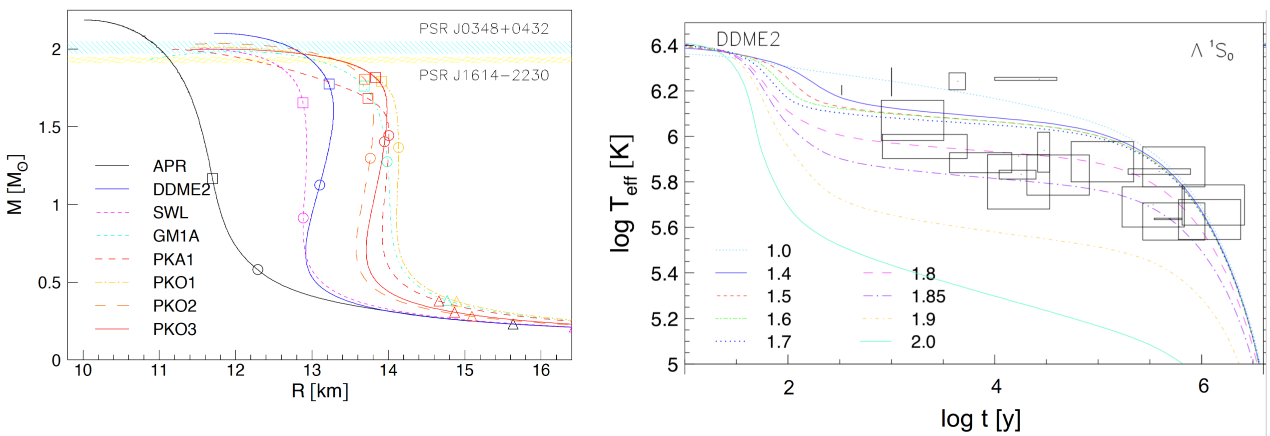

Figure 1. Left: Mass-radius relationship of neutron stars computed for a collection of relativistic field-theoretical models for the equation of state of ultra-dense matter. The open triangles, dots, and squares shown neutron stars whose central densities are equal to n_0, $2n_0$, and $3n_0$, respectively, where n_0 is the density of atomic nuclei. Right: Cooling simulations of neutron stars with masses between 1.0 and 2.0 solar masses computed for field-theoretical nuclear equation of state DDME2 [1].

neutron stars serve as the principal window on their compactness (M/R) and temperatures (T), and therefore on the equation of state of ultra-dense nuclear matter. Past X-ray observatories have allowed theoreticians to make important headway, but a satisfactory exploitation of the information about the nuclear equation of state encoded in the observed X-ray emissions from neutron stars is still lacking. The data expected from the eROSITA survey will help narrowing this gap.

Principal aim: I propose to work with Werner Becker and Axel Schwope on numerical cooling simulations of non-rotating as well as rotating neutron stars using X-ray data that will be provided by the eROSITA mission to constraint the composition of the matter in the super-dense cores of neutron stars. We will analyze the eROSITA survey data in order to search for X-ray counterparts of all rotation-powered pulsars. If no counterpart will be detected we will obtain flux upper limits. Assuming that the corresponding flux will be emitted from the whole neutron star surface we can use this flux (upper limit) to constrain the neutron star's surface temperature. Together with the neutron star's characteristic age this will allow us to compare the temperatures and temperature upper limits with the predicted cooling curves what in turn will constrain the neutron star EOS used in the computation of the neutron star's cooling curves.

Specific research goals:

- Models for the equation of state of confined hadronic matter will be provided that are based on state-of-the-art relativistic nuclear mean-field (RMF) approximations. The models are computed for nuclear parametrizations that satisfy all current constraints from studies of symmetric nuclear matter and from observations of neutron stars (high-mass constraints, mass-radius constraints from GW170817).
- The above collection of equations of state will be supplemented with models which account for quark deconfinement [3]. The latter will be based on the non-local 3-flavor Polyakov Nambu-Jona-Lasinio (n3PNJL) model, which is currently the state-of-the-art effective model of Quantum Chromo Dynamics at low energies.
- Using these models for the equation of state as input, fully general relativistic numerical calculations of the properties of non-rotating and rotating neutron stars with different gravitational and/or baryon masses will be carried out. I will provide a fully general relativistic rotation code.
- I will provide access to a fully general relativistic 2D cooling code to be used to compute the temperature evolution of neutron stars for a range of representative masses and rotational frequencies [4]. As a key innovative feature, our study will not only focus on non-rotating neutron stars, whose particle compositions are frozen in, but rather take into account rotationally driven changes in the particle compositions in the stellar cores.
- Particular emphasis will be devoted to exploring rotation-driven phase transitions in the cores of neutron stars (see Fig. 3) and to identify signals (e.g., temperature anomalies) caused by phase transitions in dense matter, such as quark deconfinement and the formation of superfluid or superconducting Cooper pairs.

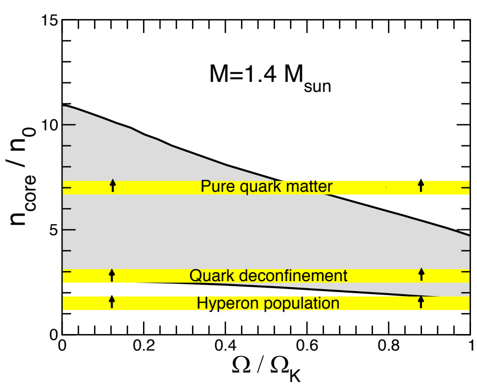

Figure 2: The phases of matter predicted by theory to exist in the core of a 1.4 M_{sun} neutron star depend strongly on the star's rotational frequency [2]. Ω_K denotes the Kepler frequency, which sets and absolute limit on rapid rotation. n_{core} is the density at the center of the neutron star, n_0 is the density of ordinary nuclear matter. The gray area shows the uncertainty in the density-frequency relation caused by the poor knowledge of the equation of state of super-dense matter.

List of potential collaborators: Werner Becker, Axel Schwope

Expected outcome: The results may be presented at the first IACHEC meeting after the X-ray data area acquired and published in a peer-reviewed research journals (A&A, ApJ).

Expected duration of the project: One year, expected to start in September 2019.

References:

[1] A. R. Raduta, J. J. Li, A. Sedrakian, F. Weber, MNRAS (in press), arXiv:1903.01295v2.

[2] F. Weber, "Pulsars as Astrophysical Laboratories for Nuclear and Particle Physics", Studies in High Energy Physics, Cosmology and Gravitation, Institute of Physics Publishing Corporation, Bristol, Great Britain, 1999.

[3] M. Orsaria, H. Rodrigues, F. Weber, G. A. Contrera, PRC 89 (2014) 015806.

[4] R. Negreiros, S. Schramm, F. Weber, PRD 85 (2012) 104019.