Quark matter and non-radial oscillations in hybrid stars

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

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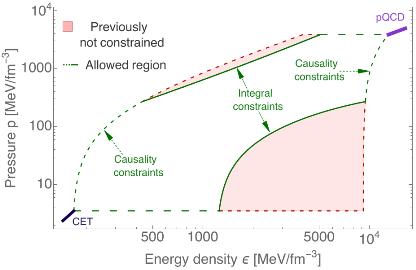
The dense matter equation of state (EOS)

- A neutron star (NS), also known as a pulsar, is one of the densest and most compact objects in the universe.
- A significant probe to reduce uncertainty can be the NS maximum mass, radii, moments of inertia, and tidal Love numbers, which are all accessible to observation.
- The NS core composition remains a mystery



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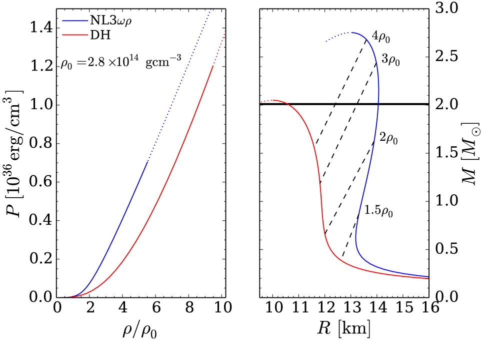
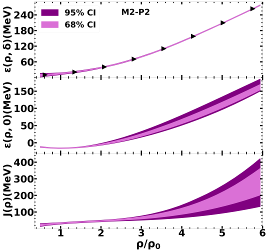
Probing the interior of Neutron Stars

- Neutrons stars provide a laboratory for testing
  - nuclear physics: high density, highly asymmetric matter
  - QCD: deconfinement, quark matter, superconducting phases
- mass-radius $\rightarrow$ equation of state $\rightarrow$ composition?





Sk Md Adil Imam et al PRC 105, 015806 (2022)
see also

- Tovar et al PRD 104 (2021)
- Mondal & Gulminelli PRD 105 (2022)
- Essick PRL 127 192701 (2021)

The possible scenario

- nucleon: Malik et al and B.K. Agrawal et al Astrophys.J. 930 (2022), Malik and B.K. Agrawal et al PRC Letter 106 (2022), Bikram Keshari Pradhan and Debarati Chatterjee et al Nucl.Phys.A 1030 (2023)
- hyperons: S. Weissenborn et al NPA 881 (2012), Micaela Oertel et al EPJA 52 (2016),Malik and Providência PRD 106 (2022)
- quark matter: Annala et al Nature Phys., 16, 907 (2020), Gorda et al arXiv:2212.10576 (2022)
- (anti) kaons: Banik et al. Phys.Rev.C 78 (2008), Char & Banik Phys. Rev. C 90(2014), Banik & Bandyopadhyay, Phys.Rev.C 64 (2001)
- dark matter
  - admixed: Arpan Das et al Phys.Rev.D 99 (2019), Violeta Sagun et al Phys.Rev.D 102 (2020)
  - two fluid: Arpan Das et al Phys.Rev.D 105 (2022), Violetta Sagun et al Phys.Rev.D 105 (2022)
- modified gravity: K. Nobleson et al JCAP 08 (2021)

Motivation

- According to the current knowledge of observational constraints on NS properties, it is impossible to determine the star's composition in a unique manner.
- In this context, it has been suggested that the study of the non-radial oscillation modes of NSs can have the possibility of providing the compositional information: This includes,
  - NS with Hyperon (*Dommes et al MNRS 455(3):2852–2870, 2016, Yu et al MNRS 464, 2622–2637, 2017, Pradhan et al PRC 103 035810, 2021*)
  - NSs with quarks and hadronic matter (*Sotani et al PRD 2011, Flores et al CQG 2014, Jaikumar et al PRD 2021*)
- This is because the non-radial oscillations depend not only upon the EOS but also on its derivatives.

Motivation for present study

- In most of these investigations, the hadronic matter description is through a parameterized form of nuclear matter EOS and the quark matter description is through a bag model or an improved version of the same.

- In the present investigation, for the nuclear matter sector we use a RMF theory. For the description of quark matter, we use a two-flavor Nambu–Jona-Lasinio (NJL) model where the parameters of the model are fixed from the physical variables like pion mass, pion decay constant, and light quark condensate that encodes the physics of the chiral symmetry breaking.

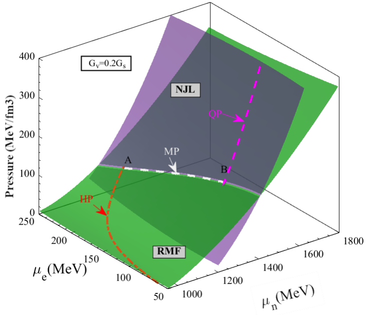
Hybrid stars and its quasi-normal modes

The hybrid equation of state (EOS)

The relativistic mean field (RMF) framework:

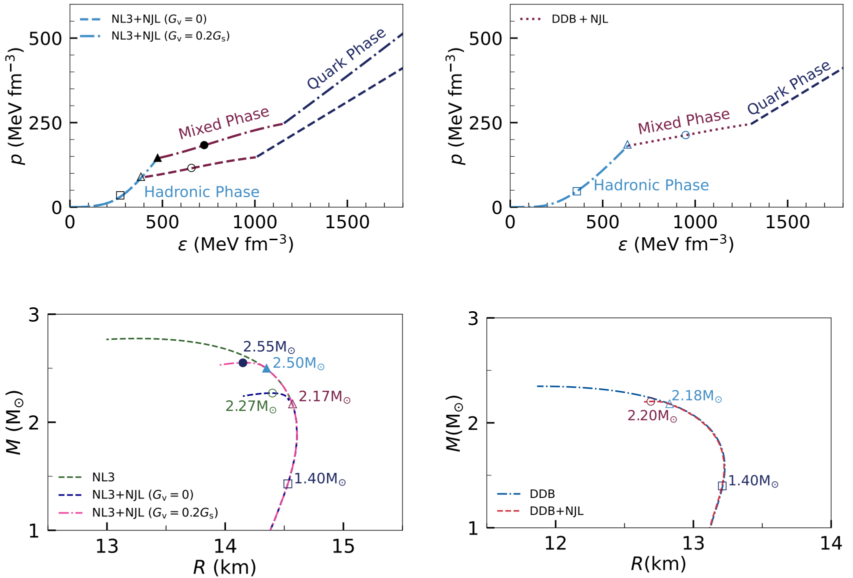
- Hadronic Phase (HP)
  - Linear model with density-dependent coupling (Malik et al Phys. Rev. D, 106(6) 063024, 2022)
  - Non-linear model with constant coupling. (G. A. Lalazissis, J. K¨onig, and P. Ring, Phys. Rev. C 55, 540 (1997))
- The quark phase (QP)
  - The Nambu–Jona -Lasinio (NJL) model with two flavors

Gibbs construction for mixed-phase (MP):



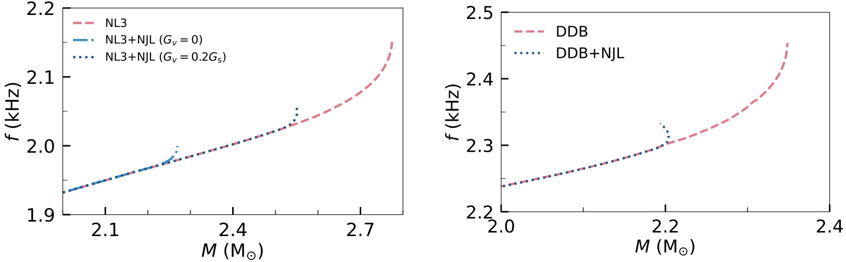
- The along the dashed portion on this line, the electrical charge neutrality is maintained.

The EOS and NS mass-radius:

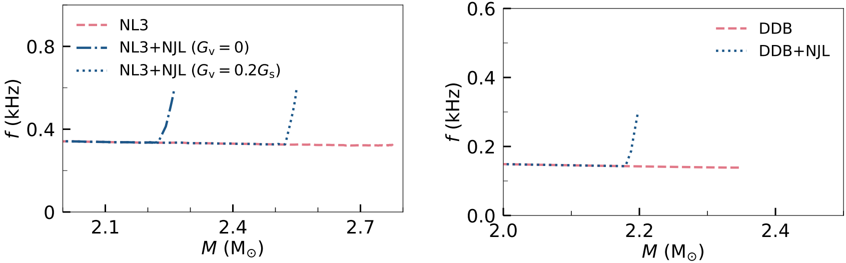


The *f* and *g* modes of oscillations:

f modes:



g modes:



Conclusion

- The EOS for hybrid stars (HS) is constructed using a RMF theory for nuclear matter and NJL model for quark matter, and the Gibbs criterion for mixed phase is used to impose the global charge neutrality condition.
- Unlike the M-R curves for which EOS is sufficient, the analysis of non-radial oscillation modes requires the speed of sound of the charge neutral matter, which shoots up at the transition between mixed phase and hadronic phase in HSs.
- Quark matter in a mixed phase with charge neutral nuclear matter enhances both quadruple fundamental modes and gravity modes. The effect is more significant for g modes than high-frequency f modes. Detecting g modes in BNS mergers with current detectors is challenging, but third-generation detectors may enable direct detection and provide conclusive insights into the composition of NS interiors.

Future work

- The effect of dark matter on these f and g can also be investigated in the two-fluid scenario.
- A detailed statistical calculation needs to be performed in order to distinguish evidence of different cases for future mock observations.

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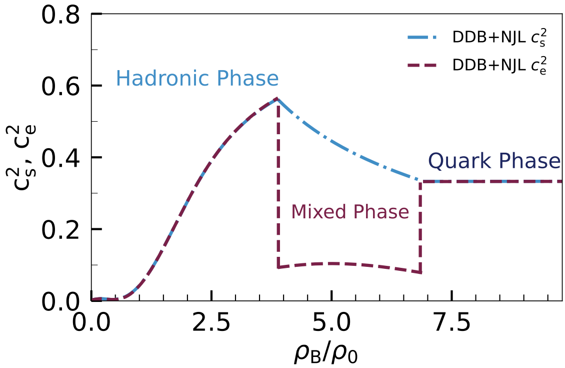
Thank you !!

Brunt-Väisäla frequency

The g mode oscillation frequencies are related to the Brunt-Väisäla frequency ($\omega_{\rm BV}$) which depends on the difference between the equilibrium sound speed (c_e^2) and adiabatic or the constant composition sound speed (c_s^2) i.e. $\omega_{\rm BV}^2 \propto (1/c_e^2 - 1/c_s^2)$



The characteristic time scale of the QNM is about 10^{-3} sec which is much smaller than the β-equilibrium time scale. Therefore, during the oscillations the composition of the matter can be assumed to be constant.