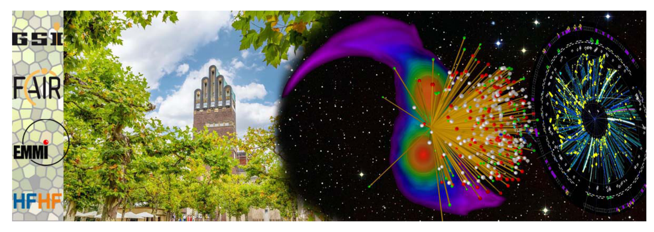
Robust universal relations in neutron star asteroseismology

arxiv:2306.09277 *(Accepted in Phys. Rev. D)*

Deepak Kumar, Tuhin Malik, Hiranmaya Mishra & Constança Providência
Department of Physics, IISER, Bhopal, India 462 066

CONTACT: *dpqraja02@gmail.com*



Abstract

We study the non-radial oscillation (NRO)s of neutron star (NS)s for a huge number of equation of state (EOS)s which satisfy nuclear saturation properties at saturation density and perturbative qunatum chromodynamics (pQCD) at asymptotically high densities. EOSs are constraint by the NS observations. We find some previously found universal relation (UR)s are not actually universal at all. We also found a new UR between NRO and radius of NS for a given mass.

Main objectives

1. To get an ensemble of EOSs which satisfy chiral effective field theory (CET) at low density and pQCD at asymptotically high density and thermodynamically consistent.
2. Constrain EOSs by NS observations like $M_\odot$, R, Λ, etc.
3. To check the robustness of previously found URs
4. To found a new UR between star's properties like mass, radius and NROs.

Introduction

NSs are the exciting cosmic laboratories to study the behaviour of matter at extreme densities. The current astrophysical observations lack behind to estimate most of the NSs macroscopic properties like its different modes of oscillations etc. So the universal relations play important roles to get macroscopic quantities which are not estimate till now in present experiments. Here we devise some universal relations relating mass, radius and non-radial oscillations on NSs. We use two types of relativistic mean field (RMF) models at low densities and pQCD at asymptotically high densities and piece-wise polytrope to interpolate in the intermediate densities. All EOSs are thermodynamically consistent and satisfy the gravitational wave (GW)s and Neutron star Interior Composition ExploreR (NICER) observations.

Mathematical section

Nuclear matter EOS at low density

The Lagrangian, including baryons (n and p) as the constituents of nuclear matter and mesons (σ, ω and ρ) as the carriers of interactions, is given as

$$\mathcal{L} = \bar{\Psi}\left[\gamma^\mu\left(i\partial_\mu - \Gamma_\omega A_\mu^{(\omega)} - \Gamma_\varrho \boldsymbol{\tau}\cdot\boldsymbol{A}_\mu^{(\varrho)}\right) - m\right]\Psi + \frac{1}{2}\left\{\partial_\mu\phi\partial^\mu\phi - m_\sigma^2\phi^2\right\} + \Gamma_\sigma\phi\bar{\Psi}\Psi - \frac{1}{4}F_{\mu\nu}^{(\omega)}F^{(\omega)\mu\nu} + \frac{1}{2}m_\omega^2 A_\mu^{(\omega)}A^{(\omega)\mu} - \frac{1}{4}\boldsymbol{F}_{\mu\nu}^{(\varrho)}\cdot\boldsymbol{F}^{(\varrho)\mu\nu} + \frac{1}{2}m_\varrho^2\boldsymbol{A}_\mu^{(\varrho)}\cdot\boldsymbol{A}^{(\varrho)\mu},$$

where $F^{(\omega,\varrho)\mu\nu} = \partial^\mu A^{(\omega,\varrho)\nu} - \partial^\nu A^{(\omega,\varrho)\mu}$ are meson field strength tensors. The $\Gamma_{\sigma,\omega,\varrho}$ are density-dependent coupling constants and given in Ref. Malik2021.

Perturbative QCD EOS at asymptotically high density

A simple fitting function for the pressure as a function of chemical potential (μ) given as

$$P_{\rm pQCD}(\mu) = \frac{\mu^4}{108\pi^2}\left(c_1 - \frac{d_1 X^{-\nu_1}}{(\mu/\mathrm{GeV}) - d_2 X^{-\nu_2}}\right)$$

where the parameters are $c_1 = 0.9008$, $d_1 = 0.5034$, $d_2 = 1.452$, $\nu_1 = 0.3553$ and $\nu_2 = 0.9101$ Ref. Fraga2013.

Piece-wise polytrope EOS at intermediate densities

The intermediate densities region is interpolated with piece-wise polytrope.

$$p_i = \kappa_i \rho^{\gamma_i}$$

The resulted EOS need to be consistent with thermodynamics.

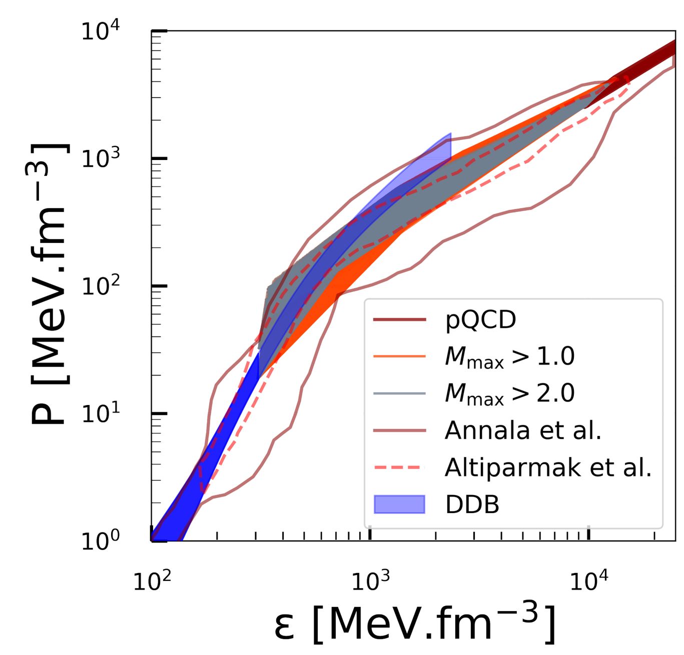


Figure 1: The cloud of EOSs.

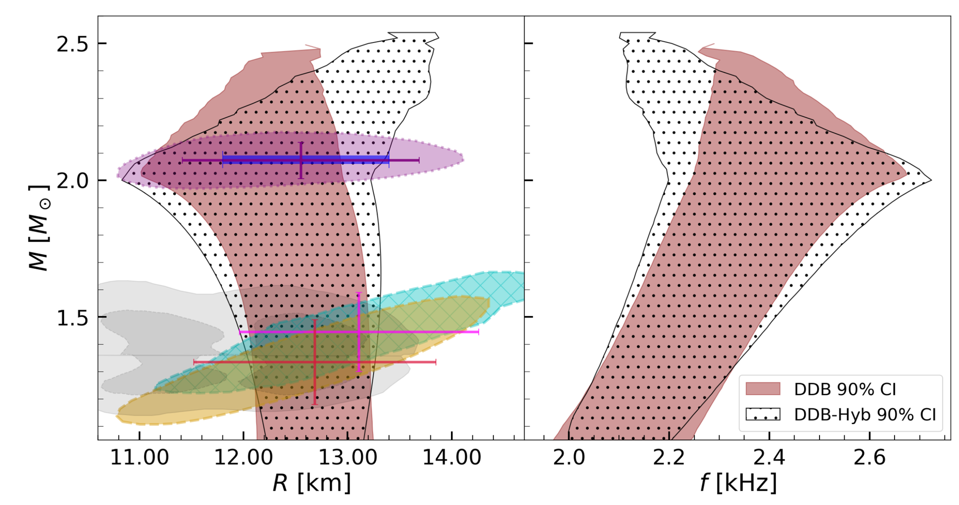


Figure 2: MR and FM clouds.

Pulsating equations

The equations governing NROs of fluid comprising neutron star matter (NSM) and the boundary condition at the surface of NS are given as

$$W' = \frac{d\epsilon}{dP}\left(\omega^2 r^2 e^{\Lambda-2\Phi}V + W\Phi'\right) - l(l+1)e^\Lambda V, \qquad V' = 2V\Phi' - \frac{1}{r^2}We^\Lambda, \qquad \omega^2 r^2 e^{\Lambda-2\Phi}V + W\Phi' = 0.$$

Results

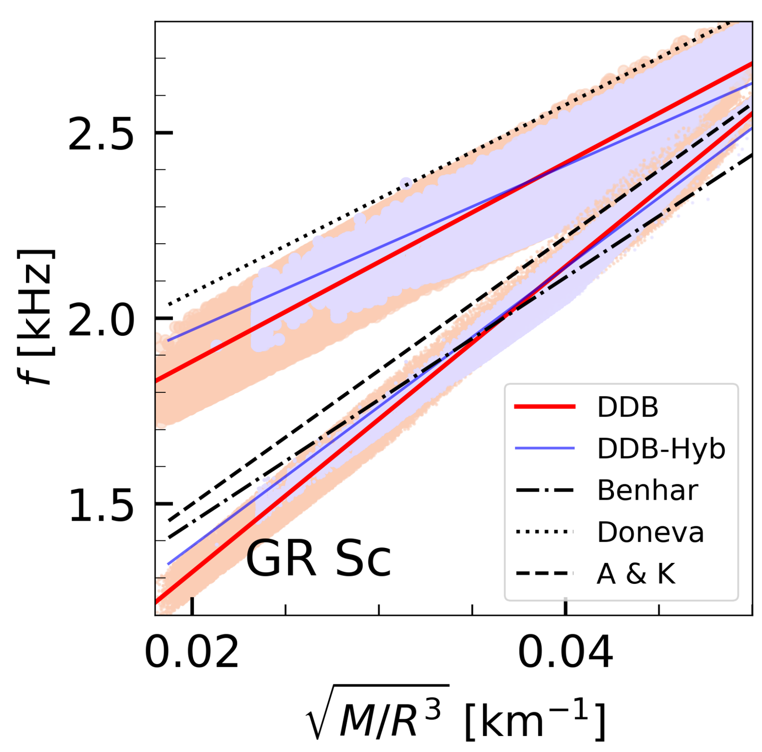


Figure 3: UR1 := $f = a\sqrt{(M/R^3)} + b$ where $a = 22.27 \pm 0.023$ (26.76 ± 0.01) kHz.km, $b = 1.520 \pm 0.001$ (1.348 ± 0.001) kHz for DDB-Hyb (DDB) set.

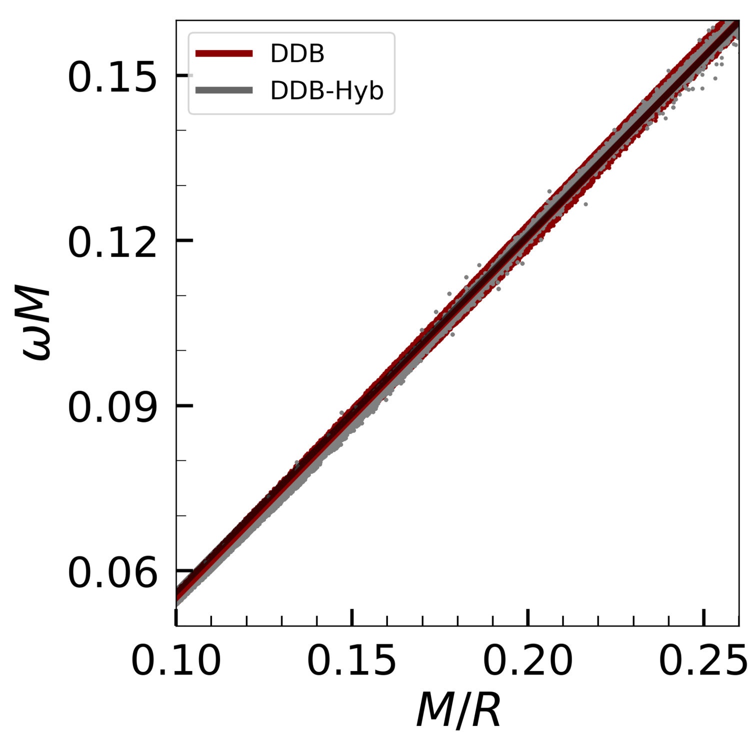


Figure 4: UR2 := $\omega M = a\left(\frac{M}{R}\right) + b$ where $a = 0.6474 \pm 4.6 \times 10^{-5}$ $(a = 0.6549 \pm 2.6 \times 10^{-5})$ and $b = -0.0085 \pm 1.05 \times 10^{-5}$ $(b = -0.0103 \pm 6.18 \times 10^{-6})$ for DDB-Hyb (DDB) set.

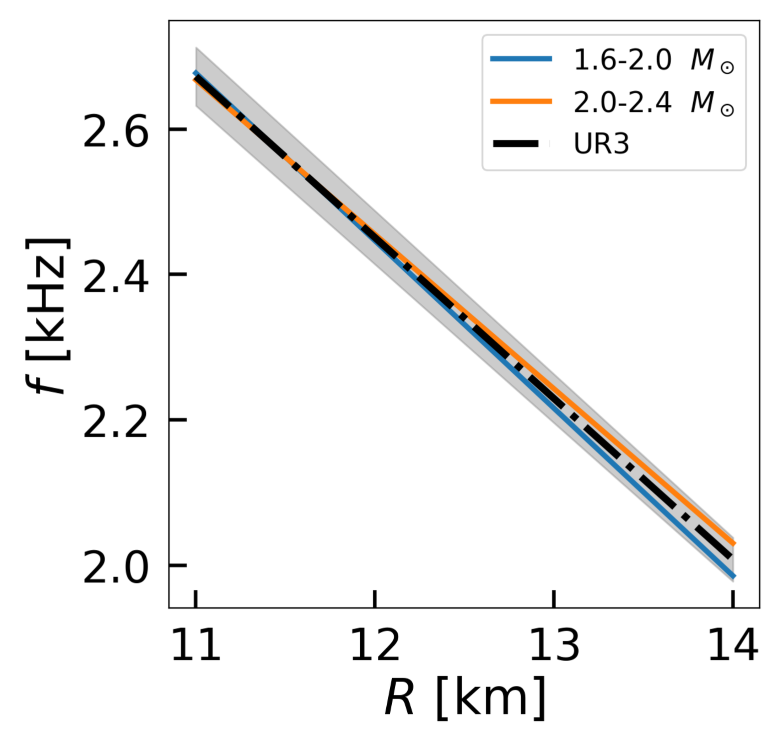


Figure 5: UR3 := linear relation between f mode frequency and NS radius R. The values of slope $m \in [-0.23, -0.21]$ and intercept $c \in [5.21, 5.0]$.

Conclusions

We find UR1 is nolonger universal and re-estimate constants present in UR2. We also find a new universal relation UR3 in between NRO f mode frequencies and radius of NSs within our models (DDB and DDB-Hyb).

Forthcoming research

I am working on rotating structure of NSs and try to constraint EOS further using the rotation frequency of NS.