Constraints on Dense Matter Equation of State from GW170817: Possibility of Different Families of Compact Stars

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MODE-SNR-PWN 2019

April 9, 2019

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Equations of State of Dense Matter from Nuclear Physics

Difficulties

- Constituents are not known.
- Interaction between constituents are not fully known.
- Uncertainties in the many-body description.

$\Rightarrow$ EOS is model dependent.

Phenomenological approaches are most popular

- Based on effective Interaction.
  1. Non-relativistic Skyrme-Interaction ($\sim$ 240)
  2. Relativistic Mean Field (RMF) models ($\sim$ 270)

Dutra et al. PRC 85, 035201 (2012); Dutra et al. PRC 90, 055203 (2014);

Oertel et al. RMP 89, 015007 (2017)

Constraining EOS from Neutron Star Observations

- Given an EOS, all the global properties M, R, I etc. can be calculated.
- Need precise determination of both M and R for a few NS.
- First major astrophysical constraint comes from the precise mass measurement of two massive NS:
  $(1.928 \pm 0.017) M_\odot$ Fonseca et al, ApJ 832, 167 (2016)
  $(2.01 \pm 0.04) M_\odot$ Antoniadis et al, Science 340, 448 (2013).
- Another significant constraint is given by GW170817 by measuring tidal deformability (Λ), an EOS-dependent quantity (LVC, PRL 119, 161101 (2017):

$$\tilde{\Lambda} \leq 800 \qquad \Lambda_{1.4} \leq 800$$

$$\tilde{\Lambda} = \frac{16}{13} \frac{(M_1 + 12 M_2) M_1^4}{(M_1 + M_2)^5} \Lambda_1 + (1 \leftrightarrow 2), \qquad \Lambda = \lambda / M^5, \qquad \lambda = \frac{2}{3} k_2 R^5$$

Several studies have been performed to constrain the EOS

- Upper bound on $R_{1.4}$:

  $R_{1.4} \leq 13.6$ km, Annala et al, PRL 120, 172703 (2018)
  $R_{1.4} \leq 13.8$ km, Fattoyev et al, PRL 120, 172702 (2018)
  $R_{1.4} \leq 13.5$ km, Nandi & Char, ApJ 857, 12 (2018)
  $R_{1.4} \leq 13.5$ km, Most et al, PRL 120, 261103 (2018)

- Lower bound on Λ :

  $\tilde{\Lambda} > 400$, Radice et al, ApJL 852, 29L (2018)

- Upper bound on $M_{\rm max}$:

  $M_{\rm max} \lesssim 2.17 M_\odot$ Margalit & Metzger, ApJL 850, L19 (2017)
  $M_{\rm max} \lesssim 2.16^{+0.17}_{-0.15} M_\odot$, Rezzolla et al, ApJL 852, L25 (2018)
  $M_{\rm max} \lesssim 2.16 - 2.28 M_\odot$, Ruiz et al, PRD 97, 021501 (2018)
  $M_{\rm max} \lesssim 2.15 - 2.25 M_\odot$, Shibata et al, PRD 96, 123012 (2018).

$\Rightarrow$ rule out very stiff and very soft EOS.

Latest from GW

Reanalysis of GW170817 data gives new bounds:

$$\Lambda_{1.4} = 190^{+390}_{-120}, \quad \Rightarrow \qquad \Lambda_{1.4} \leq 580$$

$$P(2n_0) \quad = \quad 3.5^{+2.7}_{-1.7} \times 10^{34}\,\mathrm{dyne/cm^2}$$

LVC, PRL 121, 161101 (2018)

Consequences ?

RMF model

- Interaction between baryons is described via exchange of mesons.
- The most general form of the interaction Lagrangian density:

$$
\begin{aligned}
\mathcal{L}_{\rm int} \;\; = \;\; & \sum_B \bar{\psi}_B \left[g_\sigma \sigma + g_\delta \boldsymbol{\tau} \cdot \boldsymbol{\delta} - \gamma^\mu \left(g_\omega \omega_\mu + \frac{1}{2} g_\rho \boldsymbol{\tau} \cdot \boldsymbol{\rho_\mu} + \frac{e}{2}(1+\tau_3) A_\mu \right) \right] \psi_B \\
& - \frac{\kappa}{3!}(g_\sigma \sigma)^3 - \frac{\lambda}{4!}(g_\sigma \sigma)^4 + \frac{\zeta}{4!}(g_\omega^2 \omega_\mu \omega^\mu)^2 \\
& + g_\sigma g_\omega^2 \sigma \omega_\mu \omega^\mu \left(\alpha_1 + \frac{1}{2} \alpha_1' g_\sigma \sigma \right) + g_\sigma g_\rho^2 \sigma \boldsymbol{\rho_\mu} \cdot \boldsymbol{\rho^\mu} \left(\alpha_2 + \frac{1}{2} \alpha_2' g_\sigma \sigma \right) \\
& + \frac{1}{2} \alpha_3' g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \boldsymbol{\rho_\mu} \cdot \boldsymbol{\rho^\mu}
\end{aligned}
$$

σ, ω_μ, $\boldsymbol{\rho}_\mu$ and $\boldsymbol{\delta}$ are meson fields.

- For density dependent (DD) models coupling parameters g_σ, g_ω, g_ρ and g_δ are density dependent and don't have nonlinear terms.

Based on the form of interaction Lagrangian density we group the models in several classes:

Name	Type of interaction for mesons
NL	σ SI
S271	σ SI + (ω, ρ) CC
NL3 family	σ SI + (σ, ρ) or (ω, ρ) CC
FSU family	σ SI + ω SI + (ω, ρ) CC
Z271 family	σ SI + ω SI + (σ, ρ) or (ω, ρ) CC
BSR family	σ SI + all possible (σ, ω), (σ, ρ) and (ω, ρ) CCs
BSR* family	σ SI + ω SI + all possible (σ, ω), (σ, ρ) and (ω, ρ) CCs
DD	density-dependent couplings

SI = self-interaction, CC=cross-coupling

Saturation properties of nuclear matter

Paremeters are obtained by fitting to the saturation properties of nuclear matter:

- Binding energy: $E/A \simeq -16$ MeV.
- Saturation density: $\rho_0 \simeq 0.16$ fm^{-3}
- Effective mass of nucleons: ~ 0.7
- Compressibility: $K = 210 - 280$ MeV
- Symmetry energy: $J = 28 - 35$ MeV.
- Symmetry energy slope : $L = 30 - 87$ MeV

$\Rightarrow$ 67 out of 269 RMF parameter sets satisfy these bounds.

R. Nandi, P.C., S. Pal; arXiv:1809.07108

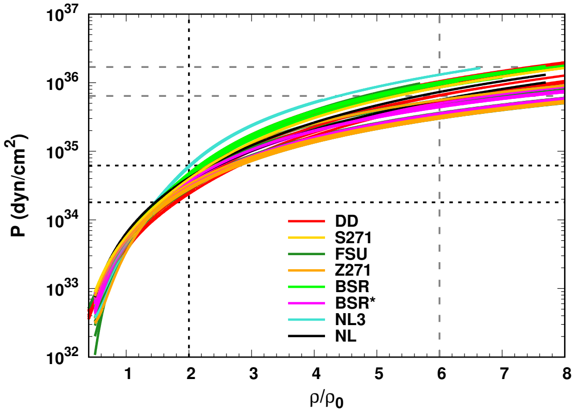


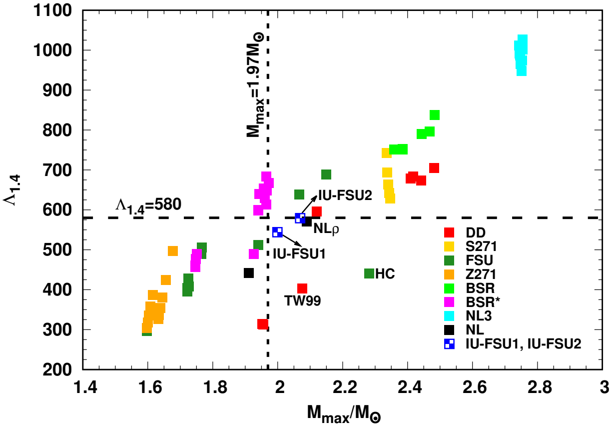
Figure: Pressure vs normalized baryon density for 67 RMF parameter sets

GW170817 bounds

$$P(2n_0) = 3.5^{+2.7}_{-1.7} \times 10^{34}\ \mathrm{dyn/cm}^2, \quad P(6n_0) = 9.0^{+2.6}_{-7.9} \times 10^{35}\ \mathrm{dyn/cm}^2$$

$\Rightarrow$ All EOS satisfy the $P(2n_0)$ constraint.

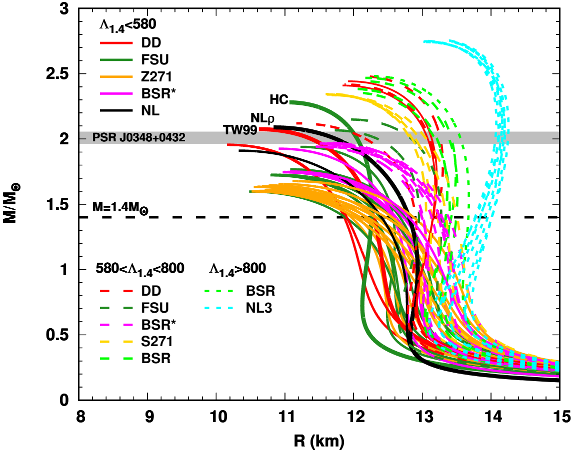
R. Nandi, P.C., S. Pal; arXiv:1809.07108



$M_{\rm max}$ constraint	GW170817 bound
$M_{\rm max} = 2.01 \pm 0.04 M_{\odot}$	$\Lambda_{1.4} = 190^{+390}_{-120}$
i.e. $M_{\rm max} \geq 1.97 M_{\odot}$	$\Lambda_{1.4} \leq 580$

$\Rightarrow$ Only 3 EOS (TW99, NLρ and HC) satisfy both the constraints

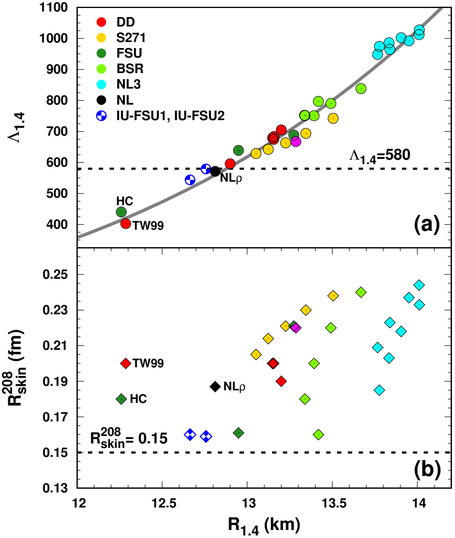
M-R Diagram



$\Rightarrow R_{1.4} < 12.9$ km

R. Nandi, P.C., S. Pal; arXiv:1809.07108

Neutron skin thickness



R. Nandi, P.C., S. Pal; arXiv:1809.07108

$R_{1.4} \lesssim 12.9$ km,
$R^{208}_{\rm skin} \lesssim 0.20$ fm

$R_{\rm skin} = \langle r_n \rangle - \langle r_p \rangle$
$R^{208}_{\rm skin} = 0.33^{+0.16}_{-0.18}$ fm
PREX, PRL108, 112502(2012)

Including hyperons

R. Nandi, P.C., S. Pal; arXiv:1809.07108

Model	$M_{\mathrm{max}}/M_{\odot}$	$R_{1.4}$(km)	$n_{1.4}$(fm^{-3})	n_{th}(fm^{-3})	$\Lambda_{1.4}$
S271v6	2.35	13.05	0.375		626
with Hyperons	1.89	13.05	0.375	0.376	
BSR3	2.36	13.40	0.348		747
with Hyperons	1.90	13.39	0.355	0.336	
DD2	2.42	13.160	0.353		683
with Hyperons	2.10	13.156	0.361	0.331	681

Hyperon-meson couplings are obtianed from SU(6) model and considering $U_{\Lambda}^{(N)} = -28$ MeV, $U_{\Sigma}^{(N)} = 30$ MeV and $U_{\Xi}^{(N)} = -18$ MeV.

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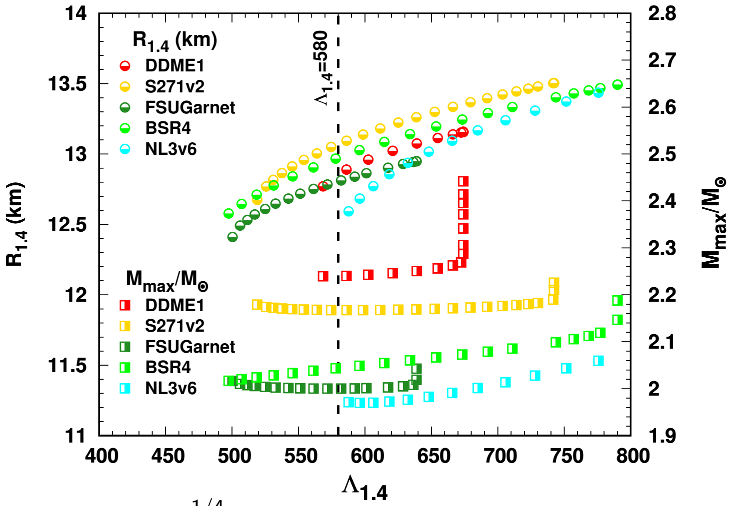
$\Rightarrow$ Hyperons don't help

Mixed phase with quarks



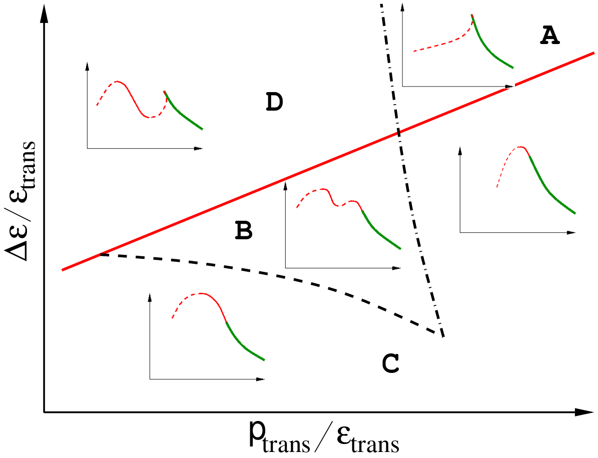
$B_{\mathrm{eff}}^{1/4}$ increases from left to right

R. Nandi, P.C., S. Pal; arXiv:1809.07108

Quarks are important

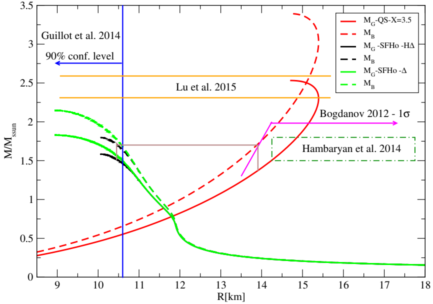
- PREX2 will be soon in operation and expected to reduce the uncertainty of $R_{\rm skin}$ of ^{208}Pb to 0.06 fm.
- If $R_{\rm skin}$ is on the larger side, quark description seems inevitable for RMF.

Hybrid Stars with Twins



Alford et al., PRD 92 (2015) 083002

Two-Families Scenario

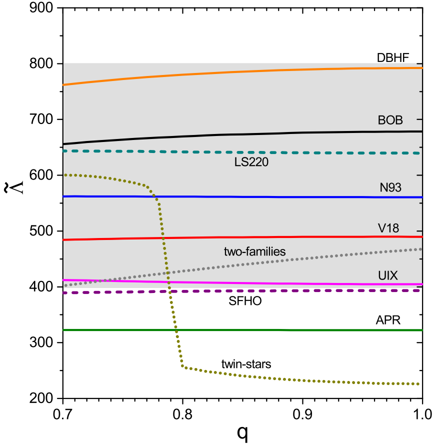


Drago et al., Eur.Phys.J. A52 (2016) 40

Main hypothesis:

- The ground state of nuclear matter is strange quark matter.
- Hadronic stars are metastable and under specific conditions, they convert into a strange quark star.
- Hadronic star and quark star would populate two separate branches.
- The heavier stars are the strange quark stars.

Tidal deformability and compact star families



- One can pick the heavier star from the quark family and the other from the hadronic family.
- Non-negligible dependence found for both two-famliy and twin-star scenario.

Burgio et al. ApJ. 860 (2018) 139

Summary

- We have performed extensive analysis of RMF models in the light of latest observational results
- Out of 269 parameter set analyzed, only a few satisfies both the tidal deformability and maximum mass constraints.
- If PREXII gives high value of R_{skin}, quarks inside may be the only possibility.
- Incorporating quarks lead to several families of compact objects.
- Further BNS observations, results from NICER will provide stricter constraints on radius thus discriminating between these models.

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Thank You