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

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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:
  
  $$(1.928 \pm 0.017)M_\odot \quad \text{Fonseca et al, ApJ 832, 167 (2016)}$$
  $$(2.01 \pm 0.04)M_\odot \quad \text{Antoniadis et al, Science 340, 448 (2013)}.$$ 

- Another significant constraint is given by GW170817 by measuring tidal deformability ($\Lambda$), an EOS-dependent quantity (LVC, PRL 119, 161101 (2017)):
  
  $$\tilde{\Lambda} \leq 800 \quad \Lambda_{1.4} \leq 800$$

  $$\tilde{\Lambda} = \frac{16}{13} \frac{(M_1 + 12M_2)M_1^4}{(M_1 + M_2)^5} \Lambda_1 + (1 \leftrightarrow 2), \quad \Lambda = \lambda/M^5, \quad \lambda = \frac{2}{3} k_2 R^5$$
Several studies have been performed to constrain the EOS

- **Upper bound on** \( R_{1.4} \):

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

- **Lower bound on** \( \Lambda \):

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

- **Upper bound on** \( M_{\text{max}} \):

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

⇒ rule out very stiff and very soft EOS.
Latest from GW

Reanalysis of GW170817 data gives new bounds:

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

\[ P(2n_0) = 3.5^{+2.7}_{-1.7} \times 10^{34} \text{ dyne/cm}^2 \]

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:

\[ \mathcal{L}_{\text{int}} = \sum_B \bar{\psi}_B \left[ g_\sigma \sigma + g_\delta \tau \cdot \delta - \gamma^\mu \left( g_\omega \omega_\mu + \frac{1}{2} g_\rho \tau \cdot \rho_\mu + \frac{e}{2} (1 + \tau_3) A_\mu \right) \right] \psi_B \]

\[ \quad - \frac{\kappa}{3!} (g_\sigma \sigma)^3 - \frac{\lambda}{4!} (g_\sigma \sigma)^4 + \frac{\zeta}{4!} (g_\omega^2 \omega_\mu \omega^\mu)^2 \]

\[ \quad + g_\sigma g_\omega^2 \sigma \omega_\mu \omega^\mu \left( \alpha_1 + \frac{1}{2} \alpha'_1 g_\sigma \sigma \right) + g_\sigma g_\rho^2 \sigma \rho_\mu \cdot \rho^\mu \left( \alpha_2 + \frac{1}{2} \alpha'_2 g_\sigma \sigma \right) \]

\[ \quad + \frac{1}{2} \alpha'_3 g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \rho_\mu \cdot \rho^\mu \]

\( \sigma, \omega_\mu, \rho_\mu \) and \( \delta \) are meson fields.

- For density dependent (DD) models coupling parameters \( g_\sigma, g_\omega, g_\rho \) and \( g_\delta \) are density dependent and don’t have nonlinear terms.
Based on the form of interaction Lagrangian density we group the models in several classes:

<table>
<thead>
<tr>
<th>Name</th>
<th>Type of interaction for mesons</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>$\sigma$ SI</td>
</tr>
<tr>
<td>S271 family</td>
<td>$\sigma$ SI + $(\omega, \rho)$ CC</td>
</tr>
<tr>
<td>NL3 family</td>
<td>$\sigma$ SI + $(\sigma, \rho)$ or $(\omega, \rho)$ CC</td>
</tr>
<tr>
<td>FSU family</td>
<td>$\sigma$ SI + $\omega$ SI + $(\omega, \rho)$ CC</td>
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<tr>
<td>Z271 family</td>
<td>$\sigma$ SI + $\omega$ SI + $(\sigma, \rho)$ or $(\omega, \rho)$ CC</td>
</tr>
<tr>
<td>BSR family</td>
<td>$\sigma$ SI + all possible $(\sigma, \omega)$, $(\sigma, \rho)$ and $(\omega, \rho)$ CCs</td>
</tr>
<tr>
<td>BSR* family</td>
<td>$\sigma$ SI + $\omega$ SI + all possible $(\sigma, \omega)$, $(\sigma, \rho)$ and $(\omega, \rho)$ CCs</td>
</tr>
<tr>
<td>DD</td>
<td>density-dependent couplings</td>
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SI = self-interaction, CC = cross-coupling
Saturation properties of nuclear matter

Parameters 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: $\sim 0.7$
- 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**

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

⇒ All EOS satisfy the \( P(2n_0) \) constraint.
\[ \frac{M_{\text{max}}}{M_\odot} \text{ constraint} \]

\[ M_{\text{max}} = 2.01 \pm 0.04 M_\odot \]

i.e. \[ M_{\text{max}} \geq 1.97 M_\odot \]

GW170817 bound

\[ \Lambda_{1.4} = 190^{+390}_{-120} \]

\[ \Lambda_{1.4} \leq 580 \]

\[ \Rightarrow \text{ Only 3 EOS (TW99, NL}_\rho\text{ and HC) satisfy both the constraints} \]
$\Rightarrow R_{1.4} < 12.9$ km
Neutron skin thickness

\[ R_{1.4} \lesssim 12.9 \text{ km}, \]
\[ R_{208}^{\text{skin}} \lesssim 0.20 \text{ fm} \]

\[ R_{\text{skin}} = < r_n > - < r_p > \]
\[ R_{\text{skin}}^{208} = 0.33^{+0.16}_{-0.18} \text{ fm} \]

PREX, PRL108, 112502(2012)

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

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<th>$M_{\text{max}}/M_\odot$</th>
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Hyperon-meson couplings are obtained from SU(6) model and considering $U_\Lambda^{(N)} = -28\,\text{MeV}$, $U_\Sigma^{(N)} = 30\,\text{MeV}$ and $U_\Xi^{(N)} = -18\,\text{MeV}$. 
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$\Rightarrow$ Hyperons don’t help
Mixed phase with quarks

\[ B_{\text{eff}}^{1/4} \] increases from left to right

\( R_{1.4} \) (km)

\( \Lambda_{1.4} = 580 \)

\( B_{\text{eff}}^{1/4} \) increases from left to right

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Dense Matter EoS

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Quarks are important

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

Alford et al., PRD 92 (2015) 083002
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-family and twin-star scenario.

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 $R_{\text{skin}}$, 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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