Constraining the nuclear matter EoS from the GW170817 merger event

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Outline

- Neutron star
- EOS
- constraints from NS observations
- Results
- Conclusion
Neutron stars

Structure of Neutron stars

Highly relativistic objects

Typical mass: $1 - 2 \, M_\odot$

Radius: $10 - 14 \, \text{km}$

Average density: $\approx 3 \times 10^{14} \, \text{g/cm}^3$

Spin period: $\approx (0.2 - 2) \, \text{s}$
A large set of possible EoS (nucleons, hyperons, quark matter, etc...)
The construction of the EoS: two possible philosophies

**Phenomenological approaches**

Based on effective density-dependent NN force with parameters fitted on nuclei properties.

- **Liquid Drop models**
  - BBP Baym et al., NPA 175, 225 (1971)
  - LS Lattimer&Swesty, NPA 535, 331 (1991)
- **TF + RMF**
  - Shen et al., NPA 637, 435 (1998)
- **ETFSI + Eff. Skyrme force**
  - BSk Goriely et al., PRC 82, 035804 (2010)
- **Hartree-Fock**
  - NV Negele&Vautherin, NPA 207, 298 (1973)
  - RHF Boussy et al., PRL 55, 1731 (1985)
  - QMC Guichon et al., NPA 814, 66 (2008)
- **Statistical models**
  - NSE Raduta&Gulminelli, PRC 82, 065801 (2010)
  - HS Hempel&Schaffner-Bielich, NPA 837, 210 (2010)

**Ab initio approaches**

The nuclear problem is solved starting from the two- and three-body realistic nucleon interaction.

- **Diagrammatic**
  - BBG Day, RMP 39, 719 (1967)
  - SCGF Kadanoff&Baym, Quantum Statistical Mechanics (1962)
- **Variational**
  - APR Akmal et al., PRC 58, 1804 (1998)
  - CBF Fabrocini&Fantoni, PLB 298, 263 (1993)
  - LOCV Owen et al., NPA 277, 45 (1978)
- **Monte Carlo**
  - VMC Wiringa, PRC43, 1585 (1991)
  - AFDMC Schmidt&Fantoni, PLB446, 99 (1999)
- **Renormalization Group method**
  - $V_{\text{low-}}$k Bogner et al., PR 286, 1 (2003)
GW170817/AT2017gfo

**GW170817** Abbott et al., PRL 119, 161101 (2017)

- chirp mass : $M_c = 1.188M_\odot$
  - mass ratio : $m_2/m_1 = 0.7-1.0$
    - primary mass $m_1 = 1.36-1.6M_\odot$
    - secondary mass $m_2 = 1.17-1.36M_\odot$
- tidal deformability : $\Lambda_{1.4} < 800$
- effective tidal deformability

$$\tilde{\Lambda} = \frac{16}{13} \frac{(M_1 + 12M_2)M_1^4}{(M_1 + M_2)^5} \Lambda_1 + (1 \leftrightarrow 2) \lesssim 800$$

arXiv:1805.11579: $70 < \tilde{\Lambda} < 720$
GW170817/AT2017gfo

**AT2017gfo**

E. Pian et al., Nature 551, 67 (2017)

Constraints from GW170817: the kilonova signal AT2017gfo

\[ \tilde{\Lambda} = \frac{16}{13} \frac{(M_1 + 12 M_2) M_1^4}{(M_1 + M_2)^5} \Lambda_1 + (1 \leftrightarrow 2) \]

\[ \tilde{\Lambda} > 400 \]
Formalism

- Tidal deformability

\[ \Lambda = \frac{2\beta^5}{3k_2} \]

- Love number \( k_2 \)

\[
\frac{dy}{dr} = - \frac{y^2}{r} - \frac{y - 6}{r - 2Gm/c^2} - rQ,
\]

\[
Q = \frac{4\pi G}{c^4} \left( \frac{(5 - y)\epsilon + (9 + y)p + (\epsilon + p)/c_s^2}{1 - 2Gm/c^2 r} \right) - \left[ \frac{2G(m + 4\pi pr^3/c^2)}{r(r^2 - 2Gm)} \right]^2,
\]

\[
k_2 = \frac{8}{5} \beta^5 (1 - 2\beta)^2 \left[ 2 - y_R + 2\beta(y_R - 1) \right] / \mathcal{R}
\]

\[
\mathcal{R} = 6\beta(2 - y_R + \beta(5y_R - 8)) + 4\beta^3 \left[ 13 - 11y_R + \beta(3y_R - 2) + 2\beta^2(1 + y_R) \right] + 3(1 - 2\beta)^2 \left[ 2 - y_R + 2\beta(y_R - 1) \right] \ln(1 - 2\beta),
\]

Boundary condition:

\[
(p, m, \omega, y)(r = 0) = (p_c, 0, 0, 2) \quad \omega_R = \omega(R), y_R = y(R).
\]

The tidal deformability depends on the compactness, hence on the EOS.
R-M relation

- Microscopic non-relativistic EoS: BHF with Bonn B, V18, N93, UIX
- Variational: APR
- Microscopic relativistic EoS: DBHF
- Microscopic EoS with hyperons: BOB(N+Y), V18(N+Y)
- Phenomenological EoS: LS220, SFHO
- All give maximum masses above 2M⊙ except the ones with hyperons.

\[ 400 < \Lambda_{1.365} < 800 \]

\[ 12 \text{ km} \lesssim R_{1.5} \lesssim 13 \text{ km} \]
Are small radii ruled out by GW170817/AT2017gfo?

Also Ozel&Freire, Ann.Rev. Astron.Astroph. 54 (2016)401  \( R=(9.9-11.2)\) km

S. Guillot, Mem. S. A. It. 87, 521 (2016).  
\( R=(9.2-11.5) \) km

Thermonuclear bursts

If small-radius NS exist, how do they fulfill the constraint of GW170817/AT2017gfo?
Binary system

❖ Three scenarios

- chirp mass : $M_c = 1.188 M_\odot$
- mass ratio $q : m_2/m_1 = 0.7 - 1.0$

<table>
<thead>
<tr>
<th>m1</th>
<th>m2</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-family</td>
<td>Hadronic star(N93...)</td>
</tr>
<tr>
<td>Two-family</td>
<td>Quark star(QSM)</td>
</tr>
<tr>
<td>Twin-stars</td>
<td>Hybrid star(DBHF+CS)</td>
</tr>
</tbody>
</table>
Binary system

One-family scenario: \( \tilde{\Lambda} \) almost independent on \( q \)

Two-families and twin-stars scenario: non negligible dependence on \( q \)

Twin-stars: large difference in the radii of the two components \((R_1, R_2) = (10.7, 13.0) \text{ km}\)
GW170817 has to be interpreted as a “mixed case”: one of the objects is made only of hadrons and the other contains deconfined quarks.

One-family-scenario: monotonic correlation between R1.5 and $\tilde{\Lambda}$. All EoS with $\tilde{\Lambda} > 400$ have R1.5 > 11.8 km, except APR and SFHO.

Two-families and twin-stars scenarios: R1.5 < 11.8 km are possible with $\tilde{\Lambda} > 400$. 

Correlations between $\Lambda$ and R$_{1.5}$
GW170817 event has added more constraints.

- GW170817 in the one-family scenario is compatible with the merging of two nucleonic neutron stars with a microscopic EoS, $M > 2M_0$ and $12 < R < 13$ km.

- The lower limit on the tidal deformability is compatible with radii of compact stars smaller than 12 km, if one assumes a population of compact stars not made by one-family only.
Thank you!