Probing the Neutron Star Radius with Gravitational Wave Events

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GW170817 Overview

Image credit: LVC
GW170817 Overview

- BNS located at ~40 Mpc
- Individual component masses highly correlated
- Chirp mass \( \mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \) well constrained

### Low-spin prior (\( \chi \leq 0.05 \))

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary inclination ( \theta_{JN} )</td>
<td>146(^{+25}_{-27}) deg</td>
</tr>
<tr>
<td>Binary inclination ( \theta_{JN} ) using EM distance constraint [108]</td>
<td>151(^{+15}_{-11}) deg</td>
</tr>
<tr>
<td>Detector-frame chirp mass ( \mathcal{M}^{\text{det}} )</td>
<td>1.1975(^{+0.0001}<em>{-0.0001}) (M</em>\odot)</td>
</tr>
<tr>
<td>Chirp mass ( \mathcal{M} )</td>
<td>1.186(^{+0.001}<em>{-0.001}) (M</em>\odot)</td>
</tr>
<tr>
<td>Primary mass ( m_1 )</td>
<td>(1.36, 1.60) (M_\odot)</td>
</tr>
<tr>
<td>Secondary mass ( m_2 )</td>
<td>(1.16, 1.36) (M_\odot)</td>
</tr>
<tr>
<td>Total mass ( m )</td>
<td>2.73(^{+0.04}<em>{-0.01}) (M</em>\odot)</td>
</tr>
<tr>
<td>Mass ratio ( q )</td>
<td>(0.73, 1.00)</td>
</tr>
<tr>
<td>Effective spin ( \chi_{\text{eff}} )</td>
<td>0.00(^{+0.02}_{-0.01})</td>
</tr>
<tr>
<td>Primary dimensionless spin ( \chi_1 )</td>
<td>(0.00, 0.04)</td>
</tr>
<tr>
<td>Secondary dimensionless spin ( \chi_2 )</td>
<td>(0.00, 0.04)</td>
</tr>
<tr>
<td>Tidal deformability ( \tilde{\alpha} ) with flat prior</td>
<td>300(^{+500}<em>{-190}) (symmetric)/300(^{+420}</em>{-230}) (HPD)</td>
</tr>
</tbody>
</table>
Quadrupolar response to the tidal potential of a binary companion

\[ \Lambda_{1.4} = 58 \]
\[ R = 9.0 \text{ km} \]
Measuring the tidal deformability

Tidal bulge in the star produces a shifted gravitational signature

Read et al. 2009
What is actually measured:

**Effective tidal deformability of the binary system**

\[
\tilde{\Lambda} = \frac{16}{13} \left( m_1 + 12m_2 \right) m_1^4 \Lambda_1 + \left( m_2 + 12m_1 \right) m_2^4 \Lambda_2 \left( m_1 + m_2 \right)^5
\]

\( \Lambda_1, \Lambda_2 \) depend on \((M/R)\) and the EOS

Expectation:

\( \tilde{\Lambda} \) measures a mass-weighted average of \((M/R)\) and the EOS
Tidal deformability from GW170817

Connecting tidal deformability to stellar radius


$\Lambda$ no longer depends on individual component masses when $M_c$ is fixed.
New universal relation between $\tilde{\Lambda}$ and stellar radius

Raithel, Özel, and Psaltis (2018); Raithel (2019).
X-ray measurements of the NS radius

**Quiescent LMXBs**

- M13
- M28
- M30
- NGC 6304
- NGC 6397
- ω Cen
- 47 Tuc X5
- 47 Tuc X7

**Thermonuclear bursters**

- 4U 1820-30
- SAX J1748.9-2021
- EXO 1745-248
- KS 1731-260
- 4U 1724-207
- 4U 1608-52

Özel & Friere 2016
Neutron star radii from GW and X-ray measurements

\[
P(R) = P(\tilde{\Lambda}) \left| \frac{\partial \tilde{\Lambda}}{\partial R} \right|
\]

\( R = 9.8 - 13.2 \text{ km} \) (90% HPD interval)

See also De et al. 2018; Zhao & Lattimer 2018 for similar results, with different set of assumptions

Raithel 2019.
Caveat for the $\tilde{\Lambda}$ - radius relationship

- $\tilde{\Lambda}$ depends more strongly on component masses for EOS with a phase transition
EOS constraints from stellar radii and GW170817

Radius constraints

Özel & Freire 2016 \((1/e)\)
Steiner, Lattimer, and Brown (68%)

GW170817 constraints

LIGO-Virgo Collaboration (90%)
Landry & Essick 2018 (loose prior, 90%)
Landry & Essick 2018 (tight prior, 90%)

Raithel (2019).
Relationship between symmetry energy $L_0$ and stellar radius

\[ E_{\text{sym}}(n) = S_0 + \frac{L_0}{3} \left( \frac{n}{n_{\text{sat}}} - 1 \right) + \frac{K_{\text{sym}}}{18} \left( \frac{n}{n_{\text{sat}}} - 1 \right)^2 + \frac{Q_{\text{sym}}}{162} \left( \frac{n}{n_{\text{sat}}} - 1 \right)^3 + \ldots \]
New framework for simplifying the symmetry energy for NS-NS mergers

$$\text{EOS} = f(B_0, K_0, Q_0, S_0, L_0, K_{\text{sym}}, Q_{\text{sym}}, \ldots)$$

Assume $$P \sim \rho^\Gamma$$ for densities near $$\rho_{\text{sat}}$$

$$\text{EOS} = f(\Gamma, L_0)$$

Raithel & Özel 2019 (in press).
Direct constraints on the slope of the symmetry energy

GW170817 points to lower values of $L_0$ than have been found by nuclear experiments.

Raithel & Özel (2019, in press).

Oertel et al. 2017
Lattimer & Lim 2013
Gravitational waves can be used to directly probe the **neutron star radius** and the **slope of the symmetry energy**

More events expected soon!