Extracting Neutron Star Radii from the Tidal Deformability of GW170817

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First measurement of Λ from GW170817 PROCHTOGOGICHTCHIC OF FITTOHT CIVEFOOLF ~
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• Constraint is on the combined, effective tidal deformability:

 $\widetilde{\Lambda}$ < 800

• Measurement "disfavors" EOS that predict less compact stars"

What does Λ measure? $\boldsymbol{\mathsf{\sim}}$

$$
\widetilde{\Lambda} = \frac{16(m_1 + 12m_2)m_1^4 \Lambda_1 + (m_2 + 12m_1)m_2^4 \Lambda_2}{(m_1 + m_2)^5}
$$

$$
\bullet \ \ \Lambda = \frac{2}{3} k_2 \left(\frac{R}{m}\right)^5
$$

- \bullet k_2 depends on the EOS and compactness (*m*1*m*2) 3*/*5
- $k_2 \sim 0.05$ -0.15 (Hinderer 2008; Hinderer et al. 2010; Postnikov et al. 2010) (*m*¹ + *m*2)¹*/*⁵

What does Λ measure? $\boldsymbol{\mathsf{\sim}}$

$$
\widetilde{\Lambda} = \frac{16(m_1 + 12m_2)m_1^4 (C_1)^5 + (m_2 + 12m_1)m_2^4 (C_2)^5}{(m_1 + m_2)^5} \left(\frac{2}{3}k_2\right)
$$

• Expectation: A measures a mass-weighted compactness $\tilde{\tilde{}}$

Evidence of a universal relation between $\stackrel{..}{\Lambda}$ and R **L** PULLE **DI d U** *m*¹ that lie within the mass range inferred for GW170817 (shown in di↵erent symbols). All values for *m*² are calcipation de concertius and chirp mass of the mass of the set of the \overline{a} and \overline{b} $\tilde{\mathsf{r}}$

- Λ_1 , Λ_2 are calculated for a range of m_1 and m_2 α indices with a freuder with a free free free α
- All combinations obey rand the model is a model in the model of the model in the model is an interesting model in the model in the mo interactions (Vines et al. 2011), point-mass spin-spin in- $M_c=1.188 M_\odot$ observed chirp mass,
- GW170817 probes radius directly, not compactness!

Faithel, Özel, and Psaltis (in prep).

Analytic origin ⇤*^N* = $\overline{1}$ \overline{z} 1
1
1 *^C*⁵ *.* (5)

--- Newtonian approximation - Universal relation of YY 2017

• Use Newtonian expression for each star: **For is so we we use intervention** $\mathsf{exp}(\mathsf{exp}$ Eall in the dependence on $\text{Eall}}$ \bullet I Ise Newtonian expression for $\overline{}$ expression, the appropriate account for the approximate and the approximate and the approximate and the approximate $\frac{1}{2}$

$$
\Lambda_N = \frac{15 - \pi^2}{3\pi^2} \left(\frac{Rc^2}{Gm} \sqrt{1 - \frac{2Gm}{Rc^2}} \right)^5 \approx \frac{350}{300}
$$

• Or in terms of universal *relations* of YY 2017: (2017) found that the relationship can be written as \mathcal{L}_max $\overline{\Omega}$ $\overline{\Omega}$ in to speed of weiverged \bullet UT In terms of universal 200 • Or in terms of univers 16 ciations o

$$
C = a_0 + a_1 \ln \Lambda + a_2 (\ln \Lambda)^2
$$

Analytic origin *^R* = 10 km 143.4 1 + 0*.*451✏² ⁺ *^O*(✏3) *R* 20.0 Analytic origin **PRINCIP CIL OFISHE**

• Expand combined effective deformability, assuming $q = (1 - \varepsilon)$ represents the deviation away from 1. We find

$$
\widetilde{\Lambda}_N = \frac{15 - \pi^2}{3\pi^2} \xi^{-5} (1 - 2\xi)^{5/2}
$$
\n
$$
\times \left[1 - \frac{3}{108} (1 - 2\xi)^{-2} (10 - 94\xi + 83\xi^2) \epsilon^2\right] + \mathcal{O}(\epsilon^3)
$$
\n
$$
\xi = \frac{2^{1/5} G \mathcal{M}_c}{Rc^2} \sum_{\text{Depends only on R}}^{\text{``effective''}} \sum_{\text{ratio}}^{\text{Deviation away}} \xi
$$

Expansion results

- Component mass dependence enters at $O(\varepsilon^2)$, and only as deviation away from equal mass ratio
- Dependence on mass even weaker for larger radii

TABLE 1 $\widetilde{\Lambda}_N$ expansion terms for the chirp mass measured from GW170817.

Radius	Coefficient	Expansion
$R=10~{\rm km}$	143.4	1+0.045 $\left(\frac{1-q}{1-0.7}\right)^2$ + $\mathcal{O}\left(\frac{1-q}{1-0.7}\right)^3$ 1+0.029 $\left(\frac{1-q}{1-0.7}\right)^2$ + $\mathcal{O}\left(\frac{1-q}{1-0.7}\right)^3$
$R = 11$ km	268.0	
$R=12$ km	465.8	1+0.020 $\left(\frac{1-q}{1-0.7}\right)^2$ + $\mathcal{O}\left(\frac{1-q}{1-0.7}\right)^2$
$R = 13$ km	764.6	$1 + 0.014 \left(\frac{1-q}{1-0.7} \right)^2 + \mathcal{O} \left(\frac{1-q}{1-0.7} \right)^2$

Raithel, Özel, and Psaltis (in prep). i, Ozei, and Psaitis (in j
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Raithel, Özel, and Psaltis (in prep). $\frac{1}{\sqrt{2}}$

$\tilde{\Lambda}$ is a direct probe of NS radius! **~**

How do we make further use of deformability measurements?

- To infer the underlying equation of state: need Bayesian inference
- We use parametric EOS, with 5 piecewise polytropes

$$
P(\text{EOS} | \{M_c, \widetilde{\Lambda}\}) = P_{\text{pr}}(P_1, ..., P_5) P(\{M_c, \widetilde{\Lambda}\} | \text{EOS})
$$
\n5 piecewise
\npolytropes
\n
$$
P(\text{Poisly})
$$
\n6. dusality
\n9.233 M_o
\n1.97 M_o < M_{max} < 2.33 M_o
\n1.97 M_o < M_{max} < 2.33 M_o
\n1.97 M_o < 4.10
\n1.97 M_o < 4.2018
\n1.97 M_o

Example inferences

- 1. A is a zero centered Gaussian, with $\sigma = 490$ $\tilde{\tilde{\lambda}}$
- 2. A is a Gaussian centered at 400 with $\sigma = 240$ ~
^
- 3. No data at all (just priors)

Also use an asymmetric *^M* ⁼ (*m*1*m*2) (*m*¹ + *m*2)¹*/*⁵ Gaussian for the chirp mass: $M_c = 1.188^{+0.004}_{-0.002}$ M_o

–– Max L solution Universal R- $\tilde{\wedge}$ relation
Marginalized results

> Marginalized to see "density" of results

i.e., integrated the priors over massradius volume

Conclusions

- \cdot $\tilde{\wedge}$ probes the radii of the neutron stars
- Full Bayesian inference is required to get the underlying EOS
- Additional measurements of $\tilde{\wedge}$ will provide new constraints on the EOS