Gravitational Waves and the EOS: Discussion

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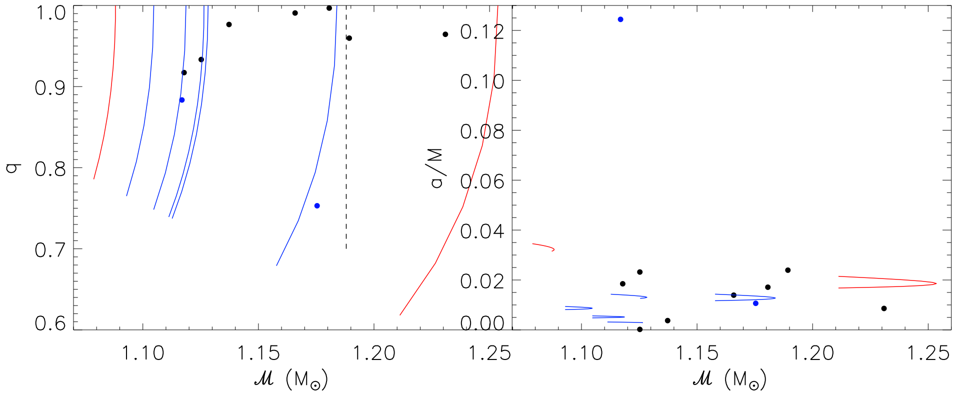
Gravitational Waves and the EOS

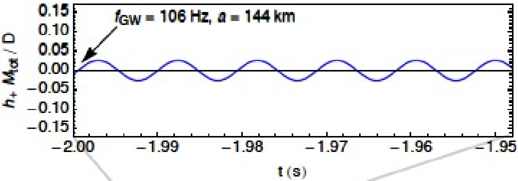
- What should we expect from future BNS and BHNS mergers?
- What's the best way to analyze GW data?
- Should the fitting parameters be tidal deformabilities or EOS parameters?
- What do we learn about the EOS from tidal deformabilities?
- What prior assumptions should be made concerning fitting parameters?
- How do prior assumptions bias data interpretations?
- Does/will GWs have evidence for quark matter?

Properties of Observed DNS

DNS with only an upper limit to m_p

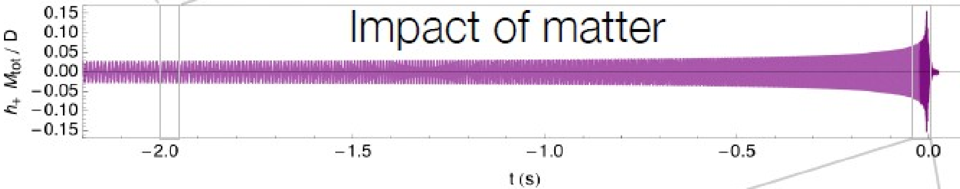
DNS with $\tau_{GW} = \infty$





Hard to modify inspiral: transfer of ~10^{46} erg at ~100 Hz modifies phase by 10^{-3} radians (Crust shattering, Tsang et al 1110.0467)

Impact of matter

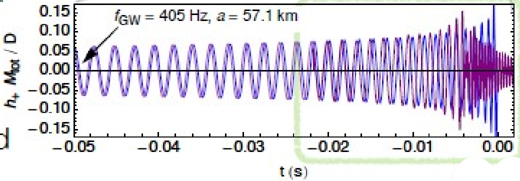


Tidal interactions lead to accumulated phase shift at higher frequencies.

$$\delta\Phi_t = -\frac{117}{256}\frac{(1+q)^4}{q^2}\left(\frac{\pi f_{GW} G\mathcal{M}}{c^3}\right)^{5/3}\bar{\Lambda}$$

For the final coalescence, numerical simulations are required

credit: Jocelyn Read



Deformability and the Radius

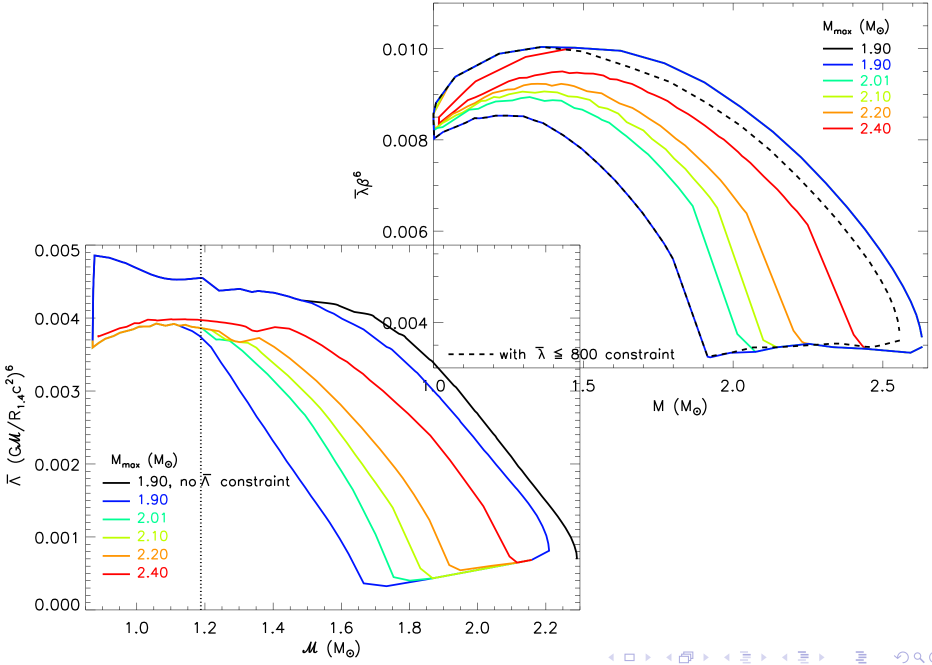
- $\Lambda = a(Rc^2/GM)^6$ for hadronic EOSs
  $a = 0.0093 \pm 0.0007$ for $M = (1.35 \pm 0.25)M_\odot$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + q^4(12+q)\Lambda_2}{(1+q)^5}$$

- $R_1 \simeq R_2 \simeq \hat{R}$ for $M = (1.35 \pm 0.25)M_\odot$

$$\tilde{\Lambda} \simeq \frac{16a}{13}\left(\frac{\hat{R}c^2}{G\mathcal{M}}\right)^6 \frac{q^{8/5}}{(1+q)^{26/5}}(12 - 11q + 12q^2)$$

- $\tilde{\Lambda} = a'(\hat{R}c^2/G\mathcal{M})^6$
  $a' = 0.0042 \pm 0.0004$ for $\mathcal{M} = (1.1 \pm 0.2)M_\odot$, $q > 0.6$
- $\hat{R} \simeq R_{1.4} = (11.2 \pm 0.2)\frac{\mathcal{M}}{M_\odot}\left(\frac{\tilde{\Lambda}}{800}\right)^{1/6}$ km



M_{max} ($M_\odot$)
1.90
1.90
2.01
2.10
2.20
2.40
$\bar{\lambda}\beta^6$
with $\bar{\lambda} \leqq 800$ constraint
M ($M_\odot$)
$\bar{\Lambda}$ $(G\mathcal{M}/R_{1.4}c^2)^6$
M_{max} ($M_\odot$)
1.90, no $\bar{\Lambda}$ constraint
1.90
2.01
2.10
2.20
2.40
$\mathcal{M}$ ($M_\odot$)

LIGO/VIRGO (2017) Parameter Determination

Although there are 11 free wave-form parameters to the lowest post- Newtonian order that includes finite-size effects, LV (2017) used a model with 13 parameters to fit the waveform:

Extrinsic:

- Sky location (2)
- Distance (1)
- Inclination (1)
- Coalescence time (1)
- Coalescence phase (1)
- Polarization (1)

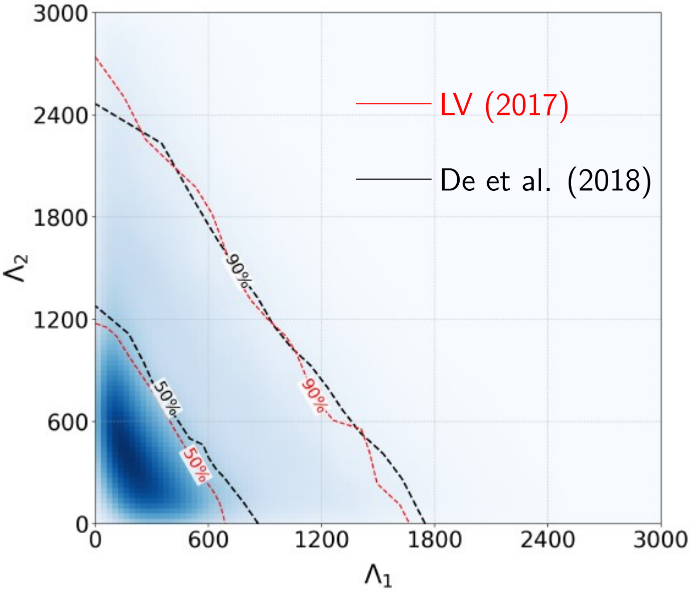
Intrinsic:

- Component masses (2)
- Spin parameters (2)
- Tidal parameters (2)

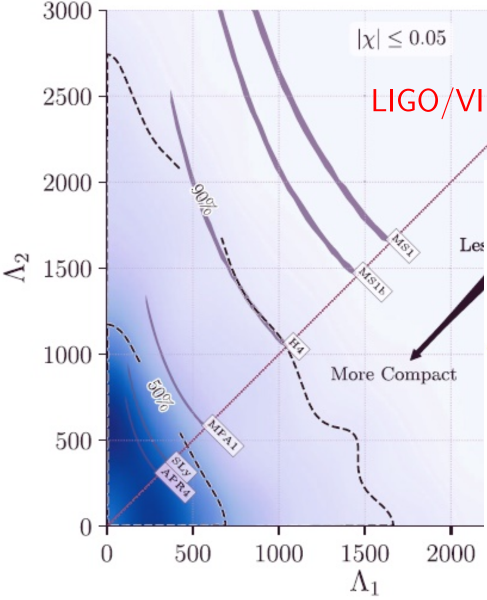
Important to Include $\Lambda_1 - \Lambda_2$ Correlations

- LIGO/VIRGO (2017) did not include these correlations, and even allowed the prior $\Lambda_1 > \Lambda_2$.
  But unless $(c^2/G)dR/dM \geq 1$ for $m_2 \leq M \leq m_1$, $\Lambda_1 \leq \Lambda_2$ always. $(c^2/G)dR/dM \leq 0.26$.
- De et al. (2018) showed that correlating Λ_1 and Λ_2 reduces the estimated $\tilde{\Lambda}$ by ~ 250 and provides a significantly better fit to GW data (Bayes factor ~ 100).
- De et al. (2018), with similar priors, can reproduce LIGO/VIRGO (2017) EOS-independent results.
- The TaylorF2 waveform model seems to overestimate $\tilde{\Lambda}$ by a factor of about 1.2.
- There are lower bounds to $\Lambda(M)$ from causality and unitary gas constraints that should be included.
- Upper bounds to $\Lambda(M)$ from causality (Friedmann et al. 2017) are model-dependent.

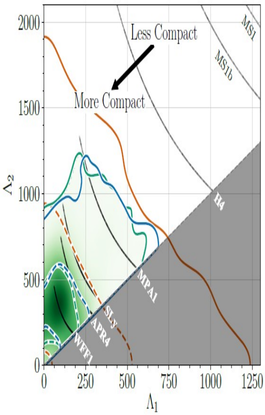
Comparison with LV (2017); Uncorrelated Λ's



GW170817 Tidal Deformability Constraints



LIGO/VIRGO (2017)



LV18

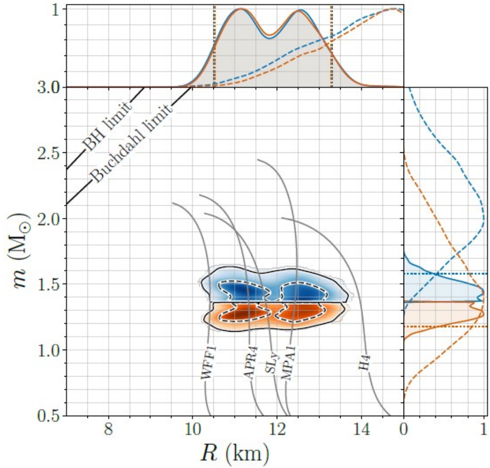
EOS priors Affect Results

- LIGO/VIRGO (2018) claims that their parameterized spectral decomposition EOS is superior to a 3-segment piecewise polytrope EOS for inferring deformabilities.
- However, introducing EOS parameters in the waveform model increases the number of fitting parameters by 3.
- The EOS parameters were not allowed to vary over the entie ranges permitted by causality, $M_{max} \geq 1.97 M_{\odot}$, and thermodynamic stability (Lindblom 2010).
- Flat priors over restricted ranges for the 5 EOS parameters result in Gaussian-like Λ priors, with therefore a strong bias toward their central values.
- This probably explains the LIGO/VIRGO (2018) claim of $\sim 50\%$ smaller uncertainties in estimated deformabilities and radii relative to De et al. (2018), although the centroids are essentially the same.

Deformability Priors

- De et al. (2018) only used their EOS parametrization to validate their deformability constraint $\Lambda_1/\Lambda_2 \simeq q^6$.
- For hadronic EOSs, one can show independently of the EOS parametrization that $q^{7.56} \leq \Lambda_1/\Lambda_2 \leq q^{5.65}$.
- The spread relative to q^6 is not significant given the quality of the GW170817 data. Introducing this uncertainty in the $\Lambda_1 - \Lambda_2$ correlation does not significantly iimpact the results (De et al. (2018)).
- Implemented through $\Lambda_1 = q^3\Lambda_s$ and $\Lambda_2 = q^{-3}\Lambda_s$ with a flat prior for Λ_s.

$R_1 = R_2$



LIGO/VIRGO (2018)