Studying the effects of tidal corrections on parameter estimation

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Background:

- **Neutron star (NS) tidal deformability**
  - A NS in a binary will become tidally deformed because the gravitational field from its companion is not constant over its finite diameter
  - The NS's tidal deformability λ, which depends on its equation of state (EOS), parameterizes how much it will deform
- **Compact binary coalescence (CBC) gravitational waveform**
  - The inspiral portion of a CBC event is approximated using post-Newtonian (PN) theory and assumes each body is a point-particle
  - Tidal effects cause NS binaries to depart from the point-particle approximation during the late inspiral portion of a CBC event
  - The leading order tidal corrections to the point-particle approximation emerge at 5PN order [1,2]

Motivation:

- **Extracting tidal deformability with gravitational-waves**
  - It has been shown [1-3] that a NS's tidal deformability may be measurable using ground-based gravitational-wave detectors
  - This work uses full Bayesian parameter estimation simulations of single, binary NS (BNS) sources to study the effects of tidal interactions in order to learn more about NS structure
- **Systematic biases from using different waveform families**
  - In approximating the true CBC gravitational waveform, slightly different perturbative techniques lead to gravitational waveform families that differ by a next-order truncation error
  - It is essential to understand the resulting systematic biases in our parameter estimation methods if we seek to extract EOS information from a gravitational-wave (GW) detection

Preliminary Results:

- **What's plotted:**
  - This work uses the following PN waveform families from `lalsimulation` with leading order (5PN) and next-to-leading order (6PN) tidal corrections: TaylorT1, TaylorT2, TaylorT3, TaylorT4, and TaylorF2
  - This work also uses `lalinference` to perform full Bayesian Markov Chain Monte Carlo (MCMC) parameter estimation simulations on BNS systems
  - In all presented figures, we use: 3 detector network (Advance LIGO and Virgo) with a zero detuning high power PSD and a network SNR of 32.4, $f_{\min} = 30$ Hz, and injected values of $\hat{\lambda}_1 = \hat{\lambda}_2 = 607$ and $m_1 = m_2 = 1.35\ \mathrm{M}_\odot$

- **Can we measure individual NS tidal deformability?**
  - We find that a NS's tidal deformability ($142 \leq \hat{\lambda}_{1.35M_\odot} \leq 2324$, [4])

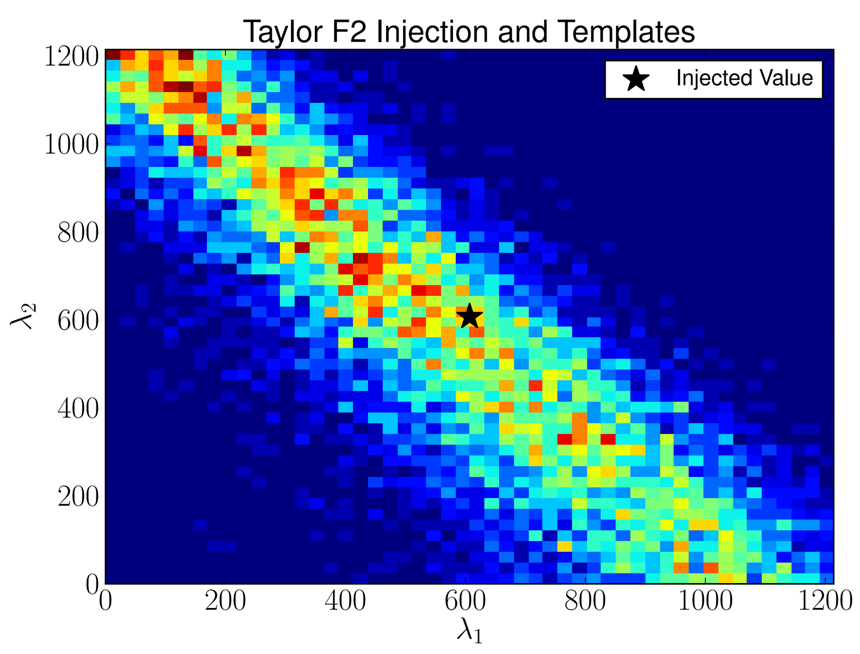
$$\hat{\lambda}_i = \frac{\lambda}{{m_i}^5} = \frac{2}{3} k_2 \left(\frac{R_i}{m_i}\right)^5,$$

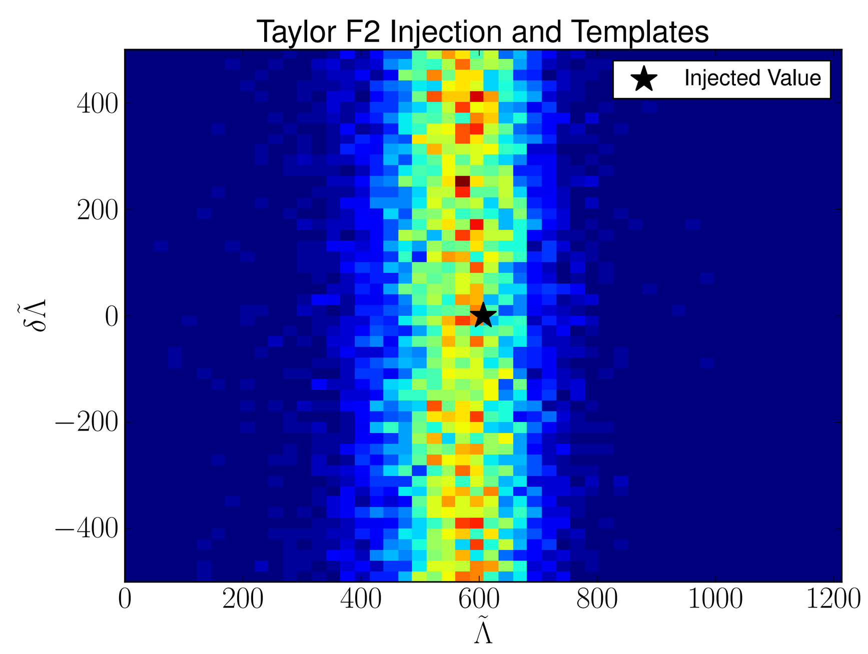
where k_2 is the Love number, is not well measured

- **What *can* we measure?**
  - If we re-parameterize according to [5,1]

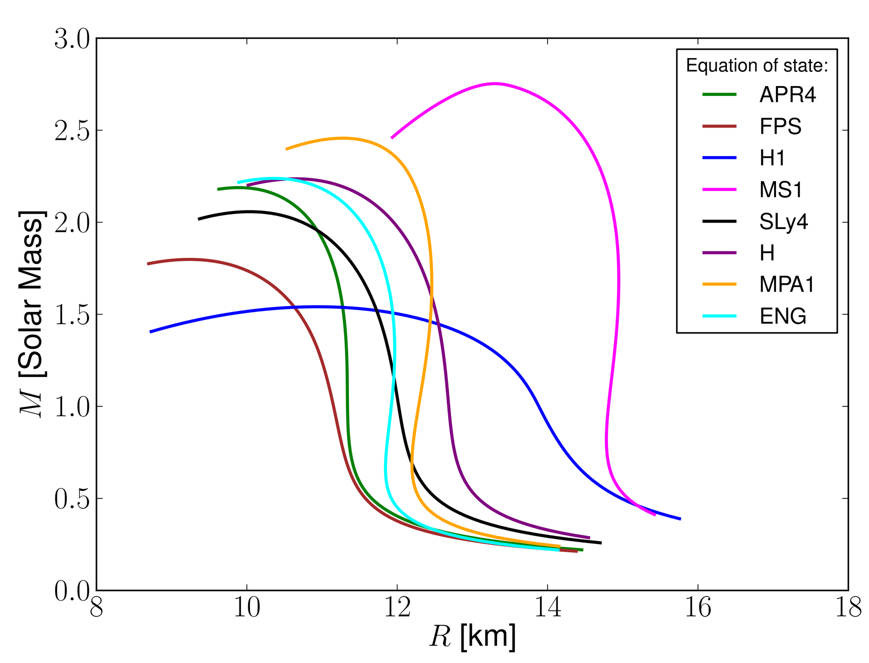
$$\begin{aligned}\tilde{\Lambda} &= \text{5PN Correction} = \frac{32}{M^5}\tilde{\lambda} \\ &= \frac{8}{13}\left[\left(1+7\eta-31\eta^2\right)\left(\hat{\lambda}_1+\hat{\lambda}_2\right)\right. \\ &\quad \left. + \sqrt{1-4\eta}\left(1+9\eta-11\eta^2\right)\left(\hat{\lambda}_1-\hat{\lambda}_2\right)\right] \\ \delta\tilde{\Lambda} &= \text{6PN} - \text{5PN Correction}\end{aligned}$$

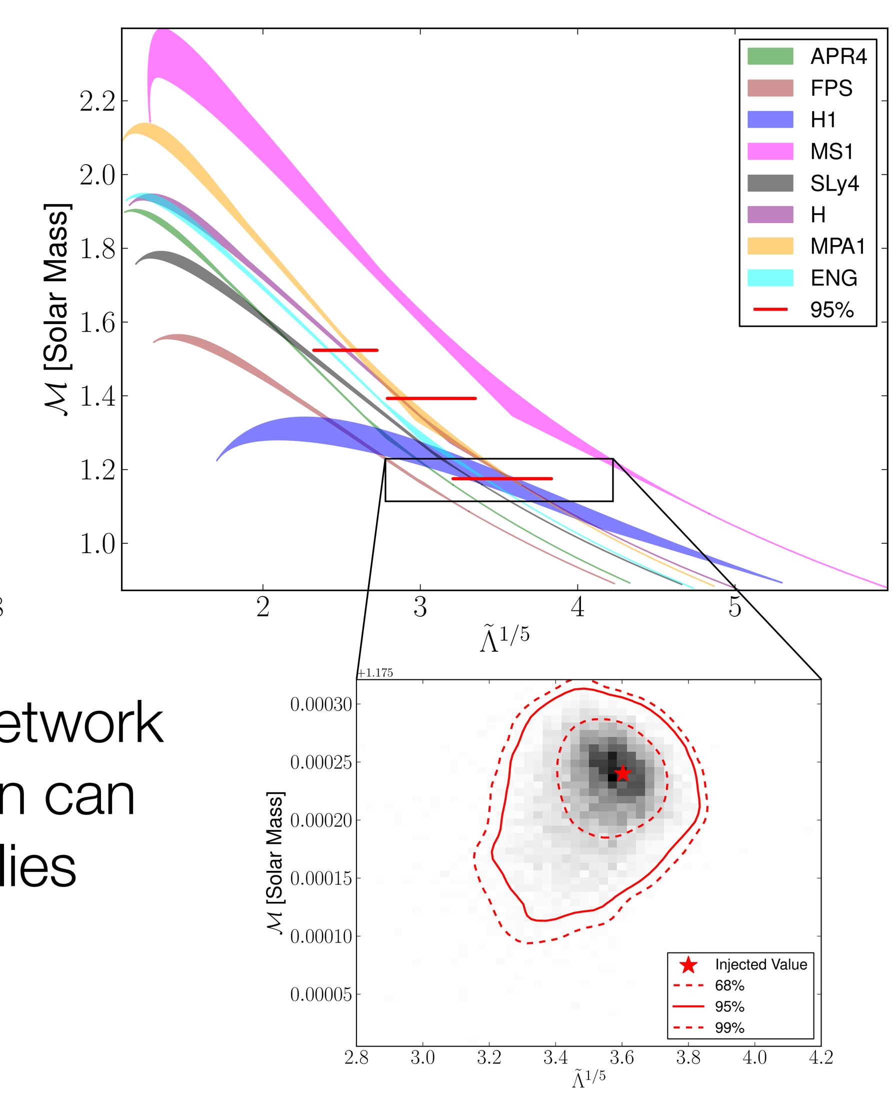
we find that we can measure $\tilde{\Lambda}$, though $\delta\tilde{\Lambda}$ is too small
  - Below are 2D marginalized posterior density functions (PDFs) as computed by our MCMC pipeline





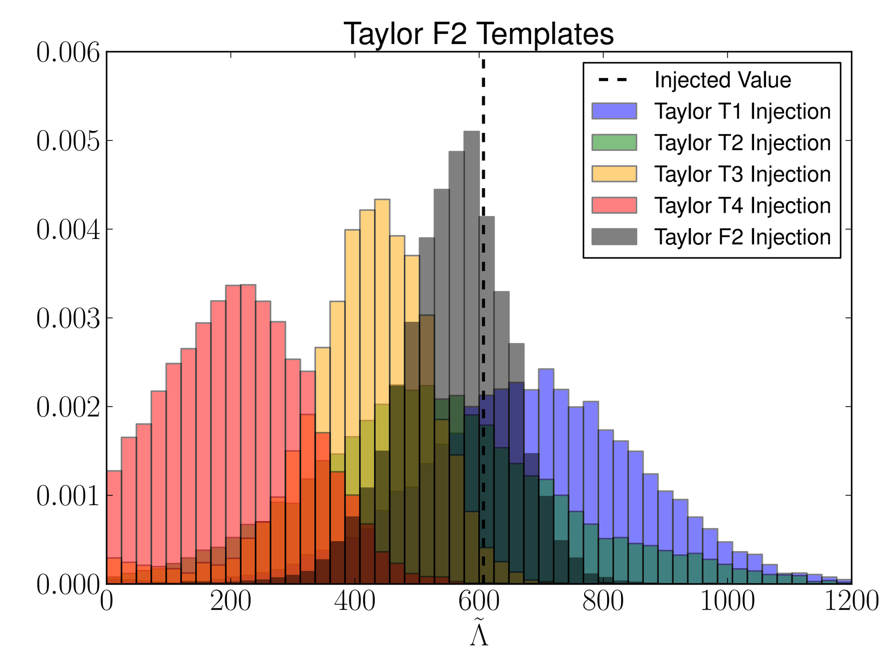
- **Can GWs help constrain the NS EOS?**
  - To visualize how a GW detection might constrain the NS EOS, we plot a 2D PDF from a single source on mass-radius-*like* curves





  - We find that a single, loud (Network SNR 32.4) BNS GW detection can rule out several NS EOS families
  - Multiple detections will highly constrain the NS EOS

- **Systematic bias?**
  - To study systematic biases, we used different waveform families for the injection and the templates
  - The systematic bias can be significant between any two waveform families



Conclusions:

- **Measurability**
  - While λ_1 and λ_2 are not well measured, $\tilde{\Lambda}$ is!
  - Since chirp mass is so well measured, several BNS observations with varying chirp masses can lead to very tight constraints on the NS EOS
- **Systematic bias**
  - There may be significant bias in the measured tidal parameter between different PN waveform families
  - Therefore, phenom/hybrid/NR waveforms will likely be needed for parameter estimation to capture the proper physics of the late inspiral (such as tidal disruption and/or hypermassive NS oscillations)

References:

[1] É. É. Flanagan and T. Hinderer. Phys. Rev. D, 77:021502, Jan 2008.

[2] T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read. Phys. Rev. D, 81:123016, Jun 2010.

[3] J. S. Read, C. Markakis, M. Shibata, K. Uryū, J. D. E. Creighton, and J. L. Friedman. Phys. Rev. D, 79:124033, Jun 2009.

[4] B. D. Lackey, K. Kyutoku, M. Shibata, P. R. Brady, and J. L. Friedman. Phys. Rev. D, 85:044061, Feb 2012.

[5] M. Favata, in preparation, March 2013.