Probing Extreme Matter through Gravitational Waves: Current Constraints and Possible Systematics

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Gravitational Waves

Gravitational waves are **ripples** which propagate on the fabric of spacetime at the speed of light.

- **Sources:** BBH, BNS sysems
- **Theory and Models:** approximations of GR
  - $\Rightarrow$ Post Newtonian (PN), Post Minkowskian (PM)
  - $\Rightarrow$ Phenomenological
  - $\Rightarrow$ EOB
- **Applications:** Astrophysics, cosmology, extreme matter and MORE!
- **Methods:** Parameter Estimation (PE) $\Rightarrow$ extracting the source's properties from the data.

Neutron Stars and Extreme Matter

Neutron stars (NS) are the collapsed core of a giant star:

- **Allow for studying cold, high-density nuclear matter**
- statements on the behavior of NS matter $\Rightarrow$ constraints on its EoS
- constraints on EoS $\Rightarrow$ limits on stellar parameters (M, R, Λ)

- Terrestrial experiments, constraints on densities below saturation $\rho_s \approx 2.7 \times 10^{14} g/cm^3$
- Astrophysical measurements, information on M and R
- Relatively new addition: GW measurements!

Focus

PE is a **very** delicate process!

The signal is submerged by noise! $\Rightarrow$ assumptions about the shape of the signal to extract it

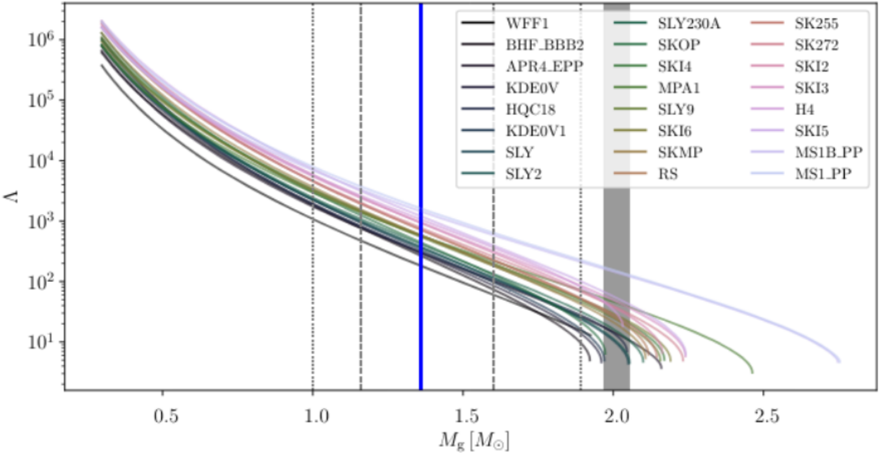
Our aim: Quantify and discuss two possible systematic errors stemming from different modelling choices:

- Low-density EoS;
- Waveform systematics.

Tidal deformability

$$\lambda_i = \frac{\text{Quadrupole deformation of the star}}{\text{External tidal field}} \rightarrow \Lambda_i = \frac{\lambda_i}{m_i^5}$$

1908.01012



Matter Contributions to the Inspiral Waveform

GW signal:

$$\tilde{h}(f) = \mathcal{A}(f)e^{i\psi(f)}$$

with:

$$\mathcal{A}(f) = \frac{1}{d_L}\sqrt{5/24}\pi^{-2/3}\mathcal{M}_c^{5/6}f^{-7/6}$$

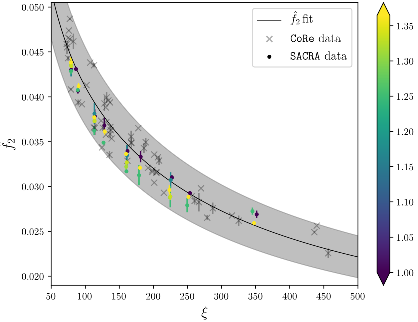
$$\psi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\nu v^5} - \frac{9}{16}\frac{v^5}{\mu M^4}\tilde{\Lambda}$$

$\Rightarrow$ GW measurements give us:

- chirp mass $\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$
- mass-weighted tidal deformability $\tilde{\Lambda} = \left[\left(11\frac{m_2}{m_1} + \frac{M}{m_1}\right)\Lambda_1 + 1 \leftrightarrow 2\right]$

Matter Contributions to the Postmerger Waveform

Postmerger waveform is also sensible to matter effects (NR simulations, semi-analytical models)



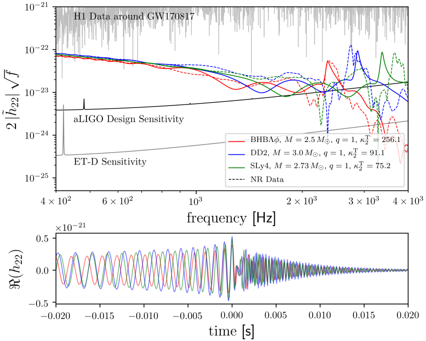
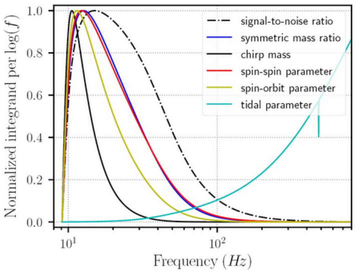
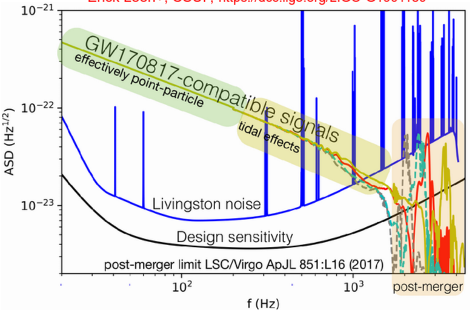


Figure: Example of time domain postmerger model, obtained by fitting some characteristic quantities from a set of NR simulation 1908.11418. $\hat{f}_2$ can be linked to $R_{1.6}$ 1508.05493

Measurability of matter effects through GWs



1203.4352, 1801.09972



$\hat{f}_2$ allows for good measurement of $R_{1.6}$ if the postmerger SNR is ≈ 8; in this scenario the inspiral signal would lead to much better constraints

Parameterized EOS

Popular choice during BNS PE: assume a functional form for the EoS. E.g: spectral parameterization

$$e(p) = \frac{e_0}{\mu(p)} + \frac{1}{\mu(p)} \int_{p_0}^{p} \frac{\mu(p')}{\Gamma(p')} dp'$$

with

$$\mu(p) = exp[-\int_{p_0}^{p} \frac{dp'}{p'\Gamma(p')}]$$

$$\Gamma(p) = exp[\sum_{i=0}^{\infty} \gamma_i \; log(p)^i]$$

During PE one can:

- sample $(m_1, m_2, \Lambda_1, \Lambda_2)$
- sample $(m_1, m_2, \gamma_{0,\dots,3}) \Rightarrow$ obtain $(m_1, m_2, \Lambda_1, \Lambda_2, R)$

Phenomenological relations between NS quantities, common between large range of EoSs.

- I-Love-Q
- C-Lambda
- De-Lattimer
- Binary-Love
- Raithel et al.
- ...

Can be used to obtain information on, e.g, R, or reduce PE parameter space

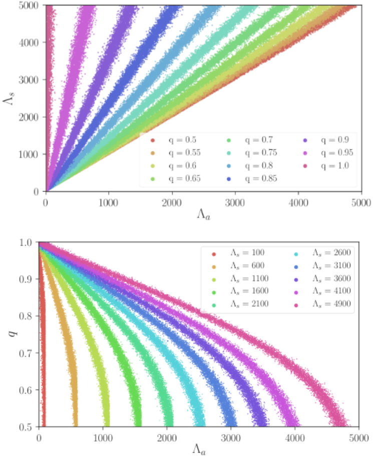
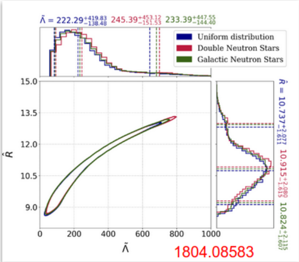
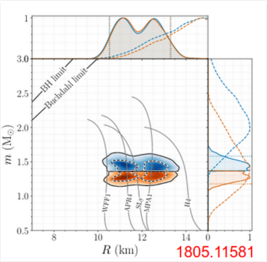


Figure: Visual representation of the Binary-Love relation, 1804.03221

Current constraints



1804.08583



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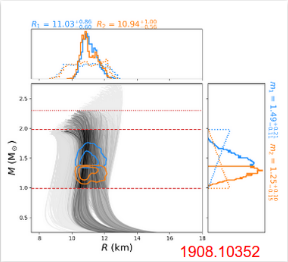

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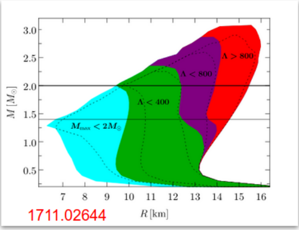
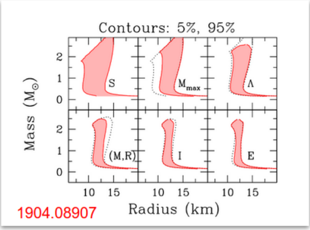


1711.02644



1904.08907

… And many more!

GW170817

First NS-NS merger observed by LVC

- analysis performed through MCMC sampling
- IMRPhenomPv2NRTidal
- spectral parameterization
- EOS has to support 1.97 $M_\odot$

$\Rightarrow$ $R_{1,2} = 11.9^{+1.4}_{-1.4}$ km

But!

- Uncertainty on R due to crust EoS
- if $\tilde{\Lambda}$ unaffected by crust $\Rightarrow$ systematics on R!

Aim: quantify effect that crust has on PE (1902.04616)

Alternative Crusts

Set of different possible crust EOS (BPS+CLDM) 1110.4043. Each of them has two parameters:

- S = symmetry energy, measures difference between the energies of pure neutron and symmetric nuclear matter;
- L = derivative of S with respect to x, the neutron/baryon fraction.

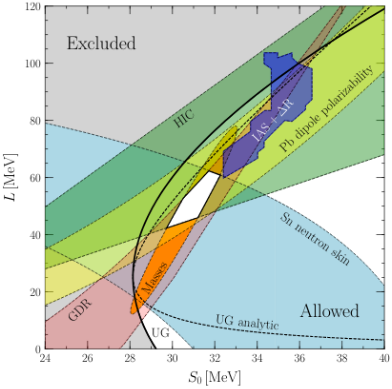


Figure: Constraints on S and L from different experiments, from 1611.07133

$30 \leq S \leq 32$ MeV and $40 \leq L \leq 60$ MeV, but these intervals are uncertain

$\Rightarrow$ We focus on the intervals $30 \leq S \leq 34 MeV$ and $30 \leq L \leq 70$

Alternative Crusts

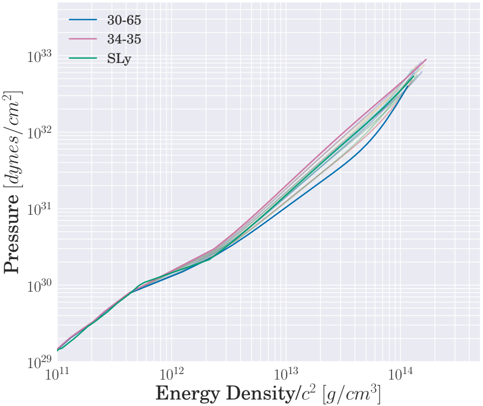


Figure: Set of different crusts EoS that we consider. Constrained by terrestrial experiments, we select the higher and lower bounds

Predictions

Assumption: masses and the core EOS are weakly affected by the choice of the crust $\Rightarrow$ we can use results from the EOS paper to predict the posterior distributions of stellar parameters R and $\wedge$ we would get with our variant crust:

- New crust + "old" parametrized core EOSs $\rightarrow$ full $\{p^i(e)\}$
- $\{p^i(e)\}$ + "old" $\{M_1^i, M_2^i\}$ $\rightarrow$ estimates of $\{\Lambda_1^i, \Lambda_2^i, R_1^i, R_2^i\}$

Reanalysis

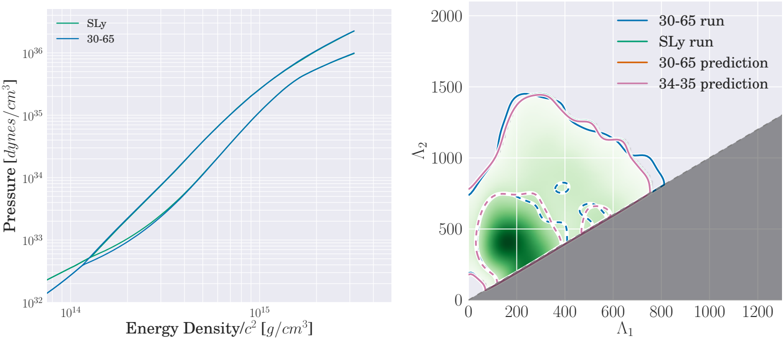
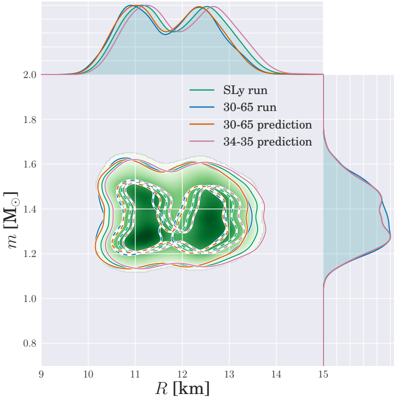


Figure: Left: 90% CLs in log scale, at higher densities they are superimposed; right: $\Lambda_1 vs \Lambda_2$ distributions, almost perfectly superimposed

R distributions systematically shifted



	R_1	R_2
SLy run	$11.9^{+1.4}_{-1.4}$	$11.9^{+1.4}_{-1.4}$
30-65 run	$11.7^{+1.4}_{-1.4}$	$11.7^{+1.4}_{-1.4}$
30-65 pred	$11.7^{+1.4}_{-1.3}$	$11.7^{+1.4}_{-1.4}$
34-35 pred	$12.0^{+1.5}_{-1.4}$	$12.0^{+1.5}_{-1.4}$

$\rightarrow$ $\Delta R^{+} = \Delta R^{c}_{34-35} - \Delta R^{c}_{SLy} \approx 0.1\mathrm{km}$

$\rightarrow$ $\Delta R^{-} = \Delta R^{c}_{SLy} - \Delta R^{c}_{30-65} \approx 0.2\mathrm{km}$

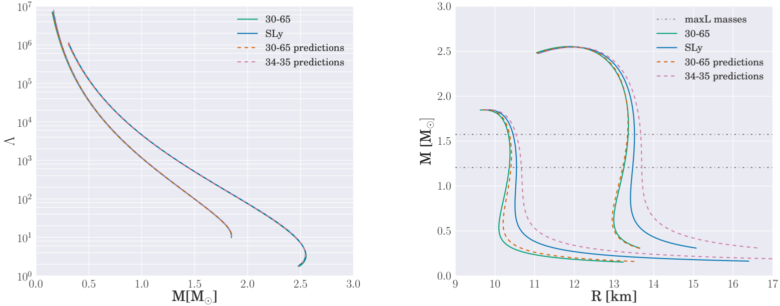
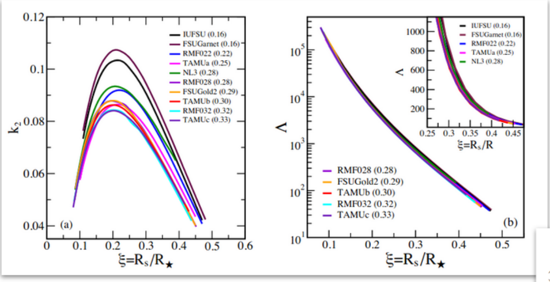


Figure: More physical insight obtained by mapping the 90% pressure-density CLs, appropriately glued to the variant crusts, into M(R) and $\Lambda(R)$ curves

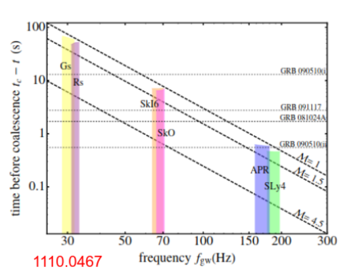
More about the crust



1812.09974

k_2 is sensitive to the crust, but Λ is not

Resonances during the inspiral might lead to the crust shattering (sGRB) at frequencies that depend on the EOS



1110.0467

Modelling systematics - Waveforms

Our ability to measure tidal effects will increase with higher SNRs. However, this also brings **additonal theoretical challenges**: Waveform templates are necessary to extract the signal (modelled analyses):

- We need accurate waveform models (how accurate?)
- How large are the biases due to waveform systematics?

GW Approximants 101

- PN models (TaylorT4, SpinTaylorT4, TaylorF2 ...) $\Rightarrow$ fast, but **not good** at higher frequencies;
- EOB (TEOBResumS, SEOBNRv4T) $\Rightarrow$ physically rich, informed by NR, computationally more expensive;
- Phenomenological waveforms $\Rightarrow$ PN + EOB + NR, faster then EOB but lack of "physical framework" behind

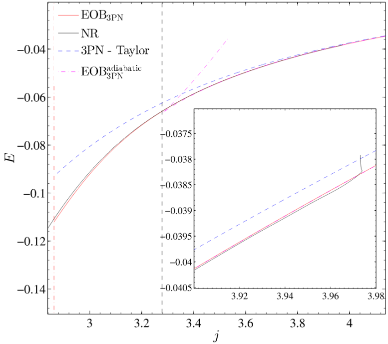


Figure: E(j) relation for a point-mass q=1 system, from Damour, Nagar, Pollney, Resswig 1110.2938

GW170817 and GW190425

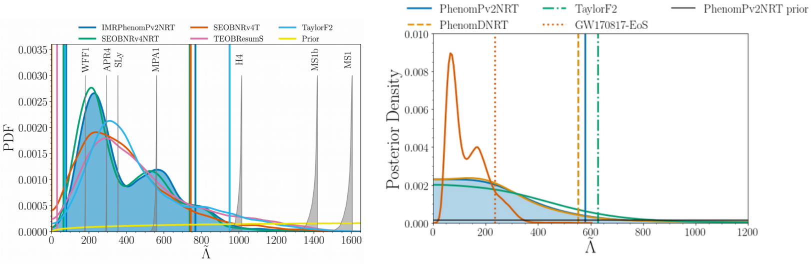


Figure: The $\tilde{\Lambda}$ distributions for GW170817 (left) and GW190425 (right). For both, waveform systematics are negligible with respect to fluctuations of the background noise.

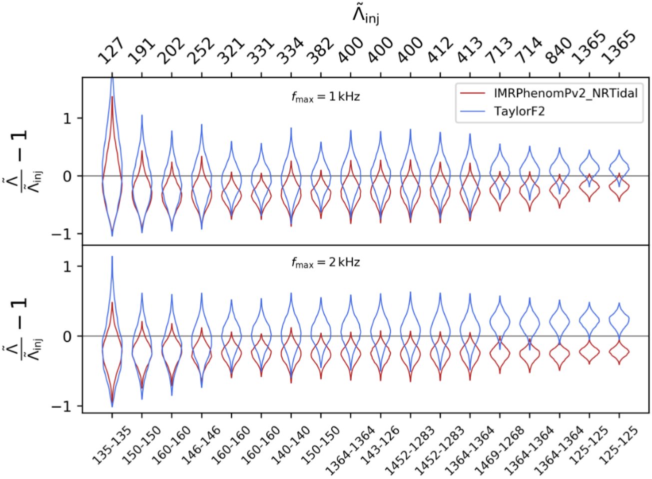
Careful: there are studies that show how it is possible to have biases with SNRs as low as 20 1904.09558

Injection studies

- 18 TEOBResumS waveforms injected;
- Recovery with: TaylorF2, IMRPhenomPv2NRTidal (spin aligned);
- Different EOS, mass ratio, low spin prior ($\chi < 0.05$);
- GW170817 - like extrinsic parameters;
- aLIGO PSD (SNR $\approx$ 80-100);
- sampling $(m_1, m_2, \Lambda_1, \Lambda_2)$

$\tilde{\Lambda}$ recovery

PRELIMINARY



IMRPhenomP underestimates $\tilde{\Lambda}$, while TaylorF2 overestimates it

Conclusions

What we learned:

- Low sensitivity of tidal parameters to the crust density
  - $\Rightarrow$ GW measurements give more direct information on higher densities;
  - $\Rightarrow$ in this region the constraints obtained from analyses are independent of uncertainties in crust;
- Systematic error is mass dependent: the lower the mass, the bigger the radii variations (crust becomes overall more important). For GW170817, $\Delta R \approx 0.3$ km;
- At higher SNRs, waveform systematics will become important in the determination of tidal parameters (Better to stay away from PN approximants)

Thank you for the attention!