The impact of the crust EOS on the analysis of GW170817

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1. Introduction

The detection of GW170817, the first neutron star-neutron star merger observed by Advanced LIGO and Virgo, and its following analyses represent the first contributions of gravitational wave data to understanding dense matter. Parameterizing the high density section of the equation of state of both neutron stars through spectral decomposition, and imposing a lower limit on the maximum mass value, led to an estimate of the stars' radii of $R_1 = 11.9^{+1.4}_{-1.4}$ km and $R_2 = 11.9^{+1.4}_{-1.4}$ km [1]. These values do not, however, take into account any uncertainty owed to the choice of the crust low-density equation of state, which was fixed to reproduce the SLy EOS model [2]. We here re-analyze GW170817 data and establish that different crust models do not strongly impact the mass or tidal deformability of a neutron star – it is impossible to distinguish between low density models with GW analysis. However, the crust does have an effect on inferred radius. We predict the systematic error due to this effect using neutron star structure equations, and compare the prediction to results from full parameter estimation runs. For GW170817, this systematic error affects the radius estimate by 0.3 km, approximately 3% of the NS radii.

2. Equation Of State

2.1 Crust EOS

Neutron stars are objects so dense that it is possible for them to develop a sturdy crust made of very neutron-rich nuclei even at the incredibly high temperatures of their surface. We retrieved a set of crust EOSs from [3]. Each EOS is characterized by **two parameters**:

- S_0 measures difference between the energies of pure neutron and symmetric nuclear matter;
- L is the slope of S.

There exist experimental constraints on both of these! Since their values are still somewhat uncertain, we focus on $S \in [30-34]$ and $L \in [30-70]$. We select $S_0 = 34$ MeV, $L = 35$ MeV; $S_0 = 30$ MeV, $L = 65$ MeV. These should give the largest impact on neutron star structure.

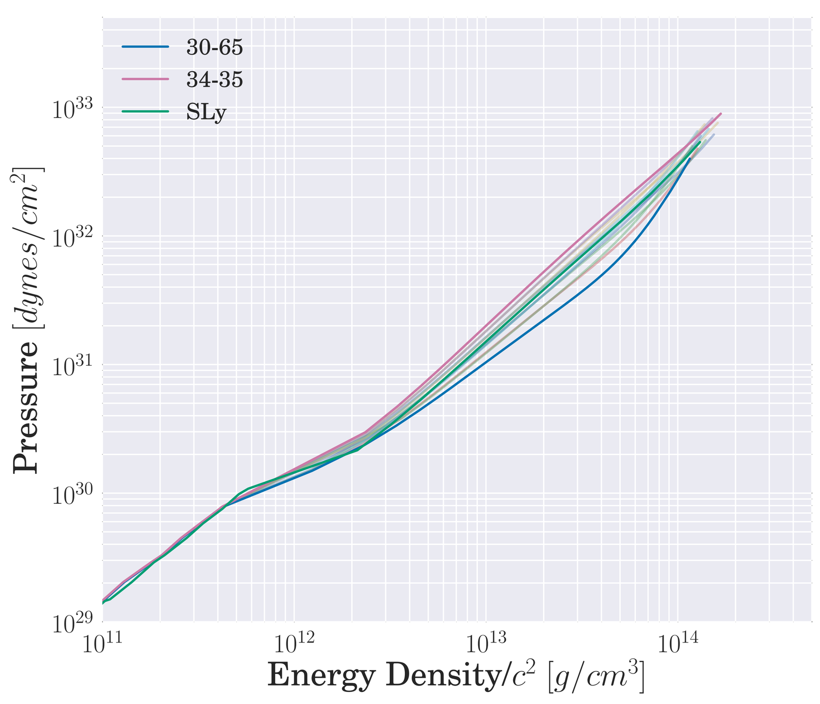

Figure 1: *The EOSs for realistic crust models with nuclear parameters $S_0 \in [30-34]$ MeV and $L \in [30-70]$ MeV. SLy is characterized by $S_0 = 32$ MeV and $L = 46$ MeV. The 34-35 MeV and the 30-65 MeV EOSs are the upper and lower limits.*

2.2 Parametrized Core EOS

When parametrizing an EOS, it is particularly convenient to choose a physically consistent model, for which pressure p is automatically a monotonically increasing function of energy density e. Through spectral decomposition [4] we express the adiabatic index $\Gamma(p) = [(e+p)/p]dp/de$ as the exponential of the sum of some smooth basis functions multiplied by some coefficients:

$$\Gamma(p) = exp[\sum_{i=0}^{\infty} \gamma_i f^i(p)] \tag{1}$$

Obtaining the expression of the energy density as a function of pressure requires then a simple integration:

$$e(p) = \frac{e_0}{\mu(p)} + \frac{1}{\mu(p)} \int_{p_0}^{p} \frac{\mu(p')}{\Gamma(p')} dp' \tag{2}$$

in which e_0, p_0 is the starting point of the decomposition in the energy density-pressure plane and

$$\mu = exp[-\int_{p_0}^{p} \frac{dp'}{p'\Gamma(p')}] \tag{3}$$

3. Re-analysis

Running on the real data of GW170817 using spectral decomposition means that every spectral coefficient $\gamma_i, i \in [0,3]$ is sampled, in place of the tidal deformabilities Λ_1 and Λ_2, by stochastically walking through the parameter space. Each set $\{\gamma_0, \dots, \gamma_3\}_i$ can be mapped through (2) in an equation of state $p_i(e)$, $i = 1, \dots, N_{samples}$. To then go from an equation of state of the form $e(p)$ to the determination of the stellar parameters M, R and Λ, one has to integrate TOV equations and solve the inner-outer matching problem related to the relativistic Love number k_2.

In our `LALInference` Markov chain Monte Carlo (MCMC) run, the hard-coded SLy crust was switched to the $S_0 = 30$ MeV $L = 65$ MeV equation of state (figure 1), and the crust-core transition point e_m, p_m changed accordingly. The choice of the other priors matches [1]. The radii found then are $R_1 = 11.7^{+1.4}_{-1.4}$ km, $R_2 = 11.7^{+1.3}_{-1.4}$ km.

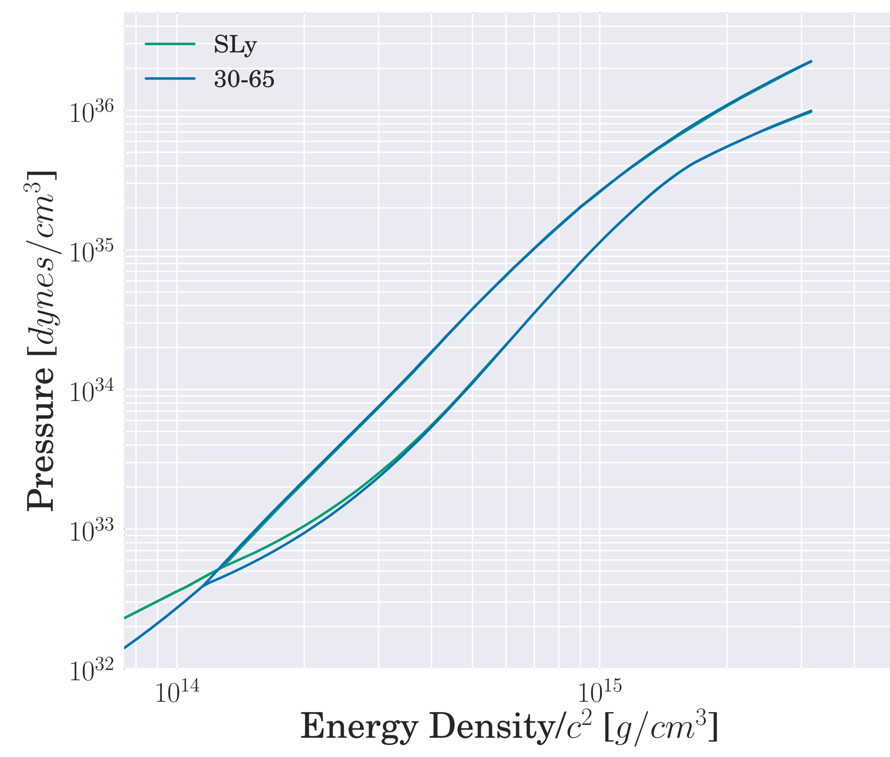

Figure 2: *90% pressure-density credible levels. They are perfectly superimposed, except for the point where they are matched to the crust: credible levels on the high density section of the EOS are independent on the choice of the crust.*

4. Predictions

4.1 From Previous Posteriors (PP)

- Assumption: masses and the core EOS are weakly affected by the choice of the crust ⇒ we can use the results from the eos paper to **predict** the posterior distributions of stellar parameters R and Λ we would get with our variant crust:
- Variant crust stitched to SLy crust-core matching point
- Crust + $\{\gamma_1^i, \gamma_2^i, \gamma_3^i, \gamma_4^i\} \to \{p^i(e)\}$
- $\{p^i(e)\}$ + $\{M_1^i, M_2^i\} \to \{\Lambda_1^i, \Lambda_2^i, R_1^i, R_2^i\}$

4.2 Crust + Previous CLs (C+C)

- More physical insight obtained by mapping the 90% pressure-density CLs, appropriately glued to the variant crusts, into M(R) and $\Lambda(R)$ curves
- **But!** 90% pressure-density CLs do **not** map into CLs on mass and radius

→ estimates from M(R) do not give the full picture

- Nonetheless, it does a reasonable job in the mass range of the binaries and suggests that the corrections increase as the mass becomes smaller

5. Results and error estimate

We find out that while the Λ distributions are all indistinguishable - and the "prediction" curves perfectly superimposed! - the radii distributions obtained with the 30-65 and 34-35 crusts are systematically shifted with respect to each other and to the one resulting from the SLy low density model. This shift measures the additional uncertainty, in radius only, due to the unknown crust equation of state. The gravitational-wave constraints on tidal deformation are insensitive to the crust. We can estimate the **systematic error on R** as $\Delta R^- = R^m_{SLy} - R^m_{30-65}$, $\Delta R^+ = R^m_{34-35} - R^m_{SLy}$ from the 2D distributions; as $\Delta R^+ = R^{95}_{34-35} - R^{95}_{SLy}$, $\Delta R^- = R^5_{SLy} - R^5_{30-65}$ from crust + CLs.

	ΔR_1^+	ΔR_1^-	ΔR_2^+	ΔR_2^-	ΔR_1^T	ΔR_2^T
Previous Posteriors	0.1	0.2	0.1	0.2	0.3	0.3
Crust+CLs	0.2	0.1	0.2	0.1	0.3	0.3

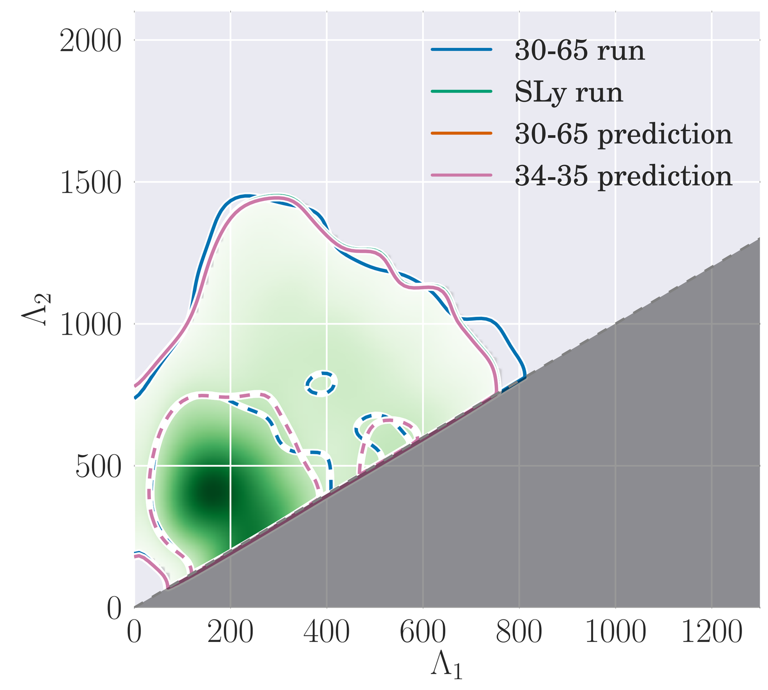

Figure 3: *Λ vs M distributions, almost perfectly superimposed. The gravitational-wave constraints on tidal deformation are insensitive to the crust*

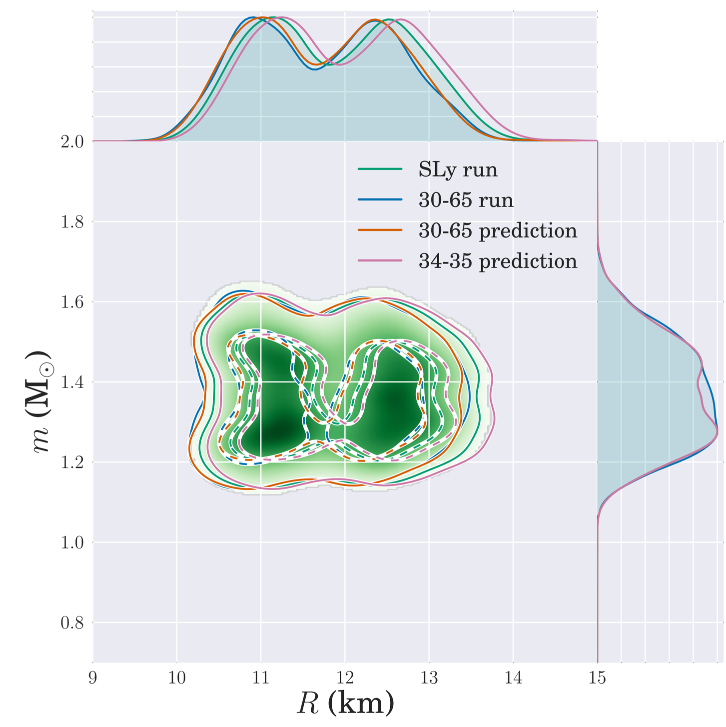

Figure 4: *M vs R distributions. Their shift measures the additional uncertainty, in radius only, due to the unknown crust equation of state*

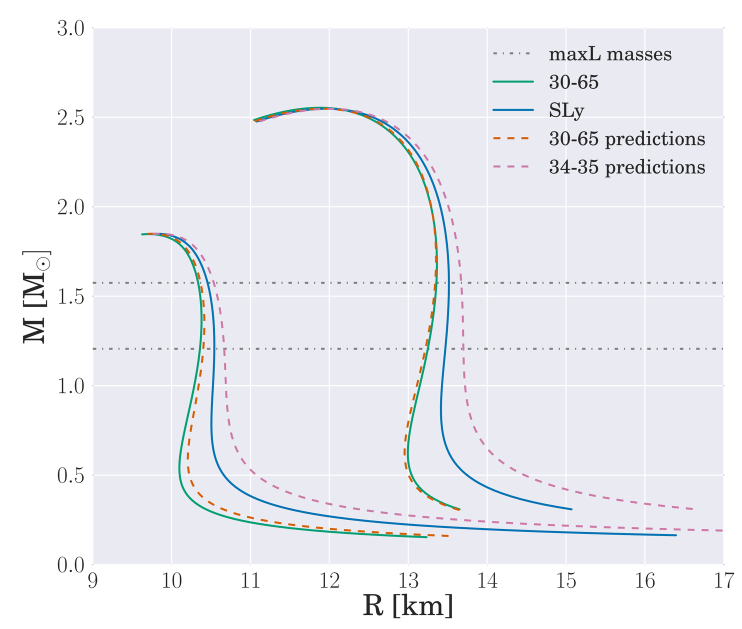

Figure 5: *The $M(R)$ curves differ more for low-mass NS*

6. Conclusions

We learned that:

- Tidal parameters have low sensitivity with respect to the crust density

  ⇒ GW measurements give more direct information on higher densities

  ⇒ in this region the constraints obtained from analyses are independent of uncertainties in crust
- The systematic error is mass dependent: the lower the mass, the bigger the radii variations (the crust becomes overall more important)

New R values for GW170817:

- $R_1 = (11.9^{+1.4+0.1}_{-1.4-0.2})$ km
- $R_2 = (11.9^{+1.4+0.1}_{-1.4-0.2})$ km.

References

[1] Abbott B P *et al.* (LIGO Scientific, Virgo) 2018 *Phys. Rev. Lett.* **121** 161101 (*Preprint* `1805.11581`)

[2] Douchin F and Haensel P 2001 *Astron. Astrophys.* **380** 151 (*Preprint* `astro-ph/0111092`)

[3] Newton W G, Gearheart M and Li B A 2013 *Astrophys. J. Suppl.* **204** 9 (*Preprint* `1110.4043`)

[4] Lindblom L 2010 *Phys. Rev.* **D82** 103011 (*Preprint* `1009.0738`)

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