Constraining neutron star equation of state using multi-band independent measurements of radii and tidal deformabilities

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Using a Bayesian approach, we combine measurements of neutron star (NS) macroscopic observables obtained by astrophysical and gravitational observations to derive joint constraints on the equation of state (EoS) of matter at supranuclear density. In our analysis we use two sets of data: (i) the masses and tidal deformabilities measured in the binary neutron star event GW170817, detected by LIGO and Virgo; (ii) the masses and stellar radii measured from observations of nuclear bursts in accreting low-mass X-ray binaries. Using two different parametrizations of the equation of state, we compute the posterior probability distributions of the EoS parameters, and then we infer the posterior distribution for the radius and the mass of the two neutron stars of GW170817. The constraints we set on the radii are tighter than previous bounds.

Introduction

The lack of information on the nature of the neutron star core at supranuclear densities has so far prevented a unique description of its EoS. In this work we have made a step forward in this search, by combining independent measurements of NS macroscopic parameters, namely the mass and the tidal deformabilities from the LIGO/Virgo event [3], and the mass and the radius derived from EM observations of low mass X-ray binaries [4], in the spirit of multi-messenger astrophysics. Including in our analysis more massive stars, i.e. those with mass and radius estimated through EM observations, we are probing the EoS in a region where the energy density is larger with respect to that probed by the LIGO/Virgo collaboration (LVC) analysis.

Parametrized equation of state

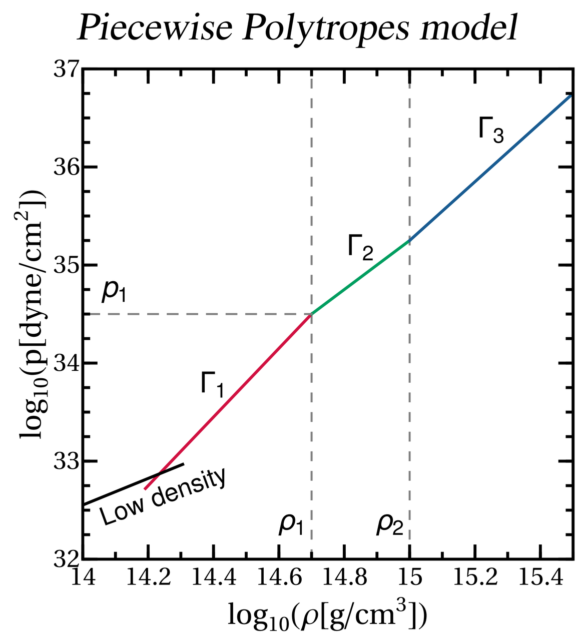
We parametrize the EoS using:

i) The piecewise polytropic model by Read *et al.* [1].

$$\vec{\theta}^{EoS} = (p_1, \Gamma_1, \Gamma_2, \Gamma_3).$$

ii) The spectral representation by Lindblom [2]. This model is based on a series expansion of the adiabatic index $\Gamma(p) = \exp[\sum_{k=0}^{3}\gamma_k(\log[(p/p_0)])^k]$, where p_0 is the pressure at the crust-core interface, which we choose as in [3]. It has been shown that most theoretical EoS are well approximated including the first four terms in the expansion, which correspond to the 4 free parameters of the model:

$$\vec{\theta}^{EoS} = (\gamma_0, \gamma_1, \gamma_2, \gamma_3).$$



The Bayesian framework

The parameters included in our analysis are: $\vec{\theta} = (\vec{\theta}^{EoS}, p^c_{i=1,...,4})$, where p^c_i are the central pressures of the stars. We reconstruct the posterior probability distribution: $\mathcal{P}(\vec{\theta}|\vec{d}) \propto \mathcal{P}_0(\vec{\theta})\,\mathcal{L}(\vec{d}|\vec{\theta})$, where $\mathcal{P}_0(\vec{\theta})$ describes the prior information on the parameters, and $\mathcal{L}(\vec{d}|\vec{\theta})$ is the likelihood function. In our case:

$$\mathcal{L}(\vec{d}|\vec{\theta}) = \mathcal{L}^{GW}(M_1, \Lambda_1, M_2, \Lambda_2) \times \mathcal{L}^{EM}(M_3, R_3) \times \mathcal{L}^{EM}(M_4, R_4)$$

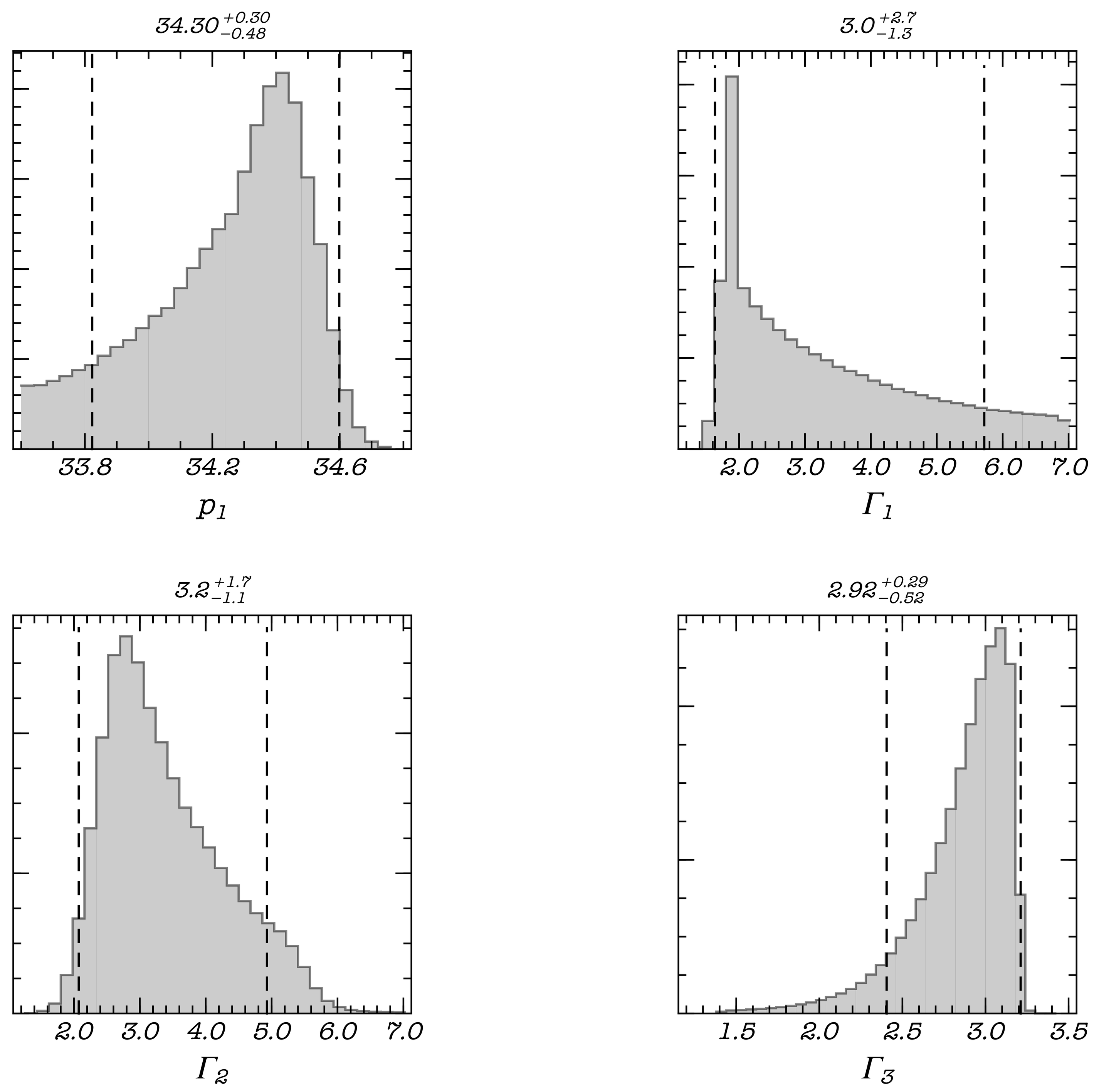
$\mathcal{L}^{GW}(M_1, \Lambda_1, M_2, \Lambda_2)$: joint probability distribution for the masses and tidal deformabilities of GW170817 inferred by the LVC using a parametrised EoS [3]. Median and 90% confidence intervals:

$M_1 = 1.46^{+0.13}_{-0.09}\,M_\odot$ $\Lambda_1 = 255^{+416}_{-171}$ $M_2 = 1.26^{+0.09}_{-0.12}\,M_\odot$ $\Lambda_2 = 661^{+858}_{-375}$.

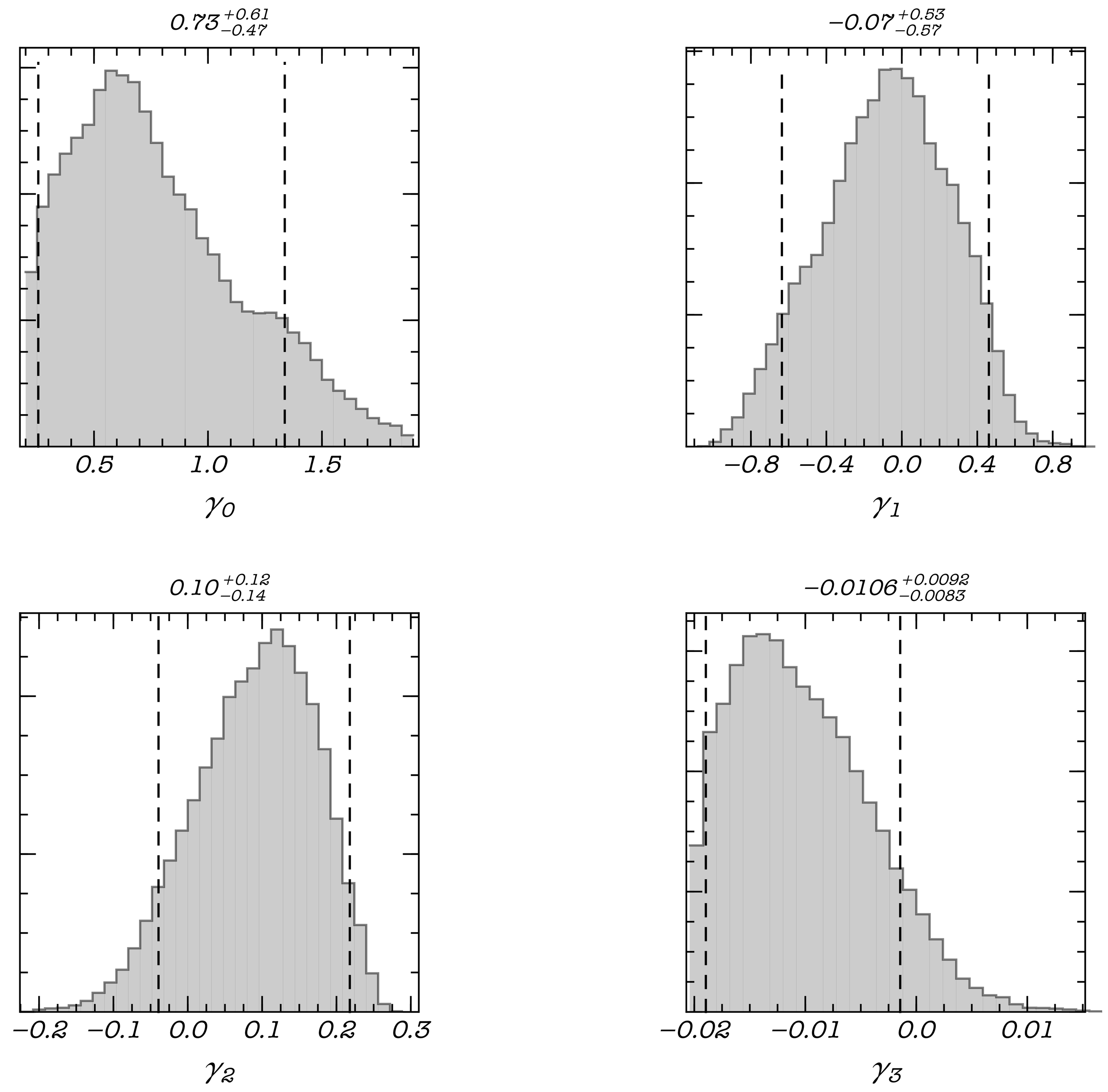
$\mathcal{L}^{EM}(M_i, R_i)_{i=3,4}$: the joint probability distributions of two NSs in low-mass X-ray binaries observed during thermonuclear bursts, namely 4U 1724-207 and EXO 1745-248 [4]. Median and 90% confidence intervals:

$M_3 = 1.81^{+0.36}_{-0.48}\,M_\odot$ $R_3 = 11.46^{+2.53}_{-2.49}$ km $M_4 = 1.60^{+0.36}_{-0.42}\,M_\odot$ $R_4 = 10.33^{+2.75}_{-2.38}$ km.

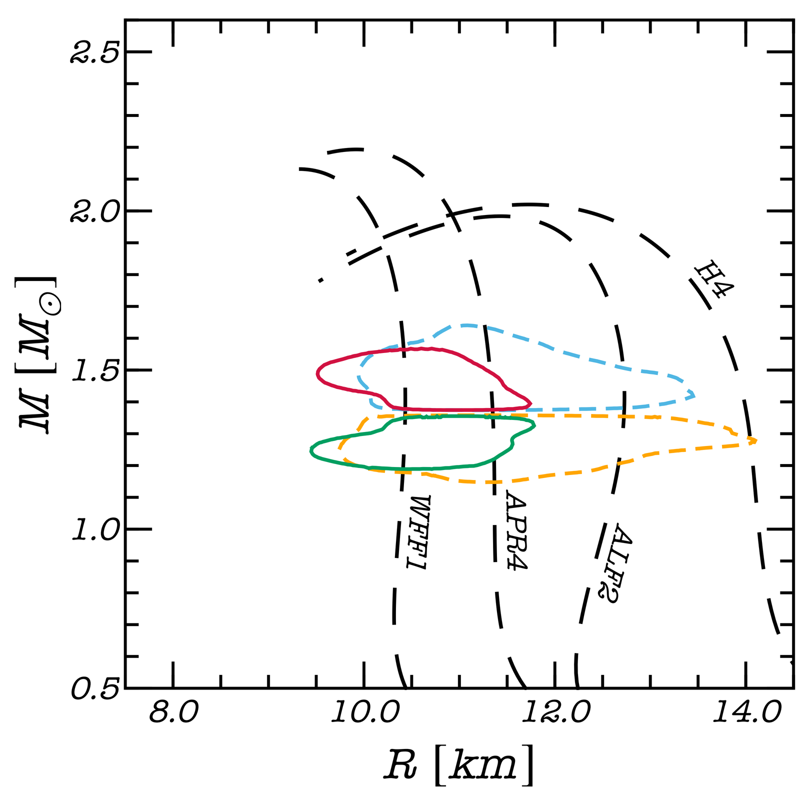
Results



Posterior distributions of the parameters of the piecewise polytropic model, derived through the multi-messenger analysis. Dashed vertical lines identify 90% confidence intervals, also shown on top of each panel with the median values.



Posterior distributions of the parameters of the spectral representation.



90% confidence regions for the posterior distribution of mass M and radius R of the two neutron stars of GW170817, built using the spectral (solid curves) and piecewise polytropic (dashed curves) EoS. Black curves identify the mass-radius profiles for some theoretical EoS.

The median values of mass and radius for the two stars, at 90% confidence level for the piecewise polytropic model:

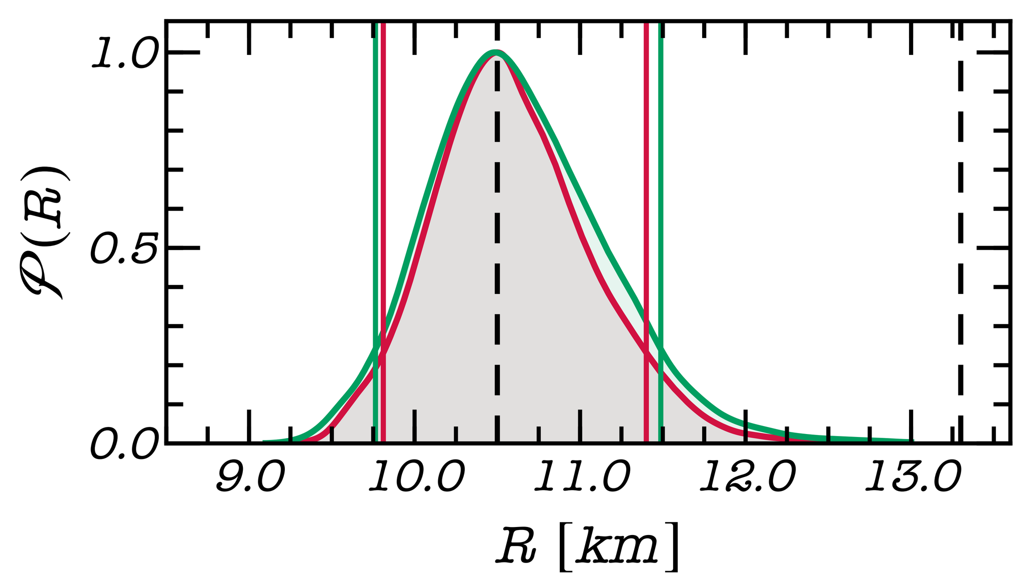
$\mathbf{M_1 = 1.45^{+0.12}_{-0.07}\,M_\odot}$ $\mathbf{R_1 = 11.29^{+1.40}_{-1.18}}$ **km** $\mathbf{M_2 = 1.27^{+0.07}_{-0.10}\,M_\odot}$ $\mathbf{R_2 = 11.39^{+1.67}_{-1.45}}$ **km**

and for the spectral representation:

$\mathbf{M_1 = 1.47^{+0.07}_{-0.09}\,M_\odot}$ $\mathbf{R_1 = 10.56^{+0.84}_{-0.75}}$ **km** $\mathbf{M_2 = 1.26^{+0.08}_{-0.09}\,M_\odot}$ $\mathbf{R_2 = 10.58^{+0.90}_{-0.82}}$ **km**

Conclusions

The analysis we perform seems to prefer configurations which are more compact than those inferred by the LVC data alone, indicating a softer equation of state in the core.



Posterior distributions for the radii of the two neutron stars of GW170817, reconstructed through the spectral representation. Red and green colors refer, respectively, to R_2 and R_1. Vertical lines correspond to intervals at 90% of probability derived by the LVC (dashed) and through our analysis (solid).

References

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[2] L. Lindblom, Phys. Rev. D **82**, 103011 (2010).

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

[4] F. Ozel, D. Psaltis, T. Guver, G. Baym, C. Heinke, and S. Guillot, Astrophys. J. **820**, 28 (2016).