Properties of the secondary component of GW190814

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GW190814

- Measured chirp mass, $\mathcal{M} = 6.09^{+0.06}_{-0.06} M_\odot$
- Mass ratio, $q = 0.112^{+0.008}_{-0.009}$
- Primary mass, $m_1 = 23.2^{+1.1}_{-1.0} M_\odot$, definitely a black hole (BH)
- Secondary mass, $m_2 = 2.59^{+0.08}_{-0.09} M_\odot$, may be a neutron star (NS)!
- No discernible tidal signature
- Spin of the secondary is also unconstrained.
- No electromagnetic counterpart has been observed.

Aim of this work (arXiv:2010.02090) is to study the odds of the secondary being a NS considering several possible physical conditions.

NS Structure

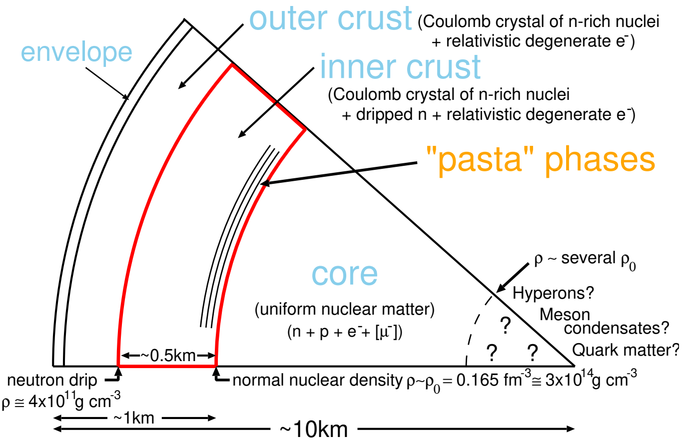
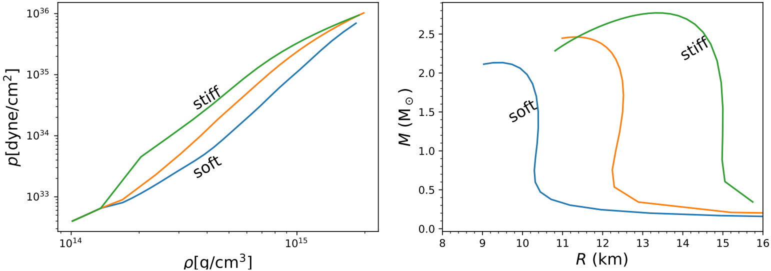


Figure: **Schematic picture of a NS Interior**

EoS and Mass-Radius

$P = P(\rho)$ ⟷ $M = M(R)$



One to one correspondence between EoS and mass-radius

Empirical EoS parameterization

pressure as a function of energy

energy per particle of nuclear matter

$$p(\rho,\delta) = \rho^2 \frac{d}{d\rho}(e_0(\rho,\delta))$$

symmetric nuclear matter

symmetry energy

$$e_0(\rho,\delta) \approx e_0(\rho) + e_{sym}\delta^2$$

$$e_0(\rho) = e_0(\rho_0) + \frac{K_0}{2}\chi^2 + \frac{J_0}{6}\chi^3$$

$$e_{sym}(\rho) = e_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \frac{J_{\rm sym}}{6}\chi^3$$

$\delta =$ "symmetry parameter" $= (\rho_{\rm n} - \rho_{\rm p})/\rho$, $\quad \chi = (\rho - \rho_0)/3\rho_0$

Prior

Prior ranges based on terrestrial experiments

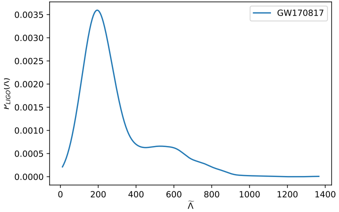
$e_0(\rho_0) = -15.9$ MeV,
$\rho_0 = 0.16\ \mathrm{fm}^{-3}$

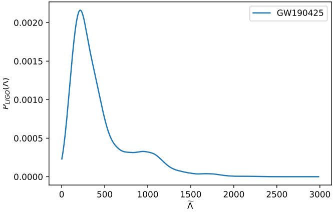
Parameter [MeV]	Prior
K_0	$\mathcal{N}(240, 30)$
$e_{\rm sym}$	$\mathcal{N}(31.7, 3.2)$
J_0	uniform(-800,3000)
L	$\mathcal{N}(58.7, 28.1)$
$K_{\rm sym}$	uniform(-800,100)
$J_{\rm sym}$	uniform(-1000,3000)

- Lowest order parameters are well determined
- uncertainties in K_0, $e_{\rm sym}$ and L are large but plenty of experimental results $\longrightarrow$ Gaussian priors
- higher order parameters are almost unconstrained $\longrightarrow$ uniform prior
- Additional constraints
  - monotonicity
  - causality
  - $2M_\odot$ criteria

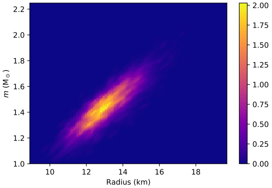
Data from earlier observations

$\widetilde{\Lambda}$ Likelihood from GW170817 & GW190425





NICER M-R Likelihood by Miller et al. 2019



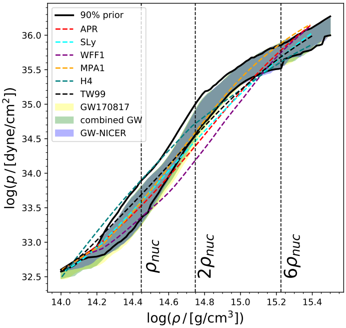
EoS posterior,

$$P(\theta|\mathrm{data}) = \mathrm{C}\mathrm{P}(\mathrm{data}|\theta) \times \mathrm{P}(\theta)\,,$$

where

$$P(\mathrm{data}|\theta) = \mathrm{P}(\widetilde{\Lambda}_{\mathrm{GW}}|\theta) \times \mathrm{P}(\mathrm{M}_{\mathrm{NICER}}, \mathrm{R}_{\mathrm{NICER}}|\theta)$$

Constraint based on earlier observations: GWs+NICER



Key features :

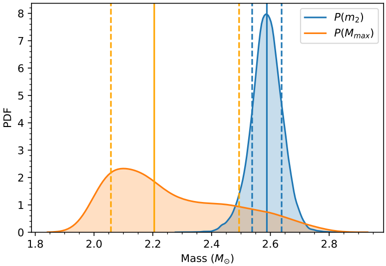
- implies stiffer EoS
- tension between nuclear physics and astrophysical observations

Reported in Biswas et al. 2020 (arXiv:2008.01582).

Quantity	170817	+190425	+NICER
$R_{1.4}$[km]	$12.66^{+0.60}_{-1.07}$	$12.73^{+0.54}_{-0.87}$	$12.72^{+0.51}_{-0.65}$
$\Lambda_{1.4}$	613^{+209}_{-257}	631^{+191}_{-212}	624^{+180}_{-171}
$M_{\max}(M_\odot)$	$2.22^{+0.44}_{-0.20}$	$2.22^{+0.41}_{-0.20}$	$2.21^{+0.42}_{-0.20}$

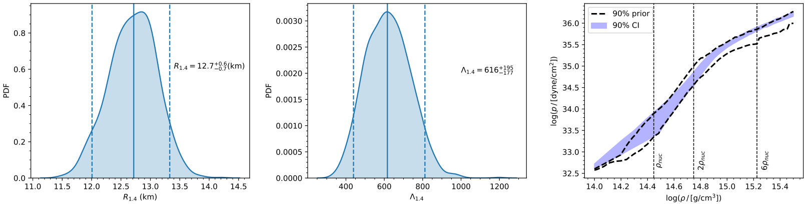
GW190814: Observation of a Lightest BH or heaviest NS?

- Used empirical EoS posterior samples from Biswas et al. 2020 to get $P(M_{\mathrm{max}})$
- Used publicly available LVC posterior of GW190814
- $P(m_2 > M_{max}) = .91$, BH = 91%, NS=9%



- rapid rotation can increase NS mass upto 20% $\Rightarrow$ another possibility

Properties assuming slowly rotating NS



- GW170817, GW190425 and NICER data are combined
- Instead of $2M_\odot$ hard cut-off full posterior of secondary mass of GW190814 is used as maximum mass threshold
- bound on $R_{1.4}$, $\Lambda_{1.4}$ agrees with LVC paper, Essick+(2020), INGO+(2020)
- Stringent constraint on high-density EoS

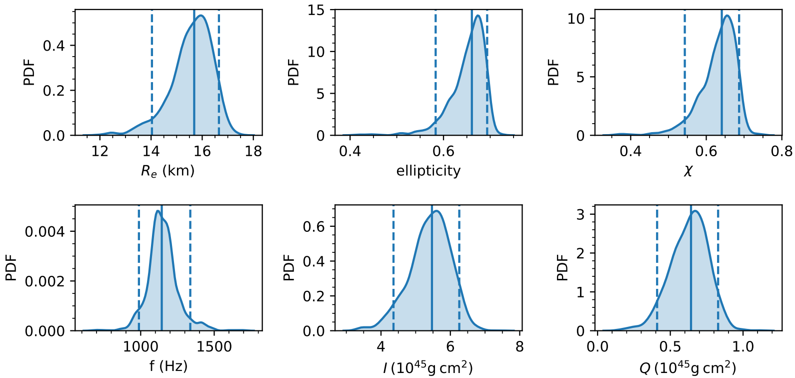
Inference technique assuming rapidly rotating NS

- GW170817, GW190425 and NICER data are used as nonrotating NS
- For nonrotating star a gaussian likelihood ($\mathcal{N}(2.14, 0.1)$) of $M_{\rm max}$ is considered.
- Used a universal relation found by Breu and Rezzolla, 2016.

$$M^{\rm rot}_{\rm rmax} = M^{\rm TOV}_{\rm max}\left(1 + a_1\left(\frac{\chi}{\chi_{\rm kep}}\right)^2 + a_2\left(\frac{\chi}{\chi_{\rm kep}}\right)^4\right)$$

- Using Bayesian inference we simultaneously sample EoS parameters and $\chi/\chi_{\rm kep}$
- These posterior samples are then used as input in RNS code to deduce several properties of the secondary
- Error introduced by universal relation is marginalized over in our calculation.

Properties assuming rapidly rotating NS



Could be the fastest rotating NS!

R-mode instability and NS temperature

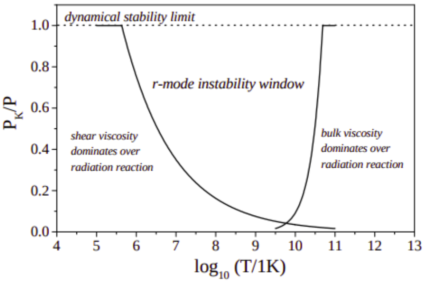


Fig. 3. The critical rotation rates at which shear viscosity (at low temperatures) and bulk viscosity (at high temperatures) balance gravitational radiation reaction due to the r-mode current multipole. This leads to the notion of a "window" in which the r-mode instability is active. The data in the figure is for the $l = m = 2$ r-mode of a canonical neutron star ($R = 10$ km and $M = 1.4 M_\odot$ and Kepler period $P_K \approx 0.8$ ms).

Figure: Andersson et al., 2000

R-modes and superfluid mutual friction

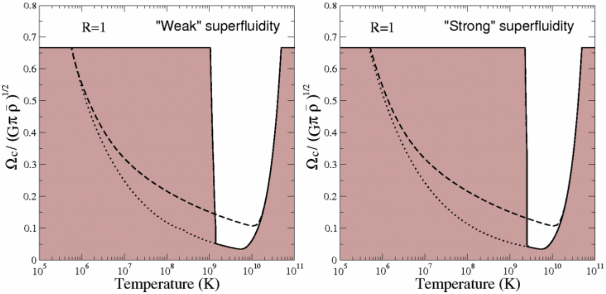
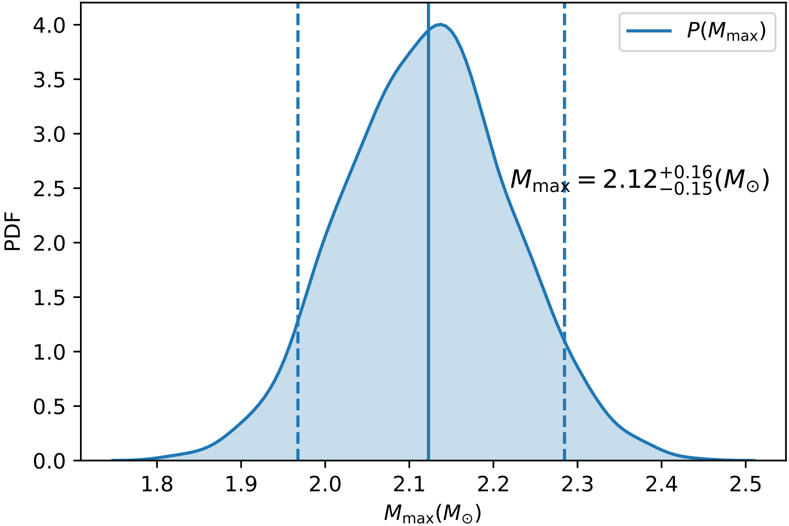


Figure 4. The r-mode instability window for $\varepsilon_p = 0.6$, calculated as a function of core temperature T and for $\mathcal{R} = 1$ in the 'weak' (left-hand panel) and 'strong' (right-hand panel) superfluidity cases. We consider a star with $M = 1.4\,M_\odot$ and $R = 10$ km. The dotted line indicates the shape the instability window has if we ignore mutual friction, while the dashed line indicates the effect that the Ekman layer at the base of the crust would have on the instability region. The results show that, when $\mathcal{R} = 1$, the mutual friction is strong enough to suppress the r-mode instability completely as soon as the core becomes superfluid.

Figure: Haskell et al., 2009

What if secondary of GW190814 is a BH



Summary:

- The probability of the secondary of GW190814 being a nonrotating NS depends on the EoS parameterization and the maximum mass threshold.
- Addition of GW190814 as an upper limit of maximum mass for nonrotating stars provides a very stringent constraint on the EoS specially in the high density region.
- Alternatively, if considered as a rapidly spinning NS, it would be the fastest rotating NS ever observed.
- However, without proper damping mechanism, it may have ended up a BH at some point of its evolution. This opens the possibility of constraining physical mechanisms, such as mutual friction in a superfluid interior.

Thank You