Constrains on the maximum mass of neutron stars with a quark core from LIGO/Virgo and *NICER*

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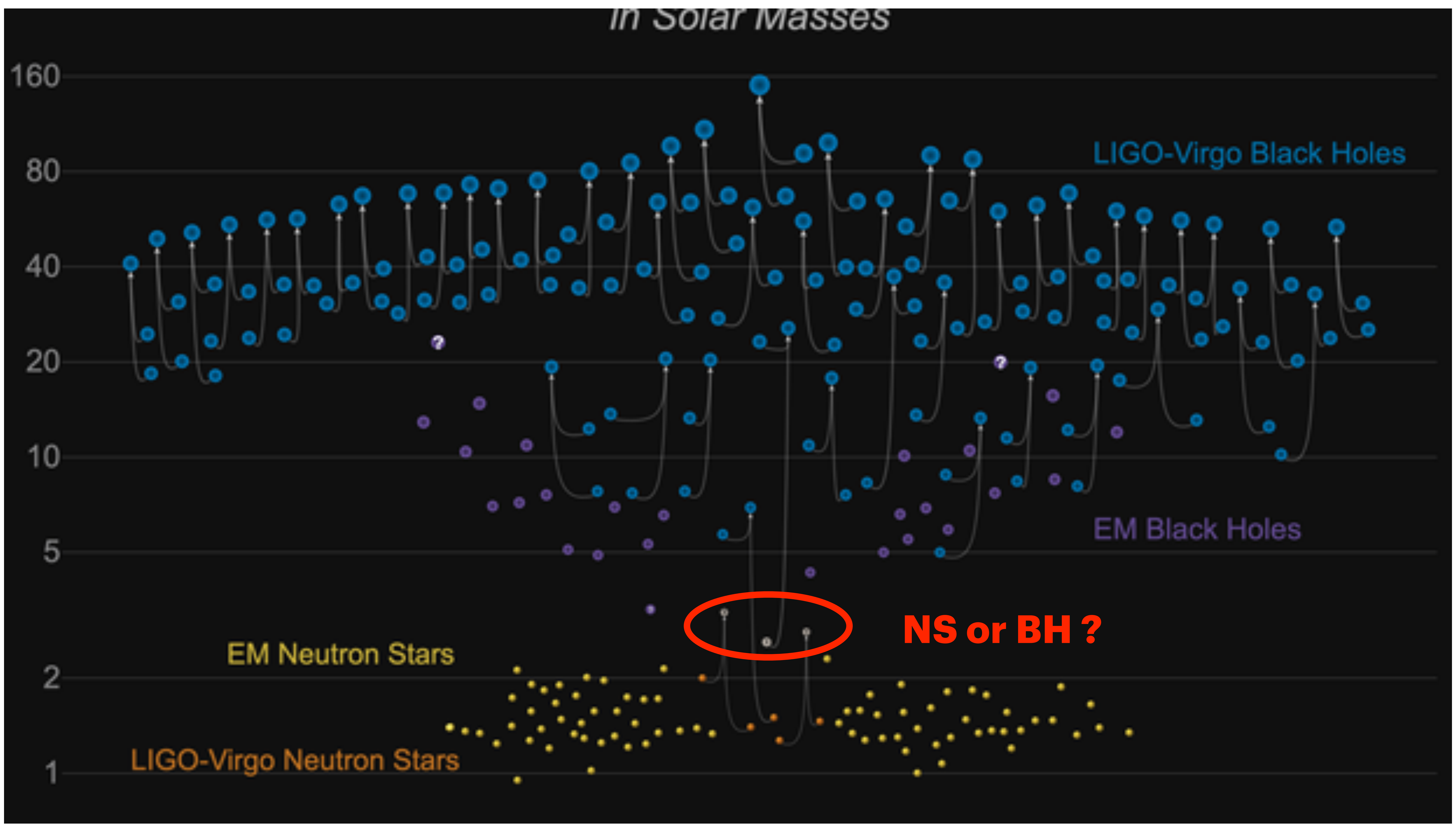
OUTLINE

- Introduction
- Constructing the EOS
- Constraining the EOS: a Bayesian approach
- Results
- Summary

Introduction

https://www.ligo.caltech.edu/news/ligo20201116



- Recently, there are few compact objects lying in the possible low mass gap $2.5 - 5\,M_\odot$ detected by LIGO/Virgo.
- The nature of these objects is still not known, due to the uncertainty of the maximum mass of NSs, $M_{\rm TOV}$

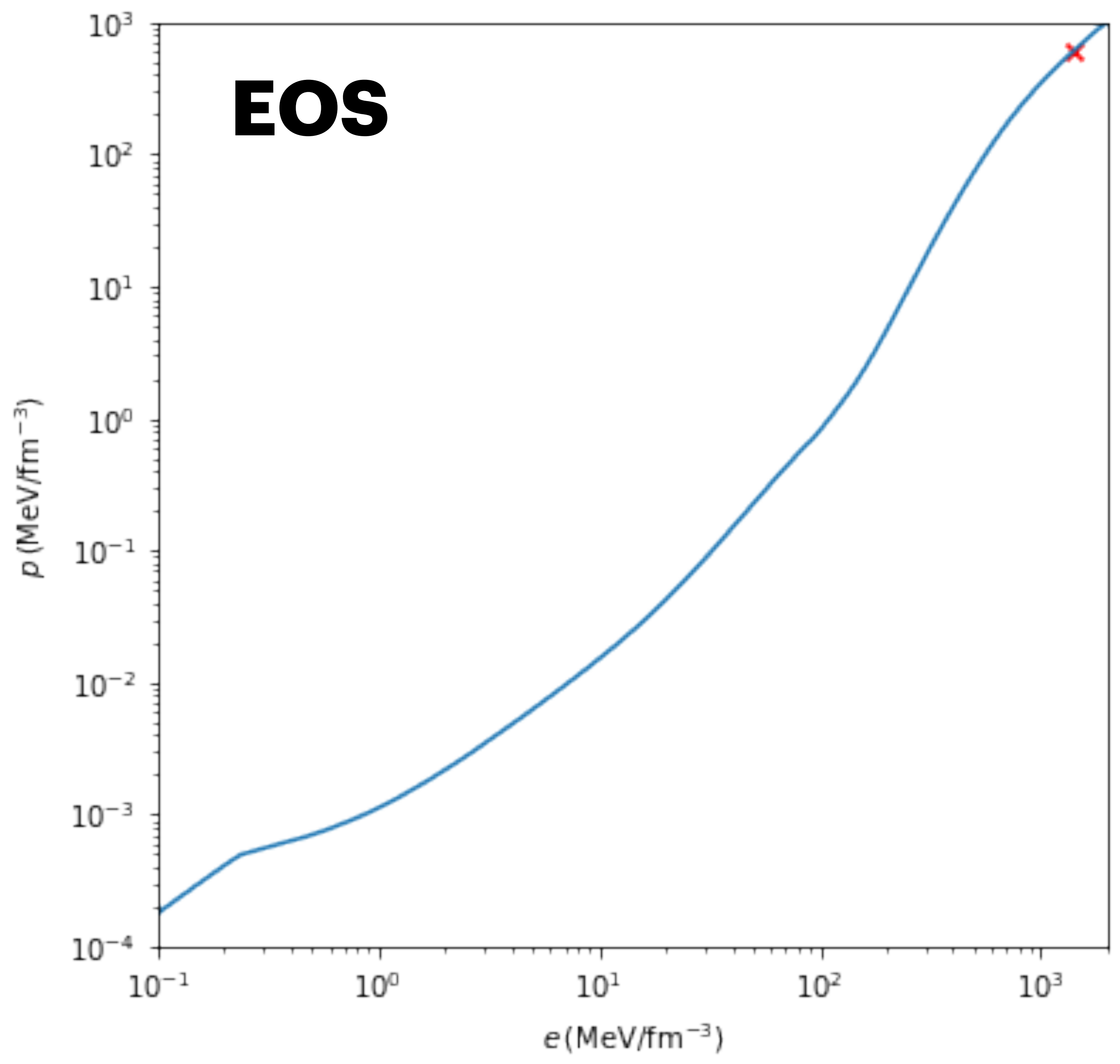
Introduction

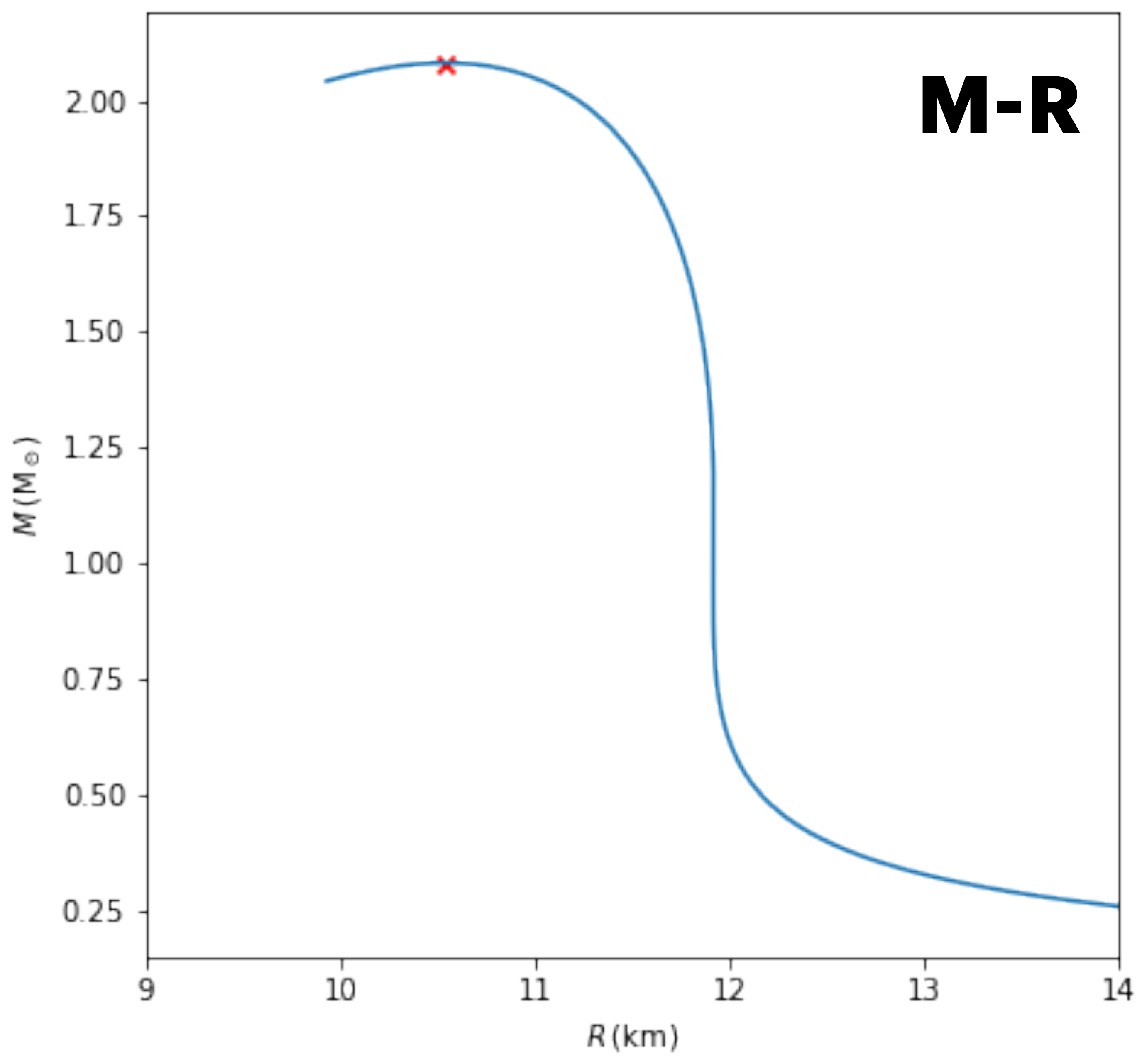
- Theoretically, the maximum mass can be derived from the underlying equation of state (EOS) through the TOV equations. Therefore, one can constrain the maximum mass by constraining the EOS.

- There are many NS observables that can put constraints on the EOS, e.g., the masses, the radii and the tidal deformability.

- However, the EOS constraints from LIGO/Virgo and NICER are usually based on e.g., the piecewise polytrope EOS model, which does not explicitly include phase transitions.

- In the following, we perform a Bayesian analysis to infer the maximum mass in the context of a first-order phase transition from hadronic matter into quark matter inside NSs' dense cores, by incorporating the available NS observations.





Constructing the EOS

We consider the EOS with a strong first-order phase transition.

- **Low density hadron matter:**

  To test the effect of low density hadronic EOS, we employ two representative EOSs, i.e.,

  soft EOS : QMF model
  or stiff EOS : DD2 model

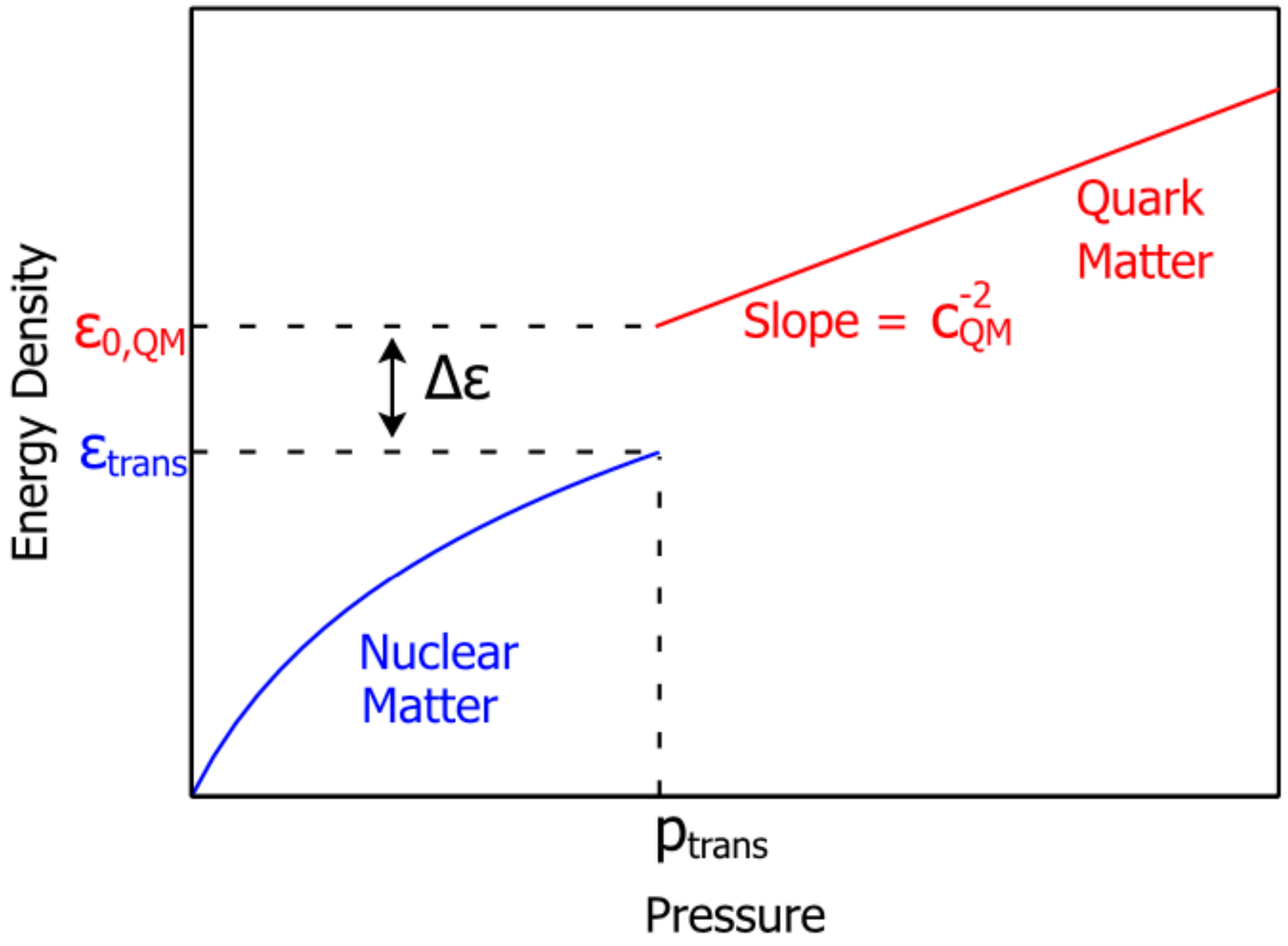
  Both two EOSs are consistent with experiment constraints at around nuclear saturation density.

- **High density quark matter — Constant Speed of Sound (CSS) parameterization**

  Parameters: $(n_{\rm trans}/n_0, \Delta\varepsilon/\varepsilon_{\rm trans}, c^2_{\rm QM})$

- **The full EOS is**

$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm HM}(p), & p < p_{\rm trans} \\ \varepsilon_{\rm HM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}), & p > p_{\rm trans} \end{cases}.$$



Alford et al. 2013

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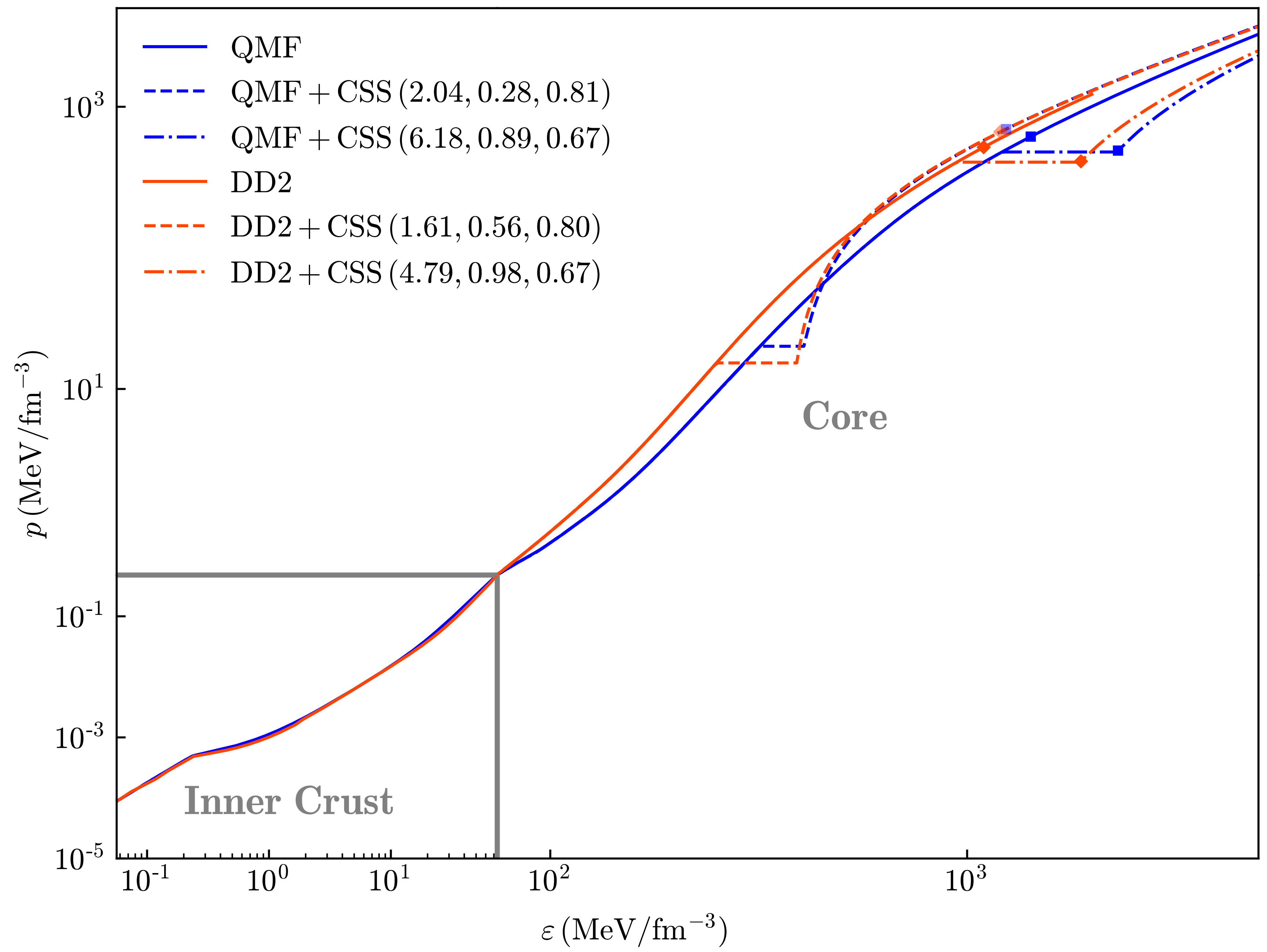
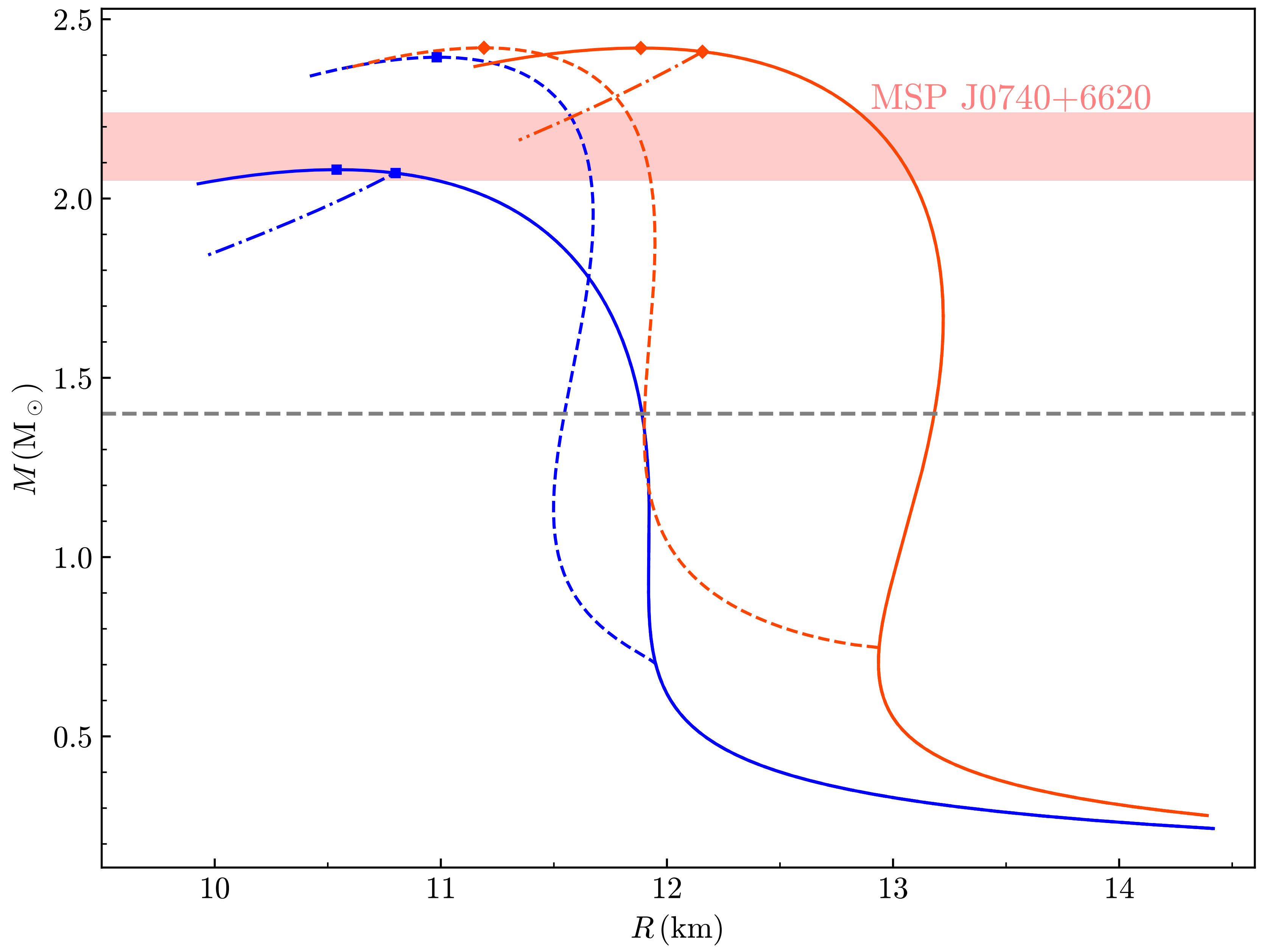




Constraining the maximum mass: a Bayesian approach

The Bayes's theorem

$$p(\boldsymbol{\theta}\,|\,\boldsymbol{d},\mathbb{M}) = \frac{p(\boldsymbol{\theta}\,|\,\mathbb{M})p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M})}{p(\boldsymbol{d}\,|\,\mathbb{M})} \propto p(\boldsymbol{\theta}\,|\,\mathbb{M})p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M})$$

$\mathbb{M}$: The QMF+CSS/DD2+CSS model

$\boldsymbol{\theta}$: parameters, including EOS parameters $\boldsymbol{\theta}_{\rm EOS} = \{n_{\rm trans}/n_0, \Delta\varepsilon/\varepsilon_{\rm trans}, c^2_{\rm QM}\}$ and $\boldsymbol{\theta}_{\rm GW}$

$\boldsymbol{d}$: observational data, including three measurements: the mass of MSP J0740+6620, the tidal deformability from GW170817 and mass-radius of PSR J0030+0451

$p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M})$: likelihood, which can be expressed as $p(\boldsymbol{d}\,|\,\boldsymbol{\theta},\mathbb{M}) = \mathscr{L}_{M_s} \times \mathscr{L}_{\rm GW} \times \mathscr{L}_{\rm PSR}$

$p(\boldsymbol{\theta}\,|\,\mathbb{M})$: prior for the parameters

Constraining the maximum mass: a Bayesian approach

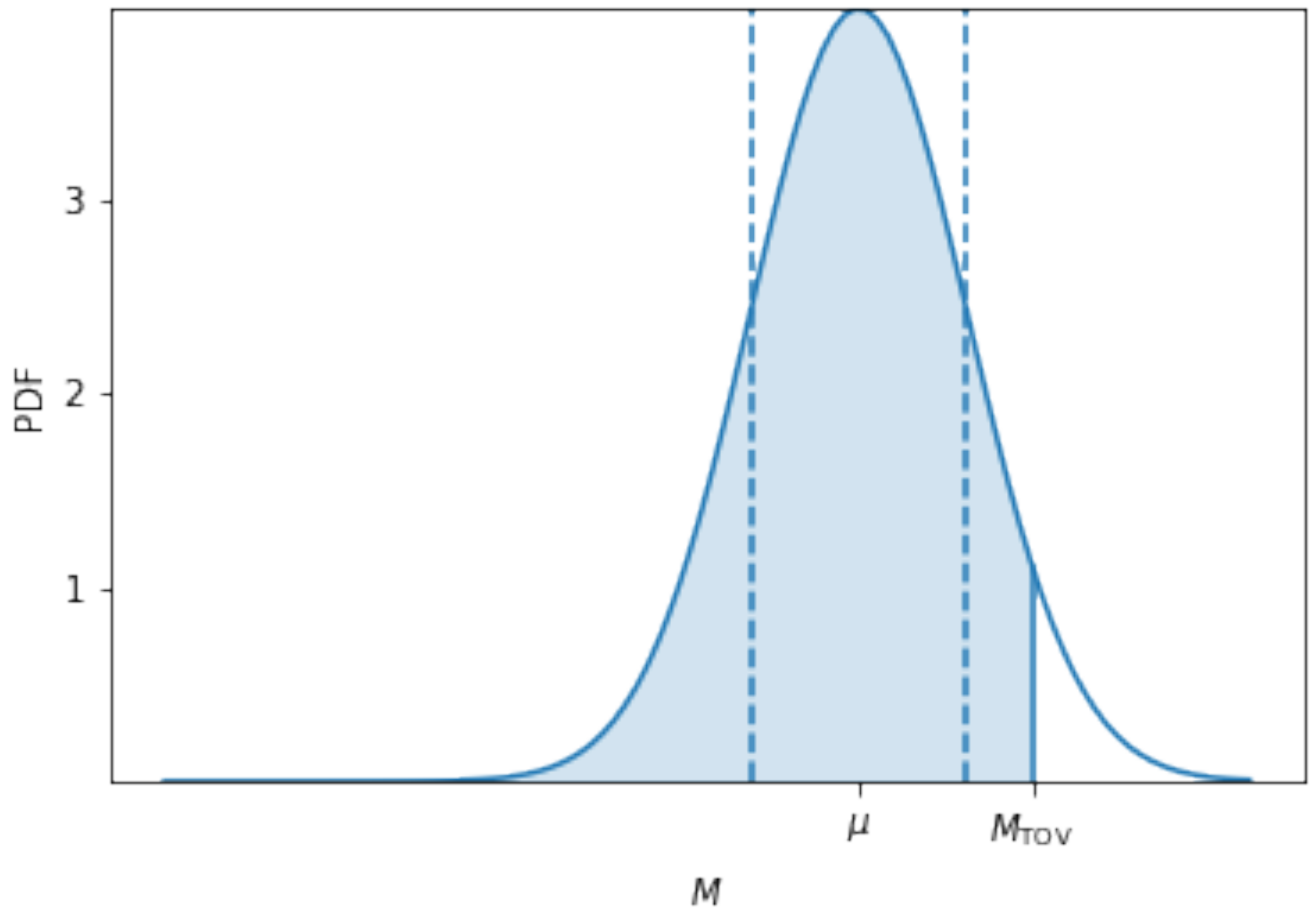
1. Lower bound on $M_{\rm TOV}$ from MSP J0740+6620

$$\mathscr{L}_{M_s} = \int_0^{M_{\rm TOV}(\boldsymbol{\theta}_{\rm EOS})} P(M_s) dM_s$$

For MSP J0740+6620, $\mu = 2.14\, M_\odot$ and $\sigma = 0.1\, M_\odot$

$$\mathscr{L}_{M_s} = \Phi(\frac{M_{\rm TOV}(\boldsymbol{\theta}_{\rm EOS}) - \mu}{\sigma})$$

$$\Phi(x) \equiv \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx$$



Constraining the maximum mass: a Bayesian approach

2. Tidal deformability from GW170817

   Assuming the noise in LIGO/Virgo detectors is stationary and Gaussian, the likelihood is often expressed as

$$\mathscr{L}_{\rm GW} \propto \exp(-2\int \frac{|\tilde{d}(f) - \tilde{h}(\boldsymbol{\theta}_{\rm GW}; f)|^2}{S_n(f)} df)$$

$\tilde{d}(f)$: the Fourier transforms of measured strain

$\tilde{h}(\boldsymbol{\theta}_{\rm GW}; f)$: the frequency domain waveform generated using parameter $\boldsymbol{\theta}_{\rm GW}$

$S_n(f)$: the power spectral density (PSD)

In our analysis, we choose the waveform template：IMRPhenomD_NRTidal

$$\boldsymbol{\theta}_{\rm GW} = \{\mathscr{M}, q, \Lambda_1, \Lambda_2, \chi_{1z}, \chi_{2z}, \varphi, \Psi, \theta_{\rm jn}, t_c, z, \alpha, \delta\}$$

$$\Lambda_1 = \Lambda_1(\boldsymbol{\theta}_{\rm EOS}; M_1) \qquad M_1 = \mathscr{M}(1+q)^{1/5}/q^{3/5}$$
$$\Lambda_2 = \Lambda_2(\boldsymbol{\theta}_{\rm EOS}; M_2) \qquad M_2 = M_1 q$$

Constraining the maximum mass: a Bayesian approach

3. Mass-radius measurement of PSR J0030+0451 from NICER

We employ a kernel density estimate of the mass-radius samples $\boldsymbol{S}$ from Riley et al. 2019 as the likelihood function, i.e.,

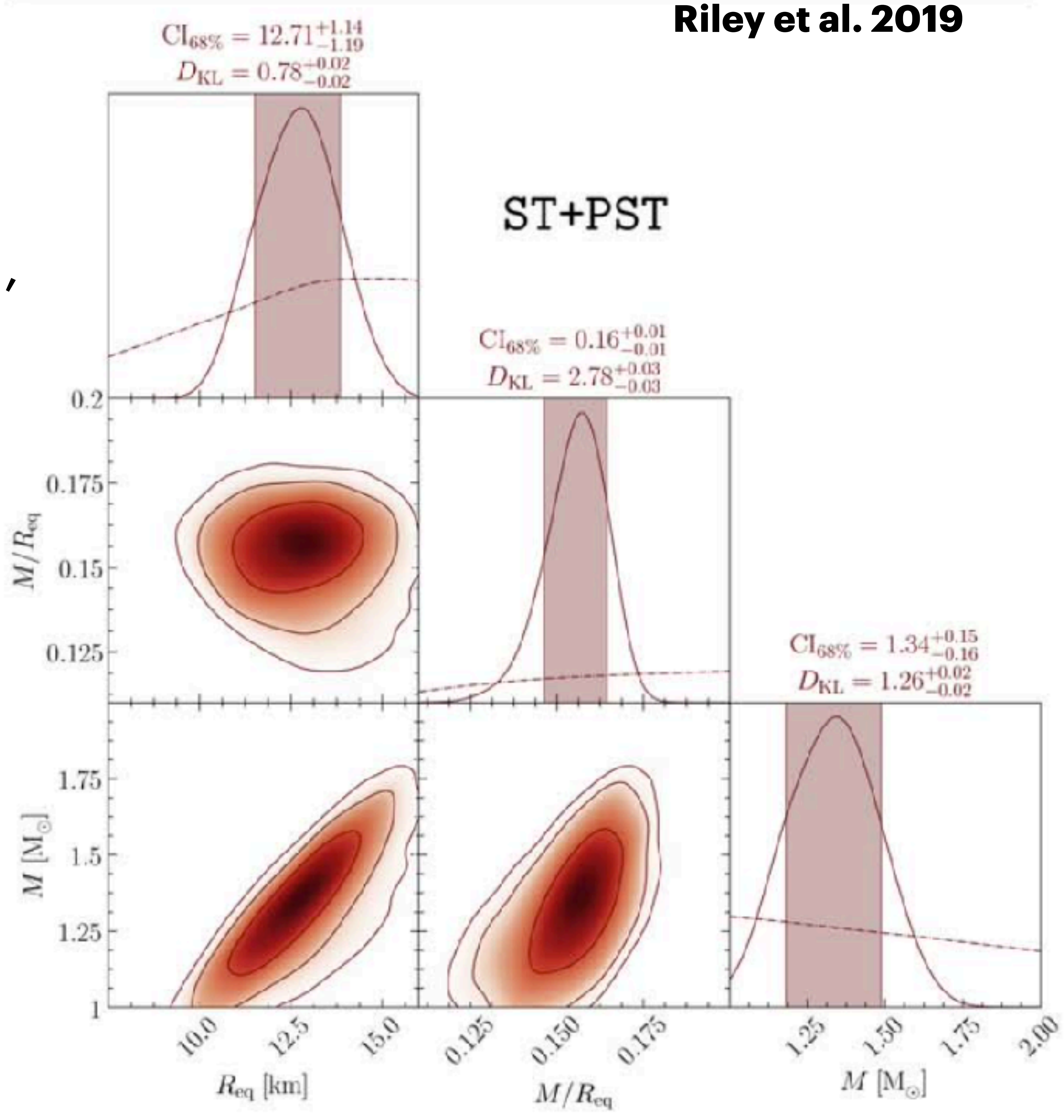
$$\mathscr{L}_{\mathrm{PSR}} = \mathrm{KDE}(M, R \,|\, \boldsymbol{S})$$

where the M and R can be mapped from the EOS and the central pressure, p_c ,

$$M = M(\boldsymbol{\theta}_{\mathrm{EOS}}; p_c)$$

$$R = R(\boldsymbol{\theta}_{\mathrm{EOS}}; p_c)$$

Riley et al. 2019



Constraining the maximum mass: a Bayesian approach

Parameters and Priors:

In total, our parameters set is

$$\boldsymbol{\theta} = \boldsymbol{\theta}_{\text{EOS}} \cup \boldsymbol{\theta}_{\text{GW}} \cup \{p_c\}$$

$$\boldsymbol{\theta}_{\text{EOS}} = \{n_{\text{trans}}/n_0, \Delta\varepsilon/\varepsilon_{\text{trans}}, c^2_{\text{QM}}\}$$

$$\boldsymbol{\theta}_{\text{GW}} = \{\mathscr{M}^{\text{det}}, q, \Lambda_1(M_1), \Lambda_2(M_2), \chi_{1z}, \chi_{2z}, \varphi, \Psi, \theta_{\text{jn}}, t_c, z, \alpha, \delta\}$$

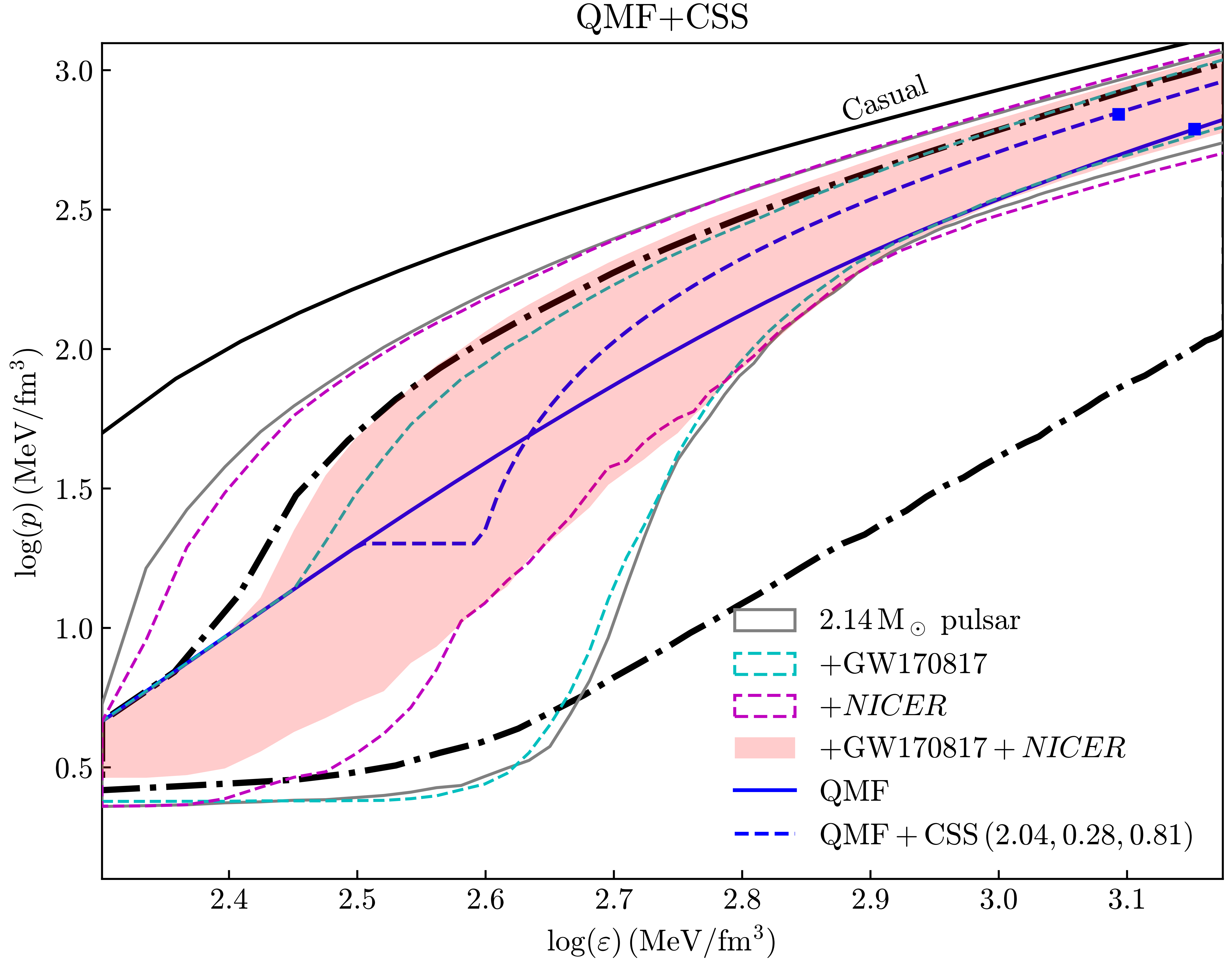
Priors for EOS parameters:

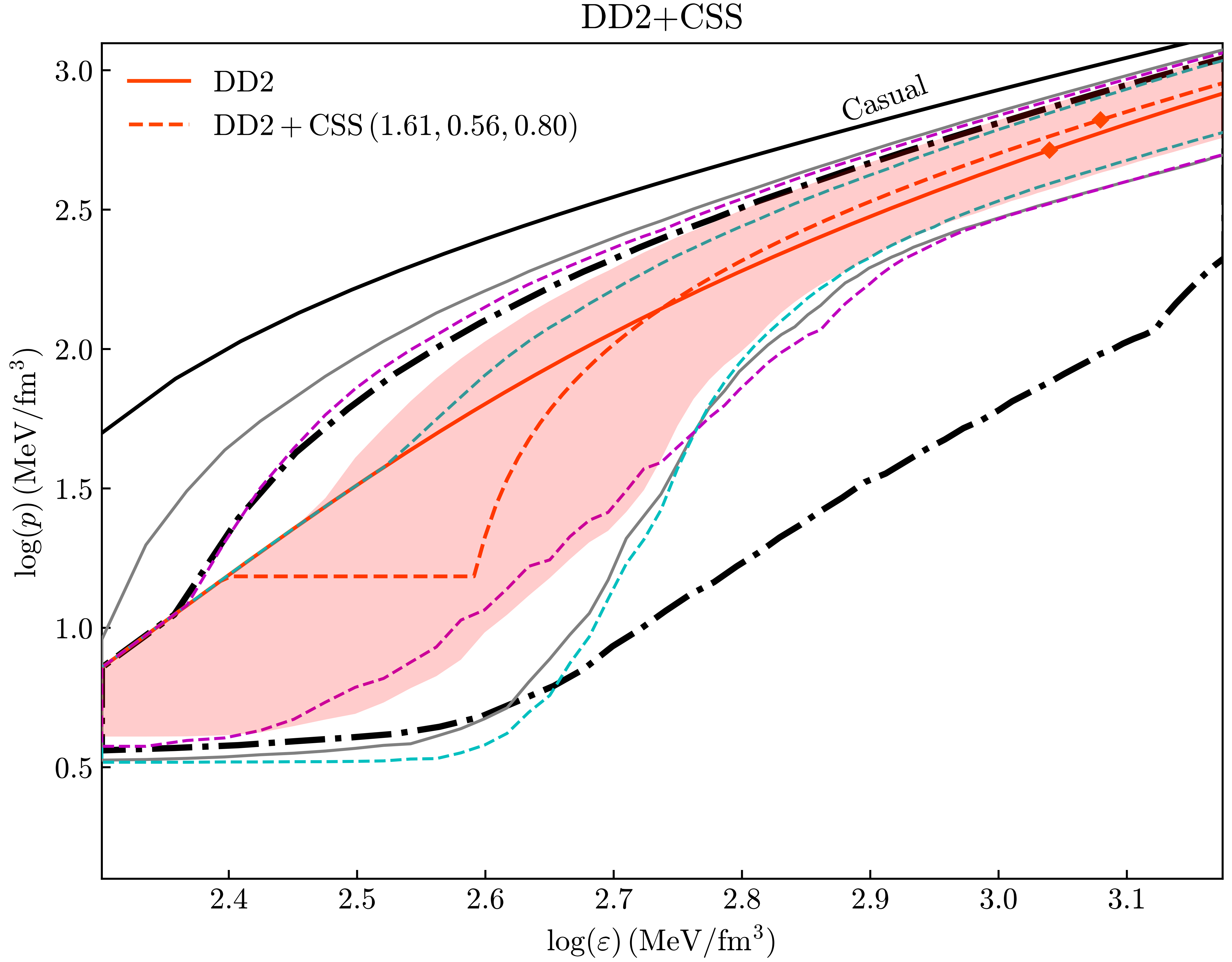
n_{trans}/n_0	U(1,7) for QMF+CSS
	U(1,6) for DD2+CSS
$\Delta\varepsilon/\varepsilon_{\text{trans}}$	U(0,2)
c^2_{QM}	U(1/3,1)

Priors for GW parameters:

$\mathscr{M}$	U(1.18,1.21) $M_\odot$
q	U(0.5,1)
χ_{1z}	U(-0.05,0.05)
χ_{1z}	U(-0.05,0.05)
φ	U(0,2π)
Ψ	U(0,2π)
$\cos\theta_{\text{jn}}$	U(-1,1)
t_c	U(1187008882,1187008883) s
z	0.0099
α	197.450374°
δ	−23.381495°

Results: the EOS

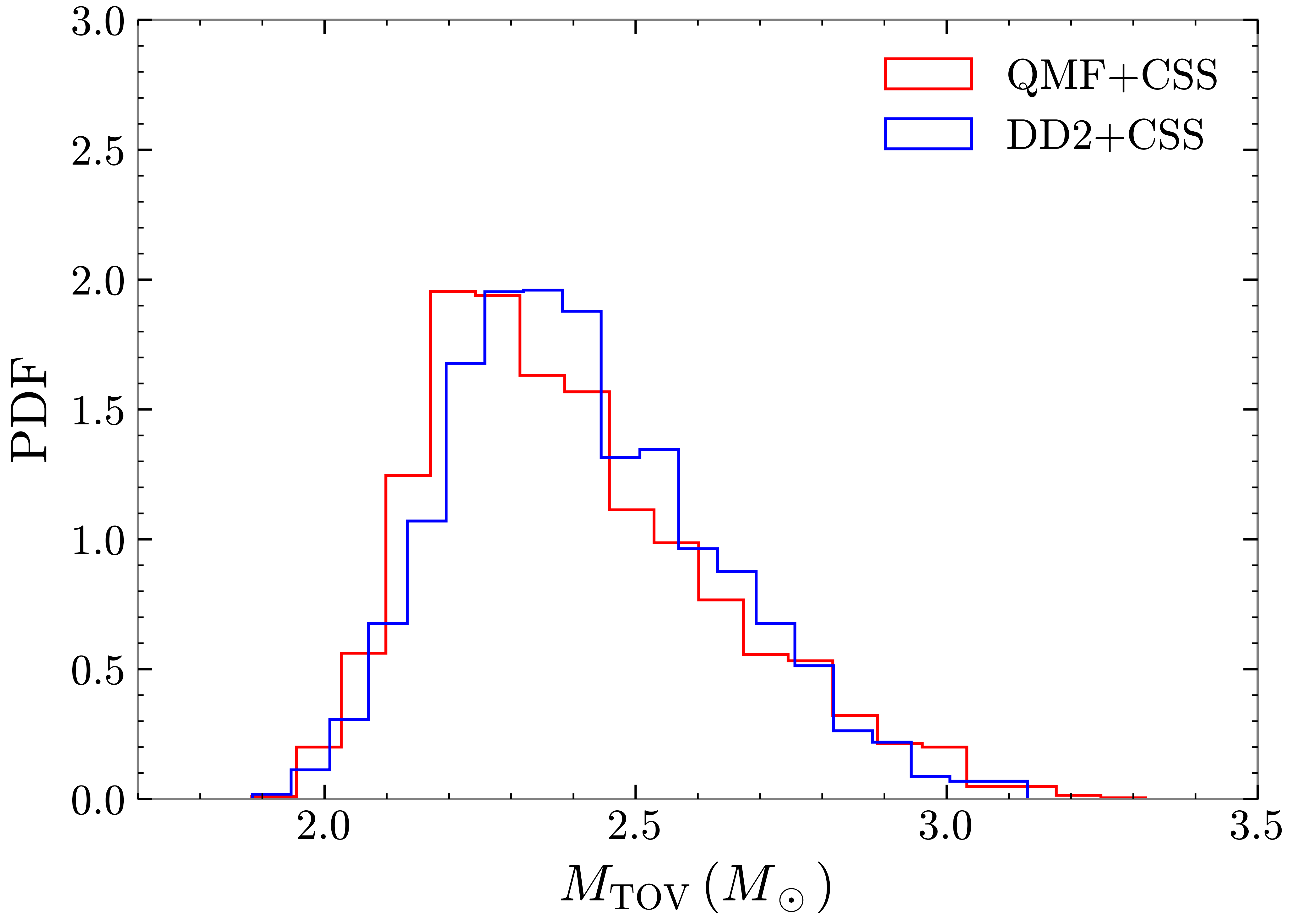




- Both GW170817 and J0030 data can put strong constraints on the EOS at densities $\sim 200 - 600\,\mathrm{MeV/fm^3}$ ($\sim 1.5 - 4\rho_0$).
- An early phase transition with a large sound speed quark core (i.e., $n_{\rm trans} \sim 2n_0$ and $c_{\rm QM} \sim 0.9$) is preferred by currently available NS observations.

Reults: NS properties

The Maximum Mass



The inferred maximum mass is found to be $M_{\rm TOV} = 2.36^{+0.49}_{-0.26}\,M_\odot$ ($M_{\rm TOV} = 2.39^{+0.42}_{-0.28}\,M_\odot$) for QMF (DD2) (90% credible interval), which is insensitive to the hadronic EOS

Our results imply that the remnant of GW170817 ($\sim 2.74\,M_\odot$) could be a massive rotating NS, while the remnant of GW190425 ($\sim 3.4\,M_\odot$) is more likely a black hole. The secondary component of GW190814 ($\sim 2.6\,M_\odot$) could also be a supermassive NS.

Reults: NS properties

Various properties for $1.4\,M_\odot$ and $2\,M_\odot$ stars (90% credible interval)

Parameters		$2.14\ M_\odot$ Pulsar	+GW170817	+NICER	+GW170817+NICER
$R_{1.4}$/km	QMF	$11.66^{+1.75}_{-1.70}$	$10.95^{+1.23}_{-0.86}$	$11.93^{+1.36}_{-0.99}$	$11.70^{+0.85}_{-0.74}$
	DD2	$12.36^{+1.49}_{-2.02}$	$11.10^{+1.66}_{-0.83}$	$12.58^{+0.79}_{-1.60}$	$11.95^{+1.04}_{-0.94}$
$\Lambda_{1.4}$	QMF	319^{+595}_{-194}	216^{+235}_{-85}	379^{+469}_{-188}	312^{+254}_{-124}
	DD2	449^{+625}_{-309}	214^{+329}_{-79}	486^{+337}_{-305}	333^{+298}_{-148}
$n^c_{1.4}/\mathrm{fm}^{-3}$	QMF	$0.45^{+0.20}_{-0.19}$	$0.52^{+0.12}_{-0.15}$	$0.41^{+0.18}_{-0.14}$	$0.48^{+0.13}_{-0.15}$
	DD2	$0.41^{+0.23}_{-0.16}$	$0.52^{+0.12}_{-0.15}$	$0.41^{+0.19}_{-0.13}$	$0.46^{+0.14}_{-0.12}$
$R_{2.0}$/km	QMF	$11.71^{+2.47}_{-1.53}$	$11.16^{+1.48}_{-0.92}$	$12.11^{+1.88}_{-1.37}$	$11.66^{+1.46}_{-1.02}$
	DD2	$12.64^{+1.84}_{-2.10}$	$11.23^{+1.70}_{-0.86}$	$12.65^{+1.17}_{-1.73}$	$12.05^{+1.18}_{-1.22}$
$\Lambda_{2.0}$	QMF	32^{+118}_{-23}	22^{+38}_{-12}	42^{+92}_{-30}	29^{+54}_{-17}
	DD2	51^{+111}_{-39}	22^{+40}_{-12}	49^{+64}_{-35}	36^{+44}_{-22}
$n^c_{2.0}/\mathrm{fm}^{-3}$	QMF	$0.57^{+0.32}_{-0.27}$	$0.65^{+0.23}_{-0.21}$	$0.52^{+0.33}_{-0.21}$	$0.60^{+0.27}_{-0.22}$
	DD2	$0.51^{+0.32}_{-0.23}$	$0.65^{+0.22}_{-0.20}$	$0.53^{+0.29}_{-0.20}$	$0.56^{+0.24}_{-0.17}$

$R_{1.4} \sim 12\,\mathrm{km}$

$\Lambda_{1.4} \sim 300$

Summary

Thank you!

- We perform a Bayesian analysis on the maximum mass of NSs with a quark core by using several recent measurements of NS observables.
- We find an early phase transition at onset density ($\sim 2n_0$) along with a large sound speed quark matter ($c_{\rm QM} \sim 0.9$) is preferred by these measurements.
- The inferred maximum mass is $M_{\rm TOV} \sim 2.4\, M_\odot$ for NSs with a quark core, which is insensitive to the hadronic EOS.