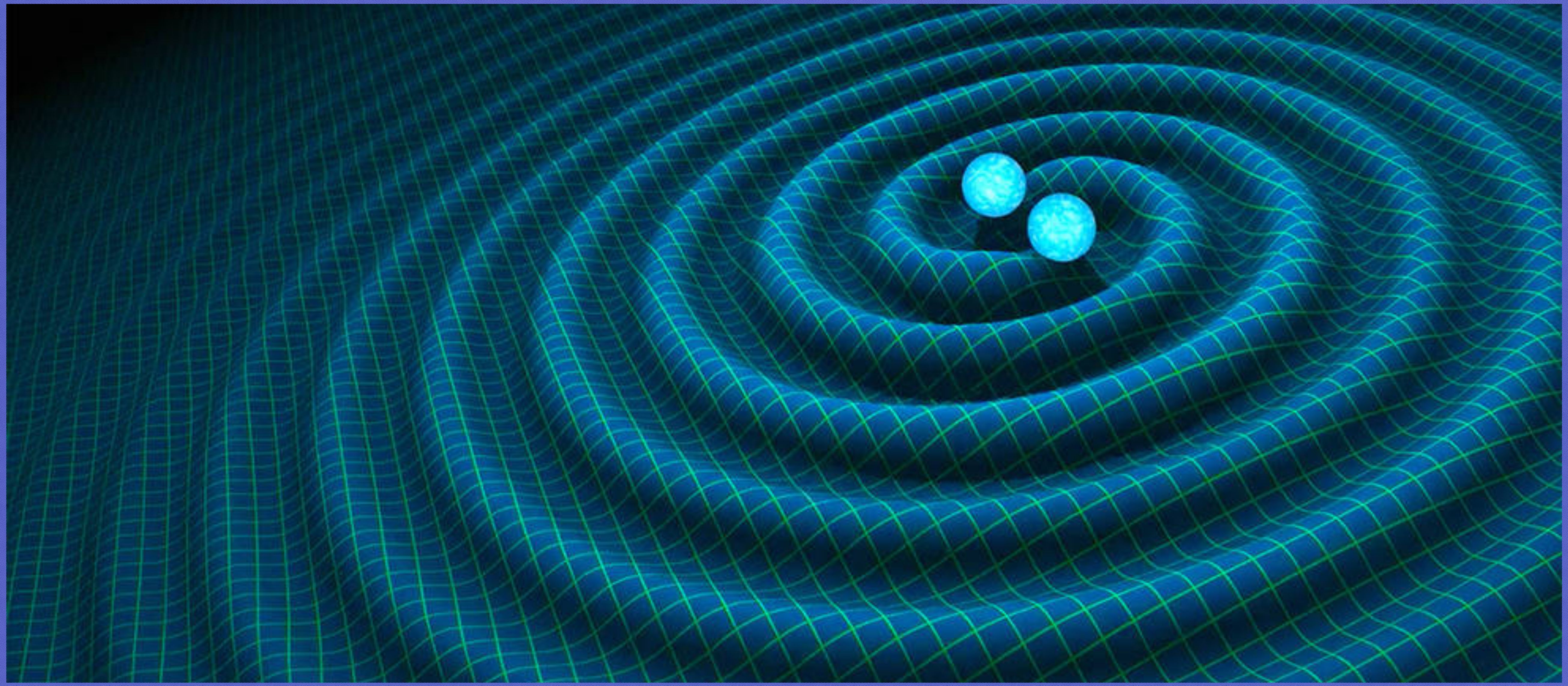
Simultaneously Constraining the Neutron Star Equation of State and Mass Distribution through Multimessenger Observations and Nuclear Benchmarks

Based on arXiv: 2408.15192 by Bhaskar Biswas & Stephan Rosswog



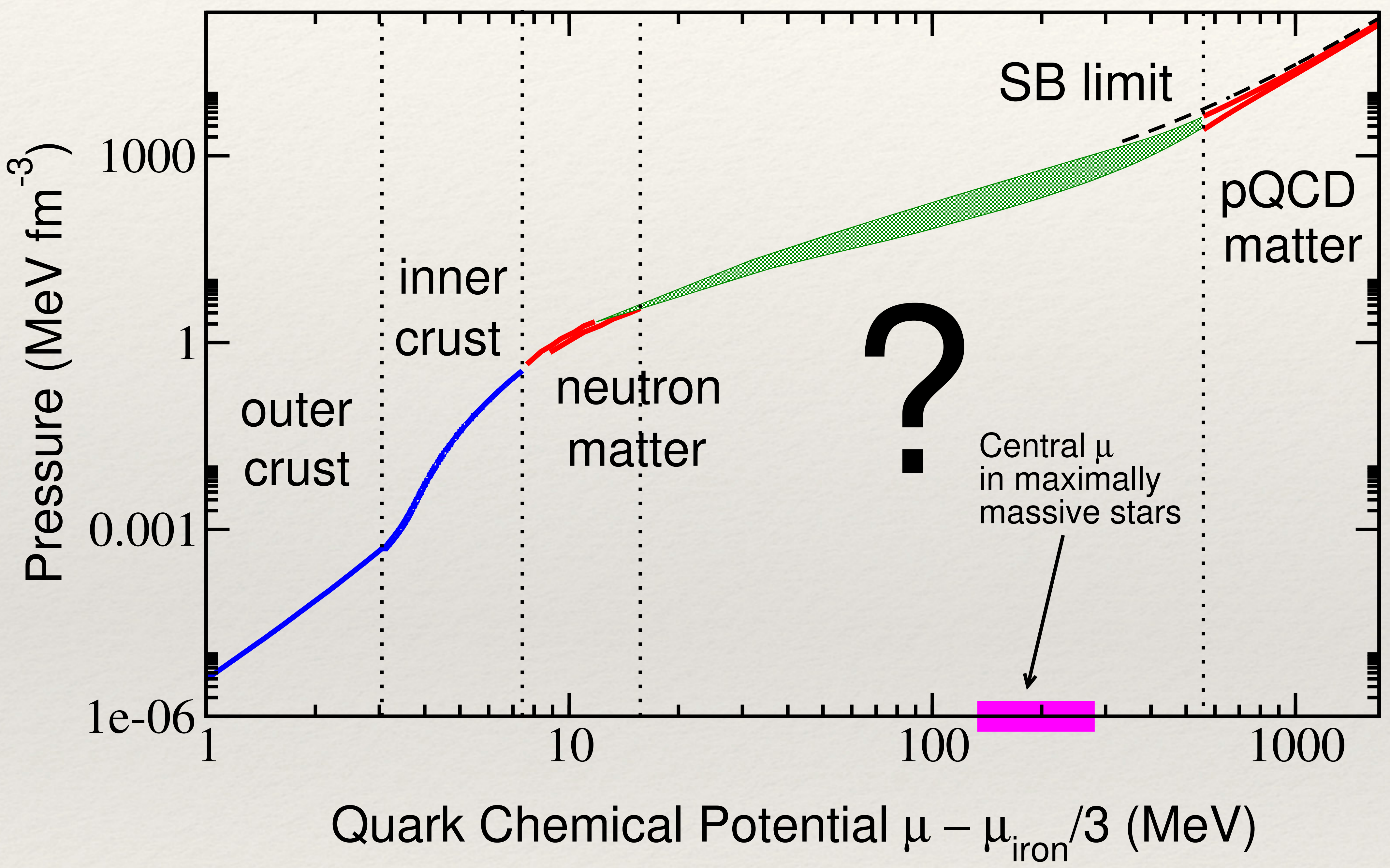
Bhaskar Biswas | Hamburg observatory

Institute for nuclear theory, Seattle

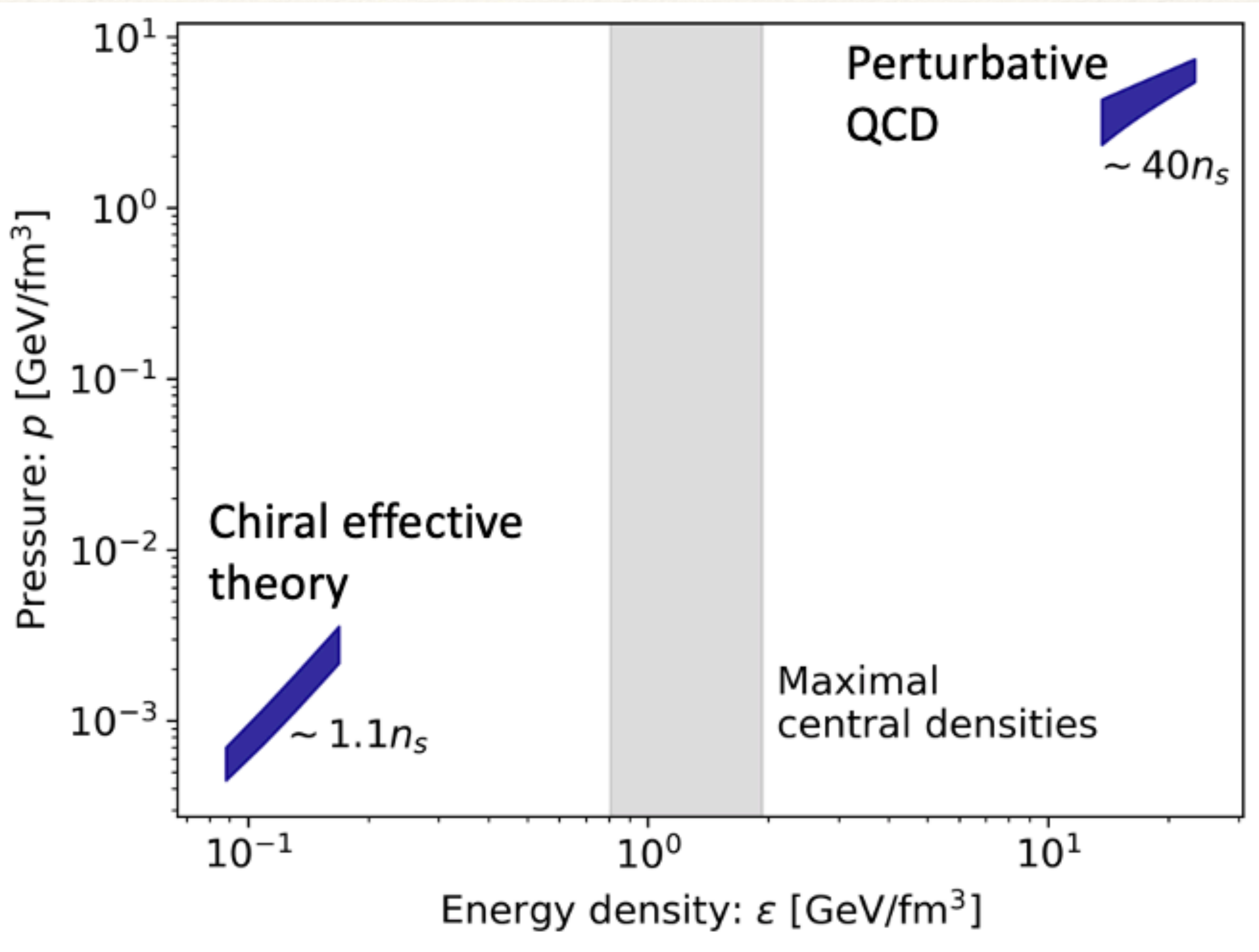
August 30, 2024

What we know about the EOS of neutron stars?

Kurkela, Fraga, Beilich, Vourinen, 2014



A. Kurkela, arXiv: 2211.11414



Low density EOS is well known; Challenges bengin near saturation saturation density

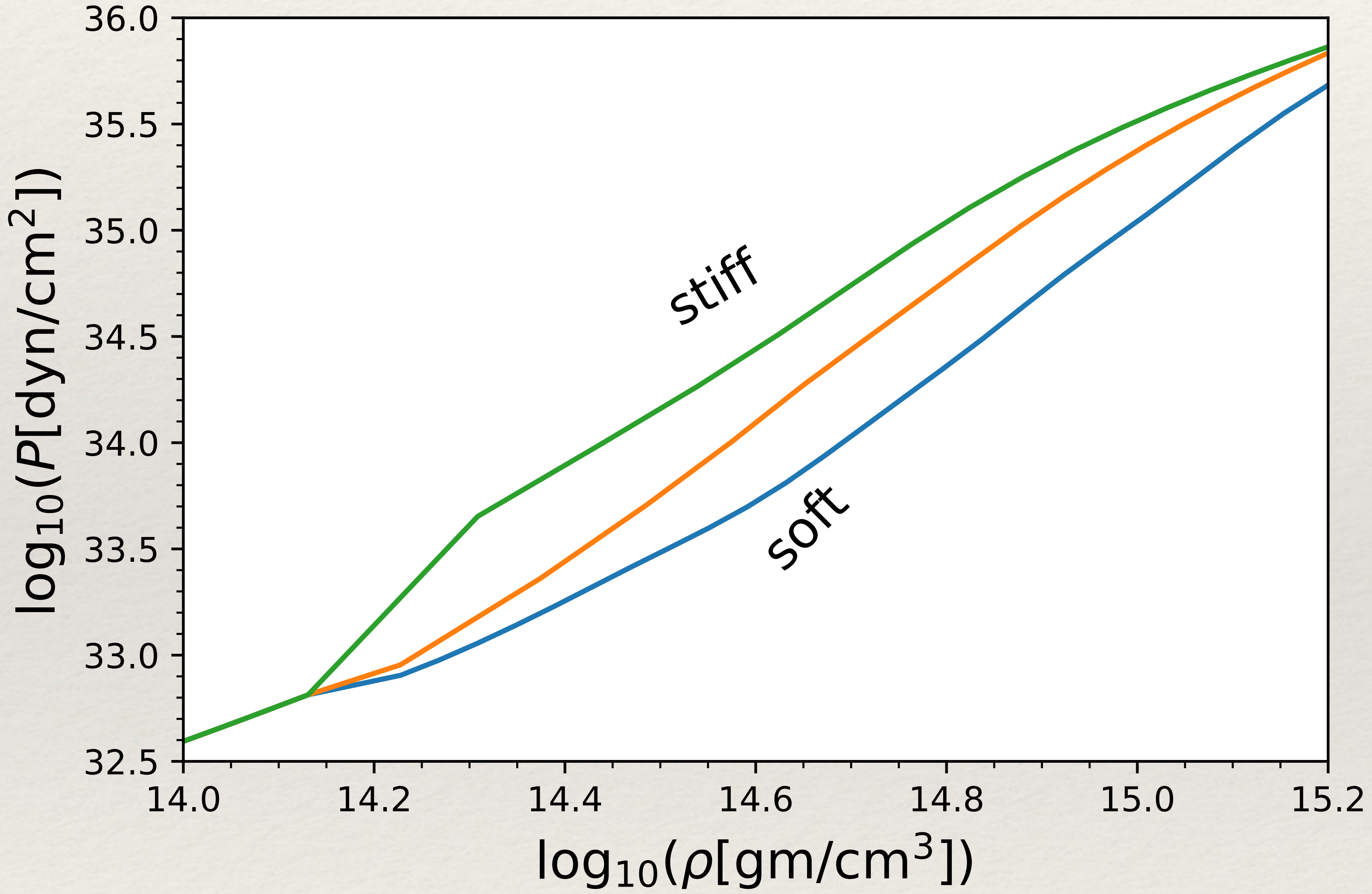
Tews et al., PRL, 110 (2013)
Hebeler et al., ApJ 773 (2013)
Drischler et al., PRL 125 (2020)

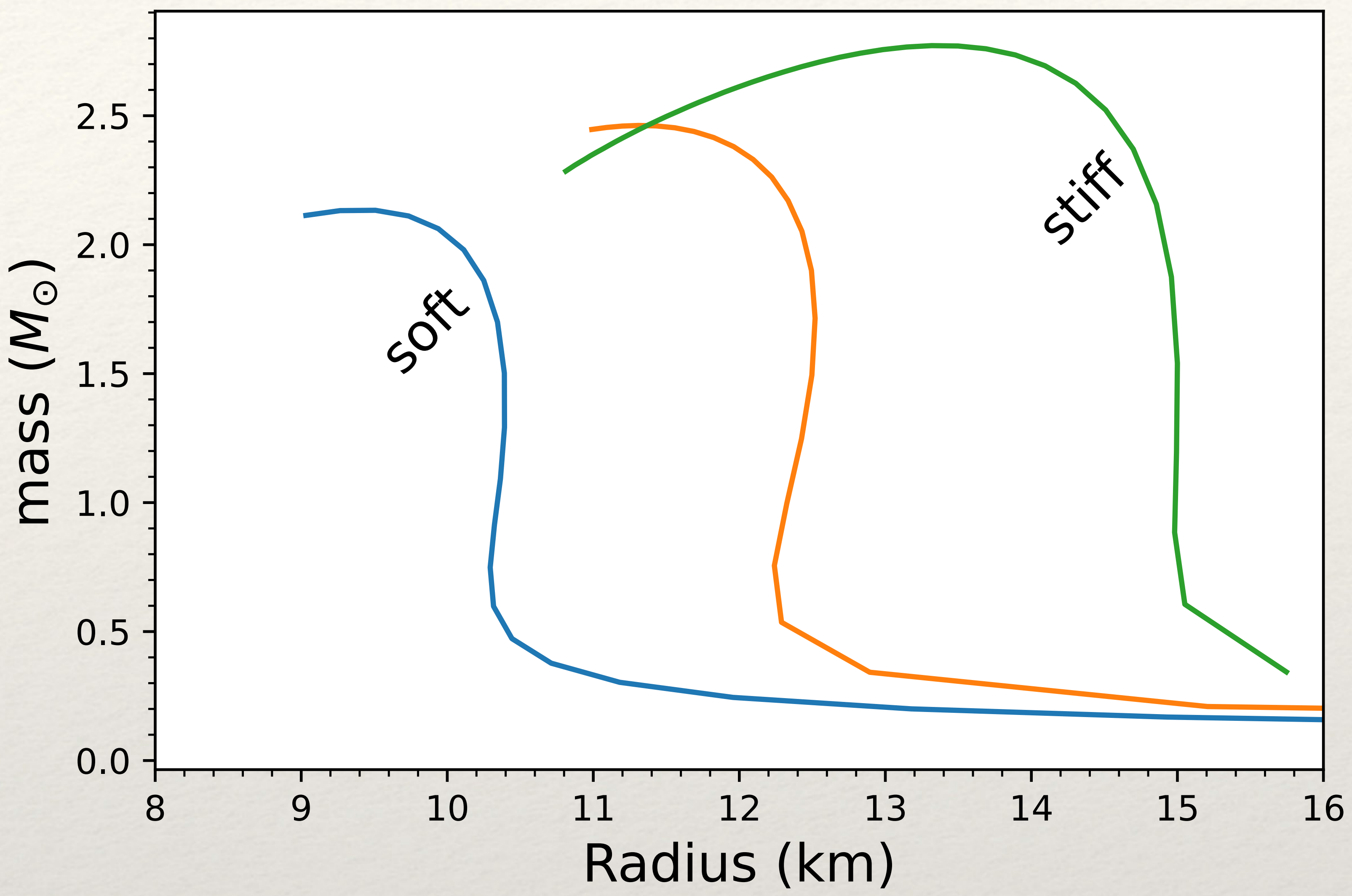
High density regime: pQCD, relative uncertainty $\pm 24\,\%$ at $\mu_B = 2.6$ GeV, $n \approx 40 n_s$

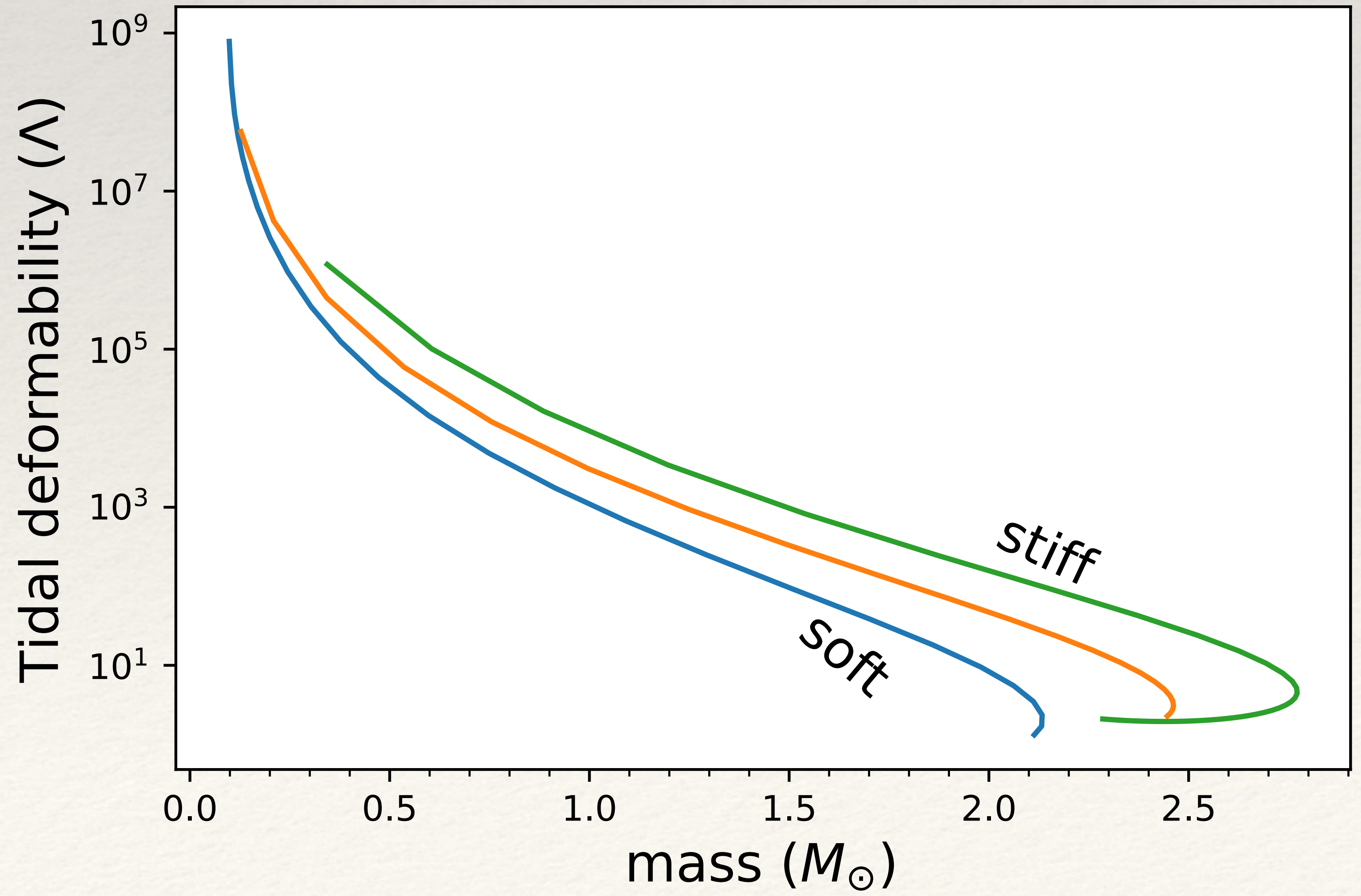
Kurkela et al., PRD 81 (2009)
Gorda et al., PRL 121 (2018)

EOS & observables

EOS, $P = P(\rho)$







- Radio observables — M
- X-ray observables — M , R
- GW observables — M , Λ

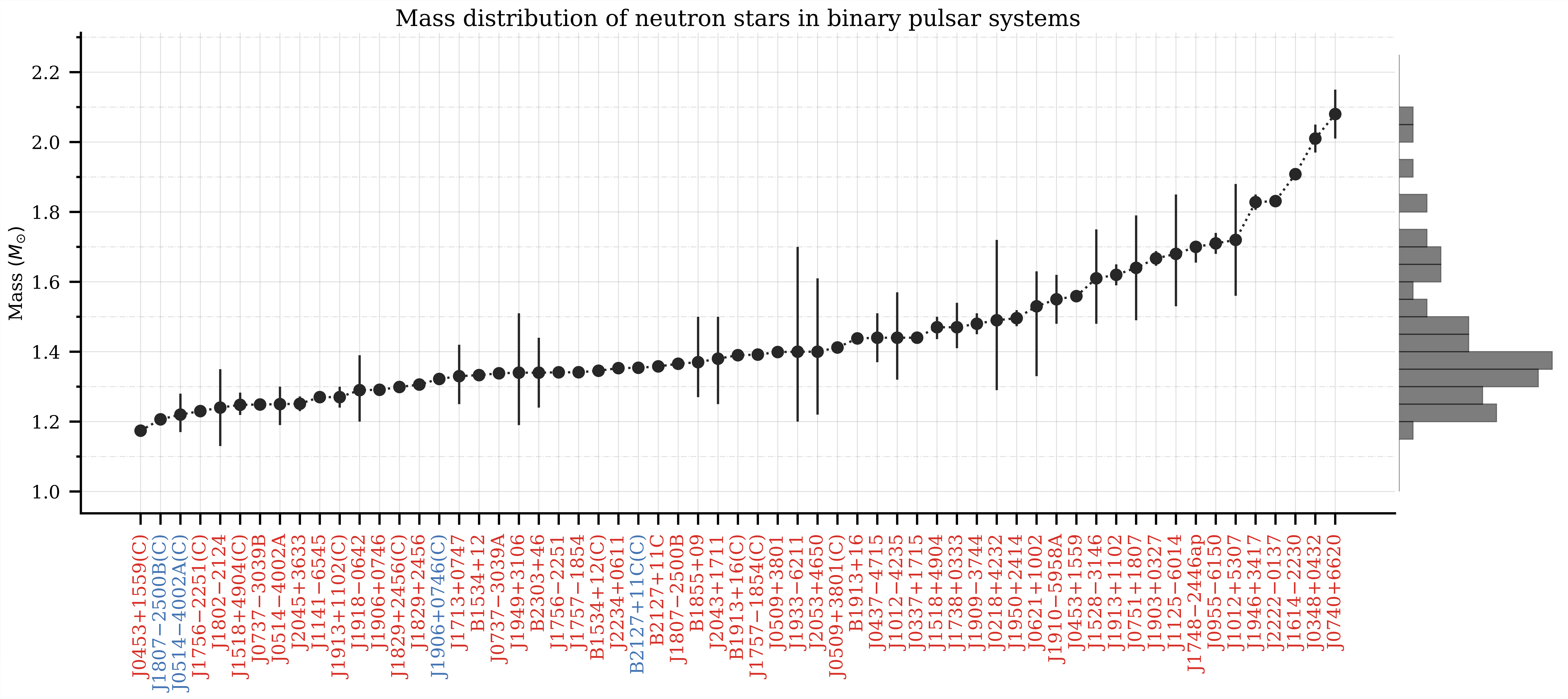
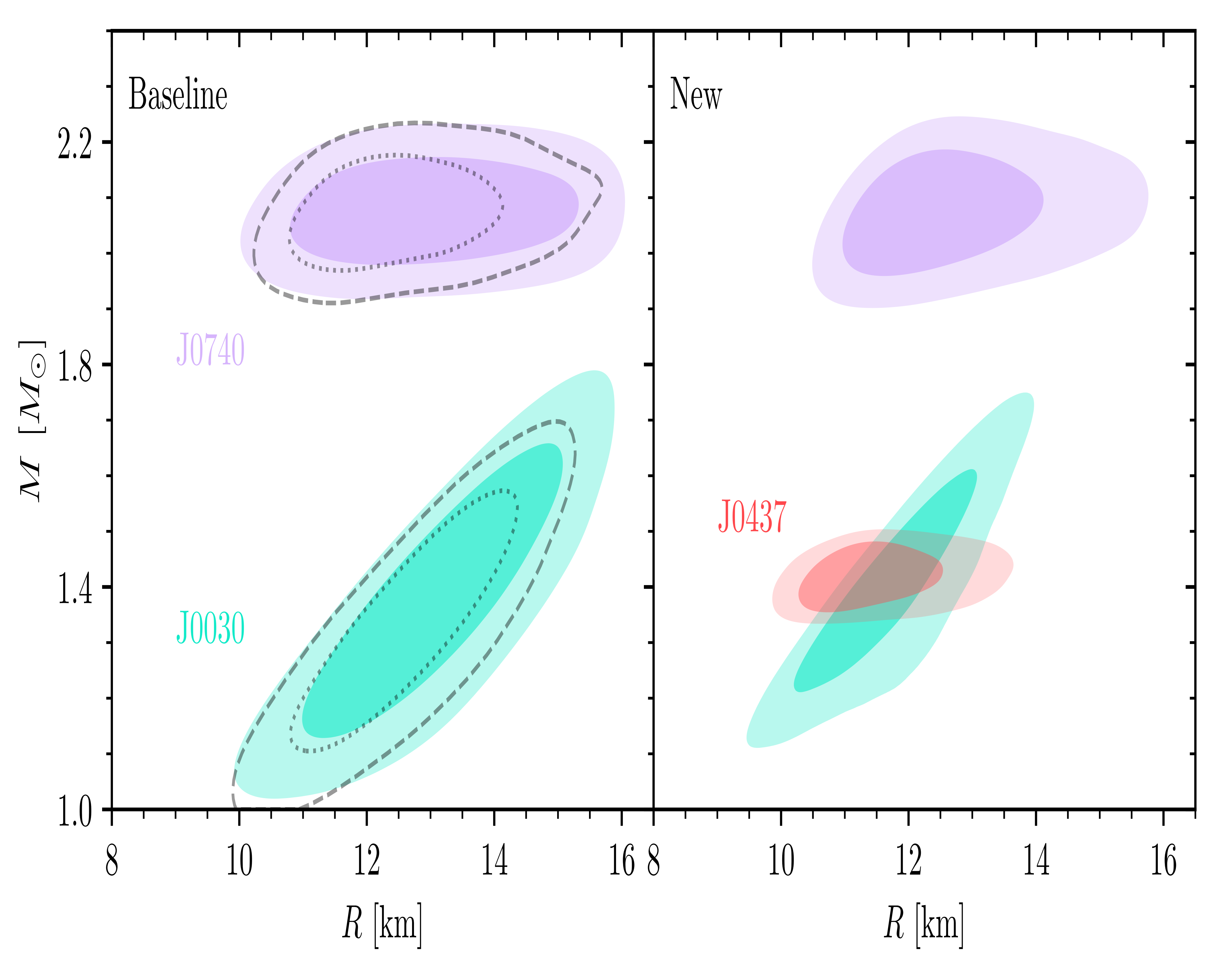


Figure: paulo freire and vivek k. krishnan 2024

A list of 136 known pulsar (PSR) masses can be found at Fan et al., PRD 109 (2024)

NICER M-R measurements



Rutherford et al., ApJL (2024)

J0030 : $M = 1.40^{+0.13}_{-0.12}\, M_\odot$, $R = 11.71^{+0.88}_{-0.83}$ km

Or,

$M = 1.70^{+0.18}_{-0.19}\, M_\odot$, $R = 14.44^{+0.88}_{-1.05}$ km

(Vinciguerra et al. 2023)

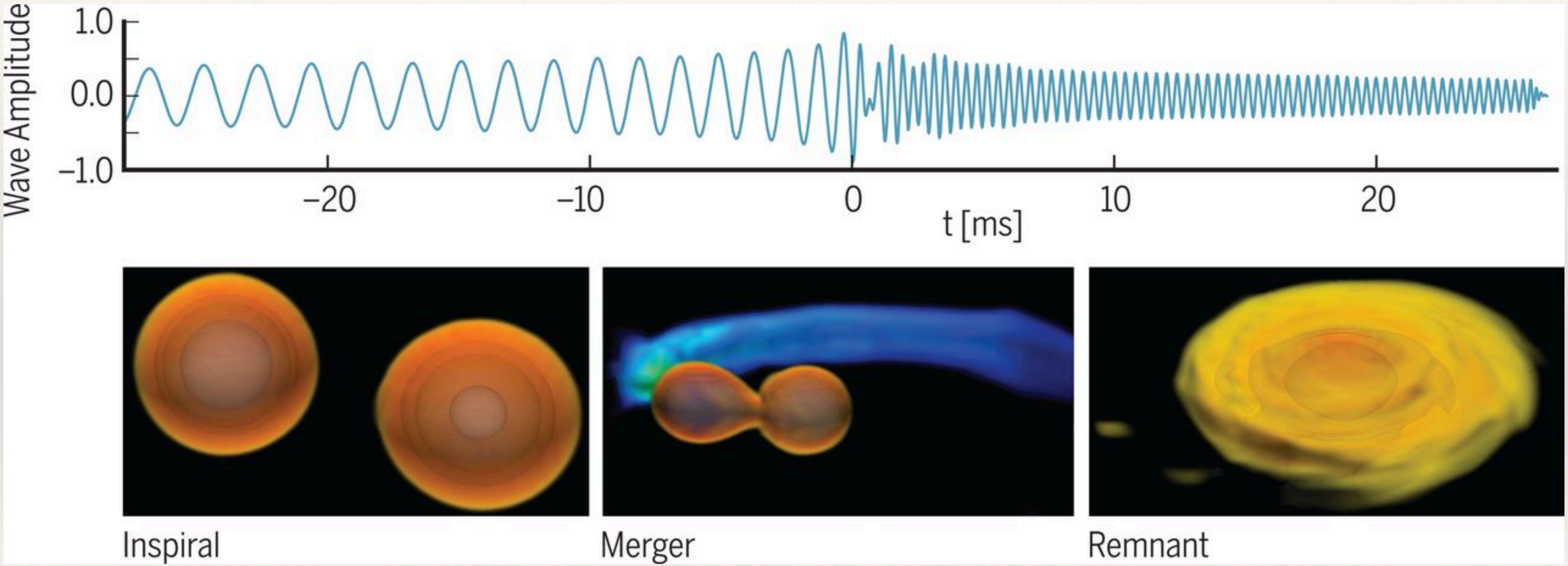
J0740 : $M = 2.07 \pm 0.07\, M_\odot$, $R = 12.49^{+1.28}_{-0.88}$ km

(Salmi et al. 2024)

J0437: $M = 1.418 \pm 0.037\, M_\odot$, $R = 11.36^{+0.95}_{-0.63}$ km

(Choudhury et al. 2024)

GW waveform of two merging NSs



Pic credit: S. Bernouzzi

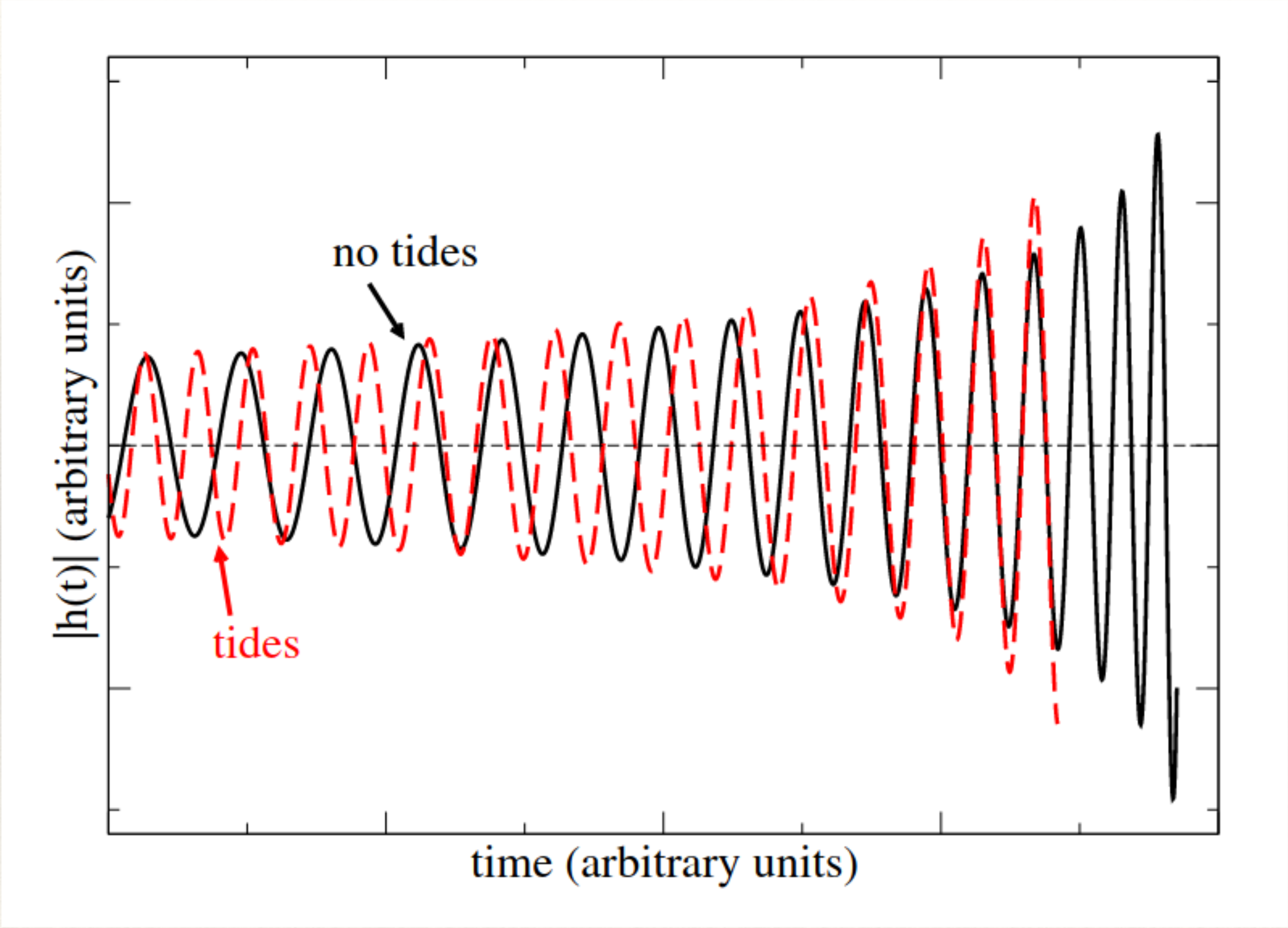
Fundamental physics with Inspiral Phase

In inspiral phase, tidal deformation of neutron star leaves an imprint on GW waveform which can tell us about the EOS

$$Q_{ij} = -\lambda \epsilon_{ij}$$

$$\lambda = \frac{2}{3} k_2 R^5$$

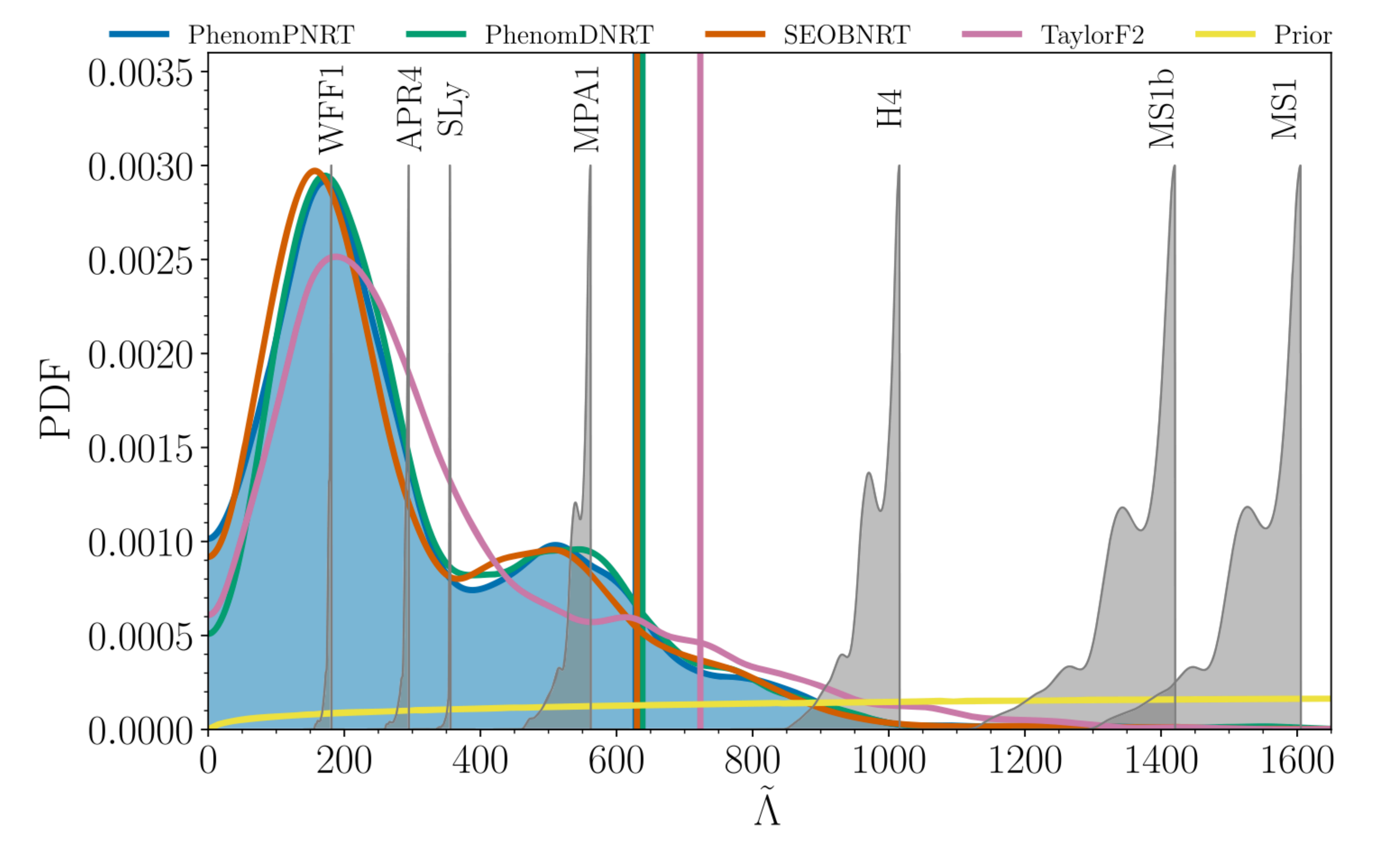
λ and k_2 are the tidal deformability and tidal Love number respectively



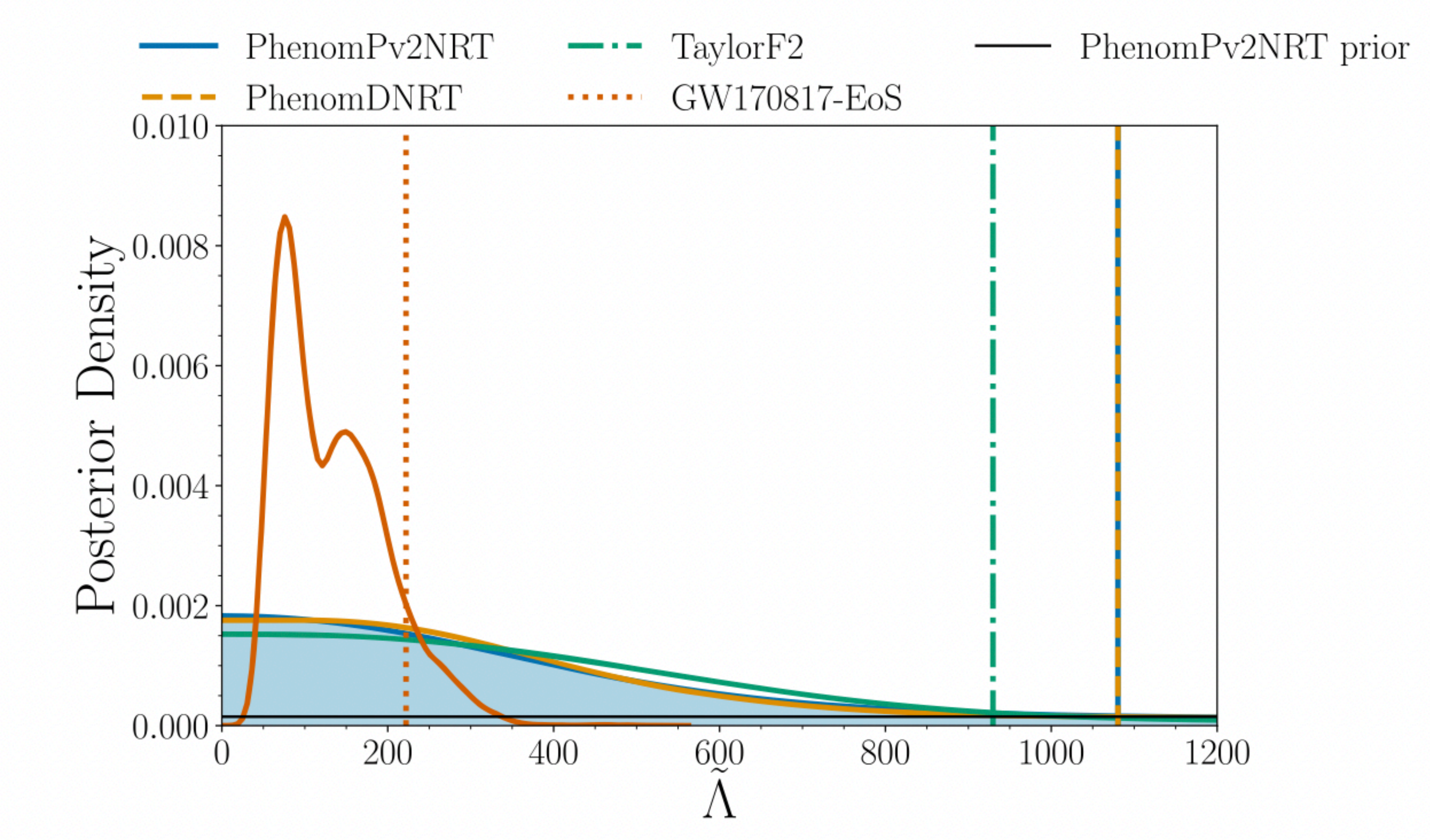
Pic. Credit : Z. Carson

Tidal deformability from BNS mergers

GW170817, LVK PRX 2019



GW190425, LVK ApJL 2020

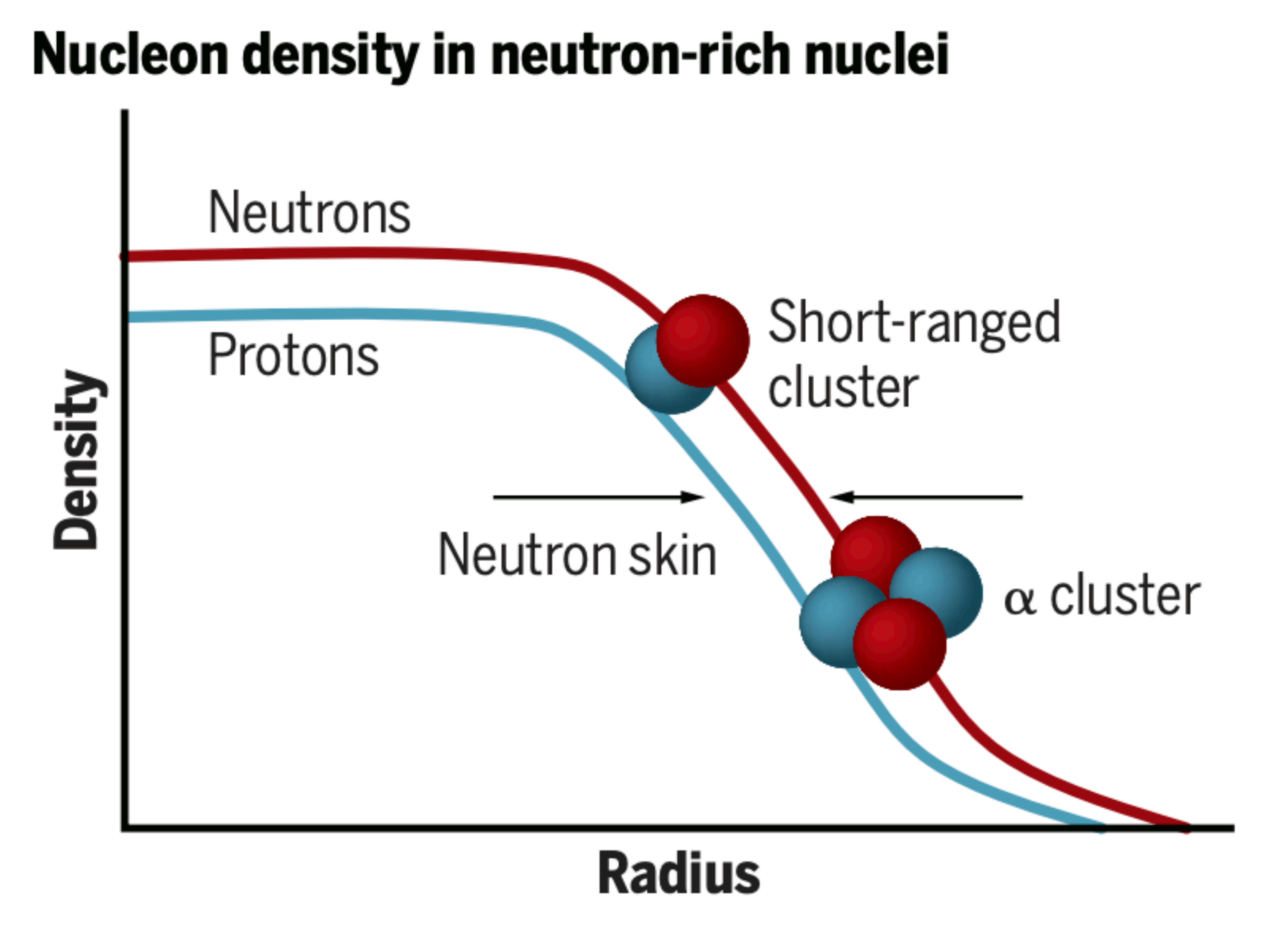


- Presence of EM counterpart
- Information on tidal deformation

- EM counterpart is not detected
- Weak measurements of tidal deformability

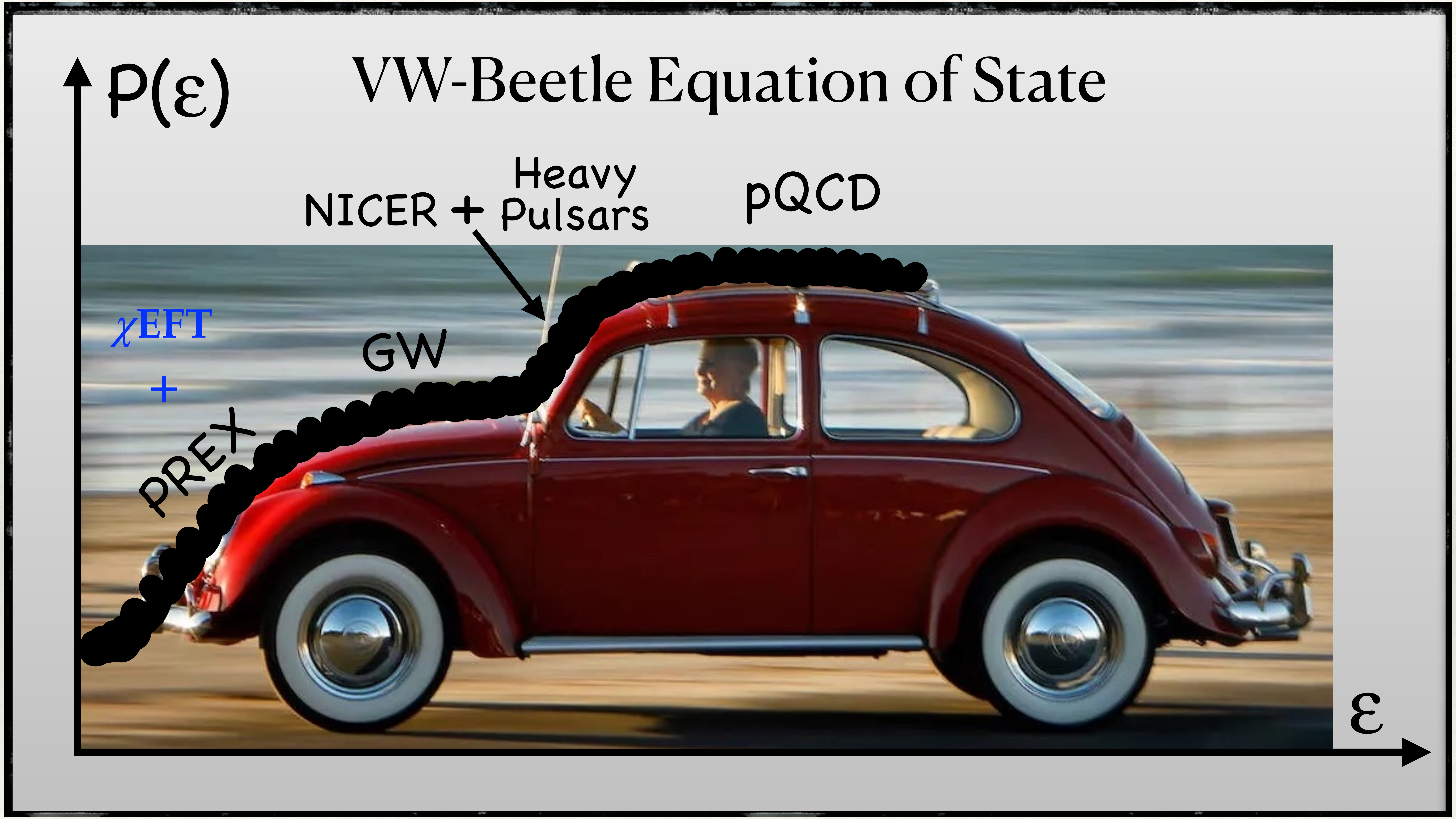
New terrestrial experiments

Hen, Science 371, 232 (2021)



- Neutron skin thickness strongly correlates with pressure
- PREX-II measured the neutron skin thickness of ^{208}Pb, $R^{208}_{\rm skin} = 0.283 \pm 0.071$
- CREX measured the neutron skin thickness of ^{40}Ca, $R^{40}_{\rm skin} = 0.121 \pm 0.026$
- Skin thicknesses are strongly correlated with slope parameter L,

$$R^{208}_{\rm skin}[{\rm fm}] = 0.101 + 0.00147 \times L[{\rm MeV}]\,.$$
$$R^{48}_{\rm skin} = 0.0416 + 0.6169 R^{208}_{\rm skin}\,.$$

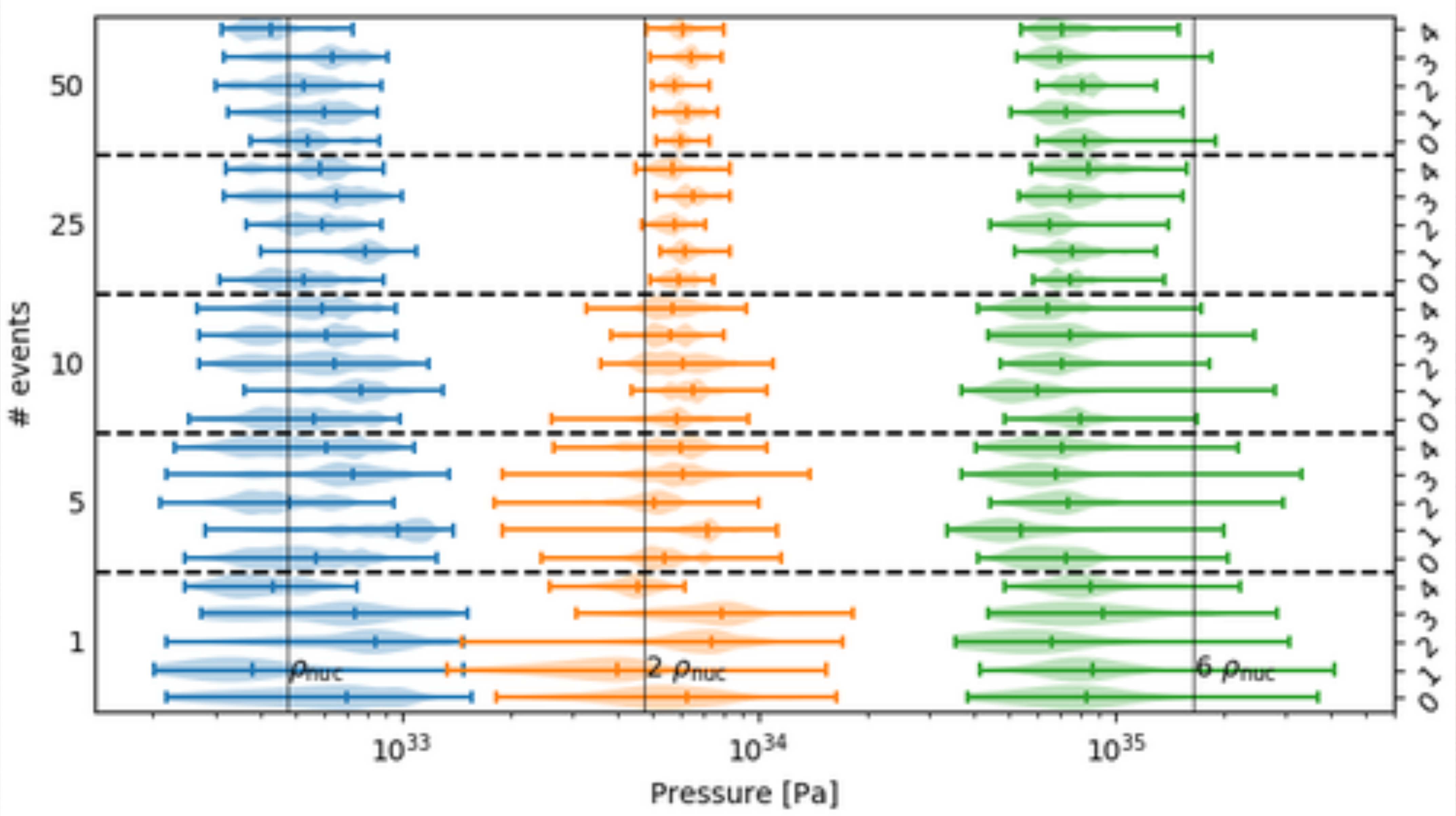


Piekarewicz, 2024

Bayesian approach to constrain NS EOS

Wrong population model biases EOS inference

Wysocki et al., arXiv: 2001.01747



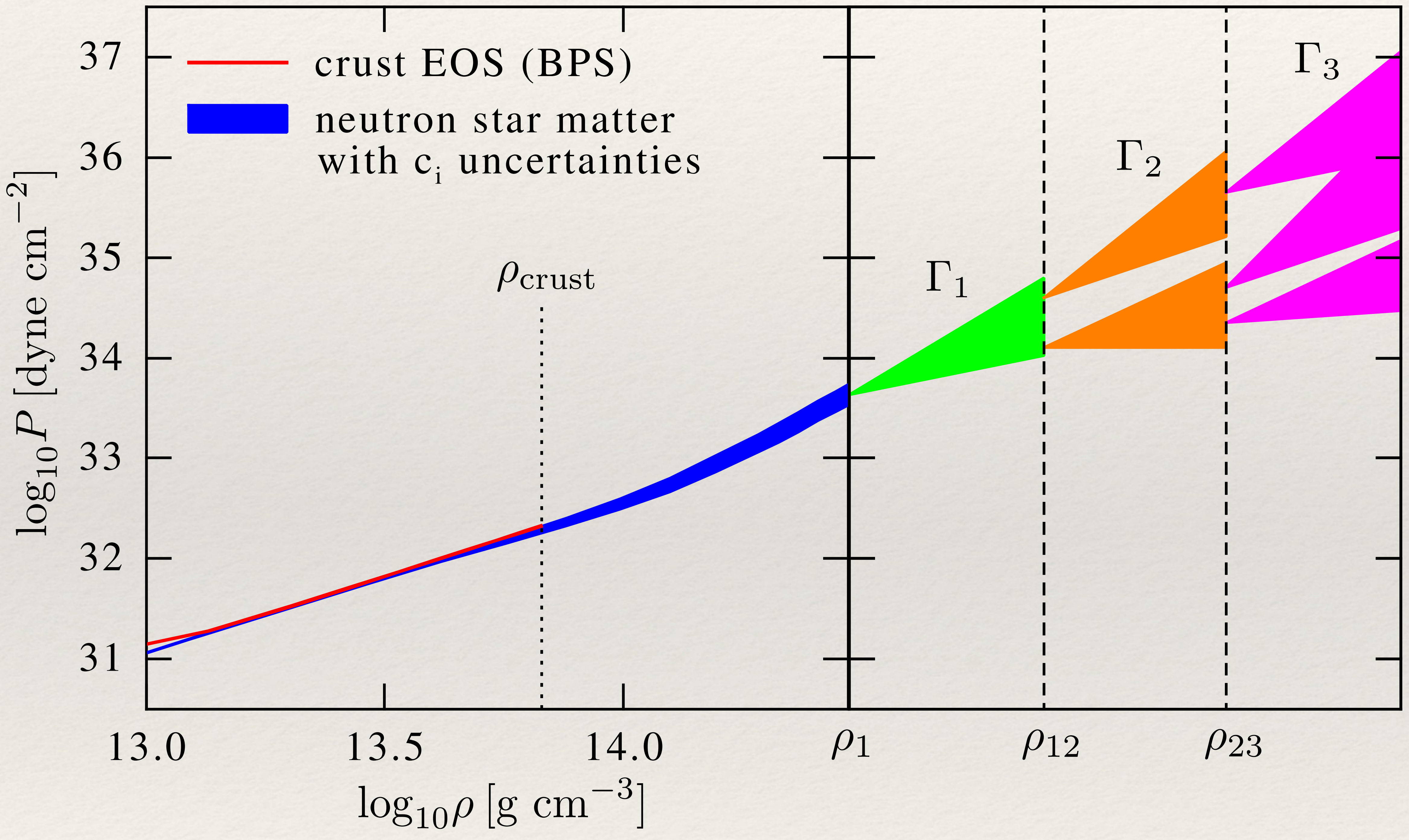
Bayesian statistics to simultaneously infer NS EOS and population model

- $P(\theta|d) \propto P(\theta)\Pi_i P(d_i|\theta)$,

Posterior **Prior** **Likelihood**

$\theta \in$ (EOS and mass population parameters)

Hybrid nuclear+PP EoS parameterization



Pic credit: Hebeler et al. ApJ, 773 (2013)

- In outer crust Sly EOS is used
- Then below $1.1\rho_0$ saturation properties of nuclear matter is used
- $$e(\rho,\delta) \approx e_0(\rho) + e_{sym}(\rho)\delta^2$$

$$e_0(\rho) = e_0(\rho_0) + \frac{K_0}{2}\chi^2 \ldots,$$

$$e_{sym}(\rho) = e_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2}\chi^2 + \ldots$$

$$\delta = (\rho_n - \rho_p)/\rho,$$
$$\chi = (\rho - \rho_0)/3\rho_0$$

- At high densities piecewise-polytrope is used with varying transition densities

Mass distribution model

- For simplicity we assume all NSs in the universe follow double Gaussian distribution

$$P_{\rm NN}(M|\mu_1,\sigma_1,\mu_2,\sigma_2,w,M_{\rm min},M_{\rm max}) = [w\mathcal{N}(M|\mu_1,\sigma_1)/B + (1-w)\mathcal{N}(M|\mu_2,\sigma_2)/C] U(M|M_{\rm min},M_{\rm max}),$$

$$U(M|M_{\rm min},M_{\rm max}) = \begin{cases} \frac{1}{M_{\rm max}-M_{\rm min}} & \text{if } M_{\rm min} \leq M \leq M_{\rm max}, \\ 0 & \text{else.} \end{cases}$$

- This assumption might not be true as GWs may follow a different distribution. (Landry and Read, 2021)

But too less detections, to make any conclusion

Priors

- Some empirical parameters are kept fixed in our analysis

$$n_0 = 0.16\,\mathrm{fm}^{-3}$$
$$e_0(n_0) = -15.9\,\mathrm{MeV}$$
$$K_0 = 240\,\mathrm{MeV}$$
$$e_{sym} = 31.7\,\mathrm{MeV}$$

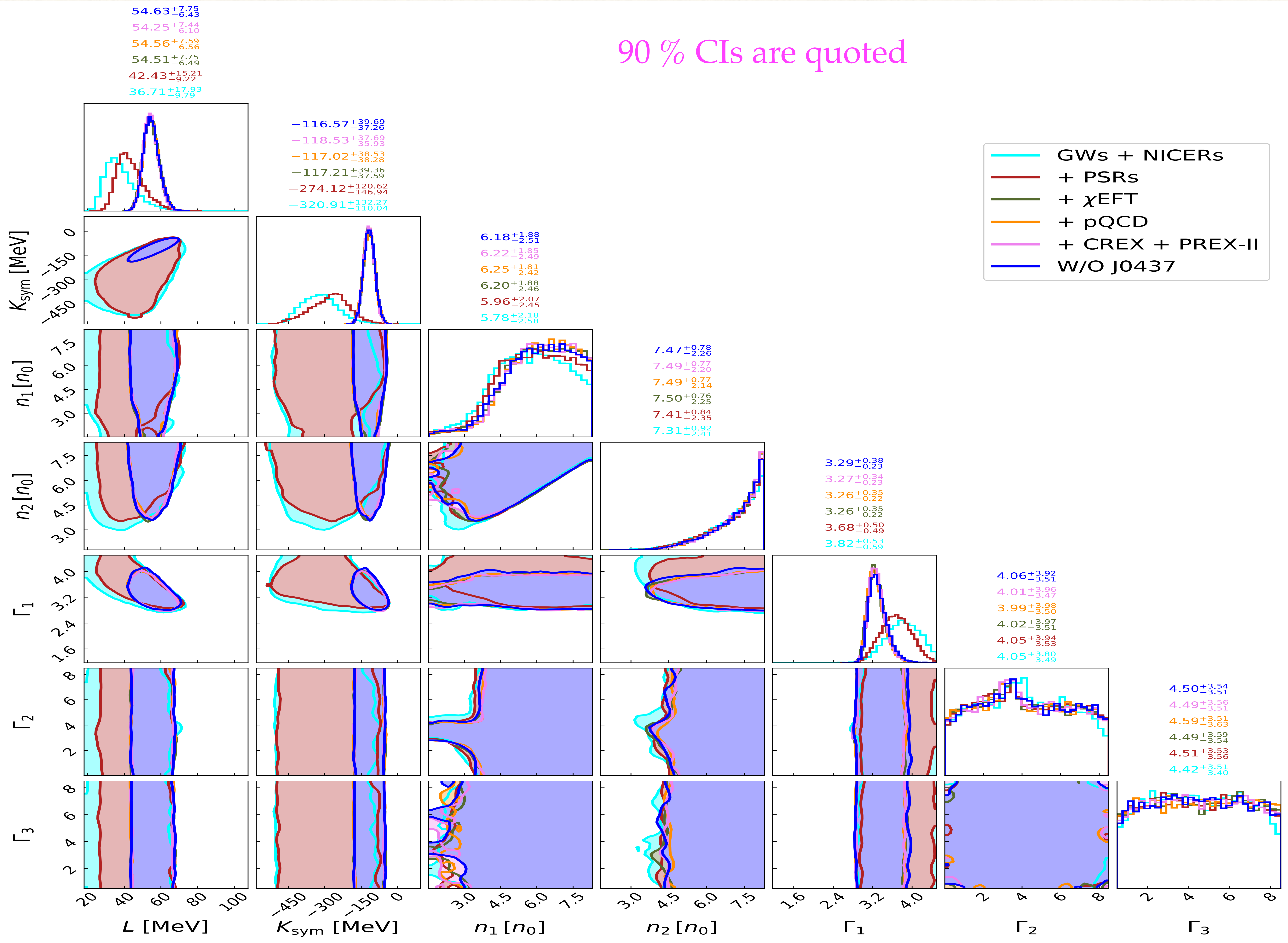
Uncertainty in n_0 and e_0 are already small.

K_0 and e_{sym} have weak influence on NS M, R, Λ.

- For all the parameters wide uniform priors are kept.

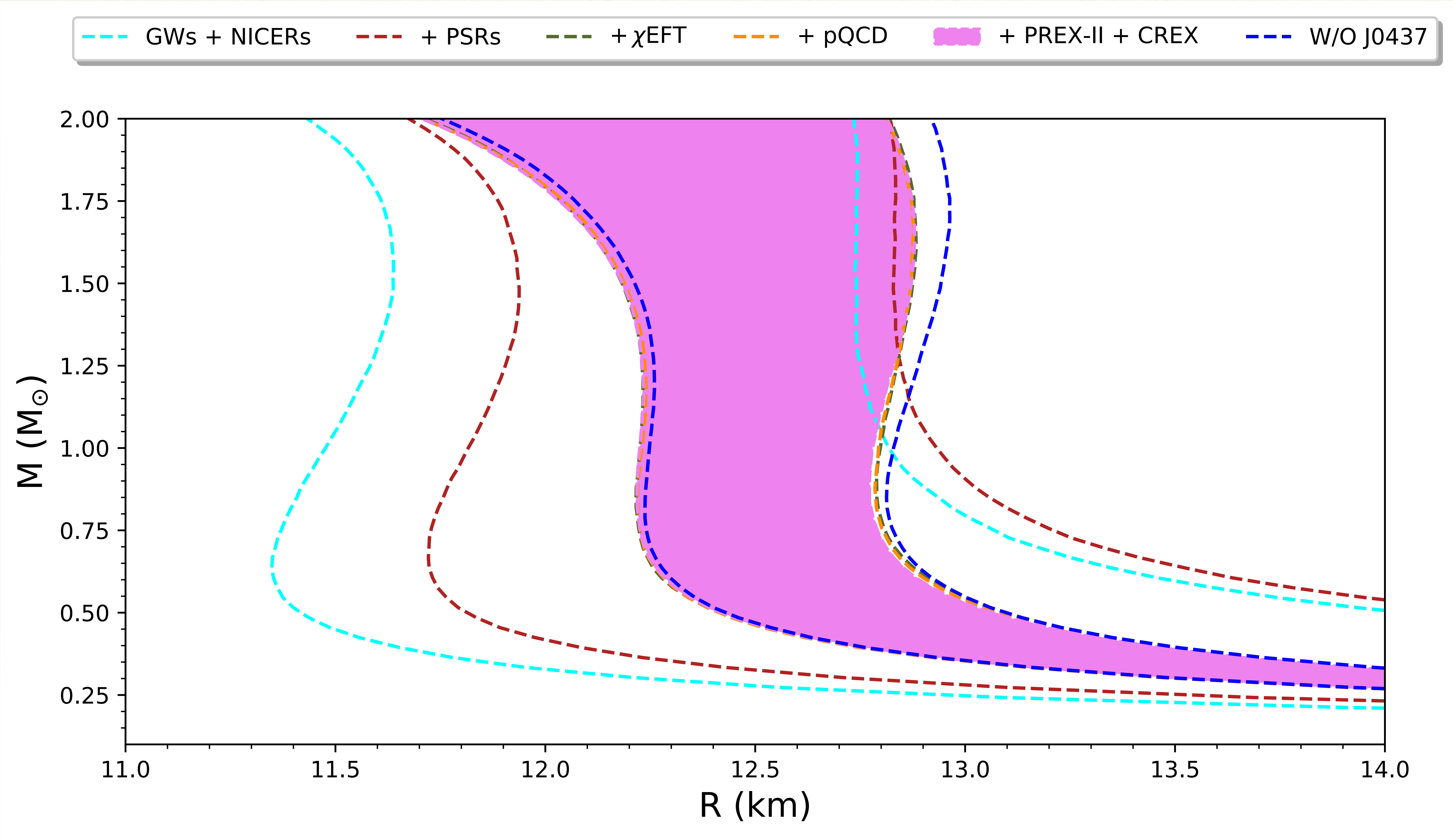
Model	Parameters	Units	Prior
EOS	L	MeV	$U(0, 150)$
	K_{sym}	MeV	$U(-600, 100)$
	n_1	n_0	$U(1.5, 8.3)$
	n_2	n_0	$U(n_1, 8.3)$
	Γ_1	-	$U(1, 4.5)$
	Γ_2	-	$U(0, 8.5)$
	Γ_3	-	$U(0.5, 8.5)$
Mass	μ_1	$M_\odot$	$U(0.9, \mu_2)$
	σ_1	$M_\odot$	$U(0.01, \sigma_2)$
	μ_2	$M_\odot$	$U(0.9, M_{max})$
	σ_2	$M_\odot$	$U(0.01, 1.0)$
	w	-	$U(0.1, 0.9)$

Posterior of EOS parameters



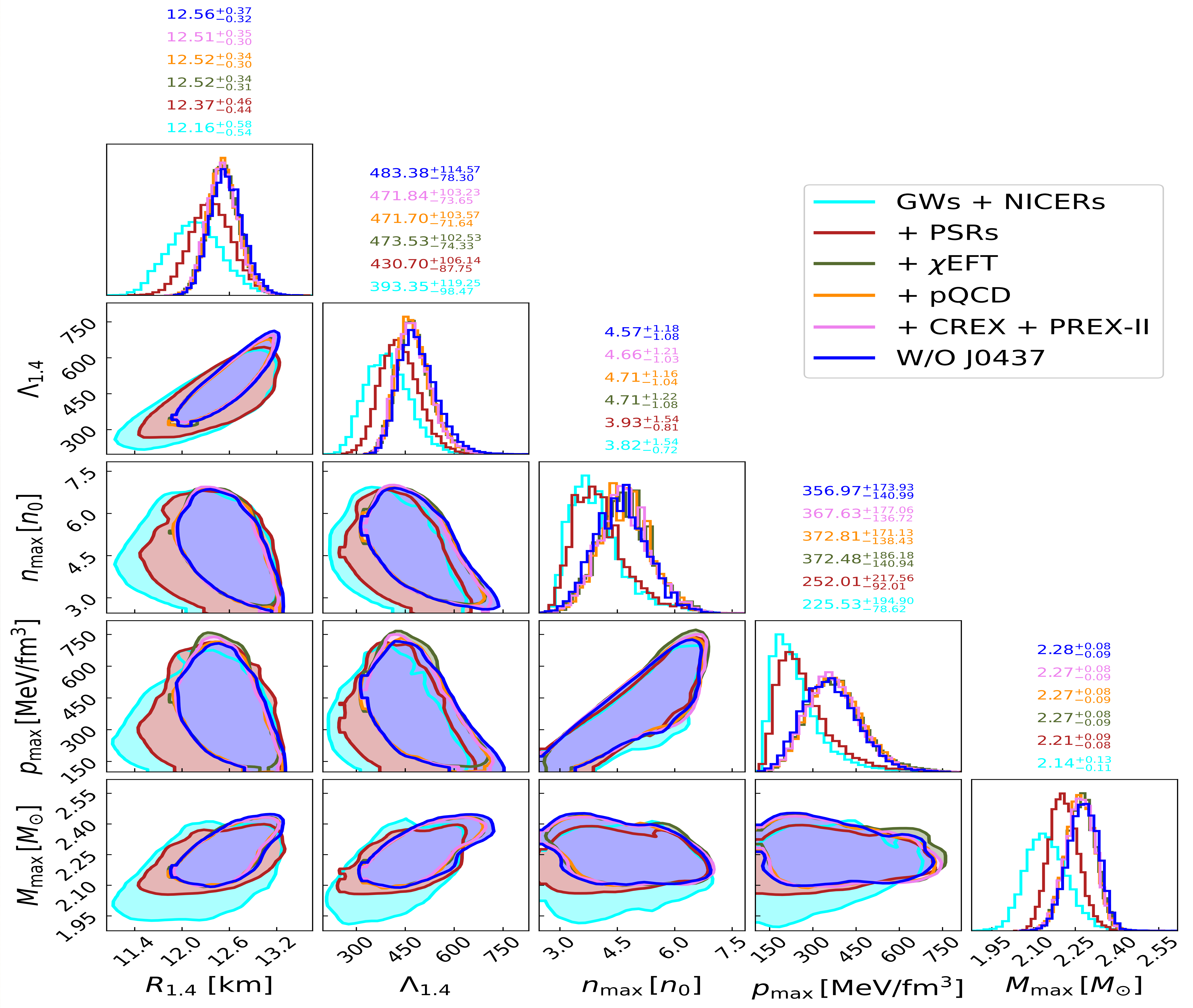
- Astrophysical Observations Constrain Nuclear Parameters
- Addition of 129 PSRs measurements have visibe impact on the EOS parameters
- Significant Impact of χEFT Calculations on Empirical Parameters
- Transition densities peaking at the higher end of the prior
- Γ_2 and Γ_3 are uninformative

Mass-radius band



- **Addition of PSRs** mass measurements overall **tightens** the M-R band
- **Significant impact** of χ EFT
- **No noticeable impact** by pQCD, CREX, and PREX-II
- PSR J0437 slightly soften the posterior

Constraints on a few key quantities



90 % CIs

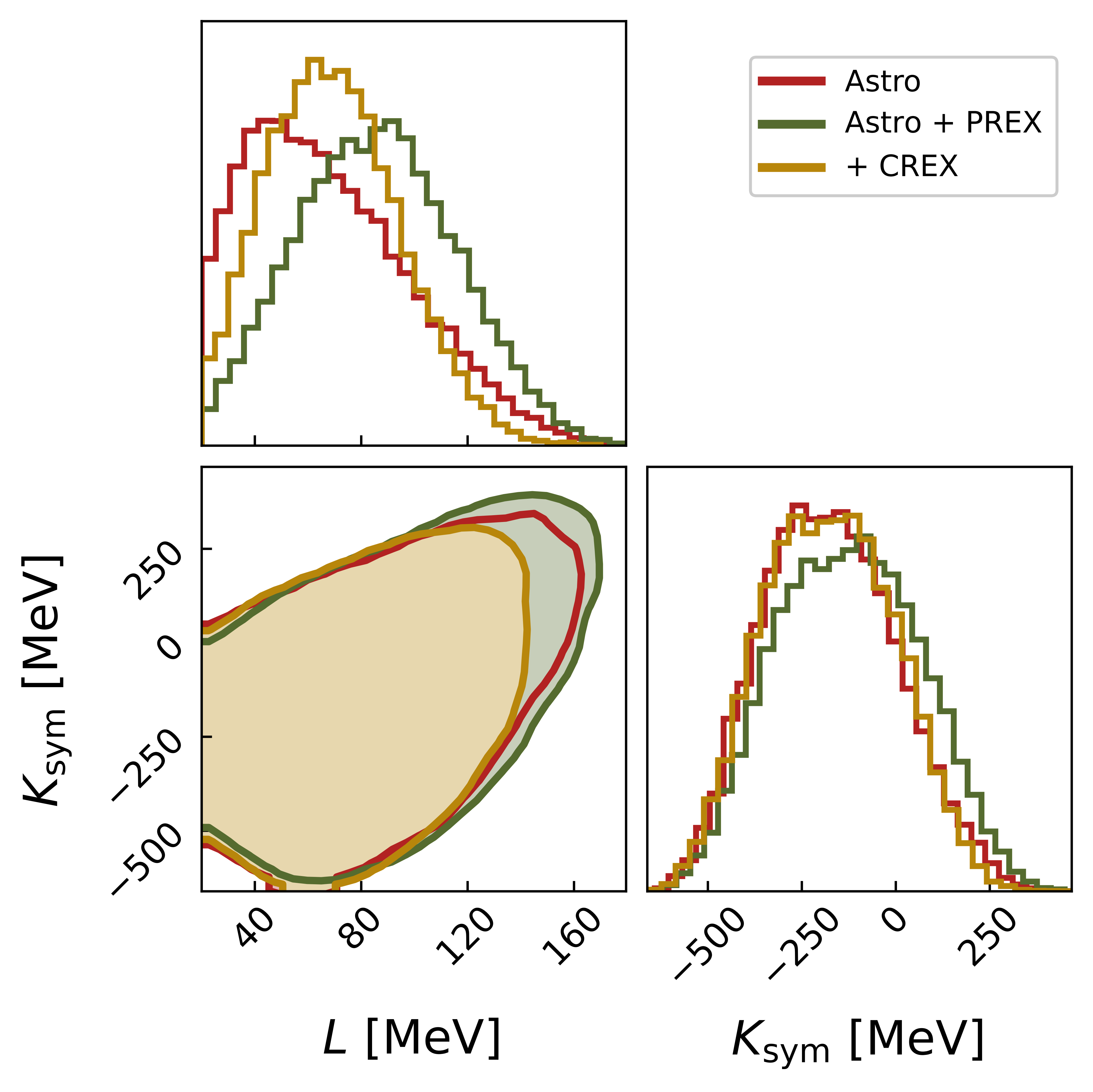
$12.21 < R_{1.4}\,[\mathrm{km}] < 12.86$

$398 < \Lambda_{1.4} < 575$

$3.63 < n_{\max}\,[\mathrm{n}_0] < 5.87$

$2.18 < M_{\max}\,[M_\odot] < 2.35$

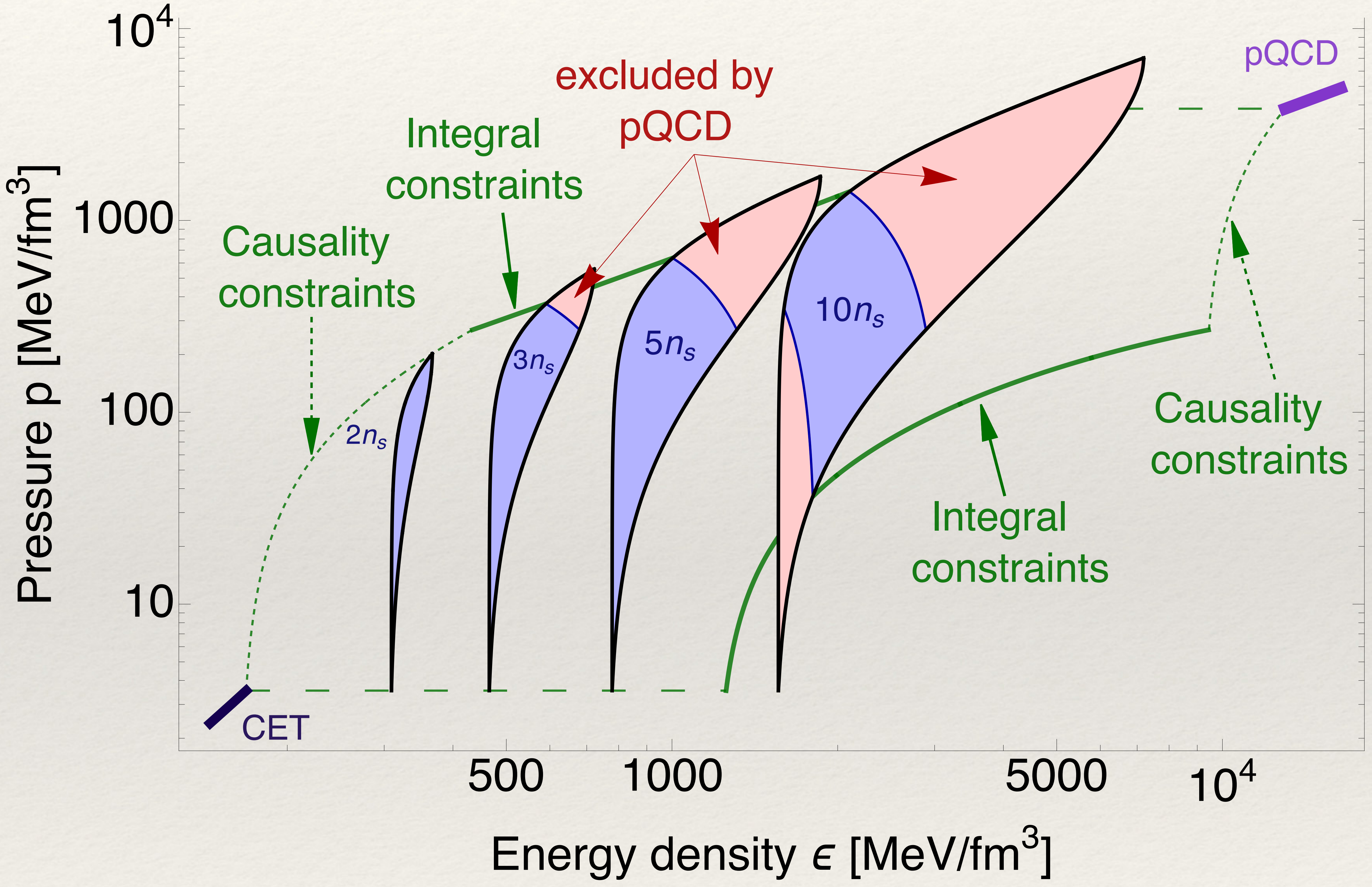
What's up with PREX-II & CREX?



- PREX-II and CREX measurements influences empirical parameters **if χEFT constraints are not added**
- The overall impact of PREX-II & CREX is overshadowed by χEFT

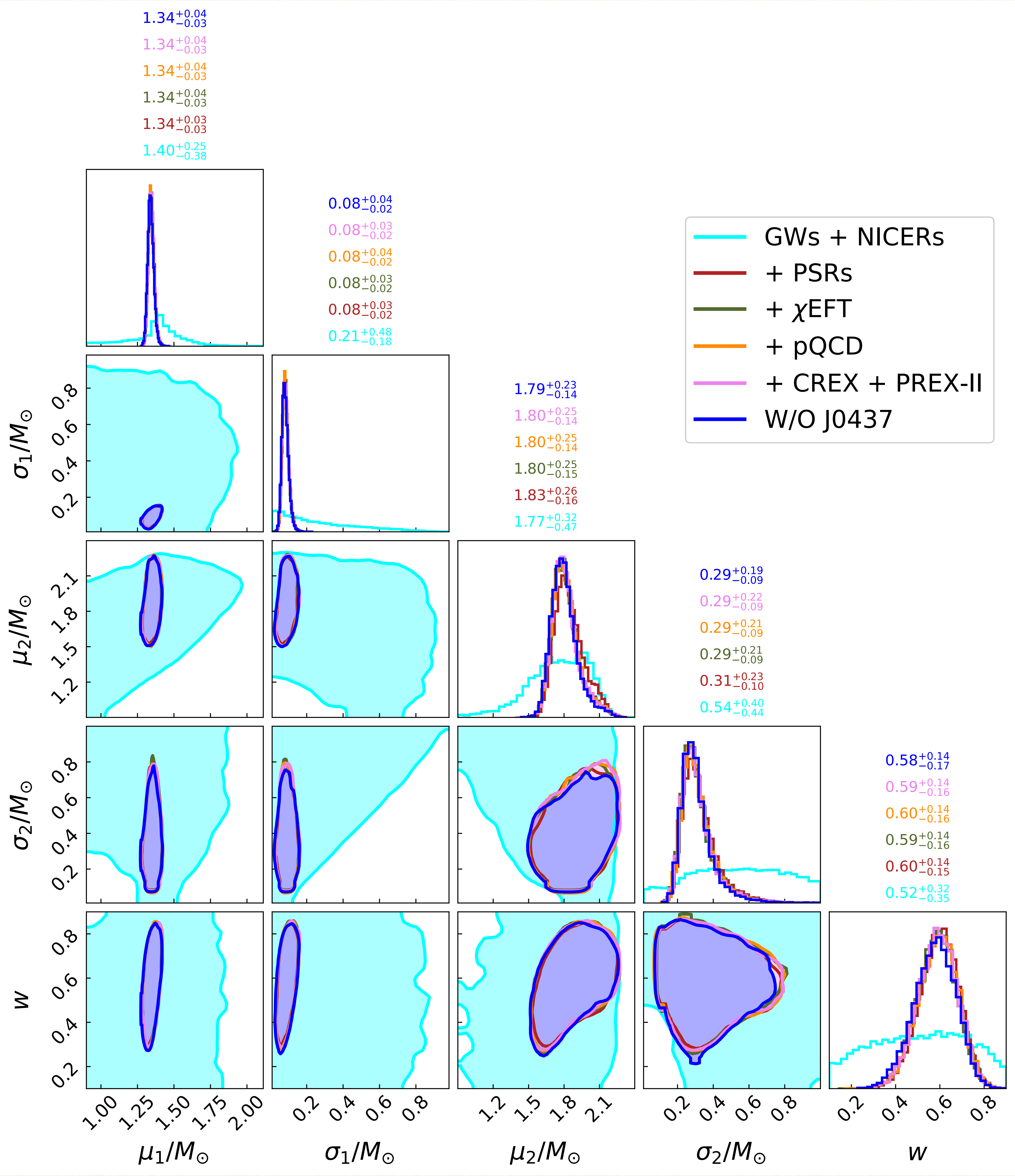
Why is pQCD uninformative?

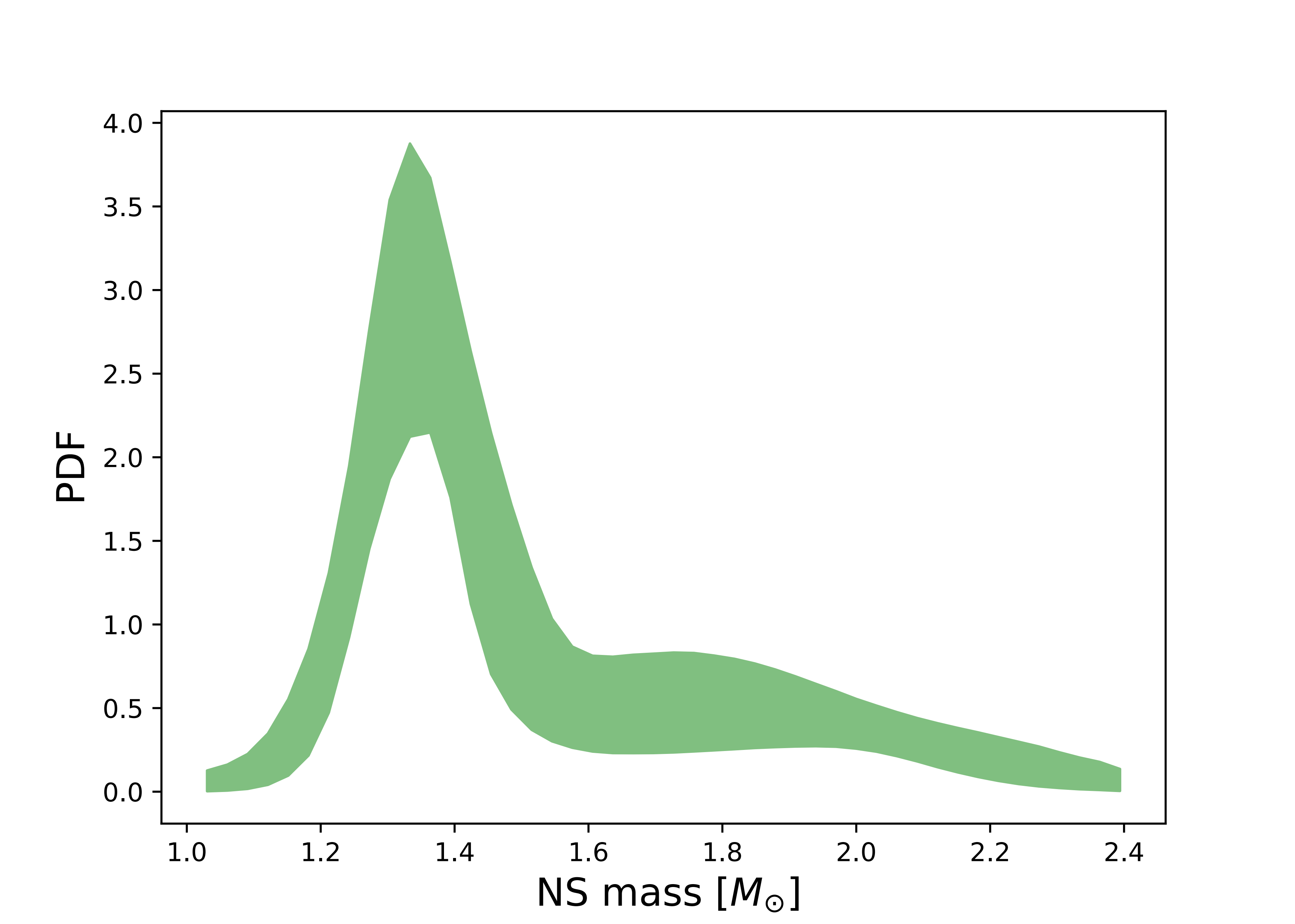
- To check if an EOS is consistent with the pQCD prediction, we assume knowledge of the EOS at a low-density limit
- This choice is arbitrary
- Previous works used an ad hoc density of $n_{\rm low} = 10\, n_s$ and conclude pQCD can rule out soft EOSs above $2.2\, n_0$
- We choose corresponds to central density of the maximum mass star and observe negligible impact



Komoltsev and Kurkela, PRL 128, 202701 (2022)

Posterior of NS mass distribution





- Overall constraint is dominated by the PSRs mass measurements
- Tight constraint on μ_1 and narrow spread
- Broader distribution for the secondary componenet

Take away points

- A comprehensive Bayesian framework to simultaneously infer NS EOS and population model is provided combining astrophysical observations and nuclear inputs
- Not only GWs and NICERs, the **addition of 129 PSRs** mass measurements overall **tightens** the M-R band
- Significant Impact of χEFT Calculations on Empirical Parameters and as well as the M-R band
- PREX-II and CREX measurements influences empirical parameters **if χEFT constraints are not added. The overall impact of PREX-II & CREX is overshadowed by χEFT.**
- Constraints coming from pQCD have a **minimal effect** on EOS inference.