Current neutron star constraints and non-trivial features in the EoS

to appear soon with J. Noronha-Hostler (ICASU/UIUC), N. Yunes (ICASU/UIUC), M. C. Miller (U. Maryland)

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Illinois Center for Advanced Studies of the Universe

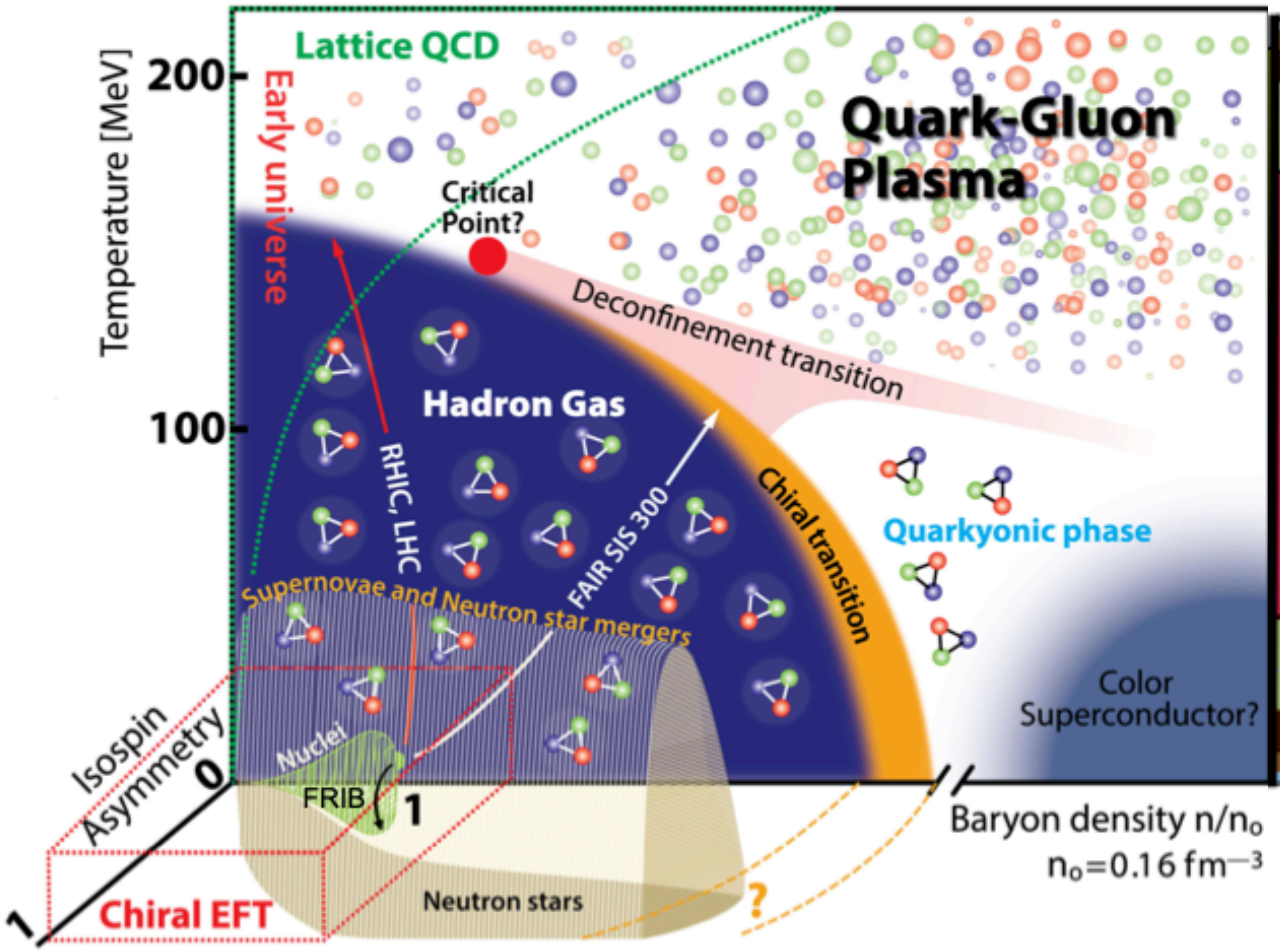
Neutron Stars as probes for the QCD EoS

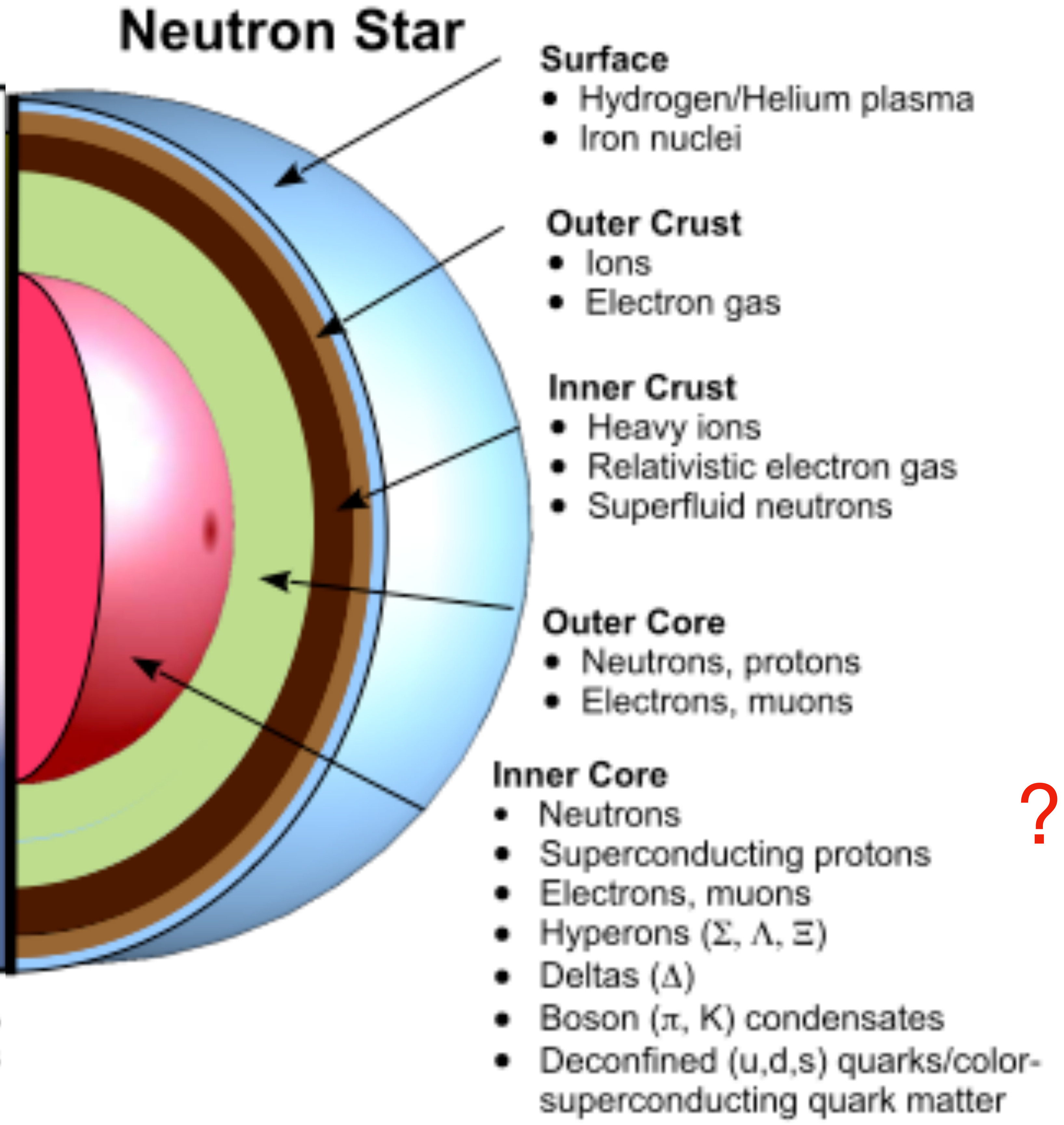
"Neutron stars are a remarkable marriage of Einstein's theory of general relativity with nuclear physics"

Yunes, Miller, Yagi. Nature Rev.Phys (2022)

β-equilibrium

$T_{Fermi}(\sim 10^{12}K) \gg T(\sim 10^{8-10}K)$



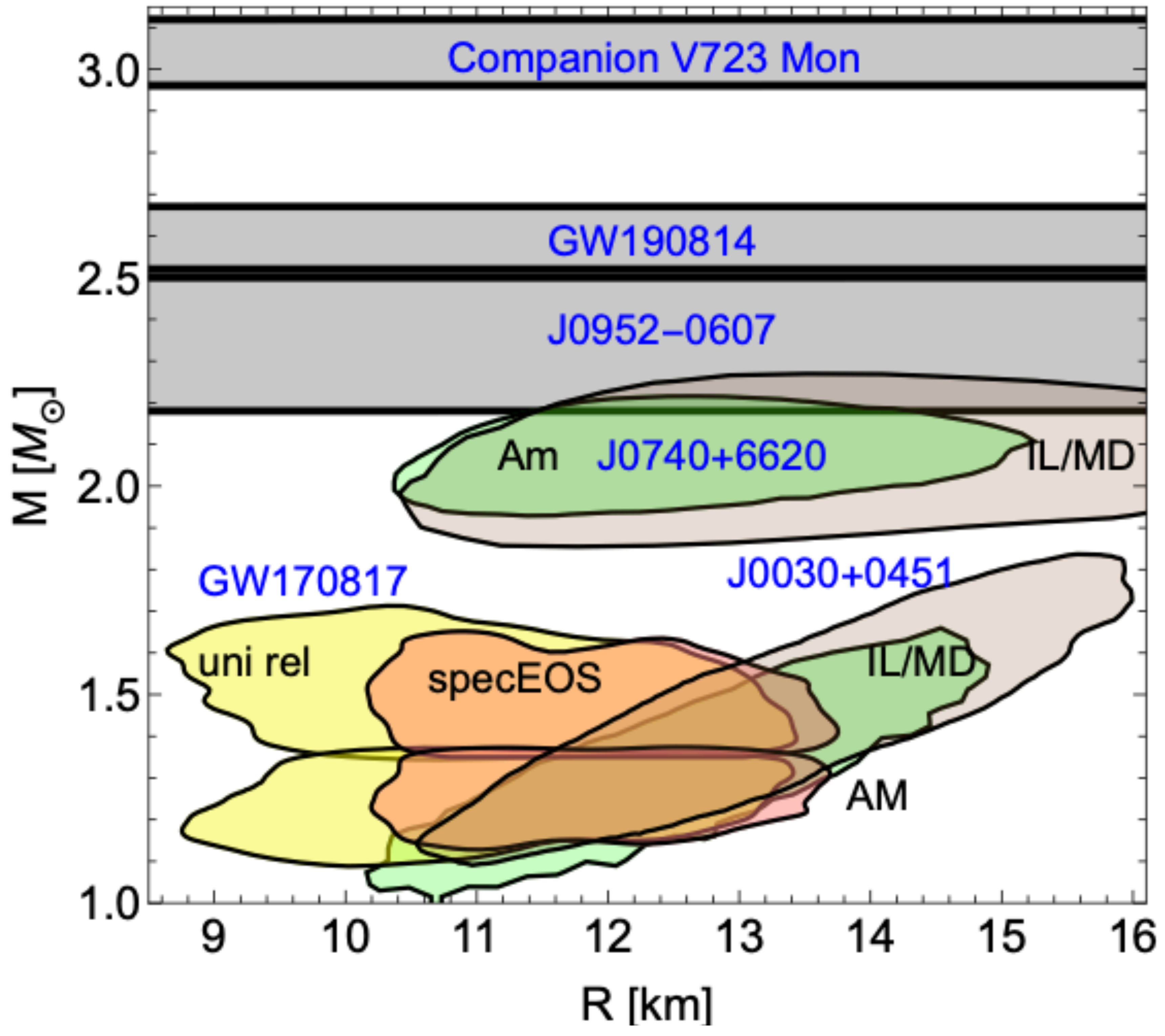


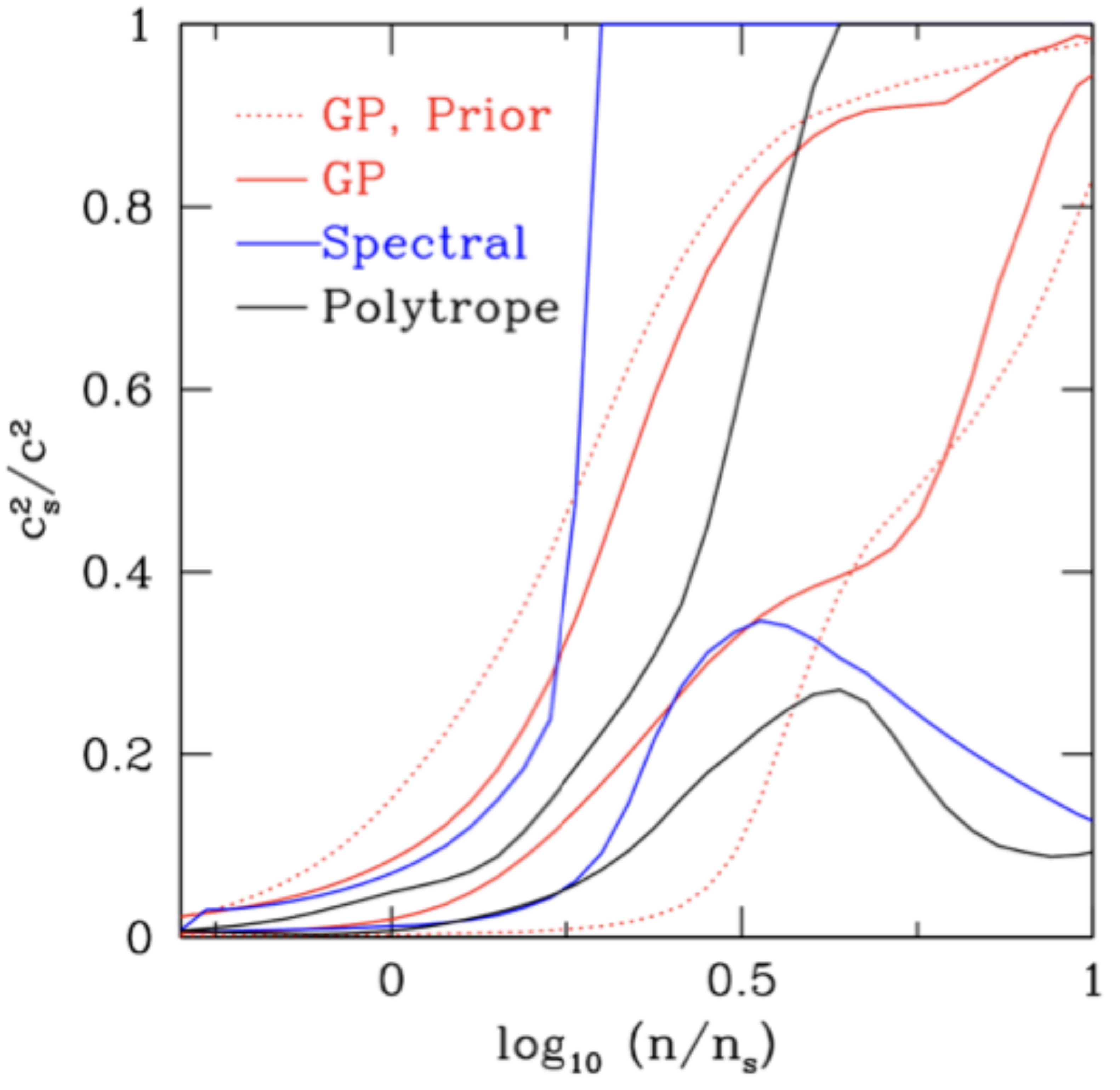
Drischler, Holt, Wellenhofer, Annu. Rev. Nucl. Part. Sci. (2021)

Weber et al. Mod.Phys.Lett.A (2014)

Current observational landscape

Electromagnetic + gravitational wave observations of NS/mergers





From: "Long Range Plan: Dense matter theory for heavy-ion collisions and neutron stars," arXiv:2211.02224, see for refs.

Bayesian analysis: Generate a family of EoS to produce a prior distribution → extract posterior using NS observations.

Shown: Constraints at 2σ level from LIGO/Virgo GW170817 and NICER J0030, J0740 used to extract $c_s^2(n_B)$ posterior with 3 different methods for generating the EoS in Miller et al. AJL (2021).

Note: GW190814, J0952-0607, V723 Mon still under debate.

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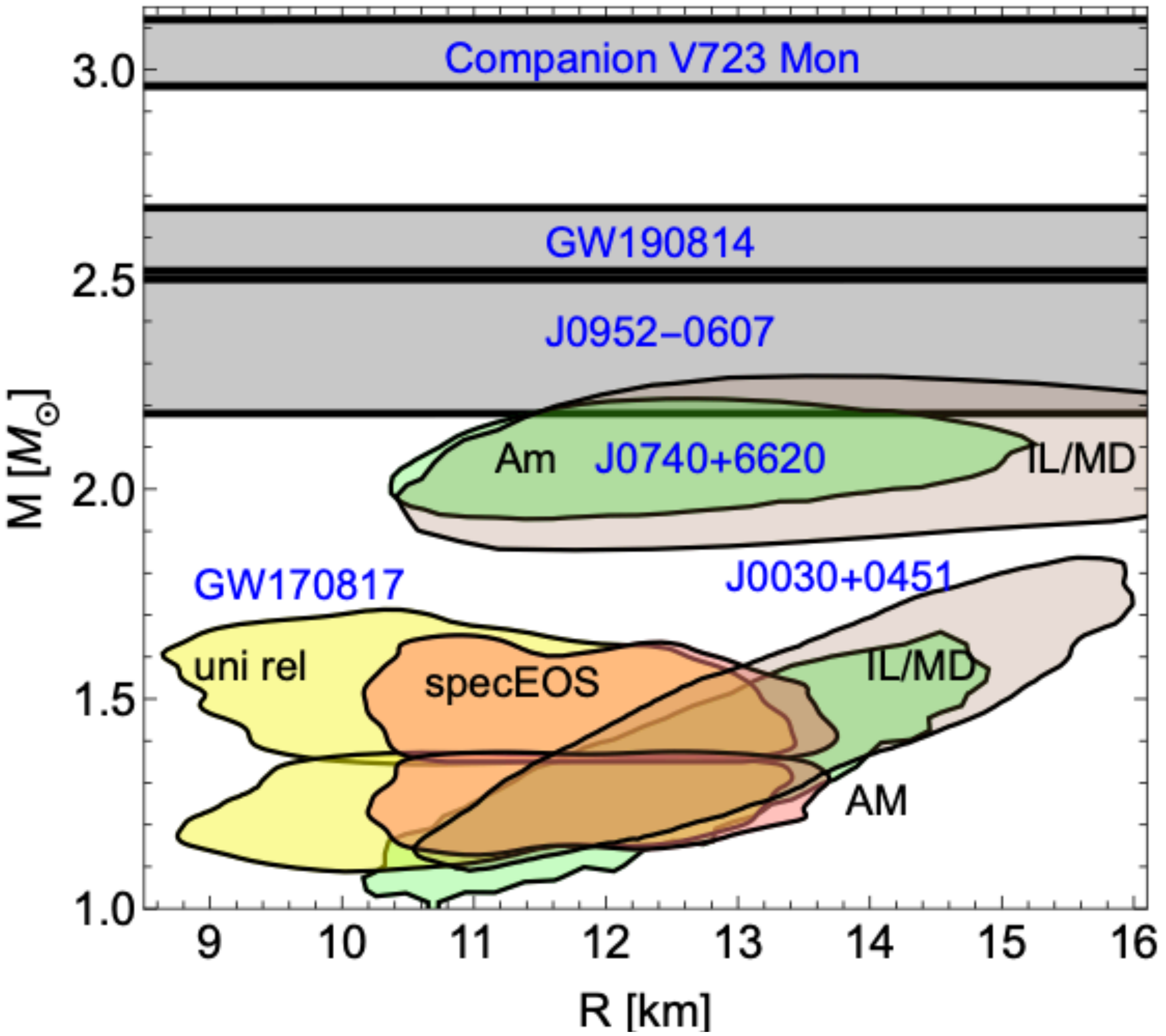

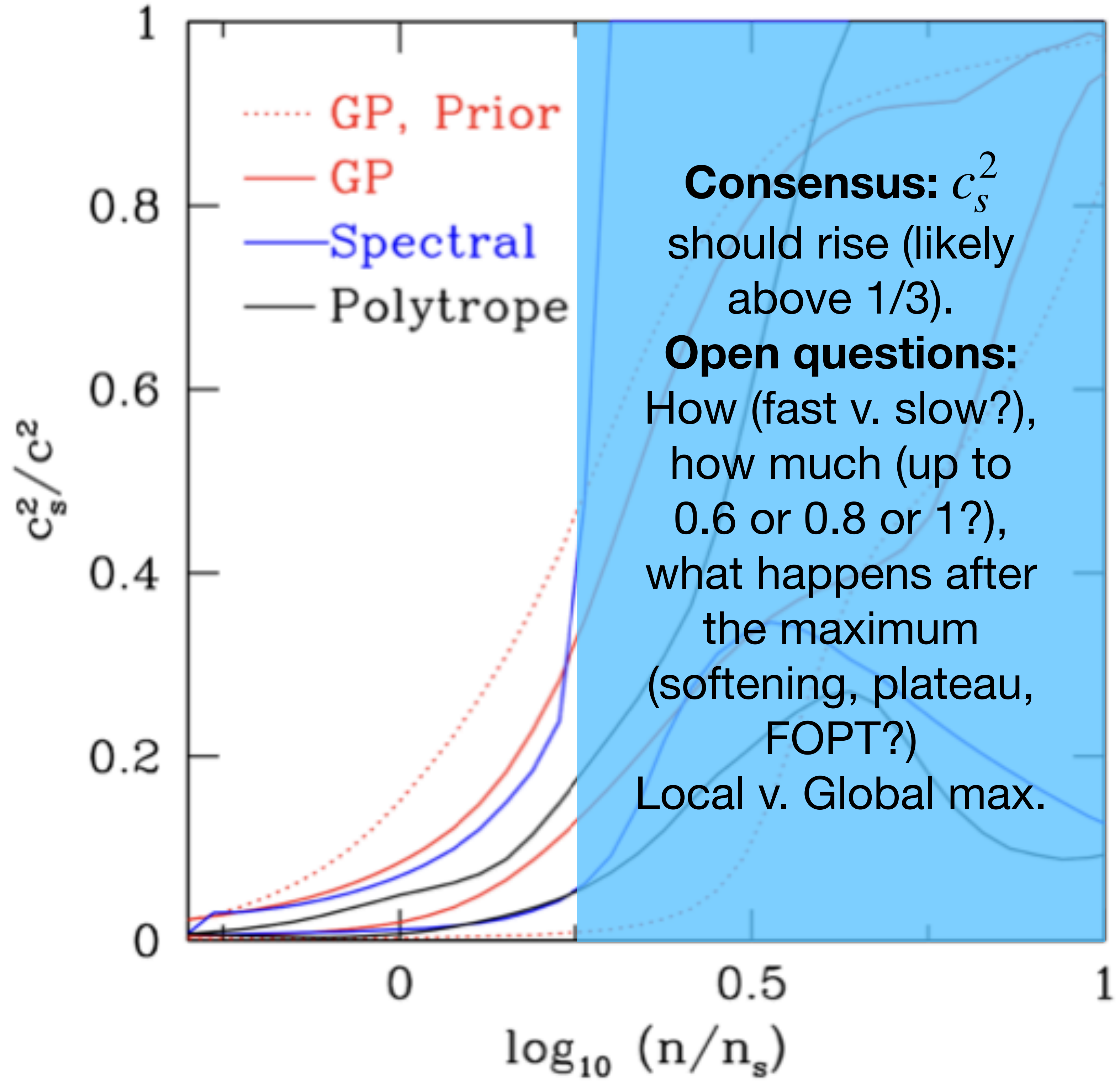

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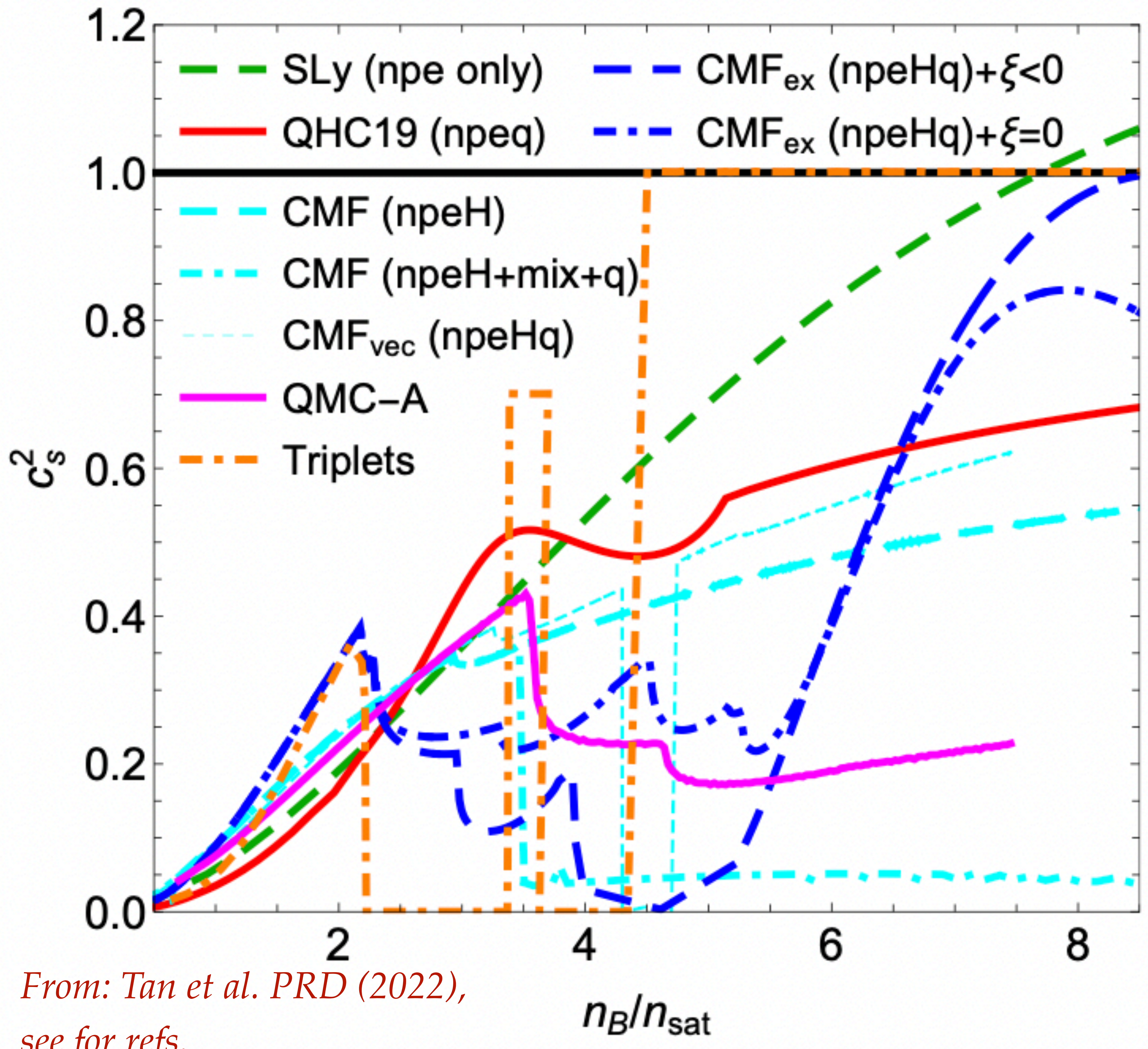
Nuclear models predict structure

EoS can be modeled with 2 thermodynamic variables e.g. $(n_B, P), (P, c_s^2), (n_B, c_s^2)\ldots$



From: Tan et al. PRD (2022), see for refs.

Crossover:

- Bump
- Spike
- Plateau
- Oscillations

1st order PT:

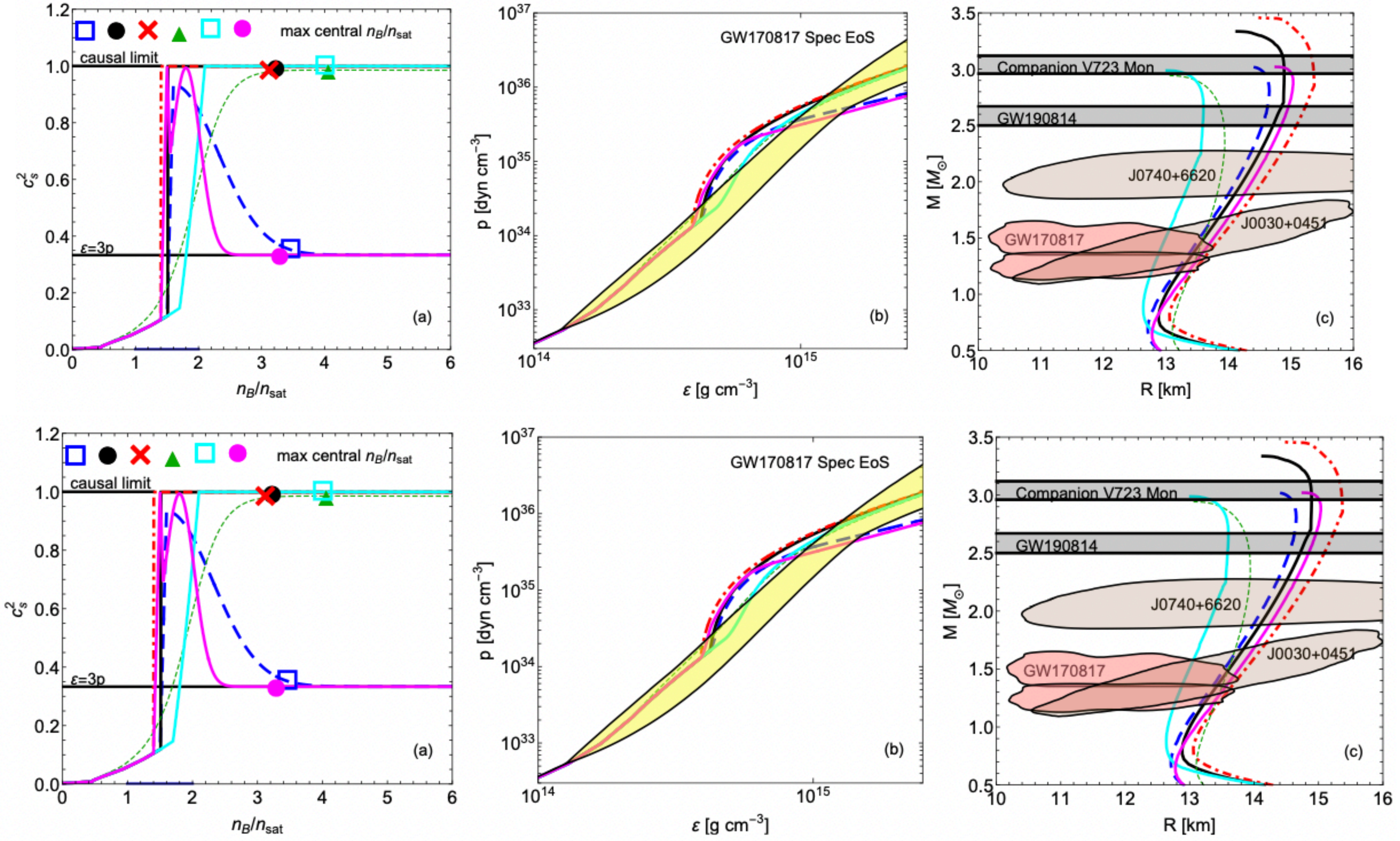
Gap in $c_s^2(n_B)$ / $c_s^2 \to 0$

Nuclear models with quark/ strange degrees of freedom lead to non-trivial structure in c_s^2

Effects of sharp/non-trivial features on NS properties

Systematic study: Tan et al. (2022)

- Sharp/non-trivial features important for producing heavy/ultra-heavy NS
- These EoS fit constraints and outside of the regime captured by e.g. spectral EoS



How do we ensure an adequate amount of EoS with non-trivial features is represented in our priors?

Non-parametric(ish) approach to EoS inference

Gaussian processes (GP)

- Stochastic process (collection of random variables)

- **Reproduces continuous functions** between $(-\infty, \infty)$ over a specified domain

In practice, for NS EoS inference:

Auxiliary variable $\phi(x) = \log(1/c_s^2 - 1)$, enforces stability and causality

L. Lindblom PRD (2010)

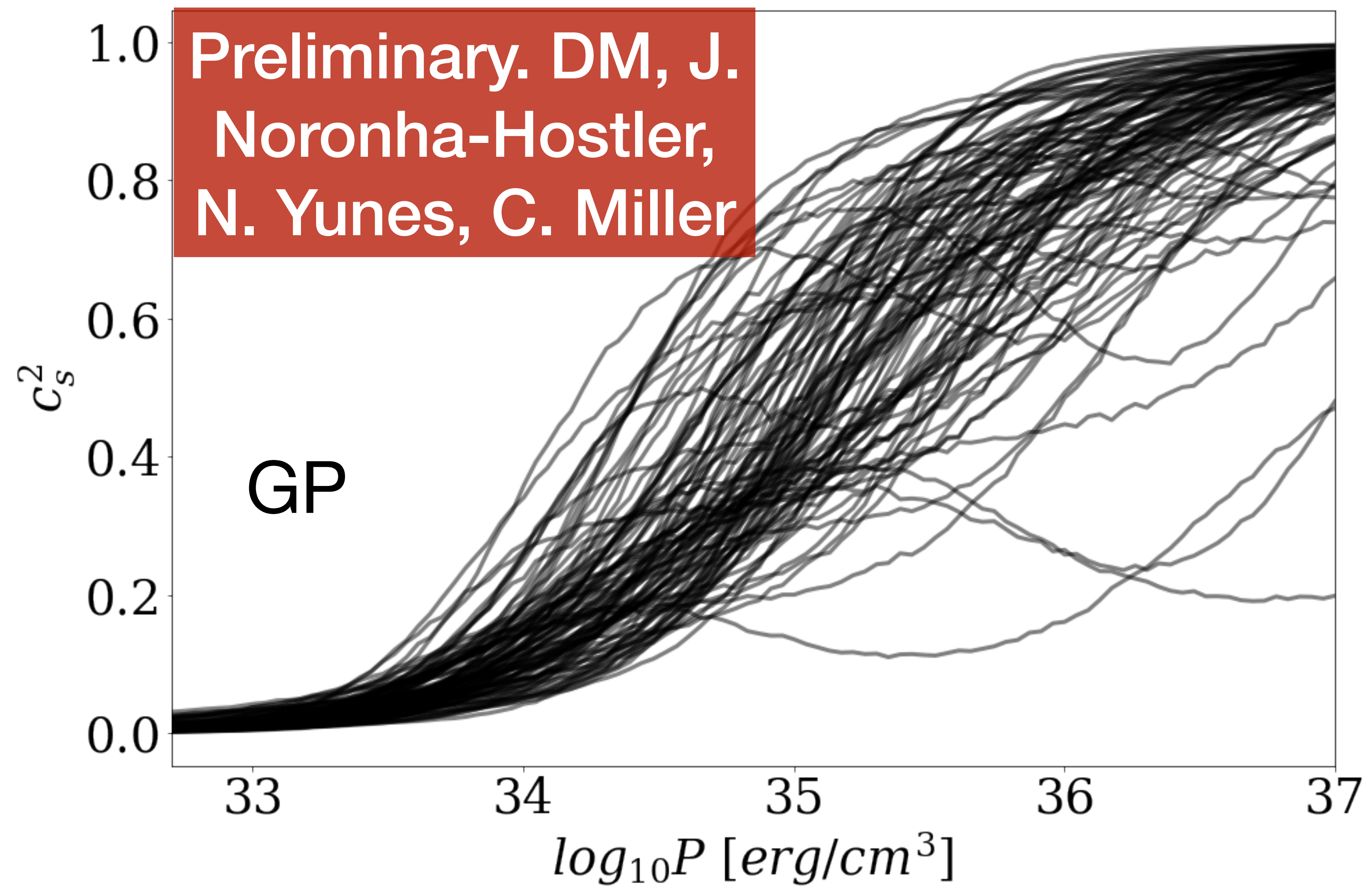
Each x_i specifies a domain point (e.g. in P, n_B)

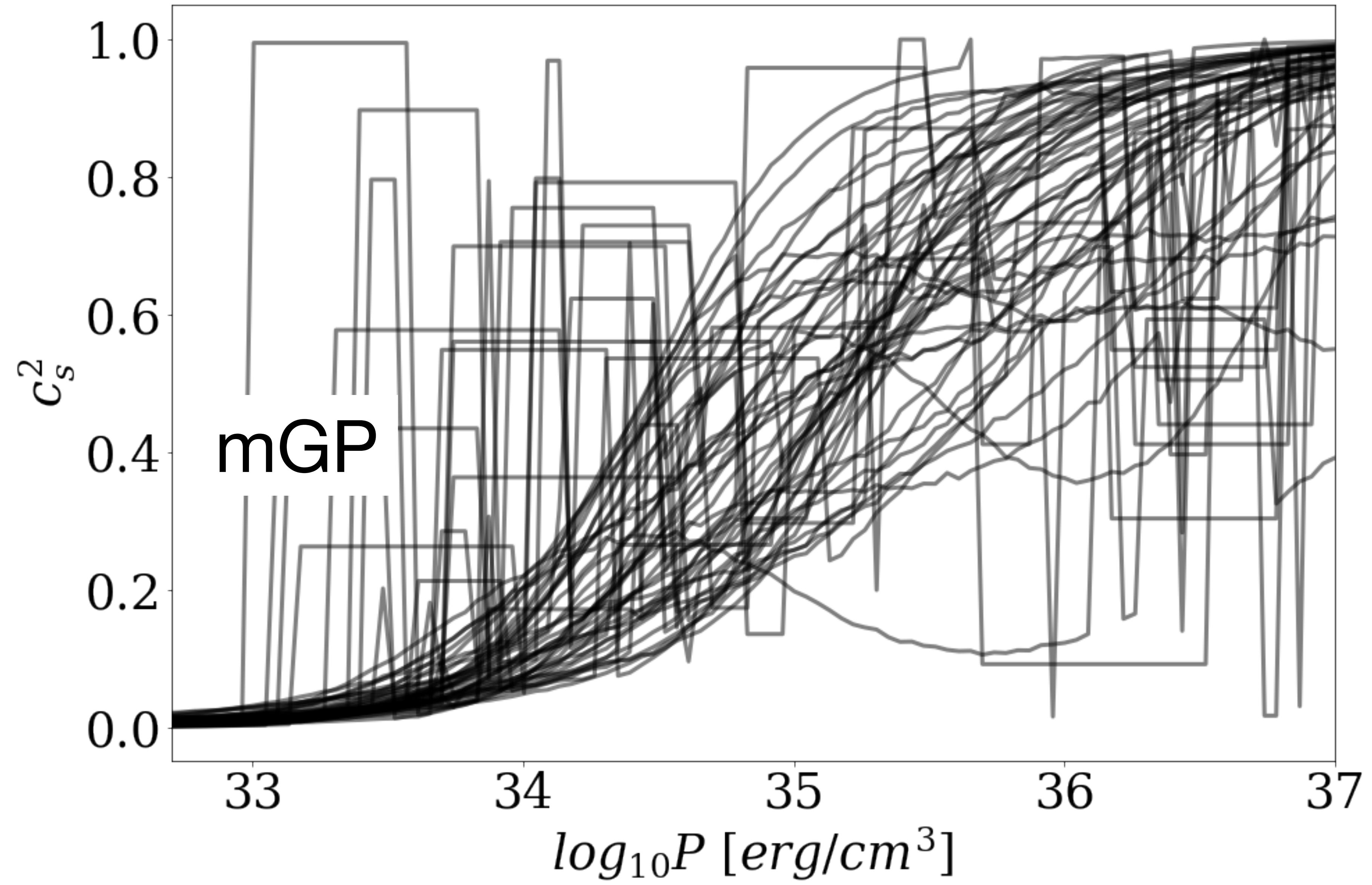
A GP sample is given by

$$\phi_k(\overrightarrow{x}) = \overrightarrow{\mu}(\overrightarrow{x}) + L\overrightarrow{u},$$

where $\overrightarrow{u} \sim \mathcal{N}(0,I)$, L: Cholesky decomposition of covariance matrix Σ.

Modified GP (mGP) EoS



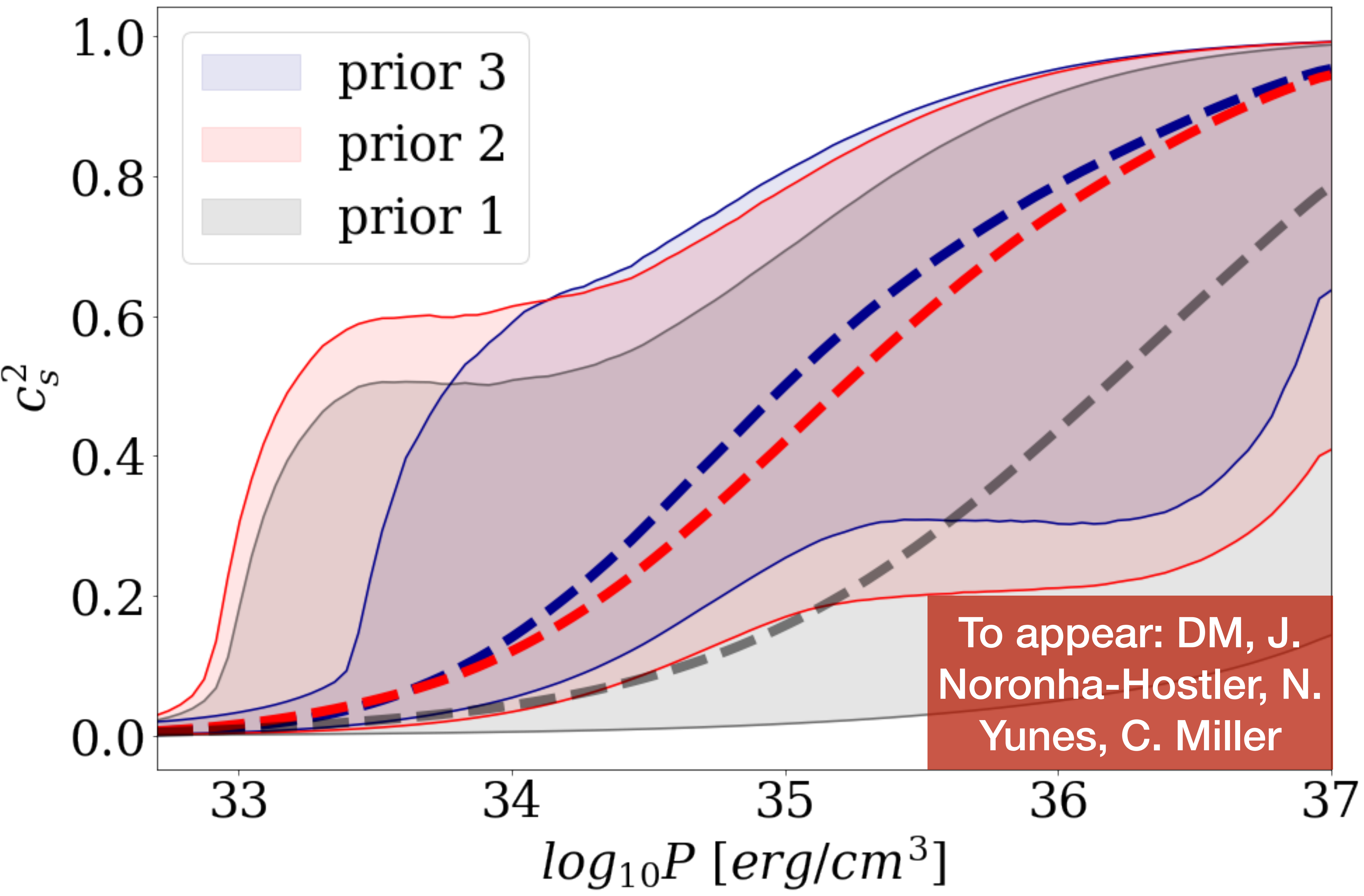


Modified: GP background + added features

- **Why:** Motivated by nuclear models and H. Tan et al (2022), **current (non-)parametric methods do not capture sharp/non-trivial features well + important for explaining heavy and ultra-heavy stars.**
- **What:** spikes, wells, plateaus, bumps, kinks added onto smooth GP background.
- **Method:** 3 modification categories — spike, spike + plateau, 2 plateaus. Final functional form depends on background GP.
- Prior contains both unmodified GP and mGP samples.
- Can be analyzed together or separately.

Sample selection

dashed: mean, solid: 90% contours



We perform a pruning of the prior to ensure we have enough EoS that meet basic constraints

- 900,000 EoS in prior 1
- of which only 281,139 in prior 2 reach $M_{max} \geq 1.4 M\odot$
- Final cut imposes
  - $M_{max} \geq 1.8 M\odot$
  - 9.0 km $\leq R_{1.4} \leq$ 18.0 km
  - 10 $\leq \Lambda_{1.4} \leq$ 2000
- **Prior 3: 104,594 total EoS split between modified and unmodified GP**

Use prior 3 with NICER/LIGO + low-density +pQCD to obtain posterior distributions

Low-density and pQCD constraints

All EoS are matched to QHC19 at 0.5 n_{sat}

+ No features allowed below $1.1\ n_{sat}$

+ Likelihood of symm. energy 32 ± 2 MeV

+ Causality/integral constraints from Komoltsev and Kurkela (PRL, 2022)

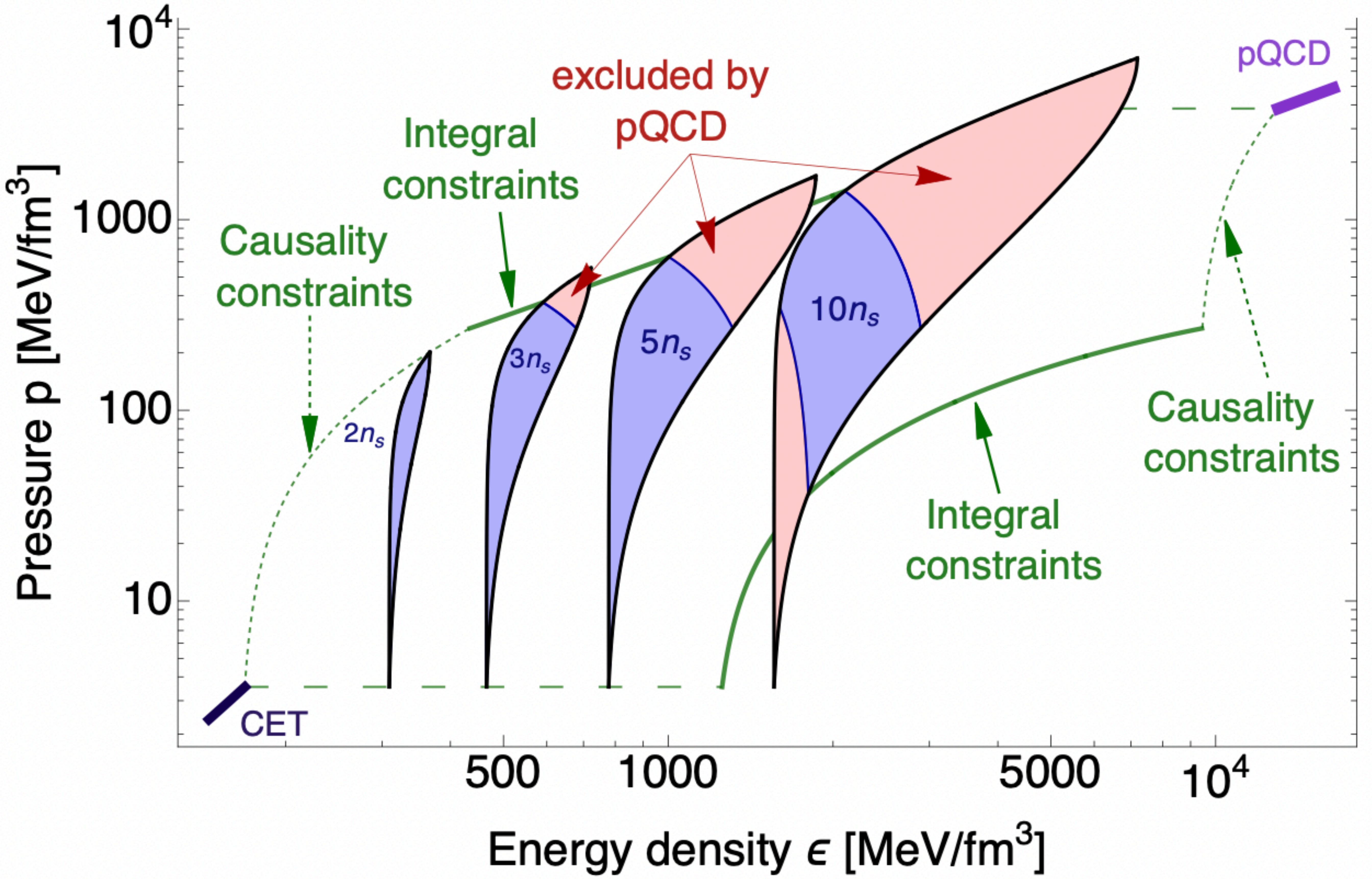
Averaged over pQCD renormalization parameter X = [1/2, 2] (log-linear).

$w_{pQCD} = 1$ when in agreement for all X.

$0 < w_{pQCD} < 1$, in tension.

$w_{pQCD} = 0$ not allowed.

From: Komoltsev, Kurkela, PRL (2022)



Questions addressed in this talk

- Are sharp features in $c_s^2(n_B)$ consistent with NICER/LIGO observations?
- Is there a clear preference for unmodified/modified GP?
- What is the global maximum of c_s^2?
- Where is the global maximum of c_s^2 in terms of the density?
- Is there conclusive evidence for a softening of the EoS within the range of n_B^{TOV} (signaling a possible phase transition to an exotic phase)?

Marczenko (arXiv:2207.13059), also Komoltsev & Kurkela PRL (2022)

Evidence for smooth vs. sharp features in the EoS

- Assume equal prior probability for all EoS:

$$P[(m)GP] = \frac{1}{N_{(m)GP}}$$

- The Bayesian evidence is

$$P[(m)GP\,|\,D] = \frac{1}{N_{(m)GP}} \Sigma_i^{N_{(m)GP}} \mathcal{L}_i$$

- Bayes factor: statistical evidence for model 1 (smooth features) against model 2 (sharp features)

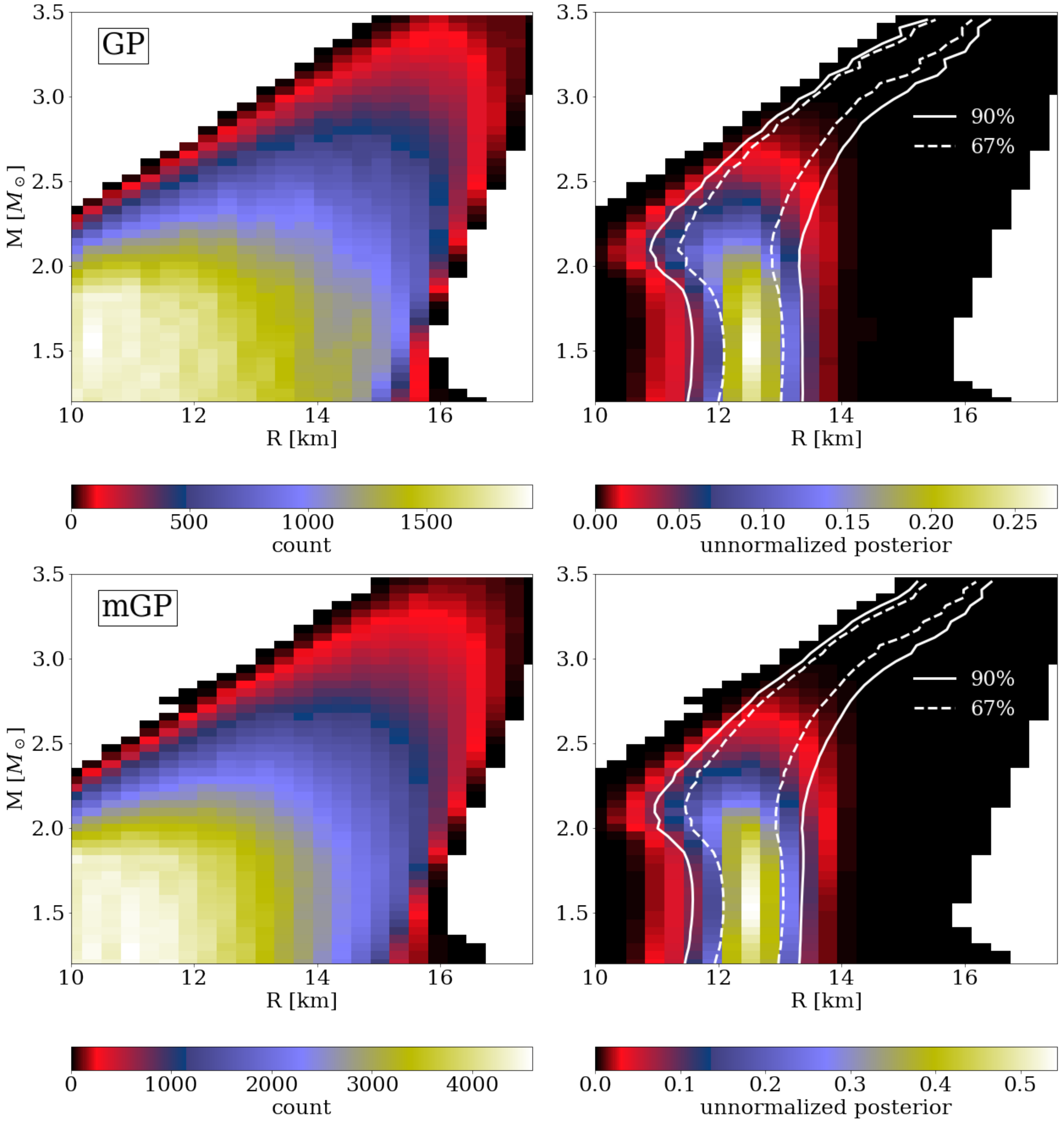
$$K = \frac{P[GP\,|\,D]}{P[mGP\,|\,D]} = \mathbf{1.126}$$

We find no evidence that GP EoS are preferred over mGP EoS

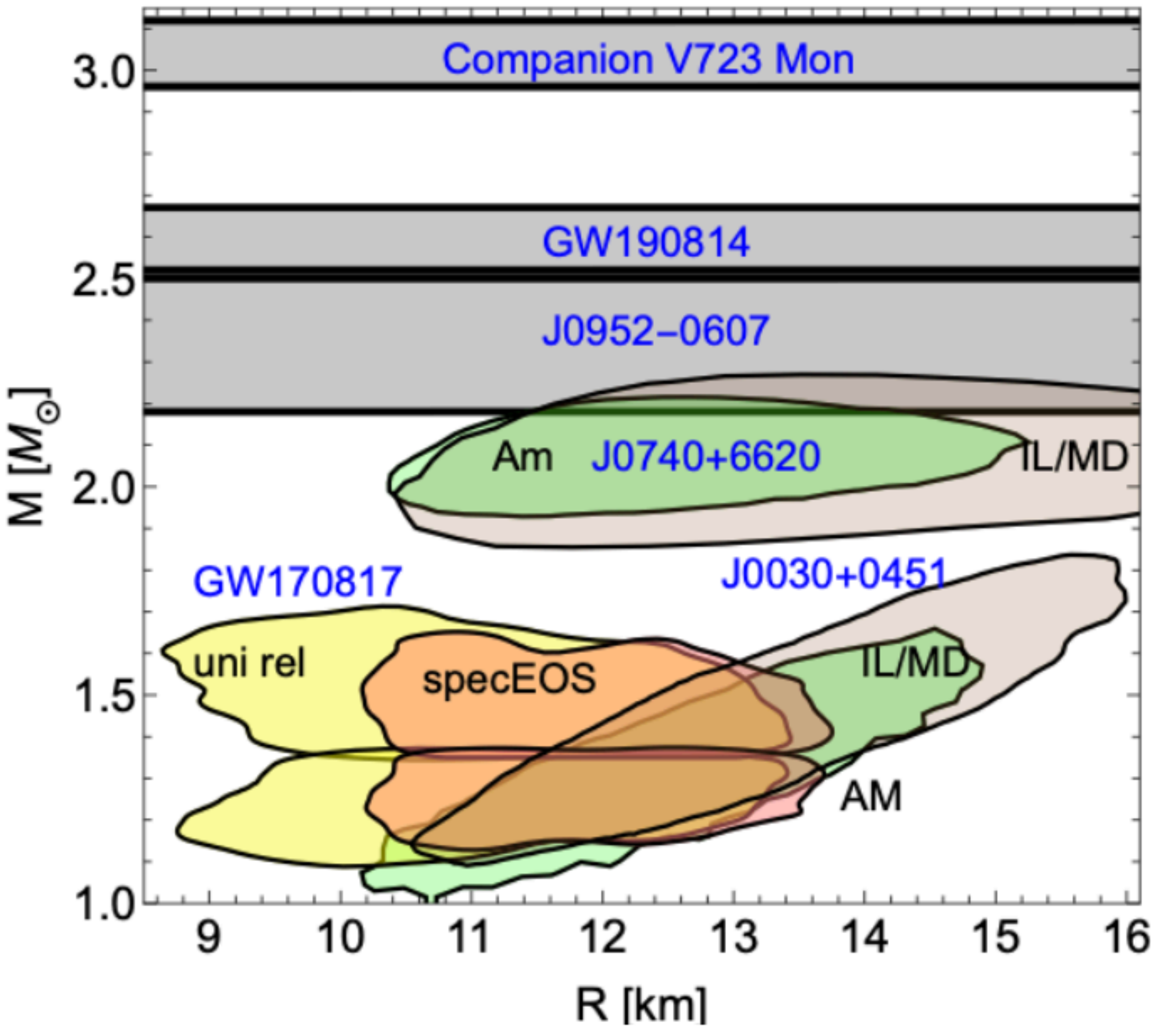
See also: previous inference study on FOPT/crossovers, Somasundaram et al. (2021), 2112.08157, piecewise linear EoS.

Posteriors: mass-radius

To appear: DM, J. Noronha-Hostler, N. Yunes, C. Miller



Both frameworks can account for current measurements



Effects of pQCD constraints

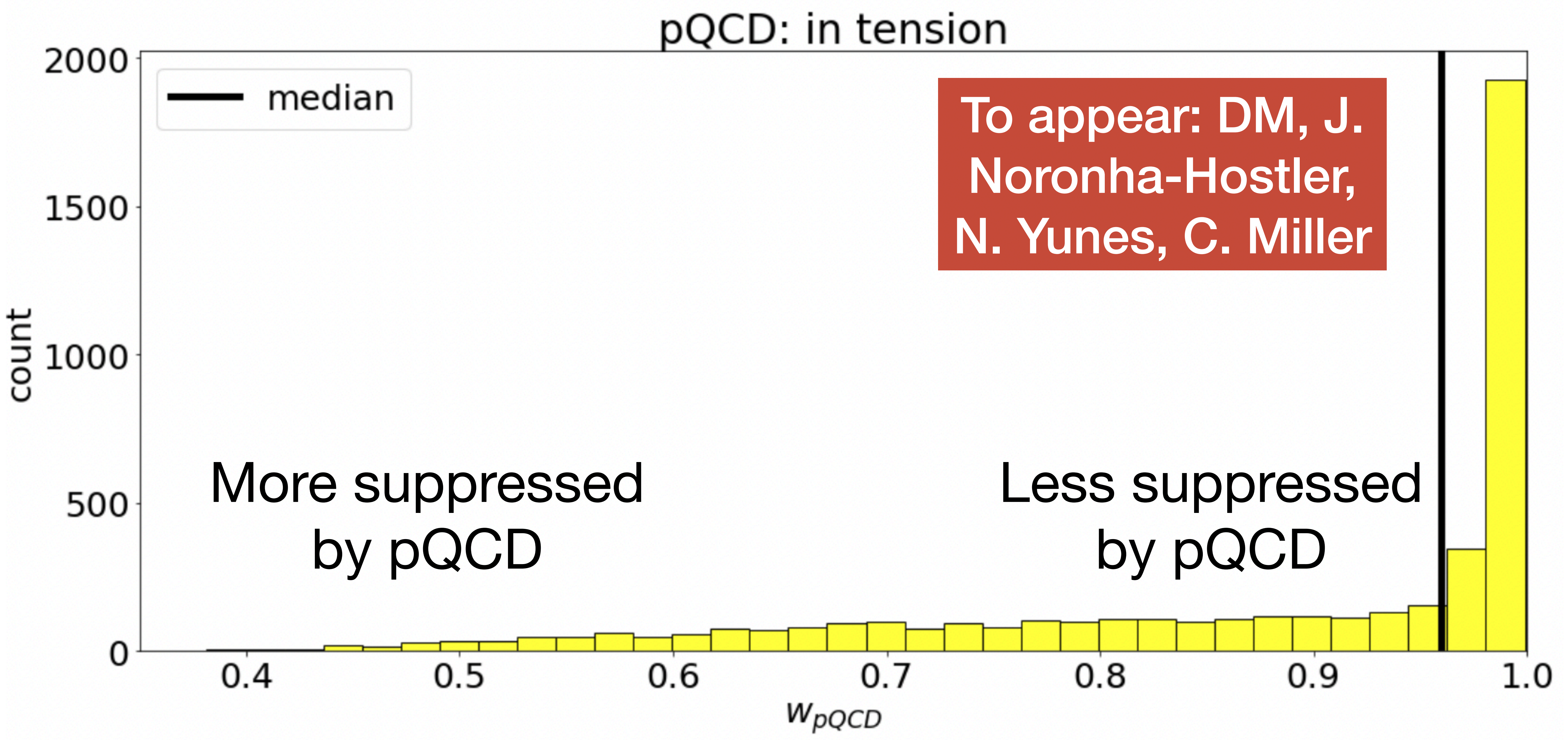
- **Show EoS only up to n_B^{TOV}**

→ **pQCD constraints imposed at n_B^{TOV}**

11 EoS ruled out (0.8%)

127,199 EoS in agreement (96.5%)

4,592 EoS in tension (3.5%) →

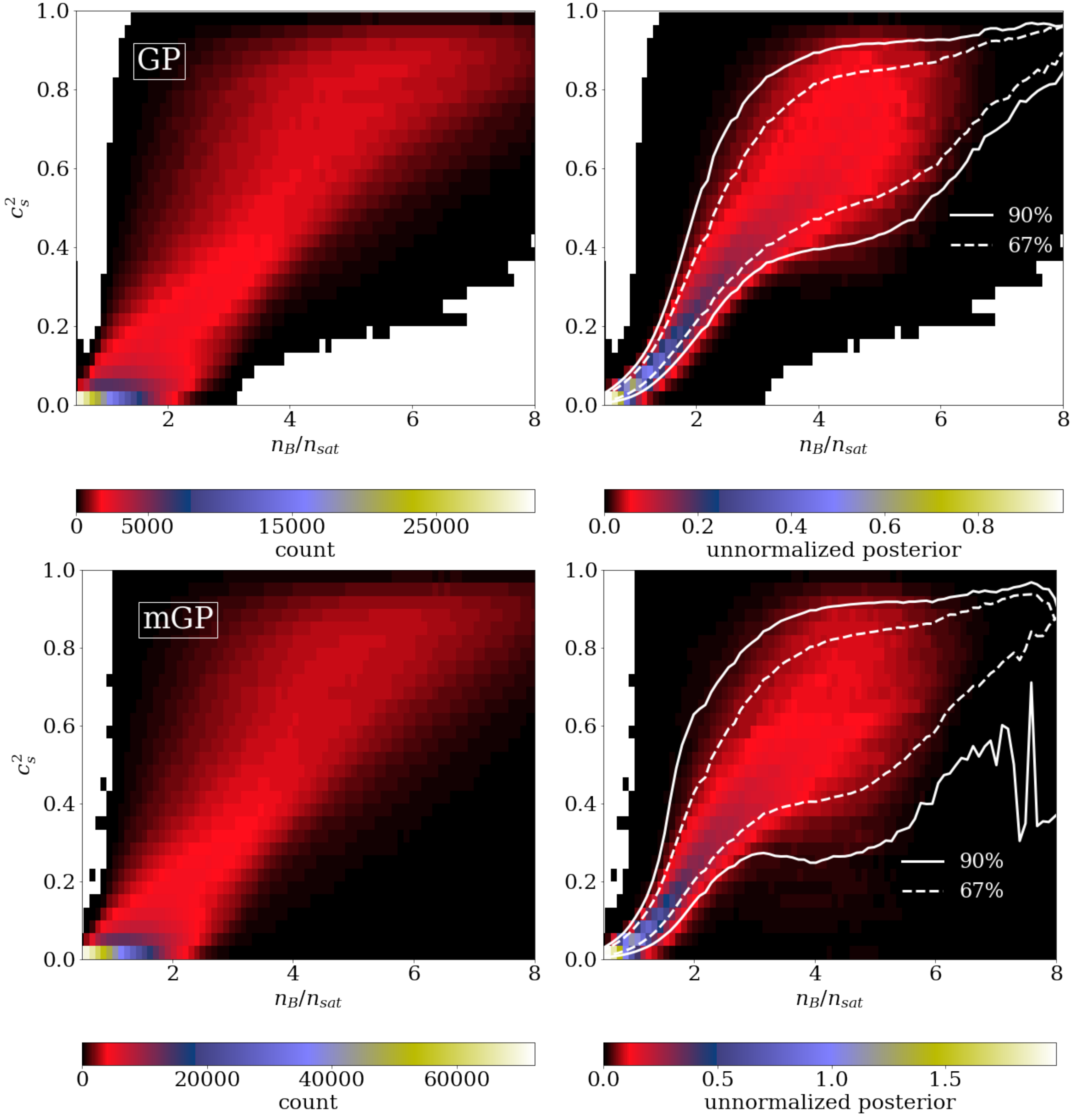


- Thermodynamic + consistency constraints can't be neglected, but the effect for pQCD renormalization parameter X = [1/2,2] imposed at max. central densities **does not affect the shape of the posteriors.**

See also: R. Somasundaram, I. Tews, J. Margueron, arXiv: 2204.14039

Posteriors: $c_s^2(n_B)$

To appear: DM, J. Noronha-Hostler, N. Yunes, C. Miller



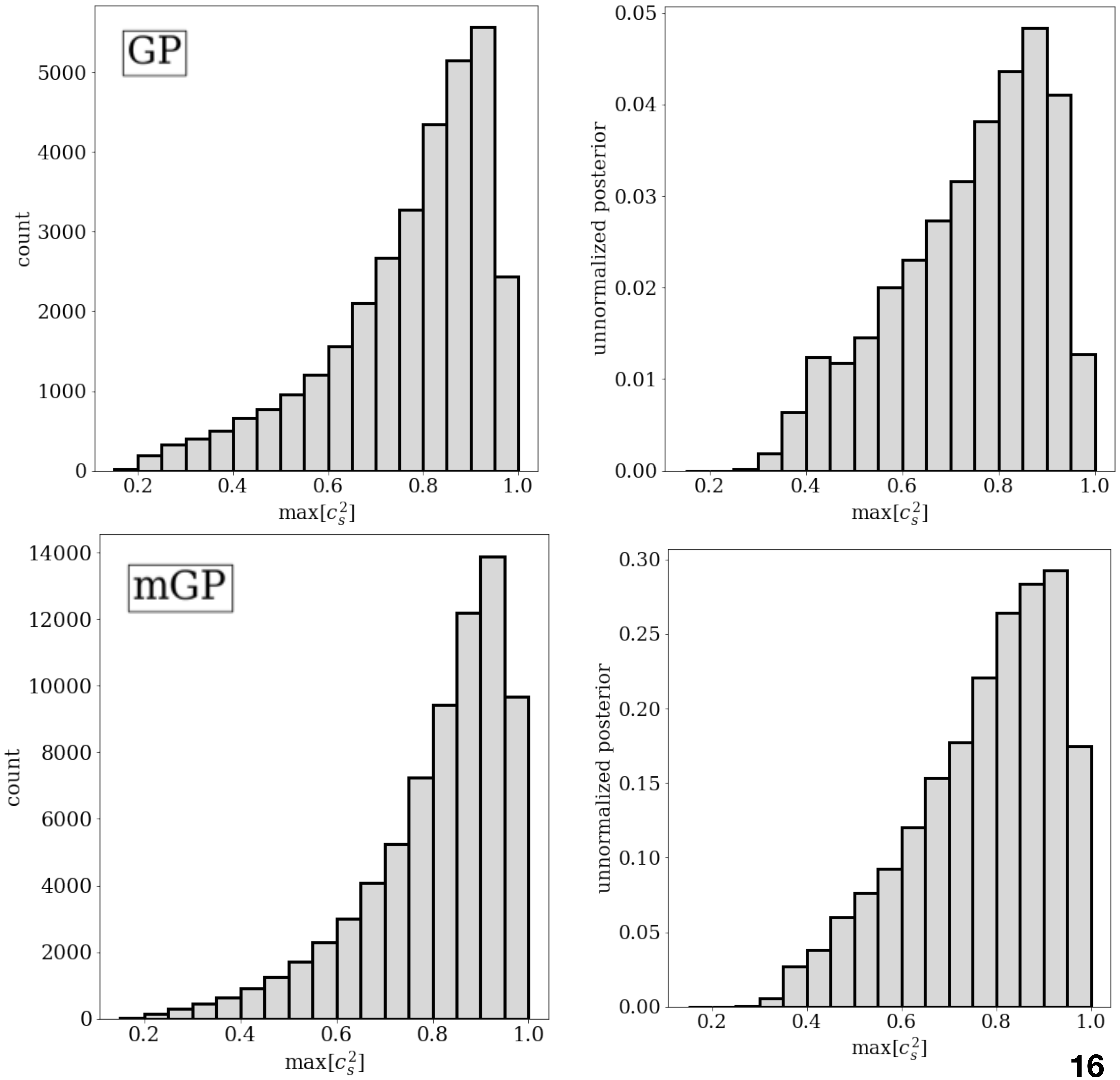
More systematic treatment below n_{sat}, see: Raaijmakers et al AJL (2021), 2105.06981

Low density regime sensitive to observations

At the 90% level, c_s^2 rises above 1/3 around ~$3n_{sat}$

We cannot conclude that there is a softening of the EoS within the range of n_B^{TOV}

What is the global maximum of the speed of sound?



Preliminary. DM, J. Noronha-Hostler, N. Yunes, C. Miller

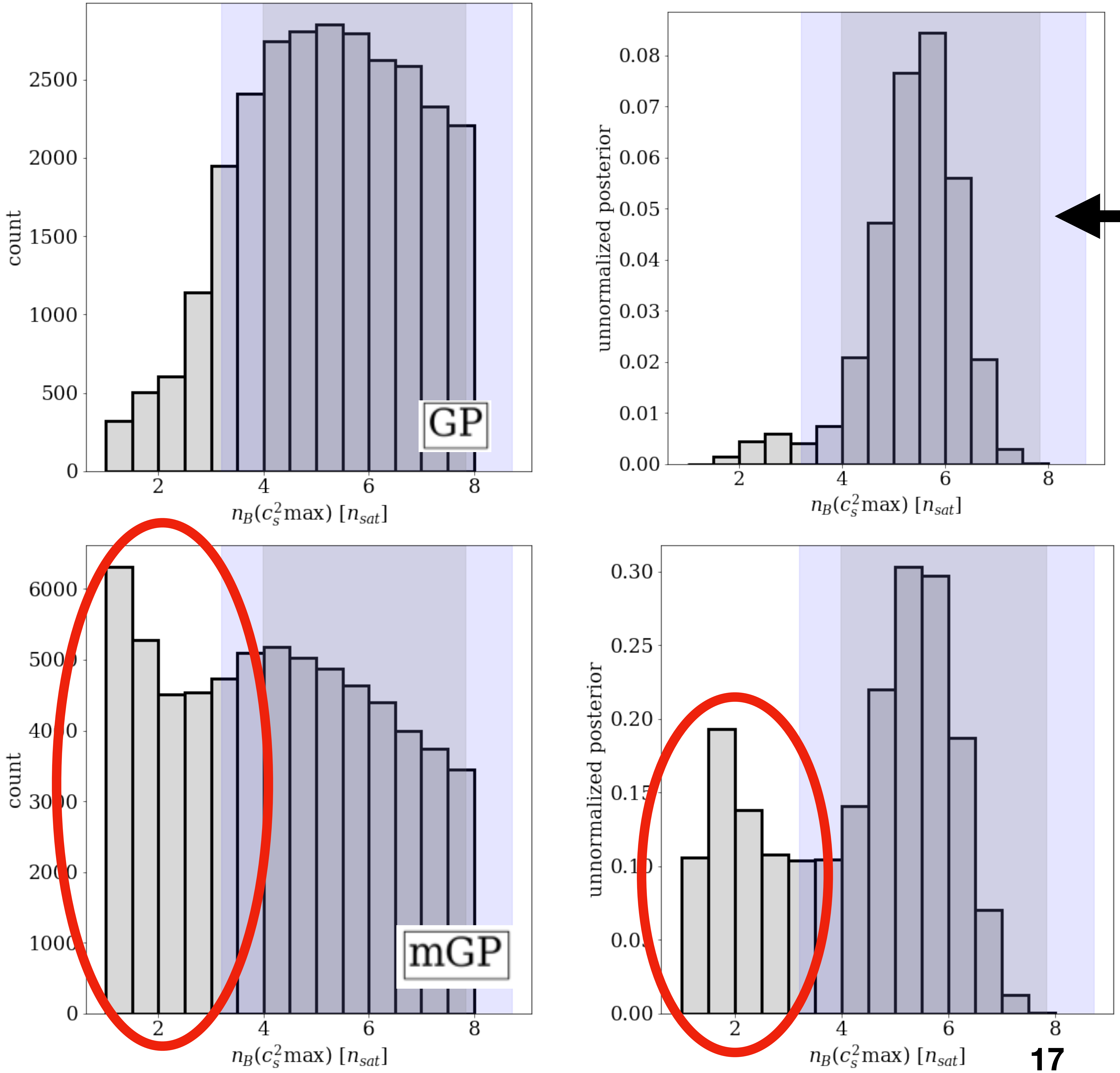
Prior 3 is biased to large values of c_s^2:

Observations **enhance** the probability of a lower c_s^2 at the global max.

→Influence of NICER/LIGO-motived cuts for prior 3 vs. biased GP is currently being investigated and will be improved for future work.

Where is the global maximum of the speed of sound?

Preliminary. DM, J. Noronha-Hostler, N. Yunes, C. Miller

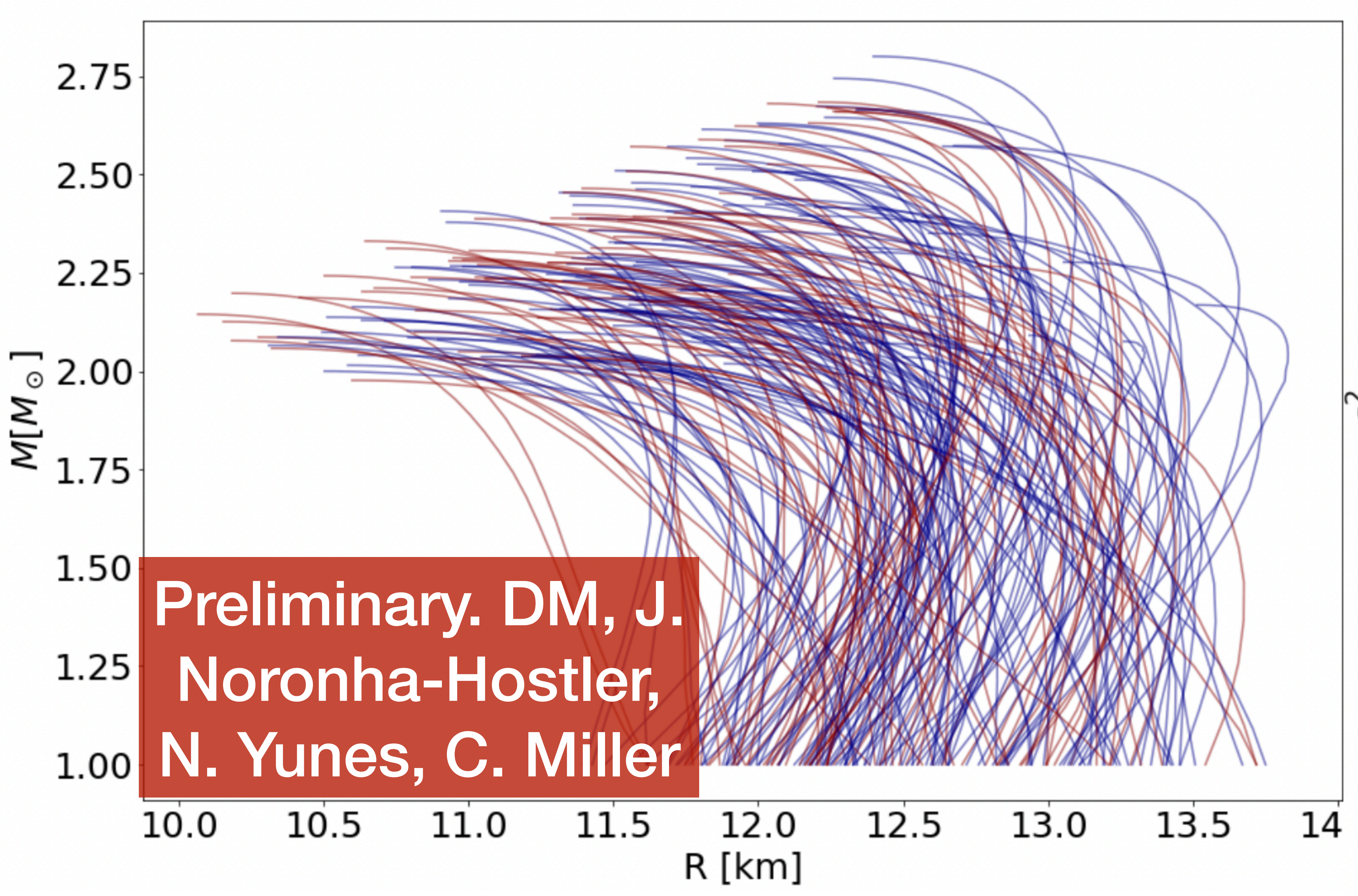


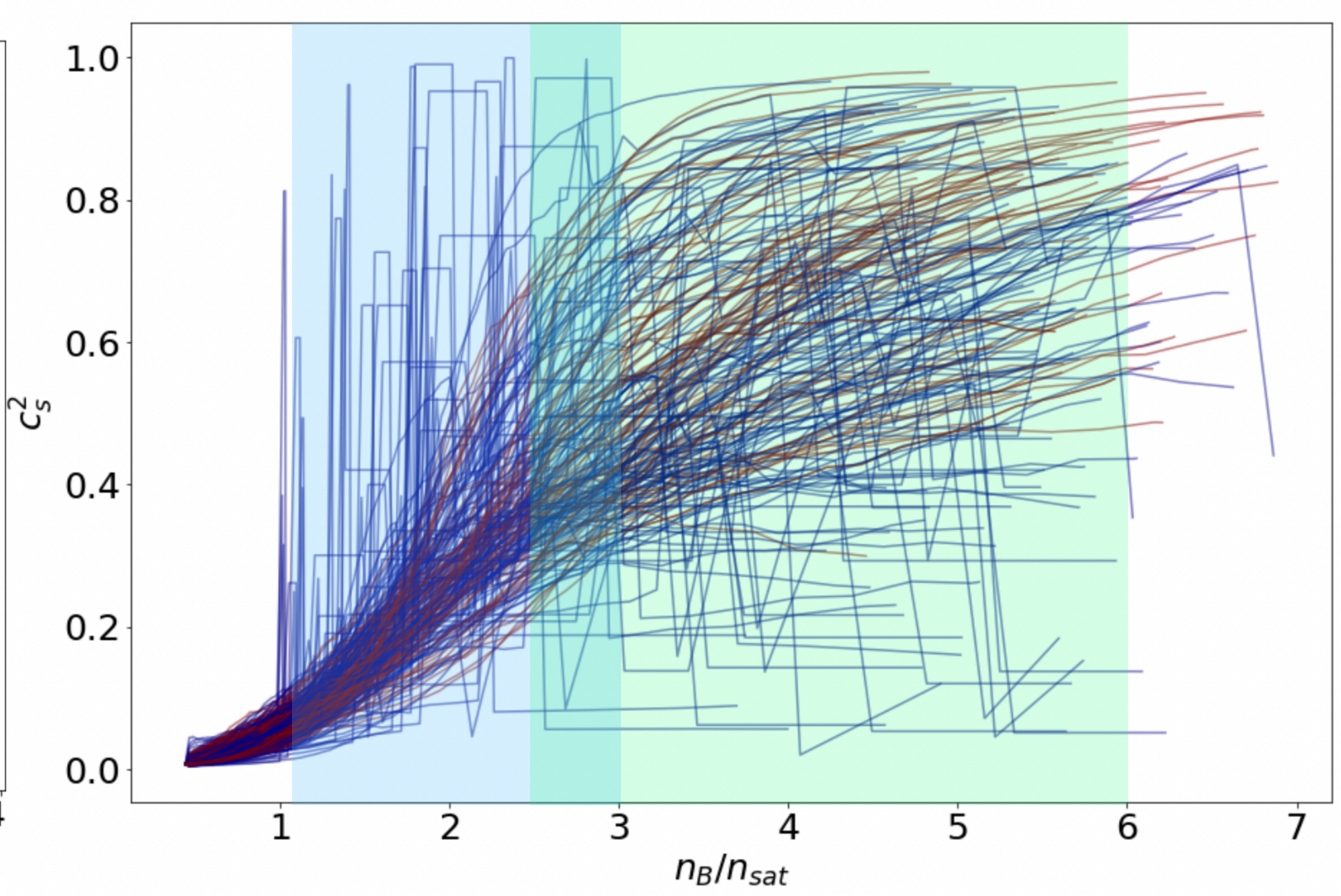
1, 2 σ: range of max. central densities

Because of constraints at and below n_{sat}, large values of c_s^2 below ~3 n_{sat} can only be achieved with sharp rises (better captured by the mGP).

The posterior distribution for $n_B(c_s^2\ \text{max})$ is bimodal

Two possibilities for the behavior of c_s^2





Sample of 200 EoS in the 90th percentile for likelihood

We're currently investigating how these two cases can be distinguished with future data

Both features can produce heavy/ultra-heavy stars

Global maximum between ~1.1-3n_{sat} or Softening: Possible PT/ crossover

c_s^2 rises monotonically to higher densities going above 1/3 between ~1.5-3n_{sat}

Summary

- Are sharp features in $c_s^2(n_B)$ consistent with NICER/LIGO observations? **Yes**
- Is there a clear preference for smooth/non-trivial features in the EoS? **No**
- What is the global maximum of c_s^2? **More work required**

  Improve low density treatment: χEFT

  Further relax assumptions about mean behavior of GP

- Where is the global maximum of c_s^2 in terms of the density? **Near i) n_B^{TOV} OR ii) $1.5 - 3n_{sat}$**

  Seen with mGP (↑)

- Is there conclusive evidence for a softening of the EoS within the range of n_B^{TOV} (signaling a possible phase transition to an exotic phase)? **No**
- What can future data tell us about the dense matter speed of sound? **More work required** It depends on whether we have i) or ii)

Outlook

EoS inference from astro. observations is a new field.

More astrophysical data is coming. Next 10 years: NICER and LIGO/Virgo O4+O5.

We're learning ways to integrate theoretical constraints with observations and experiments (talk by Ingo Tews) + robust constraints from HIC.

– Can we find a flexible common parametrization of the EOS, applicable to neutron star calculations and different types of heavy-ion collisions simulations?

Effective models (talk by Rajesh Kumar).

At Illinois: combining flexible T=0 parameterizations (this talk) with expansions into Y_Q (talk by Nanxi Yao) and finite T (graduate student Katie Zine).

– What other observables could enable the extraction of the EOS?

Breaking of universal relations (talk by Veronica Dexheimer) + GW signals (ongoing work).

Image credits: Lukas R Weih and Luciano Rezzolla

Back-up

Non-parametric(-ish) approach to EoS inference

Non-parametric, but…

<u>choice:</u> $\vec{\mu}(\vec{x})$ specifies mean behavior of $\phi_k(x)$

<u>choice:</u> Covariance matrix Σ, could be model-informed or agnostic (still requires hyperparameters)

- **This work:** agnostic limit + collection of nuclear physics models lead to parametrization in $\phi(\log P)$:

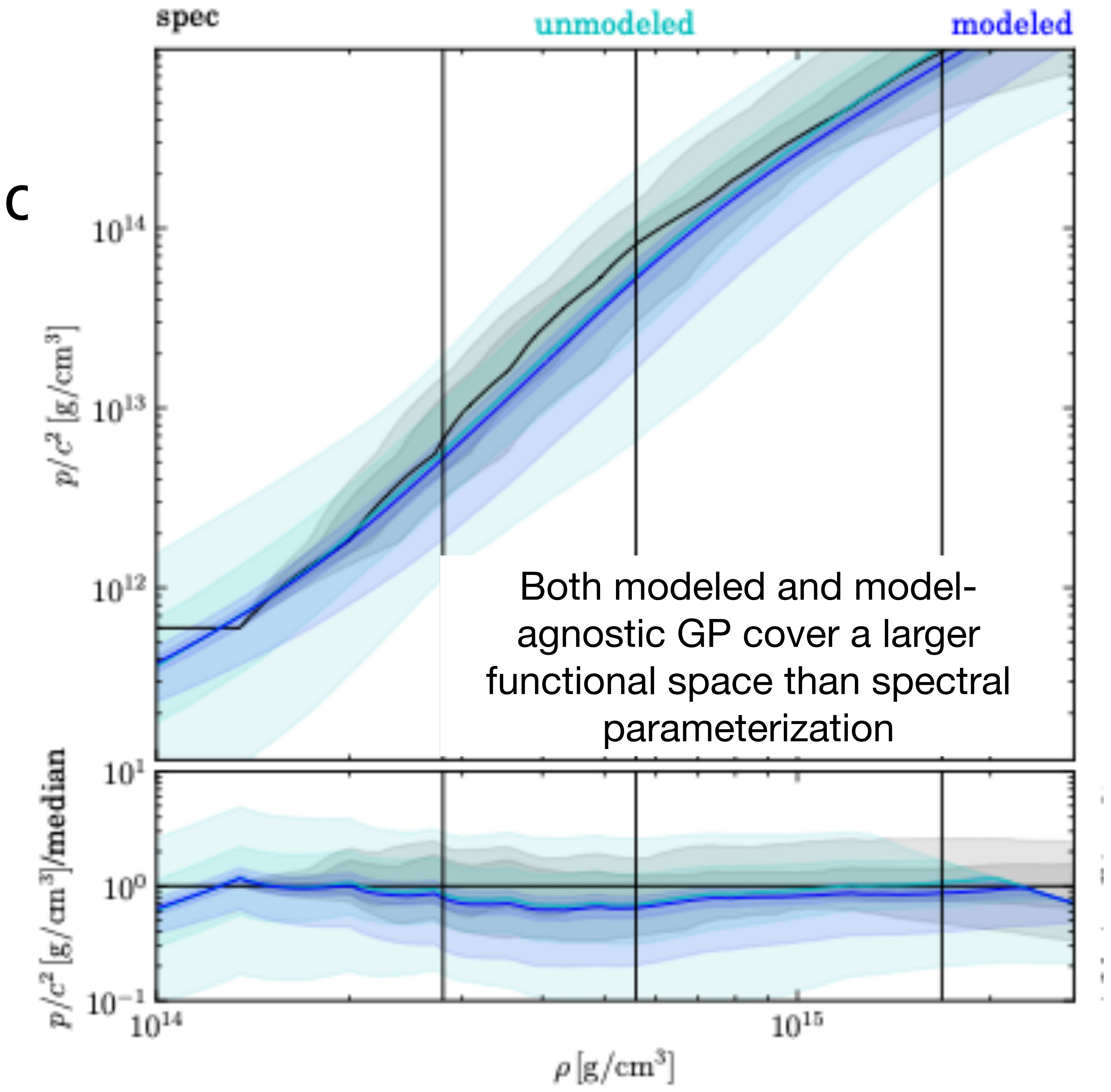
$$\mu_i(\log p_i) = a - 2(\log p_i - 32.7), \text{ hadronic: } a = 5.5$$

- Covariance matrix

$$\Sigma^{ij} = K^{ij}_{se} + K^{ij}_{wn} = \sigma^2 \exp\left(\frac{x_i - x_j}{2l^2}\right) + \sigma^2_{wn}(x)\delta(x_i - x_j)$$

- Choose $l = \sigma = 1$ following Miller et al. AJP 2021

Landry, Essick, PRD (2019)

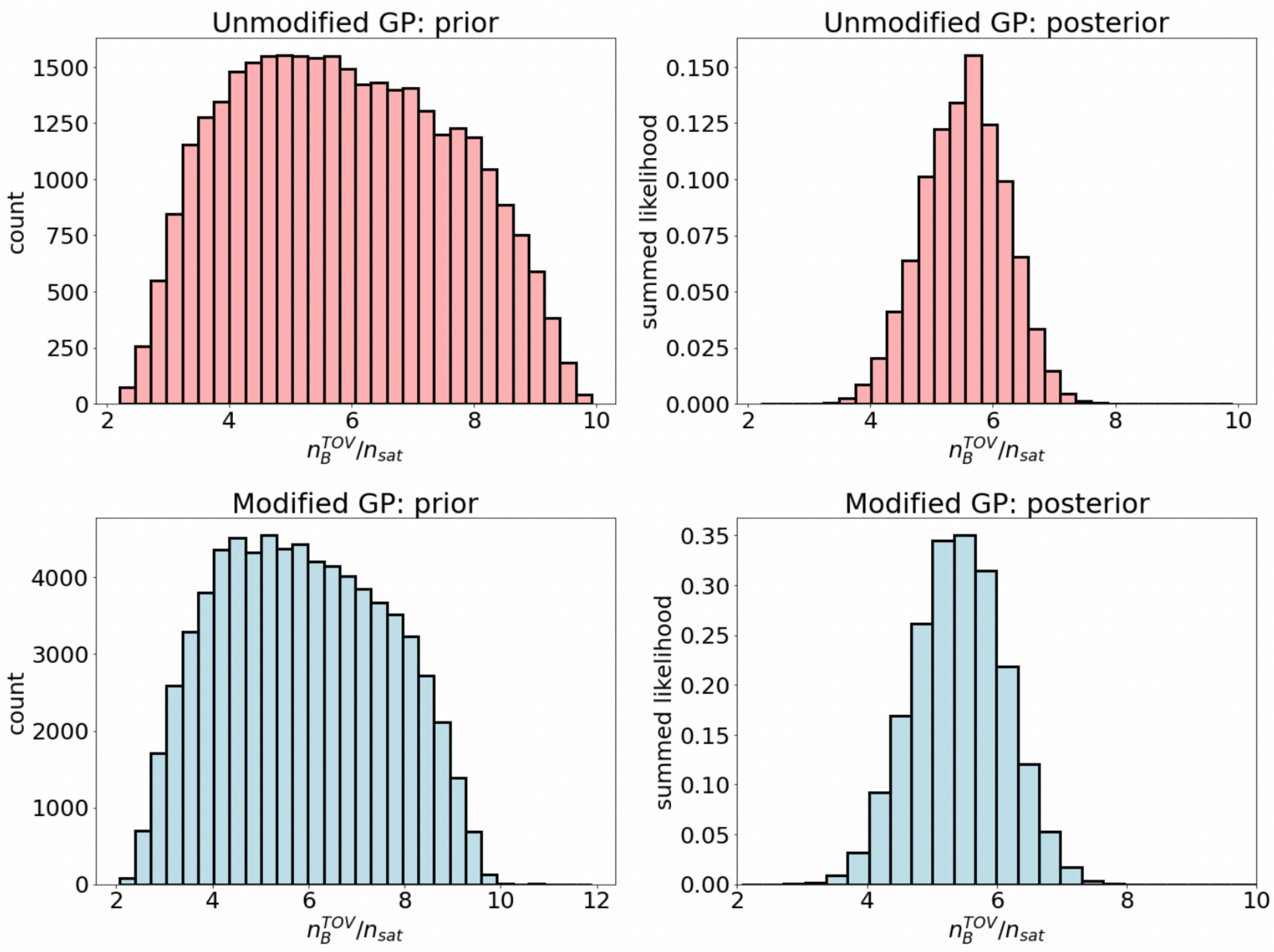


Constraints on n_B^{TOV}

Preliminary. DM, J. Noronha-Hostler, N. Yunes, C. Miller

Left: total count per bin
Right: summed likelihood per bin (not normalized)

- **General agreement:** $4n_{sat} \lessapprox n_B^{TOV} \lessapprox 8n_{sat}$
- **Modified GP: peaks at slightly lower n_B^{TOV}**
- **Likely due to strong phase transitions**



$n_B^{TOV} - n_B(c_s^2\mathbf{max})$