Impacts on the dense-matter equation of state from high-density QCD

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TU Darmstadt

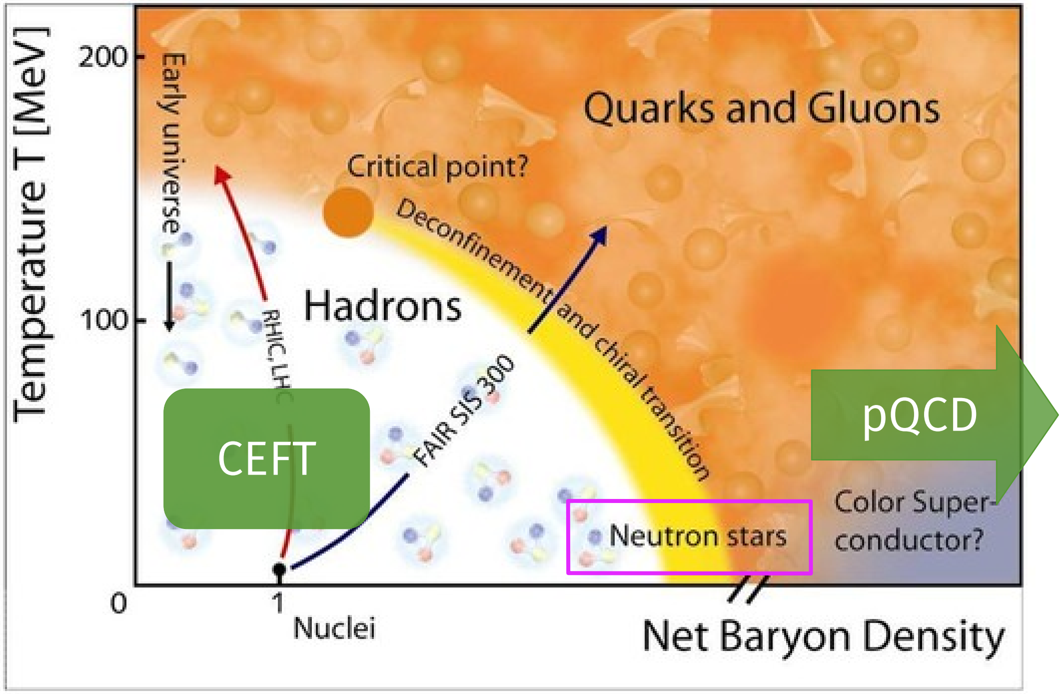
Confinement XV (2022)

04.08.2022

TG, Komoltsev, Kurkela, 2204.11877

Motivation

- EOS of dense nuclear/QCD matter still unknown, requires input from fundamental theory + NS observations



Compressed Baryonic Matter (CBM) experiment

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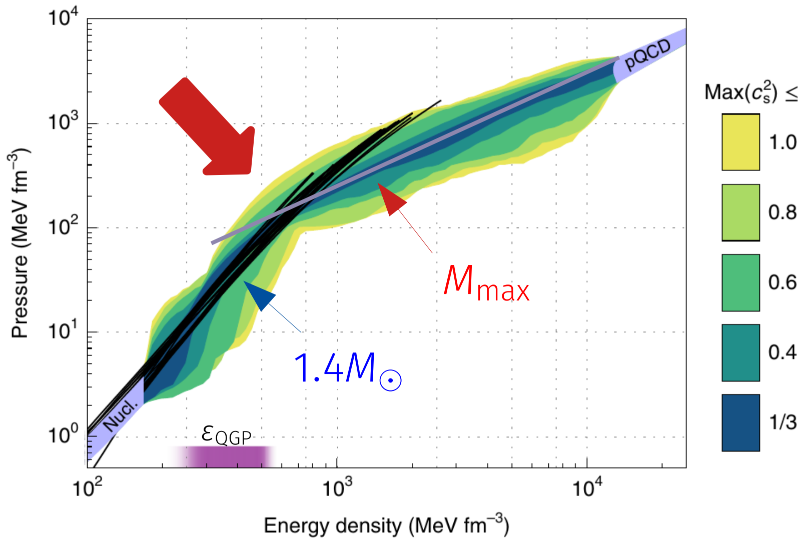
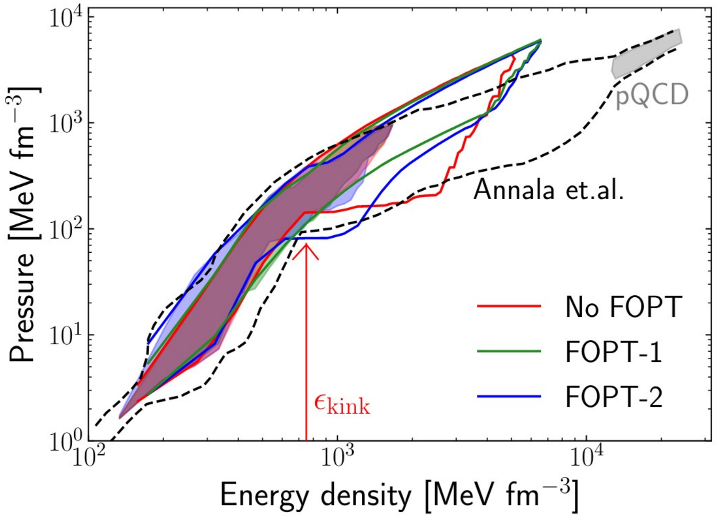
- Previous works with pQCD constraint see some nonconformal → conformal transition along physical NS sequence, while other works without it do not



TG+ Nat. Phys. 16 (2020), Altiparmak+ 2203.14974, Ecker & Rezzolla 2207.04417, Marczenko+ 2207.13059

VS.



Somasundaram+ 2112.08157, Landry+ PRD 101 (2020)

Motivation

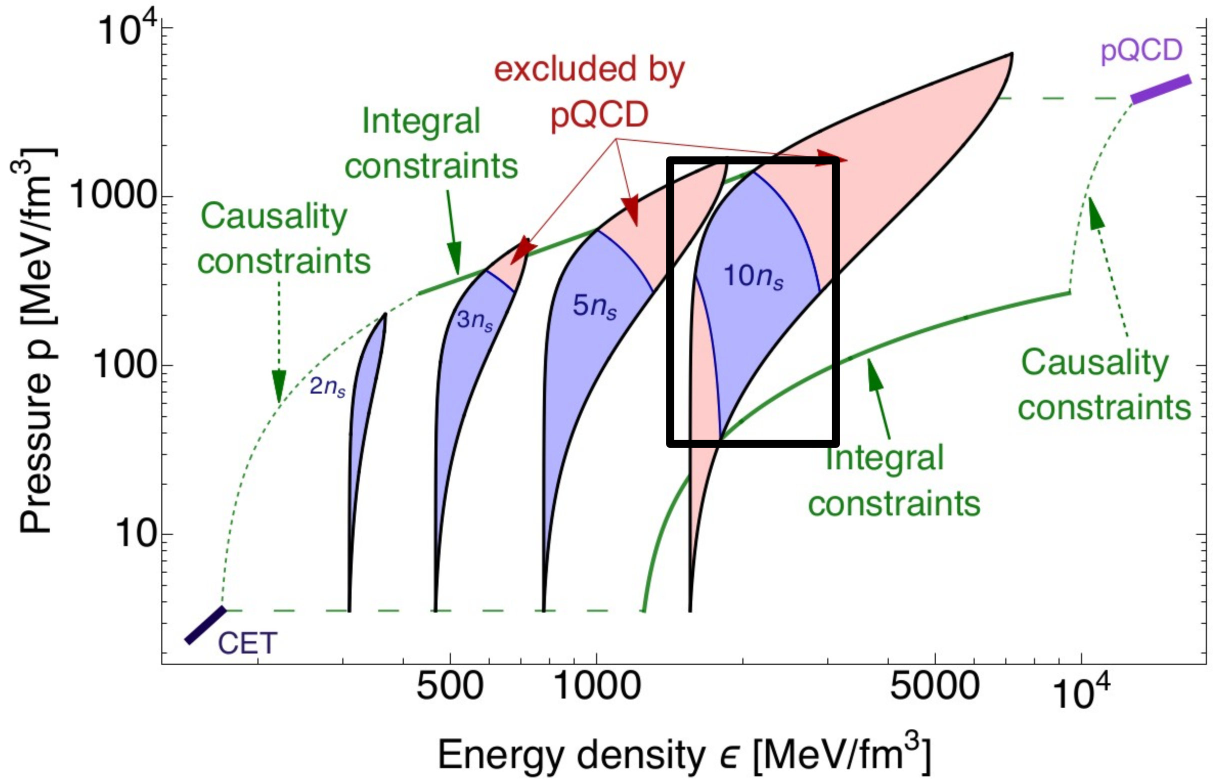
- EOS of dense nuclear/QCD matter still unknown, requires input from fundamental theory + NS observations
- Previous works with pQCD constraint see some nonconformal → conformal transition along physical NS sequence, while other works without it do not

Question: *Is the transition a genuine (p)QCD prediction, or a result of interpolation through 2 orders of magnitude in density?*

Past weakness: *Our past work has all been with hard cuts & not full measurement uncertainties*

How to feed down QCD input to lower densities

Komoltsev and Kurkela , PRL 128 (2022) (KoKu)



Want to use this $n = 10n_s$ region as high-density constraint

Setup

TG, Komoltsev, Kurkela, 2204.11877

- Use **Gaussian-Process regression** in auxiliary variable $\varphi(n) = -\ln\left(c_s^{-2}(n) - 1\right)$ to extend CEFT EOS to $10n_s$

  Similar to Landry & Essick Phys. Rev. D 99 (2019), but for function of n instead of ε

- *Condition* with low-density CEFT EOS

  95% CI matching spread of Hebeler, Lattimer, Pethick, Schwenk Astrophys. J. 773 (2013),

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- *Condition* with low-density CEFT EOS

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- Use hierarchical model, with:

$$\varphi(n) \sim \mathcal{N}\left(-\ln\left(\bar{c}_s^{-2} - 1\right), K(n, n')\right), \quad K(n, n') = \eta e^{-(n-n')^2/2\ell^2}$$

- With the hyperparameters themselves drawn from Gaussian distributions:

$$\bar{c}_s^2 \sim \mathcal{N}(0.5, 0.25^2), \quad \ell \sim \mathcal{N}\left(1.0n_s, (0.25n_s)^2\right), \quad \eta \sim \mathcal{N}(1.25, 0.25^2).$$

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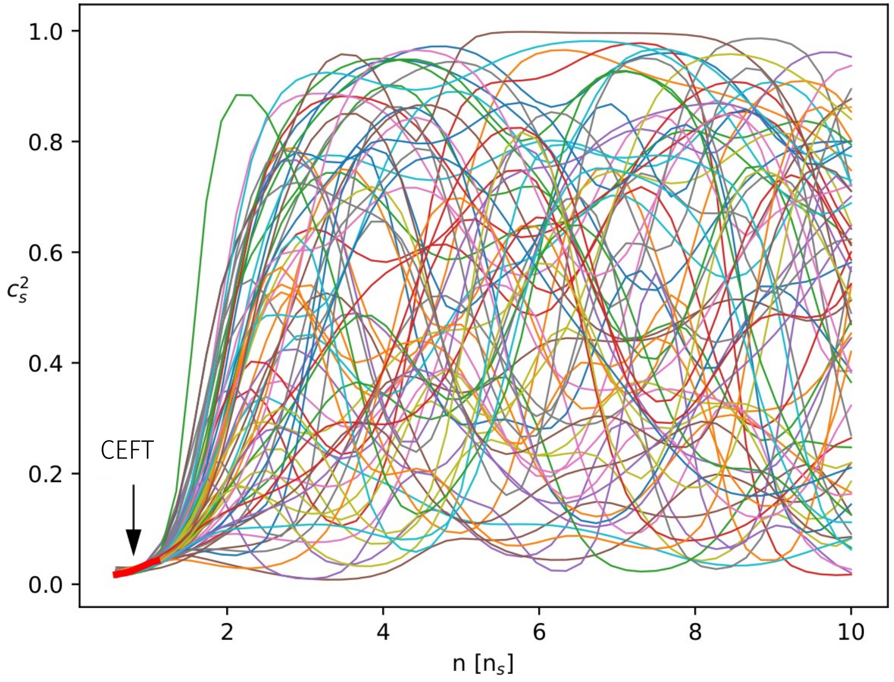

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Setup

TG, Komoltsev, Kurkela, 2204.11877

1. Use **Gaussian-Process regression** in auxiliary variable $\varphi(n) = -\ln\left(c_s^{-2}(n) - 1\right)$ to extend CEFT EOS to $10n_s$

2. **Fold in NS observations with full uncertainties**
   - High-mass pulsars *(PSR J0348+0432 and PSR J1624-2230)*
     Approximate as Gaussians
   - GW170817
     Joint distribution on q and $\tilde{\Lambda}$
   - NICER measument *(PSR J0740+6620)*
     Joint distribution on M and R

3. **Fold in QCD input as constraint at $10n_s$**

Setup: Bit more about QCD constraint/likelihood

TG, Komoltsev, Kurkela, 2204.11877

1. Define triplet of thermodynamic properties:

From TG, Kurkela, Paatelainen, Sappi, Vuorinen PRL 127 (2021), PRD 104 (2021)

$$\vec{\beta}_{\rm QCD}(X) = \{p_{\rm QCD}(\mu_H, X), n_{\rm QCD}(\mu_H, X), \mu_H\}, \quad X = \frac{3\bar{\Lambda}}{2\mu_H}$$

$X \in [1/2, 2]$ usually quantifies renormalization-scale dependence

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2. KoKu construction gives $\Delta p_{\rm min}$, $\Delta p_{\rm max}$ between $10n_s$ and pQCD for each β_H:

$$P(\mathrm{QCD}\,|\,\mathrm{EoS}) = \int d\vec{\beta}_H P(\vec{\beta}_H) 1_{[\Delta p_{\rm min}, \Delta p_{\rm max}]}(\Delta p)$$

Indicator function: $1_S(x) = \begin{cases} 0 & x \notin S \\ 1 & x \in S \end{cases}$

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3. Create distribution on these properties at high density

$$P(\vec{\beta}_H) = \int d(\ln X) w(\ln X) \delta^{(3)}(\vec{\beta}_H - \vec{\beta}_{\rm QCD}(X)), \quad w(\ln X) = 1_{[\ln(1/2), \ln(2)]}(\ln X)$$

suggested by Cacciari & Houdeau, JHEP 09, (2011)

Setup: Bit more about QCD constraint/likelihood

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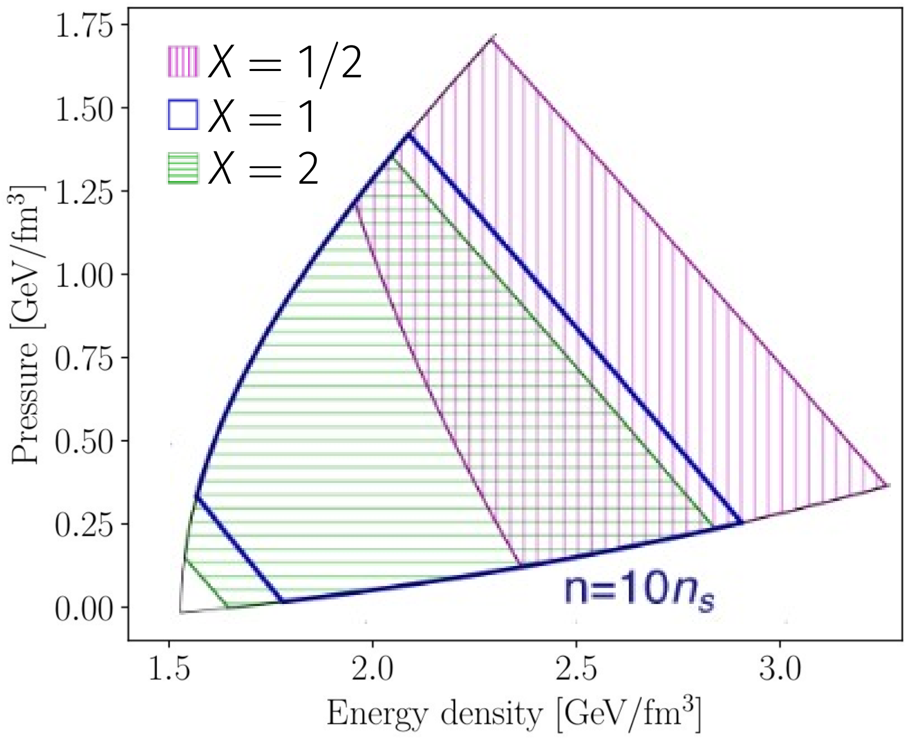
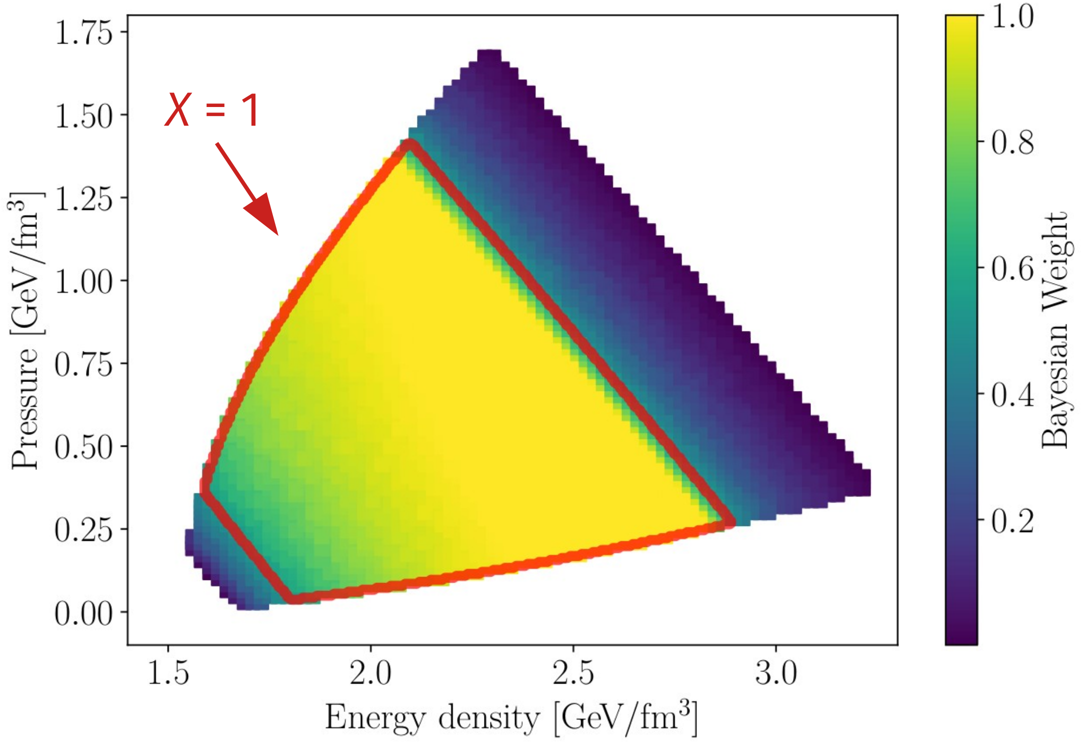
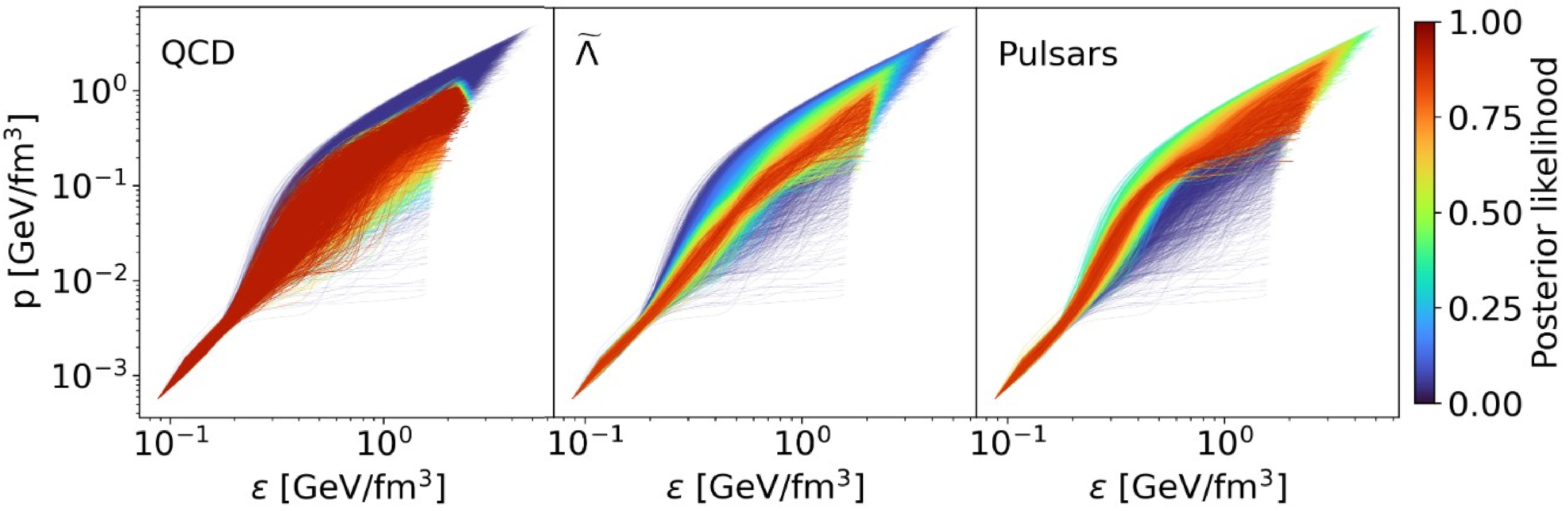


Weight of (ϵ, p) points at $n = 10n_s$



Results

TG, Komoltsev, Kurkela, 2204.11877



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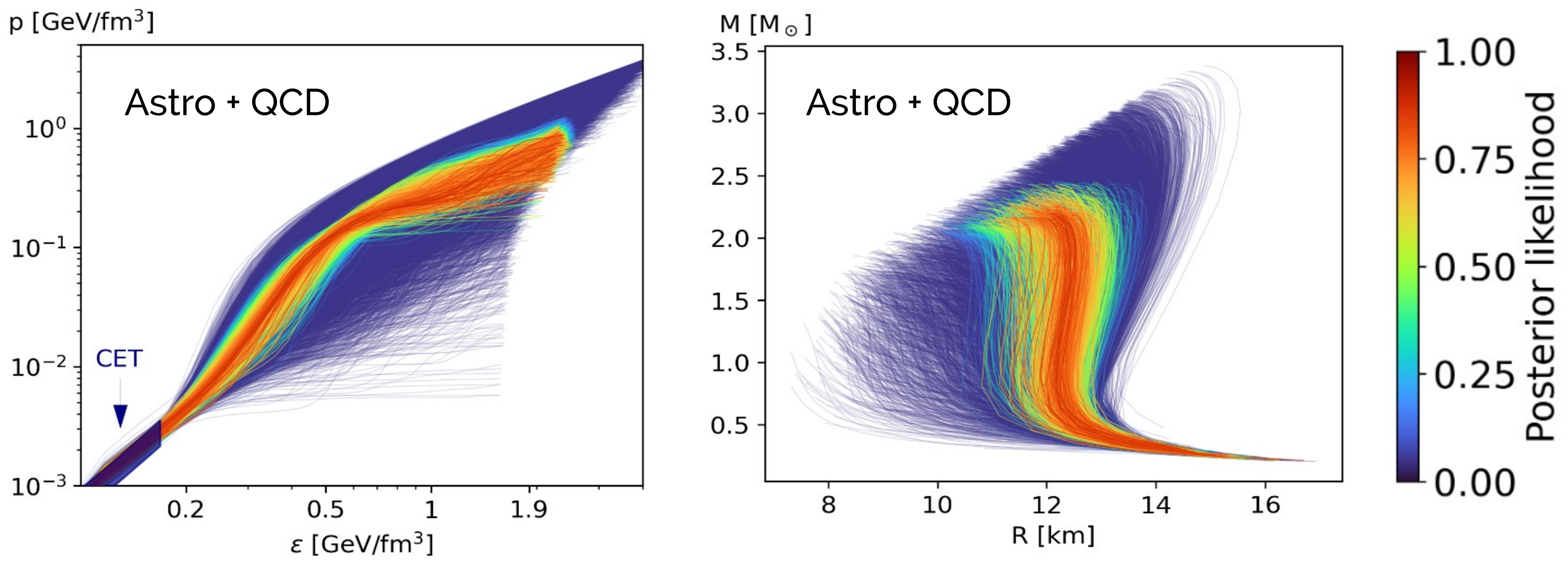

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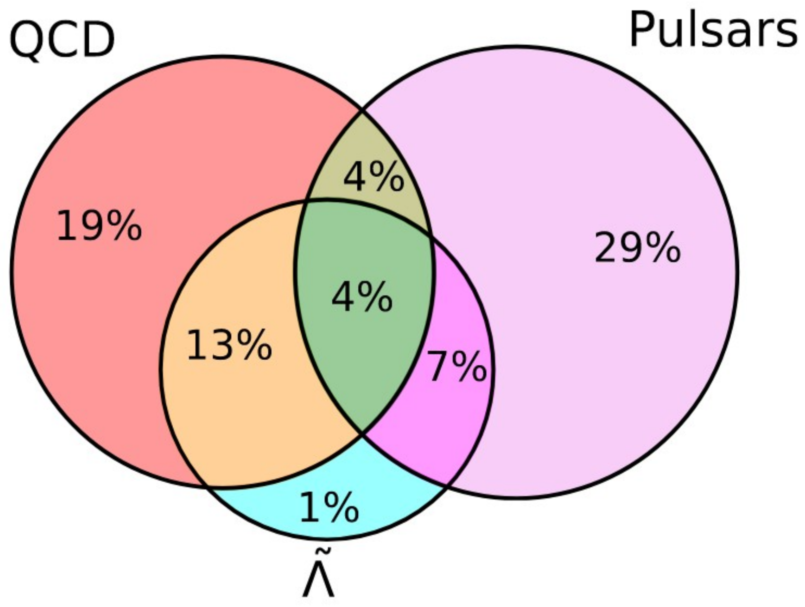
1. Inputs complementary



resample proportional to likelihood

Results

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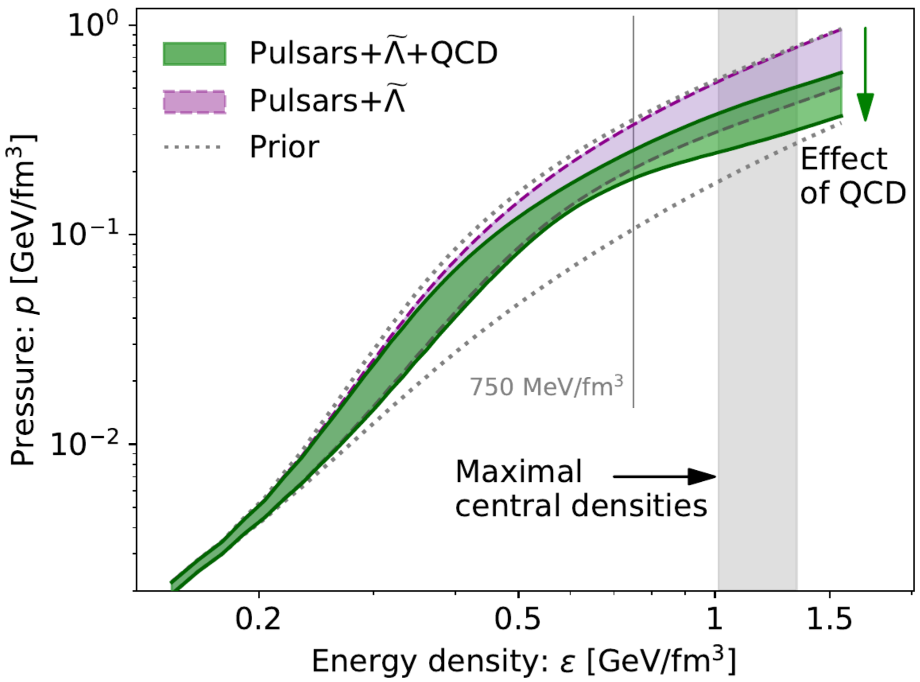
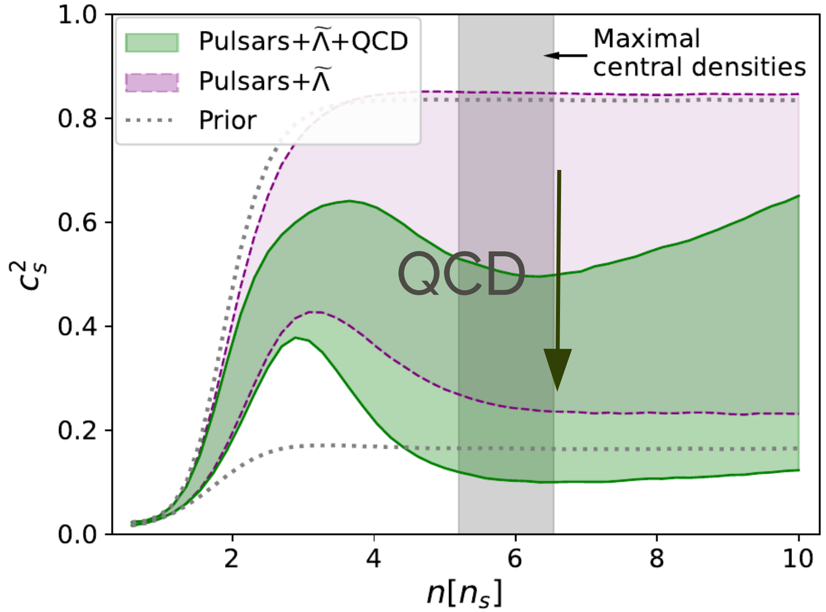
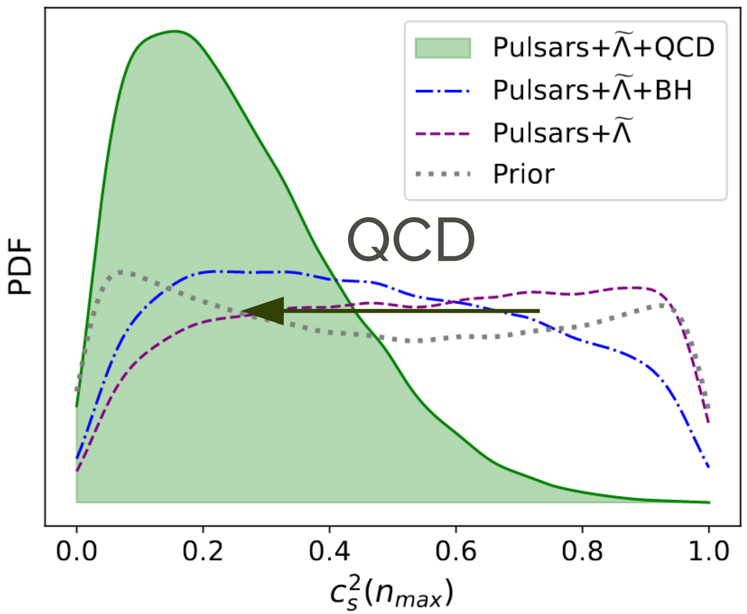
1. Inputs complementary

2. *QCD input pushes the EOS towards conformality*



68% intervals





Results

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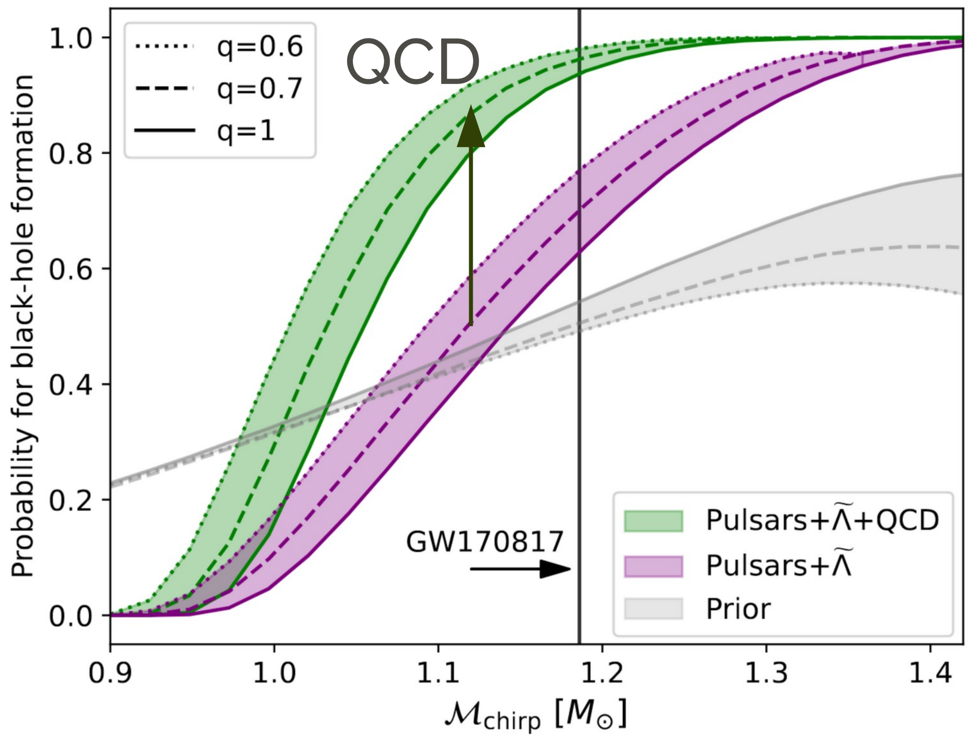
1. Inputs complementary

2. *QCD input pushes the EOS towards conformality*

3. QCD input implies BH formation



Summary

- *Should use QCD input in analysis of NS-EOS inference; it impacts the inference!*

  Jupyter notebook available on Github: OKomoltsev/QCD-likelihood-function

- QCD input at $10n_s$ *drives approach to conformality* in TOV stars / at high densities, *as indicated in hard-cut analysis*
- QCD input *complementary* to NS observational inputs
- QCD input *implies BH formation* for most NS-NS mergers

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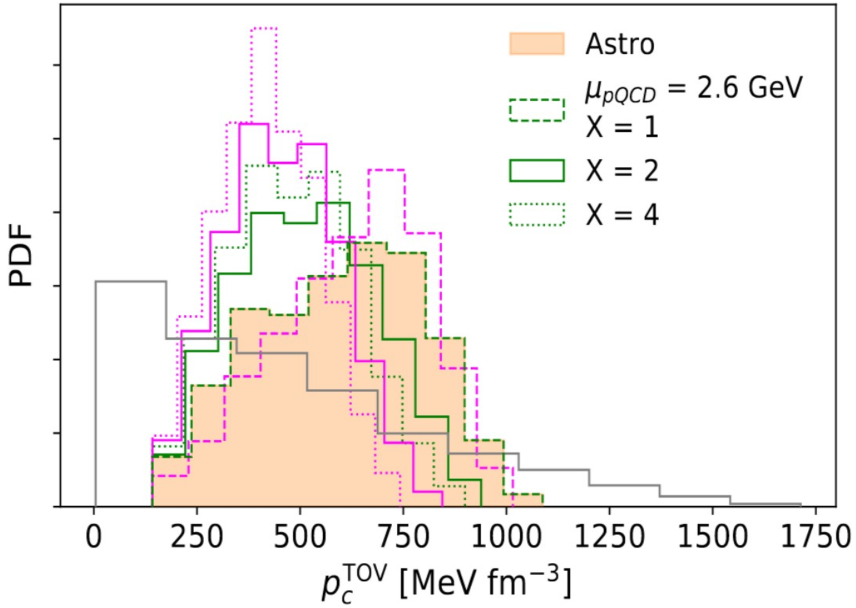
Thanks for your attention!

Backup slides

Comparison with other recent work

Somasundaram, Tews, Margueron (2204.14039) perform conservative analysis with QCD input, *broadly consistent with our results*:

- Apply QCD input exactly at the TOV point
- *Find QCD input constraints for most X values* – only small range near *X* = *1/2* not constraining beyond astro



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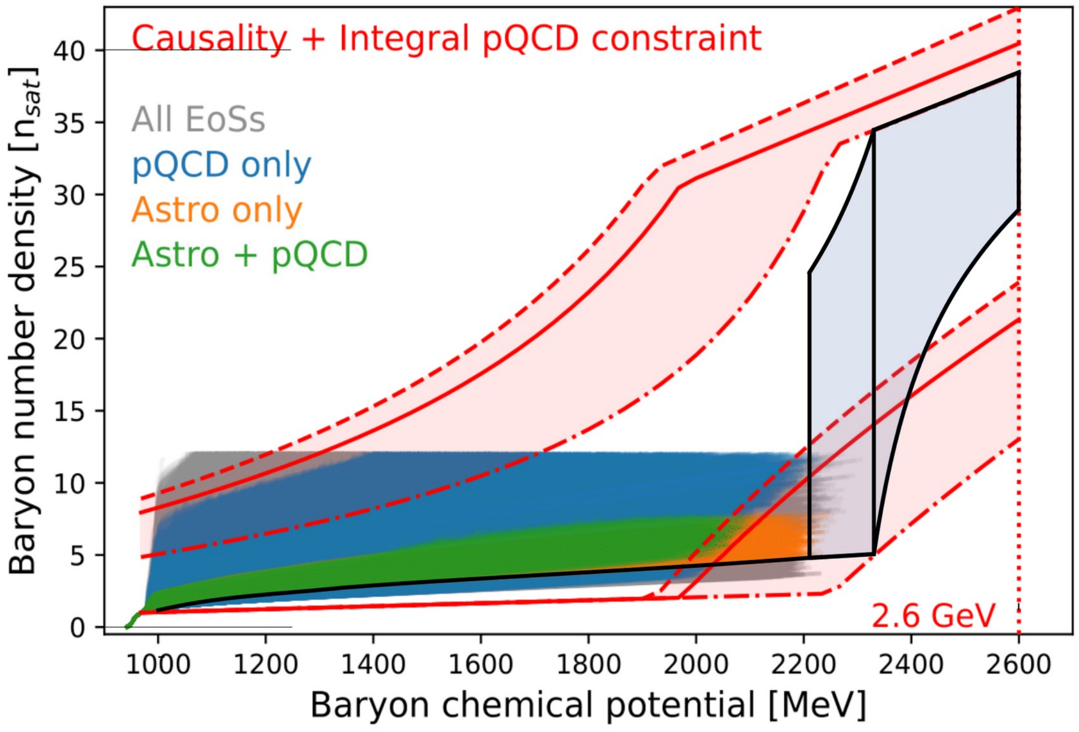
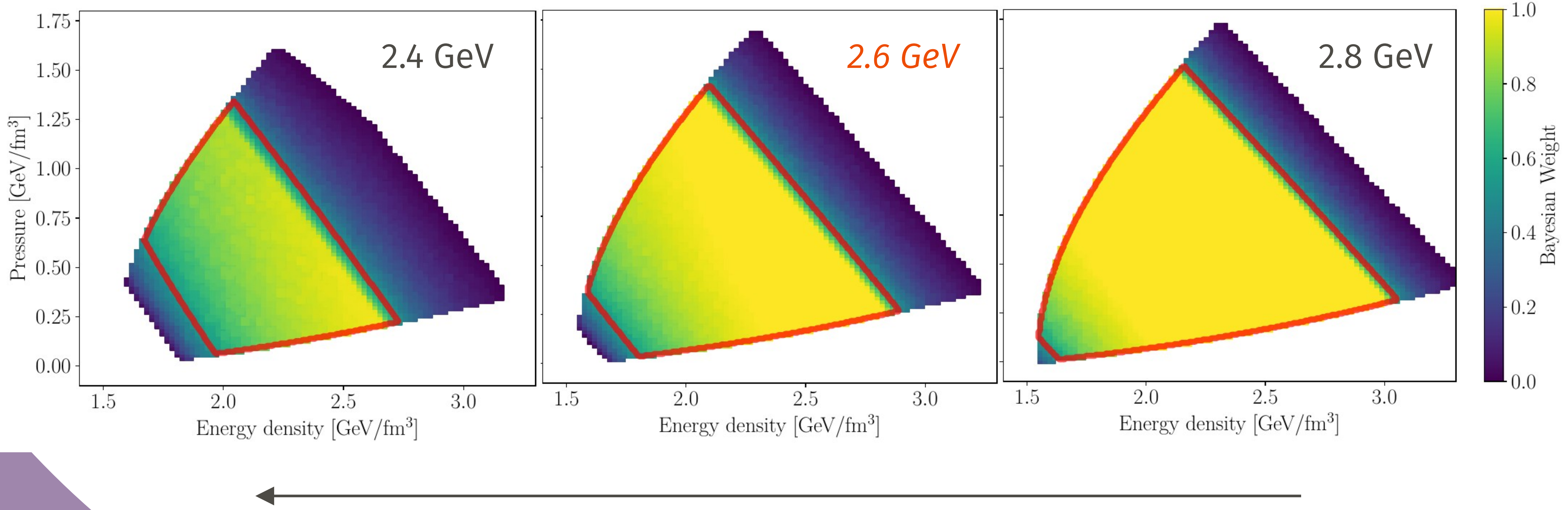
- Apply QCD input exactly at the TOV point
- *Find QCD input constraints for most X values* – only small range near *X* = 1/2 not constraining beyond astro
- These EOSs with *X* ≈ 1/2 need ***very specific behaviour beyond*** n_{TOV} to reach pQCD

1. PT at n_{TOV} of $\Delta n = 20 n_s$ $(\Delta n / n = 4)$, or
2. PT at $n_{\mathrm{TOV}} + 0.2 n_s$ of $\Delta n = 30 n_s$ $(\Delta n / n = 6)$



c.f. Fujimoto + 2205.03882 for signatures of such PTs

PQCD Likelihood dependence on μ_{QCD}



More restrictive, but pQCD less trustworthy

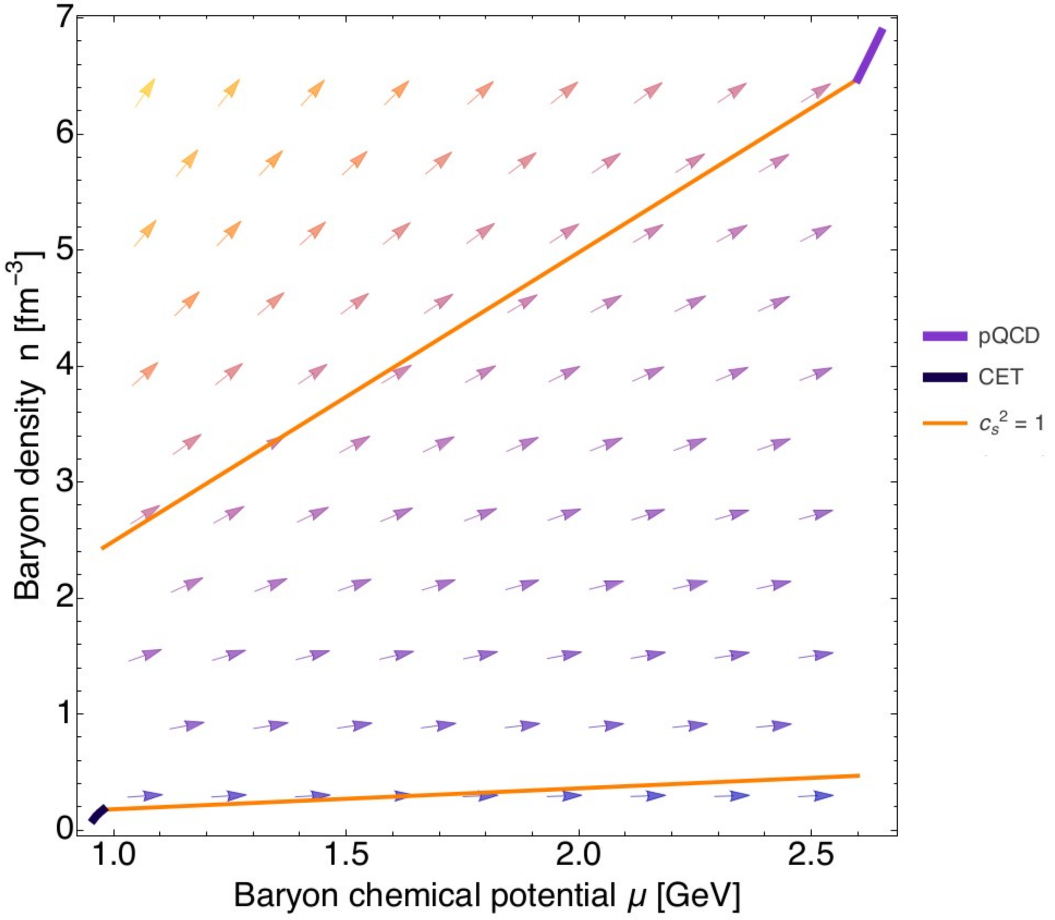
How to feed down QCD input to lower densities

Komoltsev and Kurkela, PRL 128 (2022) (KoKu)

1. Stability

2. Causality

3. Consistency



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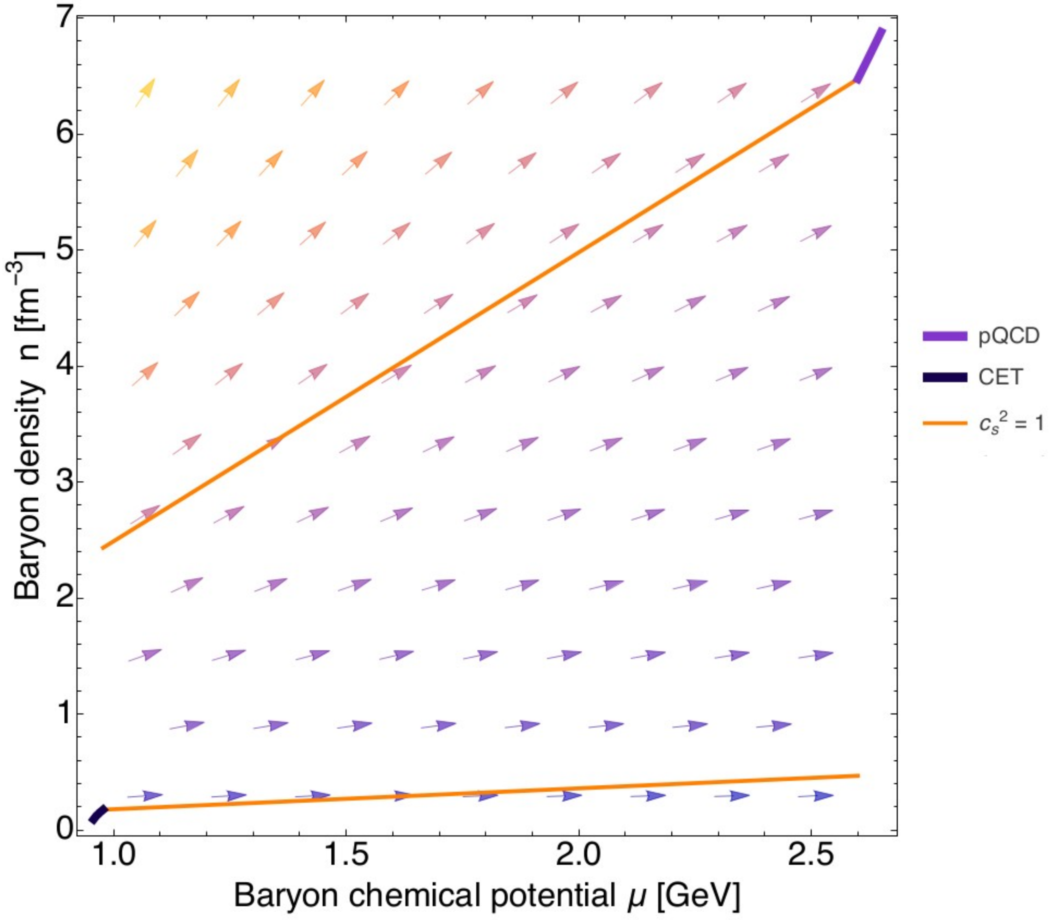

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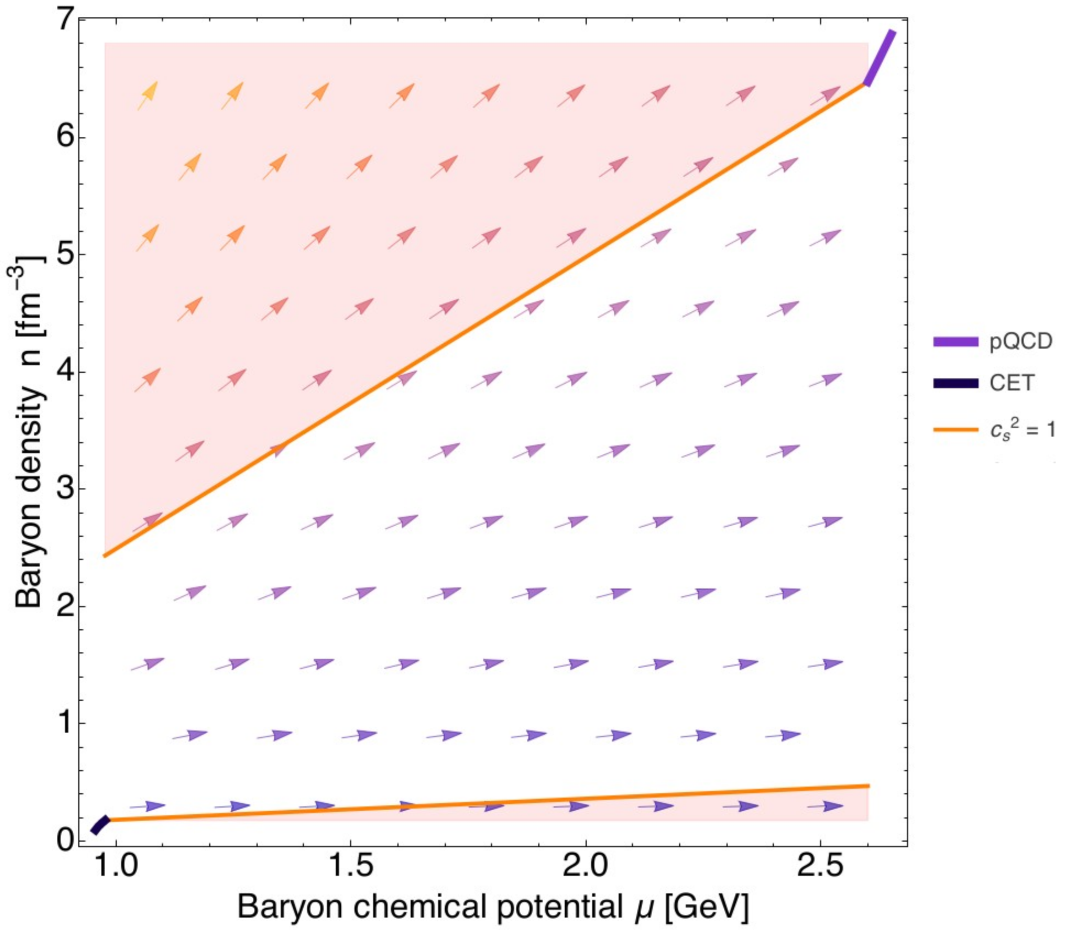

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$$\int_{\mu_{\text{CET}}}^{\mu_{\text{QCD}}} \mathrm{d}\mu\, n(\mu) = p_{\text{QCD}} - p_{\text{CET}}$$

Fixed!