

How perturbative QCD constrains the Equation of State at Neutron-Star densities

Oleg Komoltsev
June, SEWM 2022



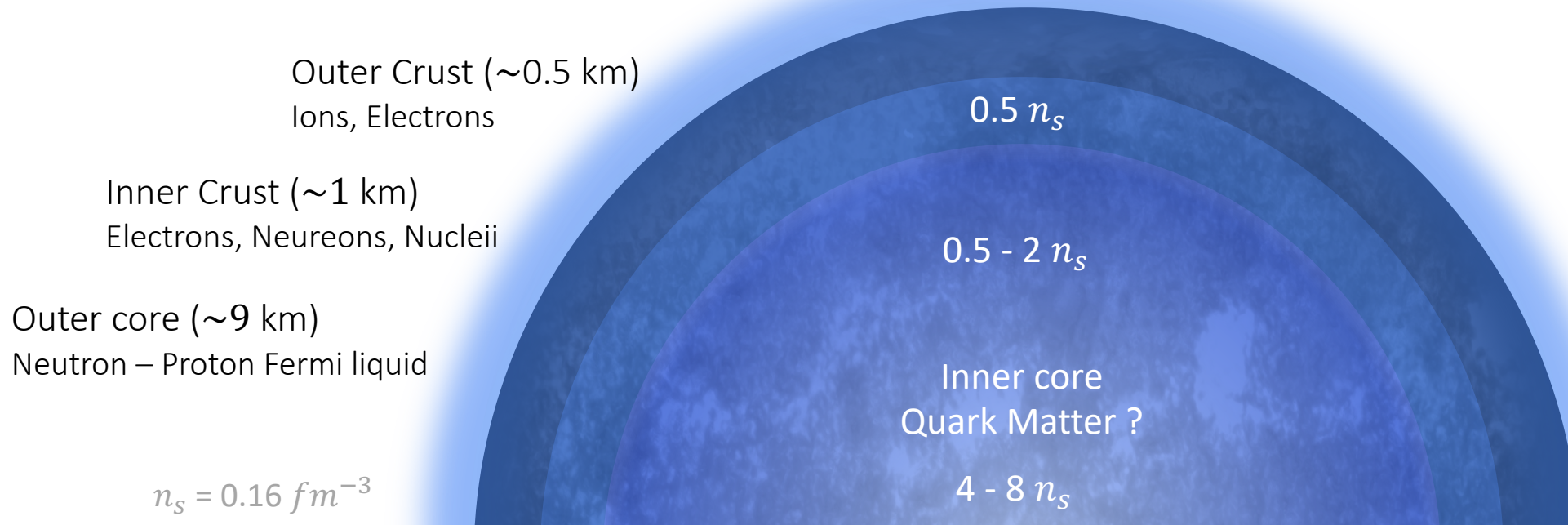
University of
Stavanger

O.K., Aleksii Kurkela
[PRL.128.20270](#)

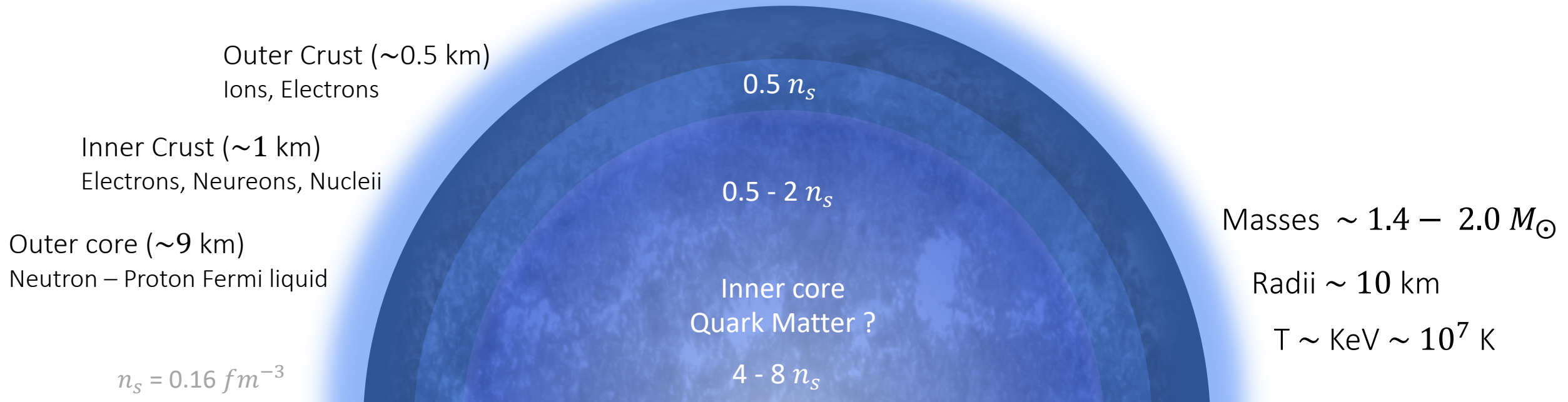
Tyler Gorda, O.K., Aleksii Kurkela
[arXiv:2204.11877](#)



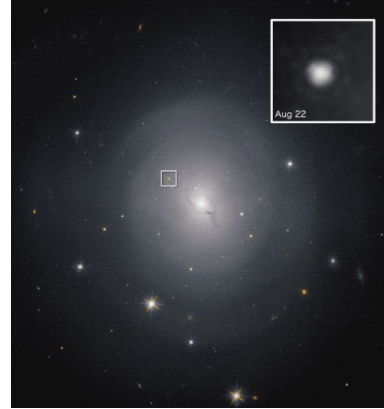
Neutron stars



Neutron stars



Neutron stars



GW170817

- Discovery of massive NSs

Antoniadis, Freire et.al. arXiv:1304.6875

- NS radius measurements

Riley, Watts et.al. arXiv:2105.06980

- Gravitational-wave

LIGO, VIRGO arXiv:1710.05832

- Multi-messenger

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Outer Crust (~ 0.5 km)

Ions, Electrons

Inner Crust (~ 1 km)

Electrons, Neutrons, Nuclei

Outer core (~ 9 km)

Neutron – Proton Fermi liquid

$$n_s = 0.16 \text{ fm}^{-3}$$

$$0.5 n_s$$

$$0.5 - 2 n_s$$

Inner core
Quark Matter ?

$$4 - 8 n_s$$

Masses $\sim 1.4 - 2.0 M_\odot$

Radii ~ 10 km

$T \sim \text{KeV} \sim 10^7$ K



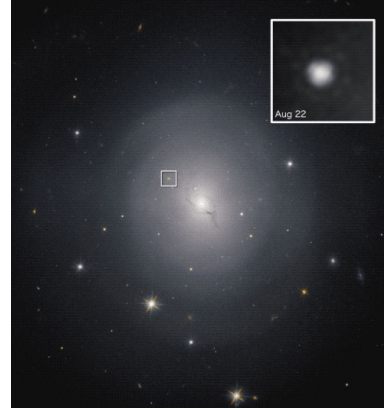
Neutron stars

Tolman–Oppenheimer–Volkoff equation

$$\frac{dp}{dr} = -\frac{Gm}{r^2} \epsilon \left(1 + \frac{p}{\epsilon}\right) \left(1 + \frac{4\pi r^3 \epsilon}{m}\right) \left(1 - \frac{2Gm}{r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

Equation of State $p(\epsilon)$



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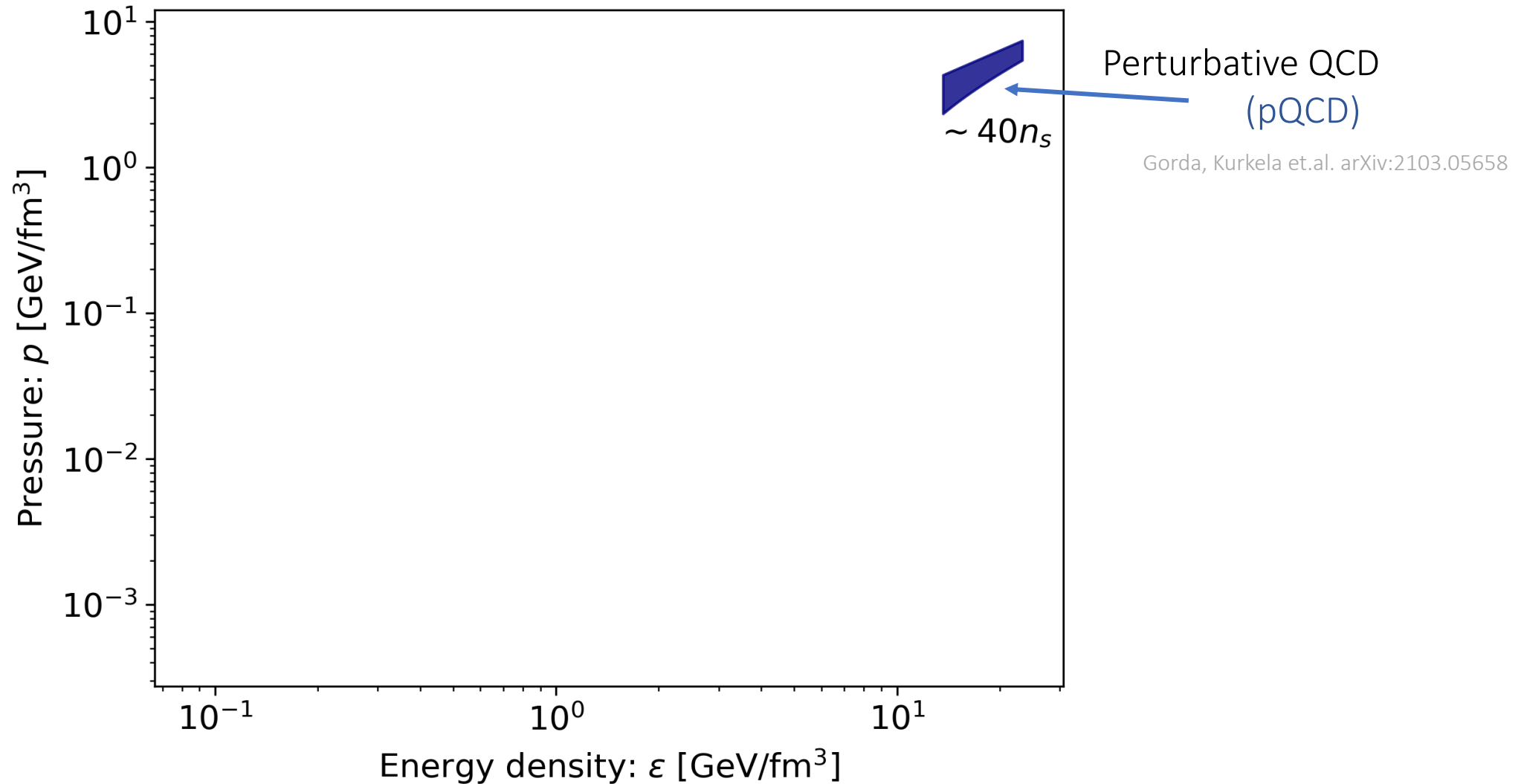
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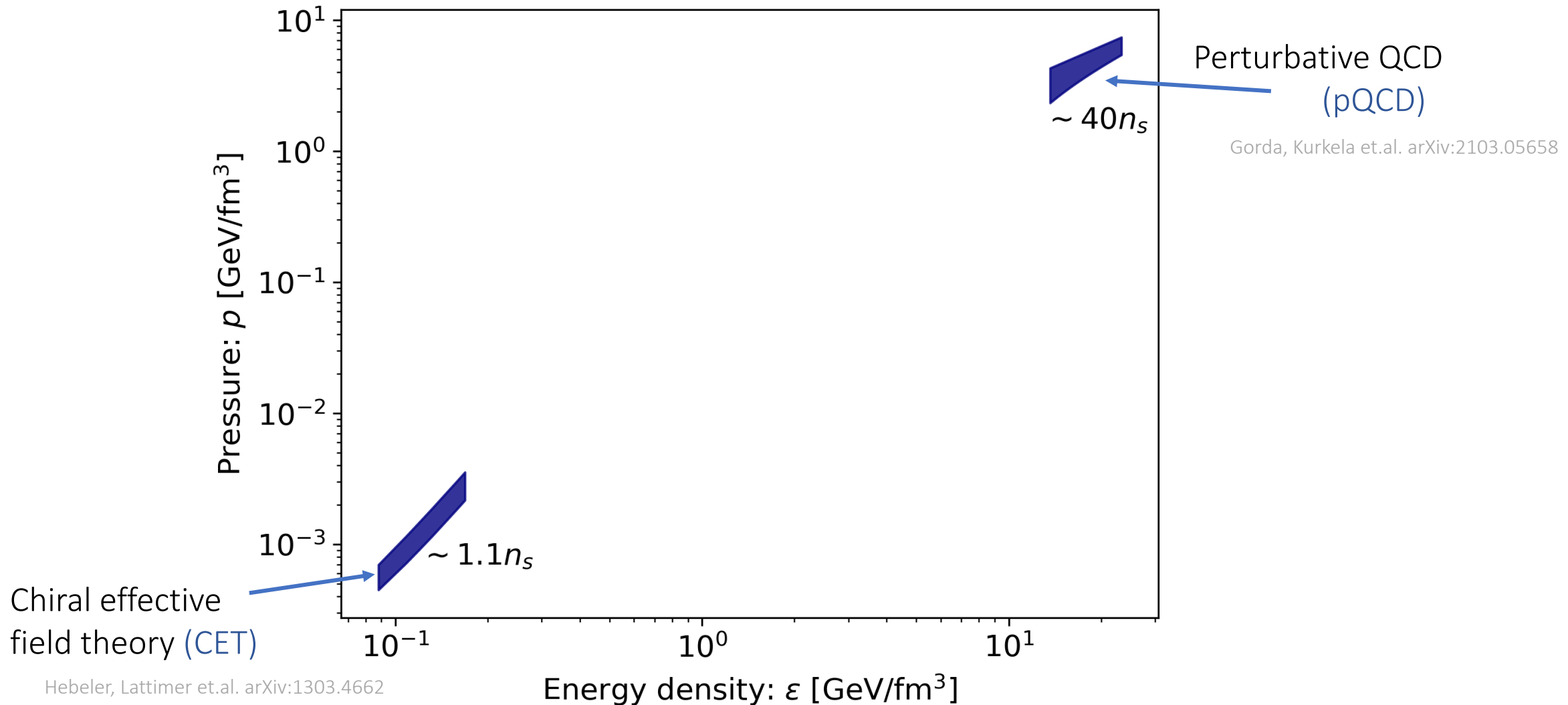
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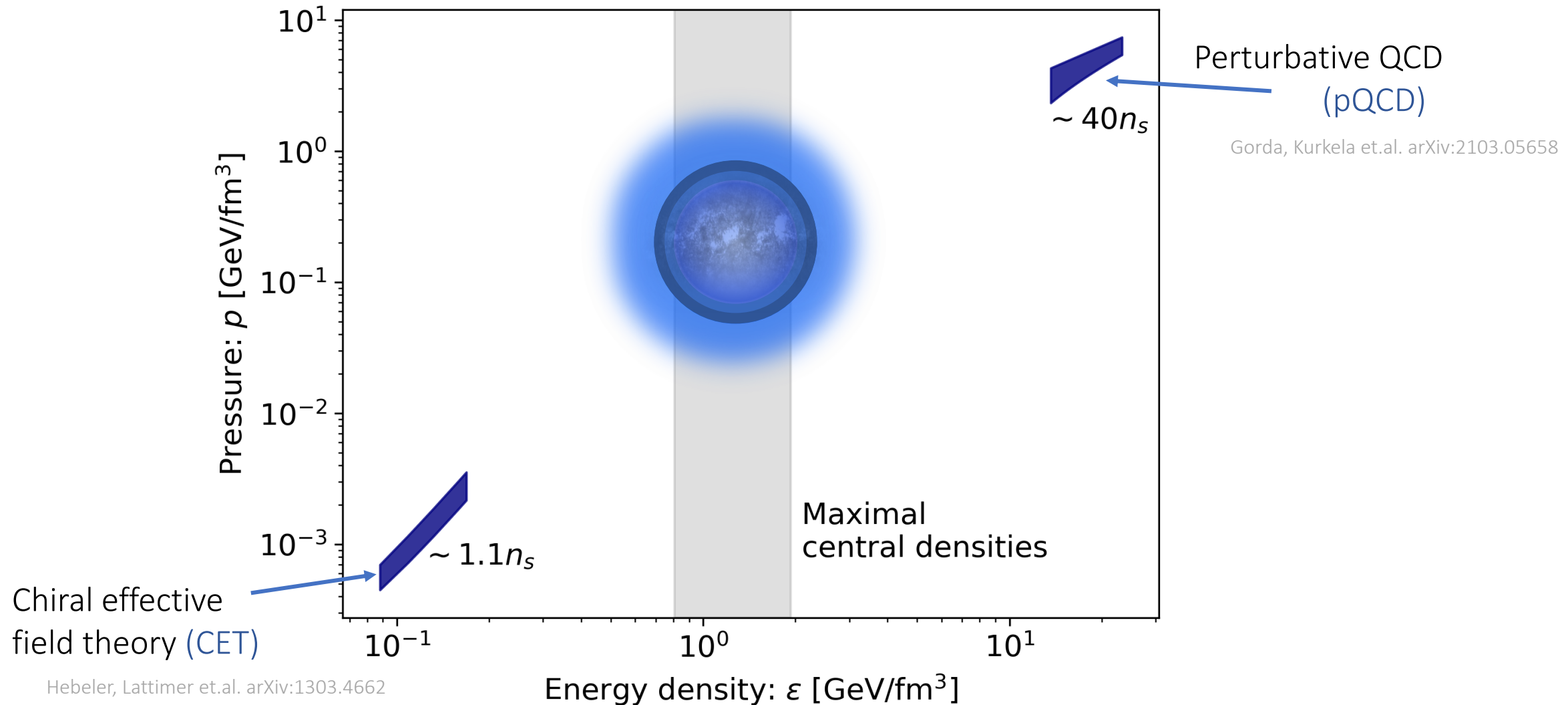
What do we know about cold and dense EoS?



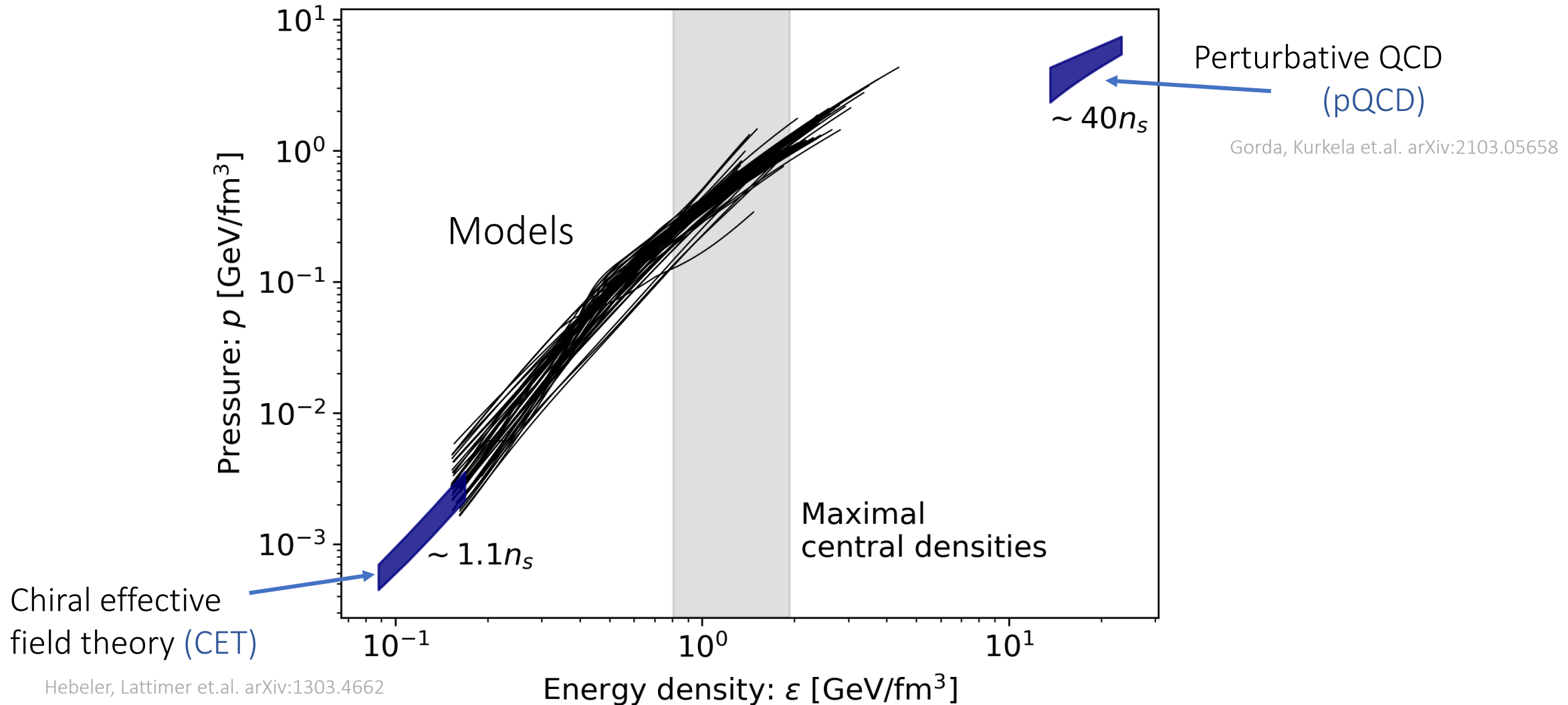
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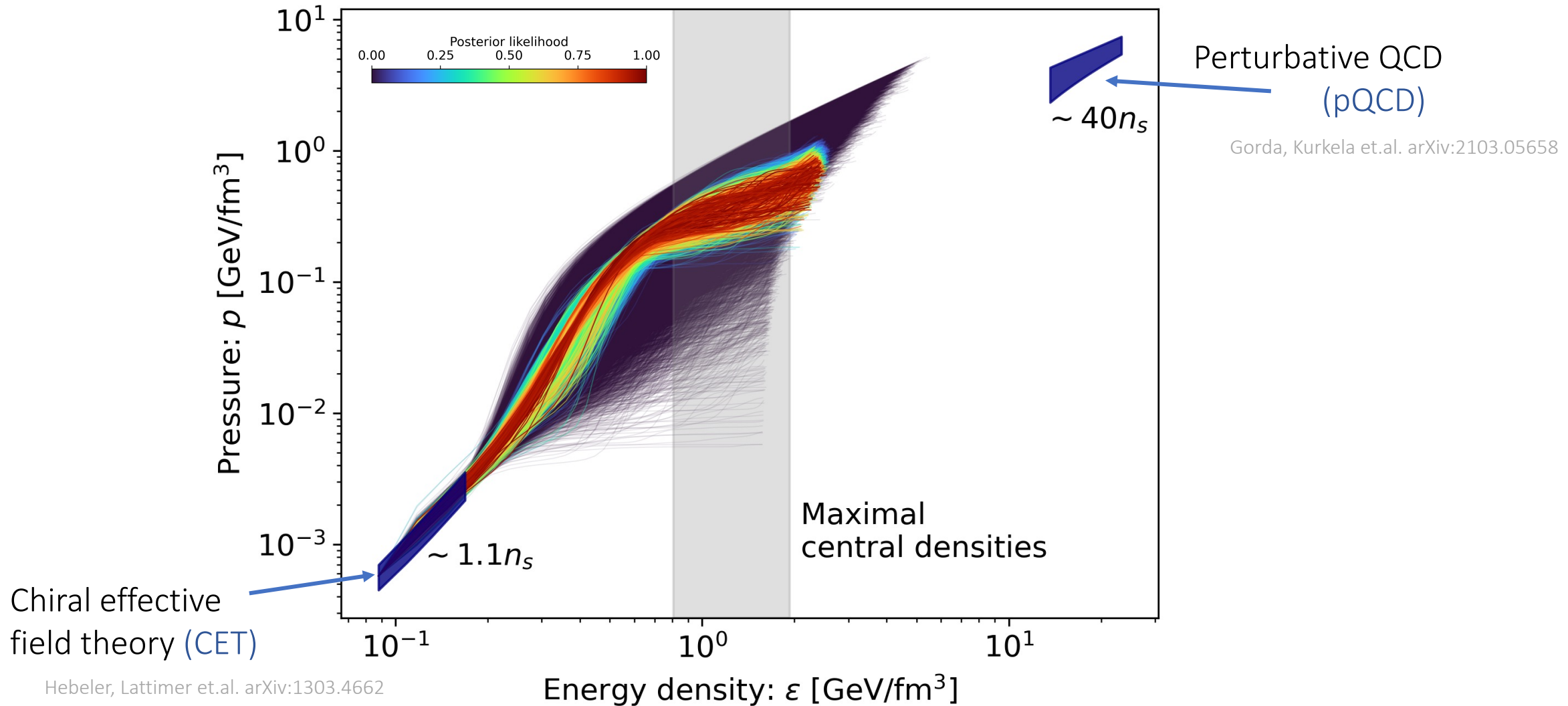
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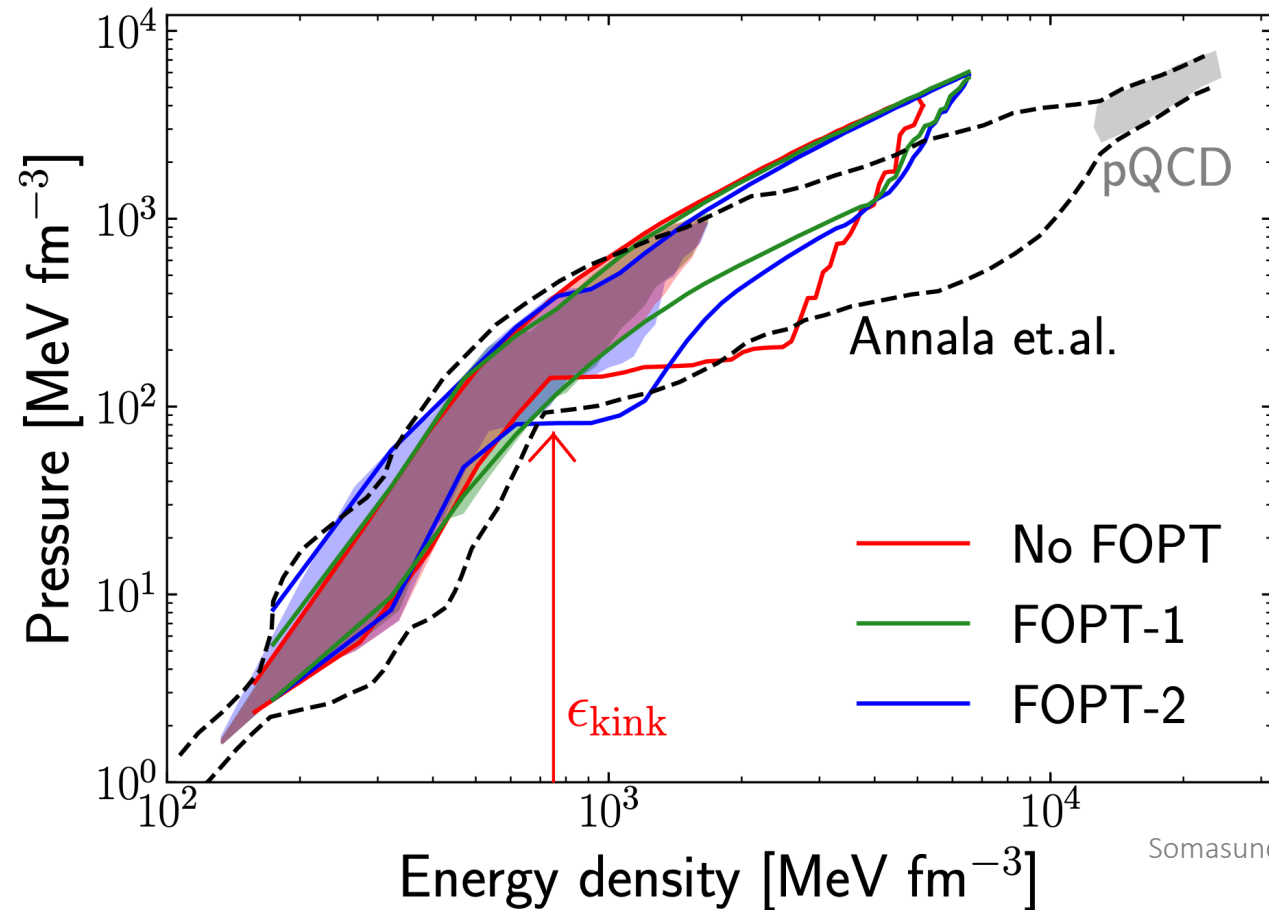
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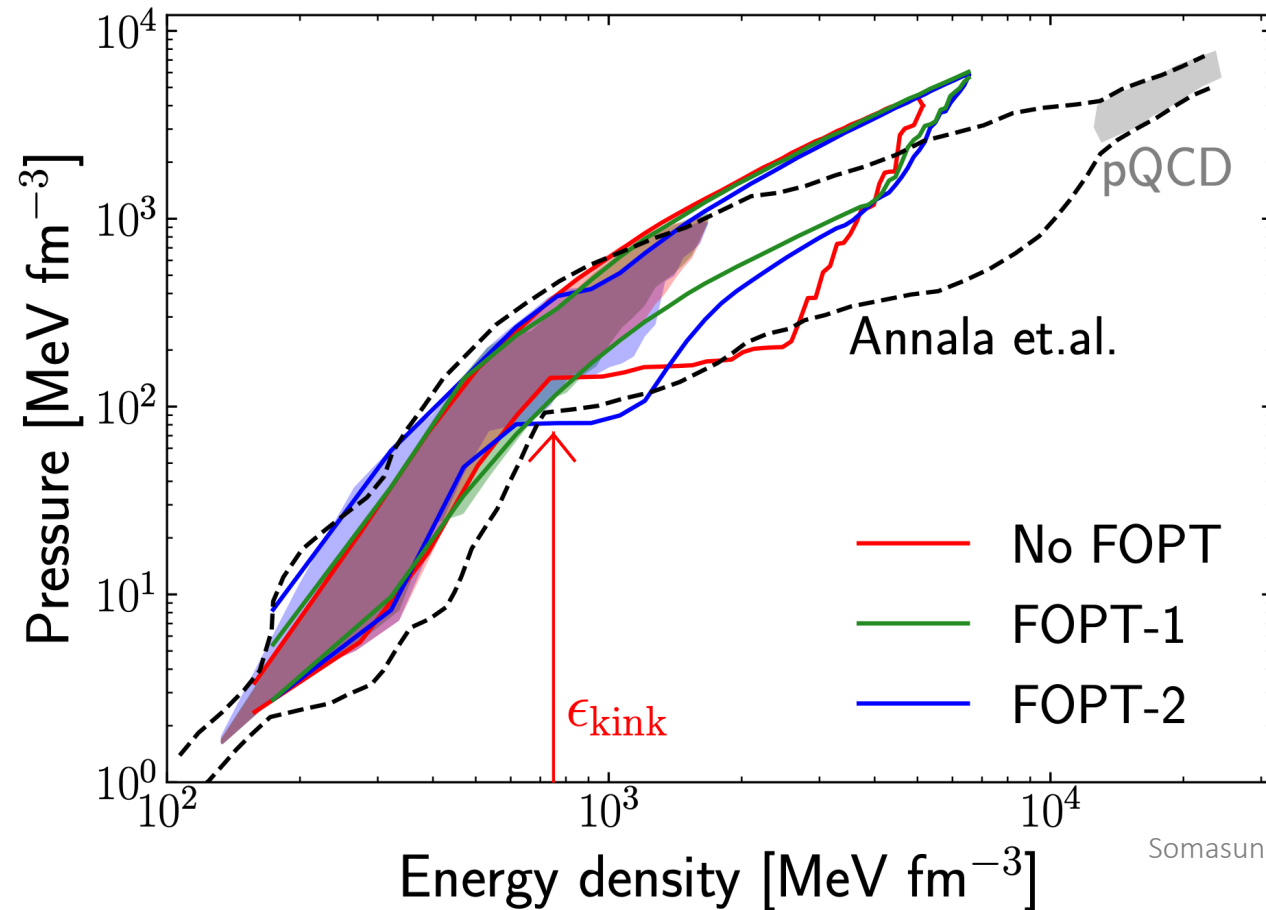


Interpolation of EoS



Somasundaram, Tews, Margueron arXiv:2112.08157

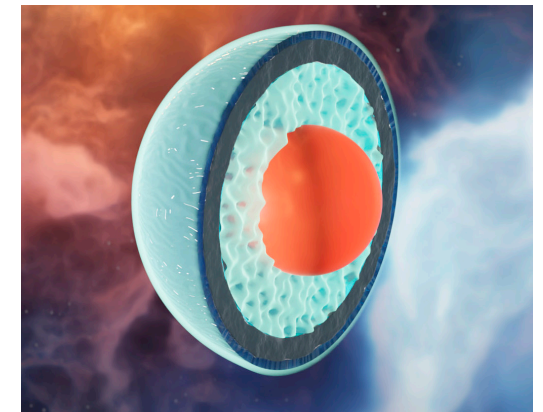
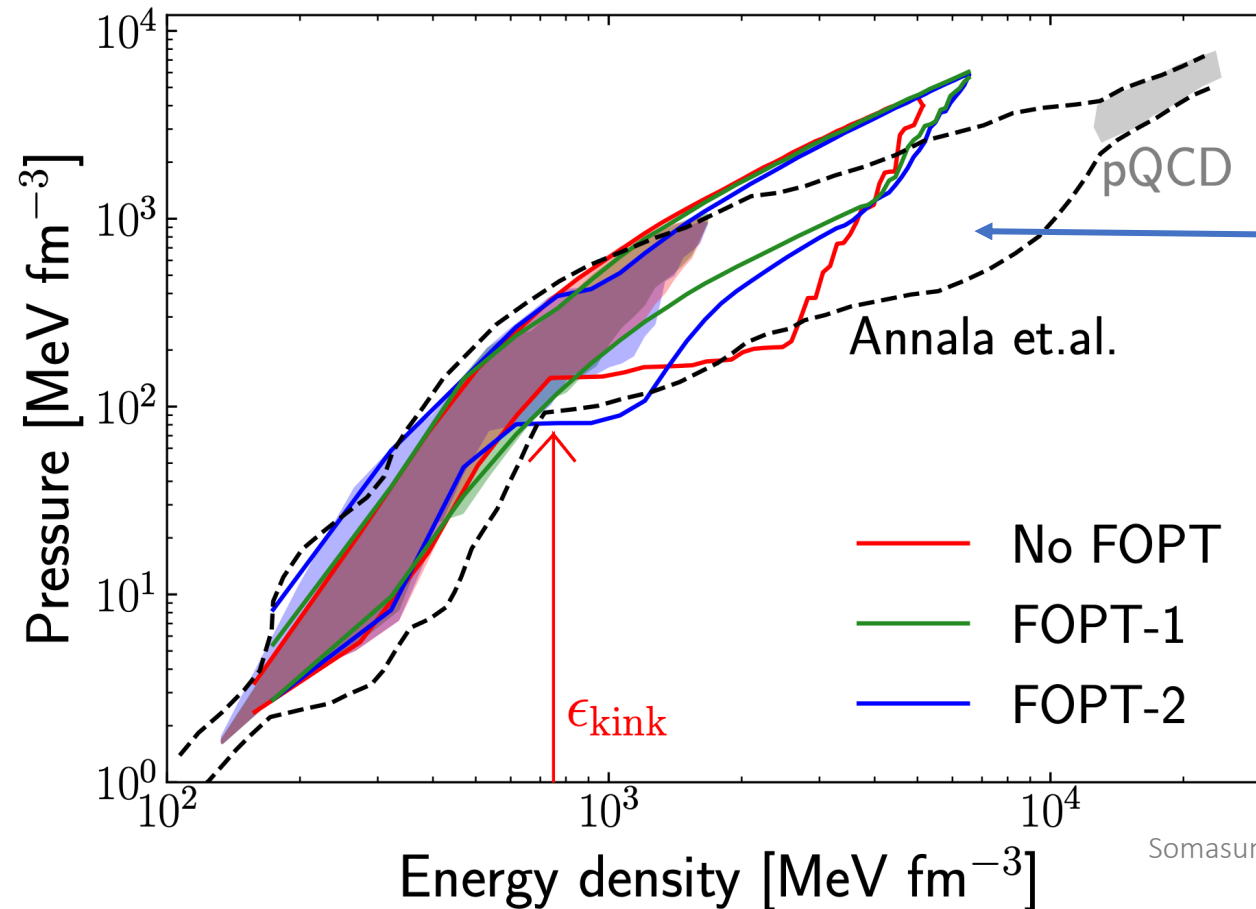
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- Is pQCD relevant for NS densities ?

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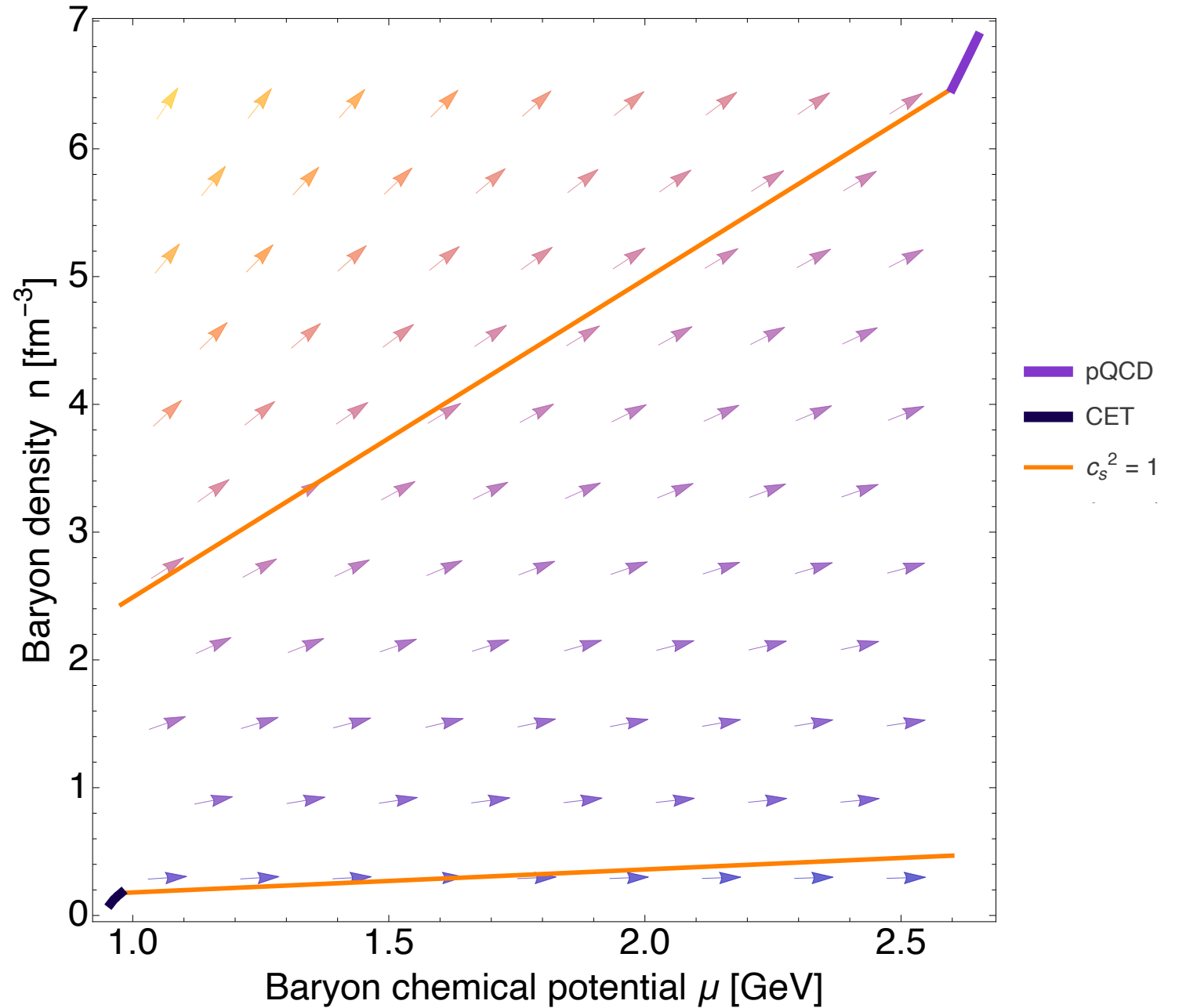


Annala et.al. Nat. Phys. **16**, 907–910 (2020)

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- Is pQCD relevant for NS densities ?
- Is softening of the EoS happening due to the choice of interpolation function ?

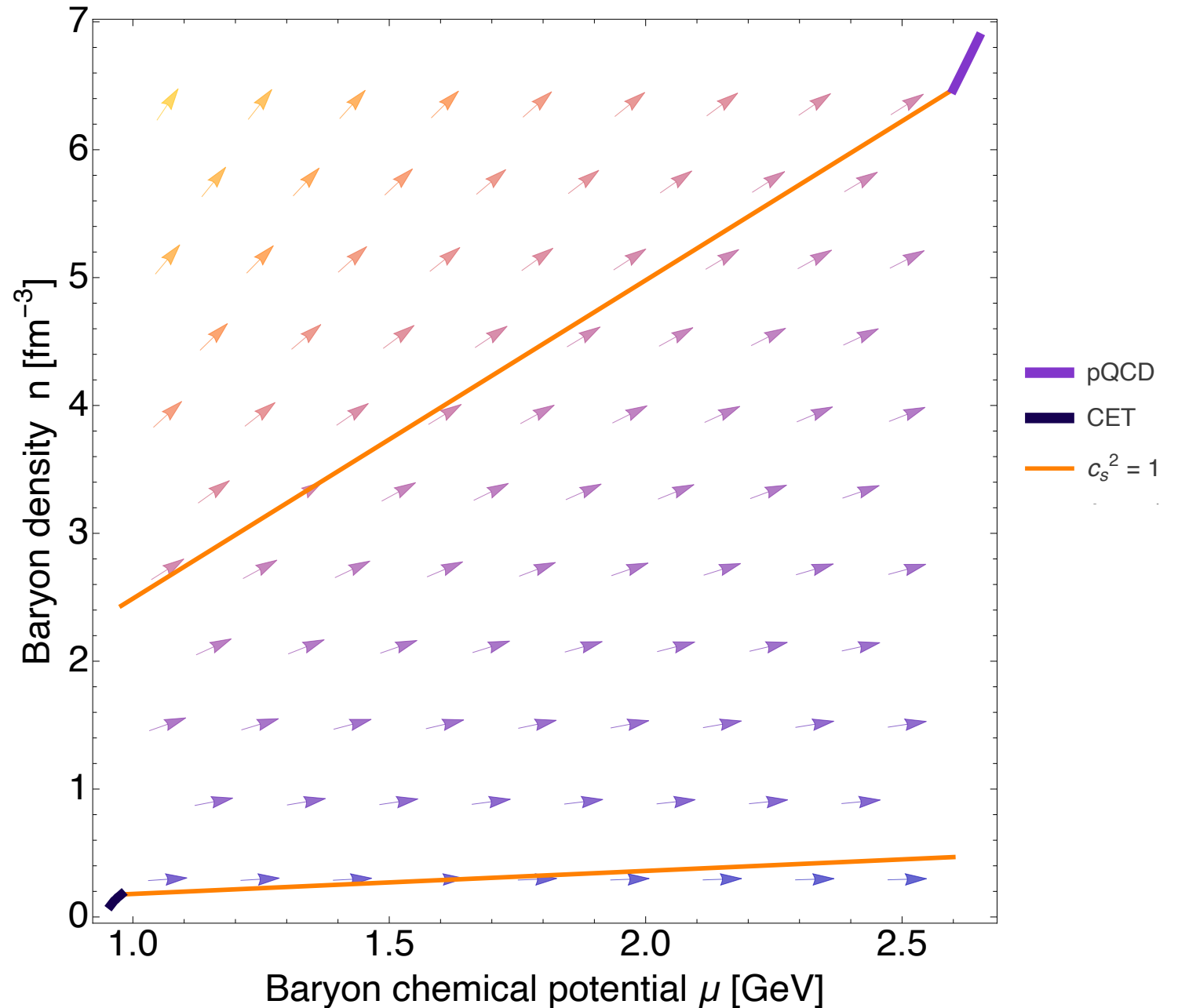
Setup



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- Stability

$$\partial_\mu^2 \Omega(\mu) \leq 0 \quad \Rightarrow \quad \partial_\mu n(\mu) \geq 0$$



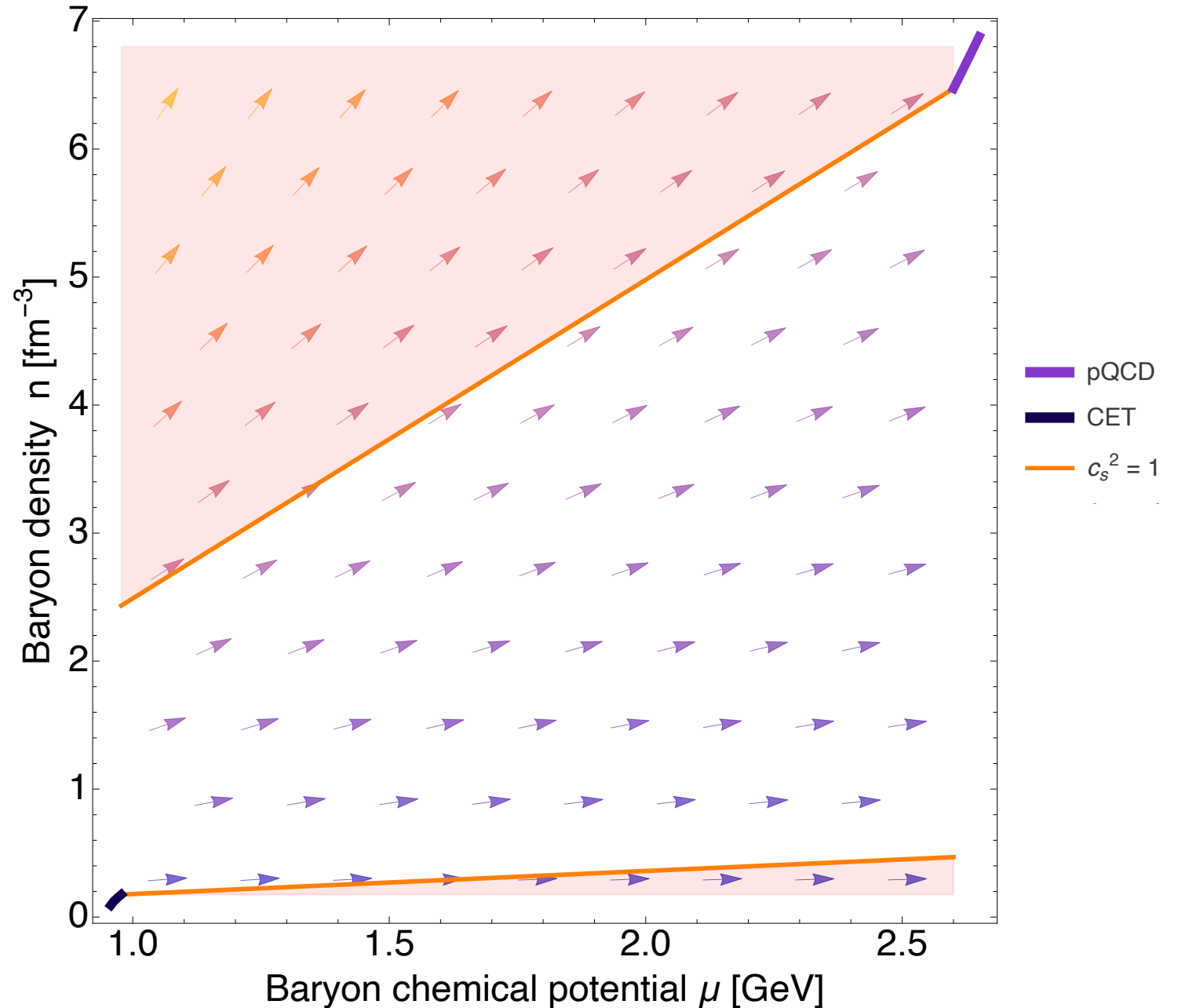
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- Causality

$$c_s^{-2} = \frac{\mu}{n} \frac{\partial n}{\partial \mu} \geq 1 \Rightarrow \partial_\mu n(\mu) \geq \frac{n}{\mu}$$



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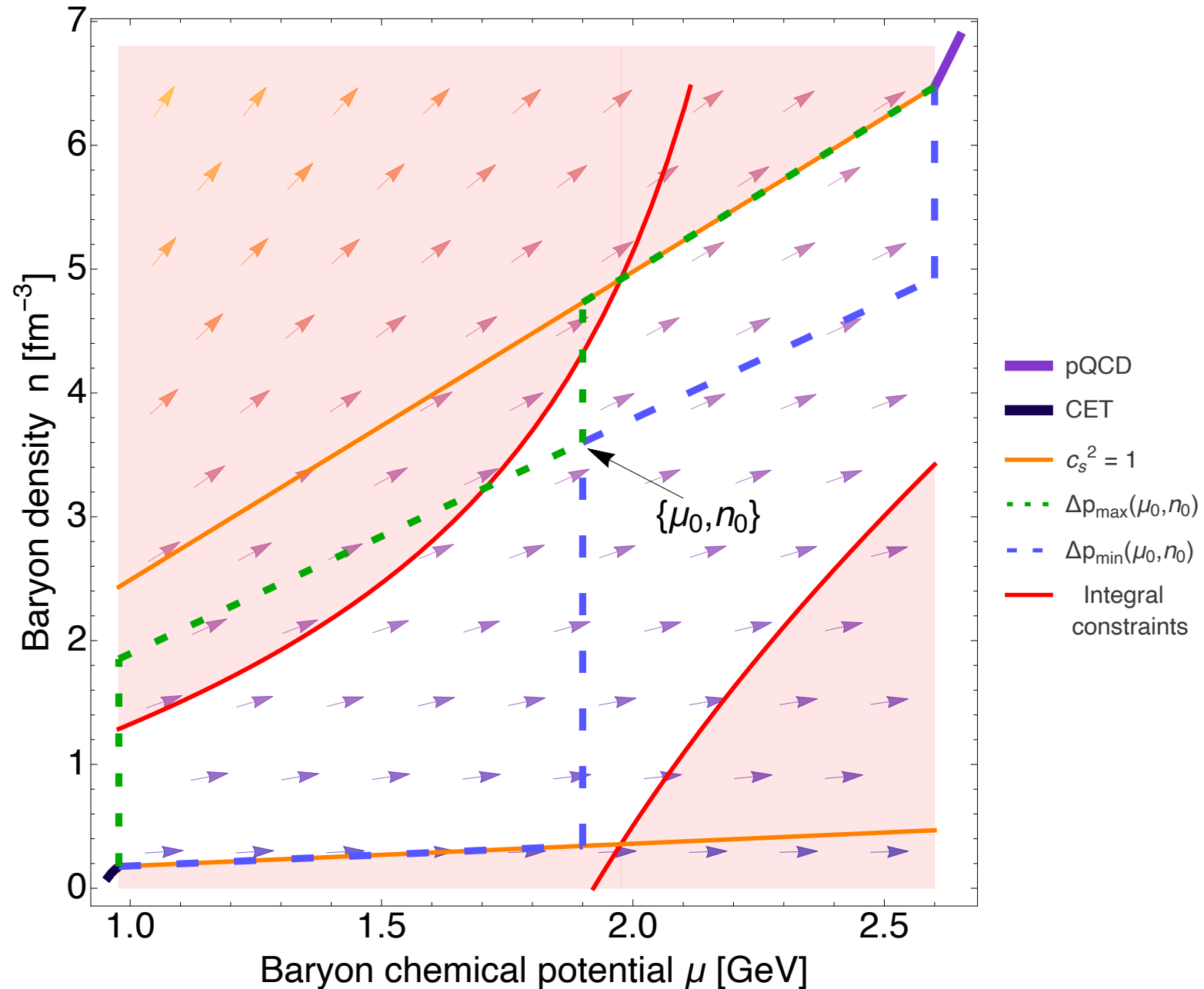
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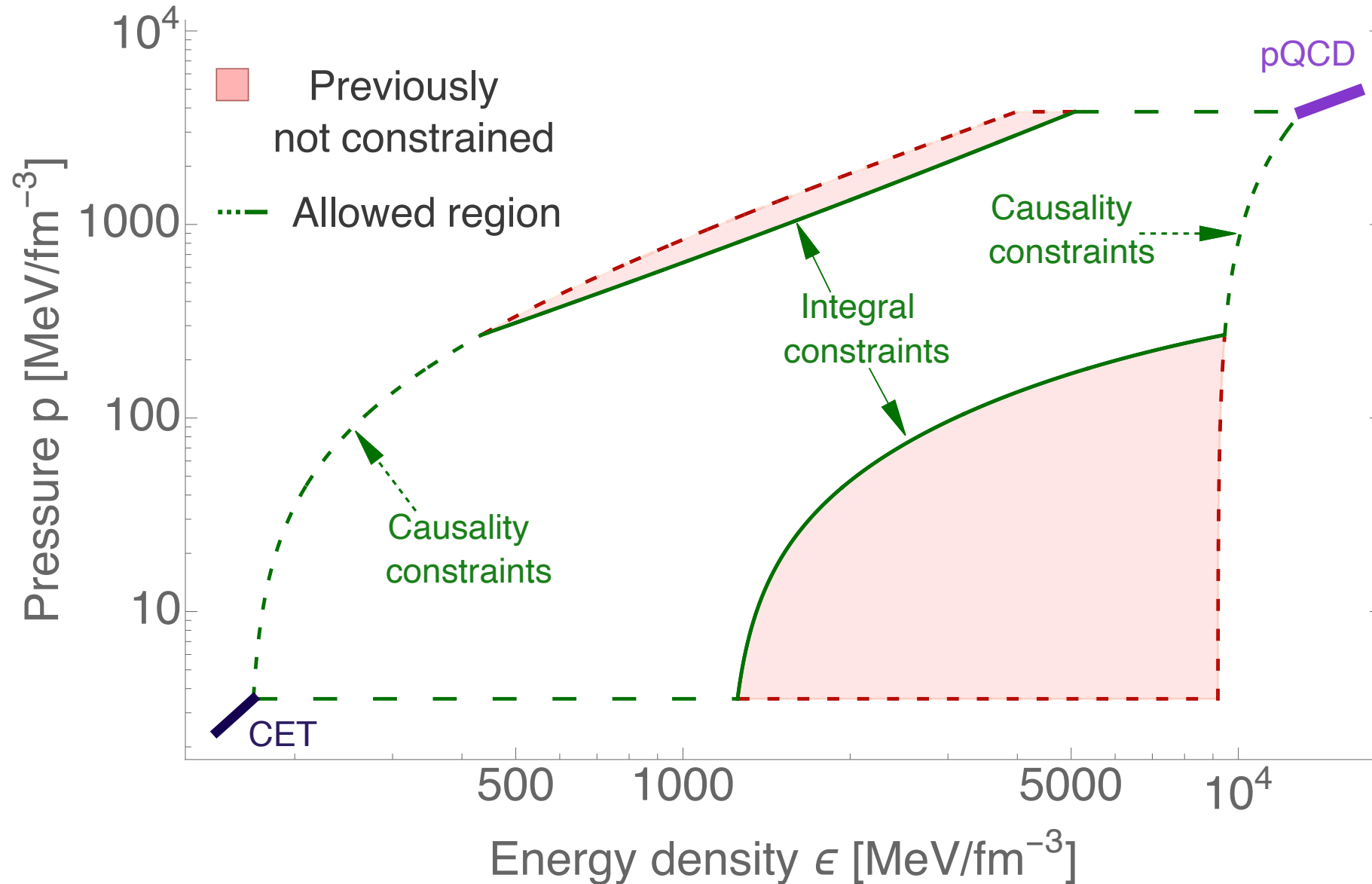
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- Consistency

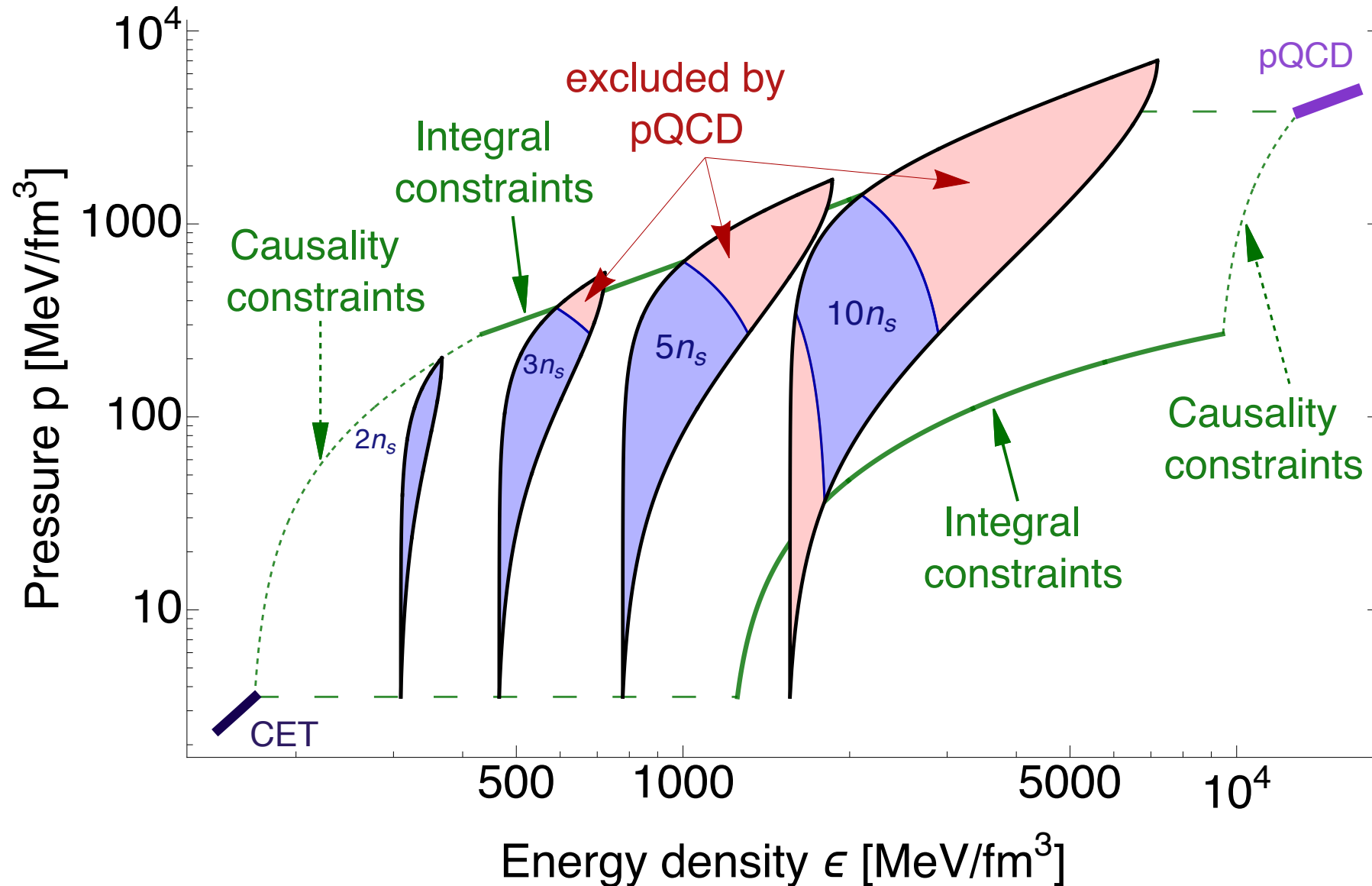
$$\int_{\mu_{CET}}^{\mu_{QCD}} n(\mu) d\mu = p_{QCD} - p_{CET} = \Delta p$$



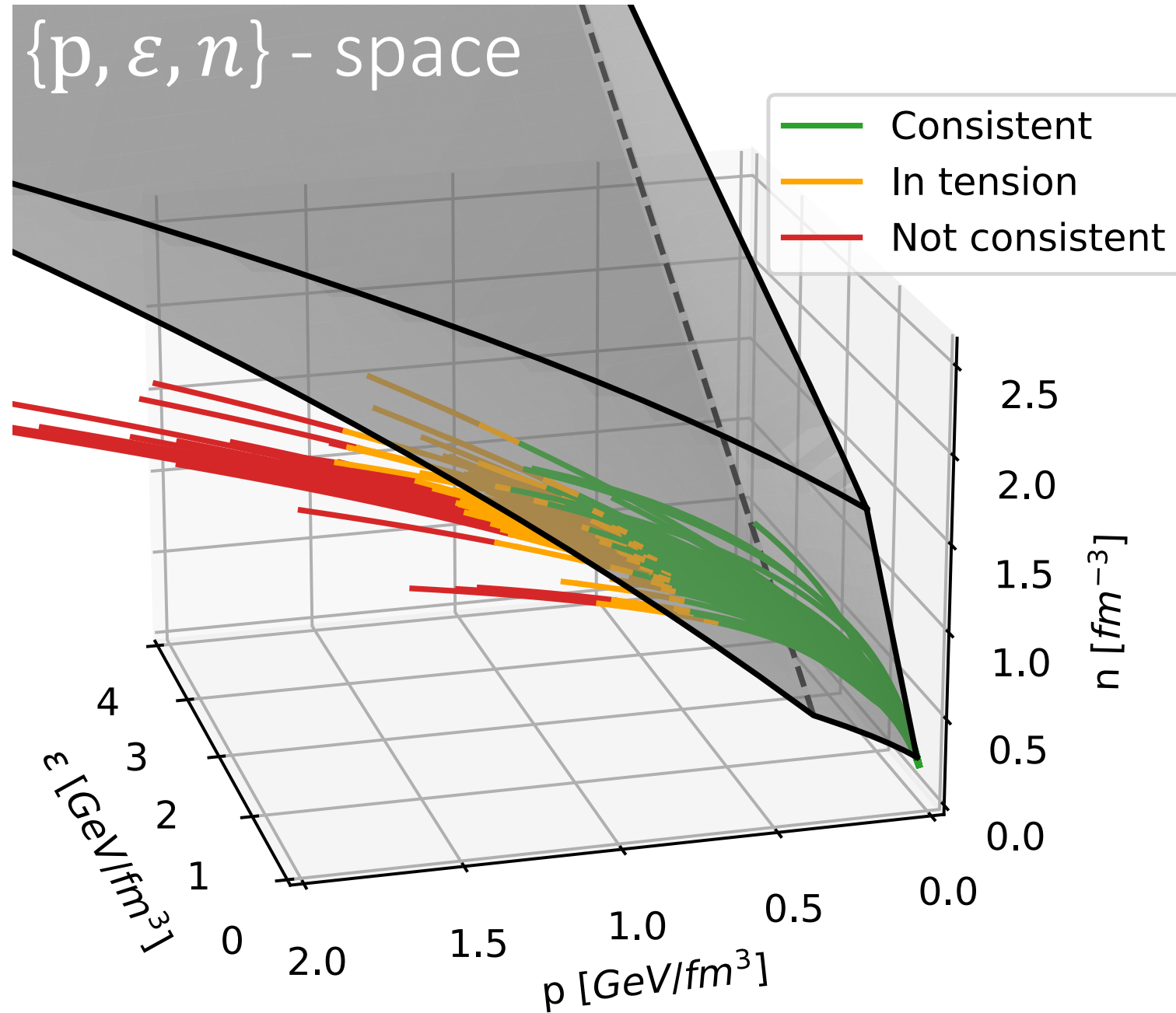
Mapping to $\epsilon - p$ -plane



Constraints for fixed n on $\epsilon - p$ -plane

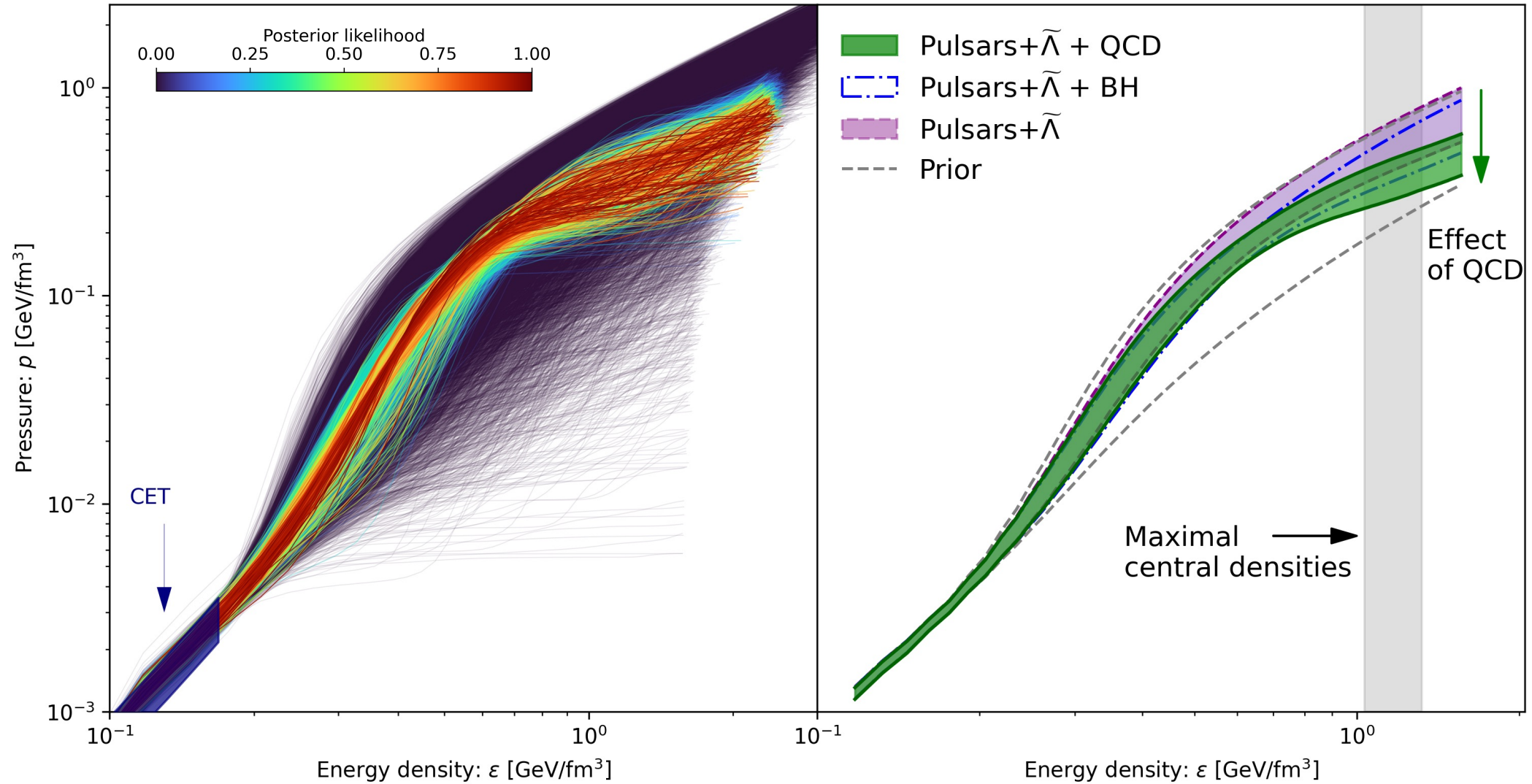


Constraints in $\{p, \varepsilon, n\}$ - space



EoSs from CompOSE database
compose.obspm.fr

Bayesian inference study



Conclusion

QCD at high densities using conditions of **causality** and **stability** offers significant and nontrivial information about the **EoS** at NS densities

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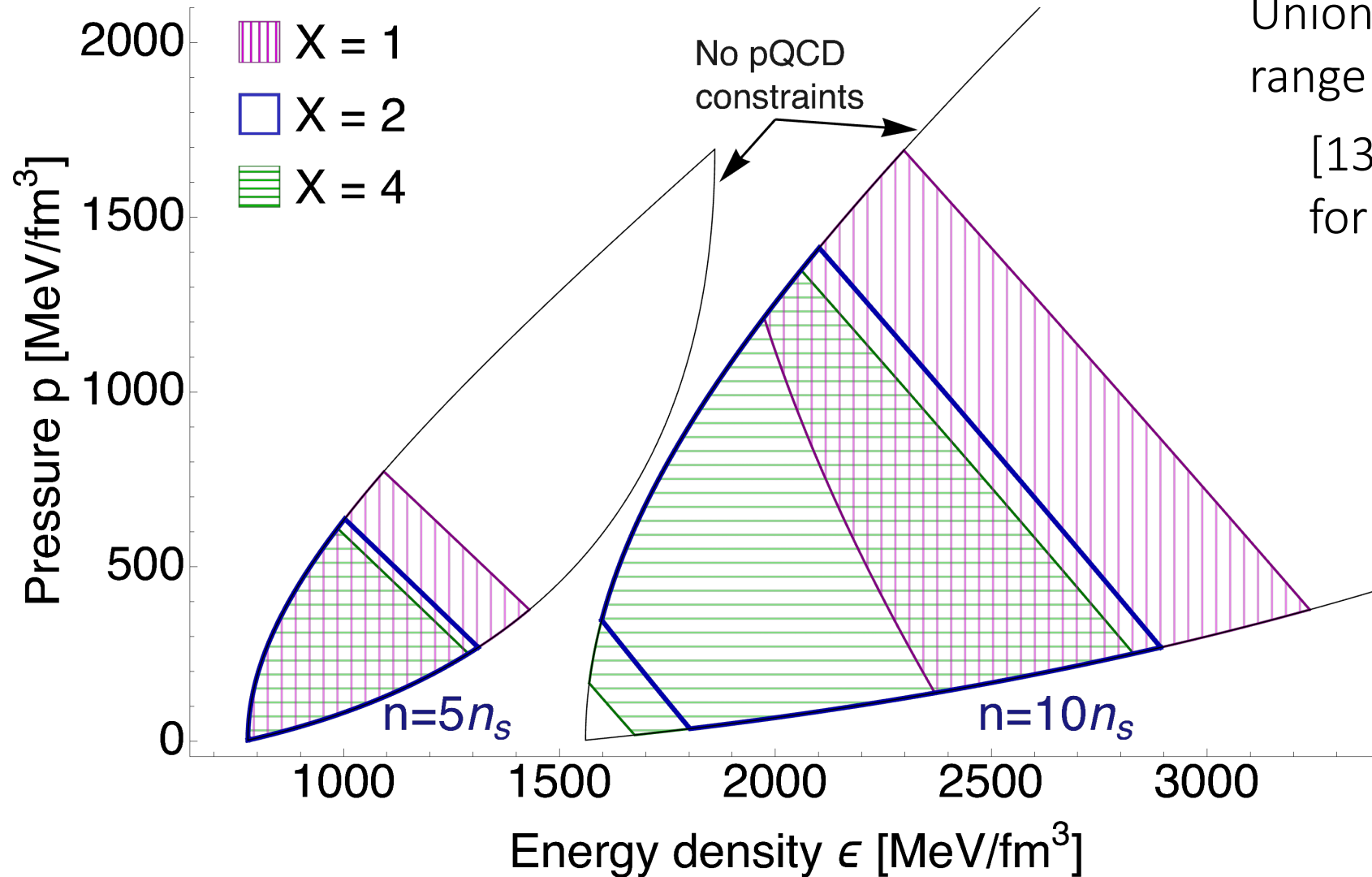
Conclusion

QCD at high densities using conditions of **causality** and **stability** offers significant and nontrivial information about the **EoS** at NS densities

- EoS in $\{\mu, n, p\}$ - space contains more information than $p(\epsilon)$
- pQCD is responsible for softening of the EoS at the NS densities
- Essential to include pQCD in any complete inference study

We provide a Python script to impose pQCD constraints at any density

Linear scale and X dependence



Union of allowed areas in range $X = [1, 4]$ excludes

[13%, 64%, 92.8%]
for $n = [3, 5, 10] n_s$

