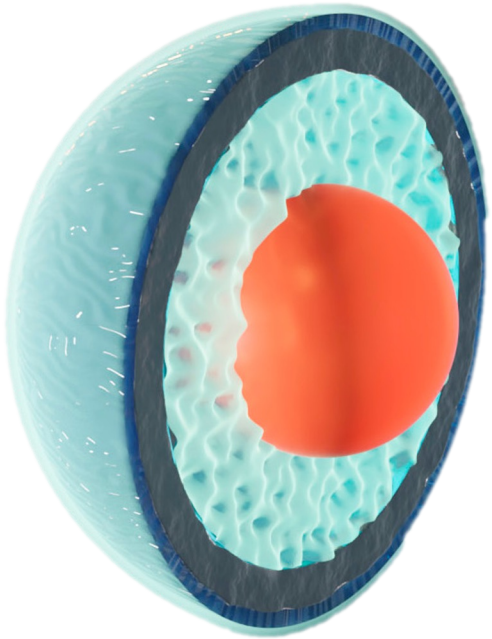
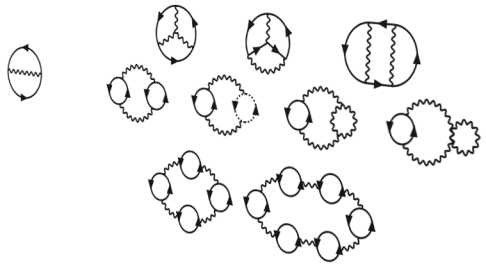
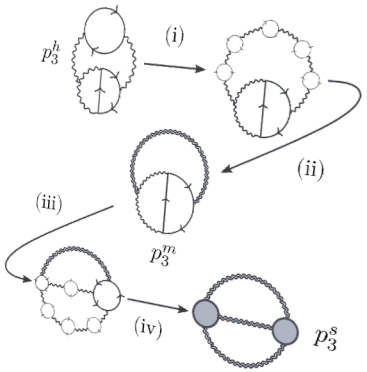


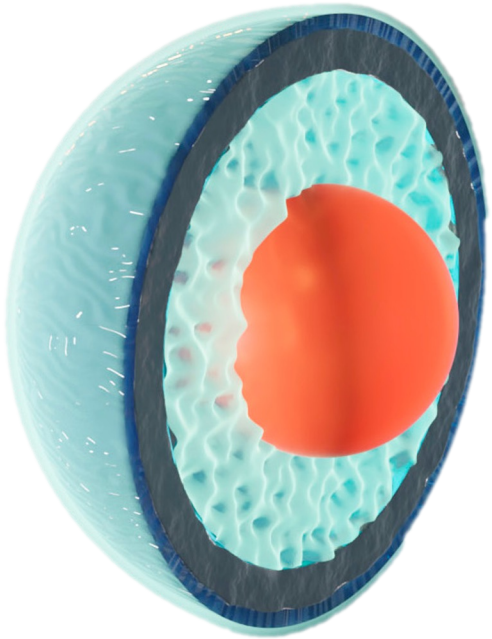




QCD in the cores of neutron stars

Oleg Komoltsev
N-PACT
August 2023

University of Stavanger



University of Stavanger

- How Perturbative QCD Constrains the Equation of State at Neutron-Star Densities
  O.K., Aleksi Kurkela
  PRL.128.20270
- Ab-initio QCD Calculations Impact the Inference of the Neutron-star-matter Equation of State
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  Astrophys.J. 950 (2023) 2, 107
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  arXiv:2303.11356

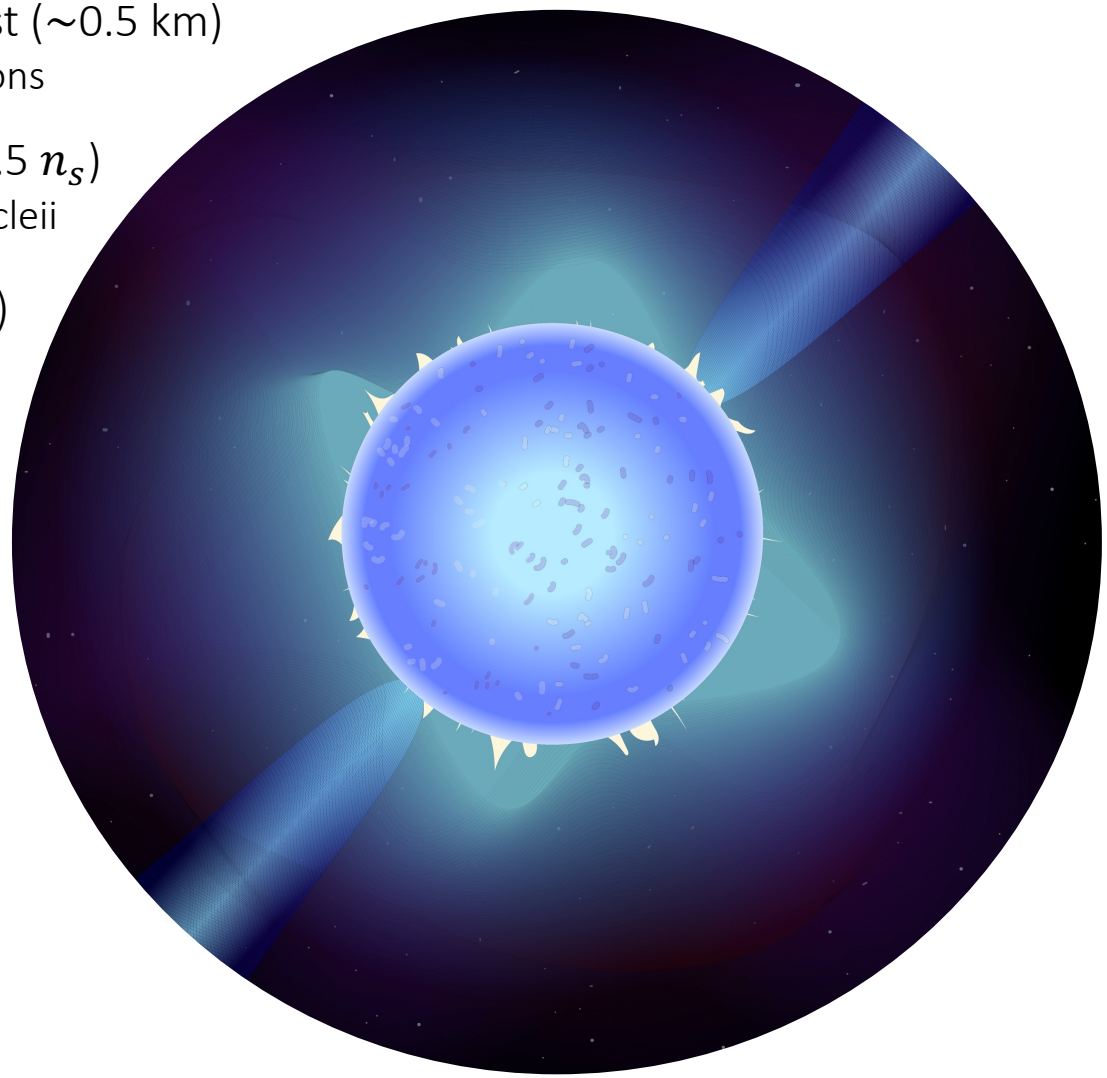
Neutron stars

Outer Crust (~0.5 km)
Ions, Electrons

Inner Crust (~1 km, 0.5 n_s)
Electrons, Neureons, Nucleii

Outer core (~9 km, 0.5-2 n_s)
Neutron – Proton Fermi liquid

Inner core (~10 km, 4-8 n_s)
Quark Matter ?



n_s = 0.16 fm^{-3}

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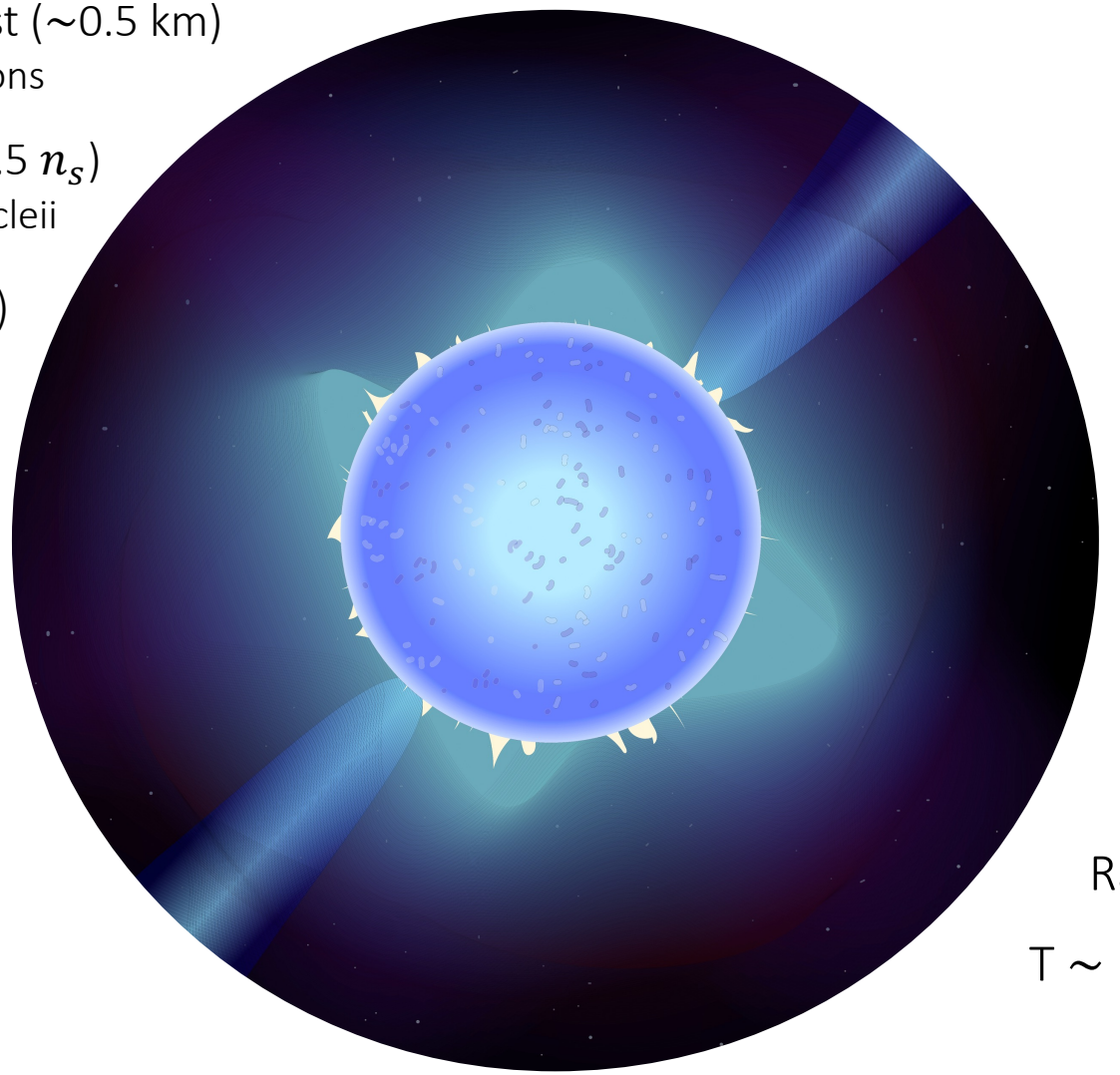


Masses $\sim 1.4 - 2.0\ M_\odot$

Radii ~ 10 km

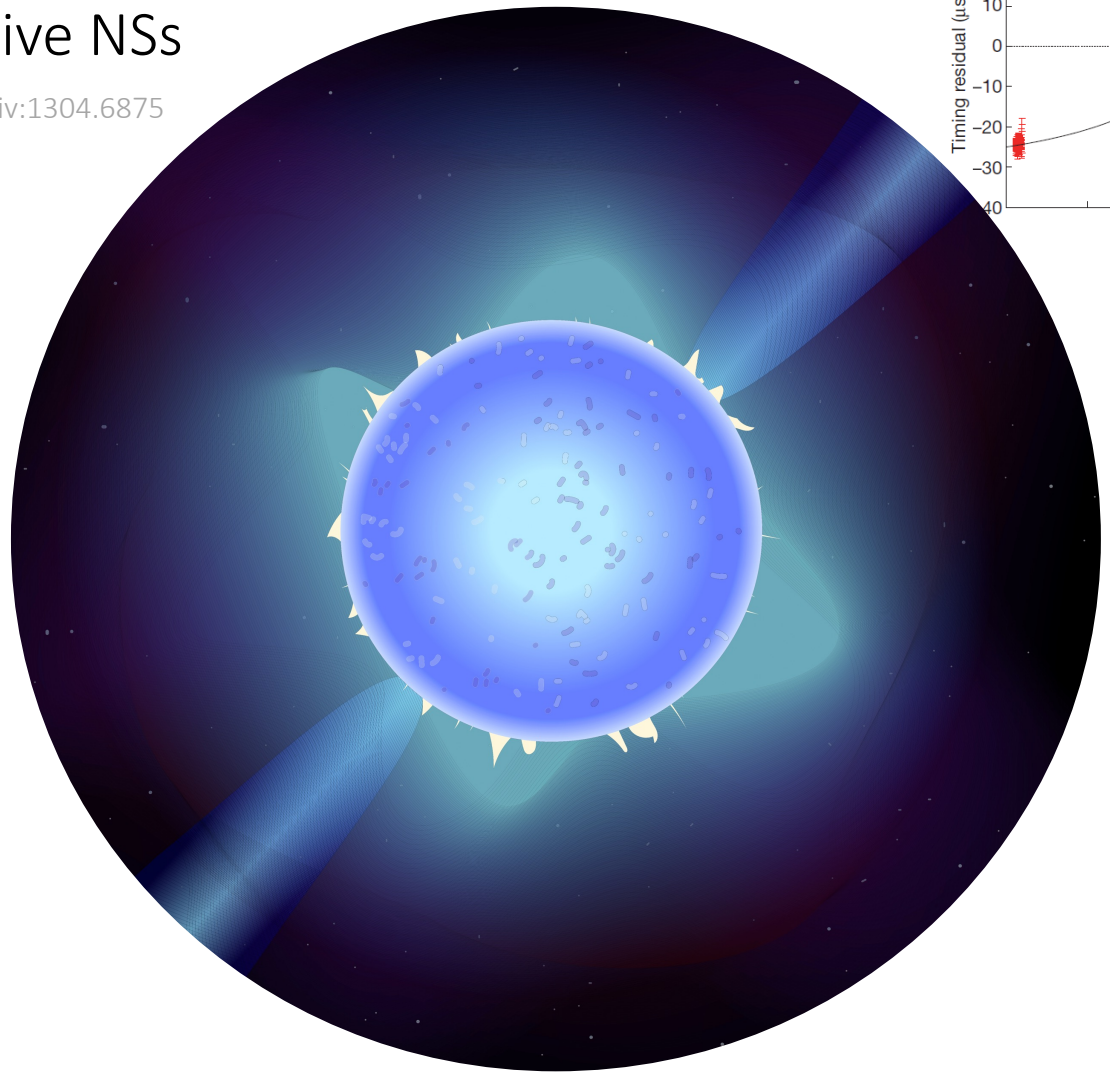
T ~ KeV ~ 10^7 K

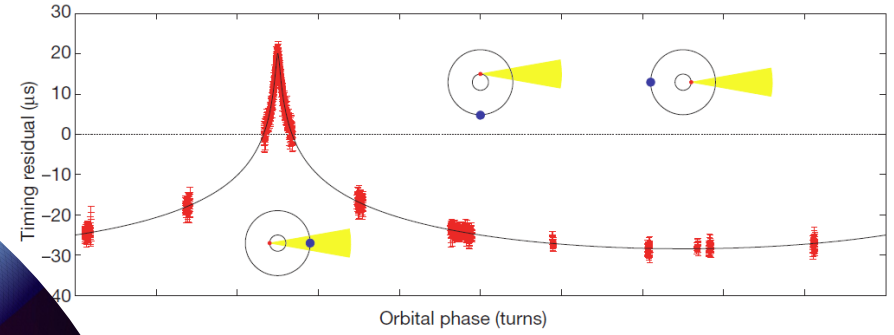
$n_s = 0.16\ fm^{-3}$

Neutron stars

- Discovery of massive NSs

Antoniadis, Freire et.al. arXiv:1304.6875





Shapiro time delay

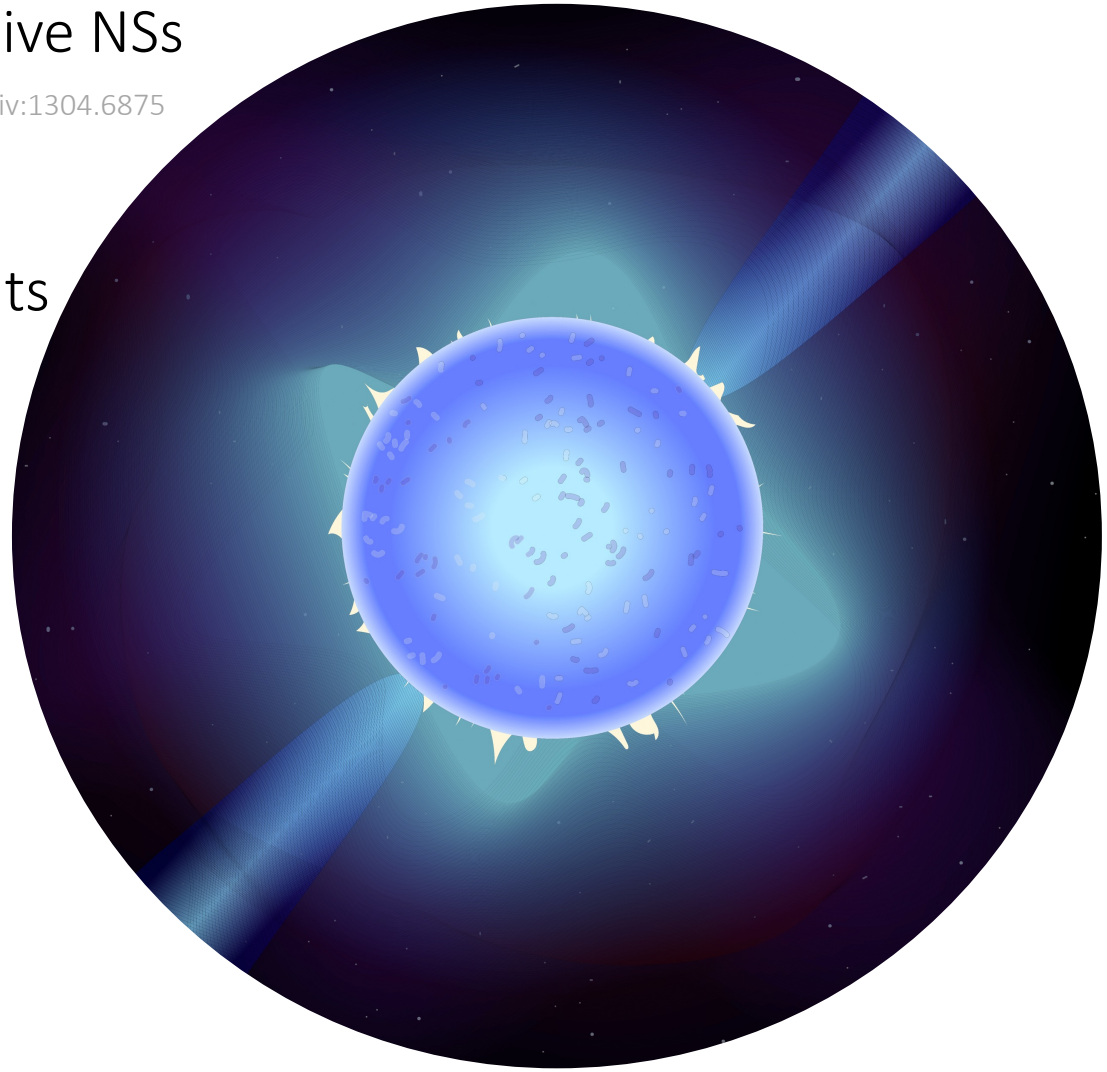
Neutron stars

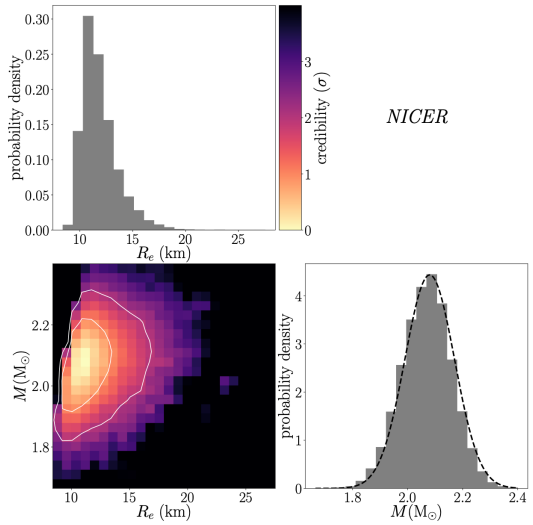
- Discovery of massive NSs

  Antoniadis, Freire et.al. arXiv:1304.6875

- NS radius measurements

  Riley, Watts et.al. arXiv:2105.06980





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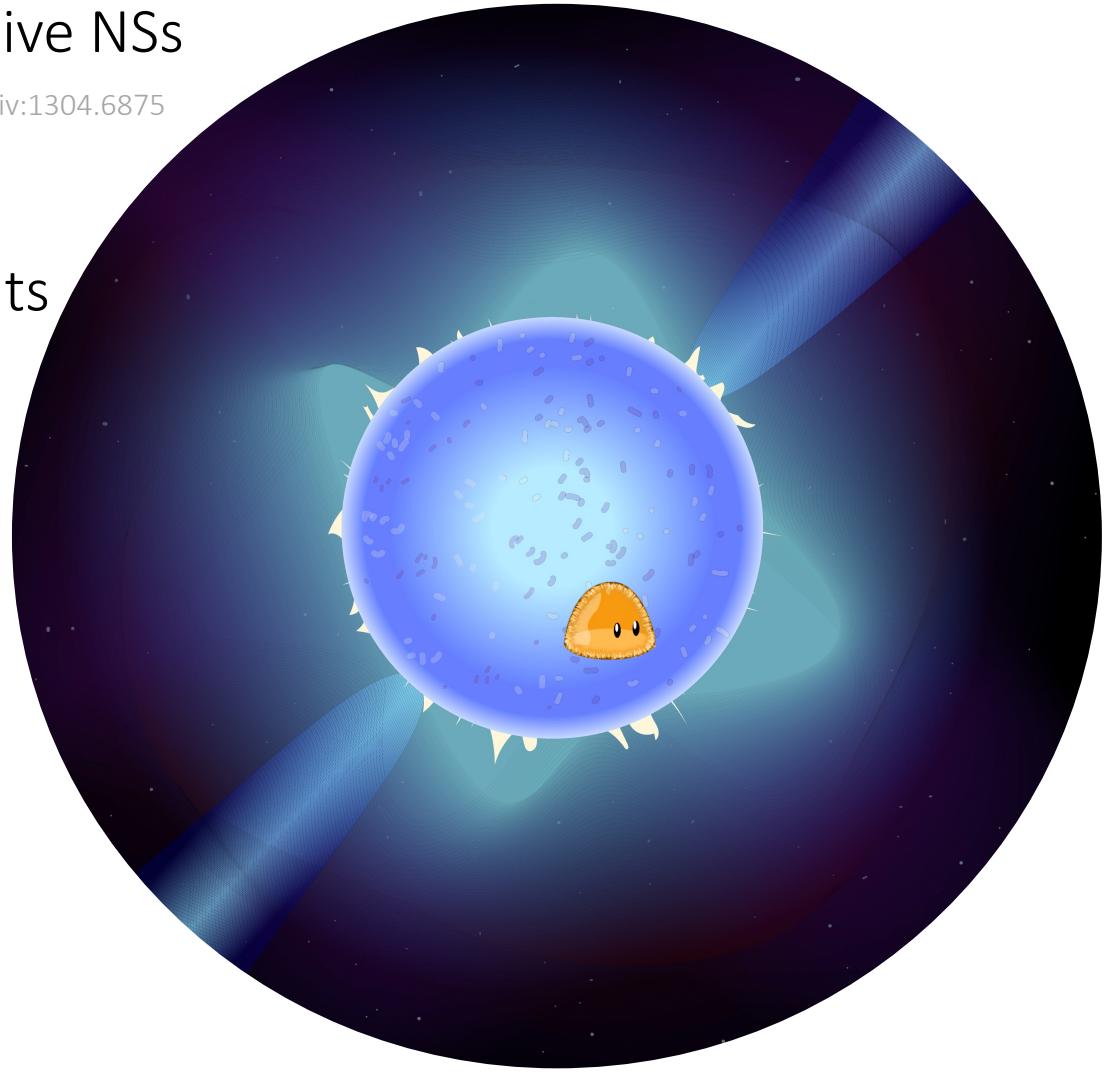

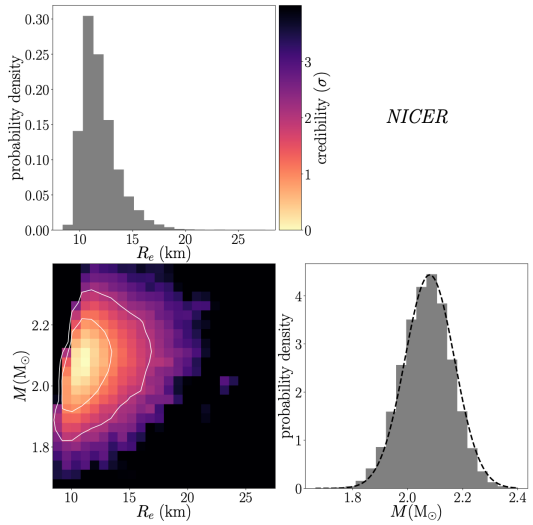

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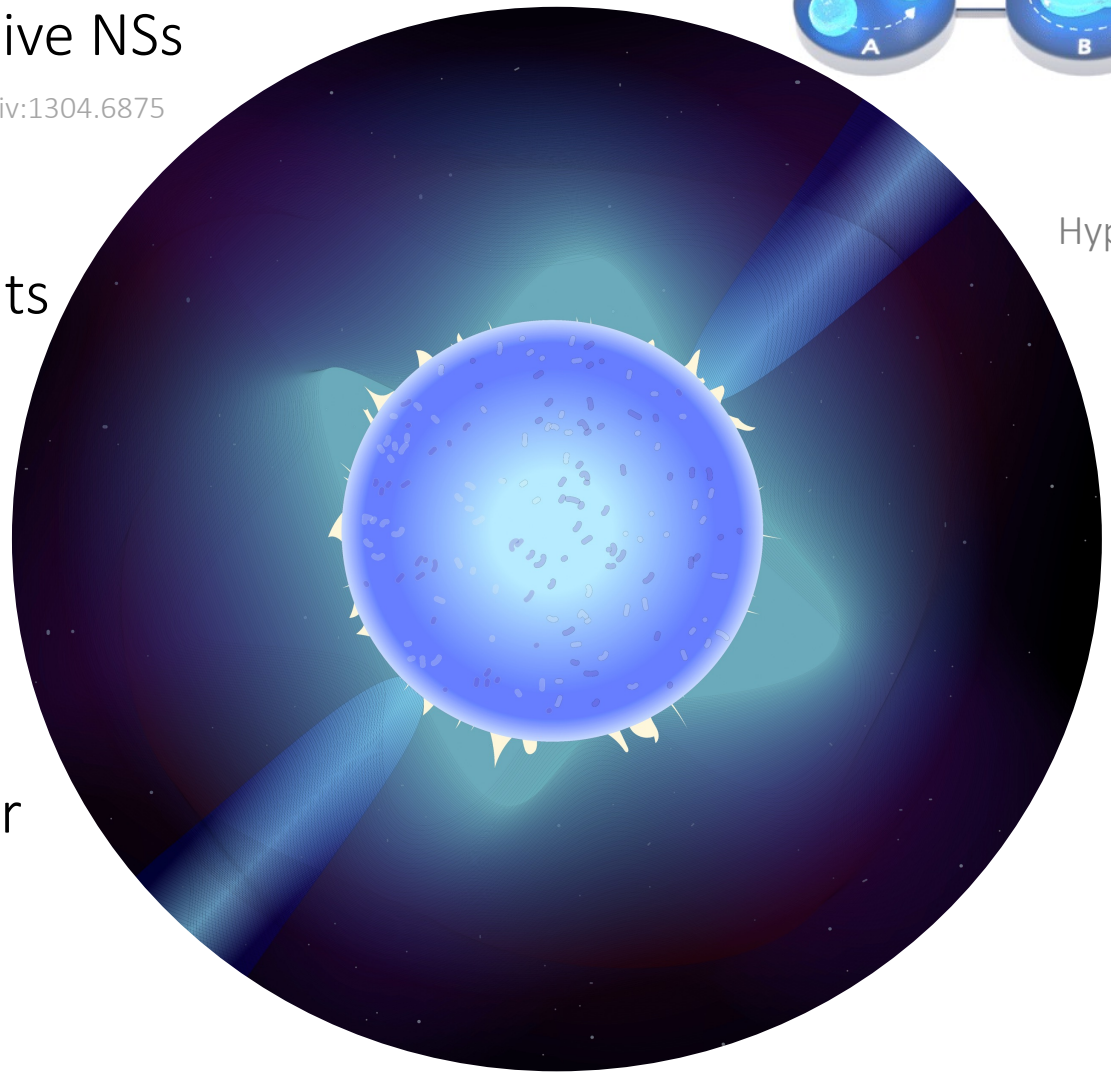
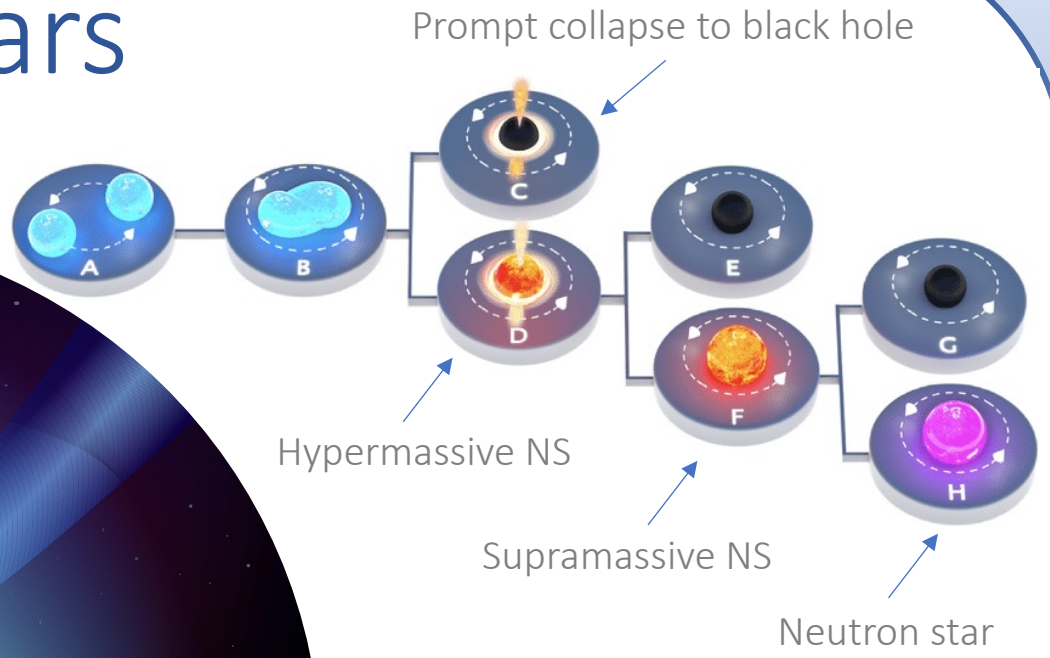
- Gravitational-wave

  LIGO, VIRGO

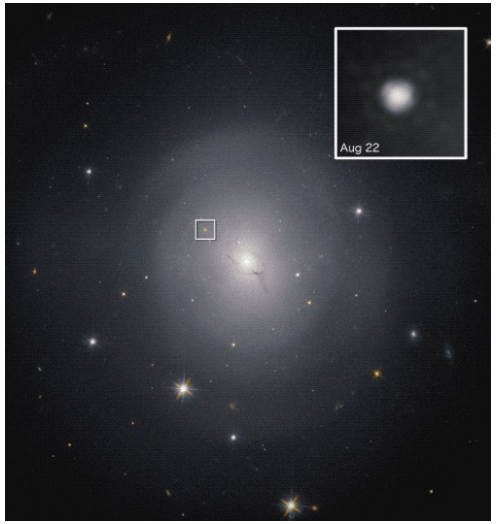
- Multi-messenger

  LIGO, VIRGO

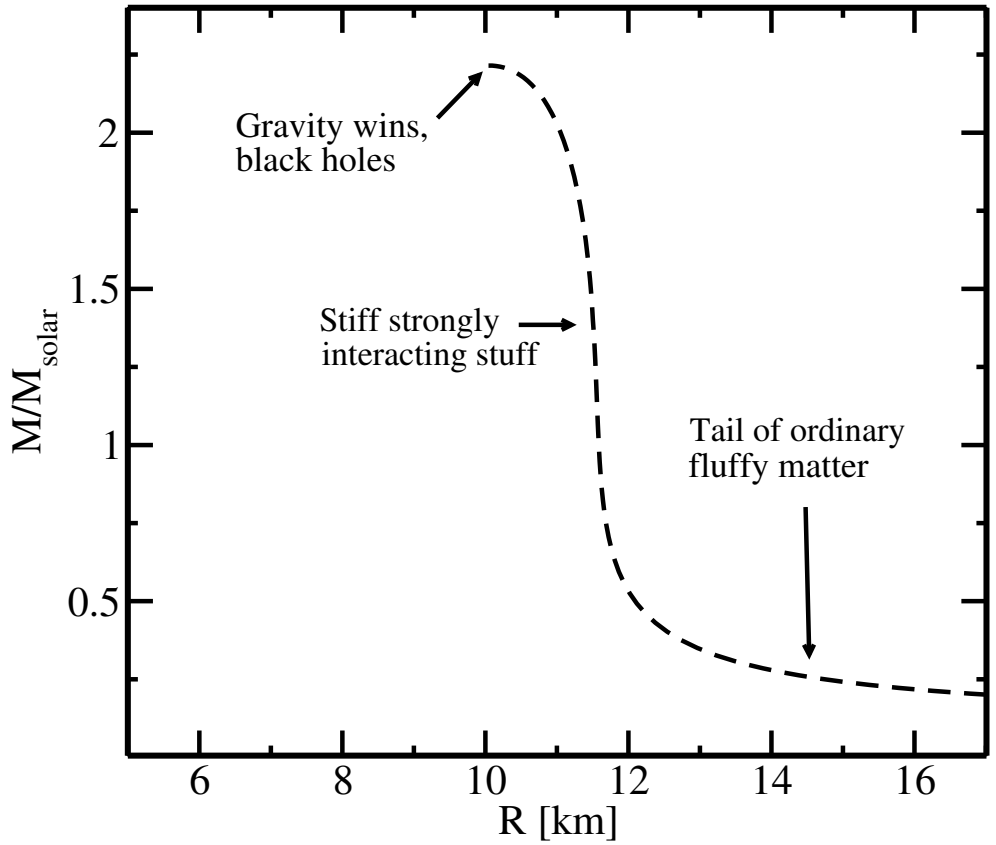




GW170817



Properties of neutron stars reflect properties of dense matter



Competition between pressure and gravity

Tolman–Oppenheimer–Volkoff equation:

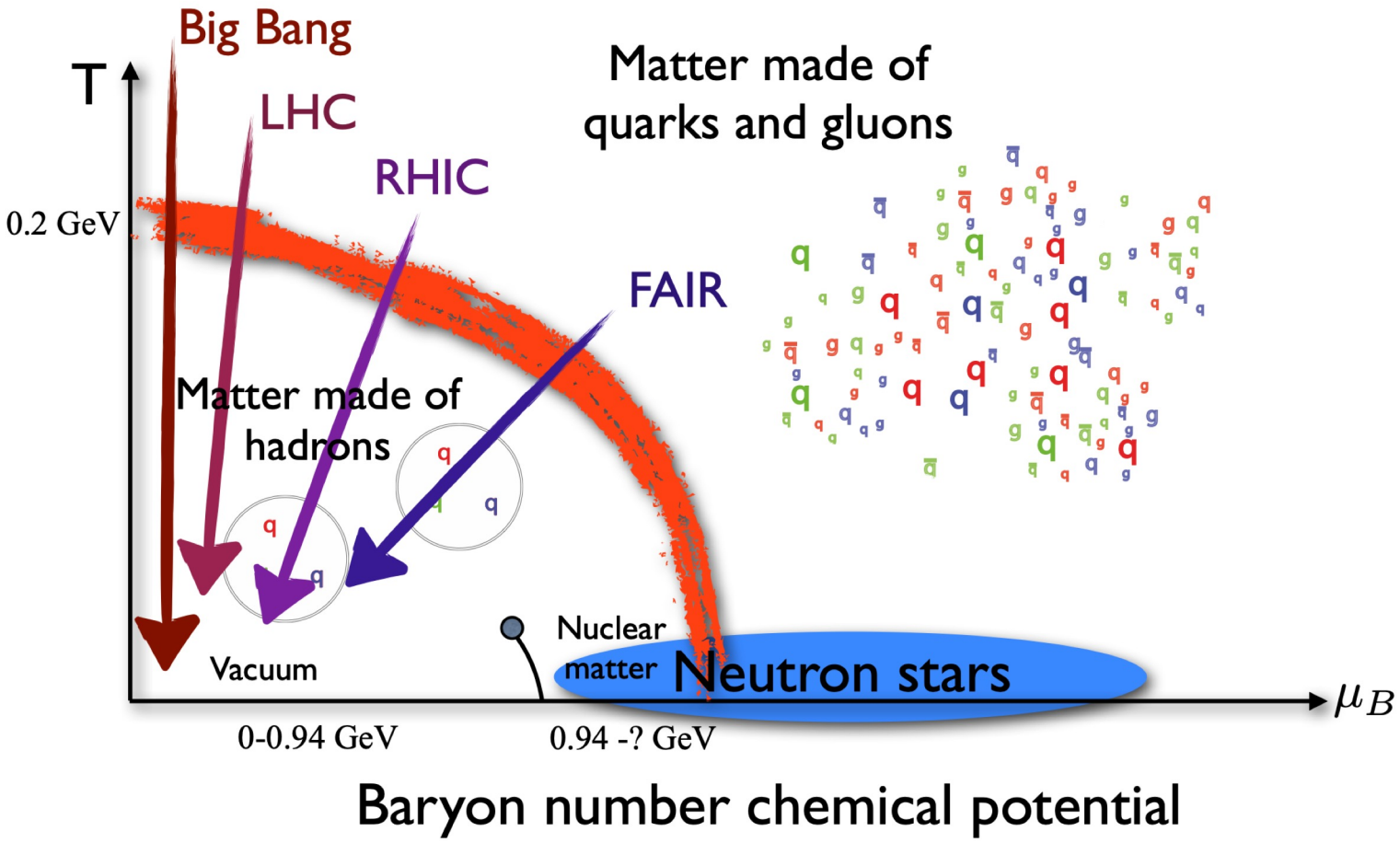
$$\frac{dp}{dr} = -\frac{Gm}{r^2}\,\varepsilon\,(1+\frac{p}{\varepsilon})(1+\frac{4\pi r^3\varepsilon}{m})(1-\frac{2Gm}{r})^{-1}$$

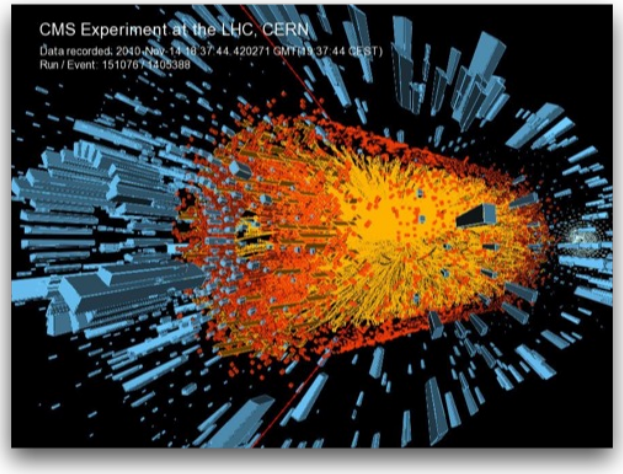
$$\frac{dm}{dr} = 4\pi r^2\varepsilon$$

Macroscopic properties determined by the EoS

$$\epsilon(P) \Leftrightarrow R(M)$$

Elementary particle matter

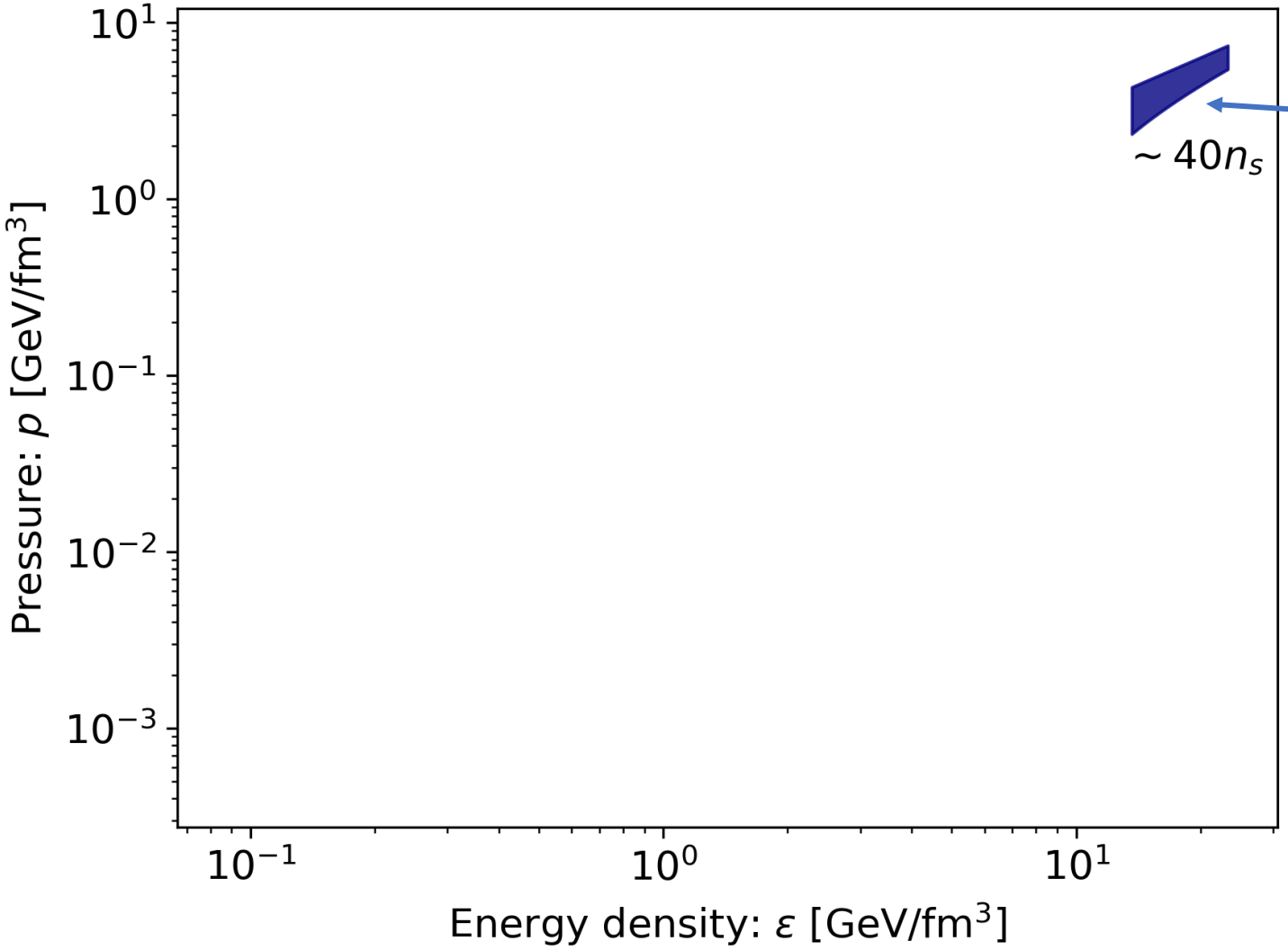




LHC, RHIC, FAIR, NICA,...

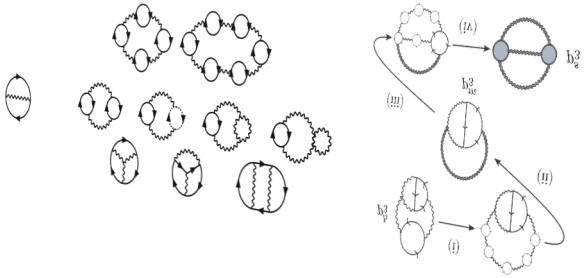
LIGO+Virgo+Kagra, NICER, eXTP,...

What do we know about EoS, theoretically?

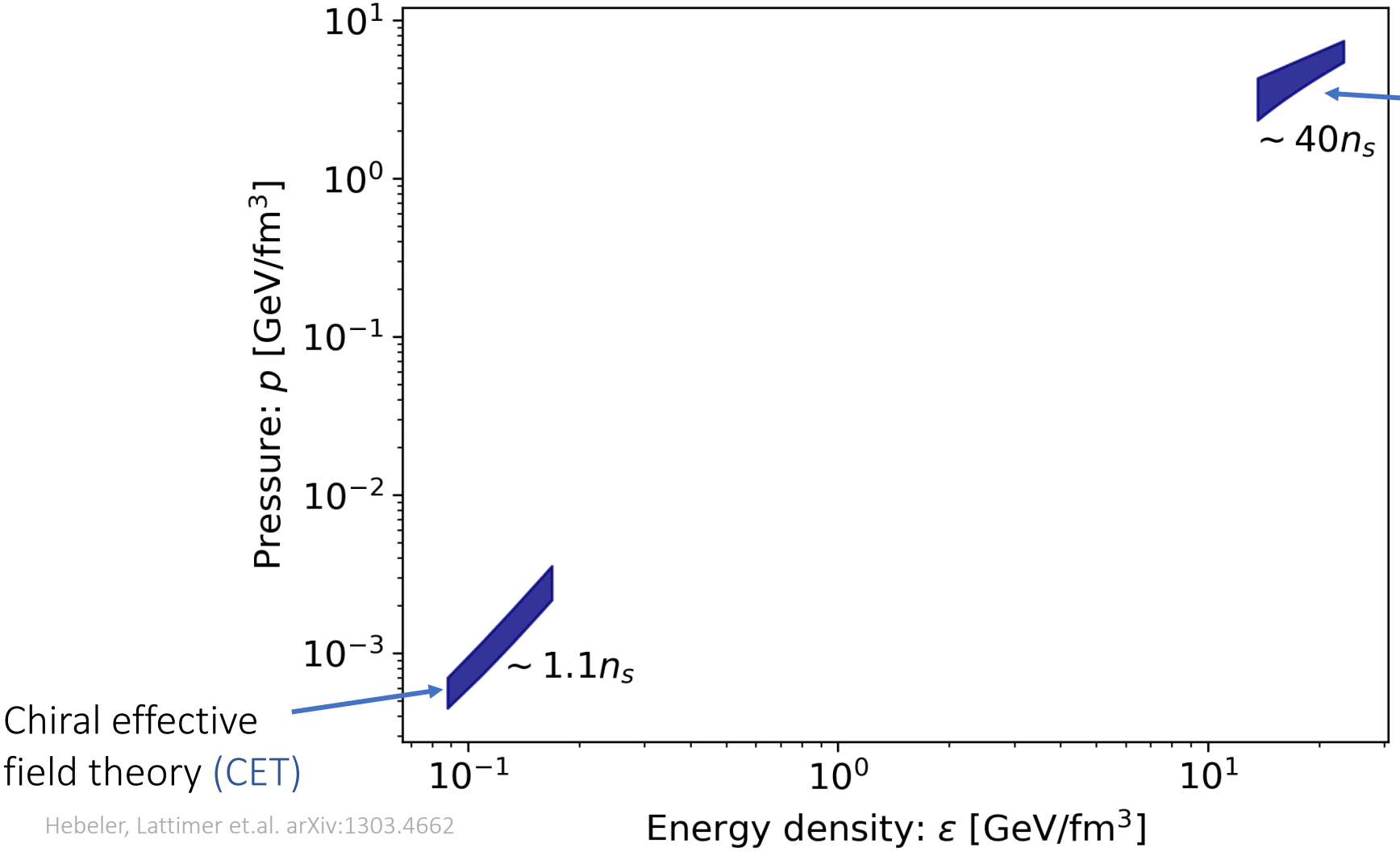


Perturbative QCD (pQCD)

Gorda, Kurkela et.al. arXiv:2103.05658



What do we know about EoS, theoretically?



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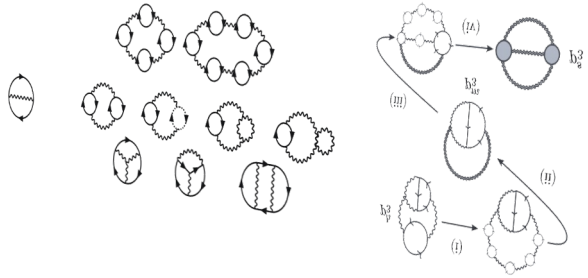

Chiral effective field theory (CET)

Hebeler, Lattimer et.al. arXiv:1303.4662

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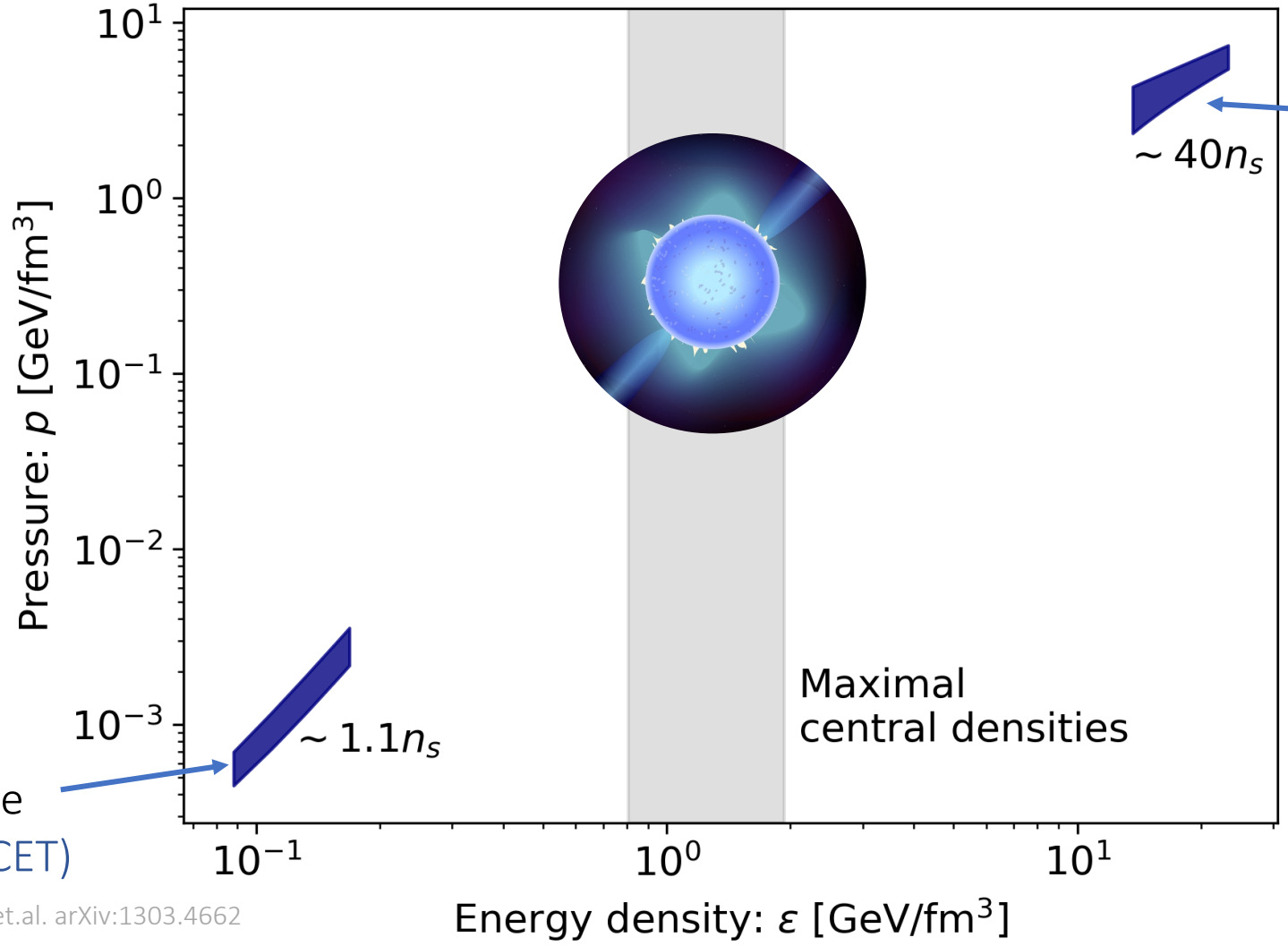

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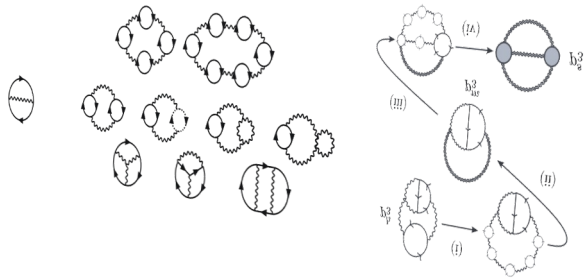

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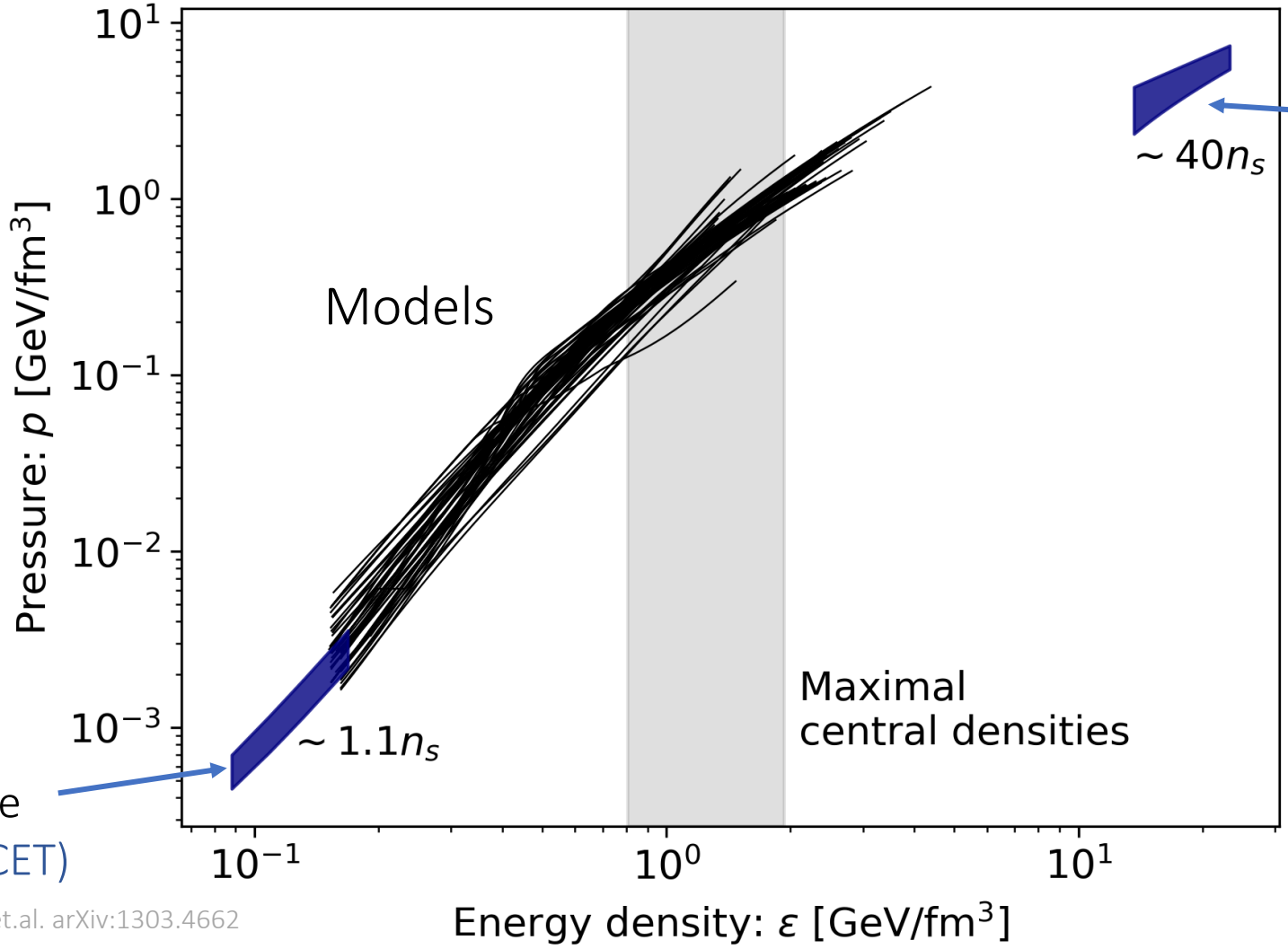

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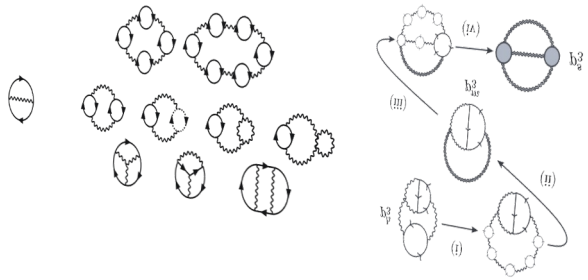

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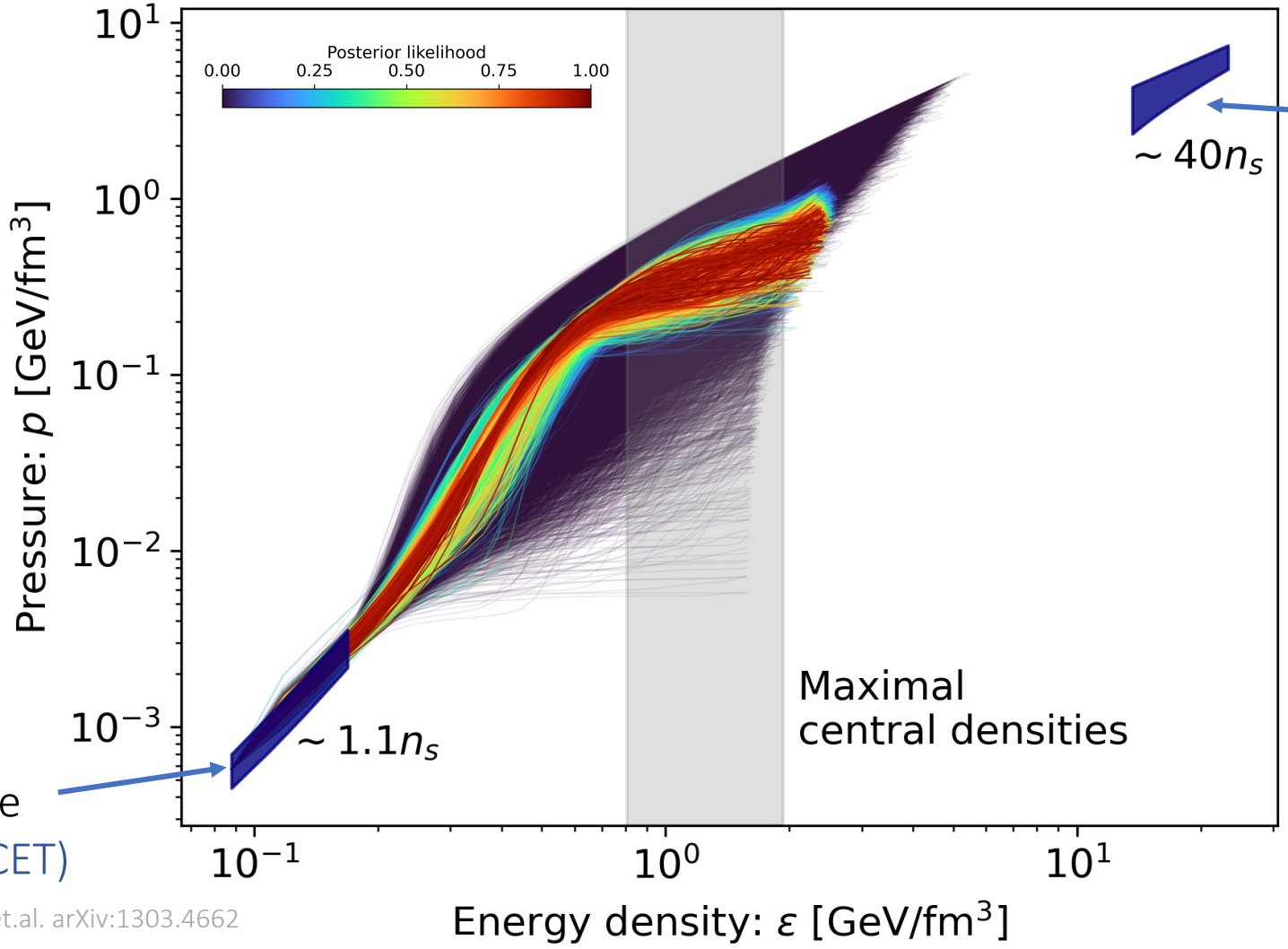

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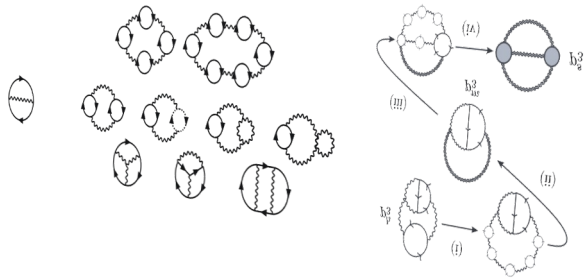

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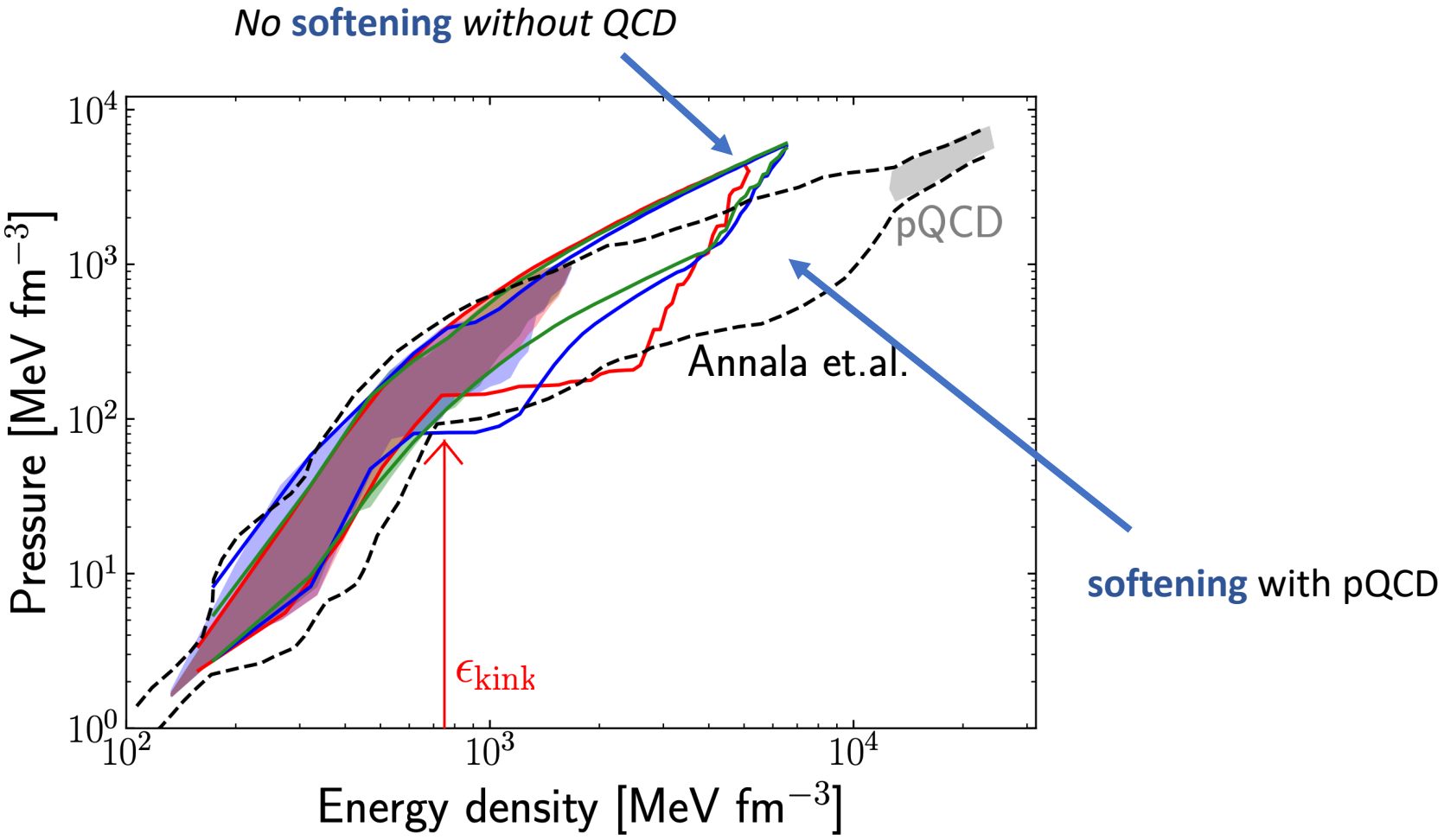
Studies with pQCD see softening of EoS



Annala, Gorda, Kurkela, Nätttilä, Vuorinen Nature Physics 16 (2020) 9
Somasundaram, Tews, Margueron 2112.08157

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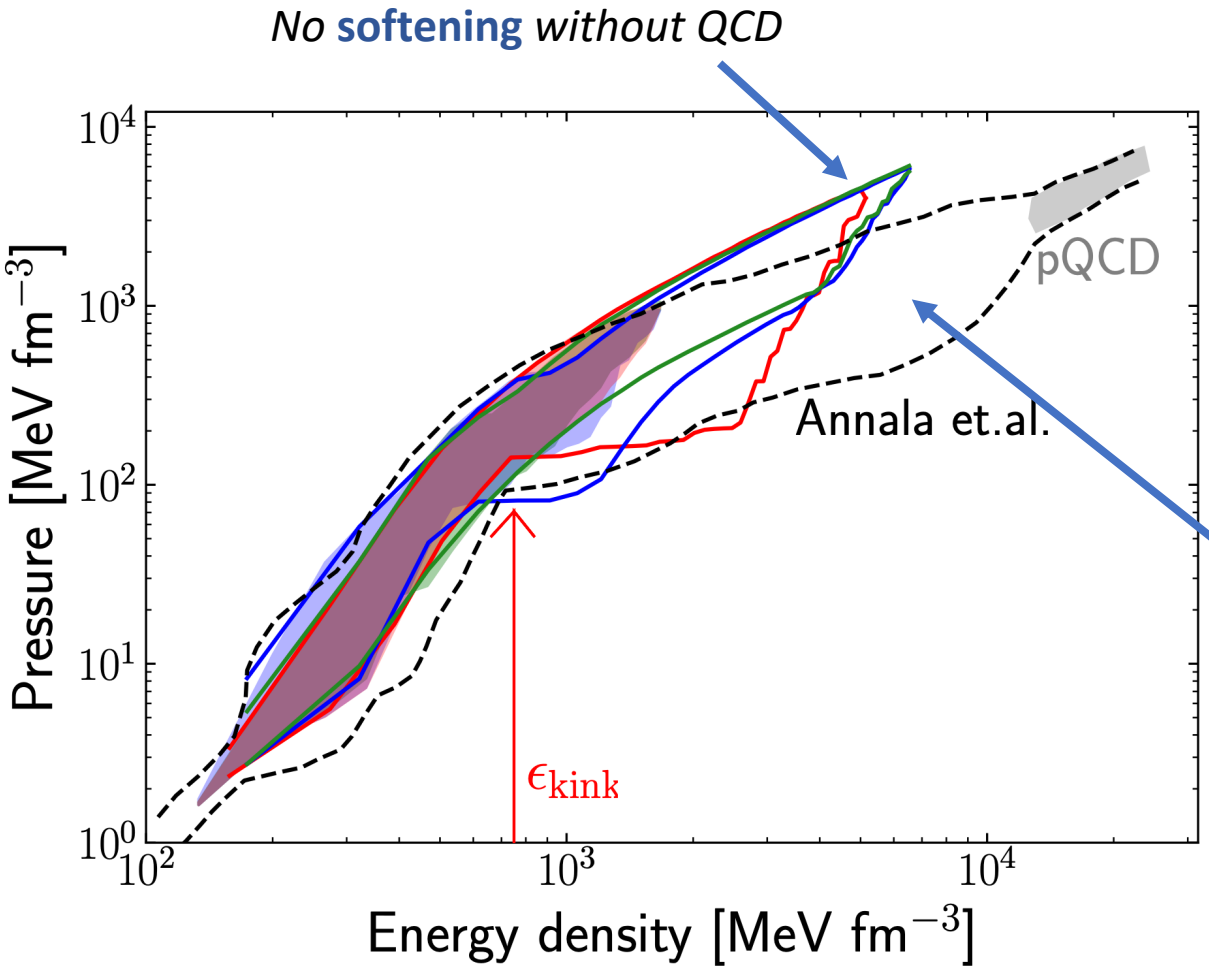

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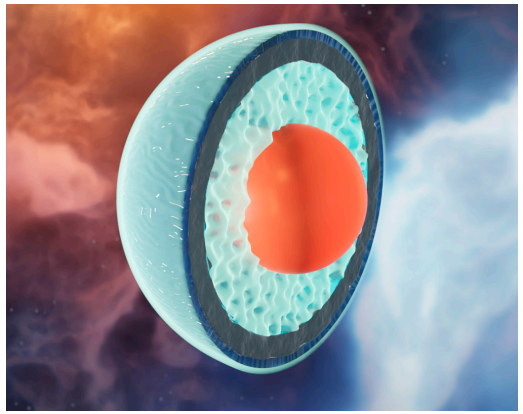
Quark matter cores?



Annala et.al. arXiv:2303.11356

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

softening with pQCD

- **Why** does QCD at $40n_s$ constrain the EoS at NS densities

  How pQCD constrains the equation of state at neutron star densities

  OK & Kurkela, PRL128 (2022) 20, 2111.05350

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  Ab-initio QCD Calculations Impact the Inference of the Neutron-star-matter Equation of State

  Tyler Gorda, O.K., Aleksi Kurkela, Astrophys.J. 950 (2023) 2, 107

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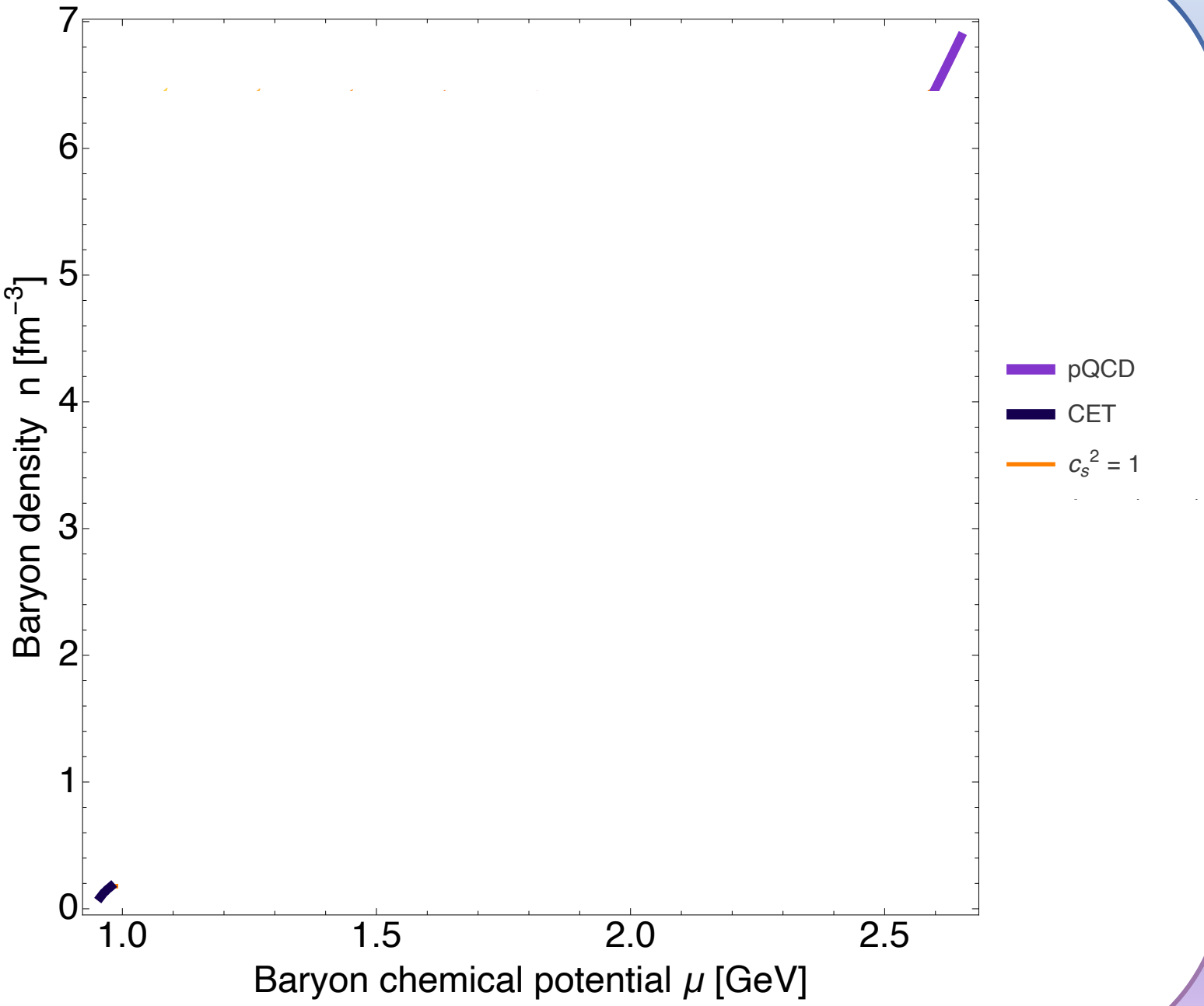
  Strongly interacting matter exhibits deconfined behavior in massive neutron stars

  Eemeli Annala, T.G., Joonas Hirvonen, O.K.,A.K., arXiv:2303.11356

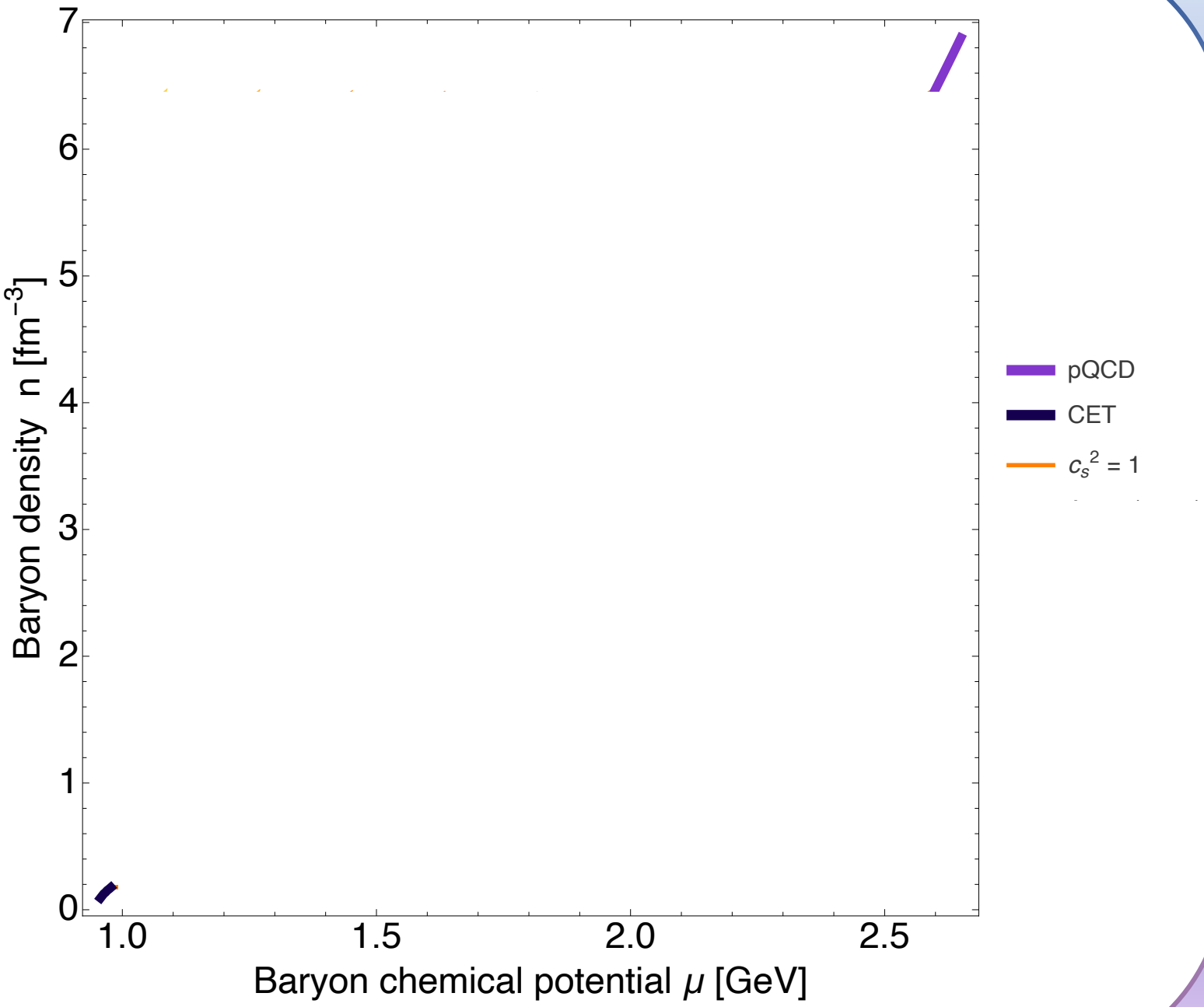
Setup


Baryon density n [fm^{-3}]
Baryon chemical potential μ [GeV]
0
1
2
3
4
5
6
7
1.0
1.5
2.0
2.5
pQCD
CET
$c_s^2 = 1$

Setup

- Stability

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



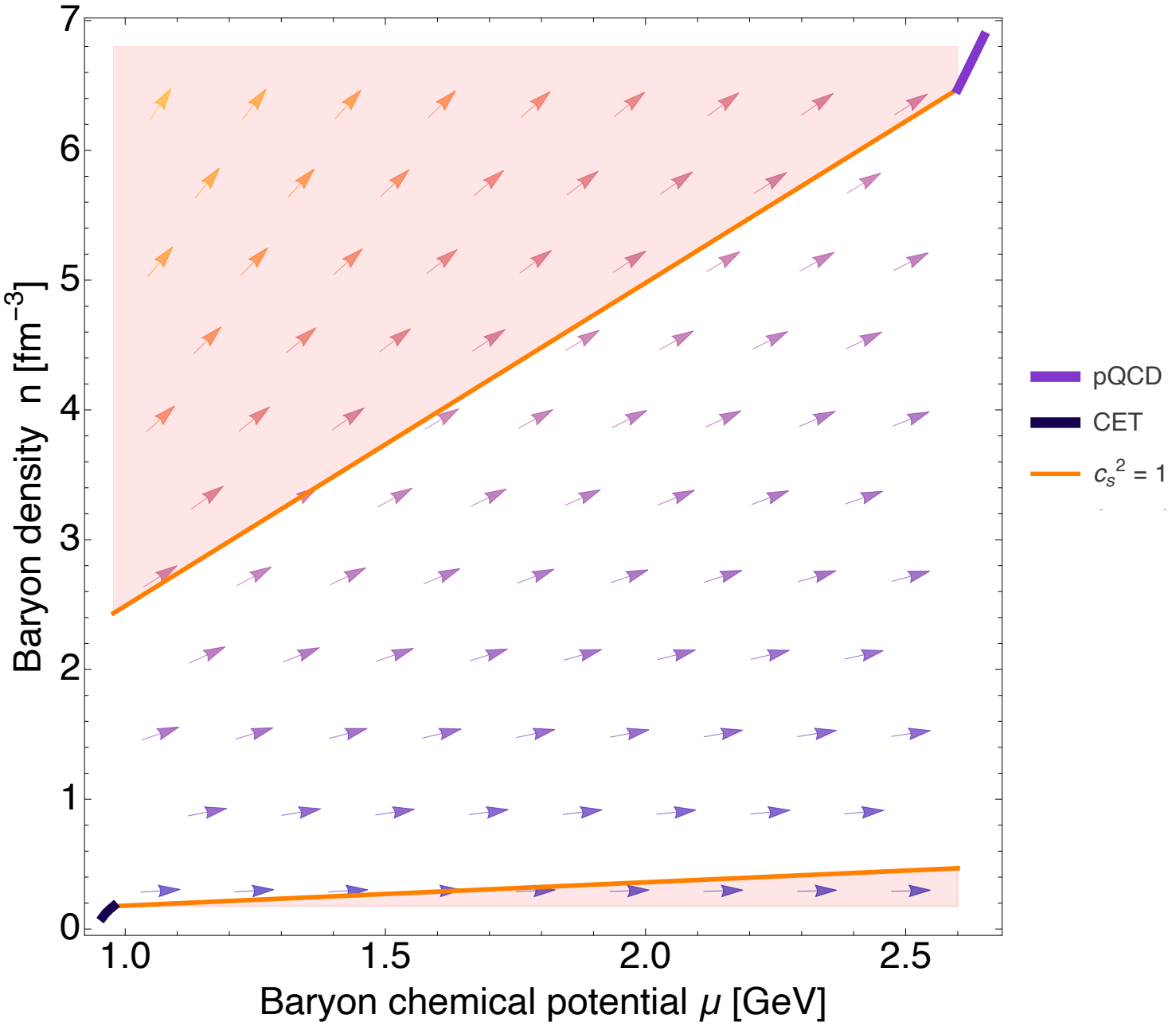
Setup

- Stability

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

- Causality

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



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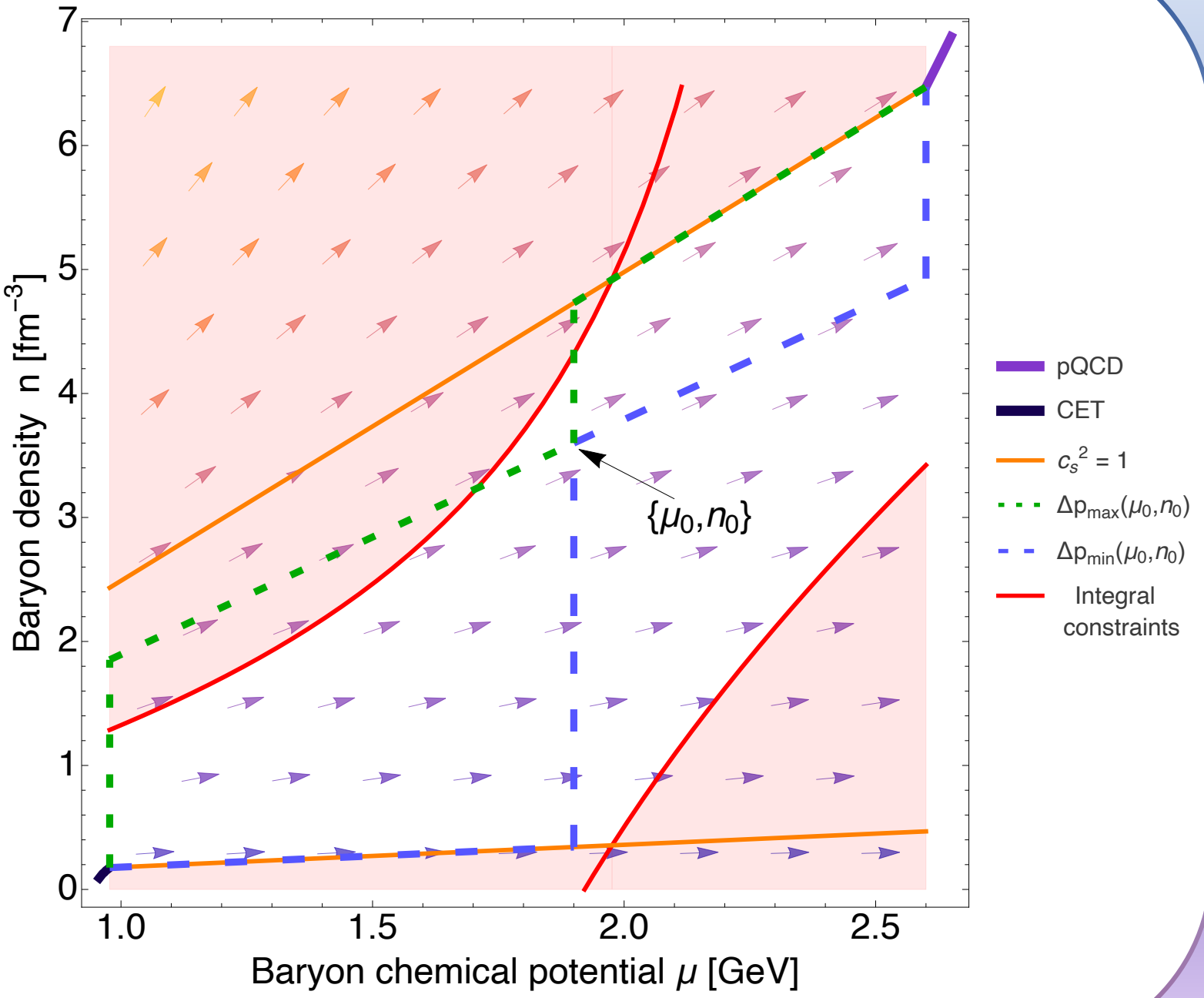
- Causality

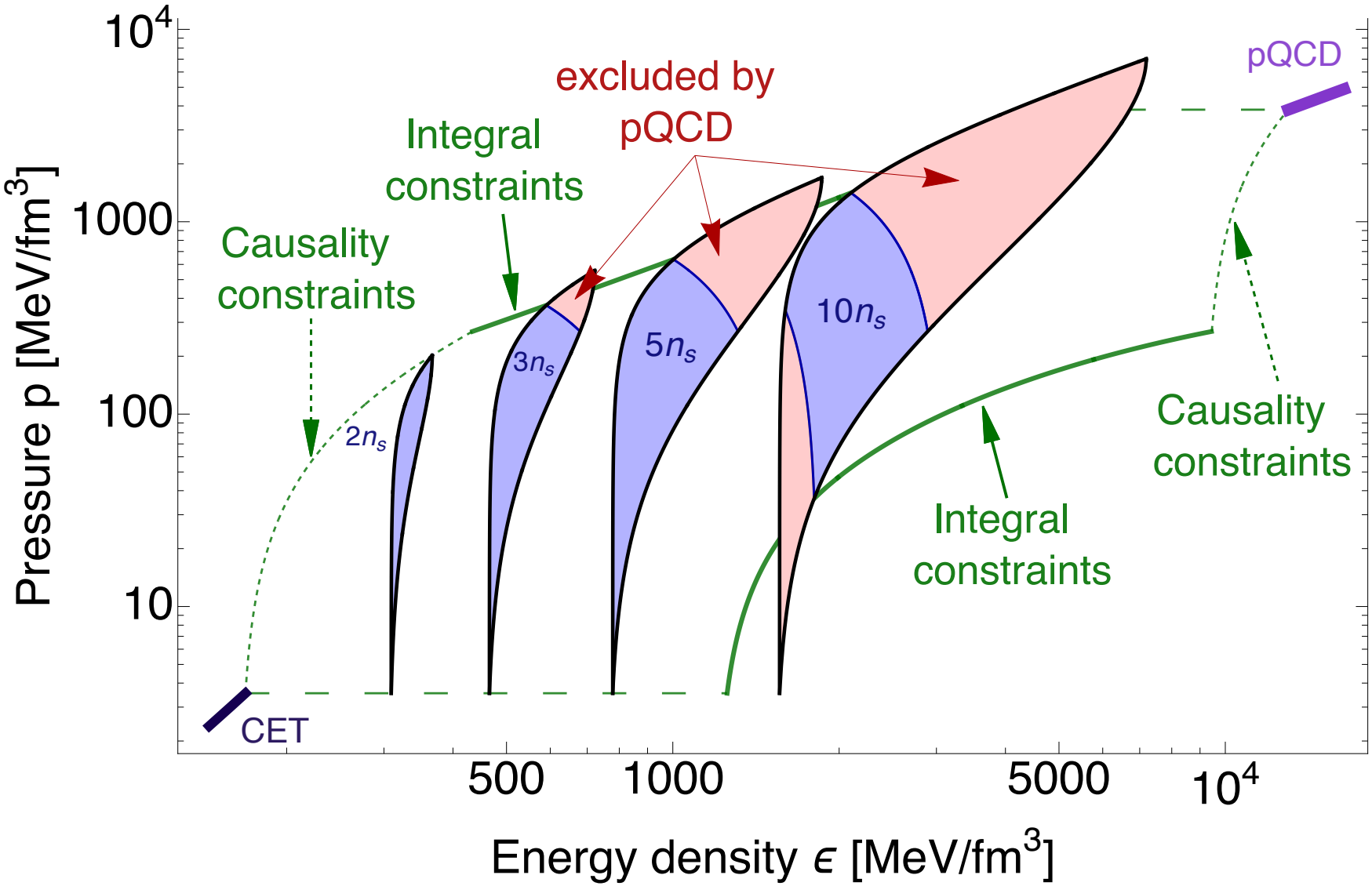
$$c_s^{-2} = \frac{\mu}{n}\frac{\partial n}{\partial \mu} \geq 1 \quad \Rightarrow \quad \partial_\mu n(\mu) \geqslant \frac{n}{\mu}$$

- Consistency

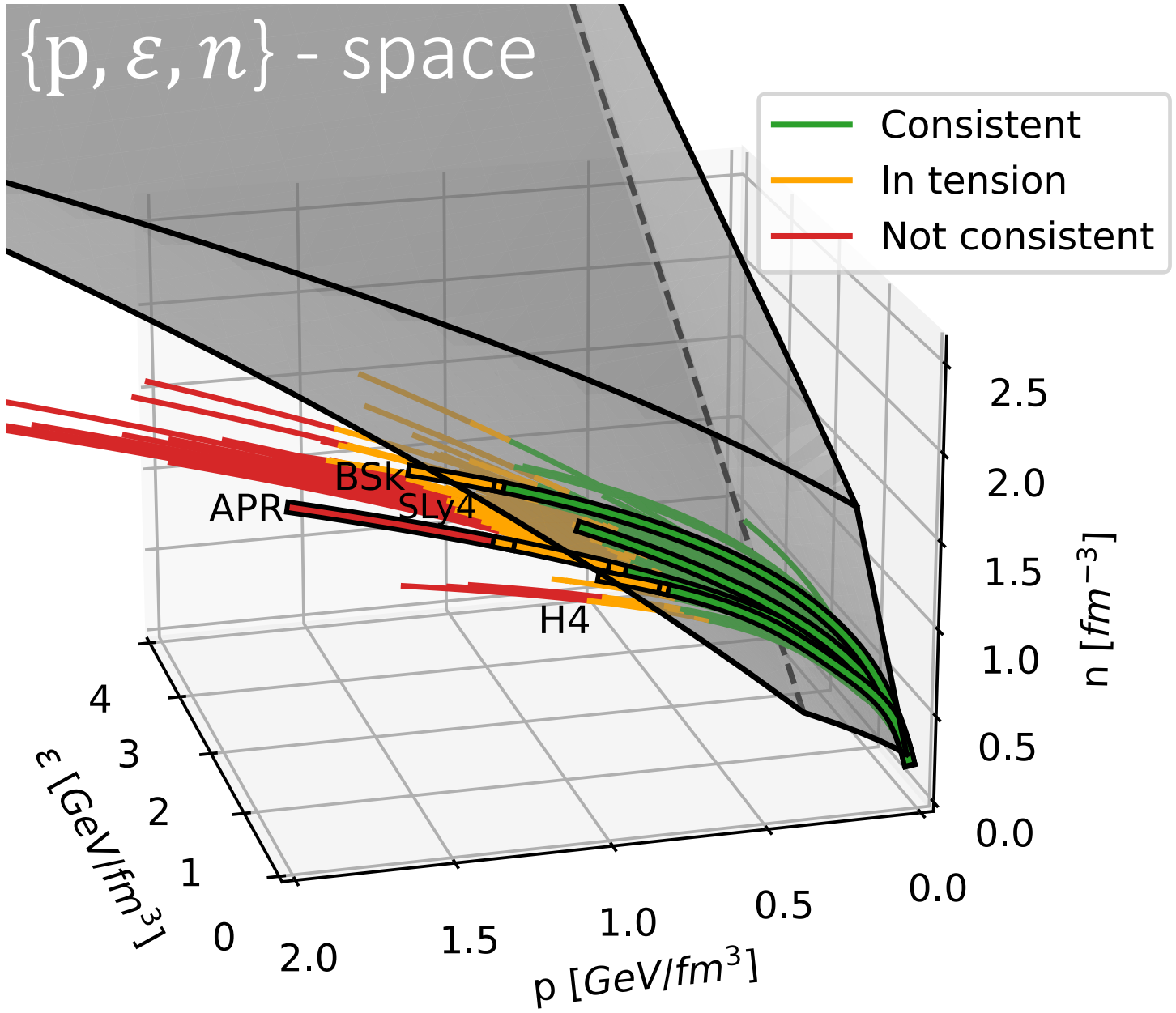
$$\int_{\mu_{CET}}^{\mu_{QCD}} n(\mu)\, d\mu = p_{QCD} - p_{CET} = \Delta p$$



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



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



EoSs from CompOSE database
compose.obspm.fr

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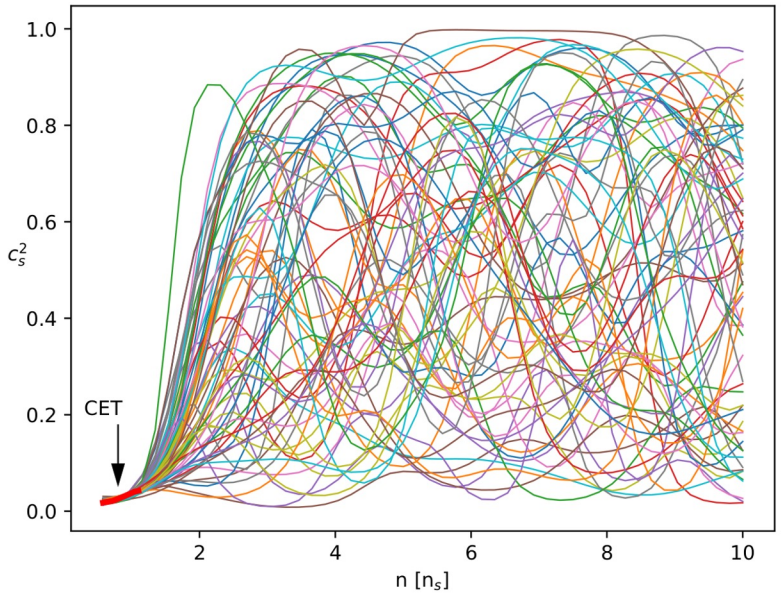
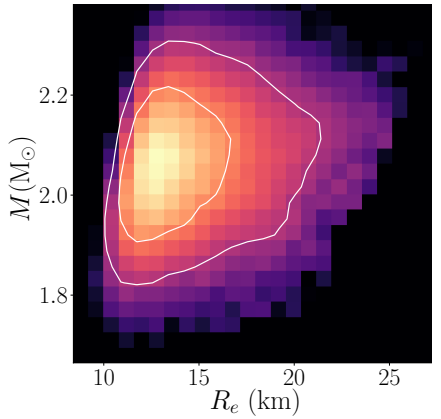
Gaussian-process based inference

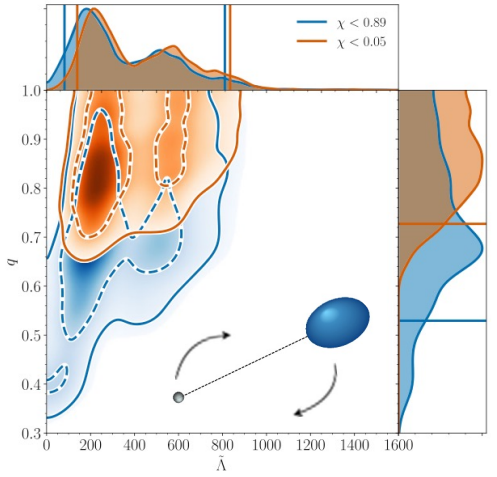


$$P(\mathrm{EoS}\,|\,\mathrm{data}) = \frac{P(\mathrm{EoS})\,P(\mathrm{data}\,|\,\mathrm{EoS})}{P(\mathrm{data})}$$

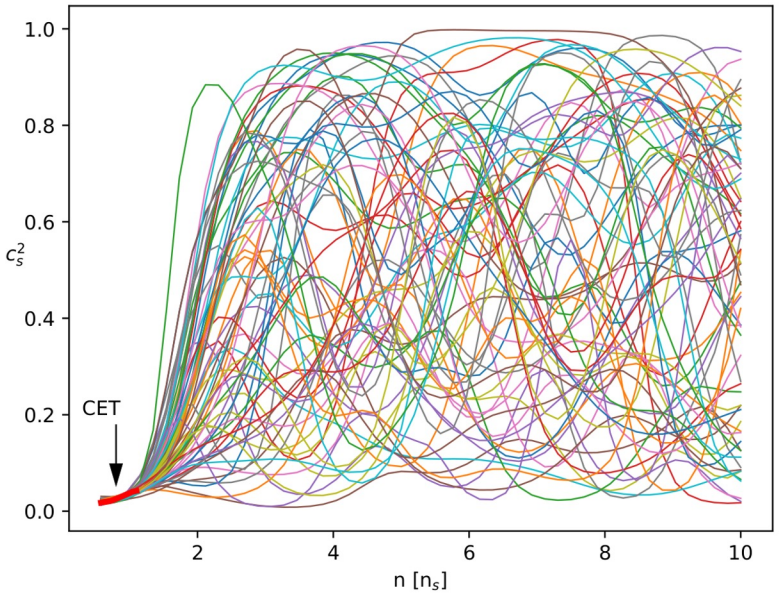
$$P(\mathrm{data}\,|\,\mathrm{EoS}) = P(\mathrm{Mass}\,|\,\mathrm{EoS})\,P(\mathrm{NICER}\,|\,\mathrm{EoS})\,P(\tilde{\Lambda}, \mathrm{BH}\,|\,\mathrm{EoS})$$

$M_{J1614\text{-}2230} = 1.908(16)$
$M_{J048+0432} = 2.01(4)$
$M_{J0740+6620} = 2.14(10)$





Gaussian-process based inference



$$P(\mathrm{EoS}\,|\,\mathrm{data}) = \frac{P(\mathrm{EoS})\,P(\mathrm{data}\,|\,\mathrm{EoS})}{P(\mathrm{data})}$$

pQCD likelihood function

$$P(\mathrm{data}\,|\,\mathrm{EoS}) = P(\mathrm{Mass}\,|\,\mathrm{EoS})\,P(\mathrm{NICER}\,|\,\mathrm{EoS})\,P(\tilde{\Lambda}, \mathrm{BH}\,|\,\mathrm{EoS})\,P(\mathrm{QCD}\,|\,\mathrm{EoS})$$

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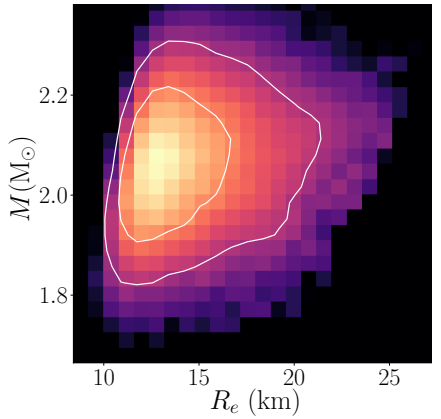
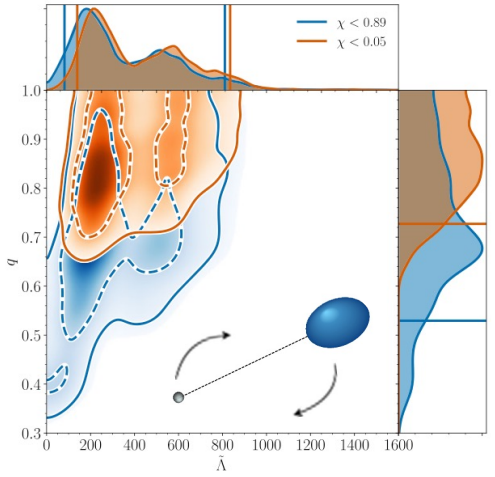
$M_{J048+0432} = 2.01(4)$
$M_{J0740+6620} = 2.14(10)$

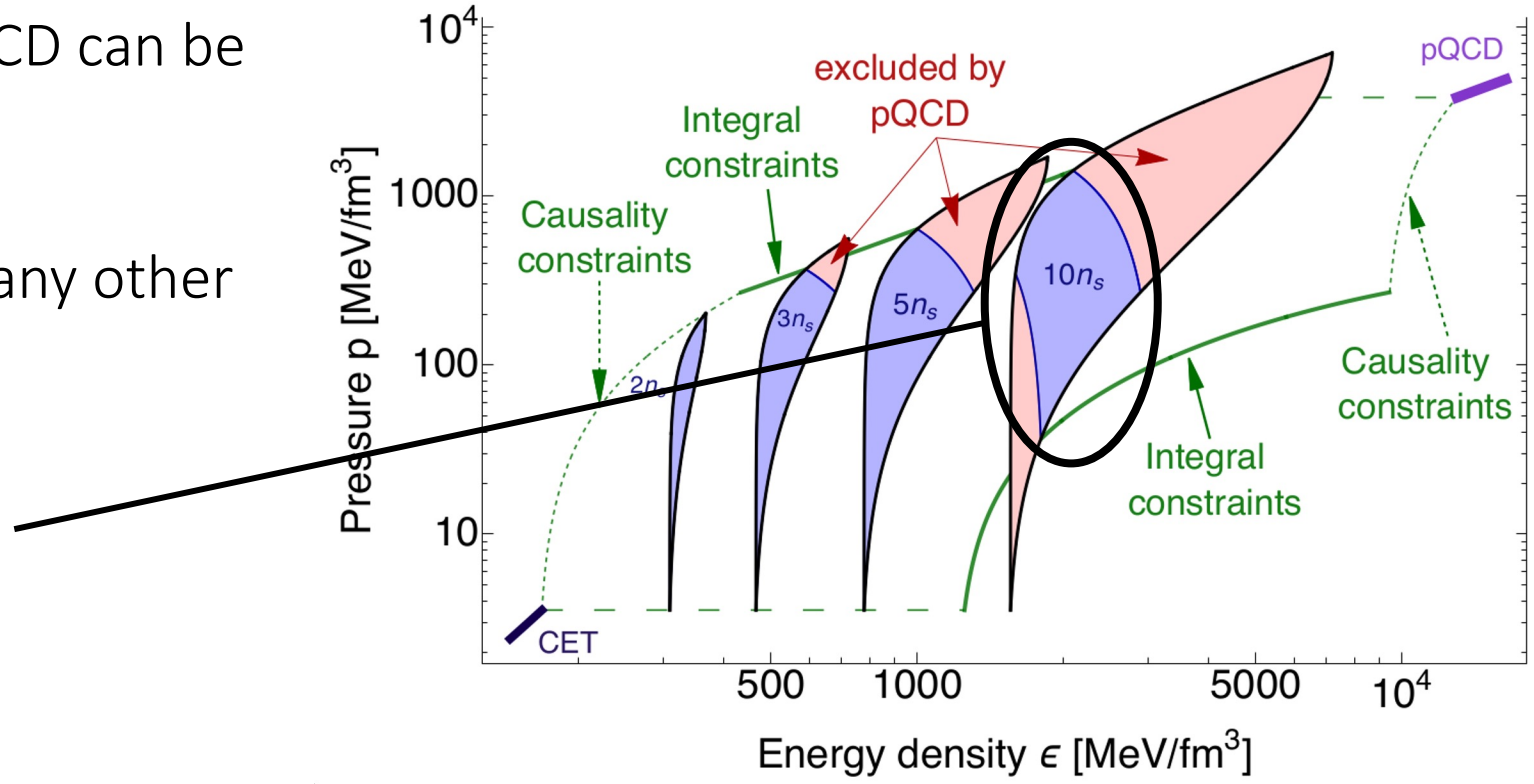




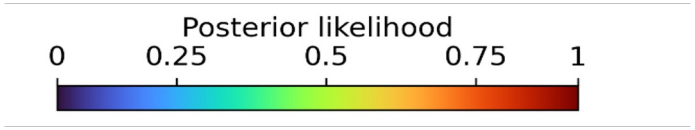
pQCD likelihood function

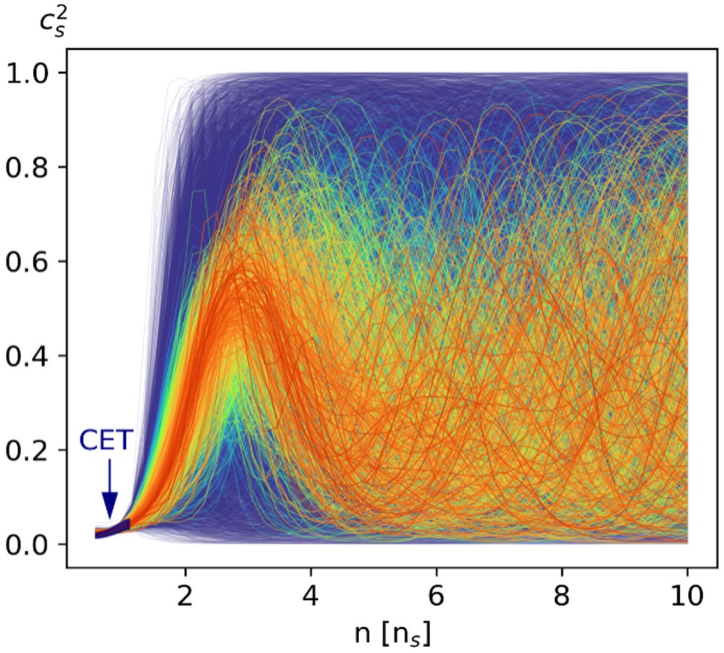
- Inference setup where QCD can be turned on/off
- Easily implmemented to any other extrapolation setup

Use this area to condition an extrapolation

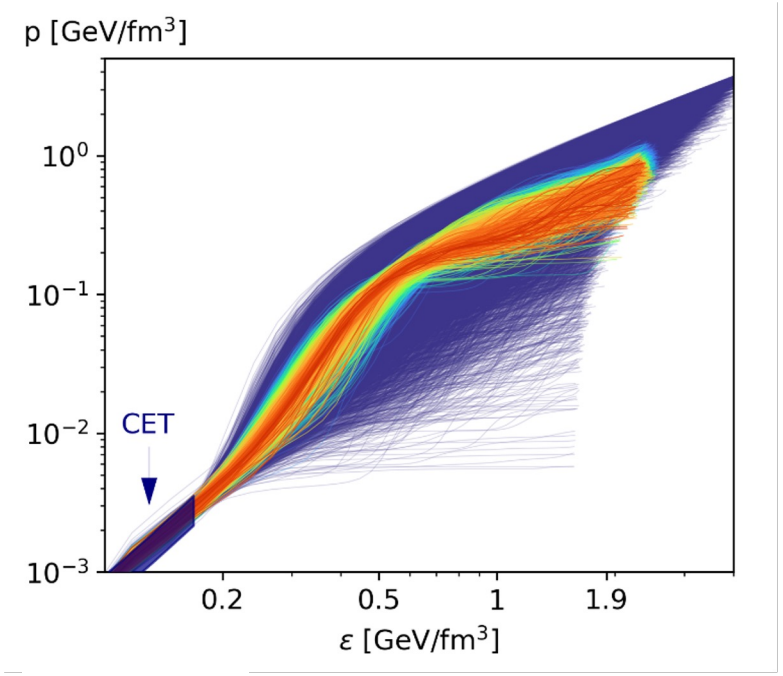


Inferred EoS:

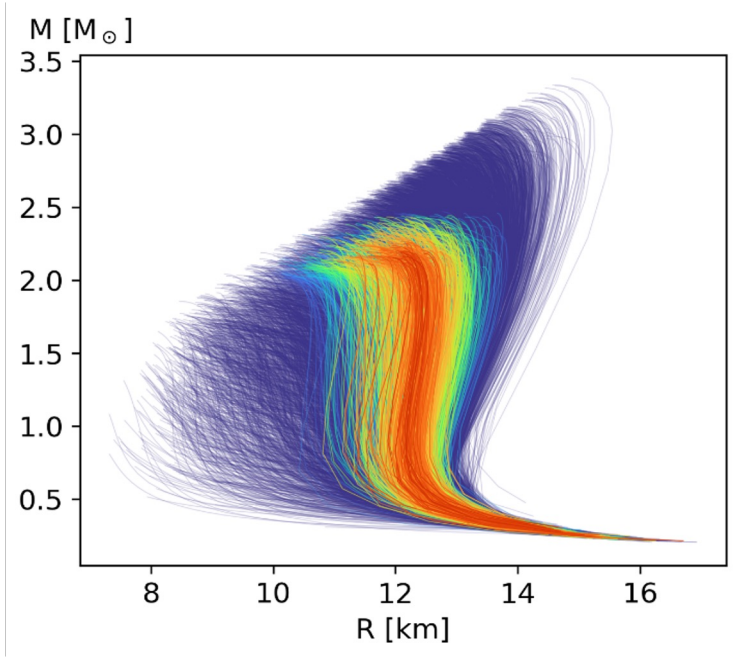




Speed of sound



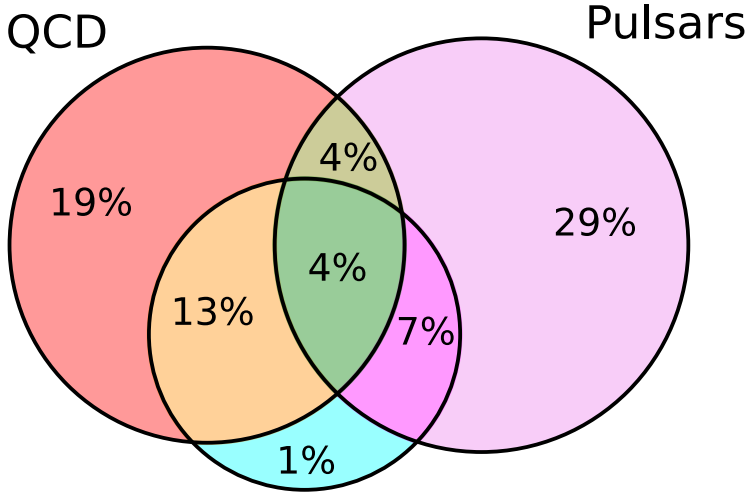
Equation of state

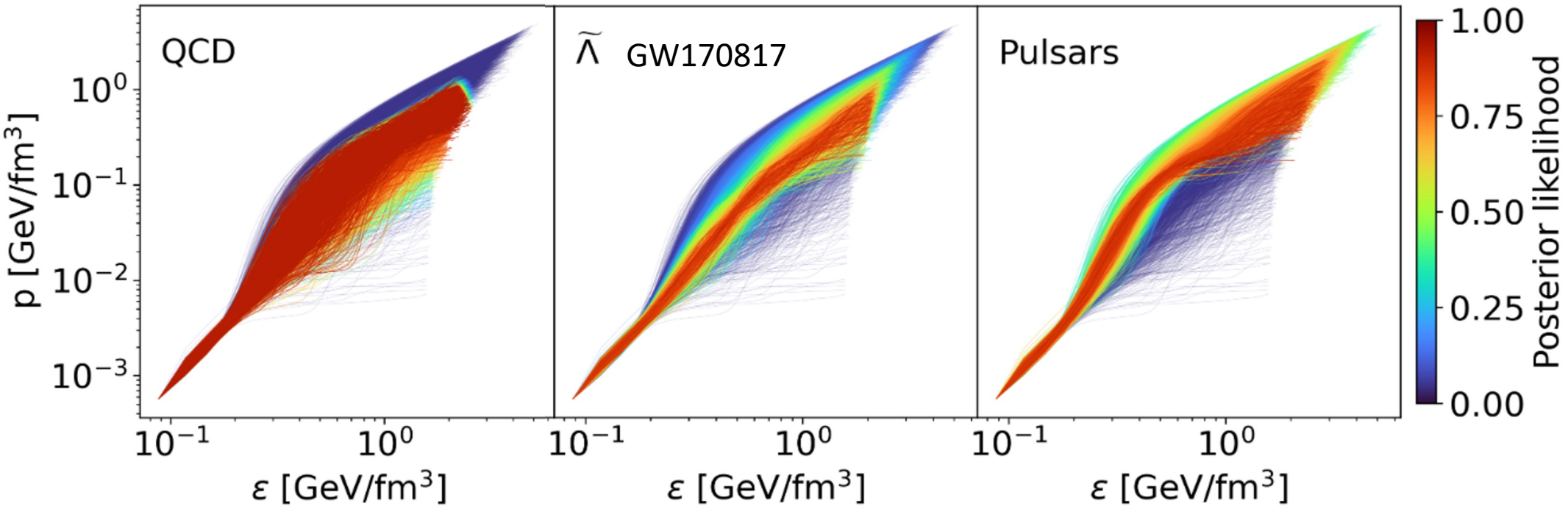


Mass-radius relation

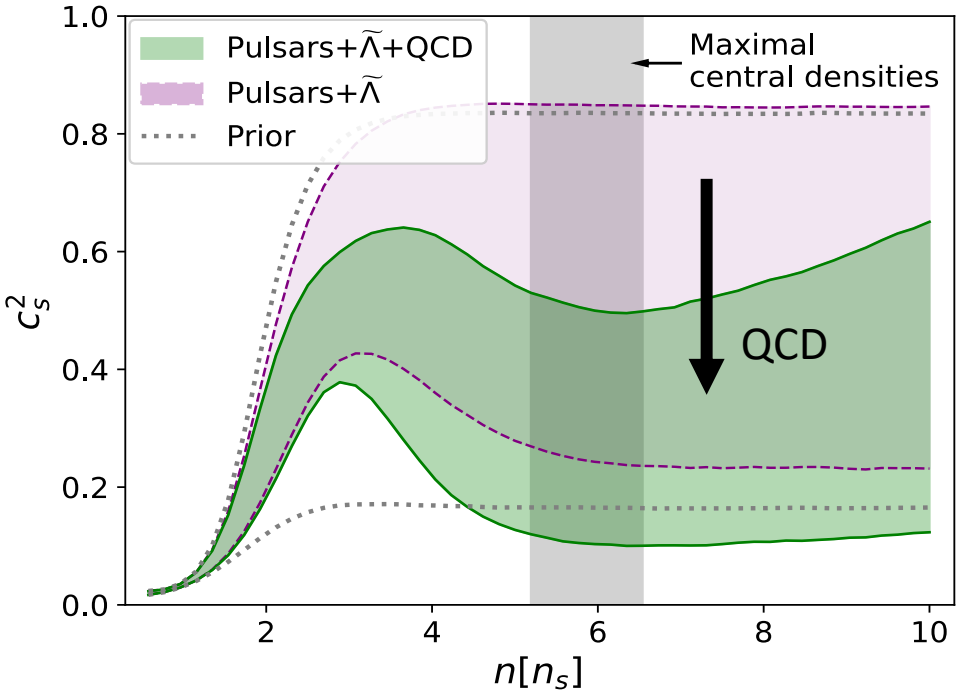
Effect of QCD

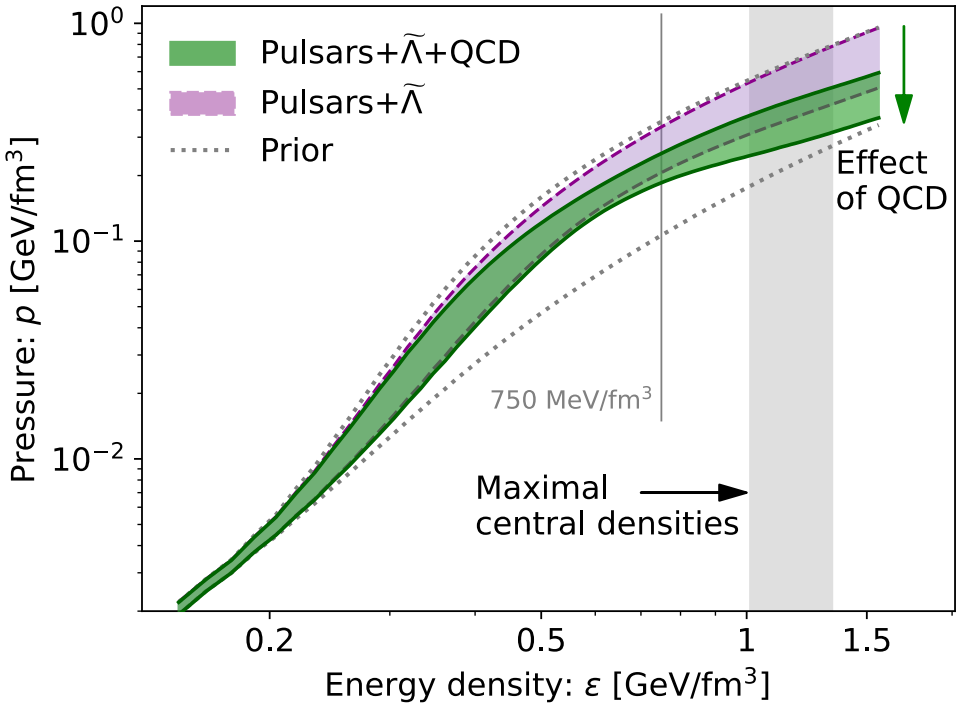
QCD input complements NS observations





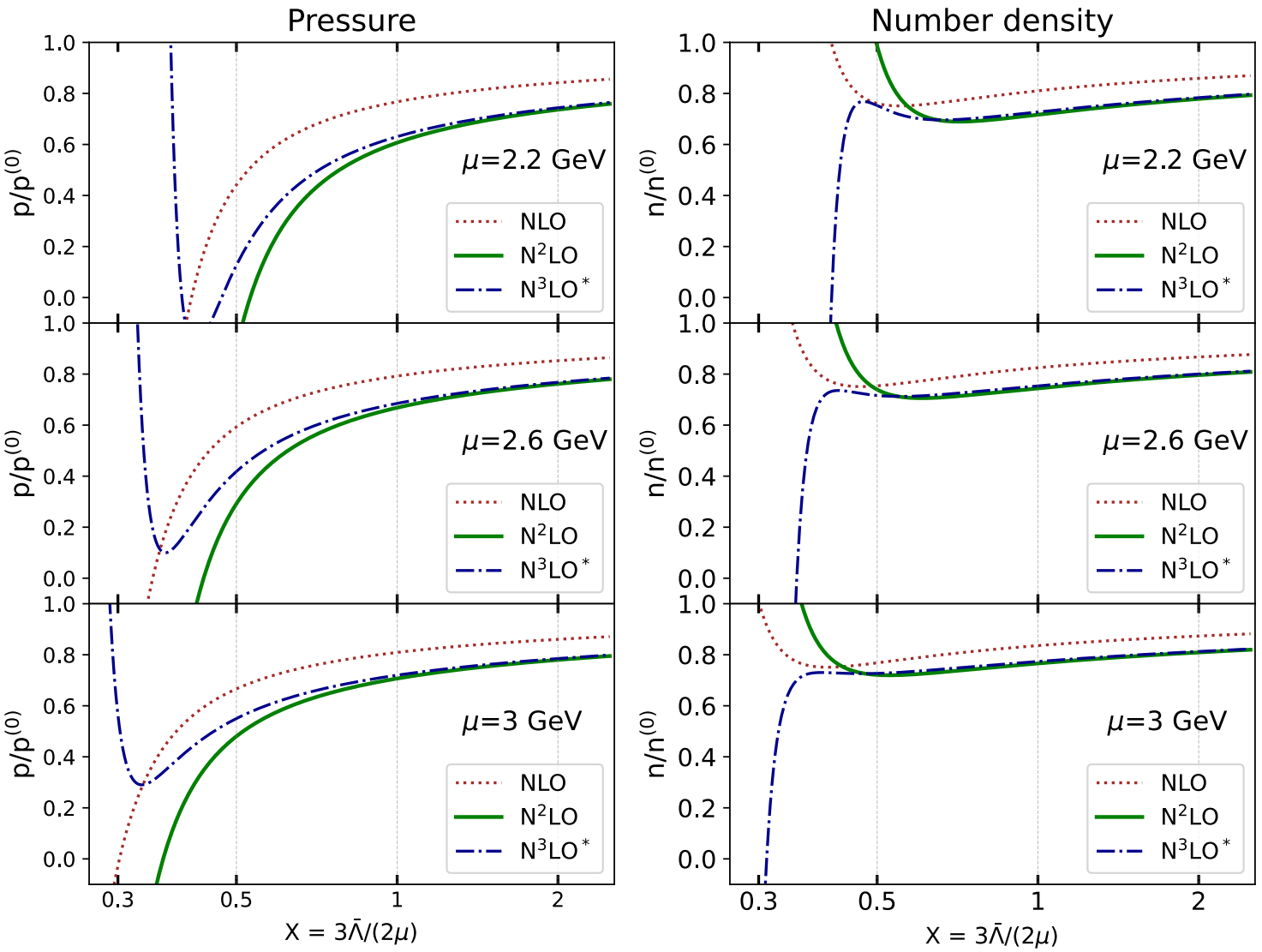
QCD responsible for the softening



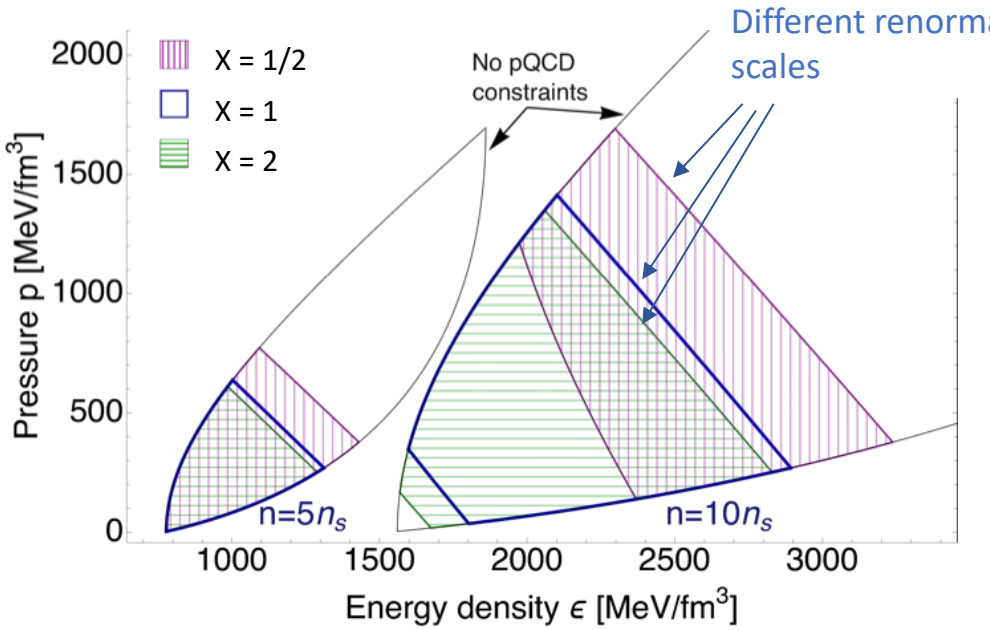


QCD pushes EoS towards conformality, softening at high densities

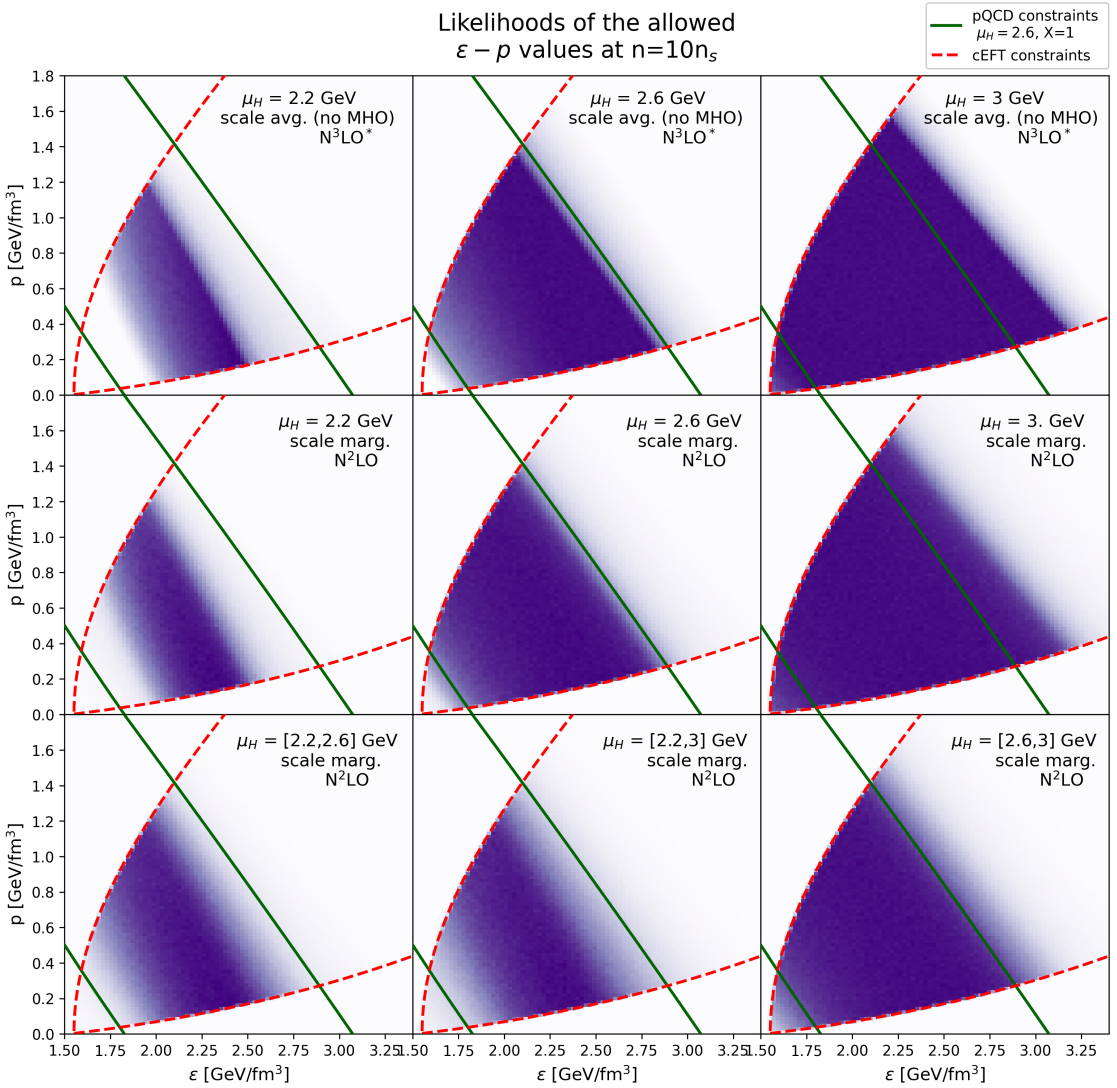
Renormalization scale dependence



Bayesian uncertainty quantification of perturbative QCD



Different Bayesian interpretation



Bayesian uncertainty quantification of perturbative QCD input to the neutron-star equation of state

T.G, O.K., A.K., Aleksas Mazeliauskas, JHEP 06 (2023) 002

- **Why** does QCD at $40n_s$ constrain the EoS at NS densities

  How pQCD constrains the equation of state at neutron star densities

  OK & Kurkela, PRL128 (2022) 20, 2111.05350

- **How** QCD affects EoS infrerence

  Ab-initio QCD Calculations Impact the Inference of the Neutron-star-matter Equation of State

  Tyler Gorda, O.K., Aleksi Kurkela, Astrophys.J. 950 (2023) 2, 107

  Bayesian uncertainty quantification of perturbative QCD input to the neutron-star equation of state

  T.G, O.K., A.K., Aleksas Mazeliauskas, JHEP 06 (2023) 002

- **Quark Matter** cores

  Strongly interacting matter exhibits deconfined behavior in massive neutron stars

  Eemeli Annala, T.G., Joonas Hirvonen, O.K.,A.K., arXiv:2303.11356

Studies with pQCD see softening of EoS

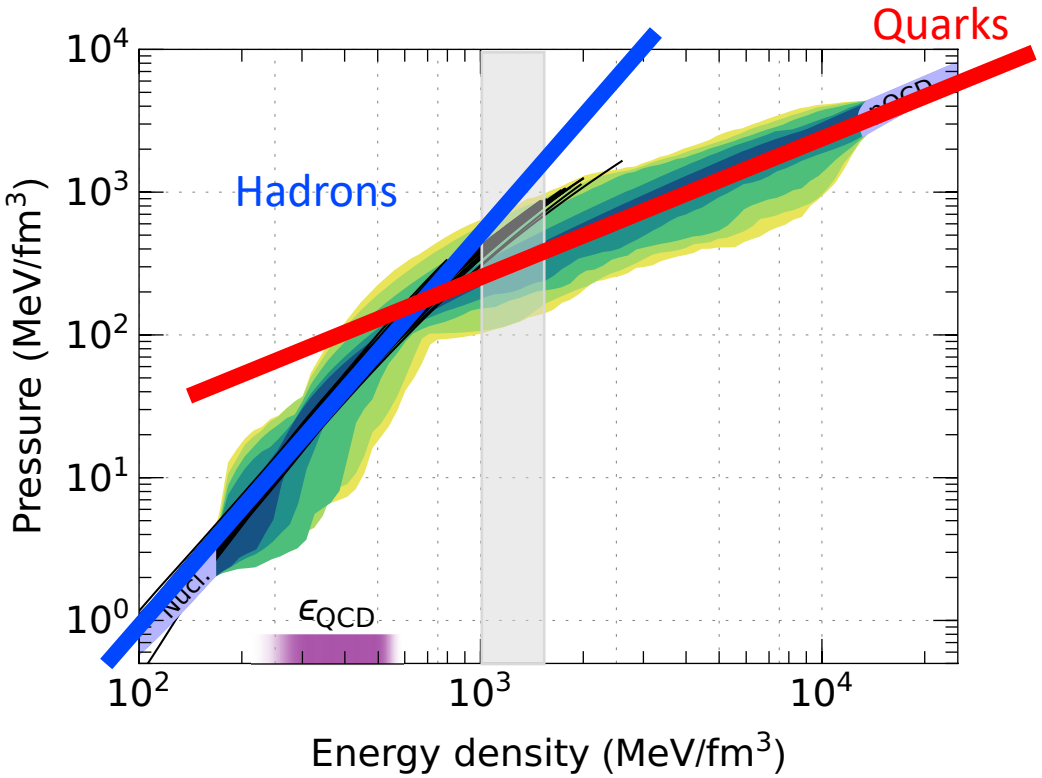
Properties of the EoS reflect the phase structure of the matter.

The cores of most massive NSs consistent with deconfined, nearly conformal Quark Matter.

Softening

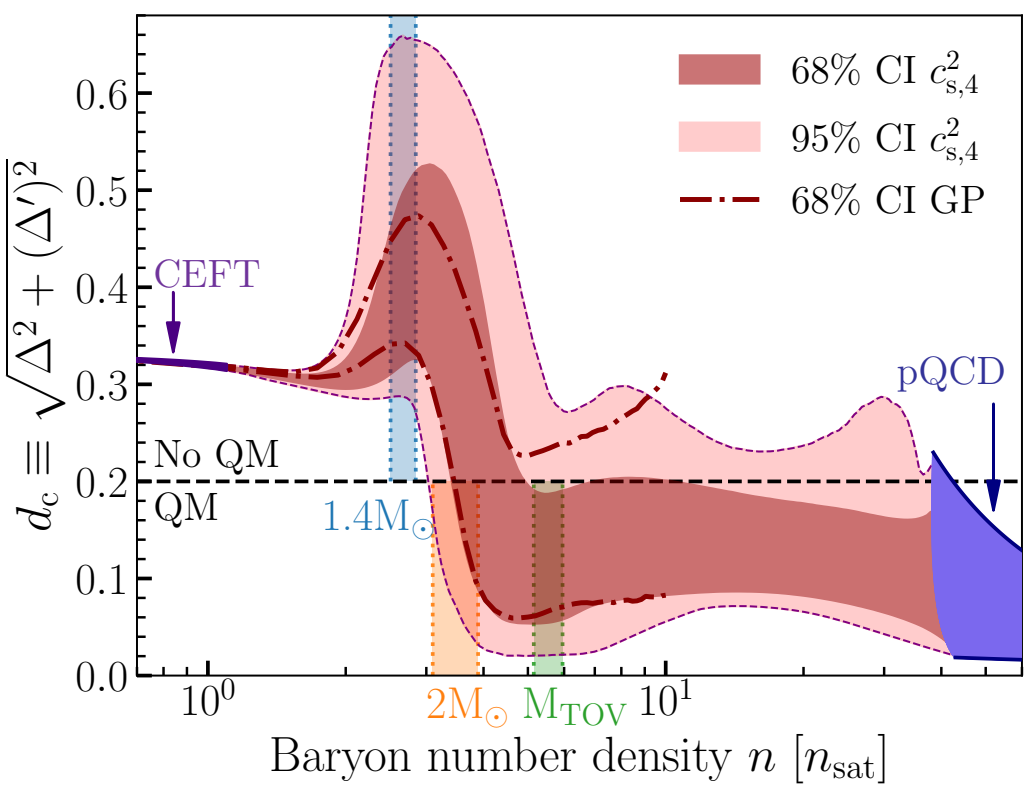
=

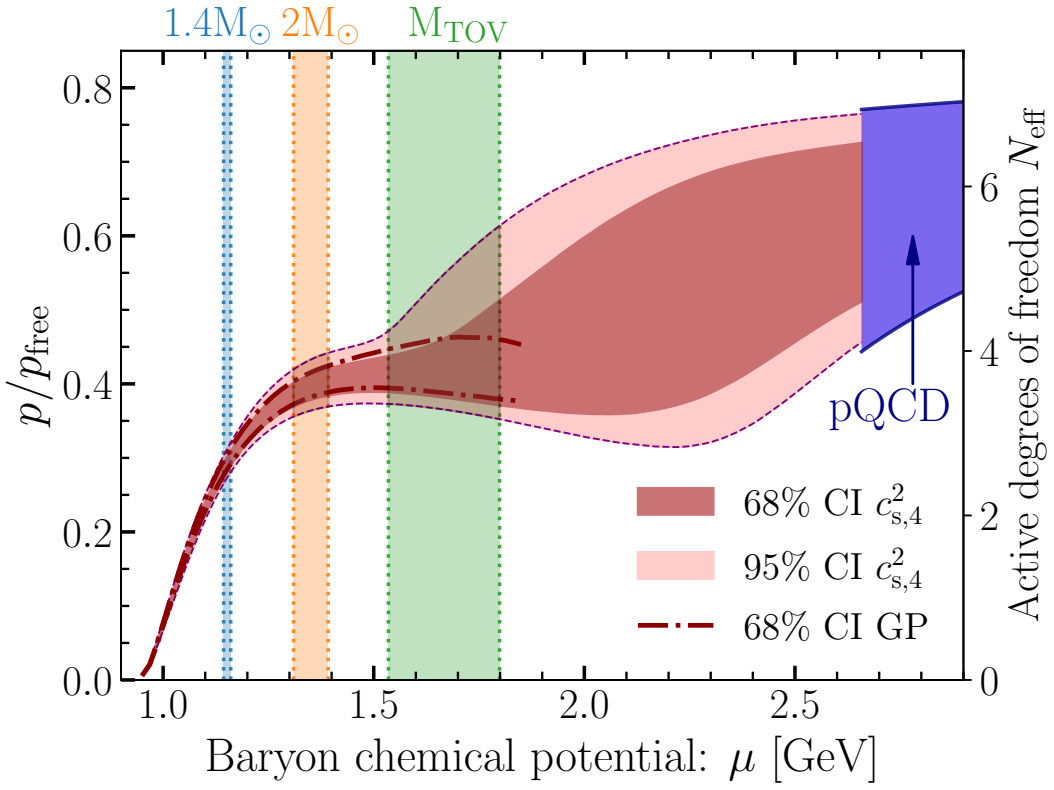
Conformalization



Annala, Gorda, Kurkela, Nätttilä, Vuorinen Nature Physics 16 (2020) 9
Also: Fujimoto, Fukushima, McLerran, Praszalowicz 2207.06753,
Kojo PRD 104, …

Quark Matter in the cores of neutron stars

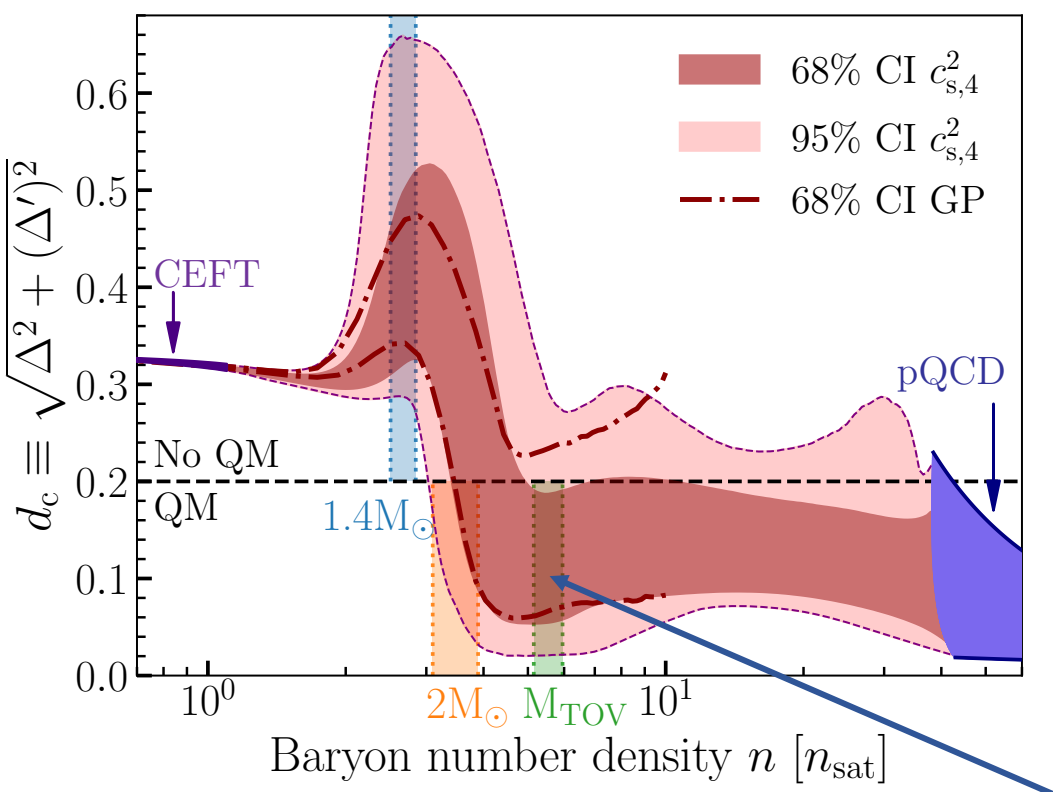


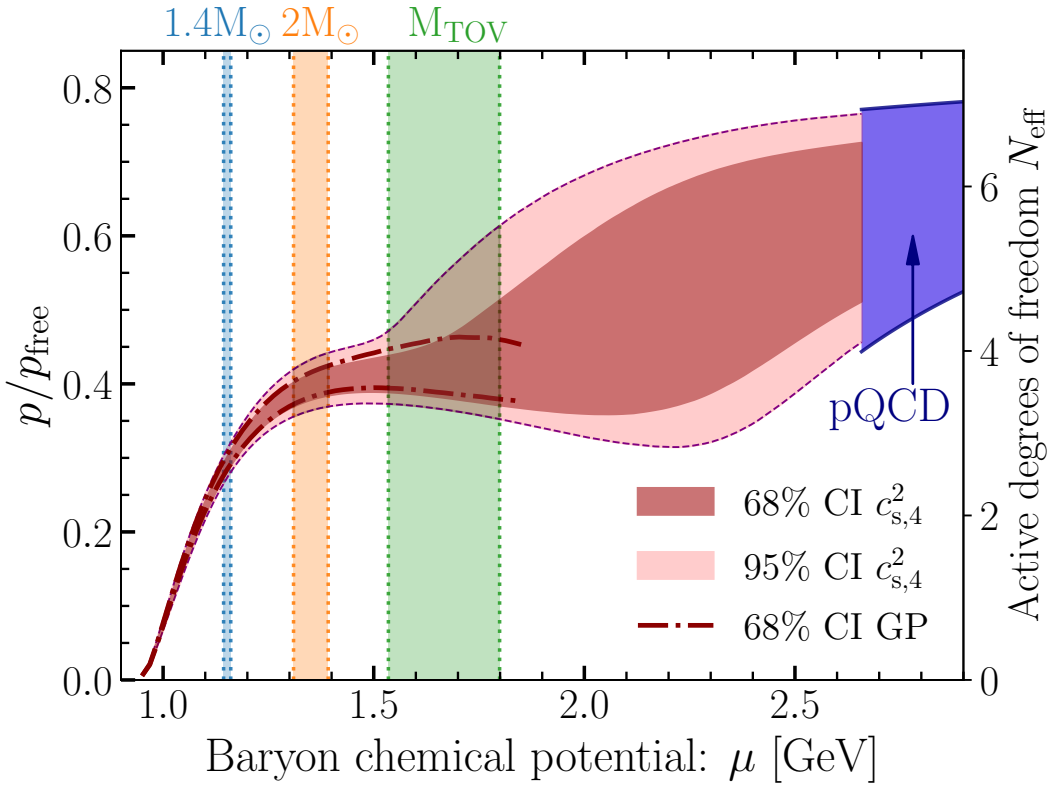


$$\Delta \equiv \frac{1}{3} - \frac{p}{\epsilon} = \frac{1}{3} - \frac{c_s^2}{\gamma},$$

$$\Delta' \equiv \frac{d\Delta}{d\log\epsilon} = c_s^2\left(\frac{1}{\gamma} - 1\right)$$

Quark Matter in the cores of neutron stars





$$\Delta \equiv \frac{1}{3} - \frac{p}{\epsilon} = \frac{1}{3} - \frac{c_s^2}{\gamma},$$

$$\Delta' \equiv \frac{d\Delta}{d\log\epsilon} = c_s^2\left(\frac{1}{\gamma} - 1\right)$$

Conformal symmetry restoration with 88% credence

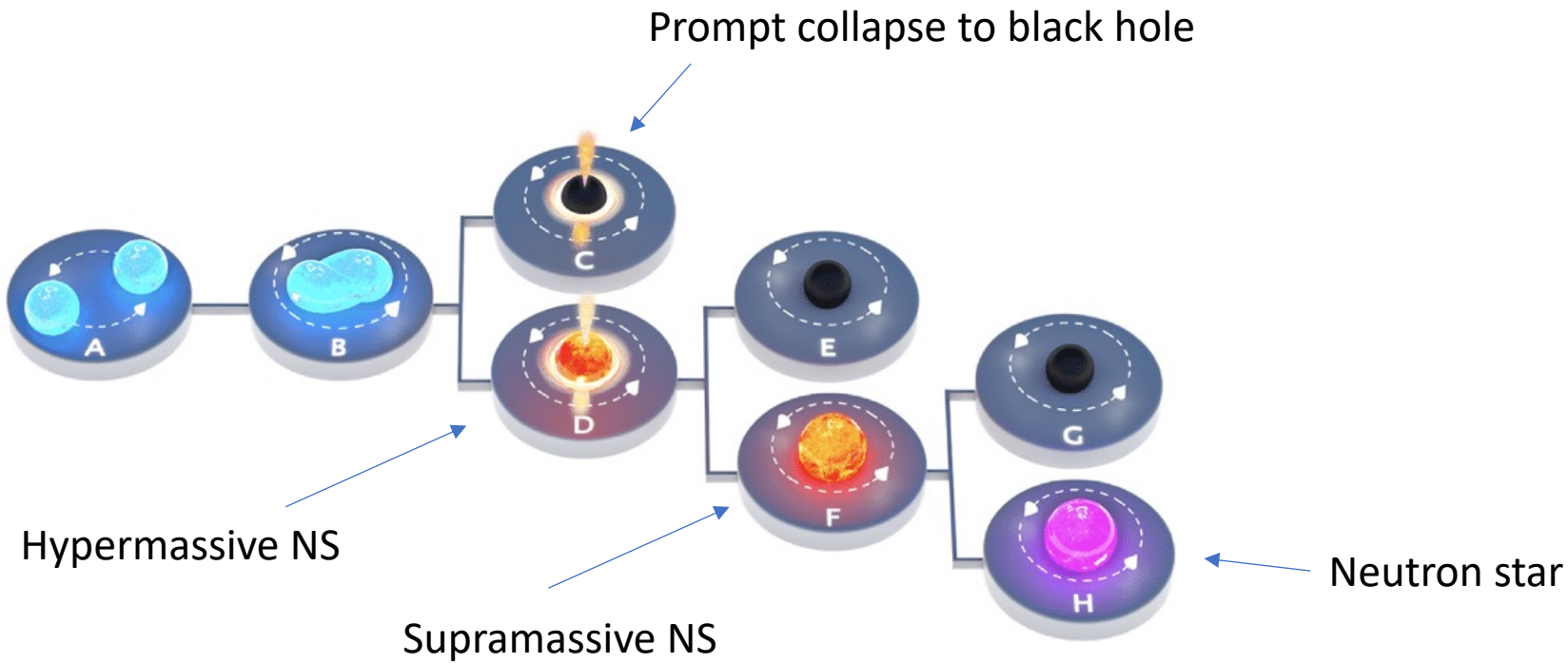
Conclusion

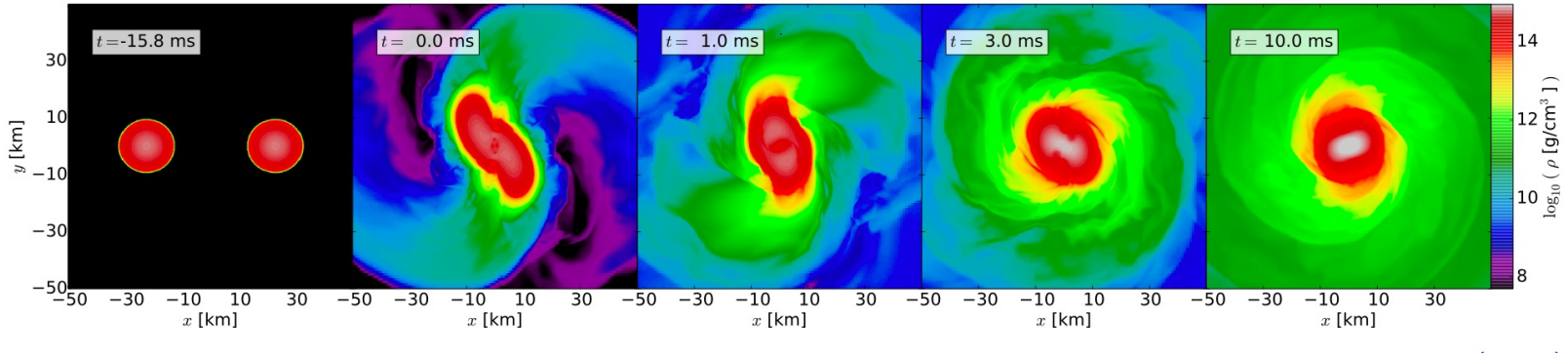
QCD at high densities offers significant and nontrivial information about the **EoS** at NS densities

- We find that strongly interacting matter exhibits deconfined behavior in massive neutron stars
- We provide a Python script to impose pQCD constraints at any density github.com/OKomoltsev/QCD-likelihood-function
- pQCD predicts that (most) binary merger producs are BHs

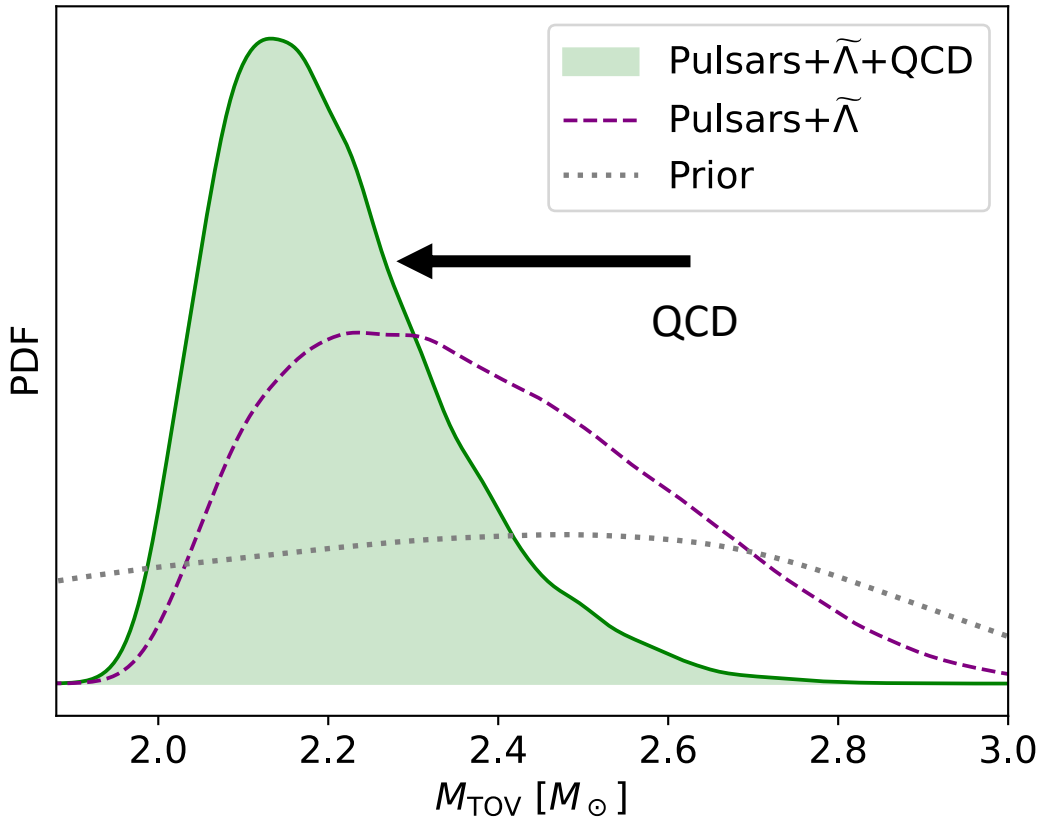
Supplemental material
Can the softening be observationally verified?

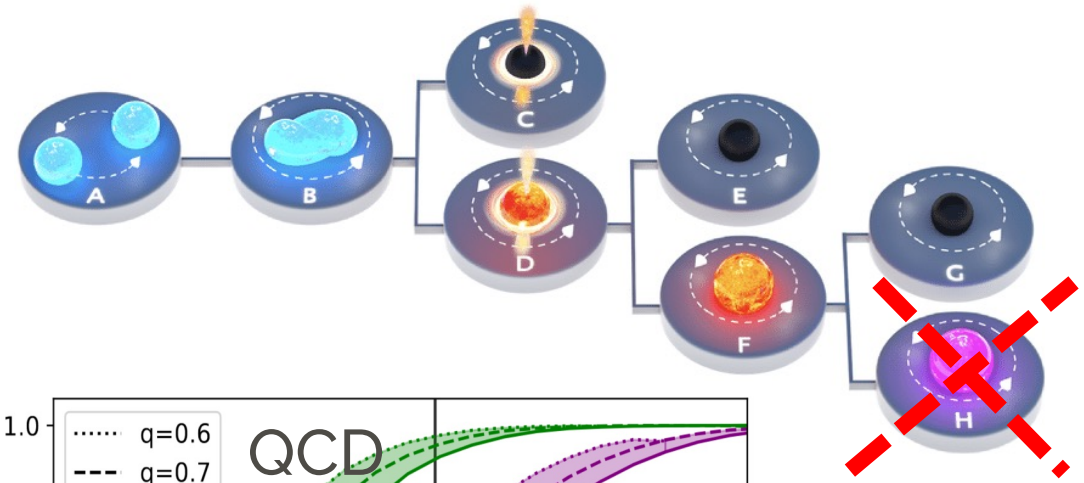
Different binary merger products:

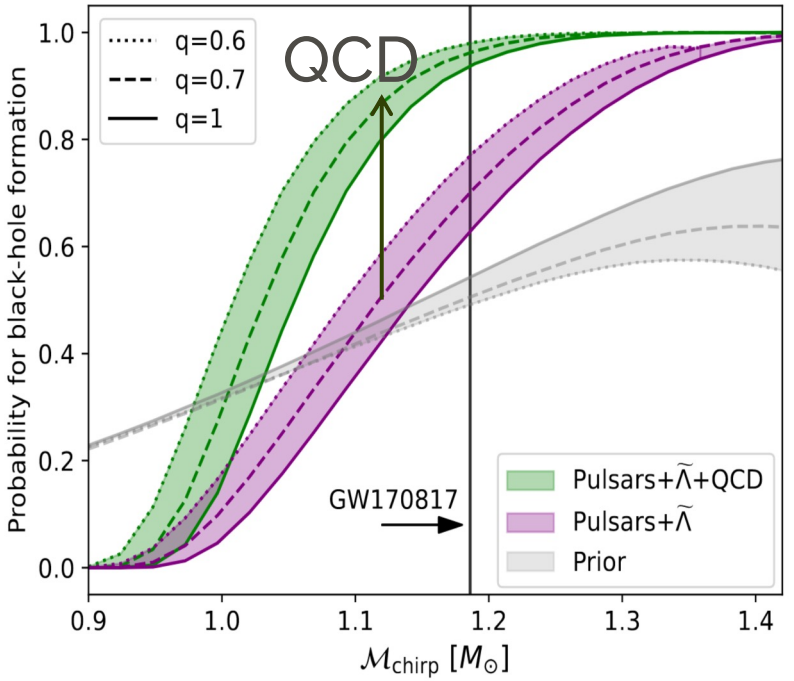




Effect of QCD:



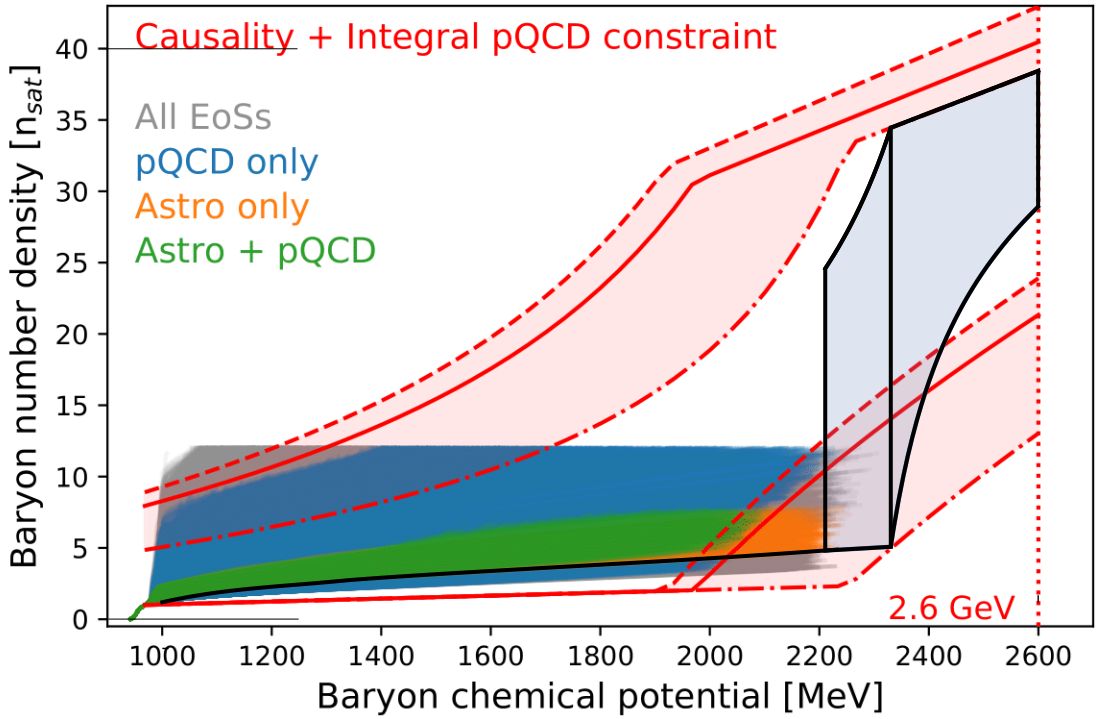




Gravitational waves from binary NS mergers

Fujimoto, Fukushima, Hotokezaka, Kyutoku 2205.03882 (2022)

Comparison with recent work



1. PT at n_{TOV} of $\Delta n = 20 n_s$ $(\Delta n/n = 4)$

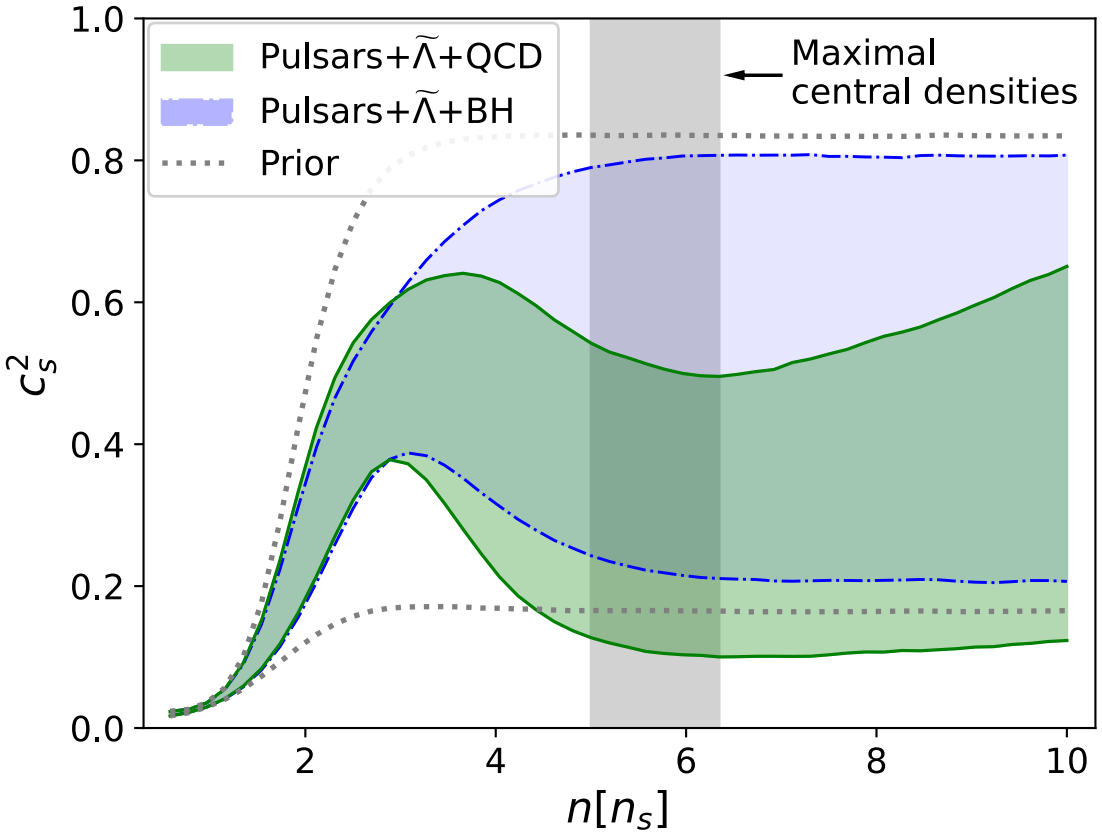
2. PT at $n_{\mathrm{TOV}} + 0.2 n_s$ of $\Delta n = 30 n_s$ $(\Delta n/n = 6)$

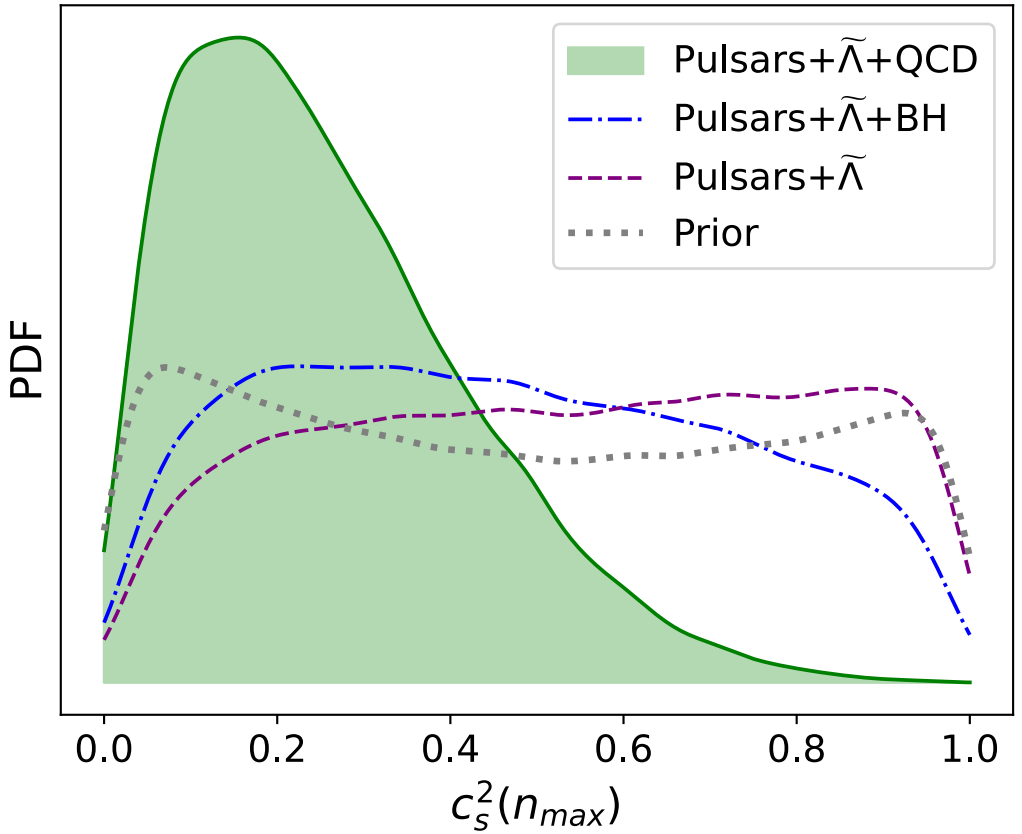
Somasundaram, Tews, Margueron (2204.14038) perform conservative analysis with QCD input:

- **Results broadly consistent with us**
- No Bayesian treatment of inputs
- Apply QCD input at $n = n_{TOV}$ instead of $n = 10 n_s$
- Constraints for most X – only for small range at X = 1-1.3 not constraining
- These EOSs with X ≈ 1 need very specific behaviour beyond nTOV to reach pQCD

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

The impact of the QCD input on the EoS





The softening is a robust prediction