Percolation and conformal limits in neutron stars

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Quark Matter in Neutron Stars?

Solid Constraints

- Low density: χEFT $(n \lesssim 1.1 n_0)$ Tews et al, 2013
- High density pQCD $(n \gtrsim 40 n_0)$ Gorda et al, 2018

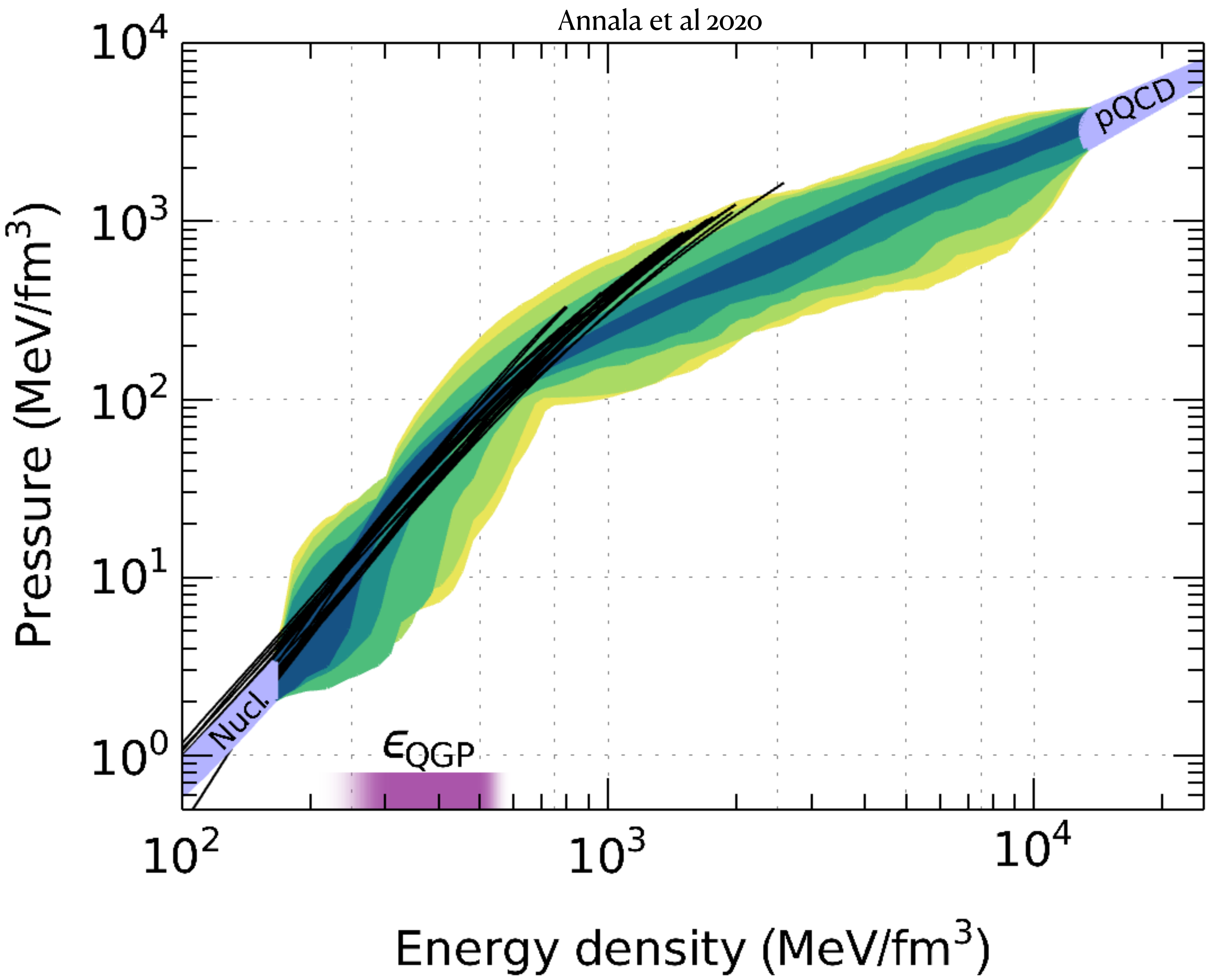
Interpolation methods

- Polytropes, CSS, Linear Speed of Sound

eg. Annala et al, 2018, 2020; Alford et al 2013, 2017, Li et al 2021

Deconfinement by polytropic index

$$\gamma = \frac{d \log p}{d \log \epsilon} \rightarrow \begin{cases} \gamma > 1.75 \rightarrow \text{Hadrons} \\ \gamma < 1.75 \rightarrow \text{Quarks} \end{cases}$$



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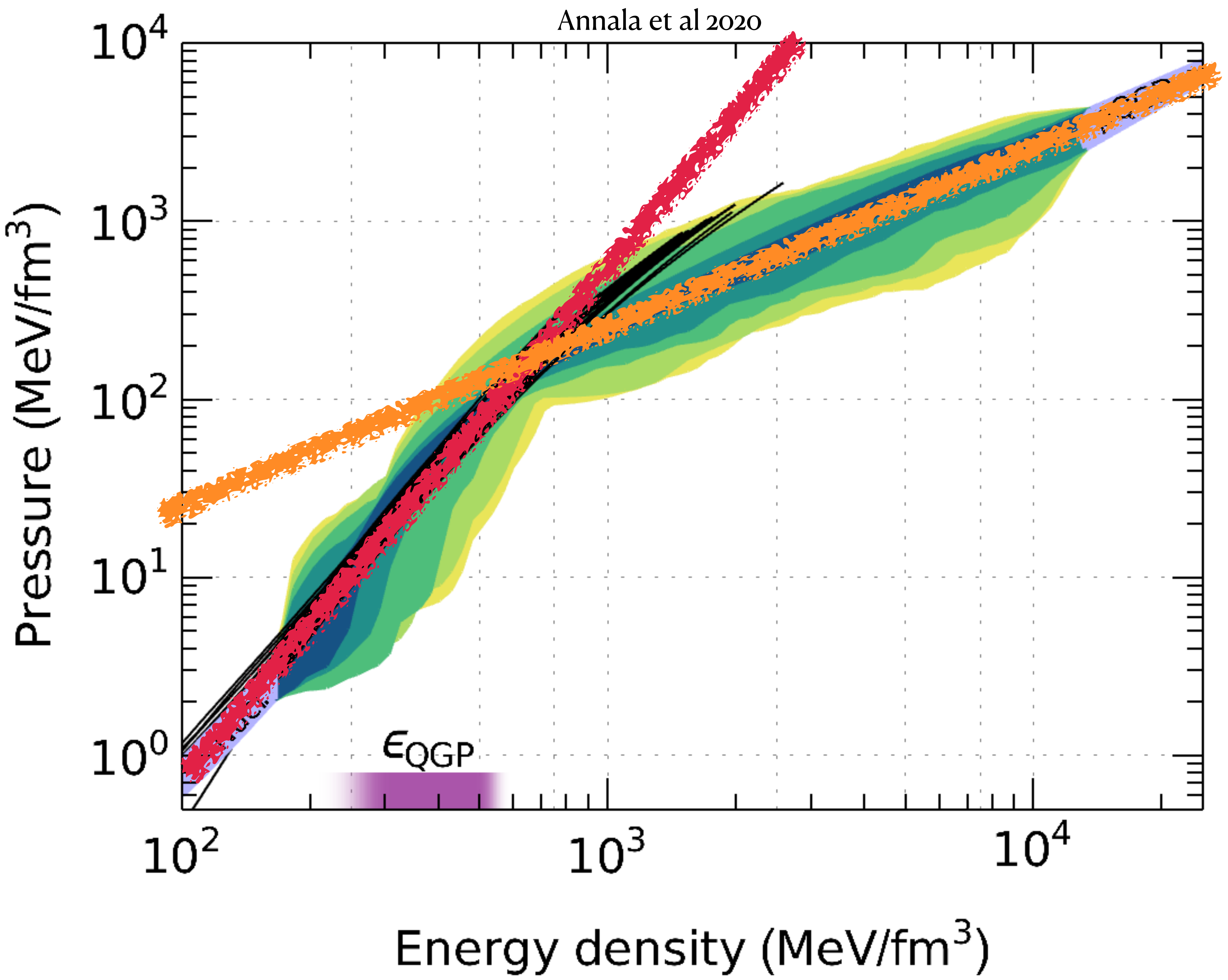


Methodology: Piecewise-linear speed of sound

Annala et al 2020

$$c_s^2 = \frac{n}{\mu}\frac{d\mu}{dn} \qquad c_{s,i}^2 = \frac{(\mu_i - \mu)c_{s,i}^2 + (\mu - \mu_i)c_{s,i+1}^2}{\mu_{i+1} - \mu_i}$$

+

χEFT + pQCD

+

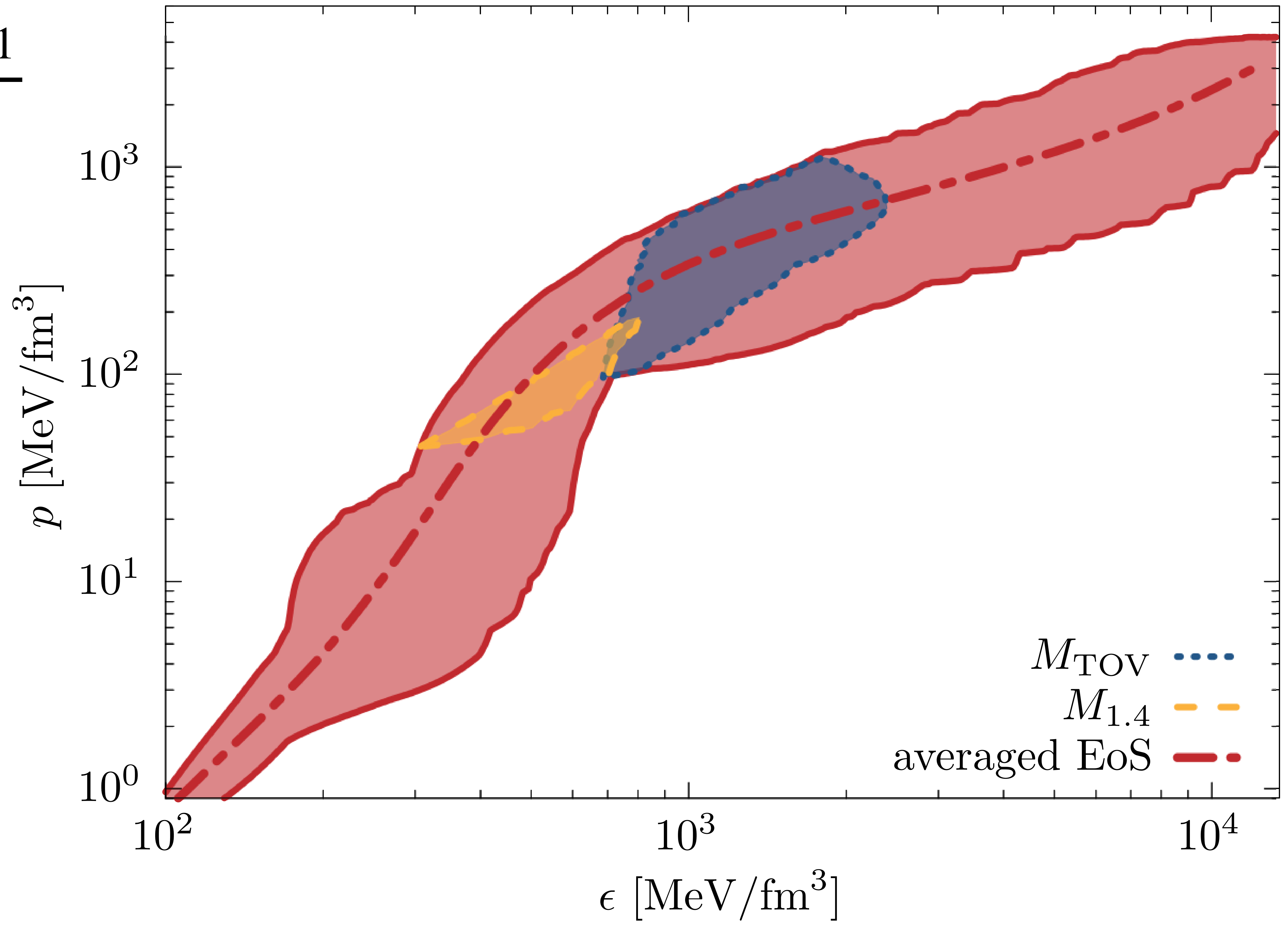
Mass measurement of J0740+6620

$M_{\rm TOV} \geq (2.08 \pm 0.07)\ M_\odot$ Fonseca et al 2021

+

Tidal Deformability from GW170817

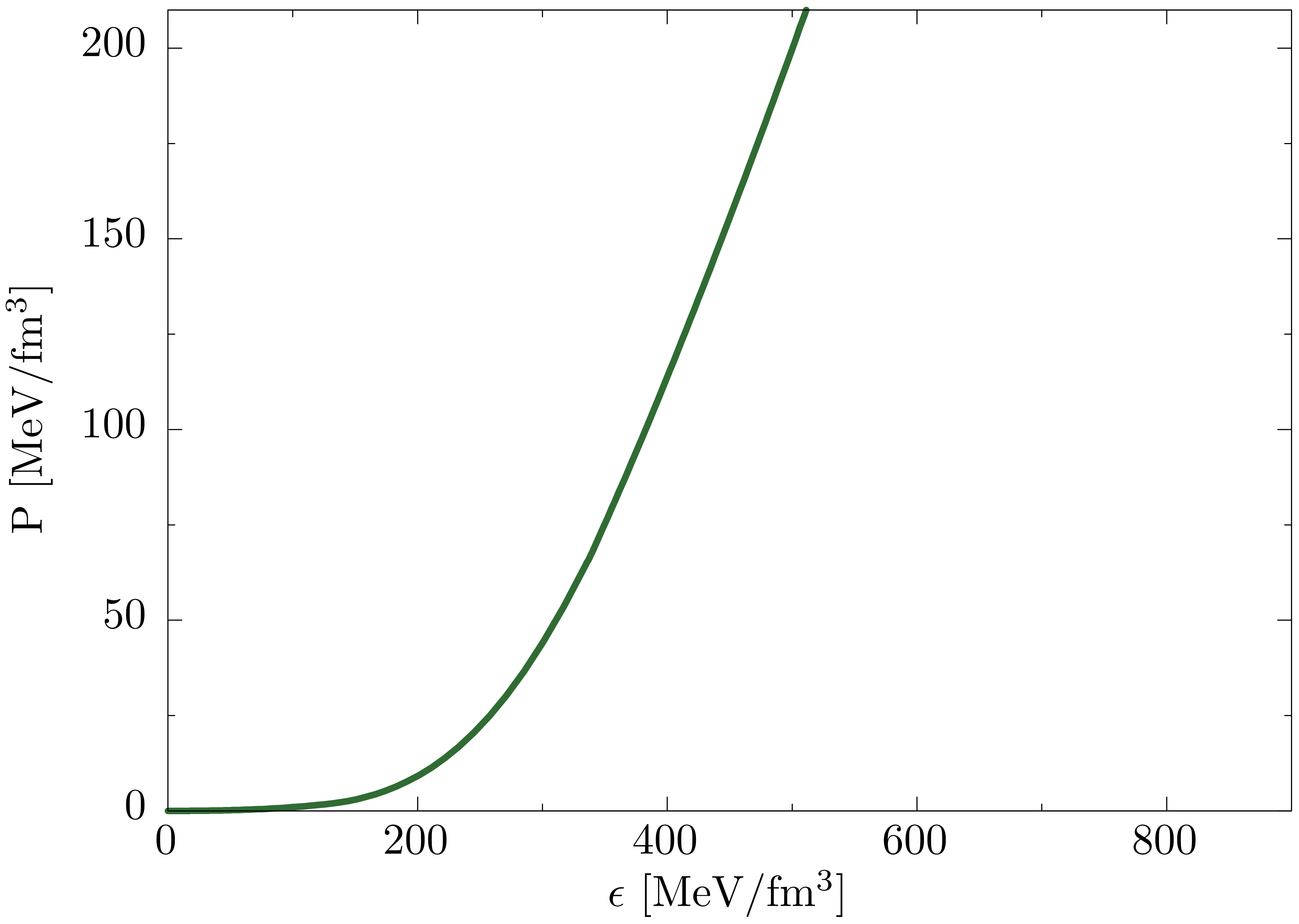
$\Lambda_{1.4 M_\odot} = 190^{+380}_{-120}$ Abbott et al 2018

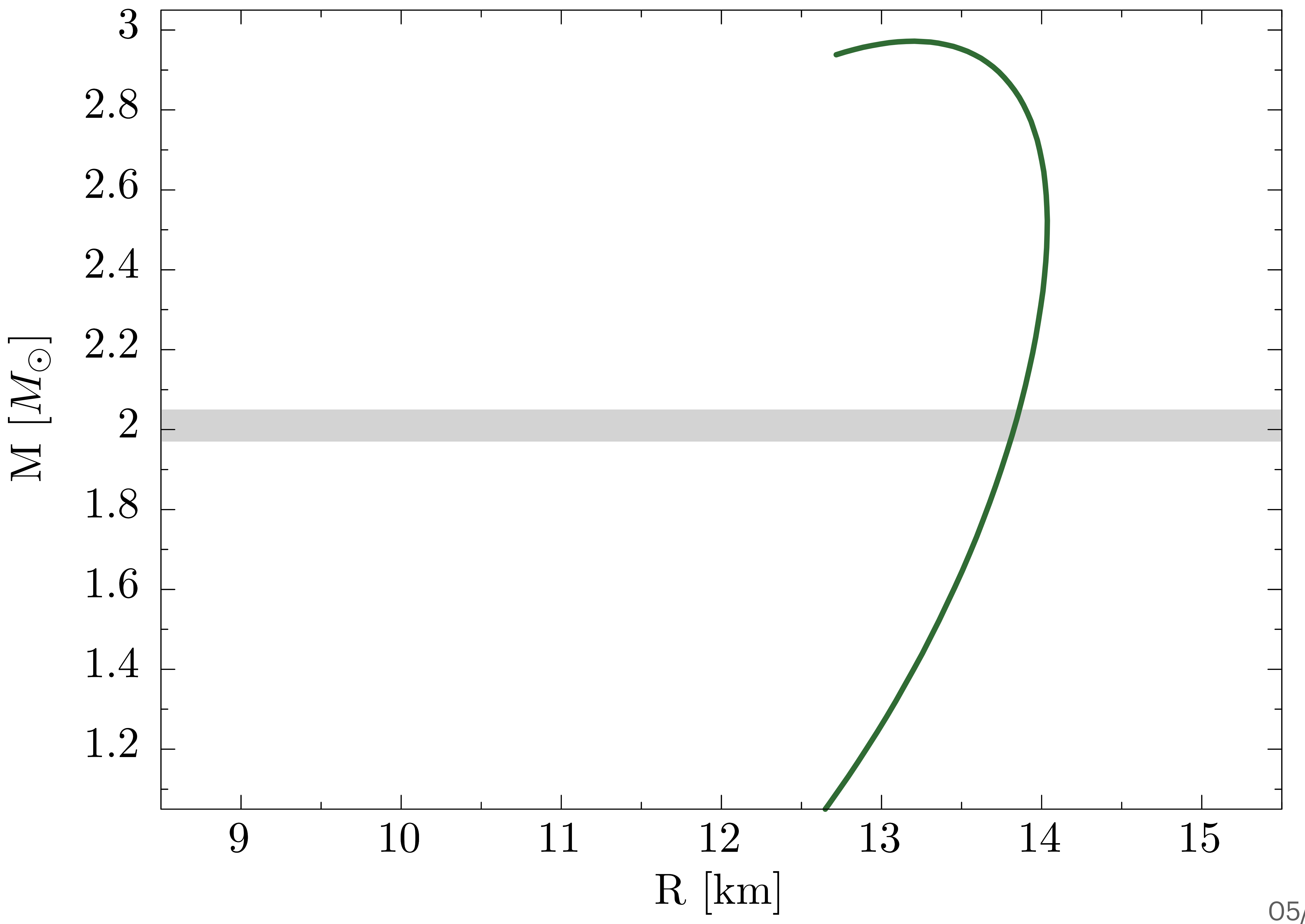


5×10^5 viable Equations of State

Neutron Star Structure

$P(\epsilon)$ ⟷ TOV Equations ⟷ $M(R)$





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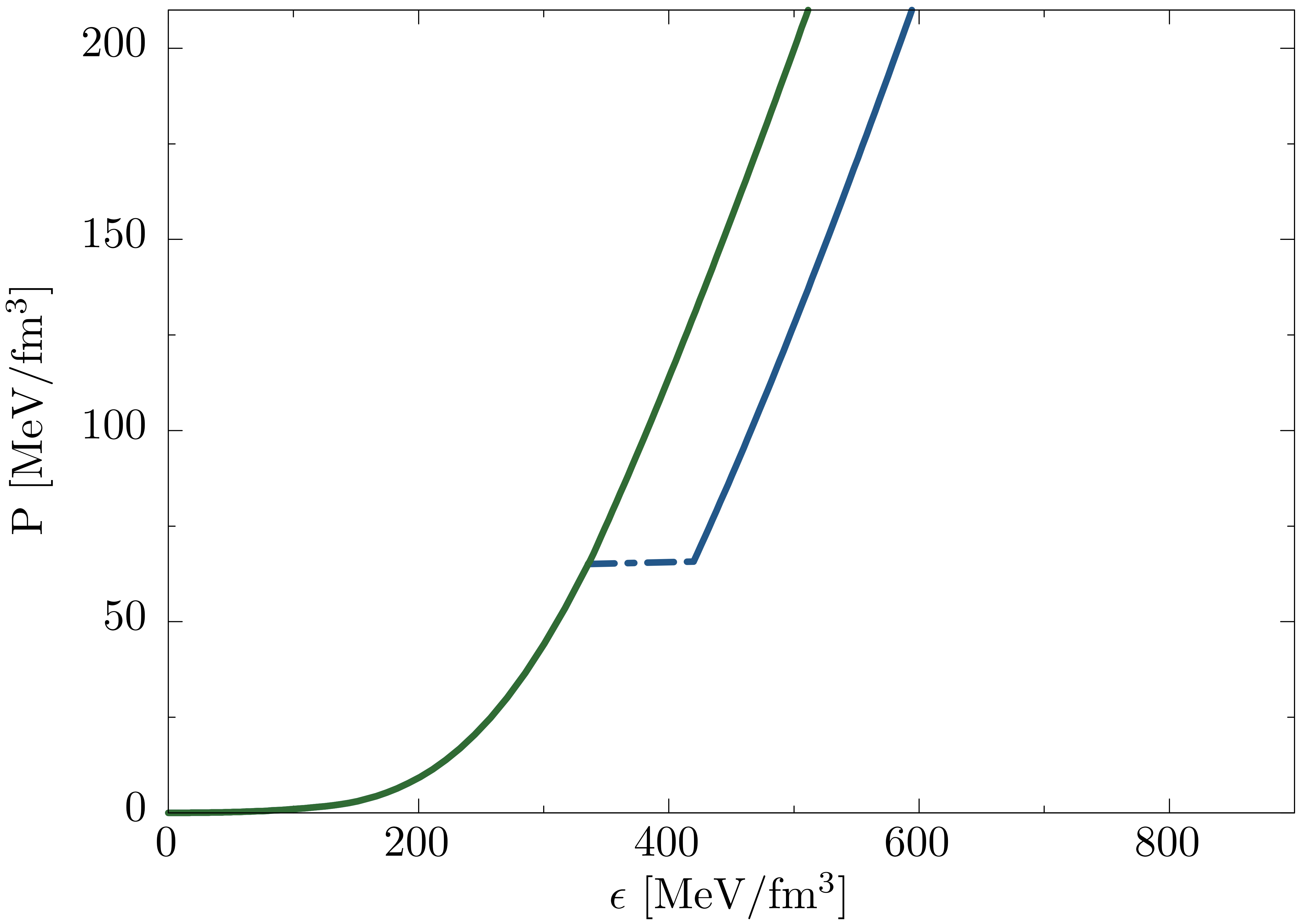

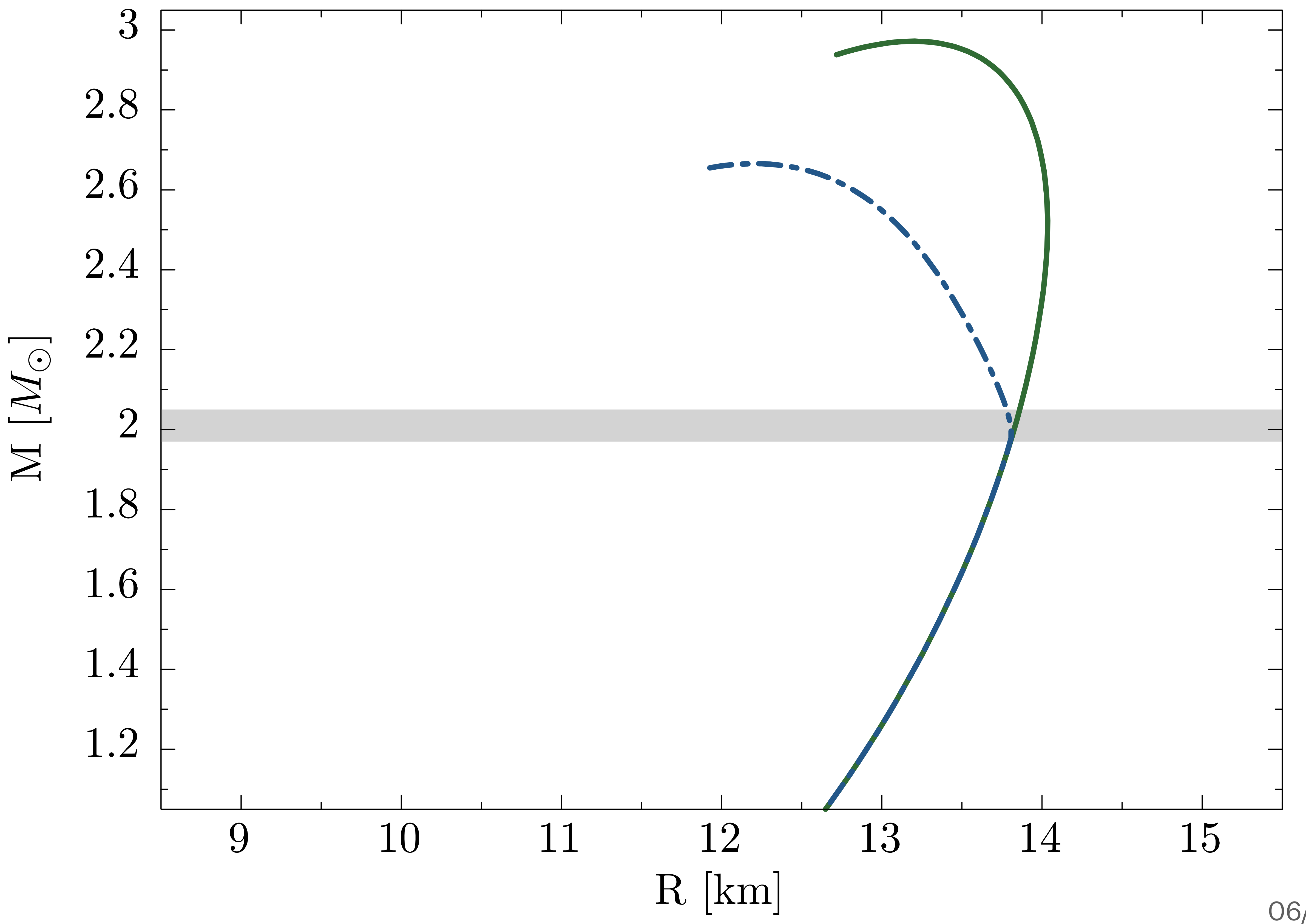

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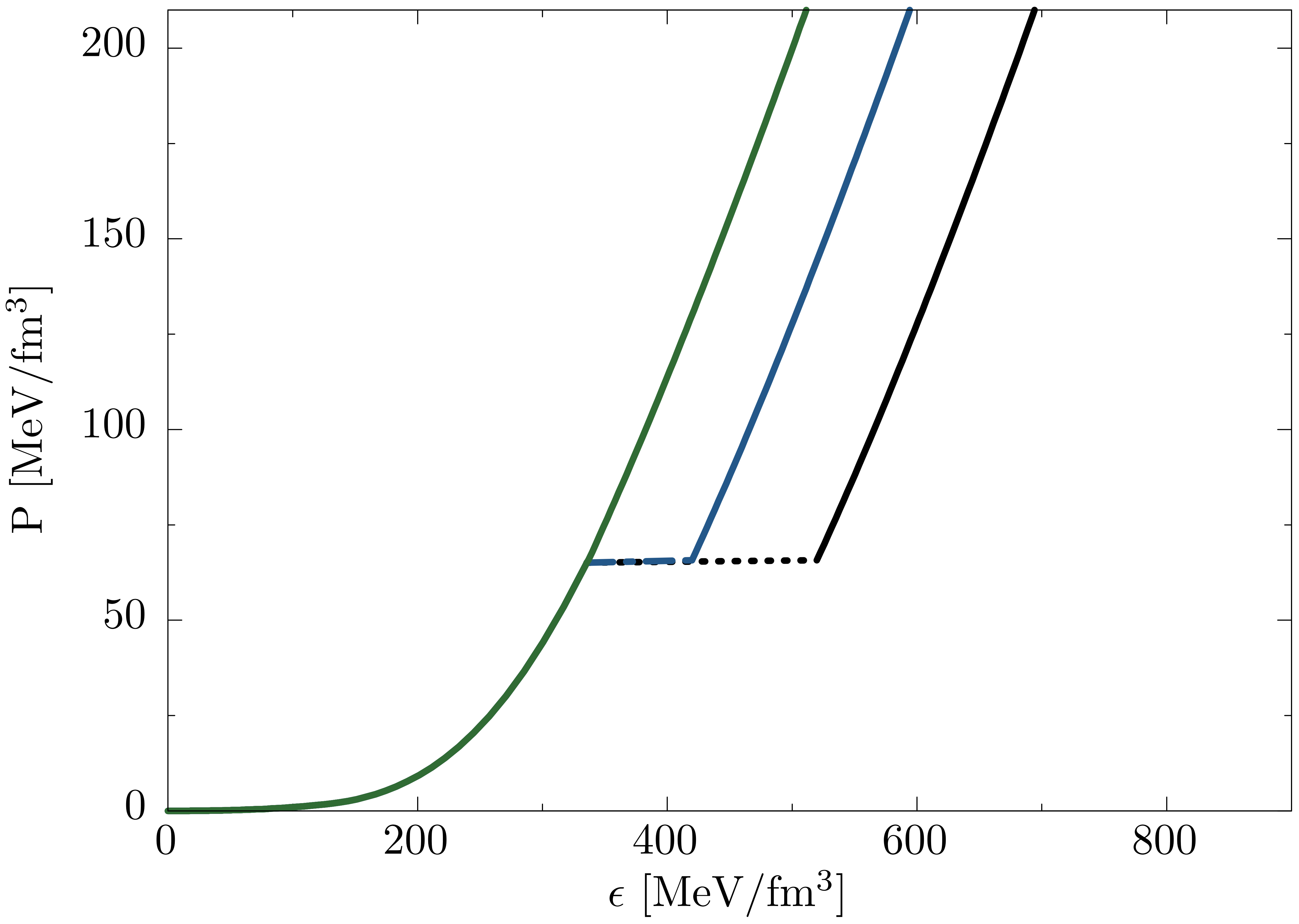

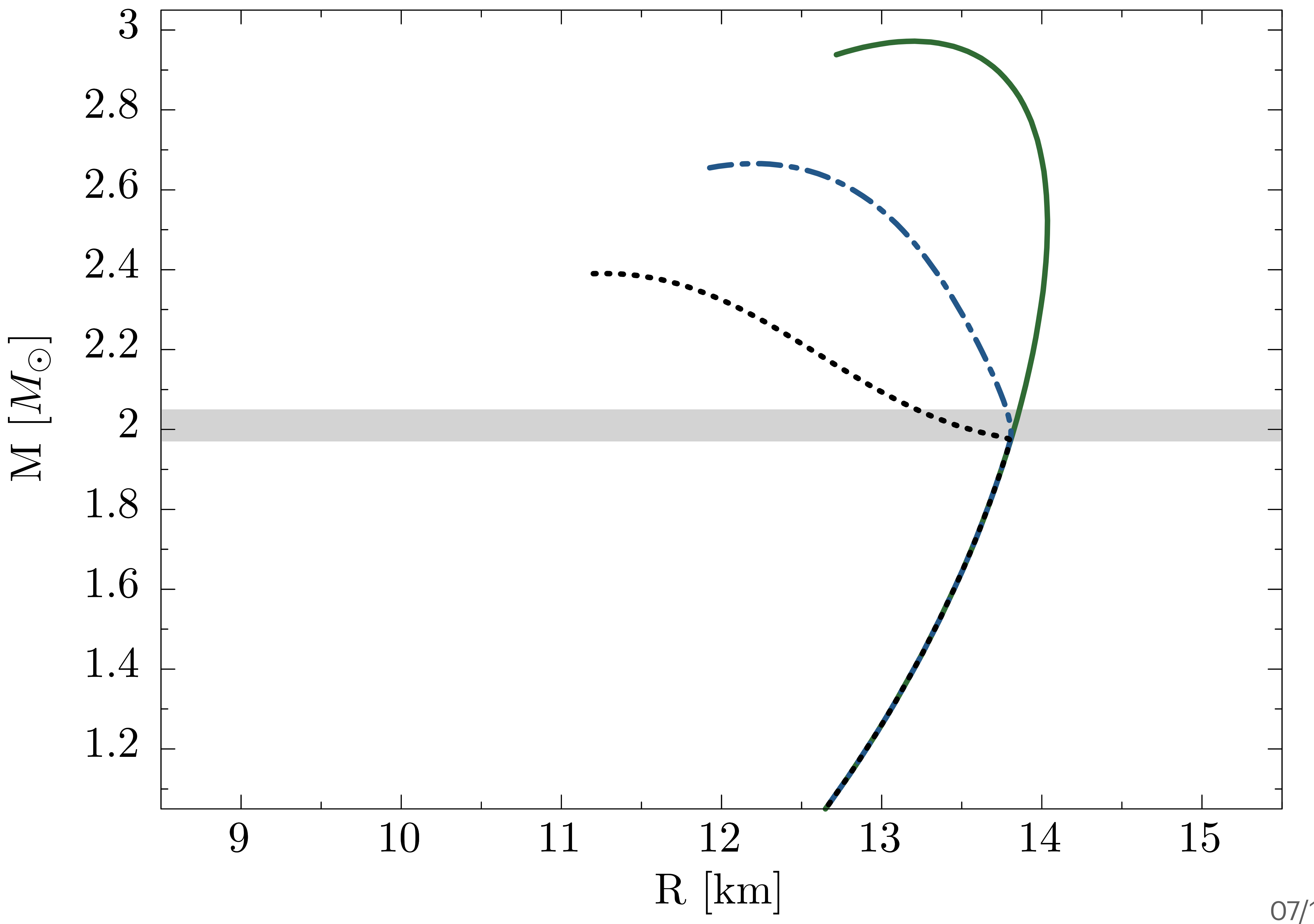

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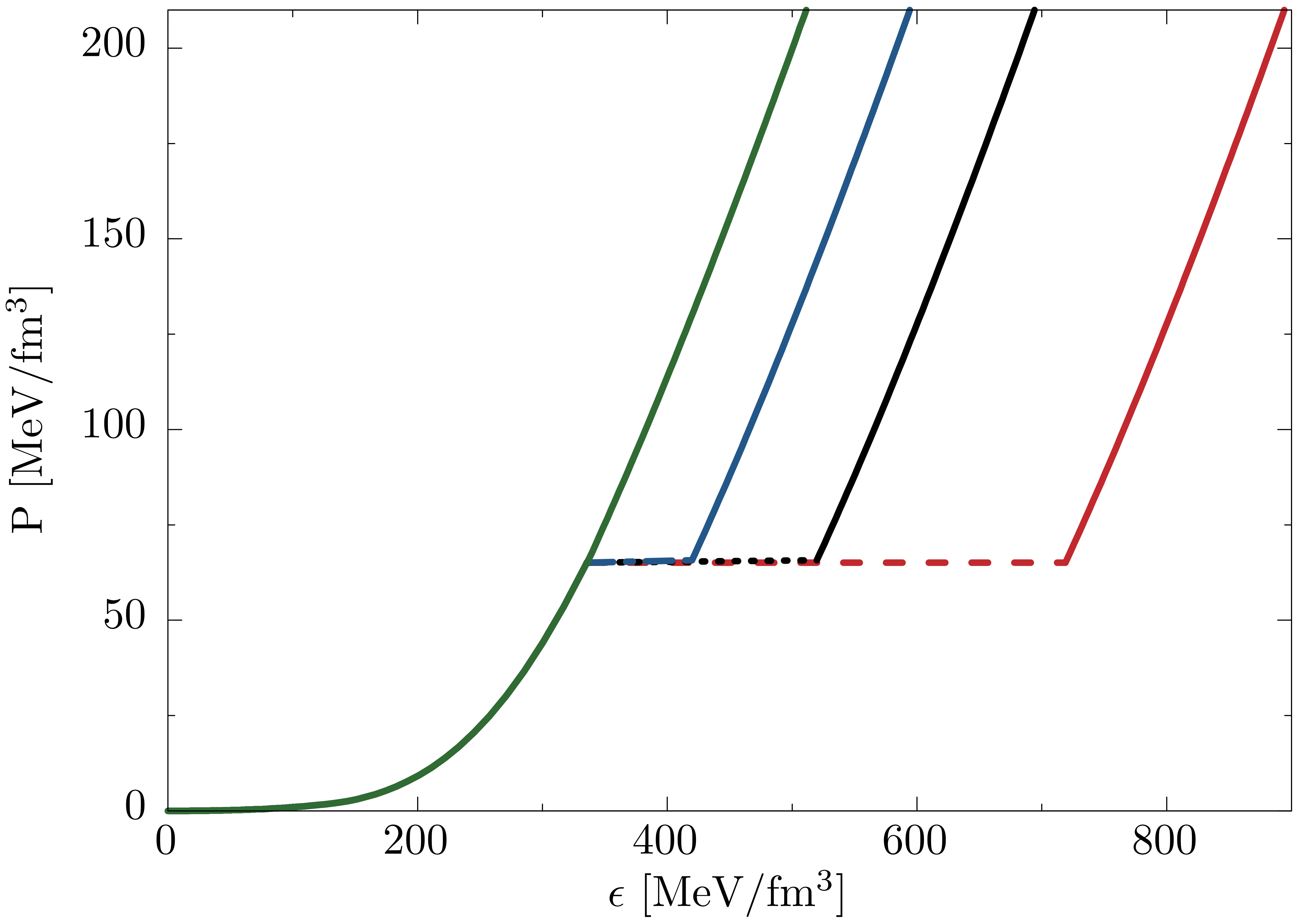
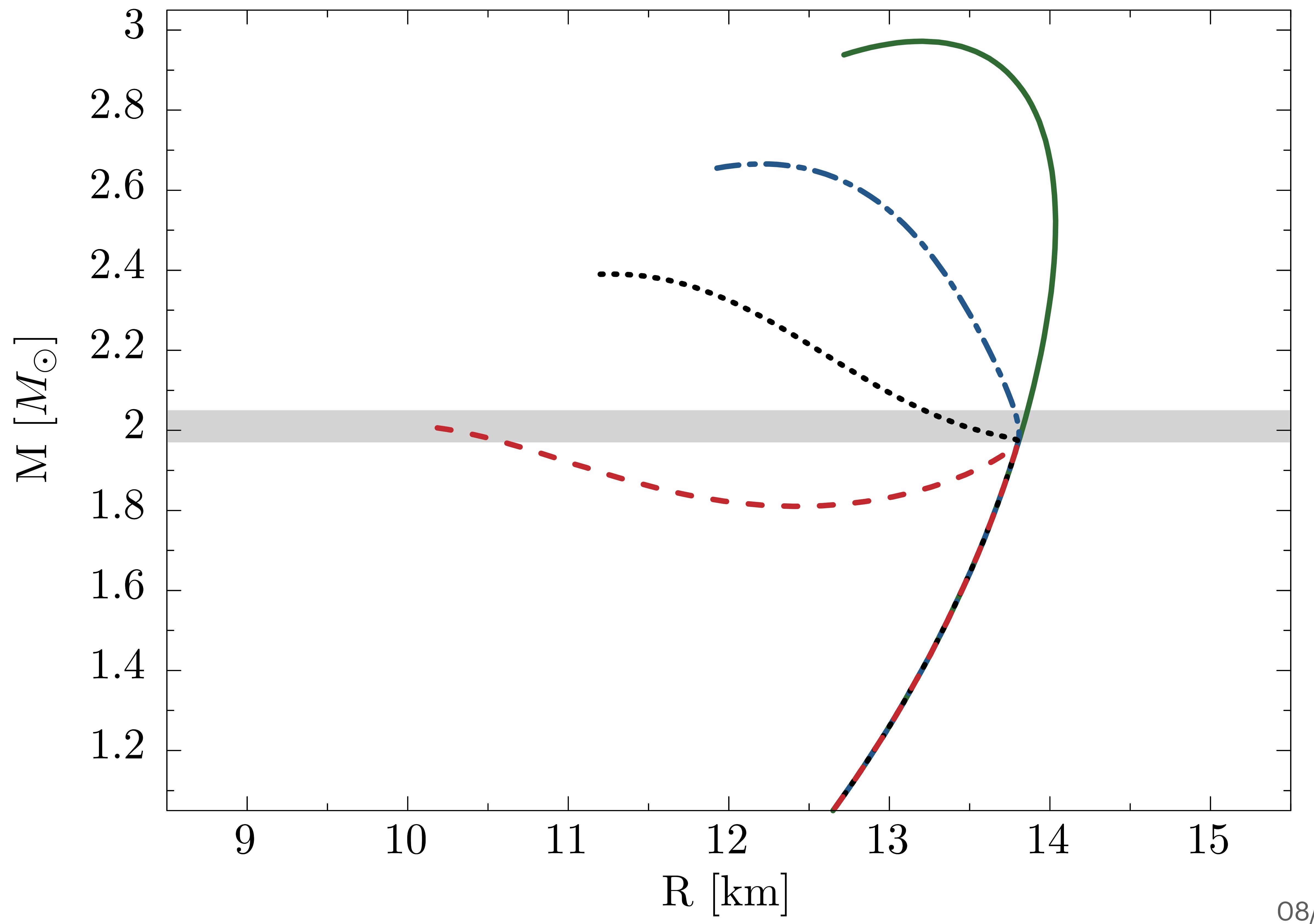
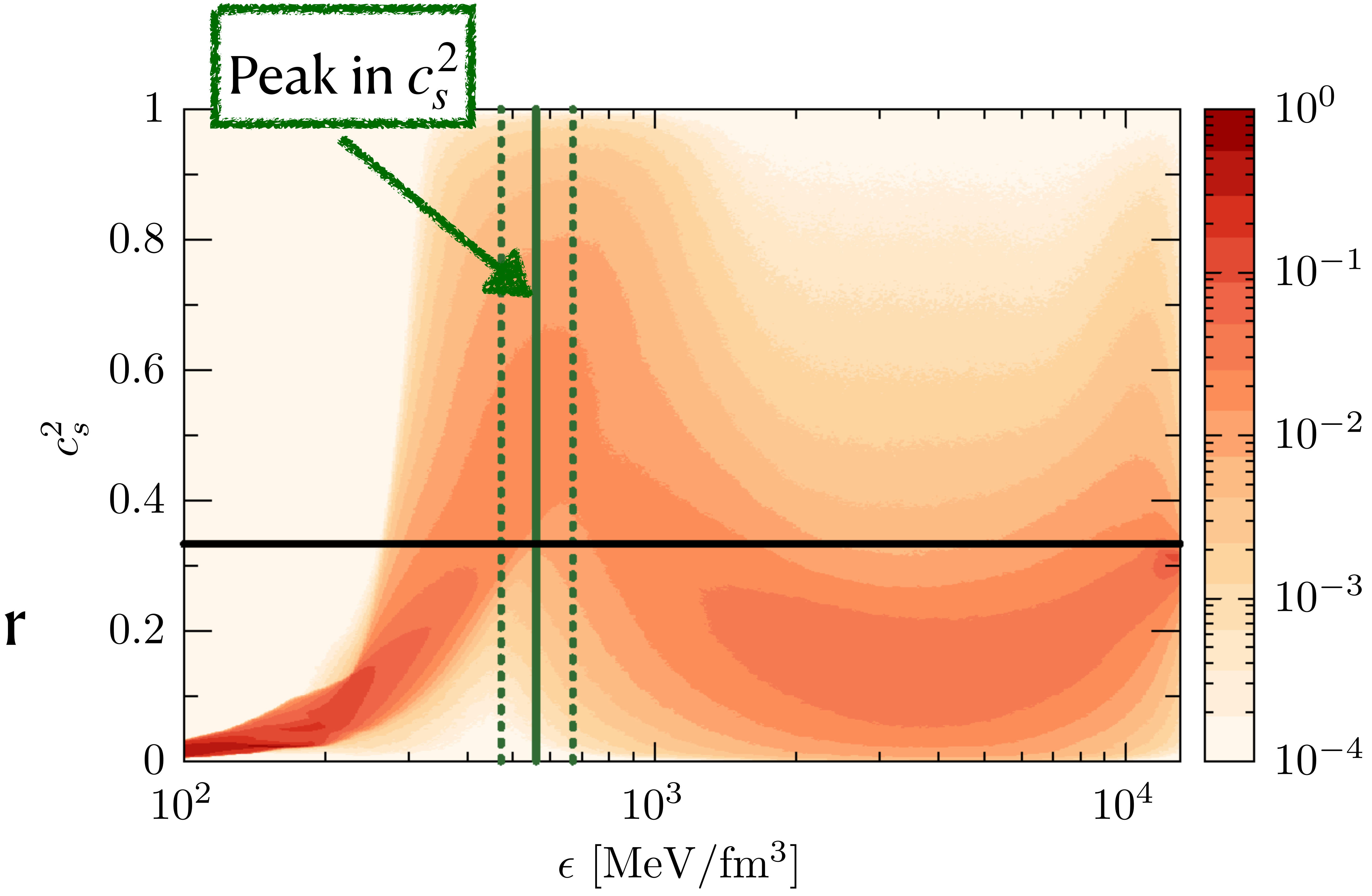




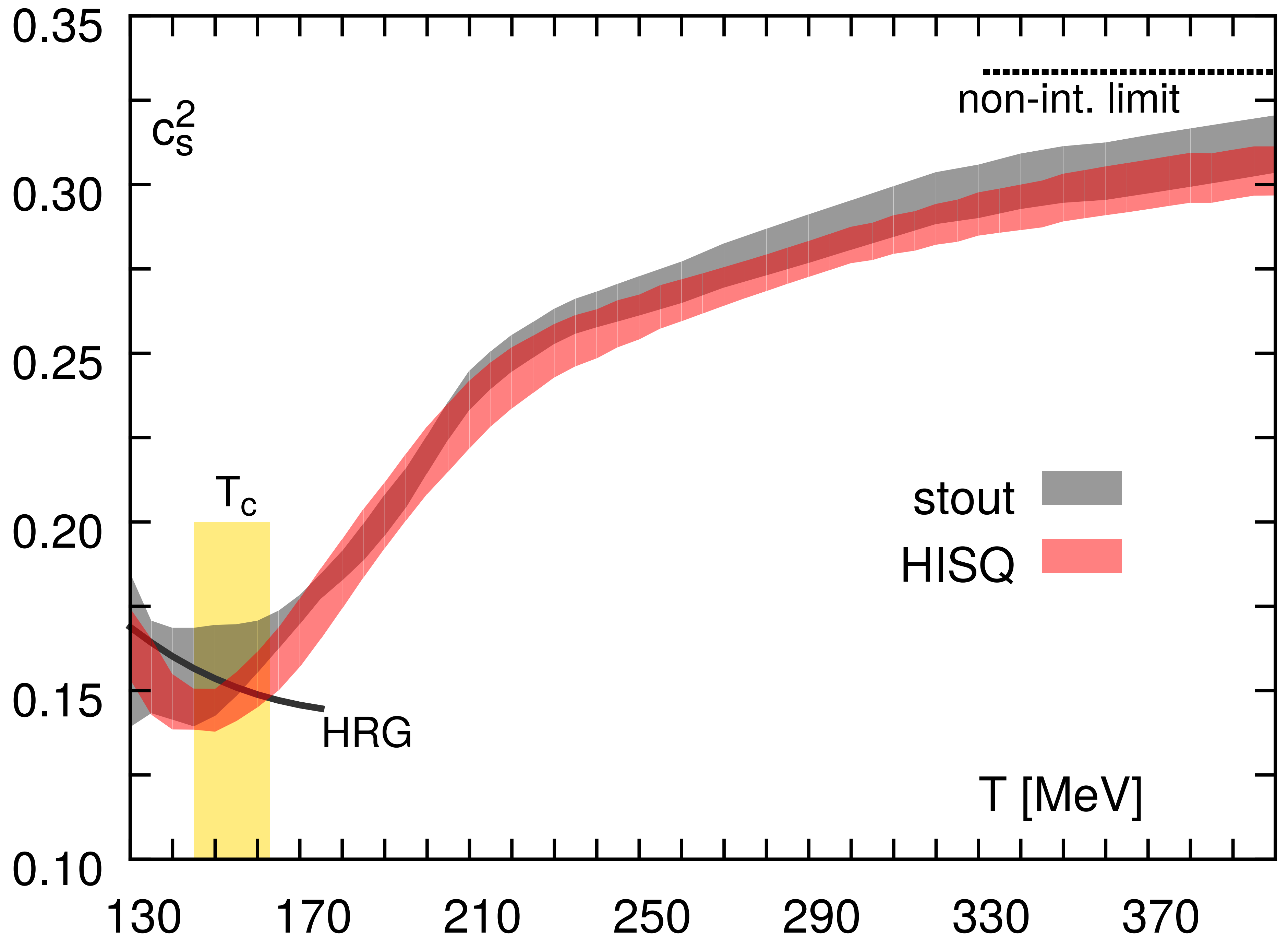
General Structure of Speed of Sound

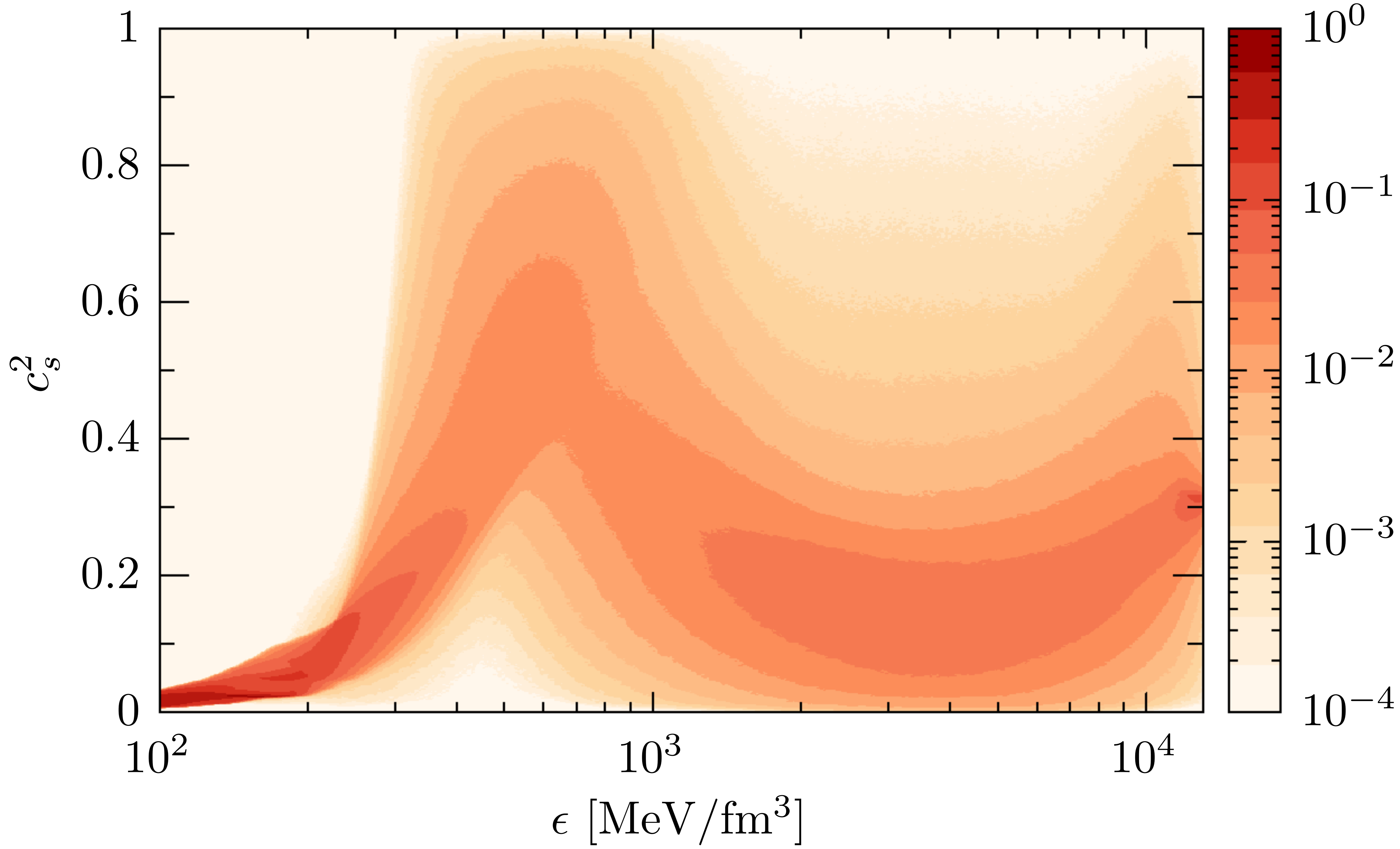
- General peak-dip structure
  Altiparmak et al, 2022

- Peak similar to quarkyonic matter
  McLerran, Reddy, 2019; Pang et al, 2023



Local maximum at $\epsilon_{\text{peak}} = 0.56^{+0.11}_{-0.09}$ GeV/fm^3 with $c_s^2 = 0.82 \pm 0.08$





$$c_s^2 = \frac{S}{T}\frac{dT}{dS} < \frac{1}{3}$$

- Attractive interactions with resonance formation
- Chiral symmetry restoration and deconfinement

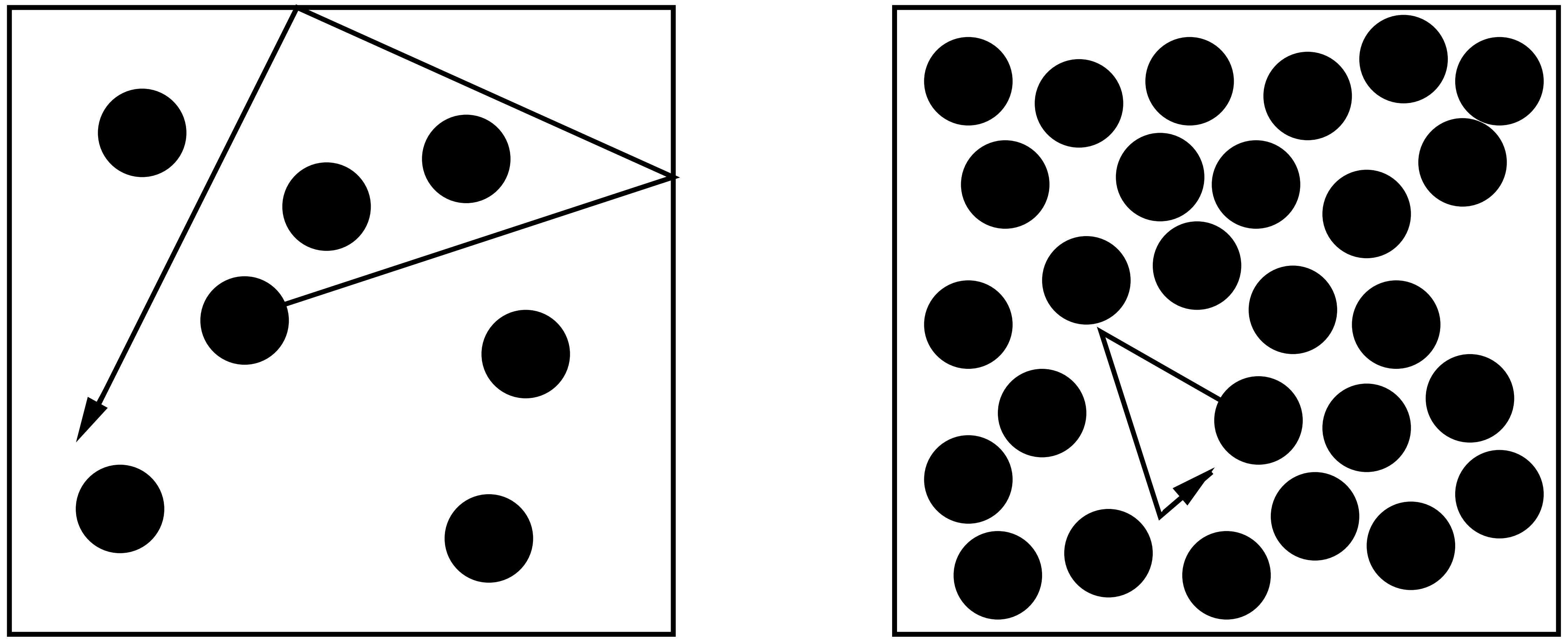
$$c_s^2 = \frac{n}{\mu}\frac{d\mu}{dn} > \frac{1}{3}$$

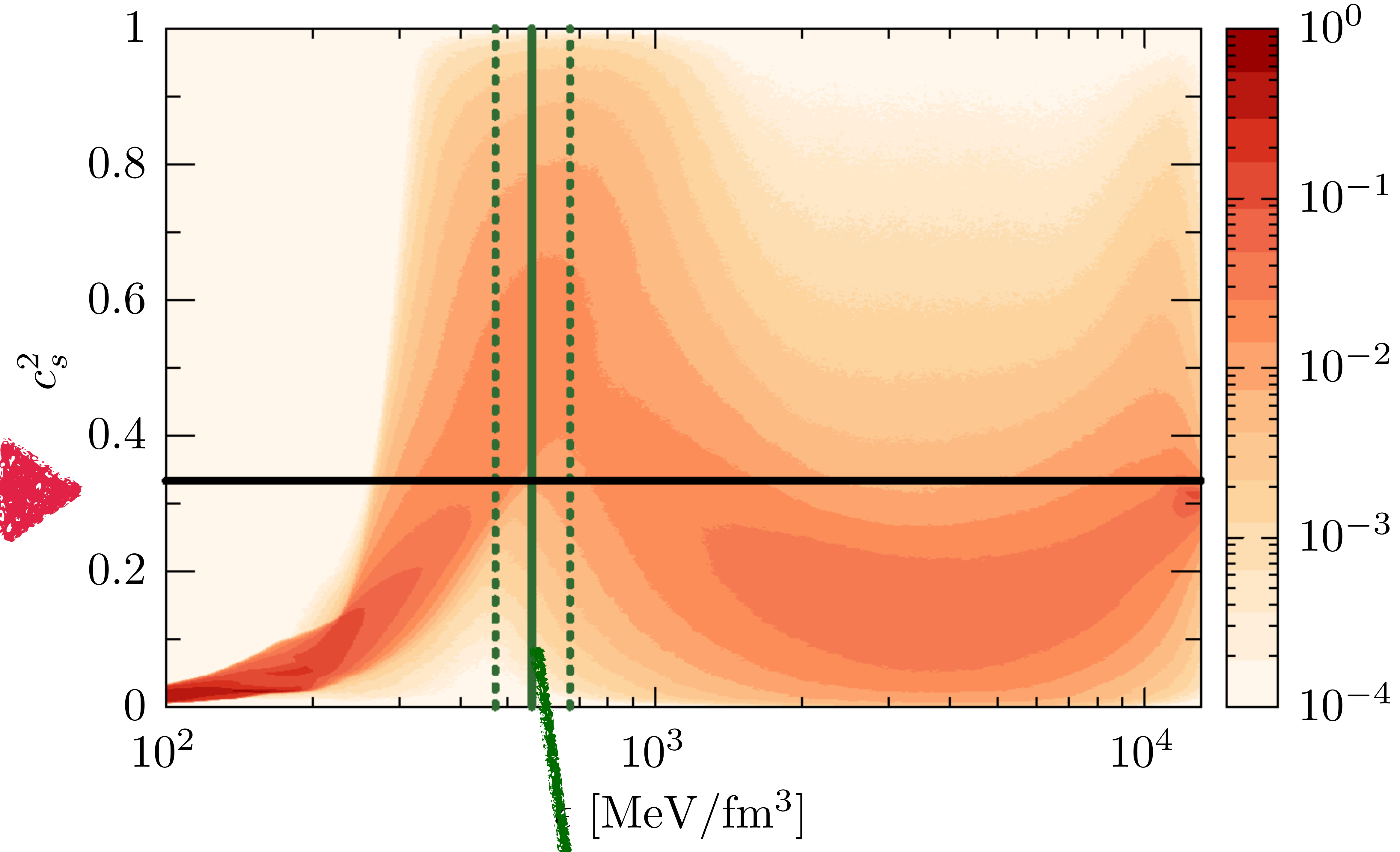
- Dominance of repulsive interactions
- Onset of quark or quarkyonic matter?

Non-monotonicity ⟷ Change of phase

Percolation theory vs speed of sound

see e.g. Satz, 1998; Castorina et al, 2009; Fukushima, 2020





Percolation theory: $n_c = 1.22/V_0$

$n_{\text{peak}} = 0.54^{+0.09}_{-0.07}\ \text{fm}^{-3}$

Avg. proton radius: $R_0 = 0.80 \pm 0.05\ \text{fm}$ → $n_c = 0.57^{+0.12}_{-0.09}\ \text{fm}^{-3}$

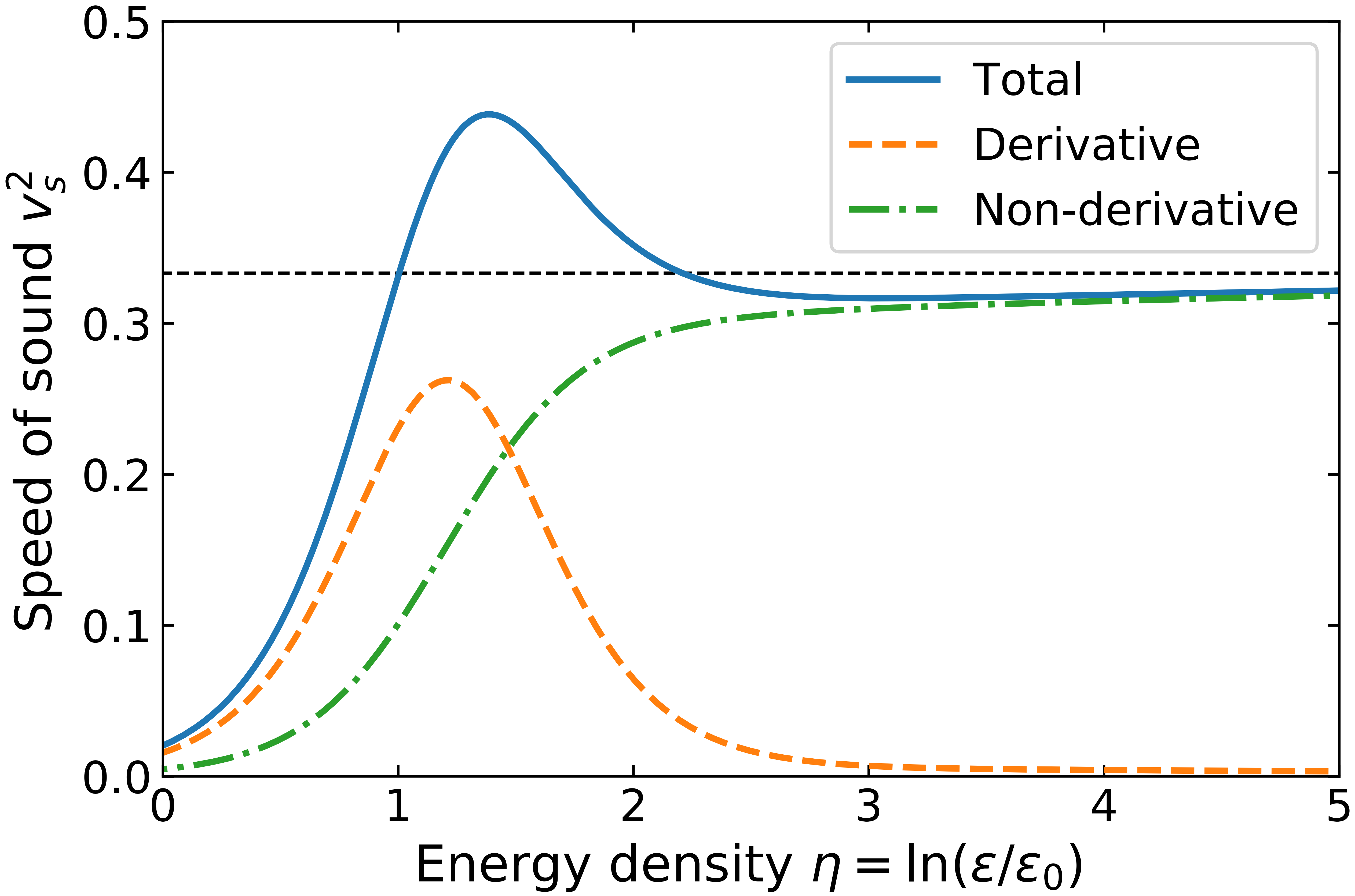
Wang et al 2022

Pb-Pb collisions at $\sqrt{s} = 2.76\ \text{TeV}$ → $n_c = 0.60 \pm 0.07\ \text{fm}^{-3}$

Andronic et al 2018

Speed of Sound as Trace Anomaly

Fujimoto et al 2022



Trace Anomaly

$$\Delta \equiv \frac{\epsilon - 3p}{3\epsilon} = \frac{1}{3} - \frac{p}{\epsilon}$$

$$c_s^2 = \frac{d\left(\epsilon \frac{p}{\epsilon}\right)}{d\epsilon} = \frac{1}{3} - \Delta - \epsilon \frac{d\Delta}{d\epsilon}$$

Trace anomaly more informative than speed of sound

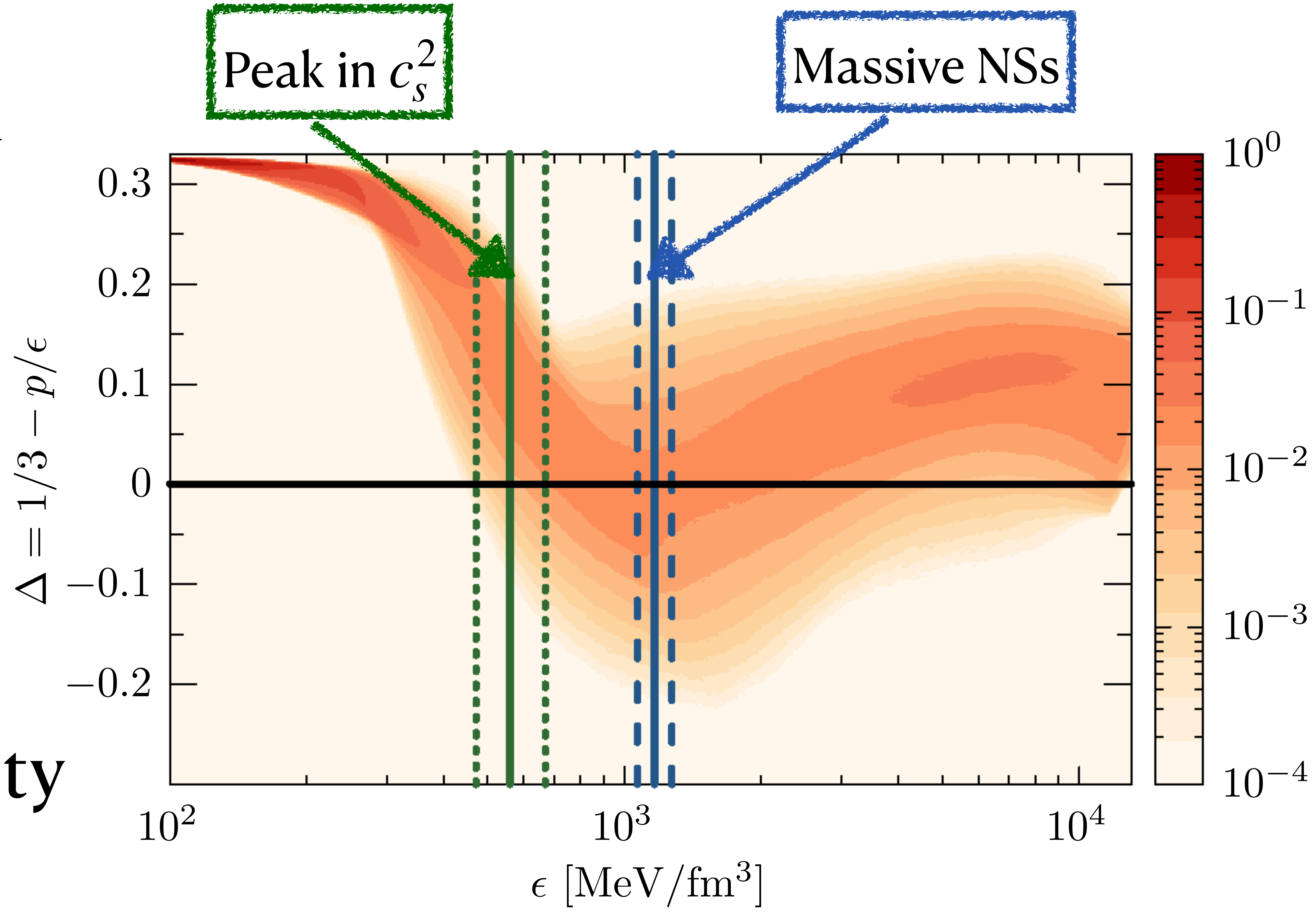
Measure of conformality

Δ monotonic up to $\simeq \epsilon_{\rm TOV}$

$$c_s^2 = \frac{1}{3} - \Delta - \epsilon\frac{d\Delta}{d\epsilon}$$

Maximum in c_s^2

Fast approach to comformality



$\Delta \simeq 0$ at $\epsilon \simeq 1$ GeV/fm^3 ⟷ $\epsilon_{\rm TOV} = 1.16 \pm 0.01$ GeV/fm^3

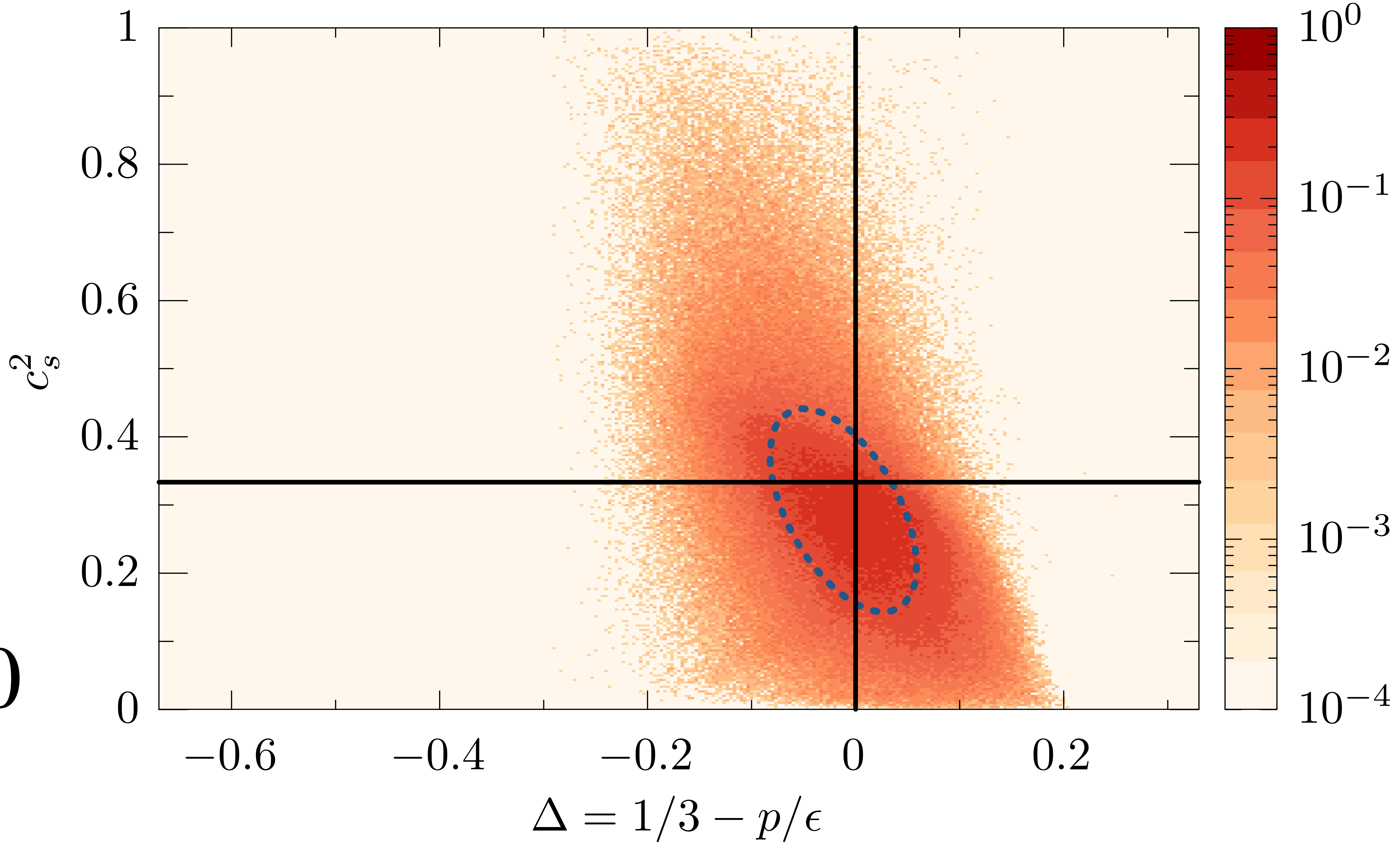
c_s^2 and Δ in Heavy Neutron Stars

Conformality:

$$c_s^2 = \frac{1}{3} \text{ and } \Delta = 0$$

$$c^2_{s,\,\mathrm{TOV}} = 0.28 \pm 0.16 \simeq \frac{1}{3}$$

$$\Delta_{\mathrm{TOV}} = -0.01 \pm 0.03 \simeq 0$$



Matter almost conformal in the cores of maximally massive NSs

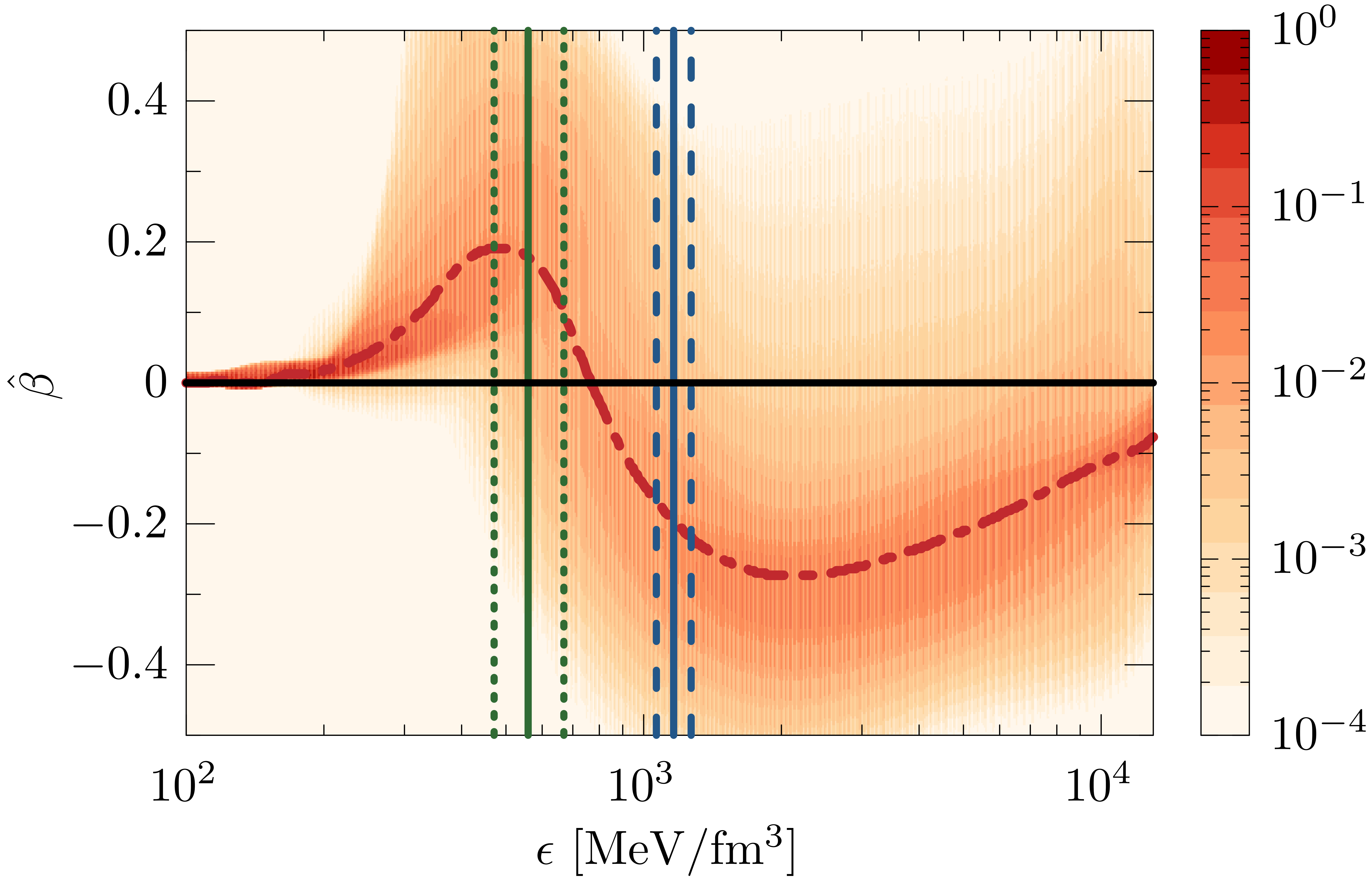
Incompressiblity & curvature of binding energy

MM, K. Redlich, C. Sasaki, to appear

$$K \equiv \frac{dP}{dn} = 9\mu(\hat{\alpha} + \hat{\beta})$$

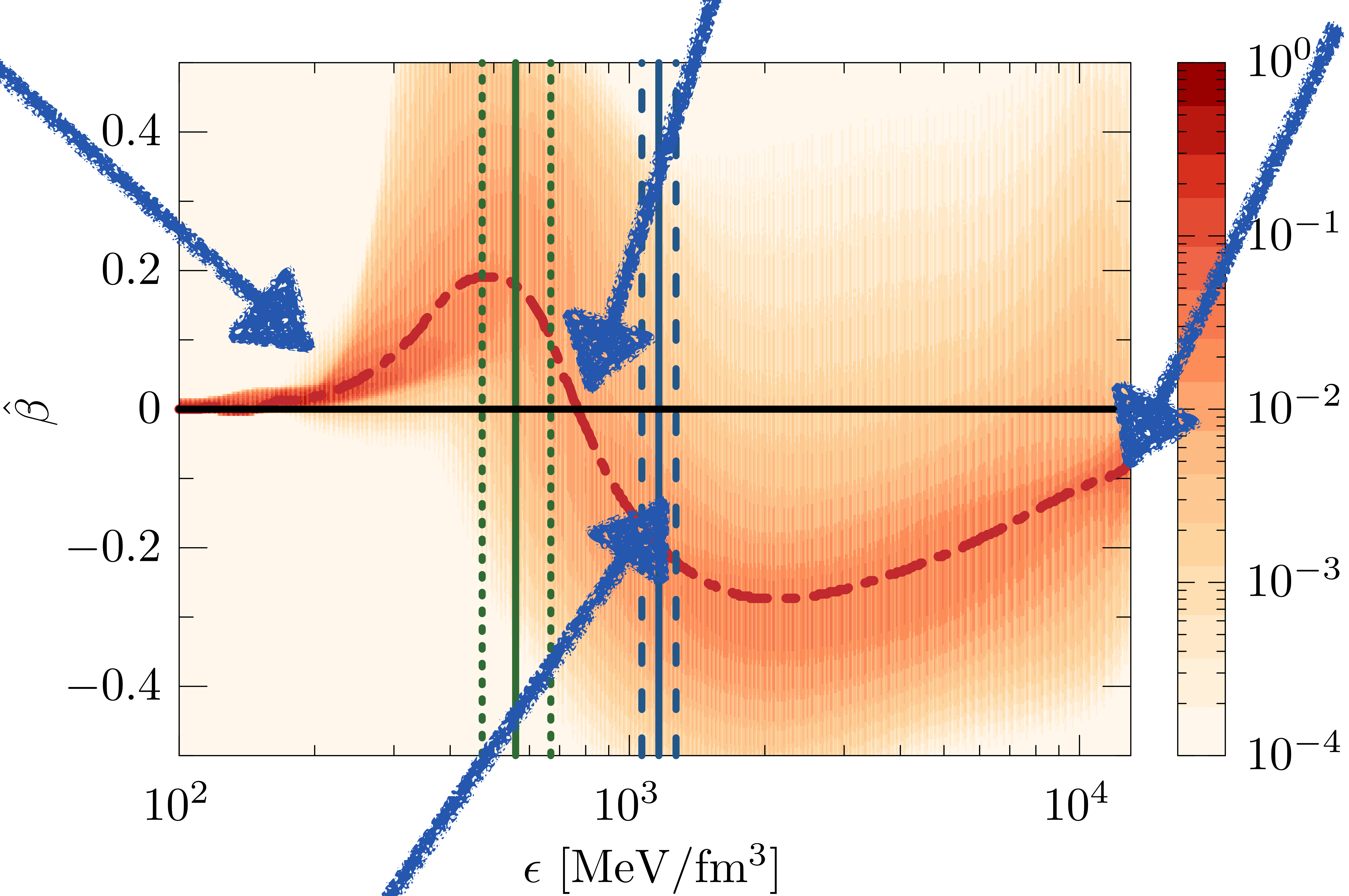
$$\hat{\alpha} \equiv 2\frac{n}{\mu}\frac{d\epsilon/n}{dn} = 2\frac{1/3 - \Delta}{4/3 - \Delta}$$

$$\hat{\beta} \equiv \frac{n^2}{\mu}\frac{d^2\epsilon/n}{dn^2} = c_s^2 - \hat{\alpha}$$



$\hat{\beta} < 0 \rightarrow$ changeover to conformal regime

$\hat{\beta} \simeq c_s^2 > 0$ $\hat{\beta} = 0$ at $\epsilon \lesssim \epsilon_{\rm TOV}$ $\hat{\beta} \simeq -1/6$



$$\hat{\beta}_{\rm TOV} = 0.22 \pm 0.05$$

Changeover consistent with percolation

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$$\hat{\alpha} \equiv 2\frac{n}{\mu}\frac{d\epsilon/n}{dn} = 2\frac{1/3 - \Delta}{4/3 - \Delta}$$

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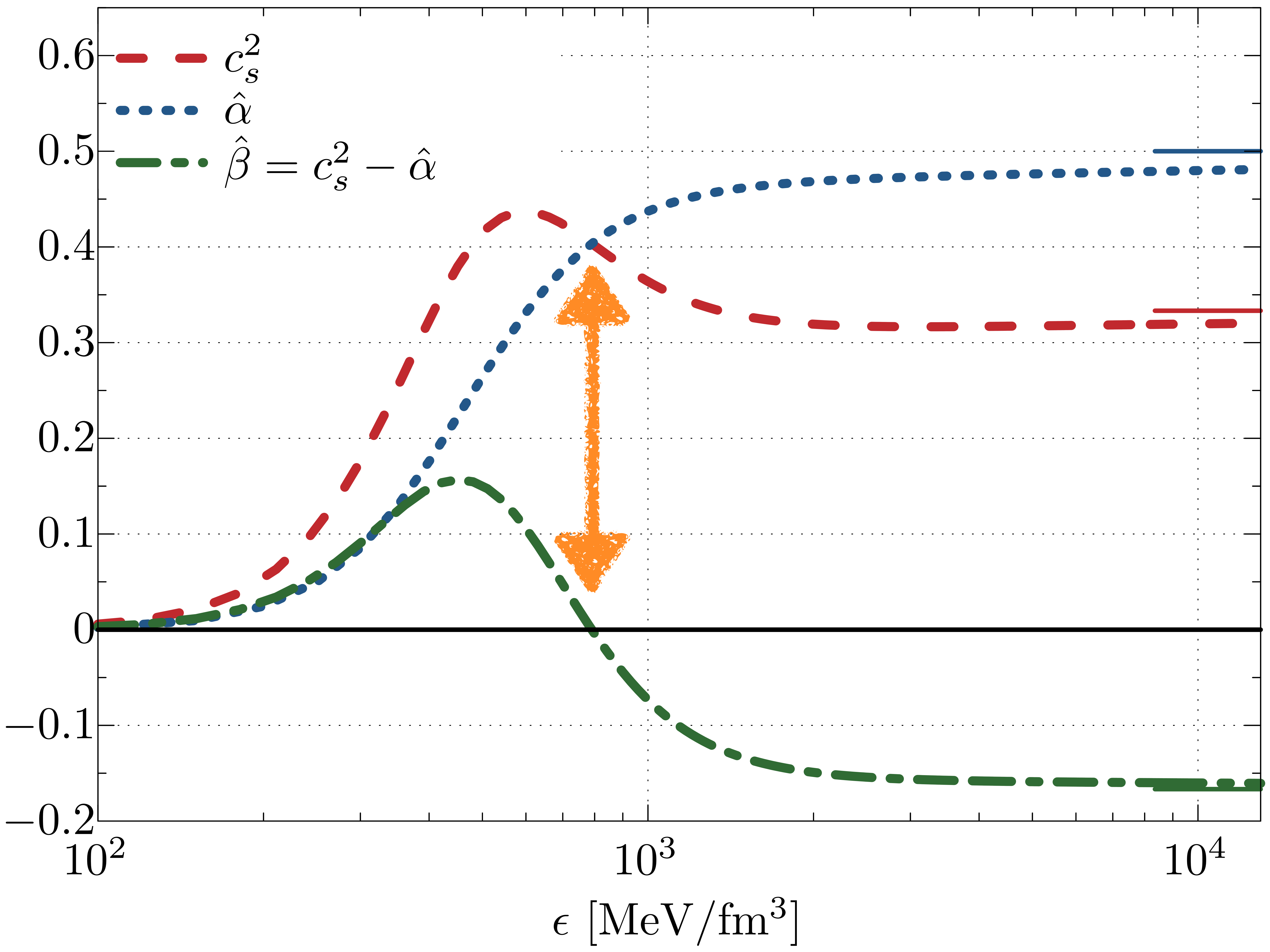
Model by Fujimoto et al 2022



Summary

Maximum of c_s^2 consistent with percolation threshold

Matter seems to be conformal in the cores of massive NSs

Thank You