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WPI HIROSHIMA UNIVERSITY



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Reaching Percolation and Conformal limits in Neutron Stars

M. Marczenko, L. McLerran, K. Redlich, C. Sasaki

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Institute of Theoretical Physics
University of Wroclaw, Poland

SKCM², Hiroshima University, Japan

Big question: quark matter in neutron stars?

- Solid constraints:

- low density ($n < 1.1n_0$): χ^{EFT} Tews *et al* (2013)
- high density ($n > 40n_0$): pQCD Gorda *et al* (2018)

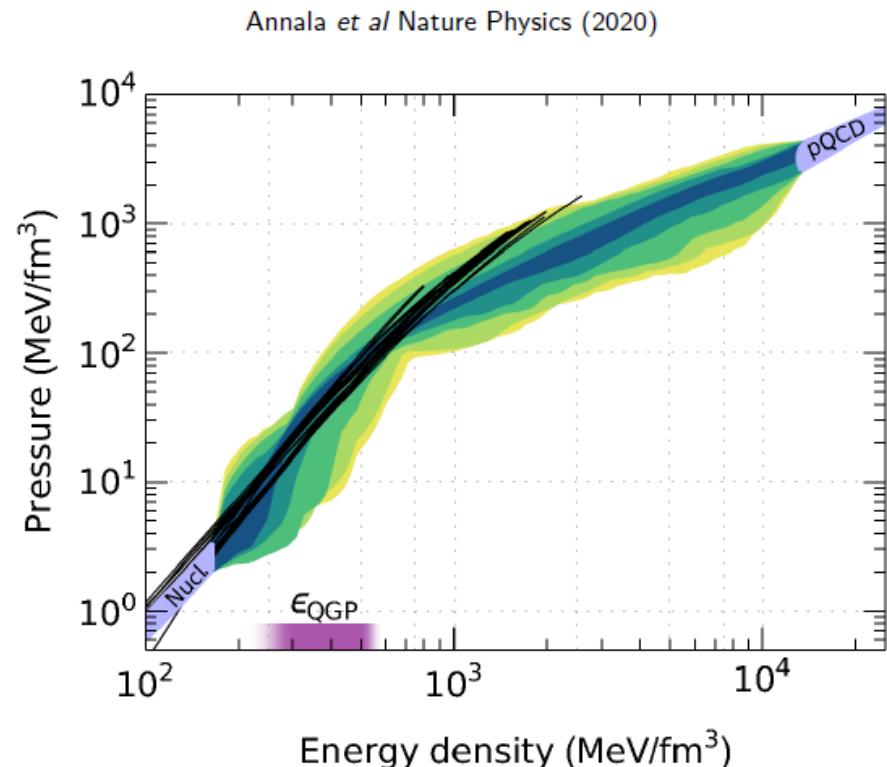
- Interpolation: multipolytropes, CSS

eg Annala *et al* (2018), (2020), Alford *et al* (2013), (2017); Li *et al* (2021)

- Phenomenological deconfinement:

$$\gamma = \frac{d \ln p}{d \ln \epsilon} \rightarrow \begin{cases} \gamma > 1.75 - \text{hadrons} \\ \gamma < 1.75 - \text{quarks} \end{cases}$$

- In LQCD: $\epsilon_{\text{QGP}} \approx 0.5 \text{ GeV/fm}^3$



We follow the piecewise-linear parametrized speed of sound method:

- Generate an ensemble of EoSs in agreement with χ EFT and pQCD

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

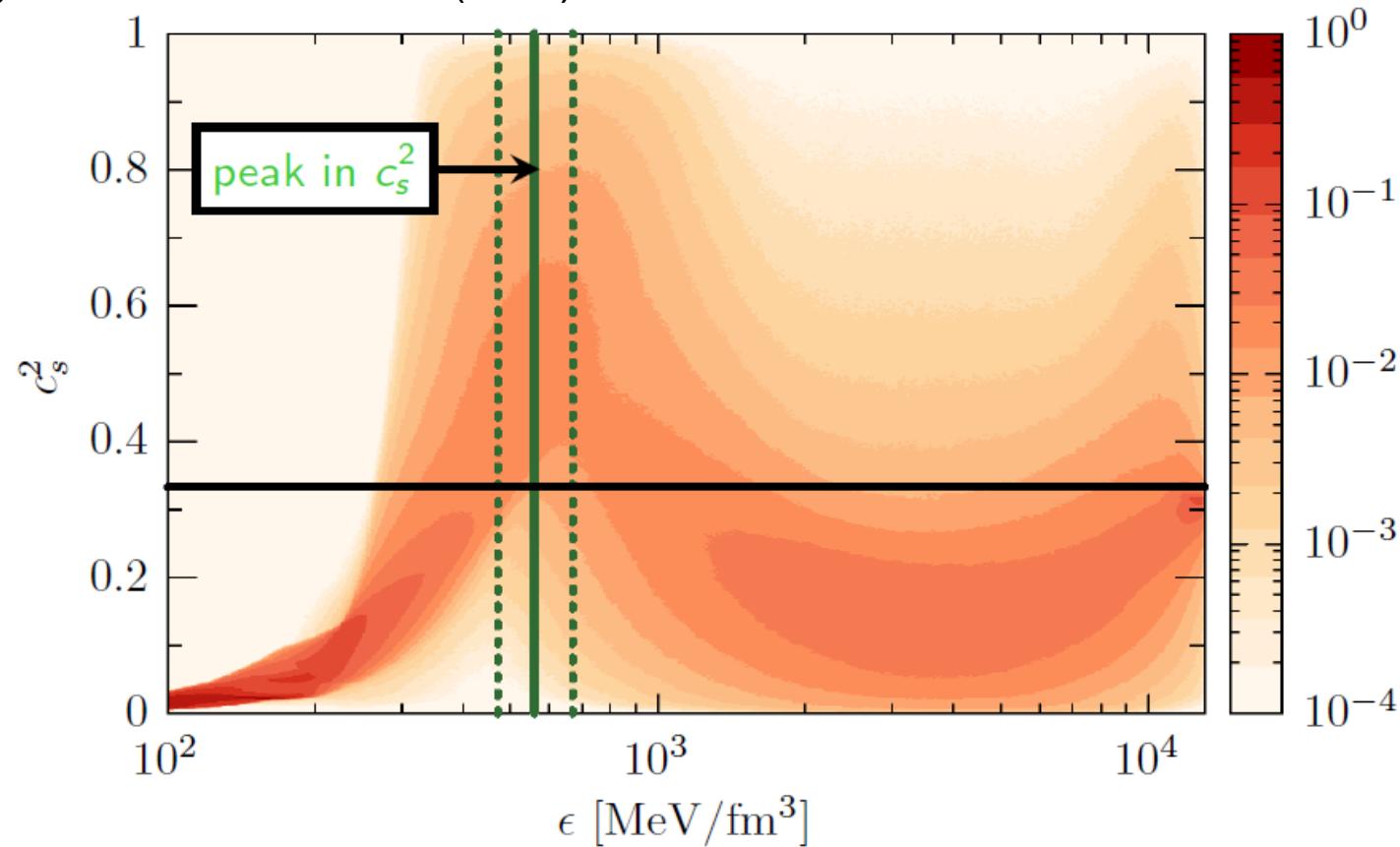
$$c_s^2 = \frac{n_B}{\mu_B} \frac{d\mu_B}{dn_B}$$

We apply solid astrophysical constraints:

- Mass measurement of J0740+6620: $M_{\text{TOV}} \geq (2.08 \pm 0.07) M_\odot$ Fonseca et al (2021)
- Tidal deformability from GW170817: $\Lambda_{1.4M_\odot} = 190^{+390}_{-120}$ Abbot et al (2018)
- We end up with ensemble of 5×10^5 viable Equations of State

General Structure of Speed of Sound

probability distribution function (PDF)



■ General peak-dip structure Altiparmak *et al* (2022); Ecker, Rezzolla (2022)

■ Peak similar to quarkyonic description of matter McLerran, Reddy PRL (2019)

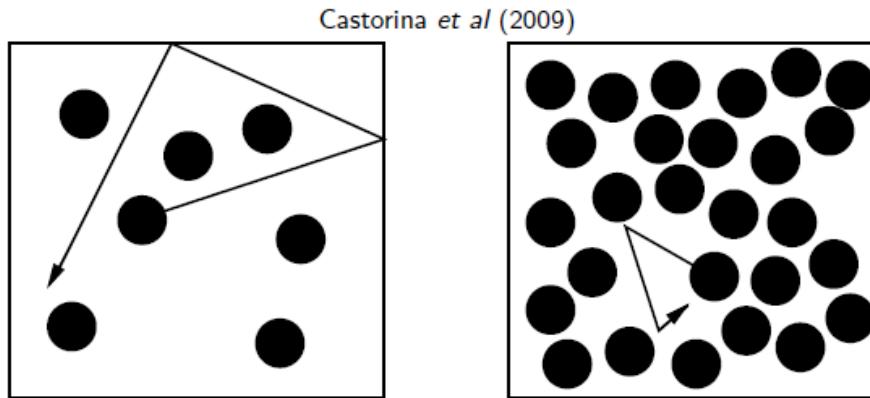
■ Local maximum at $\epsilon_{\text{peak}} = 0.56^{+0.11}_{-0.09}$ GeV/fm³ with $c_s^2 = 0.82 \pm 0.08$

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

Poster by Yuki Fujimoto

at 1σ

Percolation theory and deconfinement

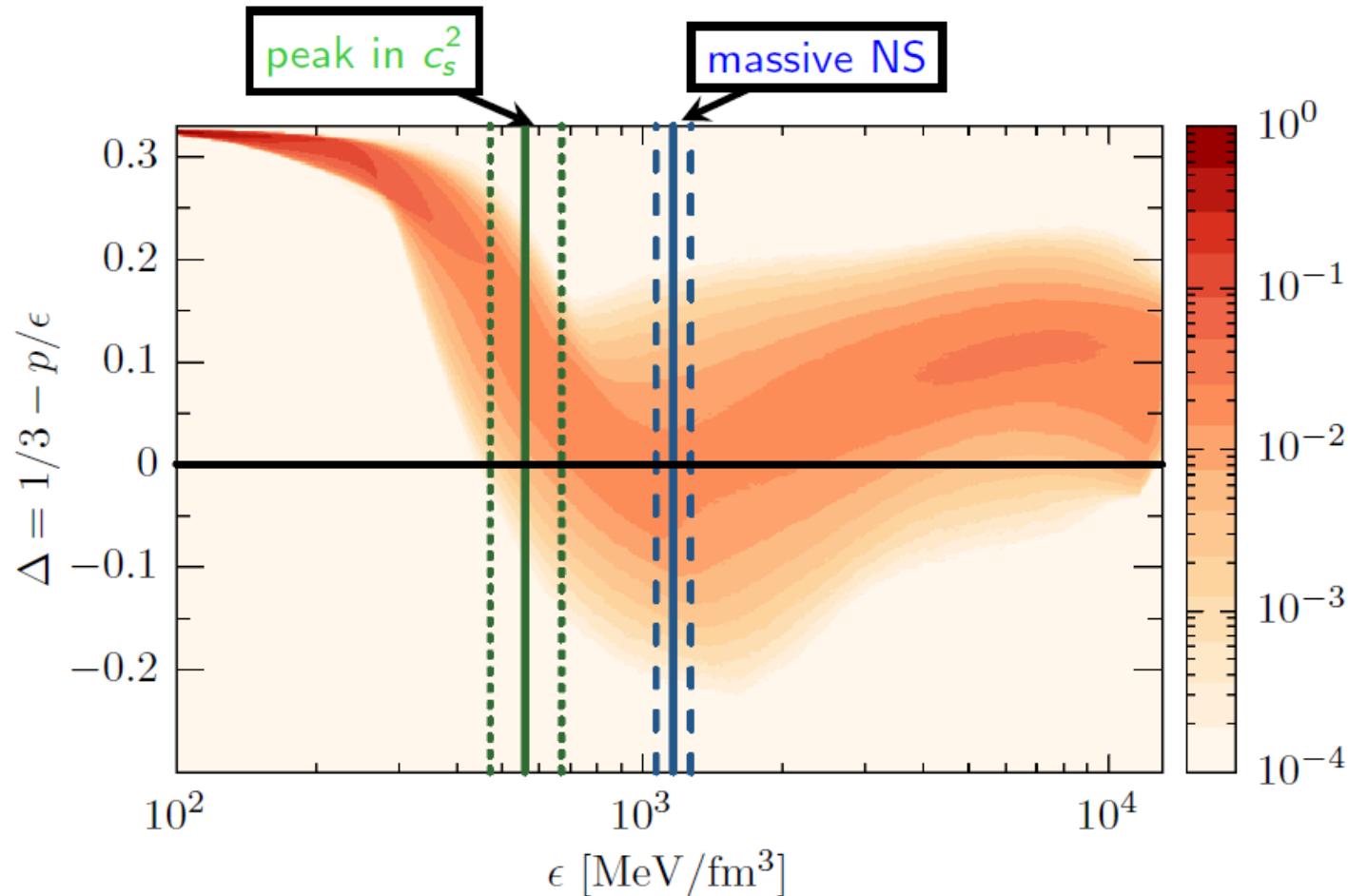


- Percolation theory: $n_c = 1.22/V_0$ see, e.g., Satz (1998); Castorina et al (2009); Fukushima et al (2020)
- Avg. proton radius: $R_0 = 0.80 \pm 0.05$ fm Wang et al (2022) → $n_c = 0.57^{+0.12}_{-0.09}$ fm $^{-3}$
- Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV → $n_c = 0.60 \pm 0.07$ fm $^{-3}$ at phase boundary
[based on the thermal model analyses, Andronic et al., Nature (2018)]

PERCOLATION THRESHOLD \iff MAXIMUM OF SPEED OF SOUND

Appearance of maximum in c_s^2
↓
Change in medium composition
↓
Limited applicability of (mean-field) hadronic models

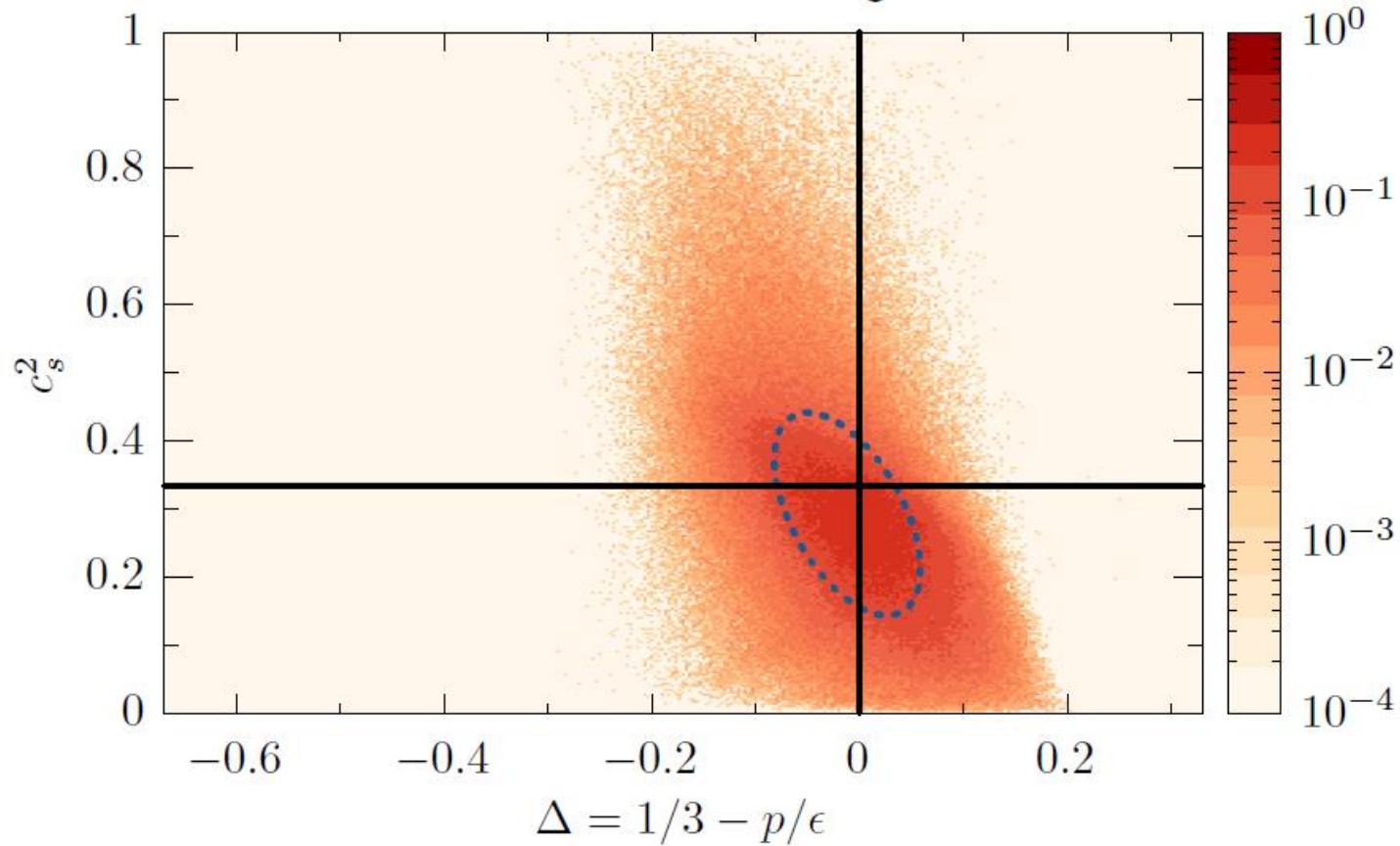
Measure of conformality: trace anomaly



- Trace anomaly monotonic even if c_s^2 has a maximum
- Peak in $c_s^2 \rightarrow$ slope of Δ
- $\Delta \simeq 0$ at $\epsilon \approx 1$ GeV/fm³ $\longleftrightarrow \epsilon_{\text{TOV}} = 1.16 \pm 0.01$ GeV/fm³

Sound speed and trace anomaly at the center of the heaviest NSs

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

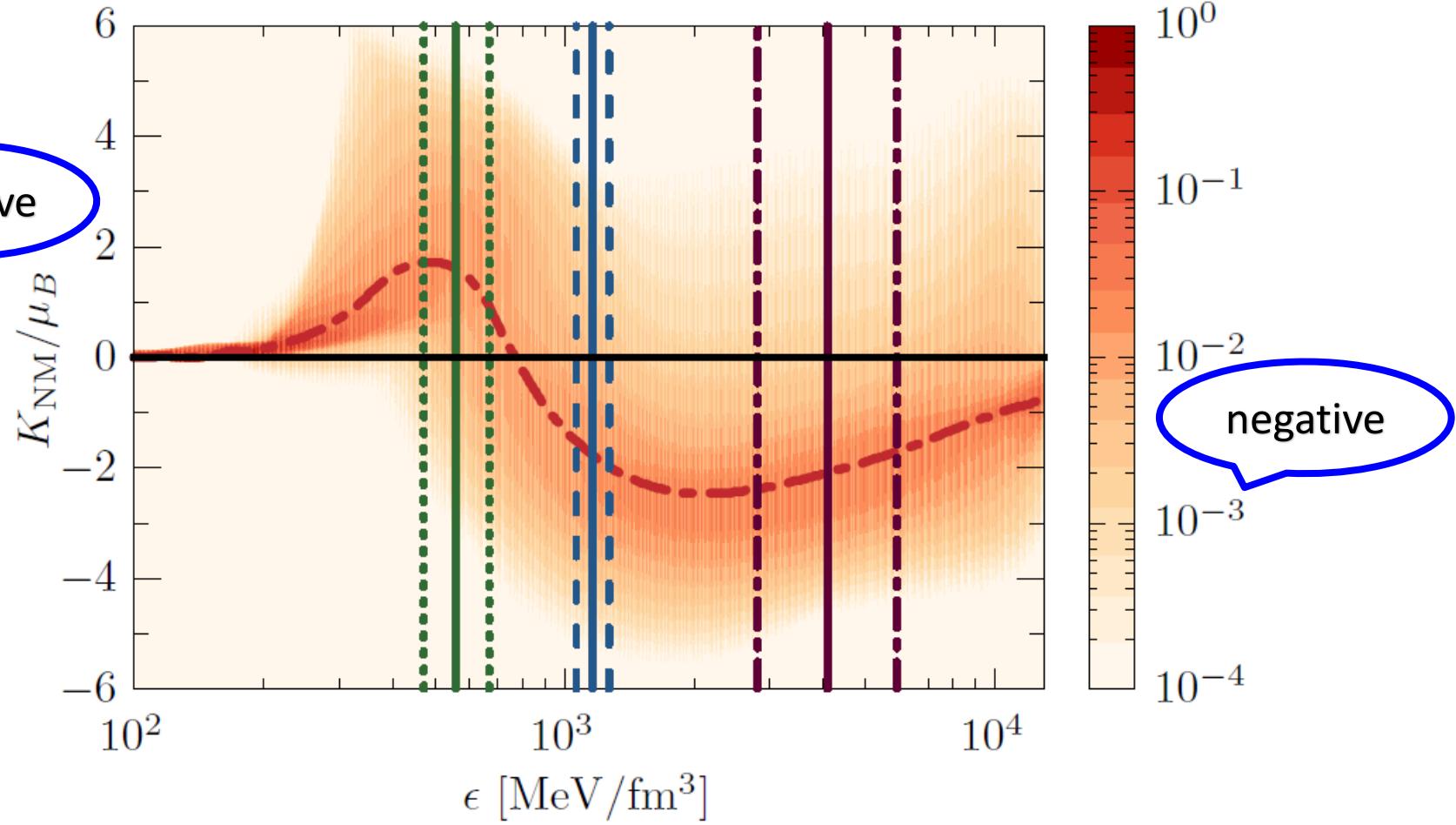


$$c_{s,\text{TOV}}^2 = 0.28 \pm 0.06 \quad \text{and} \quad \Delta_{\text{TOV}} = -0.01 \pm 0.03$$

Matter almost conformal in the cores of maximally massive NSs

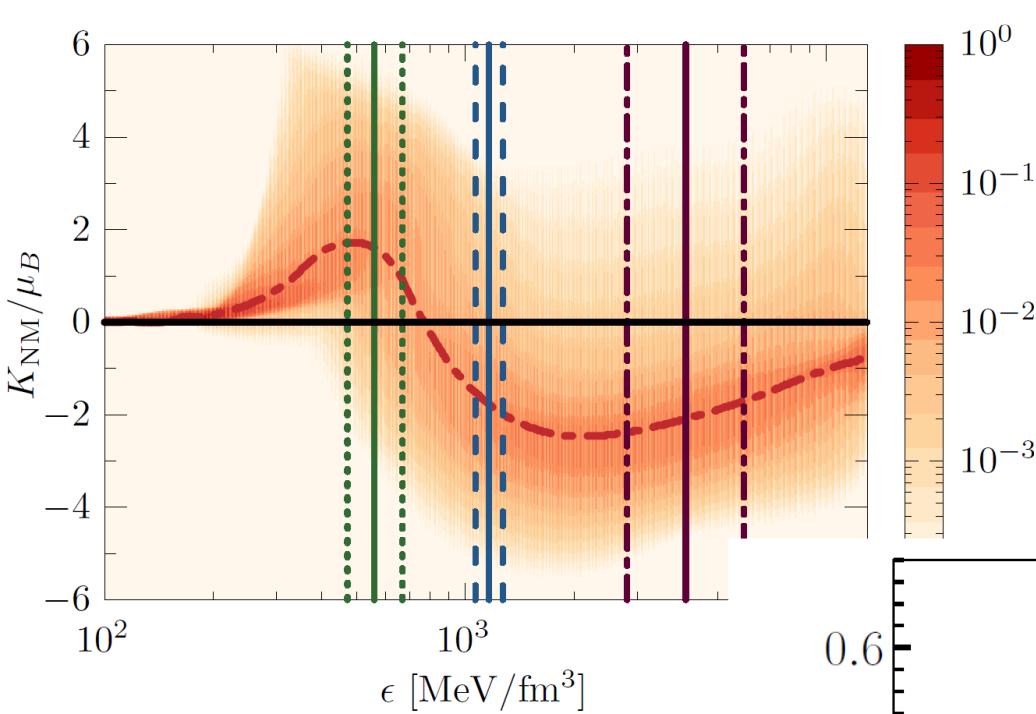
Compressibility modulus

$$K_{\text{NM}} = 9n_B \frac{\partial^2 \epsilon / n_B}{\partial n_B^2} = 9\mu_B \left(c_s^2 - 2 \frac{\Delta - 1/3}{\Delta - 4/3} \right)$$

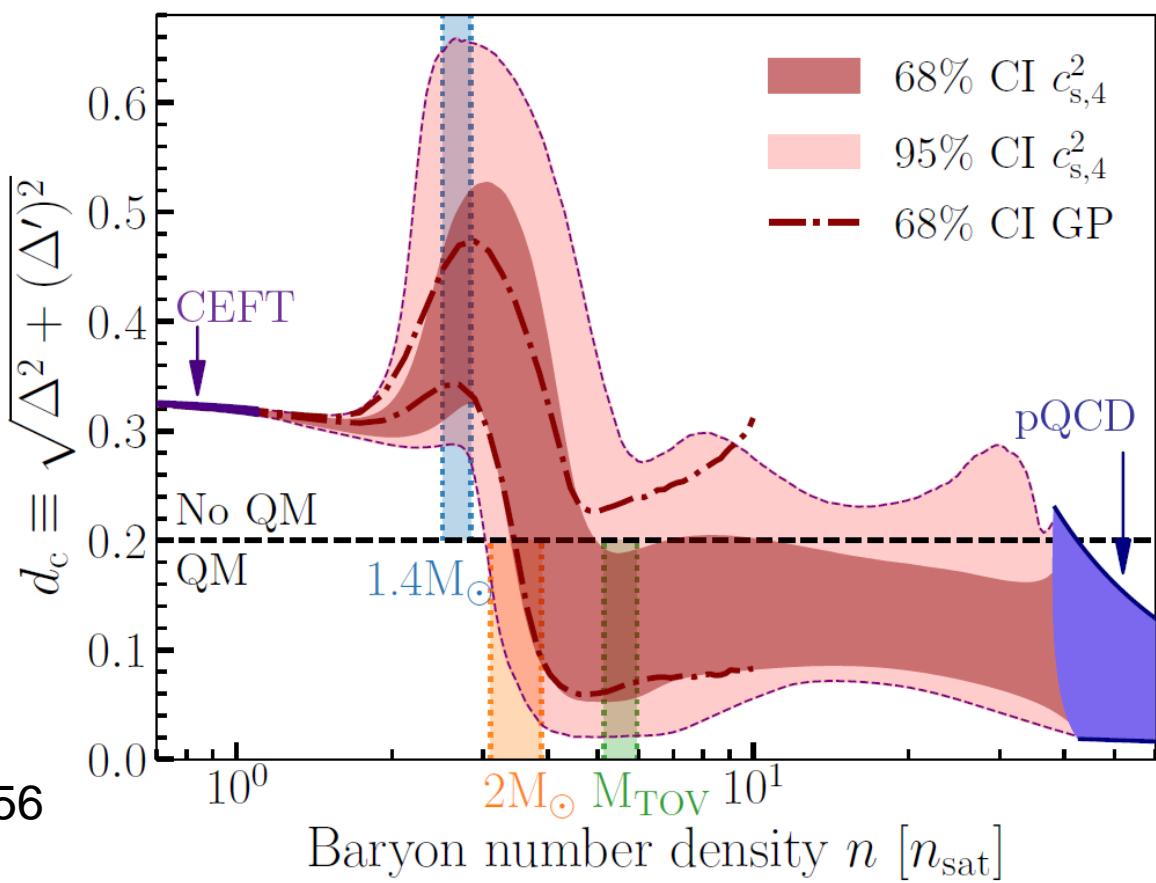


$$K_{\text{NM}}^{\text{TOV}} / \mu_B = -1.99^{+0.43}_{-0.44}$$

$$K_{\text{NM}}^{\text{pQCD}} / \mu_B = -\frac{3}{2}$$

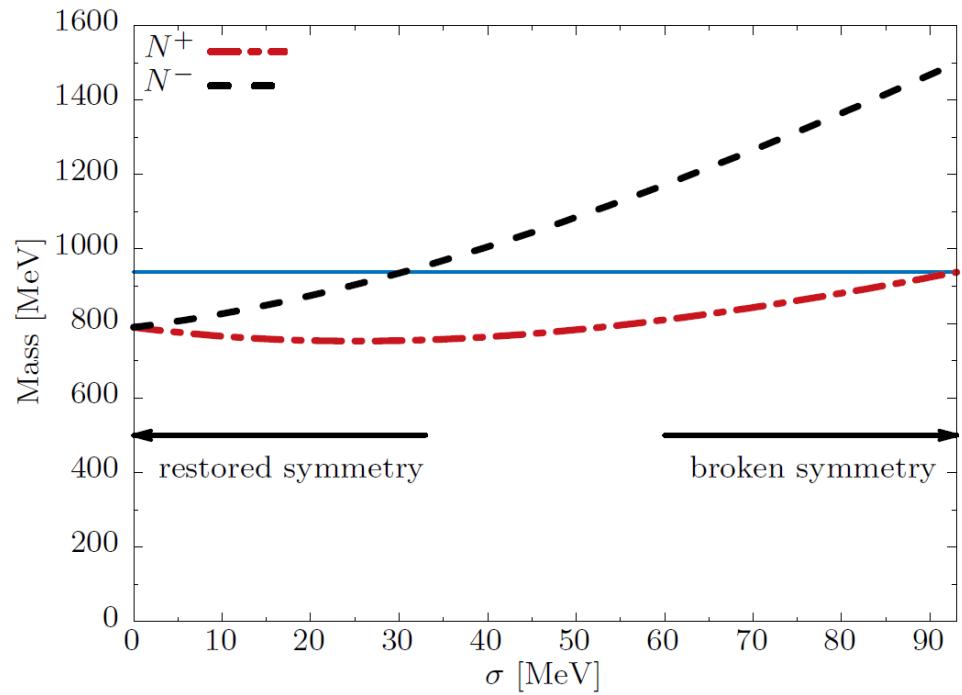
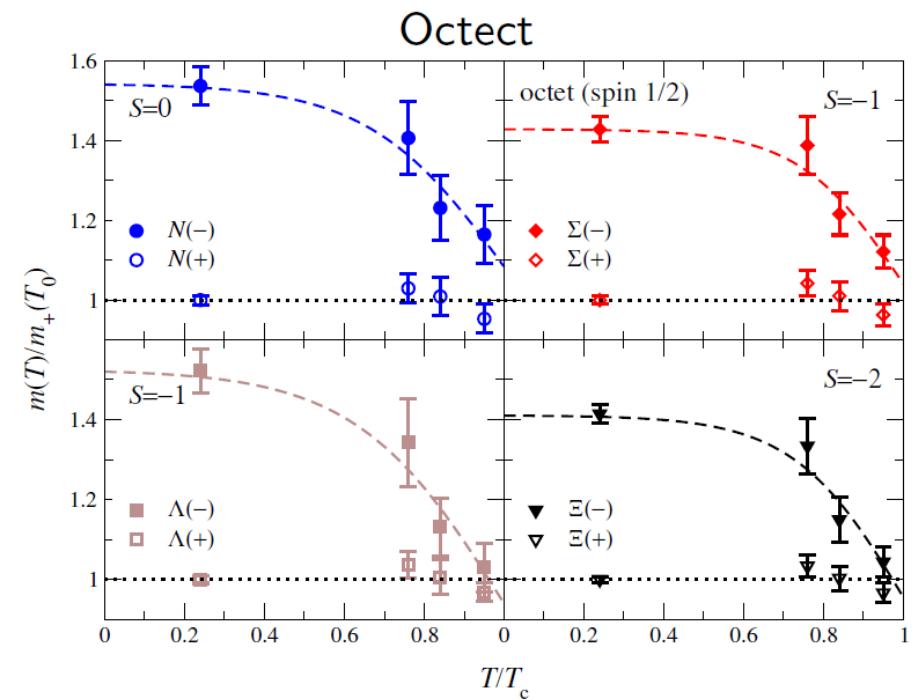


**Sign change:
from hadronic to quark/exotic**



HIGH-DENSITY MATTER IN EFFECTIVE THEORY

Parity doubling of baryons



❑ Lattice QCD at zero μ

[Aarts et al., 2016]

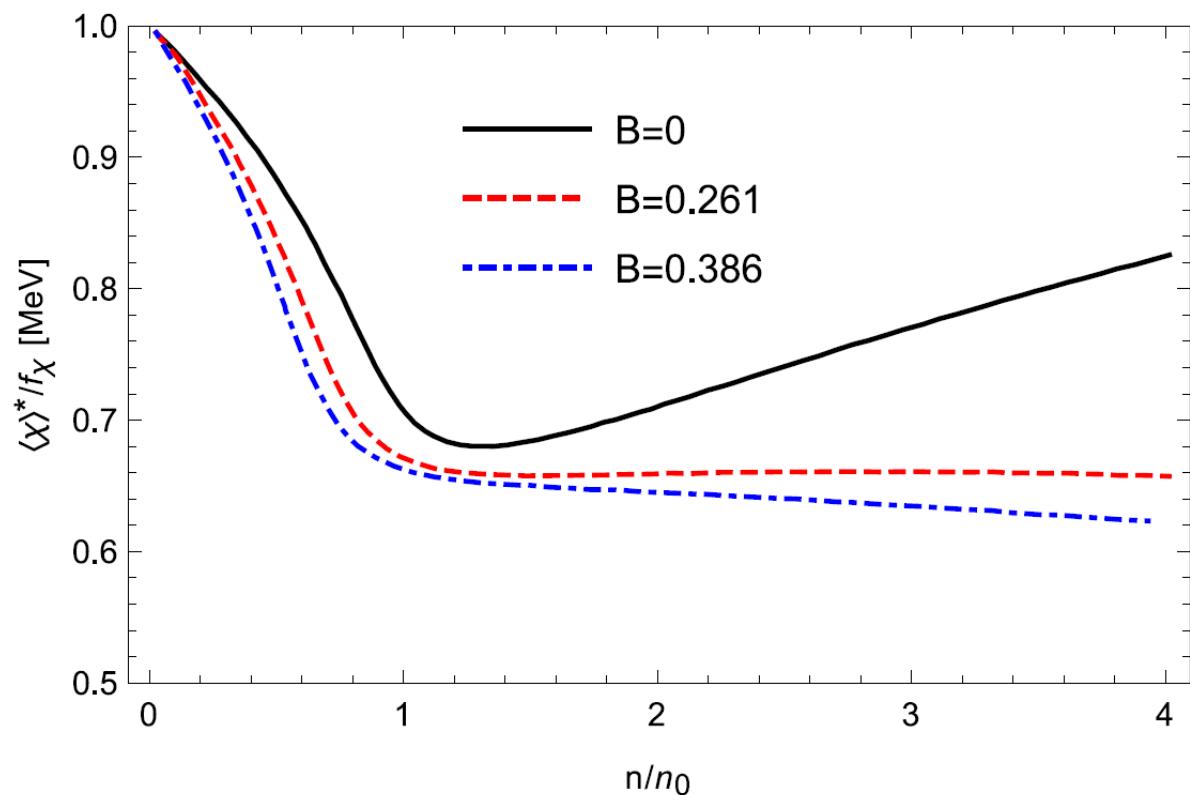
❑ Survival mass $m_N \approx m_0 \neq 0$

[DeTar, Kunihiro, 1989]

$$M_{\pm} = \sqrt{m_0^2 + c_1^2 \sigma^2} \mp c_2 \sigma \xrightarrow{\sigma \rightarrow 0} m_0$$

Emergent parity doubling

- Chiral EFT of π , ω and χ (dilaton): scale inv.
- Interplay between the m_N^* and ω NN int.



$$\frac{g_{v\omega}^* - 1}{g_{v\omega} - 1} = \frac{1}{1 + Bn/n_0}$$

$$m_N^* \propto \langle \chi \rangle^* \propto m_0$$

Trace anomaly with parity doubling

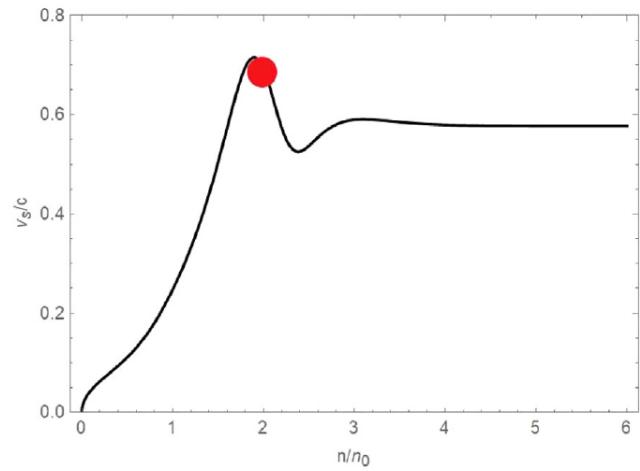
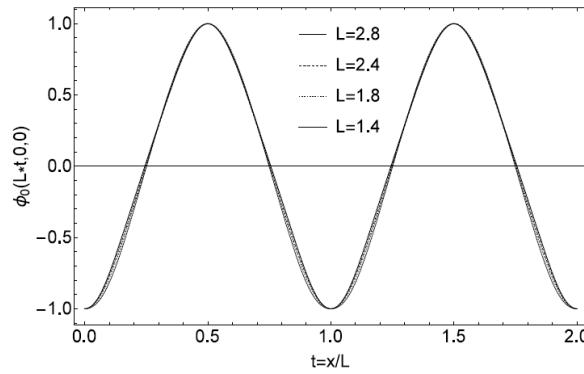
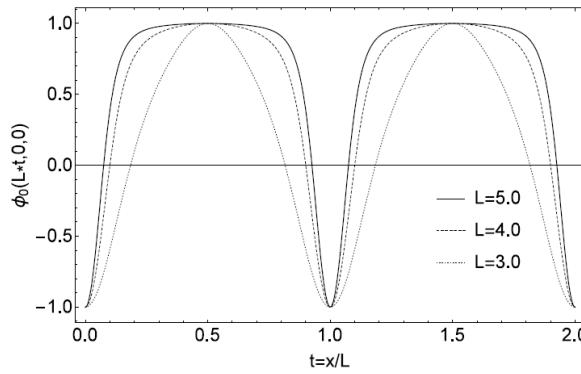
$$\langle \theta_\mu^\mu \rangle = \langle \theta^{00} \rangle - \sum_i \langle \theta^{ii} \rangle = \epsilon - 3P = 4V(\langle \chi \rangle) - \langle \chi \rangle \left. \frac{\partial V(\chi)}{\partial \chi} \right|_{\chi=\langle \chi \rangle}$$

□ Trace of EMT = $f(m_0)$

$$\frac{\partial}{\partial n} \langle \theta_\mu^\mu \rangle = 0 \quad \rightarrow \quad v_s^2 = \frac{1}{3}$$

[Paeng et al., (2016,17)]

□ Skyrme model with χ at high density



Scale invariance in the half-skyrmion phase

Summary

- ✓ Centers of maximally massive NSs may contain conformal matter.
- ✓ Maximum in c_s^2 consistent with percolation threshold.

□ Baryons at high density → CS restoration

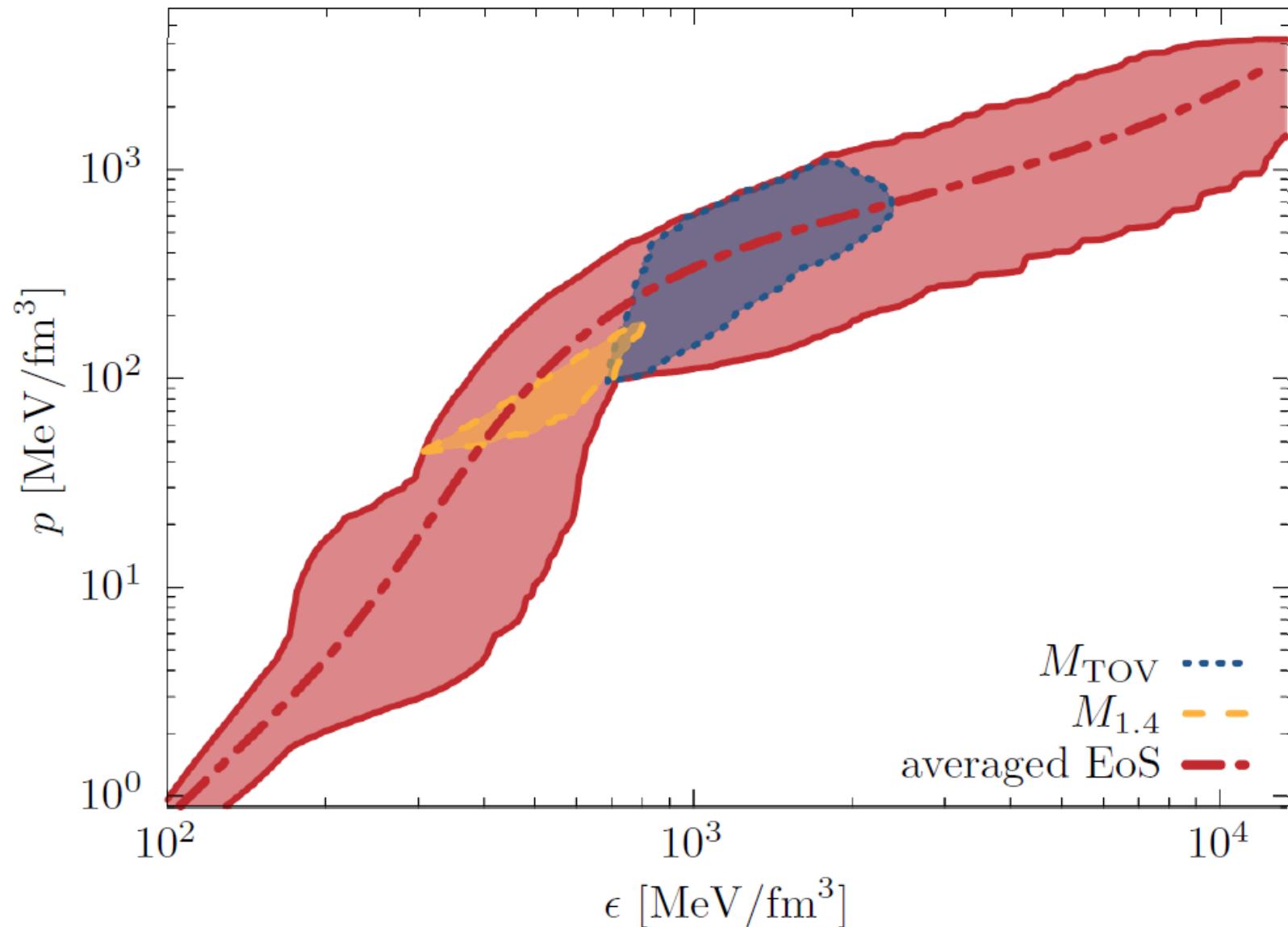
- $\gamma < 1.75$ at $\varepsilon \approx 400 - 700$ MeV/fm³
- $c_s^2 > 1/3$ at $\frac{\rho_B}{\rho_0} \approx 2 - 3$ Marczenko, Redlich, CS,
Astrophys.J.Lett. & Phys.Rev.D (2022)

Talk by Michal Marczenko, TODAY at 14:40, Ballroom C

□ Emergence of (pseudo-)conformal symmetry

BACKUP SLIDES

Equation of State



Proton radius not well established

