Reaching percolation and conformal limits in neutron stars

Michał Marczenko, Larry McLerran, Krzysztof Redlich, Chihiro Sasaki

based on arXiv:2207.13059 [nucl-th]

22nd ZIMÁNYI SCHOOL
WINTER WORKSHOP ON HEAVY ION PHYSICS
December 5-9, 2022

Big question: quark matter in neutron stars?

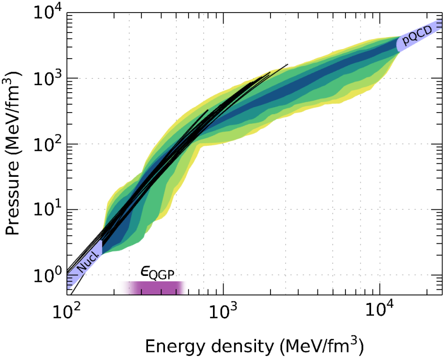
- Solid constraints:
  - low density ($n < 1.1n_0$): χEFT Tews *et al* (2013)
  - high density ($n > 40n_0$): pQCD Gorda *et al* (2018)
- Interpolation: multipolytropes, CSS

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

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

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

Annala *et al* Nature Physics (2020)



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

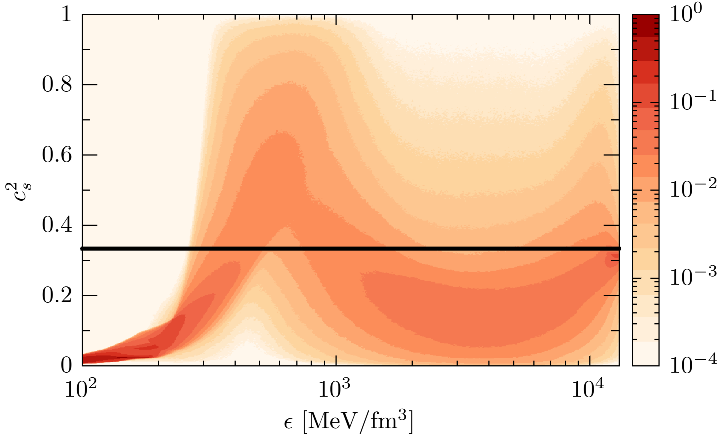
1. Generate an ensemble of EoSs in agreement with χEFT and pQCD

$$c_{s,i}^2 = \frac{(\mu_i - \mu)c_{s,i}^2 + (\mu - \mu_i)c_{s,i+1}^2}{\mu_{i+1} - \mu_i}, \quad c_s^2 = \frac{n_B}{\mu_B}\frac{d\mu_B}{dn_B}$$

2. Filter EoSs through astro constraints: $2M_\odot$ + tidal deformability from GW170817

General Structure of Speed of Sound

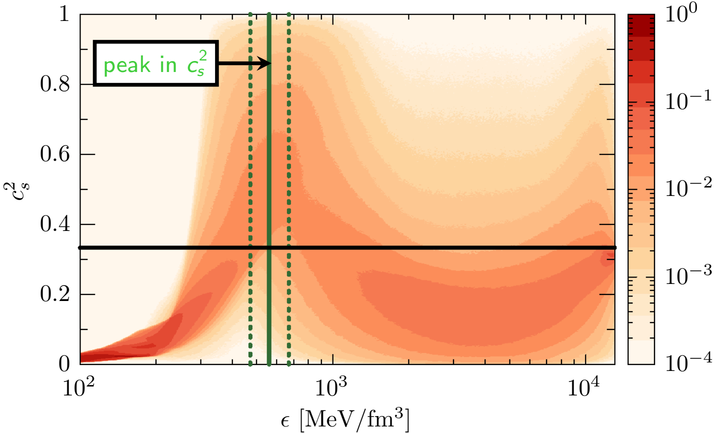
MM, L. McLerran, K. Redlich, C. Sasaki, arXiv:2207.13059 (2022)



- General peak-dip structure Altiparmak *et al* (2022); Ecker, Rezzolla (2022)
- Peak similar to quarkyonic description of matter McLerran, Reddy PRL (2019)

General Structure of Speed of Sound

MM, L. McLerran, K. Redlich, C. Sasaki, arXiv:2207.13059 (2022)

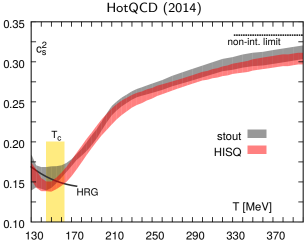


- General peak-dip structure Altiparmak *et al* (2022); Ecker, Rezzolla (2022)
- Peak similar to quarkyonic description of matter McLerran, Reddy PRL (2019)
- Local maximum at $\epsilon_{\text{peak}} = 0.56^{+0.11}_{-0.09}$ GeV/fm^3 with $c_s^2 = 0.82 \pm 0.08$

Speed of sound: hot vs dense QCD

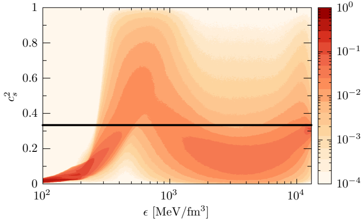
$$\text{Hot QCD: } c_s^2 = \frac{S}{T}\frac{dT}{dS} < 1/3$$

- Attractive interactions with resonance formation
- MIN: $\epsilon = 0.42 \pm 0.06 \ \mathrm{GeV/fm^3}$
- Chiral symmetry restoration and deconfinement



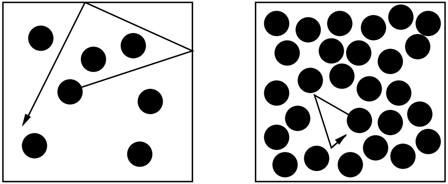
$$\text{Dense QCD: } c_s^2 = \frac{n}{\mu}\frac{d\mu}{dn} > 1/3$$

- Dominance of repulsive interactions
- MAX: $\epsilon = 0.56^{+0.11}_{-0.09} \ \mathrm{GeV/fm^3}$, $n_c = 0.56^{+0.09}_{-0.08} \ \mathrm{fm^{-3}}$
- Onset of quark or quarkyonic matter? McLerran, Reddy (2019)



NON-MONOTONICITY $\Longrightarrow$ CHANGE OF PHASE

Percolation theory and deconfinement



Castorina *et al* (2009)

- Percolation theory: $n_c = 1.22/V_0$ see, e.g., Satz (1998); Castorina *et al* (2009); Fukushima *et al* (2020)
- Avg. proton radius: $R_0 = 0.80 \pm 0.05\ \mathrm{fm}$ Wang *et al* (2022) $\longrightarrow n_c = 0.57^{+0.12}_{-0.09}\ \mathrm{fm}^{-3}$
- Pb-Pb collisions at $\sqrt{s} = 2.76\ \mathrm{TeV} \rightarrow n_c = 0.60 \pm 0.07\ \mathrm{fm}^{-3}$ at phase boundary

PERCOLATION THRESHOLD $\Longleftrightarrow$ MAXIMUM OF SPEED OF SOUND

Appearence of maximum in c_s^2

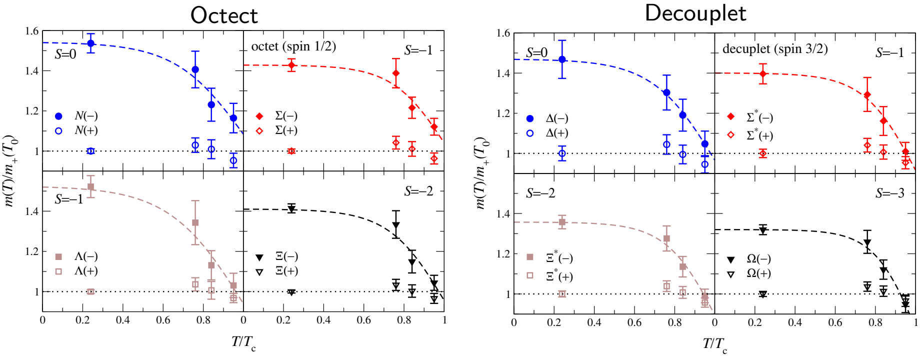
$\Downarrow$

Change in medium composition

$\Downarrow$

Limited applicability of hadronic models

Chiral symmetry (partially) restored already in the hadronic phase



Aarts *et al* PRD (2019)

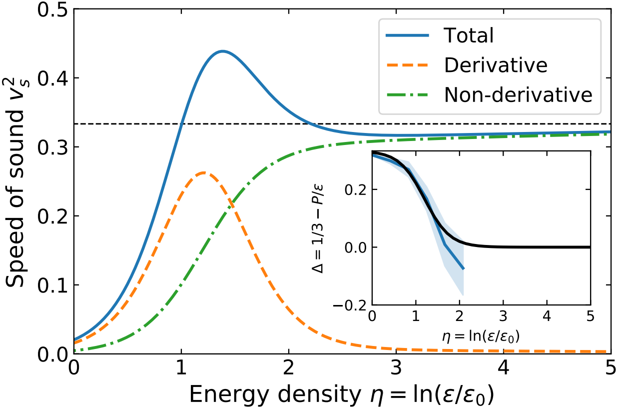
- Chiral symmetry is fundamental and should be included in NS EoS Marczenko *et al* ApJL (2022)
  - parity doublet model

    DeTar, Kunihiro PRD (1989); Jido *et al* PTEP (2000); Zschiesche *et al* PRC (2007)
  - + deconfinement

    Benic, Mishustin, Sasaki PRD (2015), Steinheimer *et al* PRC 2011, Marczenko *et al* A&A (2020)
  - + topology at Fermi surface

    Kojo PRD (2021)

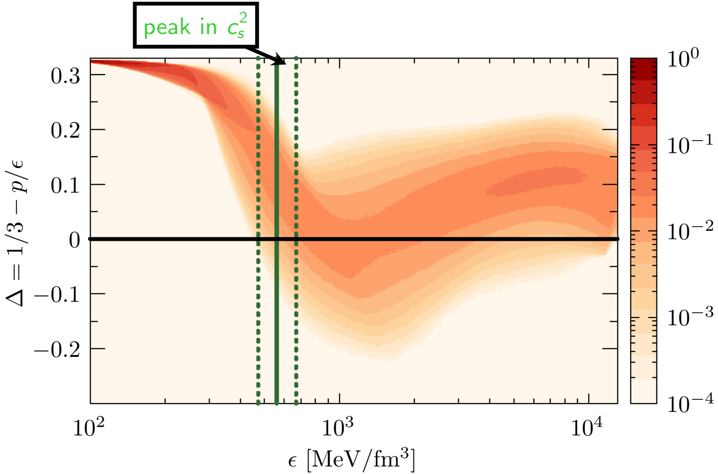
Speed of sound expressed as trace anomaly Fujimoto *et al* (2022)



Trace anomaly: $\Delta \equiv \dfrac{\epsilon - 3p}{3\epsilon} = \dfrac{1}{3} - \dfrac{p}{\epsilon}$ $\longrightarrow$ $c_s^2 = \dfrac{d\left(\epsilon \frac{p}{\epsilon}\right)}{d\epsilon} = \dfrac{1}{3} - \Delta - \epsilon \dfrac{d\Delta}{d\epsilon}$

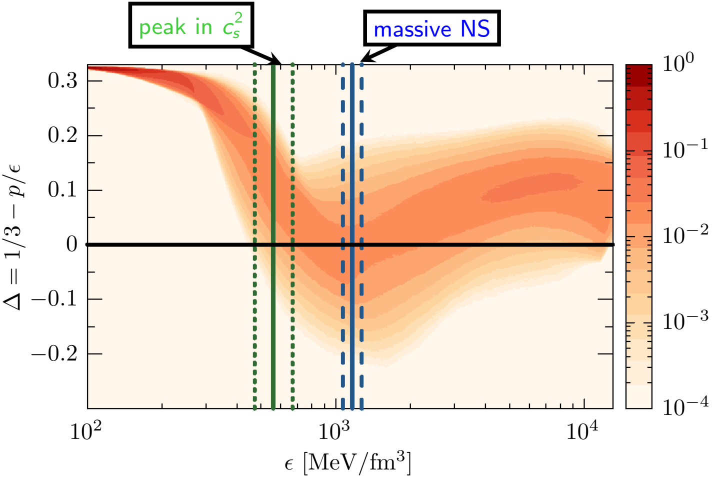
TRACE ANOMALY MORE INFORMATIVE THAN SPEED OF SOUND

Measure of comformality: trace anomaly



- Trace anomaly monotonic even if c_s^2 has a maximum
- Peak in c_s^2 → slope of Δ

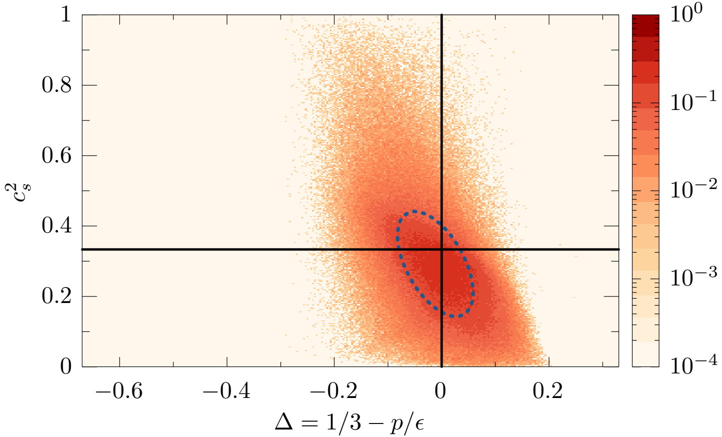
Measure of comformality: trace anomaly



- Trace anomaly monotonic even if c_s^2 has a maximum
- Peak in $c_s^2 \rightarrow$ slope of Δ
- $\Delta \simeq 0$ at $\epsilon \approx 1\ \mathrm{GeV/fm^3} \longleftrightarrow \epsilon_{\mathrm{TOV}} = 1.16 \pm 0.01\ \mathrm{GeV/fm^3}$

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

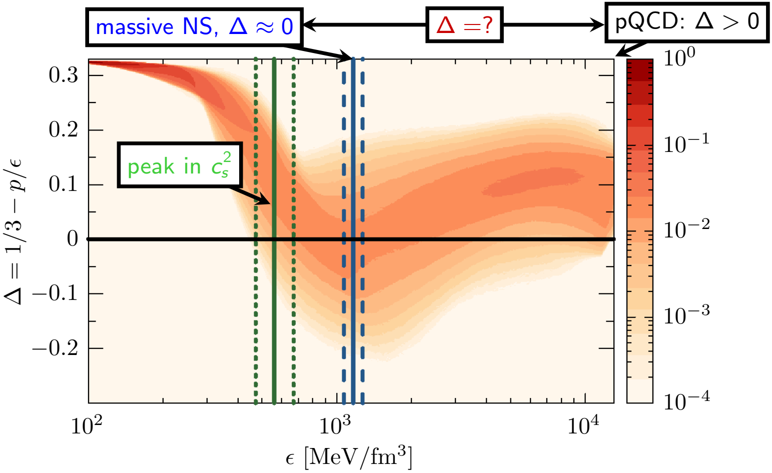
Conformality requires $c_s^2 = \frac{1}{3}$ and $\Delta = 0$



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

Matter almost conformal in the cores of maximally massive NSs

Fate of trace anomaly at large densities



massive NS, $\Delta \approx 0$

$\Delta = ?$

pQCD: $\Delta > 0$

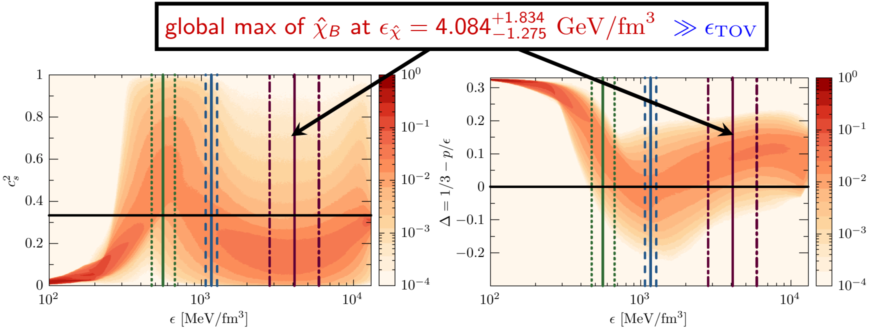
peak in c_s^2

- $\Delta(\epsilon > \epsilon_{\mathrm{TOV}}) \geqslant 0$ → consquences for mass-radius profile Fujimoto et al (2022)
- $\Delta(\epsilon > \epsilon_{\mathrm{TOV}}) < 0$ → reach pQCD → large fluctuations → remnants of criticality

Remnants of criticality: net-baryon density fluctuations

- Fluctuations are probes of criticality in BES Stephanov et al (1999); Karsch et al (2011); Friman et al (2011)

$$\hat{\chi}_B \equiv \frac{\chi_B}{\mu_B^2} = \frac{n_B}{\mu_B^3 c_s^2} \sim \frac{1}{c_s^2}$$


global max of $\hat{\chi}_B$ at $\epsilon_{\hat{\chi}} = 4.084^{+1.834}_{-1.275}\ \mathrm{GeV/fm^3} \gg \epsilon_{\mathrm{TOV}}$

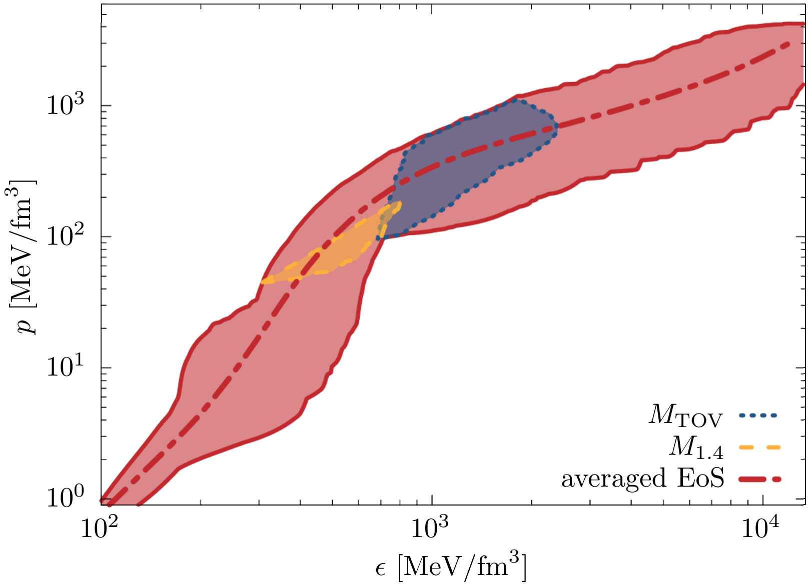
Remnants of criticality with large χ_B unlikely to be found in the cores of NSs

Summary

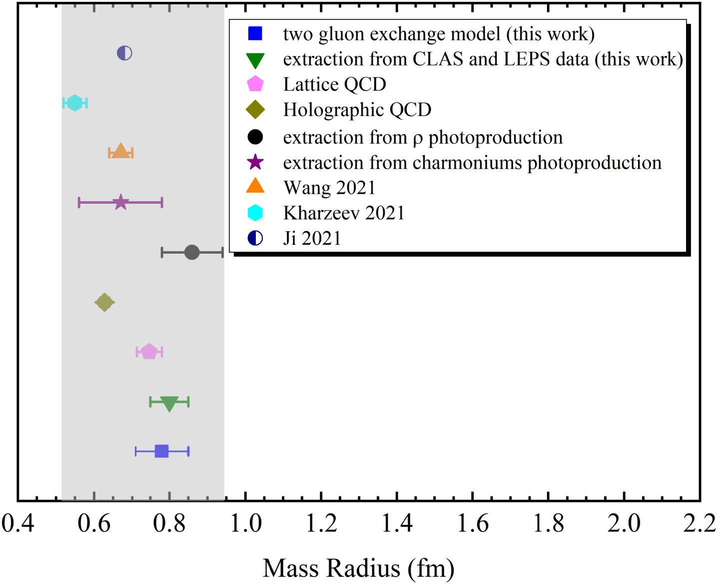
- Centers of maximally massive NSs may contain conformal matter
- Maximum in c_s^2 consistent with percolation threshold
- Remnants of criticality unlikely to be found in NSs

Thank You

Equation of State



Proton radius not well established



Wang *et al* (2022)