Reaching percolation and conformal limits in neutron stars

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XVth Quark Confinement and the Hadron Spectrum
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Big question: quark matter in neutron stars?

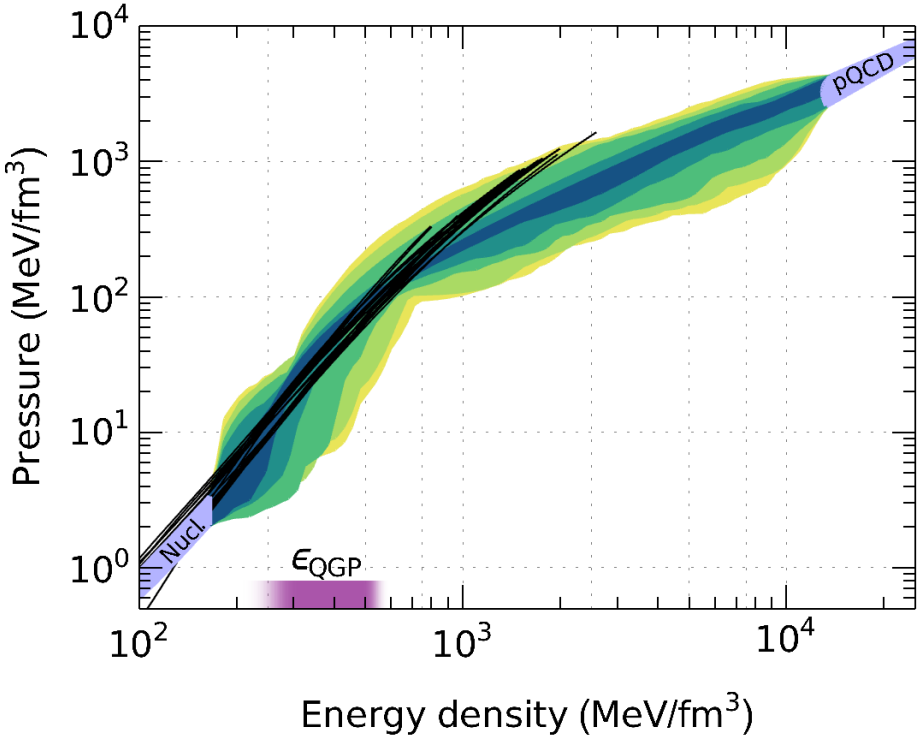
- Solid constraints:
  - low density ($n < 1.1 n_0$): χEFT Tews *et al* (2013)
  - high density ($n > 40 n_0$): pQCD Gorda *et al* (2018)
- Interpolation: multipolytropes, CSS

  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: $\epsilon_{\rm QGP} \approx 400 - 700 {\rm MeV/fm}^3$

Annala *et al* Nature Physics (2020)

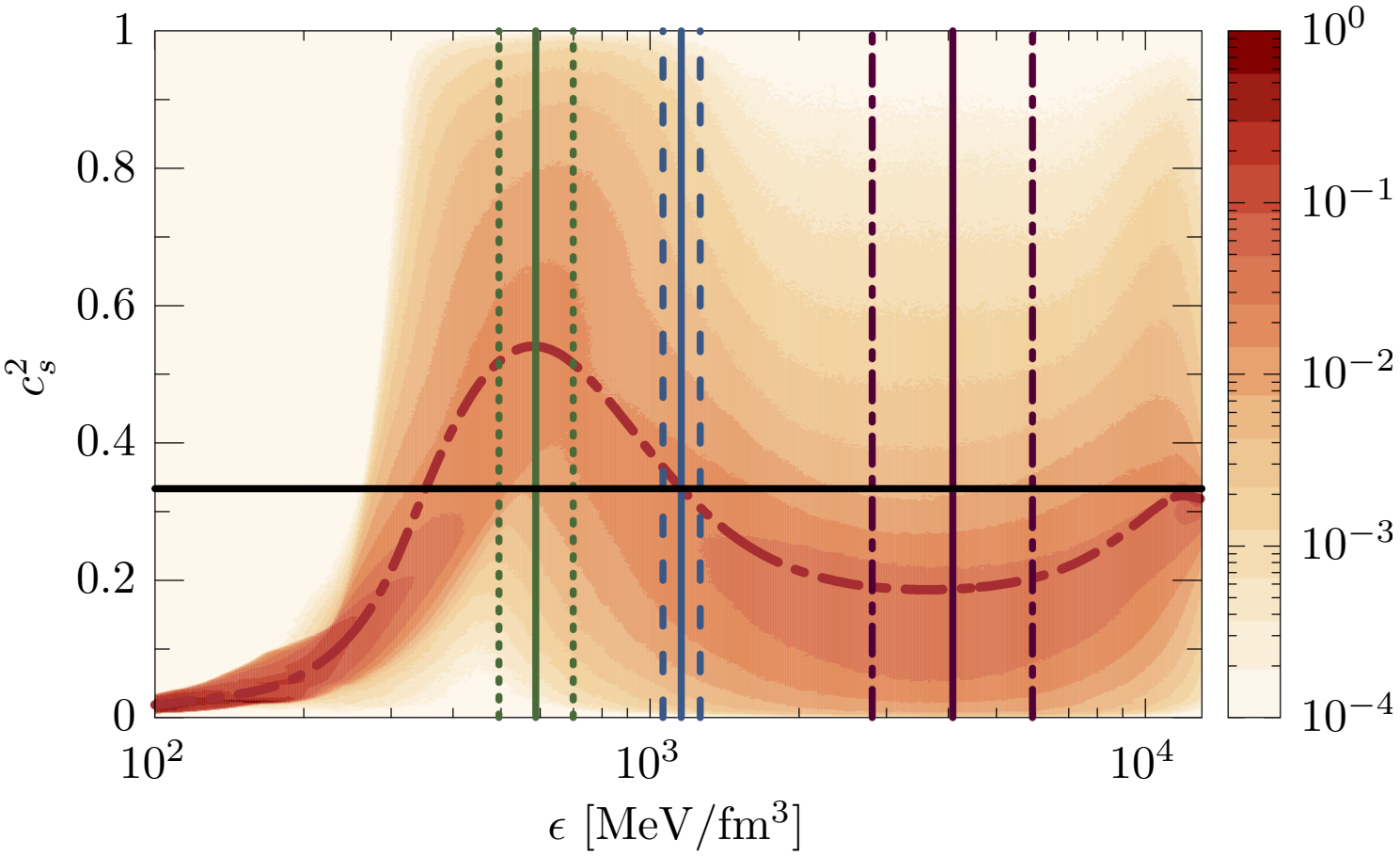


We follow the overall prescription:

- Piecewise-linear interpolation of c_s^2 + pQCD + $2M_\odot$ + tidal deformability

  used, e.g., in Annala *et al* (2020); Altiparmak *et al* (2022); Ecker, Rezzolla (2022)

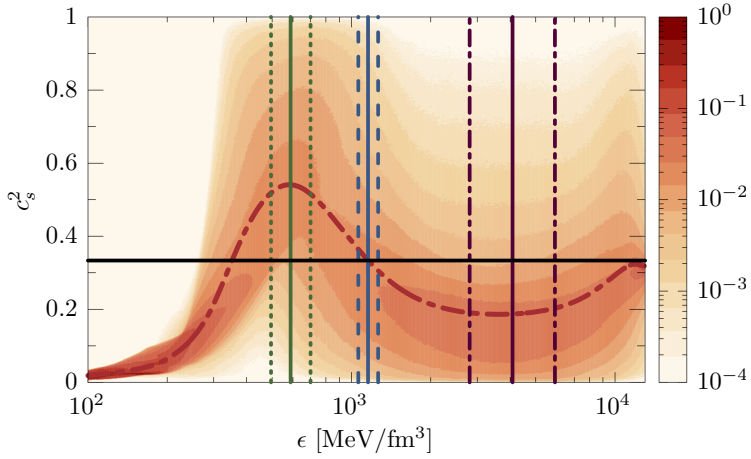
Speed of sound



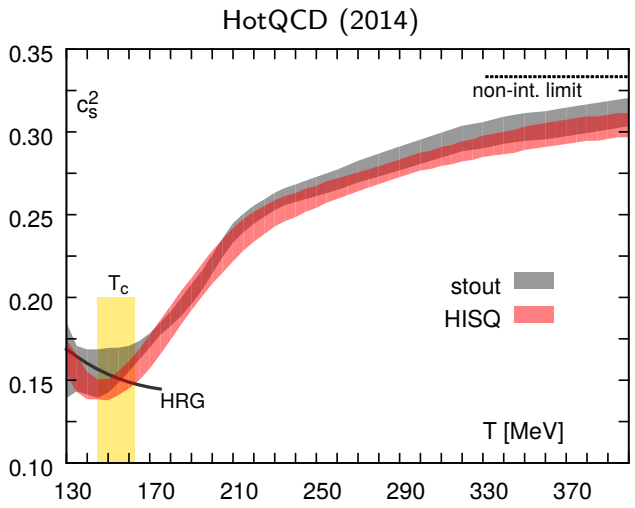
- General peak-dip structure Altiparmak *et al* (2022); Ecker, Rezzolla (2022)
- Local maximum around $\epsilon_{\rm peak} = 0.587\ {\rm GeV/fm^3}$ with $c_s^2 > 1/3$
- Peak similar to quarkyonic description of matter McLerran, Reddy PRL (2019)

Speed of sound: dense vs hot QCD

- Dense QCD: $c_s^2 > 1/3$
  - Dominance of repulsive interactions
  - MAX: $\epsilon = 0.587^{+0.112}_{-0.092}\ \mathrm{GeV/fm^3}$, $n = 0.56^{+0.09}_{-0.08}\ \mathrm{fm^{-3}}$
  - Onset of quark or quarkyonic matter? McLerran, Reddy (2019)



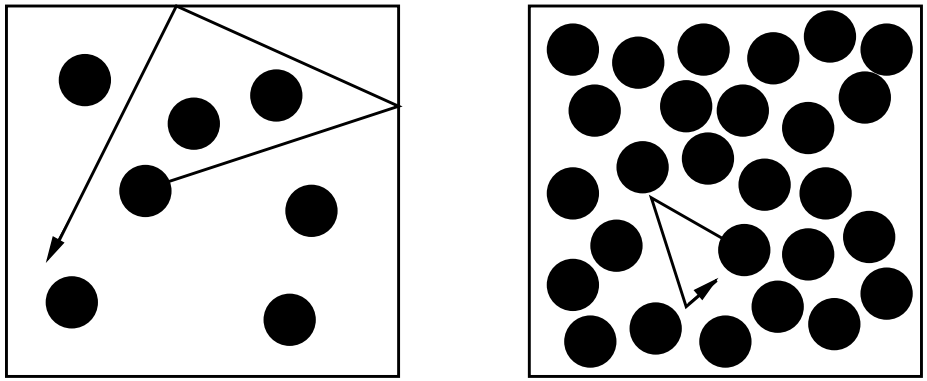
- Hot QCD: $c_s^2 < 1/3$
  - Attractive interactions with resonance formation
  - MIN: $\epsilon = 0.42 \pm 0.06\ \mathrm{GeV/fm^3}$
  - Chiral symmetry restoration and quark deconfinement



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

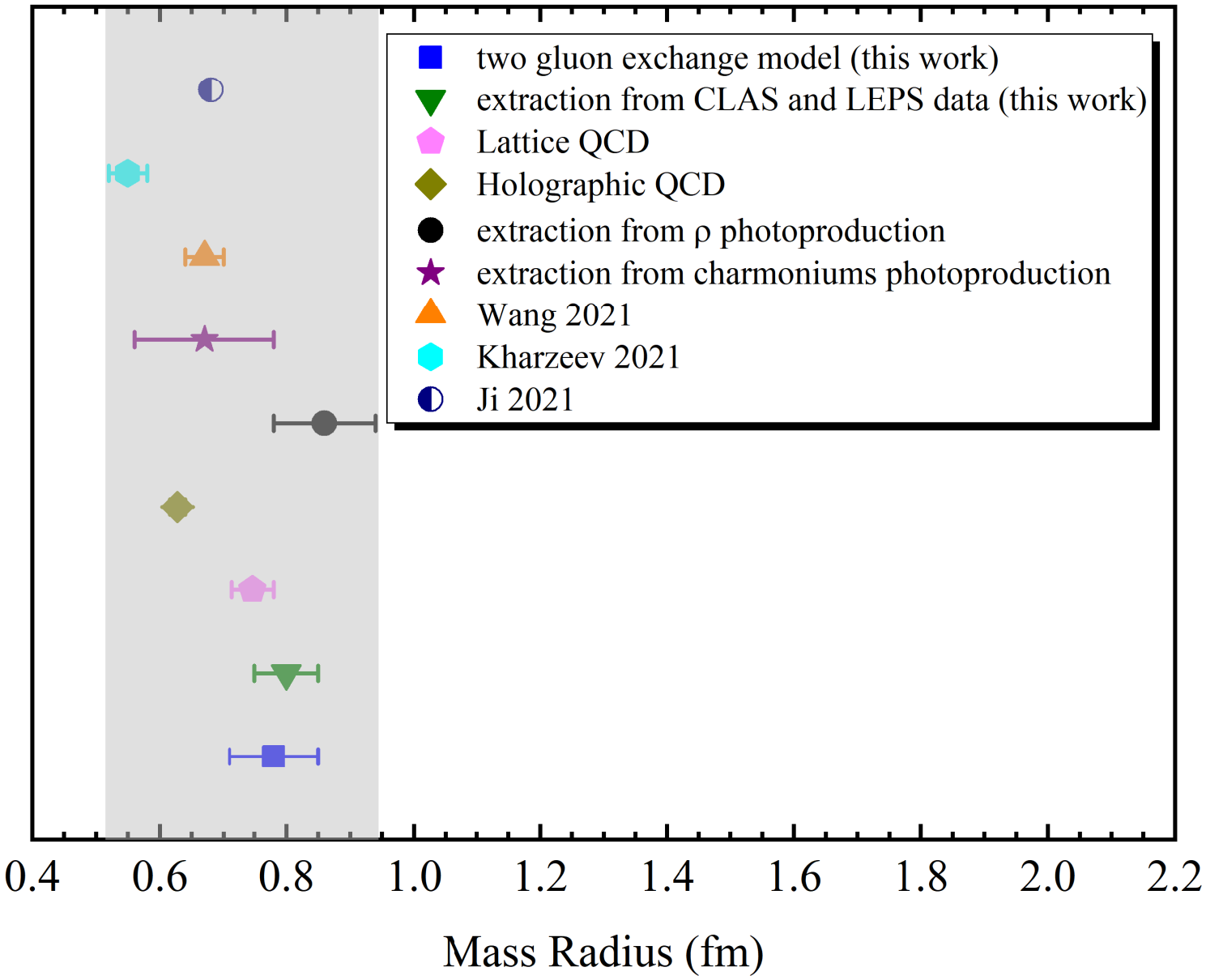
$\Downarrow$

Change in medium composition

$\Downarrow$

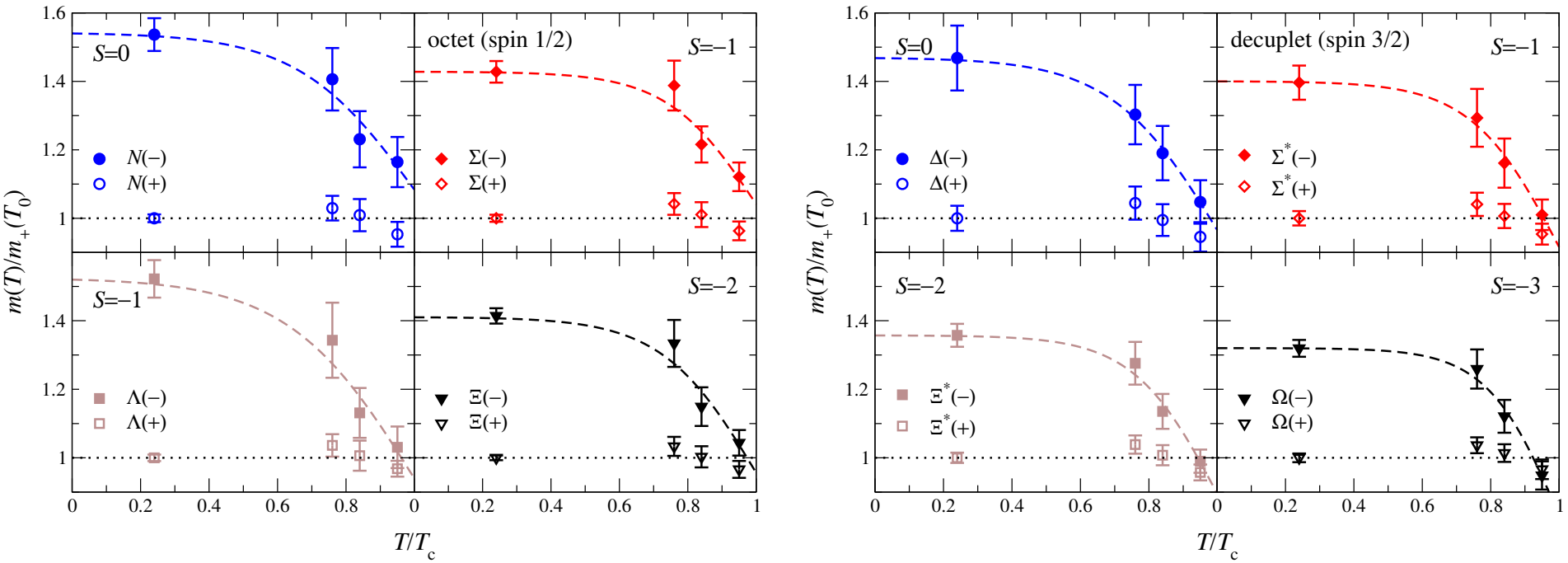
Limited applicability of hadronic (mean-field) models

However proton radius not well established



Wang *et al* (2022)

Chiral symmetry (partially) restored already in the hadronic phase



Aarts *et al* PRD (2019)

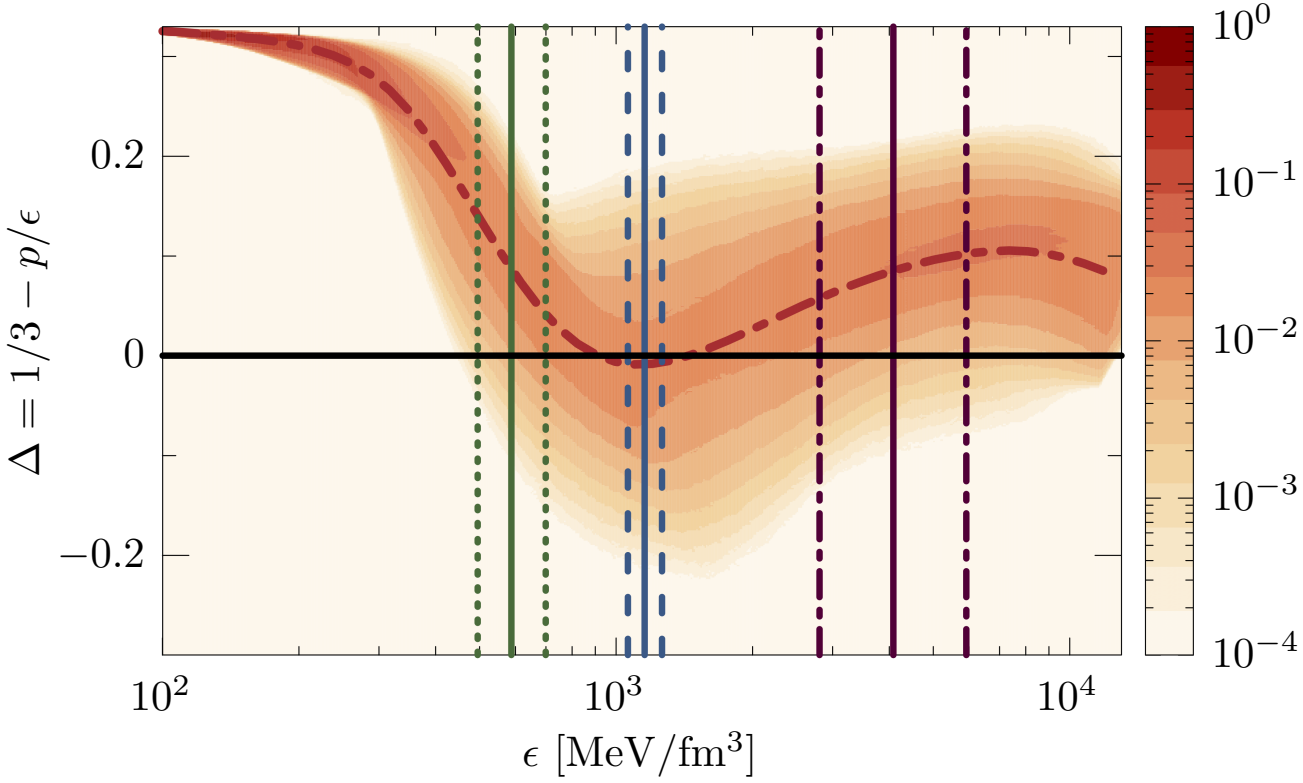
- Chiral symmetry is fundamental and should be included in NS EoS Marczenko *et al* ApJL (2022)
  - parity doublet model

    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)

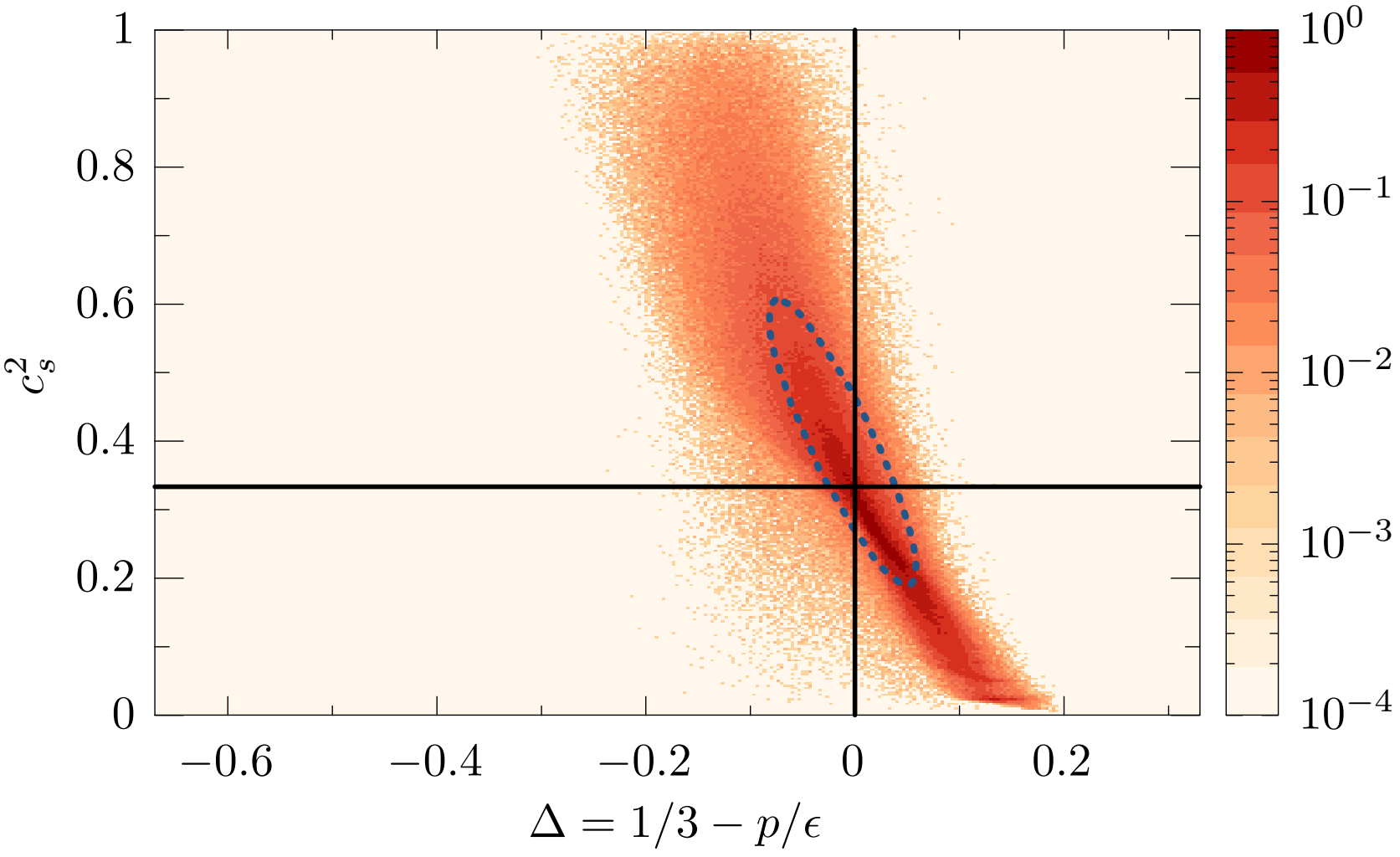
Measure of comformality: trace anomaly



- Trace anomaly: $\Delta = \frac{1}{3} - \frac{p}{\epsilon} \quad \longrightarrow \quad c_s^2 = \frac{1}{3} - \Delta - \epsilon \frac{d\Delta}{d\epsilon}$
- Trace anomaly monotonic even if c_s^2 has a maximum
- $\Delta \simeq 0$ at $\epsilon \approx 1\ \mathrm{GeV/fm}^3$ Fujimoto *et al* (2022)

(see talk by Yuki Fujimoto; Section F; Thursday)

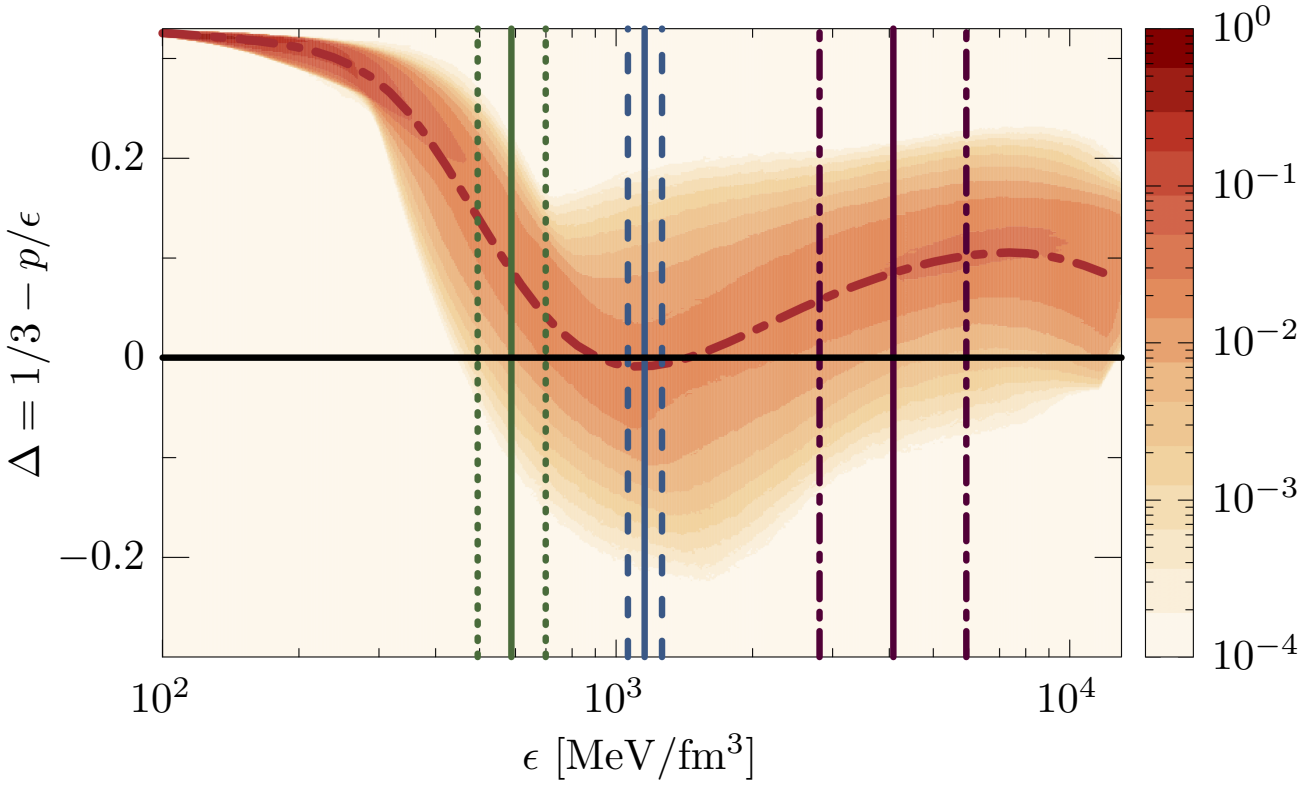
Sound speed and trace anomaly at the center of heaviest NS



Matter almost conformal in the cores of maximally massive NS

see also Annala *et al* Nature Physics (2020); Ecker, Rezzolla (2022)

Fate of trace anomaly at large densities



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

Remnants of criticality: baryon density fluctuations

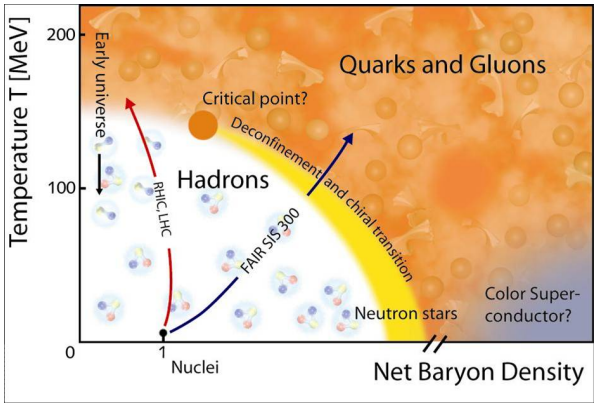
- Fluctuations $\rightarrow$ probes of criticality in BES

  Stephanov et al (1999); Karsch et al (2011); Friman et al (2011); Bazavov et al (2012)

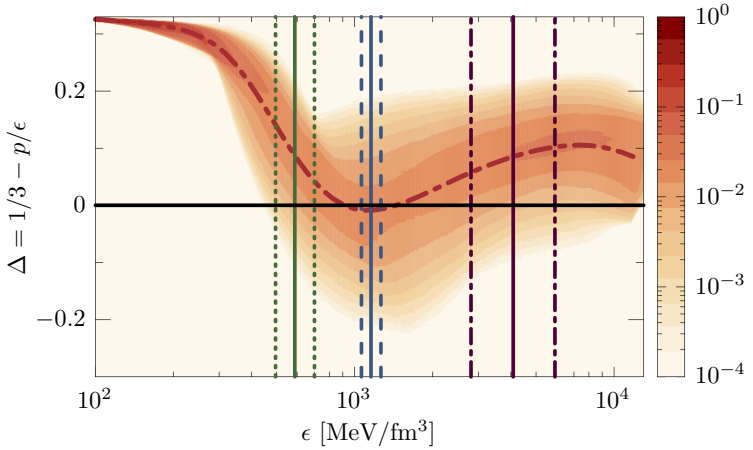
- Comulants sensitive to critical fluctuations:

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

- In QCD: chiral CP $\in Z(2) \rightarrow$ divergence at CP
- Min of $c_s^2 \sim$ Max of $\Delta \sim$ Max of χ_B
- Global maximum $\rightarrow$ largest fluctuations



- $> 93\%$ beyond gravitational stability
- $\epsilon_\chi = 4.084^{+1.834}_{-1.275}\ \mathrm{GeV/fm^3}$



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

Summary

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

Thank You