Emergent conformality in high-density matter

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Abstract. This contribution discusses baryon-rich matter in the context of recent astrophysical observations of neutron stars (NSs) and the structure of the equation of state that arises from these observations. We show that, generating an ensemble of equations of state that fulfill multimessenger constraints, the speed of sound and trace anomaly can reach their conformal values at the center of maximally massive NSs. The local peak of the speed of sound appears at values of the energy and particle densities being consistent with deconfinement and percolation conditions of QCD phase transition. Some implications of advocating a pseudo-conformal symmetry in dense matter are presented.

1 Introduction

Neutron Stars (NSs) are the densest objects found in the Universe, with densities reaching up to few times the saturation density ($n_{\text{sat}} = 0.16~\text{fm}^{-3}$). Besides nuclear matter, they are expected to host exotic forms of matter, such as quark matter. Appearence of a new form of matter is usually leads to nonmonotonic behavior of the equation of state (EoS). The structure of EoS is reflected in the behavior of the speed of sound,

$$c_s^2 = \frac{\mathrm{d}p}{\mathrm{d}\epsilon}, \tag{1}$$

where p and ϵ are the pressure and energy density. At zero temperature, the speed of sound can be expressed as follows

$$c_s^2 = \frac{n}{\mu}\frac{\mathrm{d}\mu}{\mathrm{d}n}. \tag{2}$$

At low densities, the EoS is known from the chiral effective field theory (χEFT) calculations. Asymptotically, the speed of sound reaches the conformal value of $1/3$, which is confirmed by perturbative QCD (pQCD) calculations. However, its behavior at intermediate densities relevant for NSs is not precisely known. The progress in constraining the EoS of dense matter was achieved by analyses of recent multimessenger astrophysical observations (see, e.g., [2]).

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Recently, trace anomaly was proposed as an effective measure of conformality [1],

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

The scale invariance requires $\Delta = 0$ and $c_s^2 = 1/3$. In Ref. [1] it was argued that a local maximum in the speed of sound is a consequence of a swift restoration of conformality. This is in stark contrast to a first-order hadron-quark phase transition, where the speed of sound vanishes.

In this contribution, we briefly present the properties of the speed of sound and link them to the percolation of nucleons. It is demonstrated that matter inside the cores of maximally massive NSs becomes almost conformal based on an statistical approach [3].

2 Conformality in neutron stars

We construct an ensemble of EoSs based on the piecewise-linear speed-of-sound parametrization. The detailes of the parametrization can be found in [4]. In Fig. 1, we show the confidence intervales (CIs) of the speed of sound and trace anomaly. The speed of sound increases at low densities and generates a peak above the conformal value 1/3. At high densities it converges to the pQCD result from below. Notably, the peak in c_s^2 appears at densities below the densities reached in the centers of the most massive NSs. The trace anomaly decreases monotonically up to $\simeq \epsilon_{\rm TOV} = 1.073^{+0.071(0.267)}_{-0.070(0.202)}$ GeV/fm^3. Subsequently, it increases and approaches the conformal limit, $\Delta = 0$ from above. We find the medians of the speed of sound and trace anomaly found at the centers of the most massive neutron stars $c^2_{s,\rm TOV} = 0.28^{+0.06(0.27)}_{-0.06(0.20)}$ and $\Delta_{\rm TOV} = -0.02^{+0.03(0.10)}_{-0.03(0.11)}$. They are remarkably close to their conformal values $c_s^2 = 1/3$ and $\Delta = 0$. Thus, the matter in the centers of maximally massive NSs contain matter that is almost conformal.

The peak in the speed of sound at $\epsilon_{\rm peak} = 0.500^{+0.087(0.446)}_{-0.067(0.166)}$ GeV/fm^3. The peak in the speed of sound can be phenomenologically linked to deconfinement within the percolation threshold in QCD. The critical percolation density of hadrons of a given size, $V_0 = (4/3)\pi R_0^3$, can be estimated as $n_c^{\rm per} = 1.22/V_0$ [5–9]. By considering the proton mass radius extracted from the experimental data of ϕ photoproduction measured by CLAS and LEPS collaborations [10–12], one gets $n_c^{\rm per}/n_{\rm sat} = 3.56^{+0.75}_{-0.56}$, which is consistent with our estimate for the density at which the speed of sound reaches its maximum $n_{\rm peak}/n_{\rm sat} = 3.04^{+0.43(1.94)}_{-0.35(0.88)}$. Similar value of the particle density is obtained based on thermal model analyses of particle production in heavy-ion collisions in Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV. There, one gets $n_c/n_{\rm sat} = (3.73 \pm 0.41)$. This value is also consistent with our estimate of the position of the peak in c_s^2. We conclude that the appearance of the peak in the speed of sound found inside NSs can be associated with the change in the composition of the medium. Such nonmonotonicity has been recently proposed as a signal for the onset of quarkyonic matter [13].

3 High-density matter in effective theories

How does such a (pseudo-)conformal symmetry possibly emerge in QCD at high baryon density? Below we outline some phenomenological implications from chiral effective theories.

Nucleon parity partners, the lowest nucleon and $N^*(1535)$, are expected to become approximately degenerate at a high density because of chiral symmetry restoration and carry a common mass, $m_0 \neq 0$ [14]. A non-vanishing m_0 can be generated via a VEV of dilaton field $\langle\chi\rangle$ associated with scale symmetry breaking. The key finding is that, due to interplay

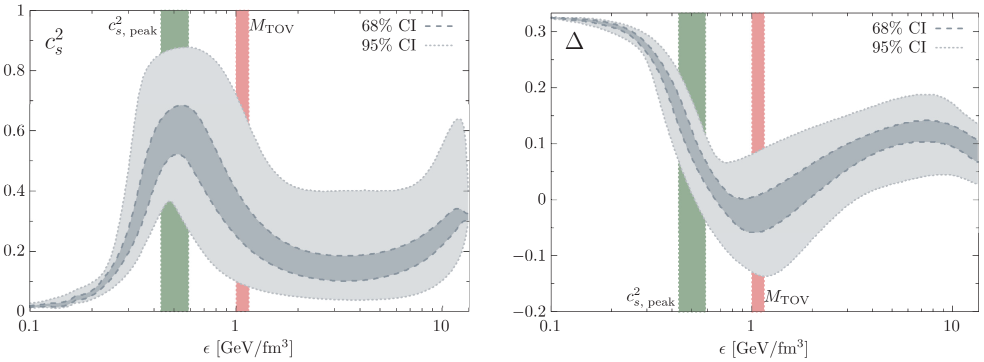

Figure 1. The speed of sound c_s^2 (left panel) and trace anomaly $\Delta = 1/3 - p/\epsilon$ (right panel) as functions of energy density. Shown are results at 1σ (68%) and 2σ (95%) confidence intervals. Green and red regions mark the 1σ estimates for energy density of the peak in the speed of sound and maximally stable neutron stars, respectively.

between the nucleon mass and the repulsion mediated by the omega meson, a nearly-constant $\langle\chi\rangle \sim m_N \sim m_0$ appears in dense nuclear matter [15].

One readily constructs the trace anomaly with the degenerate parity doublet as a function of m_0, leading to $c_s^2 = 1/3$. Scale invariance is indeed found in the half-skyrmion phase within the skyrmion-crystal simulation of dense matter [16]. It remains unclear why the scale symmetry is restored in this phase, but those findings indicate the intriguing interplay between the survival mass m_0 dominated by gluon dynamics and (partially) restored chiral symmetry at high baryon density.

4 Summary

We statistically determined the neutron star (NS) equation of state in view of current observational constraints and analyzed the properties of the speed of sound and trace anomaly. It is shown that the centers of maximally massive NSs contain matter that is nearly conformal. The peak in the sound velocity can be phenomenologically interpreted by connecting it to the phase boundary obtained in first-principles lattice QCD calculations and percolation threshold extracted from heavy-ion collisions. They are remarkably consistent with each other, which strongly indicates a phase change in dense matter.

The question to answer is the origin of emergent scale/confirmal symmetry and its mechanism in dense QCD matter. Its field theoretic formulation is vital for more fundamental understanding that can be possibly achieved within the application of advanced parity doublet models with the elusive interplay between chiral symmetry breaking and deconfinement as well as a non-trivial topology at the Fermi surface.

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