Speed of sound of strong-interaction matter at supranuclear densities

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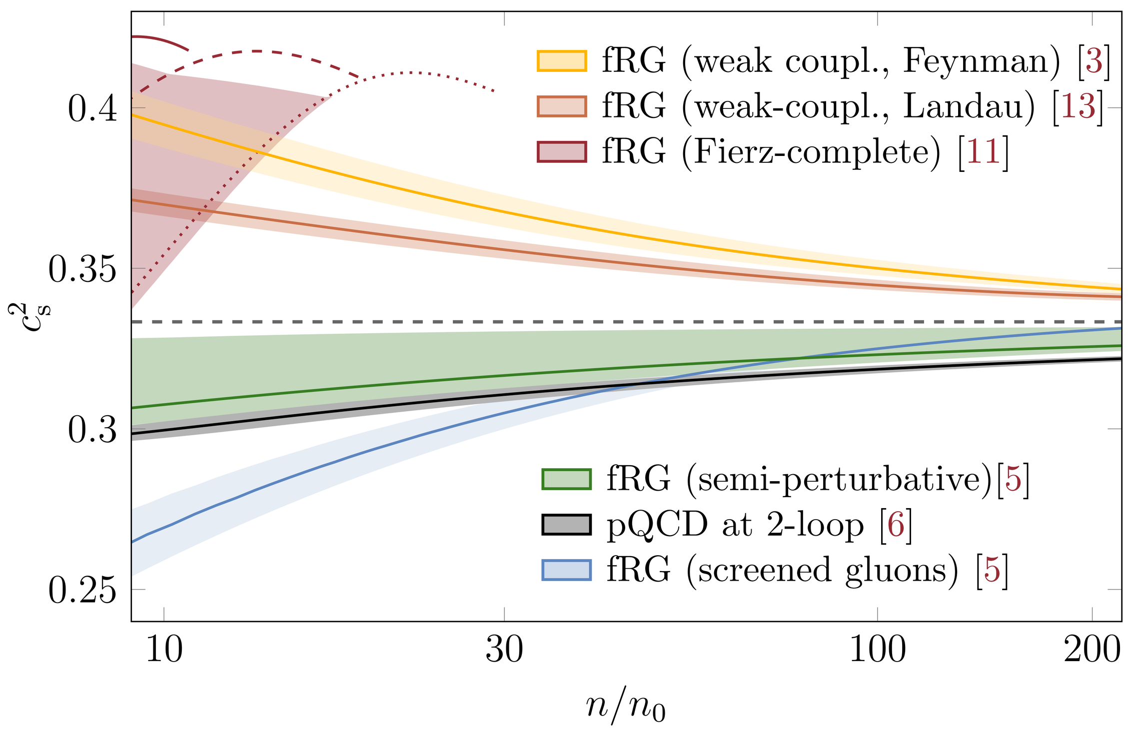
Abstract

We present results for the **zero-temperature thermodynamics** of **strong-interaction matter** at high densities which have been obtained based on first-principles functional Renormalization Group studies. In particular, we discuss **gluon screening effects** on the equation of state and the **speed of sound** in a (semi-)perturbative manner. Additionally, taking into account results from studies based on the existence of a **(color-)superconducting gap**, we present **consistent constraints** for the **speed of sound** at supranuclear densities.

Motivation

- In view of the progress in the observation of neutron stars, theoretical results for the speed of sound at high densities from quark-gluon dynamics are needed.
- First-principles studies which do not take into account a (color-) superconducting gap suggest that the speed of sound approaches the conformal (non-interacting) limit from below [1,2,5,6].
- On the other hand, initial functional Renormalization Group (fRG) studies which include a (color-)superconducting gap find that the speed of sound approaches this value from above [3].
- Taking into account gap-induced contributions and perturbative results (which do not take into account a gap), we analyze the behavior of the speed of sound at (very) high densities.



- We use the functional Renormalization Group (fRG) method (Wetterich equation [4]):

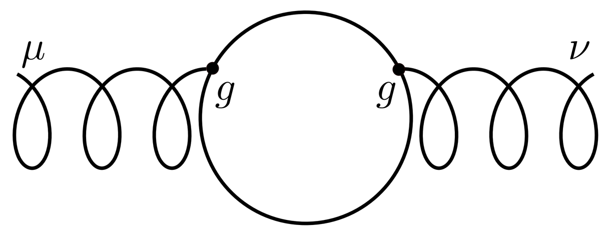
$$\partial_t \Gamma_k = \frac{1}{2}\mathrm{STr}\left\{\left[\Gamma_k^{(1,1)} + R_k\right]^{-1} \cdot \partial_t R_k\right\}.$$

- The classical (Euclidean) action of Quantum Chromodynamics (QCD) for two massless quark flavors coming in three colors is given by

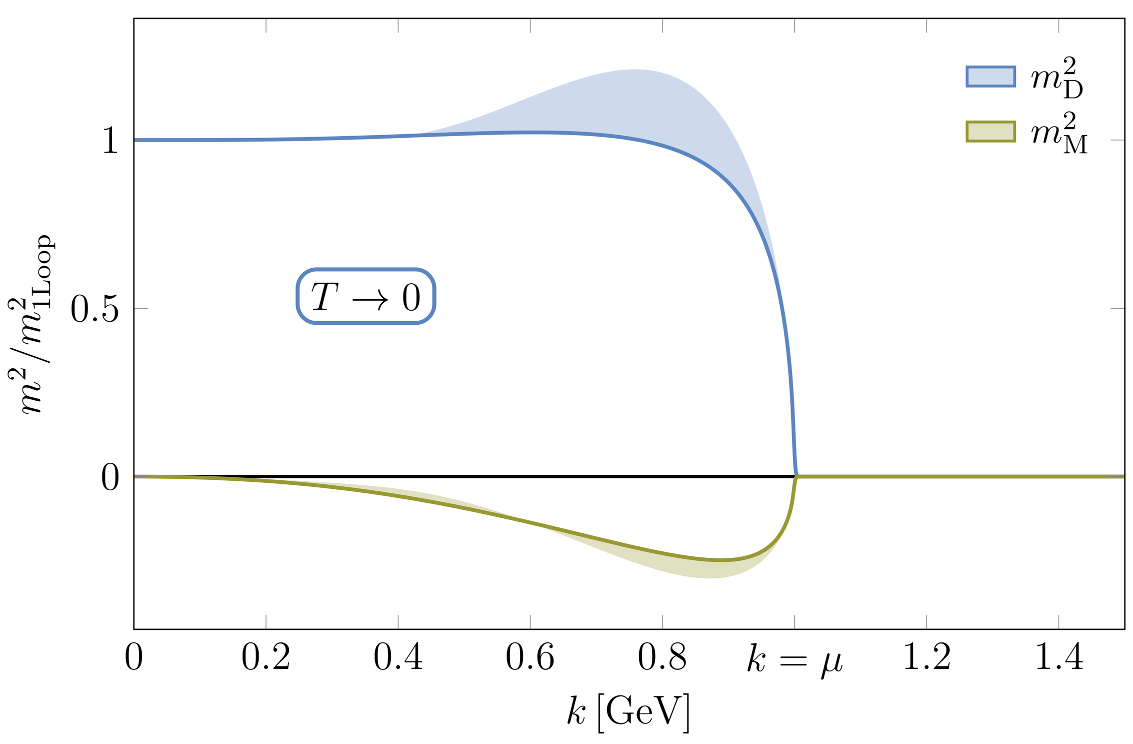
$$S = \int \mathrm{d}^4 x \left\{ \bar{\psi}\left(i\partial\!\!\!/ + \bar{g}A\!\!\!/ - i\mu\gamma_0\right)\psi + \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu}\right\}.$$

Screening Masses

- At finite chemical potential gluons receive effective screening masses via vacuum polarizations.



- Projections onto the Lorentz structure of the polarization tensor in the static limit yield the Debye mass m_{D} and the Meissner mass m_{M}.
- To include gluon screening effects, we compute the flow of the screening masses from high-momentum scales to the infrared [5]:



- Assuming a constant strong coupling g and vanishing temperature, the infrared values for the Debye mass and Meissner mass at one-loop order are given by [5,6]:

$$\bar{m}_{\mathrm{D}}^2 = g^2 N_{\mathrm{f}} \frac{\mu^2}{2\pi^2} \quad \text{and} \quad \bar{m}_{\mathrm{M}}^2 = 0\,.$$

- With this improvement, we calculate the speed of sound at high densities, see first figure. Qualitatively, results including gluon screening effects agree with pQCD outcome and with our semi-perturbative calculations.

Equation of state

- How can we find combined constraints for the speed of sound from (semi-)perturbative calculations and results that include a (color-)superconducting gap?
- As an example, consider a chirally symmetric gap associated with pairing of the two-flavor color-superconductor (2SC) type [7-9]:

$$|\Delta_0| \sim \mu g^{-5} \exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right).$$

- The gap is a non-analytic smooth function of the coupling g such that a Taylor series about $g=0$ does not exist.
- At high densities (large chemical potentials), the pressure is dominated by the non-interacting quark gas and may be expanded in the (dimensionless) gap [12]:

$$P = P_{\mathrm{SB}}\left(\gamma_0(g) + \gamma_1(g)\left(\frac{|\Delta_0|}{\mu}\right)^2 + \dots\right).$$

- In a perturbative setting at leading order in g, we set $\gamma_0 = 1 - g^2/2\pi^2$ and $\gamma_1 = 0$ [6], while for the fRG studies in the weak coupling limit we use $\gamma_0 = 1$ and $\gamma_1 = 2$ at leading order in the gap [10].
- Below, we choose the combination of the aforementioned approaches

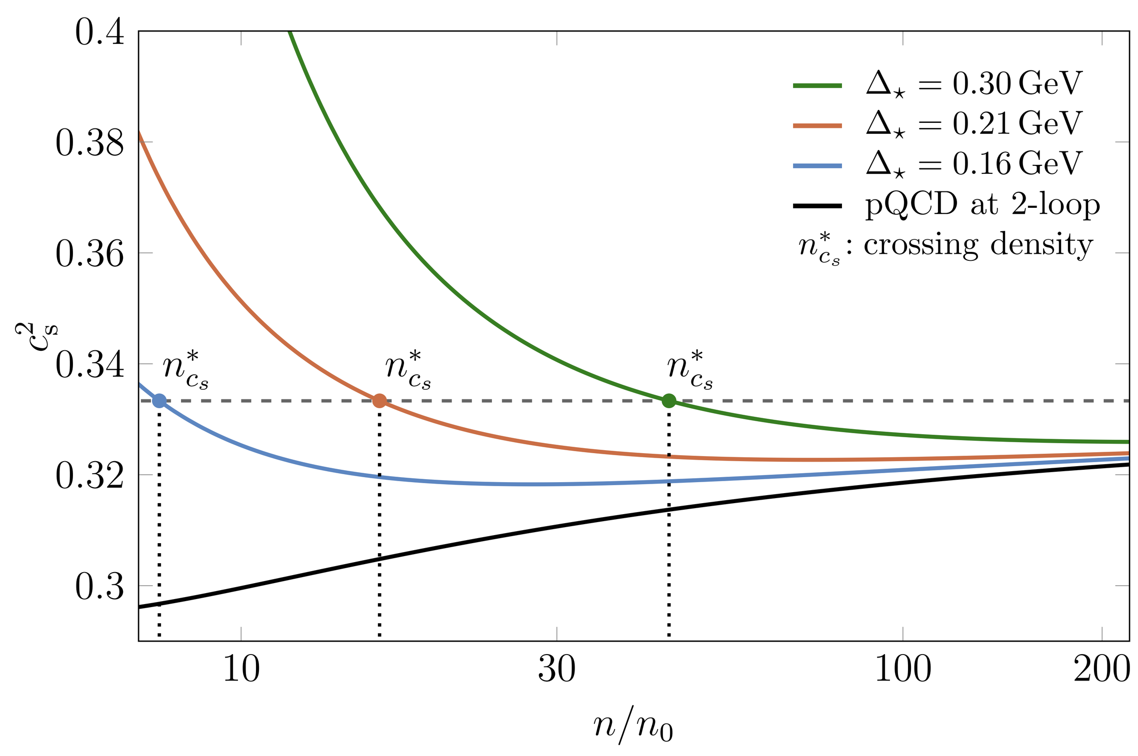
$$\gamma_0 = 1 - \frac{g^2}{2\pi^2} \quad \text{and} \quad \gamma_1 = 2\,.$$

Speed of sound I

- Since the pressure might not be sensitive to seemingly small corrections, we focus on the speed of sound in the following.
- The speed of sound (squared) as a function of chemical potential μ is given by

$$c_s^2 = \frac{1}{\mu}\left(\frac{\partial P}{\partial \mu}\right) \Big/ \left(\frac{\partial^2 P}{\partial\mu\partial\mu}\right).$$

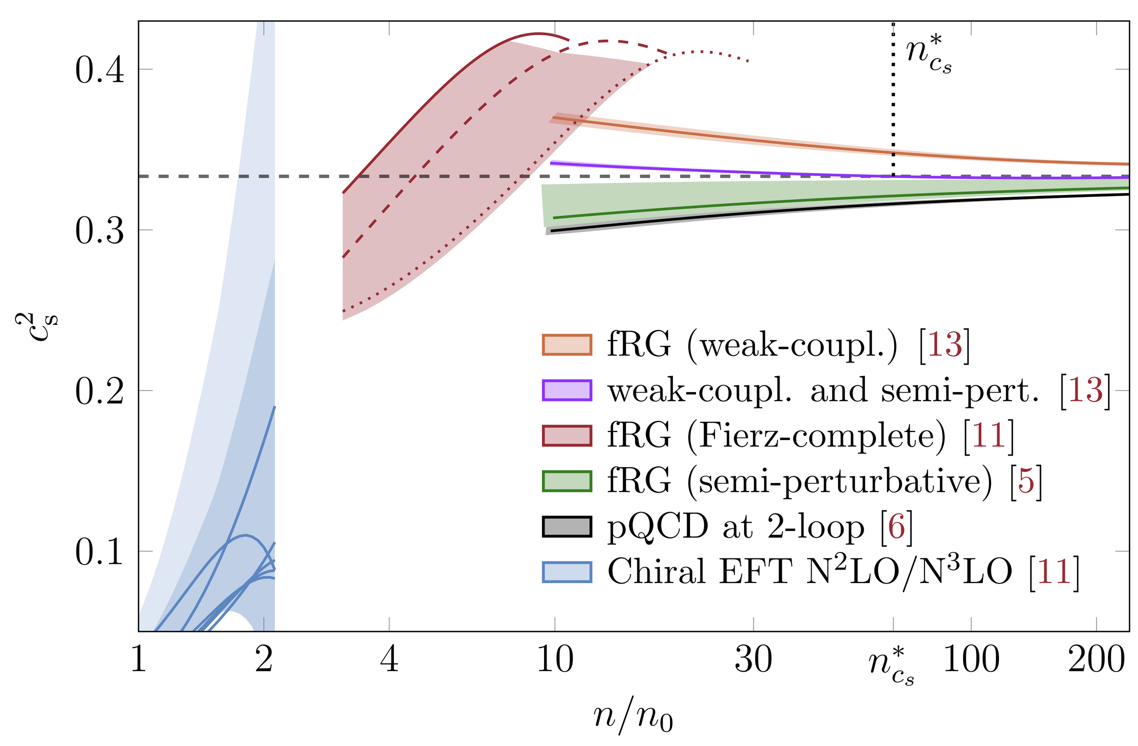
- Even small contributions to the pressure might have a sizable effect on the speed of sound since the first and second derivative contribute.
- We show results for the speed of sound as a function of density for 2-loop perturbative results combined with different gap sizes $\Delta_\star$ at $10 n_0$ [12].



- Qualitatively, gap-induced speed of sound results show a very similar behavior:
  1. At very high densities, gap contributions to the speed of sound are negligible, even for different sizes of the gap. The speed of sound approaches the conformal limit from below.
  2. Going to lower densities, the speed of sound assumes a local minimum. For densities around the minimum, gap contributions become sizable in comparison to the perturbative result.
  3. For even lower densities, gap contributions become more significant and the speed of sound crosses its asymptotic value at the "crossing density" $n^*_{c_s}$.

Speed of Sound II

- To validate above results, we improve γ_0 and the gap induced contributions by a calculation with our preliminary gap data [13] and recent semi-perturbative results (Landau gauge) [5].



- In combination (see magenta line), our speed of sound results containing gap and semi-perturbative data yield the same behavior as the previous results
- In view of chiral EFT studies at low densities and Fierz-complete results in the intermediate density regime, our results smoothly bridge the gap between the very high density regime (pQCD) and the intermediate density regime.

- The formation of a (color-)superconducting gap suggests a maximum in the speed of sound at supranuclear densities, which exceeds the non-interacting limit.
- At even higher densities, the speed of sound again crosses the non-interacting limit and approaches it from below.

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ELEMENTS

DFG

Heisenberg-Programm