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Quark condensate and chiral symmetry restoration in neutron stars

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Abstract

Based on an ***equivparticle model***, we investigate the ***in-medium quark condensate*** in neutron stars. Carrying out a ***Taylor expansion*** of the nuclear binding energy to the order of ρ^3, we obtain a series of ***EOSs*** for neutron star matter, which are confronted with the latest nuclear and astrophysical constraints. The in-medium quark condensate is then extracted from the constrained properties of neutron star matter, which decreases non-linearly with density. However, ***the chiral symmetry*** is only partially restored with non-vanishing quark condensates, which may ***vanish*** at a density that is ***out of reach*** of neutron stars.

Introduction

The ***state*** of matter at large densities, is still veiled in mystery due to the ***difficulties*** in lattice ***QCD*** simulations. It is thus essential for us to investigate the properties of dense matter with both nuclear and astrophysical constraints.

According to various investigations on the structures and reactions of finite nuclei, the ***properties*** of nuclear matter around the saturation density ρ_0 are well ***constrained*** with the binding energy, the incompressibility ***K***[1], the symmetry energy $S\ (\rho_0)$ and its slope ***L***[2]. Meanwhile, the slope of symmetry energy was shown to be linearly correlated with the neutron skin thickness[3] .

At ***large enough densities***, it is expected that HM undergoes a deconfinement phase transition and forms quark matter (QM)[4]. Meanwhile, a smooth crossover from HM to QM can also accommodate the stringent constraints from pulsar observations,which is expected to be bridged by quarkyonic matter[5]. The ***baryon density*** changes very ***rapidly*** at the ***quarkyonic transition***, and one may expect that the quarkyonic and ***chiral phase transitions*** are entangled. It is thus necessary to investigate the ***in-medium quark condensate*** inside ***neutron stars***.

Methodology

Around ρ_0, expanding the binding energy of ***symmetric nuclear matter*** (SNM) $\epsilon_0(\rho)$ and the ***symmetry energy*** $S(\rho)$ in Taylor series and omitting higher order terms

$$\epsilon_0(\rho) = \epsilon_0(\rho_0) + \frac{K}{18}\left(\frac{\rho}{\rho_0}-1\right)^2 + \frac{J}{162}\left(\frac{\rho}{\rho_0}-1\right)^3$$

$$S(\rho) = S(\rho_0) + \frac{L}{3}\left(\frac{\rho}{\rho_0}-1\right) + \frac{K_{sym}}{18}\left(\frac{\rho}{\rho_0}-1\right)^2 + \frac{J_{sym}}{162}\left(\frac{\rho}{\rho_0}-1\right)^3$$

The coefficients are the income-pressibility K and skewness J of SNM, while those of symmetry energy are the slope L, curvature K_{sym} , and skewness J_{sym}.

Here we adopt an ***equivparticle model*** to extract the quark condensate of neutron star matter[6,7]. The basic idea of equivparticle model is to define an equivalent Hamiltonian density with a ***variable quark mass***. To calculate the ***quark condensate***, we obtain

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} = 1 - \frac{1}{3n^*}\frac{E_I}{m_I}$$

$$n^* = -\frac{2}{3}\langle\bar{q}q\rangle_0 = \frac{m_\pi^2 f_\pi^2}{3m_0} = 0.985\ \mathrm{fm}^{-3}$$

The interacting part of the equivalent mass

$$m_I = \frac{E_I}{\sum_i(\langle\bar{q}_i q_i\rangle_\rho - \langle\bar{q}_i q_i\rangle_0)}$$

The interacting energy density

$$E_I = \langle H_I\rangle_\rho - \langle H_I\rangle_0$$

Results

We consider two criteria:

(a) The weaker constraints at $\rho \le \rho_{1.4}$,the tidal deformability $\Lambda_{1.4} \le 800$,radius $R_{1.4} = 12.45 \pm 1.30$ km , and maximum mass $M_{TOV} < 2.05M_\odot$.

(b) The stronger constraints at $\rho \le \rho_{TOV}$,the tidal deformability $70 \le \Lambda_{1.4} \le 580$,the radii $R_{1.4} = 12.45 \pm 0.65$km and $R_{2.08} = 12.35 \pm 0.75$ km , and the maximum mass $M_{TOV} \ge 2.05M_\odot$.

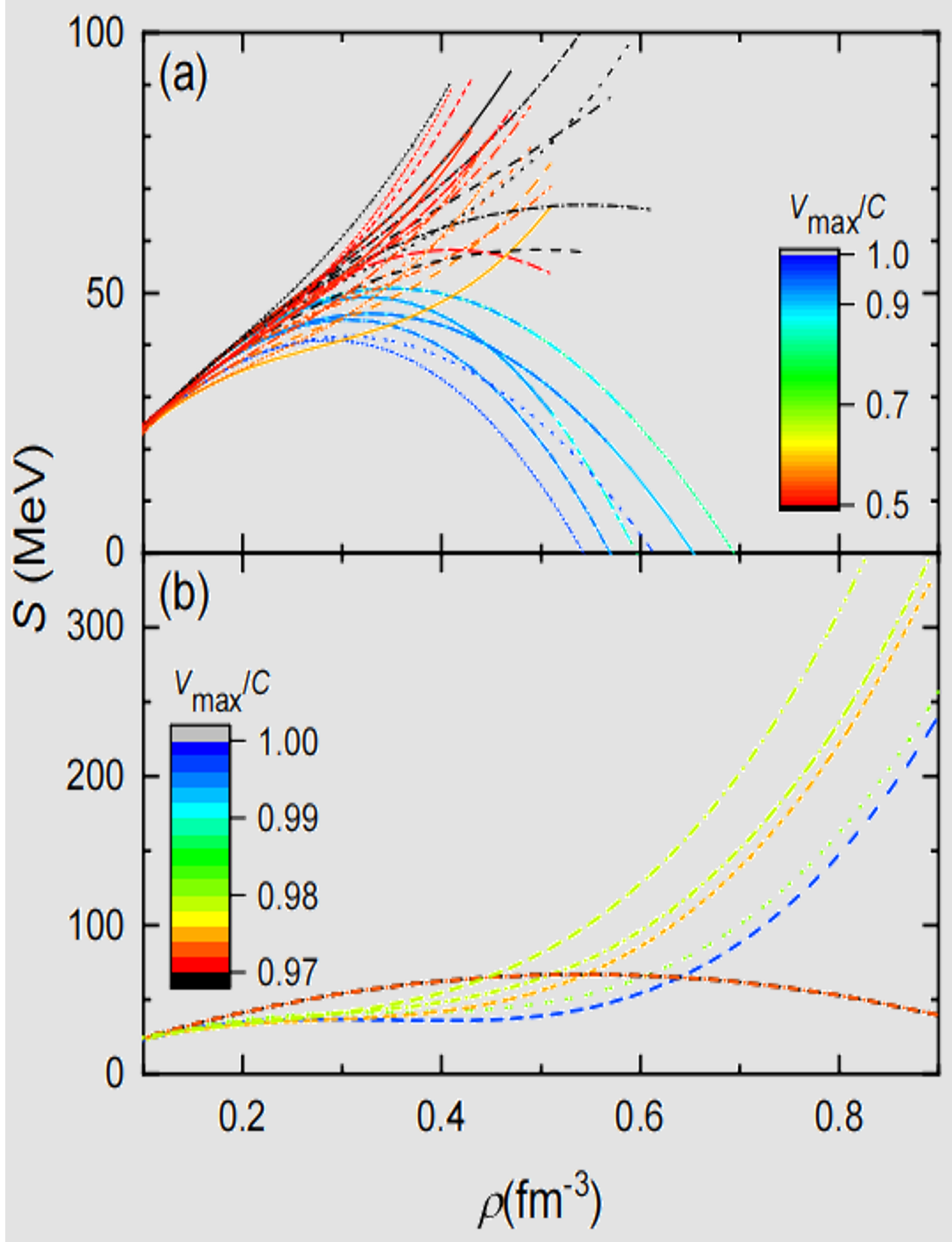

Figure 1: The symmetry energy S as functions of density ρ.

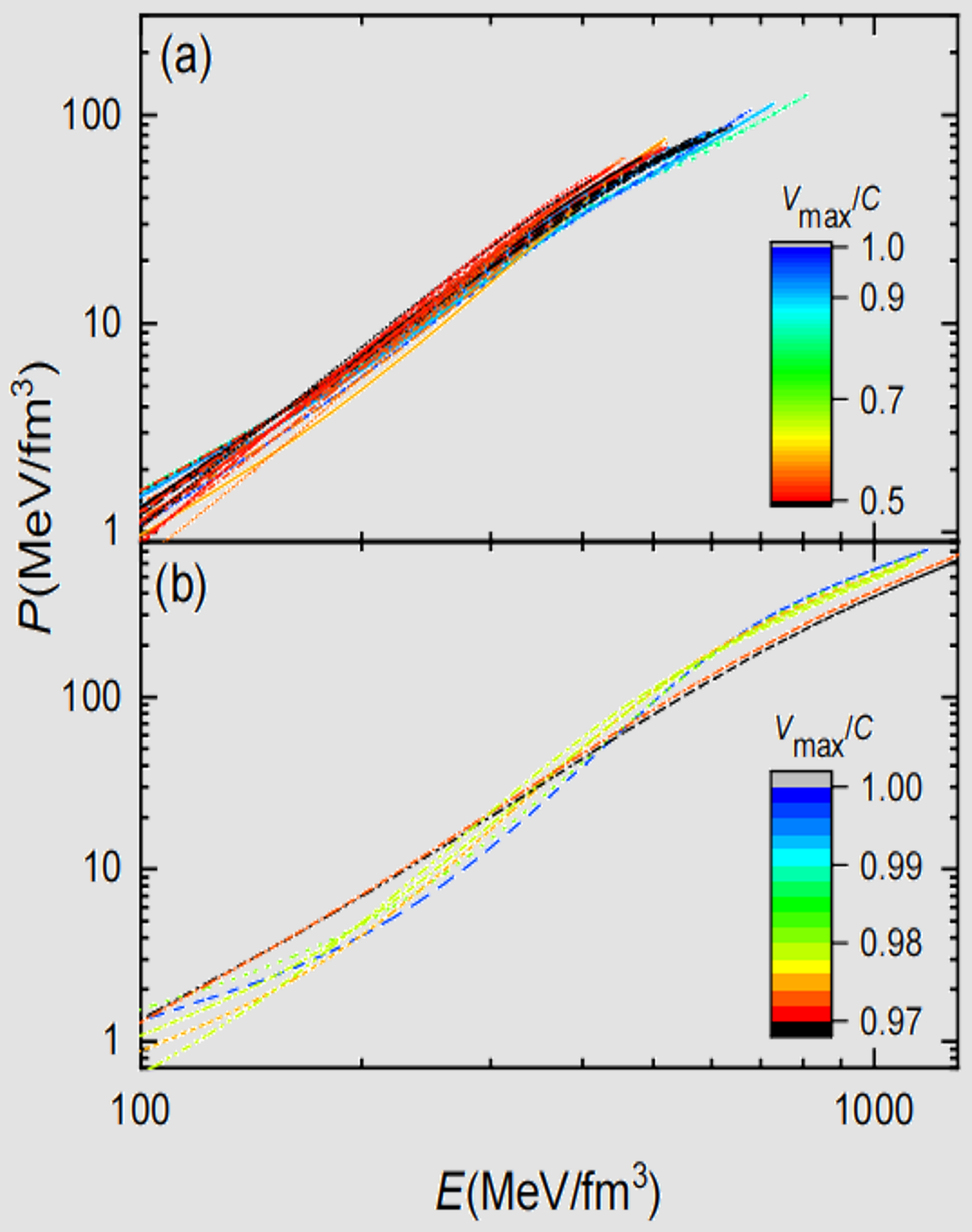

Figure 2: The EOSs of neutron star matter that meet the criteria (a) and (b).

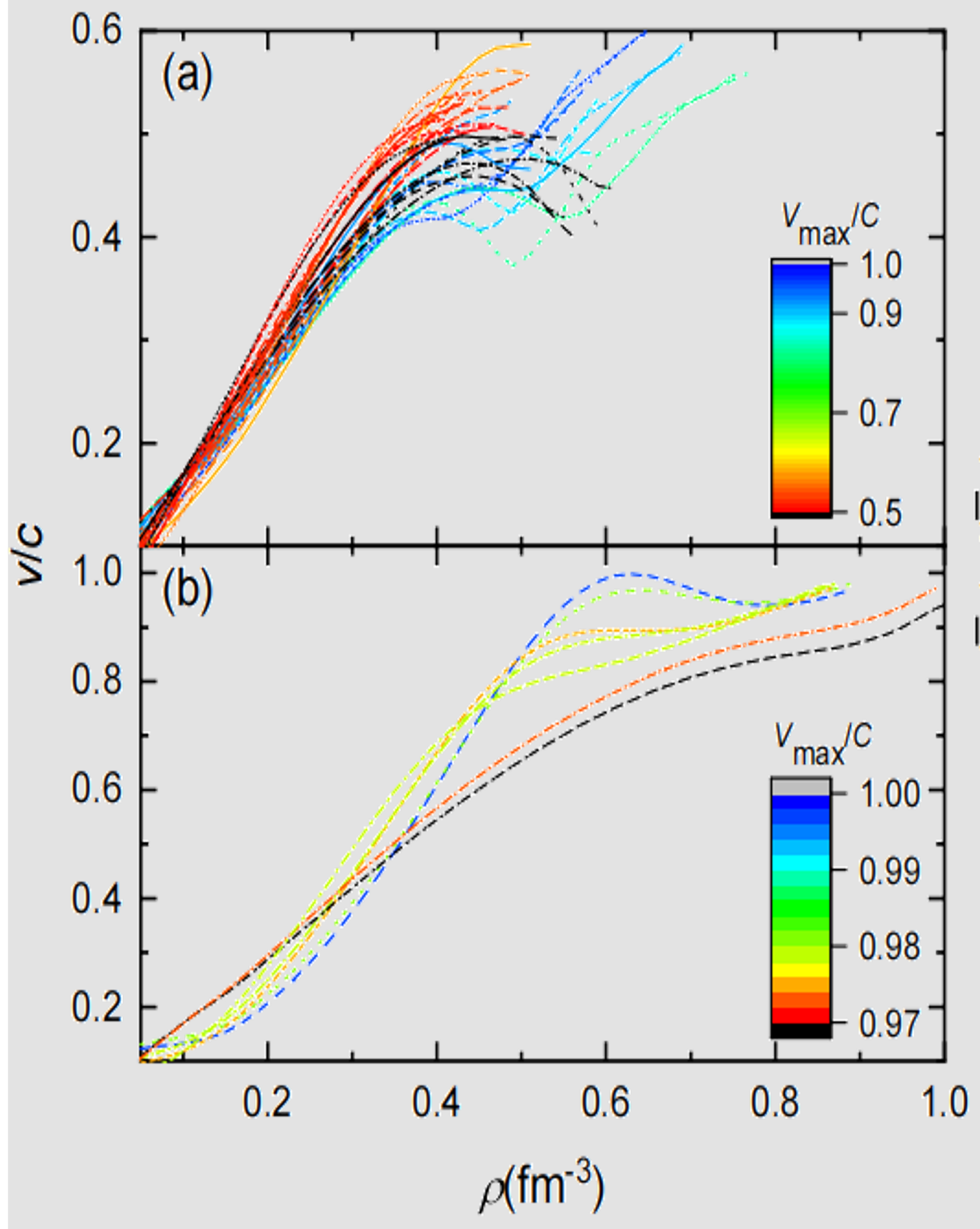

Figure 3:The velocity of sound v for neutron star matter obtained with the EOSs .

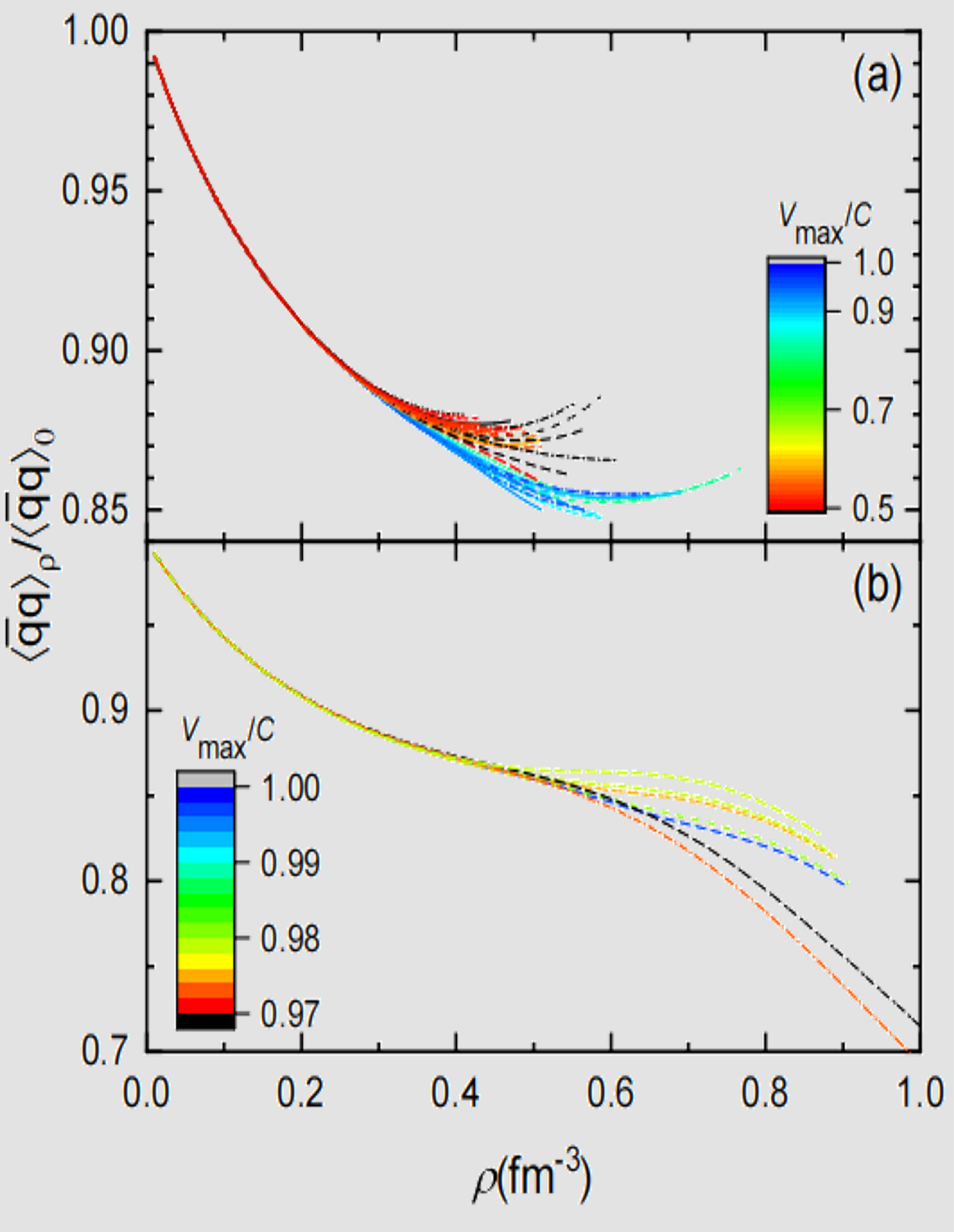

Figure 5: Relative quark condensate of neutron star matter as functions of baryon number density.

Conclusion

I. The ***symmetry energy*** at large densities are consistent with various constraints from heavy-ion collisions[8] , which may even become ***negative*** at $\boldsymbol{\rho \gtrsim 3\rho_0}$ if the constraints are limited to $\boldsymbol{\rho < \rho_{1.4}}$.

II. This deviation reaches its peak at $\boldsymbol{\rho \approx 3\rho_0 \sim 5\rho_0}$,which was interpreted as a ***phase transition*** from HM to QM[9].

III. At largest densities $\boldsymbol{\rho \approx \rho_{TOV}}$ the velocity of sound is still ***large*** and far from the conformal limit $c/\sqrt{3}$, so that a full transformation into a ***Fermi gas of quarks*** is ***unlikely***.

IV. Throughout the density range of ***neutron stars*** $(\rho \le \rho_{TOV})$, the constrained ***quark condensate*** does ***not vanish***[10].

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