Analyzing chiral condensate dependence on temperature and density

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Background

The chiral condensate describes the density of condensed quark-antiquark pairs in the QCD ground state. A nonvanishing value of the condensate signals the spontaneous breaking of chiral symmetry, which in the limit of massless quarks is an exact symmetry of the QCD Lagrangian. Strong interactions govern the dynamics of protons and neutrons. Analyzing the density and temperature dependence of the chiral condensate in nuclear matter can reveal the presence of novel phase transitions.

Motivation

We want to understand the nature of the densest observable matter in the universe, neutron stars. Astrophysical observations give limited insight into the composition of their innermost cores. By analyzing the thermodynamic properties of the chiral condensate in hot neutron matter we hope to shed light on the existence of novel phases in these dense astrophysical objects.

Method

Chiral effective field theory is used to study the behavior of the scalar quark condensate with changing temperature and density of neutron matter. Two-body and three-body chiral nuclear forces were employed to find the free energy and its dependence on the pion mass at moderate temperatures and densities.

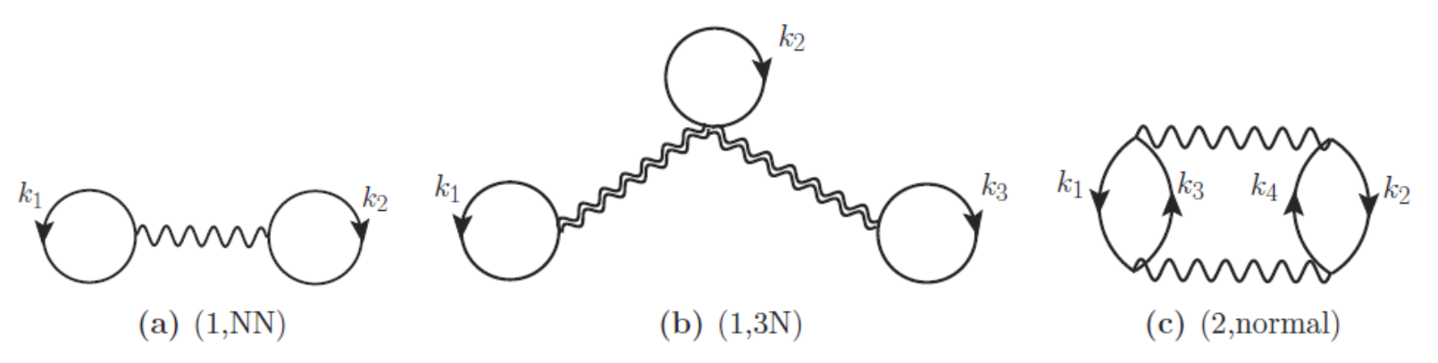

Figure 1. An illustration of the different perturbative contributions to the neutron matter free energy.[1]

Results

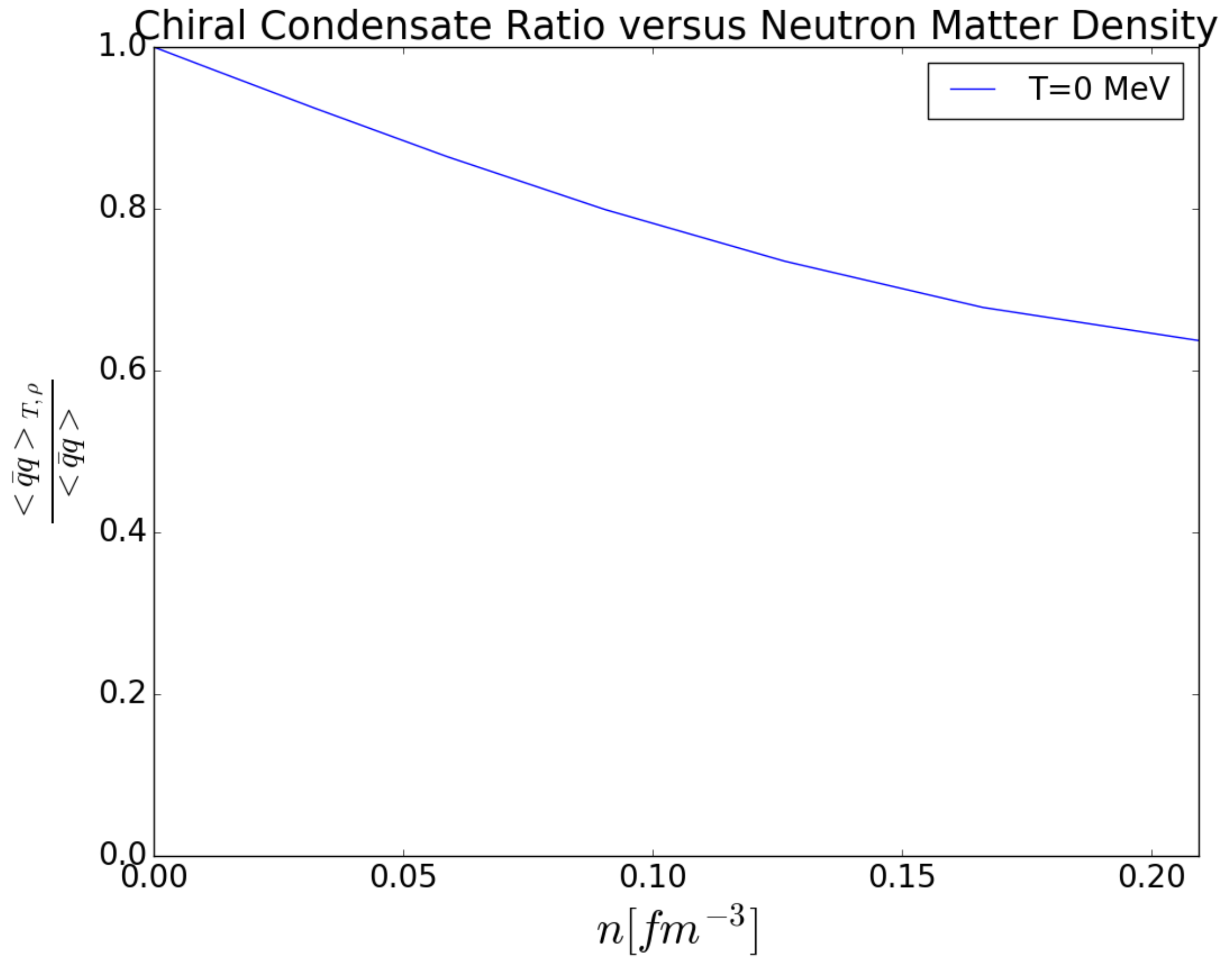

Figure 2. Condensate ratio as a function of neutron matter density.

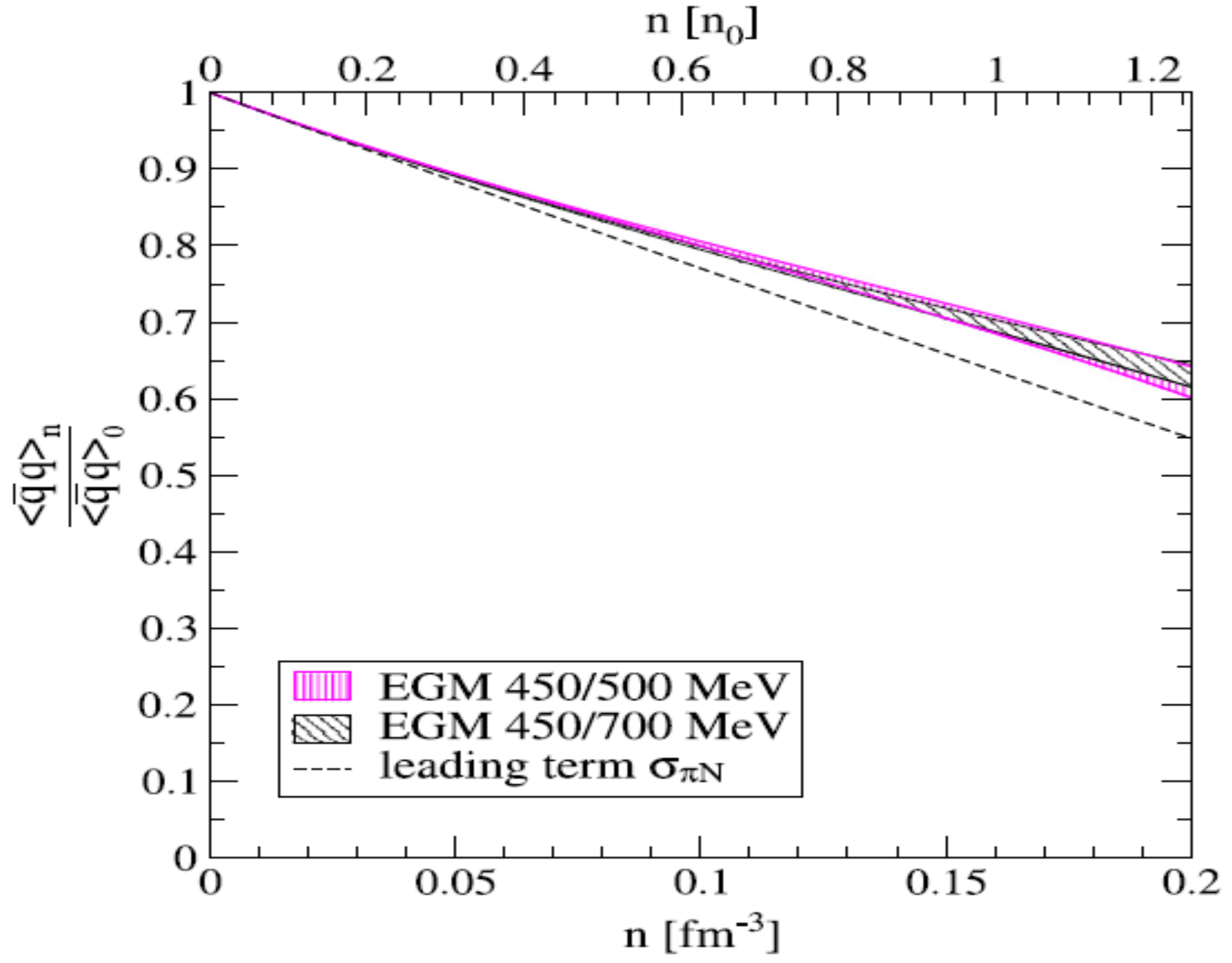

Figure 3. Condensate ratio plotted by Krüger et. al.[2], as a function of neutron matter density to be compared to Figure 2.

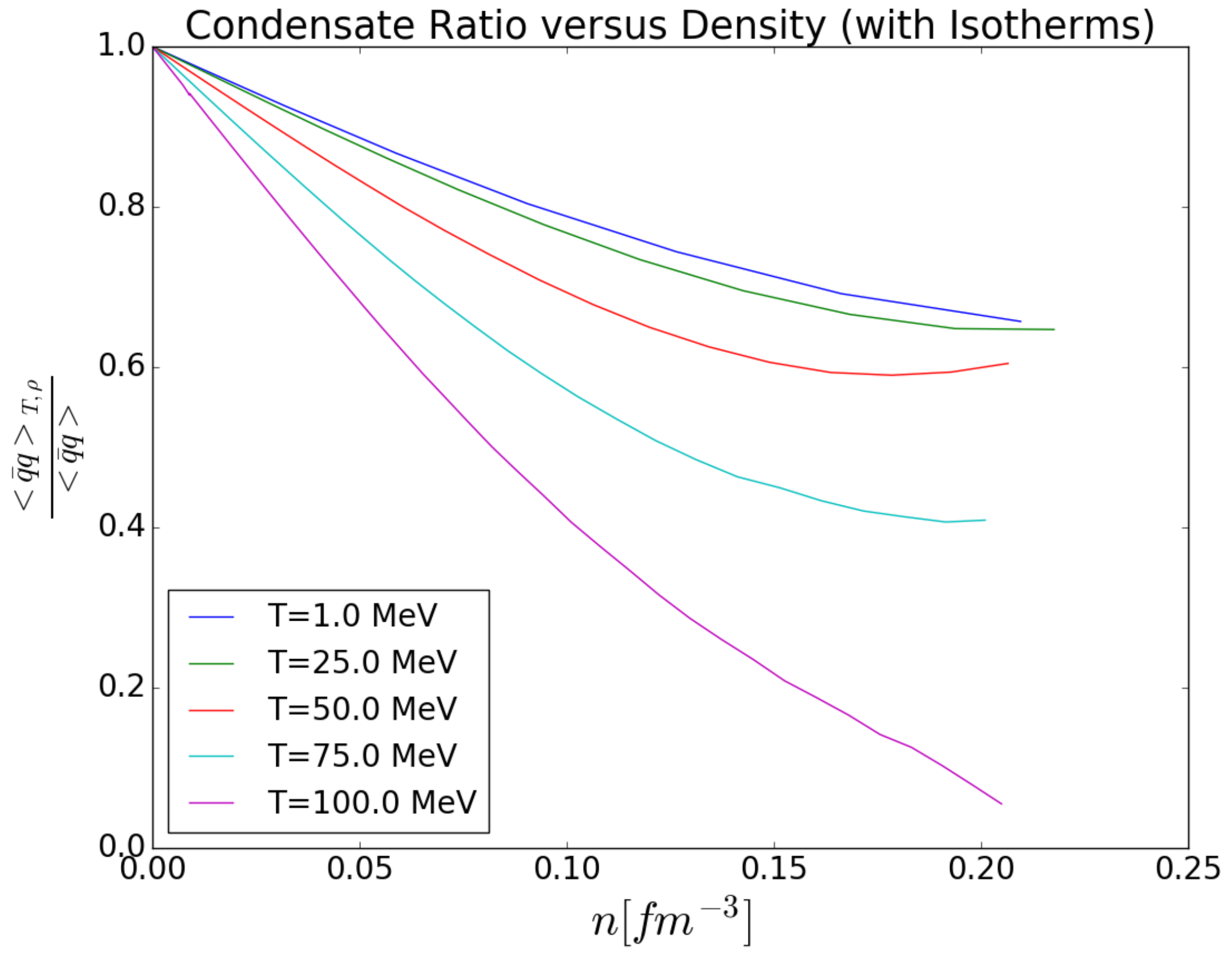

Figure 4. Condensate ratio as a function of neutron matter density at different temperatures.

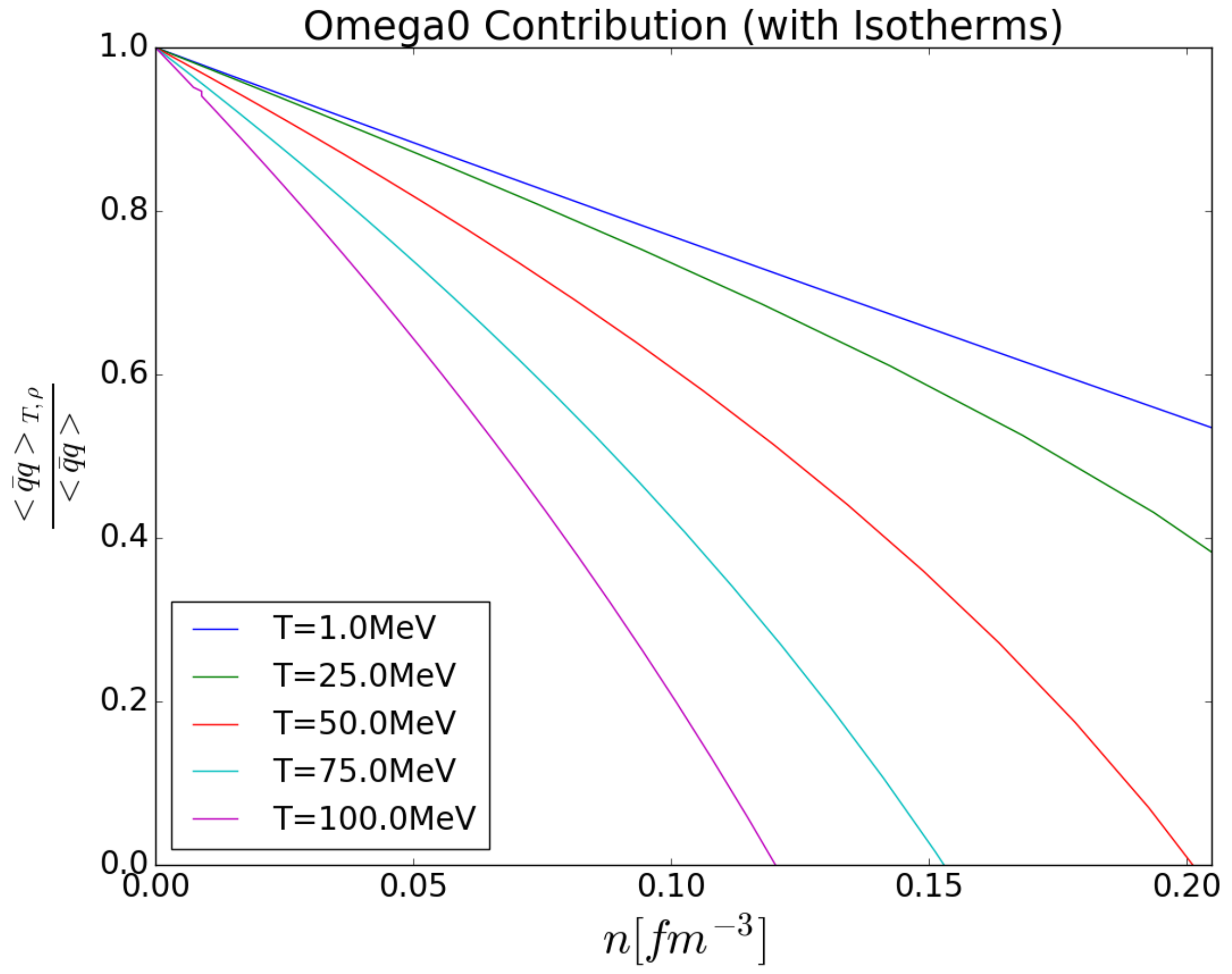

Figure 5. Condensate ratio calculated with just the Omega0 contribution.

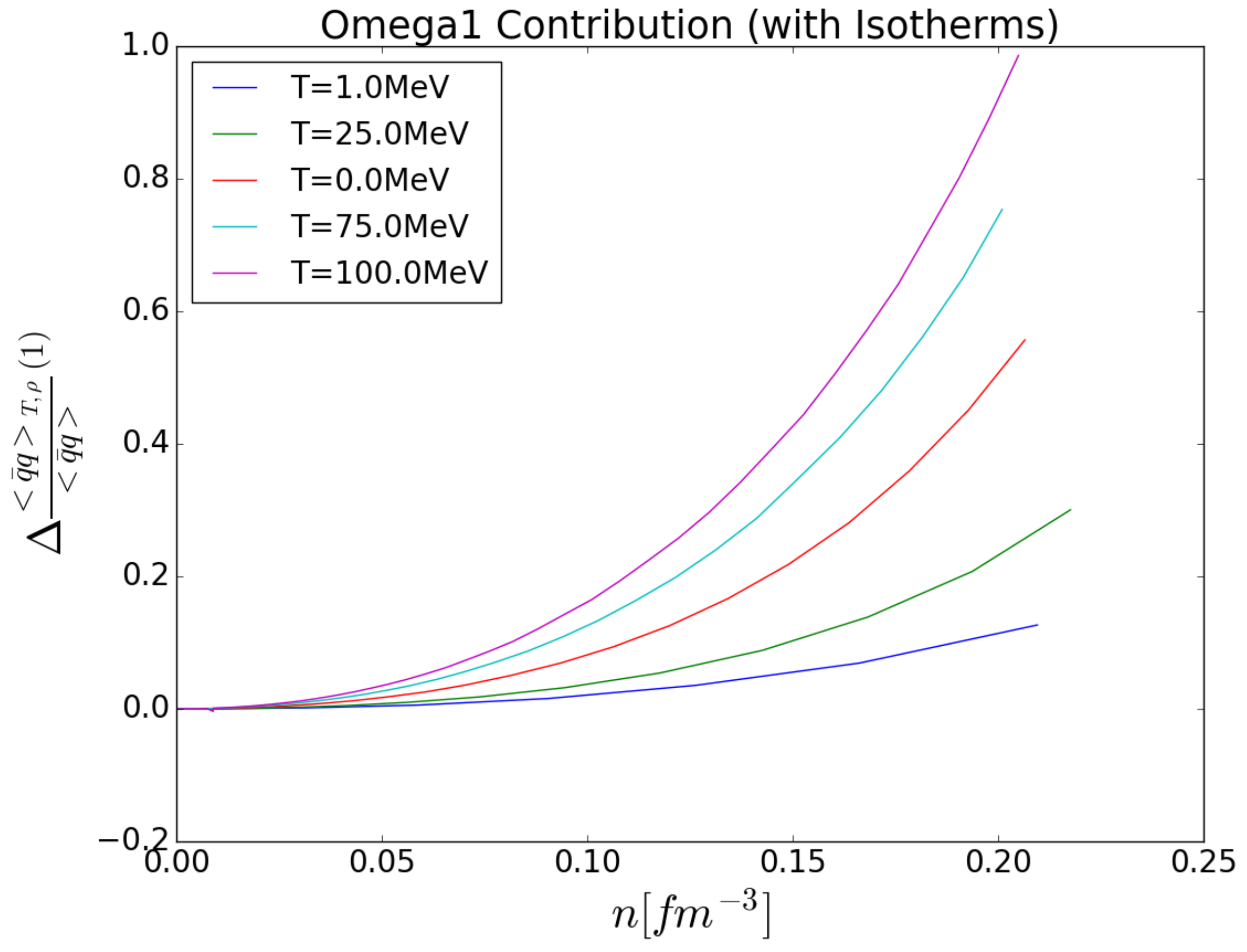

Figure 6. Change in the condensate ratio calculated with just the Omega1 contribution.

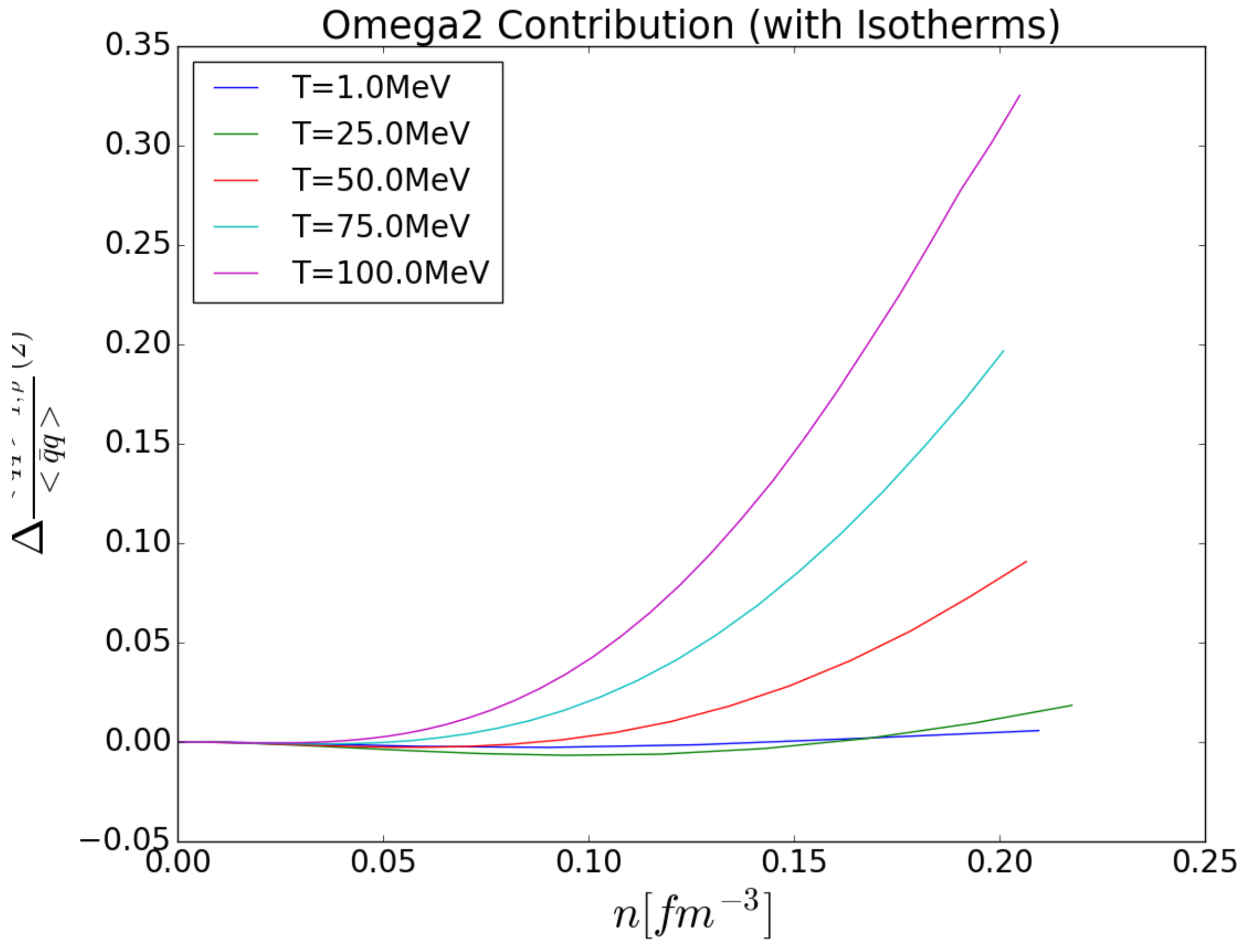

Figure 7. Change in the condensate ratio calculated with just the Omega2 contribution.

Equations

$$\rho \mathrm{F} = 2\int_0^\infty dp\, p \mathrm{K}_1 n(p) + \int_0^\infty dp_1 \int_0^\infty dp_2 \mathrm{K}_2 n(p_1) n(p_2) + \int_0^\infty dp_1 \int_0^\infty dp_2 \int_0^\infty dp_3 \mathrm{K}_3 n(p_1) n(p_2) n(p_3)$$

Free Energy Equation based on many-body kernel contributions.[3]

$$\frac{<\bar{q}q>_n}{<\bar{q}q>_0} = 1 - \frac{n}{f_\pi^2}\frac{\sigma_{\pi N}}{m_\pi^2}\left(1 - \frac{3k_F^2}{10m_N^2} + \ldots\right) - \frac{n}{f_\pi^2}\frac{\partial}{\partial m_\pi^2}\mathrm{F}$$

Chiral condensate ratio for zero temperature.[2]

$$\frac{\partial \mathrm{K}_1}{\partial m_\pi^2} = \frac{\sigma_N}{m_\pi^2}\left(1 + \frac{3\rho}{2m_N\Omega_0''} + \frac{p^2}{3m_N^2} + \frac{3p^4}{8m_N^4}\right)$$

Pion mass derivative of the one-body contribution.[3]

$$n(p) = \frac{p}{2\pi^2}\frac{1}{1+e^{\frac{\frac{p^2}{2m_N}-\mu}{T}}}$$

Partition-like function of momentum.[3]

Conclusions

Increasing temperature (up to 100 MeV) strongly reduces the chiral condensate, which indicates a fast approach to chiral symmetry at high temperatures. Nuclear correlations at higher density (up to around 0.2 fm^{-3}) hinder the restoration of chiral symmetry. The analysis of the different contributions shows that the dominant contribution is the noninteracting term.

Acknowledgments

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References

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3. S. Fiorilla et. al., “Nuclear thermodynamics and the in-medium chiral condensate”, Phys. Lett. B 714 (2012) 251.