Quark Condensate in Neutron Matter from Chiral Effective Field Theory

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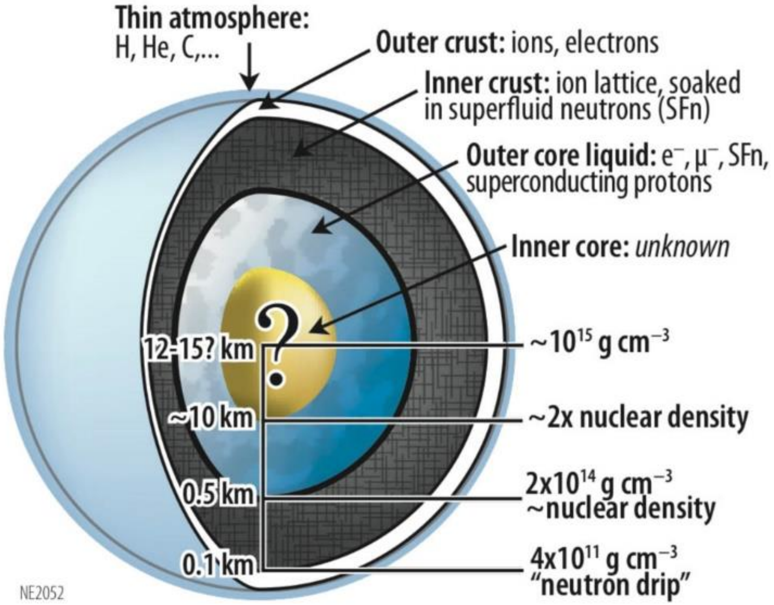
Motivation

- We want to know what goes on inside highly dense astrophysical objects, specifically neutron stars
- Neutron stars – the final stage of a massive star (~10-30 $M_{\odot}$) fit inside the width of Rhode Island three times over
- Not much is known about what happens within the inner core of such dense neutron material



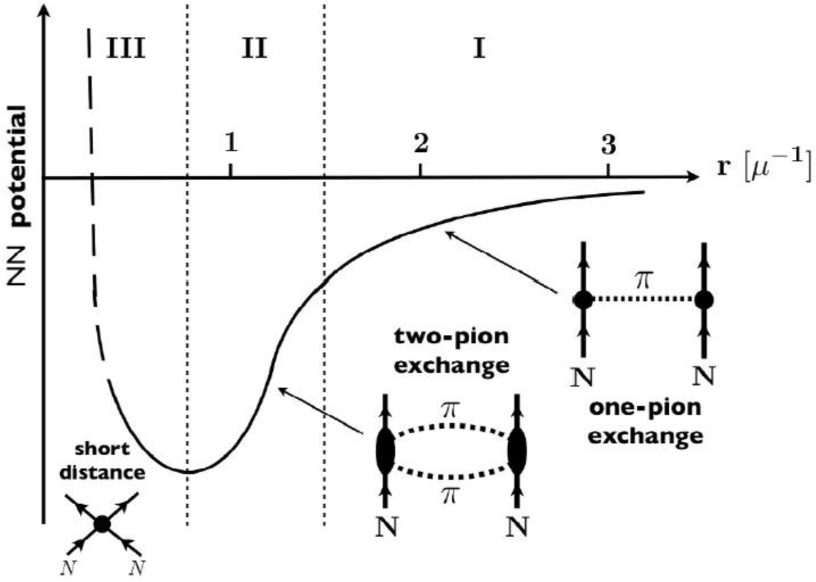
Neutron Star Diagram. Digital image. *NASA.gov*. N.p., 17 Feb. 2016. Web. 22 July 2016. <https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html>.

Background

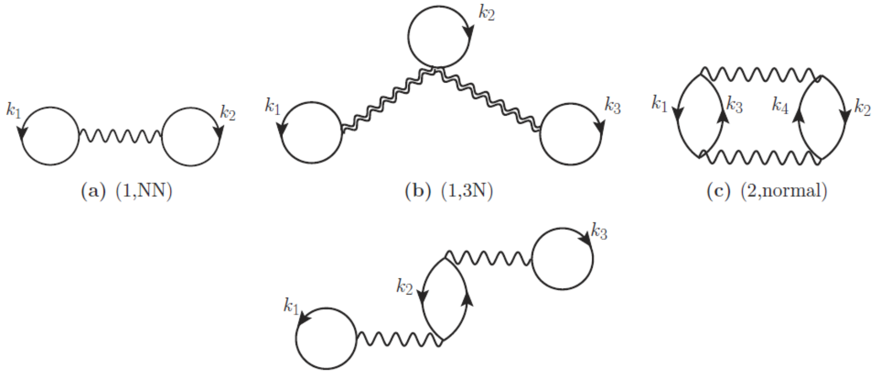
- Looking at quark properties shines light on the properties of highly dense neutron matter
- QCD asymptotic freedom suggests chiral symmetry restoration at high densities
    - Asymptotic freedom says that quarks interact weakly at high energies, not allowing them to form a condensate
- Chiral symmetry – the application of symmetry to the "handedness" of a gauge theory (in this case, the field theory QCD)
    - An approximate theory of the strong interactions based on vanishing quark masses (up and down quarks are so light next to hadronic scales)
- Chiral Condensate ($\langle \bar{q}q \rangle$) – a scalar quark density value which, when vanishing, means chiral symmetry is being restored
    - Analyzing the behavior of this condensate sheds light on the symmetry restoration phase transition of neutron matter

Chiral Symmetry Breaking Analogy

- Analogy – spontaneous magnetization in ferromagnetic material
  - Spontaneous magnetization is when ferromagnetic material (below Curie temperature) with no magnetic field applied gain an ordered spin state
- Dependence on Curie temperature, where the symmetry breaking happens
  - Above which ferromagnetic material becomes paramagnetic and the spins (spin waves or magnons) within the material have spherical symmetry
  - Below which the direction of the spins follow a preferred axis, or the magnetization direction
- As temperature decreases, ferromagnetic material's spherical symmetry vanishes
  - Looking at these temperature limits ($T \rightarrow 0 \; and \; T \rightarrow T_C$) shows the behavior of this symmetry breaking and restoration
  - Similar to looking at chiral symmetry breaking and restoration



J.W. Holt et al., “Chiral symmetry and effective field theories for hadronic, nuclear and stellar matter”, Phys. Rep. 621 (2016) 2.



(a) (1,NN) (b) (1,3N) (c) (2,normal)

(d) (2,anomalous)

C. Wellenhofer et al., “Nuclear thermodynamics from chiral low-momentum interactions”, Phys. Rev. C 89 (2014) 064009.

Chiral Effective Theory & Perturbation Theory

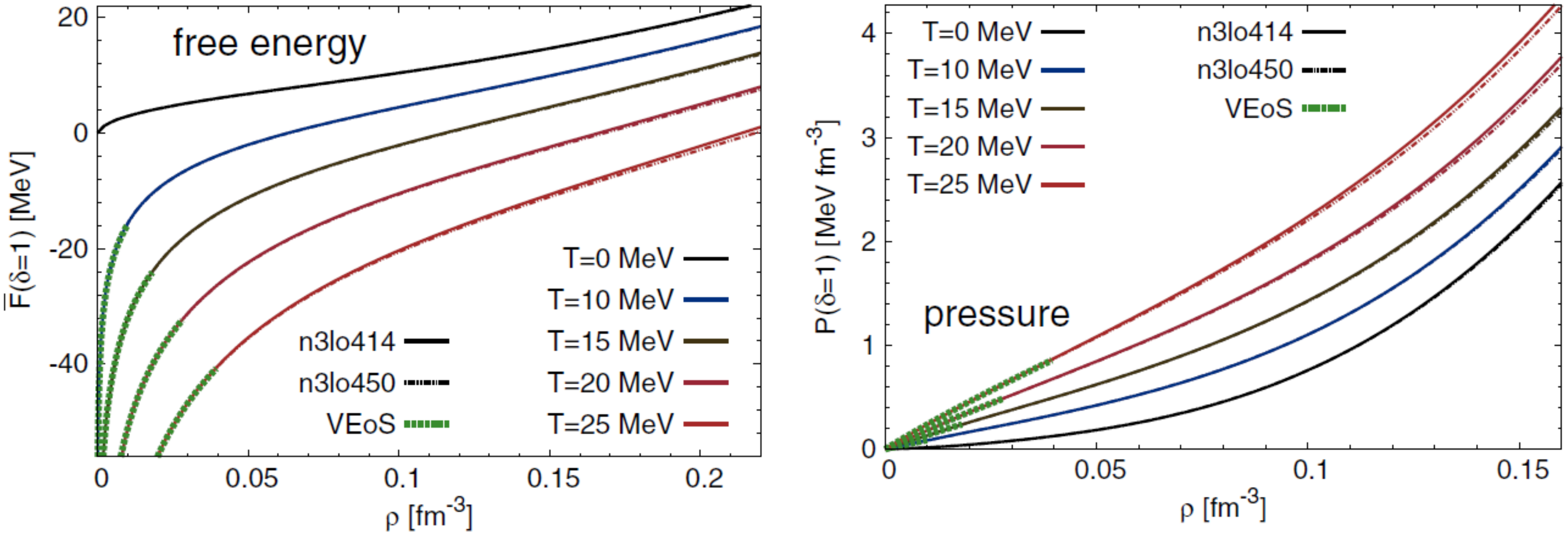
ChEFT - putting together nuclear force order-by-order

- Top figure: potential (force inferred) relation to distance

MBPT – solving for the quantum mechanical ground state of a many-body system

- First-order: expectation value of the chiral potential in the non-interacting neutron matter ground state
- Second-order: matrix elements of the potential connecting the non-interacting ground state and the excited states of the non-interacting system
- Bottom figure: perturbation theory diagrams included in present work

Pure Neutron Matter EOS



- Pure neutron matter equation of state at finite temperatures
  - Looking at the free energy and pressure of pure neutron matter (with isotherms)
  - Benchmark with virial EOS at low densities
  - This project is similar with in-medium neutron matter

C. Wellenhofer et al., “Thermodynamics of isospin-asymmetric nuclear matter from chiral effective theory”, Phys. Rev. C 92 (2015) 015801.

Deriving the Chiral Condensate

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

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

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

- Start with free energy equation based on the different many-body interaction contributions
  - K_1 is the leading contribution to the free energy density above
  - K_1 dependence on the light quark mass, which is equivalently the pion mass, is what matters
- Hellmann-Feynman theorem
  - This expectation value is the chiral condensate and the parameter is the pion mass squared

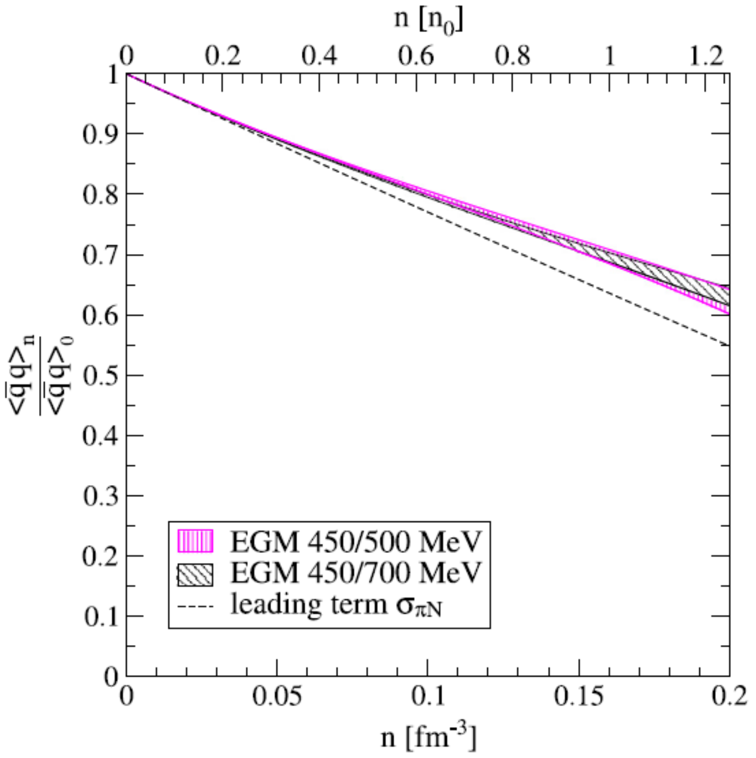
$$\langle \psi(\lambda) | \frac{d}{d\lambda} H(\lambda) | \psi(\lambda) \rangle = \frac{d}{d\lambda} E(\lambda)$$

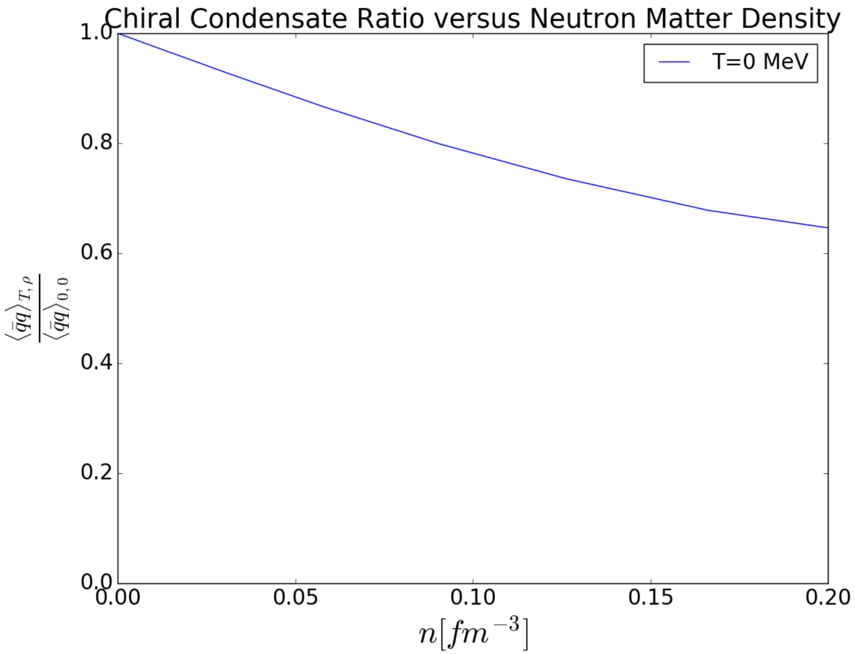
T. Cohen et al., “Quark and gluon condensates in nuclear matter”, Phys. Rev. C 45 (1992) 4.

Zero Temperature Chiral Condensate

Krüger et al. analysis with free energy and interaction energy derivatives

Analysis with just free energy derivative

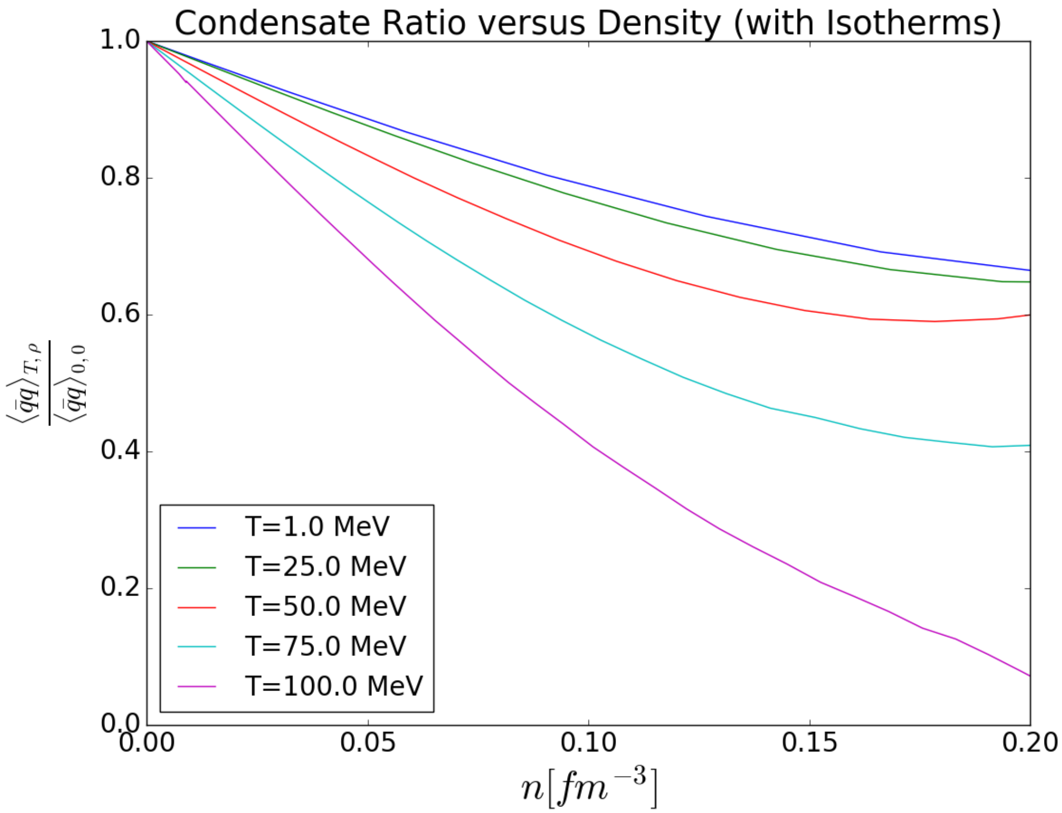




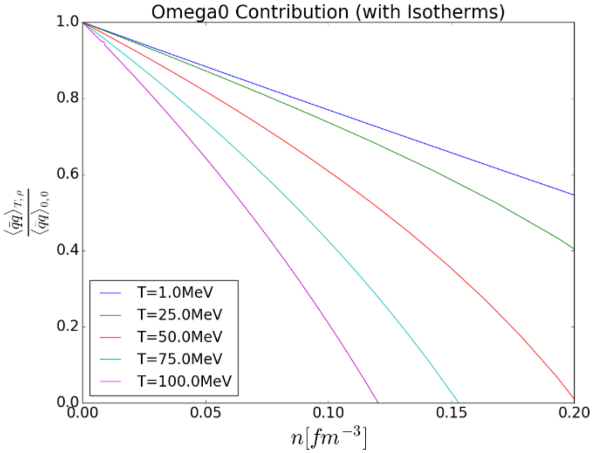
T. Krüger et al., "The chiral condensate in neutron matter", Phys. Lett. B 726 (2013) 412.

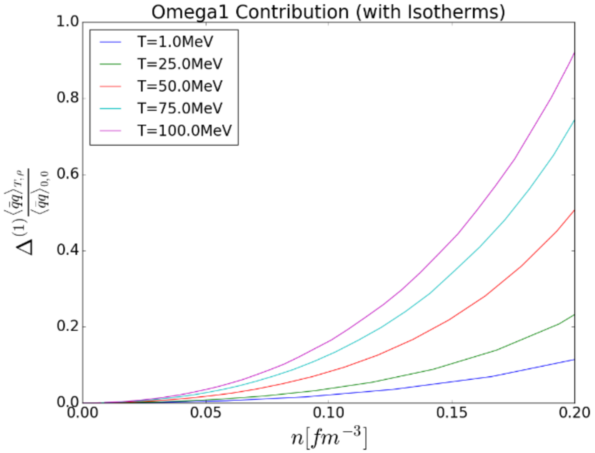
Thermodynamic Properties

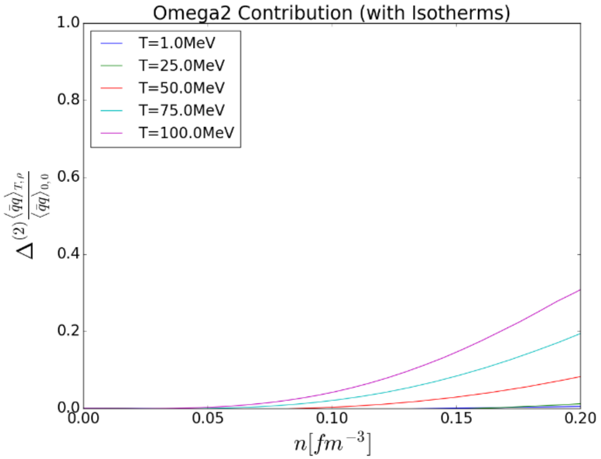
- Chiral condensate vanishing with increasing density
- Approach to zero is quickened with higher temperature systems
- Higher temperatures favor chiral symmetry
- Increasing densities seem to delay symmetry restoration



Contribution Analysis







Omega0 Contribution – first order noninteracting term found to be the dominant term
Omega1 Contribution – change in condensate with respect to the one-body term
Omega2 Contribution – change in condensate with respect to the two-body interaction term
Although the dominant term is the noninteracting term, this analysis reinforces the idea that nuclear interactions are important at high densities.

Conclusions

- With the discovery of more massive neutron stars (~2 $M_{\odot}$), the neutron matter at the core is becoming more constrained to known models and less likely to be exotic
    - This works supports that claim showing that the existence of exotic matter in neutron stars is less likely

Future Work

- Repeating analysis
    - Chiral potentials with different cutoffs (different resolution scales)
    - Chiral potentials at lower orders in the expansion which would help with uncertainties

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