

Stable gapless color superconducting phases

of dense quark matter

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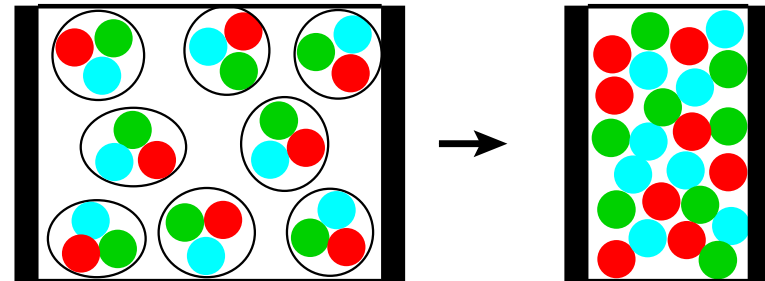
References

- I. Shovkovy and M. Huang, Phys. Lett. B **564** (2003) 205,
hep-ph/0302142 (17 Feb 2003)
- M. Huang and I. Shovkovy, Nucl. Phys. A **729** (2003) 835,
hep-ph/0307273 (22 Jul 2003)

Matter at high density

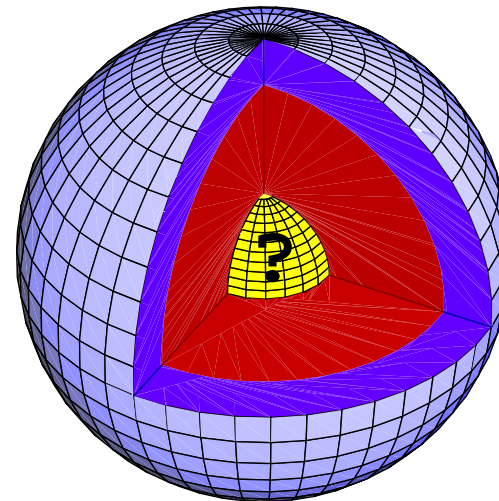
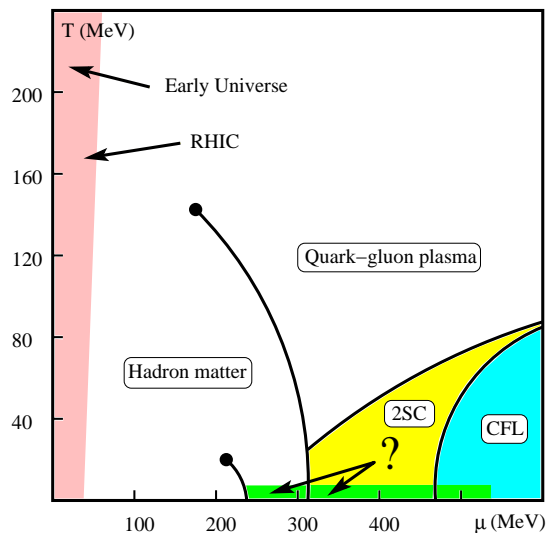
Why do we study this?

- (i) fundamental properties of QCD
- (ii) properties of compact stars



(i) No lattice results, $\mu_q \gg \Lambda_{QCD}$

(ii) Densities in stars $\rho_c \gtrsim 5\rho_0$



Color superconductivity

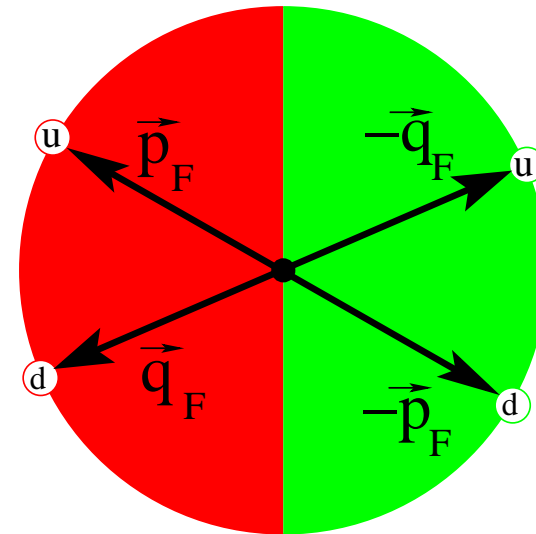
Dense quark matter is a color superconductor. [Barrois,78], [Bailin&Love,84]

Simplest case, 2SC

- $N_f = 2$: “up” and “down” quarks
- $p_F^{\text{up}} = p_F^{\text{down}} = \mu_q$
- $T = 0$: ground state – Fermi gas ($\alpha_s = 0$)

$$\langle \mathbf{u}_p \mathbf{d}_{-p} \rangle = - \langle \mathbf{u}_q \mathbf{d}_{-q} \rangle \neq 0$$

$$\begin{array}{c}
 p \quad k \\
 \swarrow \quad \searrow \\
 \text{---} \text{---} \\
 \swarrow \quad \searrow \\
 p-k \\
 \text{---} \text{---} \\
 \swarrow \quad \searrow \\
 -p \quad -k
 \end{array}
 = \bar{\mathbf{3}}_a + \mathbf{6}_s$$



Cooper instability \rightarrow color superconductivity

$$(|\bullet\bullet\rangle - |\bullet\bullet\rangle)_{\bar{\mathbf{3}}} \otimes (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)_0 \otimes (|u,d\rangle - |d,u\rangle)$$

Neutrality vs. color superconductivity

Matter in the bulk of a star should be

(i) electrically and color neutral:

$$Q_{\text{el}} = 0, \quad Q_{\text{color}} = 0$$

(ii) β -equilibrated: $\mu_d = \mu_u + \mu_e$

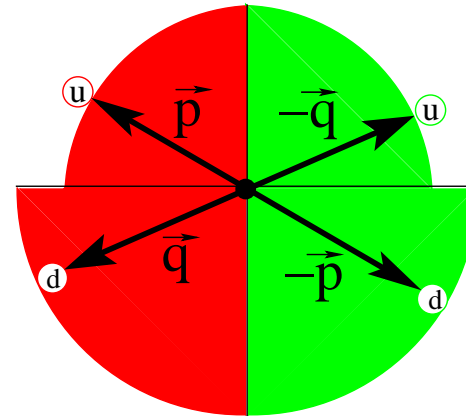
↓

$$p_F^{\text{up}} \neq p_F^{\text{down}}$$

↓

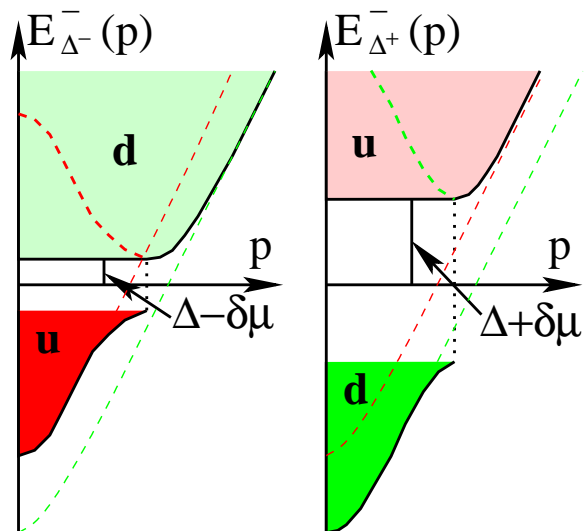
The “best” Cooper pairing is distorted:

The mismatch parameter is
$$\delta\mu \equiv \frac{p_F^{\text{down}} - p_F^{\text{up}}}{2} = \frac{\mu_e}{2} \neq 0$$



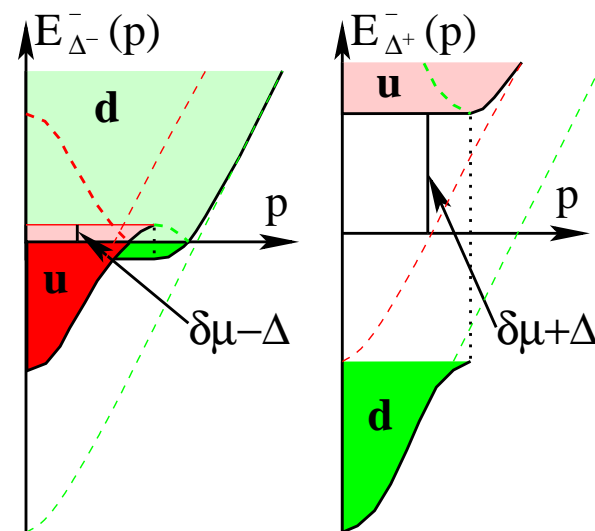
Regular 2SC vs. gapless 2SC

“Small” mismatch ($\delta\mu < \Delta$)



Energy gaps:
 $(\Delta - \delta\mu)$ & $(\Delta + \delta\mu)$

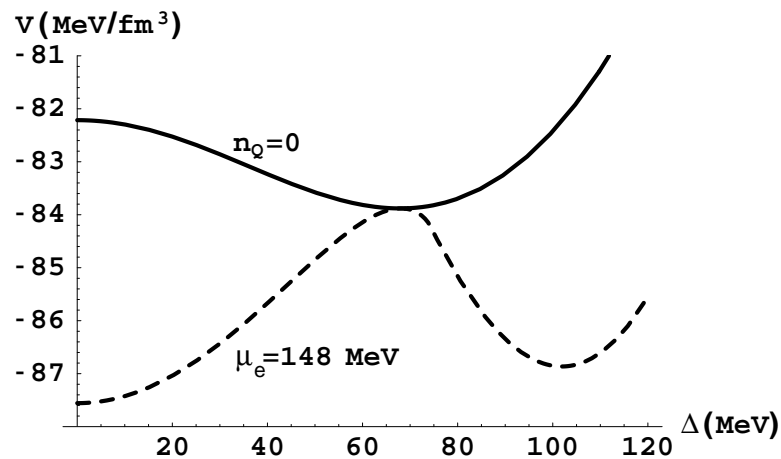
“Large” mismatch ($\delta\mu > \Delta$)



Energy gaps:
0 & $(\Delta + \delta\mu)$

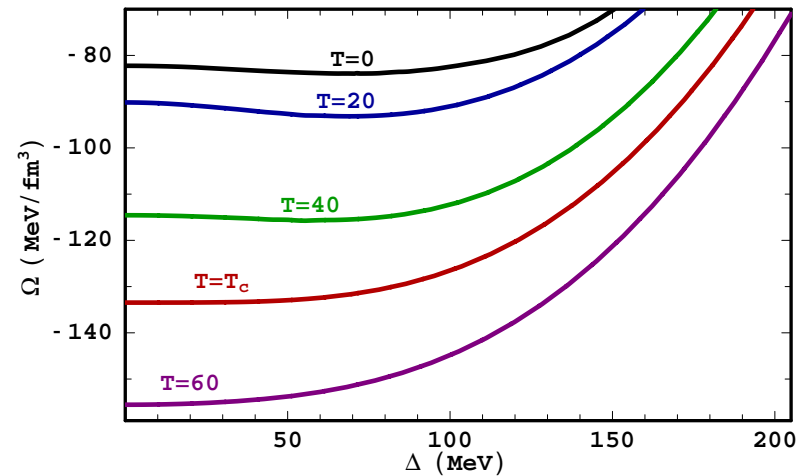
Stability of g2SC phase

Eff. potential at $T = 0$



(Mixed phase? — unlikely)

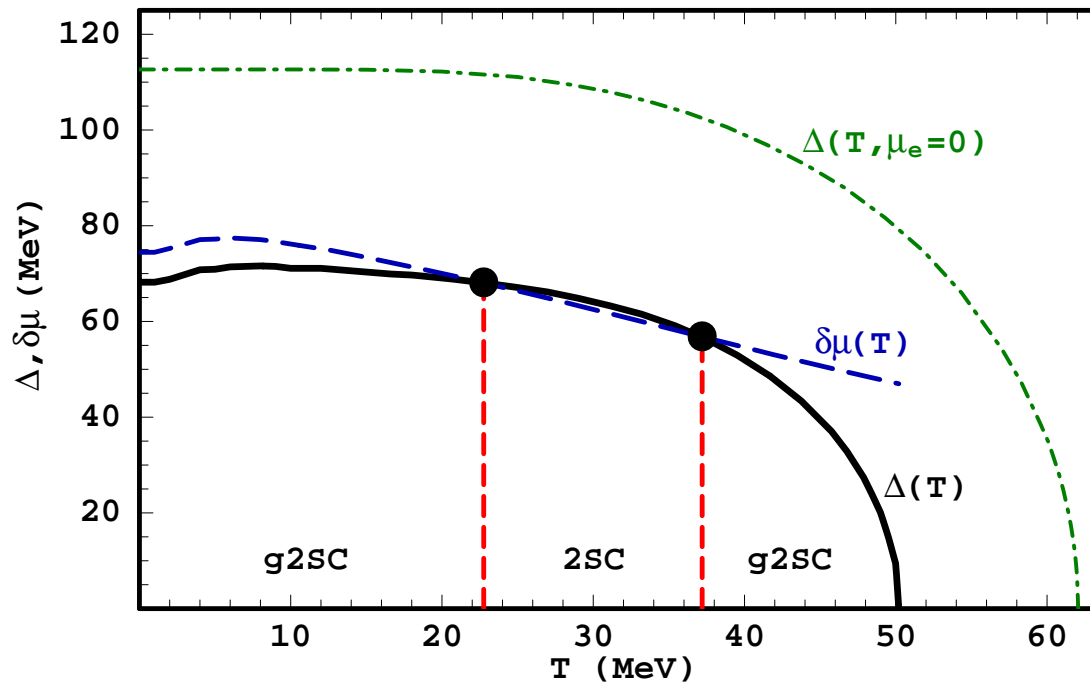
Eff. potential at $T \neq 0$



(Note: 2nd order phase transition)

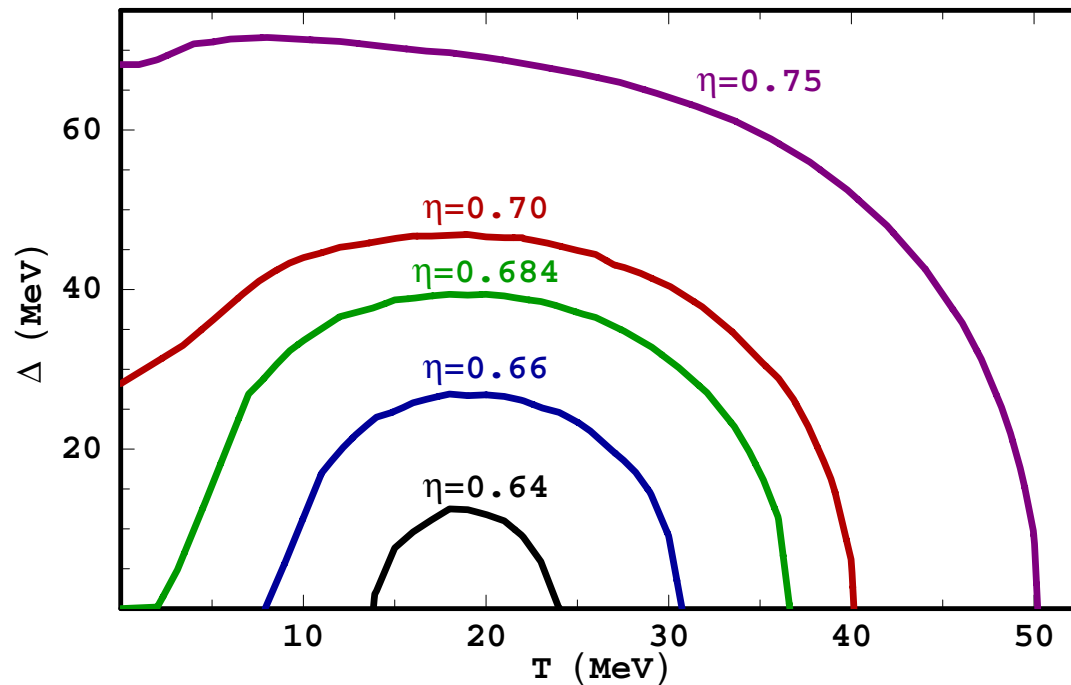
Thus, g2SC is stable provided $Q = 0$ is enforced *locally*

Temperature dependence of the gap. I.



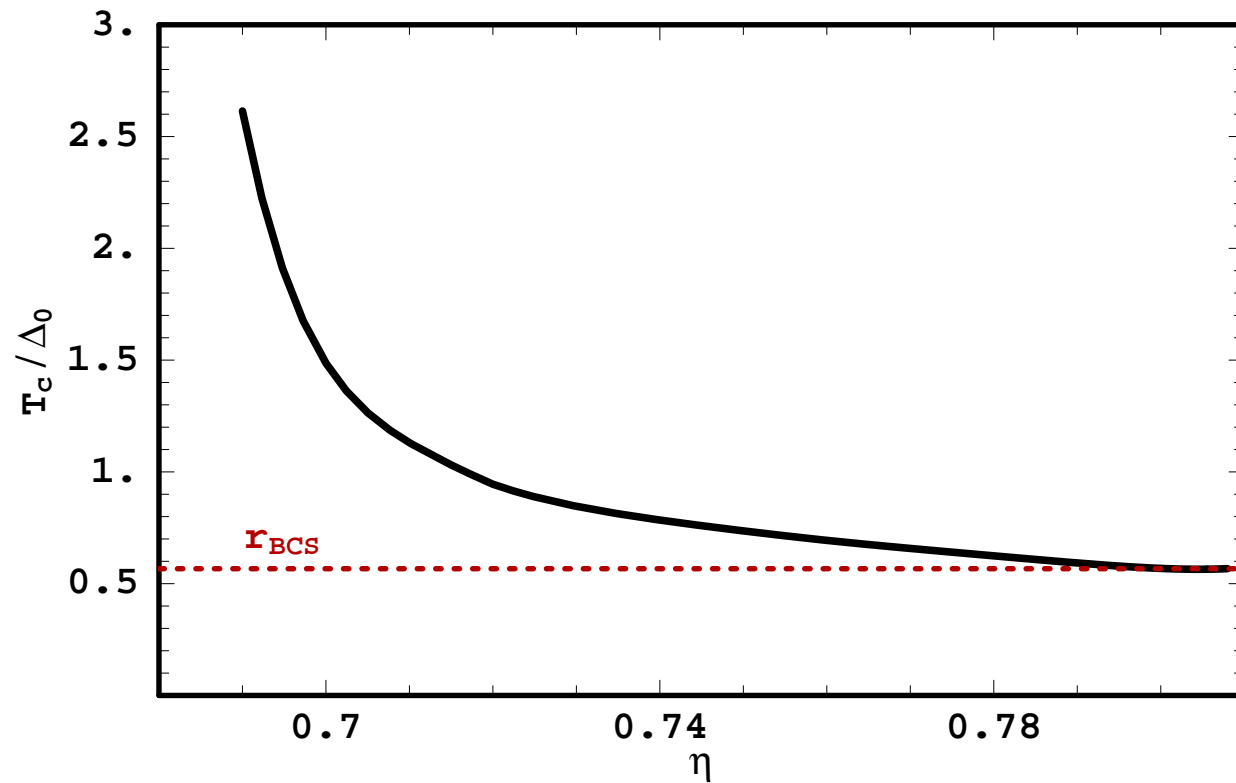
- *Nonmonotonic* temperature dependence
- Transitional behavior: g2SC \rightarrow 2SC \rightarrow g2SC \rightarrow normal phase

Temperature dependence of the gap. II.



- Extreme *nonmonotonic* temperature dependence
- Transitional behavior: normal phase \rightarrow g2SC \rightarrow normal phase

Nonuniversal ratio T_c/Δ_0



- The ratio is *not universal* (unlike in BCS)
- The value of T_c/Δ_0 can be *arbitrarily* large

Summary

- The g2SC phase is a new state of matter that may exist in cores of compact stars
- The g2SC phase is stable if the neutrality is enforced locally
- The spectrum of low-energy excitations in the g2SC phase has extra gapless modes (these should affect transport properties)
- Temperature dependence of the gap is nonmonotonic
- Ratio T_c/Δ_0 is nonuniversal, and can be arbitrarily large
- A gapless phase of $N_f = 3$ quark matter is also possible
- Similar gapless phases may appear in asymmetric nuclear matter and in trapped cold gases of fermionic atoms (e.g., ${}^6\text{Li}$ and ${}^{40}\text{K}$)

Additional references

[1] Unstable Sarma phase:

G. Sarma, J. Phys. Chem. Solids **24** (1963) 1029.

[2] Asymmetric nuclear matter:

A. Sedrakian and U. Lombardo, Phys. Rev. Lett. **84** (2000) 602.

[3] Interior gap superfluidity (atomic gases):

W. Liu, F. Wilczek, Phys. Rev. Lett. **90** (2003) 047002.

[4] Breached pairing superfluidity:

E. Gubankova, W. Liu, F. Wilczek, Phys. Rev. Lett. **91** (2003) 032001.

[5] Gapless color flavor locked phase:

M. Alford, C. Kouvaris, K. Rajagopal, hep-ph/0311286.