Gapless color superconductivity

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References

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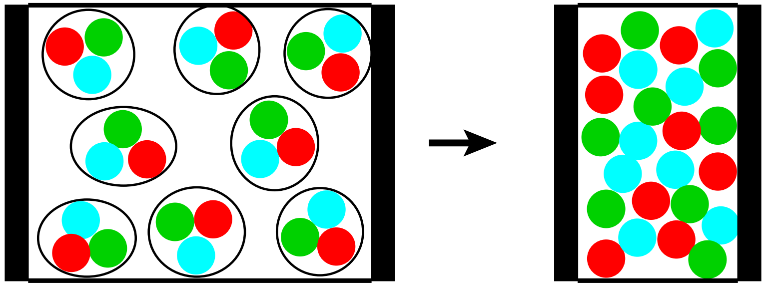
Matter at high density

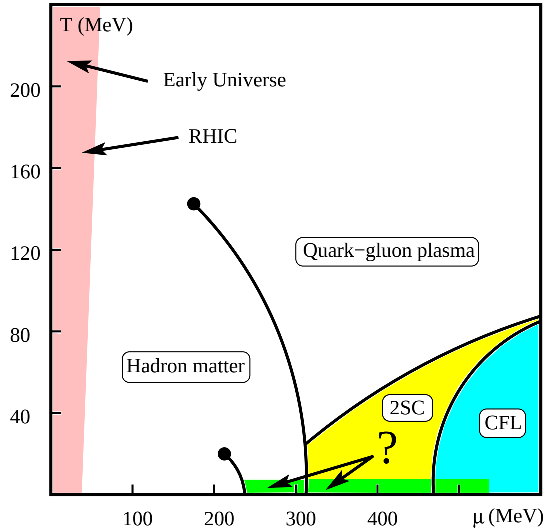
Why do we study this?

(i) fundamental properties of QCD

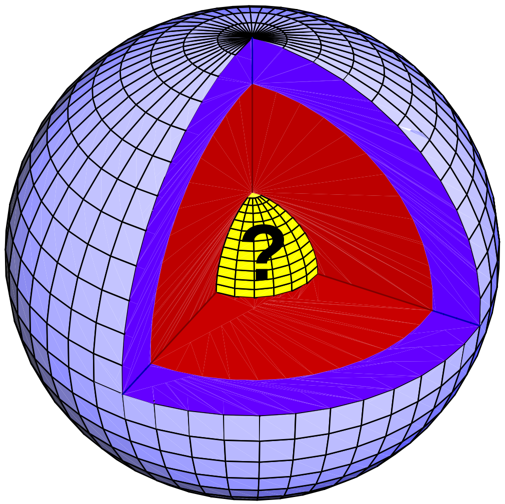
(ii) properties of compact stars



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



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

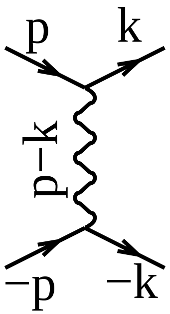


Color superconductivity

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

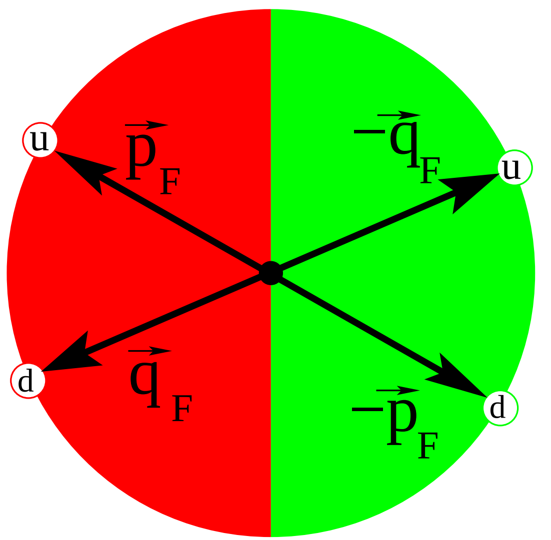
Simplest case, 2SC

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



$$= \bar{3}_a + 6_s$$

$$\langle u_p\, d_{-p} \rangle = -\langle u_q\, d_{-q} \rangle \neq 0$$



Cooper instability → color superconductivity

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

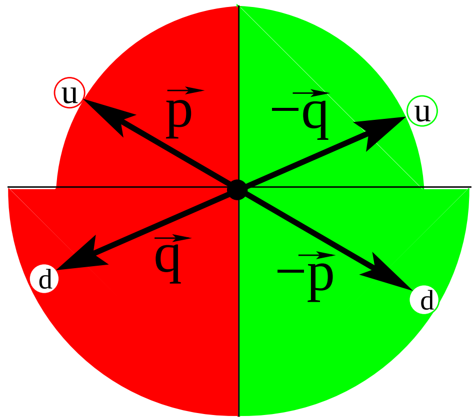
Neutrality vs. color superconductivity

Matter in the bulk of a star should be

(i) electrically and color neutral:

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

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



$$\Downarrow$$

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

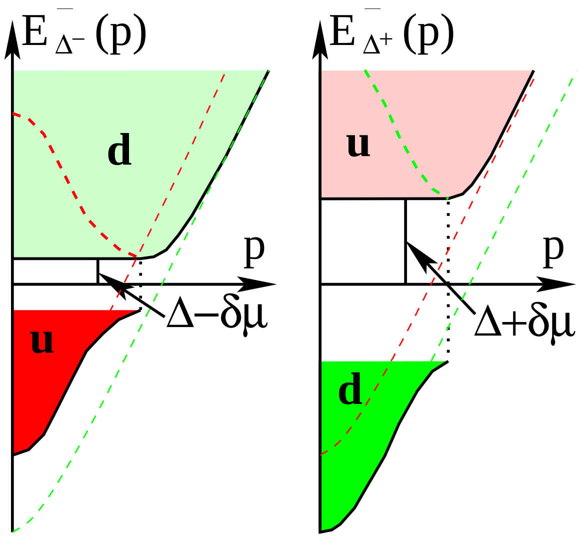
$$\Downarrow$$

The "best" Cooper pairing is distorted:

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

Regular 2SC vs. gapless 2SC

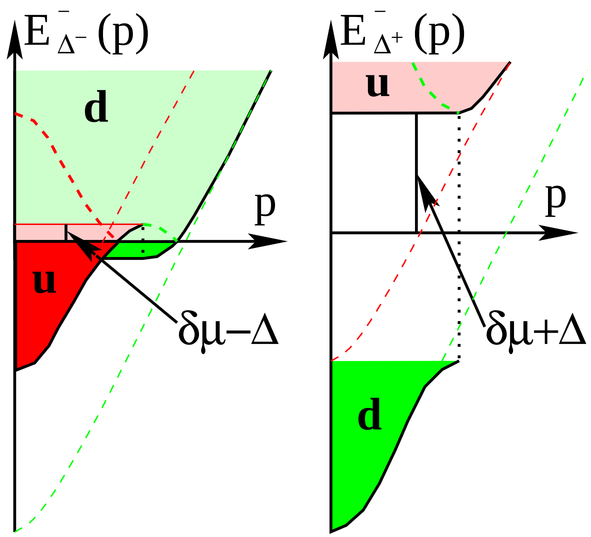
“Small” mismatch ($\delta\mu < \Delta$)



Energy gaps:

$(\Delta - \delta\mu)$ & $(\Delta + \delta\mu)$

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

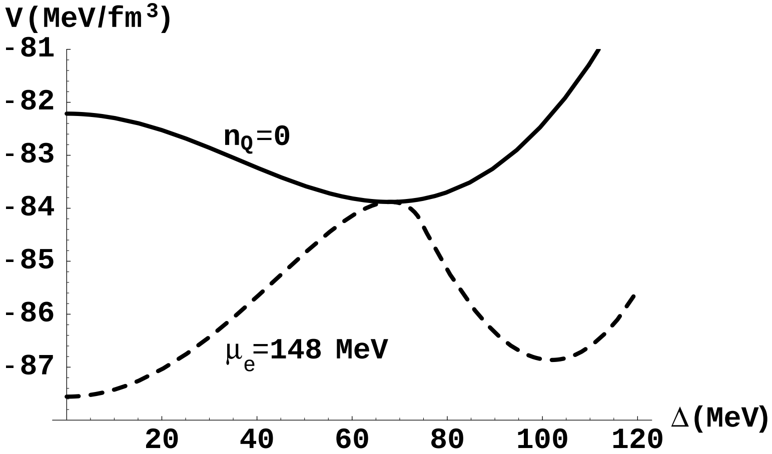


Energy gaps:

$\underline{\underline{0}}$ & $(\Delta + \delta\mu)$

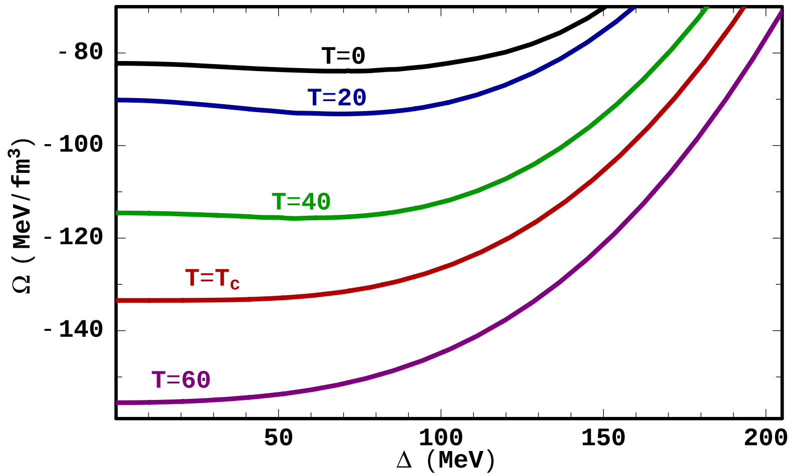
Stability of g2SC phase

Eff. potential at $T = 0$



(Mixed phase? — unlikely)

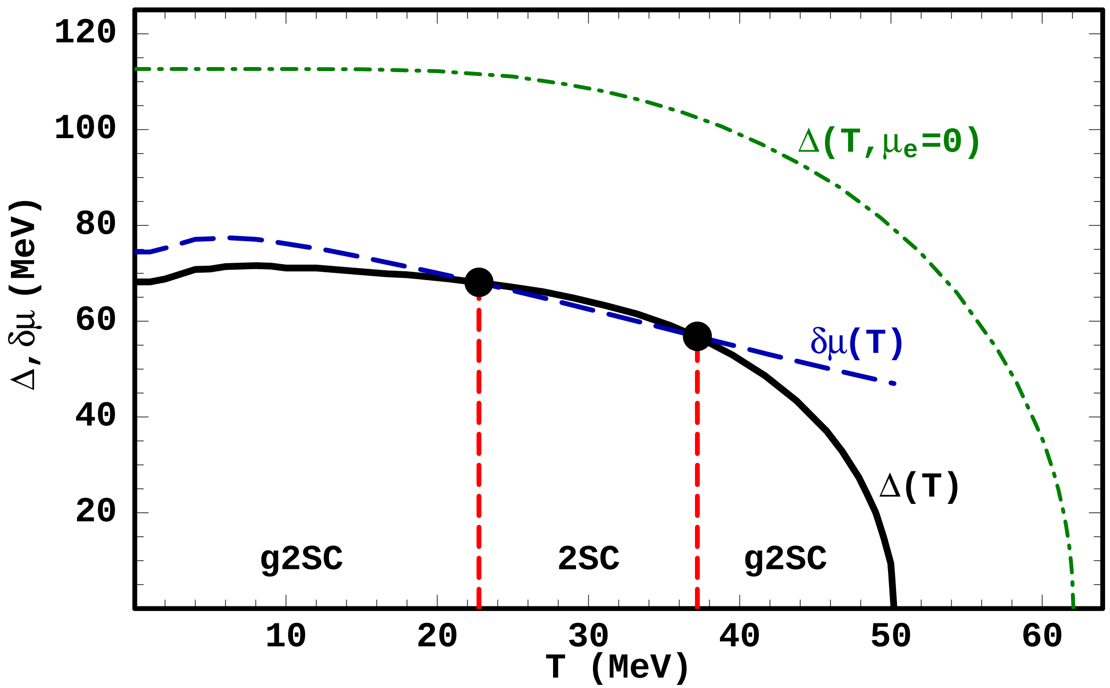
Eff. potential at $T \neq 0$



(Note: 2nd order phase transition)

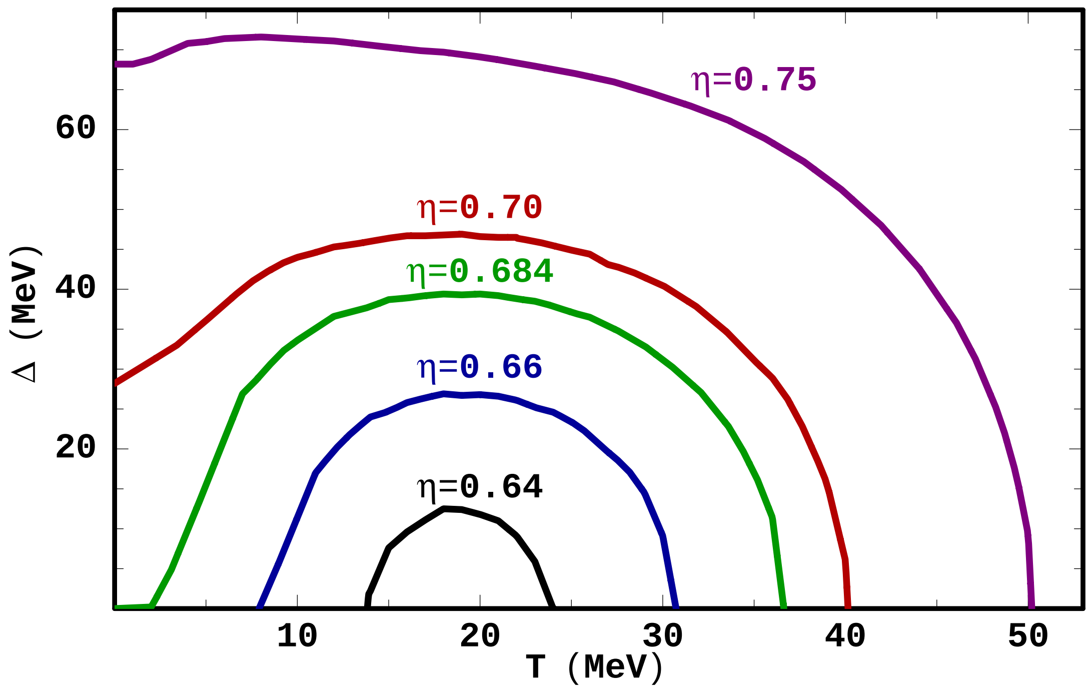
Thus, g2SC is stable provided $Q = 0$ is enforced *locally*

Temperature dependence of the gap. I.



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

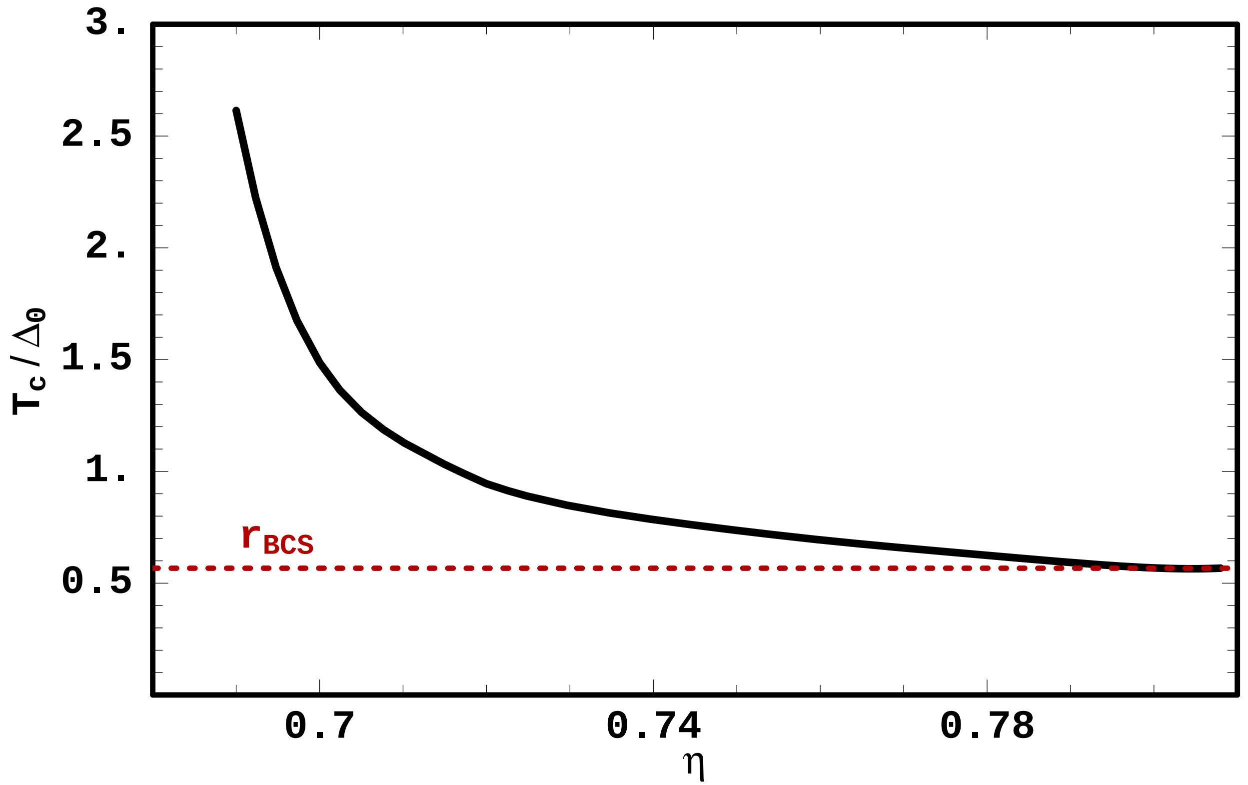
Temperature dependence of the gap. II.



- 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}Li and ^{40}K)

Additional references

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

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[3] Interior gap superfluidity (atomic gases):

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

[4] Breached pairing superfluidity:

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[5] Gapless color flavor locked phase:

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