Compact stars

as

a laboratory of gapless superconductivity

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References

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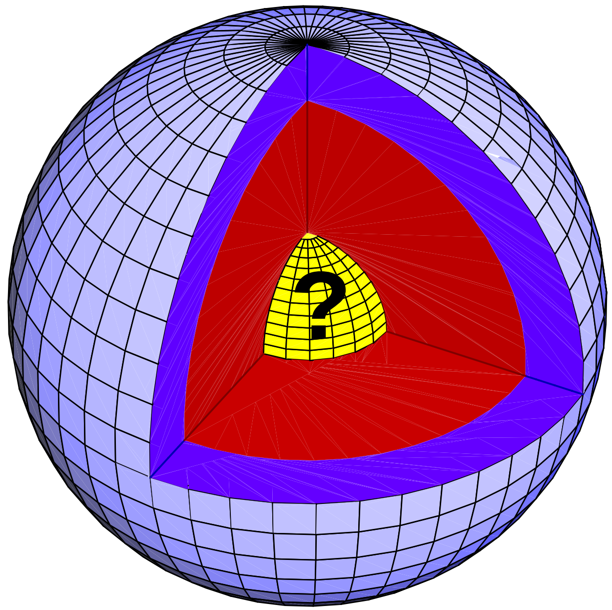
Highest density in the Universe

Central densities in compact stars can be rather large, $\rho \lesssim 10\rho_0$

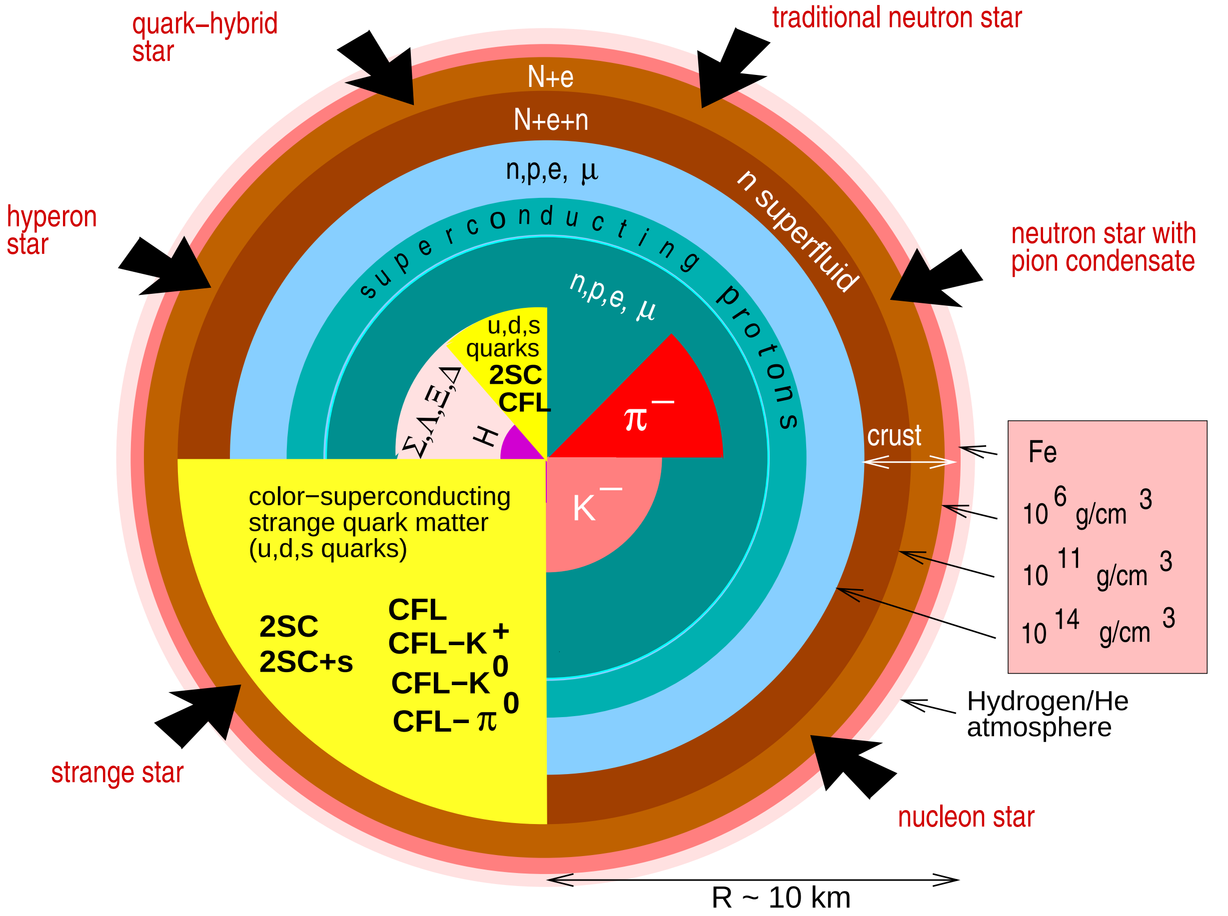
Main questions:

- Is there deconfined quark matter?
- Is there color superconductivity?
- Is there anything exotic?
- Where does the theory stand?
- How to "detect" new phases?
- Is there enough data from stars?



What can the theory tell on these issues?

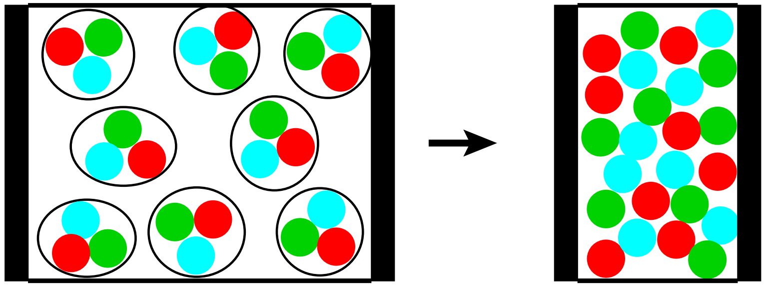
Phases of matter inside compact stars



[figure from F. Weber, astro-ph/0407155]

Dense matter might be deconfined

- "Squeezing" baryonic matter hard should produce quark matter:



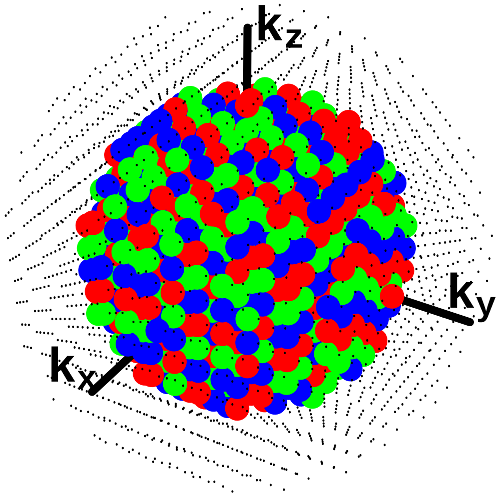
- Conjecture: quark matter may exist in stars
  [Ivanenko&Kurdgelaidze,'65], [Itoh'70], [Collins&Perry,'75]
- What is the ground state of quark matter?
- What is the effect of charge neutrality and β-equilibrium?

Ground state of dense quark matter

Educated guess:

(i) Quarks are fermions ($s = \frac{1}{2}$)
(ii) Interaction is weak ($\alpha_s \ll 1$)

$\Big\} \Rightarrow$ Fermi liquid (?)



(cf., electron gas in metals/alloys)

Further refinement:

(i) Degenerate Fermi surface
(ii) Attractive interaction (?)

$\Big\} \Rightarrow$ Cooper instability

(cf., the Cooper instability in superconducting metals/alloys)

Different color superconducting phases

- $N_f = 2$: 2SC phase (spin-0 gap $\sim$ 10 - 100 MeV):

$$\langle \left(\bar{\Psi}^C\right)^a_i \gamma_5 \Psi^b_j \rangle \sim \varepsilon^{3ab} \epsilon_{ij} \Delta$$

- $N_f = 3$: CFL phase (spin-0 gap $\sim$ 10 - 100 MeV):

$$\langle \left(\bar{\Psi}^C_L\right)^{a,\alpha}_i \epsilon_{\alpha\beta} \left(\Psi_L\right)^{b,\beta}_j \rangle = -\langle \left(\bar{\Psi}^C_R\right)^{a,\dot{\alpha}}_i \epsilon_{\dot{\alpha}\dot{\beta}} \left(\Psi_R\right)^{b,\dot{\beta}}_j \rangle \sim \sum_I \Delta \varepsilon^{abI} \epsilon_{ijI}$$

- $N_f = 1$: A-phase (spin-1 gap $\sim$ 0.01 - 1 MeV):

$$\langle \left(\bar{\Psi}^C\right)^a \gamma^i_\perp \Psi^b \rangle \sim \sum_I \Delta \mathcal{C}^i_I \varepsilon^{abI}, \quad \text{where} \quad \mathcal{C} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & i & 0 \end{pmatrix}$$

Physical properties of 2SC phase

- Pressure/equation of state:

$$P \simeq \frac{\mu^4}{2\pi^2} - B + \boxed{\frac{\mu^2\Delta^2}{\pi^2}} \qquad \text{may be (un-)important}$$

- Transport/specific heat is dominated by
  - Unpaired "blue-up" and "blue-down" quarks
  - 1 pseudo-NG boson that results from breaking $U(1)_A$
  - 3 gluons of unbroken $\mathrm{SU}(2)_c$ (decoupled from blue quarks)
  - low energy photon of $\tilde{\mathrm{U}}(1)_{\mathrm{em}}$
- No superfluidity $\rightarrow$ no rotational vorticies
- No electromagnetic Meissner effect $\rightarrow$ no magnetic flux tubes
- Neutrino emissivity/cooling rate is large (direct URCA)

Physical properties of CFL phase

- Pressure/equation of state:

$$P \simeq \frac{3\mu^4}{4\pi^2} - B + \boxed{\frac{3\mu^2\Delta^2}{\pi^2}} \qquad \text{may be (un-)important}$$

- Transport/specific heat is dominated by [Shovkovy & Ellis, 2002]
  - 1 NG boson (ϕ) that results from breaking $U(1)_B$
  - low energy photon of $\tilde{\mathrm{U}}(1)_{\mathrm{em}}$
  - 1 pseudo-NG boson (η') that results from breaking $U(1)_A$
  - 8 ($\times$3 polarizations) light plasmons with mass $\sim \Delta$ (?)

    [Gusynin & Shovkovy, hep-ph/0108175]
- Superfluidity $\to$ rotational vorticies
- No electromagnetic Meissner effect $\to$ no magnetic flux tubes
- Neutrino emissivity/cooling rate is suppressed ($\sim e^{-\Delta/T}$)

Color superconductivity in stars. Really?

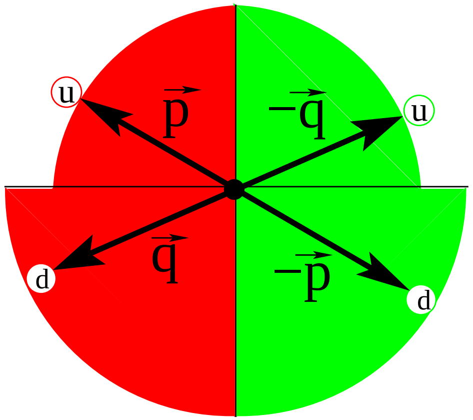
Matter in stars should be neutral and β-equilibrated:

$$n_Q = 0 \quad \text{and} \quad \mu_d = \mu_u + \mu_e$$

- Neutral matter (in β-equilibrium) appears when $\boxed{n_d \approx 2n_u}$
- The "best" 2SC phase appears when $\boxed{n_d \approx n_u}$

The "best" Cooper pairing is distorted by the following mismatch parameter:

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



Then, what happens?

Appearance of a gapless phase

Mismatch parameter μ_e is **not** a free model parameter,

$$n_Q \equiv -\frac{\partial \Omega}{\partial \mu_e} = 0 \qquad \Rightarrow \qquad \mu_e = \mu_e(\mu, \Delta)$$

Three dynamical regimes determined by the coupling strength η:

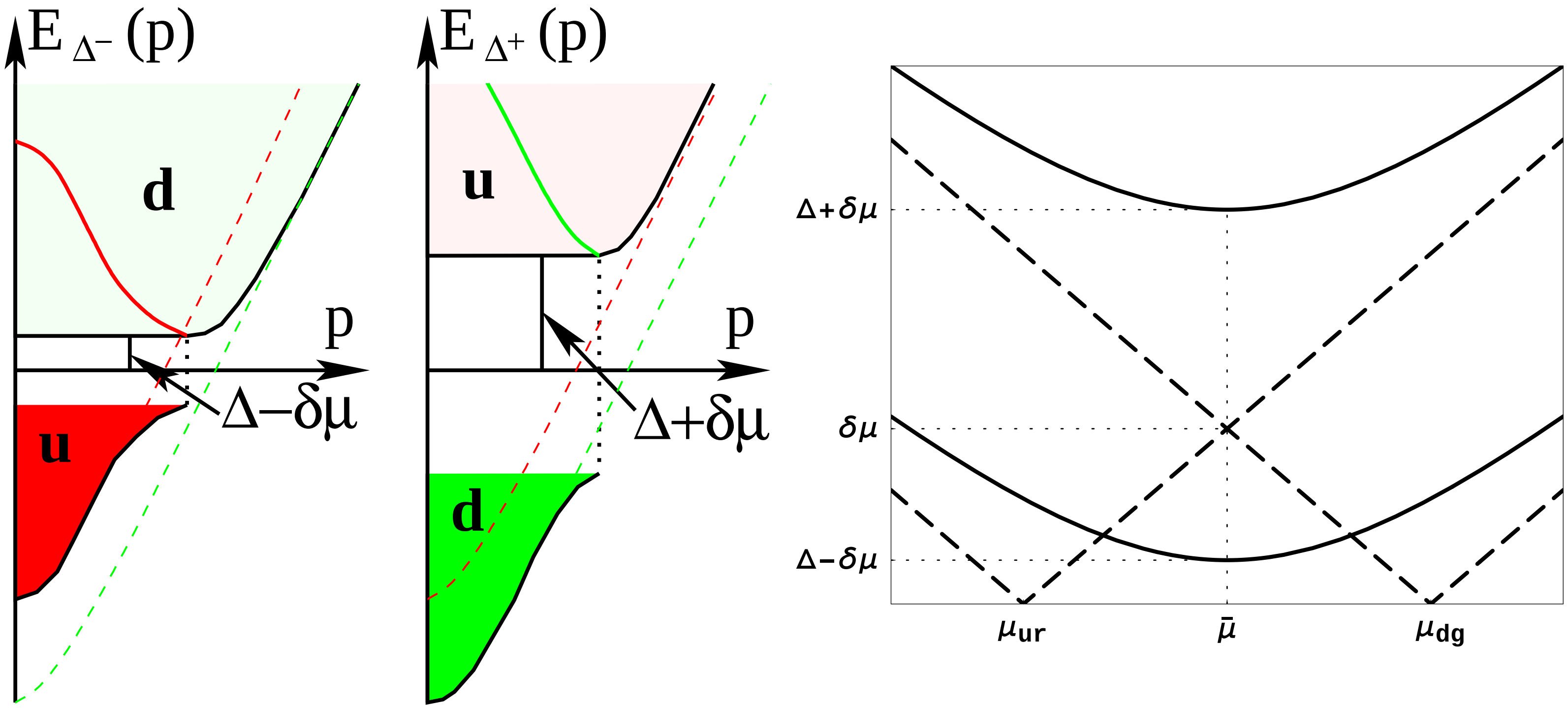
1. Weak: $\eta \lesssim 0.7$ — the mismatch does not allow Cooper pairing: normal phase is the ground state

2. Strong: $\eta \gtrsim 0.8$ — strong coupling wins over the mismatch between the Fermi surfaces: 2SC is the ground state

3. $0.7 \lesssim \eta \lesssim 0.8$ — regime of intermediate coupling strength: the ground state is the gapless 2SC phase [hep-ph/0302142]

Quasiparticle spectrum in 2SC phase

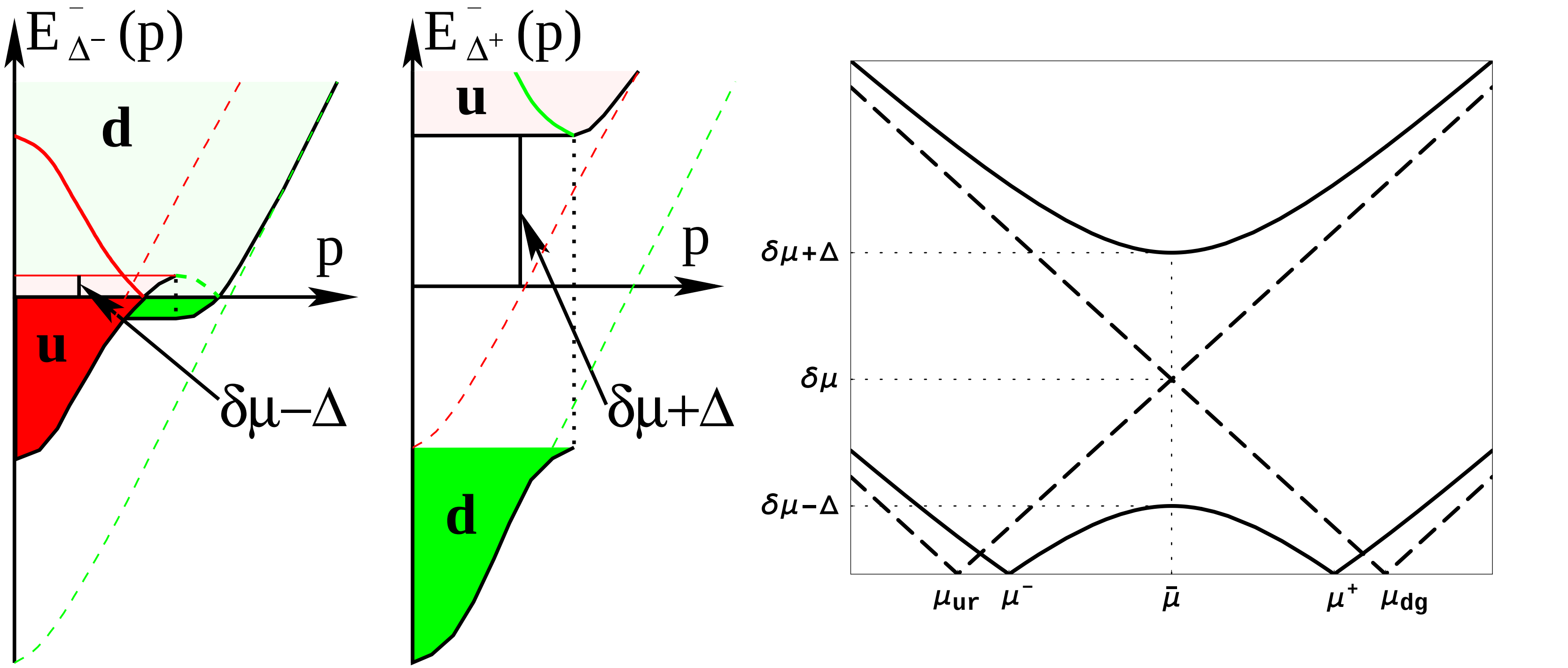
"Strong" coupling (2SC phase)



The energy gaps in the quasiparticle spectra are $\boxed{\Delta - \delta\mu}$ & $\boxed{\Delta + \delta\mu}$

Quasiparticle spectrum in g2SC phase

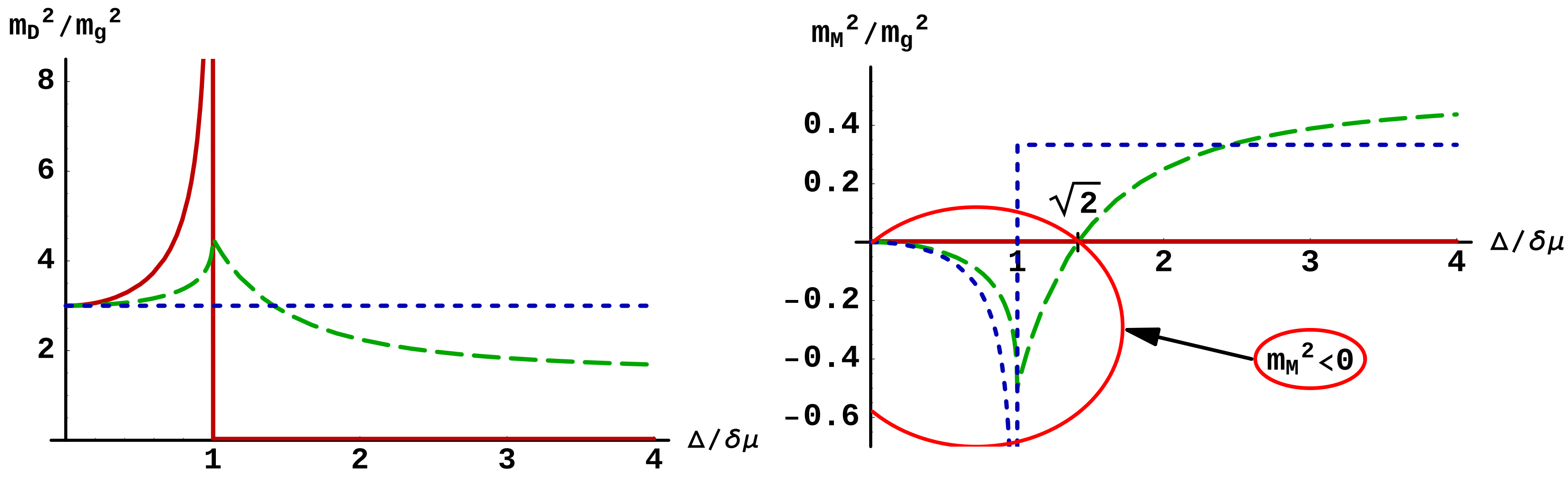
"Intermediate" coupling (gapless phase)



The energy gaps in the quasiparticle spectra are $\boxed{0}$ & $\boxed{\Delta + \delta\mu}$

Chromomagnetic instability

Recent results for gluon screening masses
[Huang & Shovkovy, hep-ph/0407049; hep-ph/0408268]:



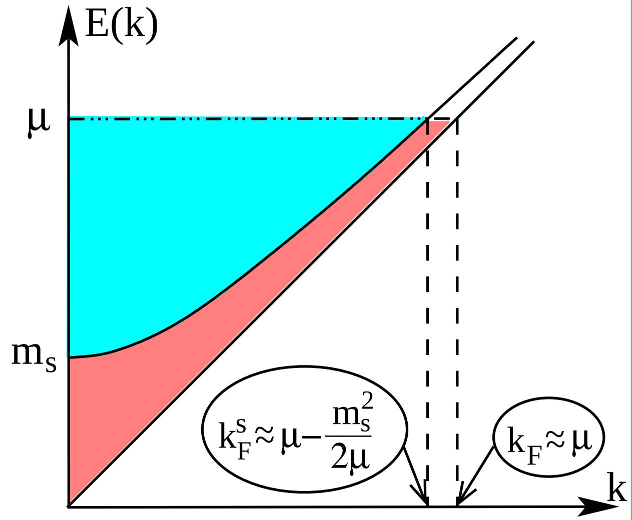
$A = 1, 2, 3$ — red solid line

$A = 4, 5, 6, 7$ — green long-dash line

$A = \tilde{8}$ — blue short-dash line

Finite strange quark mass, $0 < m_s < \infty$

Fermi momentum of strange quarks is lowered:



$$k_F^s \simeq \mu - \frac{m_s^2}{2\mu}$$

The ground state of strange quark matter may have:

- only spin-1 condensates of same flavor
- only superconductivity of up and down quarks (2SC or g2SC)
- crystaline pairing (nonzero momentum pairing, LOFF)

Recently, other possibilities were proposed as well . . .

Gapless $N_f = 3$ quark matter

- Distorted color-flavor pairing:

$$\Delta_{ij}^{\alpha\beta} \simeq \Delta_1\ \epsilon_{1ij}\varepsilon^{1\alpha\beta} + \Delta_2\ \epsilon_{2ij}\varepsilon^{2\alpha\beta} + \Delta_3\ \epsilon_{3ij}\varepsilon^{3\alpha\beta} + \ldots$$

- Control (mismatch) parameter:

$$\delta\mu \equiv \frac{\mu_{bd} - \mu_{gs}^{\text{eff}}}{2} \approx -\frac{\mu_8}{2} + \frac{m_s^2}{4\mu} \approx \boxed{\frac{m_s^2}{2\mu}}$$

where $\mu_{gs}^{\text{eff}} \simeq \mu_{gs} - \dfrac{m_s^2}{2\mu}$ and $\mu_8 \simeq -\dfrac{m_s^2}{2\mu}$ (blue color is special)

- Gapless CFL phase with $\Delta_1 < \Delta_2 < \Delta_3$:

$$T = 0: \qquad \delta\mu \equiv \frac{m_s^2}{2\mu} > \Delta_0$$

[Alford et al. hep-ph/0311286]

Nonzero temperature

- There can exist many phases at $T \neq 0$
  [Iida et al, hep-ph/0312363], [Rüster et al, hep-ph/0405170], [Fukushima al, hep-ph/0408322]
- Zoo of phases:

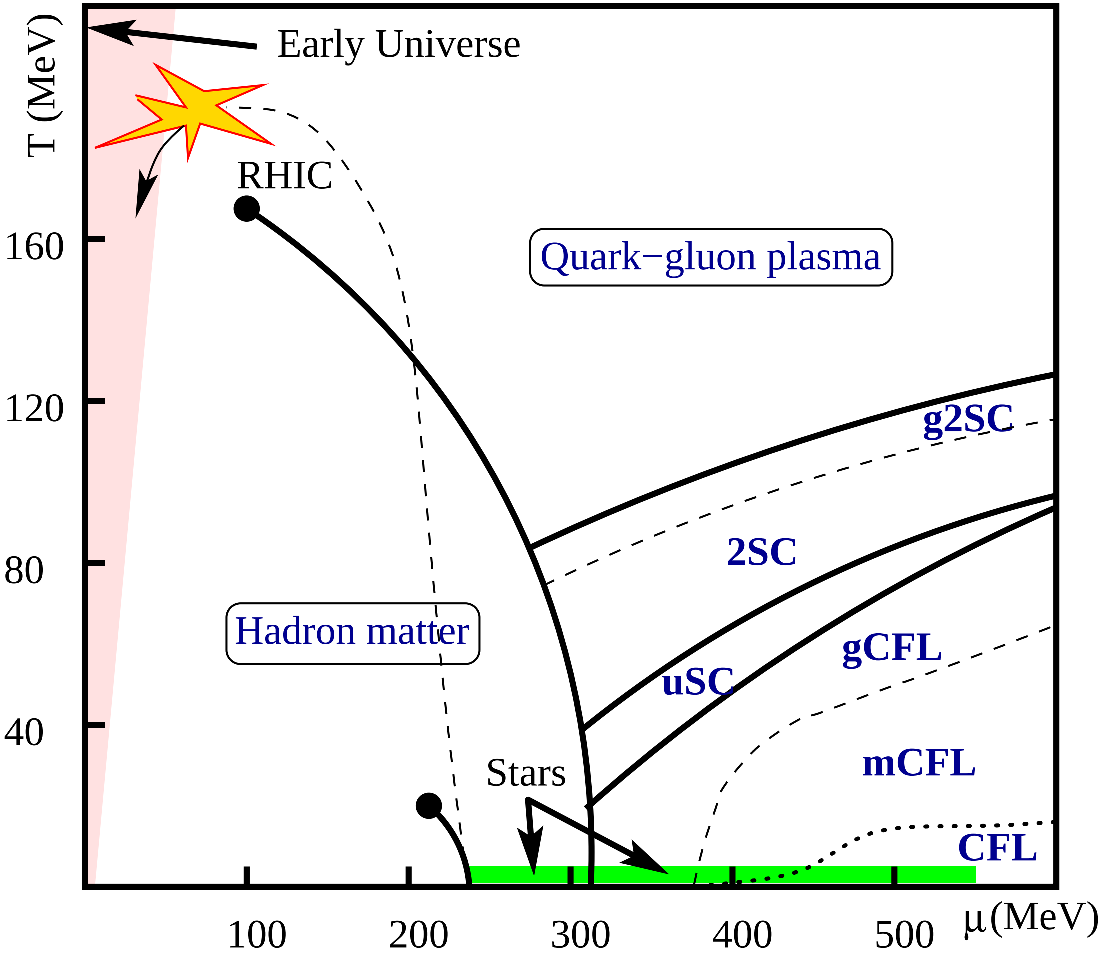
$$
\begin{array}{rllll}
\text{CFL:} & \Delta_1 \neq 0, & \Delta_2 \neq 0, & \Delta_3 \neq 0, & (\mu_e \approx 0) \\
\text{mCFL:} & \Delta_1 \neq 0, & \Delta_2 \neq 0, & \Delta_3 \neq 0, & (\mu_e \neq 0) \\
\text{uSC:} & \Delta_1 = 0, & \Delta_2 \neq 0, & \Delta_3 \neq 0, & \\
\text{dSC:} & \Delta_1 \neq 0, & \Delta_2 = 0, & \Delta_3 \neq 0, & \\
\text{2SC:} & \Delta_1 = 0, & \Delta_2 = 0, & \Delta_3 \neq 0, & \\
\text{NQM:} & \Delta_1 = 0, & \Delta_2 = 0, & \Delta_3 = 0, &
\end{array}
$$

plus g2SC and gCFL as special cases of 2SC and mCFL.

Overview of phases with strangeness

- Color-flavor locked (CFL) phase
  - "Enforced pairing": $n_u = n_d = n_s$ $(T \simeq 0)$
    [Rajagopal, Wilczek, 2001]
  - Natural insulator, $n_{\rm el} \simeq 0$
  - Little specific heat and low neutrino emissivity
- Metallic CFL phase $(n_{\rm el} \neq 0)$
  - $T = 0$: gapless CFL phase (no "enforced pairing")
  - $T \neq 0$: thermal effects $\rightarrow n_{\rm el} \neq 0$
  - Large specific heat and high neutrino emissivity
- uSC phase: only *ud*- & *us*-pairing (no *ds*-pairing)
- dSC phase: only *du*- & *ds*-pairing (no *us*-pairing)

Phase diagram



Based on results of [Rüster, Shovkovy, Rischke, hep-ph/0405170]

Current status

- Sufficiently cold and dense matter is a color superconductor
- Neutrality and β-equilibrium may strongly affect the properties of dense matter
- There can exist many different CSC phases (e.g., 1SC, 2SC, g2SC, CFL, gCFL, mCFL, uSC, dSC, LOFF, CFL+K^0, CFL+η)
- Some features of $T-\mu$ phase diagram start to develop
- A search for signature-type observables of color superconductivity inside stars is under way

Outlook

- A systematic study of competition between different phases in dense QCD should be completed
- Physical properties (transport, in particular) of QCD phases should be addressed in detail
- The status of gapless phases should be resolved (addressing, e.g., the chromomagnetic instability, spontaneously induced currents)
- The most promising observable(s), (dis-)proving the presence of CSC inside stars, should be proposed
- A rigorous approach to treat QCD at nonzero densities should be developed