Quark matter at high temperature/density

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I. The phases of quark matter

Low temperatures and densities : confined, broken chiral symmetry.

High temperatures $(T \gtrsim 170 \text{ MeV})$: quark-gluon plasma (QGP)

- chiral symmetry restored
- deconfinement
- signatures sought at heavy-ion colliders

High densities $(n_{\text{quark}} \gtrsim 1 \text{ fm}^{-3})$: color superconductivity

- Quarks *pair* in color non-singlets.
- Rich variety of phases depending on which colors and flavors participate.

Conjectured QCD phase diagram
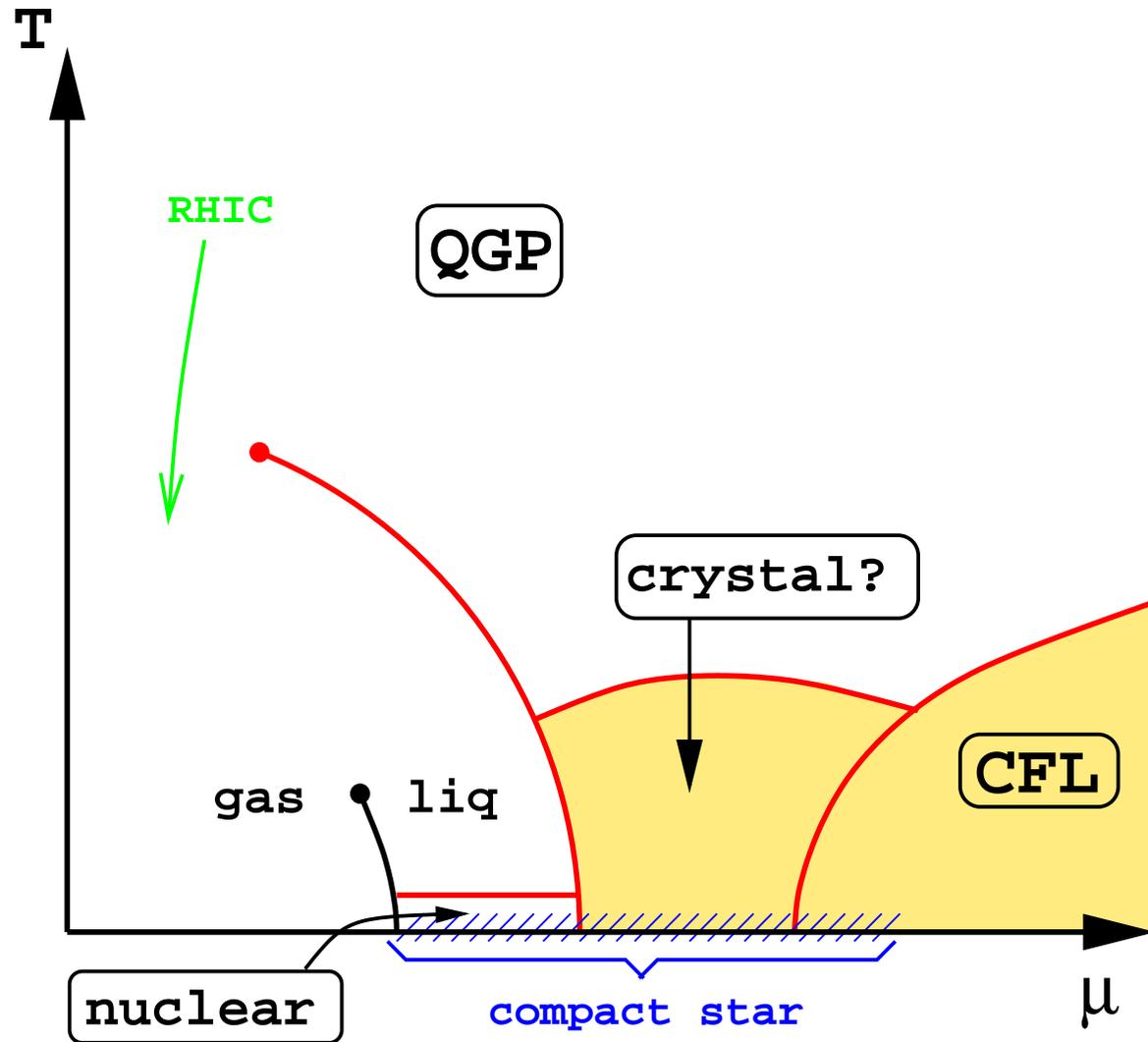
heavy ion collisions: chiral critical point and first-order line

compact stars: color superconducting quark matter core

High-density QCD calculations

Guess a color-flavor-spin pairing pattern P; minimize free energy wrt Δ: gap equation for Δ.

$$\text{---}\bullet\text{---} = \langle q_{ia}^{\alpha} q_{jb}^{\beta} \rangle_{1PI} = P_{ij\ ab}^{\alpha\beta} \Delta$$
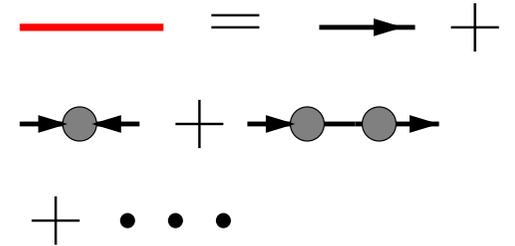
1. Weak-coupling methods. First-principles calculations direct from QCD Lagrangian, valid in the asymptotic regime, currently $\mu \gtrsim 10^6$ MeV.

2. Nambu–Jona-Lasinio models, ie quarks with four-fermion coupling based on instanton vertex, single gluon exchange, etc. This is a semi-quantitative guide to physics in the compact star regime $\mu \sim 400$ MeV, not a systematic approximation to QCD.
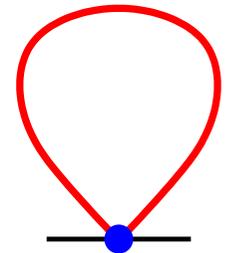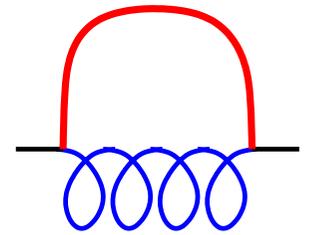
NJL gives $\Delta \sim 10-100$ MeV at $\mu \sim 400$ MeV.

Both methods agree on the favored pairing pattern.