Several Issues in Color Superconductivity

First part: M. Buballa and M. Oertel

- 2SC versus CFL: influence of the strange quark mass
- Neutron stars: constraints by neutrality

Color superconductivity

Cold dense deconfined strongly interacting matter:

- Attractive interaction $\longrightarrow$ pair condensation
- Most important example (color $\bar{3}$ channel):

$$\langle\bar{\psi}_{\alpha a A}(\lambda^i)_{ab}(\tau^j)_{AB}(\gamma_5 C)_{\alpha\beta}\bar{\psi}_{\beta b B}\rangle = \Delta_{ij}$$

- λ^i and τ^j any antisymmetric $SU(3)$ matrix

- Two idealized cases:
  - $\underline{M_s \rightarrow \infty}$:
    Only u, d-quarks condense
    $\longrightarrow$ only Δ_{ij} with $j = 2$ nonzero
  - Only two out of three quark colors are "gapped"
    $\longrightarrow$ $SU(3)_c$ broken down to $SU(2)_c$
  - Chiral symmetry restored

  - $\underline{M_s = M_u = M_d}$:
    u, d and s-quarks condense
    Most favored state: $\Delta_{22} = \Delta_{55} = \Delta_{77}$
  - "Color-Flavor-Locked (CFL)"-state:
    $\mathrm{SU}(3)_c \times \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ broken to $\mathrm{SU}(3)_{c+V}$
    $\longrightarrow$ color and chiral symmetry broken

Realistic case: $M_u = M_d < M_s$

Which condensation pattern? Step 1: $\mu_u = \mu_d = \mu_s = \mu$

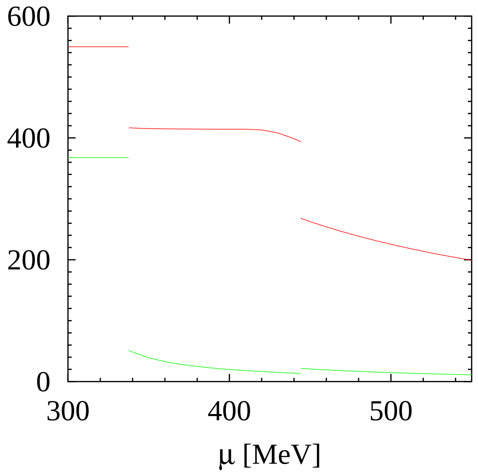
- $\underline{M_s \approx \mu}$: $\quad p_F^u \approx \mu \gg p_F^s = \sqrt{\mu^2 - M_s^2}$

  $\underline{M_s \ll \mu}$: $\quad p_F^u \approx p_F^s$

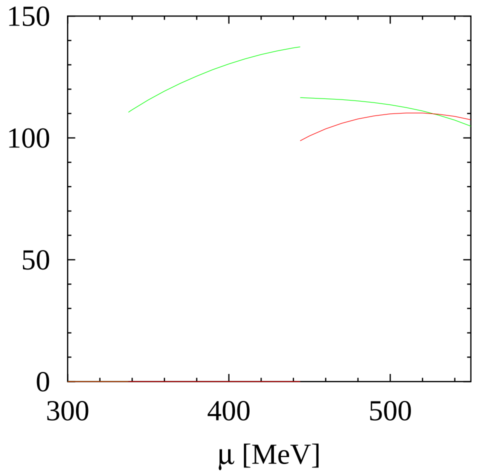
- Influence masses $\Leftrightarrow$ phases:

NJL calculation: Masses related to $\langle \bar{u}u \rangle, \langle \bar{d}d \rangle, \langle \bar{s}s \rangle$

Masses M_u, M_s



Condensates Δ_{22}, Δ_{55}



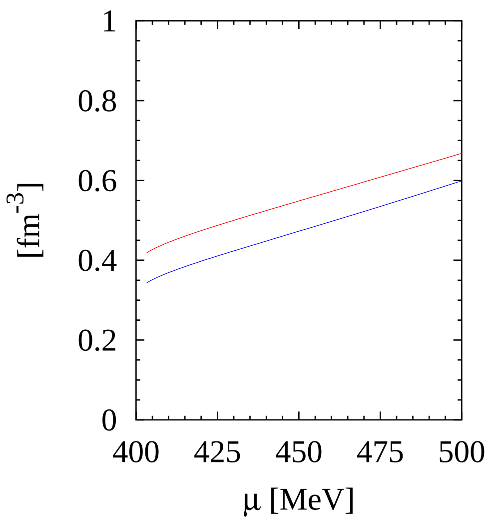
(M.B., M.O., NPA '02)

Bulk matter in compact stars

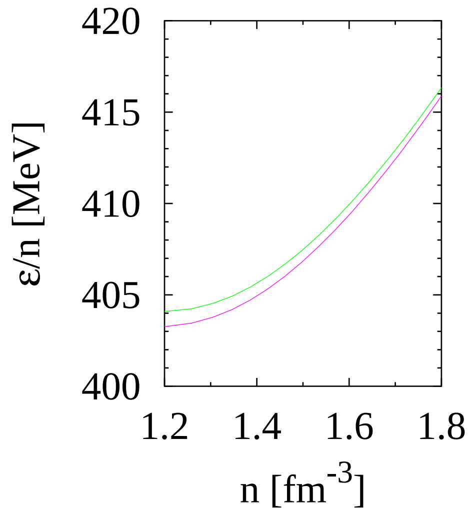
- Constraints:
  - β-equilibrium
  - (electric) charge neutrality
  - color singlet $\Rightarrow$ color neutrality

- Color neutrality: $n_r = n_g = n_b$

$n_r = n_g, \quad n_b$



$n_r = n_b, \quad \mu_r = \mu_b$



(M.B., J. Hošek, M.O., PRD '01)

$\Rightarrow$ minor effect

β-equilibrium + charge neutrality

- β-equilibrium:

  $d \leftrightarrow u + e^- + \bar{\nu}_e \leftrightarrow s \quad \Rightarrow \quad \mu_d = \mu_s = \mu_u + \mu_e$

- charge neutrality:

  $\frac{2}{3} n_u - \frac{1}{3} n_d - \frac{1}{3} n_s - n_e = 0$

- simple estimate: massless u and d, no s, no pairing

  assumption: $n_e \approx 0$

  $\Rightarrow \; n_d \approx 2 n_u \;\; \Rightarrow \;\; \mu_d \approx 2^{1/3} \mu_u$

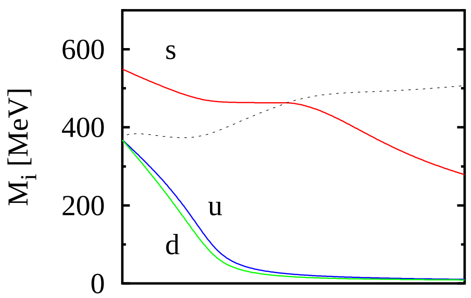
  $\Rightarrow \;\; \mu_e \approx (2^{1/3} - 1)\, \mu_u \simeq \frac{1}{4}\, \mu_u$

  $\Rightarrow \;\; n_e \approx \frac{1}{3 \cdot 64}\, n_u \approx 0.005\, n_u$

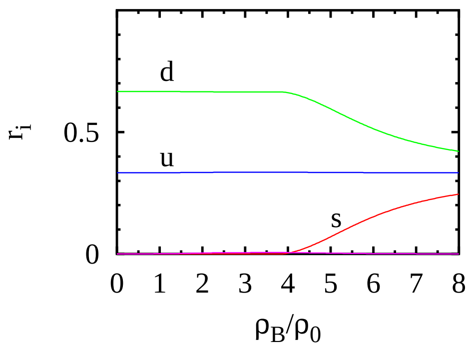
  $\rightarrow$ almost no electrons

- NJL-calculation: massive u, d, and s, no pairing

masses:



fractions:



(M.B., M.O., PLB '99)

Consequences for diquark pairing

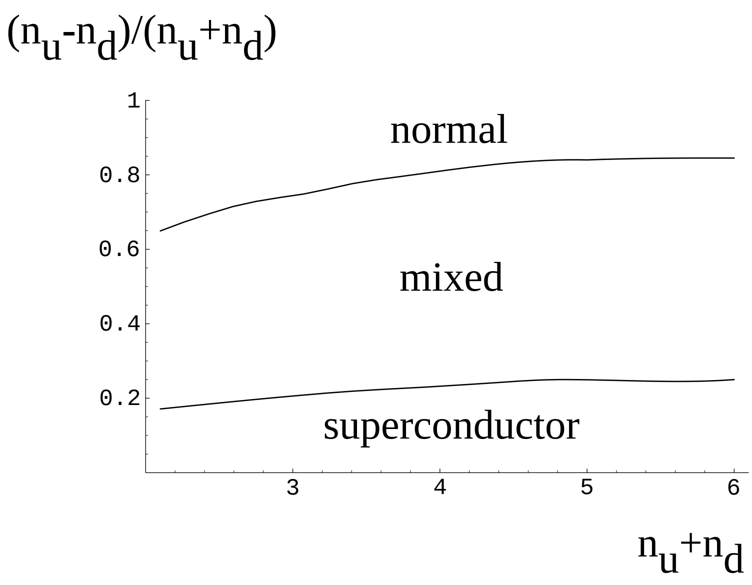
- <u>case 1:</u> M_s large $\Rightarrow$ no strange quarks

  - $n_d \simeq 2\,n_u \quad \Rightarrow \quad \mu_d \simeq 2^{1/3}\,\mu_u \simeq \frac{5}{4}\,\mu_u,$
  - stability criterion: (Rajagopal, Wilczek, PRL '01)

$$\Delta \;>\; \sqrt{2}\,\delta\mu$$

example: $\mu_u = 400$ MeV $\quad \Rightarrow \quad \mu_d = 500$ MeV
$\Rightarrow \Delta \;>\; 140$ MeV

  - Model analysis:



(P. Bedaque, NPA '02)

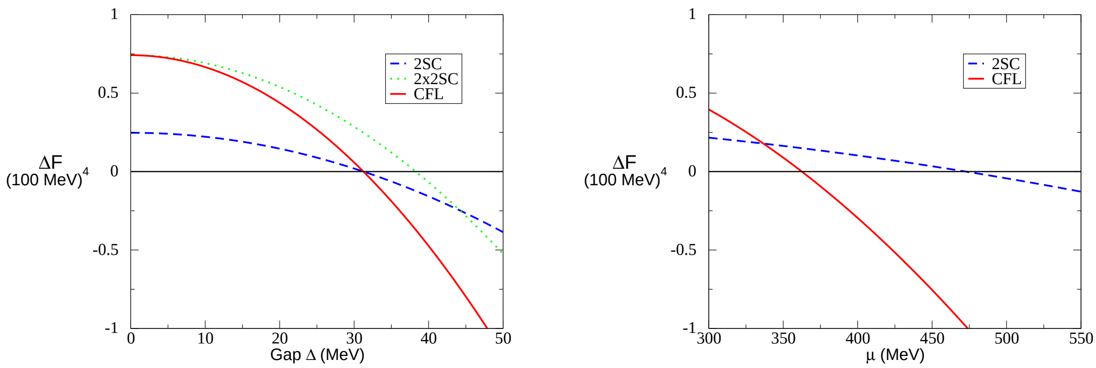
Consequences for diquark pairing

- <u>case 2:</u> M_s small $\Rightarrow$ expansion in M_s

(Alford, Rajagopal, hep-ph/0204001)

$\rightarrow$ $p_F^d = p_F^u + \frac{M_s^2}{4\bar{\mu}} \quad p_F^s = p_F^u - \frac{M_s^2}{4\bar{\mu}}$

$\rightarrow$ equal probability for ud- and us-pairing



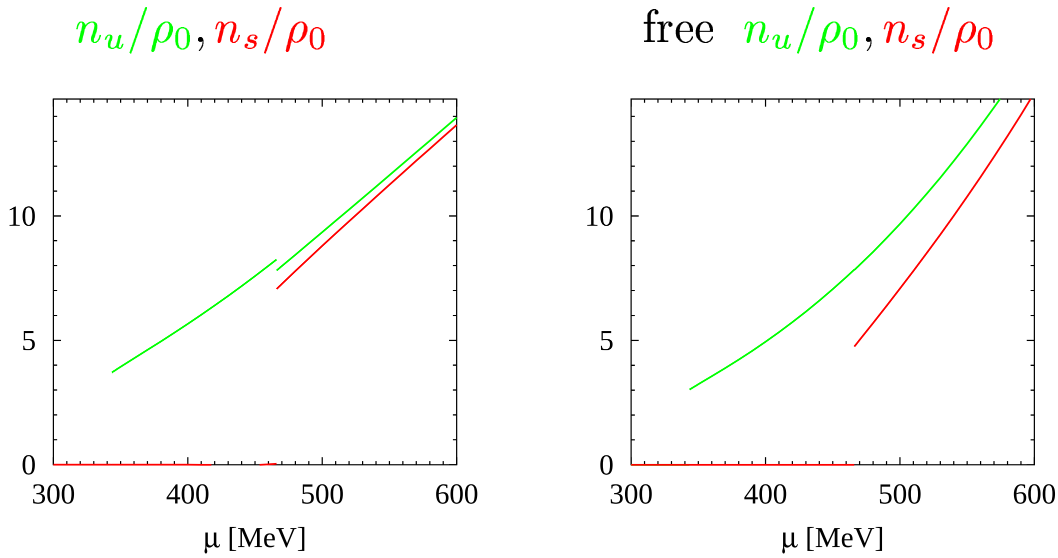
(Alford, Rajagopal, hep-ph/0204001)

Is the CFL phase charge neutral?

Argument (Rajagopal, Wilczek, PRL '01):
Densities equal $\rightarrow$ charge neutrality enforced

Model calculation:

densities including pairing	$\Leftrightarrow$	"free ones"
$-\frac{\partial\Omega}{\partial\mu_i}$		$\frac{1}{\pi^2}(\mu_i^2 - M_i^2)^{3/2}$



(M.B., F. Neumann, M.O., preliminary result)