Chirally symmetric and confining quarkyonic matter with a diffused quark Fermi surface

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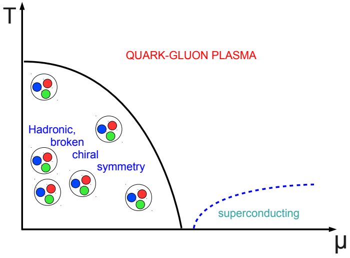
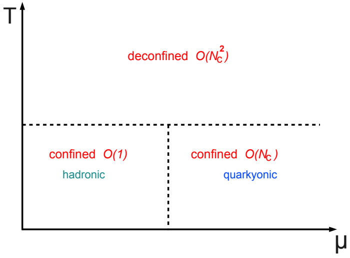
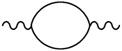
The McLerran - Pisarski argument (2007)



Traditional phase diagram



Large N_c phase diagram

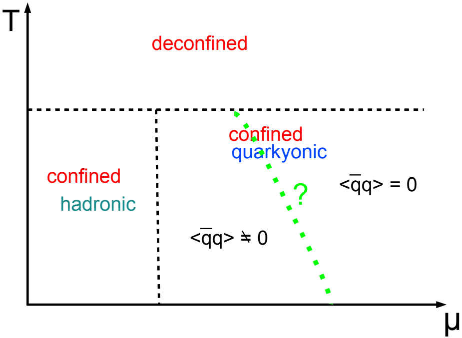


$$\sim \frac{1}{N_c}, \qquad N_c \to \infty$$

At large N_c limit one should obtain the same gluon dynamics in the vacuum and in the matter because of the absence of quark loops in both cases.

At large chemical potential a pressure $\sim N_c$. For a pure hadron gas it must be ~ 1. For a deconfining quark-gluon matter it must be $\sim N_c^2$. Then the deconfining quark-gluon matter at small temperatures should not exist.

Chiral symmetry in quarkyonic matter?????



- definition: quarkyonic matter - dense matter with confinement
- no words about chiral symmetry in the definition

A key question is to clarify whether existence of conning but chirally symmetric dense, cold matter is possible?

The model

A. Le Yaouanc et al; S. Adler & A. Davis (1984): The Hamiltonian relies on the quark current-current interaction via the instantaneous linear inter-quark potential of the Coulomb type:

$$\hat{H} = \hat{H}_0 + \frac{1}{2}\int d^3x d^3y J^a_\mu(\vec{x},t) K^{ab}_{\mu\nu}(\vec{x}-\vec{y}) J^b_\nu(\vec{y},t)\,,$$

$$K^{ab}_{\mu\nu}(\vec{x}-\vec{y}) = g_{\mu 0} g_{\nu 0} \delta^{ab} V_{CONF}(|\vec{x}-\vec{y}|)$$

The Fourier transform of the linear potential is not defined, hence an infrared regularization is required, among different equivalent regularizations we use one suggested by
R. Alkofer & P. A. Amundsen (1988):

$$V_{CONF}(p) \equiv V(p) = \frac{8\pi\sigma}{(p^2+\mu^2_{IR})^2}$$

Chiral symmetry breaking in vacuum

The energy, self-energy and dynamical quarks mass:

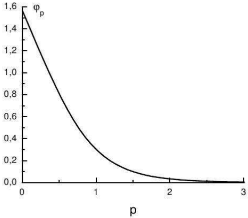
$$E(p) = \sqrt{A_p^2 + B_p^2}\,,$$

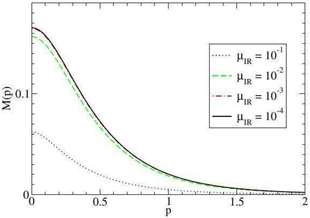
$$\Sigma(\vec{p}) = A_p + (\vec{\gamma}\hat{\vec{p}})[B_p - p]\ , \qquad M(p) = p\frac{A_p}{B_p}$$

$$A_p = \frac{\sigma}{2\mu_{IR}} sin\varphi_p + A_p^f\ , \qquad B_p = \frac{\sigma}{2\mu_{IR}} cos\varphi_p + B_p^f$$

The gap equation:

$$A_p cos\varphi_p - B_p sin\varphi_p = 0$$

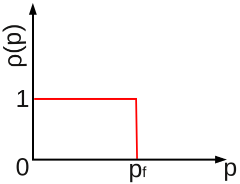


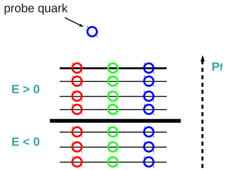


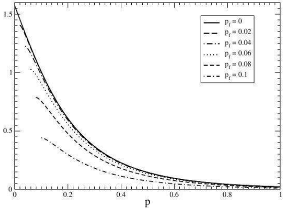
Finite chemical potential

L.Glozman & R. Wagenbrunn (2008): To include finite chemical potential, all occupied levels below P_f has to be removed from the gap equation, because of Pauli blocking.

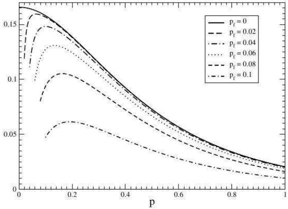
- liquid phase
- rotational and translational symmetries







chiral angle

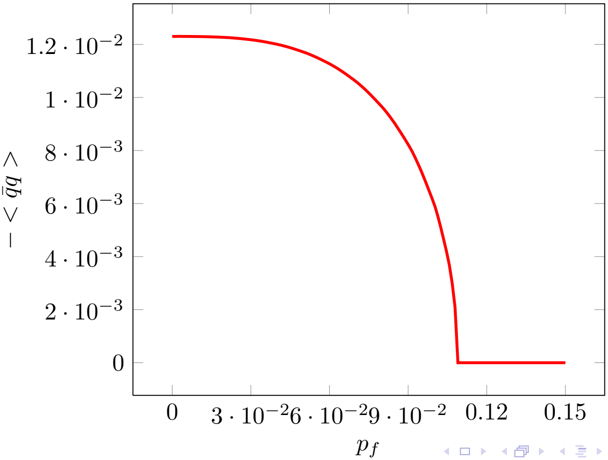


dynamical mass

Chiral symmetry restoration

Above the critical Fermi momentum $P_F > P_F^{cr}$, chiral symmetry gets restored:

$$\varphi_p = 0; \quad M(p) = 0; \quad <\bar{q}q>= 0;$$



Chiral symmetry restoration

$$\varphi_p = 0 \quad \Longrightarrow \quad M(p) = 0; \quad <\bar{q}q>= 0; \quad A_p = 0$$

But the energy and self-energy operator:

$$E(p) = \sqrt{A_p^2 + B_p^2}\,,$$

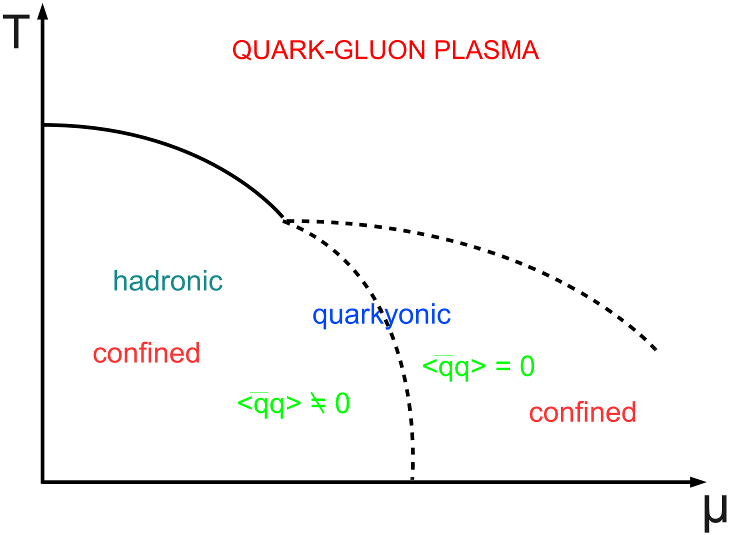
$$\Sigma(\vec{p}) = A_p + (\vec{\gamma}\hat{\vec{p}})[B_p - p] \longrightarrow infrared\ divergent,$$

because of divergence

$$B_p = \frac{\sigma}{2\mu_{IR}} cos\varphi_p + B_p^f.$$

Quarks are still confined.

Possible QCD phase diagram

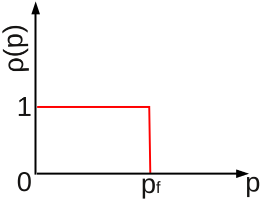


Effects of a diffusion of the quark Fermi surface

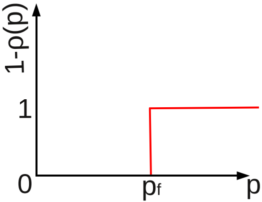
- Valence quarks interact near the Fermi surface
- Some levels above "Fermi momentum" must be occupied with some probability
- Some levels below the "Fermi momentum" with some probability must be empty
- Rigid quark Fermi surface gets diffused

What will be effect of such diffused quark Fermi surface on chiral restoration phase transition? Will it survive?

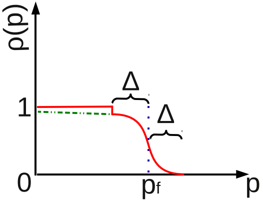
Quark distribution functions



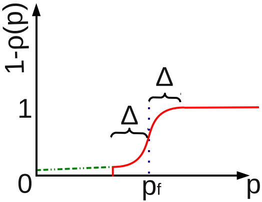
Fermi-gas distribution



Integration area



Diffused distribution

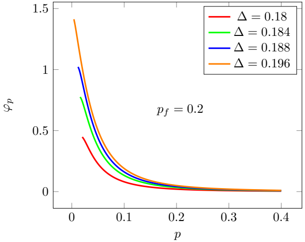


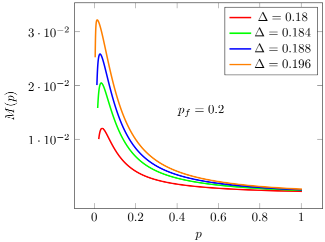
Integration area

Solutions of the gap equation beyond the Fermi-gas approximation

We parametrize distribution function as:

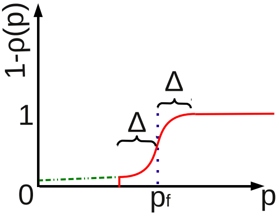
$$\rho(p) = \Theta(p_F - \Delta - p) + \Theta(p + \Delta - p_F)\frac{1}{e^{\frac{p-p_F}{\Delta}} + 1}$$

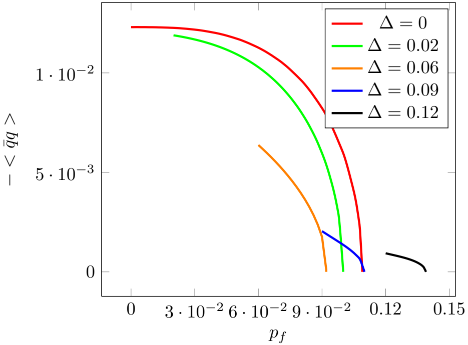




Chiral angle φ_p and dynamical mass of quarks $M(p)$ as a functions of the momentum p at different values of diffusion Δ. p and Δ are units of $\sqrt{\sigma}$

Quark condensate





Quark condensate in units of $\sigma^{3/2}$ as a function of the Fermi momentum p_f, which is in units of $\sqrt{\sigma}$ at different fixed values of diffusion Δ.

Chiral symmetry restoration in meson excitations

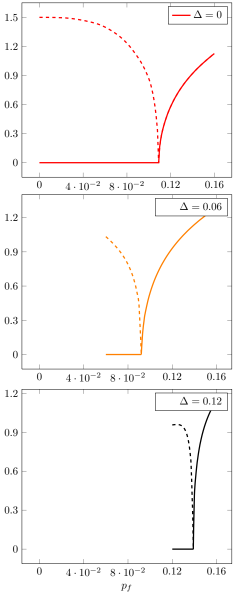
Bethe-Salpeter equation:

$$\chi(m,\vec{p}) = -i\int \frac{d^4q}{(2\pi)^4} V(|\vec{p}-\vec{q}|)\,\gamma_0 S(q_0+m/2,\vec{p}-\vec{q}) \times \chi(m,\vec{q}) S(q_0-m/2,\vec{p}-\vec{q})\gamma_0 (1-\rho(q))$$

In the Nambu-Goldstone mode of chiral symmetry there must be a massless excitation mode that is associated with the massless pion, energies of all other mesons must be finite.

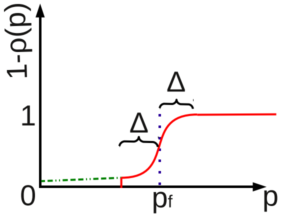
In the Wigner-Weyl mode, when $M(p) = 0; \ \varphi_p = 0$, the Bethe-Salpeter equations for the pseudoscalar and scalar mesons bound states become identical and consequently energies of these states coincide.

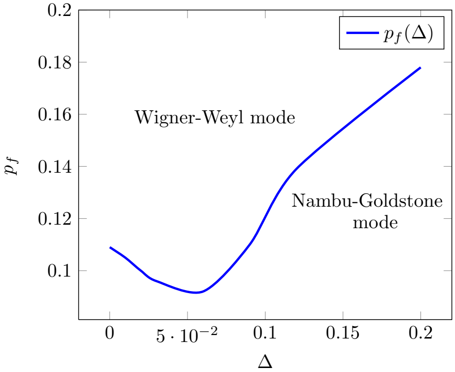
Chiral symmetry restoration in meson excitations



Masses of the pseudoscalar (solid) and scalar (dashed) mesons in units of $\sqrt{\sigma}$ as functions of the Fermi momentum p_f, which is in units of $\sqrt{\sigma}$ at different fixed values of diffusion Δ.

The critical line in the p_f and Δ plane





For each fixed Δ the phase transition persists at p_f above the critical line.

Conclusions

- Interacting valence quarks imply the diffused Fermi surface.
- A chiral phase transition, previously observed for a rigid quark Fermi surface, survives.
- For any reasonable diffusion width there always exists such a "Fermi momentum", that the chiral restoration phase transition does take place.