Confined but chirally symmetric dense and cold matter

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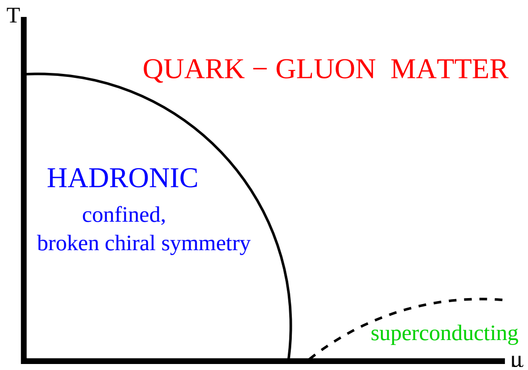
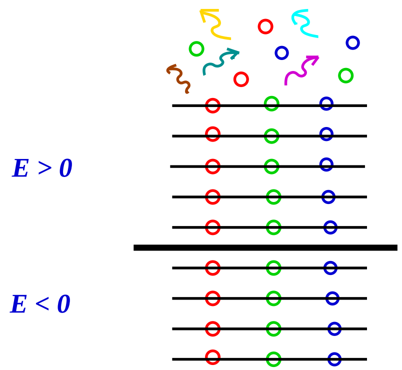
Contents of the Talk

- Quarkyonic matter at finite chemical potential and not high T
- Generalized 't Hooft Model
- Inclusion of a finite chemical potential
- Chiral symmetry restoration
- Quarkyonic matter
- Possible phase diagram
- Chirally symmetric hadrons and Casher argument

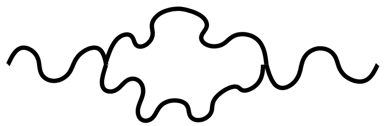
The McLerran - Pisarski argument (2007)

Traditional picture:



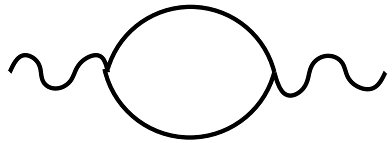


The system is deconfined and a pressure $\sim N_c^2$. Is it correct at large N_c? Not!



$g^2 N_c T^2$

At T > T_c deconfinement (Debye Screening)



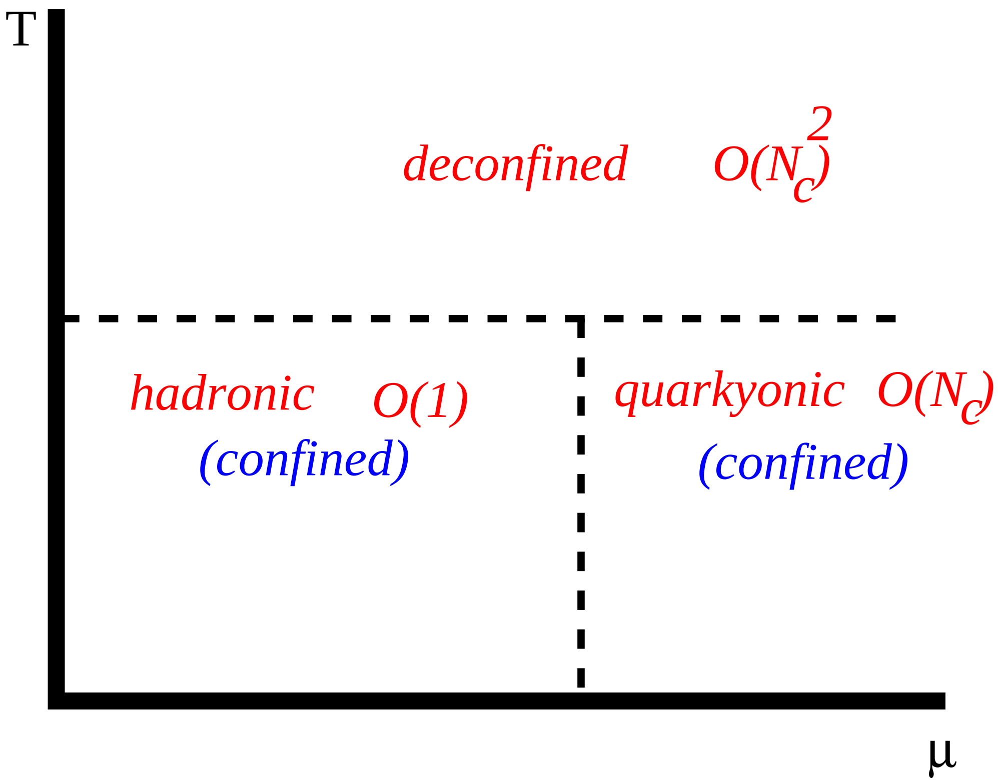
$\sim 1 / N_c$

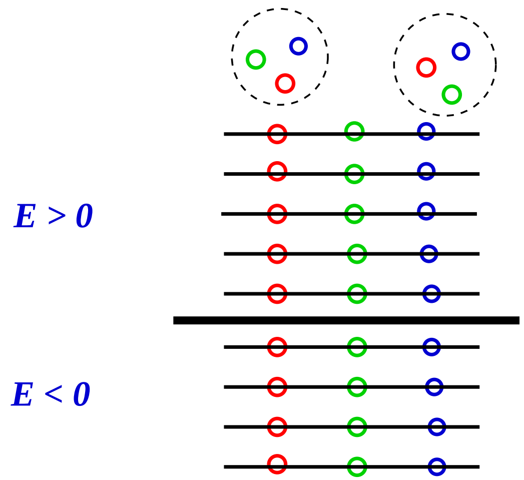
At small T no deconfinement, no screening by quarks
at any fixed chemical potential!

The baryon medium does not affect gluodynamics; Wilson loop is the same as in vacuum; At not high temperature quarks and gluons are confined at ANY density.

The McLerran - Pisarski argument (2007)

In the large N_c world at large chemical potential a pressure $\sim N_c$. For a pure hadronic 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 . Instead - QUARKYONIC phase with confined hadrons on top of the quark Fermi sea.





Confined and chirally symmetric matter?!

At some critical density the standard quark-antiquark condensate of the vacuum must vanish because of Pauli blocking.

Above the chiral restoration point: confined matter with vanishing quark condensate, i.e. built with confined but chirally symmetric hadrons?!? It is in conflict with many previous models and naive intuition.

Confined, chirally symmetric matter

We cannot solve QCD even at large N_c To address the issue we need a solvable model that is

(i) manifestly chirally symmetric

(ii) manifestly confining

(iii) provides spontaneous breaking of chiral symmetry

At large density and small temperatures a matter could be a Fermi liquid or a crystal. Depends on fine details of the microscopic dynamics, that is not under control. Apriori we do not know what it will be. Below we address the first possibility.

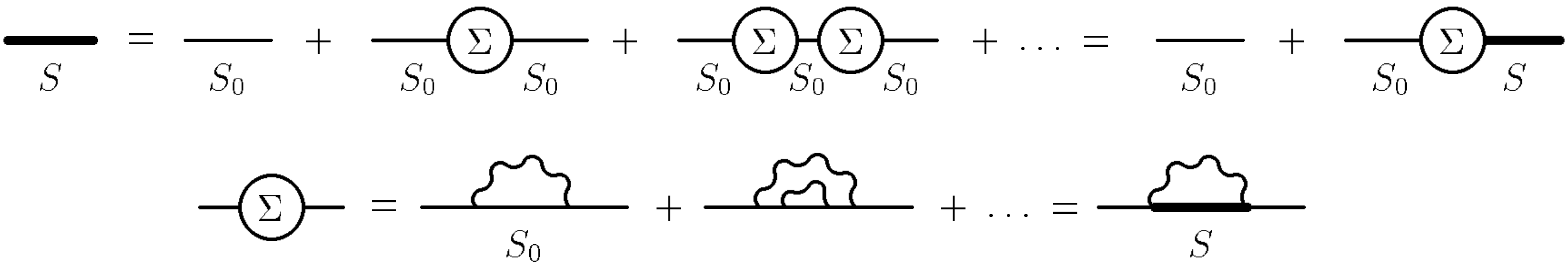
If it is a Fermi liquid, then, by assumption, there are both rotational and translational invariancies.

Generalized ’t Hooft model in vacuum

In 1+1 ’t Hooft model the only interaction is the Coulomb (linear) potential. Seen in 3+1 dim in variational Coulomb gauge calculations: Szczepaniak -Swanson; Reinhardt-Feuchter; and in Coulomb gauge lattice:Nakagawa-Nakamura-Saito-Toki; Voigt-Ilgenfritz-Muller-Preussker-Sternbeck.

Chiral symmetry breaking is via the Schwinger-Dyson (gap) equation. Infrared regularization is required. Adler & Davis, 1984.

$$S = S_0 + S_0 \Sigma S$$



$$\Sigma(\vec{p}) = A_p + (\vec{\gamma}\hat{\vec{p}})[B_p - p].$$

Chiral symmetry breaking part - A_p.

Generalized 't Hooft model in vacuum

The gap equation:

$$i\Sigma(\vec{p}) = \hbar \int \frac{d^4k}{(2\pi)^4} V_{CONF}(\vec{p}-\vec{k})\gamma_0 \frac{1}{S_0^{-1}(k_0,\vec{k}) - \Sigma(\vec{k})}\gamma_0.$$

Infrared regularization is required.

$$\frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{4} V(r_{ij}) = \sigma r_{ij}; \qquad V(p) = \frac{8\pi\sigma}{(p^2+\mu_{IR}^2)^2}$$

The self-energy

$$\Sigma(\vec{p}) = A_p + (\vec{\gamma}\hat{\vec{p}})[B_p - p].$$

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

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

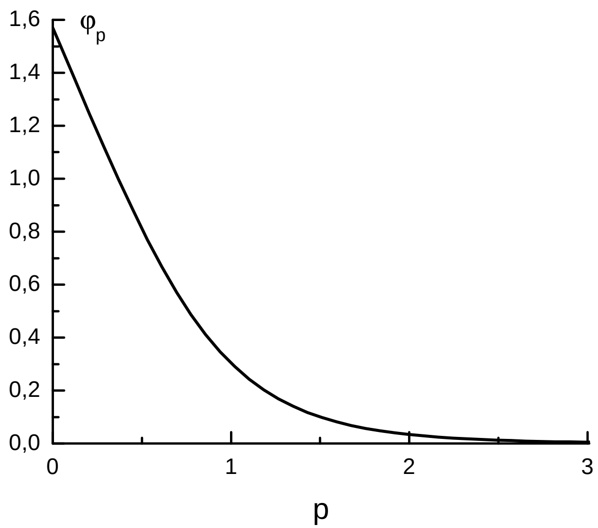
All color-singlet quantities are infrared finite and well-defined.

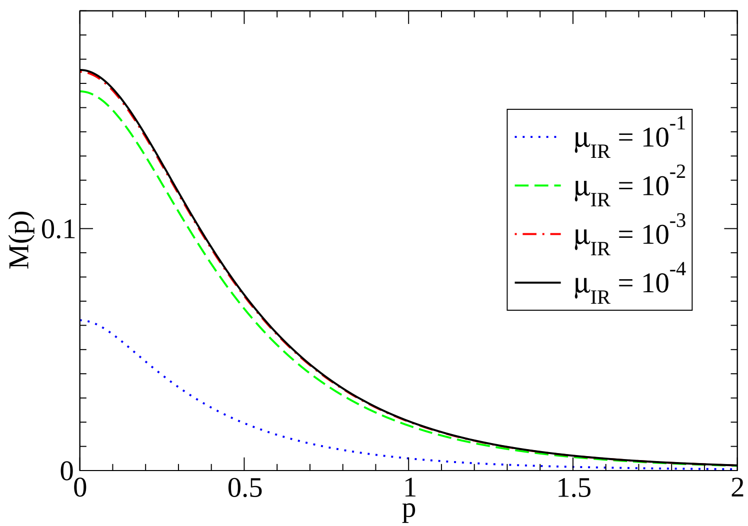
E.g. the gap equation:

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

The dispersive law is:

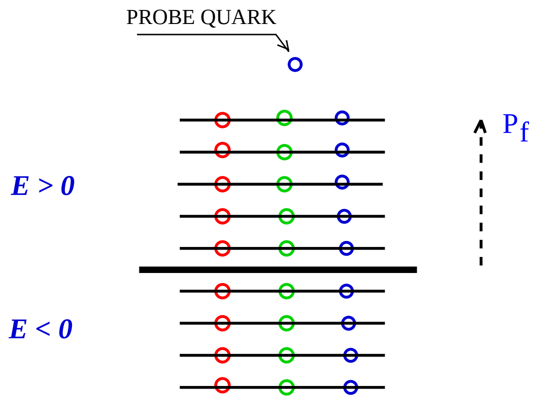
$$E_p = A_p \sin\phi_p + B_p \cos\phi_p; \qquad \tan\varphi_p = \frac{A_p}{B_p}$$

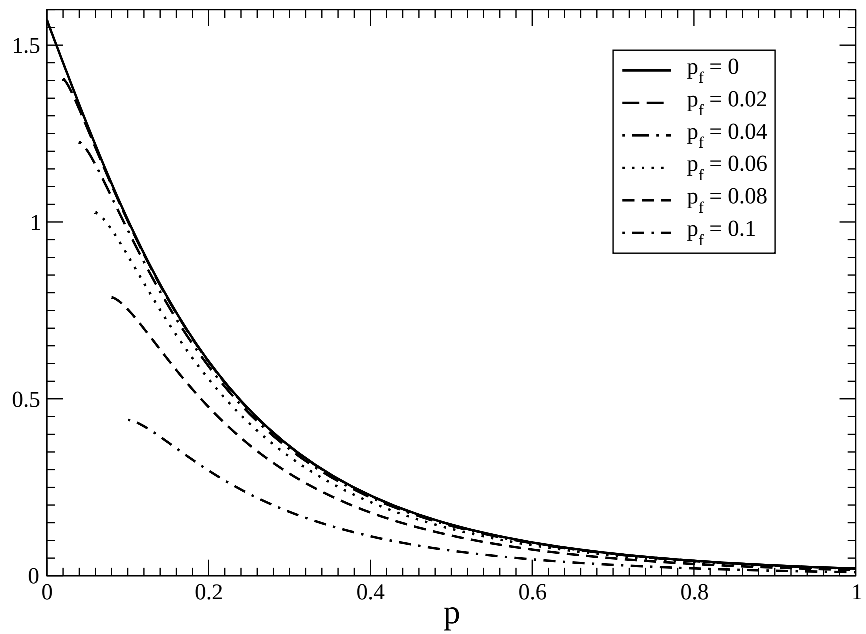




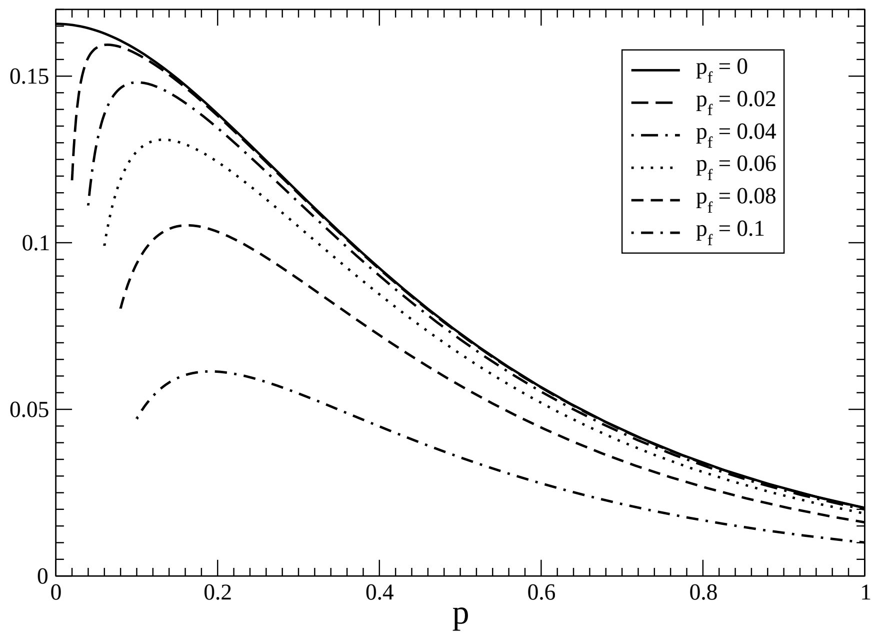
Inclusion of a finite chemical potential

We have to remove from the gap equation all occupied levels below P_f - Pauli blocking.





chiral angle

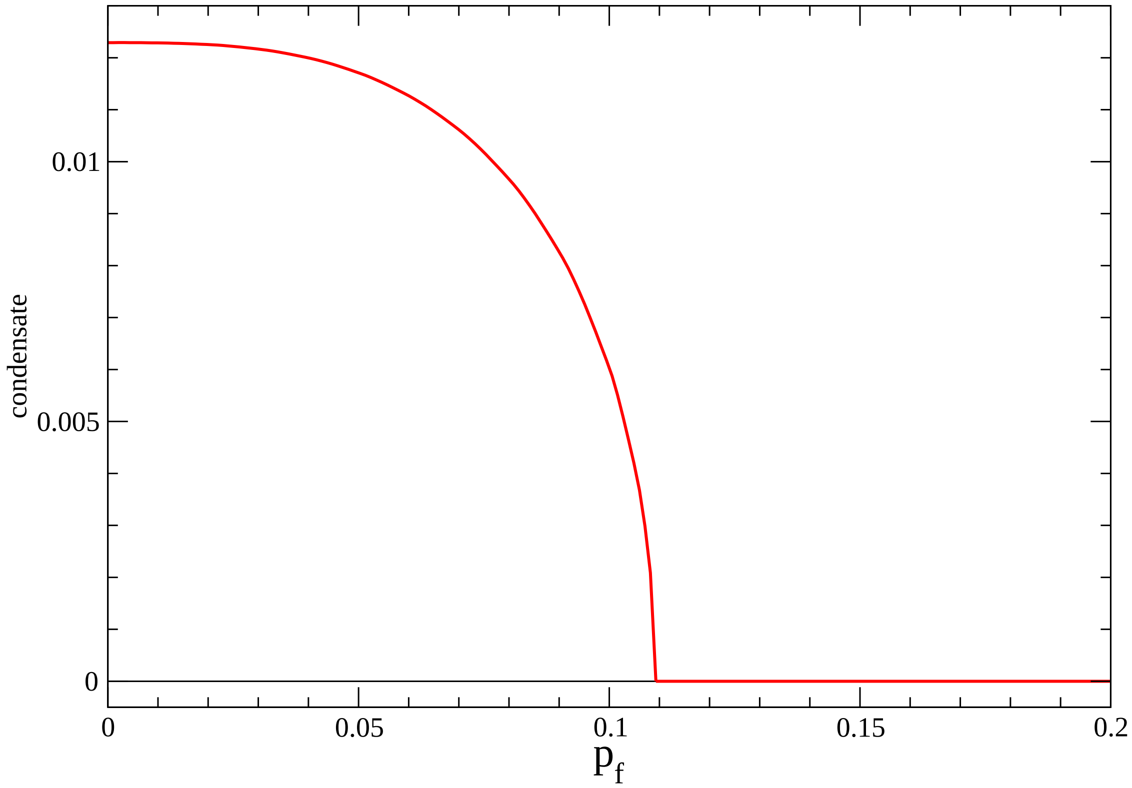


dynamical mass

Chiral symmetry restoration

Above the critical Fermi momentum, $P_f > P_f^{cr}$, there is no nontrivial solution of the gap equation. Chiral symmetry gets restored:

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



Chiral symmetry restoration

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

Then in the self-energy operator,

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

$$A_p = 0; \qquad B_p \to infrared \;\; divergent$$

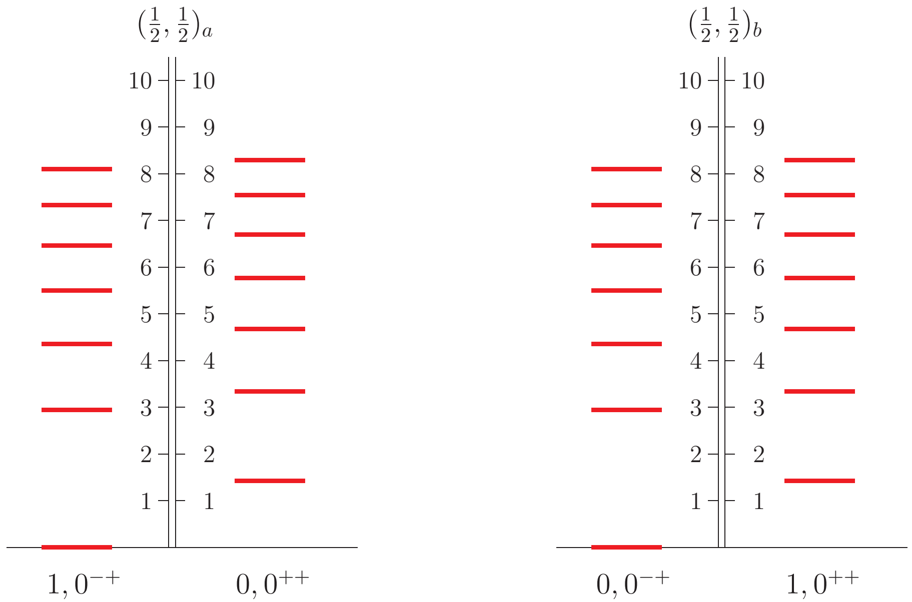
Quarks are still confined, because a single-quark Dirac operator is still infrared-divergent.

A single quark is removed from the spectrum at any chemical potential.

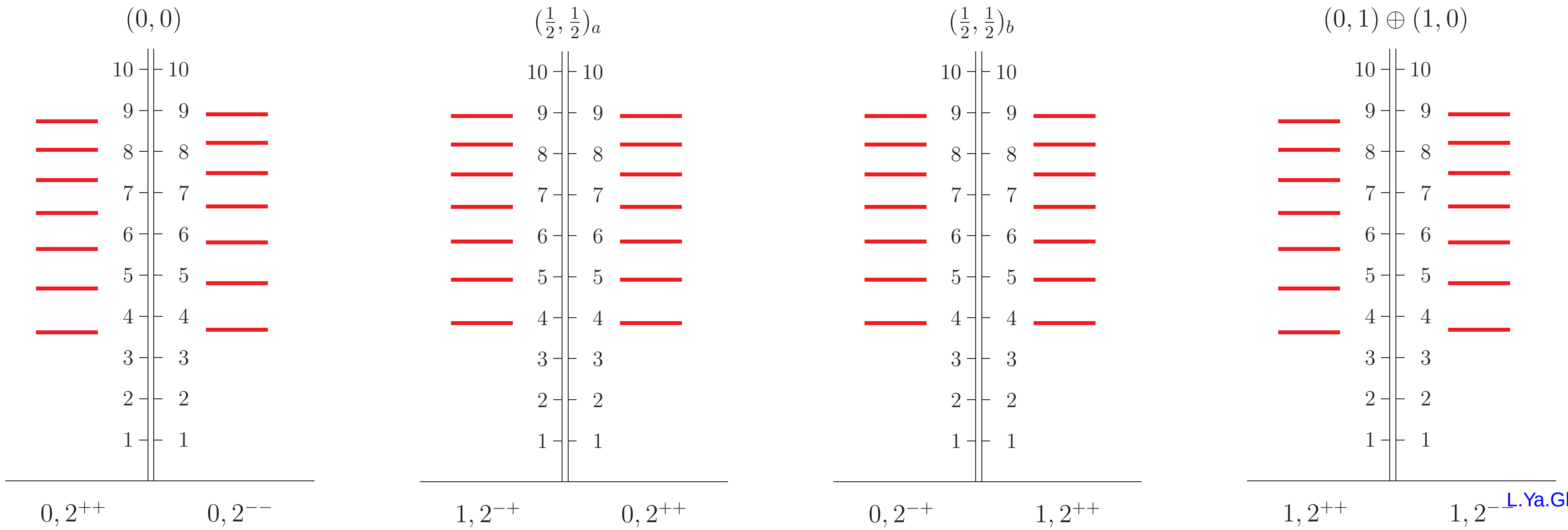
There canNOT be colored single quarks on top of Fermi sea.

Mesonic spectra below the chiral restoration point

$J = 0$

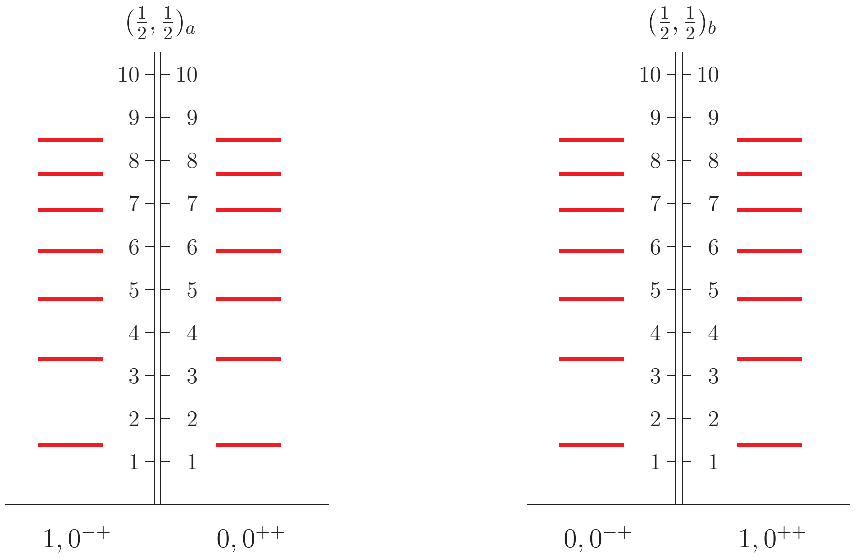


$J = 2$

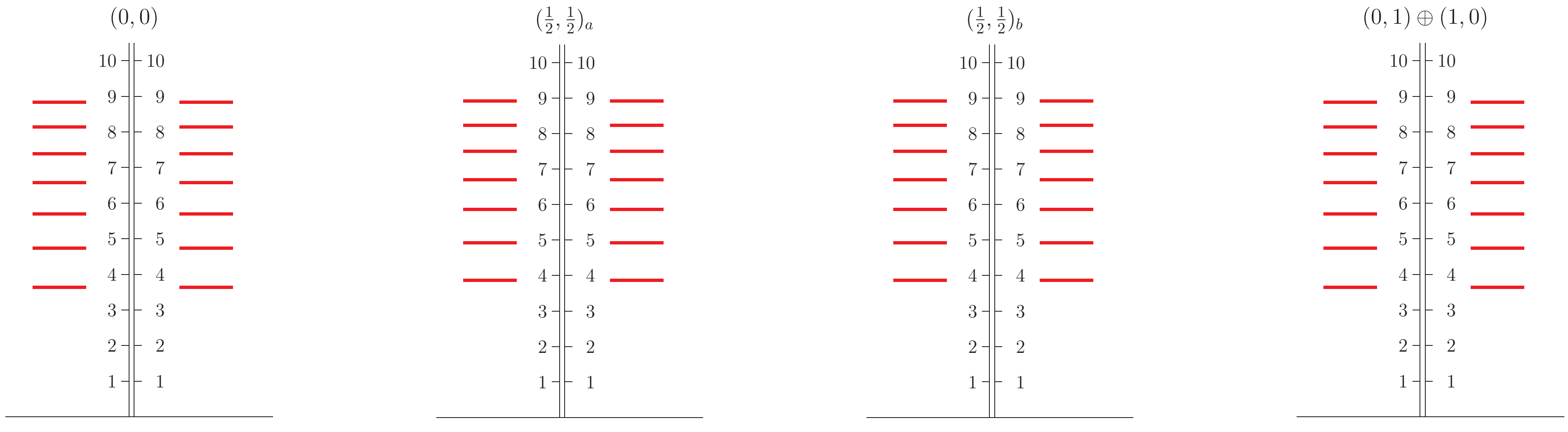


Mesonic spectra above the chiral restoration point

$J = 0$

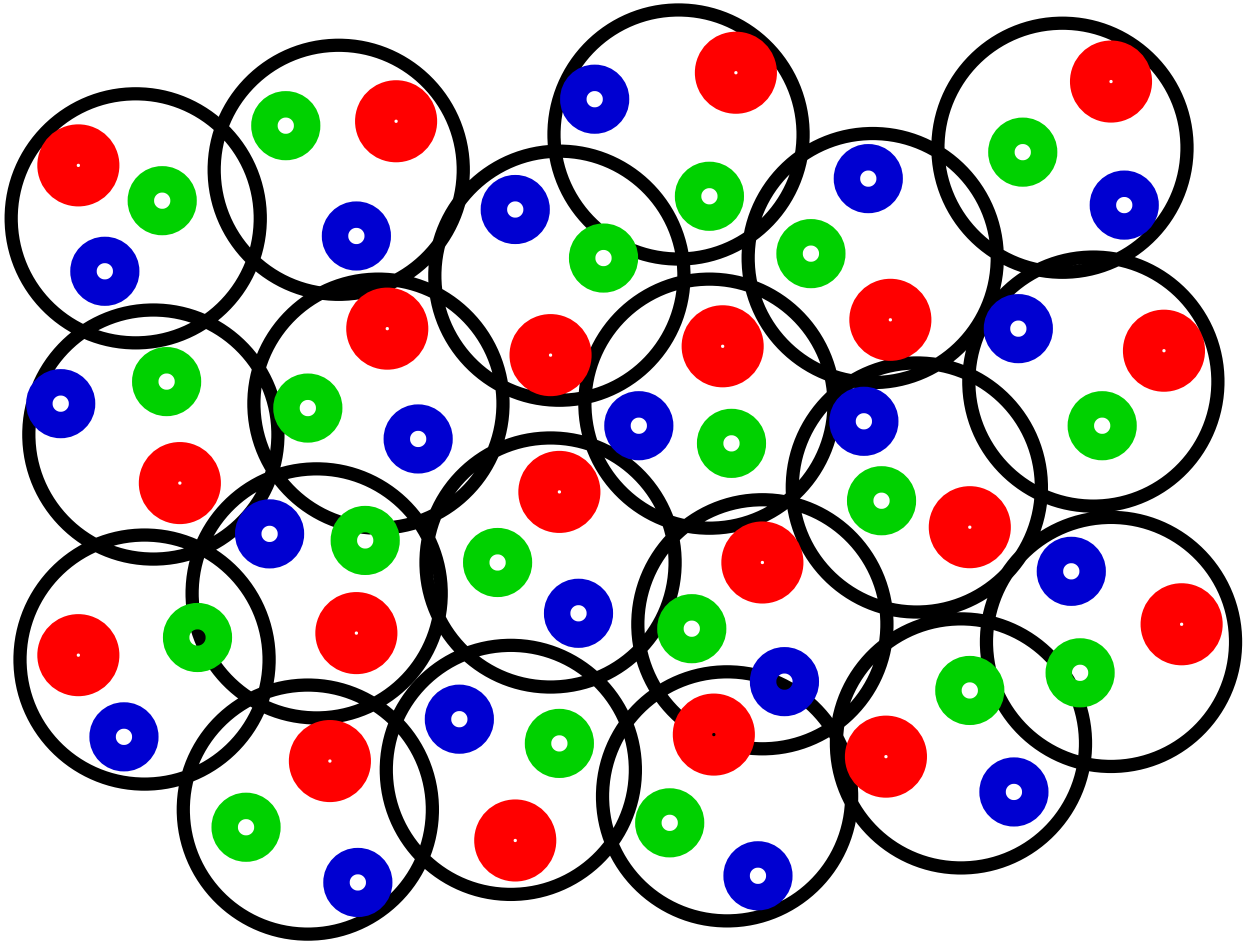


$J = 2$



Quarkyonic matter - my view

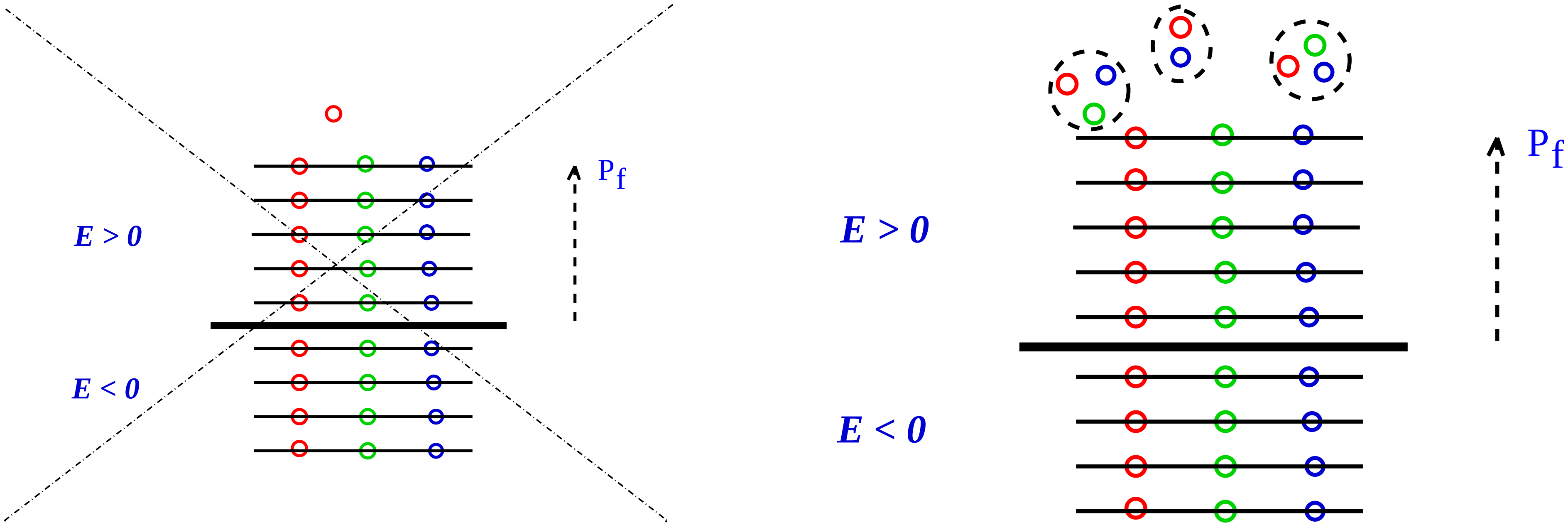
The quarks are NOT free (confinement is there), but can move within the matter by hoping from one baryon to another.



The idea to have at the same time confinement and a Fermi sea of free quarks is inconsistent.

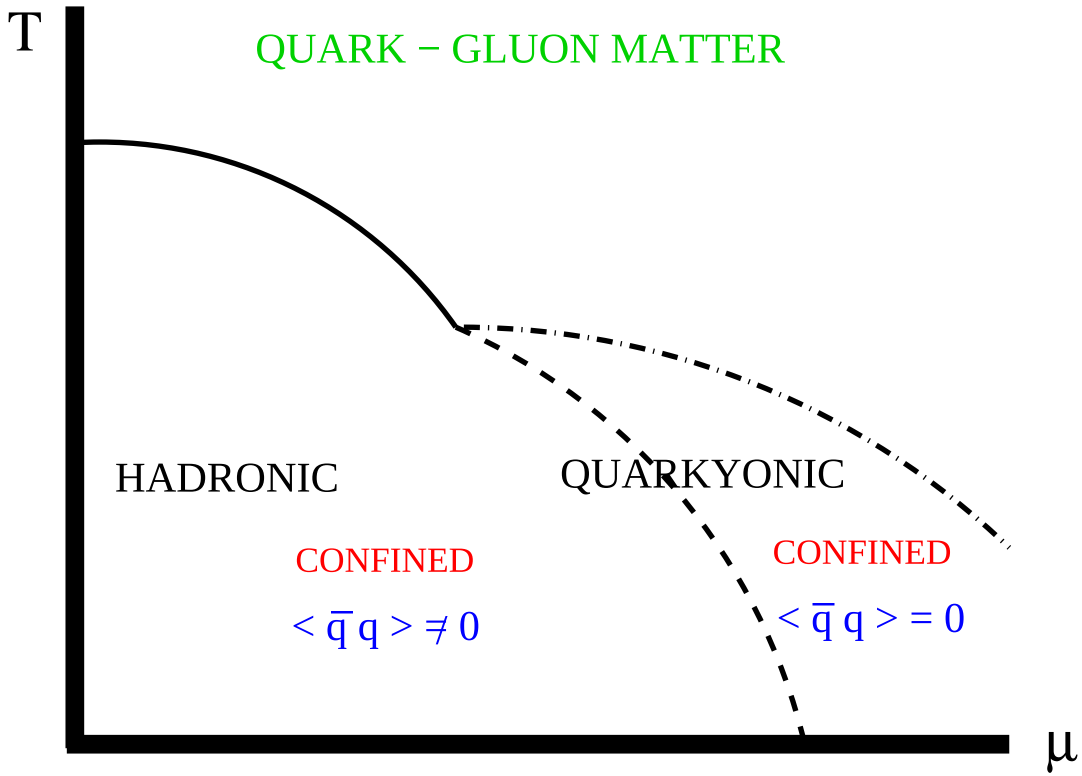
Quarkyonic matter

A quark excitation of the quark Fermi sea is impossible (a single quark Dirac operator is always infrared-divergent). Hadronic color-singlet excitation - possible.



It is valid both below and above chiral restoration point.

Possible phase diagram

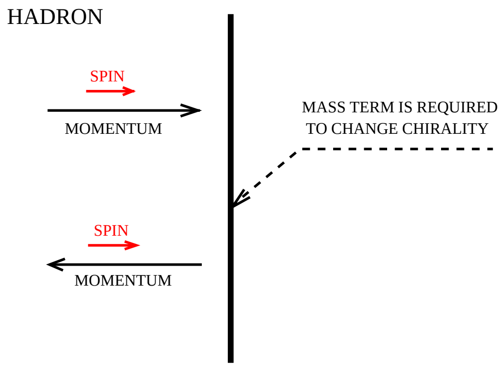


The confined phase with vanishing quark-antiquark condensate consists of chirally symmetric hadrons that are in overlap. The mass has manifestly chirally symmetric origin.

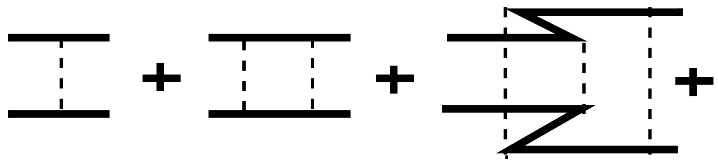
A challenge: what happens at the Fermi surface? Will be there chiral symmetry breaking phenomena like chiral density waves?

Chirally symmetric hadrons and Casher argument

Casher: If quark is confined, then chiral symmetry must be spontaneously broken.At the confining border there is no spin flip (angular momentum conservation). Then chirality must be flipped. Similar in Bag model.



At $T = \mu = 0$ consistent with the 't Hooft anomaly matching conditions. Is it true in a dense matter? Apparently not! Then, what is wrong in Casher's argument? With the instantaneous Coulomb-like interaction there is a synchronous motion of a quark and an antiquark



Consequently the spin flip of the quark is always compensated by the spin flip of the antiquark – no angular momentum violation. No chiral symmetry breaking is required.