Confining but chirally symmetric dense and cold matter

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L.Ya.G. and R. F. Wagenbrunn, PRD 77 (2008) 054027

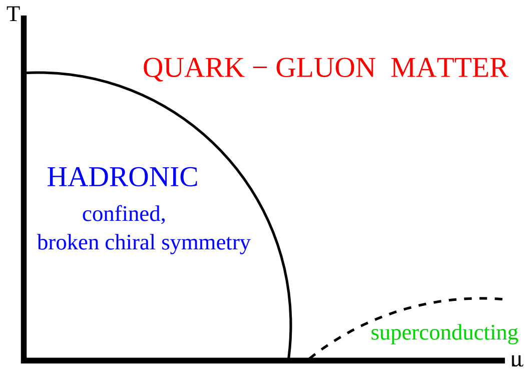
L.Ya.G., PRD 79 (2009) 037504

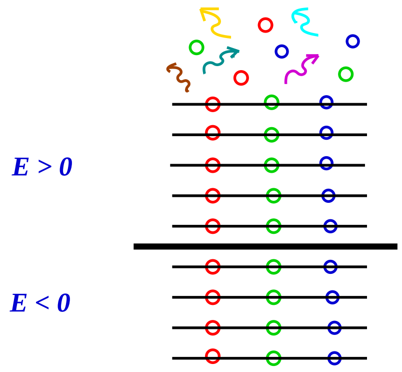
L.Ya.G., PRD 80 (2009) 037701

Contents of the Talk

Traditional picture

Traditional picture:





Why did people believe it for 30 years?

It was taken for granted that in the confining mode the origin of mass was the quark condensate of the vacuum. Then there cannot be a phase with confinement but with vanishing quark condensate. Is it true?

The key problems:

What is the mass origin of the QCD matter?

Is it possible to have a mass generation mechanism for confined hadrons not related to spontaneous breaking of chiral symmetry?

What do we know on this?

What is the hadron mass origin in QCD?

Gell-Mann - Levy sigma model, Nambu - Jona-Lasinio mechanism and many "Bag-like" microscopical models:

Chiral symmetry breaking in a vacuum is the source of the hadron mass in the light quark sector.

Is it true? Or, better to say, is it entirely true?

Evidence for the chiral symmetry breaking in a nucleon

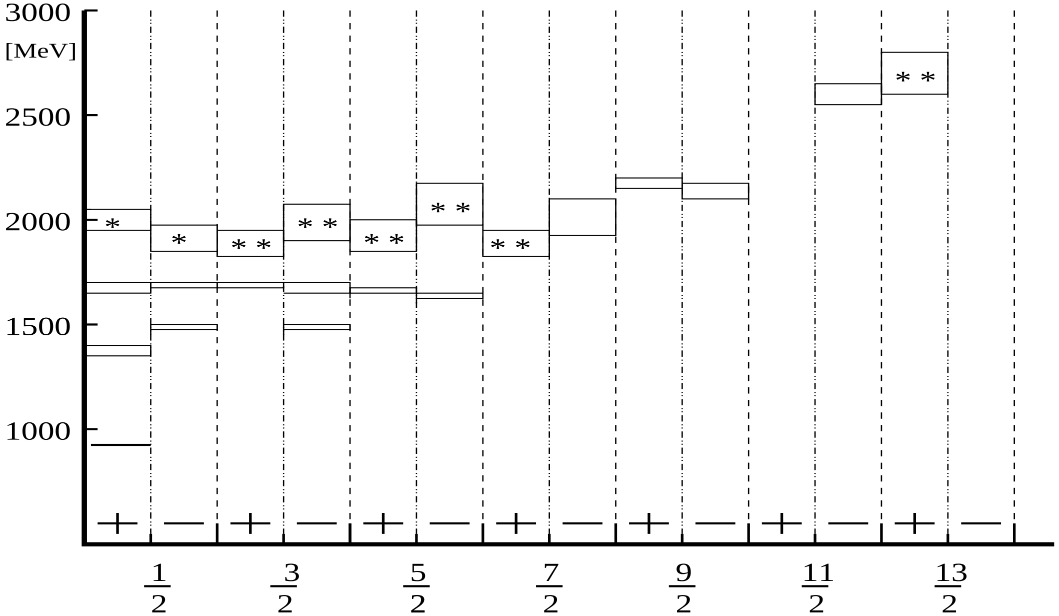
- No approximately degenerate chiral partner
- Large axial charge, $G_A = 1.26$
- Large pion-nucleon coupling constant, $g \sim 13$

Implications:

- Origin of the nucleon mass is (at least mostly) spontaneous breaking of chiral symmetry in the vacuum: $< \bar{q}q > \rightarrow M_N$
- Nonlinear realization of chiral symmetry in the nucleon

The axial rotation transforms nucleon into itself plus pion

Low and high lying baryon spectra.



Low-lying spectrum: spontaneous breaking of chiral symmetry dominates physics.

High-lying spectrum: parity doubling is indicative of EFFECTIVE chiral symmetry restoration.

If correct, mass of excited baryons comes mostly from the chirally symmetric dynamics and baryons decouple from the quark condensate of the vacuum.
L.Ya.G., 2000; T.D. Cohen and L.Ya.G, 2001; L.Ya.G., Phys. Rep. 444 (2007) 1

$B_\pm \to N\pi$ decays; L.Ya.G., PRL 99(2007)191602

If the state is a member of an approximate chiral multiplet, then its decay into $N\pi$ must be suppressed, $(f_{BN\pi}/f_{NN\pi})^2 \ll 1$. If, on the contrary, this excited nucleon has no chiral partner and hence its mass is due to chiral symmetry breaking in the vacuum, then it should strongly decay into $N\pi$, $(f_{BN\pi}/f_{NN\pi})^2 \sim 1$.

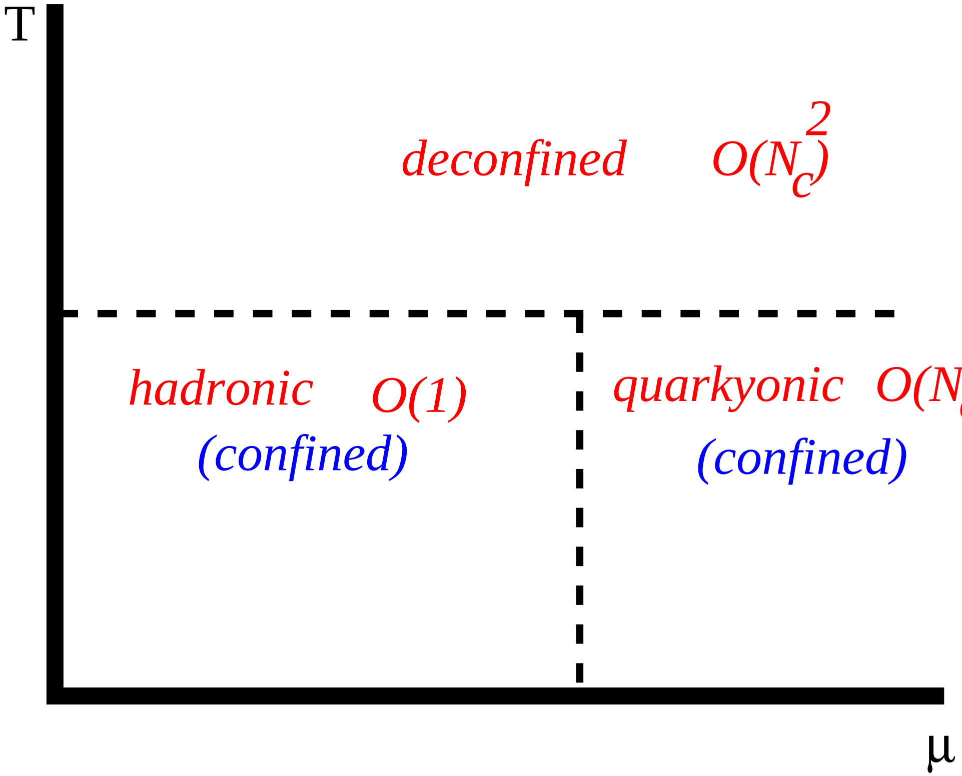
Spin	Chiral multiplet	Representation	$(f_{B_+N\pi}/f_{NN\pi})^2$	$(f_{B_-N\pi}/f_{NN\pi})^2$
1/2	$N_+(1440) - N_-(1535)$	$(1/2,0) \oplus (0,1/2)$	0.15	0.026
1/2	$N_+(1710) - N_-(1650)$	$(1/2,0) \oplus (0,1/2)$	0.0030	0.026
3/2	$N_+(1720) - N_-(1700)$	$(1/2,0) \oplus (0,1/2)$	0.023	0.13
5/2	$N_+(1680) - N_-(1675)$	$(1/2,0) \oplus (0,1/2)$	0.18	0.012
7/2	$N_+(?) - N_-(2190)$	?	?	0.00053
9/2	$N_+(2220) - N_-(2250)$	?	0.000022	0.0000020
11/2	$N_+(?) - N_-(2600)$	?	?	0.00000064
3/2	$N_-(1520)$	no chiral partner		2.5

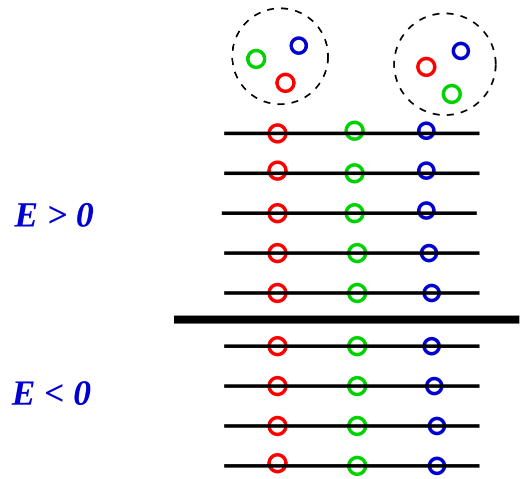
A 100% correlation of decays with the parity doublet patterns!

The McLerran - Pisarski argument (2007)

In the large N_c world at low temperatures confinement persists up to any large density. In the large N_c world there are neither quark-antiquark nor quark-quarkhole loops. No Debye screening of the confining gluon propagator. Confinement in a medium is the same as in a vacuum.

Then the deconfining quark-gluon matter at small temperatures should not exist . Instead - QUARKYONIC phase . One cannot excite independent quarks - only color singlet hadrons.





L.Ya.Glozman

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-antiquark condensate, i.e. built with confined but chirally symmetric hadrons?!

In order to proceed we need an assumption.

At large density and small temperatures the matter could be a Fermi liquid or a crystal. Depends on fine details of the microscopic dynamics, that is not under control.

However.

Nuclear matter at $N_c = 3$ is a liquid. Color-superconductor is also a liquid.

Then at $N_c = 3$ the phase between the two is most naturally also a liquid.
If it is a Fermi liquid, then, by assumption, there are both rotational and translational invariancies.

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

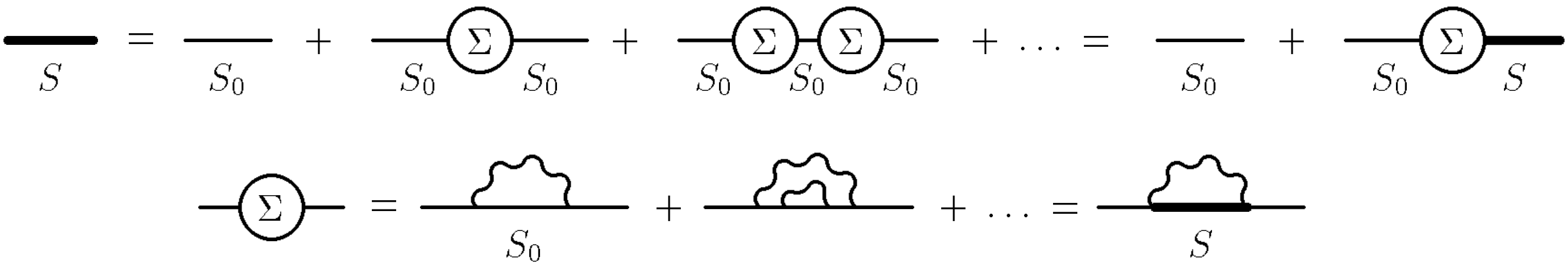
(iii) provides spontaneous breaking of chiral symmetry

Generalized 't Hooft model in a 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 a 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

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

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

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

Generalized 't Hooft model in a vacuum

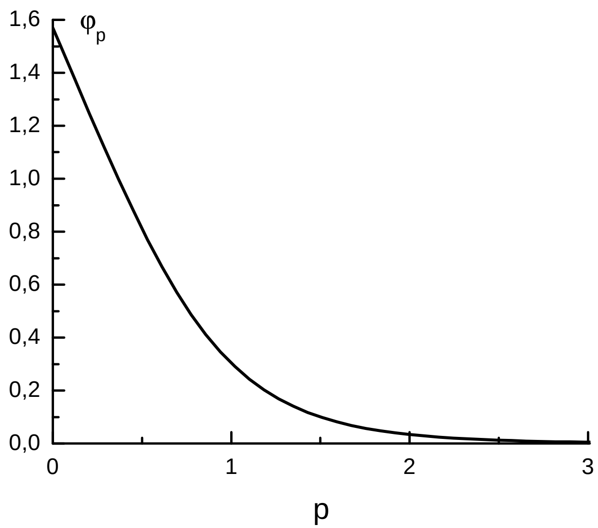
All color-singlet quantities are infrared finite and well-defined.

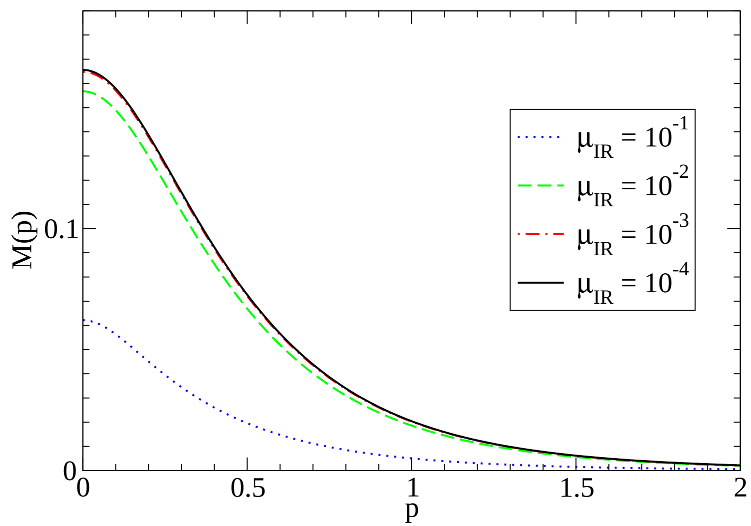
E.g. the gap equation:

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

The dispersive law is:

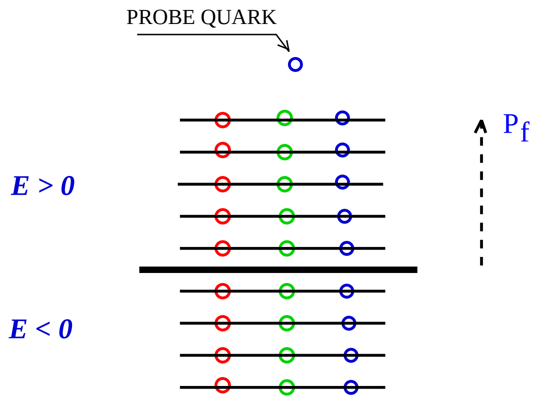
$$E_p = A_p \sin\phi_p + B_p \cos\phi_p; \qquad \tan\varphi_p = \frac{A_p}{B_p}$$

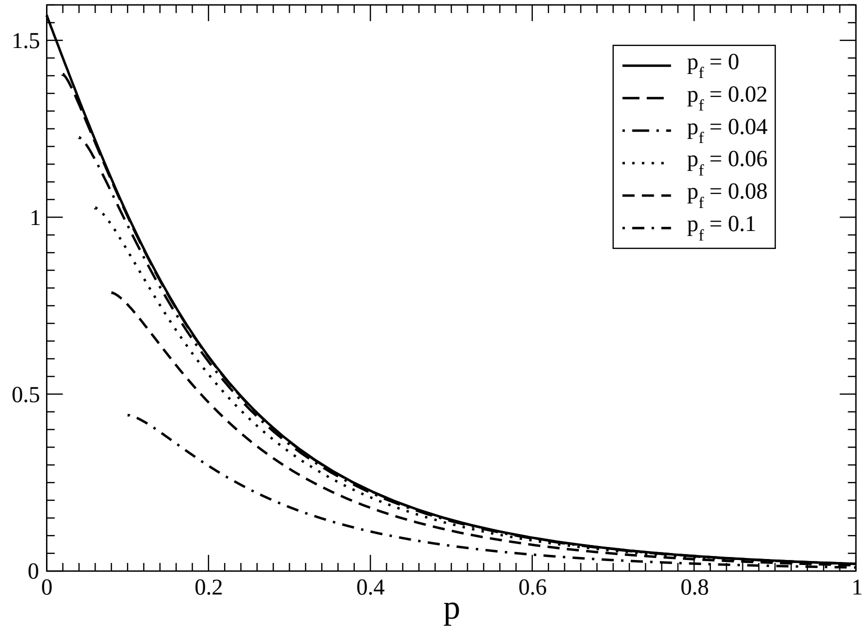




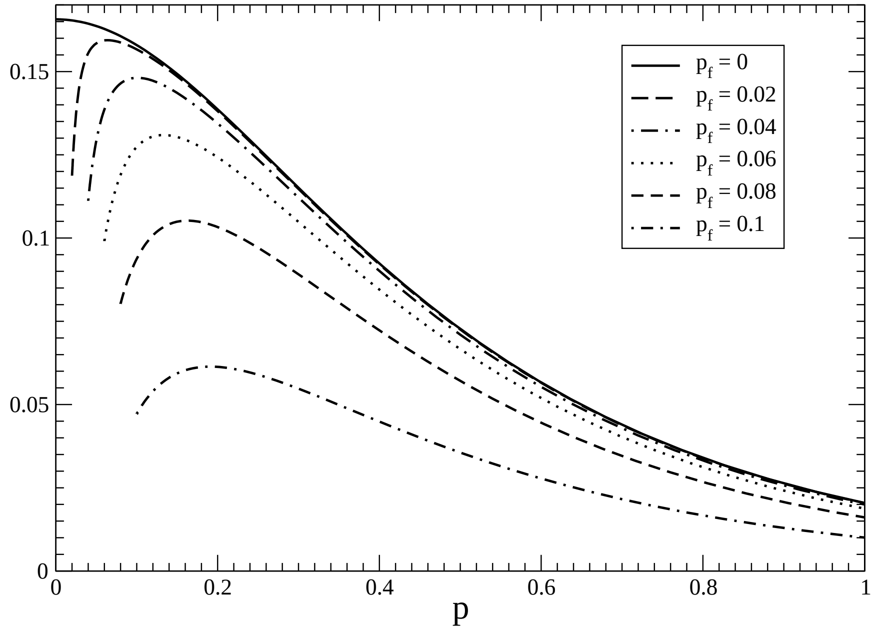
Inclusion of a finite chemical potential

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





chiral angle

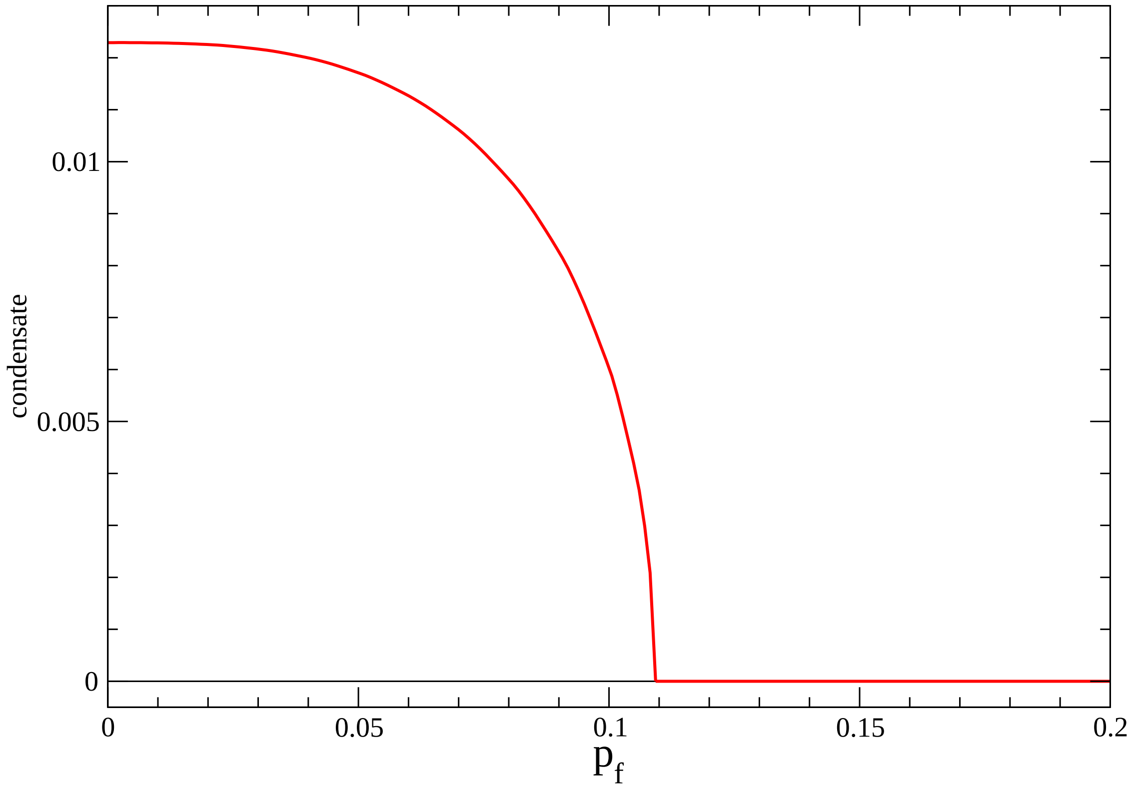


dynamical mass

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,

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

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

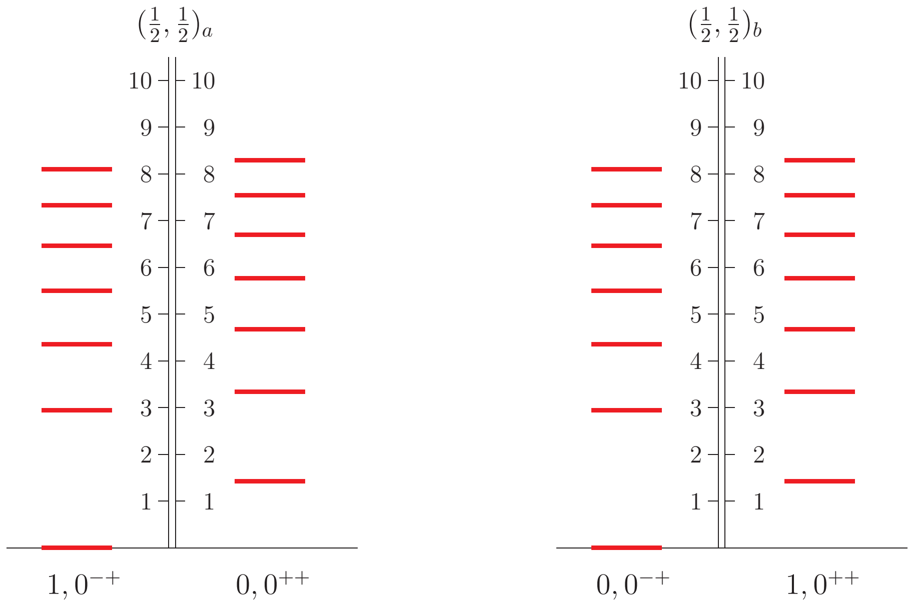
Quarks are still confined, because a single-quark energy is still infrared-divergent:

$$E(p) = \sqrt{A_p^2 + B_p^2} = \frac{\sigma}{2\mu_{IR}} + E_{fin}(p)$$

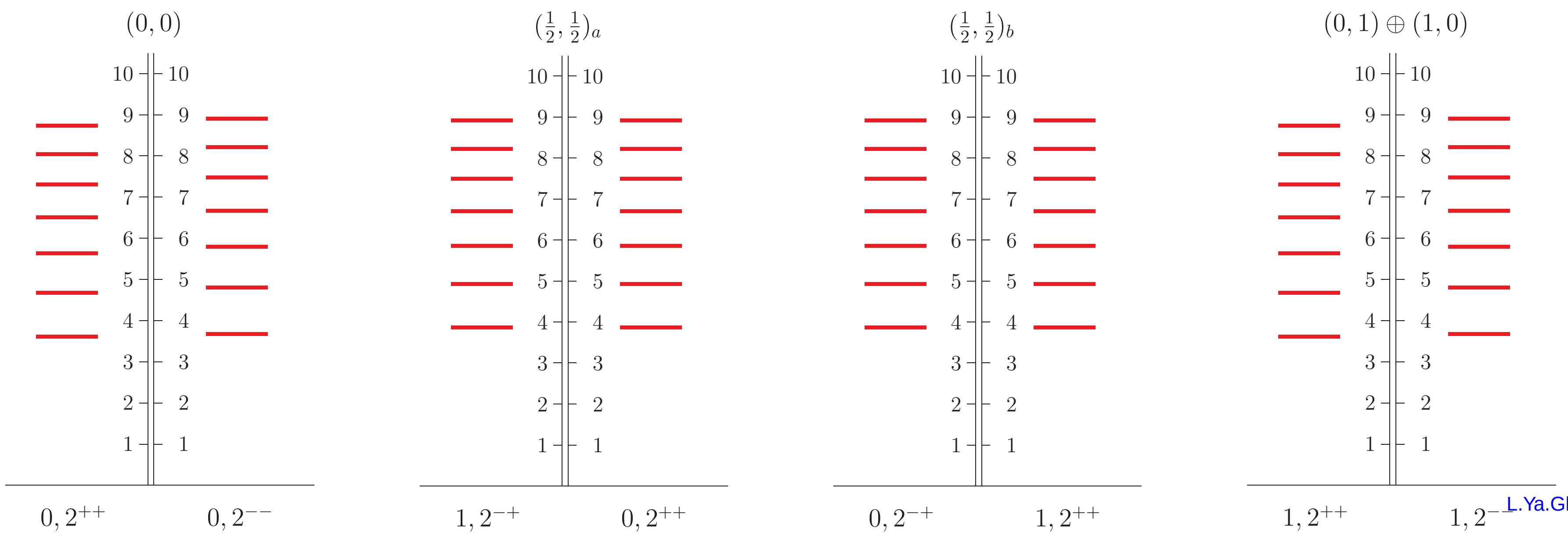
A single quark is removed from the spectrum at any chemical potential.

Mesonic spectra below the chiral restoration point

$J = 0$

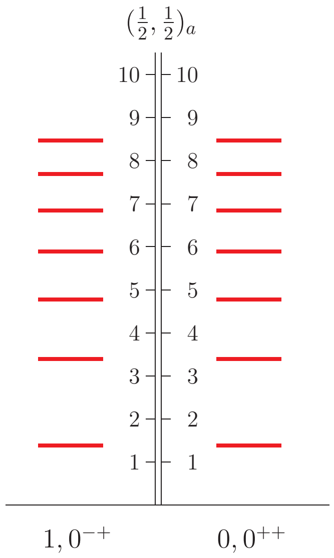


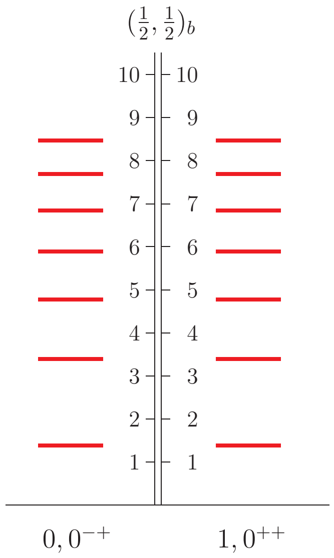
$J = 2$



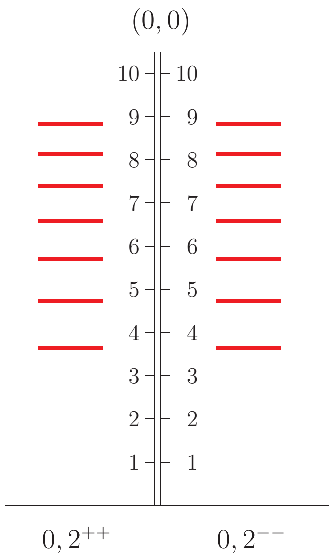
Mesonic spectra above the chiral restoration point

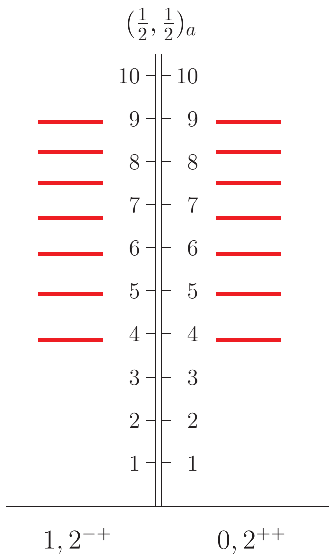
$J = 0$

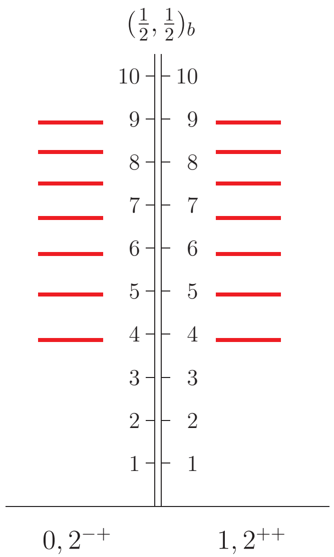


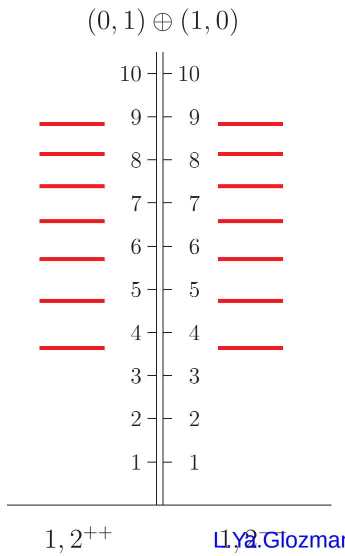


$J = 2$



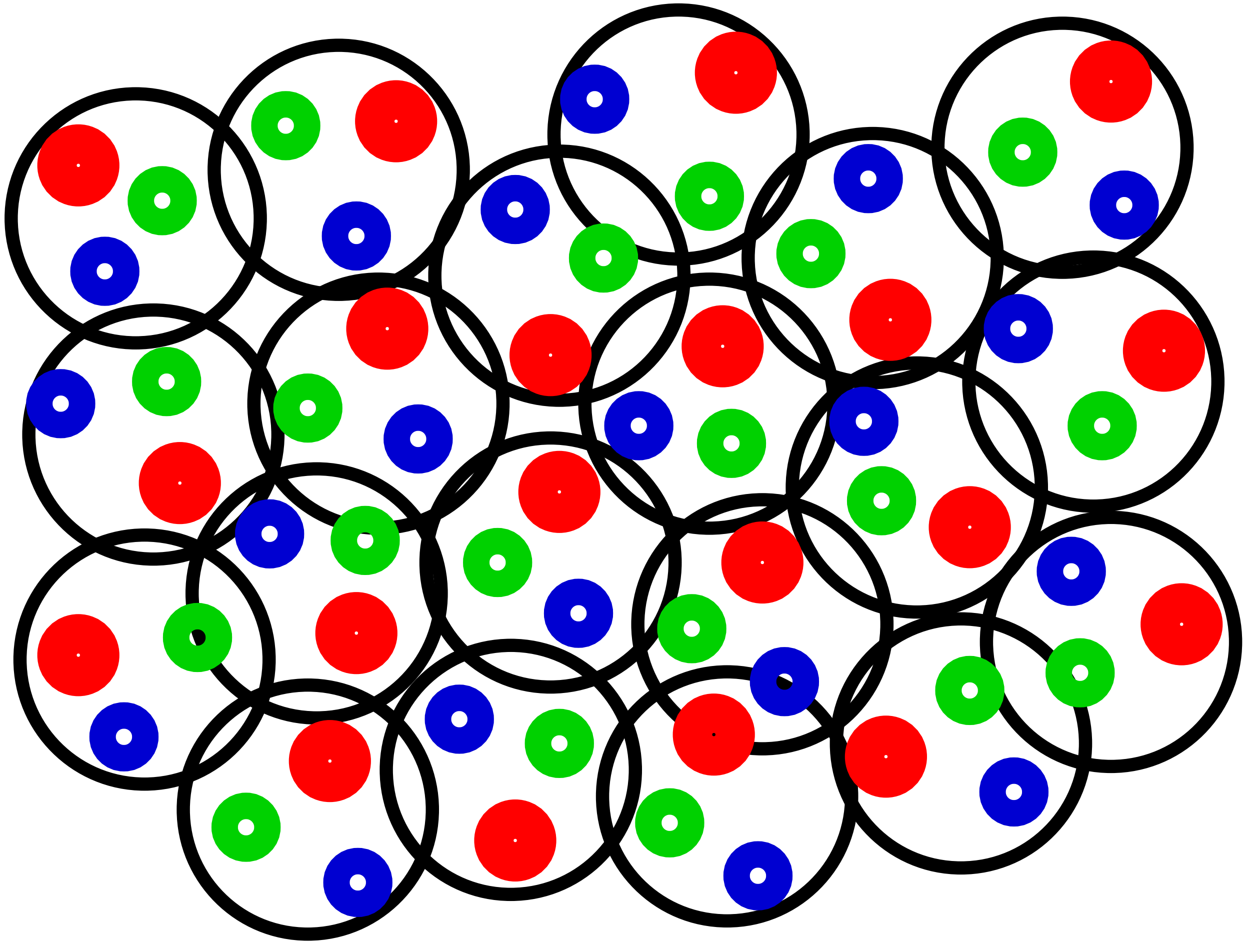






Quarkyonic matter - my view

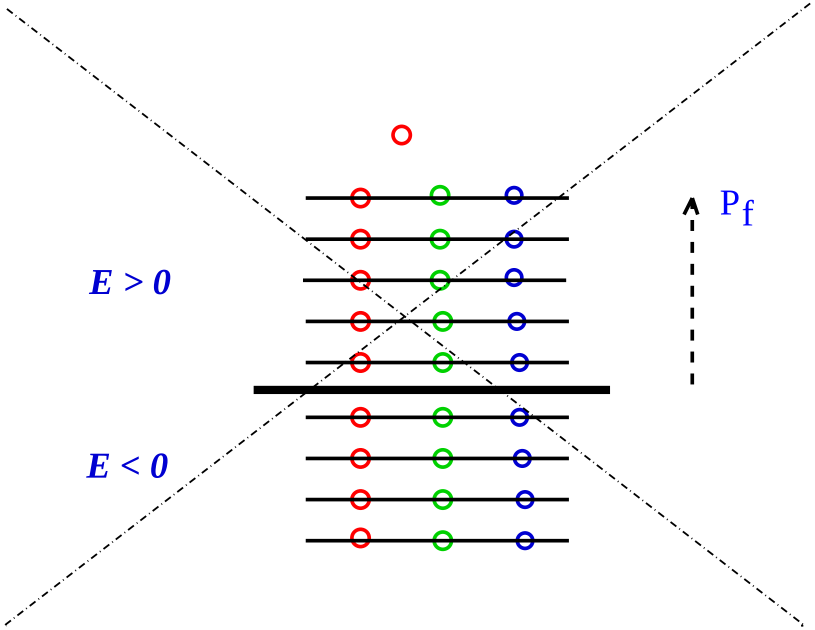
The quarks are NOT free (confinement is there), but can move within the matter by hoping from one baryon to another.

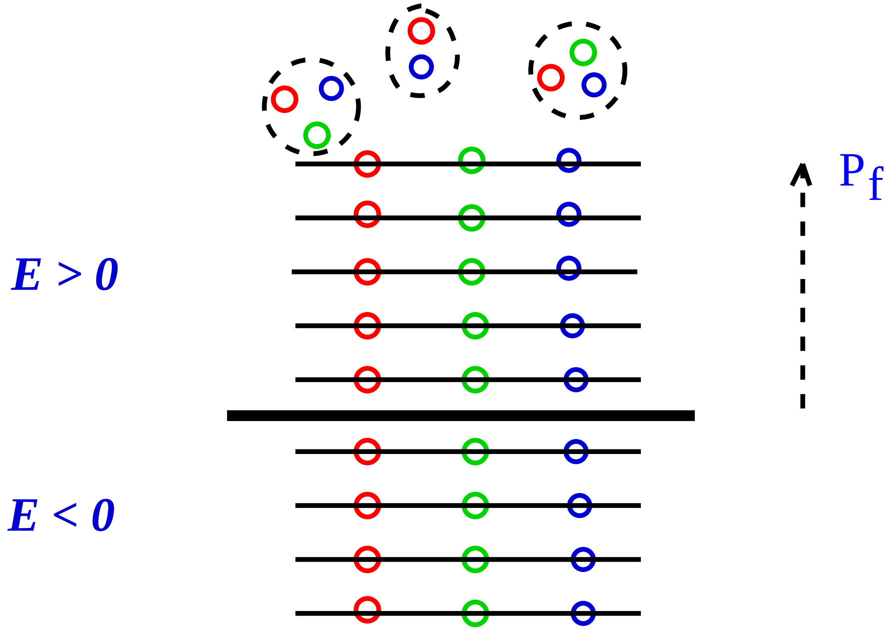


The idea to have at the same time confinement and a Fermi sea of free quarks is inconsistent.

Quarkyonic matter

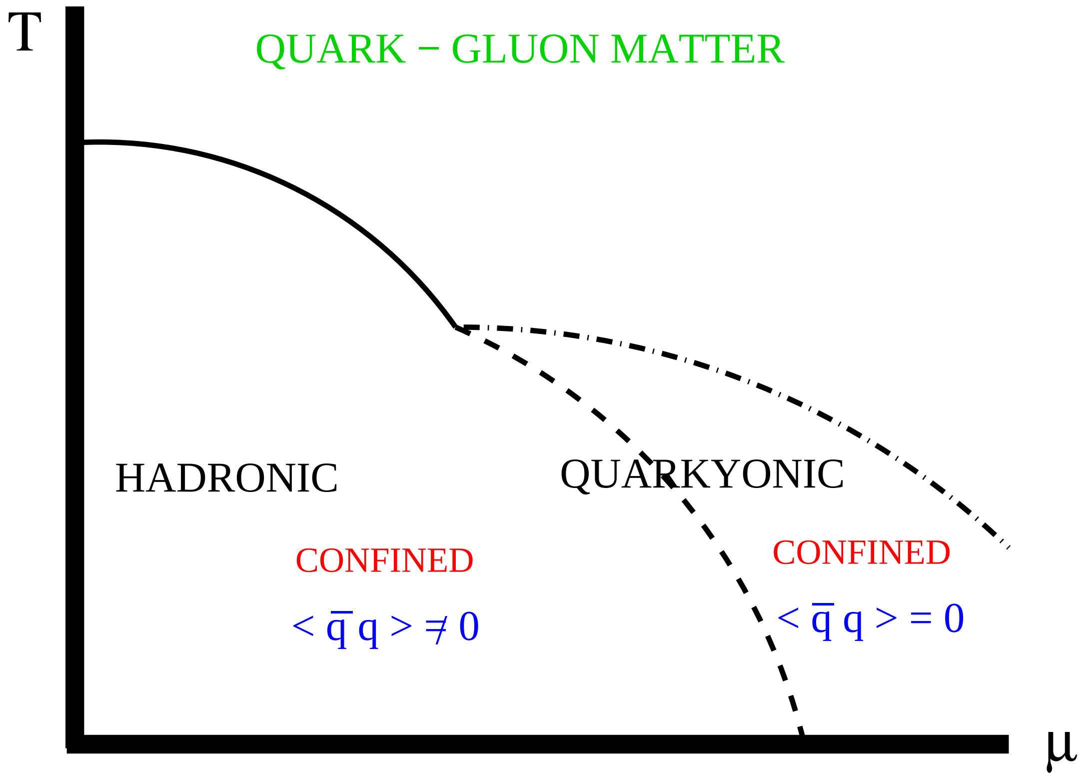
A quark excitation of the quark Fermi sea is impossible (a single quark Dirac operator is always infrared-divergent). Hadronic color-singlet excitation - possible.





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. A mass has manifestly chirally symmetric origin.

Chiral density waves in the confining mode?

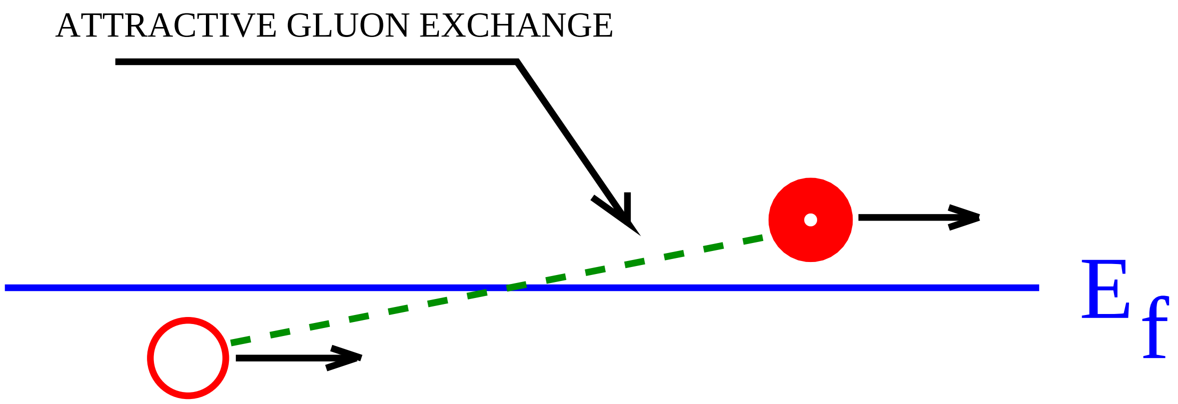
A challenge: what happens at the Fermi surface? Will be there chiral symmetry breaking phenomena like chiral density waves?

Deryagin, Grigoriev, Rubakov (1992)

Shuster, Son (2000), ...

Kojo, Hidaka, McLerran, Pisarski (2010)

Inhomogeneous quark-quarkhole chiral symmetry breaking condensate near a Fermi surface - chiral density waves.

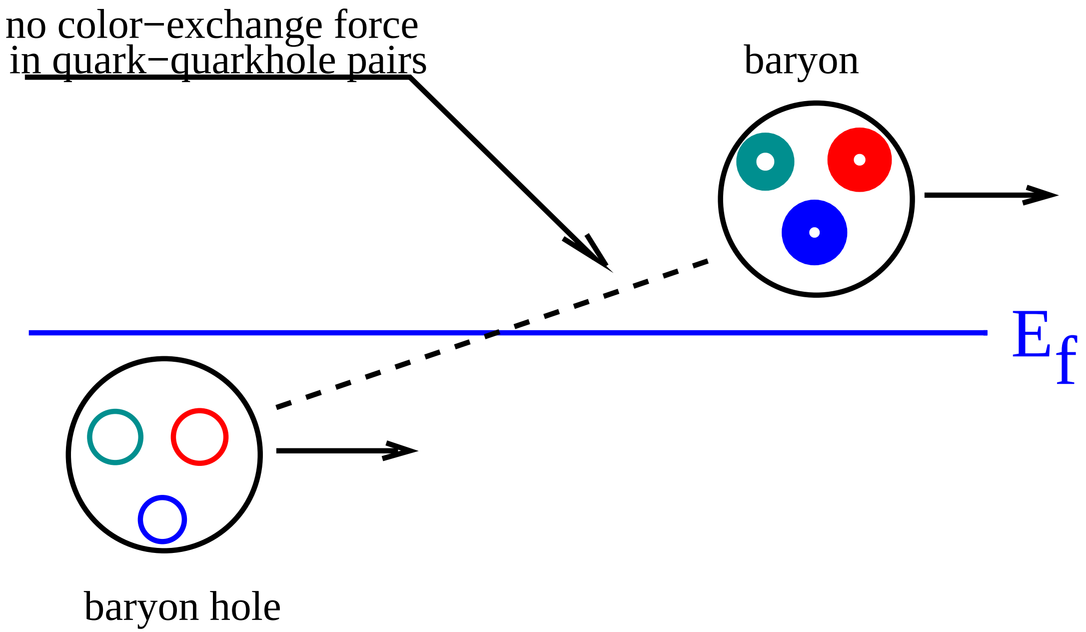


Reason: There is an attractive interaction due to a gluon-exchange force between the left quark and the right quark hole with similar large momenta.

An implicit assumption - quarks are in a gas mode. In a Fermi-gas there is no confinement.

Chiral density waves in the confining mode?

Will it happen in a mode with confinement?

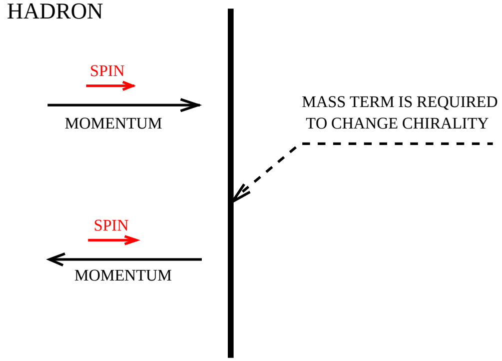


No color-exchange interaction at the quark - quarkhole level. No inhomogeneous quark-quarkhole condensate.

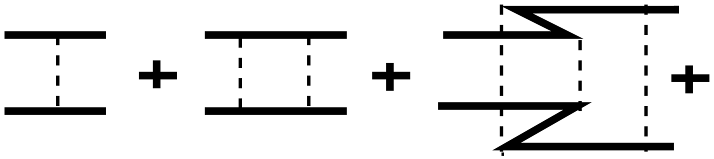
So if there is an inhomogeneous condensate, then only at the baryon-baryonhole level, like in old Migdal's pion condensate.

Chirally symmetric hadrons and the 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.