Quarkyonic Matter

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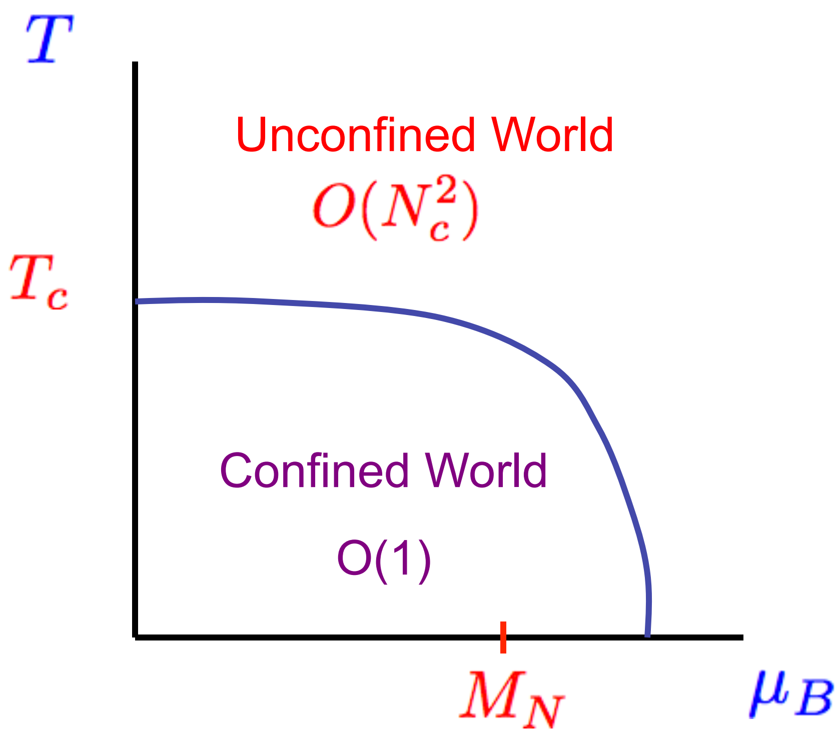
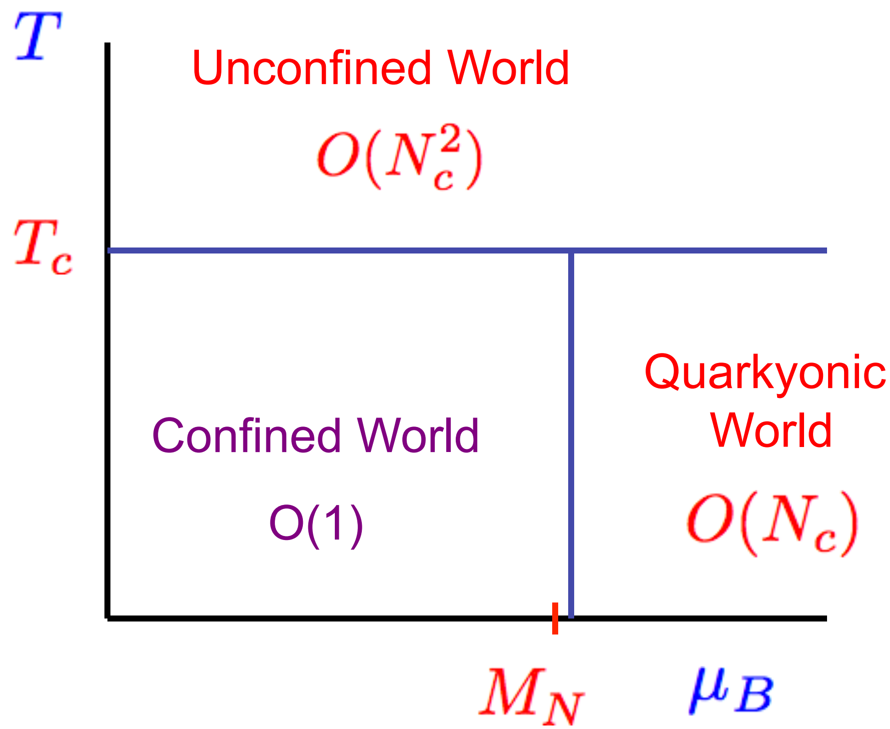
A. Andronic, D. Blaschke, J. Cleymans, K. Fukushima, H. Oeschler, P. Braun Munzinger, K. Redlich, c. Sasaki, H. Satz ,J. Stachel,



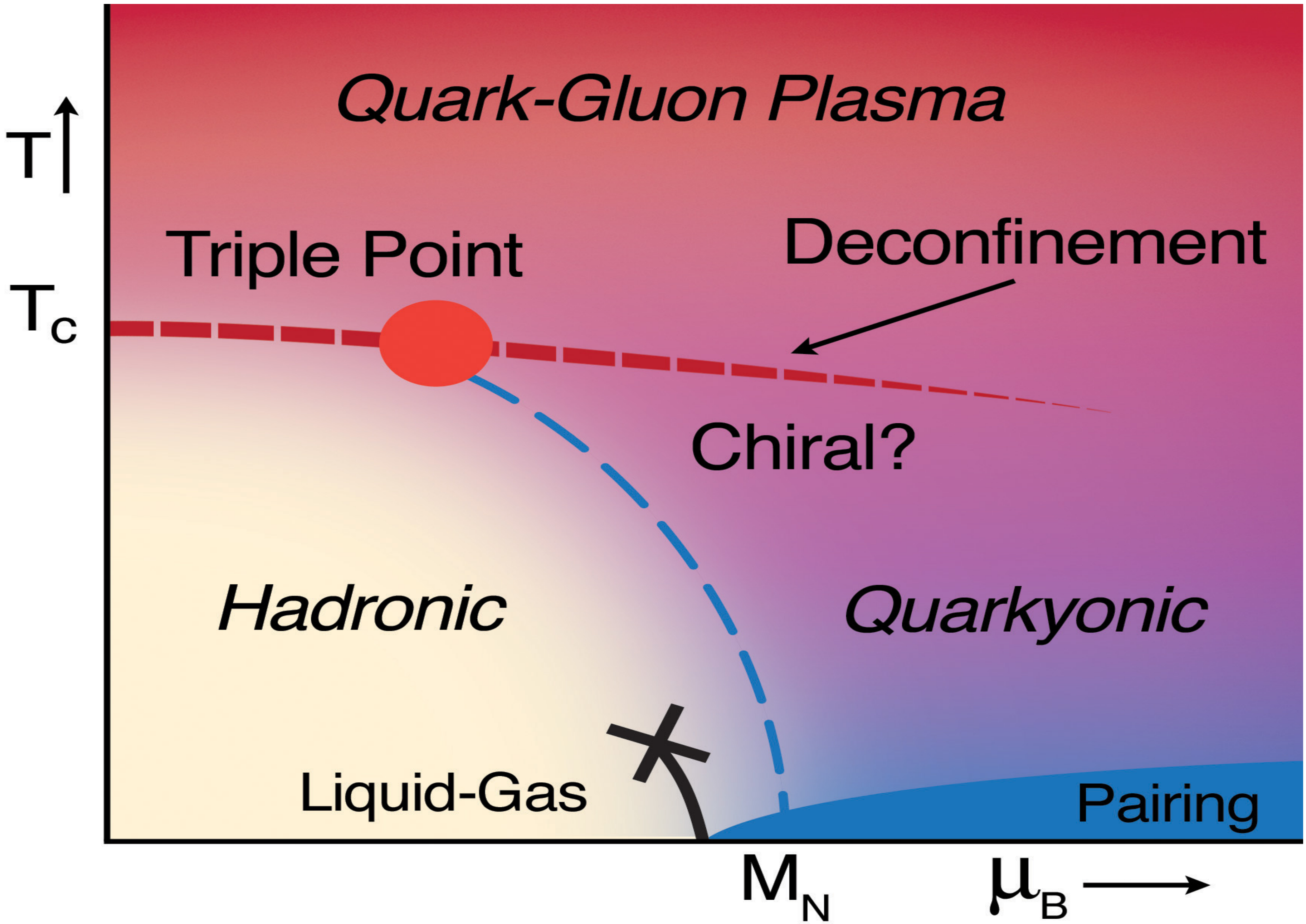
Conventional Wisdom



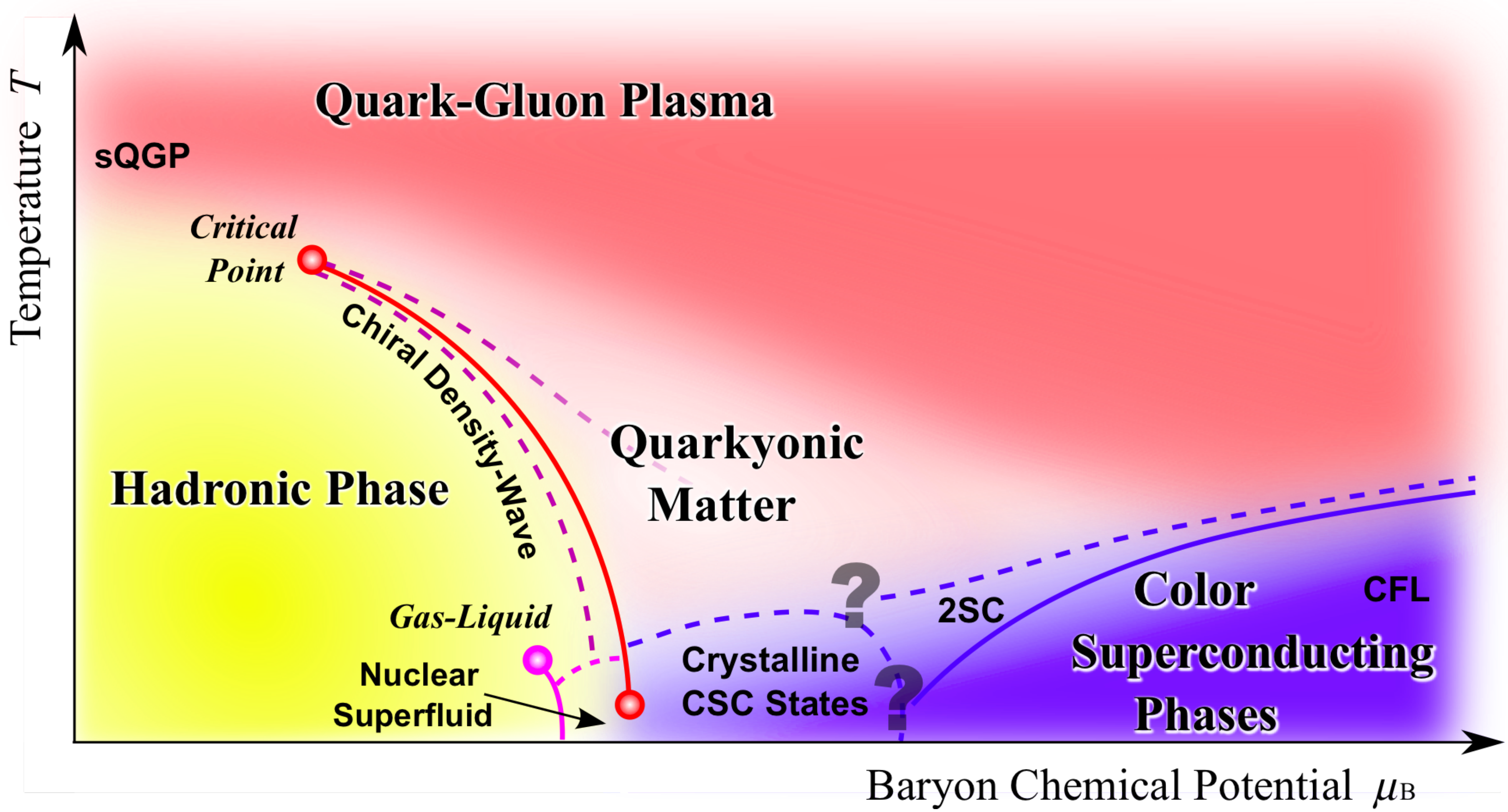
Large N

Will argue real world looks more like large N world

Somewhat Realistic Plot:



Recent Conception by Hatsuda and Fukushima



Brief Review of Large N

$$N_c \rightarrow \infty \qquad g^2 N_c \ finite$$

Mesons: quark-antiquark, noninteracting, masses ~ Λ_{QCD}

Baryons: N quarks, masses M ~$N_c \Lambda_{QCD}$, baryon interactions ~ N_c

Spectrum of Low Energy Baryons:

Multiplets with I = J; I,J = 1/2 -> I,J = N/2

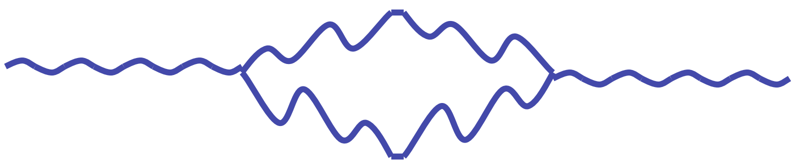
$$M_B(I,J) \sim M_N(1 + O(I^2/N_c^2, J^2/N_c^2, IJ/N_c^2))$$

$$M_\Delta - M_N \sim \Lambda_{QCD}^2/N_c$$

$$e^{(\mu_B - M_B)/T} = 0 \ if \ \mu_B < M_B$$

The confined world has no baryons because baryons are very massive!

Confinement at Finite Density:



$$g^2 N_c T^2 \sim \alpha_N T^2$$

Generates Debye Screening => Deconfinement at Tc

$$g^2 \mu_Q^2 \sim \alpha_N \mu_Q^2 / N_c$$

$\mu_Q = \mu_B / N_c$

Quark loops are always small by 1/N_c

For finite baryon fermi energy, confinement is never affected by the presence of quarks!

T_c does not depend upon baryon density!

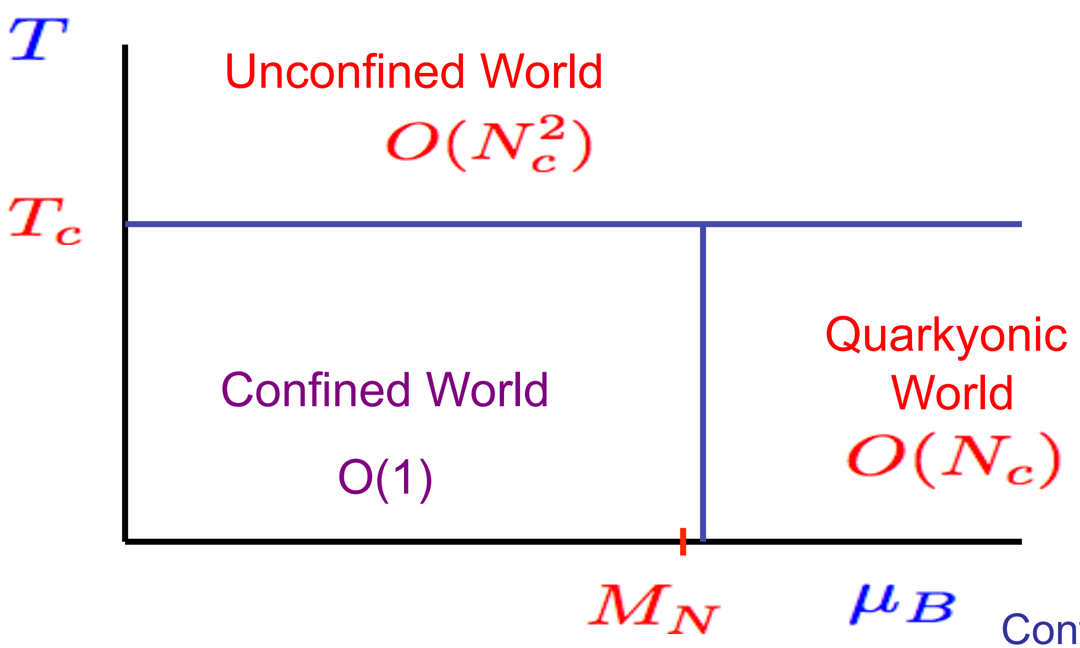
Confinement remains to very high baryon number density

Finite Baryon Density:

$$e^{(\mu_B - M_B)/T} = 0 \; if \; \mu_B < M_B$$

No baryons in the confined phase for $\mu_B < M_B$

For $\mu_B >> M_B \; (\mu_Q >> \Lambda_{QCD})$ weakly coupled gas of quarks.



Large N

If T < T_c, no free gluons, degrees of freedom are ~ Nc

Quarkyonic Matter:

Confined gas of perturbative quarks!

Confined mesons and glueballs

Confined: Mesons and Glueballs

Quarkyonic: Quarks, Mesons, Glueballs

Unconfined: Quarks and Gluons

Some Properties of Quarkyonic Matter

Quarks inside the Fermi Sea: Perturbative Interactions => At High Density can use perturbative quark Fermi gas for bulk properties

At Fermi Surface: Interactions sensitive to infrared => Confined baryons

Perturbative high density quark matter is chirally symmetric but confined => violates intuitive arguments that confinement => chiral symmetry

Quarkyonic matter appears when

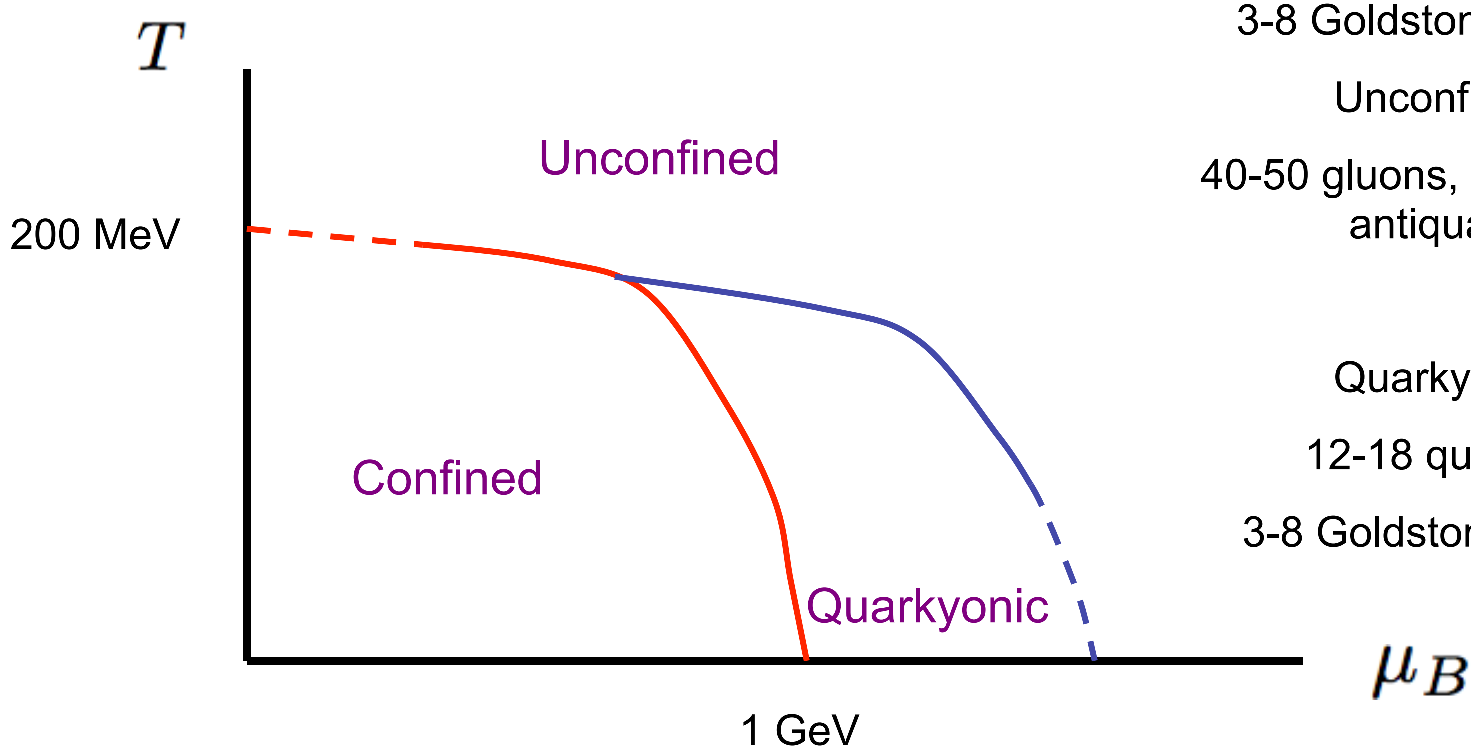
$$\mu_B = M_B \; (\mu_Q = 330MeV)$$

(Can be modified if quark matter is bound by interactions. Could be “strange quarkyonic matter”?

Seems not true for N = 3)

Guess for Realistic Phase Diagram for N = 3

Will ignore not include effects of Color Superconductivity



Number of degrees of freedom:

Confined

3-8 Goldstone Bosons

Unconfined

40-50 gluons, quarks and antiquarks

Quarkyonic

12-18 quarks +

3-8 Goldstone Bosons

Width of the Transition Region:

$$k_F \sim \Lambda_{QCD}$$

Baryons are non-relativistic: $k_F/M_N \sim v \sim 1/N_c$

$$\mu_B \sim M_N + k_F^2/2M_N \sim N_c\Lambda_{QCD}(1 + O(1/N_c^2))$$

$$\mu_Q \sim \Lambda_{QCD}(1 + O(1/N_c^2))$$

Nuclear physics is in a width of order $1/N_c^2$ around the baryon mass!

Nuclear matter is non-relativistic, and there is a narrow transition between confined and quarkyonic world

A PNJL model in large N_c

With Redlich and Sasaki

- thermodynamic potential: $(N_c \times N_c$ matrix $L)$ [Fukushima, Ratti et al.]

$$\Omega = \mathcal{U}(\Phi, \bar{\Phi}) + \frac{M^2}{2G} - 2N_c N_f \int \frac{d^3p}{(2\pi)^3} E\, \Theta(\Lambda - |\vec{p}|)$$
$$- 2N_f T \int \frac{d^3p}{(2\pi)^3} \mathrm{Tr} \left[\ln \left(1 + L e^{-(E-\mu)/T} \right) + \ln \left(1 + L^\dagger e^{-(E+\mu)/T} \right) \right]$$

- $N_c = 3$:

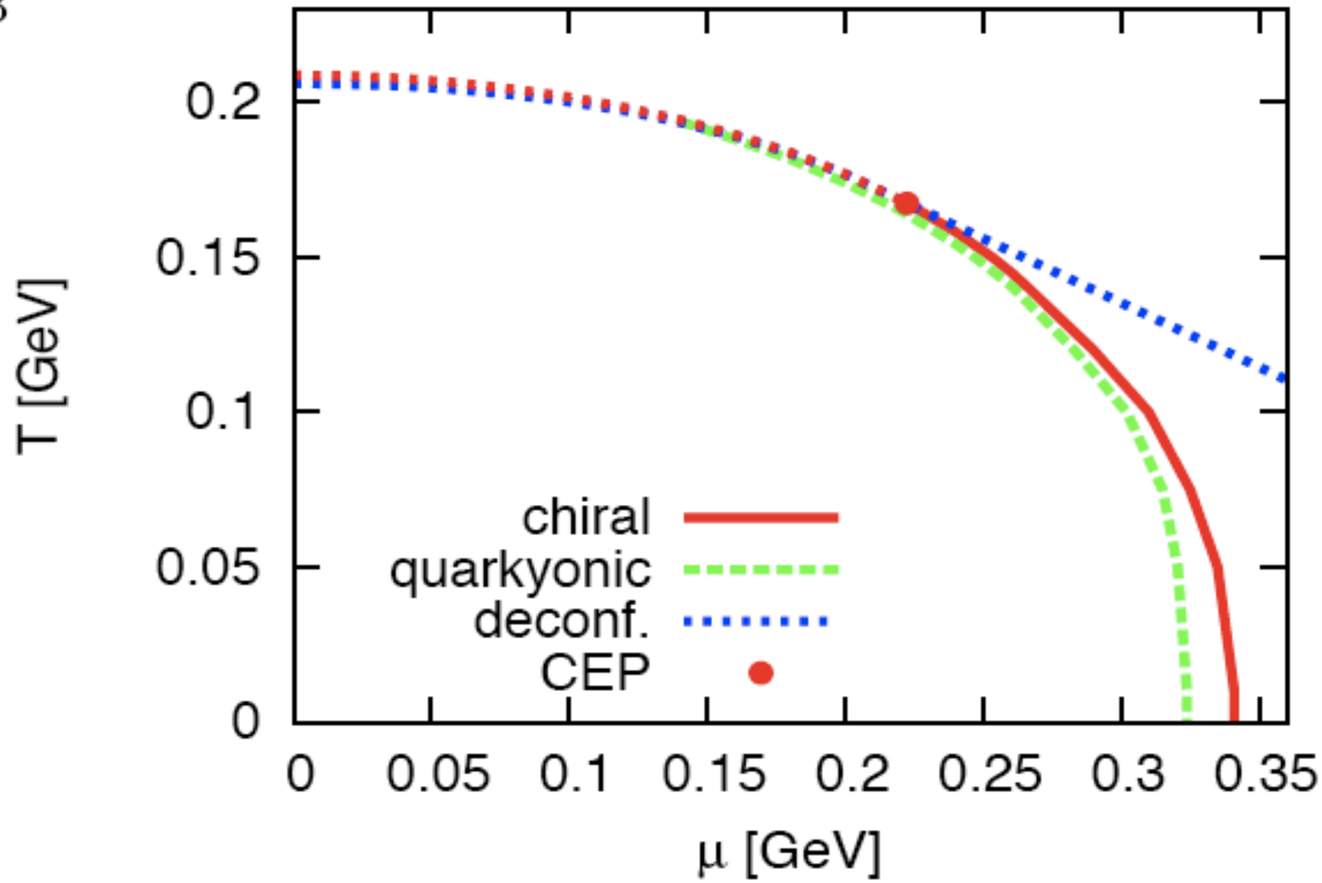
$$\mathrm{Tr} \ln \left(1 + L e^{-(E-\mu)/T} \right)$$
$$= \ln \left[1 + 3\Phi e^{-(E-\mu)/T} + 3\bar{\Phi} e^{-2(E-\mu)/T} + e^{-3(E-\mu)/T} \right]$$

at low temperature $\Phi \sim 0$ and "baryons" contribute to thermodynamics
$\Rightarrow$ model mimics confinement

- "baryons" are very massive: suppressed for $M > \mu$. then for $\mu > M$?

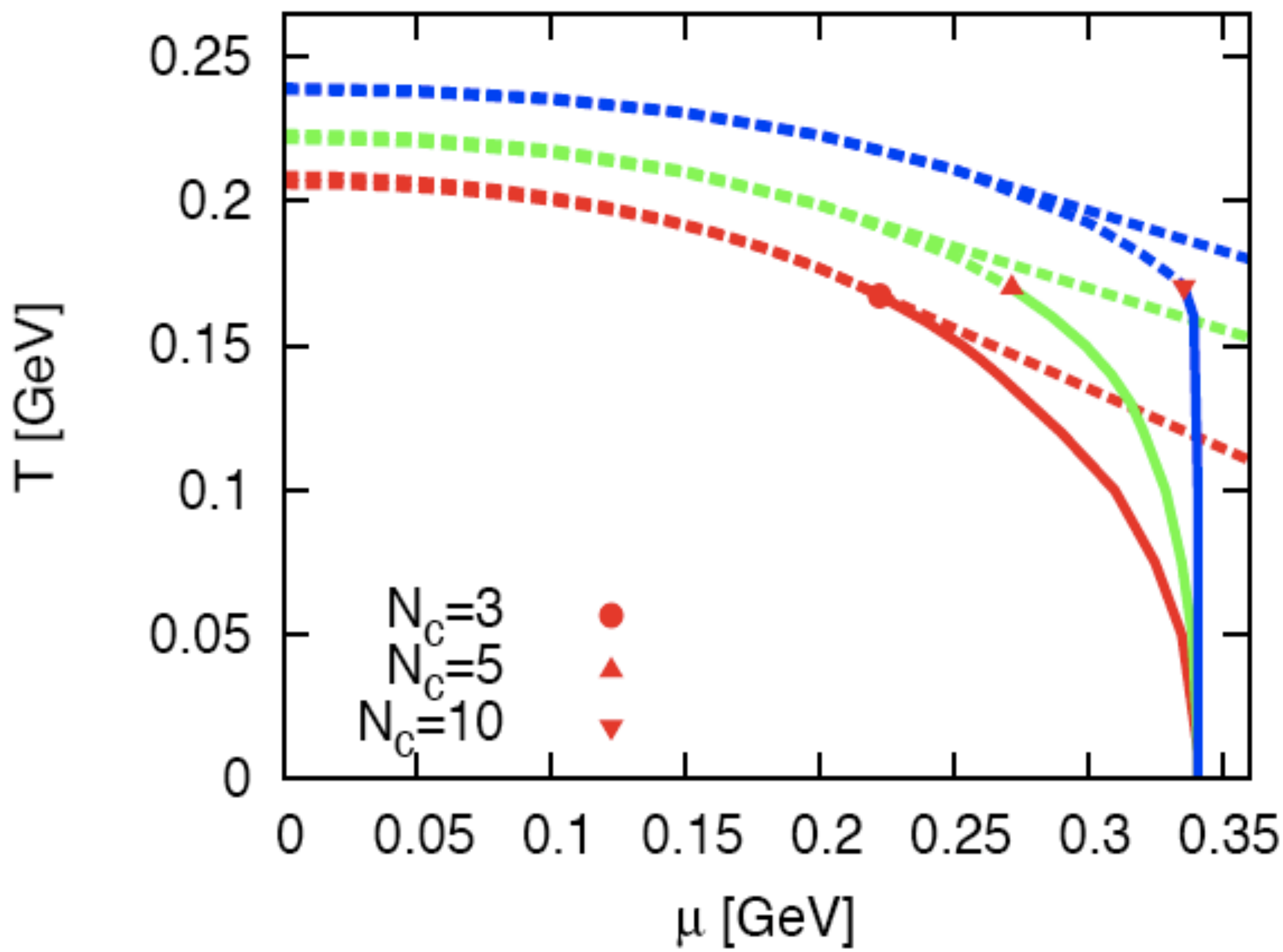
Phase diagram for various N_c

- $N_c = 3$



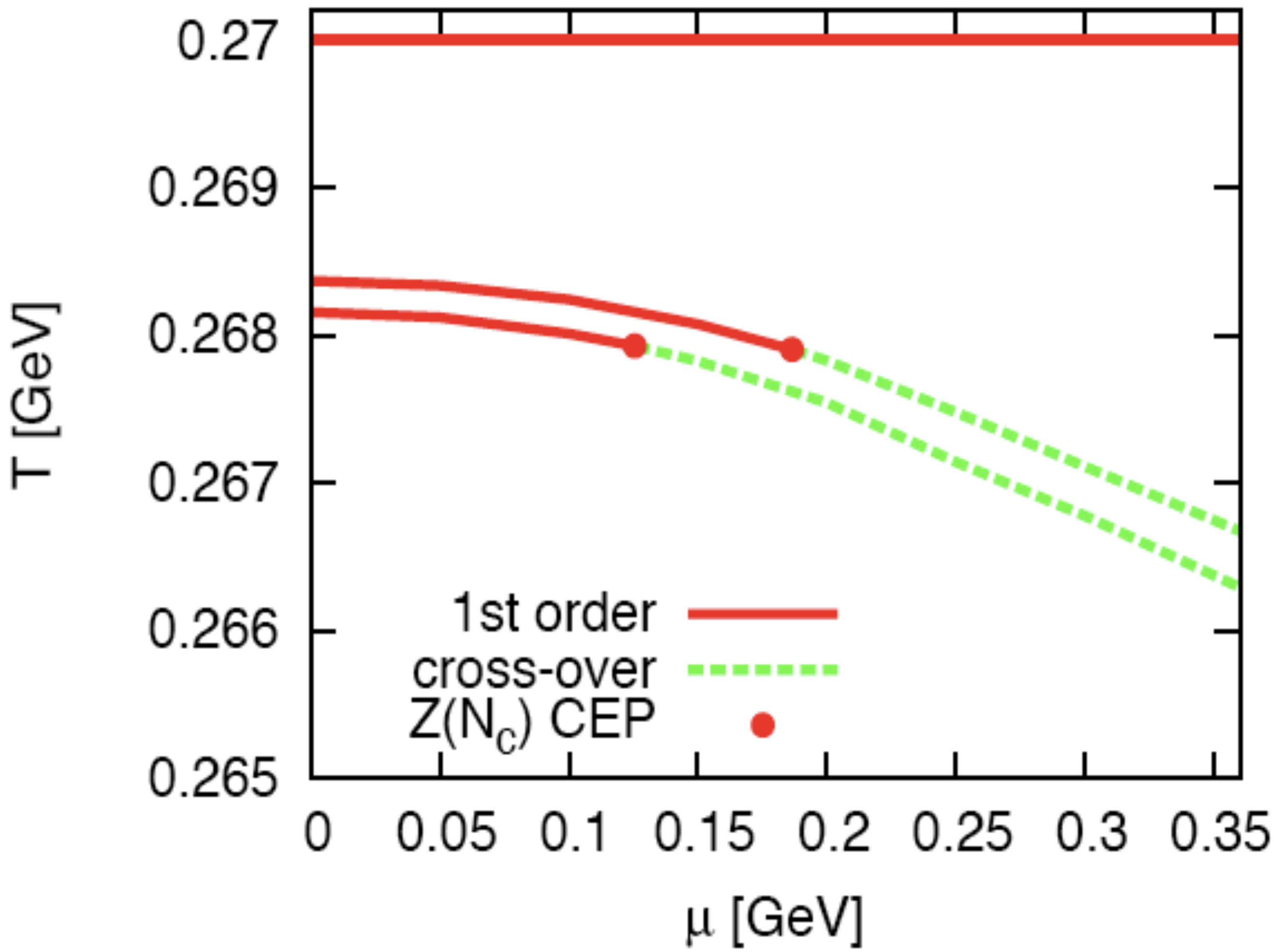
weak chiral transition along quarkyonic line, might be destroyed by effect of deconf. $\Rightarrow$ CEP

- $N_c = 3, 5, 10$



chiral CEP shifts to larger μ when increasing N_c

- for large but finite $N_c = 350, 400$



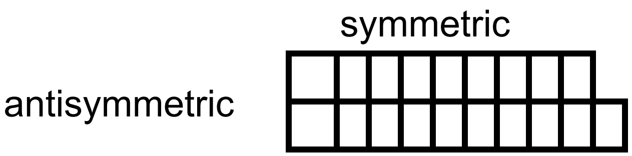
$N_c \leq 316$: cross over , $N_c \geq 317$: 1st order

$\Rightarrow$ appearance of a CEP associated with $Z(N_c)$ symmetry

Finite Nc, Nf/Nc fixed

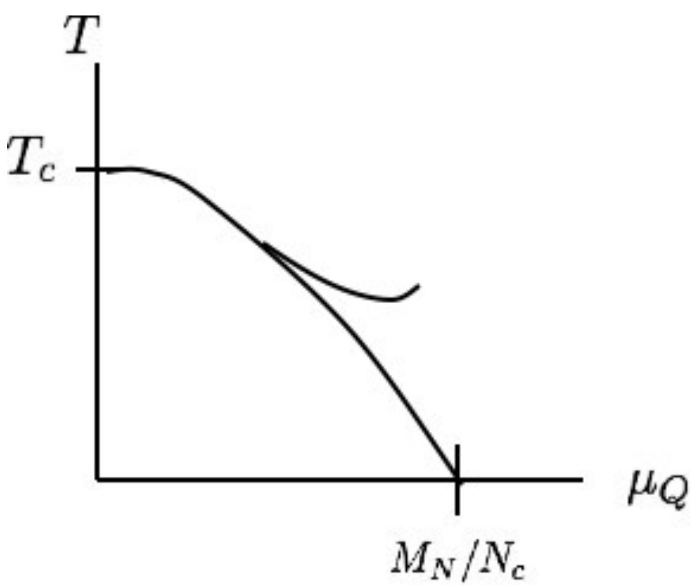
Number of states for the lowest mass baryon with I = 1/2 and J = 1/2

$$e^{N_c F(N_f/N_c)}$$



Antisymmetric in color =>

Symmetric in spin-flavor



$$\rho_B \sim e^{N_c F(N_f/N_c) + \mu_B/T - M_B/T}$$

Confinement is not an order parameter

Baryon number is

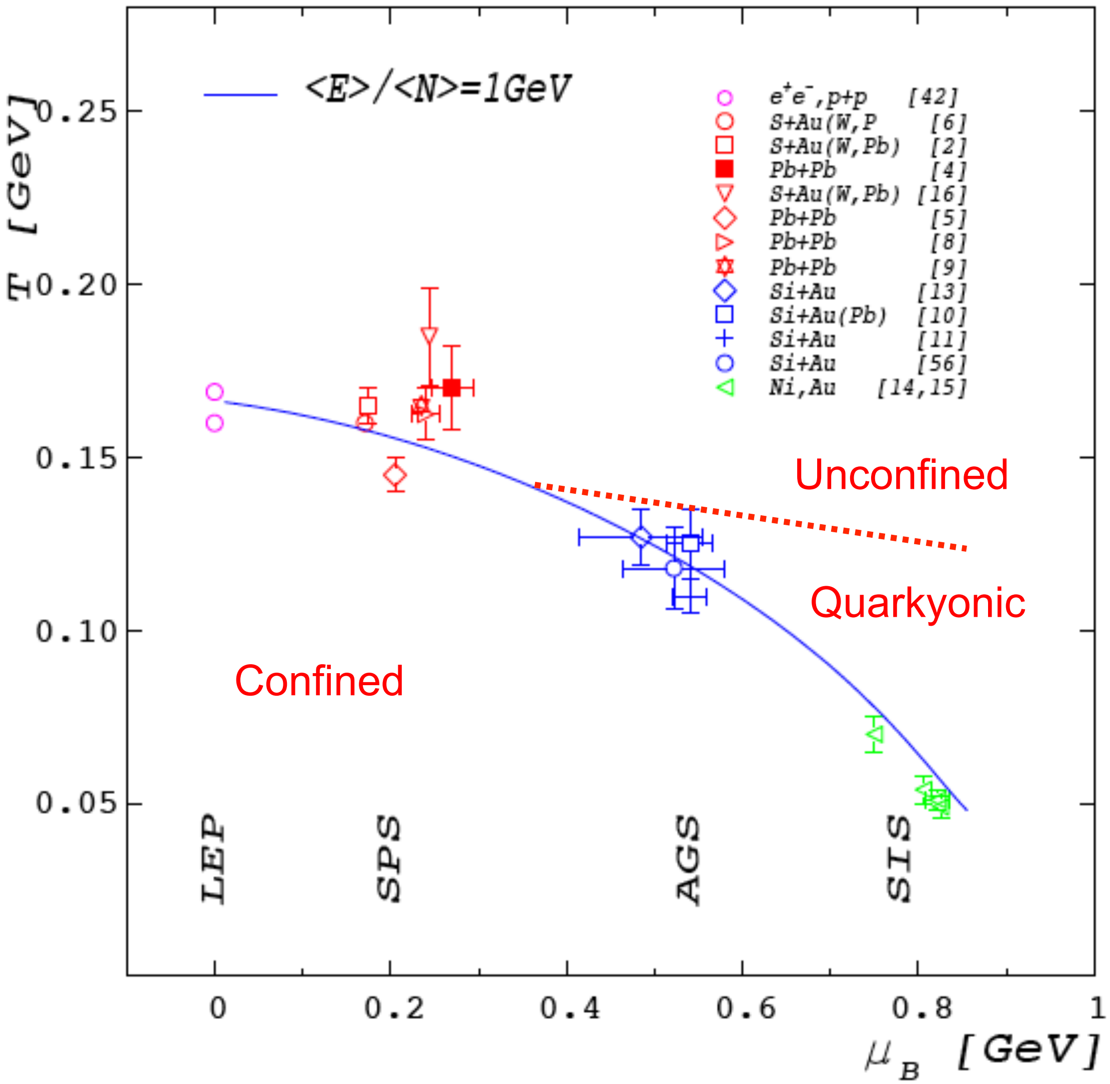
Phases are baryonless and quarkyonic

Approximately:

Confined Nf

Quarkyonic Nc Nf

De-confined Nc Nf + Nc^2



Maybe it looks a little like this?

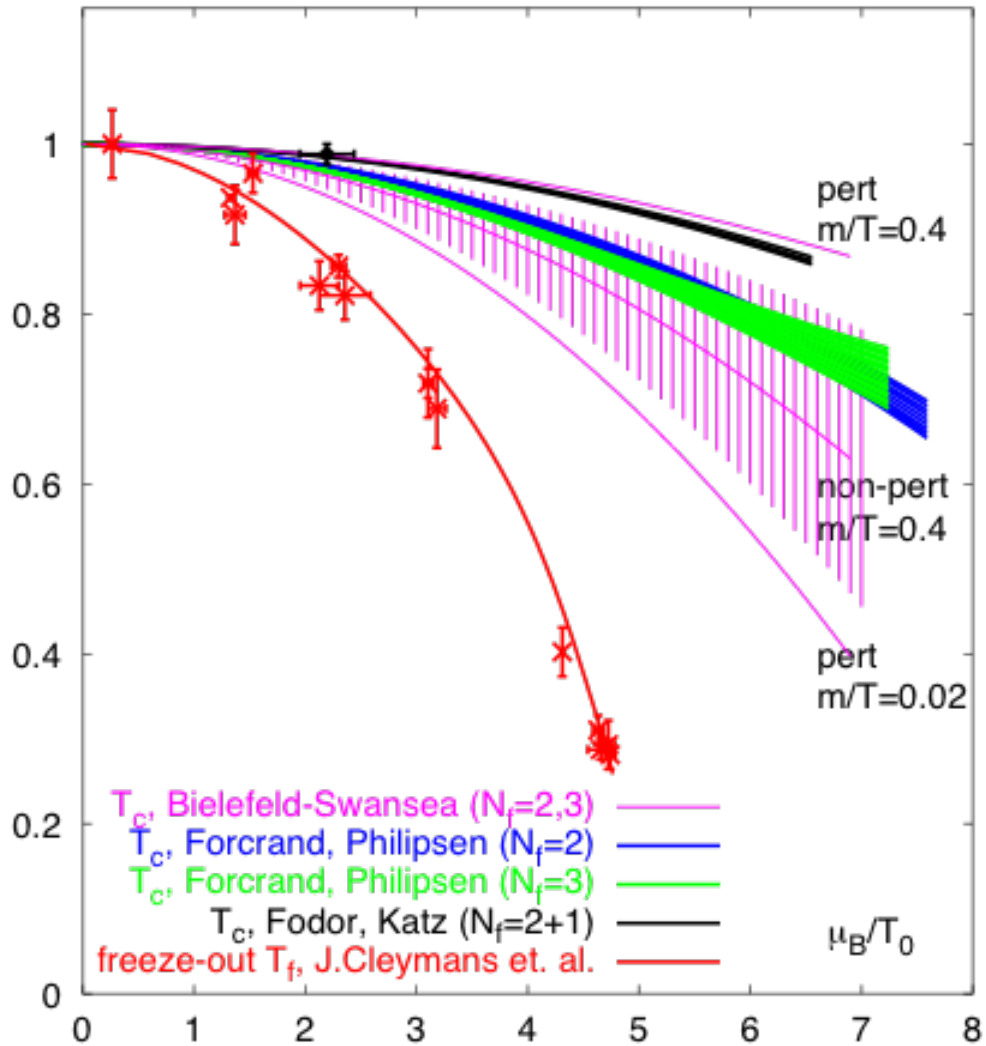
Maybe somewhere around the AGS there is a tricritical point where these worlds merge?

Decoupling probably occurs along at low T probably occurs between confined and quarkyonic worlds. Consistent with Cleymans-Redlich-Stachel-Braun-Munzinger observations!

Experiment vs. Lattice

Lattice “transition” appears *above* freezeout line? Schmidt ‘07

N.B.: small change in T_c with μ?



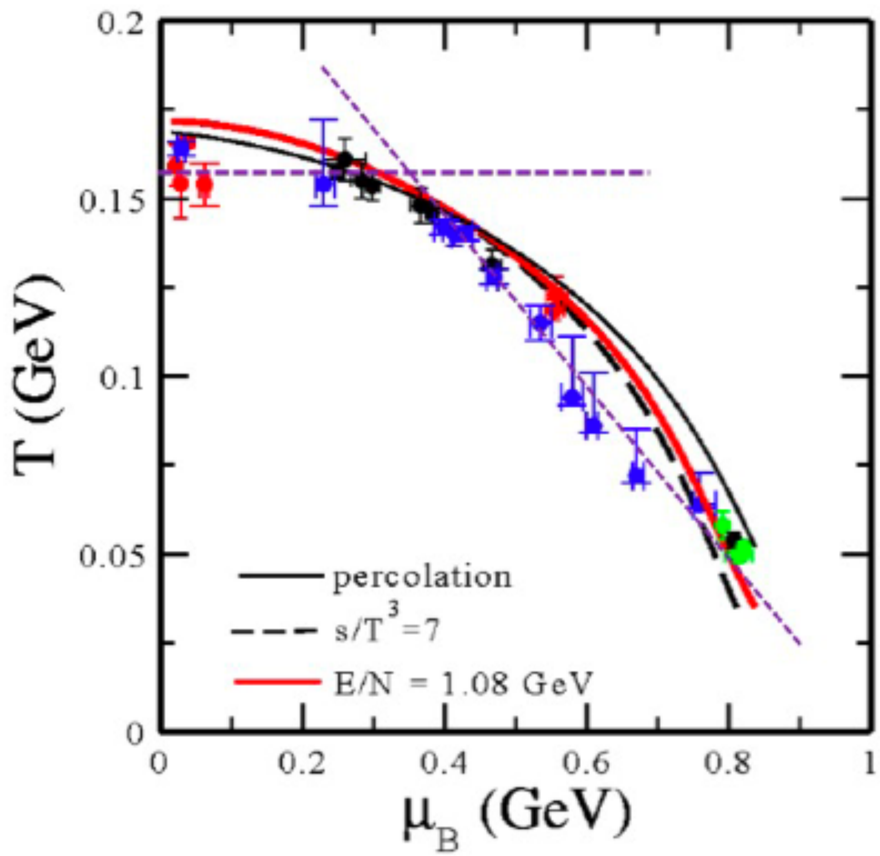
$T \uparrow$

$\mu_{quark} \rightarrow$

Have we already seen the Quakryonic phase boundary, and the Triple Point?

A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, J. Stachel,

Reinhard Stock, Francesco Becattini, Thorsten Kollegger, Michael Mitrovski, Tim Schuster

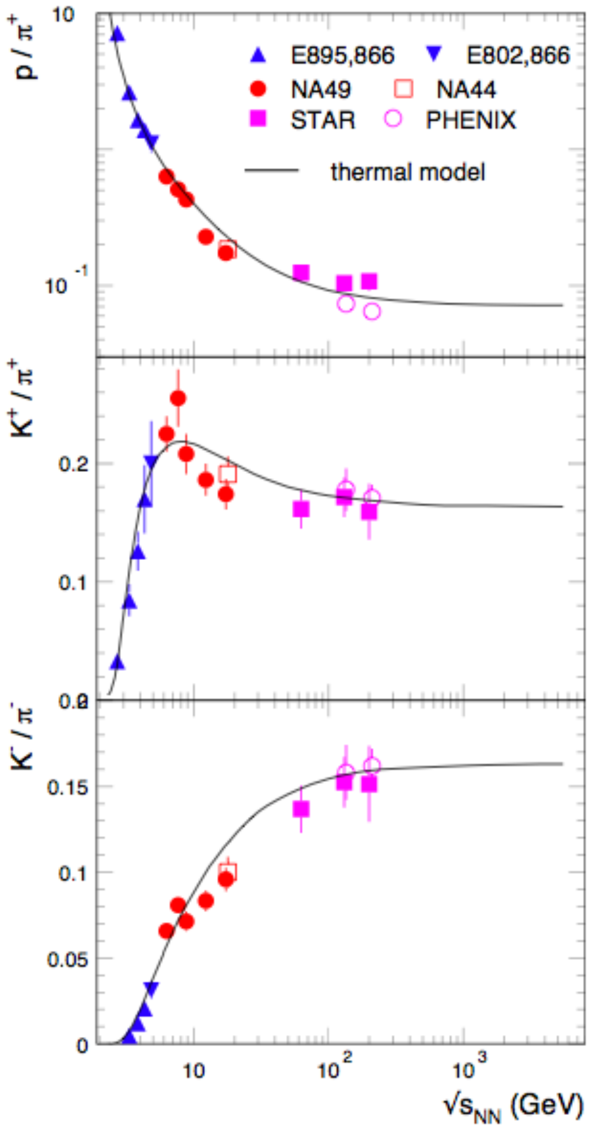


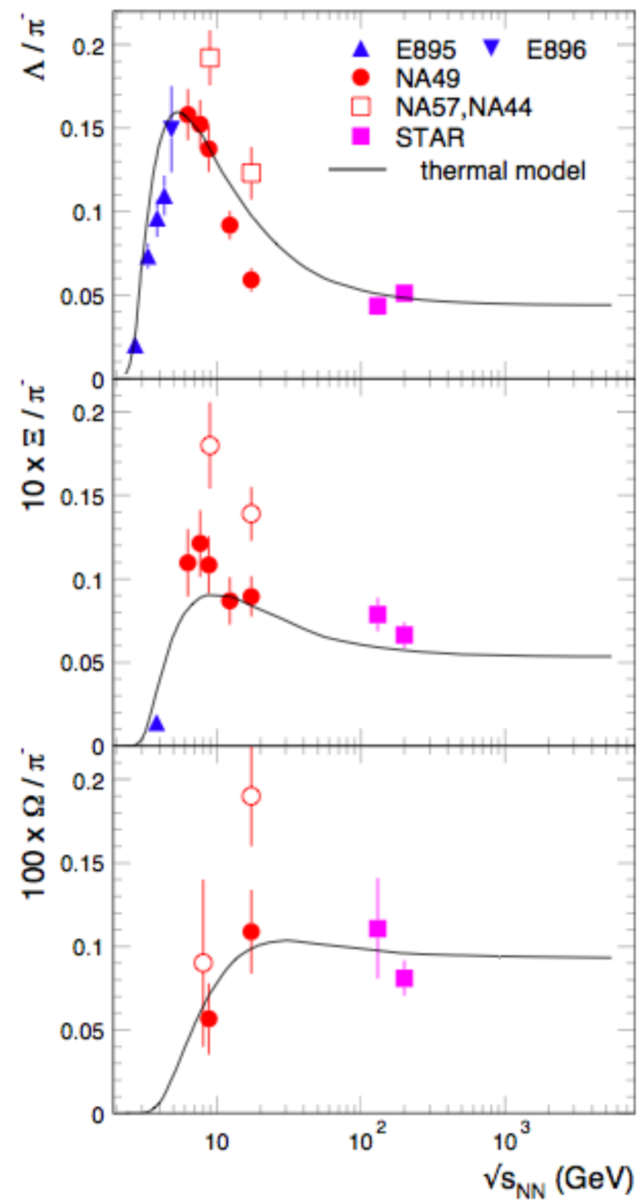
Dashed line indicate simple models of deconfinement and quarkyonic transition

Measured abundances fall on curve with fixed baryon chemical potential and temperature at each energy: suggests a phase transition with a rapid change in energy density

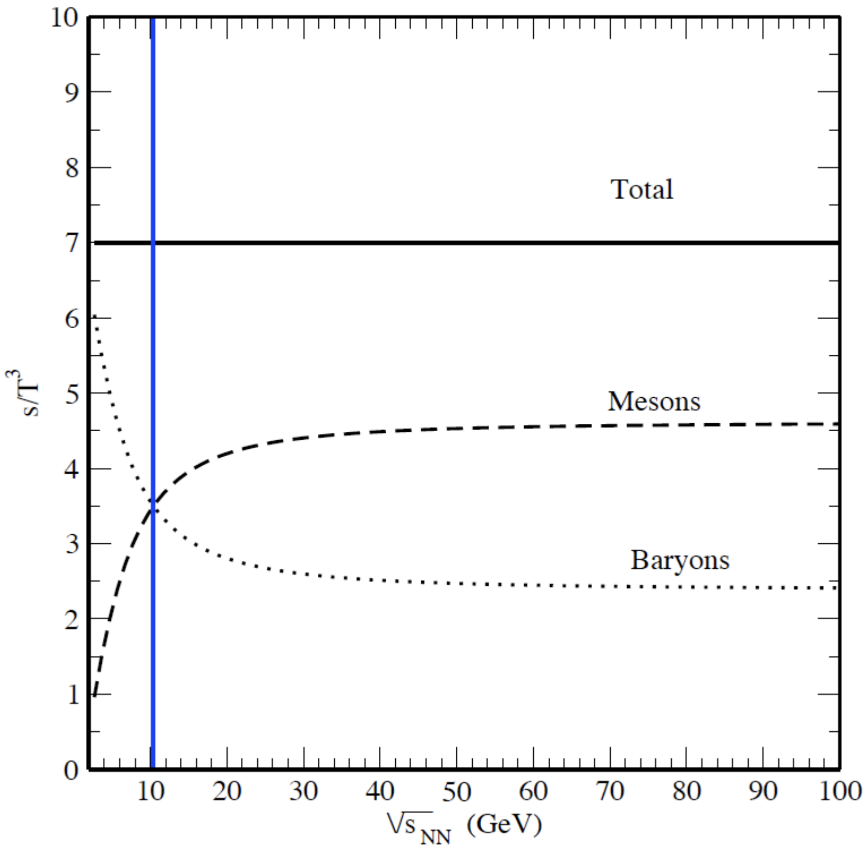
High density low T points deviate from expectations of deconfinement transition

Marek's Horn is near position of a triple point. Well described in statistical models:

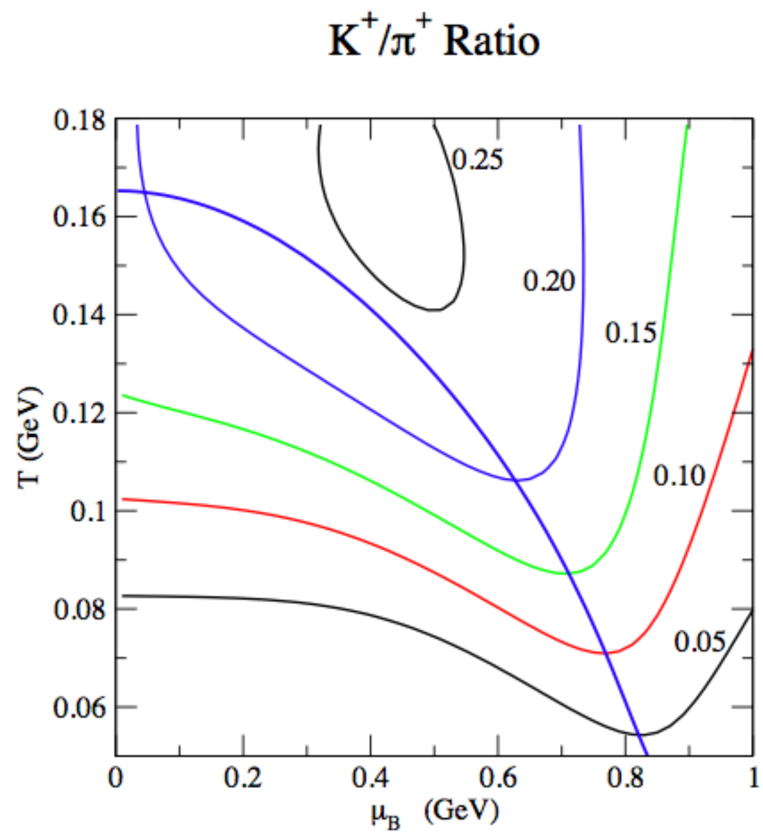




At the triple point is where the matter changes between baryon rich and meson rich:



Peaks in strangeness abundance are qualitatively understood as due to a triple point:



The Non-Perturbative Fermi Surface:

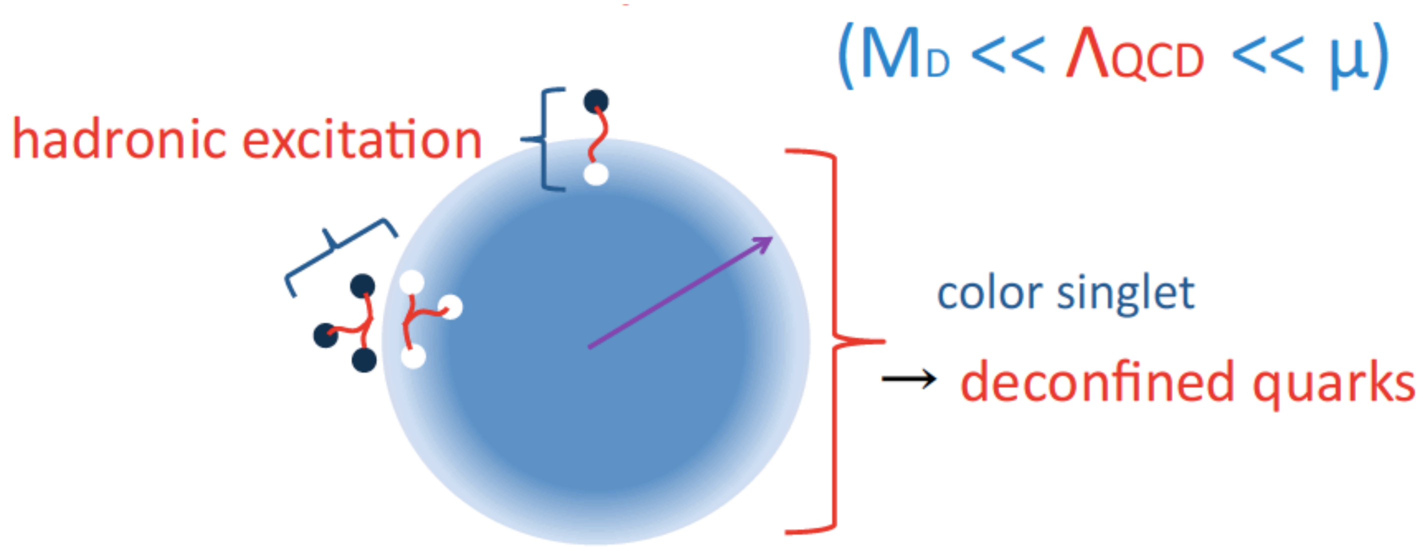
T. Kojo, Y. Hidaka, R. Pisarski and L. McLerran

Deep in the Fermi sea, a momentum of order the Fermi momenta must be exchanged in interactions

$$\alpha_S(\mu_Q) << 1$$

Near the Fermi surface, $\delta K \leq \Lambda_{QCD}$ interactions are strong

Excitations are confined and color singlet



$$E = \mu_B + \Delta E, \ particle, \ k_F \sim \mu_B$$
$$E = \mu_B - \Delta E, \ hole, \ k_F \sim -\mu_B$$
$$antiparticle, \ E = \mu_B + \Delta E, k_F \sim \mu_B$$

If form a bound state with negative biding energy =>

Chiral condensate

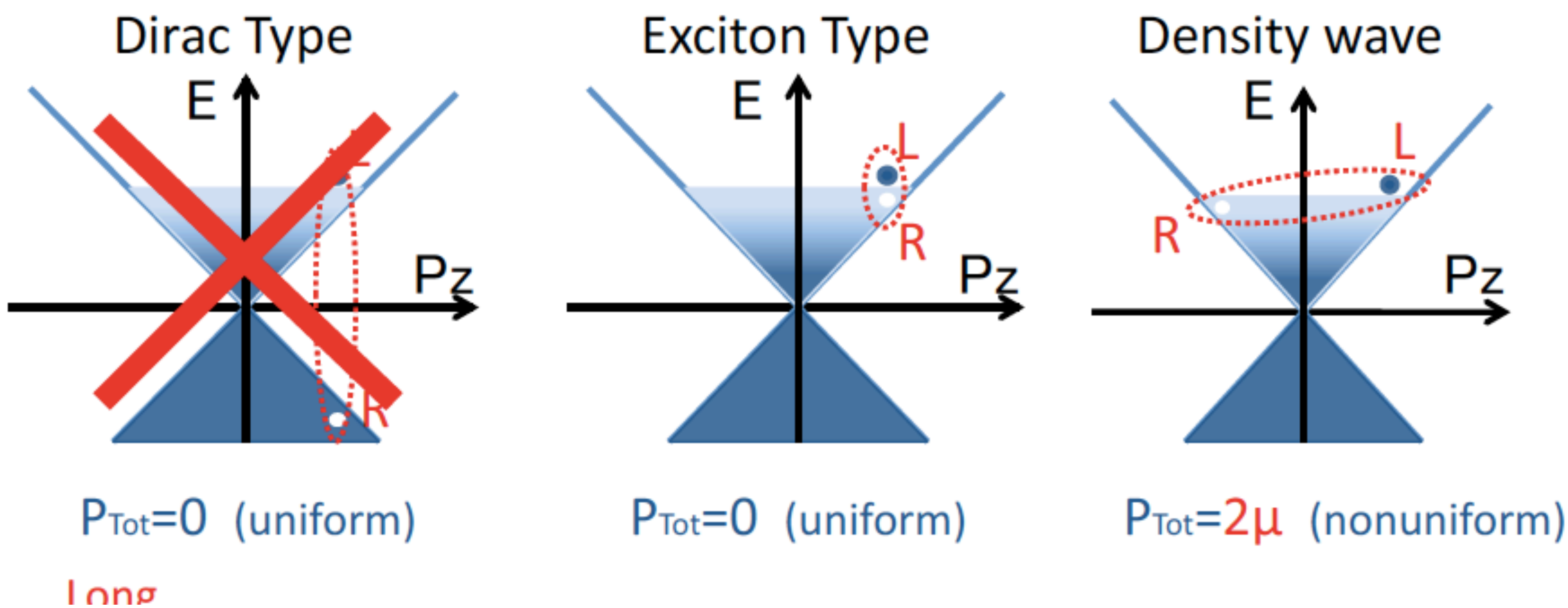
Condensate breaks translational invariance => crystal

Chiral symmetry breaking of order

$$\Lambda^2_{QCD}/\mu^2_Q$$

Quarkyonic phase at most weakly breaks chiral symmetry

- Candidates which spontaneously break Chiral Symmetry



The Quarkyonic Chiral Spiral:

Near Fermi surface, theory dimensionally reduces to 1+1 D ‘t Hooft model

2Nc “Goldstone Bosons”

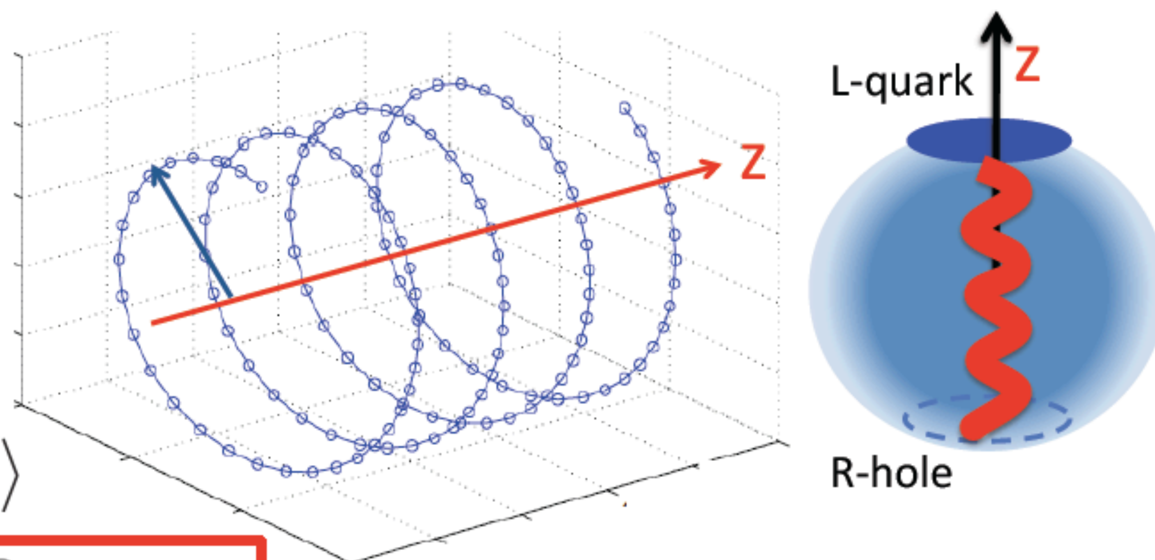
Translationally non-invariant chiral condensate

Condensate breaks parity and induces a periodic electric field

Implications for structure and cooling of neutron stars

- Chiral rotation evolves in the longitudinal direction:

$\langle \bar{\Psi}\Psi \rangle$ → $\langle \bar{\psi}\psi \rangle$



$\langle \bar{\Psi} i \Gamma_5 \Psi \rangle$ → $\langle \bar{\psi}\gamma^0\gamma^z\psi \rangle$ (not conventional pion condensate in nuclear matter)

M. Sadzikowski, Phys. Lett. B642, (2006), 2006
with pion condensates