重イオン衝突実験で探る 核物質・クォーク物質研究

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Talk Plan

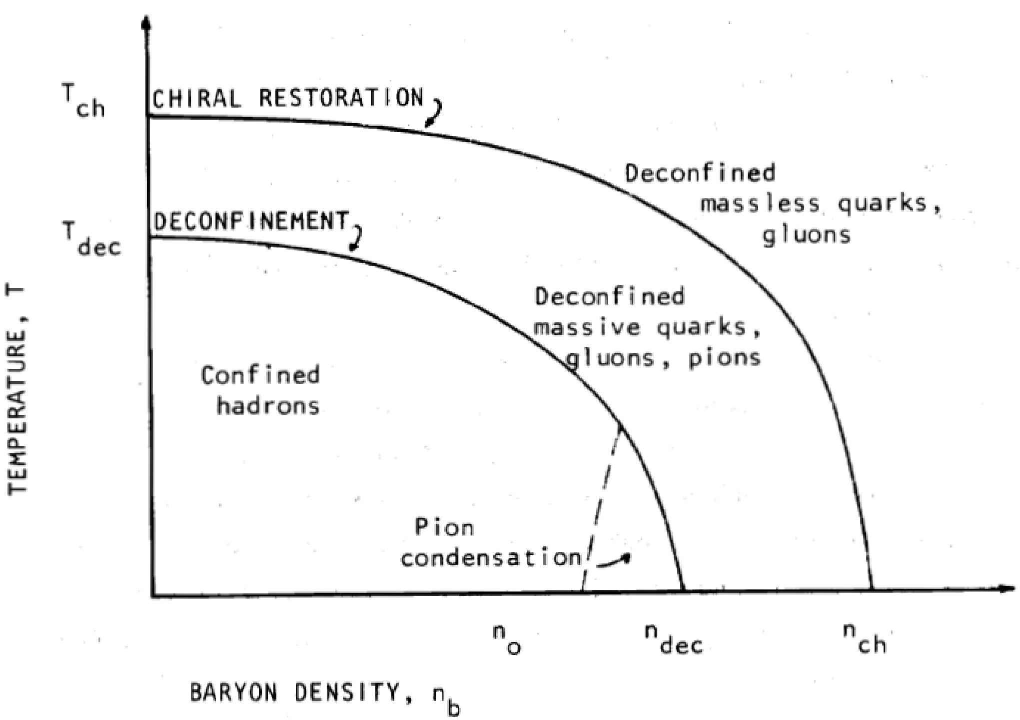
- QCD Phase Boundary and the Critical Point
- Liquid-gas Phase Transition of Nuclear and Quark Matter
- In-medium Chiral Symmetry
- Diquarks and Exotic Hadrons at High Density
- Deconfinement and Hadron Resonances
- Inhomogeneous Phases
- Effect of the Magnetic Field in HIC

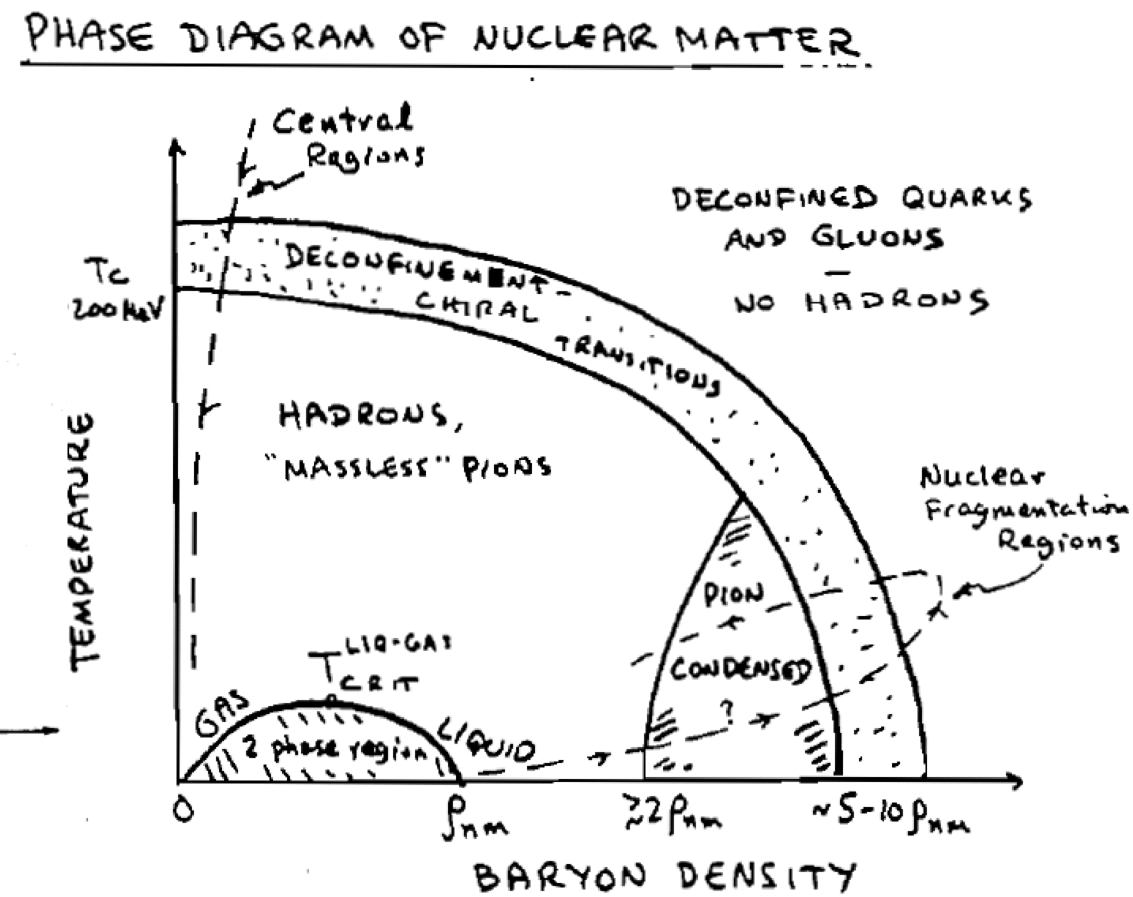
QCD Phase Boundary and the Critical Point

Two Historical Phase Diagrams

Diagram-1982 Lattice → **Diagram-1983**

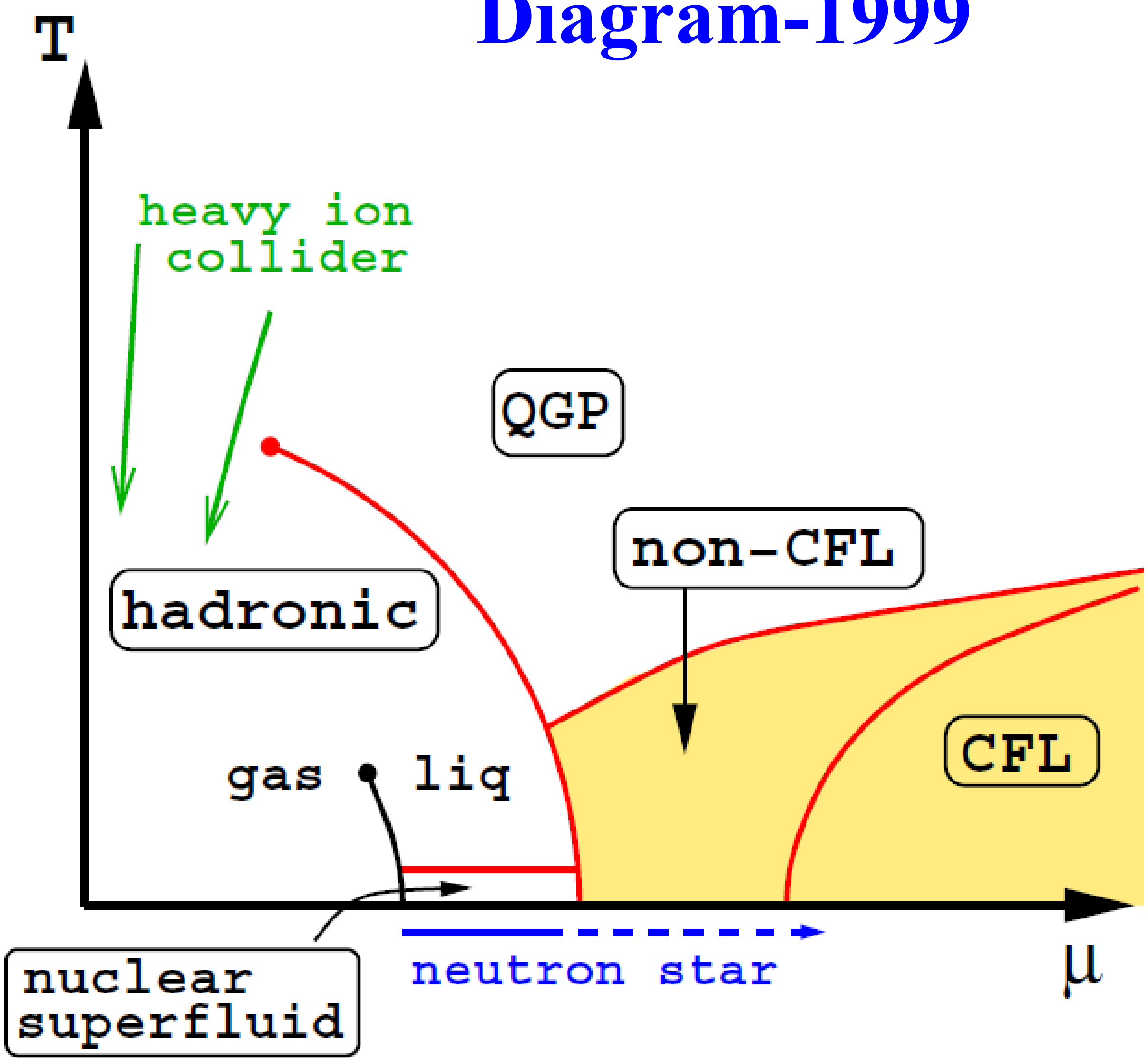
Baym





Color Superconductivity

Diagram-1999



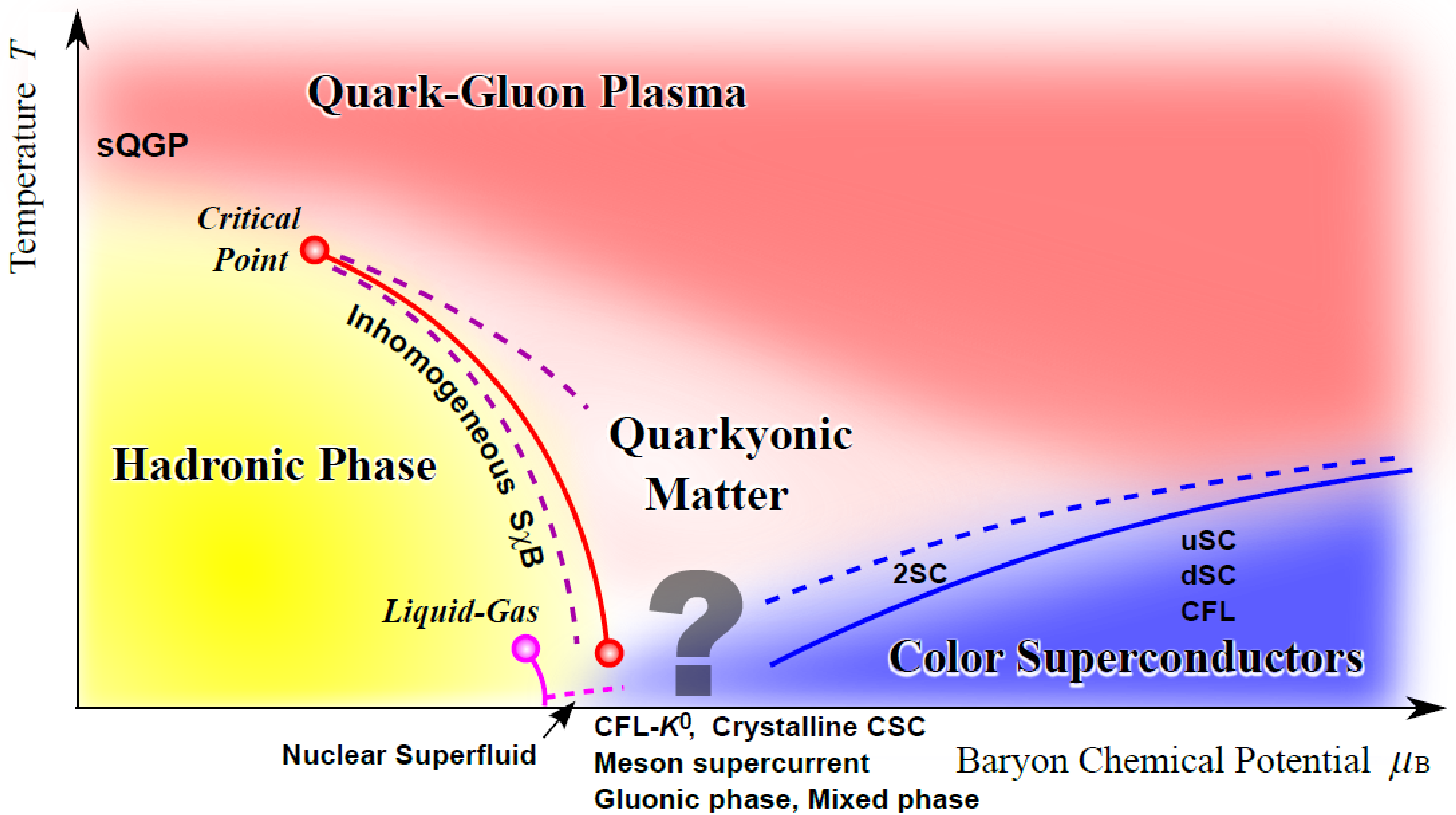
Alford

Non-CFL includes:
2SC, dSC, uSC, etc...
Crystalline SC

Chromomagnetic Instability
Crystallography
Gritch problem

Alford, Blaschke, Casalbuoni, KF, Huang, Kunihiro, Rajagopal, Rischke, Ruggieri, Schmitt, Shovkovy, etc...

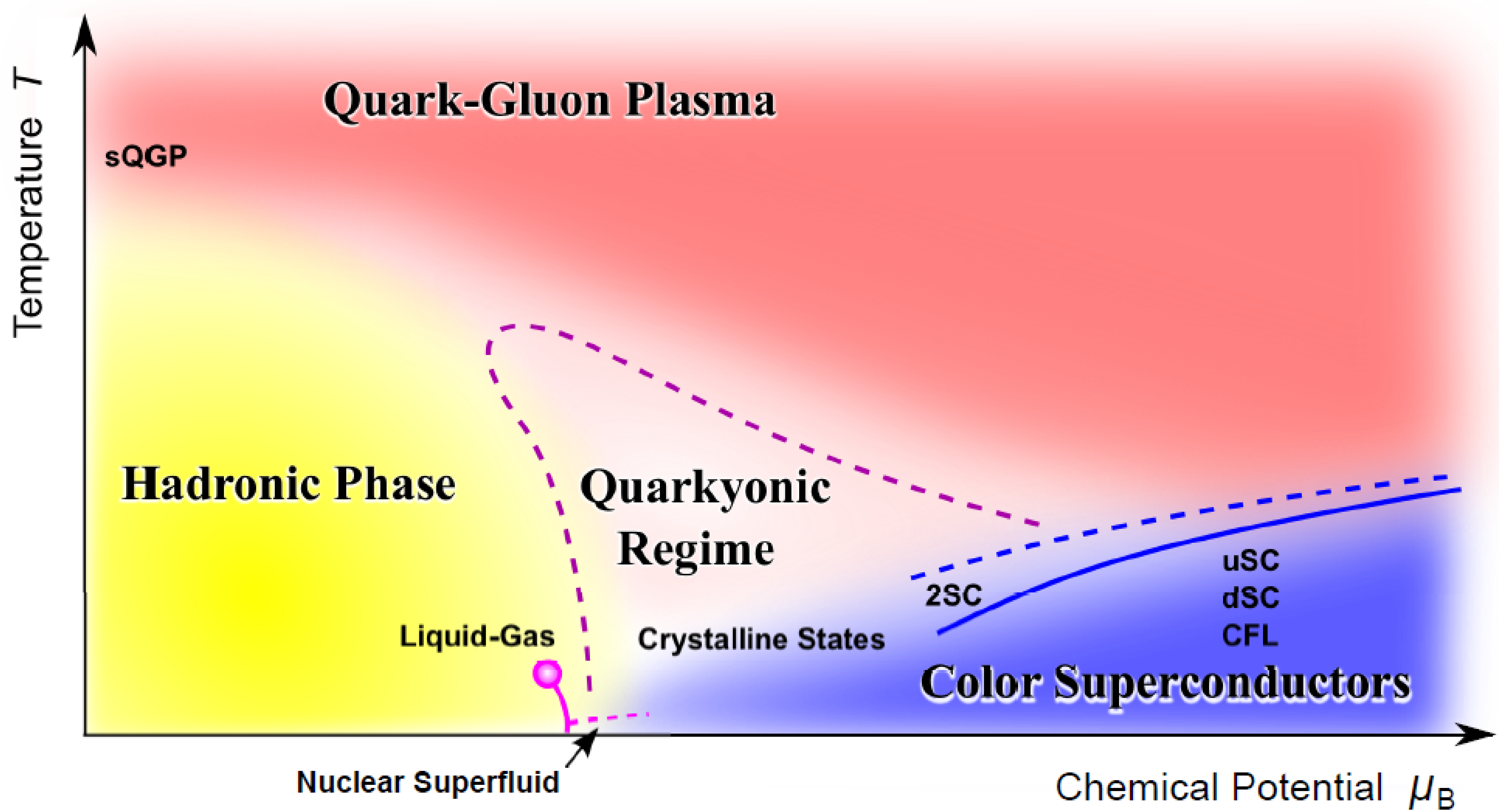
Diagram-2010



KF-Hatsuda (2010)

Diagram-2013

Most likely scenario for the moment KF-Sasaki (2013)



QCD Critical Point

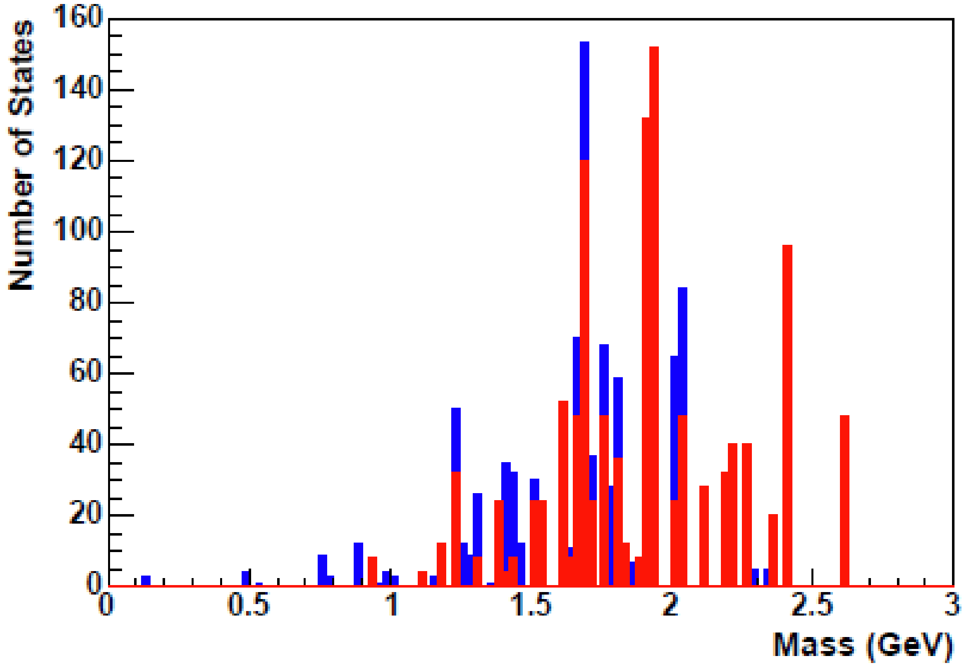
- Asakawa-Yazaki (1989) is the first model study in which a 1st-order phase transition was discovered.
- Wilczek (1992) pointed out that the terminal of the 1st-order boundary is a 2nd-order critical point that belongs to the Z(2) universality class.
- Stephanov-Rajagopal-Shuryak (1998) addressed a possibility to find it experimentally.
- QCD critical point search has been one of the most popular subjects in this field since then.

QCD Critical Point

- Nobody knows if it exists or not.
- Nobody has a good argument of why it should exist.
- Even if it exists, to find it experimentally, the nature must be very kind to us.
- So far no hint to the critical point has been found in the beam energy scan (BES) at RHIC.
- More and more theorists are converted to anti-believers of the QCD critical point.

Thermal Statistical Model

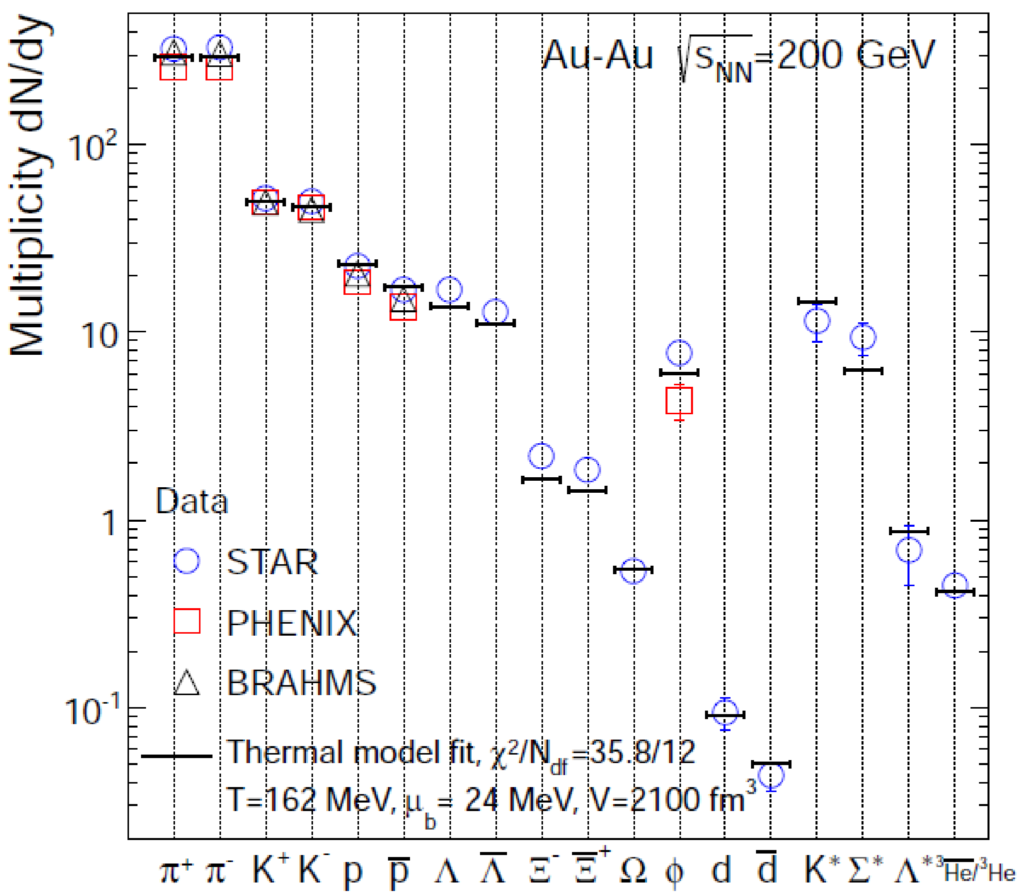
Non-interacting stable and unstable hadrons at temperature ***T***, baryon chemical potential μ_B , strangeness chemical potential μ_s , electric chemical potential μ_Q , where μ_s and μ_Q are constrained by the collision condition.

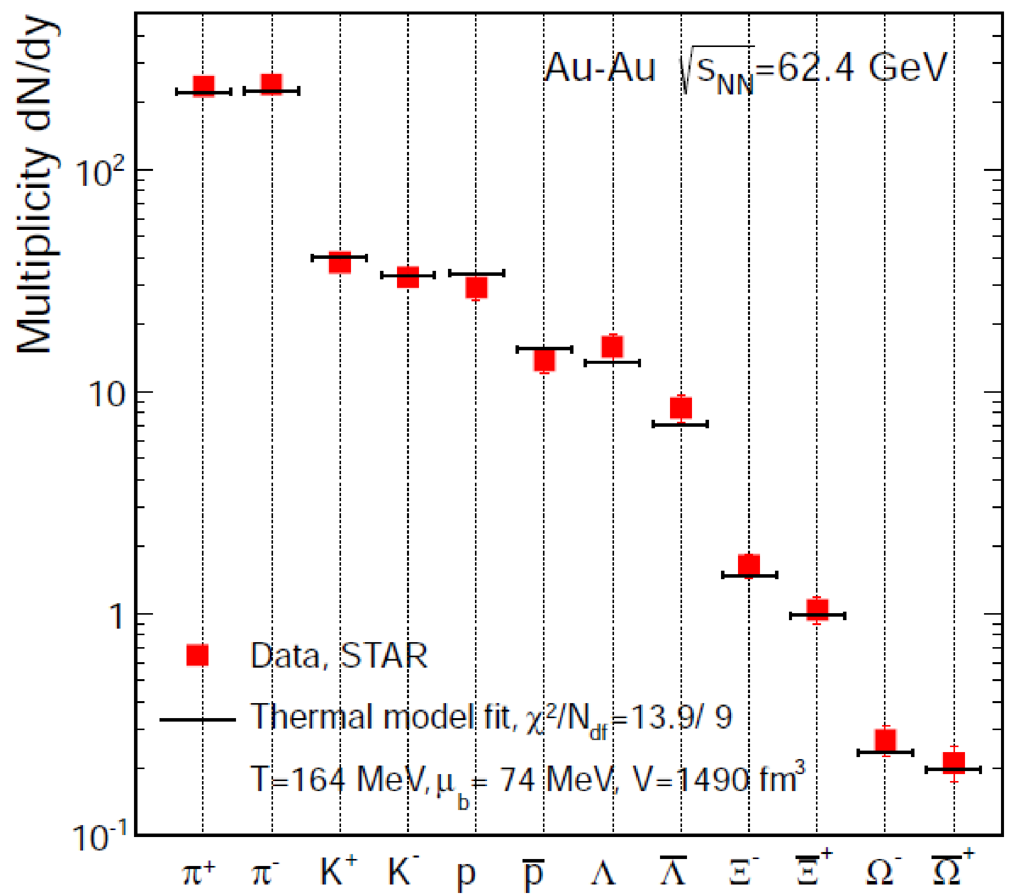


Included mesons (blue) and baryons (red): figure from THERMUS2.0 manual

Successful Fit

Particle yield ratio determined by the thermal weight

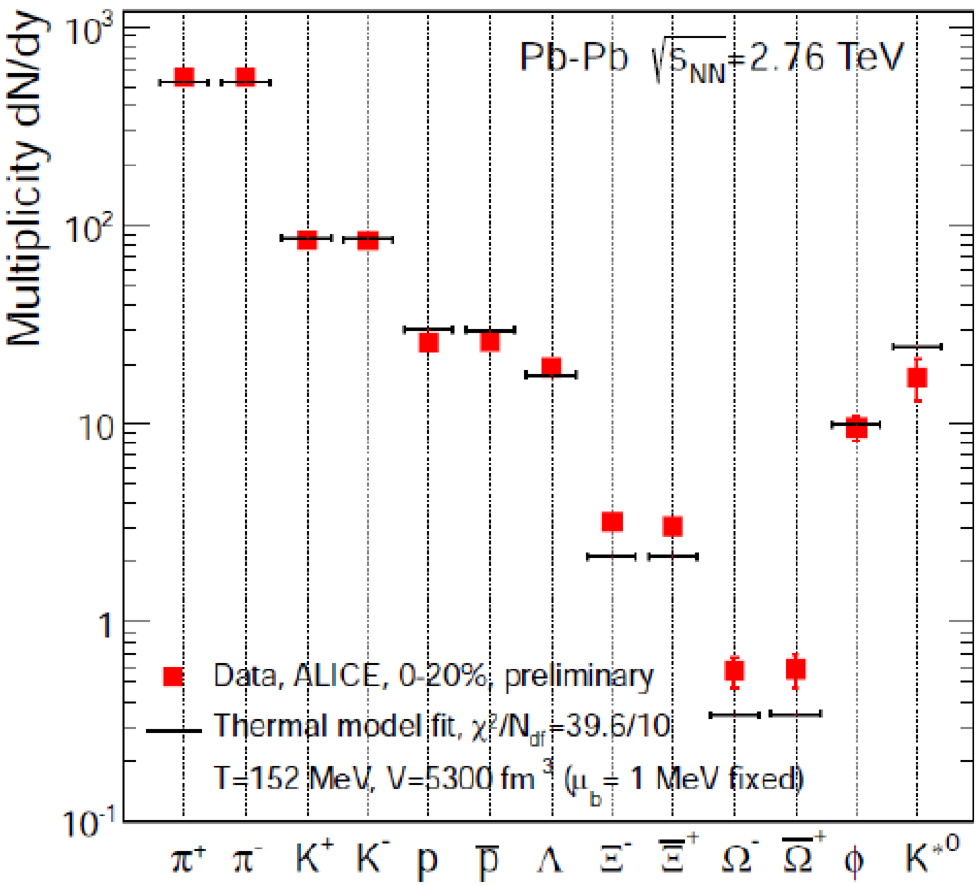


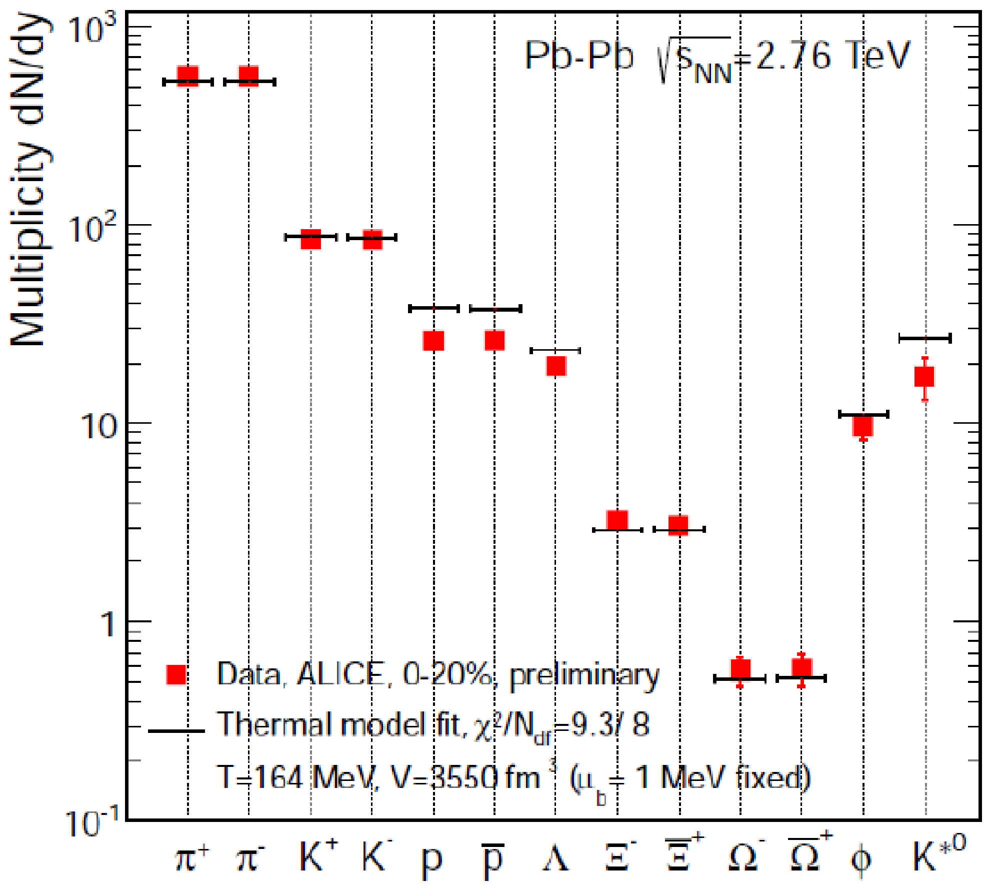


Taken from PBM's slides

Successful Fit

Particle yield ratio determined by the thermal weight

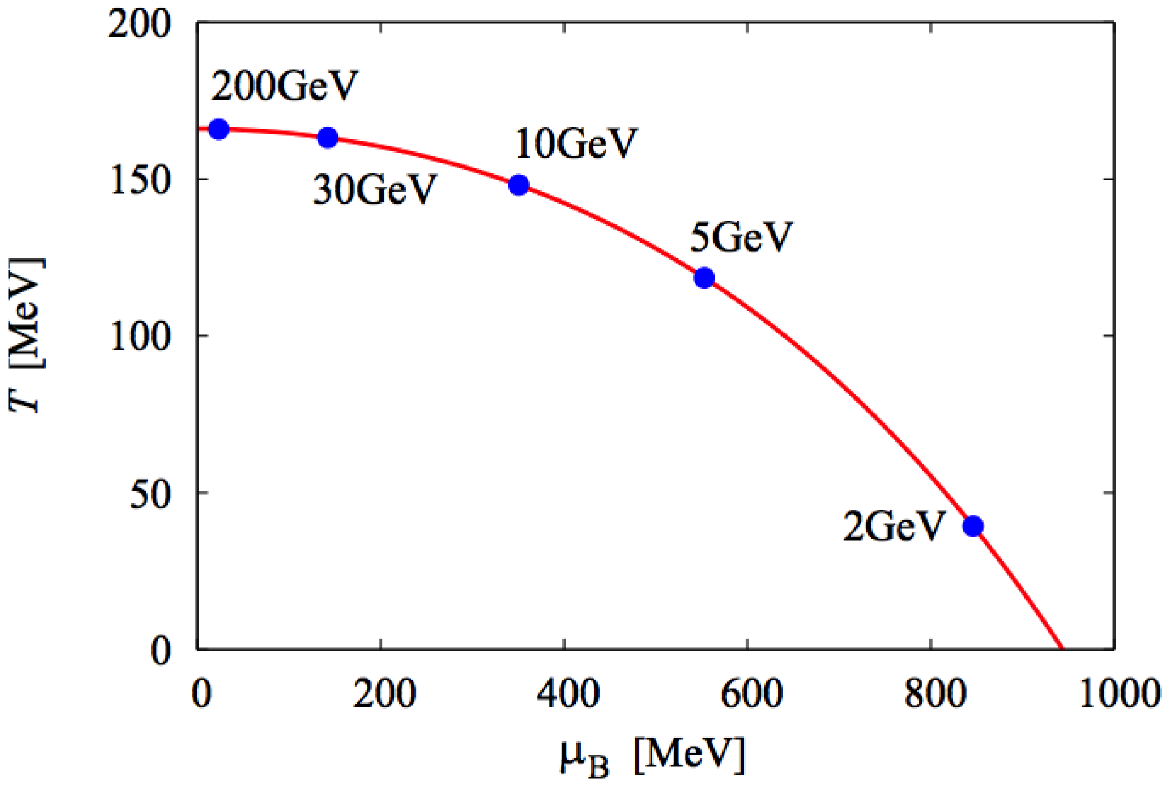




Taken from PBM's slides

Chemical Freeze-out Line

Higher baryon density at lower collision energy



T and μ_B are parametrized as a function of $\sqrt{s_{NN}}$

Cleymans-Oeschler-Redlich-Wheaton (2006)

Fluctuations

Fluctuations generally diverge at critical point of the 2nd-order phase transition

$$\delta N = N - \langle N \rangle$$

$$\sigma^2 = \langle \delta N^2 \rangle$$

$$s\sigma^3 = \langle \delta N^3 \rangle$$

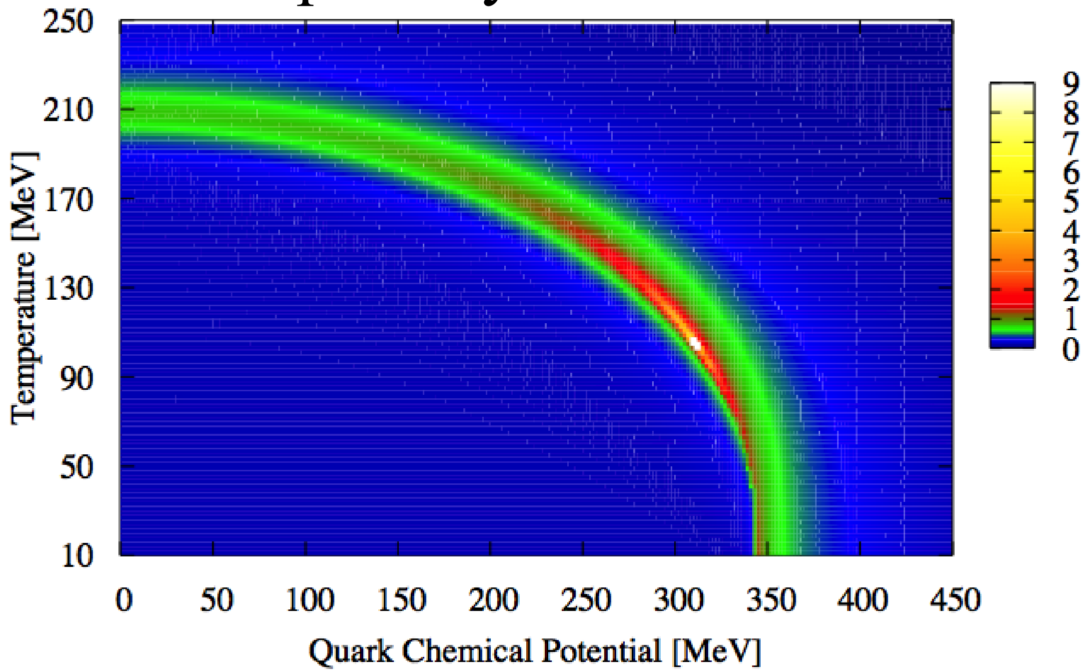
(skewness)

$$\kappa\sigma^4 = \langle \delta N^4 \rangle - 3\sigma^4$$

(kurtosis)

Stephanov (2009)

Susceptibility from a model



Fukushima (2008)

Lattice-QCD and Hadron Resonance Gas

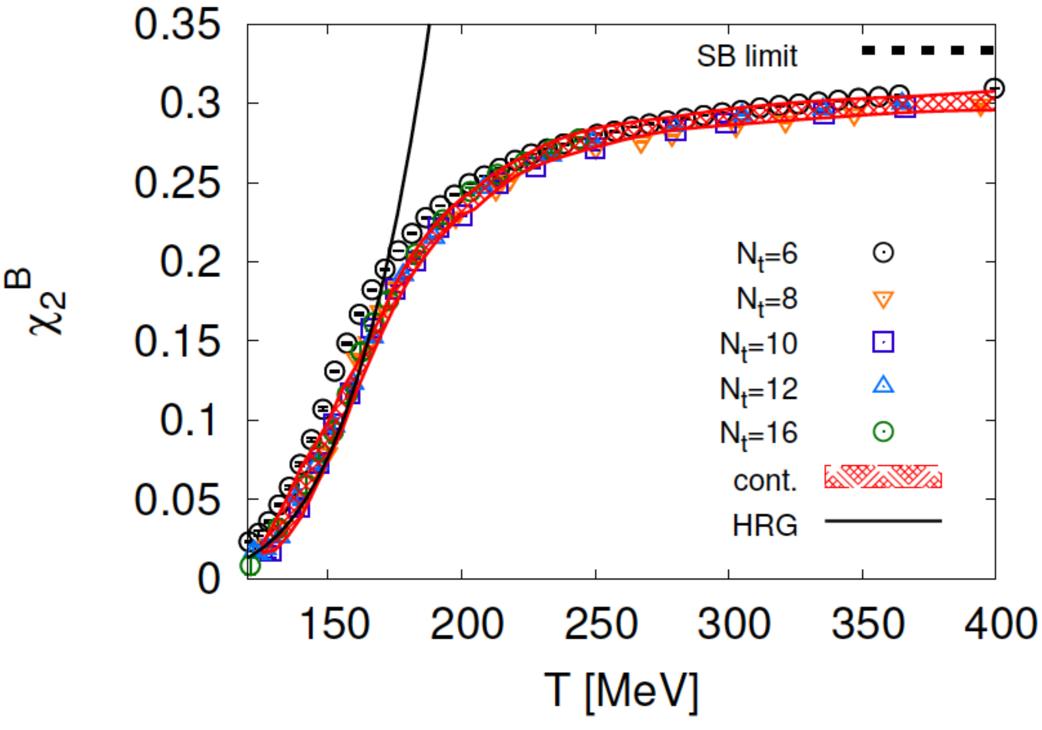
Non-interacting gas of hadron resonance can reproduce the high-*T* lattice-QCD result

Predictions from HRG

$$\kappa\sigma^2 = 1$$

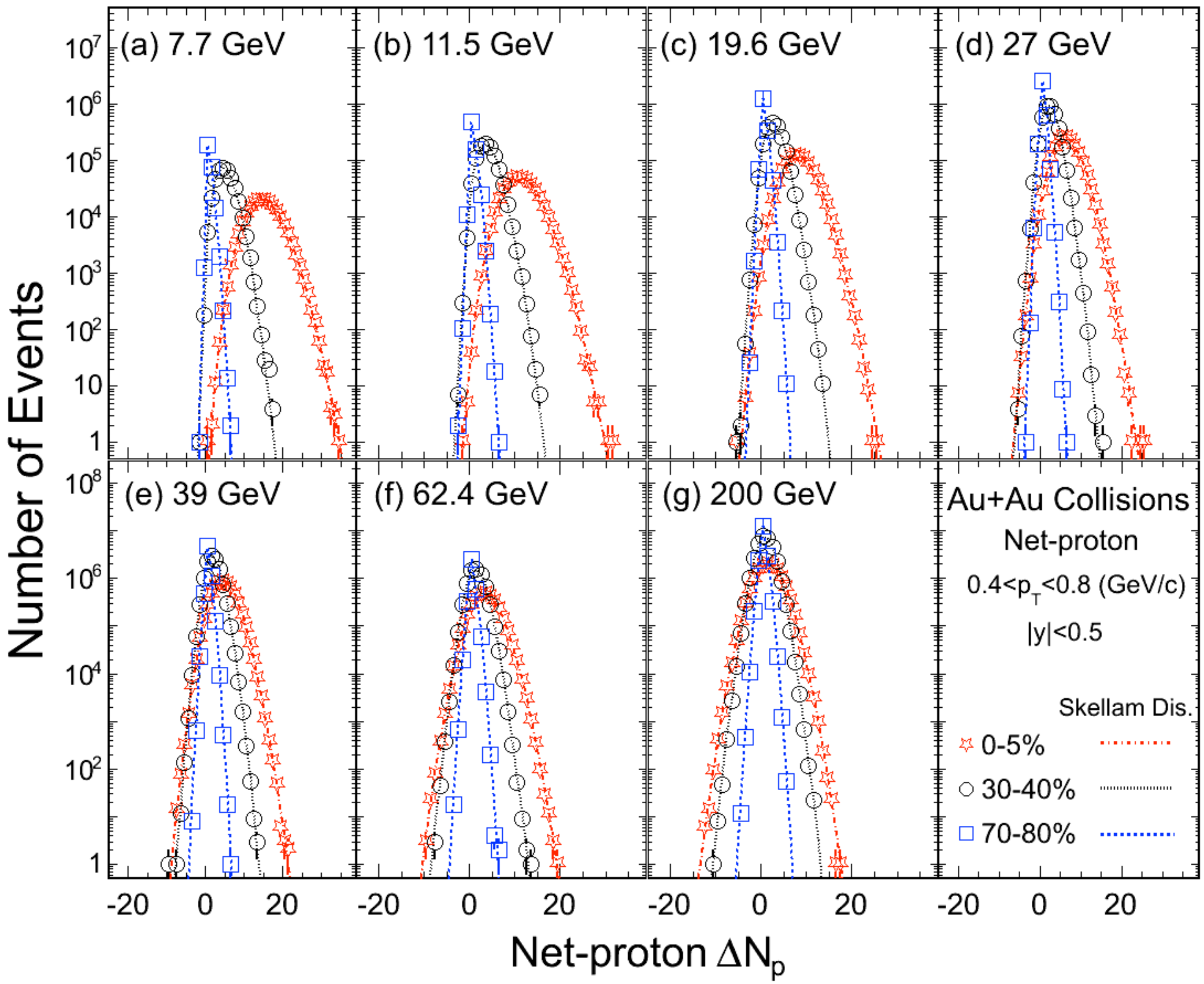
$$s\sigma = \tanh(\mu_B/T)$$

Borsanyi et al. (2012)



Beam Energy Scan

Experimentally observed fluctuations



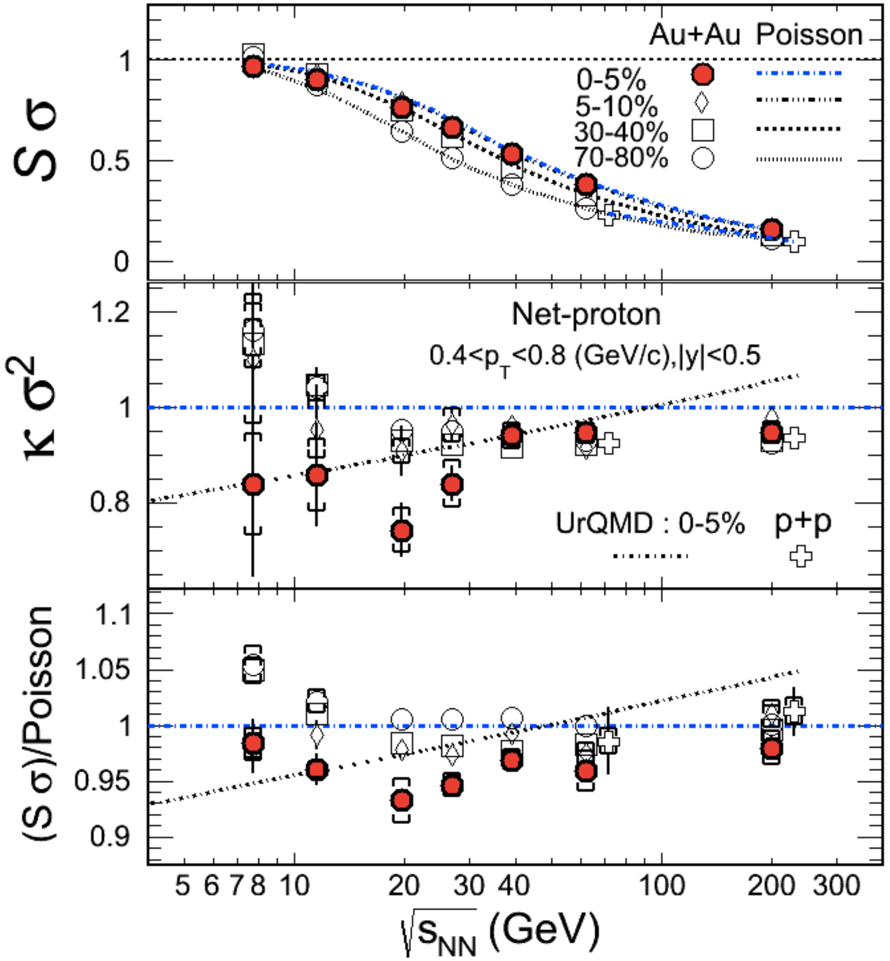
Proton distribution Different from baryon-number

Asakawa-Kitazawa (2011)

Taken from Nu Xu's slides

Results from BES-I

No criticality but some deviations?



No enhancement and no signal for the QCD critical point.

Some deviations from the HRG (Poisson distribution).

Could be explained by UrQMD.

My (biased) Opinion

QCD critical point search is almost hopeless... why?

- Lattice-QCD at high *T* and zero μ_B has confirmed the O(4) scaling law – critical behavior!
- Chemical freeze-out temperature is known to be very close to the QCD phase transition.
- If fluctuations are good signatures, sizable enhancement must have been observed already in the Au-Au collision at 200GeV.

Physics of the 1st-order Transition

Free energy vs the dynamical quark mass (T =0)

$$\Omega[M]/V = -\int_0^{\mu} d\mu' \rho(\mu')$$

Matter part favors M =0
(ρ is then the largest)

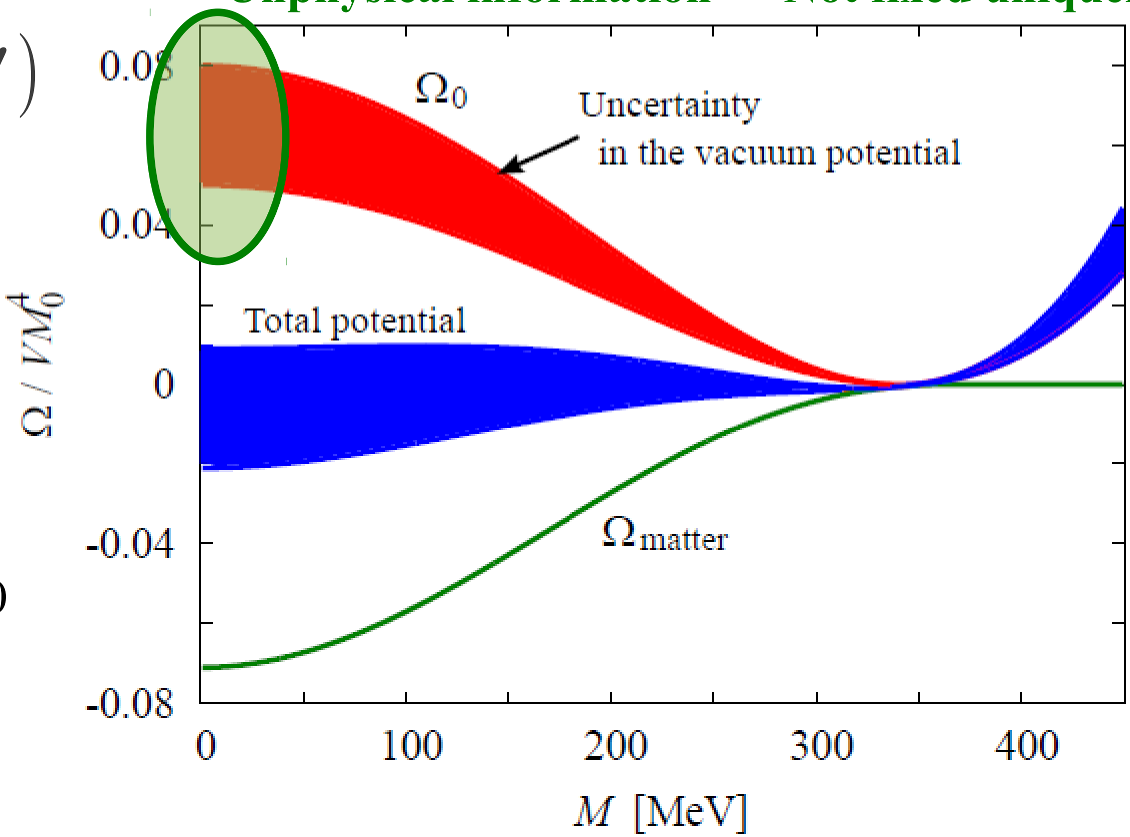
+

Vacuum part favors $M = M_0$

↓

Double-well shape
1st-order phase transition

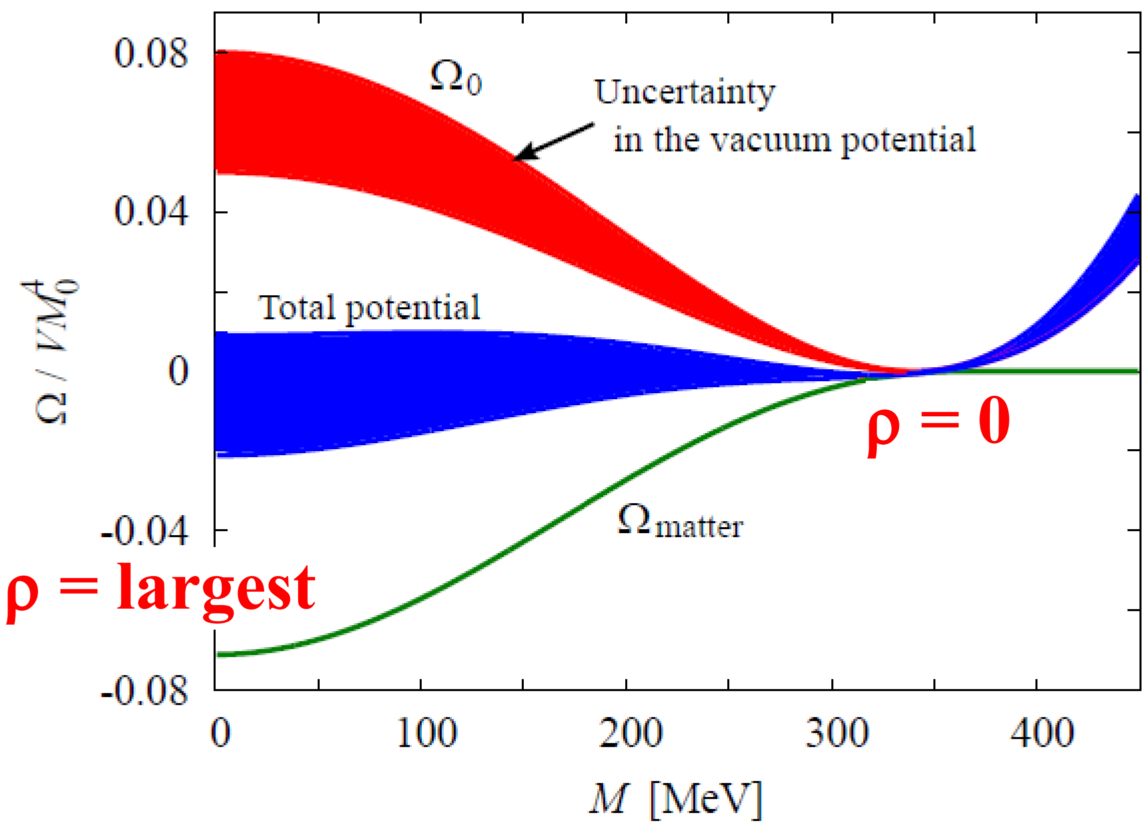
Unphysical information ← Not fixed uniquely



Vector Interaction

Vector interaction in the mean-field approx.

$$L_v = -g_v (\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) \rightarrow \Delta\Omega = g_v \rho^2$$



Pushed up at $M = 0$

With some $g_v > 0$
the double-well shape gone

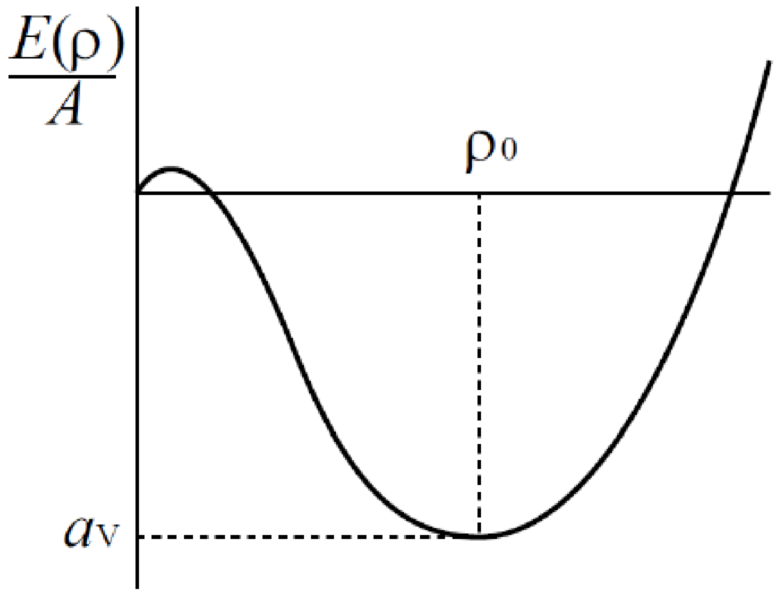
No 1st-order transition and
no critical point

Liquid-gas Phase Transition of Nuclear and Quark Matter

Saturation → Critical Point

Self-bound fermionic system → 1st-order

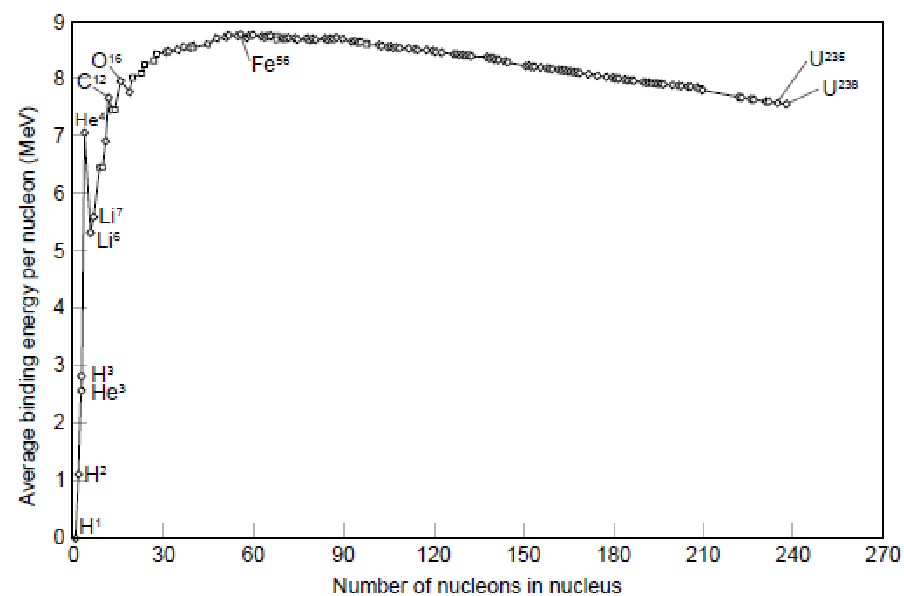
Schematic picture of the (symmetric) nuclear saturation curve



$$\rho_0 = 0.17\,\mathrm{fm}^{-3}$$
$$a_v = 16.3\,\mathrm{MeV}$$

Weizsäcker-Bethe mass formula

$$B = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_{\mathrm{sym}} \frac{(N-Z)^2}{A} + \delta_A$$



Relativistic Mean-field Model

Walecka model

This naturally incorporates
the vector interaction

$$L = \bar{\psi}[i\gamma_\mu \partial^\mu + \underbrace{(\mu_B - g_\omega \omega^0)}_{\mu_B^*}\gamma_0 - \underbrace{(M_N - g_\sigma \sigma)}_{M_N^*}]\psi - \frac{1}{2}m_\sigma^2 \sigma^2 + \frac{1}{2}m_\omega^2 (\omega^0)^2$$

Solve the in-medium chemical potential and the in-medium nucleon mass self-consistently.
Parameters are fixed to reproduce the nuclear matter properties:

$$\left.\frac{\varepsilon}{\rho}\right|_{\rho=\rho_0} - M_N = -16.3\,\mathrm{MeV} \quad , \quad \left.\frac{d(\varepsilon/\rho)}{d\rho}\right|_{\rho=\rho_0} = 0$$

Compressibility needs
the potential terms, etc...

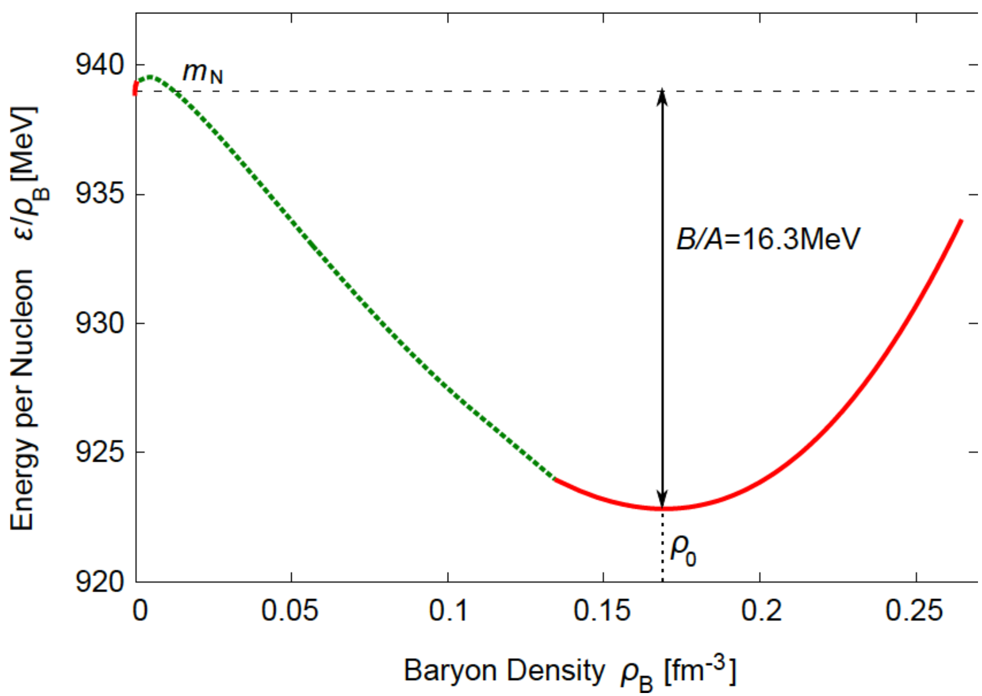
$$M_N = 939\,\mathrm{MeV}, \quad m_\sigma = 550\,\mathrm{MeV}, \quad m_\omega = 783\,\mathrm{MeV}, \quad g_s = 10.3, \quad g_\omega = 12.7$$

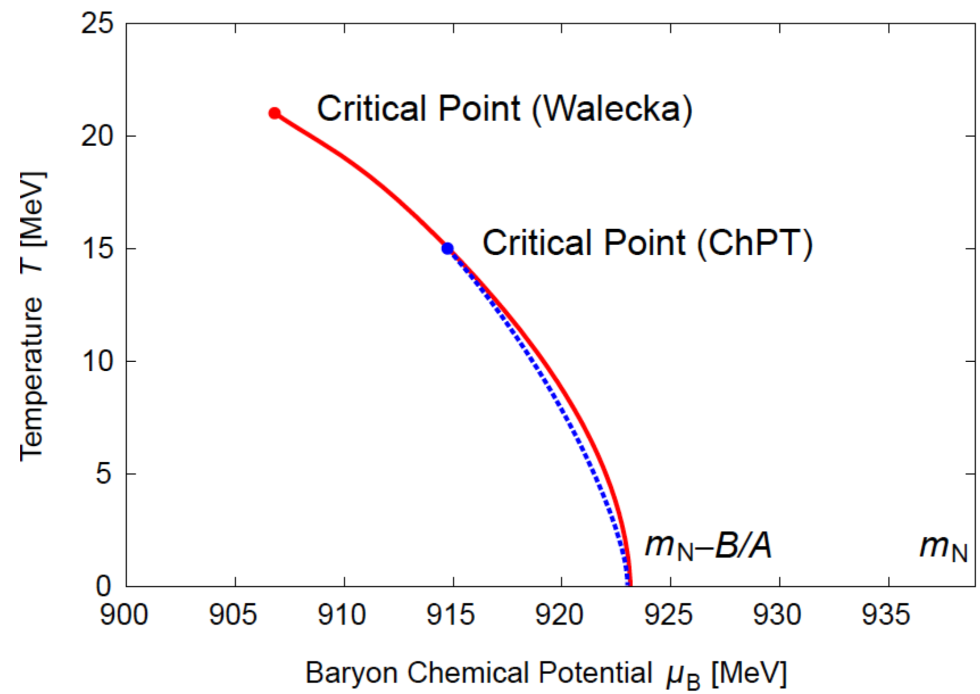
Buballa (1996)

Mean-field Solution

1st-order Phase Transition

Fukushima-Sasaki (2013)





At the saturation point

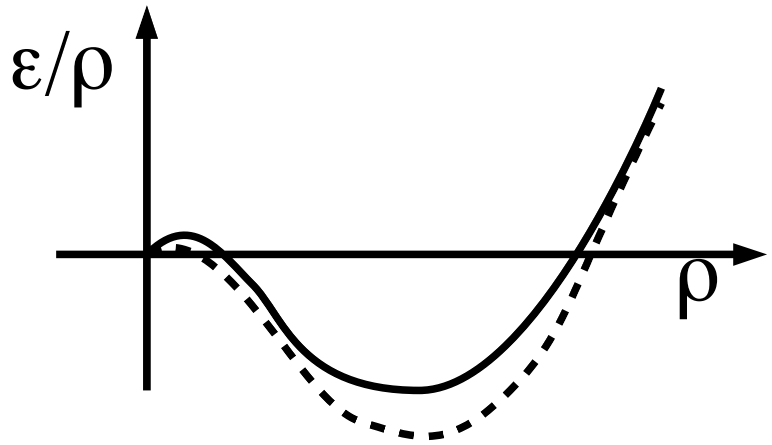
$$\frac{d(\varepsilon/\rho)}{d\rho} = \frac{\mu_B}{\rho} - \frac{\varepsilon}{\rho^2} = \frac{p}{\rho^2} = 0$$

Condition for the 1st-order phase transition:

Liquid-gas transition

Quark Matter

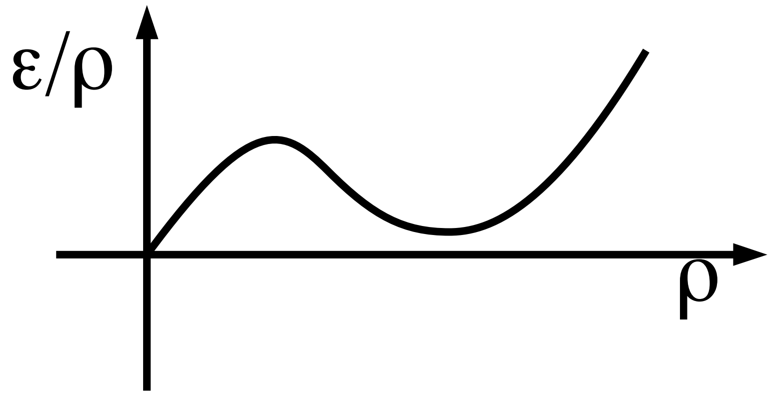
Is it a self-bound system? → Quark droplet?



1st-order phase transition
→ QCD critical point

Any more stable state would exhibit the 1st-order one too.

Even when the quark droplet is only meta-stable

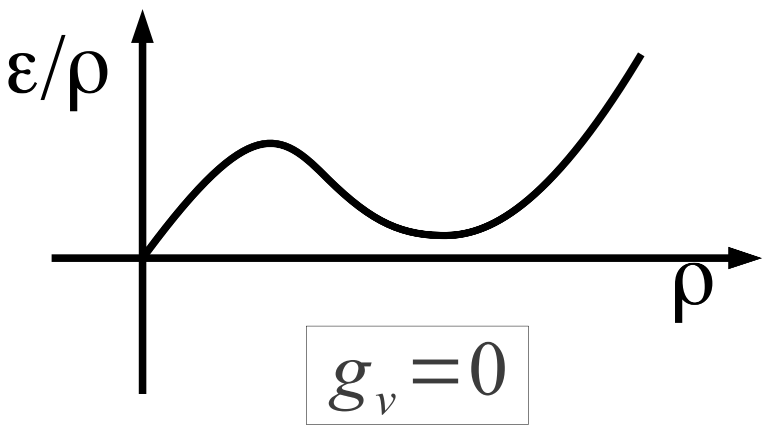


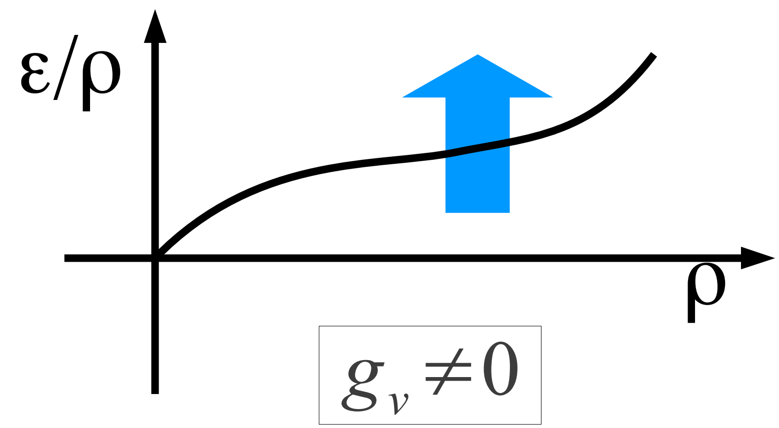
$$\frac{d\,(\varepsilon/\rho)}{d\,\rho} = \frac{\mu_B}{\rho} - \frac{\varepsilon}{\rho^2} = \frac{p}{\rho^2} = 0$$

1st-order phase transition
→ QCD critical point

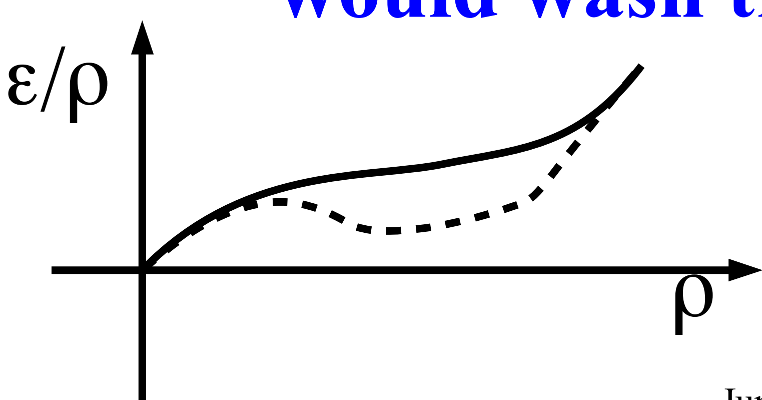
Vector Interaction Again

$$L_v = -g_v(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) \rightarrow \Delta\Omega = g_v\rho^2$$





It is obvious at a glance that the vector interaction would wash the 1st-order transition out.



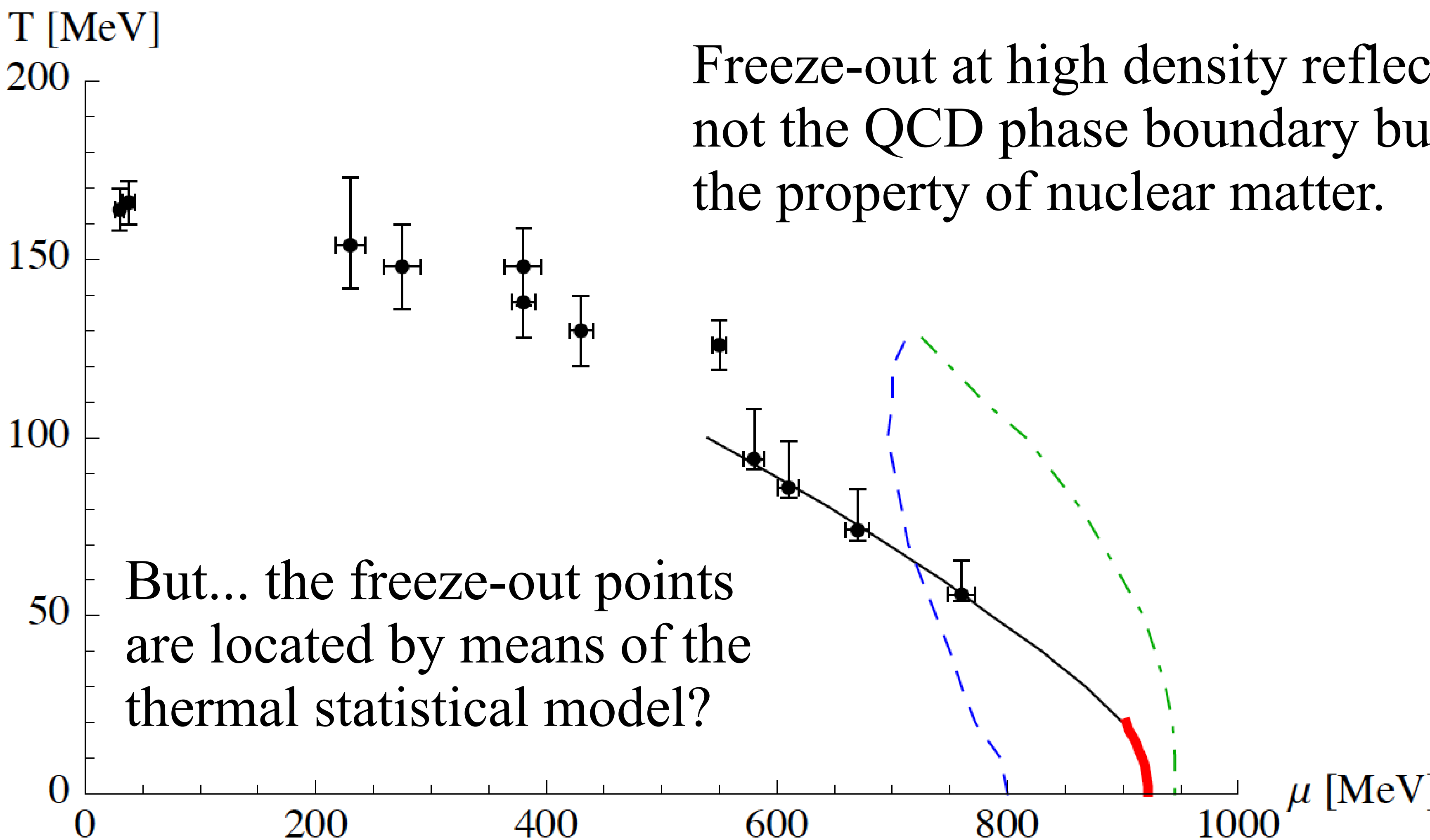
Is there any chance to find another branch of solution?

Messages

- Theorists have misunderstood physics of the QCD critical point for many years.
- True order parameter is not the chiral condensate but the density $\rightarrow$ liquid-gas phase transition!
- Fujii (2003) pointed it out first and Son-Stephanov (2004) confirmed this.
- No clear difference between the QCD critical point and the critical point of nuclear matter.

Possibility

Floerchinger-Wetterich (2012)



Freeze-out at high density reflects not the QCD phase boundary but the property of nuclear matter.

But... the freeze-out points are located by means of the thermal statistical model?

In-medium Chiral Symmetry

Comments on Chiral Symmetry

- Theoretical speaking, the chiral phase transition is much more well-defined than deconfinement. Lattice-QCD people would say that the QCD phase transition is only chiral and deconfinement is not really relevant (← not totally correct, though).

- Experimentally speaking, however, chiral symmetry restoration has never been observed in the heavy-ion collision experiments. Di-lepton (vector meson)?

- Nobody knows how baryon mass should behave when chiral symmetry gets restored.

Comments on Chiral Symmetry

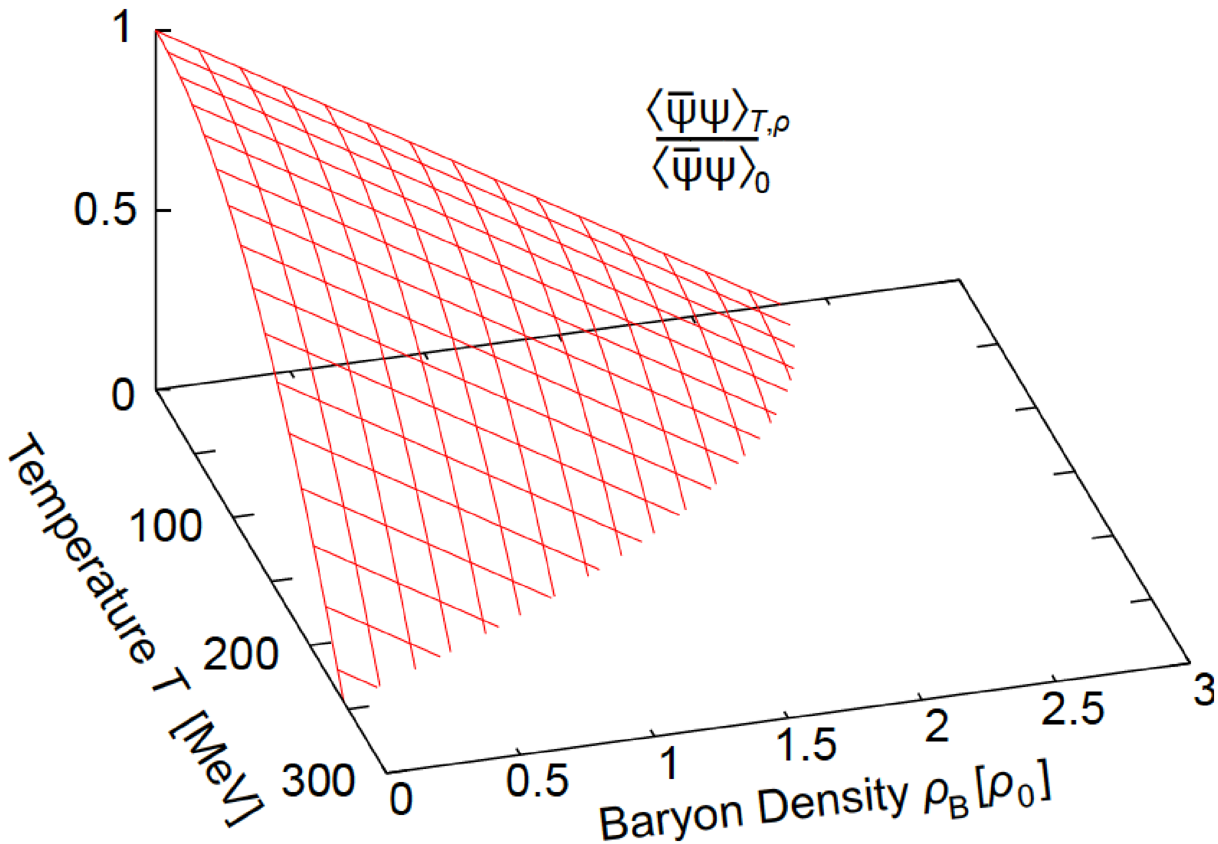
- Success of the thermal statistical model seems to suggest that chiral symmetry restoration plays no role to understand the experimental data?

- Lattice-QCD results are more puzzling – they are consistent with the hadron resonance gas model, and at the same time, they show the critical behavior!

  (Scaling part of the free energy is only a minor contribution to the whole energy.)

Chiral Condensate

Lowest-order prediction from the ChPT



Fukushima-Sasaki (2013)

Along the T-direction, the curvature is determined with f_π only (Low-energy theorem)

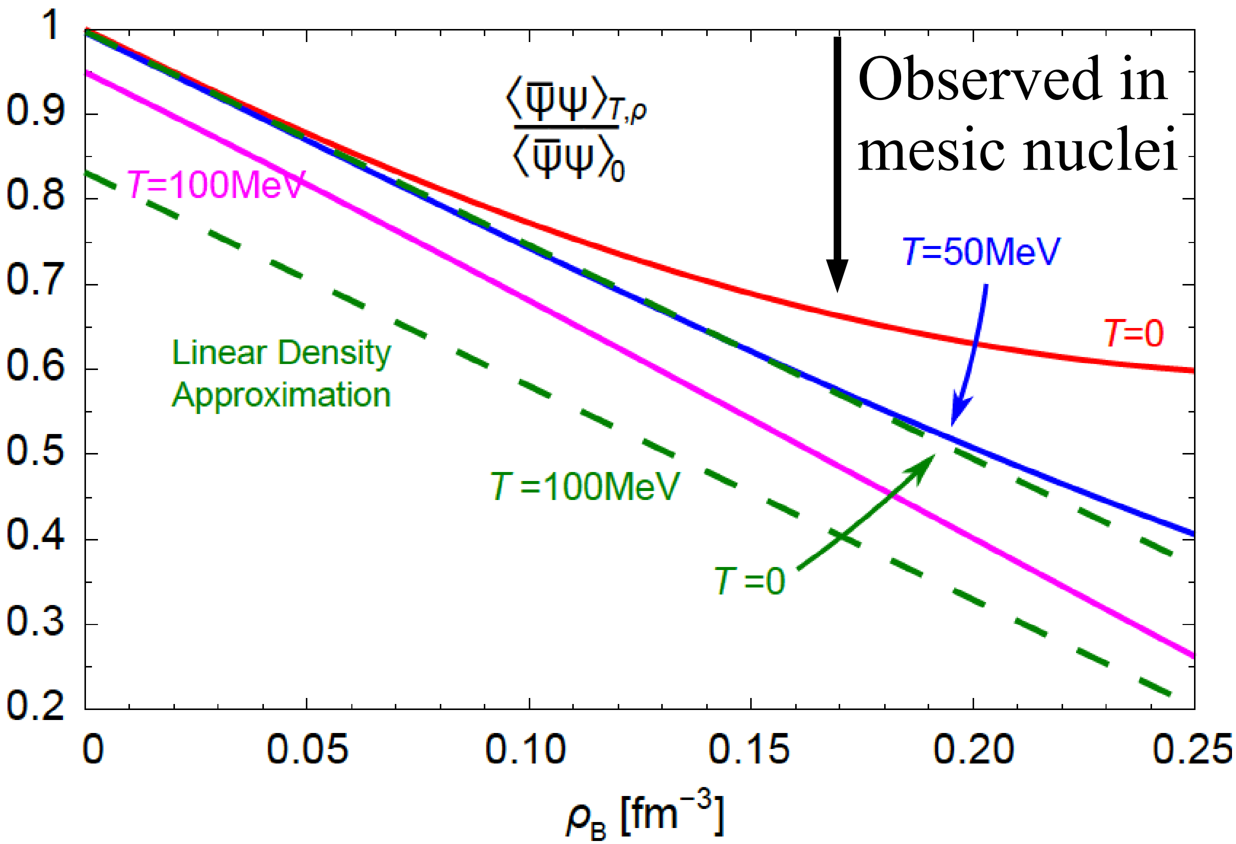
Along the ρ_B-direction, the slope is determined with f_π and the nuclear σ term;

$$\sigma_{\pi N} = m_q \frac{m_N}{m_q} \simeq 45 \text{ MeV}$$

Chiral Condensate

Three-loop ChPT

adapted from **Fiorilla-Kaiser-Weise (2012)**



No sign of chiral sym. restoration at T=0.

Linear density approx. may work at T~50MeV.

Chiral symmetry may well be half restored at normal nuclear density and T=100MeV (reachable with the energy ~ 5GeV)

Baryon Mass

- Chiral symmetry breaking → Baryon mass

Nambu-Jona-Lasinio (1961)

- Quarks are massless if chiral symmetry is exact. What about baryons?
- Baryons ~ quarks (standard assignment) → Low-lying baryons should become massless
- Baryon mass can be given in a way consistent with chiral symmetry (mirror assignment) **DeTar-Kunihiro (1989)** Baryons can remain massive at very high density.

Diquarks and Exotic Hadrons

Diquark and Nucleon

Nucleon = Diquark + Quark **Ishii-Bentz-Yazaki 1995**

$$\text{quark} + \text{quark} = \mathbf{3} + \mathbf{3} = \bar{\mathbf{3}} + \mathbf{6}$$

scalar diquark

$$\text{quark} + \text{diquark} = \mathbf{3} + \bar{\mathbf{3}} = \mathbf{1} + \mathbf{8}$$

nucleon

Color anti-symmetric + Spin anti-symmetric
→ Flavor anti-symmetric (singlet) $[ud]_0$

This diquark is a diquark that forms a condensate in color superconductivity at very high density. Diquark correlation is strengthened at higher densities.

Lattice-QCD

MEM analysis of the diquark spectral functions

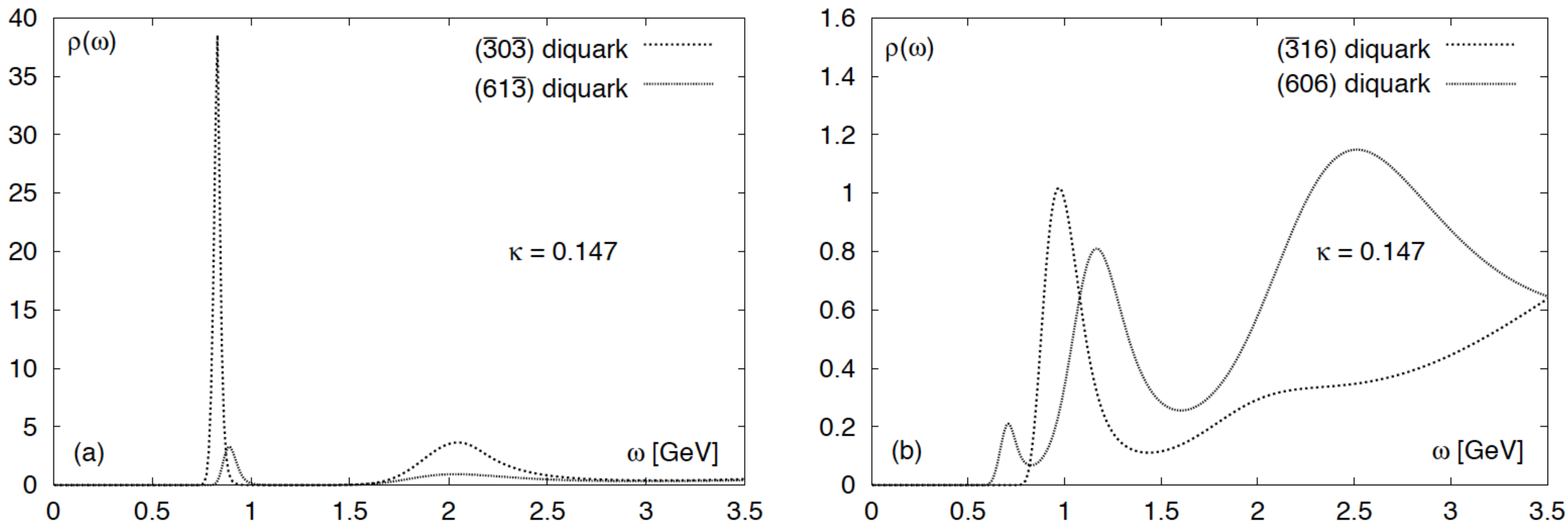


Figure 2: Spectral functions for color anti-triplet (a) and sextet diquark states (b).

Wetzorke-Karsch (2000)

Jaffe-Wilczek Model

$\Theta^+ = [ud]_0 + [ud]_0 + \bar{s}$ L=1 for two diquarks

$$M_\Theta \simeq 2 \times 420([ud]_0) + 560(\bar{s}) + 450(L=1) = 1850\,\mathrm{MeV}$$

Jaffe-Wilczek (2003)

Jaffe (1977) had considered $qq\bar{q}\bar{q}$ picture for the nonet of scalar mesons where a_0(980) is the heaviest even though it contains no strange quark.
Wilczek extended this picture with a student Selem.

Diquarks and Heavy Quarks

Extension of the constituent quark model with magnetic (spin) interaction including diquarks

Lee-Yasui (2008)

Table 4. The binding energy $B_{T^1_{cc(bb,cb)}} = m_{T^1_{cc(bb,cb)}} - m_M - m_{M^*}$ of $T^1_{cc(bb,cb)}$ against decay to pseudoscalar and vector mesons, M and M^*, as shown below. The unit is in MeV. The tetraquarks can be stable for $B_{T^1_{cc(bb,cb)}} < 0$.

T^1_{cc}	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
	-79.3	-8.7	-8.7
	$\bar{D}^0 + D^{*-}$, $\bar{D}^{*0} + D^-$	$\bar{D}^0 + D_s^{*-}$	$D^- + D_s^{*-}$
T^1_{bb}	$udbb$	$usbb$	$dsbb$
	-124.3	-62.3	-62.3
	$B^+ + B^{*0}$, $B^{*+} + B^0$	$B^+ + B_s^{*0}$	$B^0 + B_s^{*0}$
T^1_{cb}	$ud\bar{c}b$	$us\bar{c}b$	$ds\bar{c}b$
	-59.0	+2.9	+2.9
	$B^{*+} + D^-$, $B^{*0} + \bar{D}^0$	$B_s^{*0} + D^0$	$B_s^{*0} + D^-$

Table 5. The binding energy of pentaquarks $B_{\Theta_{qs}} = m_{\Theta_{s\bar{q}}} - m_M - m_B$ ($B_{\Theta_{qss}} = m_{\Theta_{qss}} - m_M - m_B$) of $\Theta_{qs}(ud\,us\,\bar{q})$ ($\Theta_{qss}(us\,ds\,\bar{q})$) for $q = u$, s, c and b, respectively, against decays to meson M and baryon B states. The unit is in MeV. The pentaquarks can be stable for $B_{\Theta_{qs}(\Theta_{qss})} < 0$.

Θ	$M+B$	$\bar{u}$	$\bar{s}$	$\bar{c}$	b
$ud\,us\,\bar{q}$	$ud\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
$us\,ds\,\bar{q}$	$ds\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
	$ud\,s+s\bar{q}$	256.8	142.5	28.4	-10.7

RHIC can be an exotica factory
Detect through quark number scaling

Speculation at High Baryon Density

- Diquark correlation must be enhanced at higher baryon density $\rightarrow$ eventually color-superconductor
- Exotic hadrons composed from diquarks should be more and more favored at higher density. *Penta-quarks, tetra-quarks, H-dibaryon*
- Color-flavor locked (CFL) state is a state with H-dibaryon condensate and collective excitations (mesons) are all four-quark (two-diquark) states.
- Nuclear matter may be smoothly connected to CFL!

Schaefer-Wilczek (1998)

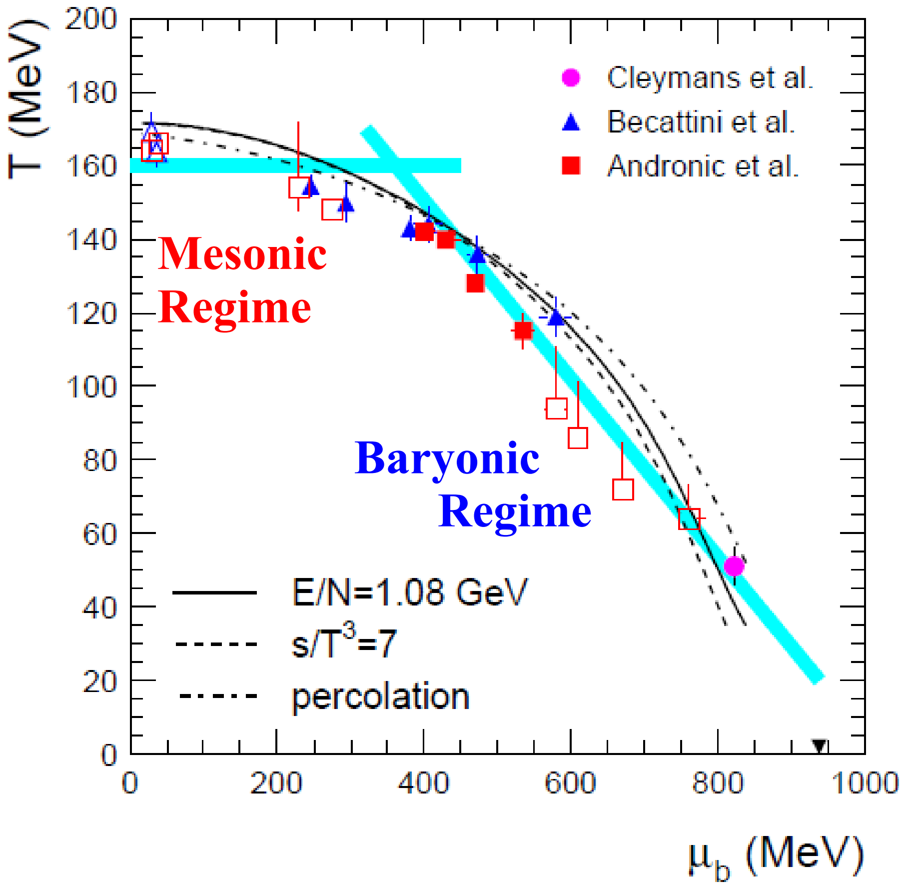
Deconfinement and Hadron Resonances

Color Deconfinement

- Deconfinement at high T is well investigated in the lattice-QCD simulation, but the underlying physics is not fully understood.
- It is said that there is no phase transition of deconfinement but only a smooth crossover. If so, quarks are deconfined at any T (though suppressed)?
- Deconfinement is not necessary to understand the rapid increase in physical degrees of freedom.
- Deconfinement may not happen at high density...

Interpretation of Statistical Model

Freeze-out curve interpreted as the Hagedorn transition



Andronic-Blaschke-Braun-Munzinger-Cleymans-KF -McLerran-Oeschler-Pisarski-Redlich-Sasaki (2010)

Mesonic Hagedorn Transition

$$Z \sim \int dm\, \rho(m)\, e^{-m/T}$$

$$\rho(m) \sim e^{m/T_H}$$

$$T_c = T_H$$

Baryonic Hagedorn Transition

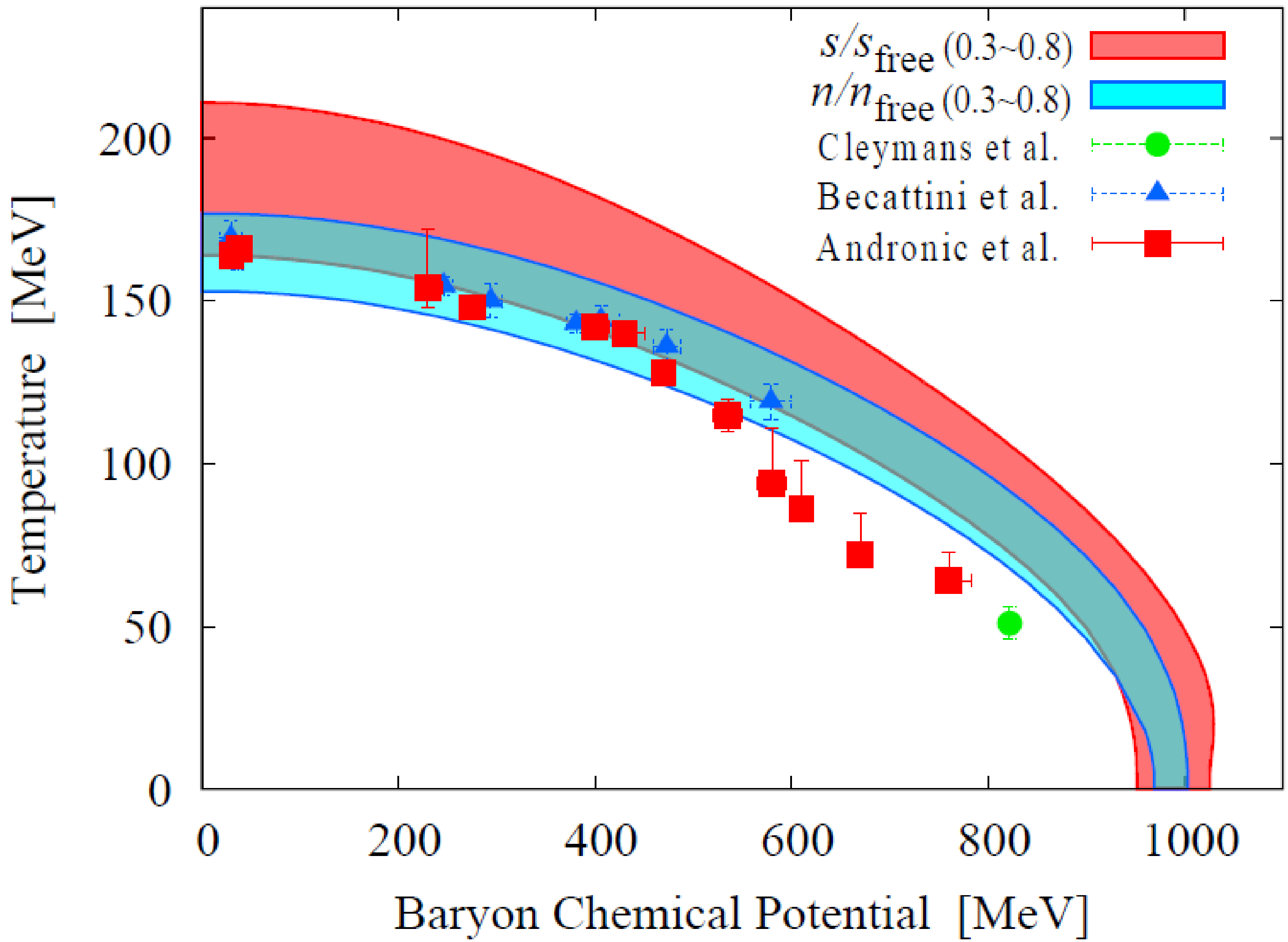
$$Z \sim \int dm\, \rho_B(m)\, e^{-(m_B - \mu_B)/T}$$

$$\rho(m) \sim e^{m_B/T_B}$$

$$T_c = (1 - \mu_B/m_B)\, T_B$$

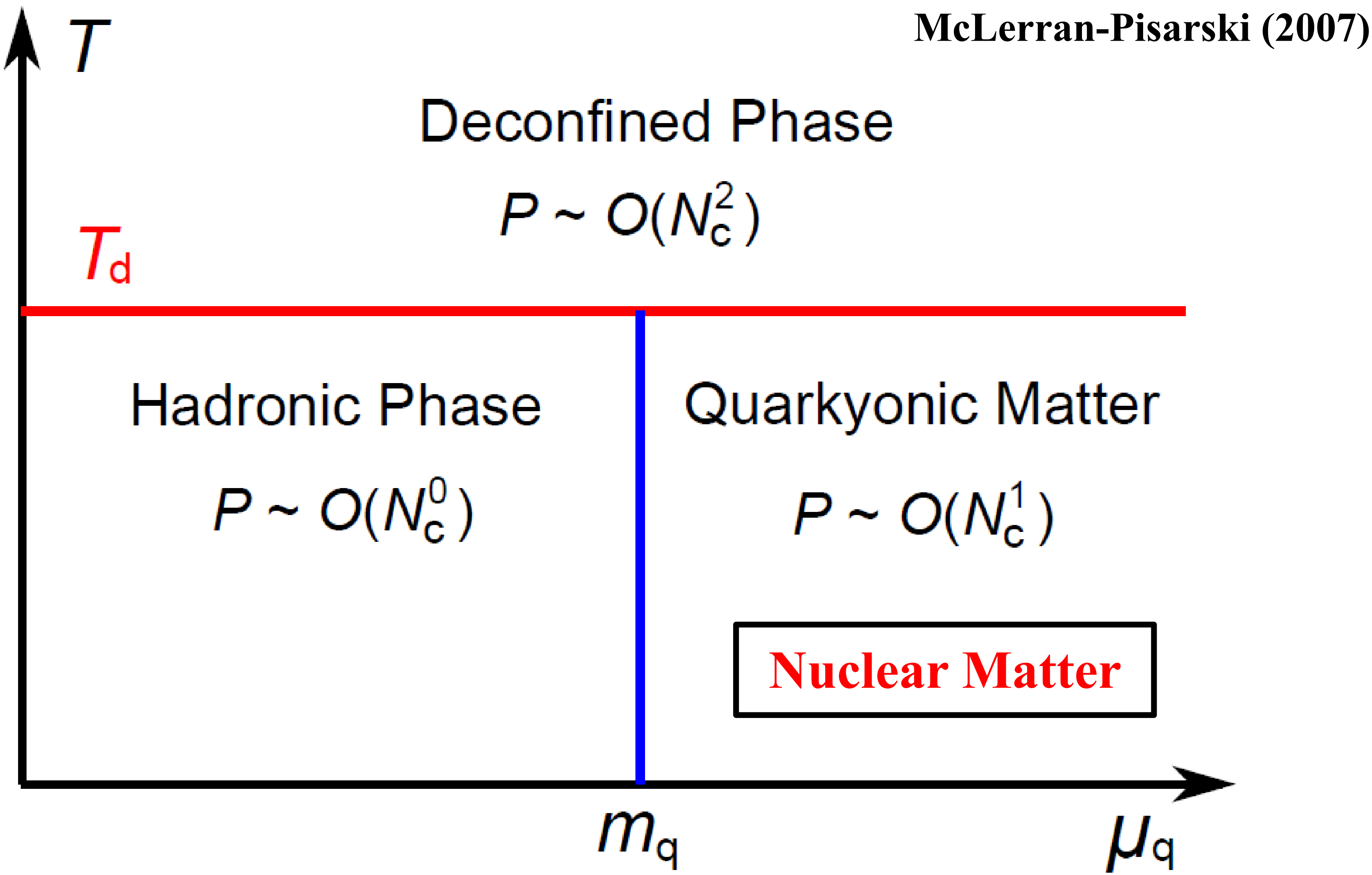
Hadrons Overshoot QGP

Thermodynamics from the Statistical Model



Fukushima (2010)

Deconfinement at Large N_c

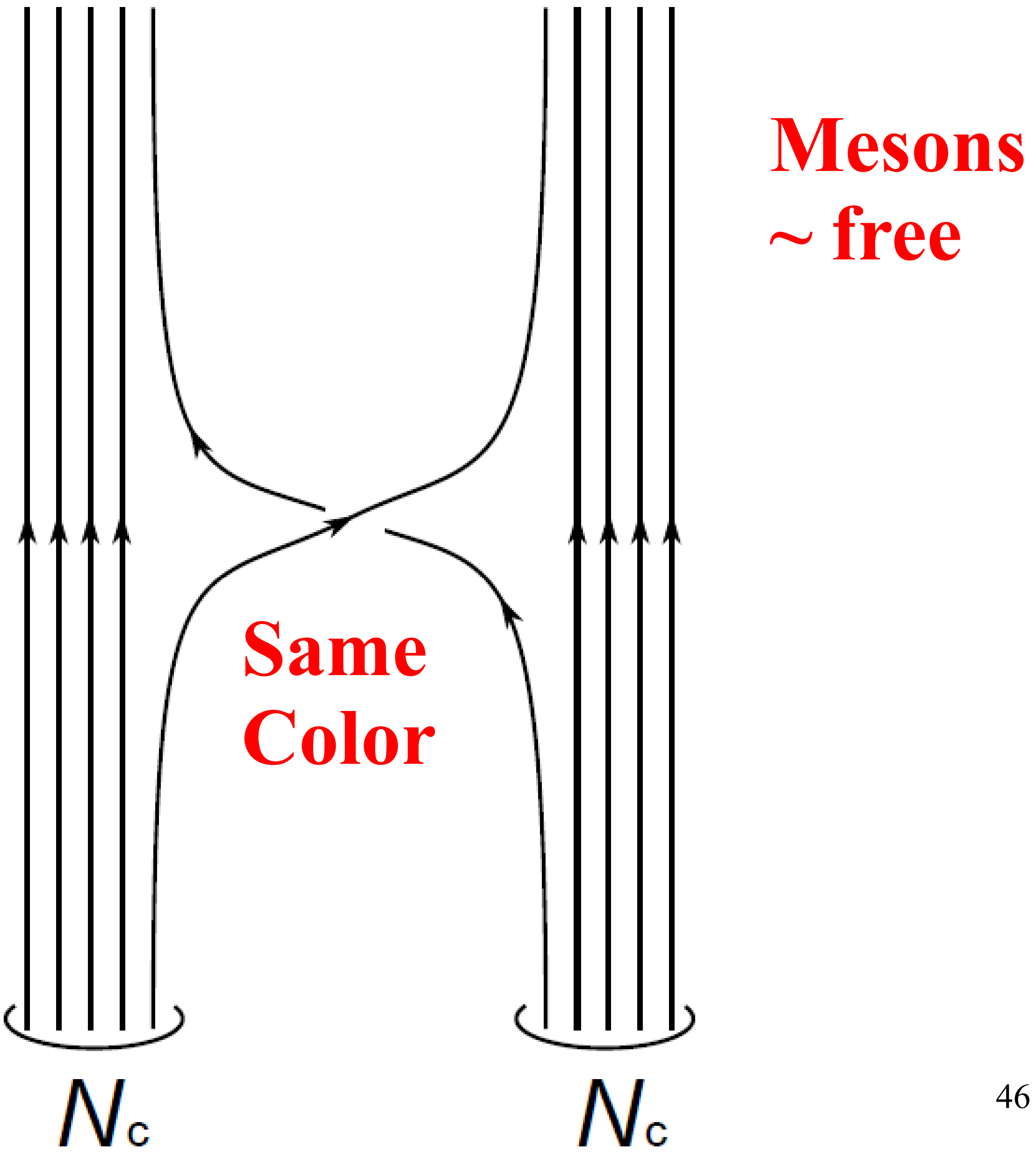


Strong Baryon Interactions

One-meson exchange

$$\sim O\left(N_c\right)$$

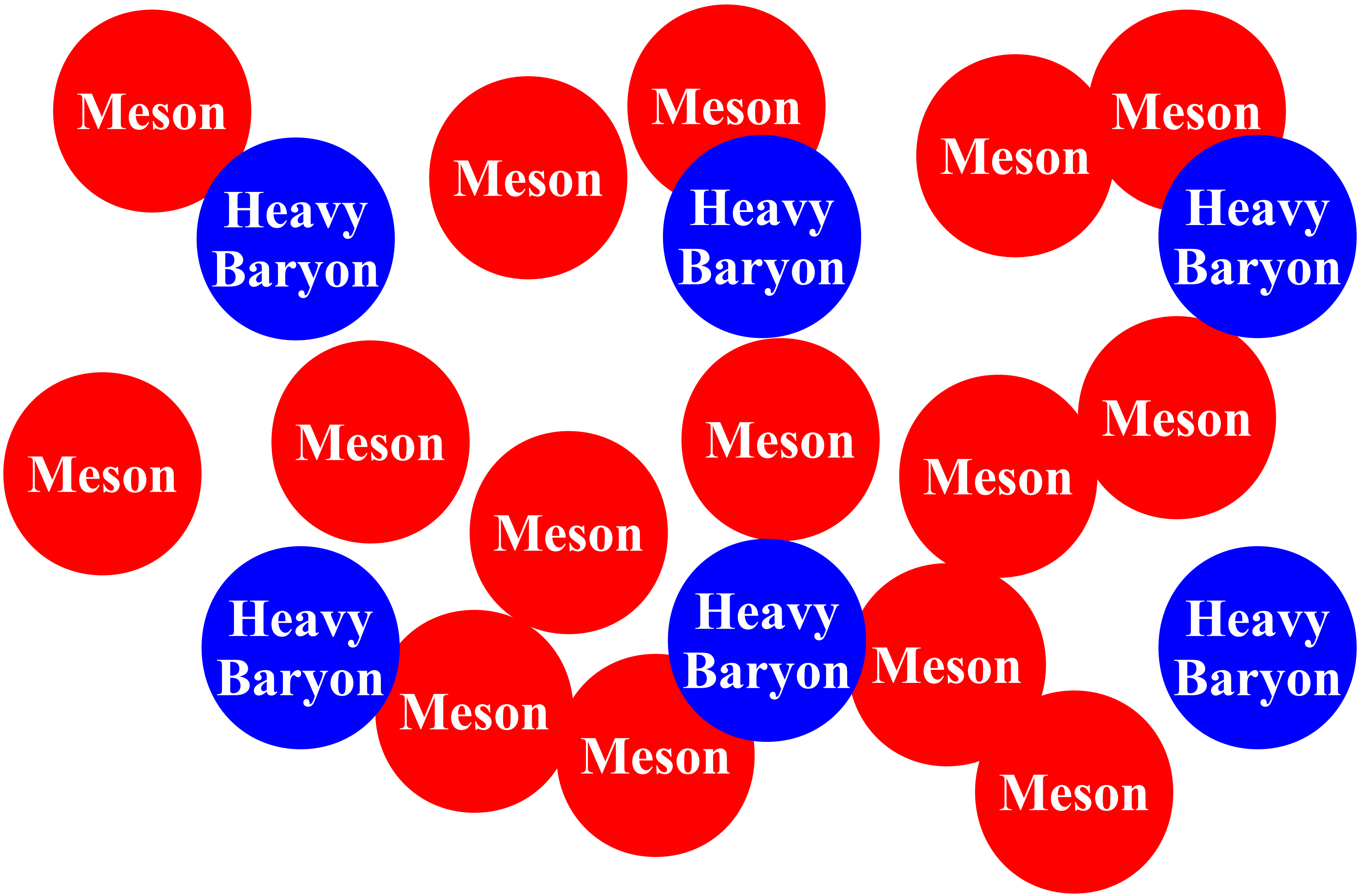
Also diagrams involving gluons to make the same color exchanges



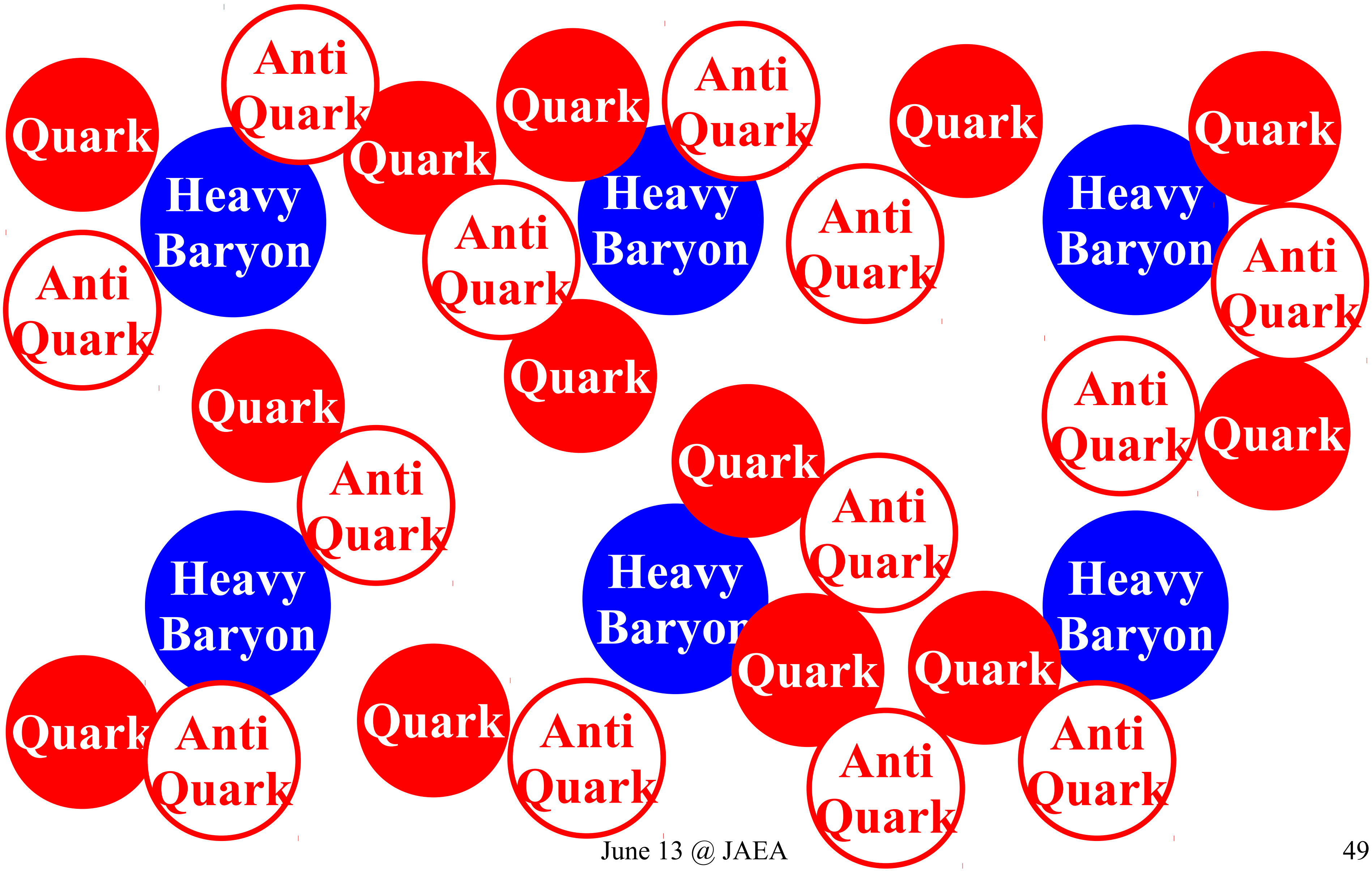
Dense Nuclear Matter

Skyrme-Crystal

Dense Nuclear Matter



Quarkyonic Matter



How Quarks Emerge?

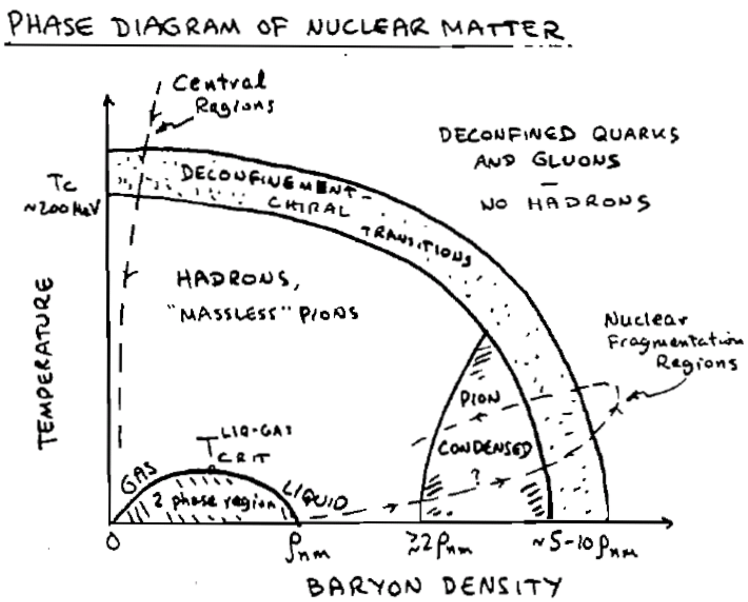
- At high T and low μ_B many non-interacting meson resonances will become indistinguishable from quarks (and gluons).
- At high μ_B and low T exchanged particles of strong interactions of many baryons will become indistinguishable from quarks.
- Existence of quarks cannot be clearly probed even in the deconfined phase because of confinement.

Theoretical Possibility

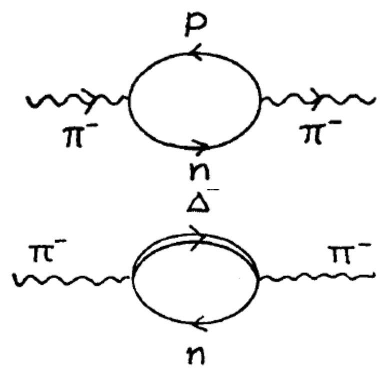
- It is known that deconfinement should be even smoother crossover at higher density (center symmetry is more broken).
- It has been confirmed that chiral symmetry is partially restored at normal nuclear density.
- Why not partial deconfinement in nuclear matter?
- Problem is that there is no well-defined measure (even in theory!) for deconfinement. Signature?

Inhomogeneous Phases

P-wave Pion Condensation



Sawyer-Scalapino, Migdal (1972)

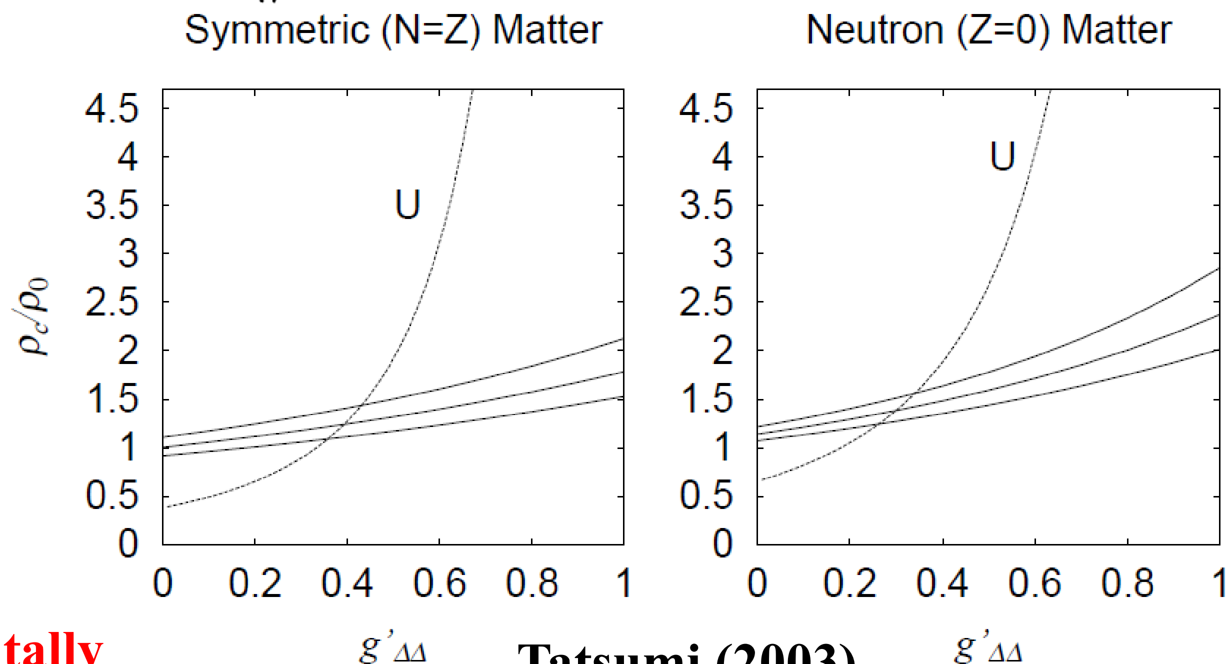


+ short-range int.

Landau-Migdal parameters

$$f + g\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + f'\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 + g'(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)$$

$$g'_{NN},\quad g'_{N\Delta},\quad g'_{\Delta\Delta}$$



Not well-constrained experimentally

Tatsumi (2003)

Analogue in Quark Matter

Chiral spiral in one direction

Deryagin-Grigoriev-Rubakov (1992)

$$\psi(x)=e^{i\gamma_5\tau_3 q z}\psi'(x) \quad \text{with} \quad \chi=\langle\bar{\psi}'\psi'\rangle$$

$$\Rightarrow \quad \langle\bar{\psi}\psi\rangle=\chi\cos(2qz)$$
$$\langle\bar{\psi}\gamma_5\tau_3\psi\rangle=\chi\sin(2qz)$$

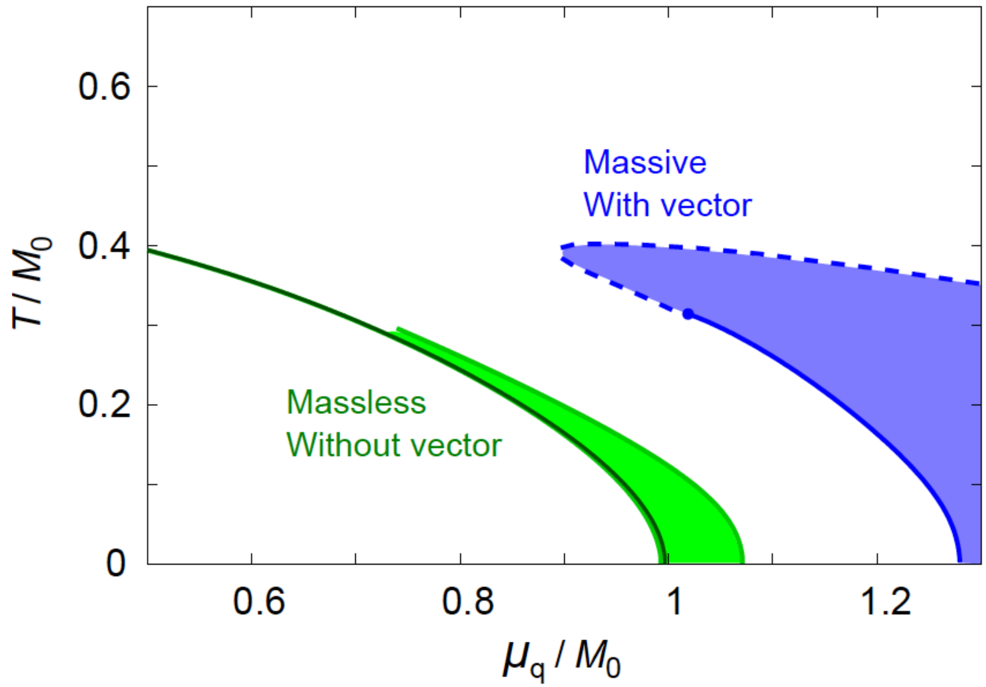
Nakano-Tatsumi (2004)

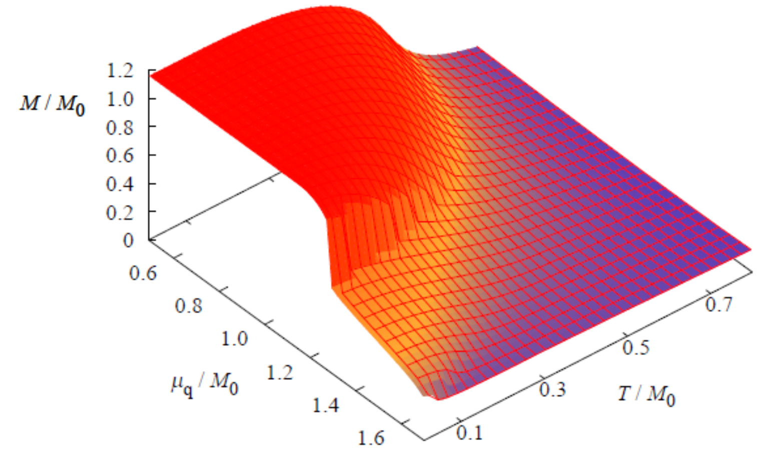
Quasi-particle dispersion relation

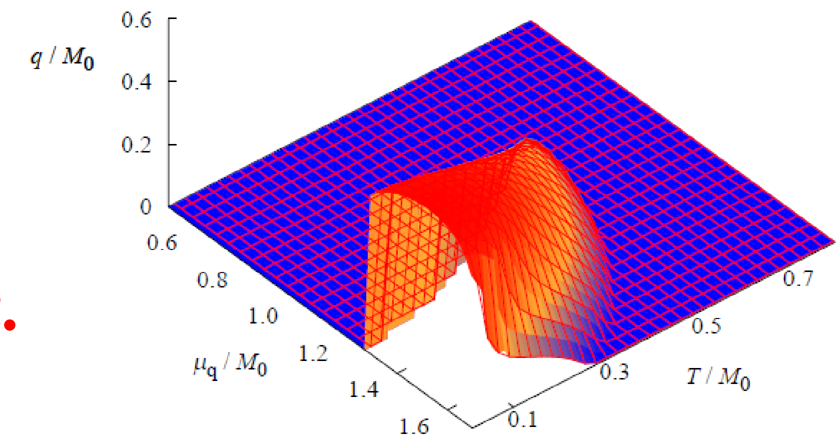
$$\omega=\sqrt{p_\perp^2+\left(\sqrt{p_z^2+M^2}\pm q\right)^2}$$

The system can develop a density however large *M* is if *q* ~ *M* is chosen!

Phase Diagram with Inhomogeneity







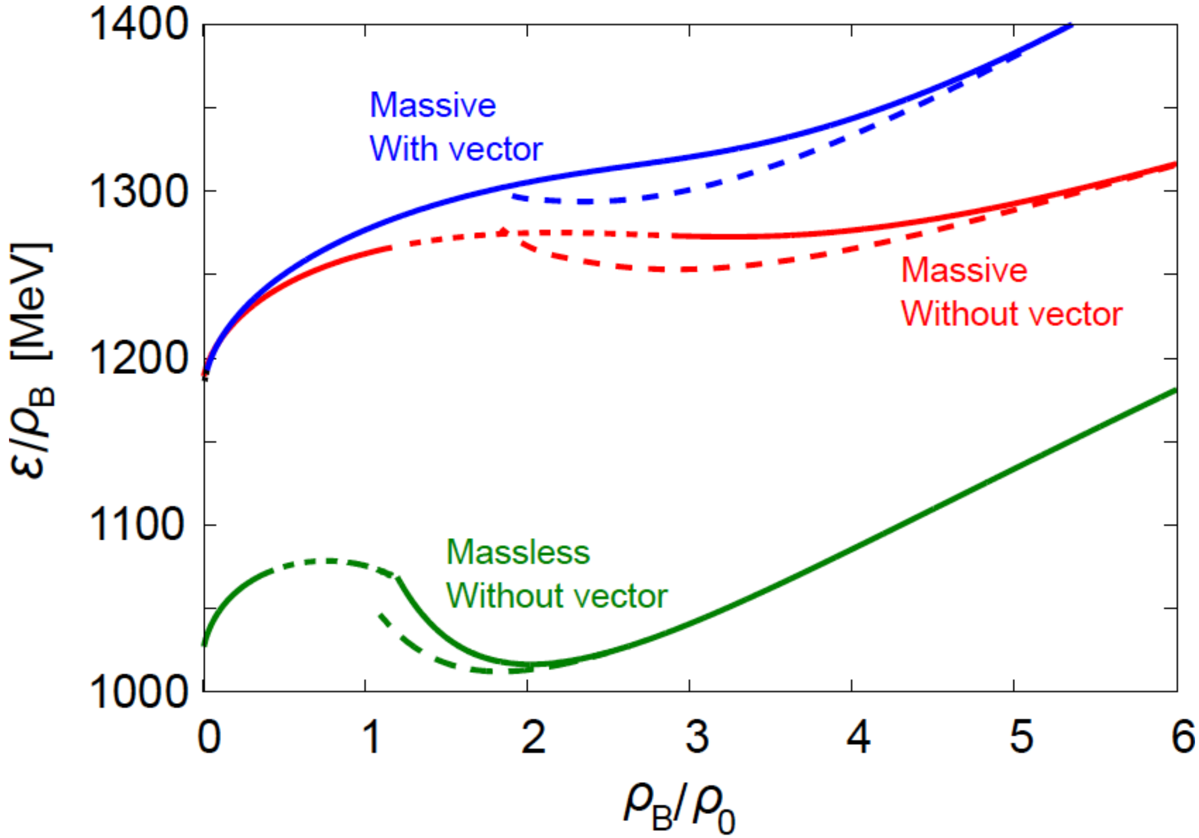
Inhomogeneity survives even with g_v that washes the CP out.

All model studies so far favor this kind of inhomogeneity.

$q \sim M$

Fukushima (2012)

Saturation Curves

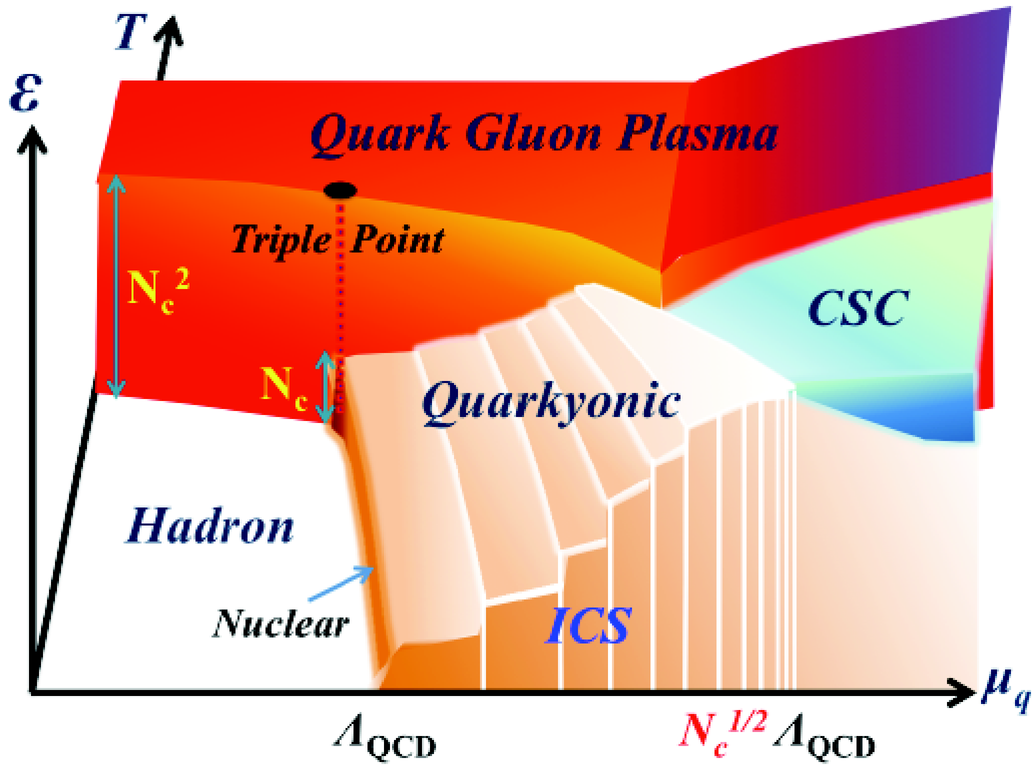


Fukushima (2012)

It is natural (but not necessary) that the 1st-order transition with a smaller energy occurs at smaller density.
Less affected by the vector interaction.

Patch Problem and Successive Phase Transitions

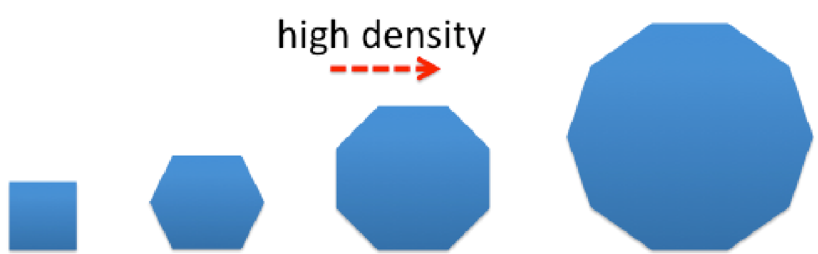
Kojo-Hidaka-Fukushima-McLerran-Pisarski (2011)

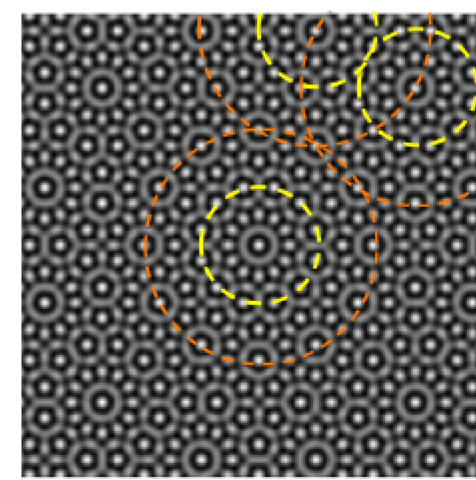


1-D modulation = 1 patch

How to cover the Fermi surface by patches ?

Quasi-crystal ?

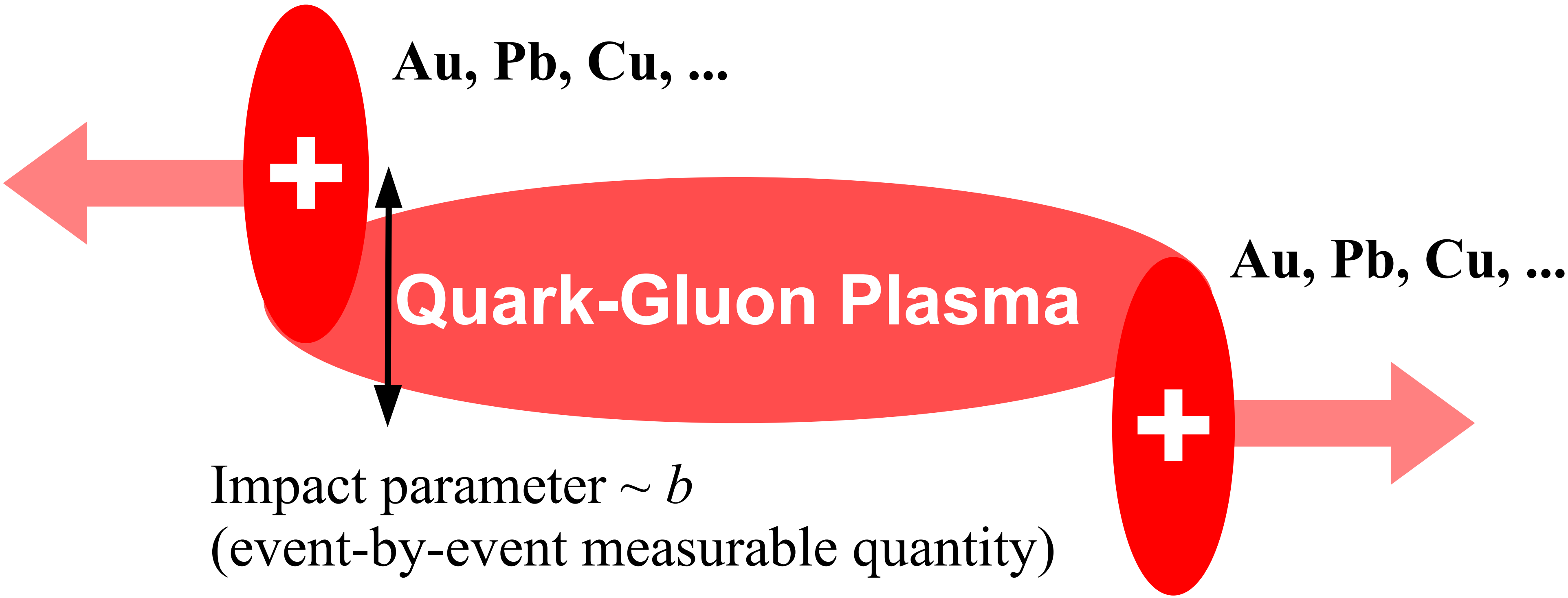




Effects of the Magnetic Field in HIC

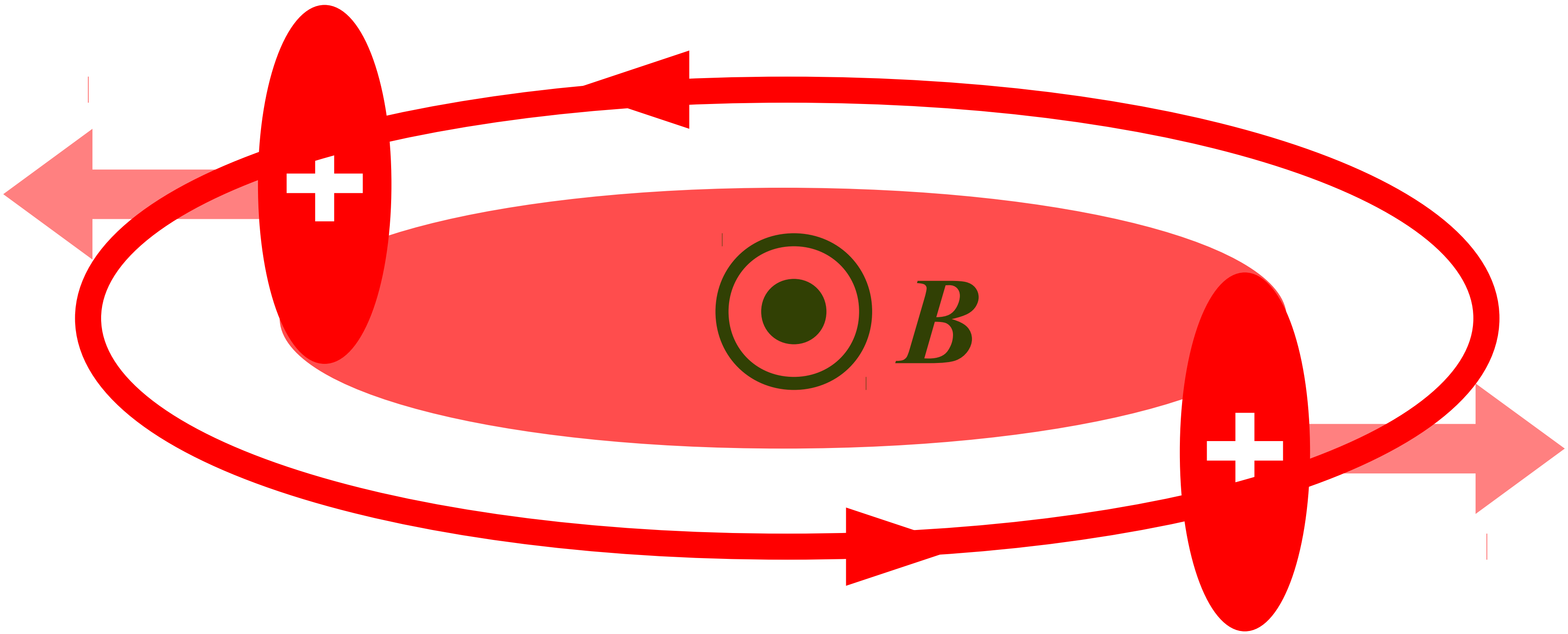
Magnetic Field in HIC

Moving almost at the speed of light



Magnetic Field in HIC

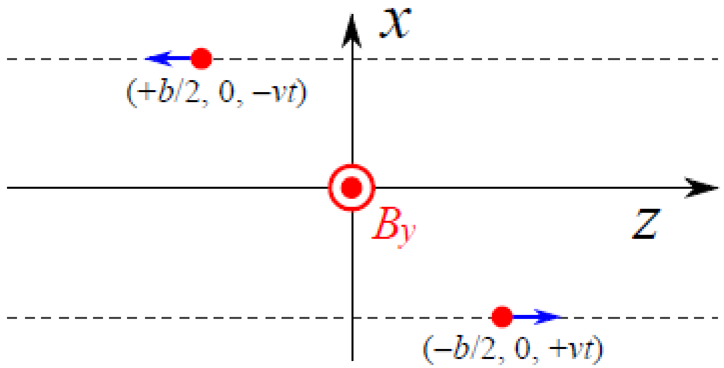
Strong B generated due to Electrodynamics

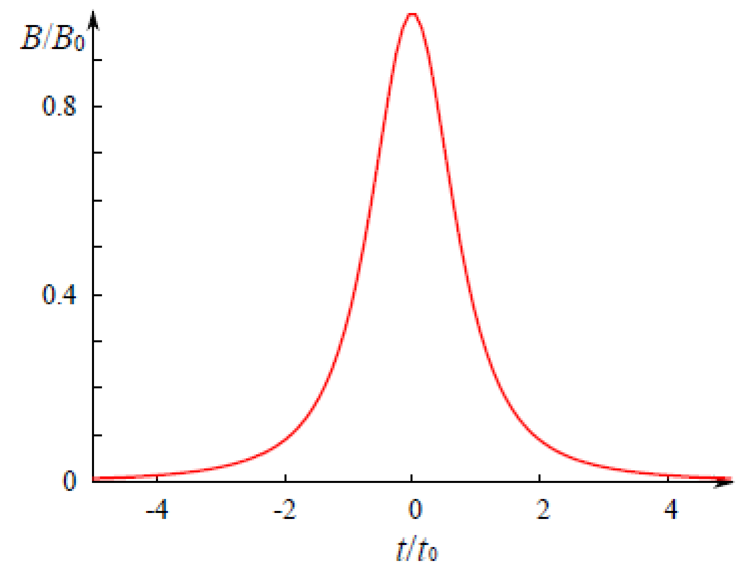


on top of the Quark-Gluon Plasma

Order Estimate of B

Lienard-Wiechert potential





$$eB(t) = \frac{eB_0}{\left[1 + (t/t_0)^2\right]^{3/2}}$$

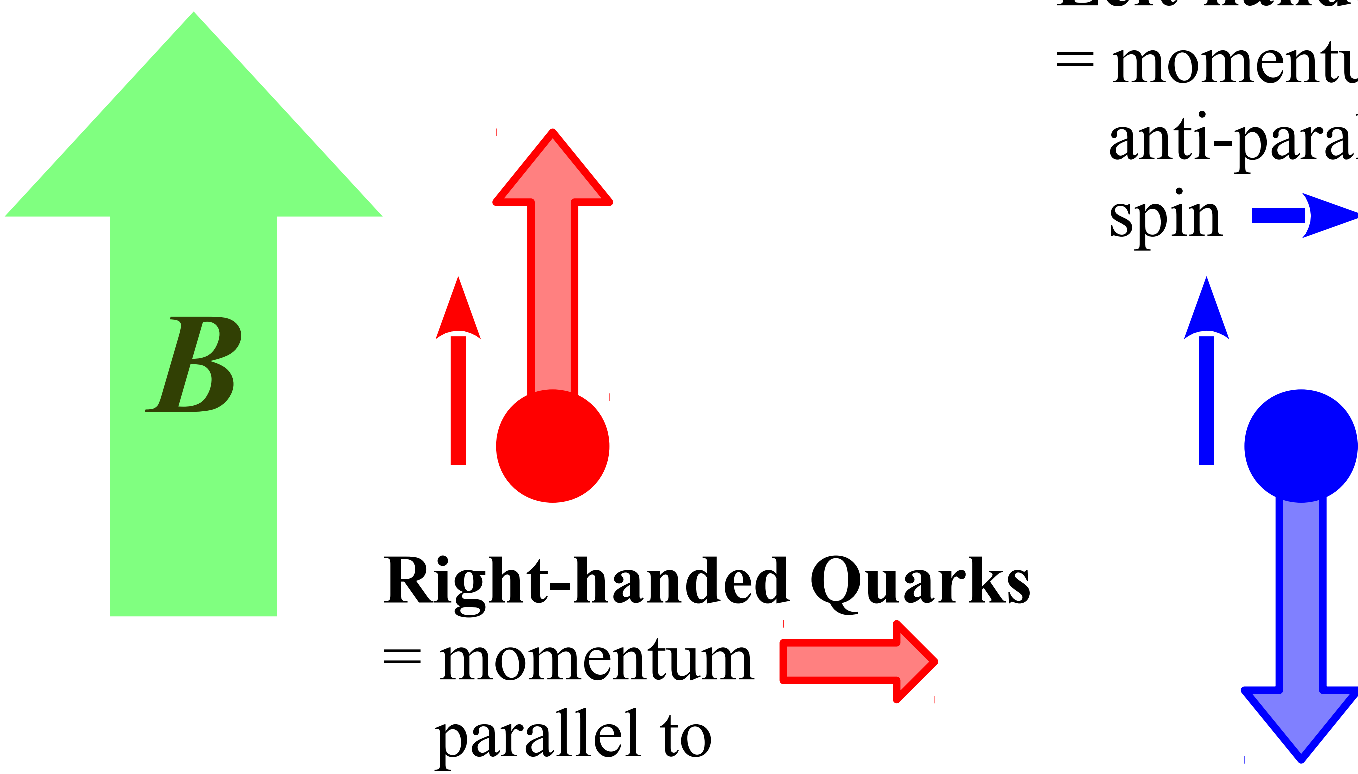
Discussed by Rafelski, Mueller, … (~1976)

$$eB_0 = (47.6\,\mathrm{MeV})^2 \left(\frac{1\,\mathrm{fm}}{b}\right)^2 Z \sinh(Y) \quad , \quad t_0 = \frac{b}{2\sinh(Y)}$$

Strongest *B* in the Universe (QCD scale!)

Chiral Magnetic Effect

Classical Picture



Left-handed Quarks
= momentum
anti-parallel to
spin

Right-handed Quarks
= momentum
parallel to
spin

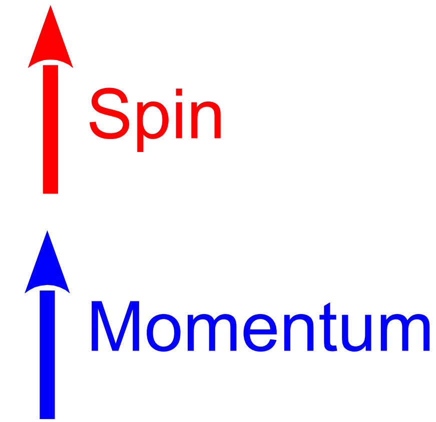
$$\boldsymbol{J} \neq 0 \quad \text{if} \quad N_5 = N_R - N_L \neq 0$$

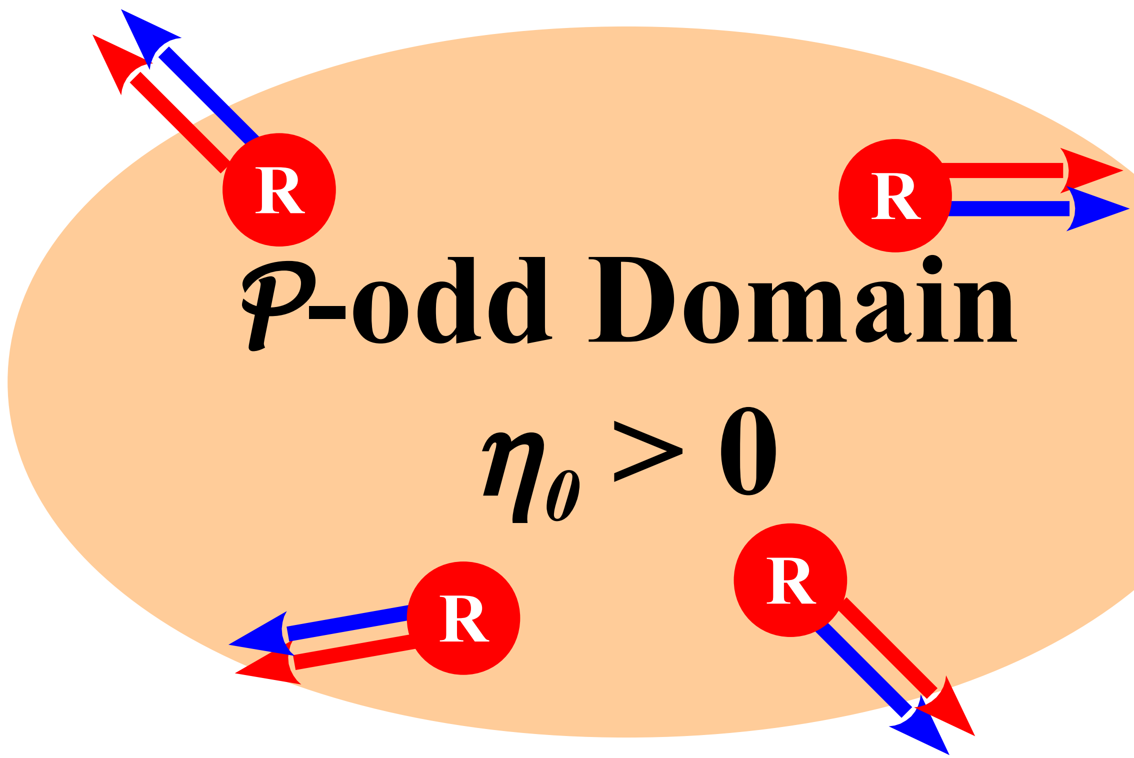
Kharzeev-McLerran-Warringa (2007)
Fukushima-Kharzeev-Warringa (2008)

Charge Separation

Without *B* Fields

Net Current $\langle J \rangle = 0$

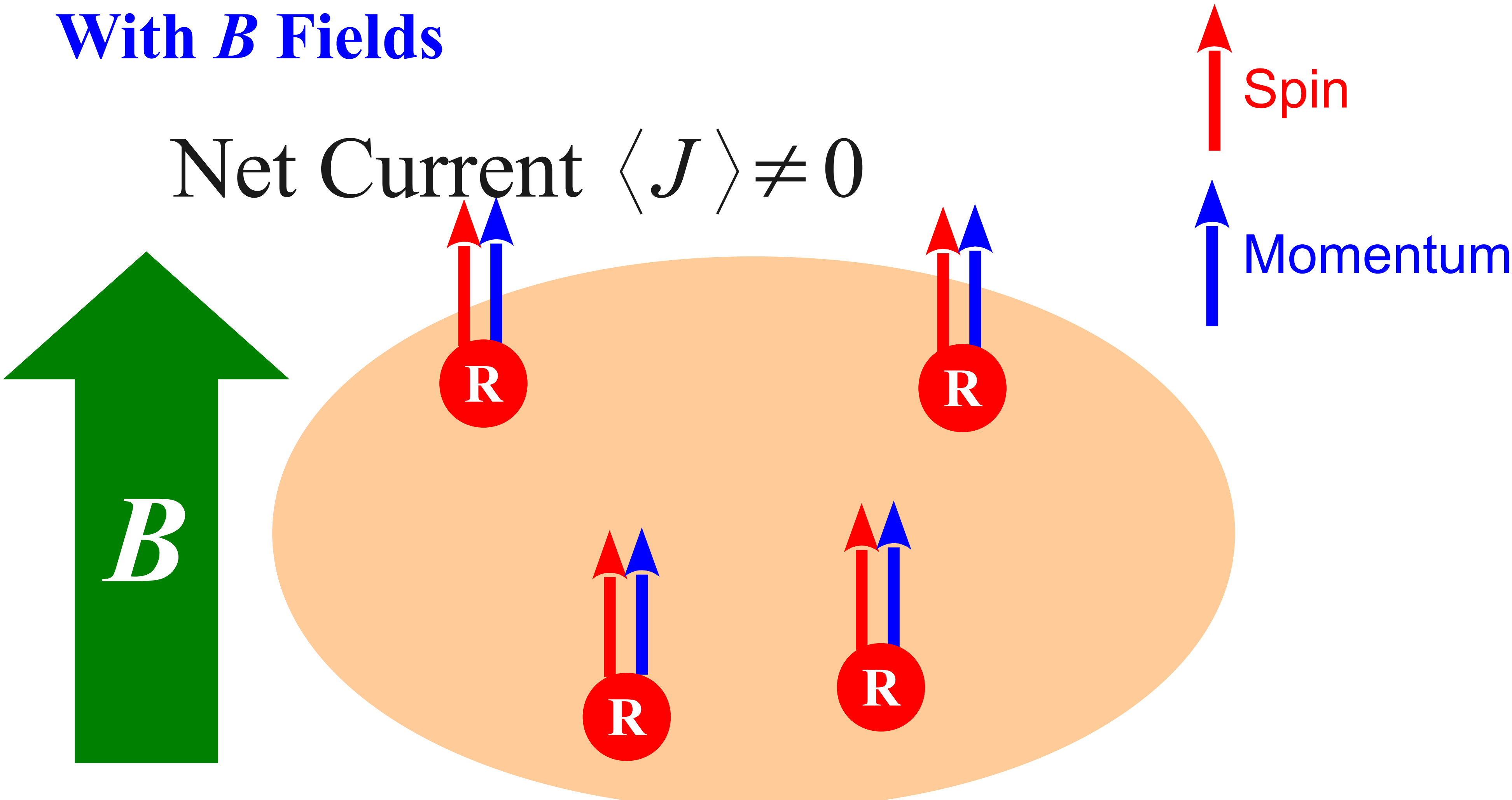




Charge Separation

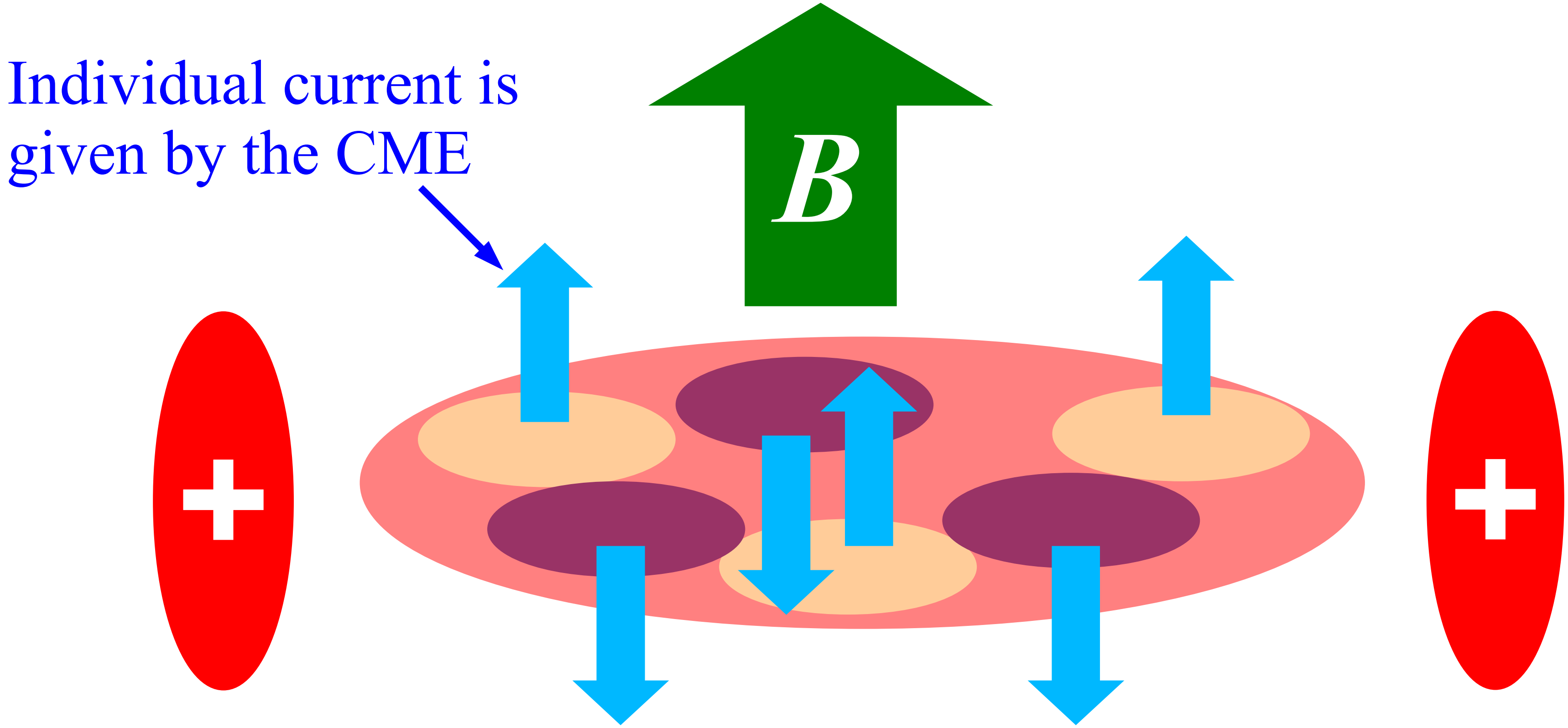
With *B* Fields

Net Current $\langle J \rangle \neq 0$



Kharzeev-McLerran-Warringa

Charge Separation Fluctuations

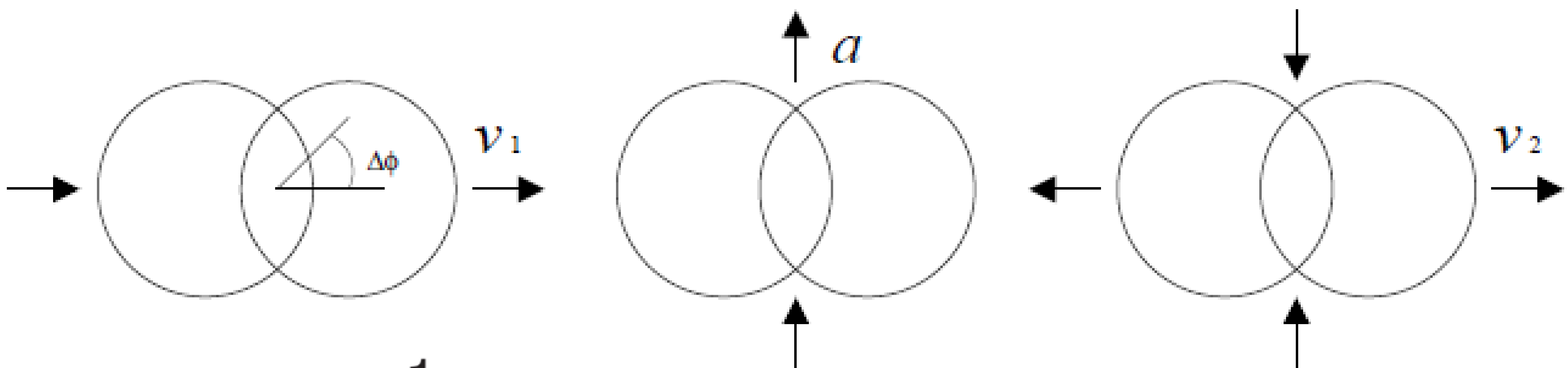


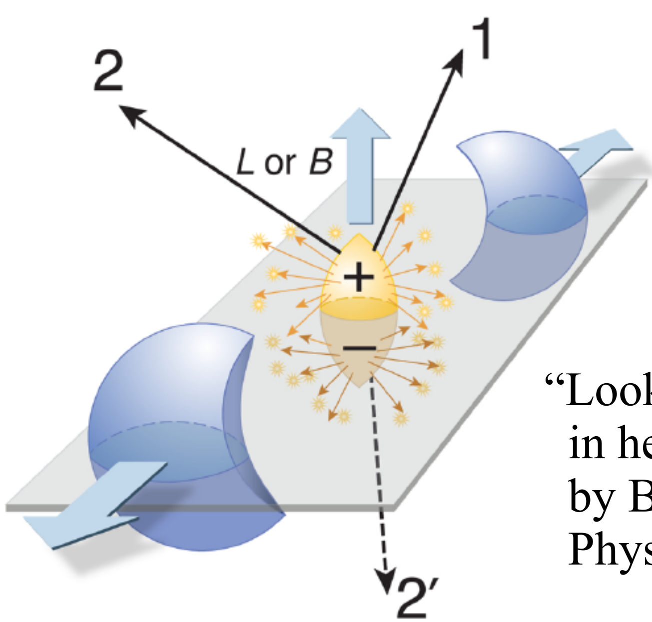
$$\langle (\text{Charge Separation}) \rangle = 0$$

$$\langle (\text{Charge Separation})^2 \rangle = \text{large}$$

Fluctuation of Charge Separation

$$\frac{\mathrm{d}N_\pm}{\mathrm{d}\phi} \propto 1 + 2v_{1\pm}\cos(\Delta\phi) + 2a_\pm \sin(\Delta\phi) + 2v_{2\pm}\cos(2\Delta\phi) + \cdots$$





"Looking for parity violation
in heavy-ion collisions"
by Berndt Müller
Physics 2, 104 (2009)

B: Azimuthal angle

v_1 : Directed flow

v_2 : Elliptic flow

First Results from STAR@RHIC

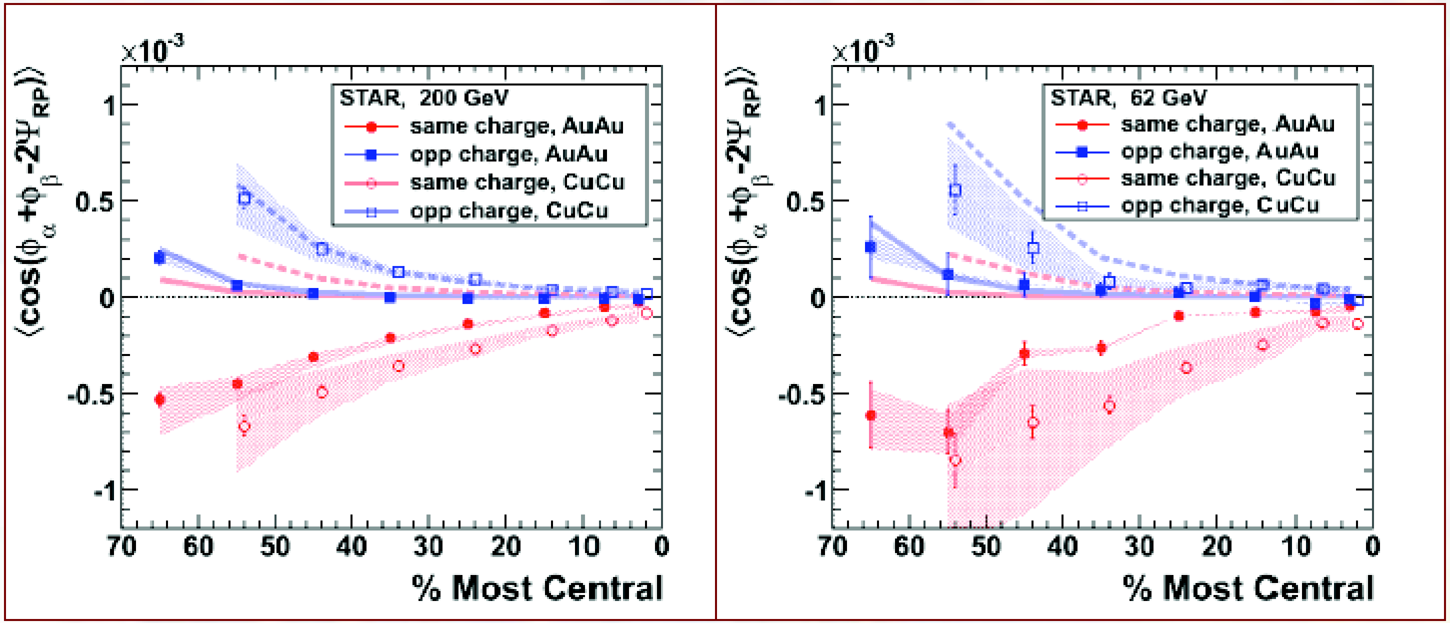
3-Particle Correlation (fluctuation measurement)

$$\langle\langle \cos(\Delta\phi_\alpha + \Delta\phi_\beta) \rangle\rangle \equiv \left\langle\!\!\left\langle \frac{1}{N_\alpha N_\beta} \sum_{i=1}^{N_\alpha} \sum_{j=1}^{N_\beta} \cos(\Delta\phi_{\alpha,i} + \Delta\phi_{\beta,j}) \right\rangle\!\!\right\rangle$$

$$= \langle\langle \cos\Delta\phi_\alpha \cos\Delta\phi_\beta \rangle\rangle - \langle\langle \sin\Delta\phi_\alpha \sin\Delta\phi_\beta \rangle\rangle$$

$$= \left(\langle\langle v_{1,\alpha} v_{1,\beta} \rangle\rangle + B^{\text{in}}_{\alpha\beta}\right) - \left(\langle\langle a_\alpha a_\beta \rangle\rangle + B^{\text{out}}_{\alpha\beta}\right).$$

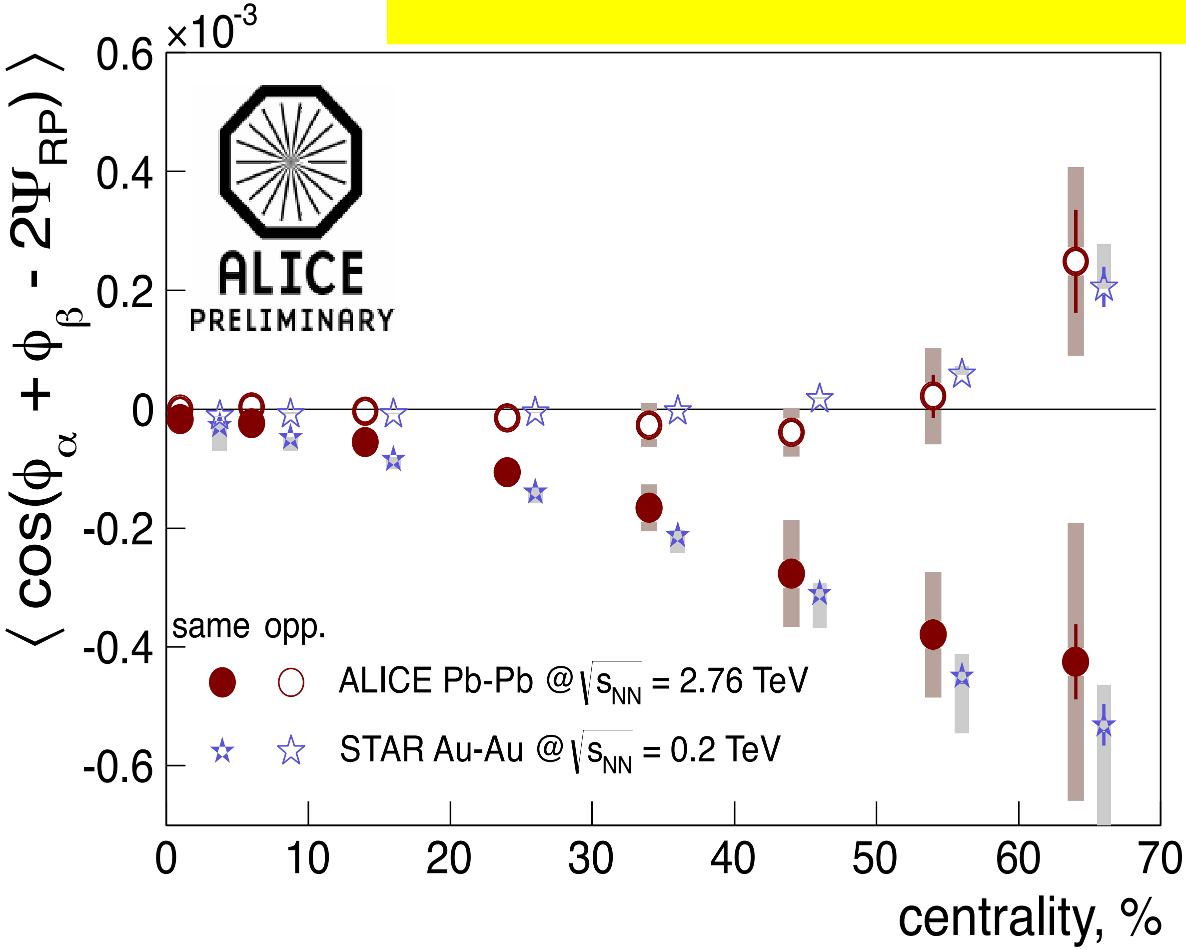
STAR Results



Voloshin STAR

Reconfirmation at ALICE@LHC

STAR Collaboration: Phys. Rev. Lett. **81**, 251601 (2009)
STAR Collaboration: Phys. Rev. **C81**, 054908 (2010)



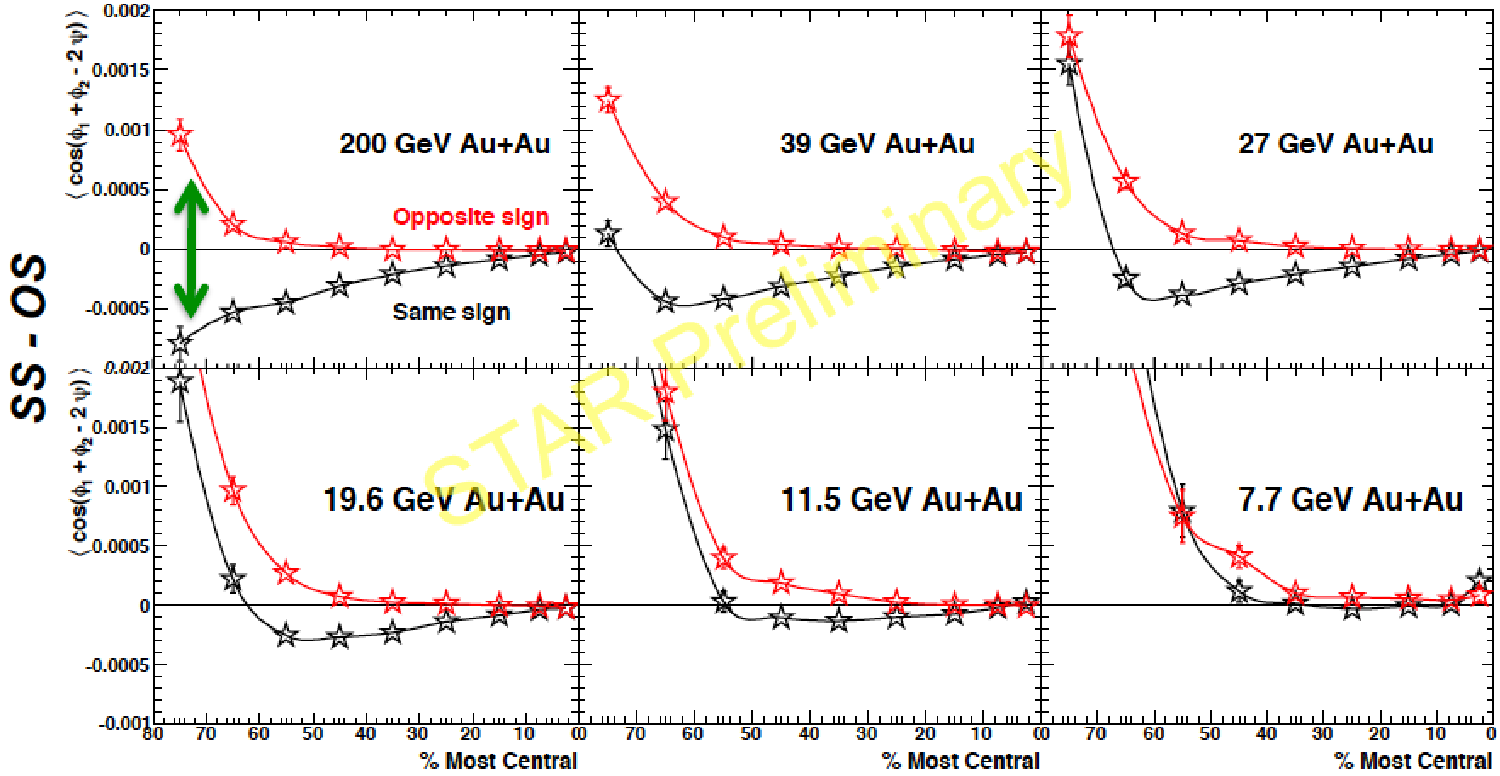
Local Parity Violation?

Charge Conservation?

Data from ALICE presented at CPODD

Results from STAR BES-I

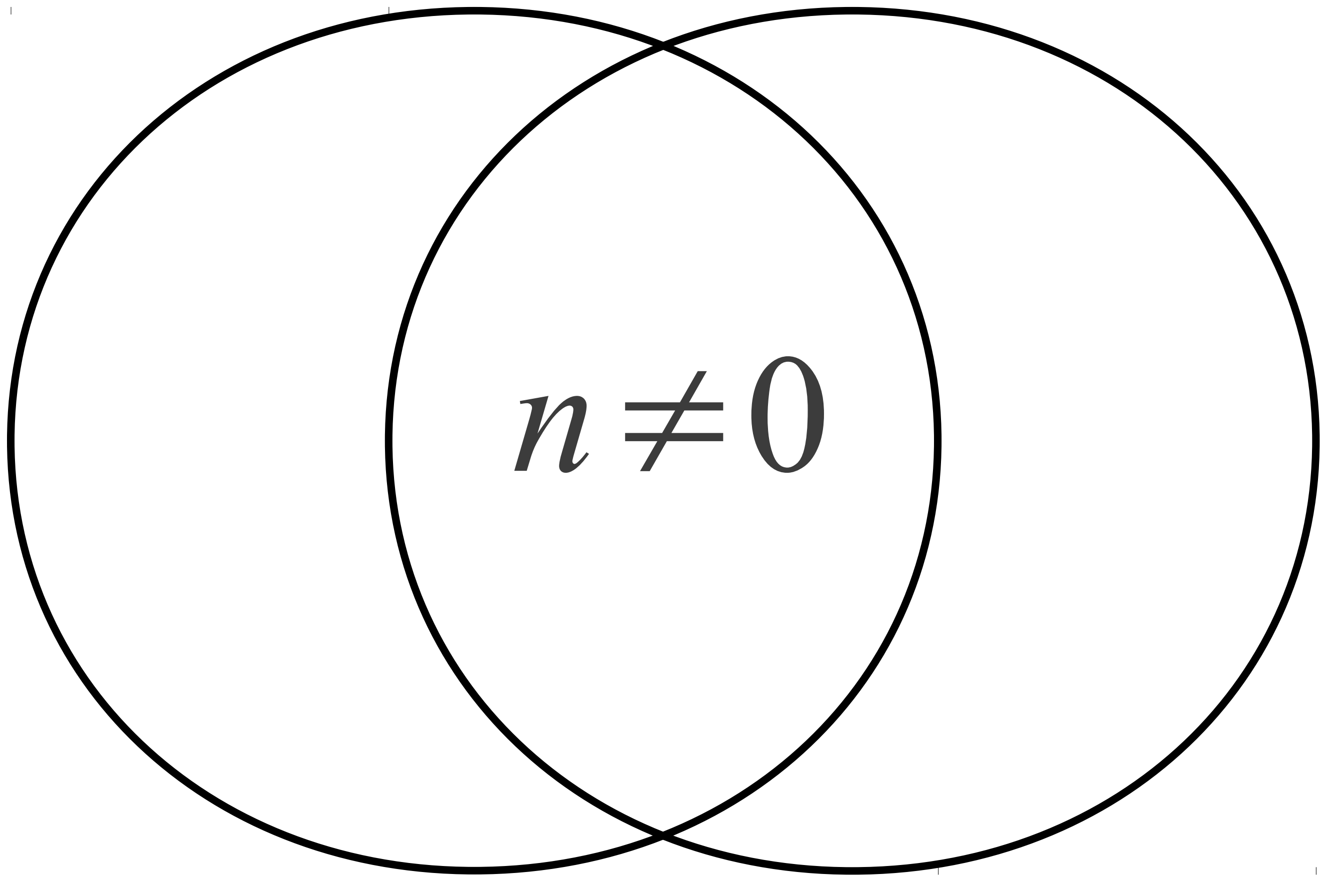
Qualitative difference at lower collision energy



Taken from Nu Xu's slides

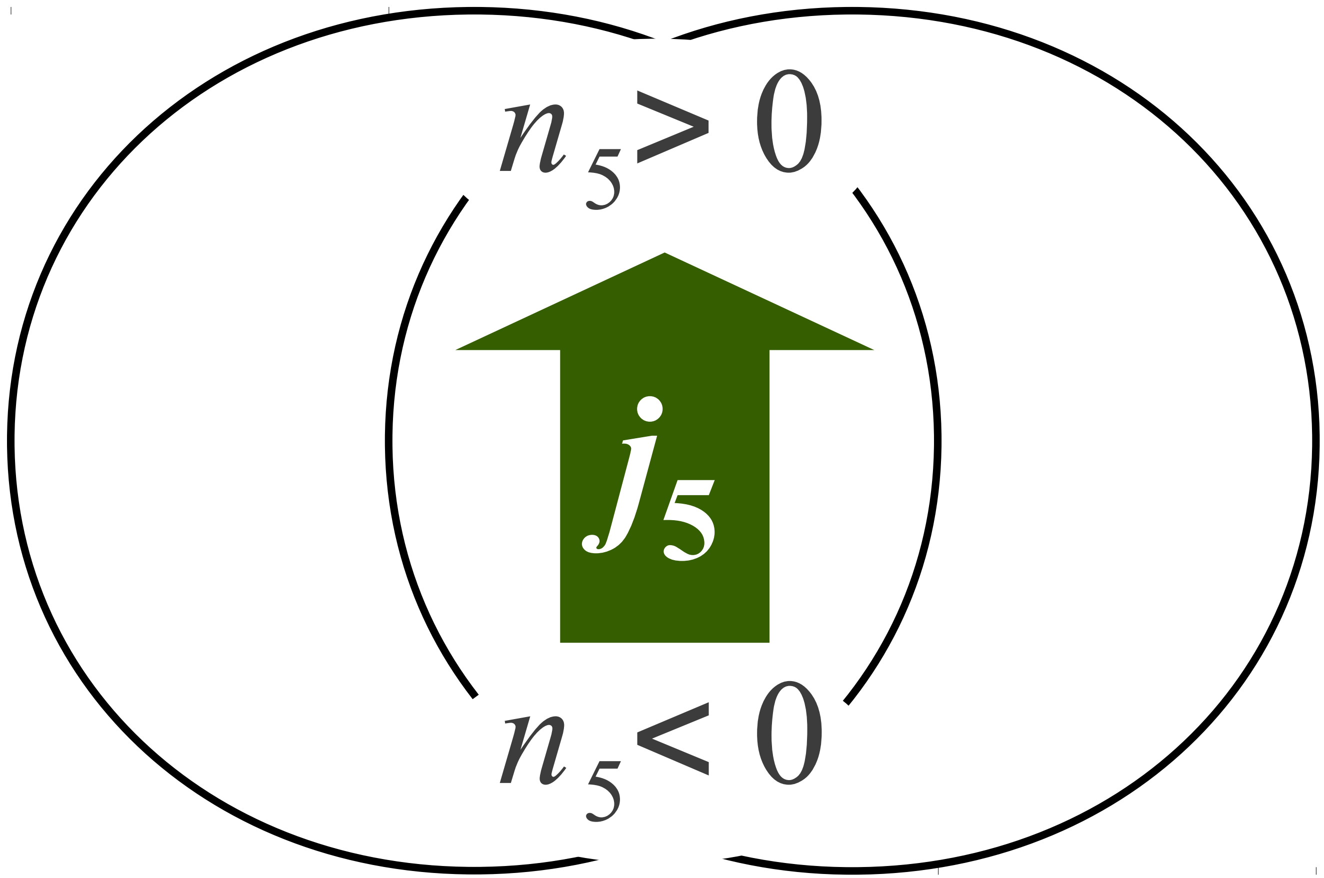
Interpretation is not yet established... future problem!

Chiral Magnetic Wave



Burnier-Kharzeev-Liao-Yee (2011)

Chiral Magnetic Wave



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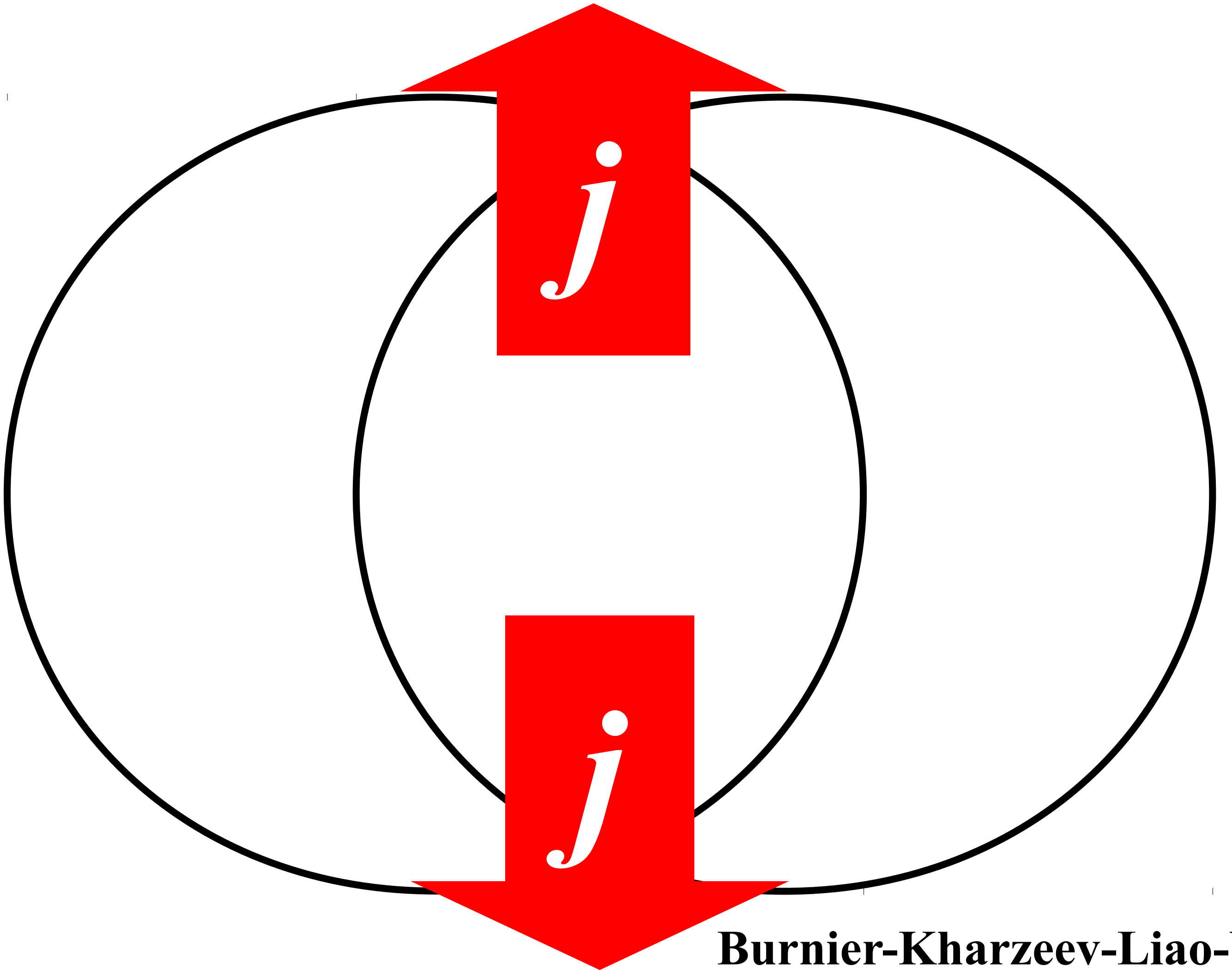

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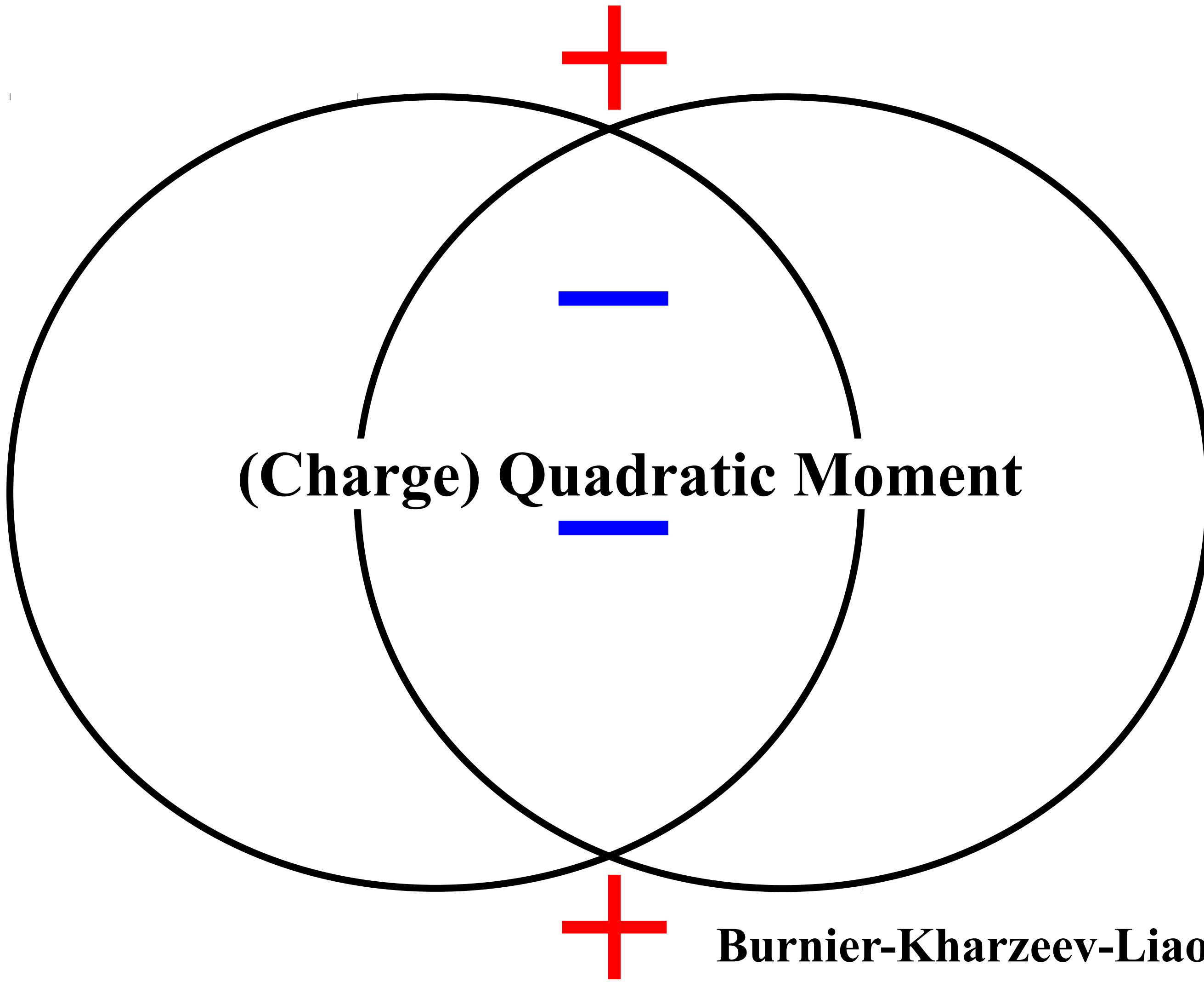

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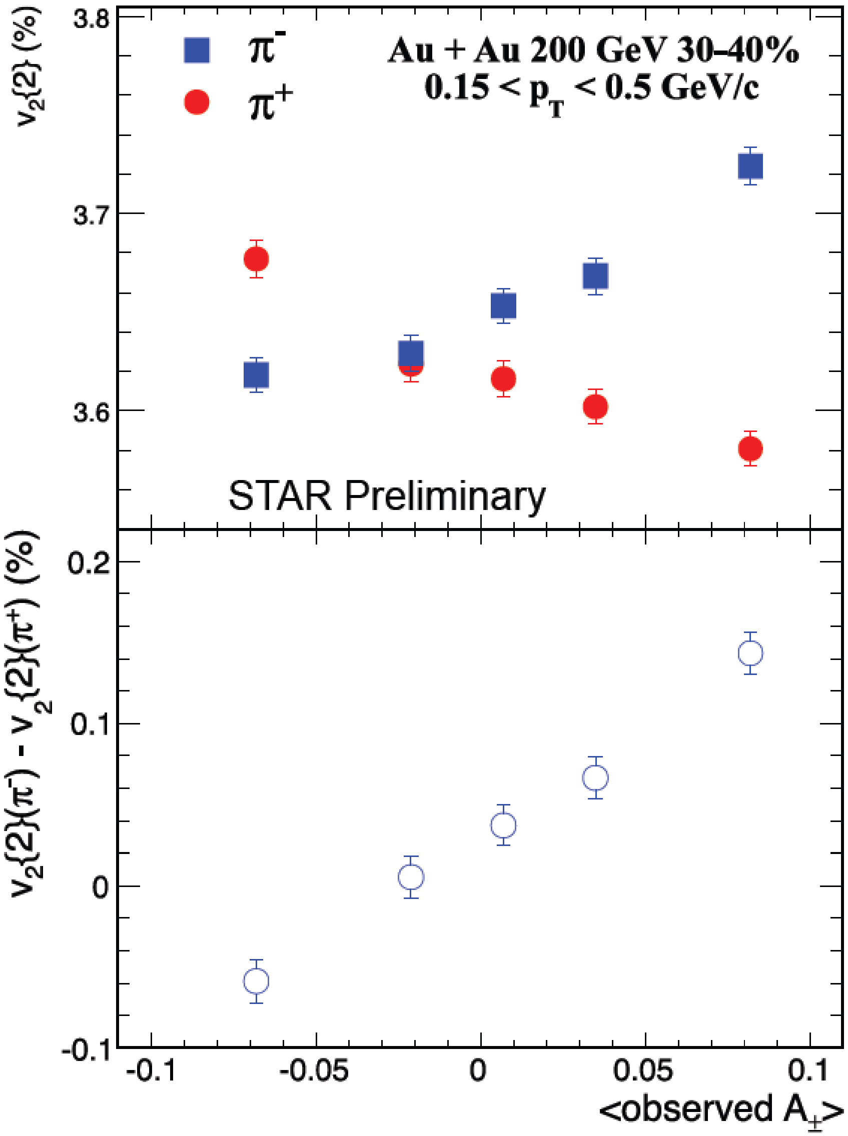

q_e: quadratic moment

$$v_2^{\pm} = v_2 \mp \frac{q_e}{\rho_e} A_{\pm}$$

$$A_{\pm} = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$$

So far so good... but the background estimate?

STAR data presented at CPODD

Summary

Challenges in HIC at high baryon density

- Critical point of not QCD but nuclear matter and associated critical fluctuations.
- (Partial) restoration of chiral symmetry
- Exotic hadrons and diquark correlations or precursory phenomena of color superconductivity
- Quarkyonic matter: indication of quark deconfinement and inhomogeneous structures
- Topological phenomena with magnetic field and baryon density – condensed matter physics of QCD