Quest for the QCD phase diagram in extreme environments

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Typical Extreme's

High Temperature

up to $T \sim \Lambda_{\mathrm{QCD}} \sim 200\mathrm{MeV}$

Relativistic Heavy-Ion Collision

High Baryon Density

up to $\rho_{\mathrm{B}} \sim (\Lambda_{\mathrm{QCD}})^3 \sim 1\mathrm{fm}^{-3}$

Relativistic Heavy-Ion Collision, Neutron Star

Strong Magnetic Field

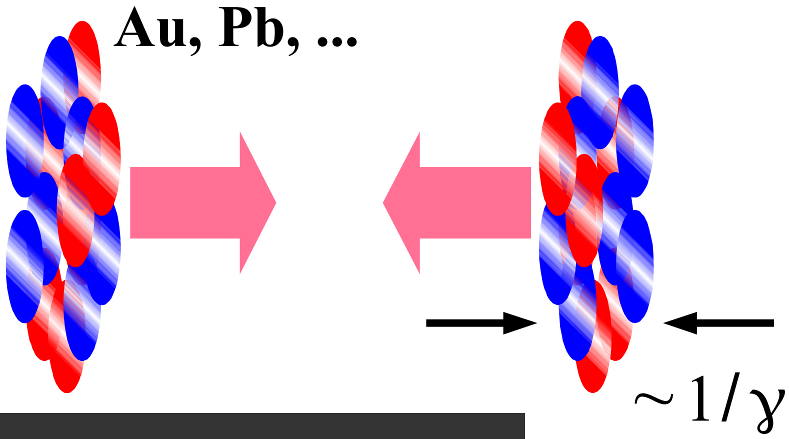
up to $eB \sim (\Lambda_{\mathrm{QCD}})^2 \sim 10^{18}$ gauss

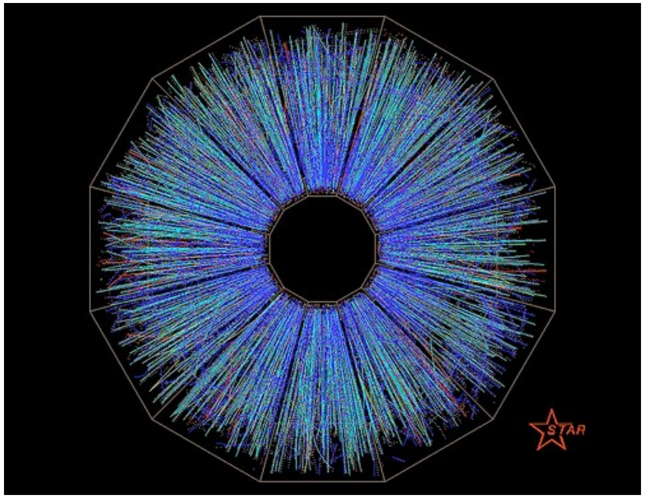
Relativistic Heavy-Ion Collision, Neutron Star

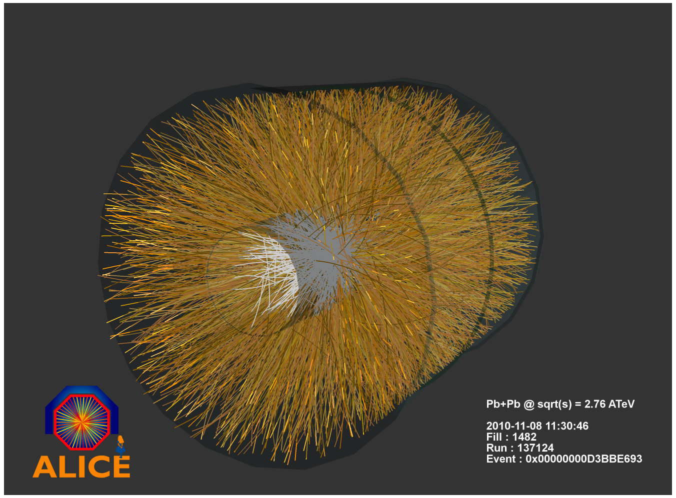
Relativistic Heavy-Ion Collision

LHC: $\sqrt{s_{NN}} = 2.7\,\mathrm{TeV} \rightarrow \gamma \sim 1400$

RHIC: $\sqrt{s_{NN}} = 200\,\mathrm{GeV} \rightarrow \gamma \sim 100$



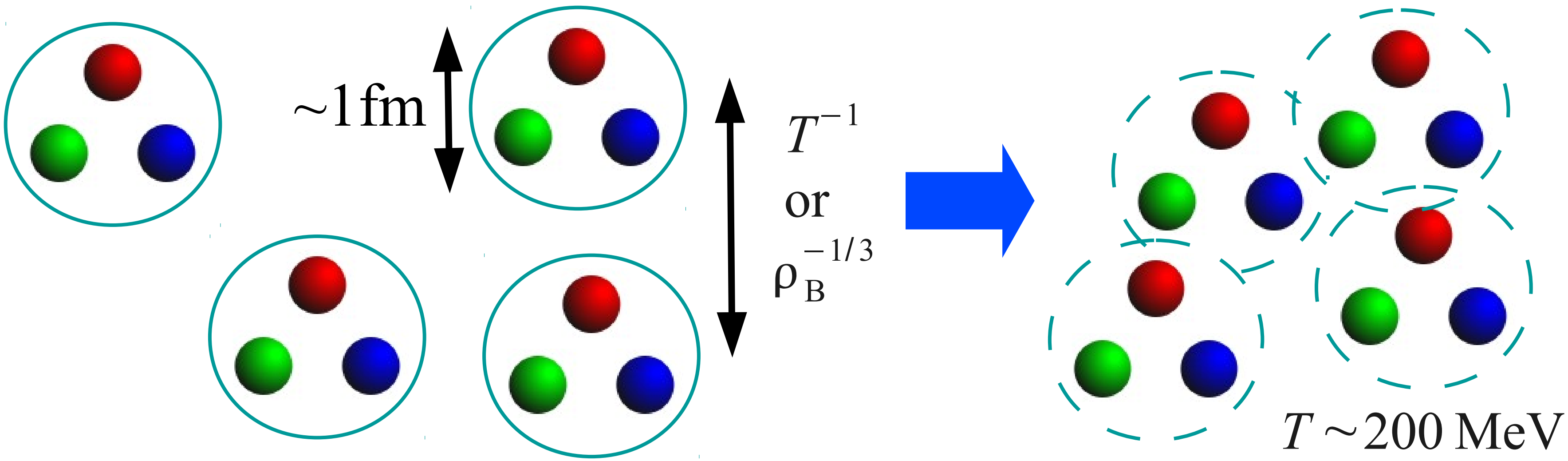




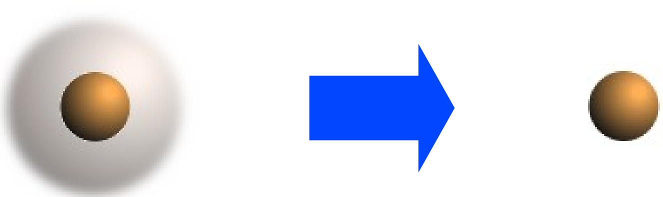
Thermalization achieved (elliptic flow by a hydro-model)
Initial temperature > 200MeV (distribution of thermal photon)

Two Major Phase Transitions in QCD

Quark Deconfinement Transition (Center Symmetry)



Chiral Phase Transition (Chiral Symmetry)

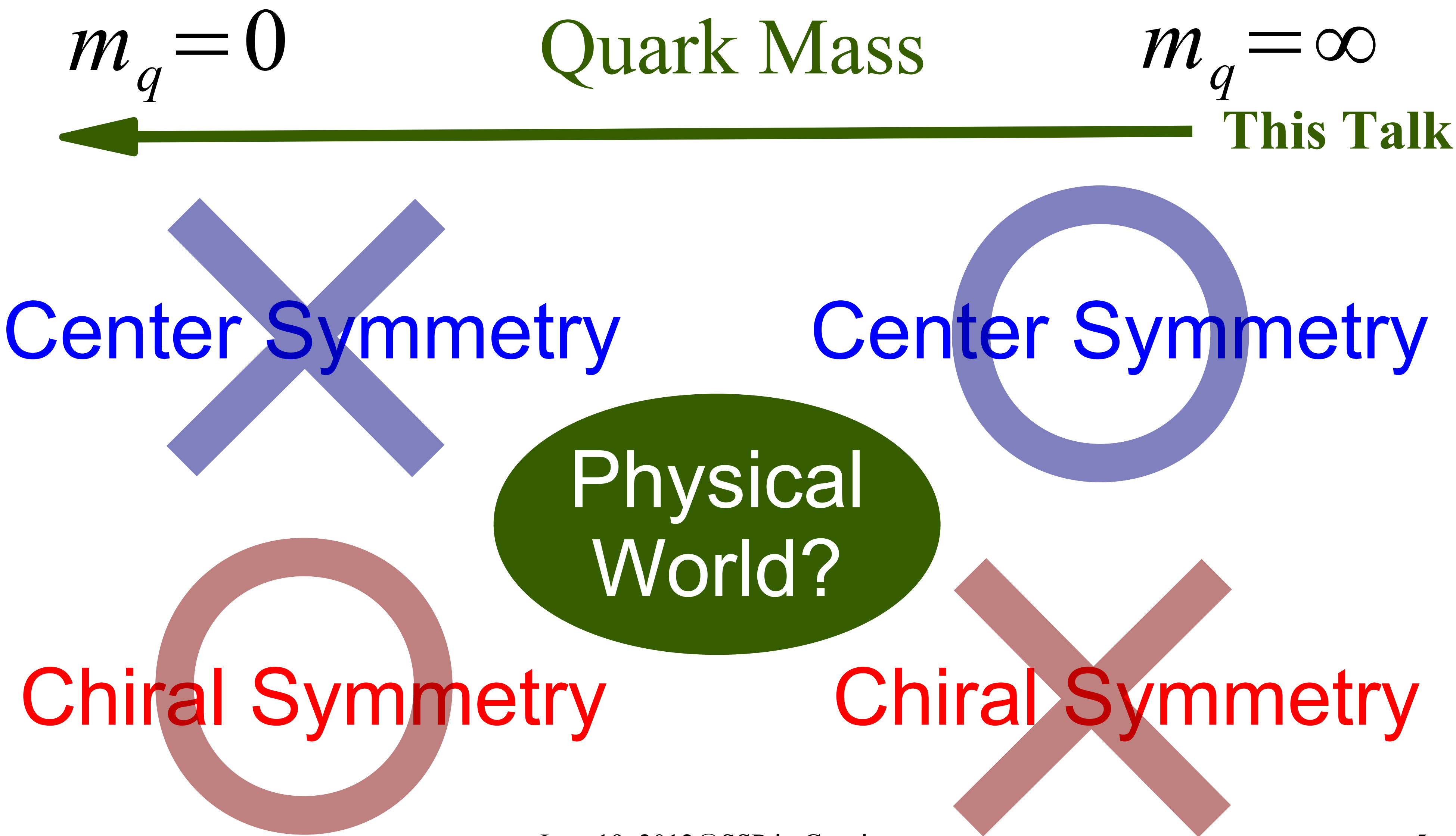


"Bare" Quarks
$m_q \sim$ 3-6 MeV

"Constituent" Quarks
$M_q \sim 350$ MeV

Nambu-Jona-Lasinio

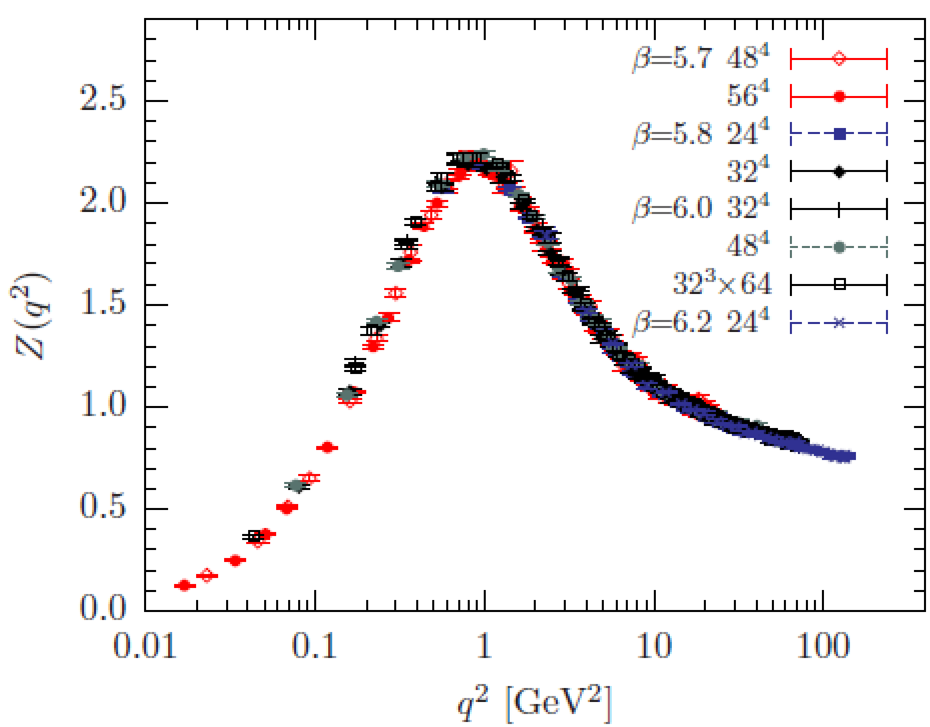
Symmetry Entanglement

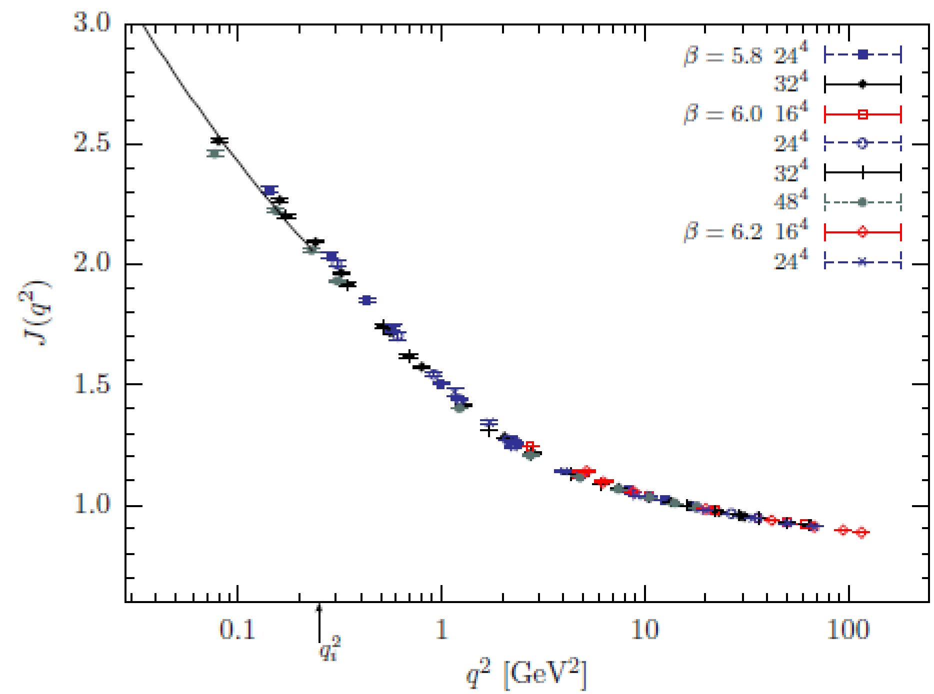


Understanding "Deconfinement"

Confinement understood from the non-perturbative propagators of gluons and ghosts in the Landau gauge

Ilgenfrits-Muller-Preussker-Sternbeck-Schiller-Bogolubsky (2007)



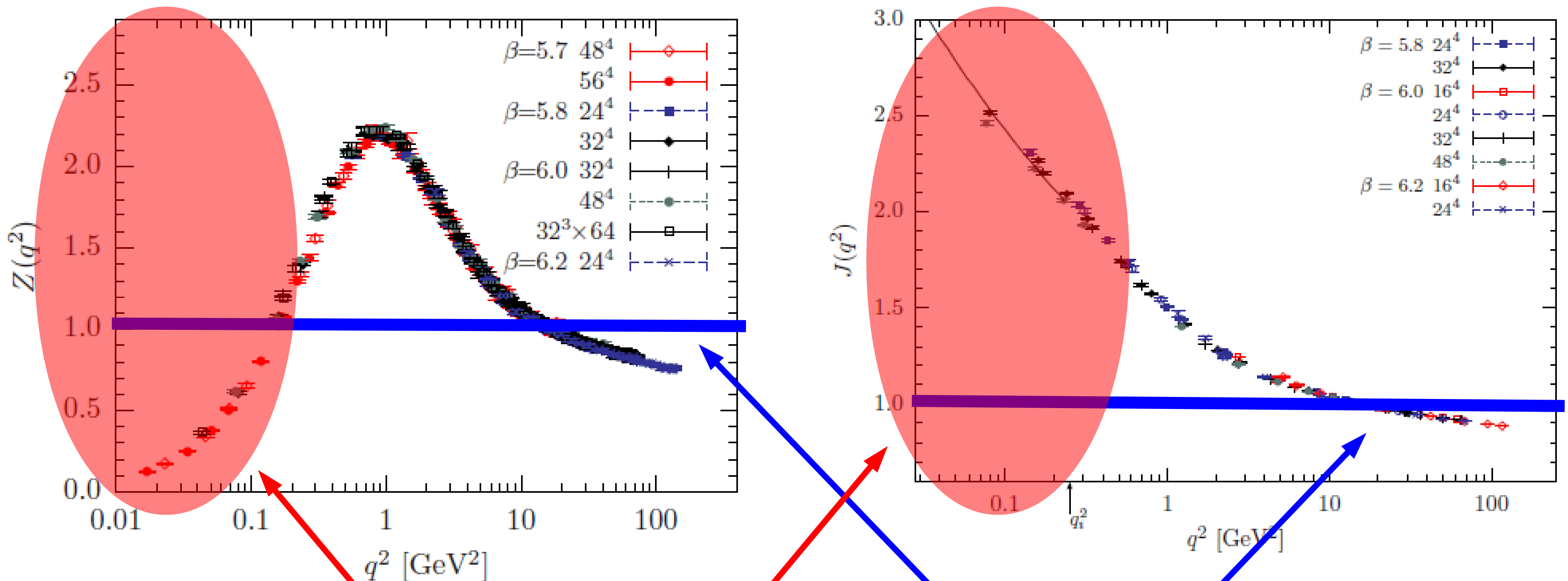


Gluons IR suppressed

Ghosts IR enhanced (confinement)

Gribov's scenario

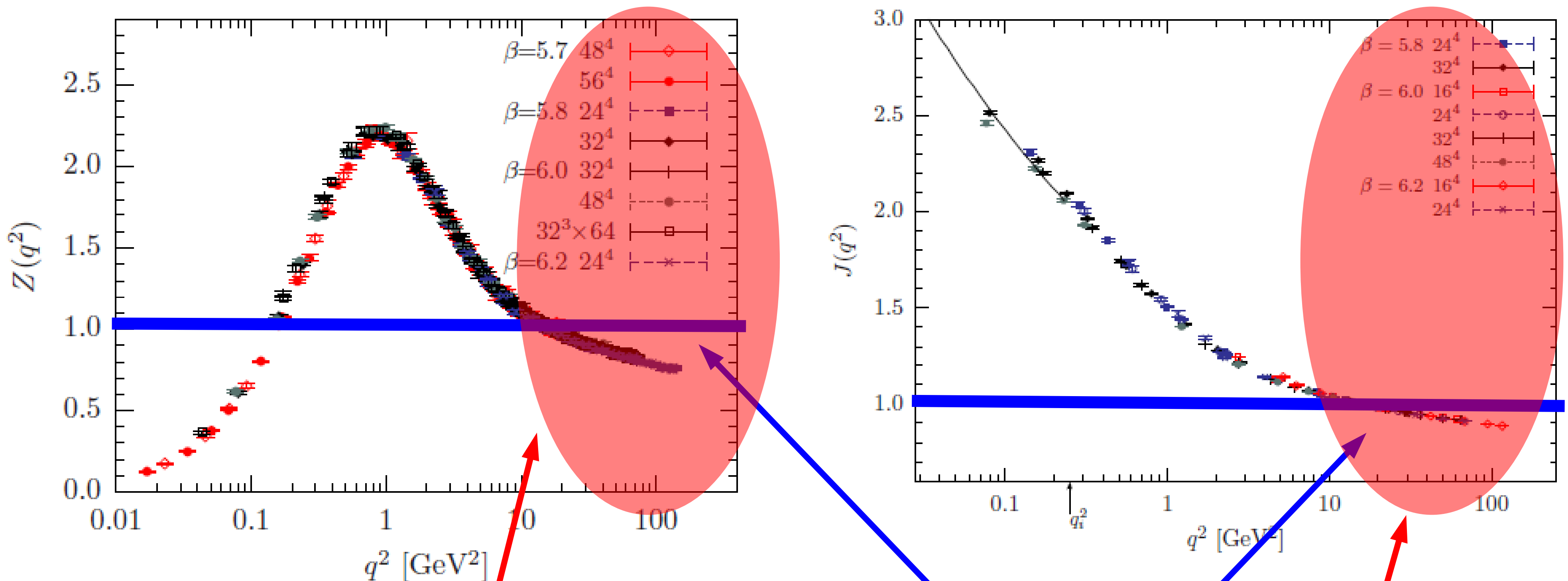
Confinement at Low Temperature



Perturbative Limit

Ghost Dominance → Color Confinement

Deconfinement at High Temperature



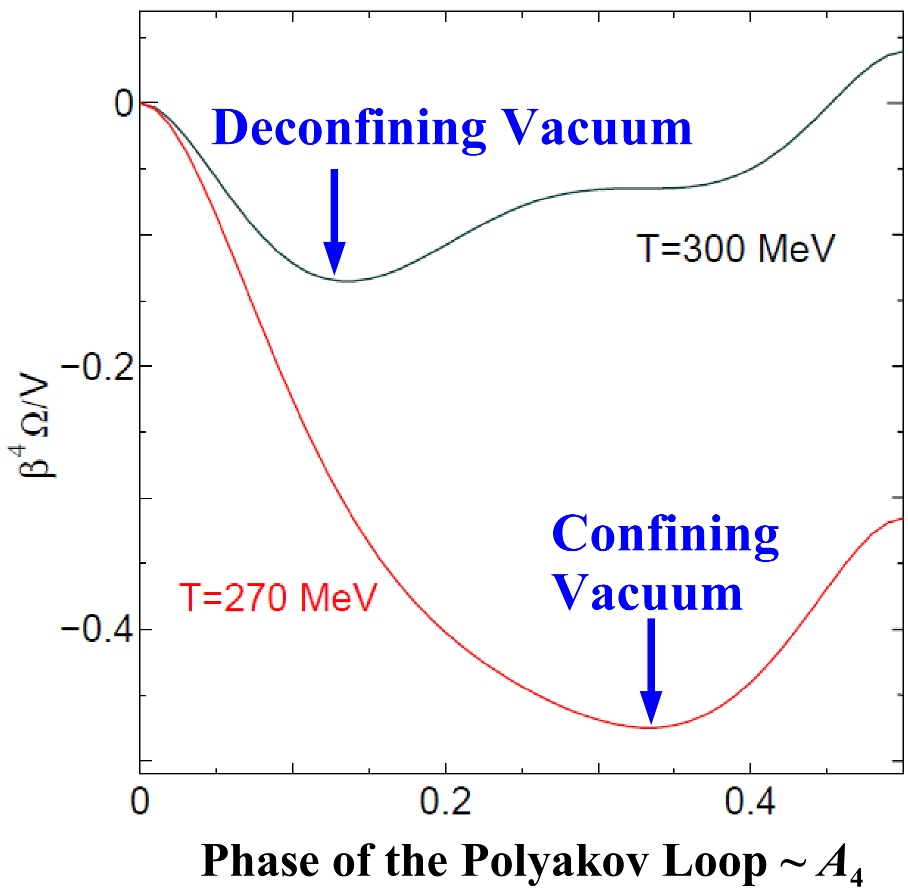
Perturbative Limit

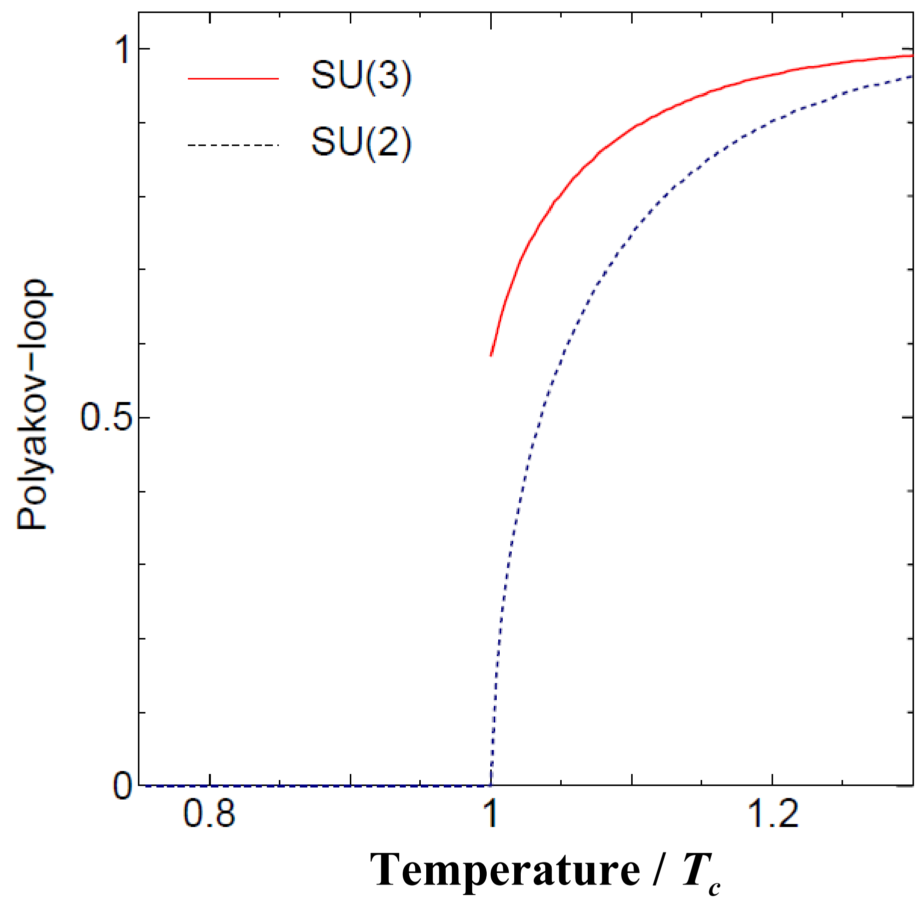
All Excitations with $p \sim 2\pi T \rightarrow$ Perturbative Limit
Two Transverse Gluons (unphysical ones canceled)

Phase Transition from Propagators

$$\ln Z = -\frac{1}{2}\,\mathrm{tr}\ln D^{-1}_{\mathrm{gluon}}(A_4) + \mathrm{tr}\ln D^{-1}_{\mathrm{ghost}}(A_4) + \cdots$$

Balance between gluons and ghosts





Confinement → Deconfinement

Braun-Gies-Pawlowski, KF-Kashiwa

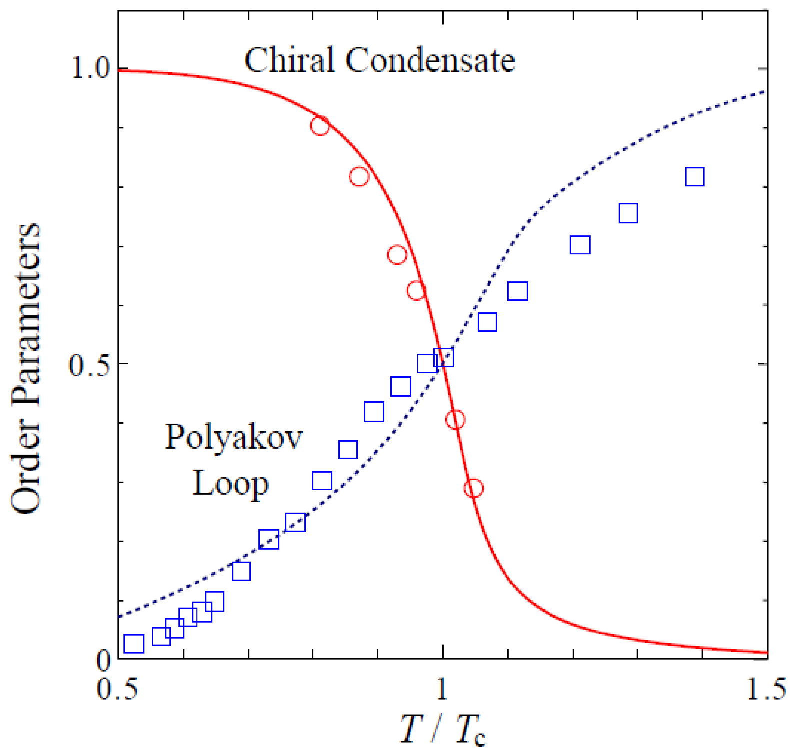
Dynamical Quarks at Finite m_q

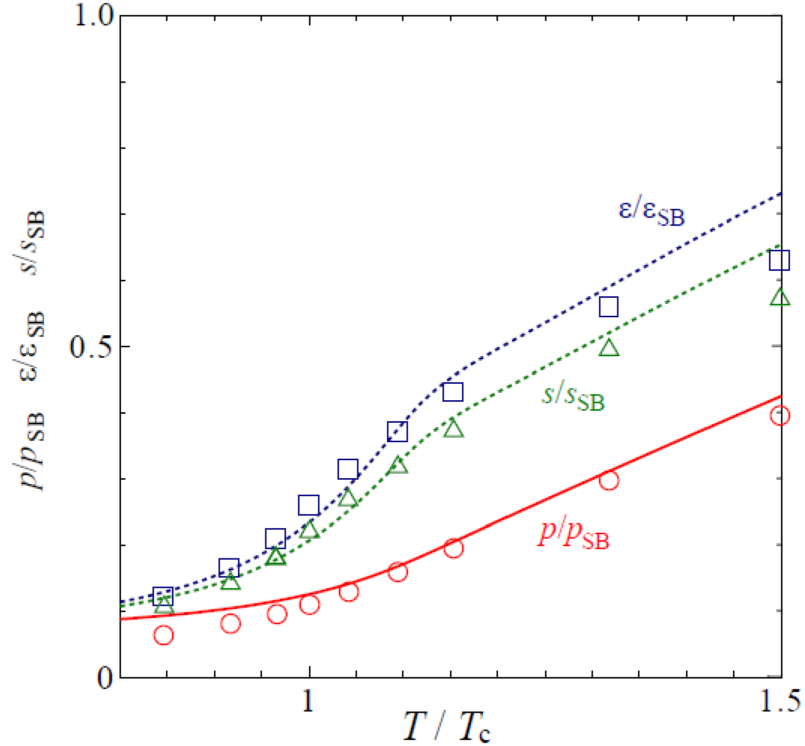
$$\ln Z_F = \mathrm{tr}\ln\left(1+e^{-(E-\mu)/T}\right) + \mathrm{tr}\ln\left(1+e^{-(E+\mu)/T}\right)$$

Partition func. for quarks

$$\rightarrow \mathrm{tr}\ln\left(1+L\,e^{-(E-\mu)/T}\right) + \mathrm{tr}\ln\left(1+L^\dagger e^{-(E+\mu)/T}\right)$$

Coupling through the covariant derivative

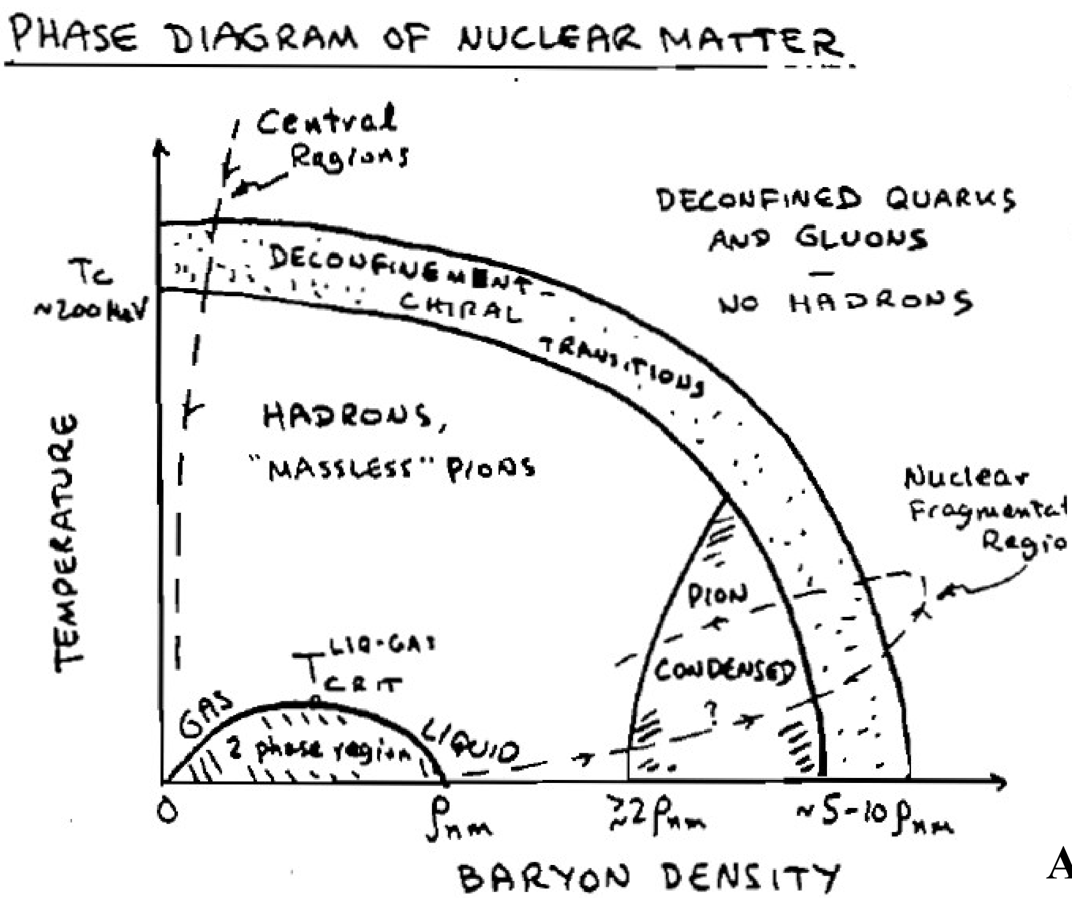


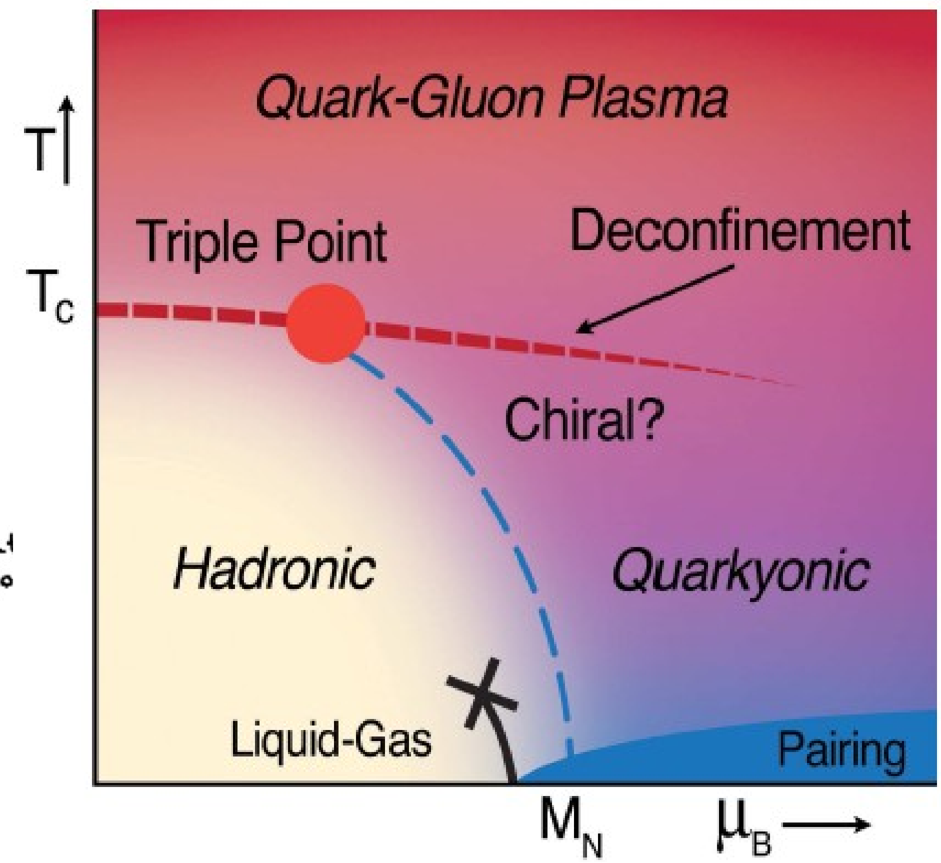


KF-Kashiwa (2012)

Phase Diagrams including Density

Prototype in 1983 and Update in 2009



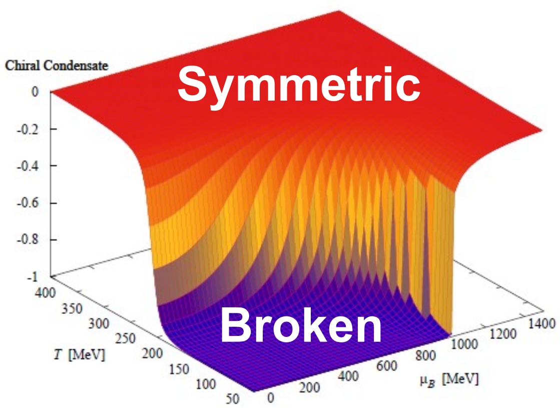


Andronic-Blaschke-Braun-Cleymans-Munzinger-
-KF-McLerran-Oeschler-Pisarski-Redlich-
-Sasaki-Satz-Stachel (2009)

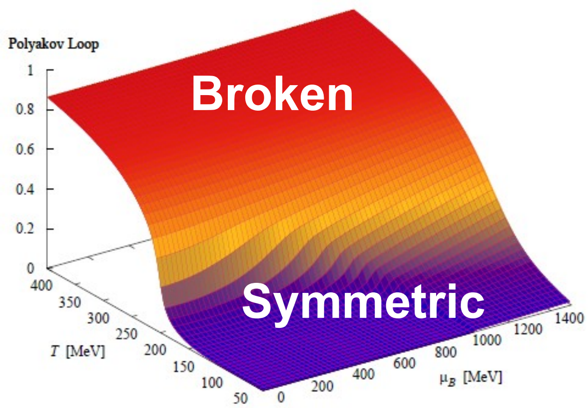
Modern Picture

Typical Model Results

Chiral Symmetry

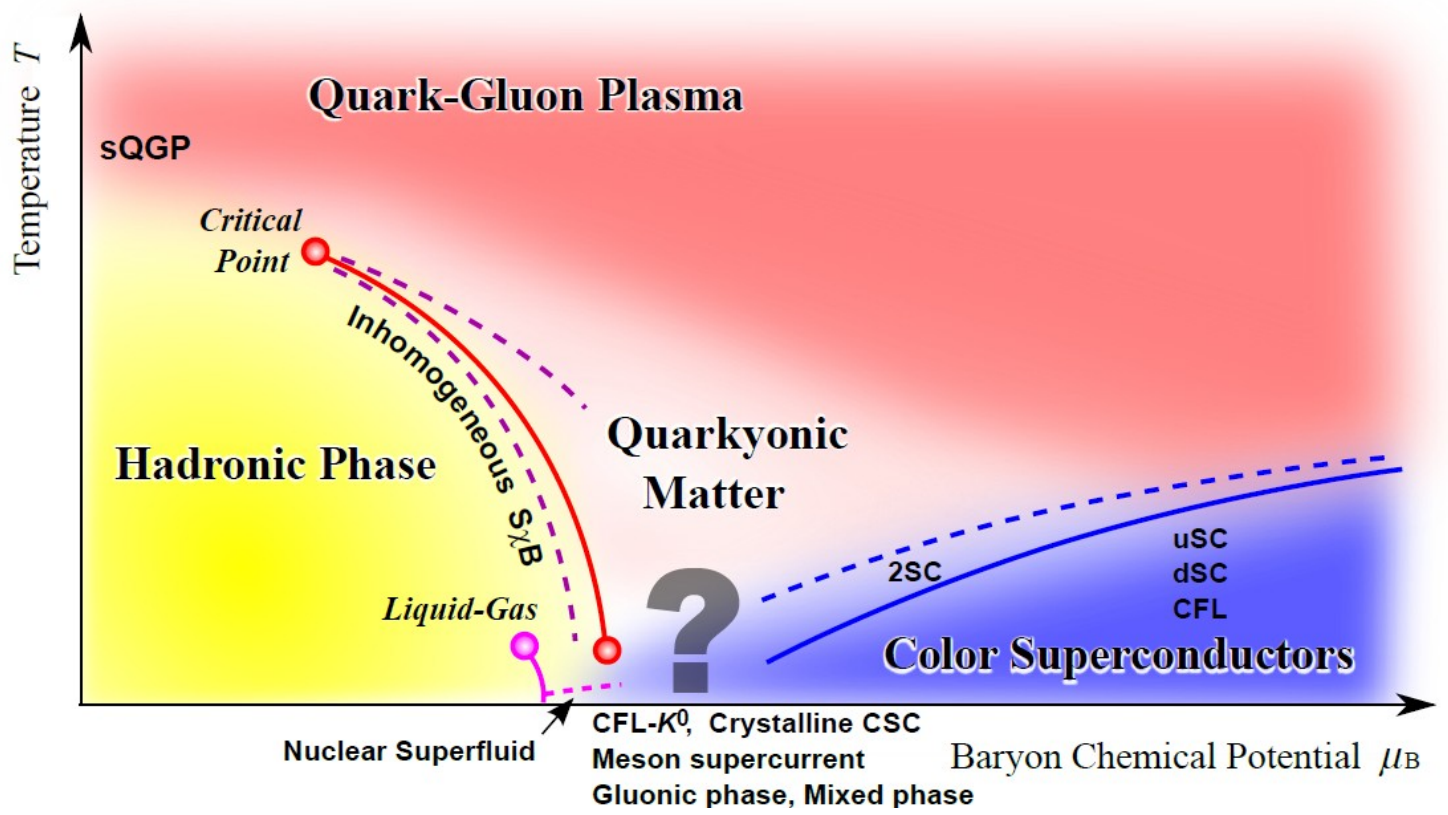


Center Symmetry



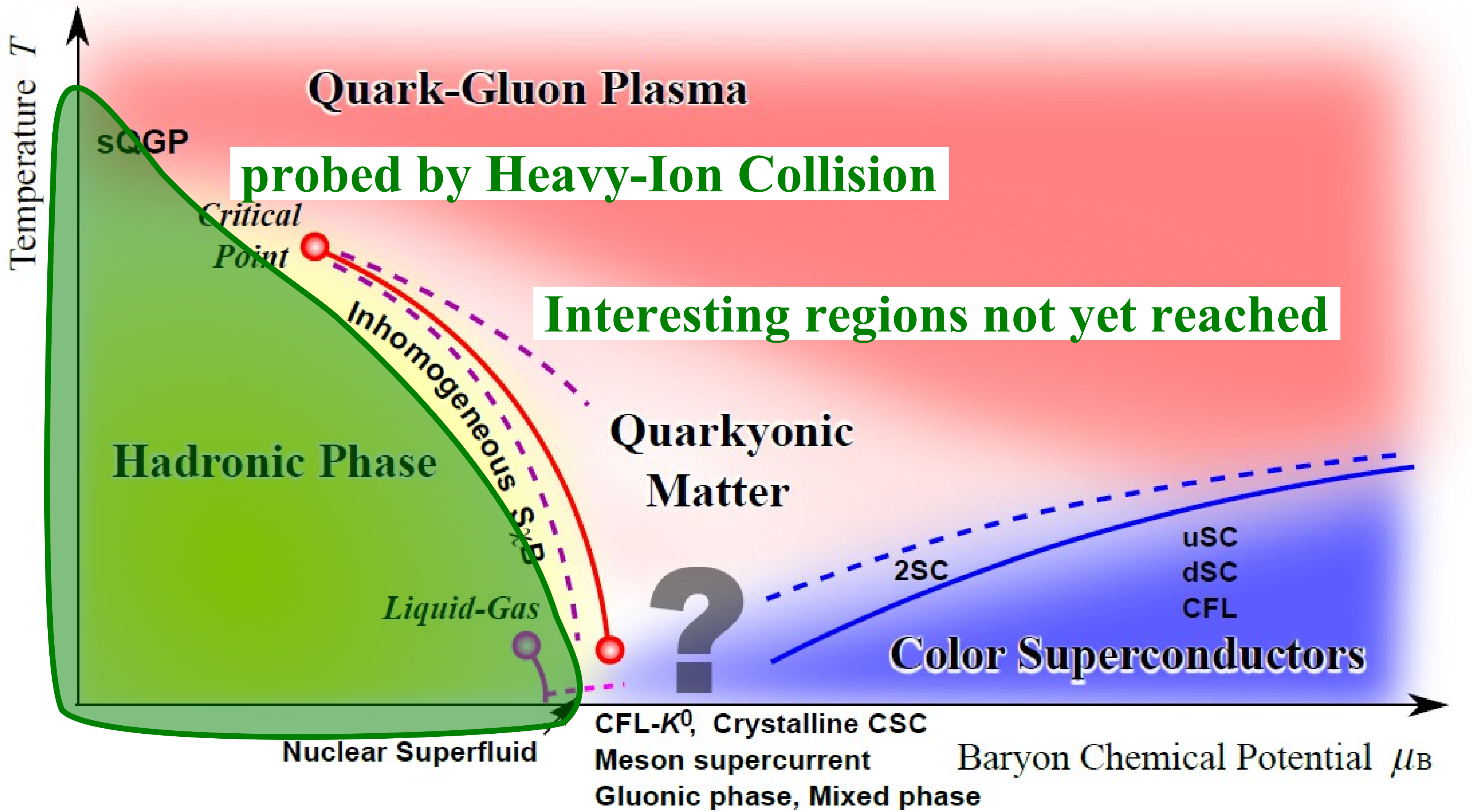
KF (2008)

Conjectured Phase Structure



KF-Hatsuda (2010)

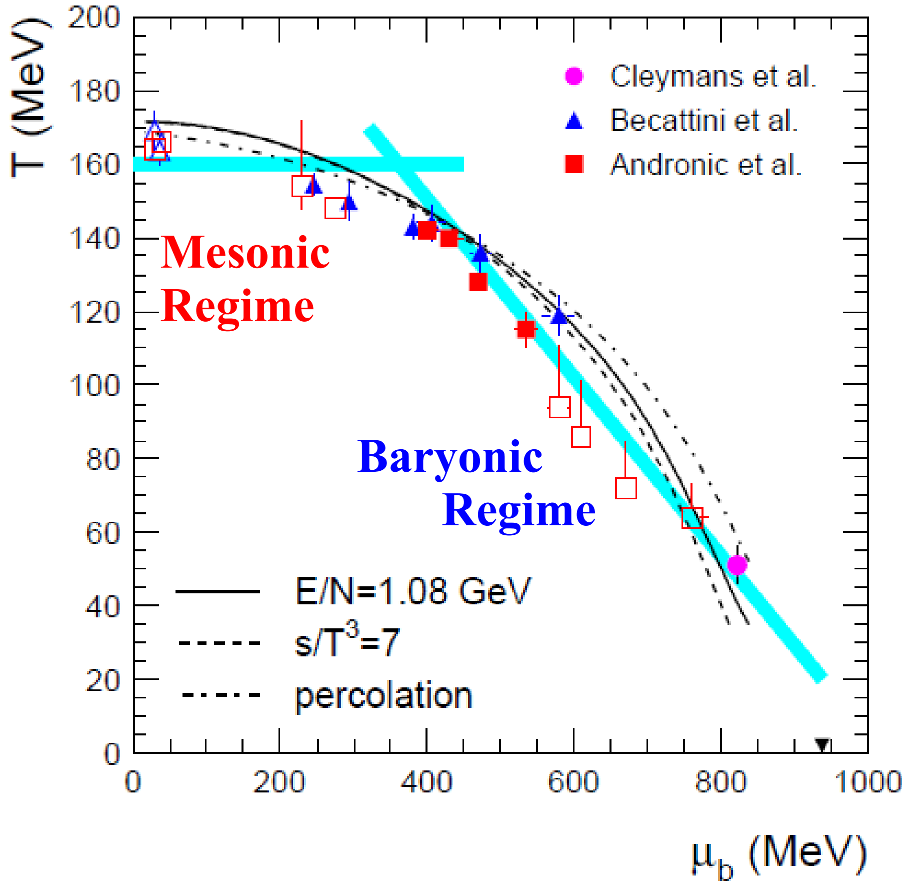
Experimental Confirmation



KF-Hatsuda (2010)

Interpretation of Data

Freeze-out points are located by the particle yields
Two regimes in **meson-dominance** and **baryon-dominance**



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

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

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

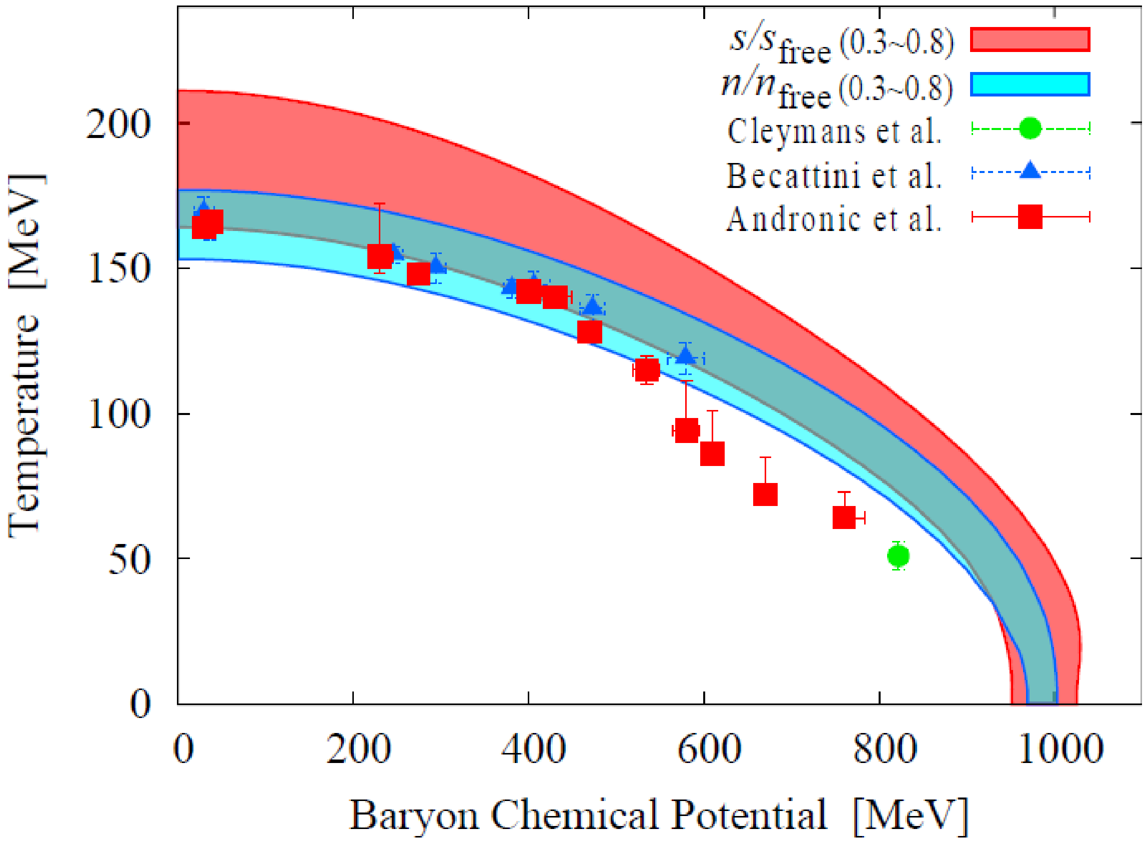
$$T_c = (1 - \mu_B/m_B)\, T_B$$

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

Thermodynamics

Statistical Model Interpretation

KF (2010)

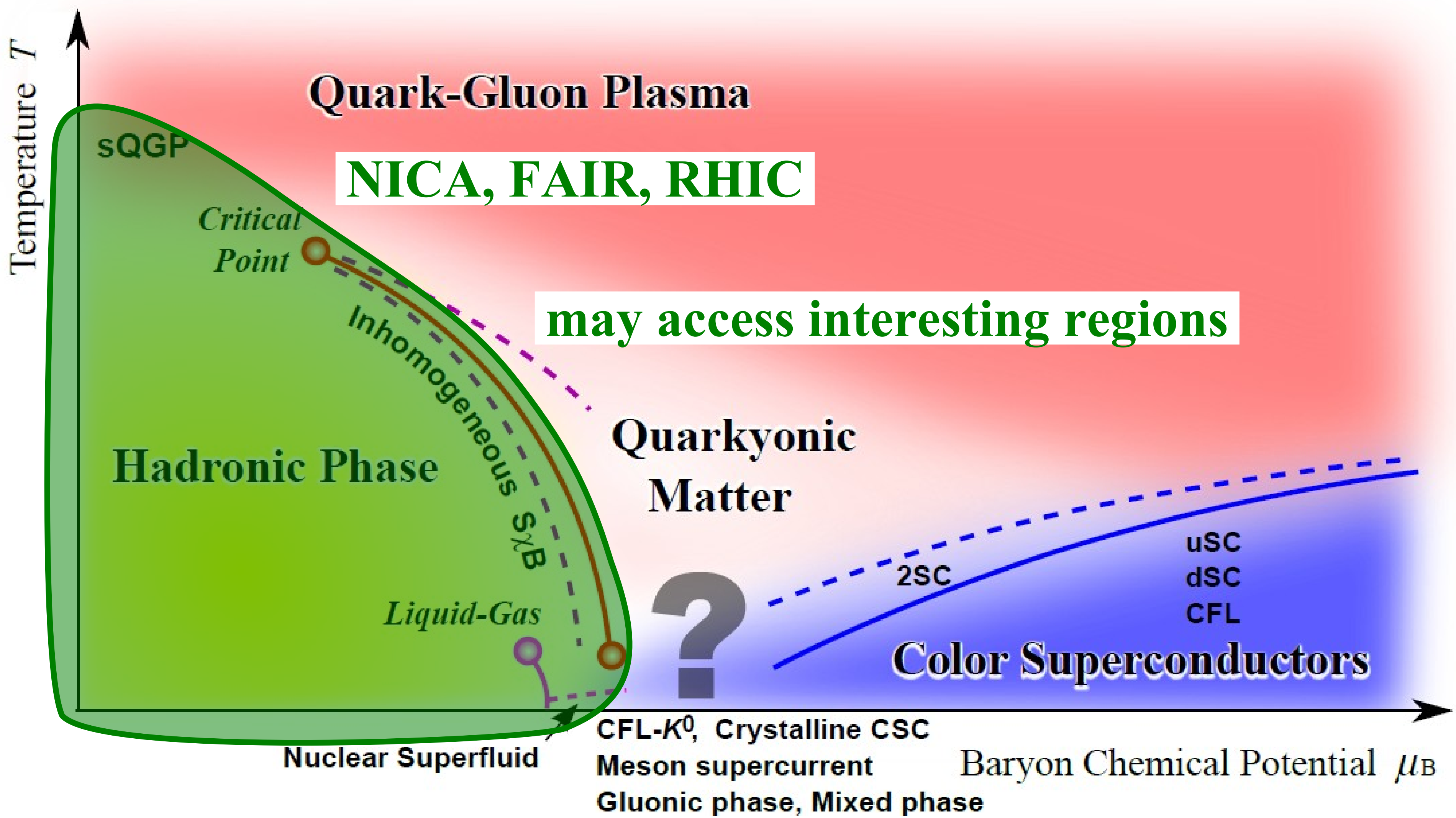


Gluon Deconfinement
~ Increasing entropy

Quark Deconfinement
~ Increasing density

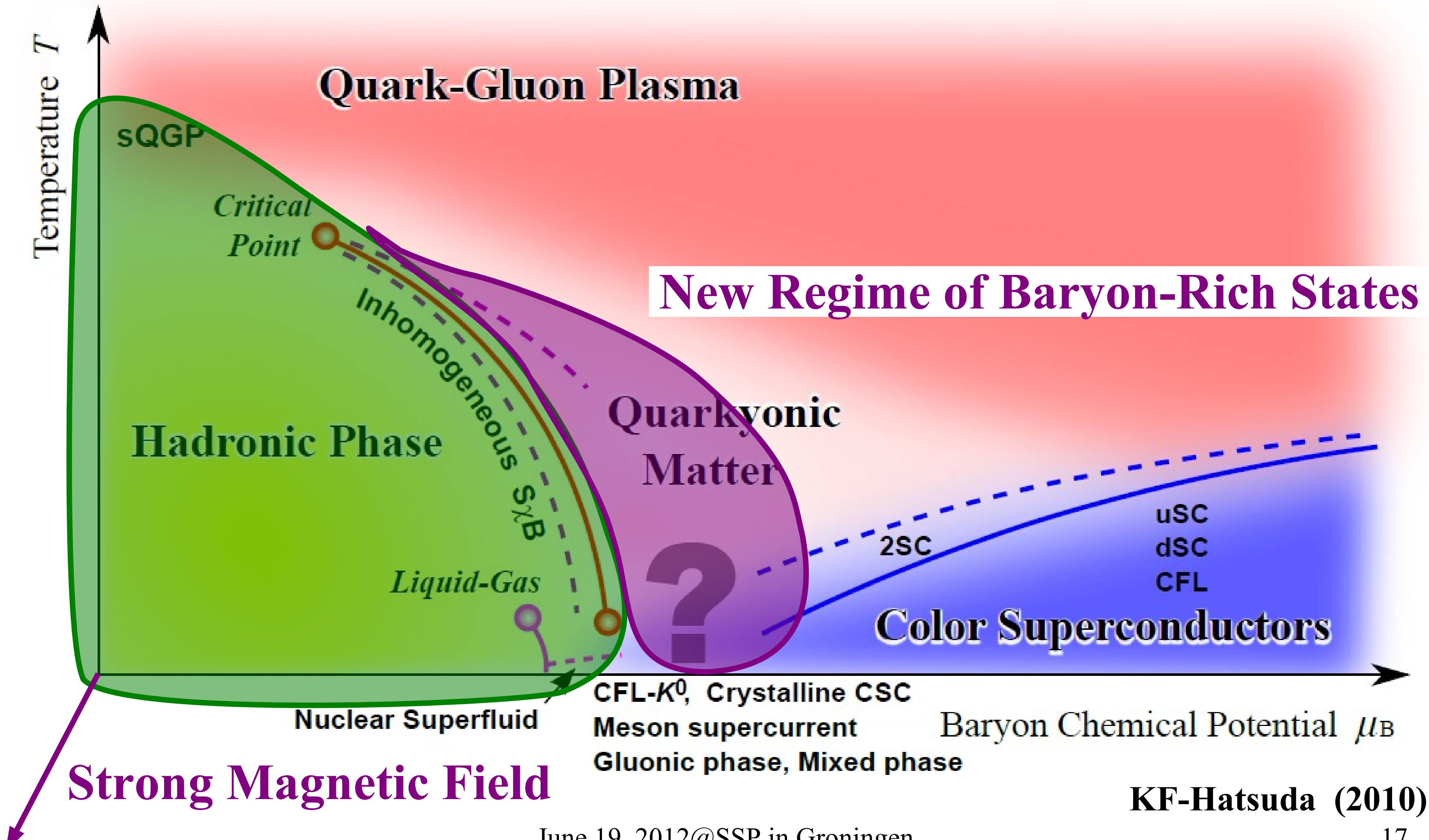
Thermodynamic quantities taken over by (quasi-)gluons and (quasi-)quarks (beyond the Hagedorn limit)

Experimental Challenges



KF-Hatsuda (2010)

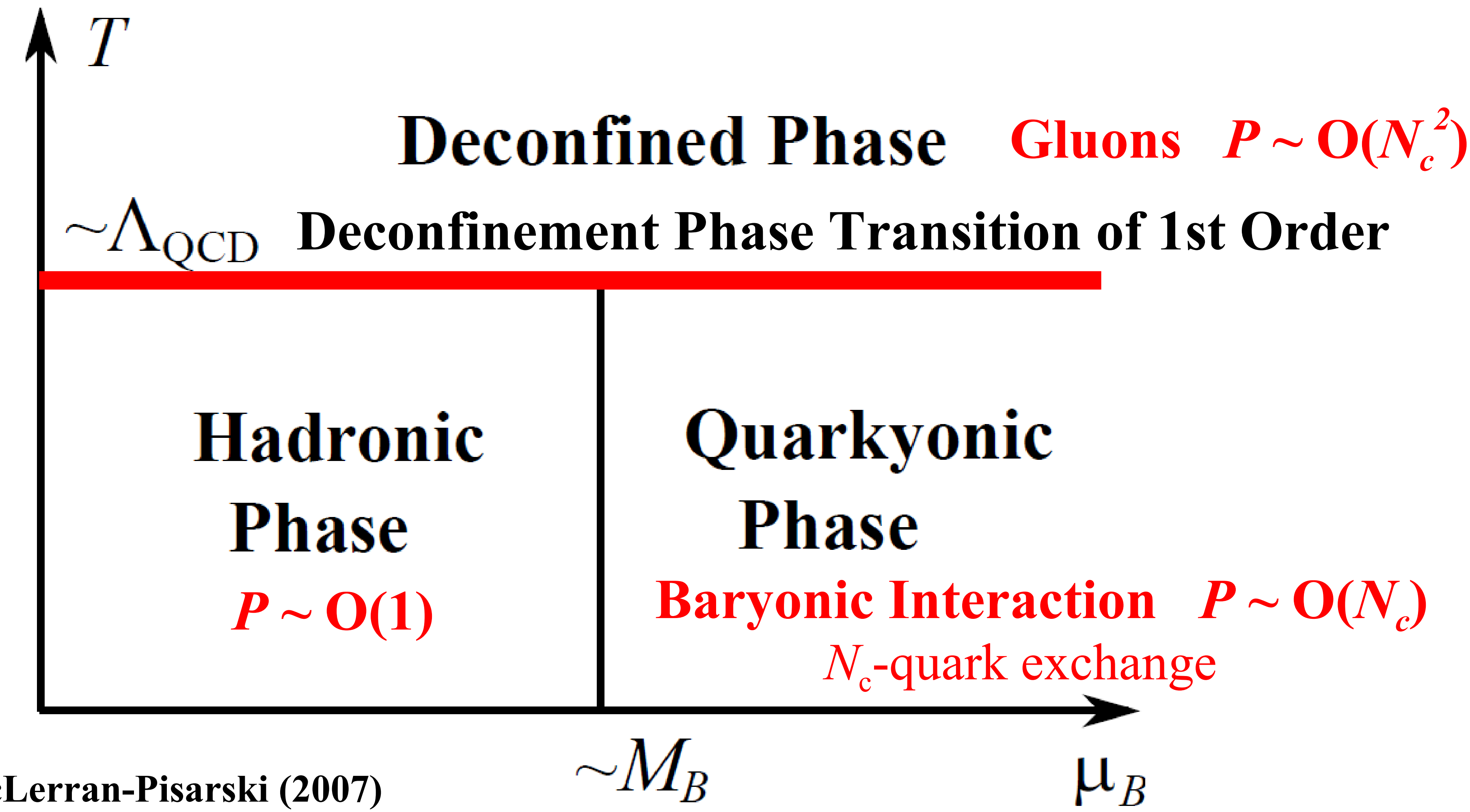
Theoretical Speculations



KF-Hatsuda (2010)

New Regime at Large μ_q and N_c

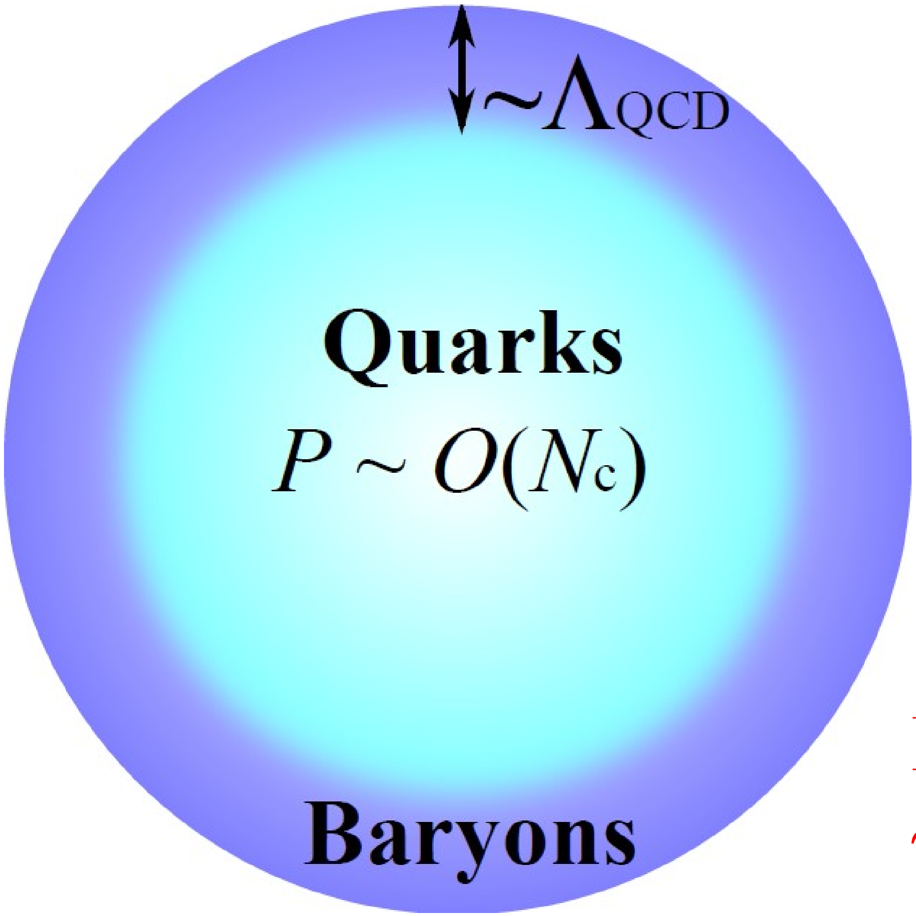
Phase Diagram of Large-N_c QCD



McLerran-Pisarski (2007)

Quarkyonic Matter

Structure of the Fermi Sphere



Ground state of large-N_c quark matter at $\mu_q >> \Lambda_{QCD}$

McLerran, Pisarski
Hidaka, Kojo

Interacting Baryon Crystal
~ Quasi-quark Gas

Quarkyonic Chiral Spiral $(\mu_q >> \Lambda_{QCD})$

Choose one direction z with $p_z \sim \mu_q$ $(p_x, p_y \sim \Lambda_{QCD})$
(1+1)D system effectively

$$\bar{\psi}(i\gamma^z \partial_z + \mu\gamma^0)\psi$$

$$= \bar{\psi}'(i\gamma^z \partial_z)\psi' \qquad \psi = e^{i\gamma^0\gamma^z \mu z}\psi'$$

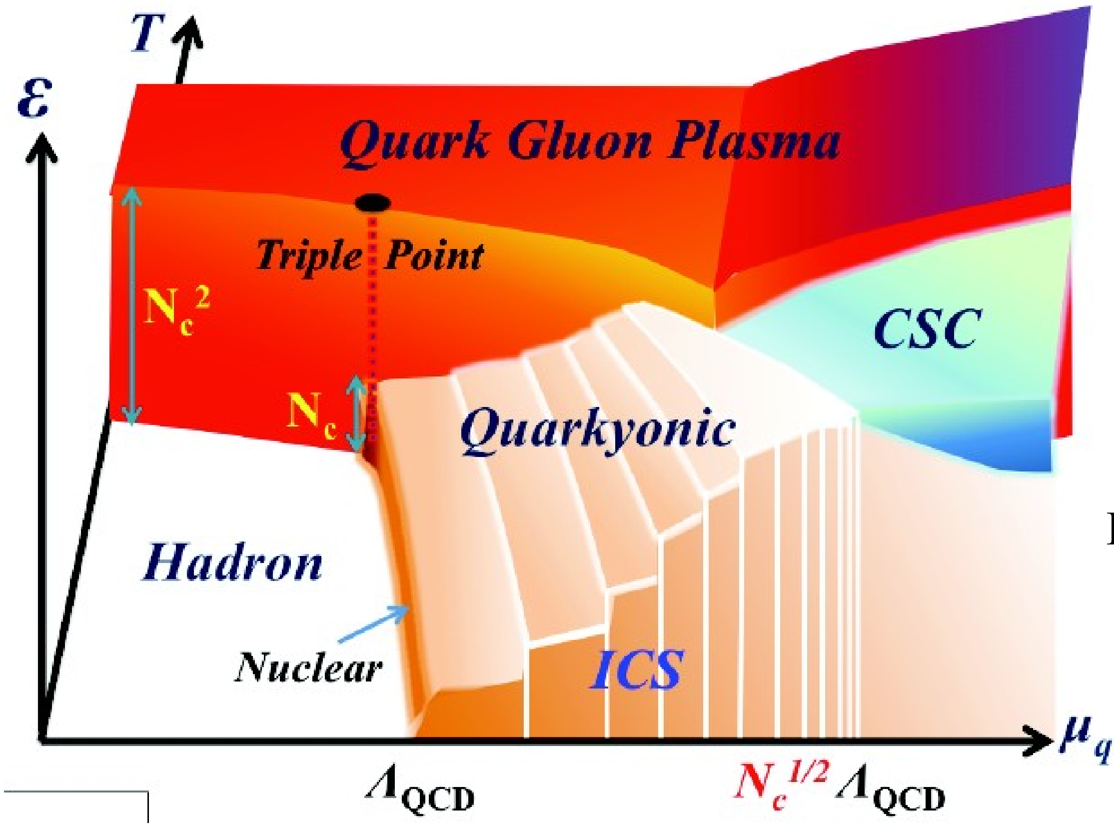
$\langle \bar{\psi}'\psi' \rangle =$ Homogeneous condensate at zero density

$$\langle \bar{\psi}\psi \rangle = \langle \bar{\psi}'\psi' \rangle \cos(2\mu z)$$

$$\langle \bar{\psi}\gamma^0\gamma^z\psi \rangle = \langle \bar{\psi}'\psi' \rangle \sin(2\mu z)$$

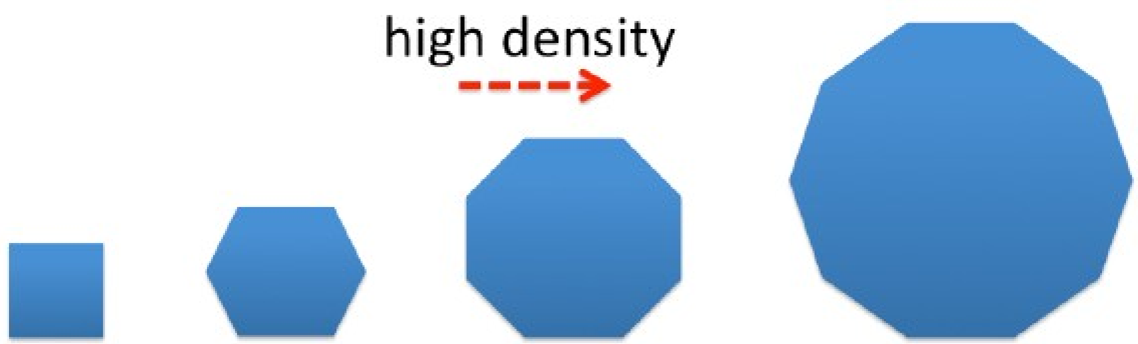
This quasi-(1+1)D system forms "one patch"

Interweaving Chiral Spirals

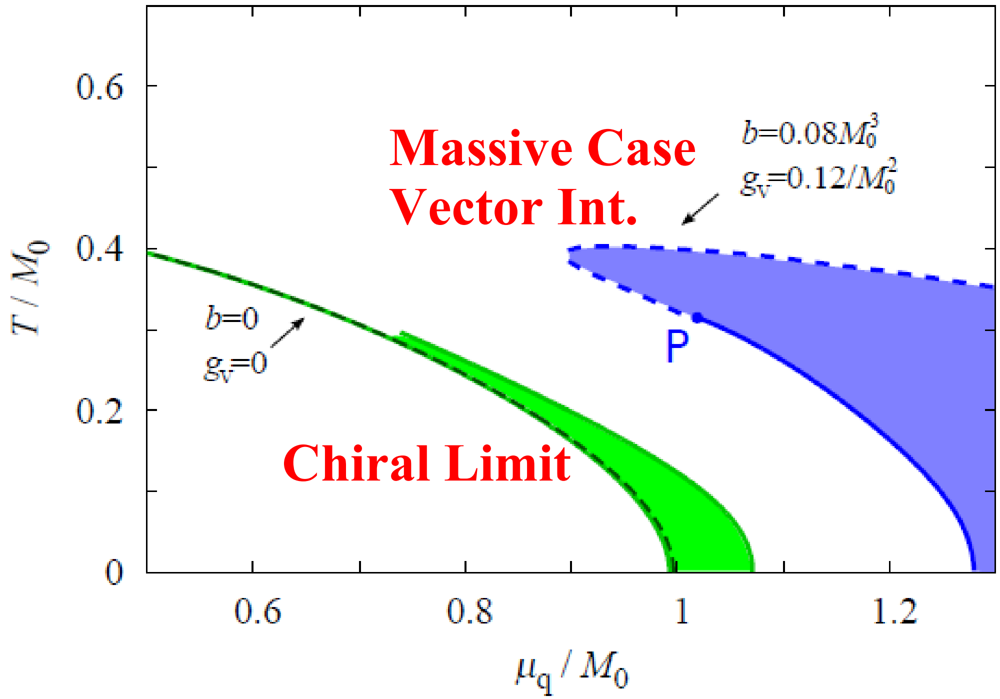


As the Fermi sphere enlarges, the patch number increases, forming a chiral quasi-crystal.

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



Some Generic Features



$$E_p = \sqrt{p_x^2 + p_y^2 + \left(\sqrt{p_z^2 + M^2} - q\right)^2}$$

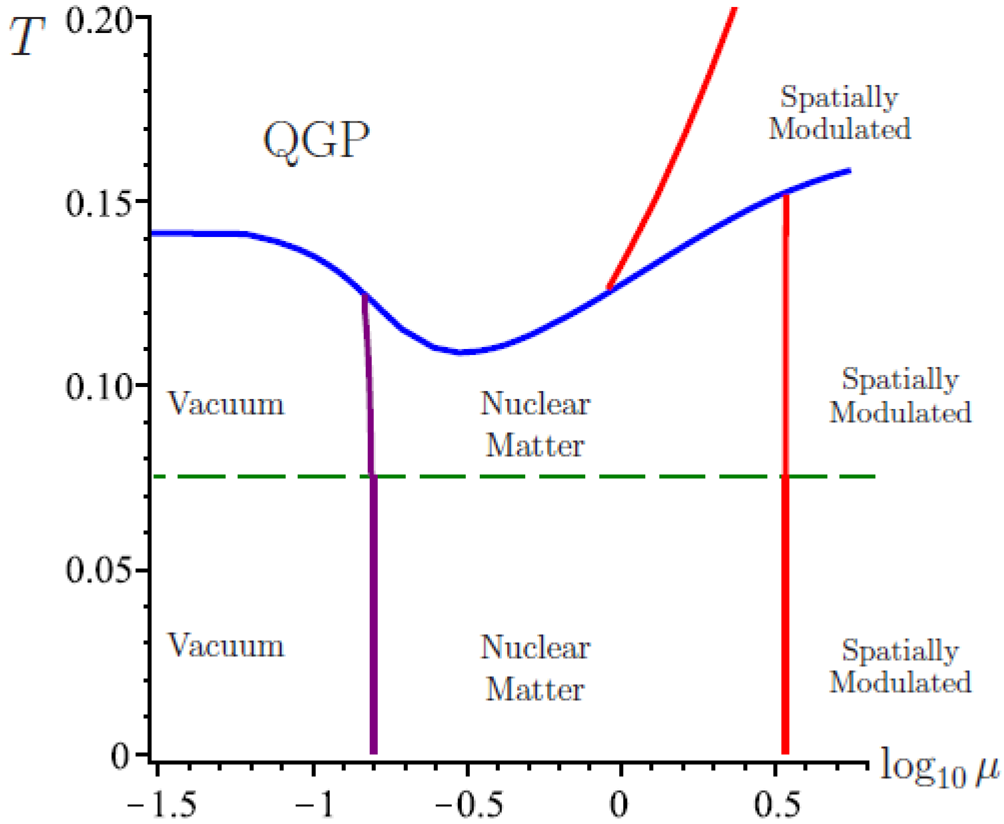
Effect of the dynamical mass M significantly canceled by q

Even when N_c and μ_q are not infinitely large, the chiral spiral is favored near the phase boundary of chiral symmetry

Nakano-Tatsumi (2003), KF (2012)

Holographic Evidence

State-of-the-art phase diagram in holographic model



Instability to inhomogeneous states is seen (in a different way from QCD...)

Nakamura-Ooguri-Park, Chuang-Dai-Kawamoto-Lin-Yeh (2010)

Density Effect ~ Magnetic Field Effect

Energy dispersion relation in *B*

$$\omega^2 = p_z^2 + 2|eB|(n+1/2) + m^2 - 2seB$$

Transverse motion = Harmonic Oscillator

Fermions (*s*=1/2) have zero mode – dominant at large *B*
Quasi-(1+1)D system is realized along the *B* direction.

Very strong *B* + Any μ_q → Chiral Spiral

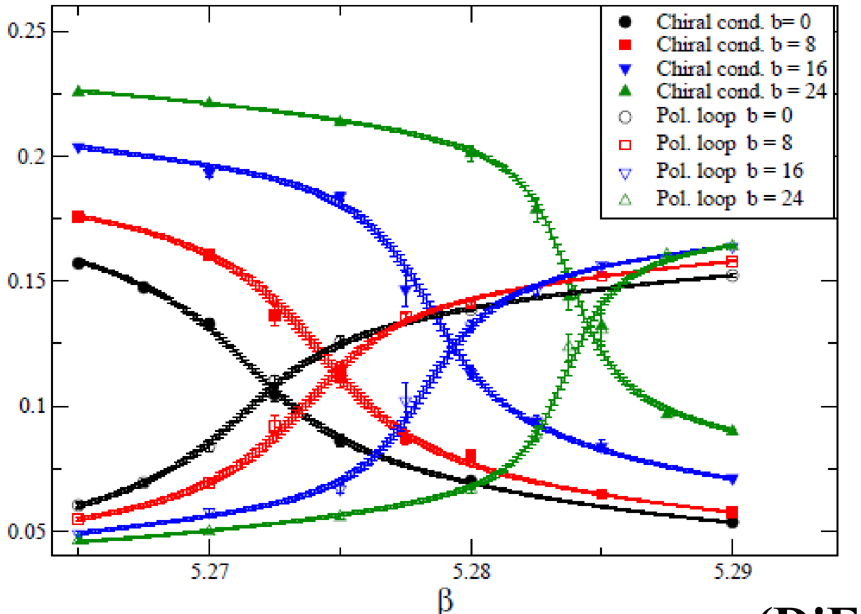
Basar-Dunne-Kharzeev

Very strong *B* + Attractive Int.
→ Cooper Instability → Magnetic Catalysis

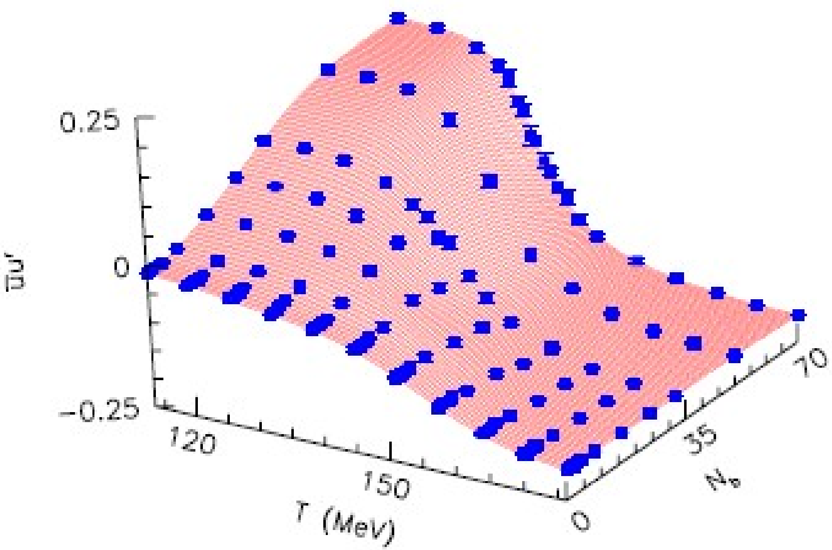
Klimenko, Gyusynin-Miransky-Shovkovy

B Effect on the Phase Diagram

QCD phase transitions affected by *B*



(D'Elia et al)



(Fodor et al)

Monte-Carlo simulation is possible (no sign problem)

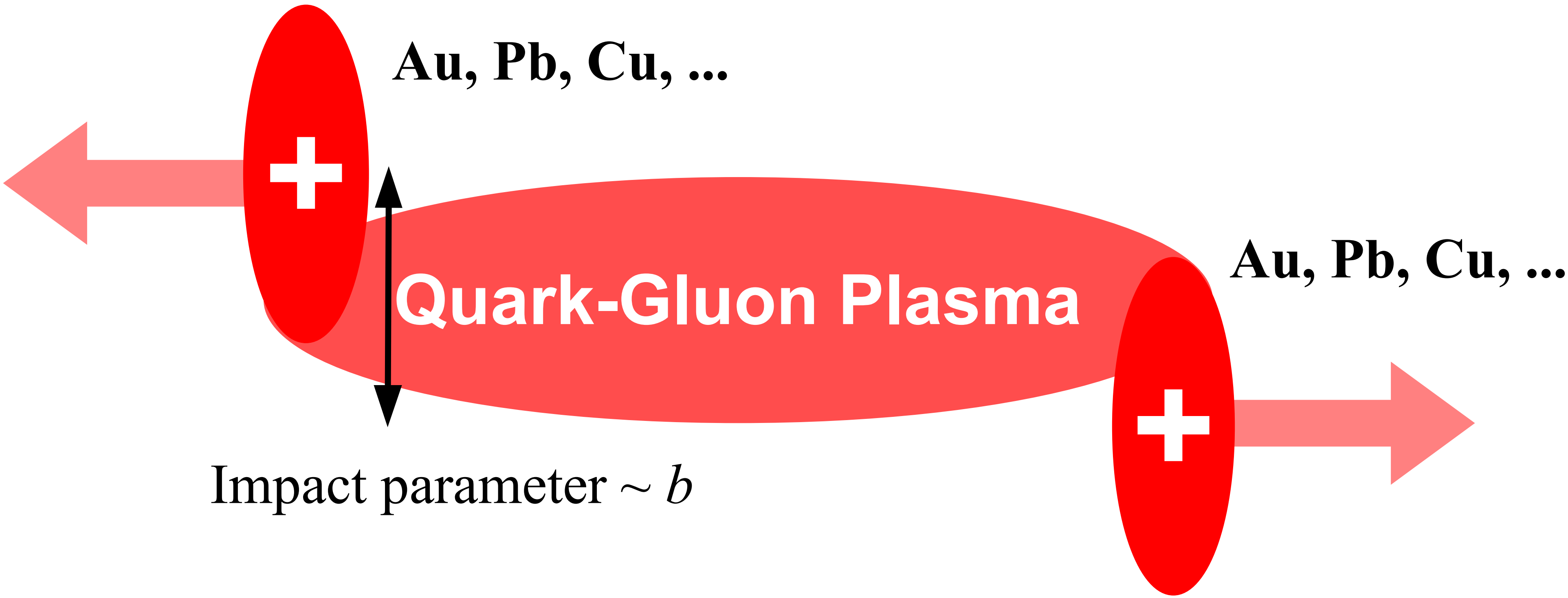
T_c increases or decreases?

We can learn lessons for the high-density QCD!

Reality in Experiments

Relativistic Heavy-Ion Collision

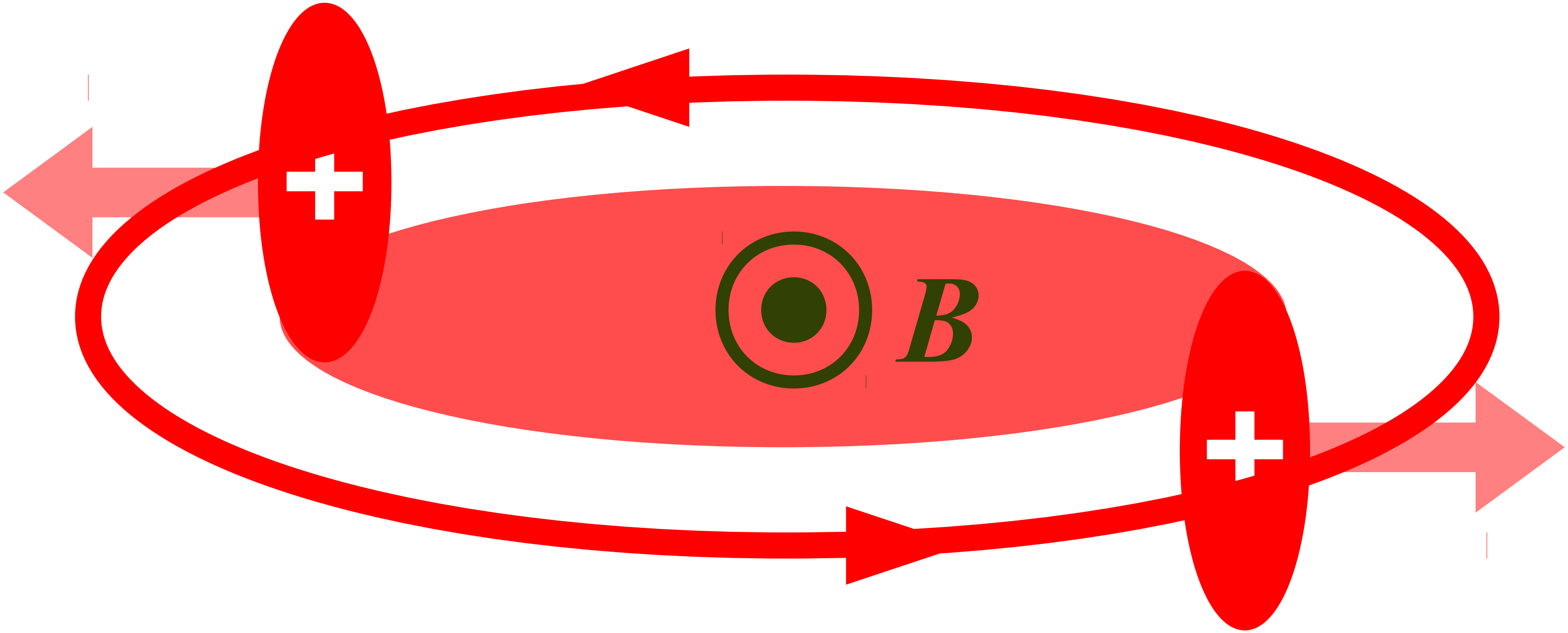
Moving almost at the speed of light



Impact parameter ~ b

Origin of the Magnetic Field

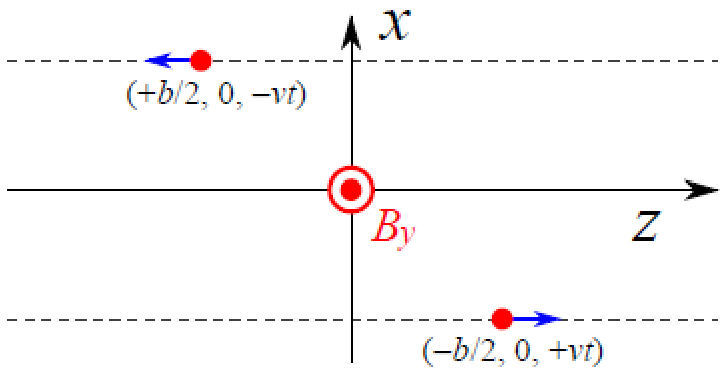
Strong B generated due to Electrodynamics

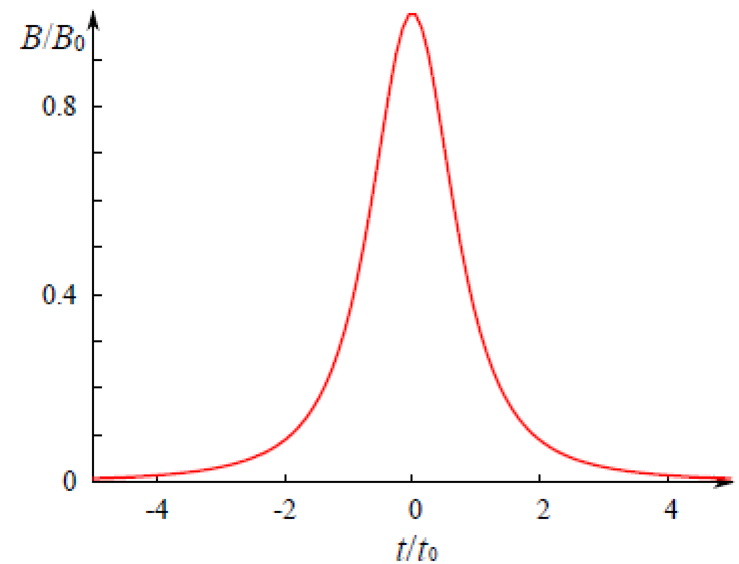


on top of the Quark-Gluon Plasma

Point-charge Approximation

Lienard-Wiechert potential





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

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

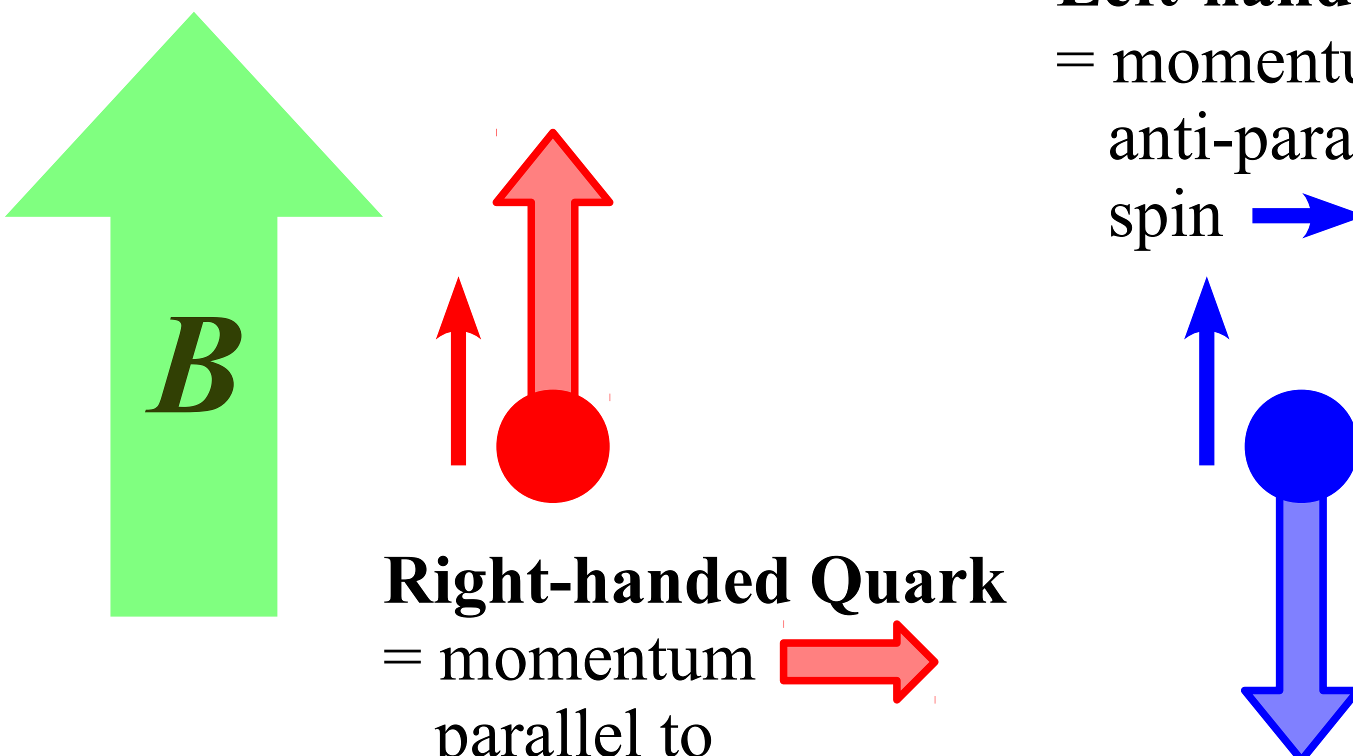
$\sim 10^{18}$ gauss

Interesting phenomena expected!

Discussed by Rafelski, Mueller, … (~1976)

Chiral Magnetic Effect

Classical Picture



Left-handed Quark
= momentum anti-parallel to spin

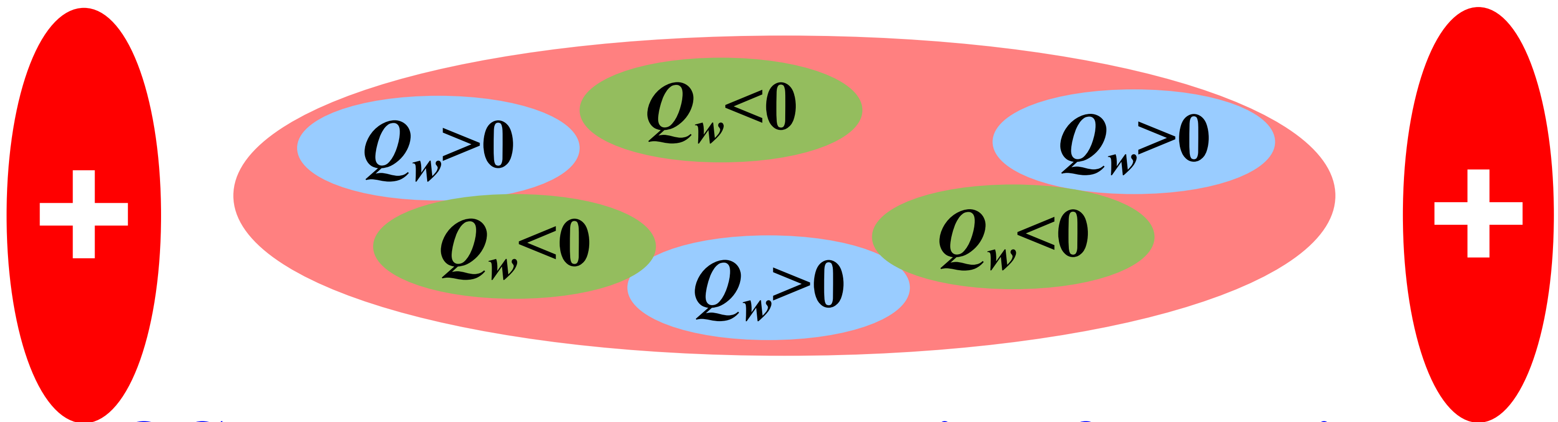
Right-handed Quark
= momentum parallel to spin

Finite Chirality
($\mathcal{P}$ and $C\mathcal{P}$ odd)

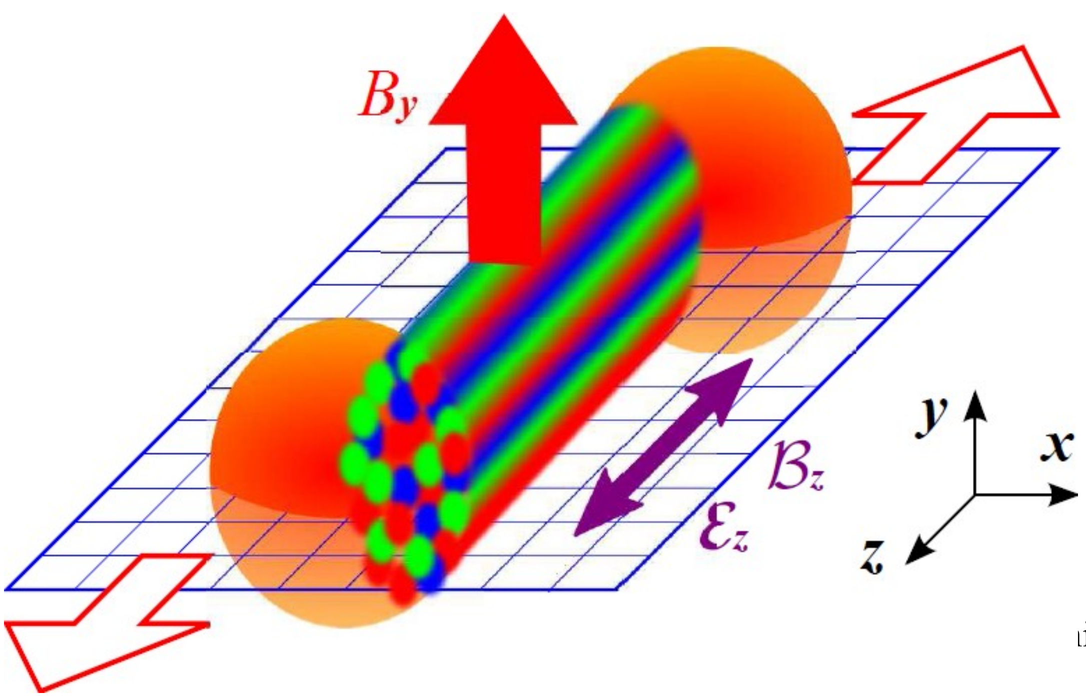
$$\boldsymbol{J} \neq 0 \quad \text{if} \quad N_5 = N_R - N_L \neq 0$$

Kharzeev-McLerran-Warringa (2007)

Local Parity Violation (LPV)



QCD vacuum has topological fluctuations



Initial condition of HIC (Color Glass Condensate) accommodates topological fluctuations

Current Generation through Anomaly

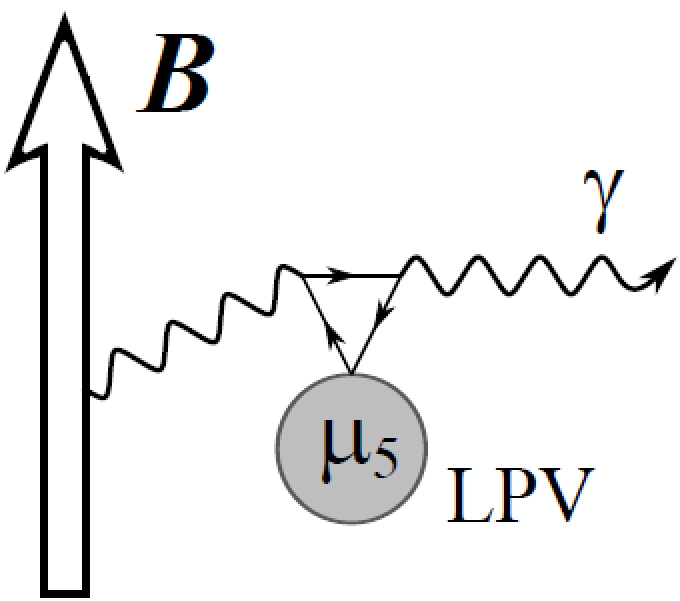
Chiral Magnetic Effect → Charge Separation

$$\boldsymbol{j} = N_c \sum_{\text{flavor}} \frac{q_f^2 \mu_5}{2\pi^2} \boldsymbol{B}$$

Vilenkin (1980), Metlitski-Zhitnitsky, KF-Kharzeev-Warringa

Photon Production from the CME

$$\Gamma_p = \int N_c \sum_f \frac{q_f^2 B_z(x)}{2\pi^2} \cdot \frac{\partial_t \theta(x)}{2N_f} \cdot A_z(x)$$



Reverse process of the Primakoff effect

$\gamma + \gamma^*$ (background) $\rightarrow$ (neutral meson)

$\Downarrow$

$(\mathrm{LPV}) + \gamma^* \rightarrow \gamma$

KF-Mameda (2012)

Soft photon production is under active discussions

Summary

QCD phase diagram – Chiral and Center Symmetry

- *High Temperature* – Phase transitions well understood from the zero-T properties of confinement.
- *High Baryon Density* – Inhomogeneous states favored near the phase boundary of homogeneous states.
- *Strong B Field* – Effects on the phase diagram not yet understood. Anomalous phenomena ($\mathcal{P}$ and $C\mathcal{P}$ odd effects)

Experimental efforts focused on the baryon-rich matter and the visible effects of the strong B:

- Systematic fluctuation measurements to confirm the local parity violation / critical point / inhomogeneity