Extreme QCD Matter

Fate of chiral symmetry in strong magnetic fields

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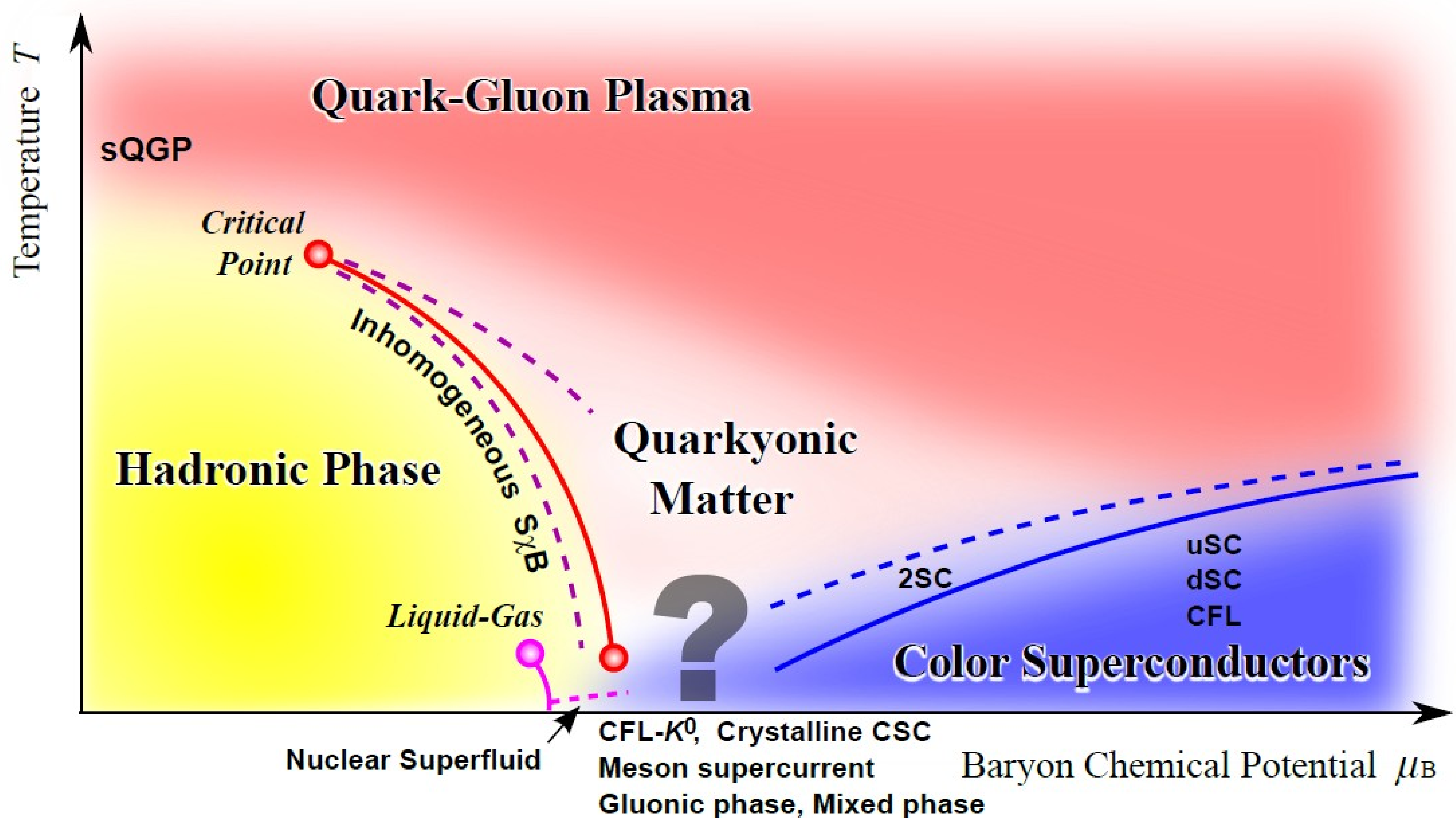
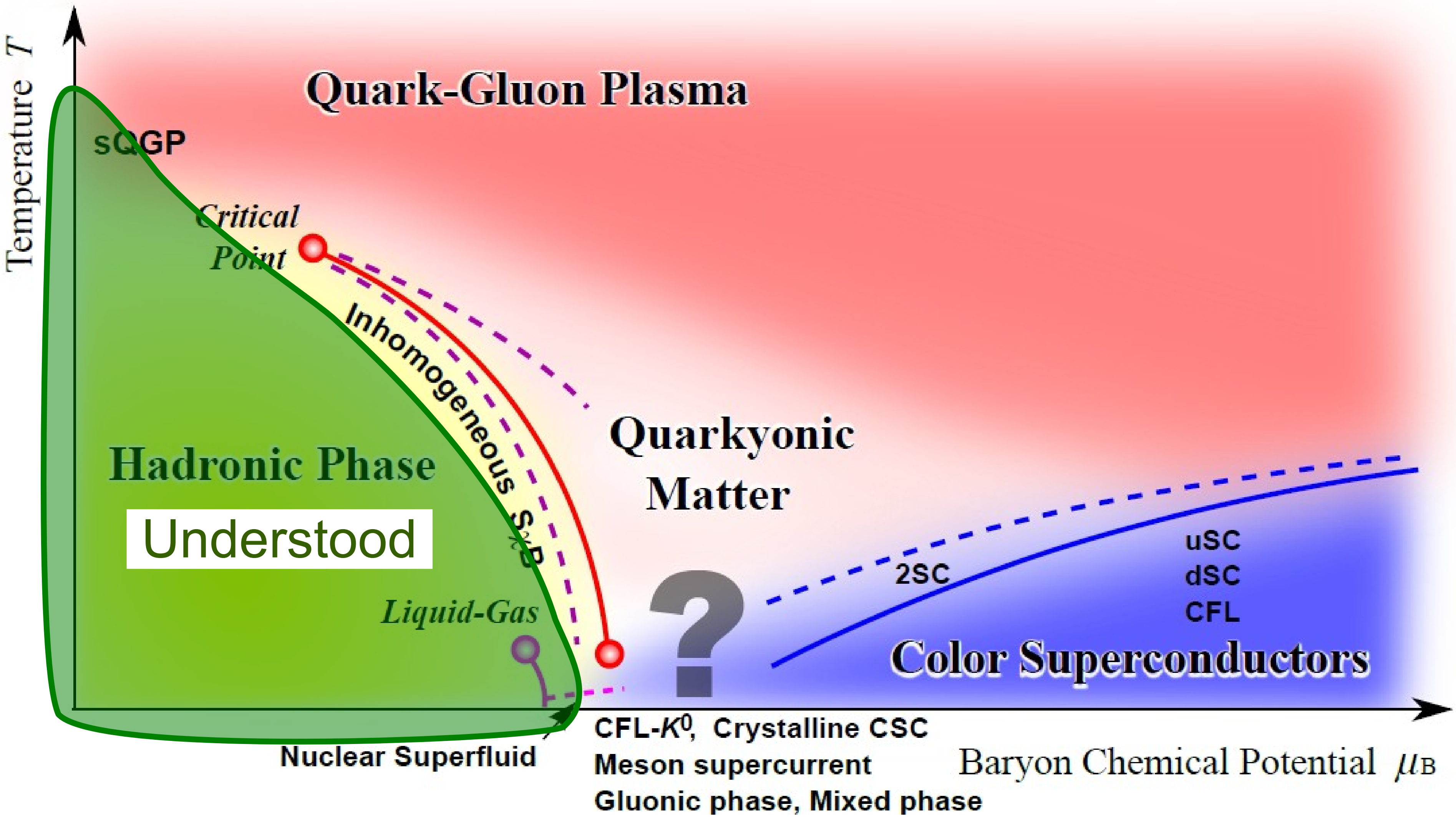
What and how are we studying?

QCD Phase Diagram



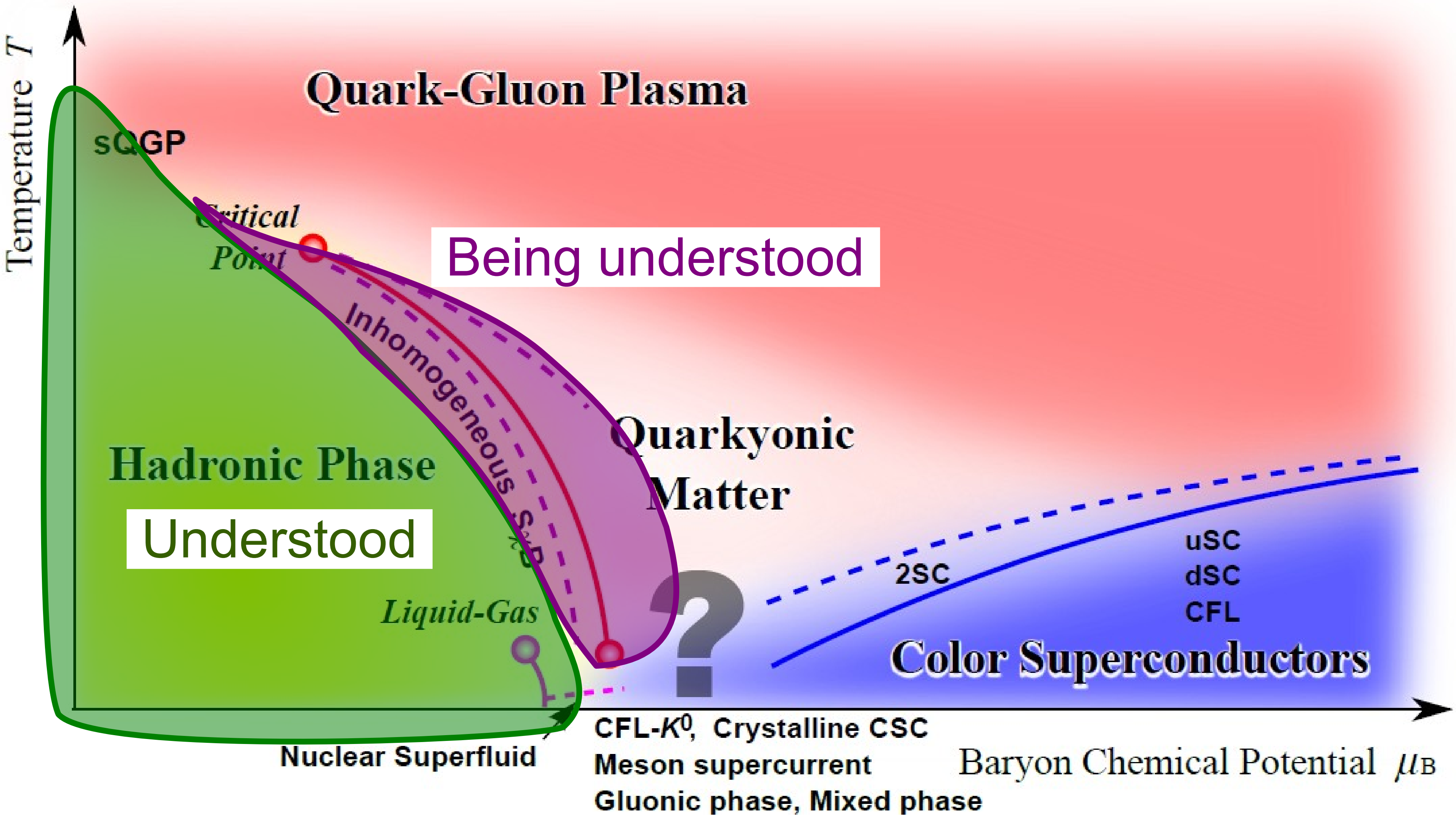
KF-Hatsuda (2010)

QCD Phase Diagram



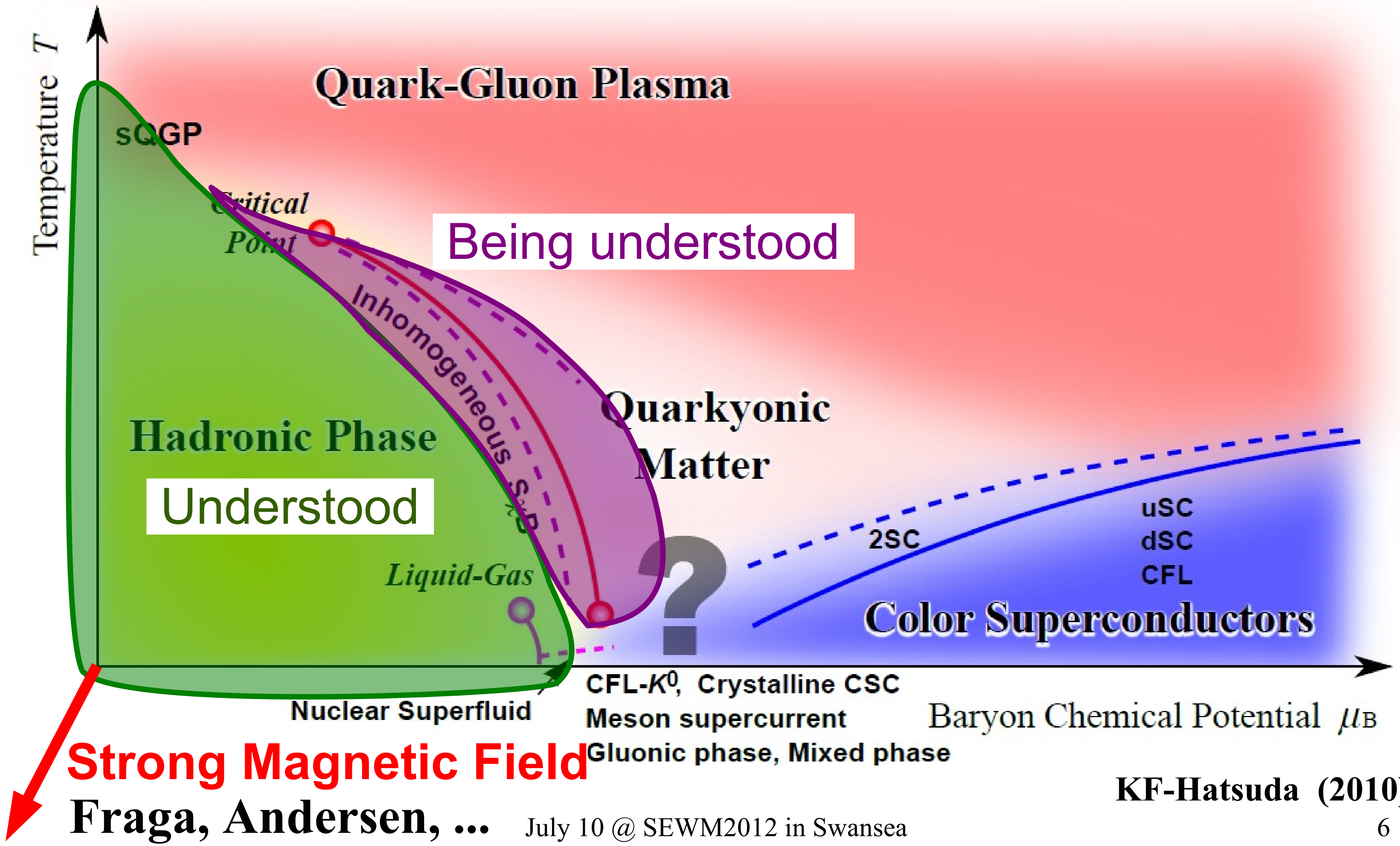
KF-Hatsuda (2010)

QCD Phase Diagram



KF-Hatsuda (2010)

QCD Phase Diagram



Fraga, Andersen, ...

KF-Hatsuda (2010)

Typical Extreme's

High Temperature

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

Relativistic Heavy-Ion Collision

High Baryon Density

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

Relativistic Heavy-Ion Collision, Neutron Star

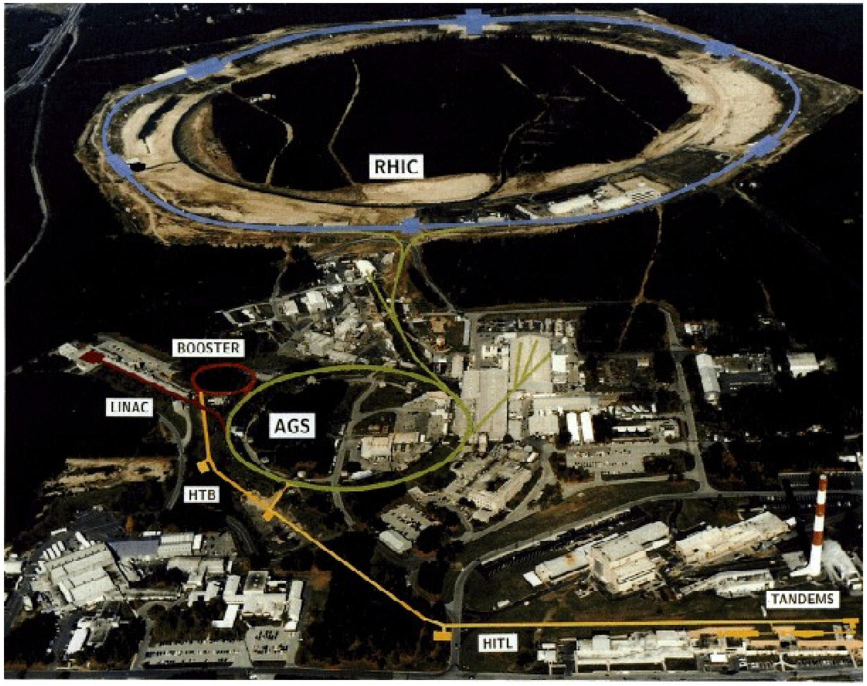
Strong Magnetic Field

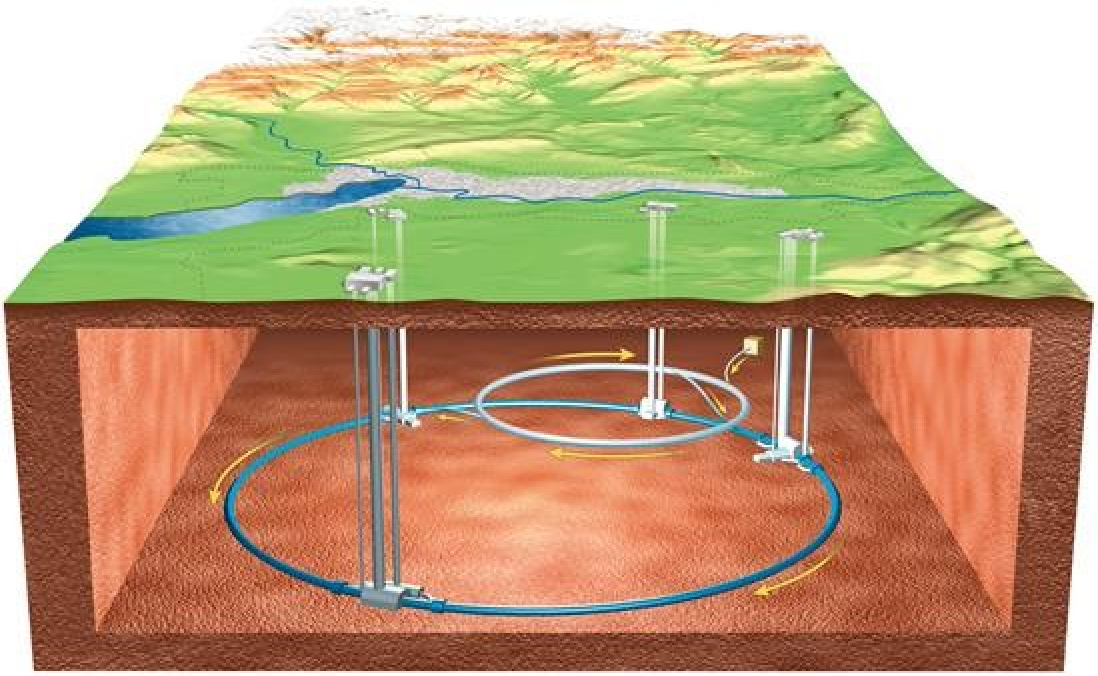
up to $eB \sim (\Lambda_{QCD})^2 \sim 10^{18}$ gauss

Relativistic Heavy-Ion Collision, Neutron Star

Experimental Facilities

RHIC **LHC**



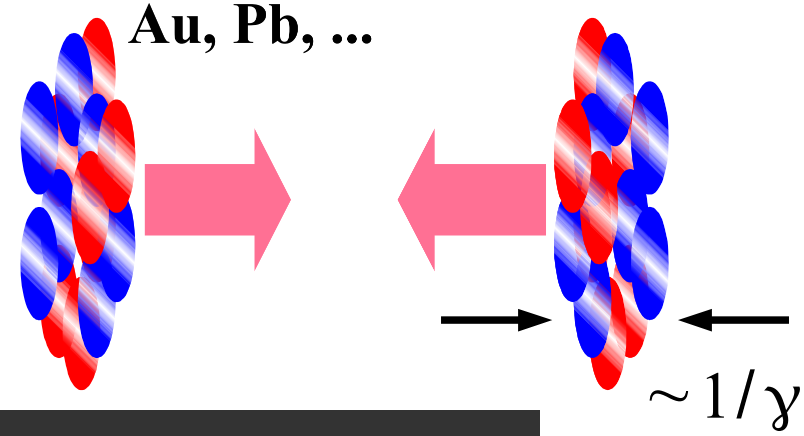


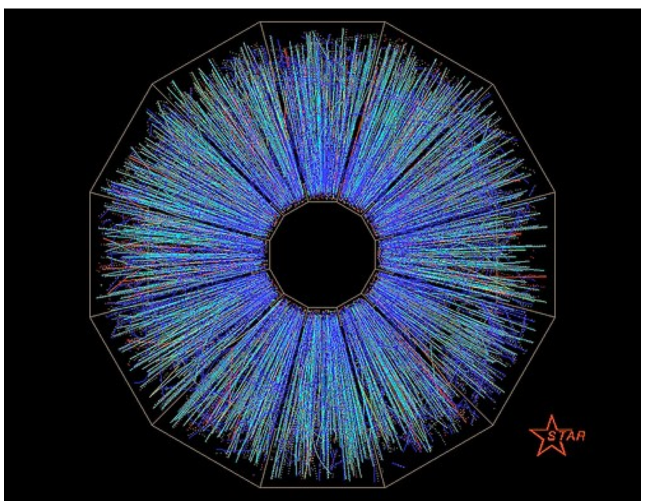
Heavy-ions collide → A new state of matter
(Au, Pb, …) (Quark-gluon plasma)

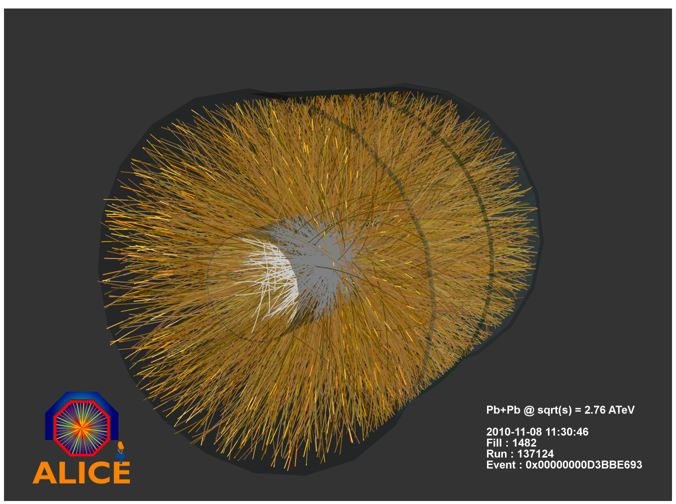
Relativistic Heavy-Ion Collision

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

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





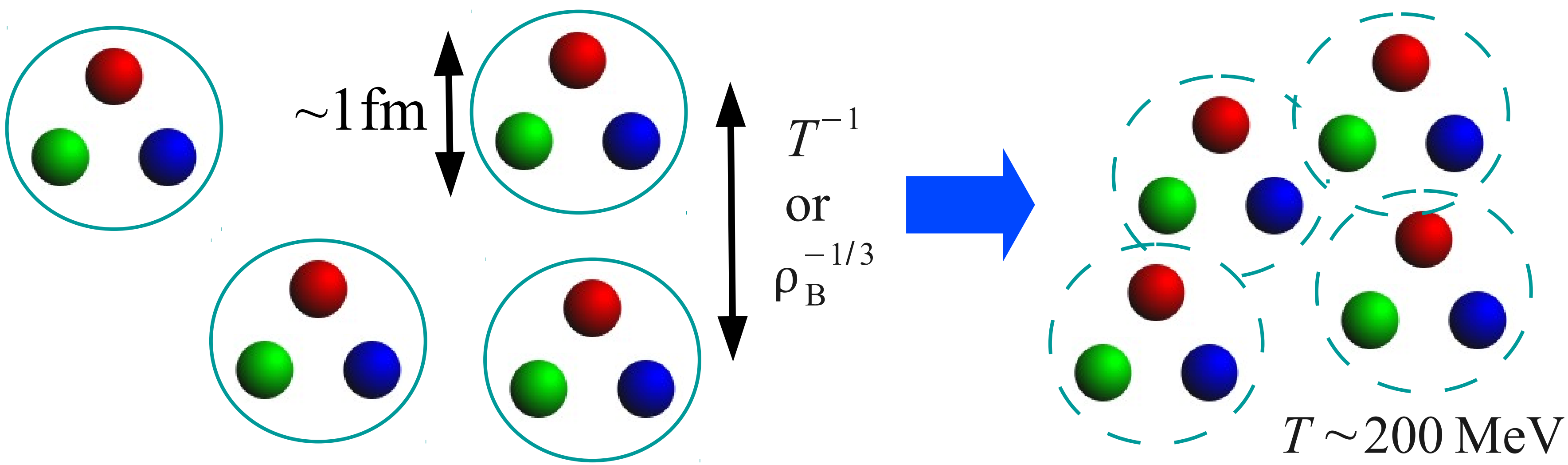


Thermalization achieved (elliptic flow by a hydro-model)
Initial temperature > 200MeV (distribution of thermal photon)

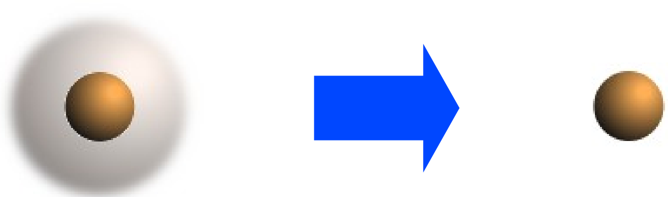
QCD phase transition at high T

Two Major Phase Transitions in QCD

Quark Deconfinement Transition (Center Symmetry)



Chiral Phase Transition (Chiral Symmetry)



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

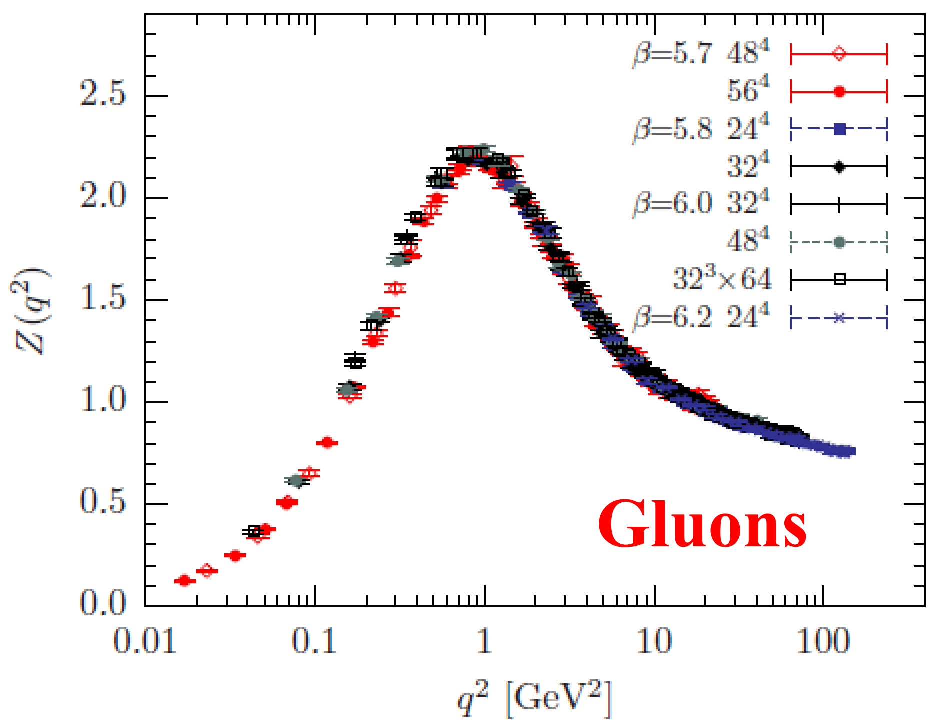
"Constituent" Quarks
$M_q \sim 350$ MeV

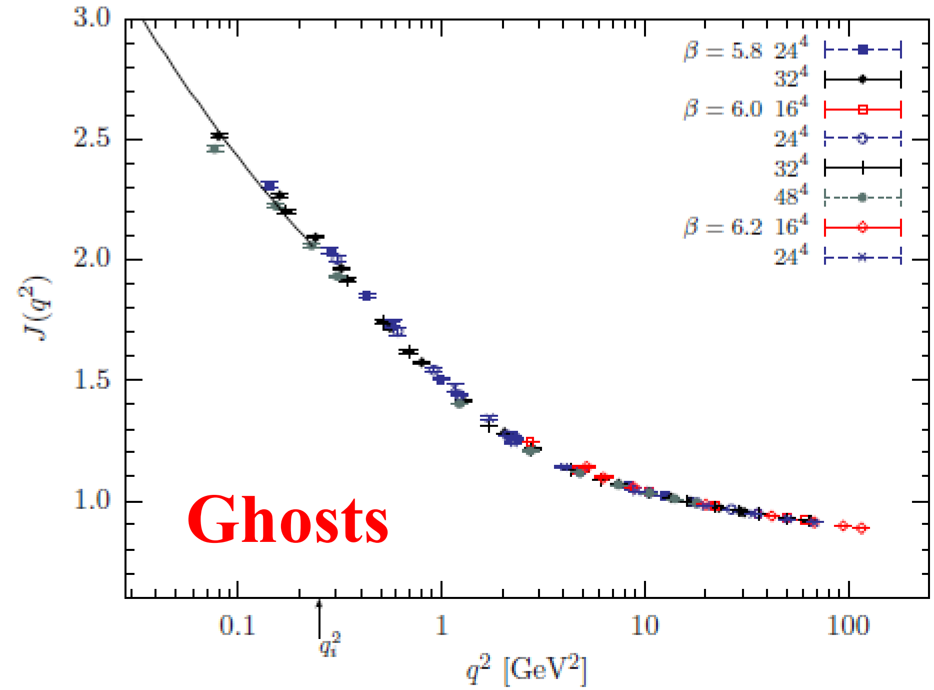
Nambu-Jona-Lasinio

Deconfinement from Confinement

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

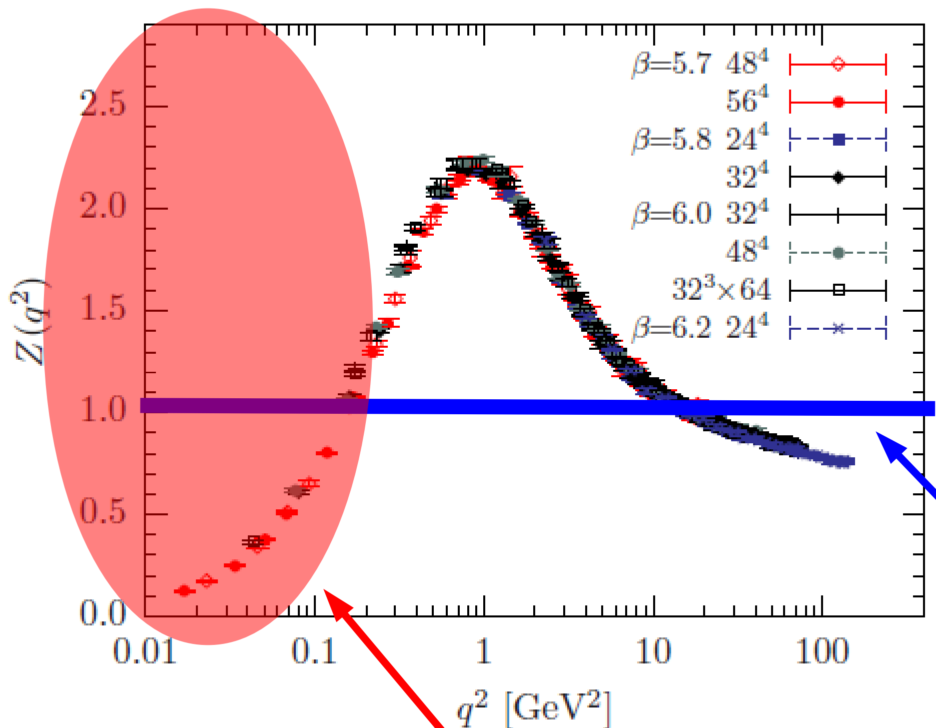
Ilgenfrits-Muller-Preussker-Sternbeck-Schiller-Bogolubsky (2007)

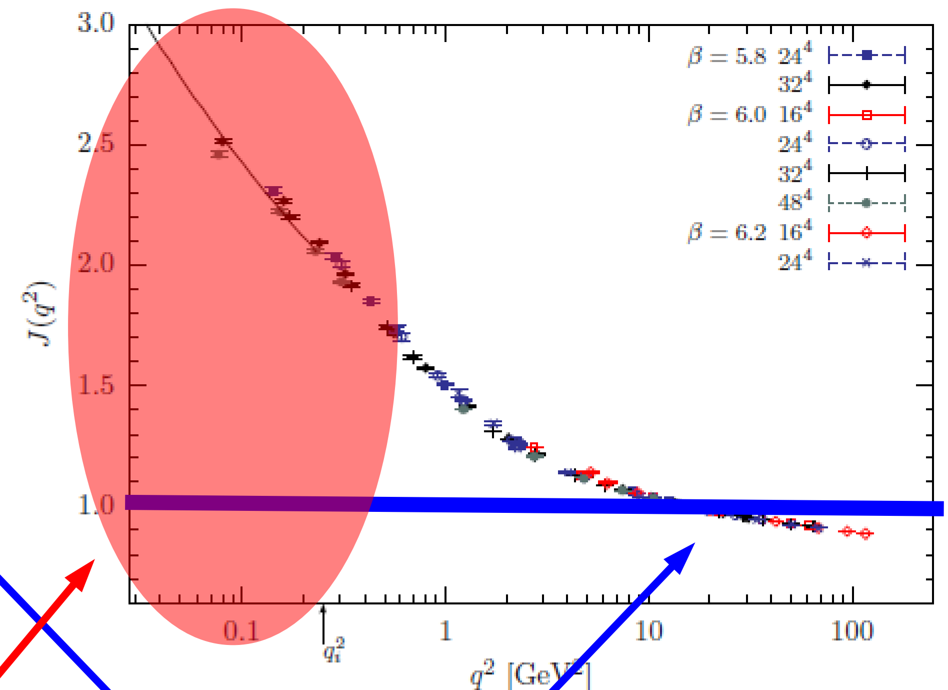




Behavior of the “dressing functions” (propagator residue)

Confinement at Low T



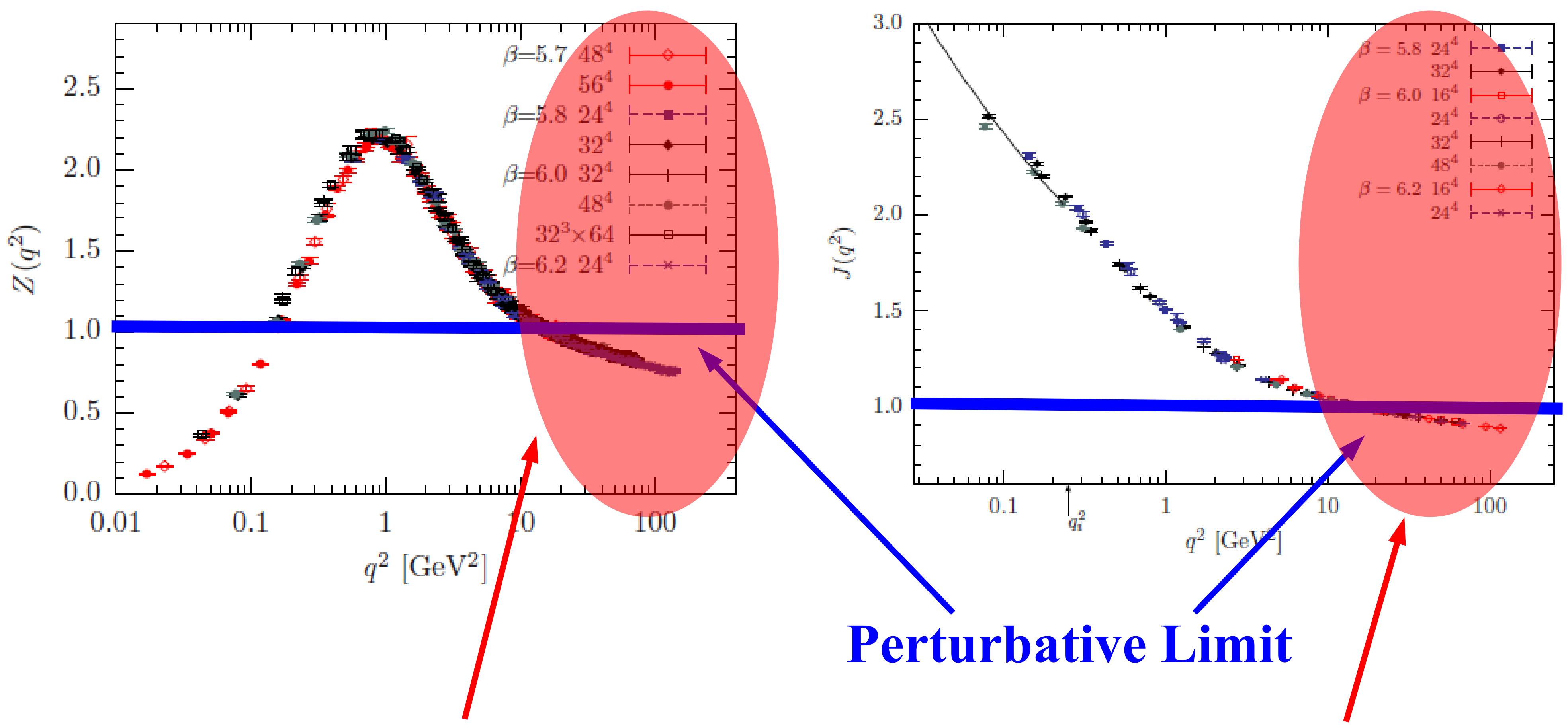


Perturbative Limit

Ghost Dominance → Color Confinement

(c.f. Kugo-Ojima / Gribov-Zwanziger)

Deconfinement at High T

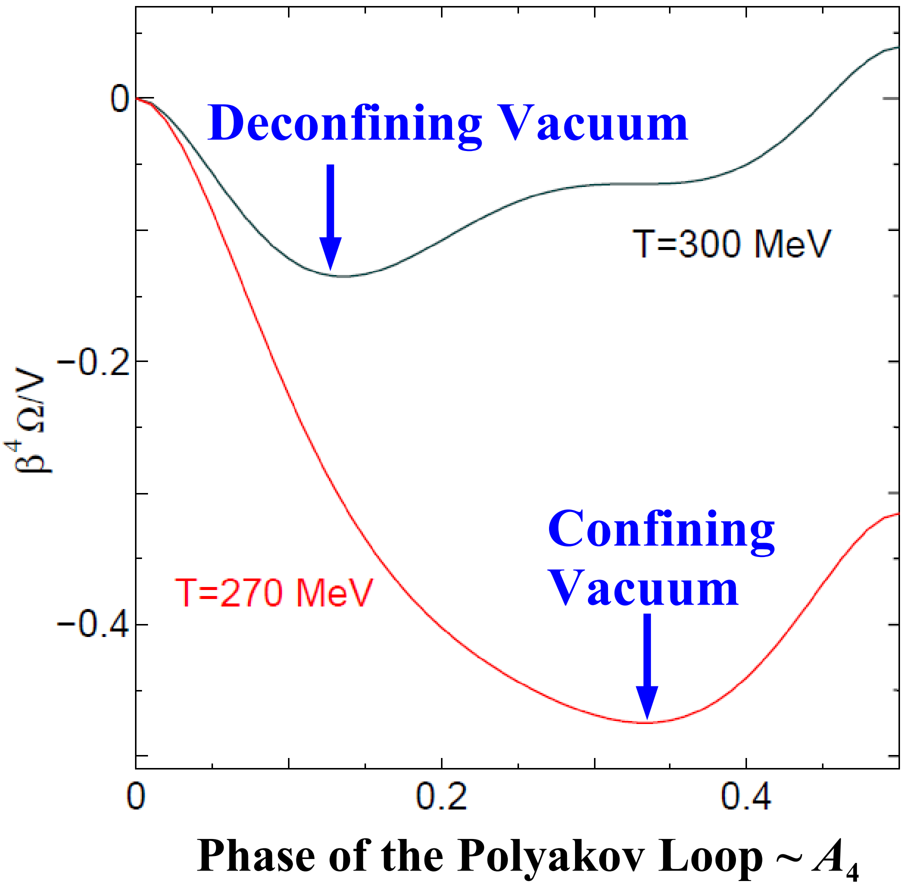


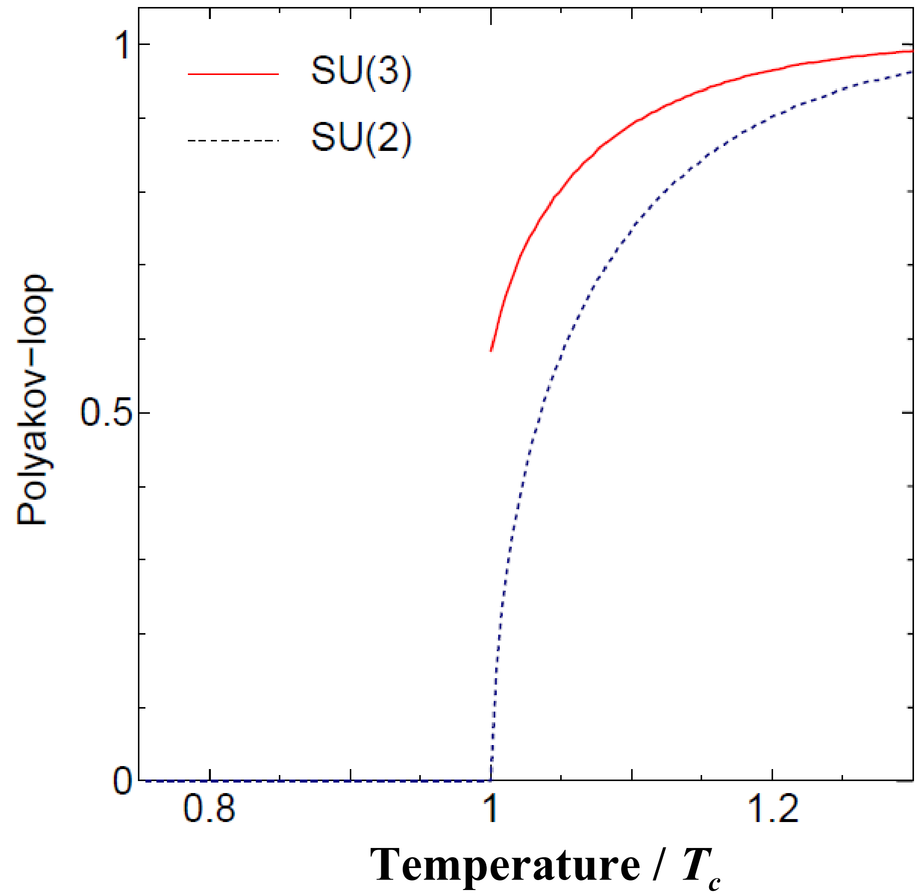
All Excitations with $p \sim 2\pi T$ → Perturbative Limit
Two Transverse Gluons (unphysical ones canceled)

Phase Transition from Propagators

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

Balance between gluons and ghosts





Confinement → Deconfinement

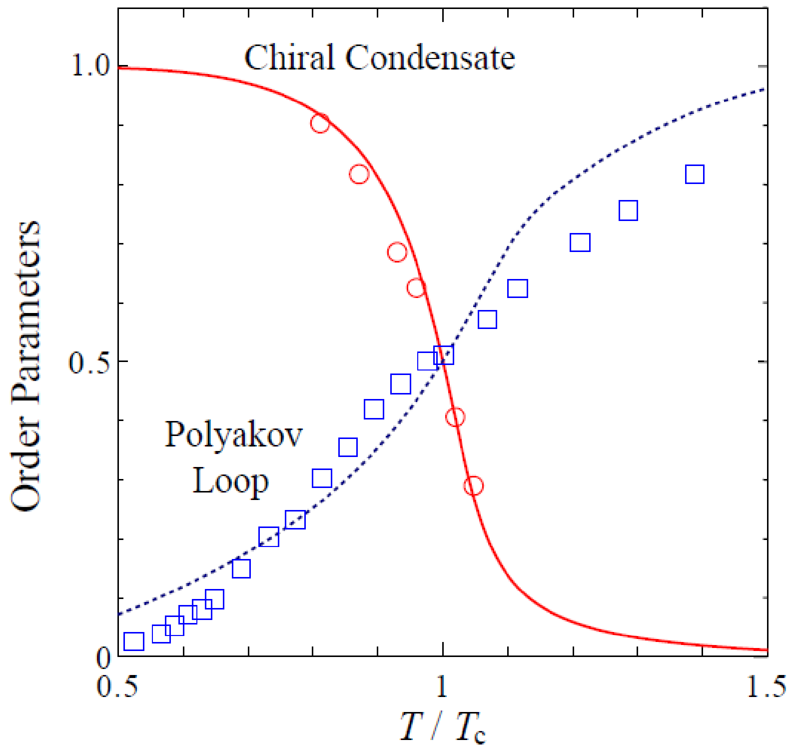
Braun-Gies-Pawlowski, KF-Kashiwa

Dynamical Quarks

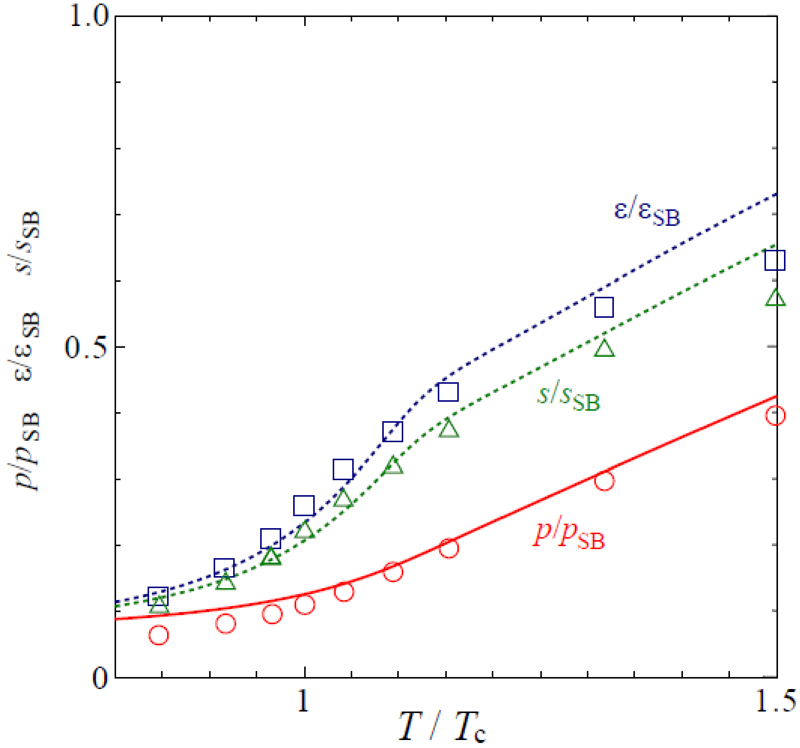
$$\mathrm{tr}\ln\left(1+L\,e^{-(E-\mu)/T}\right)+\mathrm{tr}\ln\left(1+L^{\dagger}\,e^{-(E+\mu)/T}\right)$$

Partition func. for quarks

Full evaluation of the Dirac det on top of A_4 background



Simultaneous Crossovers



Thermodynamics near T_c

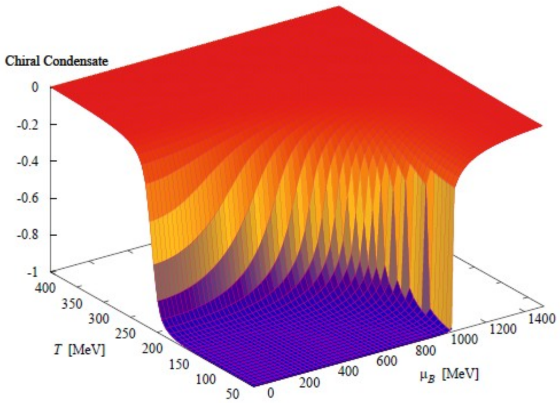
KF-Kashiwa (2012)

Phase structure with baryon density

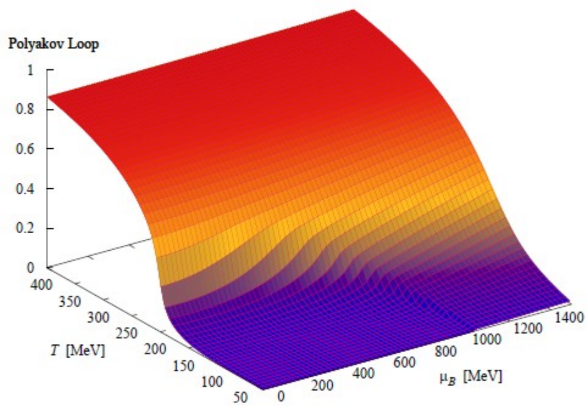
Old Picture

Typical Model Results

Chiral Symmetry

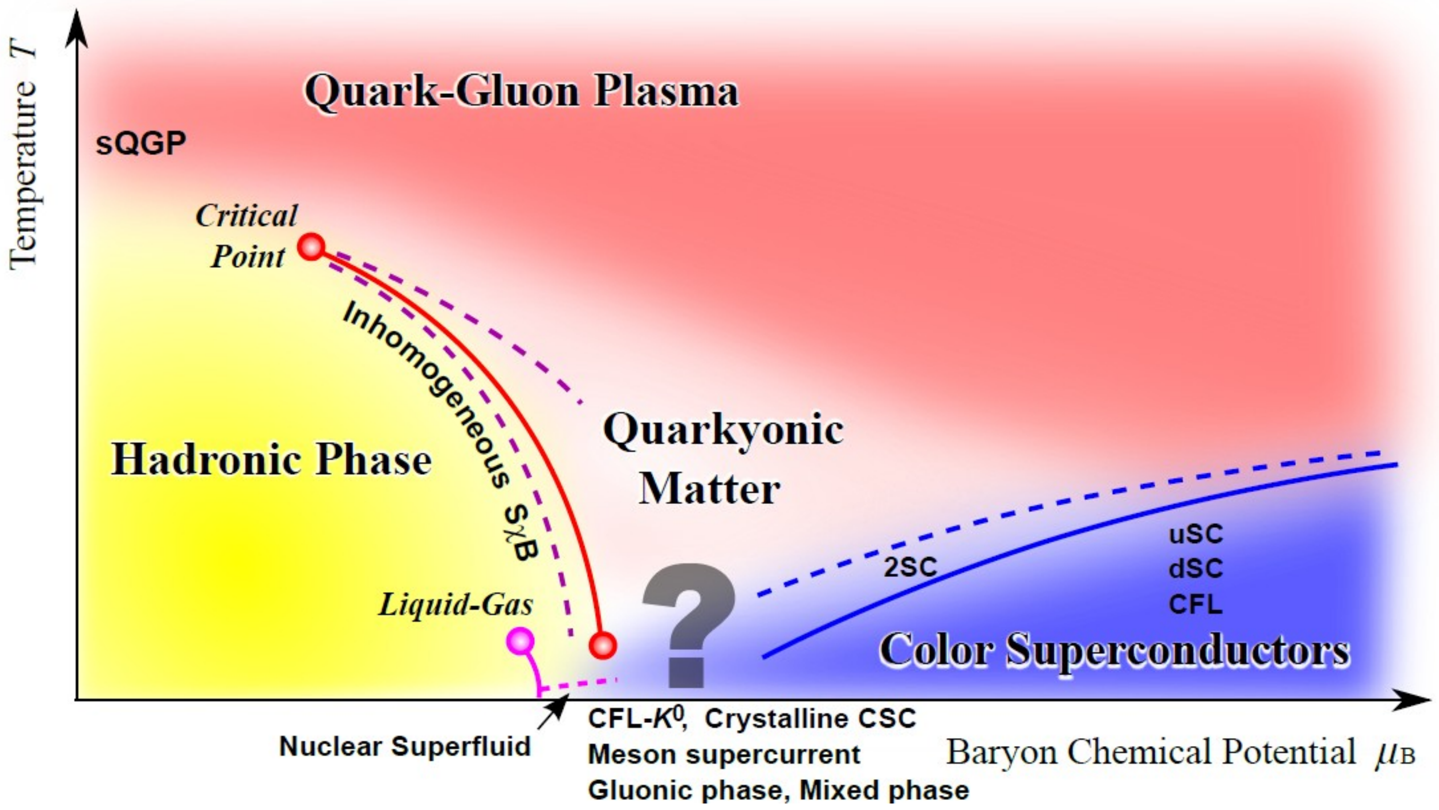


Deconfinement



KF (2008)

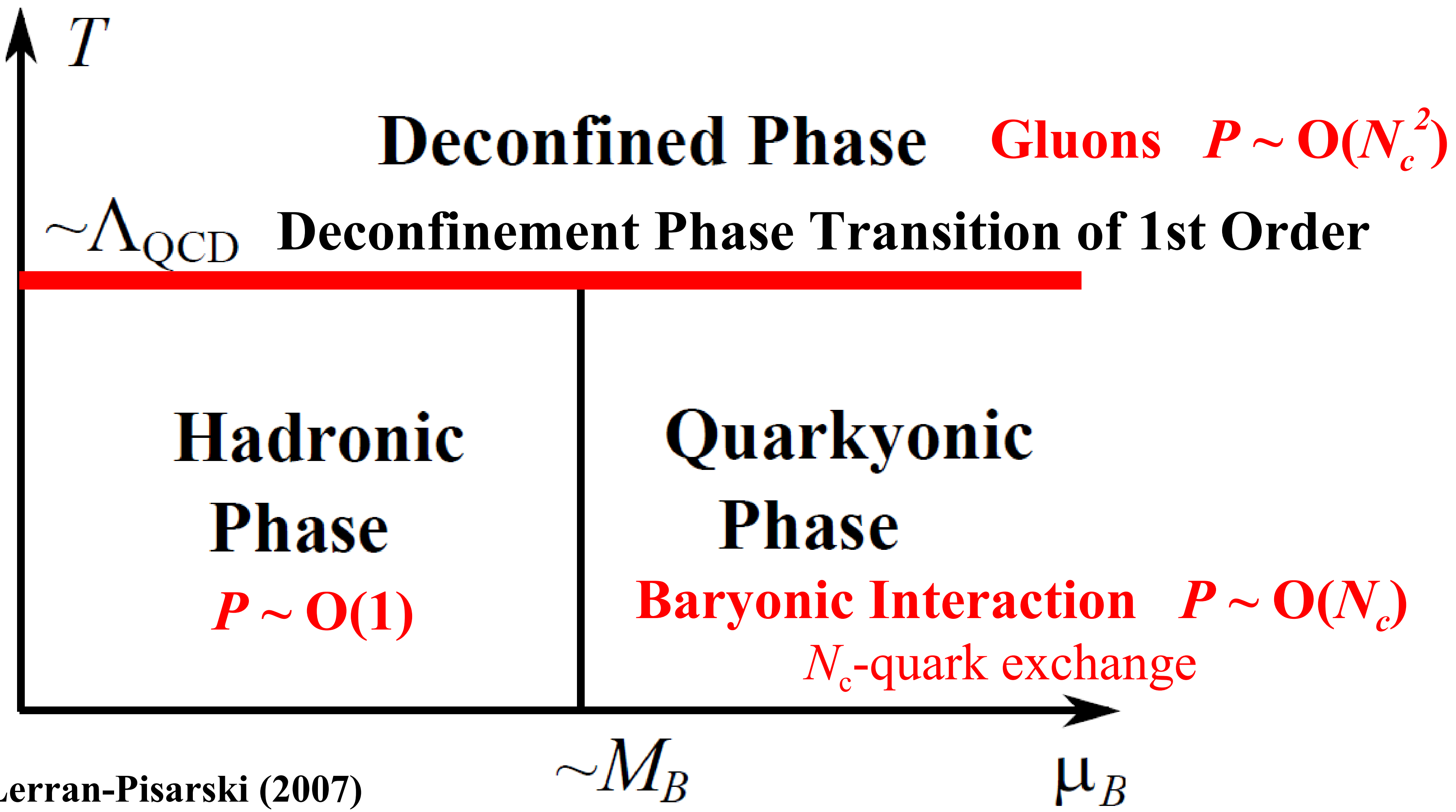
Conjectured Phase Structure



KF-Hatsuda (2010)

New Regime at Large μ_q and N_c

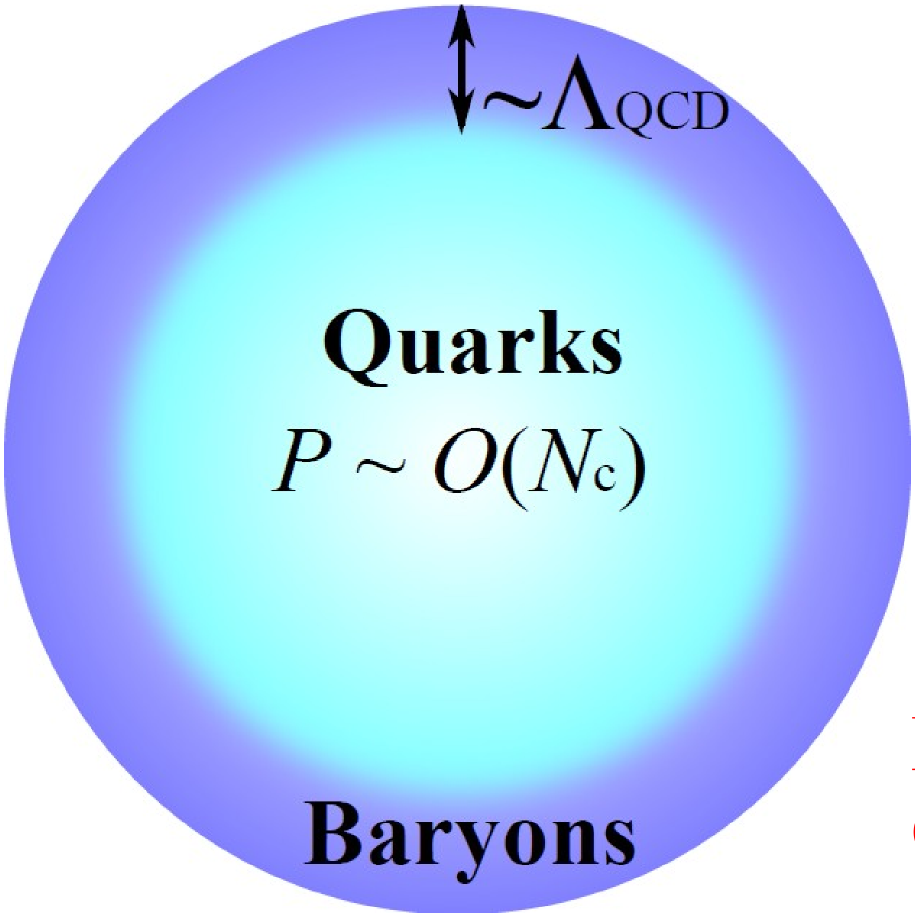
Phase Diagram of Large-N_c QCD



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

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

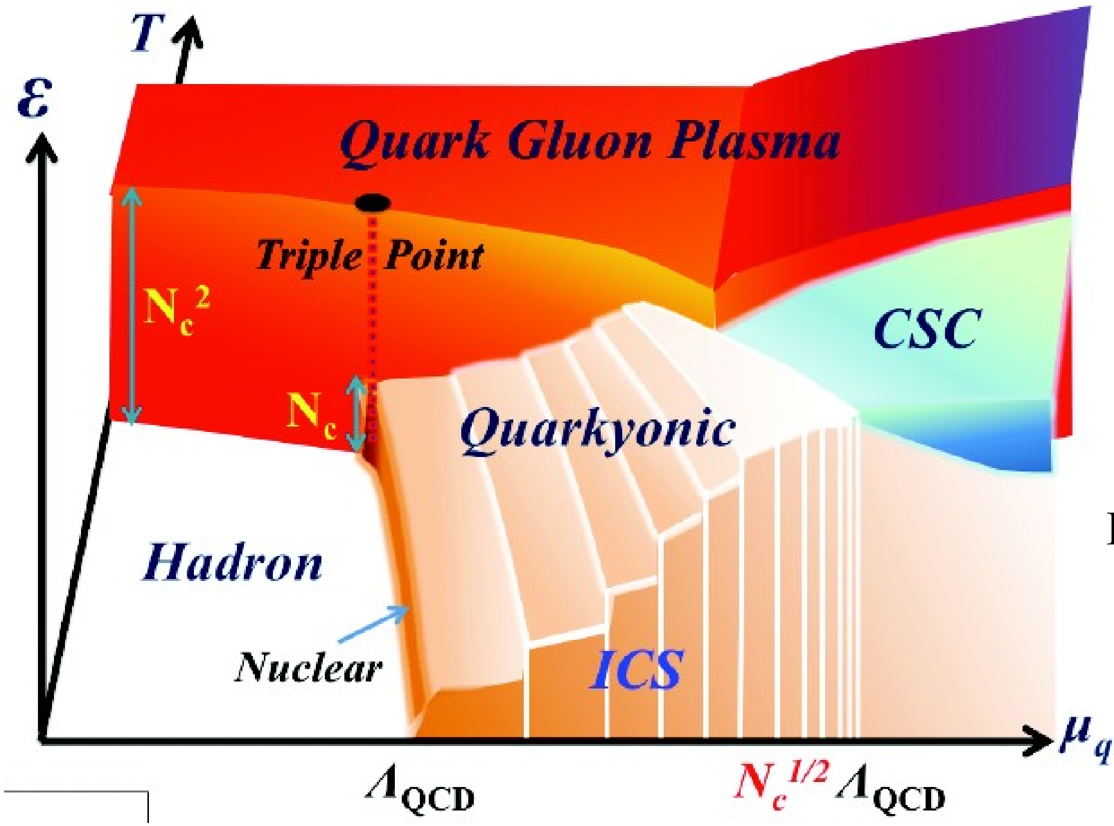
$$= \bar{\psi}'(i\gamma^z \partial_z)\psi' \qquad \psi = e^{i\gamma^0\gamma^z \mu z}\psi'$$

$\langle \bar{\psi}'\psi' \rangle =$ 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"

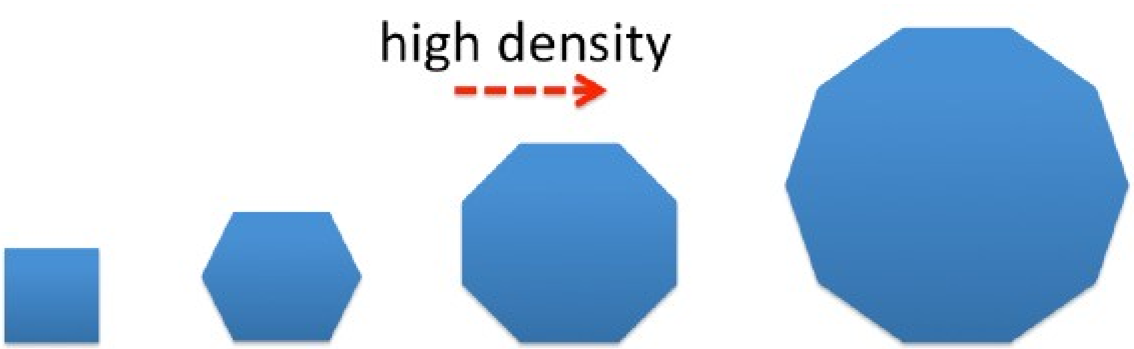
Interweaving Chiral Spirals



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

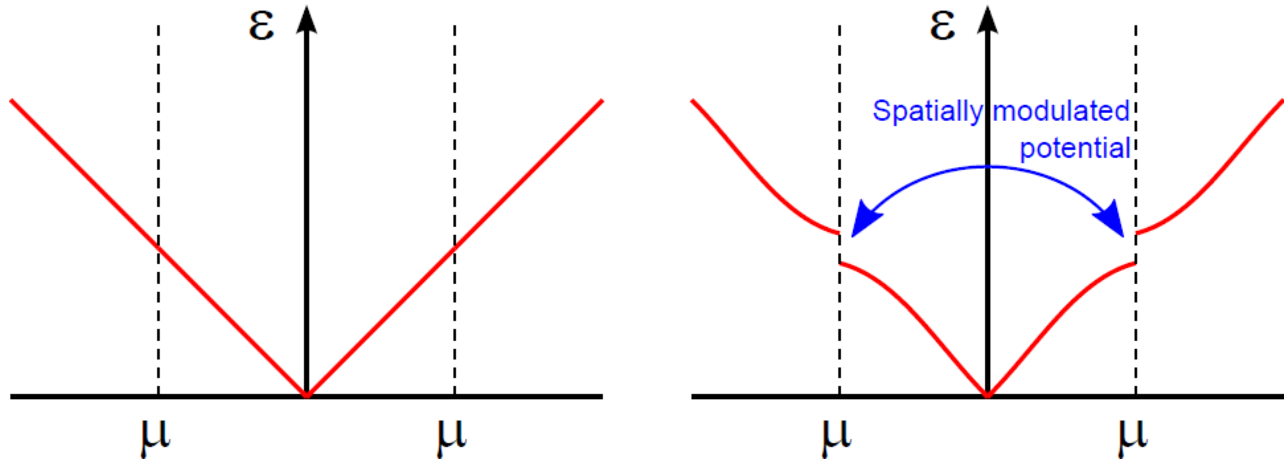
Kojo-Hidaka-KF-McLerran-Pisarski (2011)

(Kojo on Thursday)

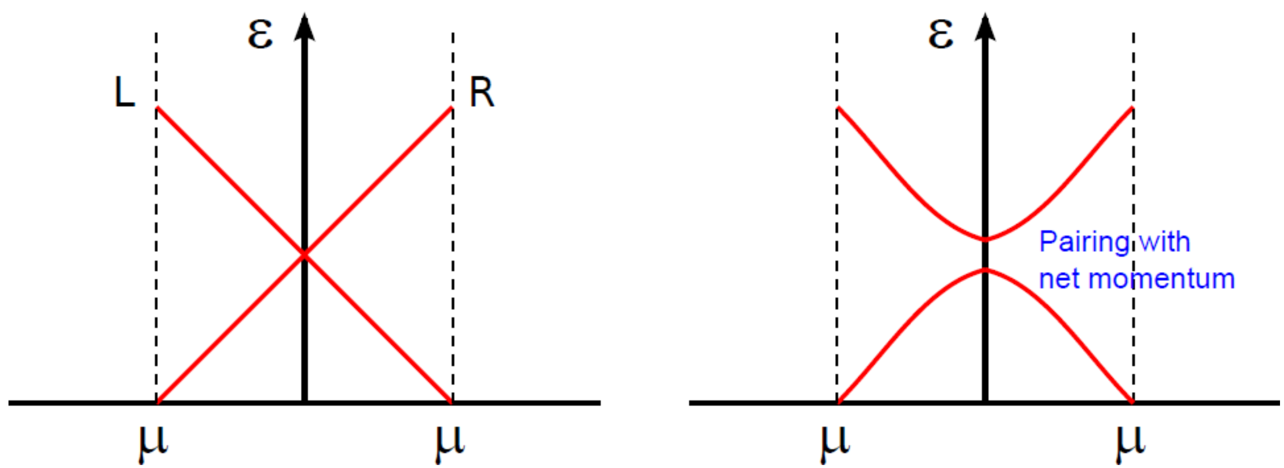


Charge and Spin Density Waves

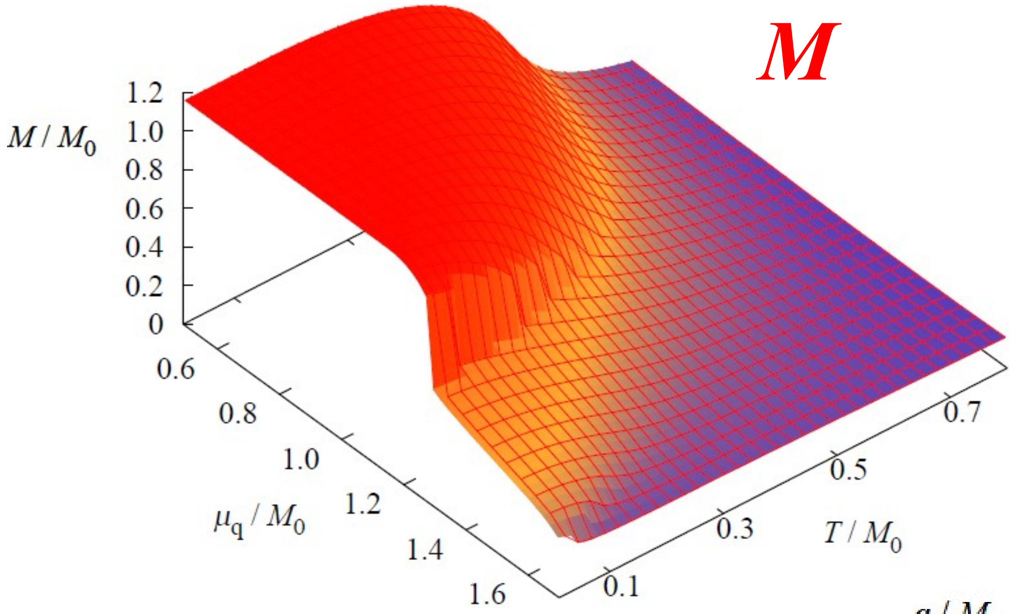
Peierls Instability (Gross-Neveu model)



Overhauser Instability (Chiral Gross-Neveu model)

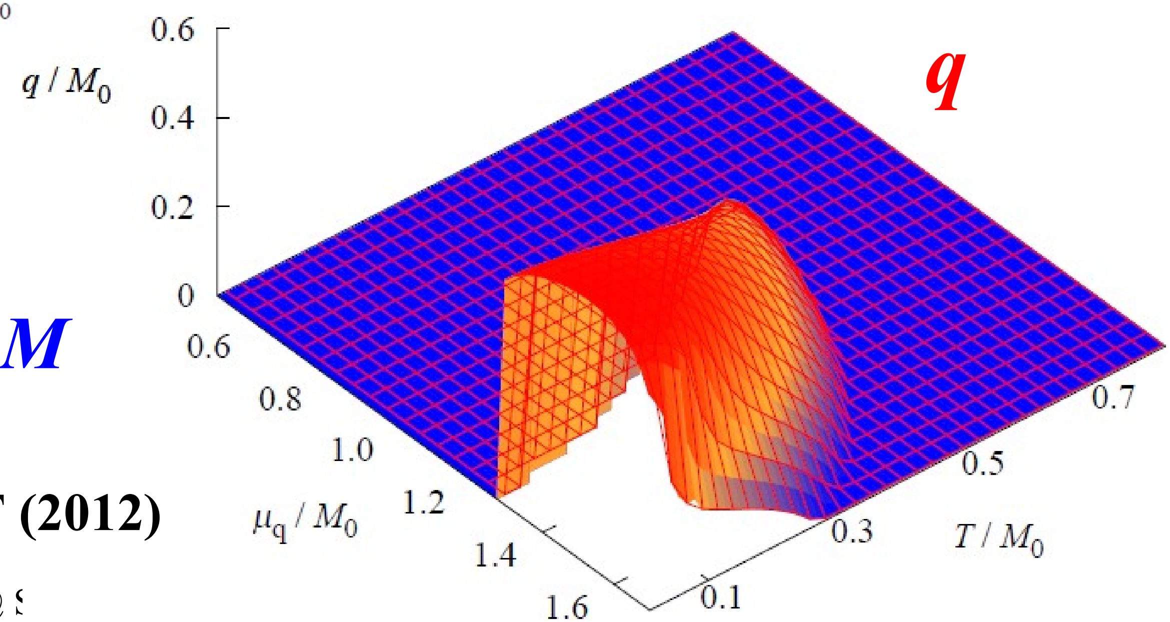


Generic Features



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

Effect of the dynamical mass
M significantly canceled by *q*



No suppression by *M*
on the density with *q* ~ *M*

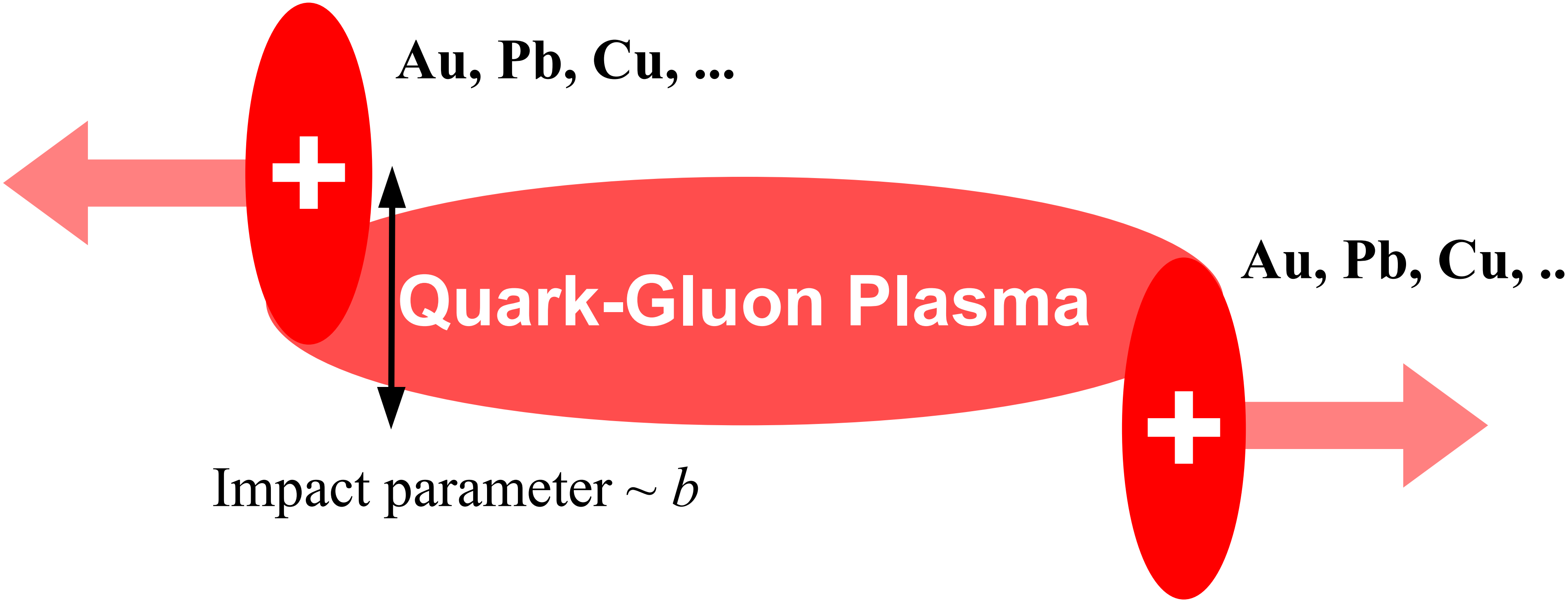
KF (2012)

Inclusion of the magnetic field

Origin of the Magnetic Field

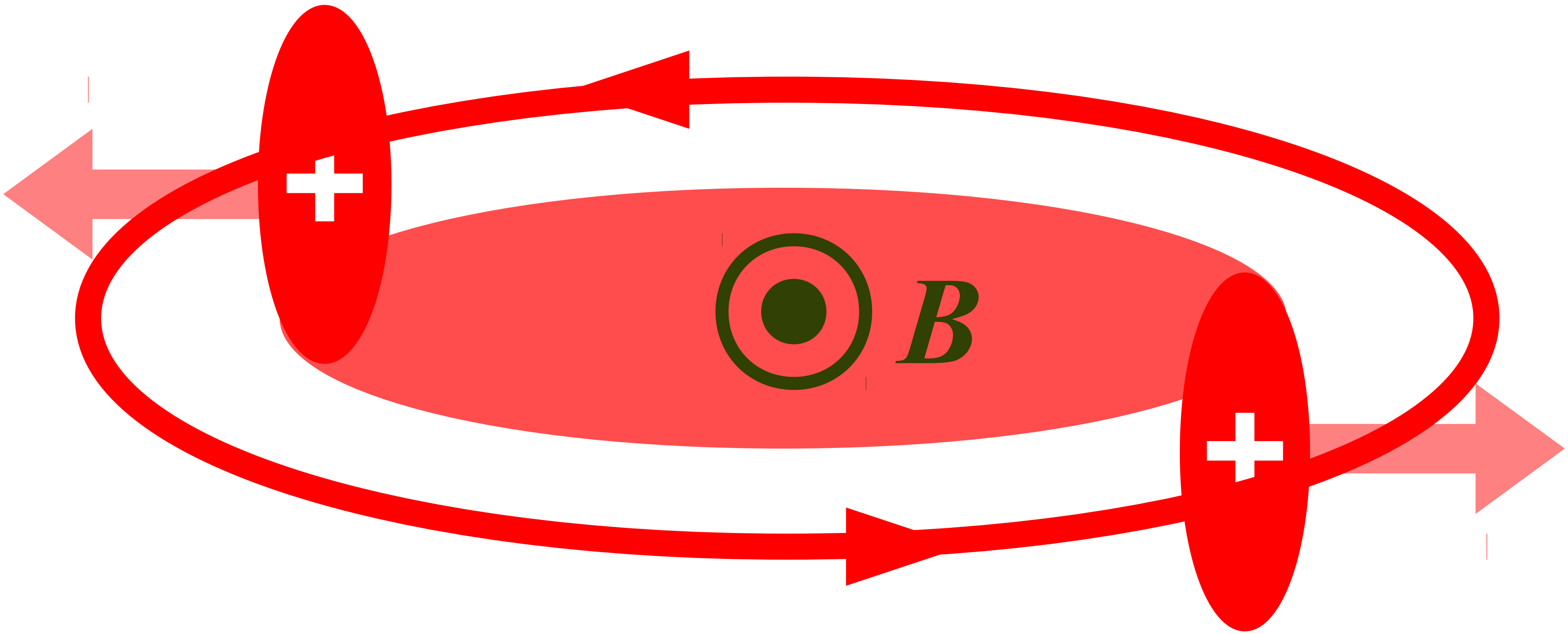
Relativistic Heavy-Ion Collision

Moving almost at the speed of light



Origin of the Magnetic Field

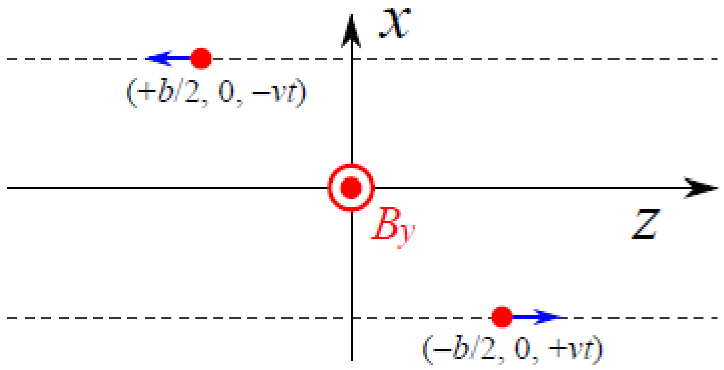
Strong B generated due to Electrodynamics

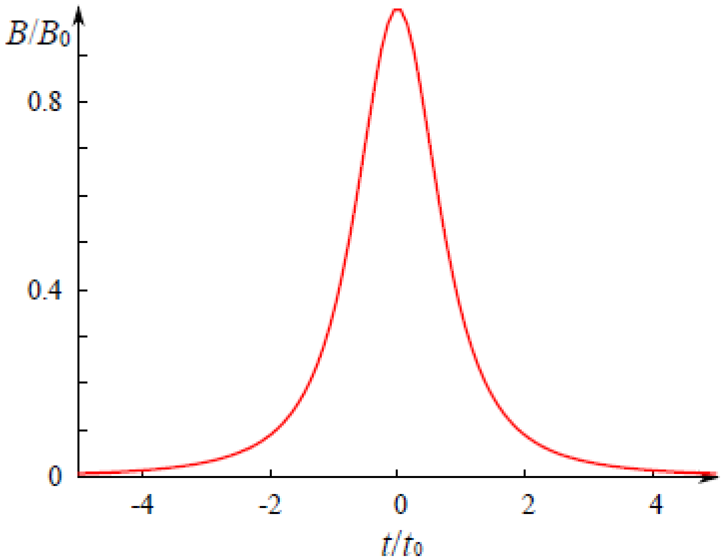


on top of the Quark-Gluon Plasma

Point-charge Approximation

Lienard-Wiechert potential





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

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

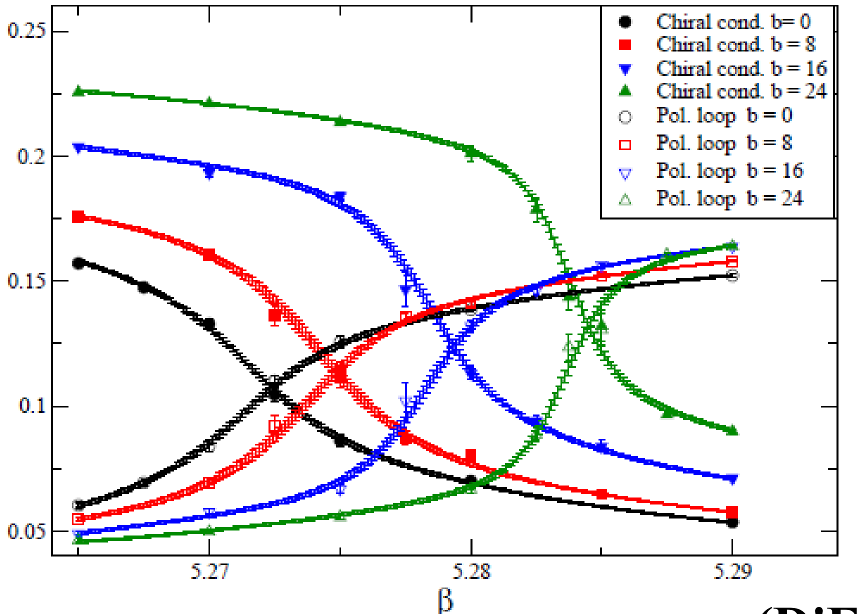
$\sim 10^{18}$ gauss

Interesting phenomena expected!

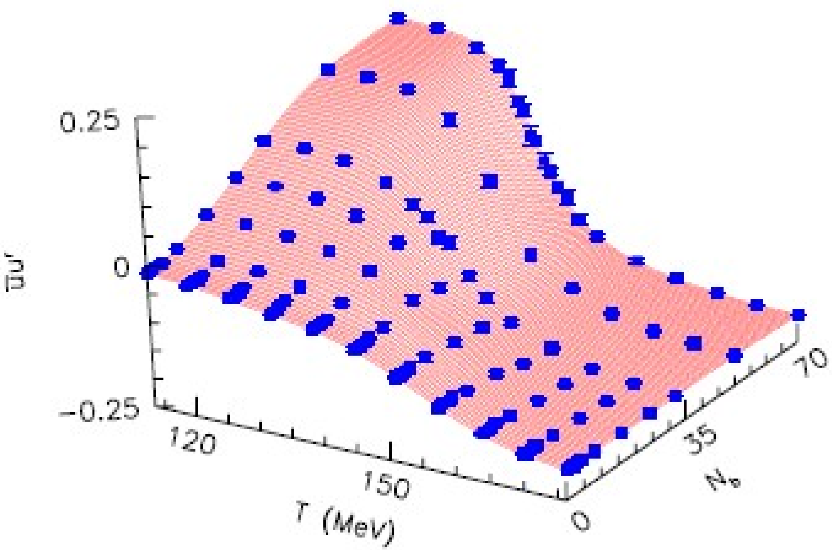
Discussed by Rafelski, Mueller, … (~1976)

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?

Chiral condensate (at zero *T*) enhanced by *B*

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

Magnetic Catalysis

Fermion (quark) Loop

$$V_q = i\,\mathrm{tr}\ln\left(iD_q^{-1}(p,\sigma)\right)$$

$$= \frac{eB}{8\pi^2}\int_{1/\Lambda^2}^{\infty}\frac{ds}{s^2}e^{-\sigma^2 s}\coth(eBs)$$

$$\sim \# - eB\sigma^2\ln\left(\Lambda^2/\sigma^2\right)$$

Potential curvature has a log singularity and is negative!

Chiral symmetry is always broken
because the symmetric state has a barrier
(Similar to the Cooper instability)

Klimenko, Gyusynin-Miransky-Shovkovy

Magnetic Inhibition

Meson (Neutral Pion) Loop

$$V_m = -\frac{i}{2}\,\mathrm{tr}\ln\big(iD_m^{-1}(p,\sigma)\big)$$

$$= \frac{i}{2}\int_{1/\tilde{\Lambda}^2}^{\infty}\frac{ds}{s}\int\frac{d^4p}{(2\pi)^4}\,e^{is\,D_m^{-1}(p,\sigma)}$$

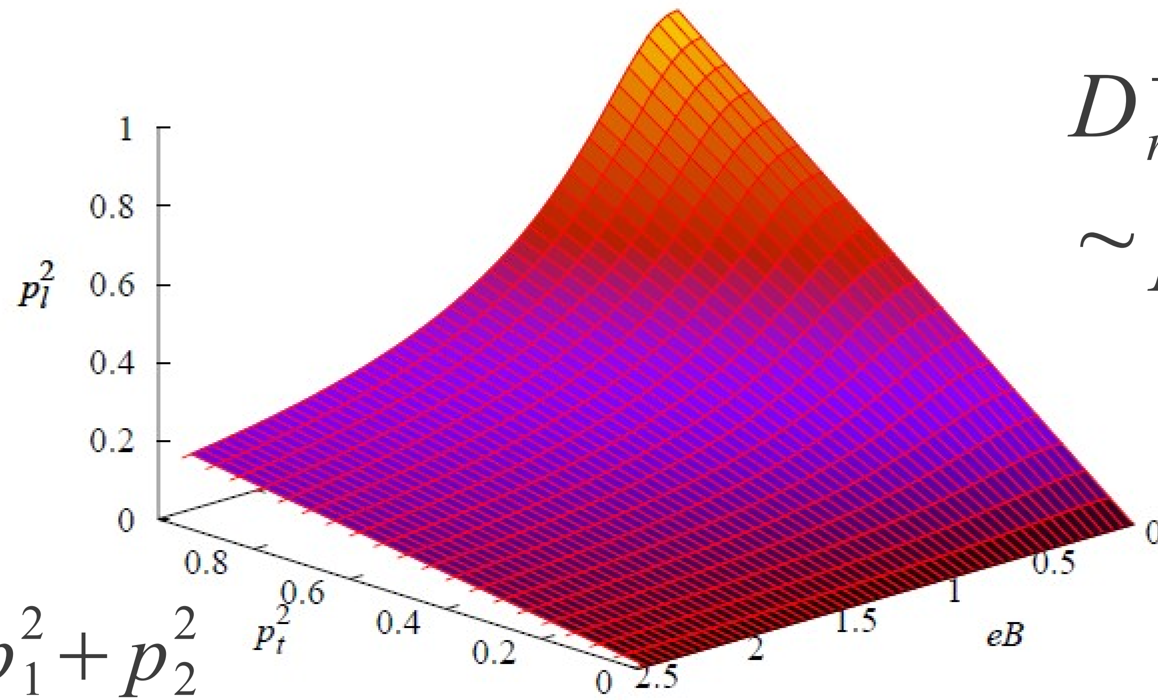
$$\sim -\#\frac{\tilde{\Lambda}^4}{v_\perp^2} \sim -\frac{\tilde{\Lambda}^4}{\sigma^2} \quad \text{at very strong } eB$$

Power singularity can overcome the logarithmic one.
Symmetry should be restored eventually.
(Regularization is very subtle, see Gyusynin-Miransky-Shovkovy)

Meson Velocity in B

Dispersion relation as a function of *B*

$$p_0^2 - p_3^2$$



$$p_1^2 + p_2^2$$

$$D_m^{-1} \sim p_l^2 - v_\perp^2 p_t^2$$

Even neutral mesons are dimensionally reduced at strong B
Infrared-singularity (Marmin-Wagner theorem)

Fukushima-Hidaka (2012)

Schematic Picture

(1+1)D Quarks
Magnetic Catalysis

(1+1)D π^0
Magnetic Inhibition

More breaking of chiral symmetry

Restoration of chiral symmetry

~ (π^0 size inverse squared) ***B***

This is a prediction to be tested in the lattice simulation.
(This may be an explanation for the decrease in T_c ?)

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 even without the QCD CP. (Overhauser effect)
- □ *Strong B Field* – Effects on the phase diagram not yet understood. Anomalous phenomena ($\mathcal{P}$ and $C\mathcal{P}$ odd effects)

What is the ground state of QCD at infinite *B* ?

- □ *Chiral symmetry* – Chiral condensate enhanced due to the magnetic catalysis but neutral mesons overcome eventually.
- □ *Deconfinement* – Not understood yet but...