The Structure of QCD Phase Diagram

~ Facts and Fictions ~

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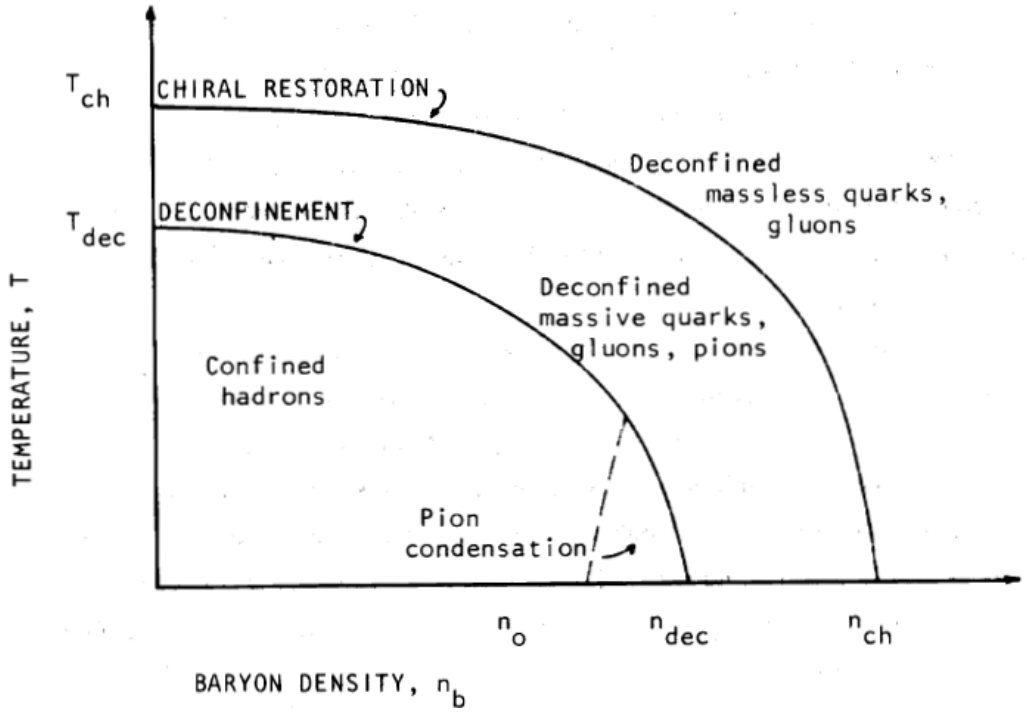
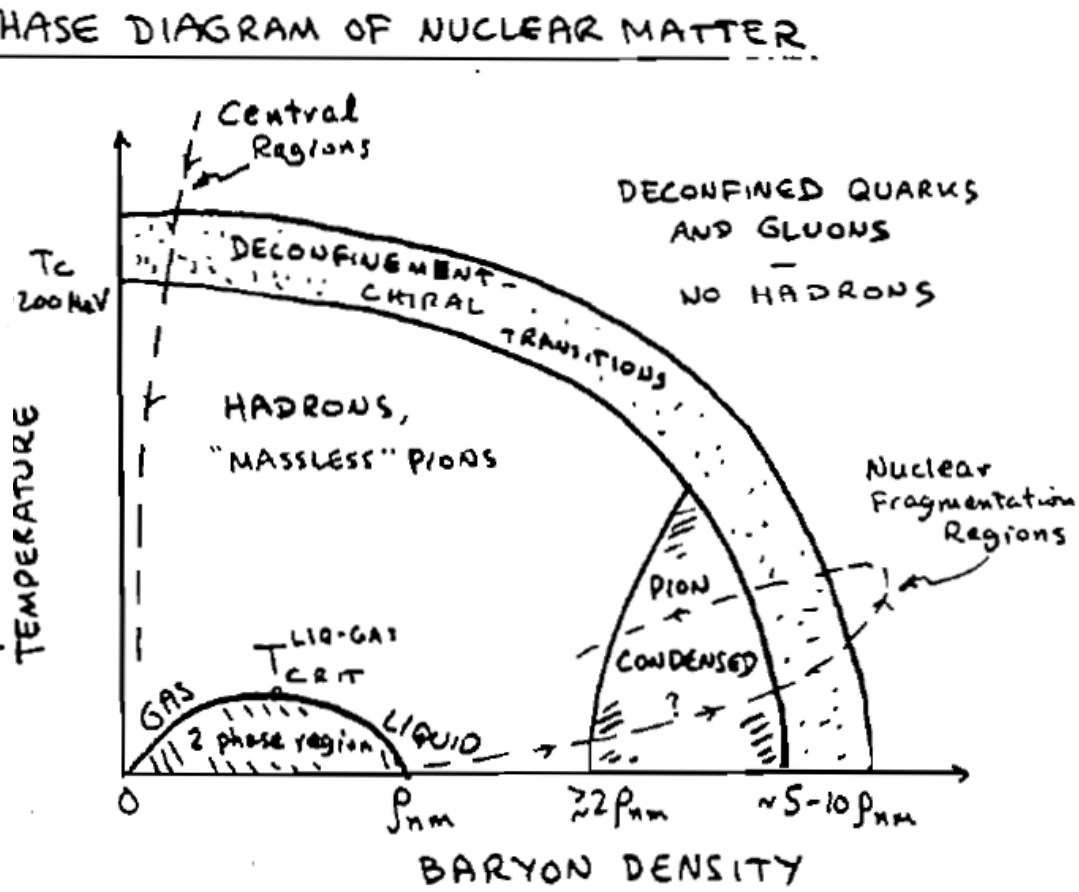
Phase Diagram Candidates

Two Historical Phase Diagrams

Diagram-1982 Lattice **Diagram-1983**

Baym



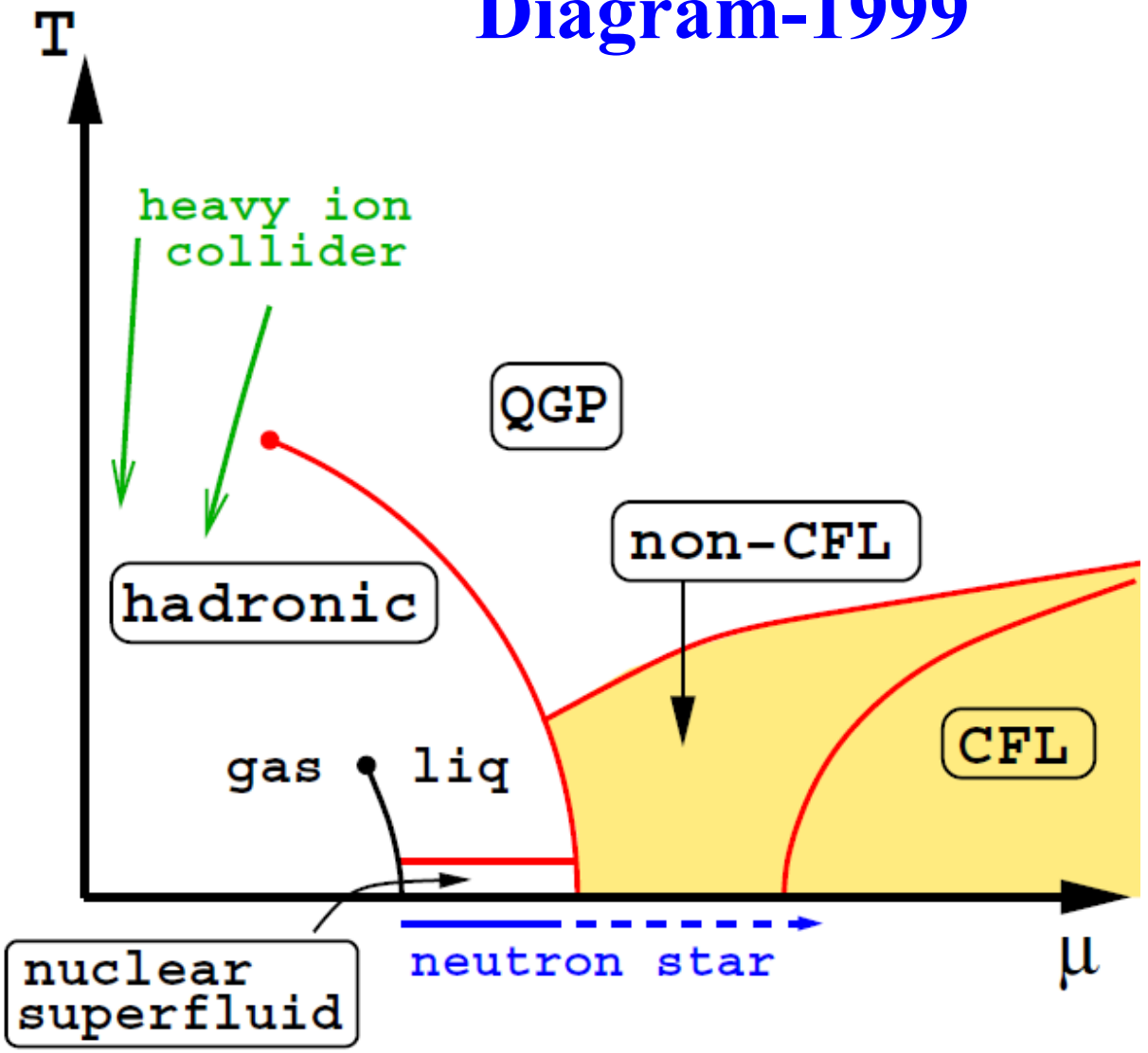


Anomaly matching

Color Superconductivity

Diagram-1999

Alford



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

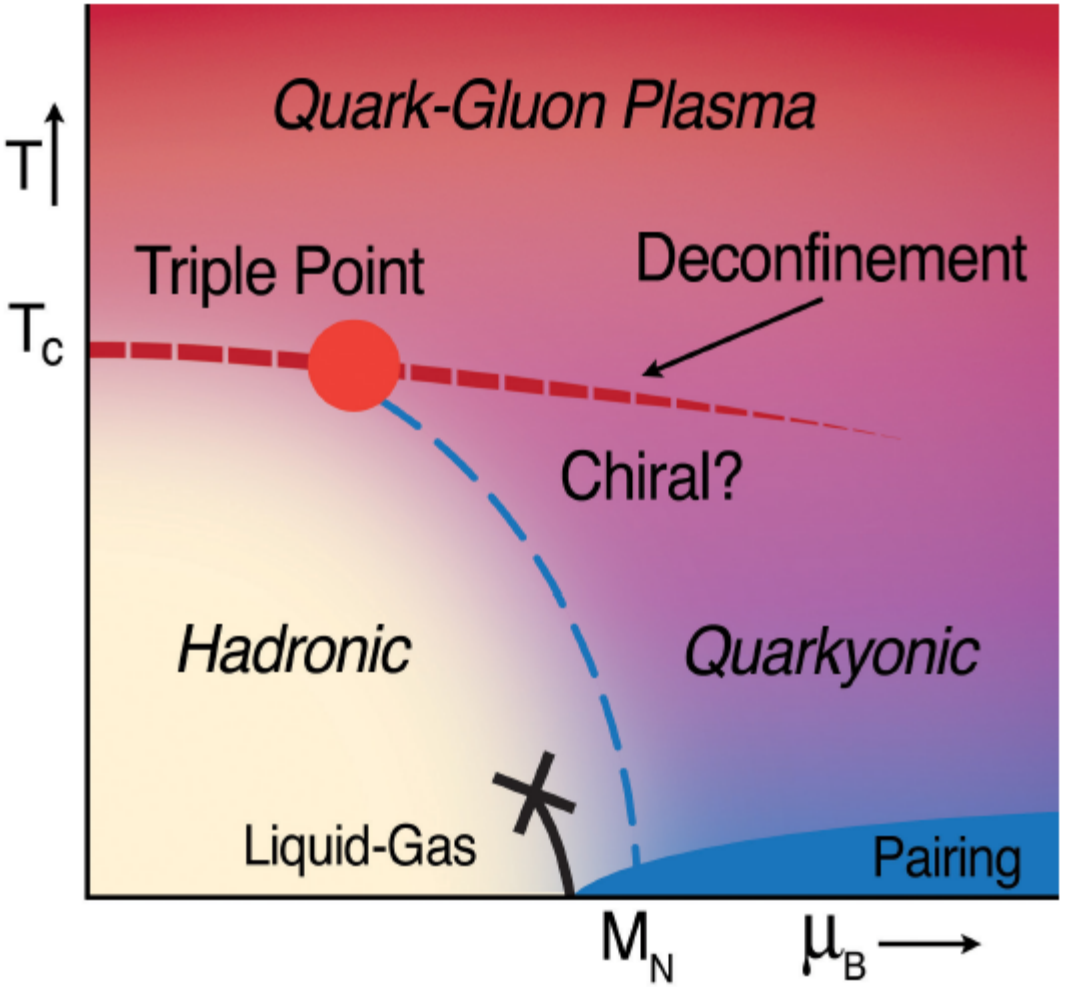
Chromomagnetic Instability
Crystallography
Gritch problem

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

Too difficult

Triple-Point-Like Structure

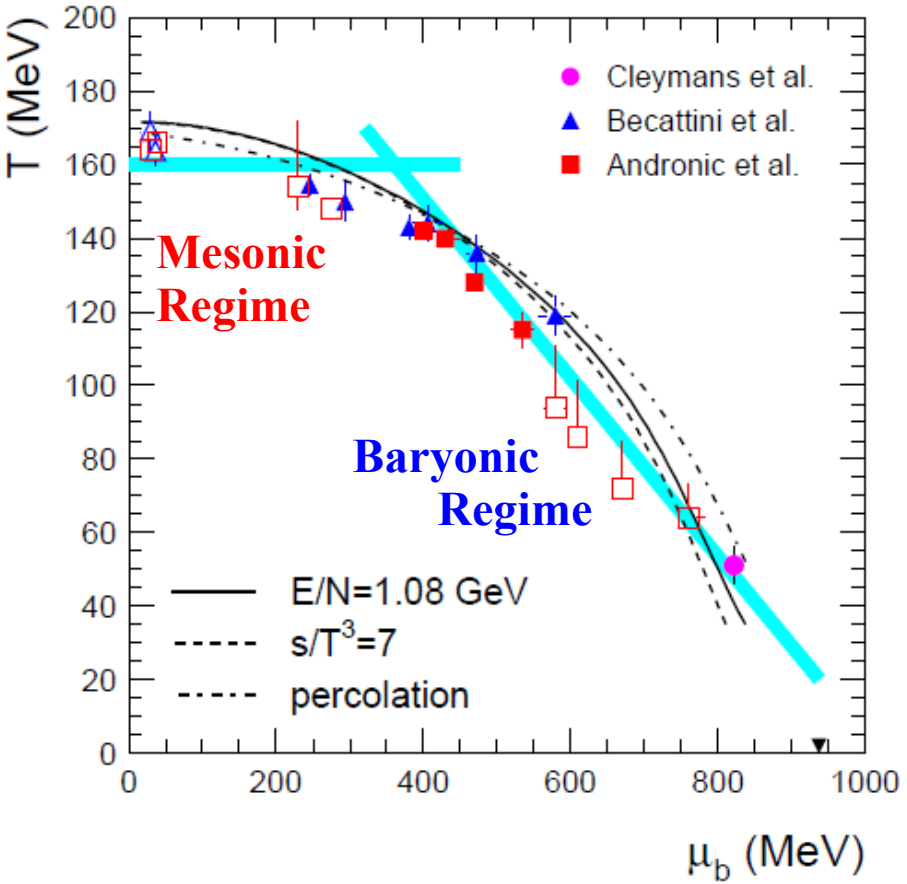
Diagram-2009



Andronic, Blaschke, Braun-Munzinger, Cleymans, KF, McLerran, Oeschler, Pisarski, Redlich, Sasaki, Satz, Stachel

Interpretation of Statistical Model

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

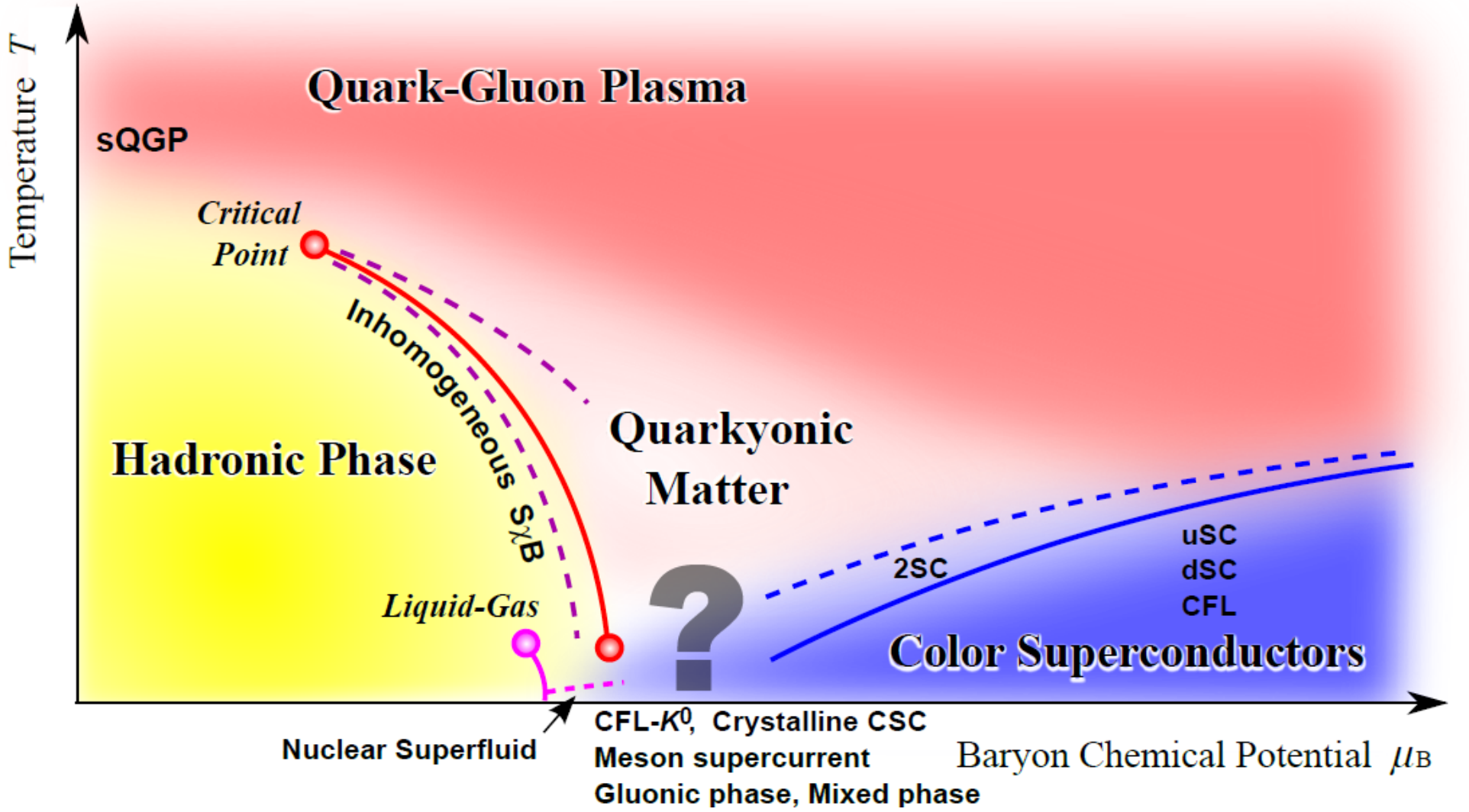
$$Z \sim \int dm\, \rho_B(m)\, e^{-(m_B-\mu_B)/T}$$

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

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

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

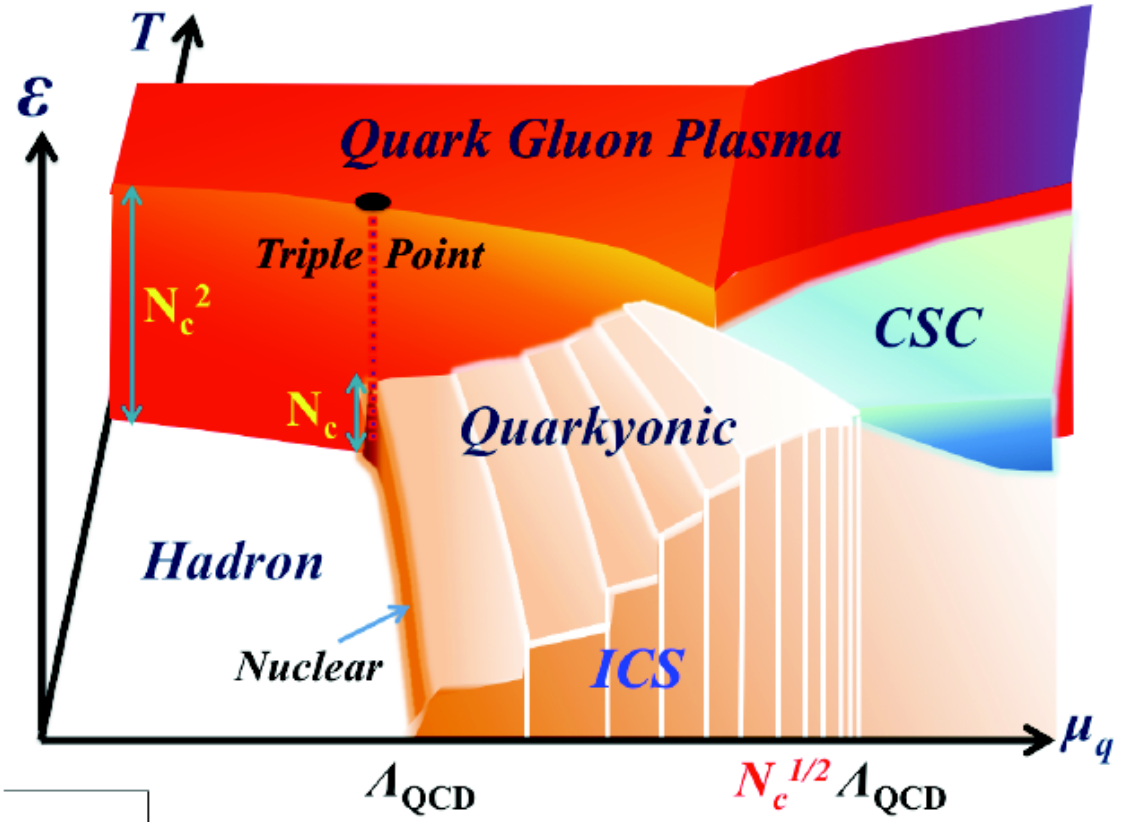
Diagram-2010

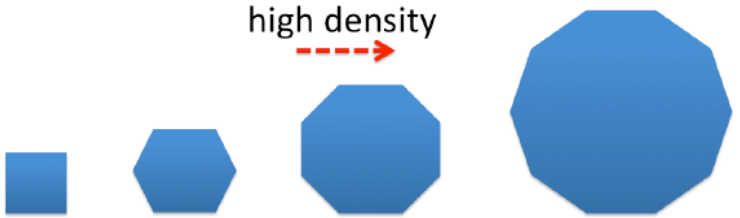


KF-Hatsuda (2010)

Interweaving Chiral Spirals

Diagram-2011





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

Too Difficult Again

Let's get back to the basics!

Policy for simplification

If there is ANY counter-example (model or whatever), remove it from the phase diagram.

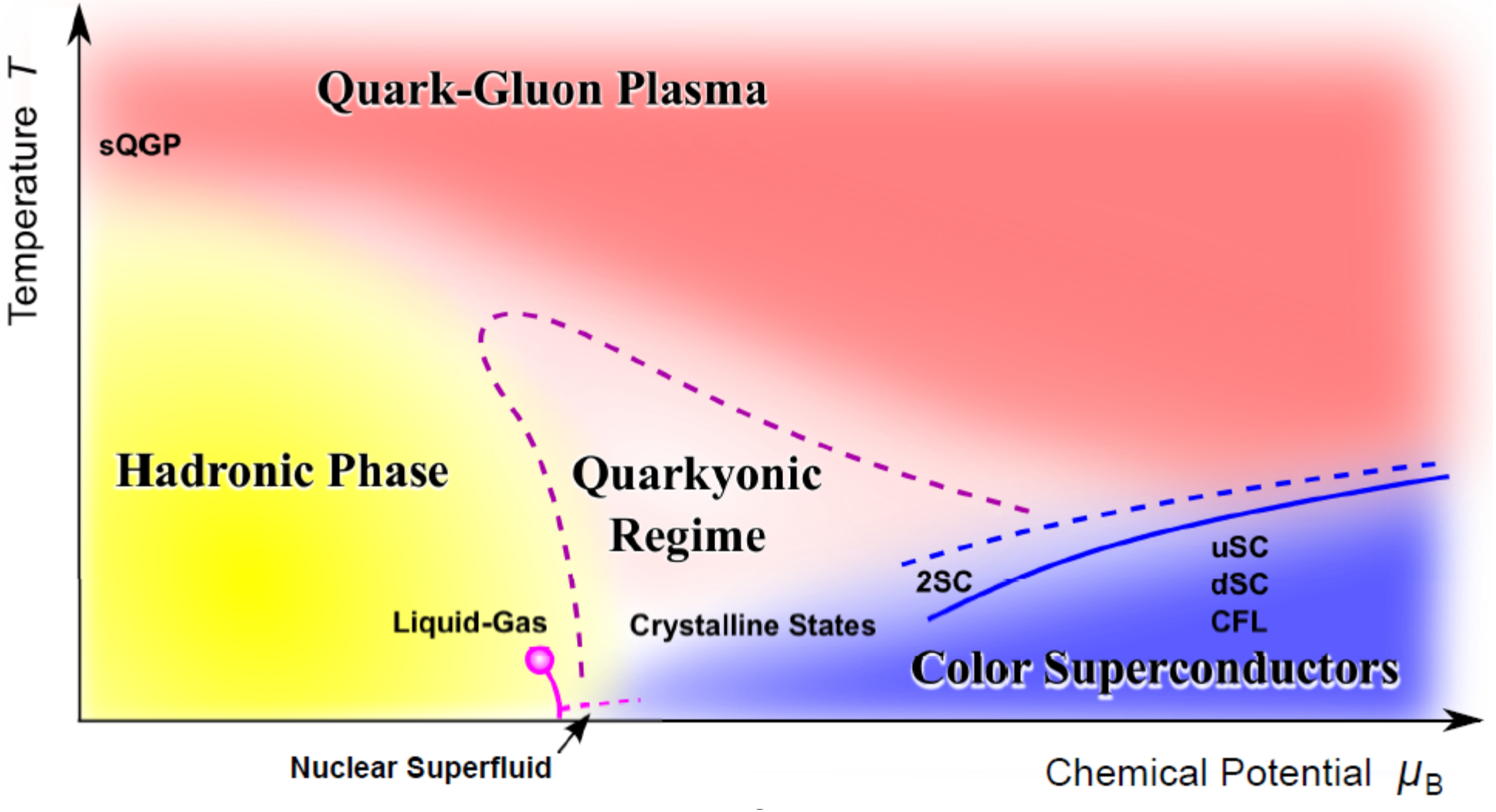
If there is NO concrete example to falsify, leave it on the phase diagram (however odd it looks).

This should be a fair and unbiased criterion

Diagram-2013

Remaining (so-far) "Facts"

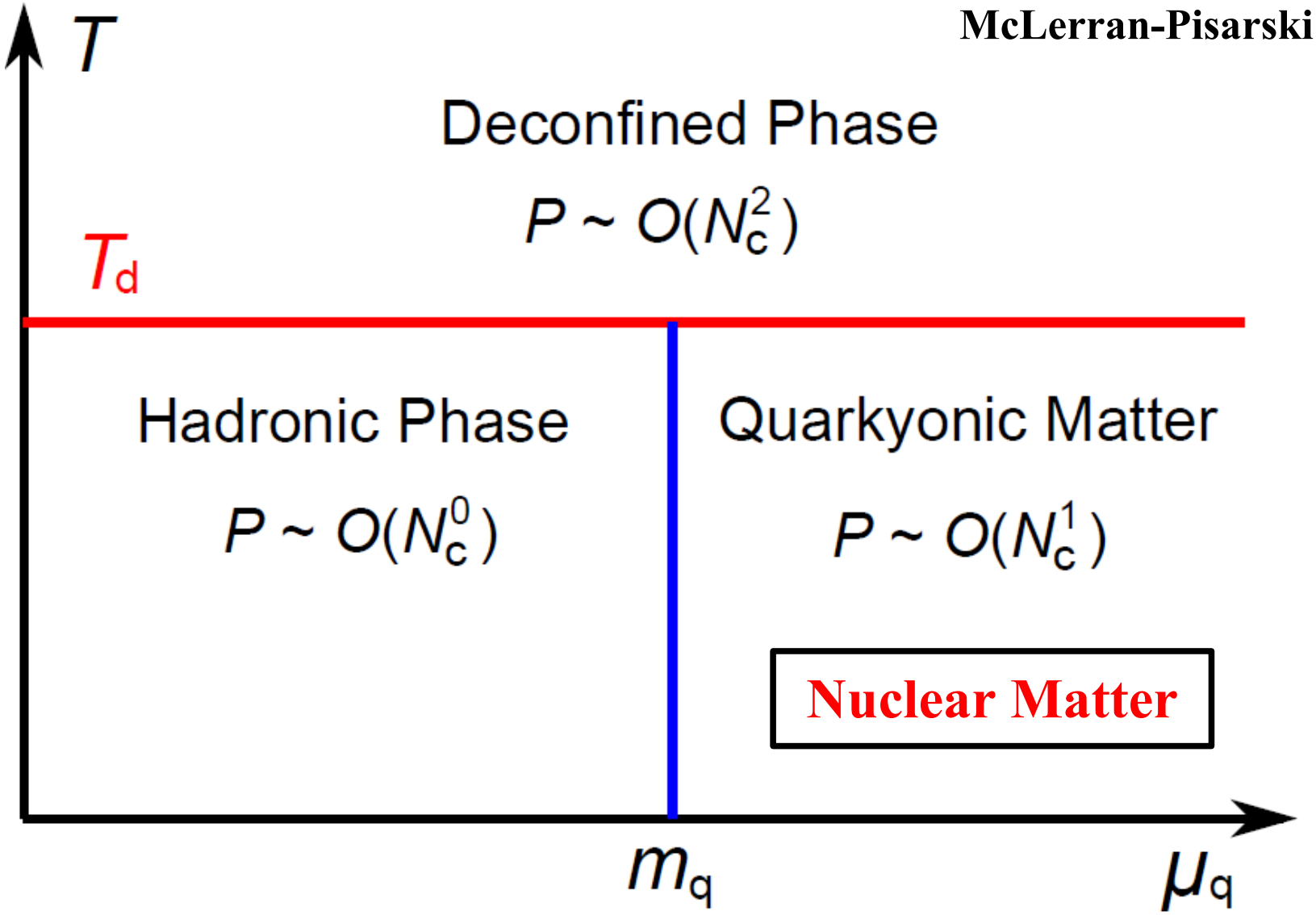
KF-Sasaki (2013)



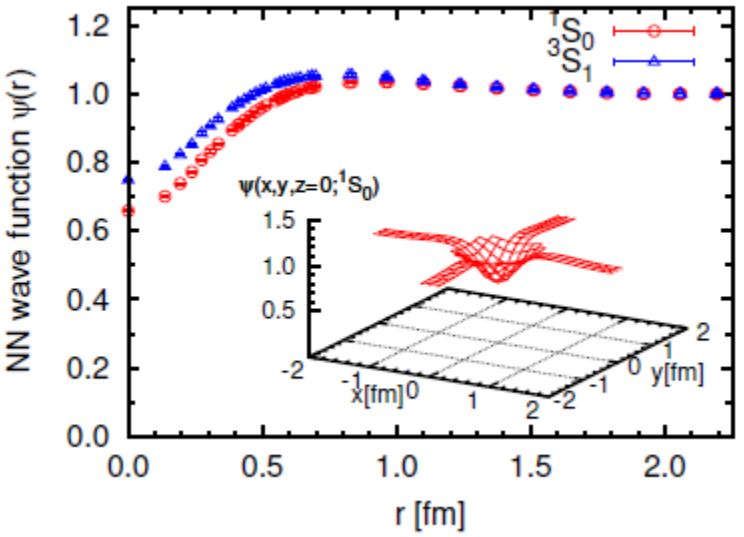
Quarkyonic Matter (Regime)

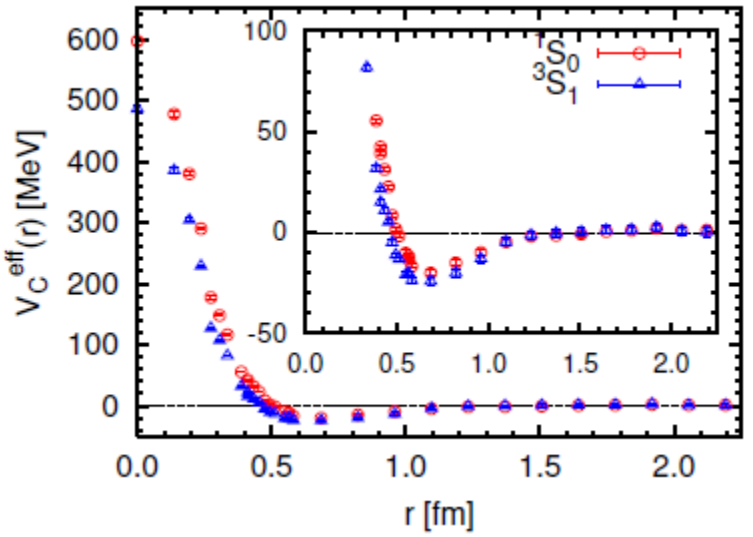
Phase Diagram at Large N_c

McLerran-Pisarski (2007)



Ordinary Nuclear Matter





Symmetric nuclear matter
Saturation (self-binding)
Exchanges of π, 2π, etc
(Lattice-QCD; Aoki et al.)

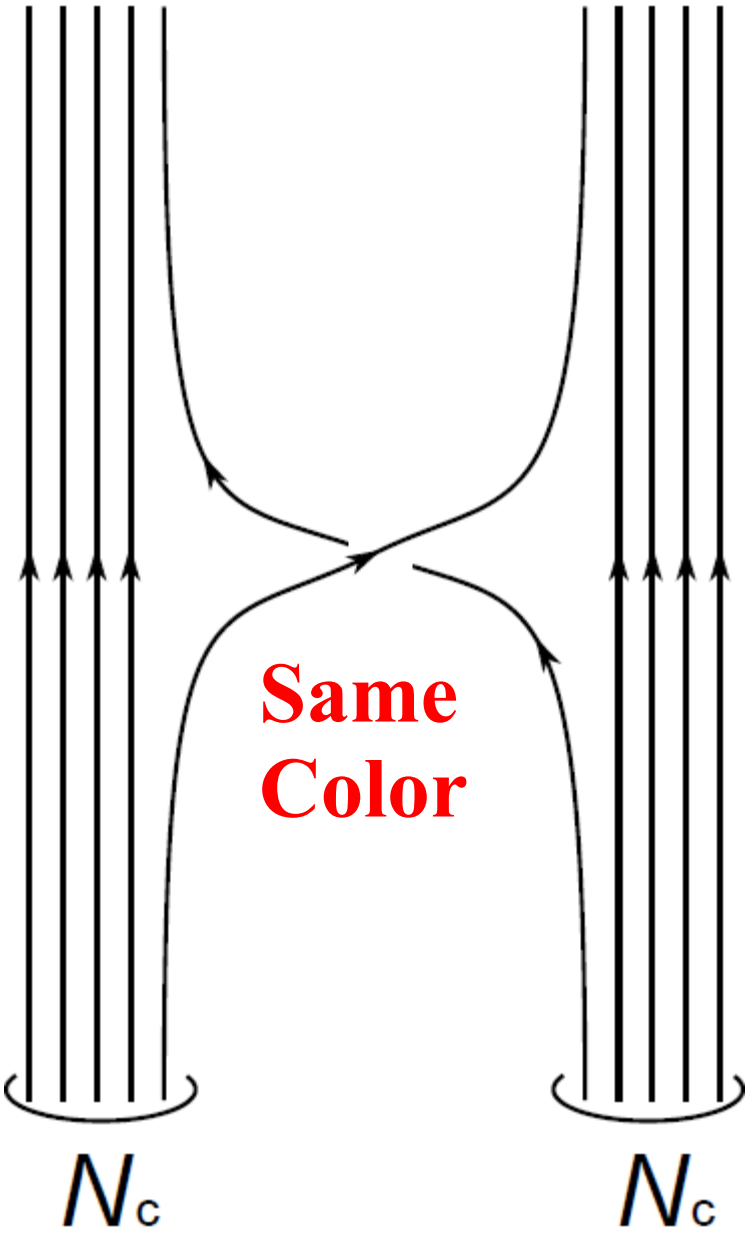
Potentials in all interaction channels including hyperons can be estimated from the lattice-QCD
(H-dibaryons?)

Strong Baryon Interactions

One-meson exchange

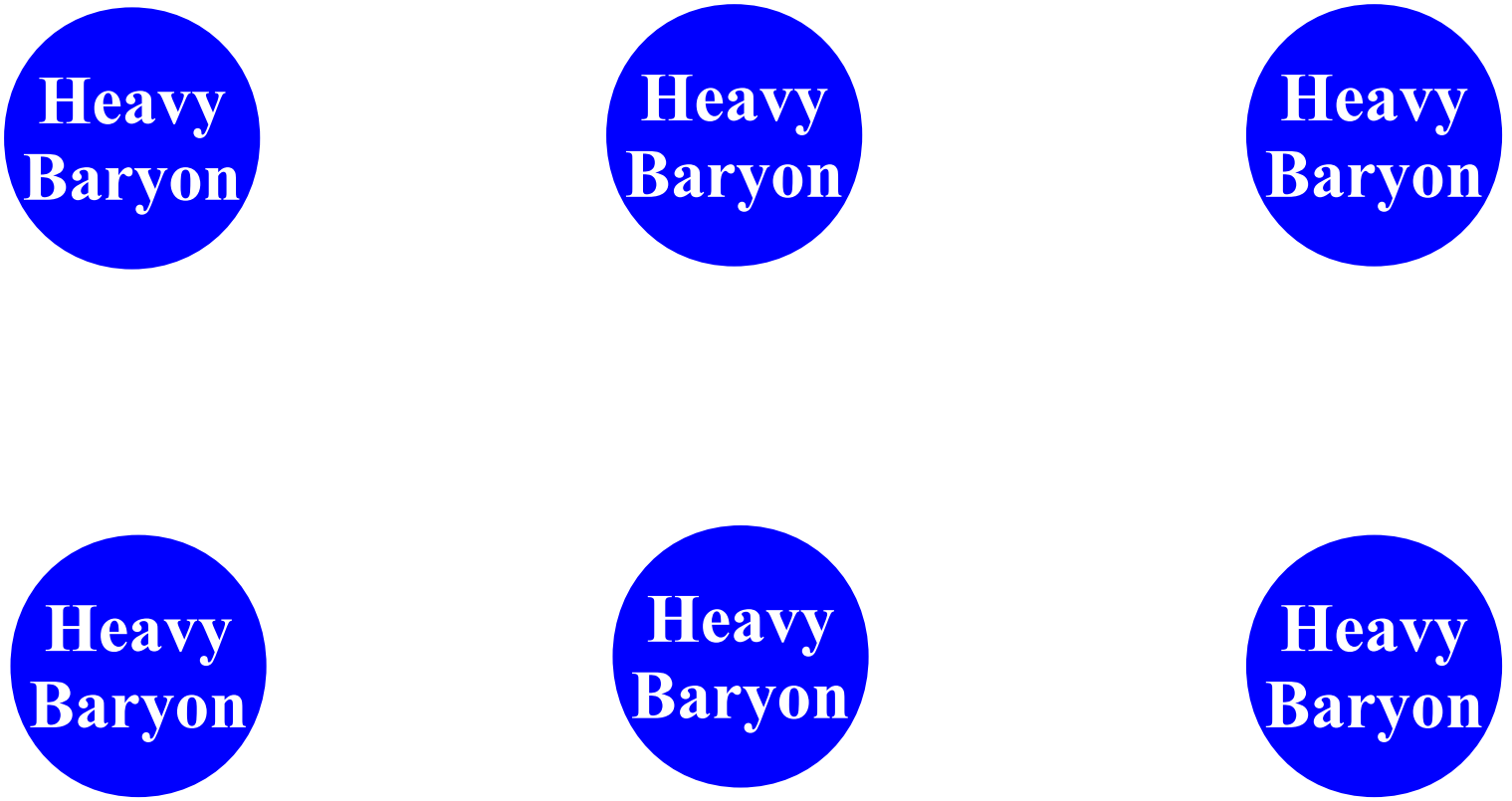
$$\sim O(N_c)$$

Also diagrams involving gluons to make the same color exchanges



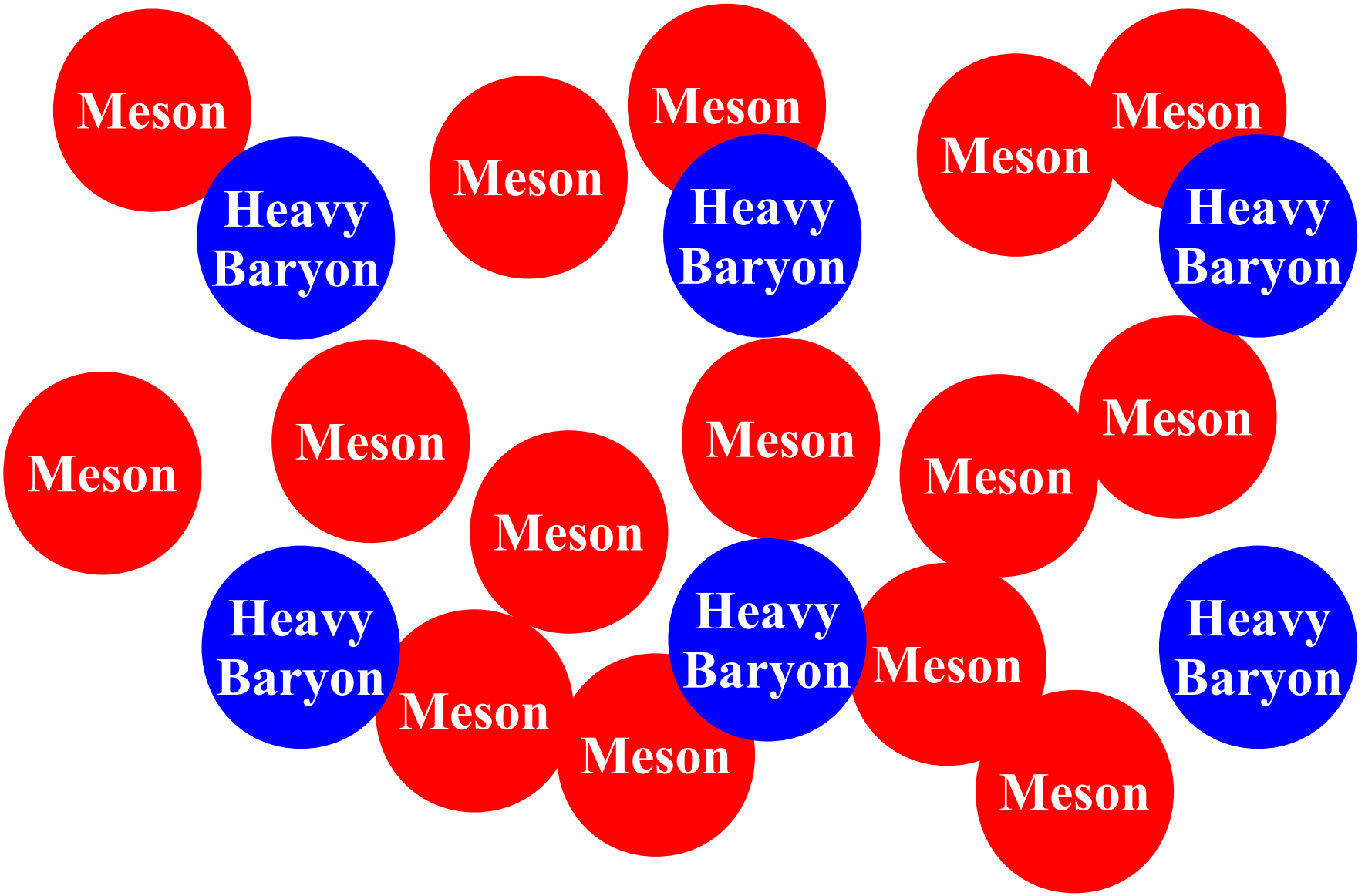
Mesons ~ free

Dense Nuclear Matter

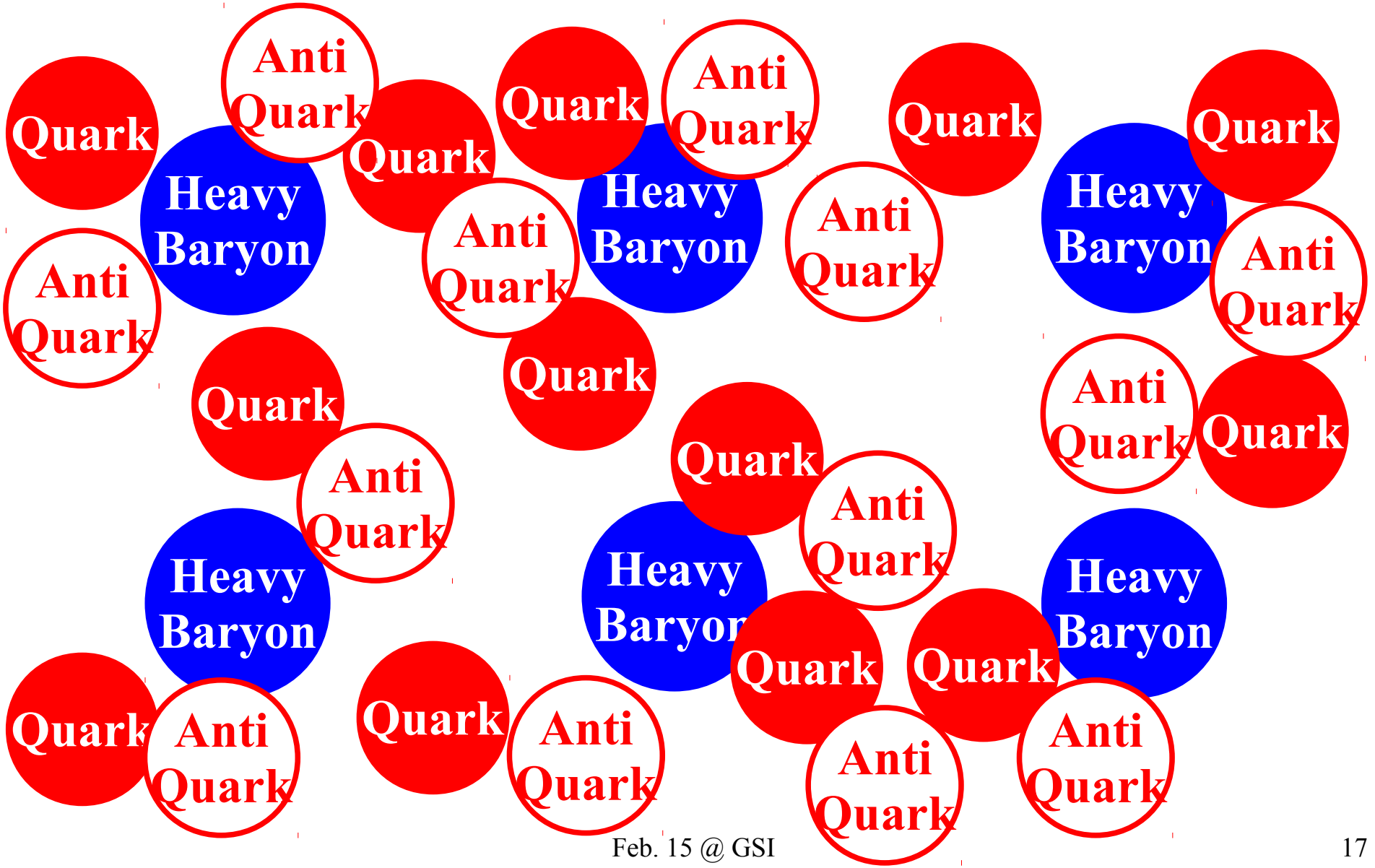


Skyrme-Crystal

Dense Nuclear Matter



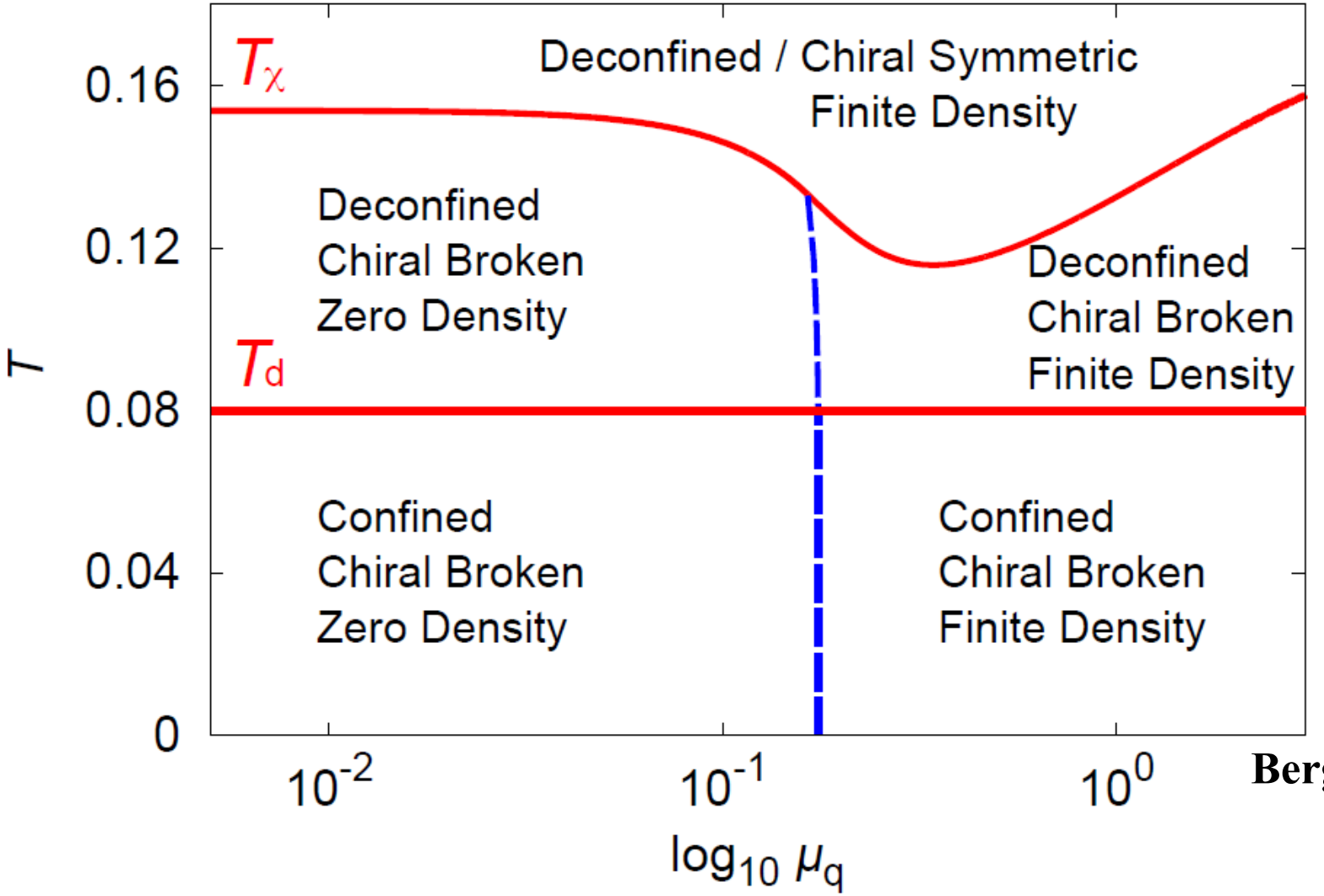
Quarkyonic Matter



Holographic Dual

Sakai-Sugimoto model (dual to large-N_c QCD)

Same degrees of freedom and symmetry as QCD

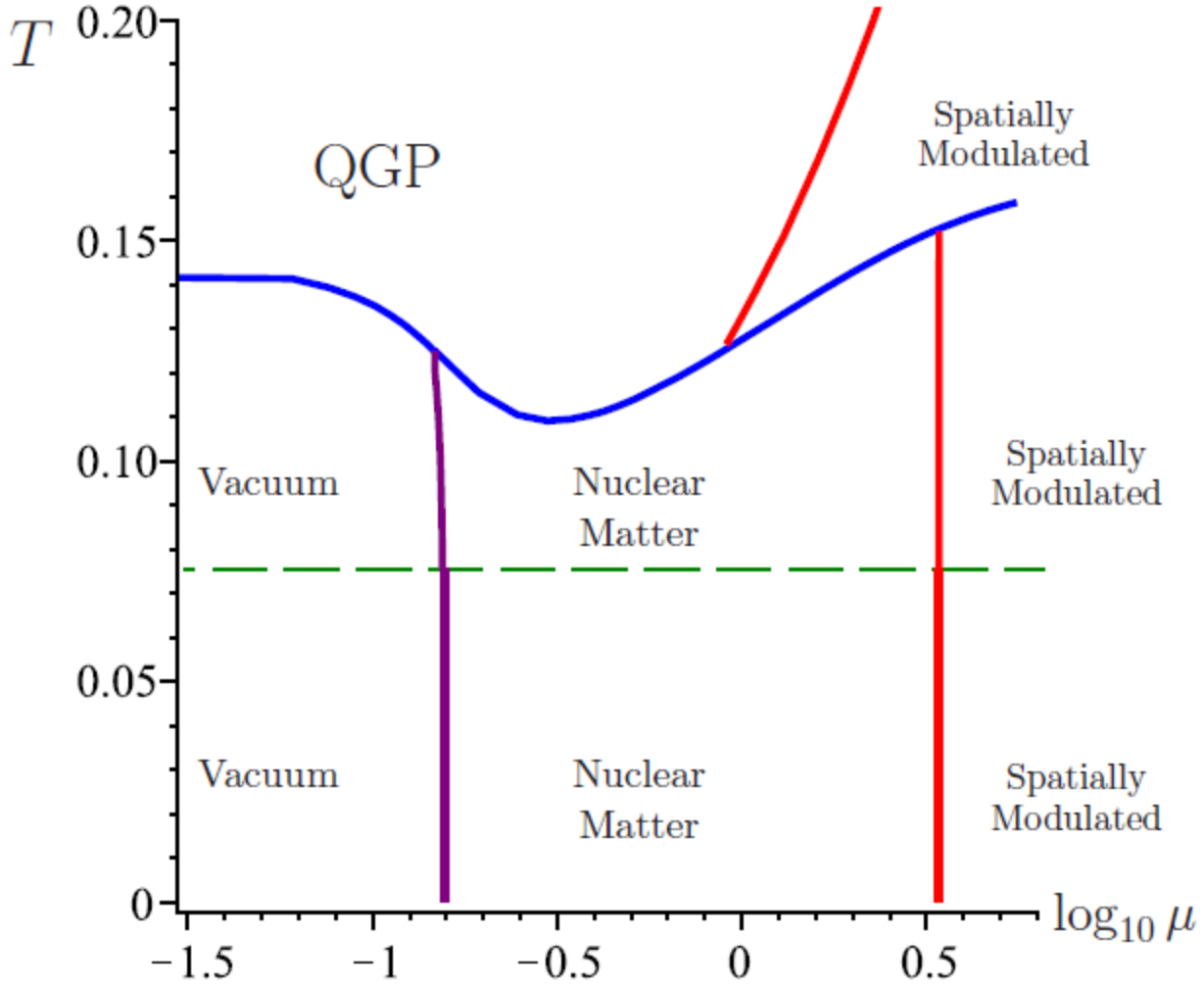


D4 deconfining Density source from baryons than quarks

Bergman et al. (2007)

More on Holographic Dual

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



Definition:
~ Formal / Phenomenological ~

Formal Definition

KF-Sasaki (2013)

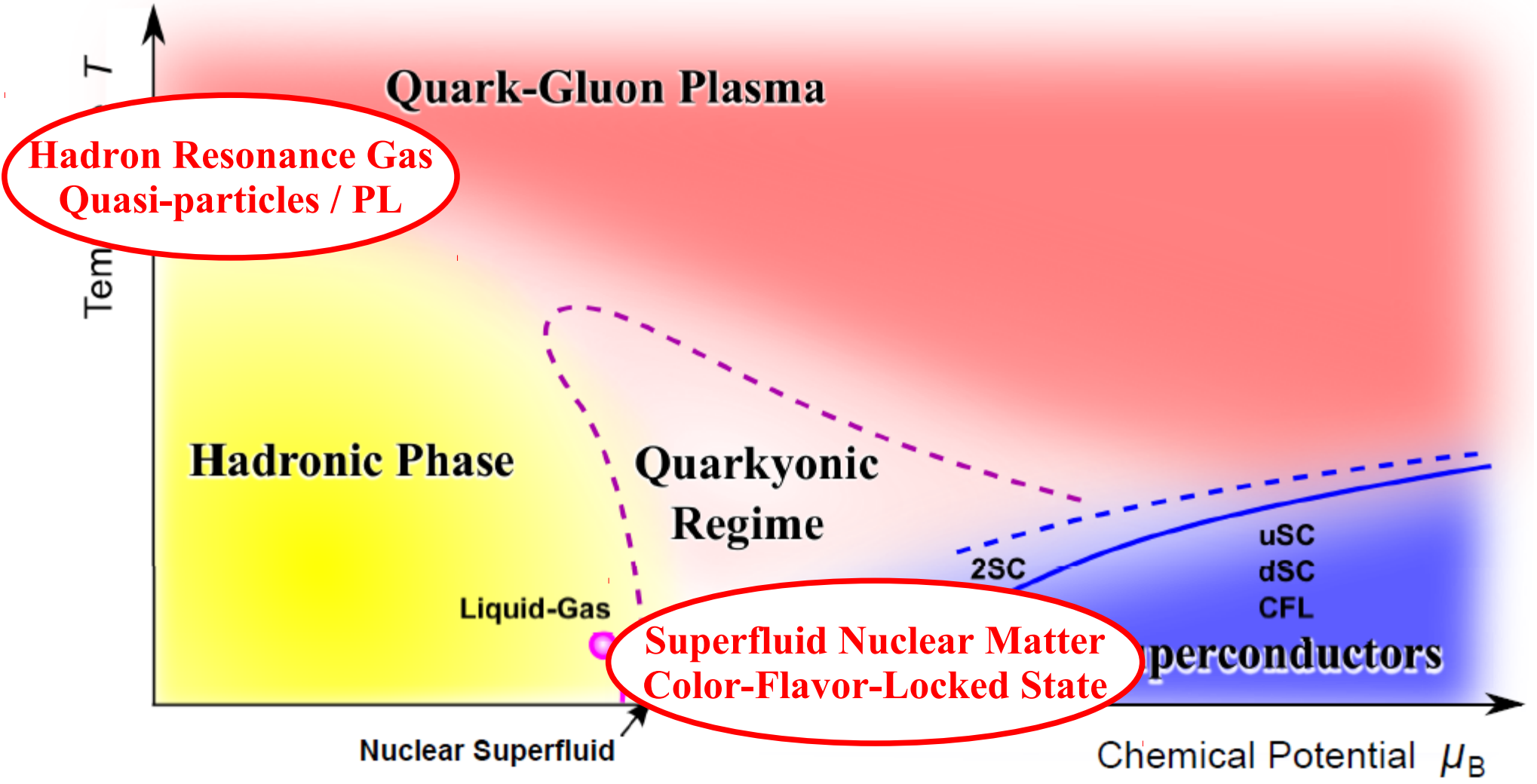
A state of matter that satisfies the McLerran-Pisarski conjecture

Conjecture:

A dense system of strongly interacting baryons be a dual to a system of quarks

One manifestation of the "Quark-Hadron Duality"

Quark-Hadron Dualities



Similarity and Dissimilarity

- Hadron resonance gas can describe thermodynamic properties (including fluctuations) up to the crossover regions.

  How free HRG melts into a quark-gluon plasma?

  Percolations **Mesons ~ free at large N_c**

- In the quarkyonic regime baryons melt into quarks.

  Strong Interactions **Baryons ~ $O(N_c)$ at large N_c**

  We surely know that free HRG cannot be a right description of nuclear matter!

Deviation from free HRG (baseline)

- **Critical fluctuation**

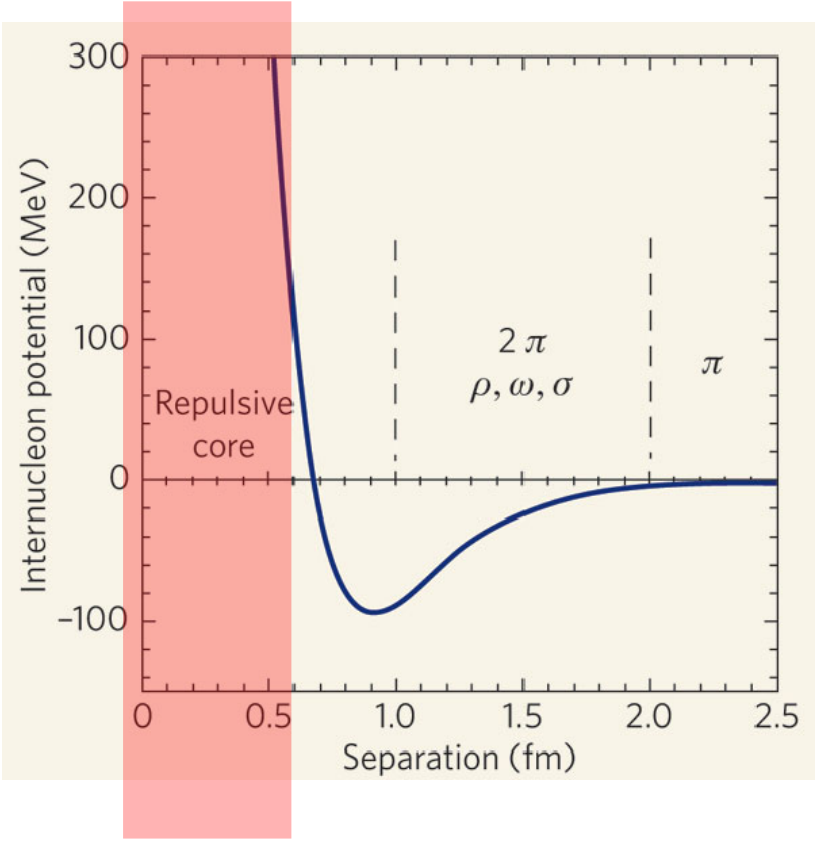
  If fluctuations are affected by criticality of chiral phase transition (that belongs to O(4) at zero density and Z_2 at the QCD critical point), fluctuations (skewness, kurtosis, etc) should deviate from the estimate of free HRG.

- **Strongly interacting baryons**

  If interactions among particles dominate the system properties, free HRG breaks down.

Interactions in the framework of HRG

Van der Waals Corrections



$$V \rightarrow V - \sum \nu_i N_i$$

$$\mu \rightarrow \mu - \sum \nu_i P_i$$

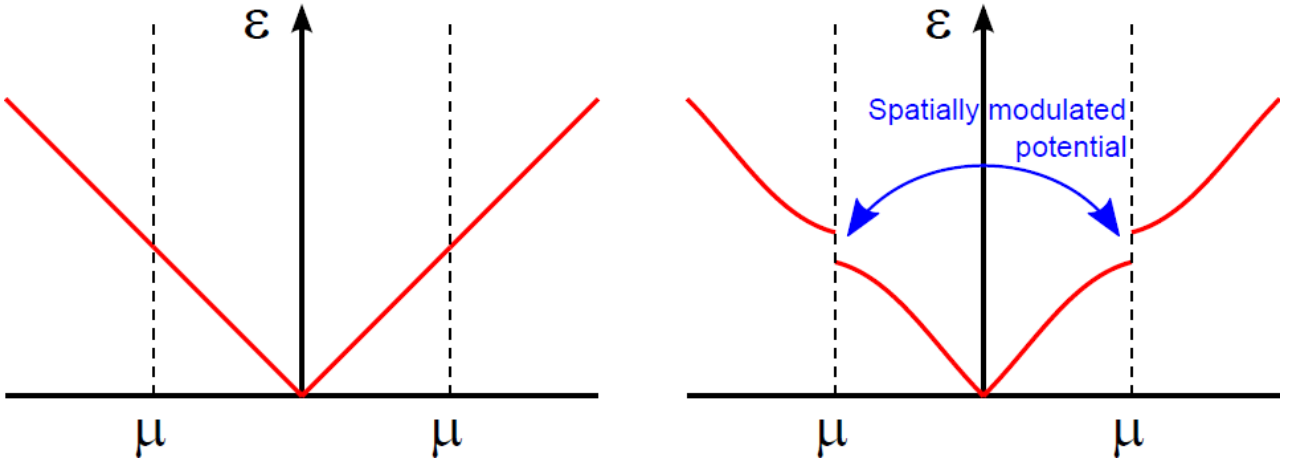
This is not sufficient to take account of interacting baryons

Theory needs to be established to access Quarkyonic Regime

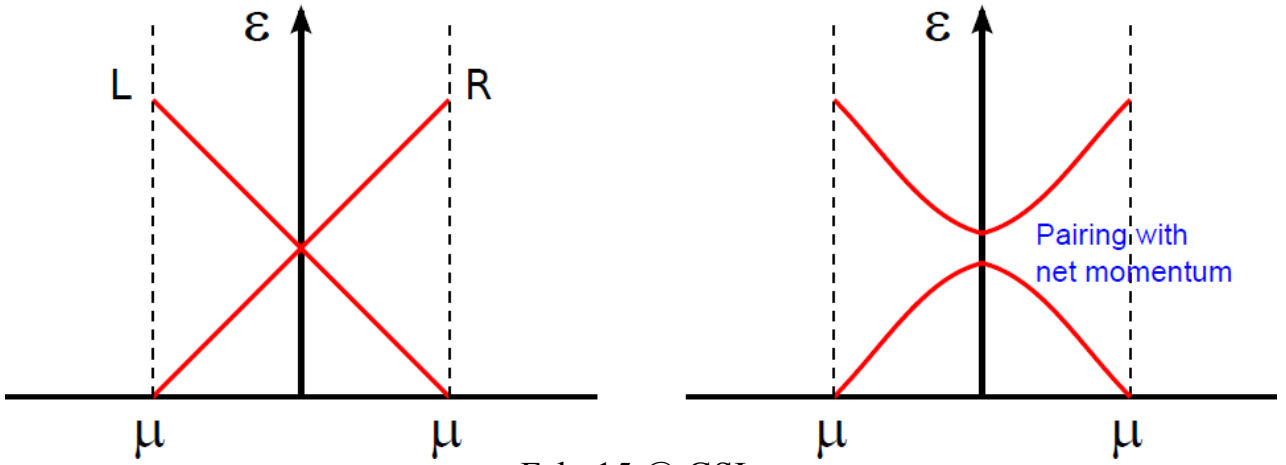
Ground State Structure

Charge and Spin Density Waves

- **Peierls Instability** (Gross-Neveu model)



- **Overhauser Instability** (Chiral Gross-Neveu model)



In-medium Confinement

Whenever a gap opens near the Fermi surface, the low-energy (smaller than the gap size) effective theory is a pure Yang-Mills theory that is a confining theory.

Color superconductor / Pion condensation
Rischke-Son-Stephanov / Son-Stephanov (2000)

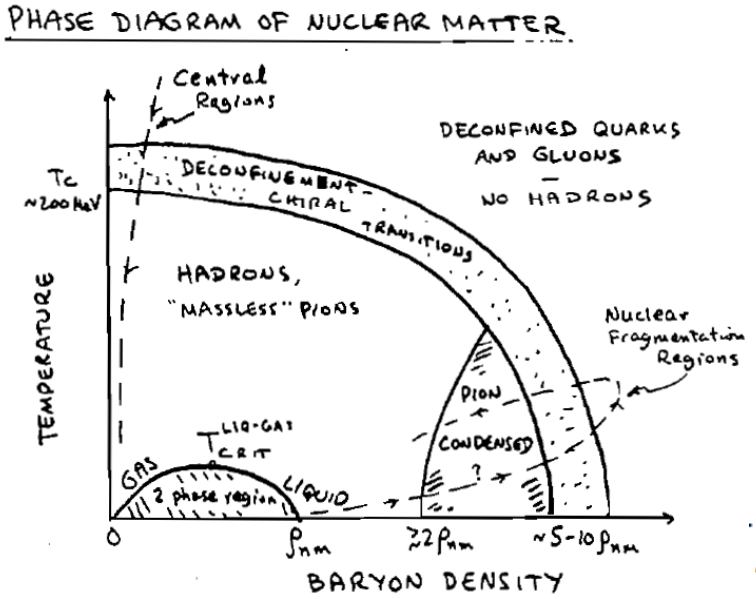
Inhomogeneous condensate → Gap → Confinement

Dual chiral-density wave **Nakano-Tatsumi / Buballa-Nickel-...**

Quarkyonic chiral spiral **Hidaka-Kojo-McLerran-Pisarski (2010)**

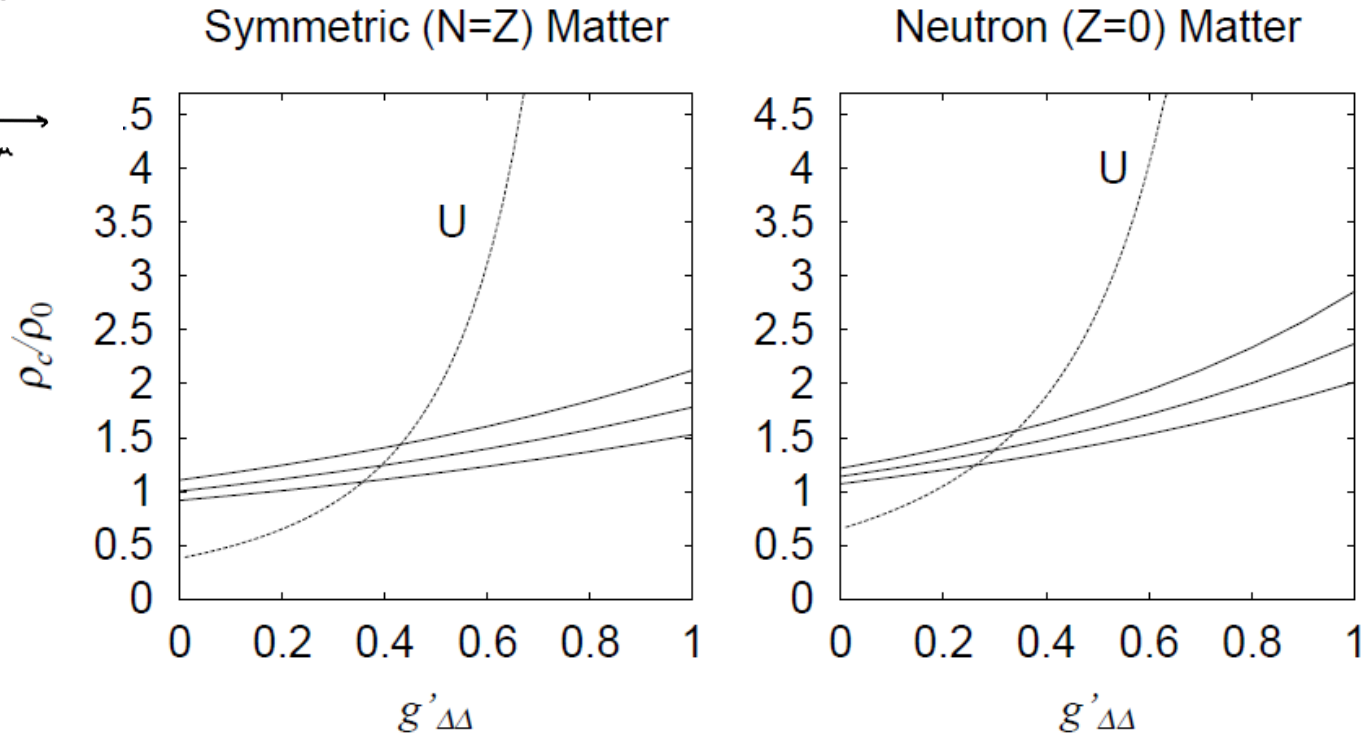
Many chiral models have no critical point.
Any chiral model (so far) favors inhomogeneity.

p-wave Pion Condensation



p-wave pion condensation is still a likely possibility.

Sakai-Tatsumi et al. (2003)



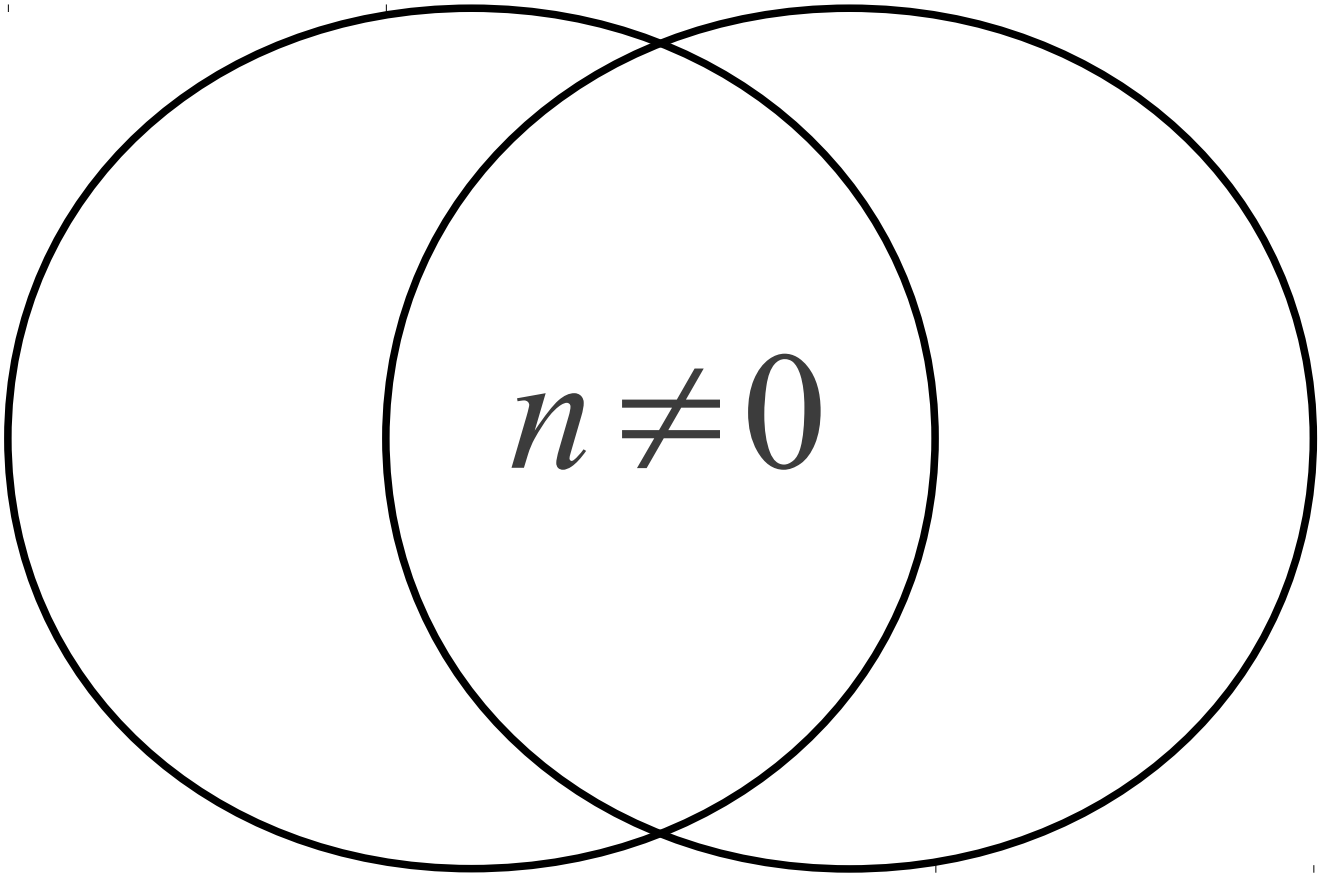
Determination of Landau-Migdal parameters

Challenges at High Densities

- **Mechanism of Deconfinement**
  - Qualitative change of major degrees of freedom
  - Deviation from a free hadron resonance gas
- **Crystalline Structure of Condensates**
  - Condensed matter physics of QCD
  - Mixed phase ~ Density fluctuations
  - Spiral in chiral circle / Local parity violation
- **Phenomena related to the Baryon Number**
  - Topological configurations / anomaly

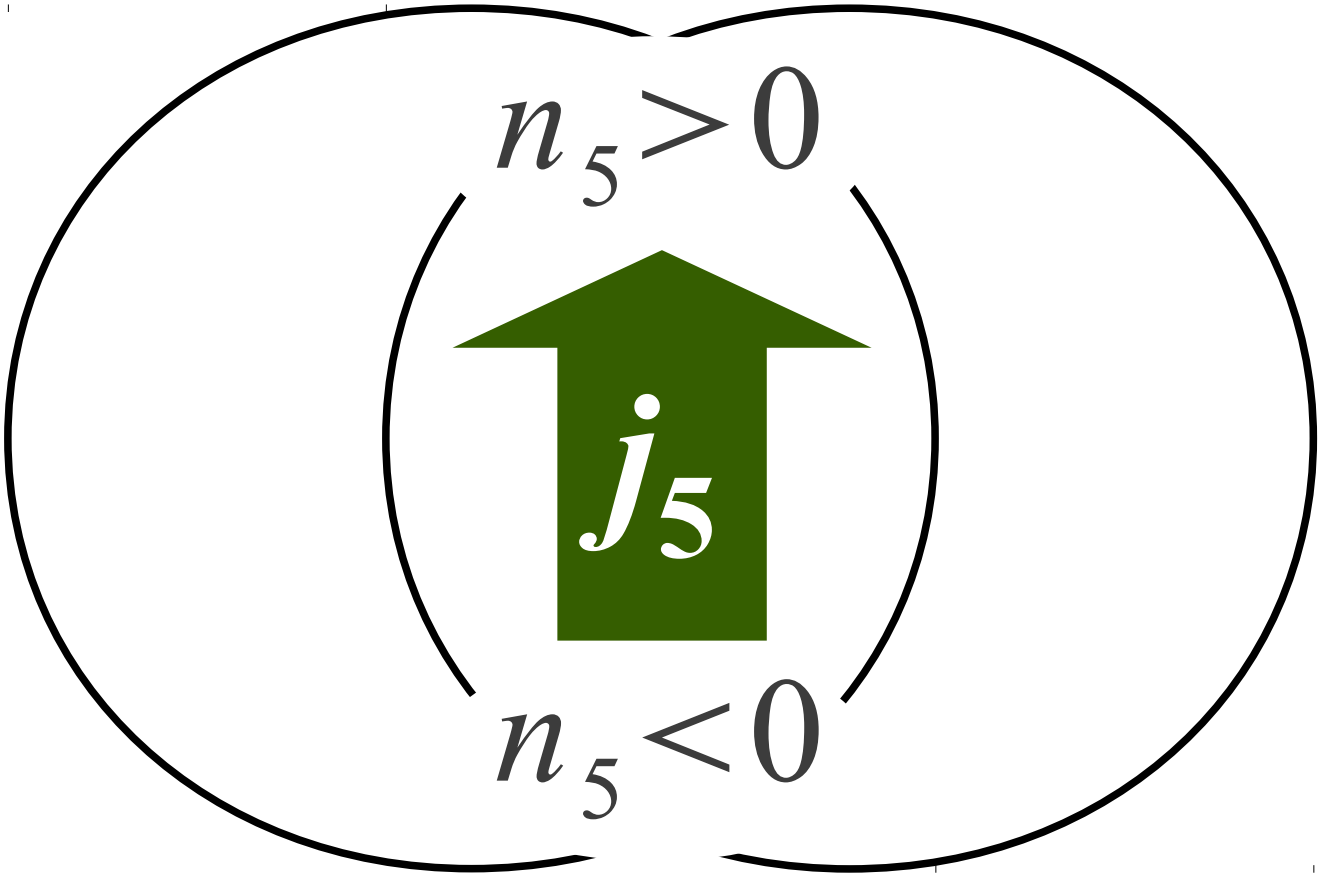
e.g. Chiral Magnetic Wave

Chiral Magnetic Wave



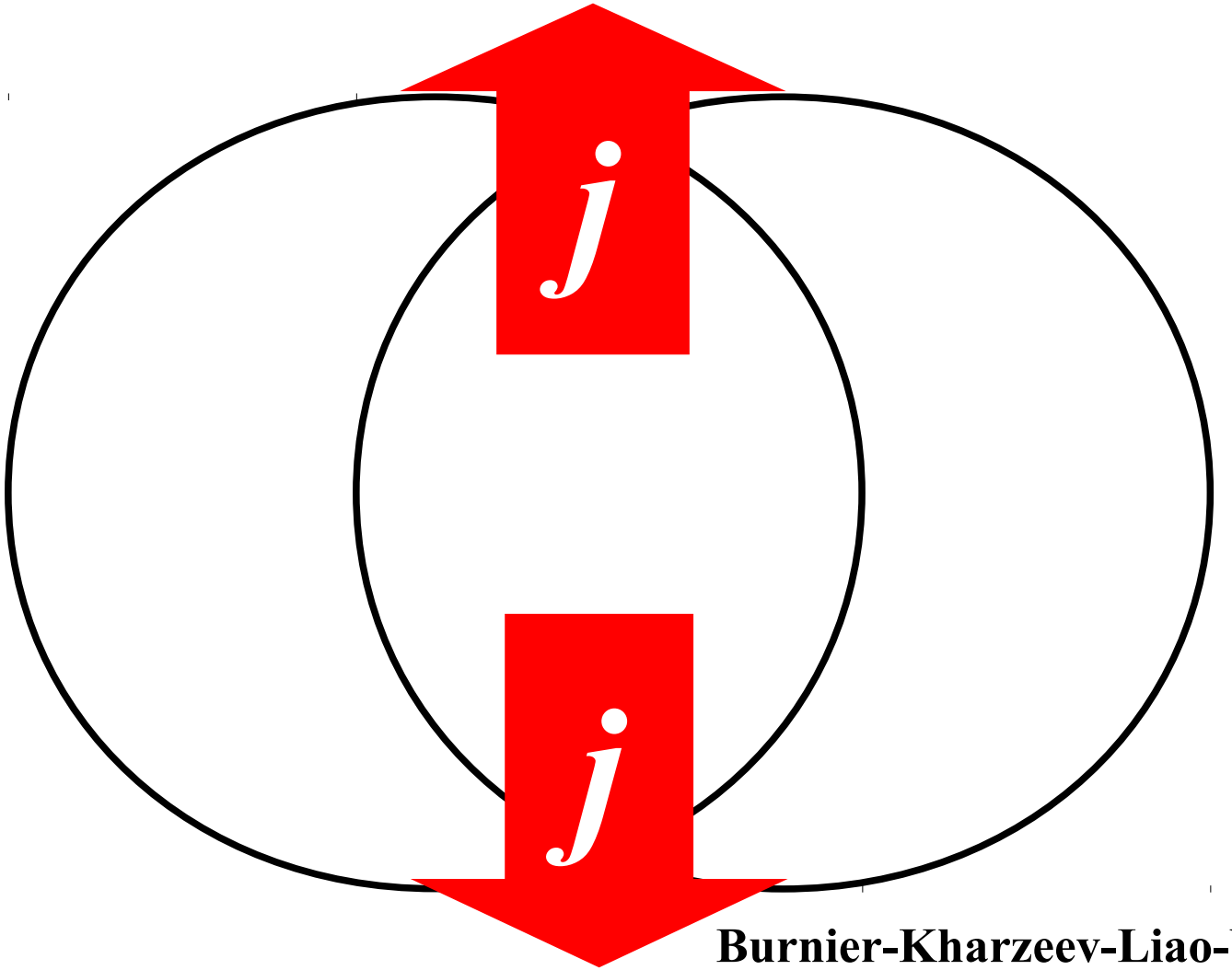
Burnier-Kharzeev-Liao-Yee (2011)

Chiral Magnetic Wave



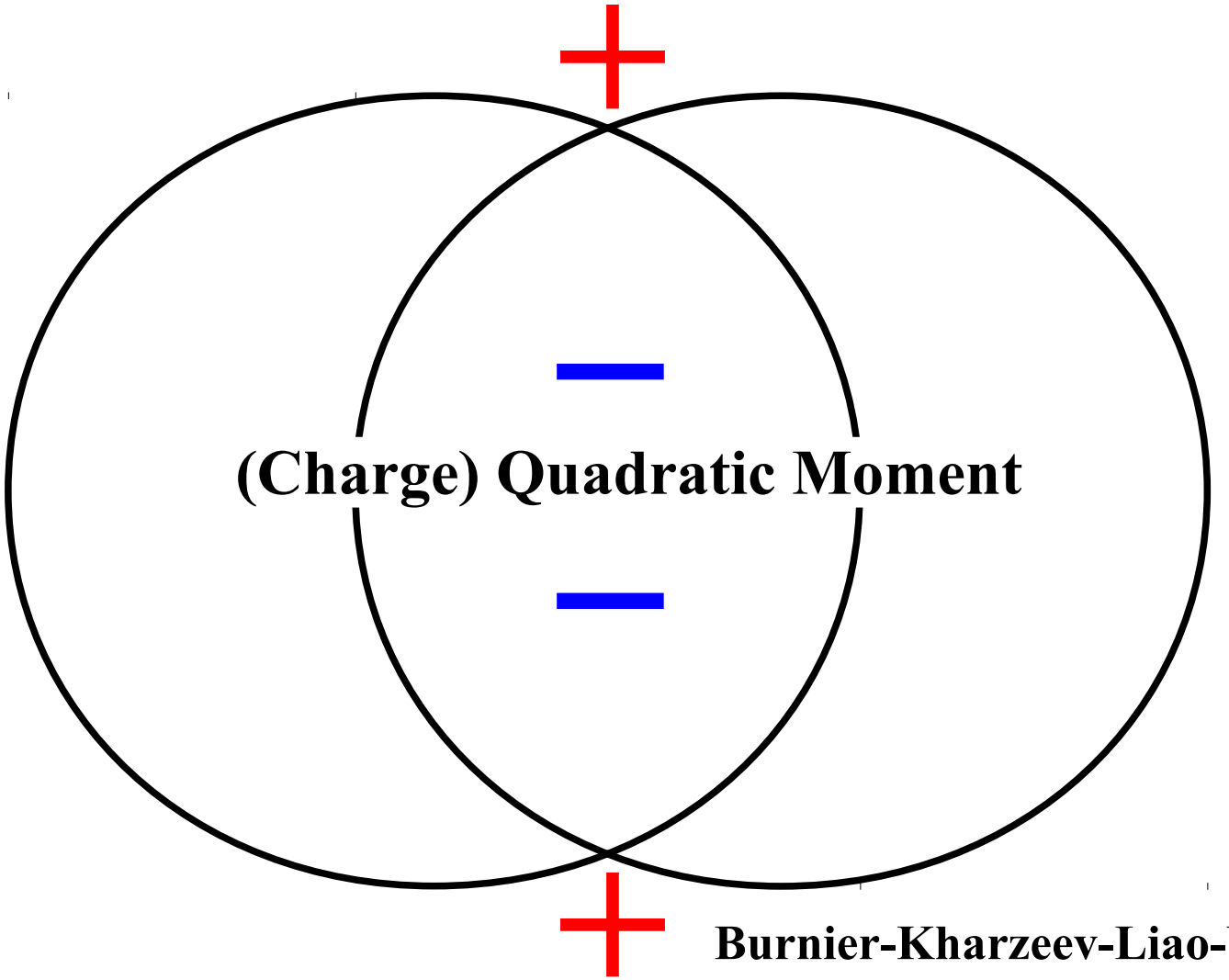
Burnier-Kharzeev-Liao-Yee (2011)

Chiral Magnetic Wave



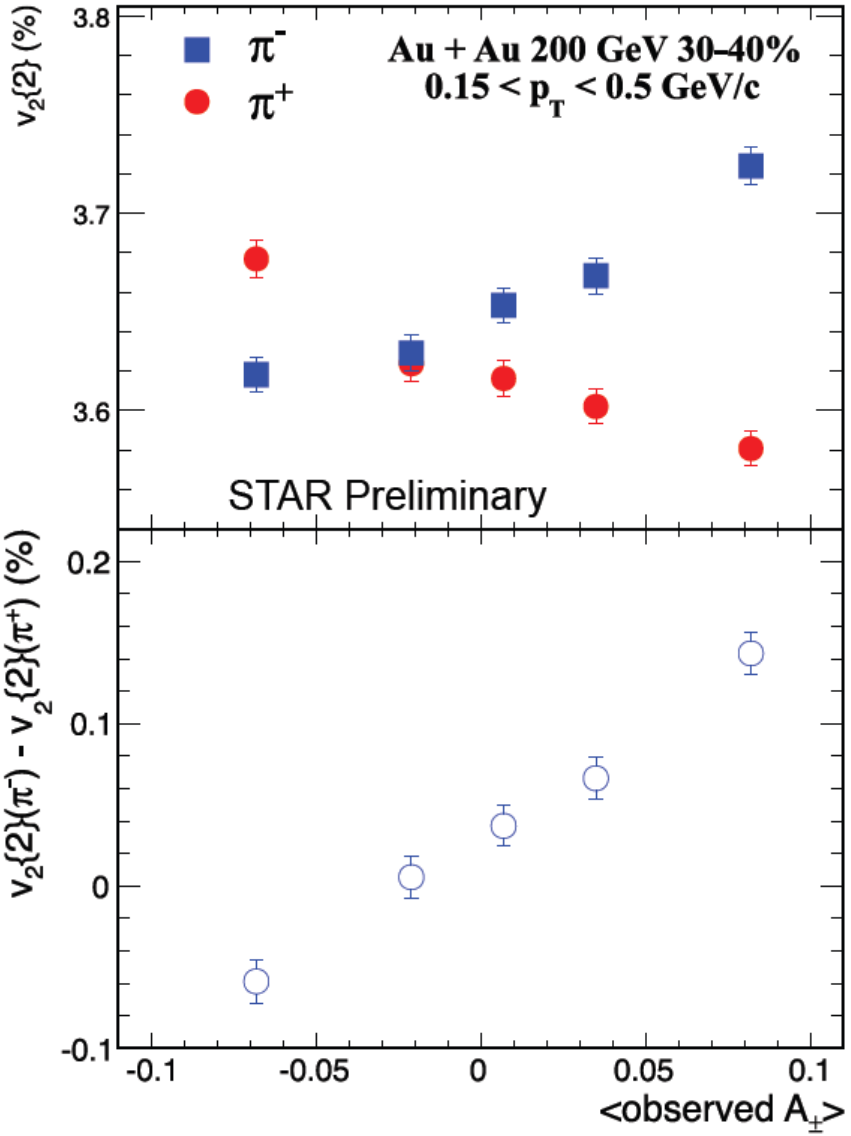
Burnier-Kharzeev-Liao-Yee (2011)

Chiral Magnetic Wave



Burnier-Kharzeev-Liao-Yee (2011)

Chiral Magnetic Wave



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?

STAR data presented at CPODD

Conclusion

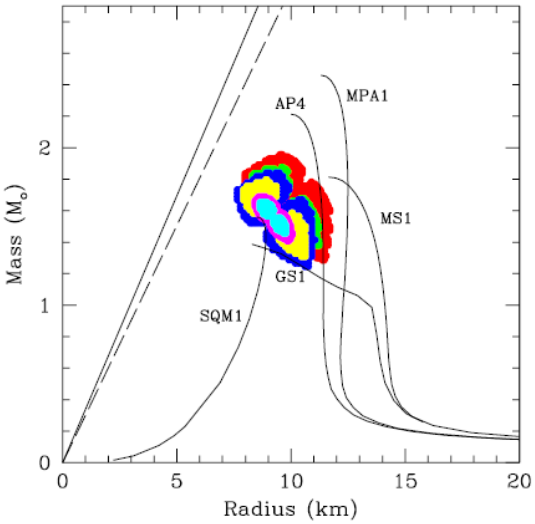
- Even without any sharp structure, the QCD phase diagram contains rich physics at high density.

  c.f. BEC-BCS crossover in a ultracold gas

- I do not try to exclude anything.

  Only I did not assume anything.

  c.f. neutron star physics
  Baym, Lattimer, Ozel...



- Observable?

  Comparison with HRG / EM probes / LPV / ...