Phase Diagram of QCD

Kenji Fukushima

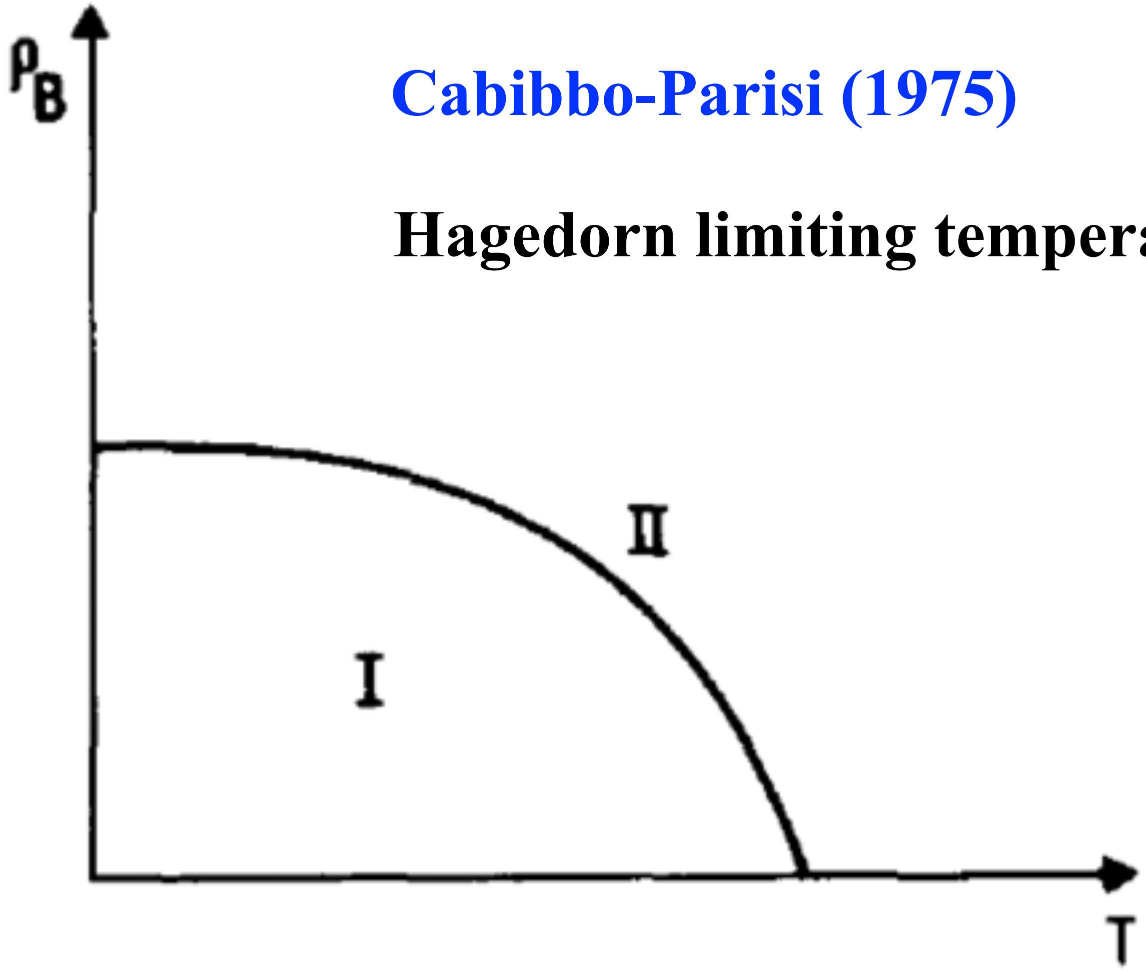
The University of Tokyo

— QCD Phase Structure III in CCNU Wuhan —

A bit about the History

as an introduction to diquarks

Birth of the QCD Phase Diagram



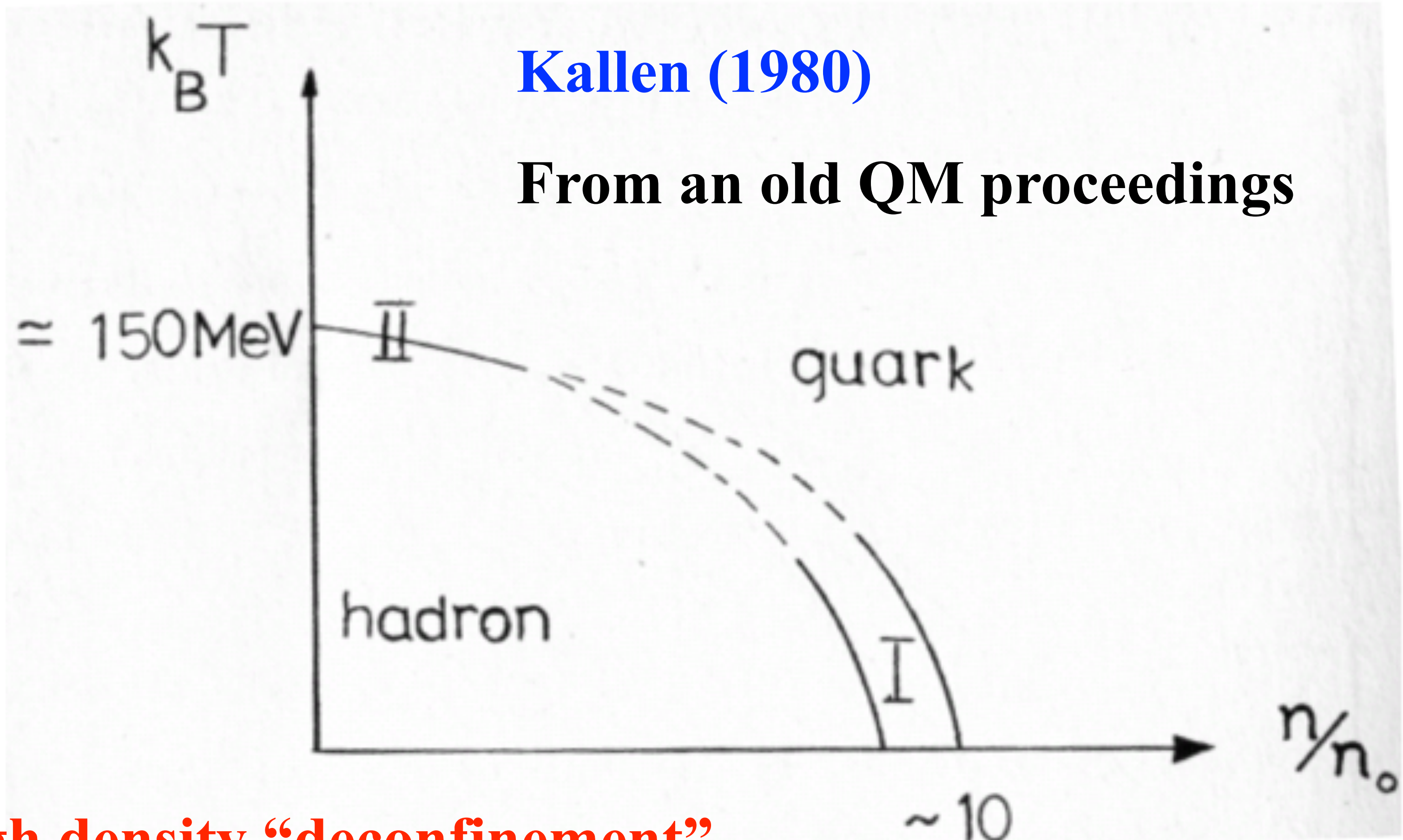
Cabibbo-Parisi (1975)

Hagedorn limiting temperature

Forgotten Candidate

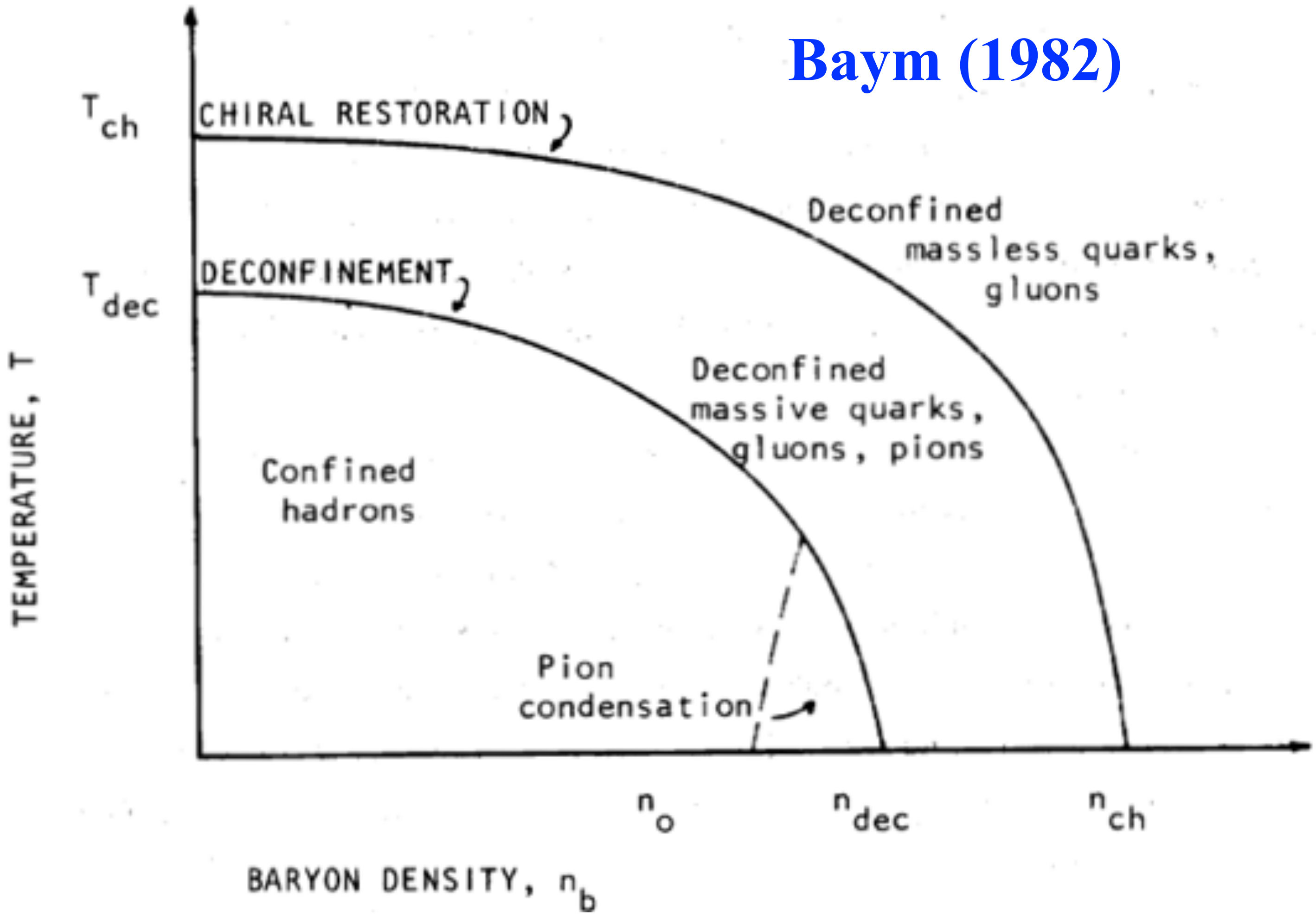
Kallen (1980)

From an old QM proceedings



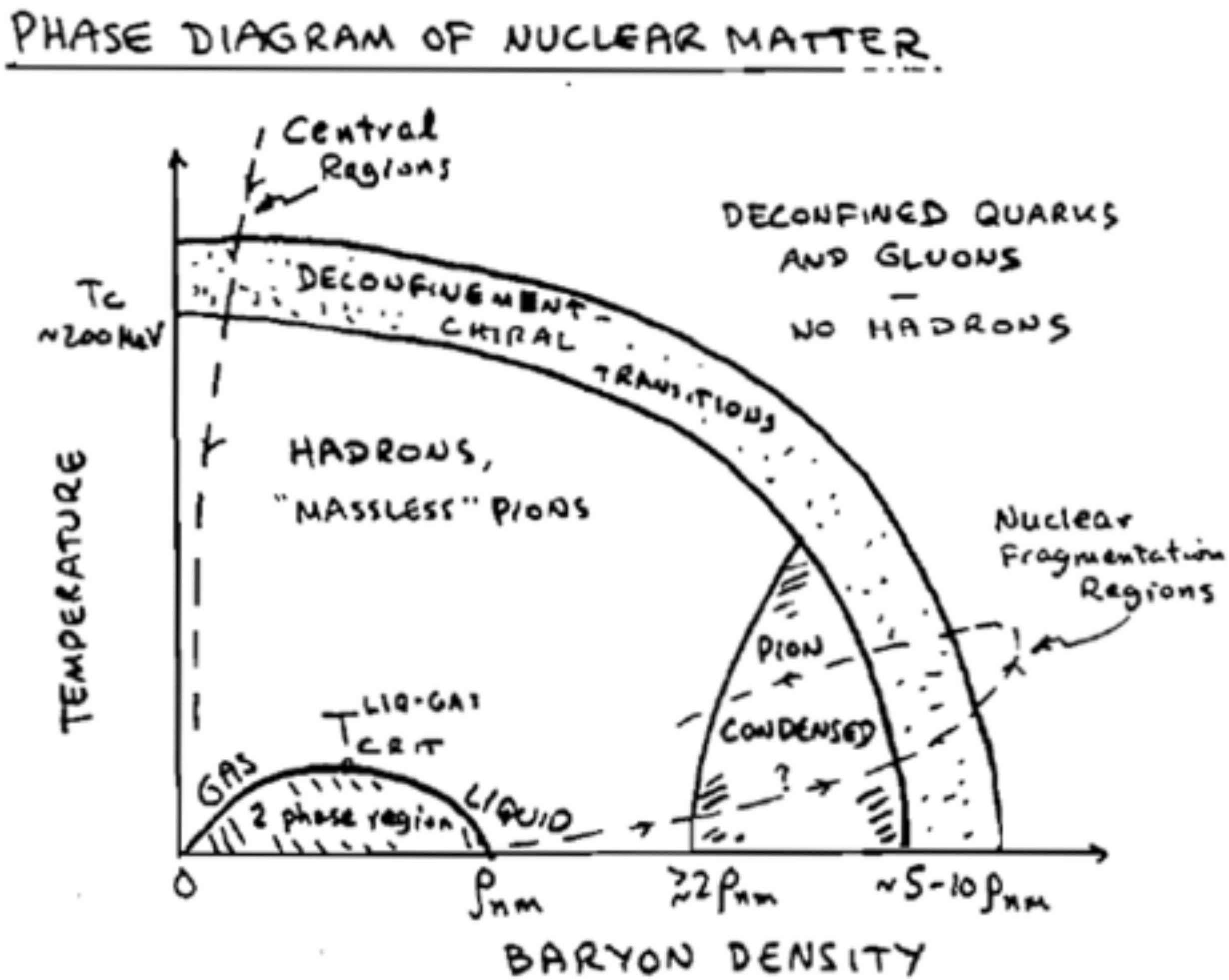
High density "deconfinement"

Forgotten Candidate

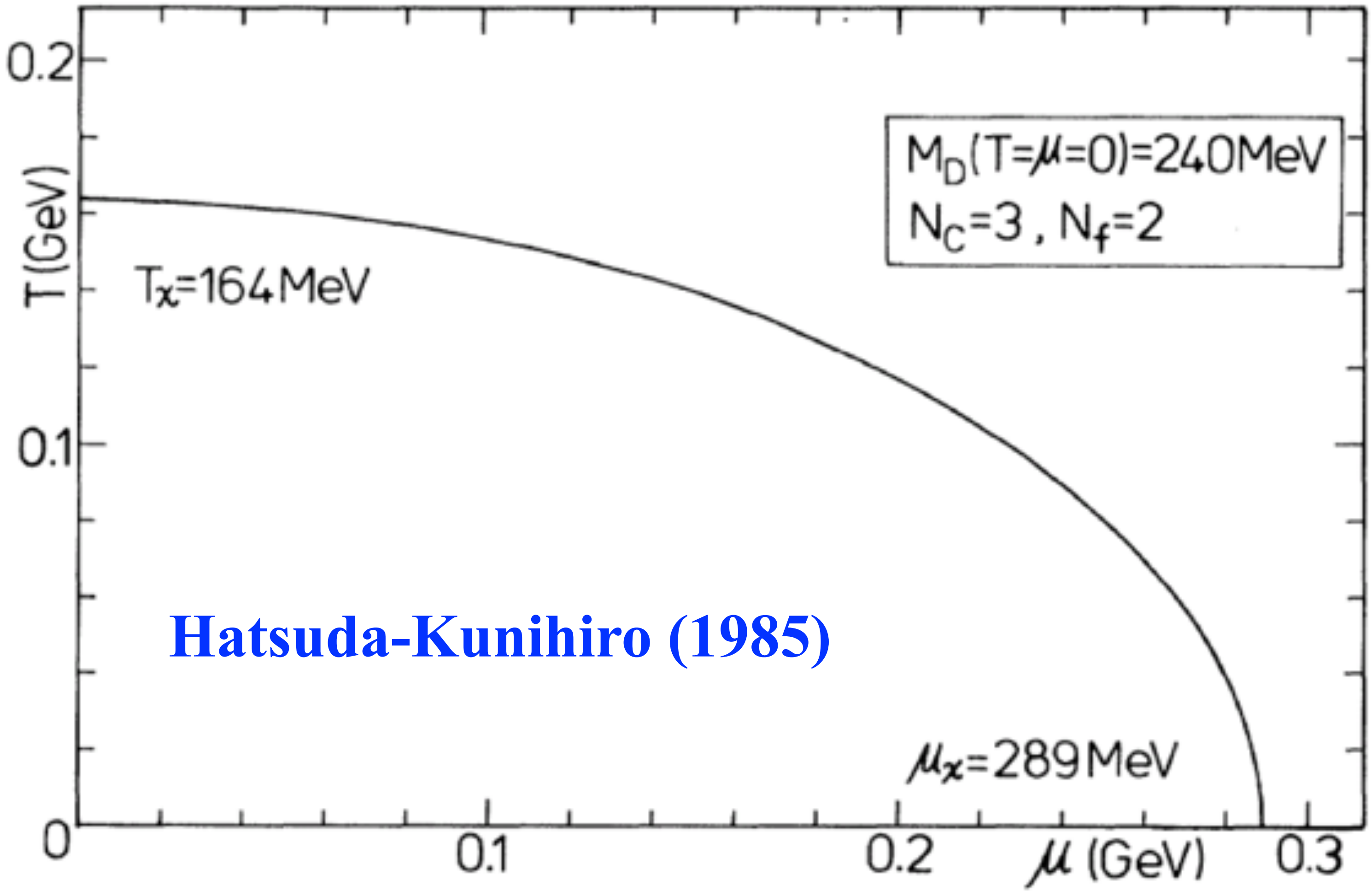


Prototype of Phase Diagram

Baym (1983)

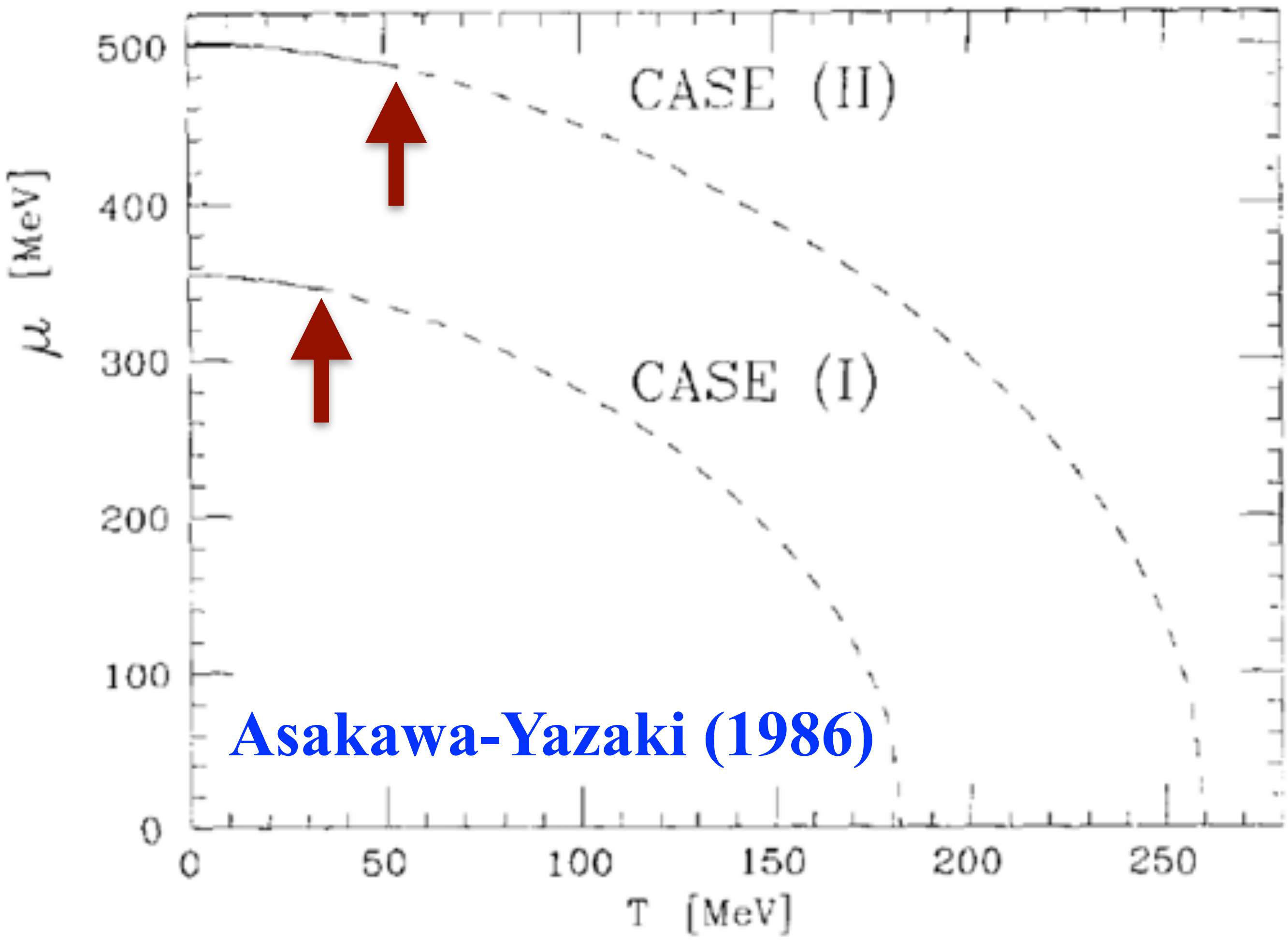


Chiral Phase Diagram

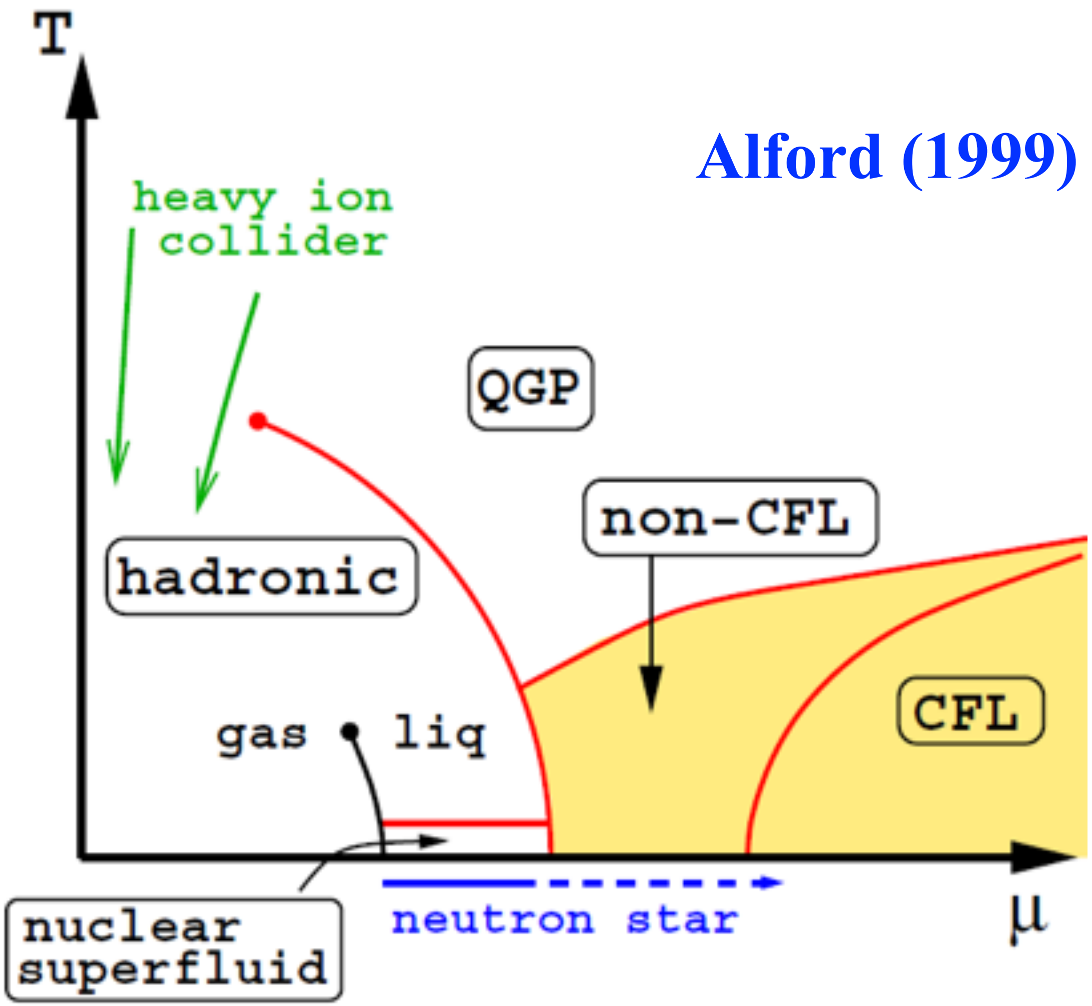


Hatsuda-Kunihiro (1985)

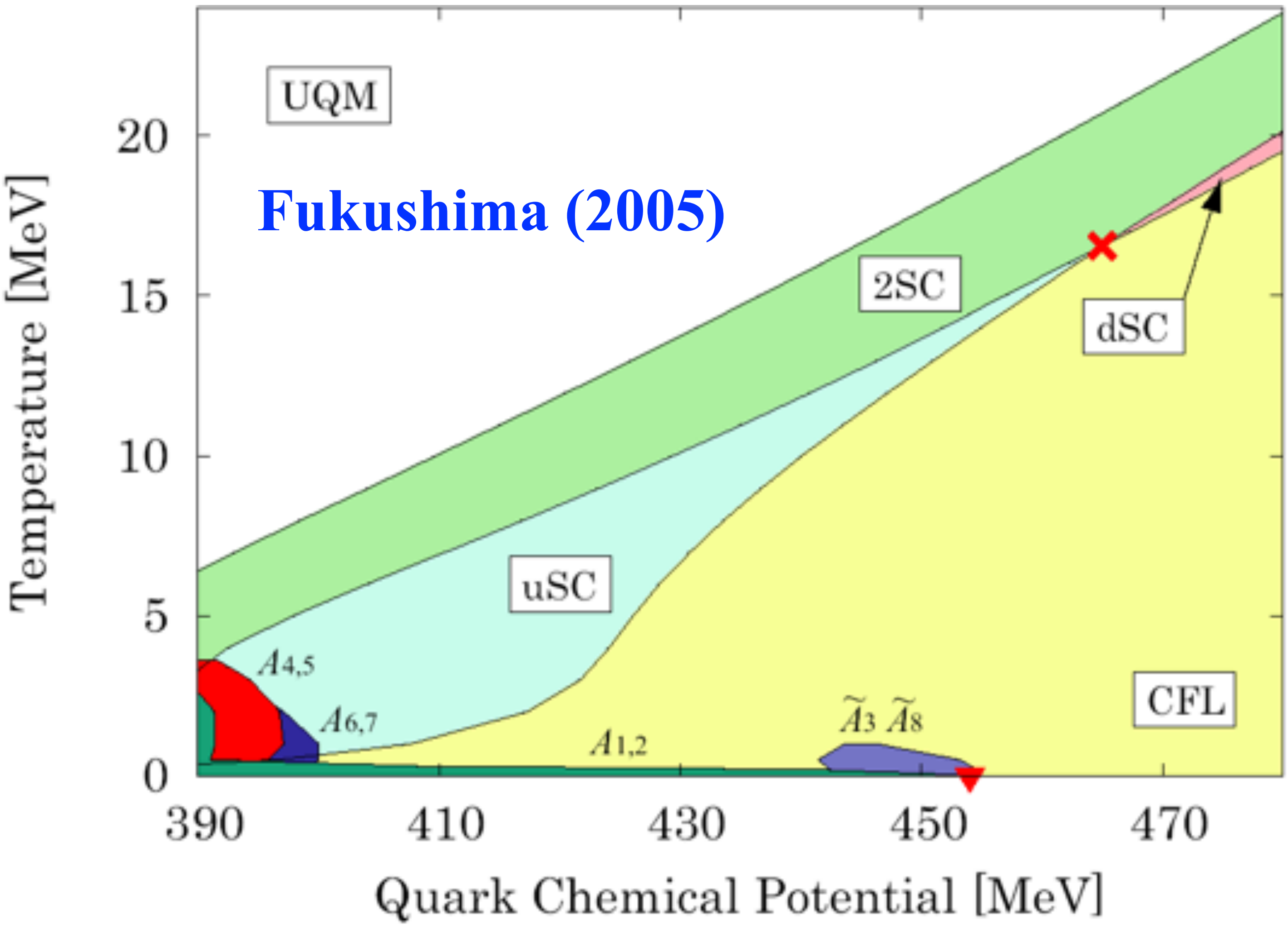
QCD Critical Point



Color Superconductivity



Chromomagnetic Instabilities



Some of Highlights

"Charge Neutrality Effects on 2-flavor Color Superconductivity"
Mei Huang, **Pengfei Zhuang**, Weiqin Chao: hep-ph/0207008

"Breached Pairing Superfluidity at Finite Temperature and Density"
Jinfeng Liao, **Pengfei Zhuang**: cond-mat/0307516

"Pion Condensation in Baryonic Matter: from Sarma Phase to Larkin-Ovchnnikov-Fudde (Fulde)-Ferrell Phase"
Lianyi He, Meng Jin, **Pengfei Zhuang**: hep-ph/0604224

"Neutral Color Superconductivity Including Inhomogeneous Phases at Finite Temperature"
Lianyi He, Meng Jin, **Pengfei Zhuang**: hep-ph/0610121

My First? Contact

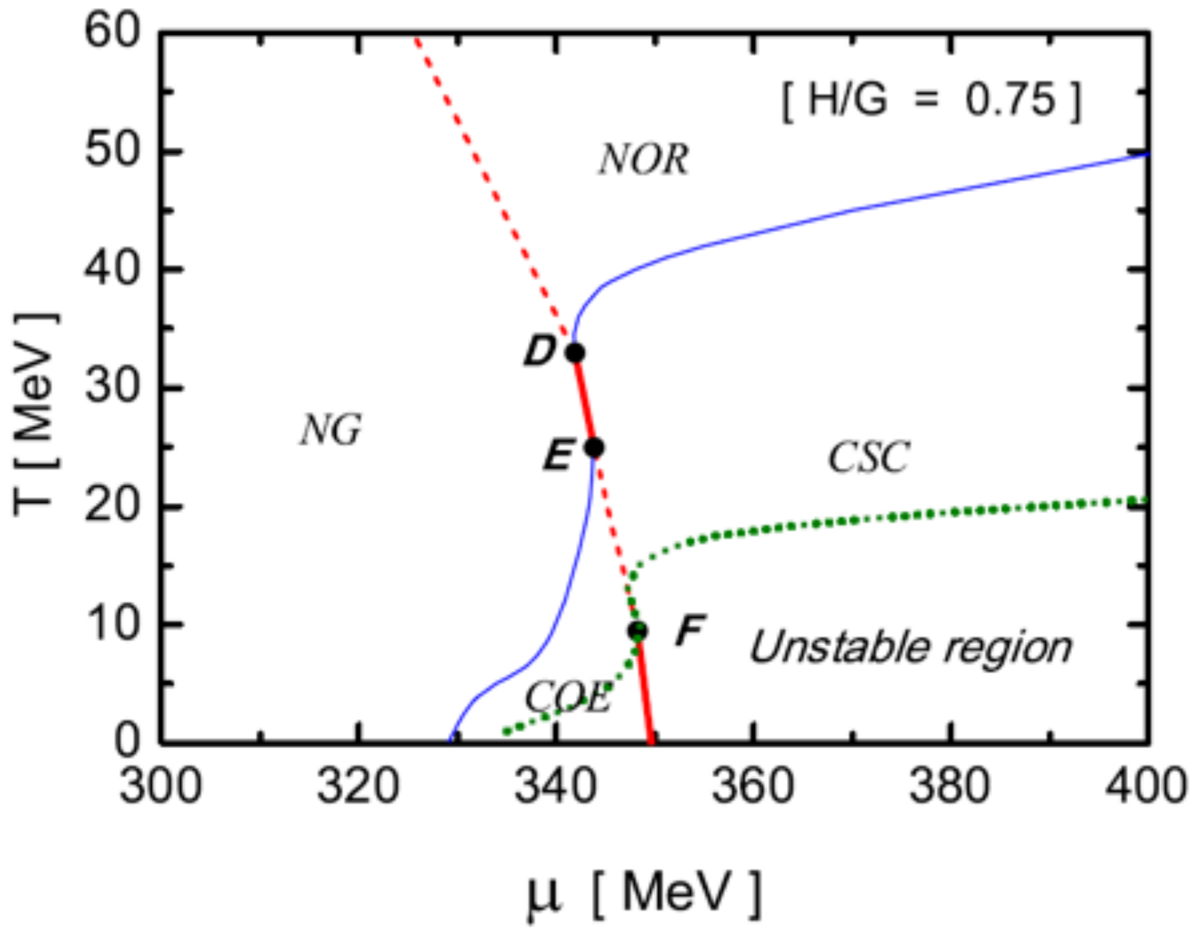
NEW FRONTIERS IN QCD 2008

Fundamental Problems in Hot and/or Dense Matter

Peschanski	Robert	Saclay																											
Redlich	Krzysztof	Wroclaw U.																											
Rho	Mannque	Saclay																											
Rischke	Dirk	Frankfurt																											
Romatschke	Paul	Univ. of Washington																											
Shovkovy	Igor	Western Illinois U.																											
Sin	Sang-Jin	Hanyang U.																											
Venugopalan	Raju	BNL																											
Wambach	Jochen	Darmstadt																											
Last Name	First Name	Affiliation	January				February																						
			28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Weise	Wolfram	Munich Tech. U.																											
Zhuang	Peng-Fei	Tsinghua U.																											

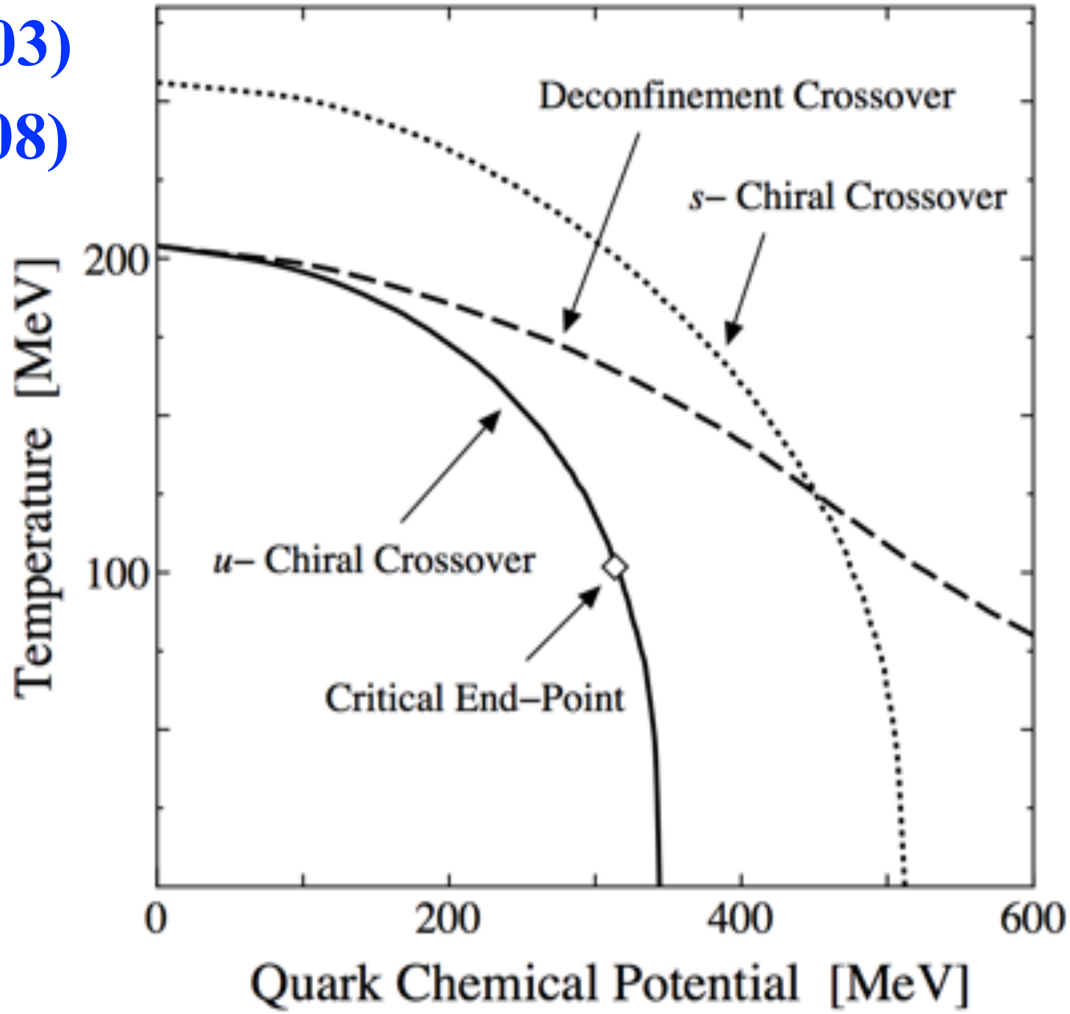
Many QCD Critical Points?

Zhang-Fukushima-Kunihiro (2008)

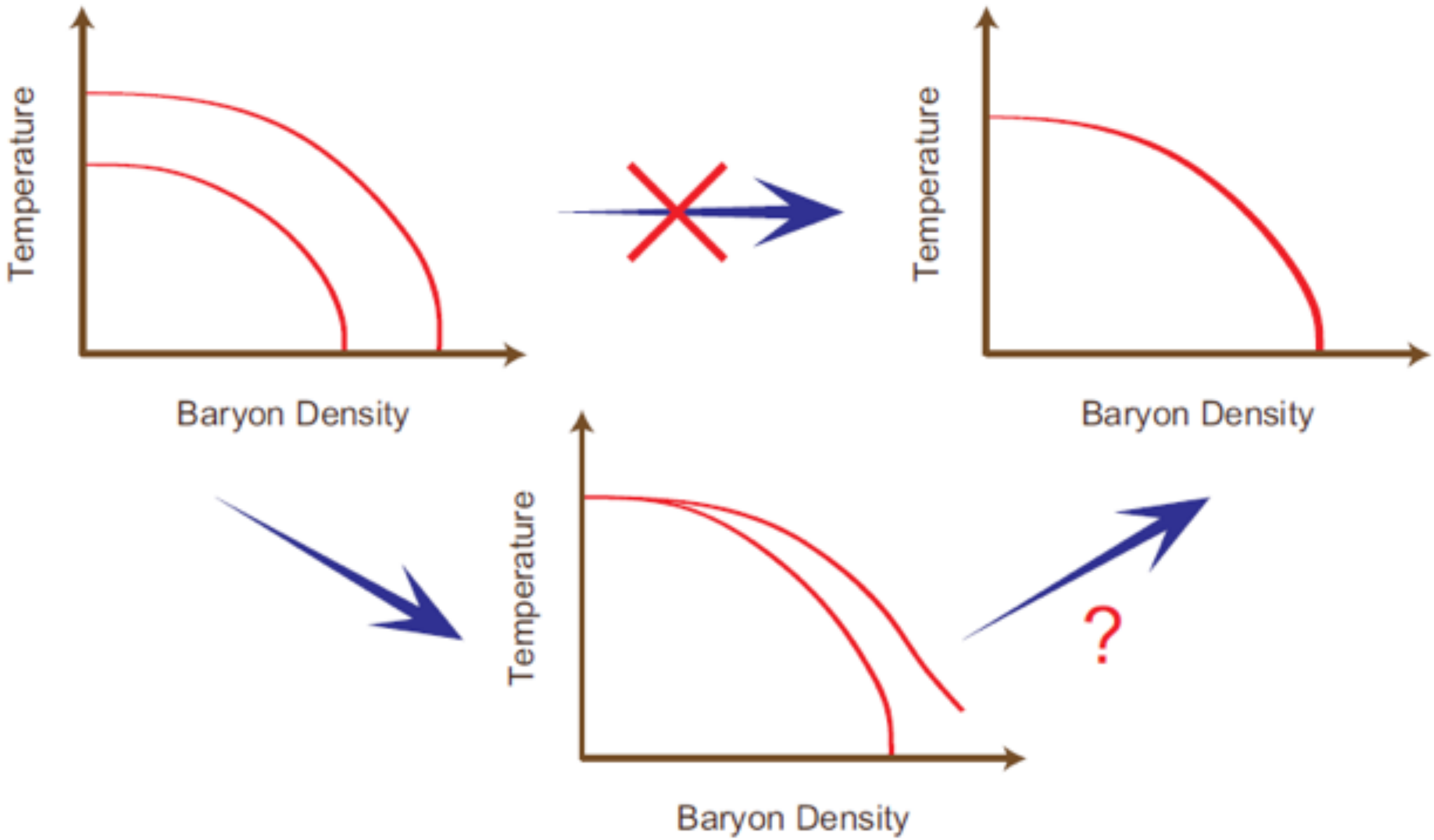


Polyakov Loop

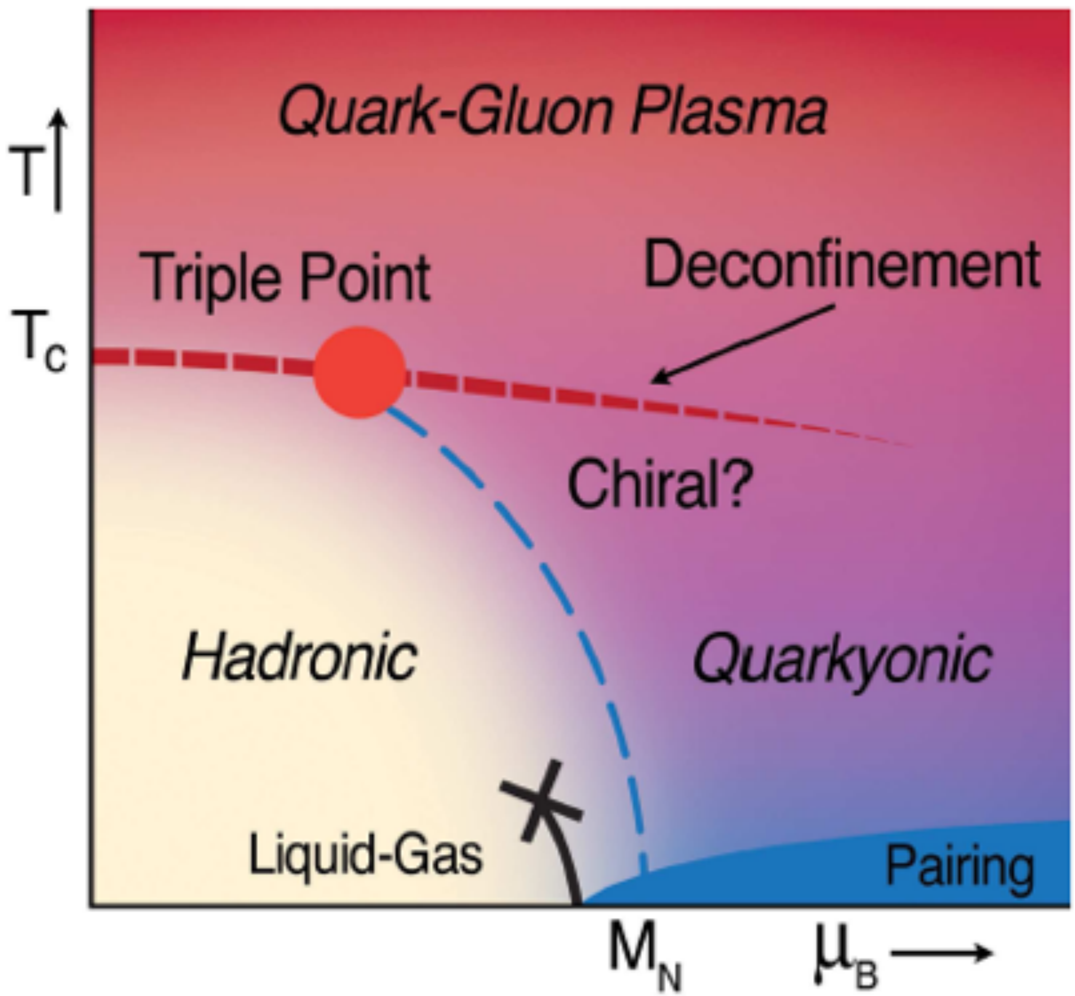
Fukushima (2003)
(2008)



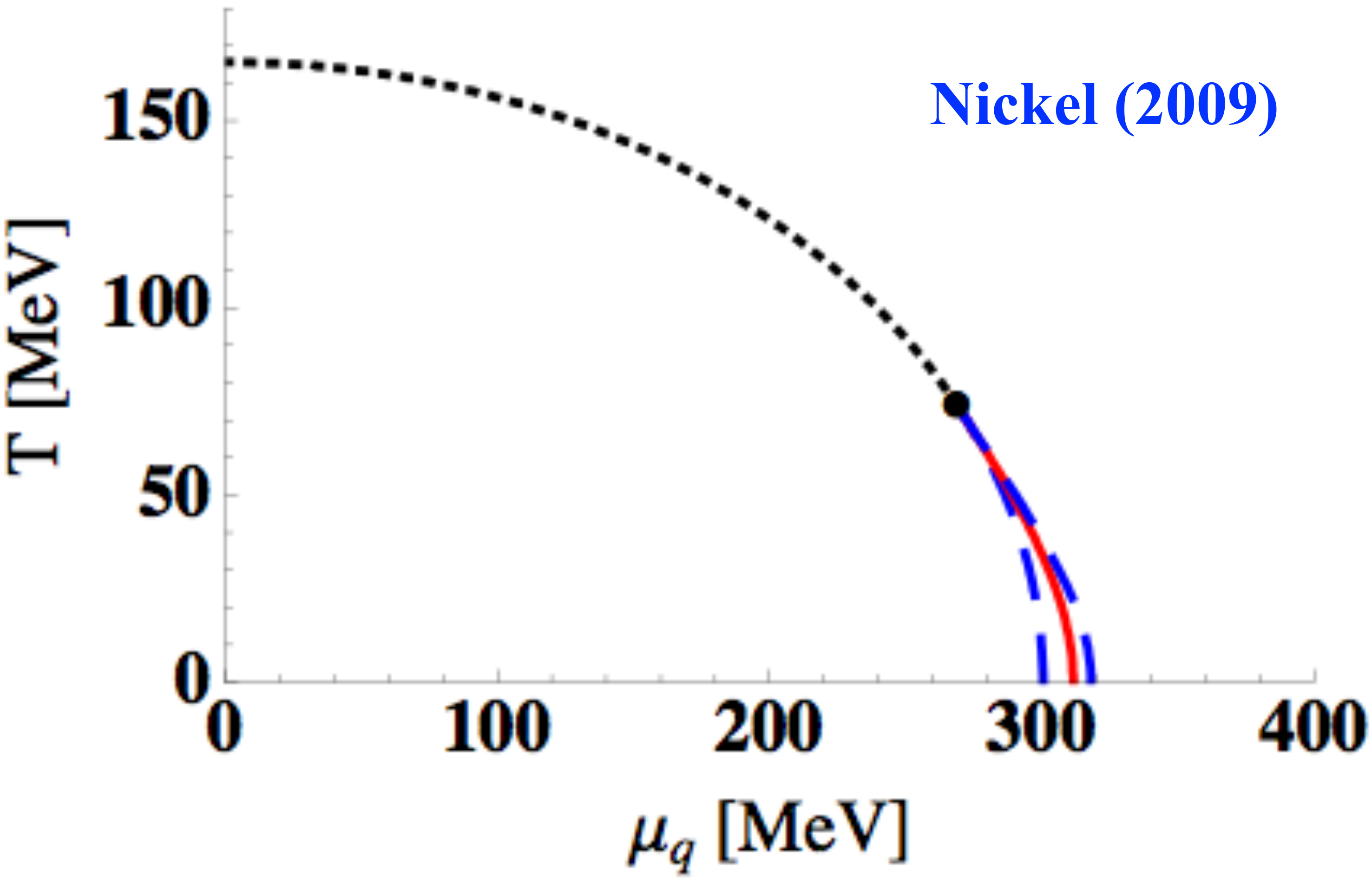
Revival of Interest



BNL-Kyoto-... Diagram

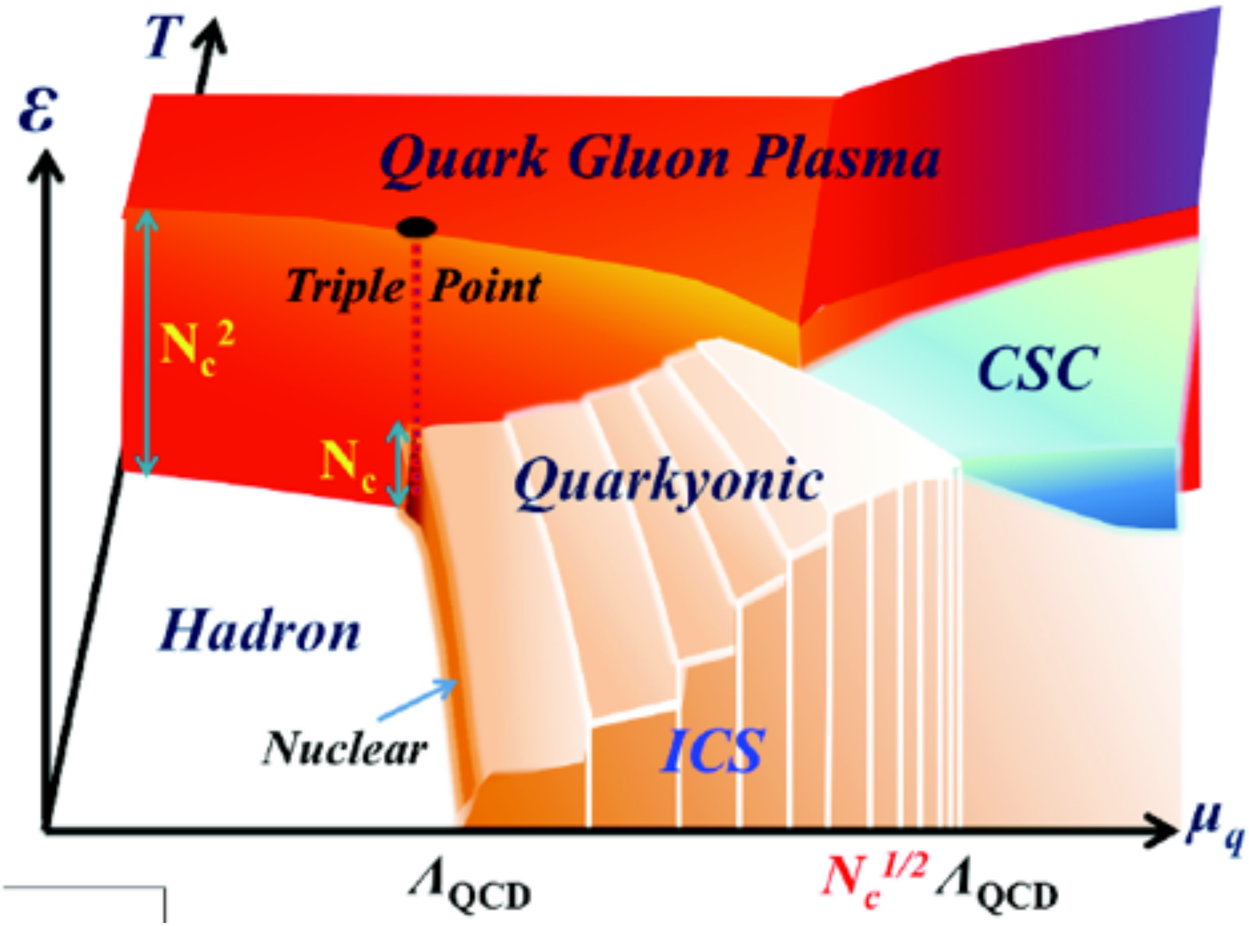


Inhomogeneity

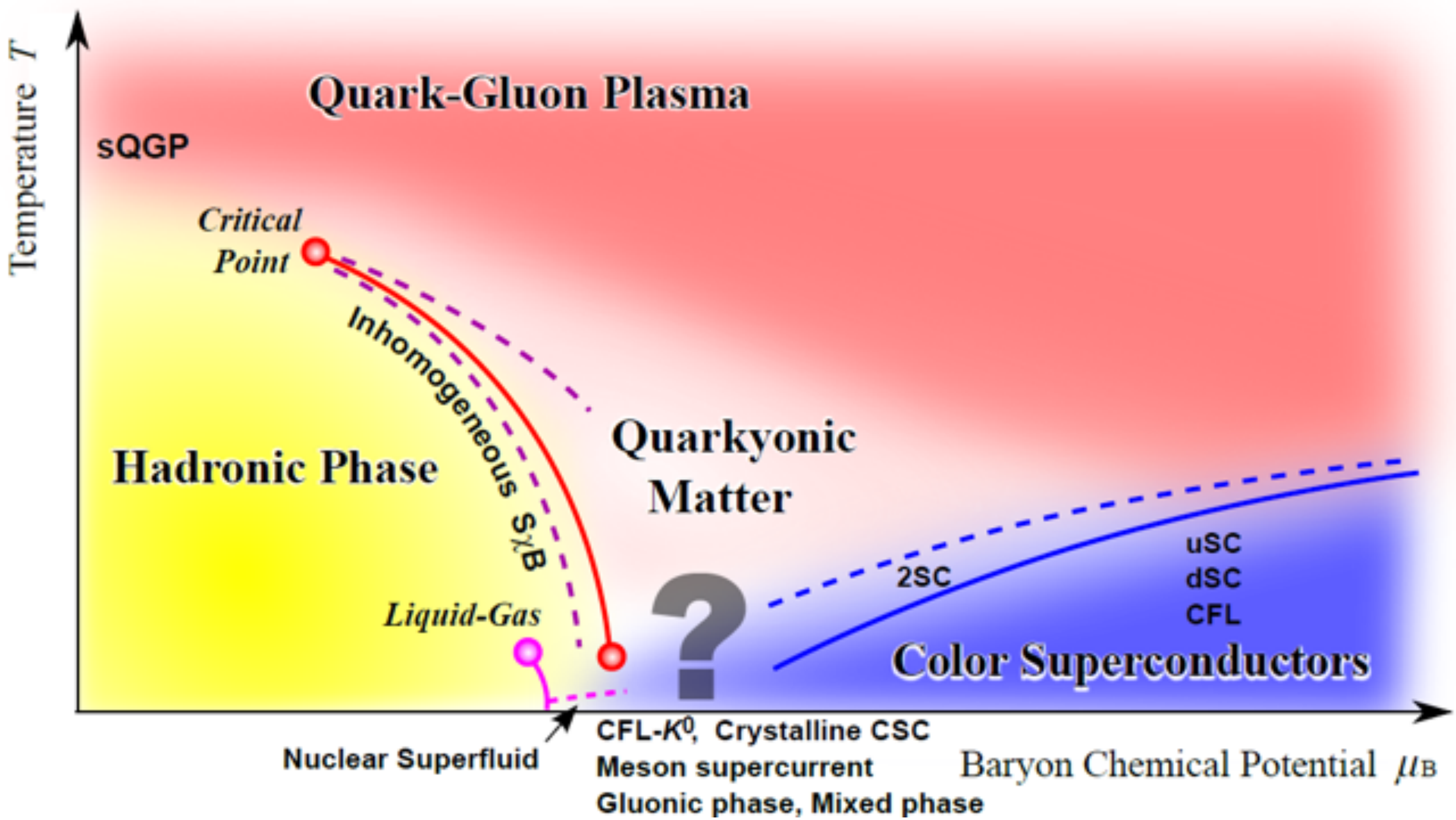


Quarkyonic Chiral Spirals

Kojo-Hidaka-Fukushima-McLerran-Pisarsky (2010)



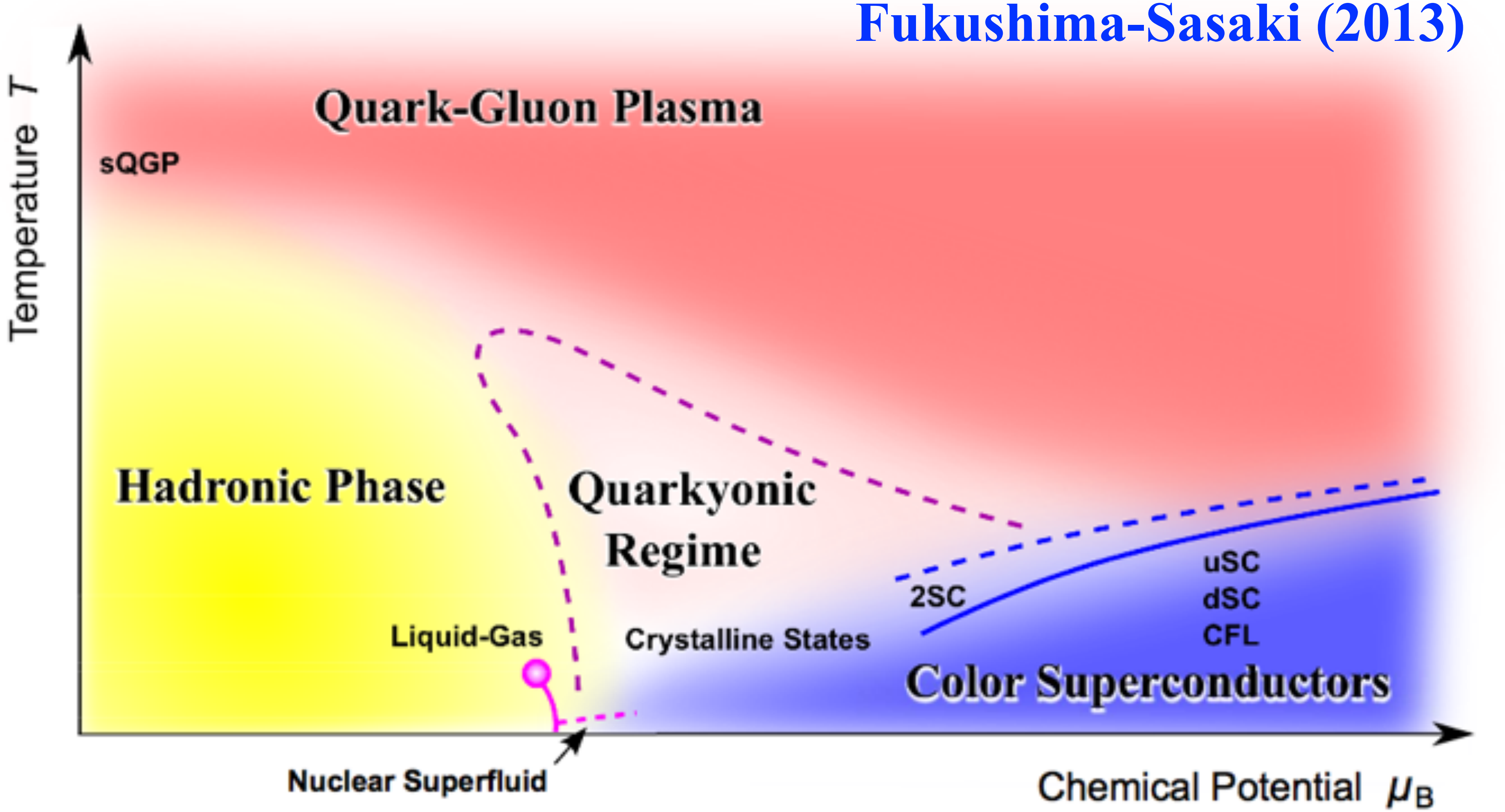
Summary



Temperature T
Quark-Gluon Plasma
sQGP
Critical Point
Inhomogeneous
SχB
Quarkyonic Matter
Hadronic Phase
Liquid-Gas
?
2SC
uSC
dSC
CFL
Color Superconductors
Nuclear Superfluid
CFL-K0, Crystalline CSC
Meson supercurrent
Gluonic phase, Mixed phase
Baryon Chemical Potential μB

Alternative Summary

Fukushima-Sasaki (2013)

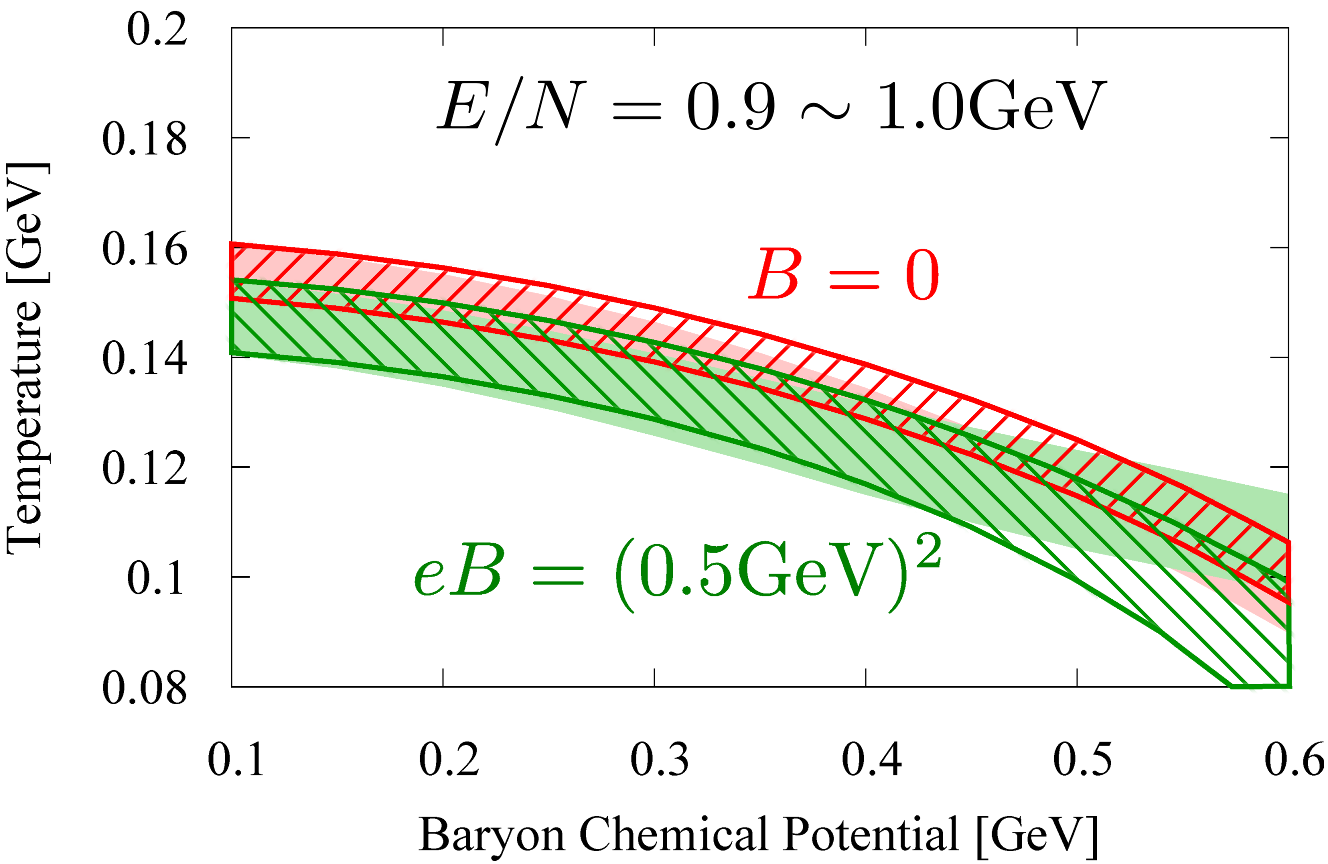


Interesting Topics Ongoing

- **Finite isospin / chiral / chemical potentials**
  - □ First-order phase transition? Confirmable with lattice
  - □ Pion superfluid / LOFF (Ask Pengfei for details)
- **Finite *B* (not *E*) with/without *T* and density**
  - □ (Inverse) Magnetic catalysis
  - □ CP in anisotropic pure Yang-Mills theory
- **Finite rotation (angular momentum)**
  - □ Similar to *B* / similar to finite density
  - □ Topological currents
- **Finite curvature (curved space-time)**
  - □ Chiral symmetric mass gap / Early Universe

Xu-guang
Jinfeng…

Magnetic Shift of Chemical Freezeout



Slanting lines

With conservation of S and Q

Shaded lines

Without conserv. of S and Q

KF-Hidaka (2016)

More about the Diquark

Never ending project with Jan…

Biggest Question Mark???

Nuclear Matter

?

Quark Matter

Diquarks

Bare vs Constituent

$$\text{Meson} \sim q\bar{q} + q\bar{q}q\bar{q} + q\bar{q}q\bar{q}q\bar{q} + \cdots$$

$$\text{(Vacuum Re-organized)}$$

$$\sim q_{\text{con}}\bar{q}_{\text{con}} + \text{(Bag Constant)}$$

How can we be so sure about $M \sim q\bar{q}$, $B \sim qqq$

beyond quantum num of Quark Model ?

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

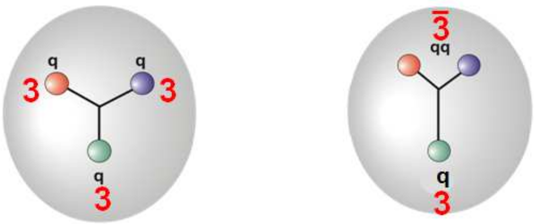
6) James Joyce, Finnegan's Wake (Viking Press, New York, 1939) p.383.

Primeval expression of diquarks

Who was the First?

Perhaps these missing states really do not exist. If baryons were diquark–quark systems, Fig. 2, as Lichtenberg and Tassie noted more than 40 years ago [4], the number of states would be restricted and in fact be very like that currently observed.

Pennington (2011)



Prog. Theor. Phys. Vol. 36 (1966), No. 4

Baryon Resonances in a Quark Model

Masakuni IDA and Reido KOBAYASHI

We suppose that baryons consist of a qq pair (or a diquark) and another quark moving around it with orbital angular momentum L. In order that for $L=0$ our model can produce the $1/2^+$ octet and the $3/2^+$ decuplet, which belong to the "56" of $SU(6)$, the qq pair must be in a $^3S_1$ state and form an $SU(3)$ sextet. Unwanted

If you know, let me know!

Exotica (scalar nonet)

Volume 60B, number 2 PHYSICS LETTERS 5 January 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

R.L. JAFFE* and K. JOHNSON

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Mass. 02139, USA

mentally observed "resonances". In particular we are led to classify the 0^{++} enhancements known as the ϵ, S^* and δ as $QQ\bar{Q}\bar{Q}$ states. If correct, this assignment disrupts further the already uneasy state of the P-wave mesons in the quark model.

broad exotic $QQ\bar{Q}\bar{Q}$ states and the P-wave baryons states overlap broad $4Q\bar{Q}$ states. In such cases one might expect that mixing effects will play an essential role in an unravelling of partial widths. This may provide a clue to an understanding of some of the elusive P-wave states such as the A_1.

Can explain why a_0(980) heaviest without strangeness

Exotic component is to be mixed (via instanton int.)

Classification

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \otimes \mathbf{6}$$

Quantum numbers and operators			
J^P	Color	Flavor	Operator
0^+	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\psi}_C \gamma_5 \psi$, $\bar{\psi}_C \gamma_0 \gamma_5 \psi$
1^+	$\bar{\mathbf{3}}$	$\mathbf{6}$	$\bar{\psi}_C \gamma_i \psi$, $\bar{\psi}_C \sigma_{0i} \psi$
0^-	$\bar{\mathbf{3}}$	$\mathbf{6}$	$\bar{\psi}_C \psi$, $\bar{\psi}_C \gamma_0 \psi$
1^-	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\bar{\psi}_C \gamma_i \gamma_5 \psi$, $\bar{\psi}_C \sigma_{ij} \psi$

Diquark Phenomenology

ΔI=1/2 rule in non-leptonic weak decay

$$\Delta I = 1/2 \quad \gg \quad \Delta I = 3/2$$

$$\times \sim 20$$

Stech, Neubert, Xu, Dosch (1987~)

Fierz transformed interaction:

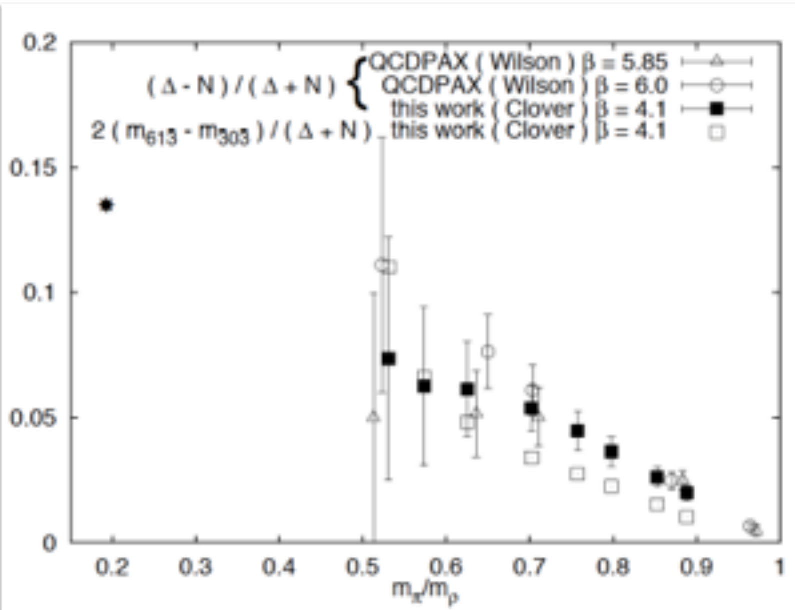
$$V_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ud} V_{us} \left[c_- (ud)^\dagger_{\bar{3}} (su)_{\bar{3}} + c_+ (ud)^\dagger_6 (su)_6 + \cdots \right]$$

$$\Delta I = 1/2 \qquad \Delta I = 1/2, 3/2$$

Enhanced by diquarks

Diquark on Quenched Lattice

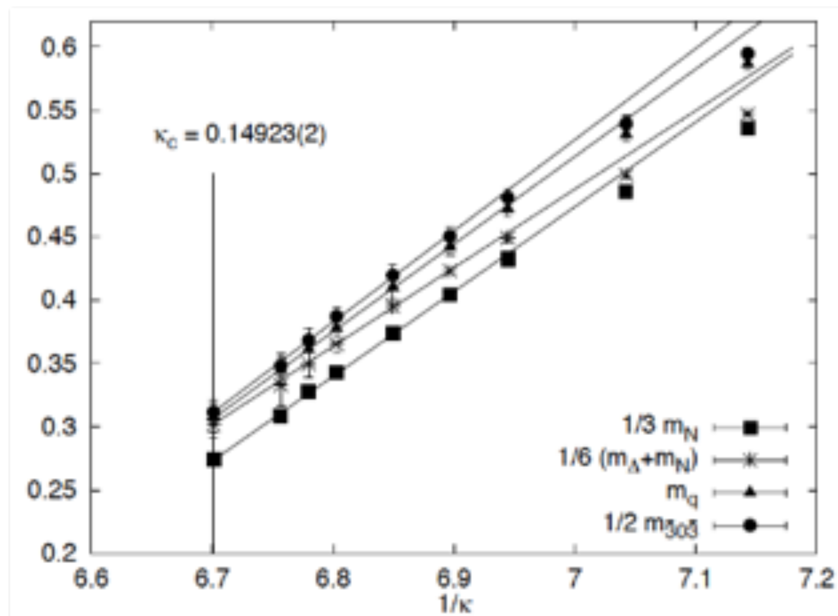
Lattice in Landau gauge (Hess-Karsch-Laermann-Wetzorke 1998)



Mass splitting from *S*=1 and *S*=0

$$m_{\text{bad}} - m_{\text{good}} \approx \frac{1}{2}(m_\Delta - m_N)$$

$$m_{\text{good}} = 694(22)\,\text{MeV}$$
$$(m_\pi \simeq 350\,\text{MeV})$$

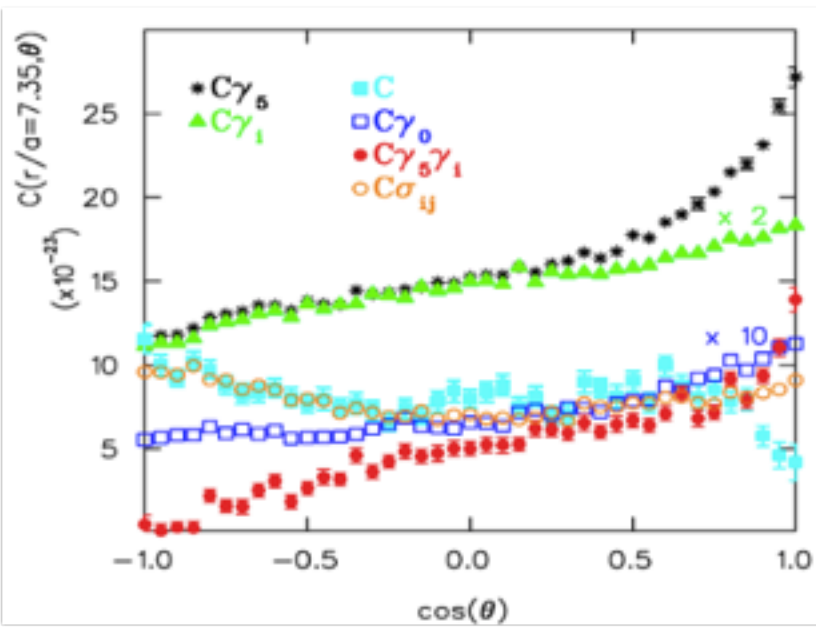


Diquark on Lattice

Density-density correlator (Alexandrou-de Forcrand-Lucini 2005)

Idealized : static-light-light baryon system

$$C(\boldsymbol{r}_u, \boldsymbol{r}_d) = \langle N | \rho^u(\boldsymbol{r}_u) \rho^d(\boldsymbol{r}_d) | N \rangle$$



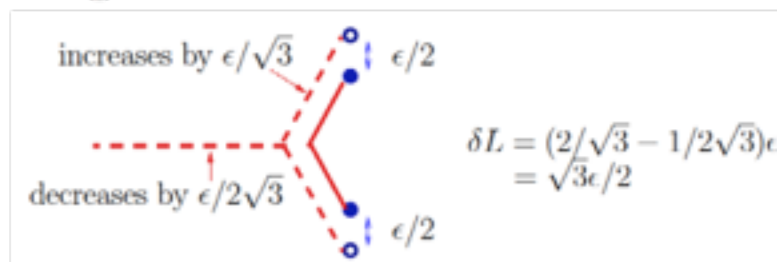
Lucini et al. (2006)

Correlation $0^+ > 1^+ \gg 0^-$

Characteristic diquark size

$\sim 1.1 \pm 0.2$ fm Leinweber (1993)

Larger than meson size



Diquark and Deconfinement

Deconfinement in pQCD

pQCD justifies itself at high T

All gluons are screened by gT or g^2T

pQCD does not justify itself at high μ

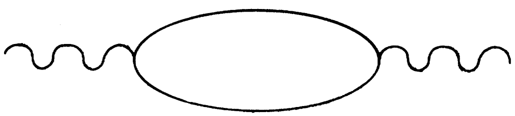
Magnetic gluons never screened

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England

(Received 6 January 1975)



Insufficient justification

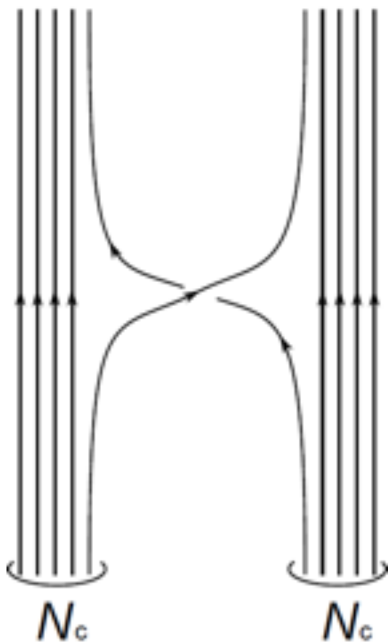
Color super justifies pQCD at high μ

All gluons are screened by $g\mu$

No Deconfinement?

Large-N_c Baryonic (Quark) Matter

$\mathcal{O}(1)$ → $\mathcal{O}(N_c)$



$N_c\Lambda_{QCD}^4$

Quarkyonic Matter

McLerran, Pisarski
Hidaka, Kojo
Fukushima, Sasaki

Deconfinement Revisited

CFL (3-flavor CSC) reads:

$SU(3)_C$ broken completely

All 8 gluons get massive (Meissner effect)

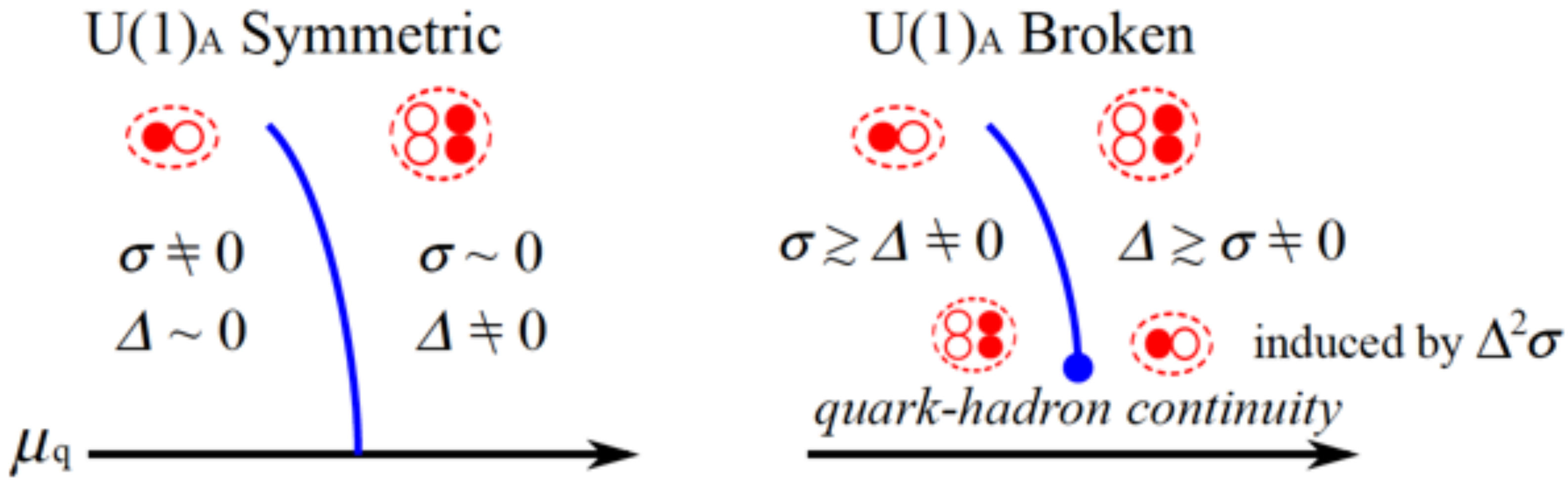
No confinement remains

Can this be a "definition" of deconfinement ?

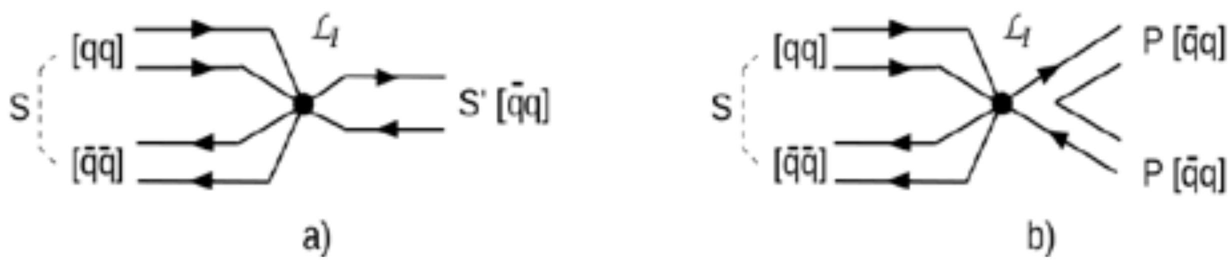
Private communications with Gordon Baym

If so, quark matter is realized only through diquarks

Continuity from NM to QM

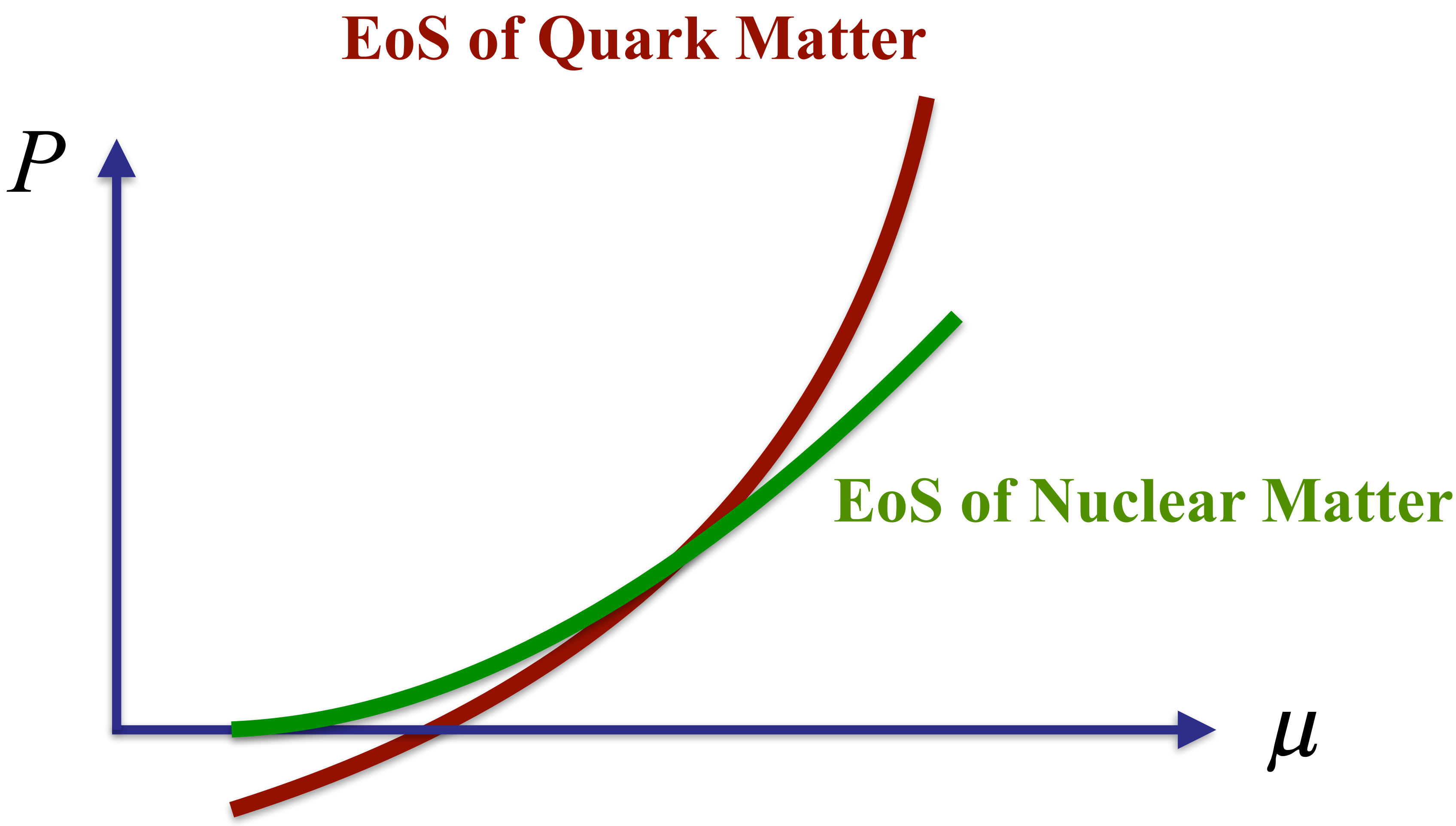


$$\pi^+ \sim (u)(\bar{d}) \sim (\bar{d}\,\bar{s})(su)$$

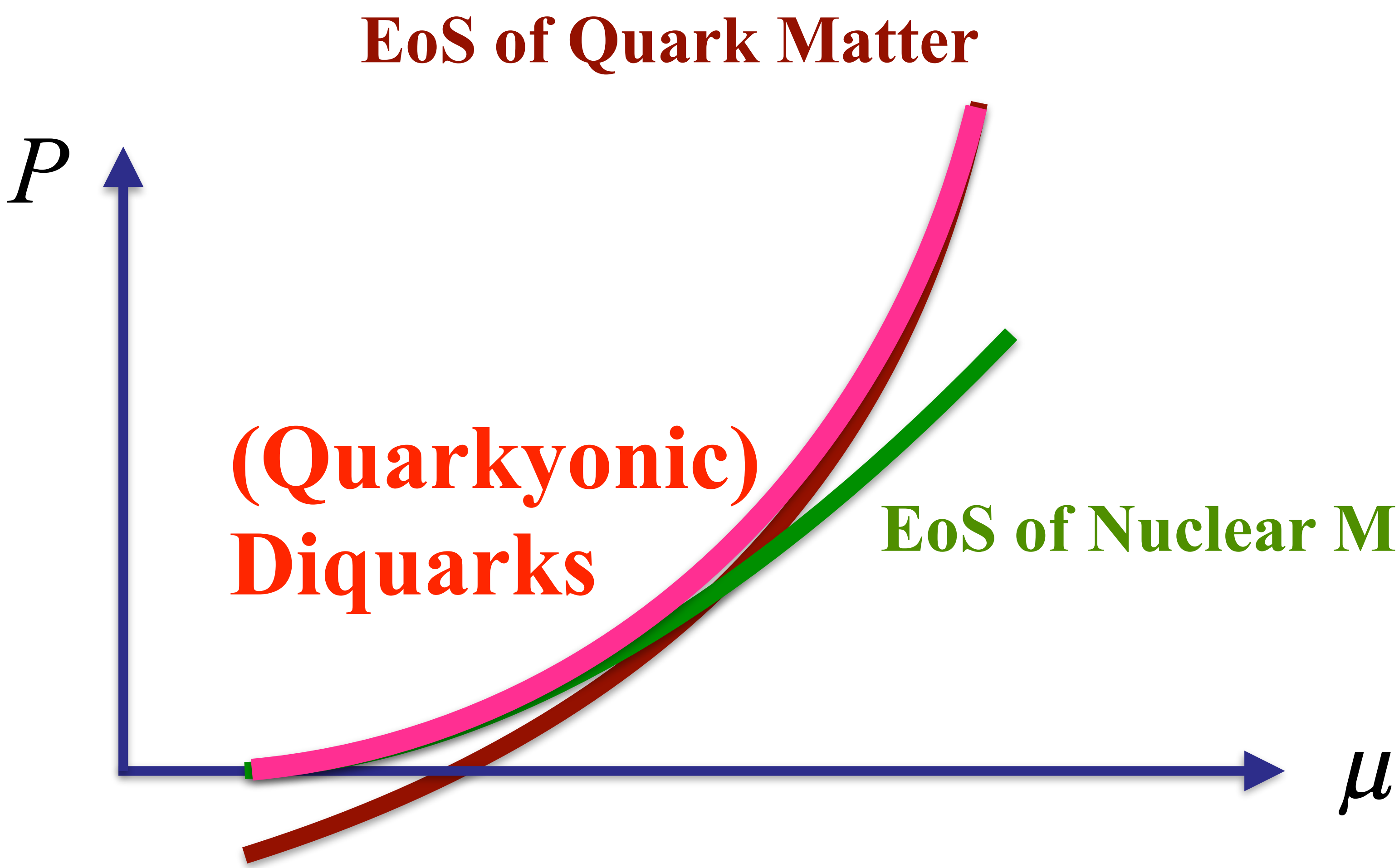


('t Hooft-Isidori-Maiani-Polosa-Riquer 2008)

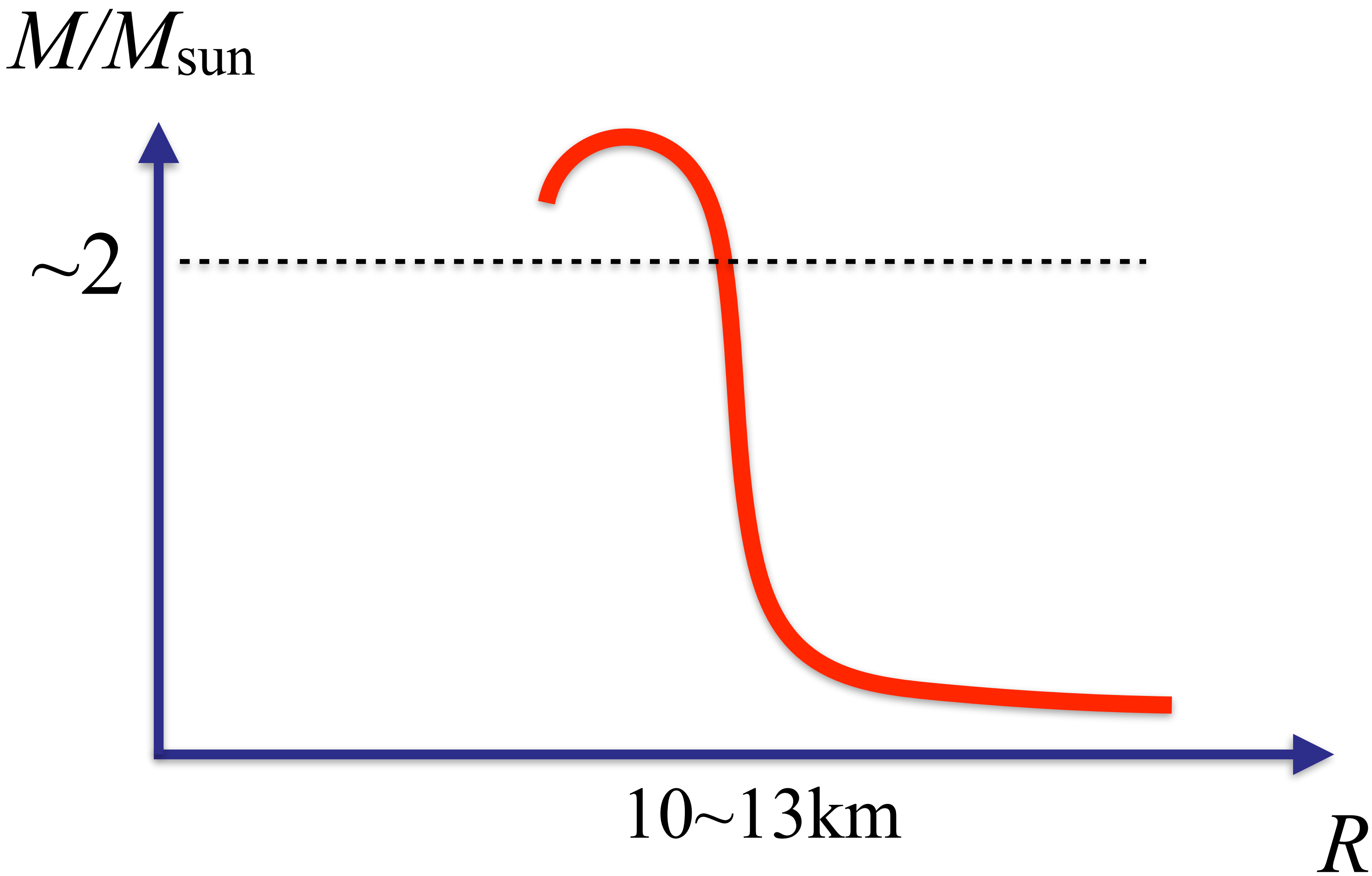
Diquark Continuity



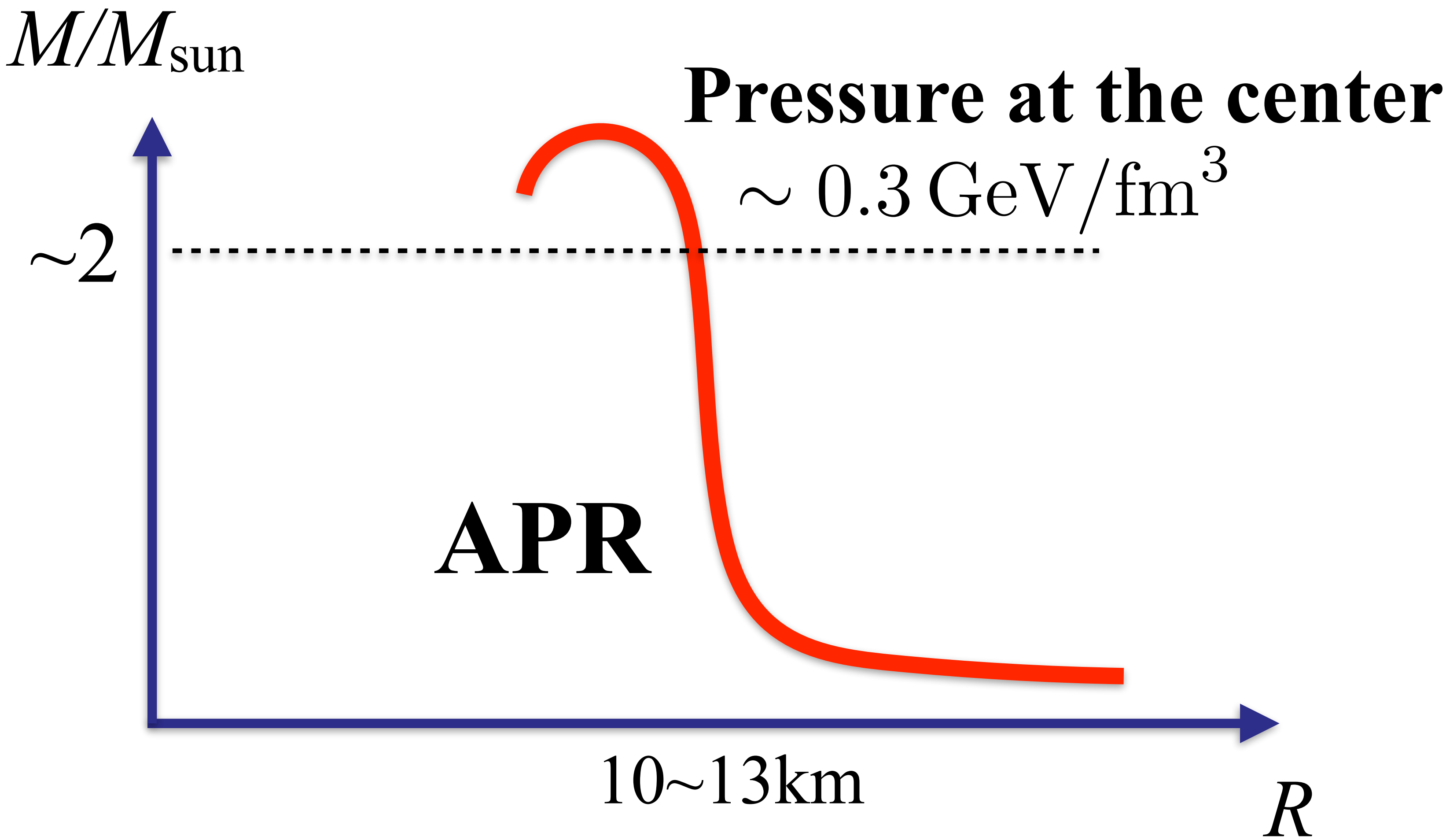
Diquark Continuity



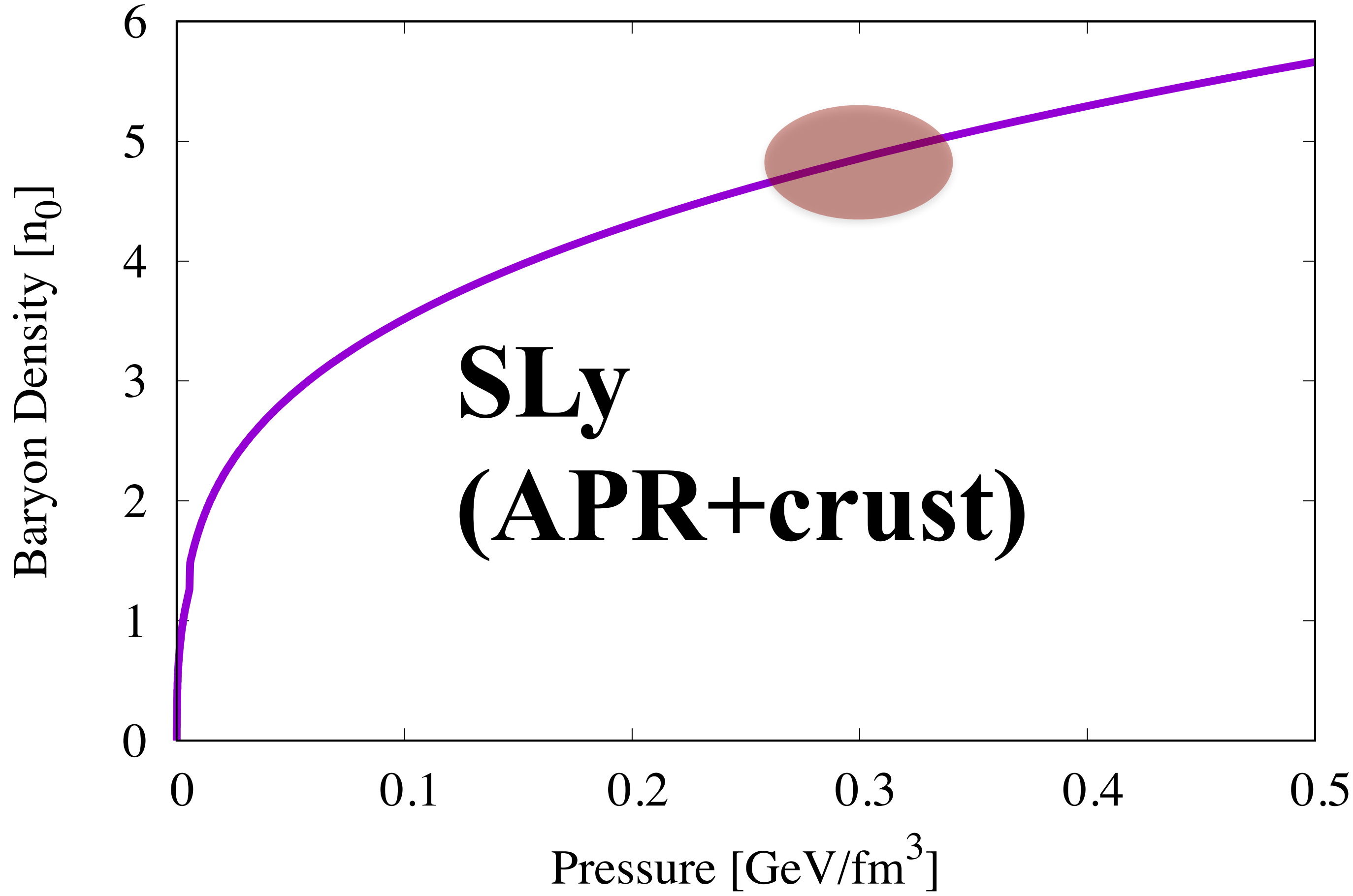
Implication to the M-R Relation



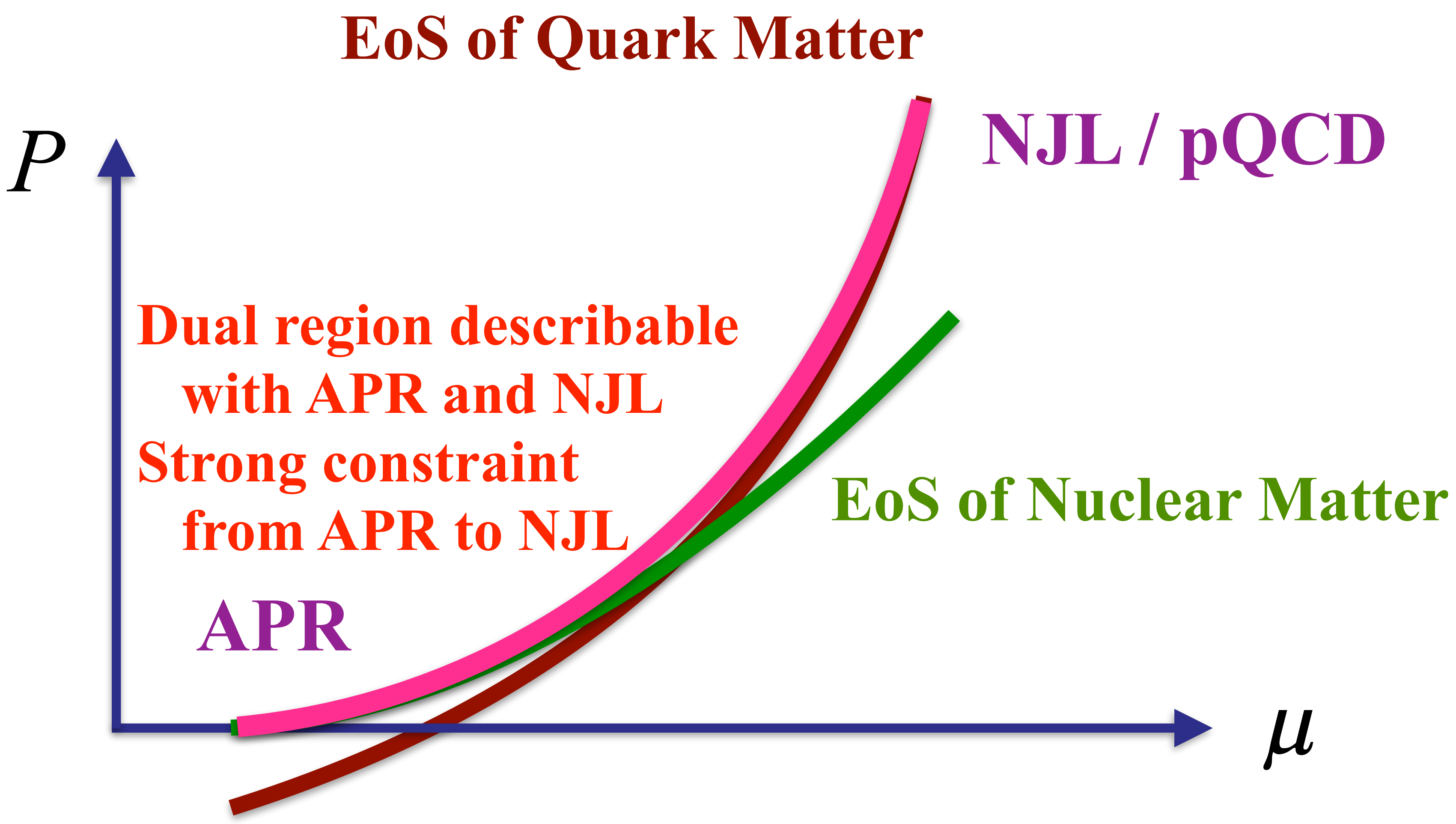
Implication to the M-R Relation



Cannot be right!?



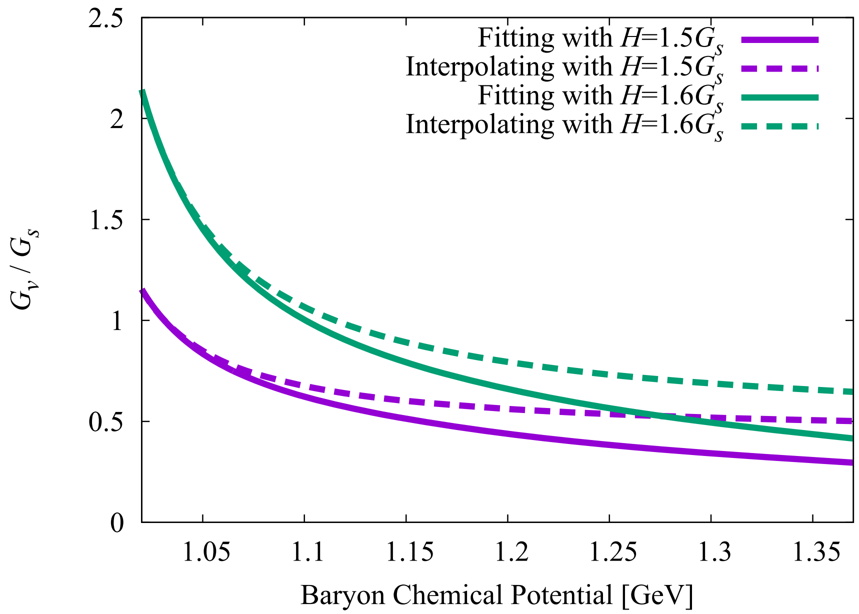
Duality Hypothesis



APR-constrained NJL

All non-perturbative effects renormalized in G_V

APR can be reproduced with "running" vector interaction



Best fit function ~ inverse log

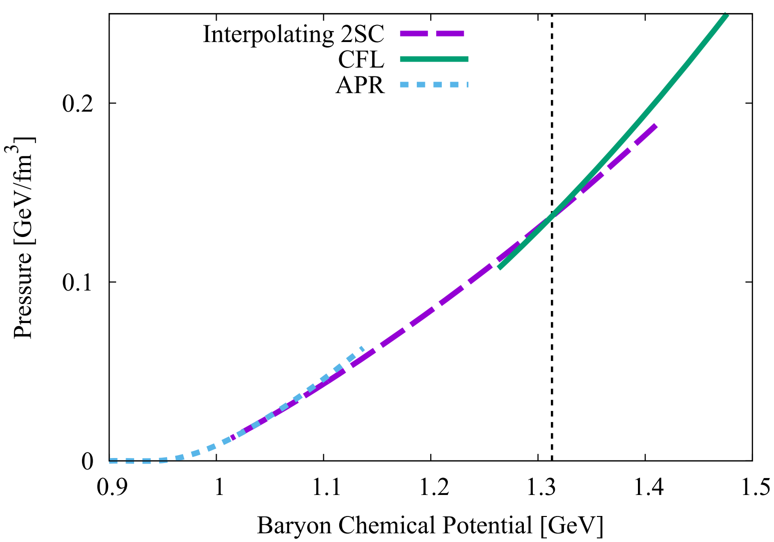
cf. $\alpha_s(\mu) = \dfrac{1}{b\log(\mu/\Lambda)}$

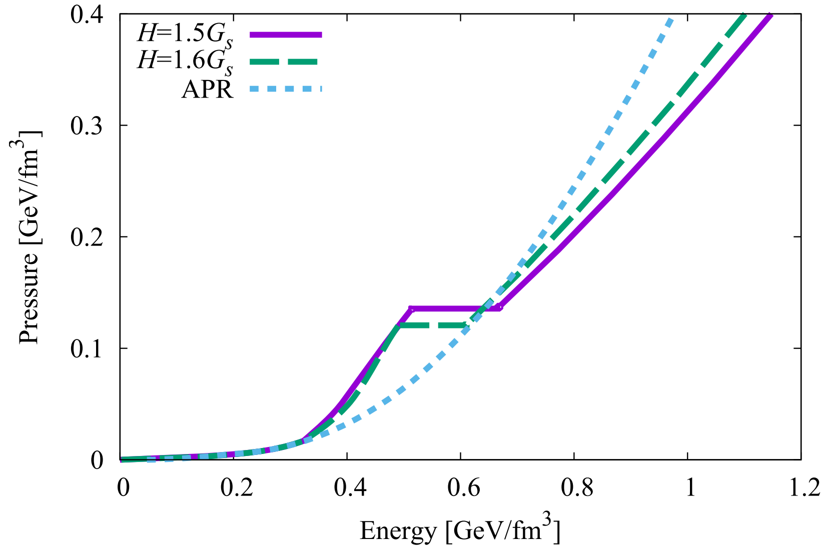
Suggestive!!!

Nuclear matter knows the running coupling?

APR-constrained NJL

Fukushima-Kojo (2015)



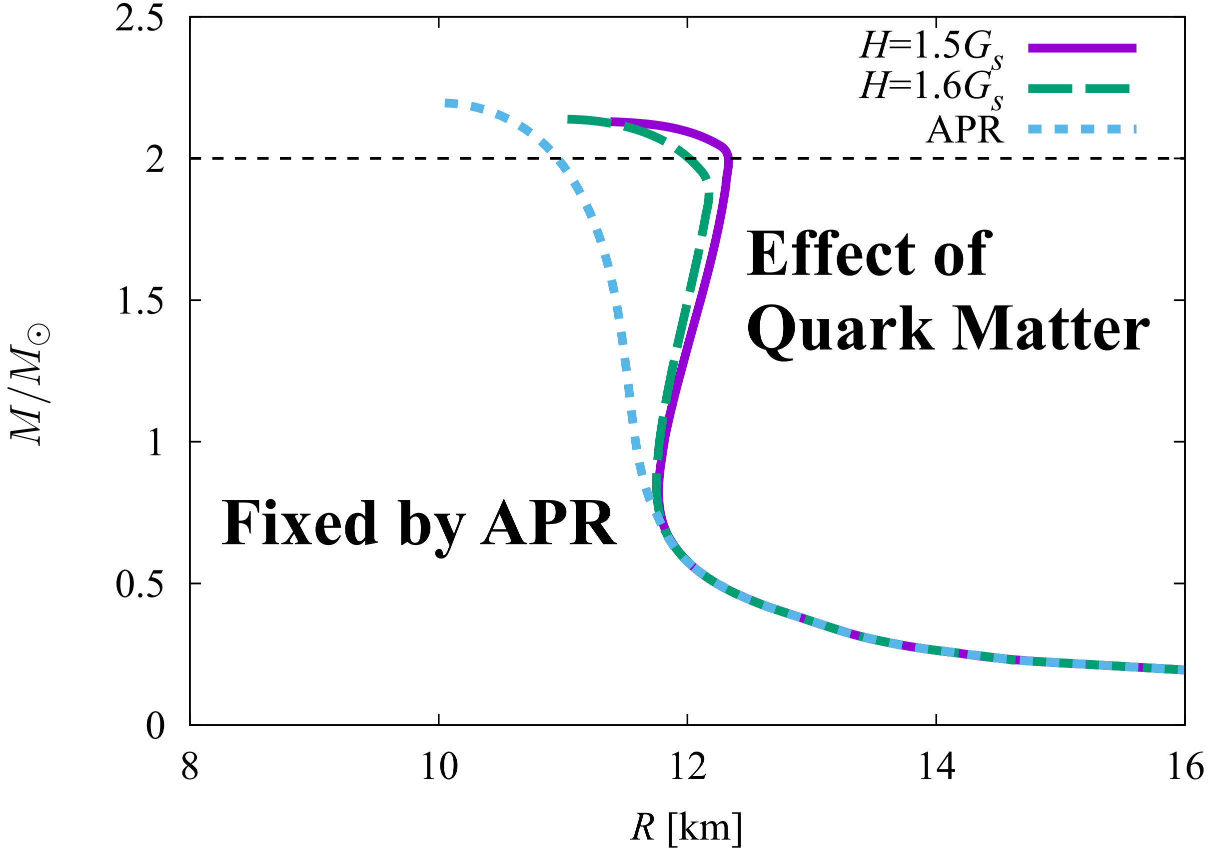


Weak 1st-order Phase Transition (2SC-CFL)

Single unified theory covering all the densities!

M-R Relation

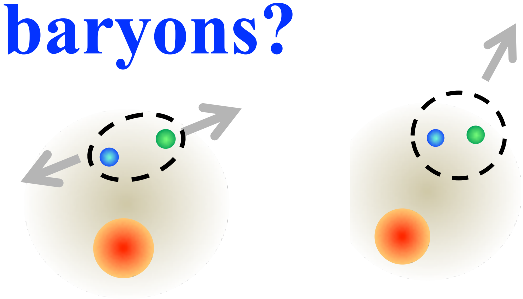
Fukushima-Kojo (2015)



Summary and Speculation

Summary

- **Nuclear Matter = 2SC + Chiral Cond. + 6-diquark**
  - □ More reasonable than CFL-NM continuity
  - □ Chance to access the diquark superfluid phase in HIC?
  - □ Enhanced fluctuations from (critical) diquarks
  - □ Refined HRG with diquarks?
- **New Model = APR-constrained NJL**
  - □ Microscopic information superseding parametrization
  - □ Less crazier than using APR to ~5 n_0 !   (Ask Toru!)
- **Spectroscopy of Qqq baryons?**



Provocative Speculation