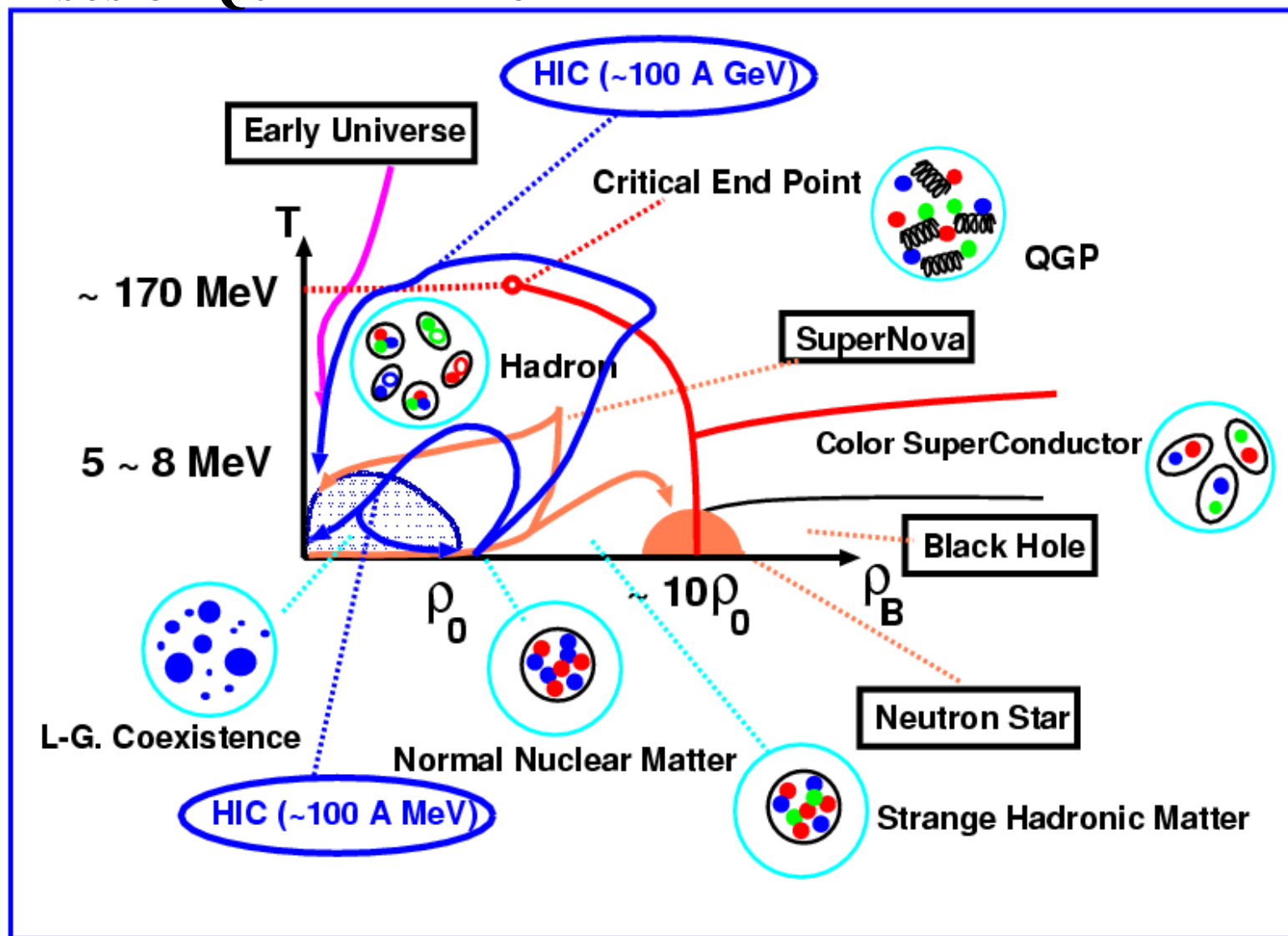


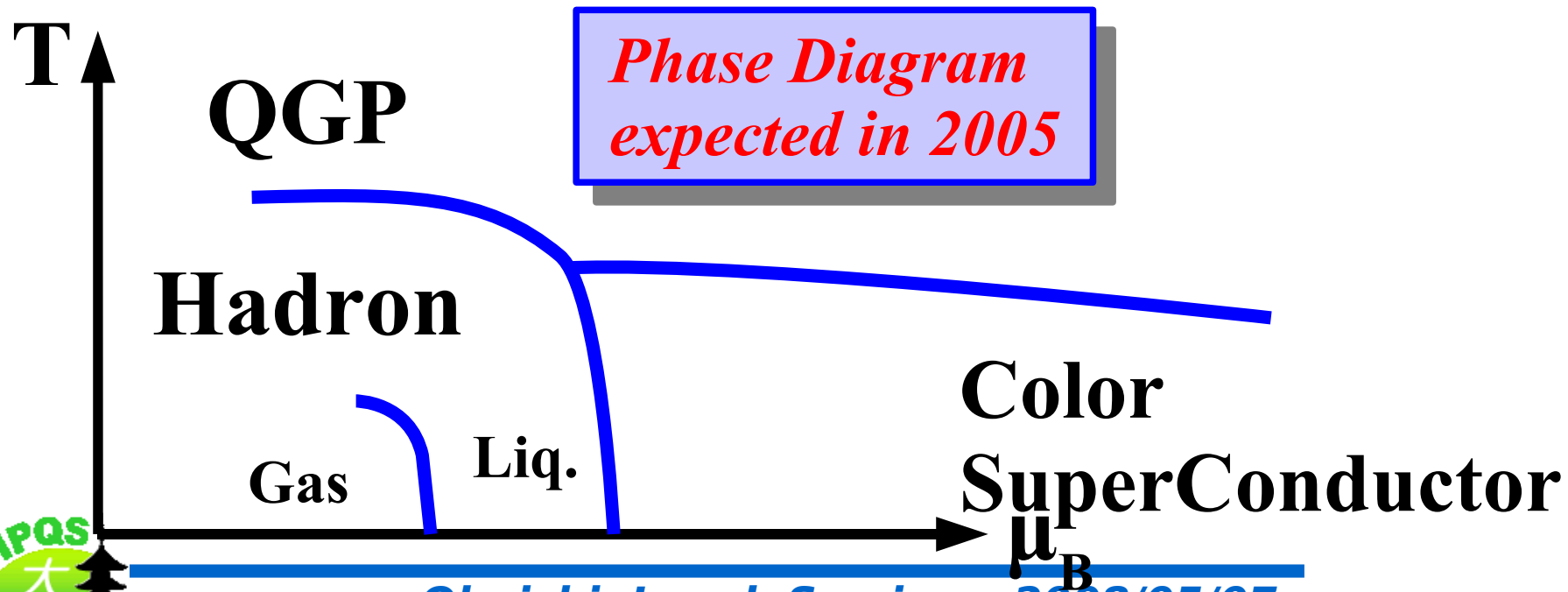
# A New (?) Phase of Quark Matter (A. Ohnishi)

- Particles in QCD: Quarks ( $N_c$ ), Gluons ( $N_c^2-1$ ), Hadrons ( $O(1)$ )
- Expected Phases of Quark Matter



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  - Quark-Gluon Plasma (Deconfined,  $\chi$  restored)
  - Color SuperConductor (Diquarks are condensed)
  - **Quarkyonic Phase (High density, partially  $\chi$  rest., confined)**

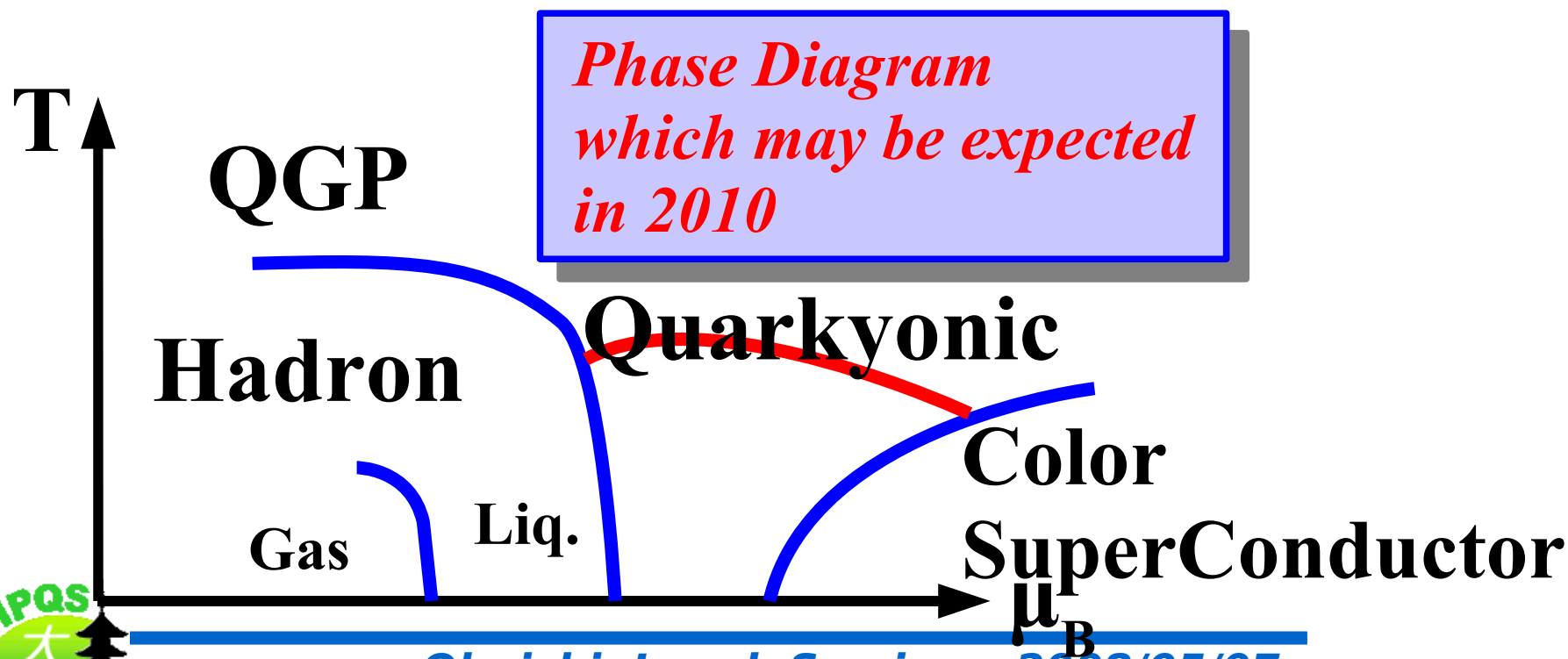


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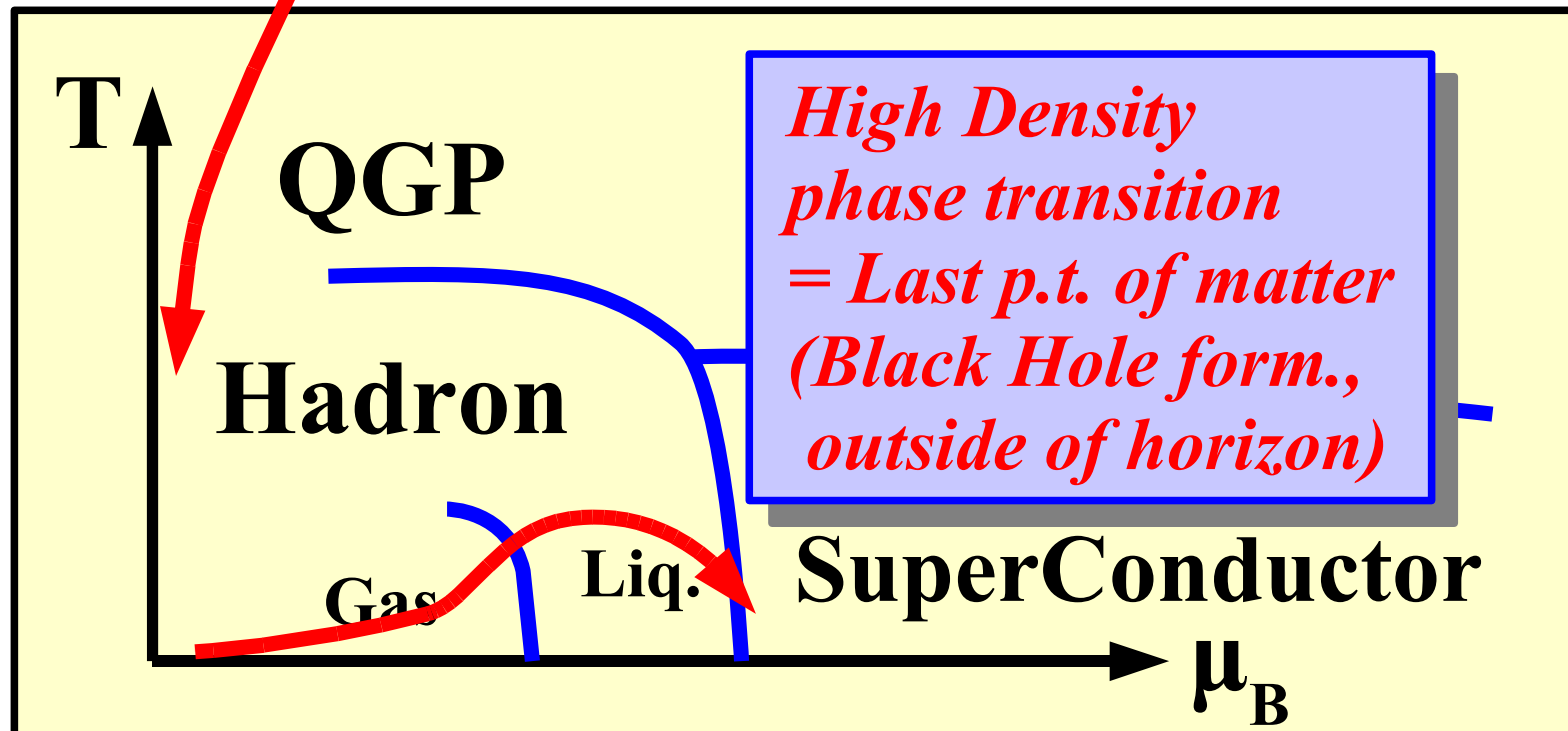
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# Why do we want to study QCD phase diagram ?

*High T phase transition  
= Latest vacuum p.t.  
of our universe (Big Bang)*



*High Density  
phase transition  
= Last p.t. of matter  
(Black Hole form.,  
outside of horizon)*

*Study of QCD phase transition  
→ Where do we come from, where do we go ?*

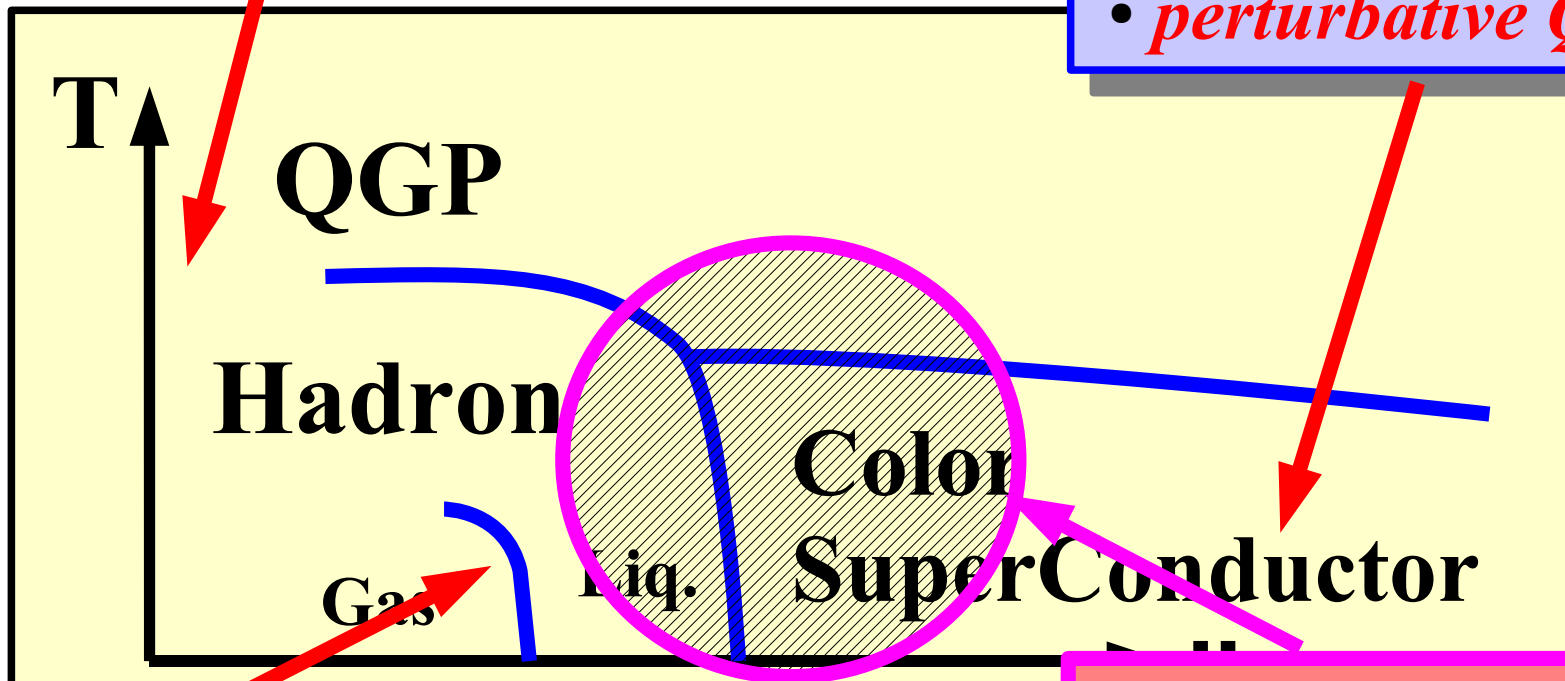
# How Far Do We Know ?

*High T P.T. is observed*

- *RHIC Experiment*
- *Lattice QCD MC simulation*

*High Density Limit is proven to be CSC (Color SuperConductor)*

- *perturbative QCD*



*Liquid Gas P. T. is*

- *expected in Mean Field*
- *and Observed in Caloric Curve*

*Little is known for High Density Phase Transition Region !*

# A Conjecture from Large $N_c$ : Quarkyonic Phase

Pisarski, McLerran, 2007

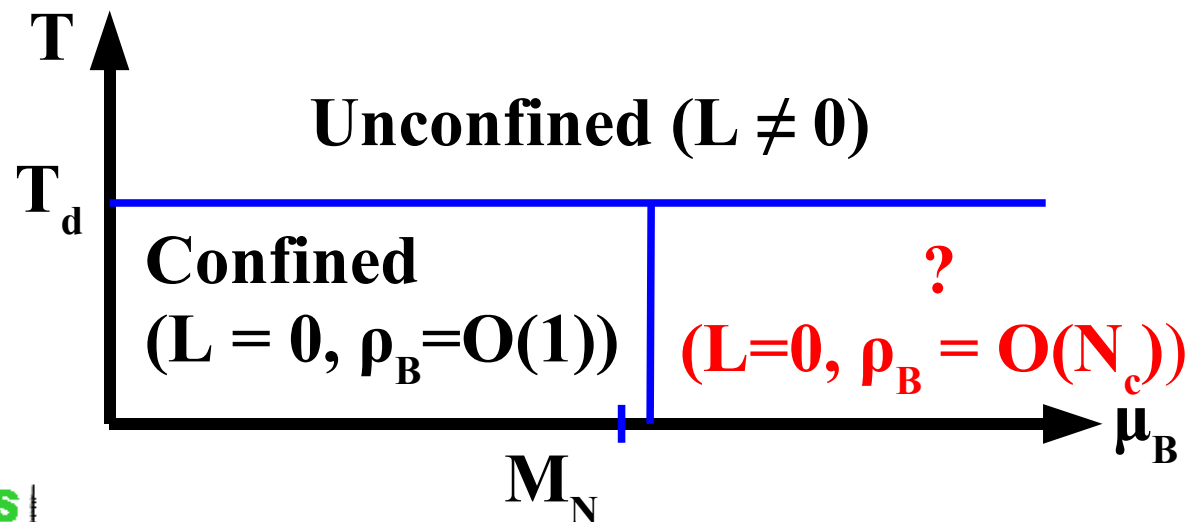
## ■ Discussion at large $N_c$

- Pressure: **Gluon** =  $O(N_c^2)$ , **Quark** =  $O(N_c)$ , **Hadron** =  $O(1)$

→ **DECONFINEMENT** phase transition  
(order parameter = Polyakov loop) is independent  
from quark chemical potential  $\mu$  as far as  $\mu = O(1)$ .

- Large  $\mu$  ( $N_c \mu > M_B$ ) but low  $T$  ( $T < T_d$ )

→ **Weakly interacting quark gas, but no free gluons (confined).**  
= **High Density *Confined* Phase**



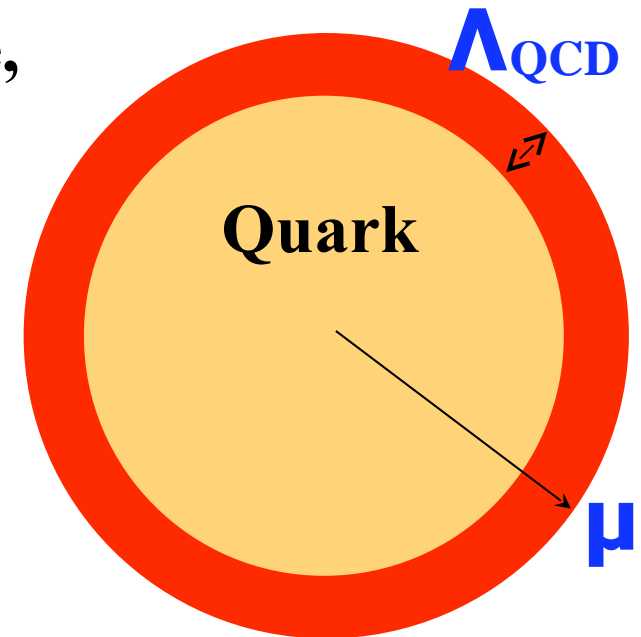
*What is this ?*

# A Conjecture from Large $N_c$ : Quarkyonic Phase

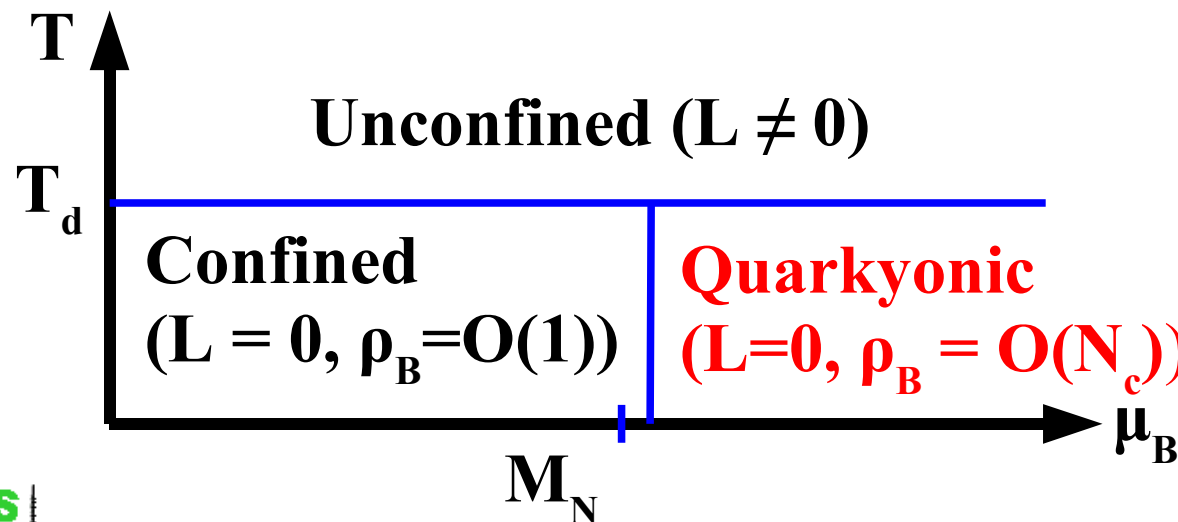
*Pisarski, McLerran, 2007*

- **Confined High Density Matter at Large  $N_c$**   
 = **Quarkyonic** Phase  
 (**Quarks** deeply inside the Fermi Sphere,  
 with **baryonic** excitations)

*Do we really see this phase at  $N_c=3$  ?  
 What happens to Chiral Symmetry ?*



*Confined*  
 → **Baryonic Excitation**



# In QCD with $N_c=3$

## ■ Lattice QCD MC with finite $\mu$

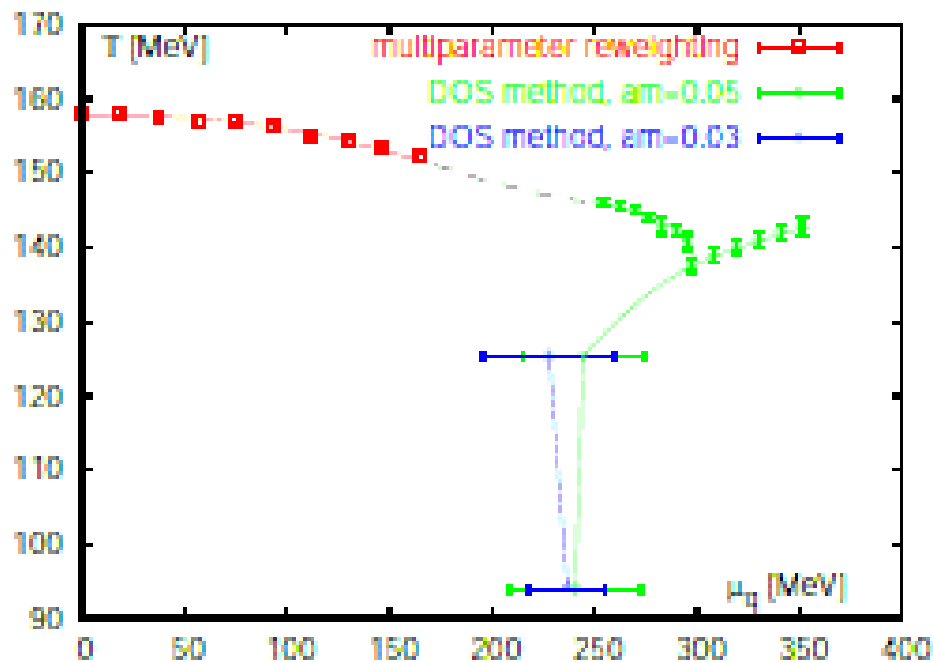
*(Density of States method; Fodor, Katz, Schmidt, 2007)*

Phase transition at  $\mu \sim M_N/3$ ,  $T < T_d$  (We do not know what !)

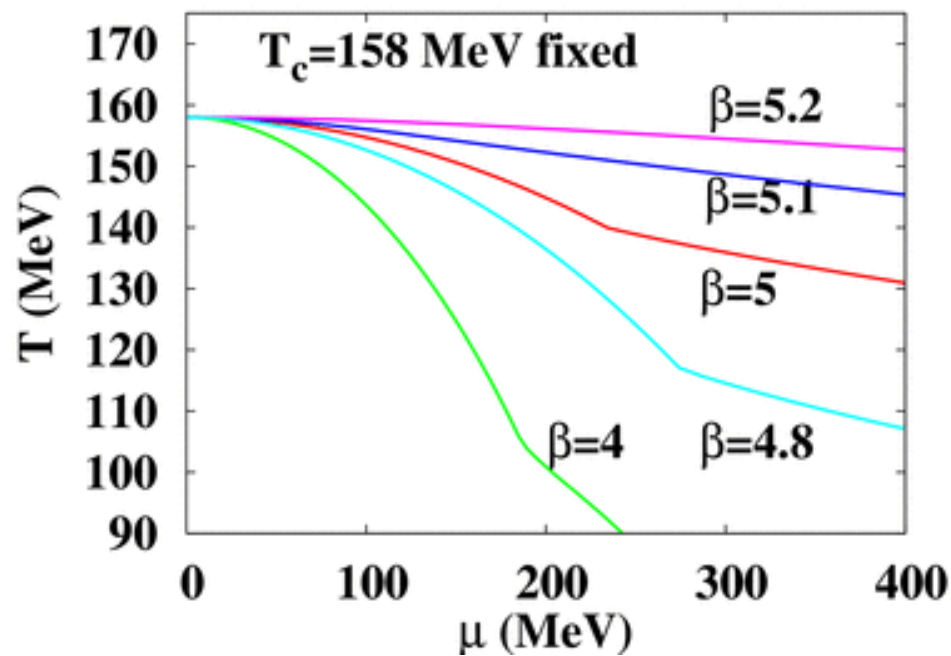
## ■ Strong Coupling Lattice QCD *(Miura, AO, arXiv:0805.xxxx)*

Phase transition at similar  $(T, \mu)$  to FKS

→ What is this ?



*Fodor, Katz, Schmit, 2007*



*Miura, AO, in prep.*

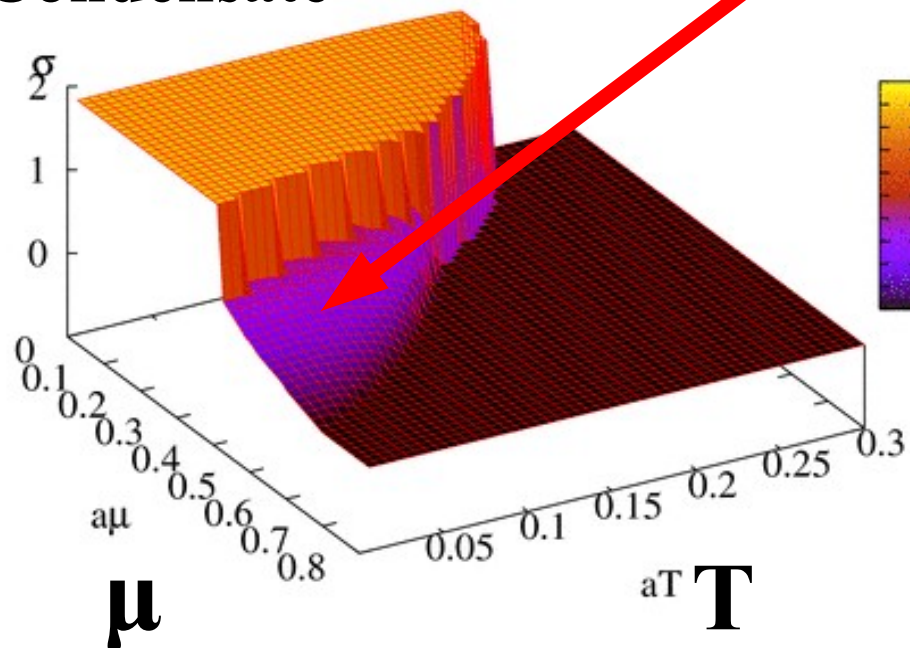


# What is the 3rd Phase in SC-LQCD ?

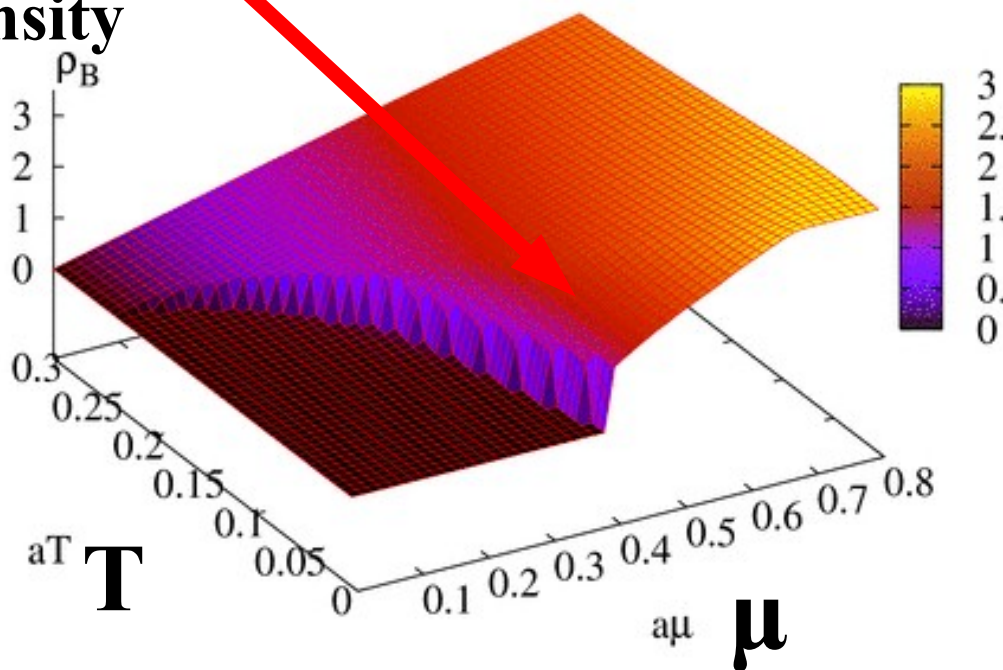
- Chiral Symmetry is Partially Restored (~ half of the hadron phase)
- Baryon Density is High (~ fully chiral restored phase)

→ This may correspond to the *Quarkyonic* phase at large  $N_c$

Chiral  
Condensate

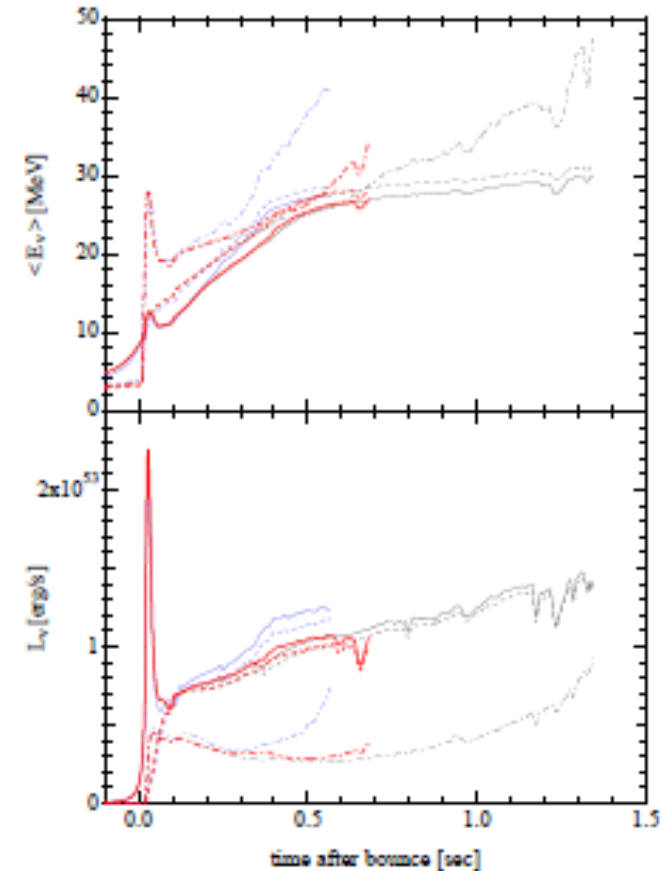
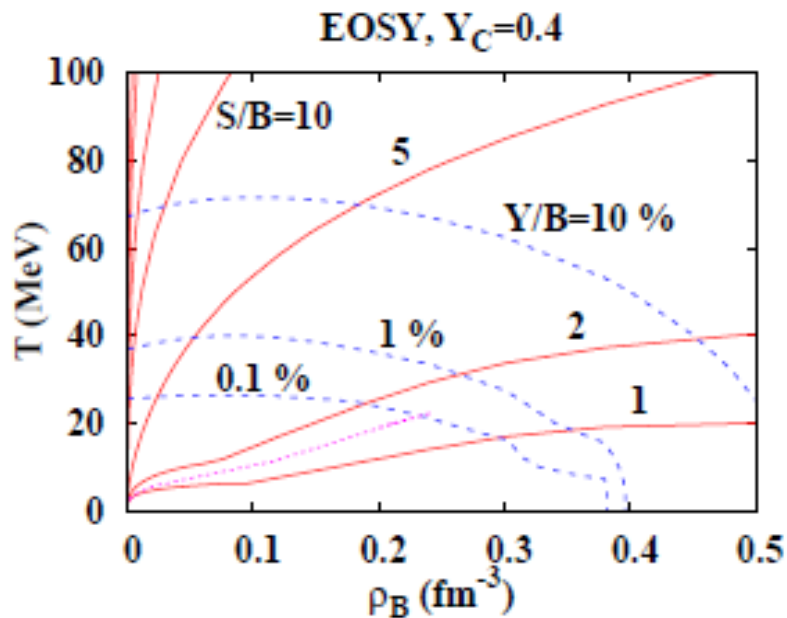


Baryon  
Density



# Where do we see Quarkyonic matter ?

- Do we see Quarkyonic matter in our universe ?
  - $\rho_c \sim 2 \rho_0 \rightarrow$  Appears during the core collapse stage of supernova
  - $\rho_c \sim 5 \rho_0 \rightarrow$  Appears in the core region of neutron stars
  - $\rho_c \sim 10\rho_0 \rightarrow$  may appear during the Black Hole formation

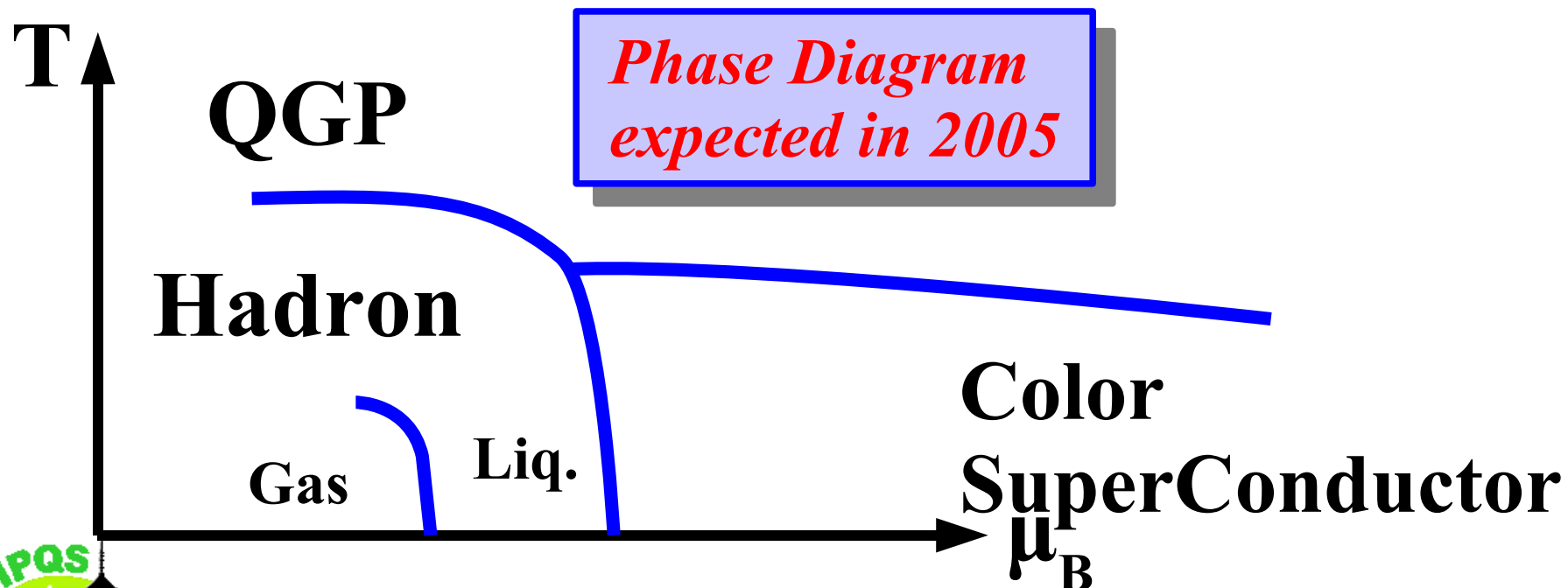


Ishizuka, AO, Tsubakihara,  
Sumiyoshi, Yamada, arXiv:0802.2318

Sumiyoshi, Ishizuka, AO,  
Yamada, Suzuki, in prep.

# Summary

- QCD matter has several order parameters, which make the phase structure rich.
- A high density, Quarkyonic phase may exist (partially chiral restored, *confined* (small Polyakov loop)), which is supported by large  $N_c$ , lattice QCD MC, and Strong Coupling LQCD, Skyrmionic crystal, HIC data (?), .....



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