Overview : QCD Phase Diagram

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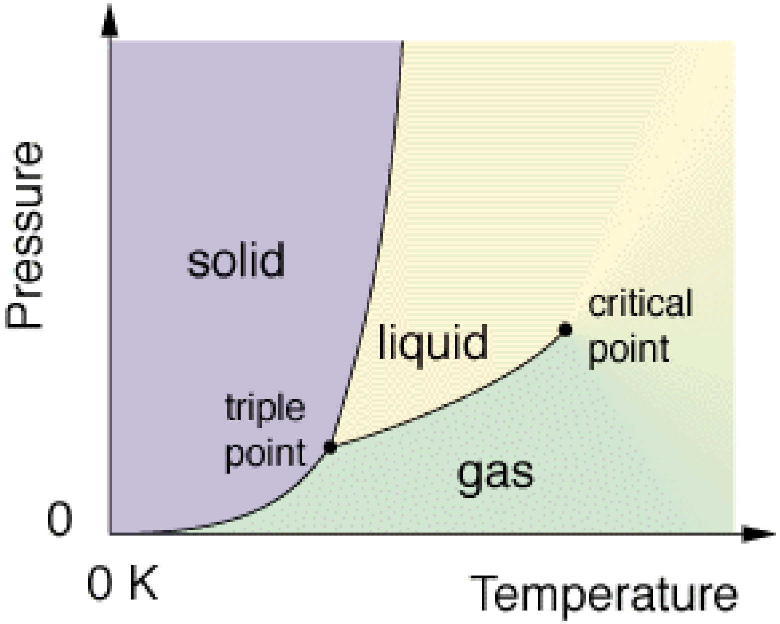
(Univ. Tokyo)

H_2O



Outline of this talk

1. Possible phase structure in QCD
   – what we know and what we do not know

2. Phases in hot QCD

3. Phases in dense QCD

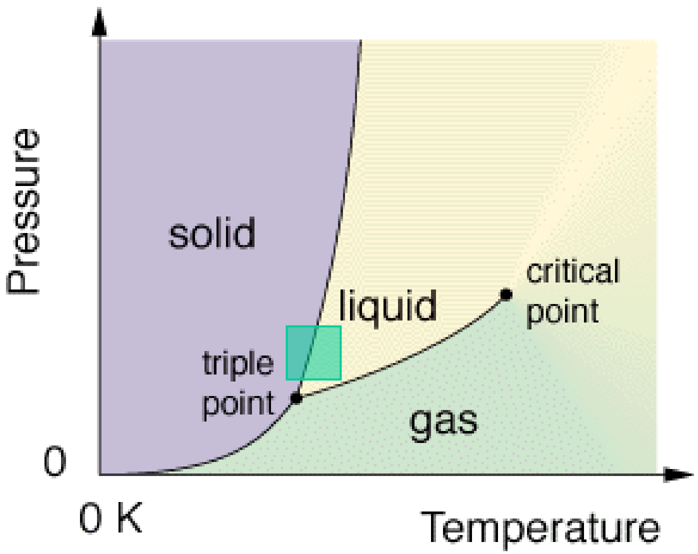
4. Future experimental facilities

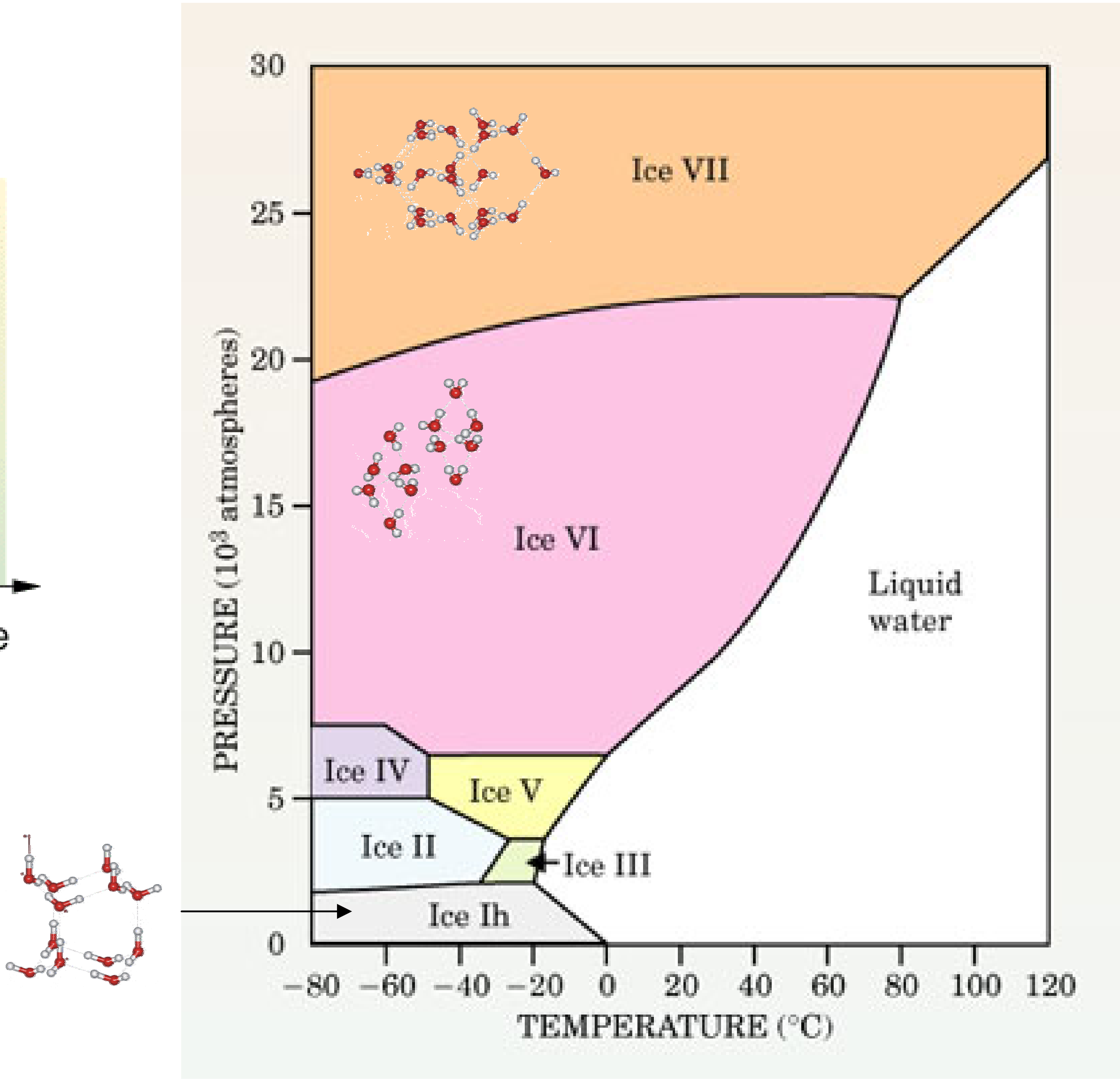
5. Summary

More on H_2O

Physics Today, Dec. vol.58 (2005)

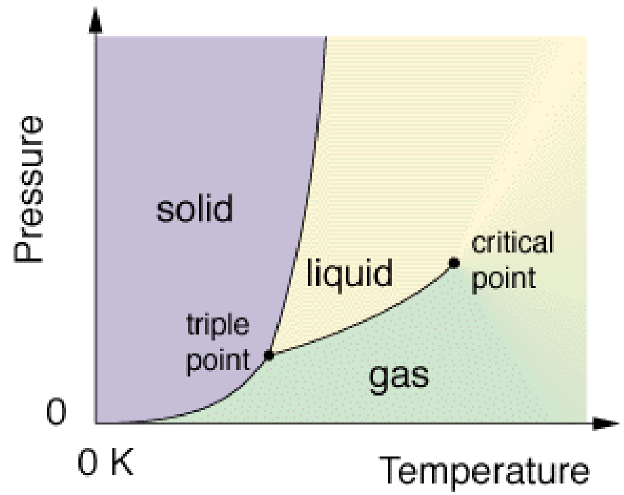
http://www.lsbu.ac.uk/water/phase.html



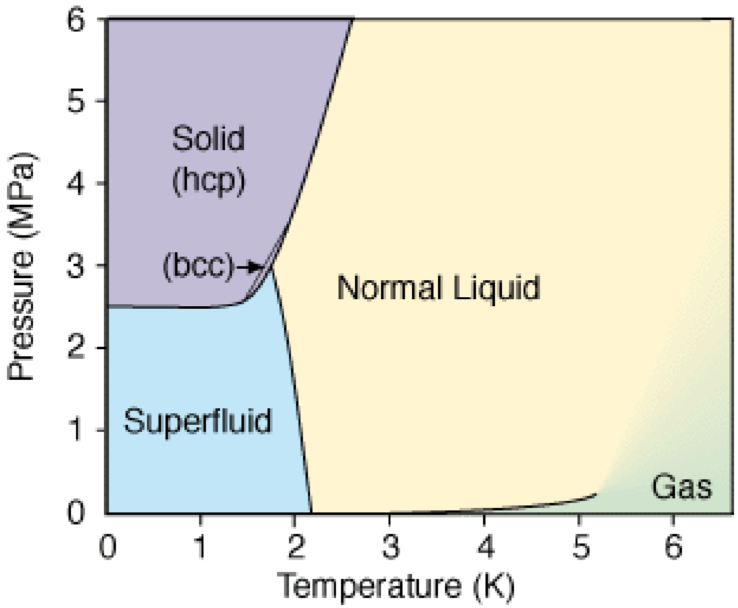


Quantum phases of ^3He & ^4He

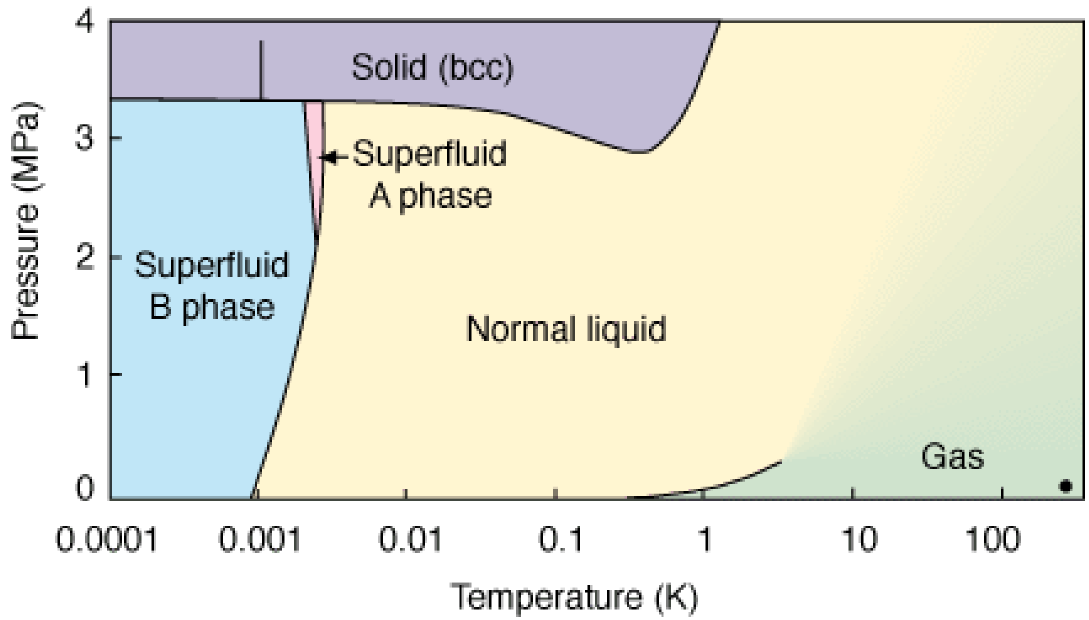
H_2O



^4He

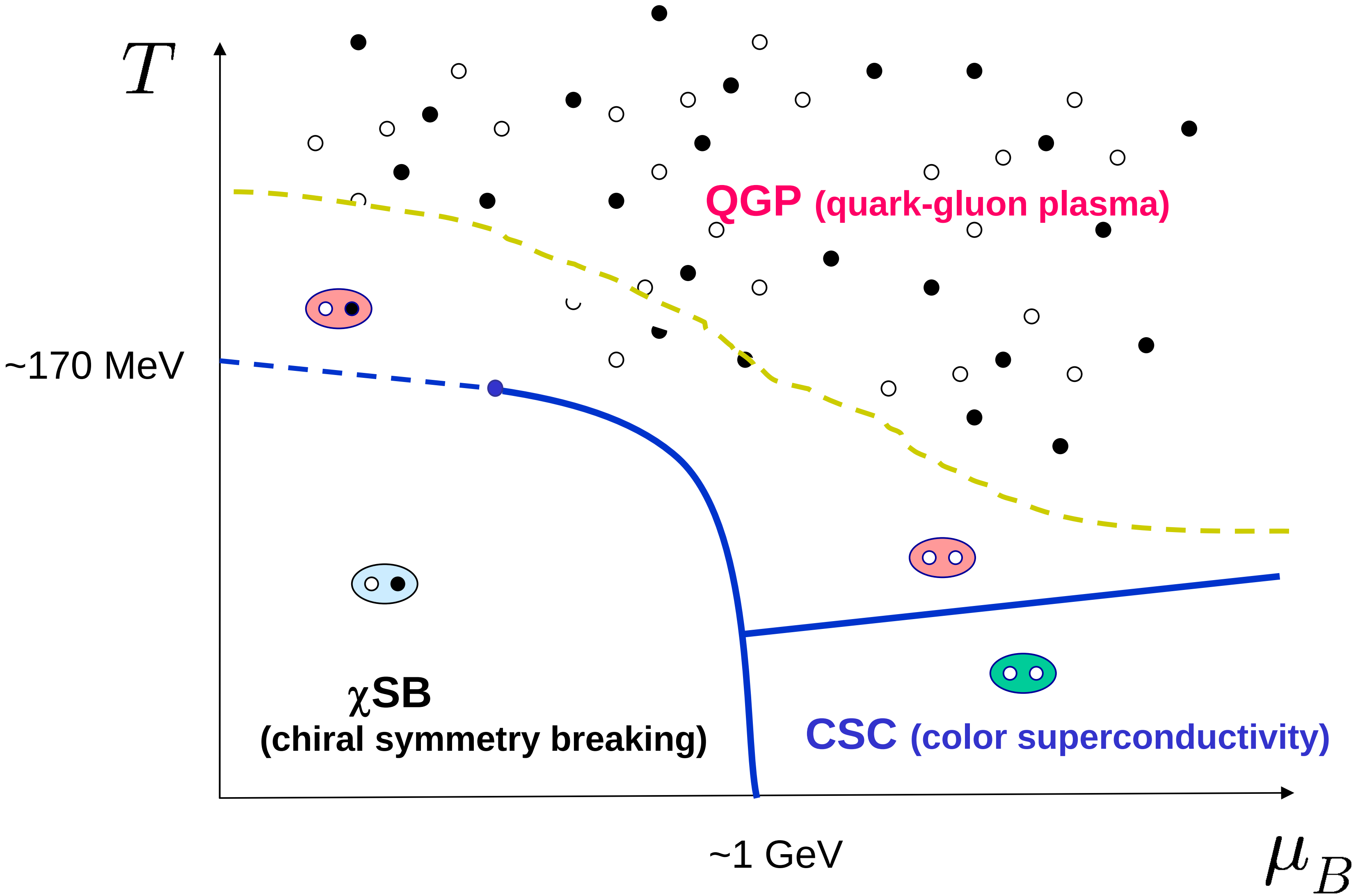


^3He



http://boojum.hut.fi/research/theory/typicalpt.html

Phases in QCD ? – a schematic picture --



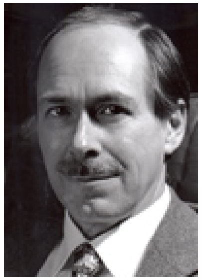
Theory behind: Quantum Chromo Dynamics

1965 $SU_c(3)$ YM theory as a model of strong interaction

$$L = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

Nambu ('65)

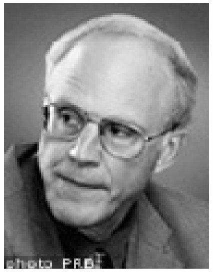
1965-1972 Precursors of asymptotic freedom

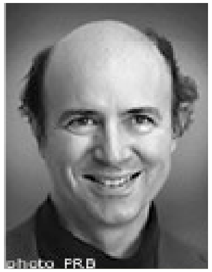


Vanyashin & Terenteev ('65), Khriplovich ('69), 't Hooft ('72)

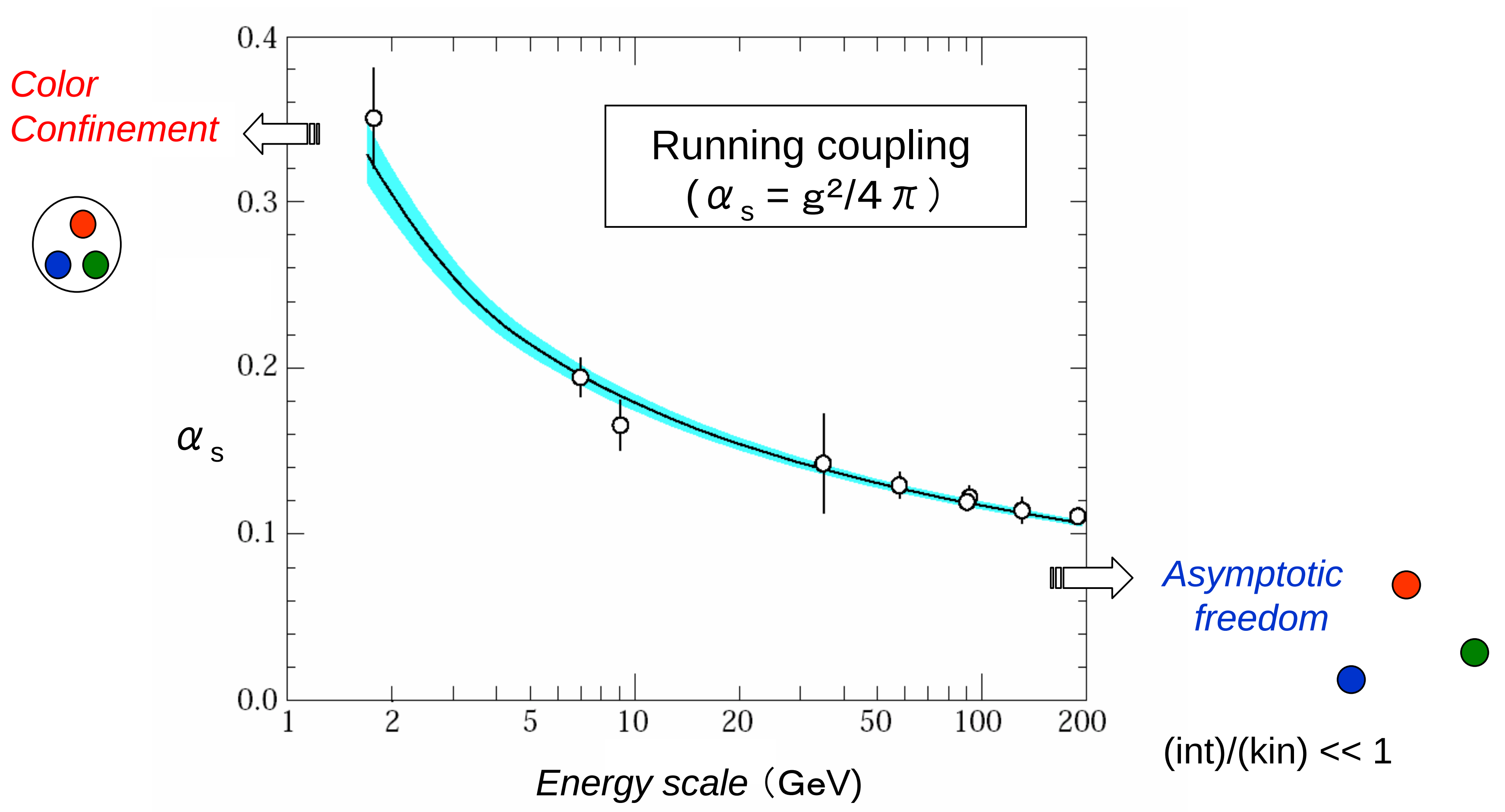
1973 Discovery of asymptotic freedom

Gross & Wilczek, Politzer ('73)





Theory behind: Quantum Chromo Dynamics



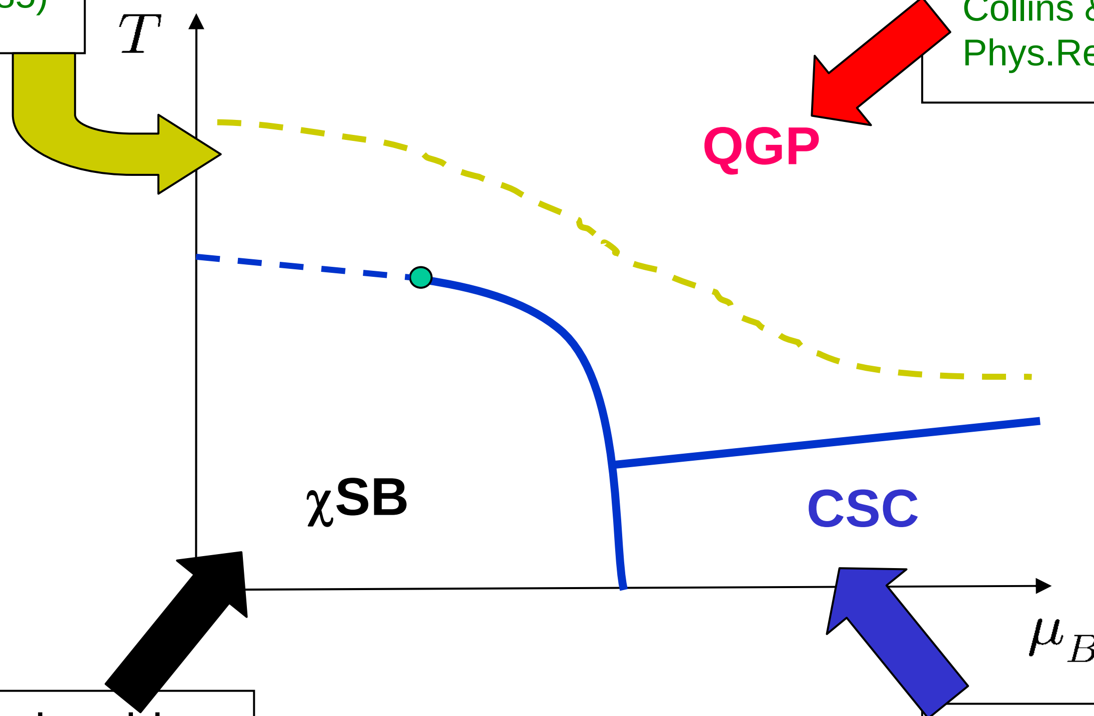
Origin of each "phase"

strong residual force
→ **pre-formed pairs**

Hatsuda & Kunihiro,
Phys.Rev.Lett. 55 (1985)

Asymptotic freedom
+ Debye screening
→ **deconfinement**

Collins & Perry,
Phys.Rev.Lett. 34 (1975)



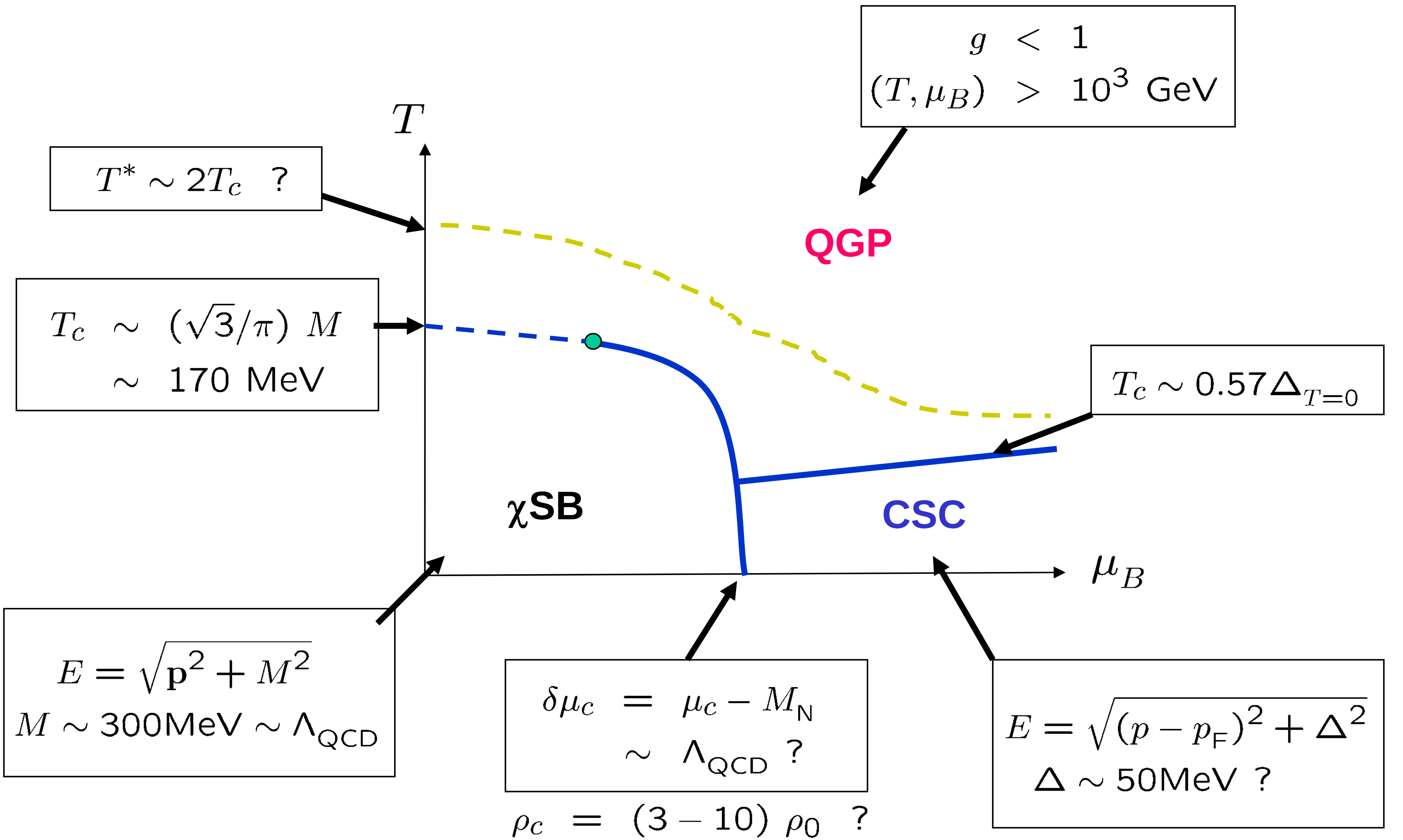
quark - anti-quark pairing
→ **chiral instability**

Nambu & Jona-Lasinio,
Phys.Rev. 122 (1961)

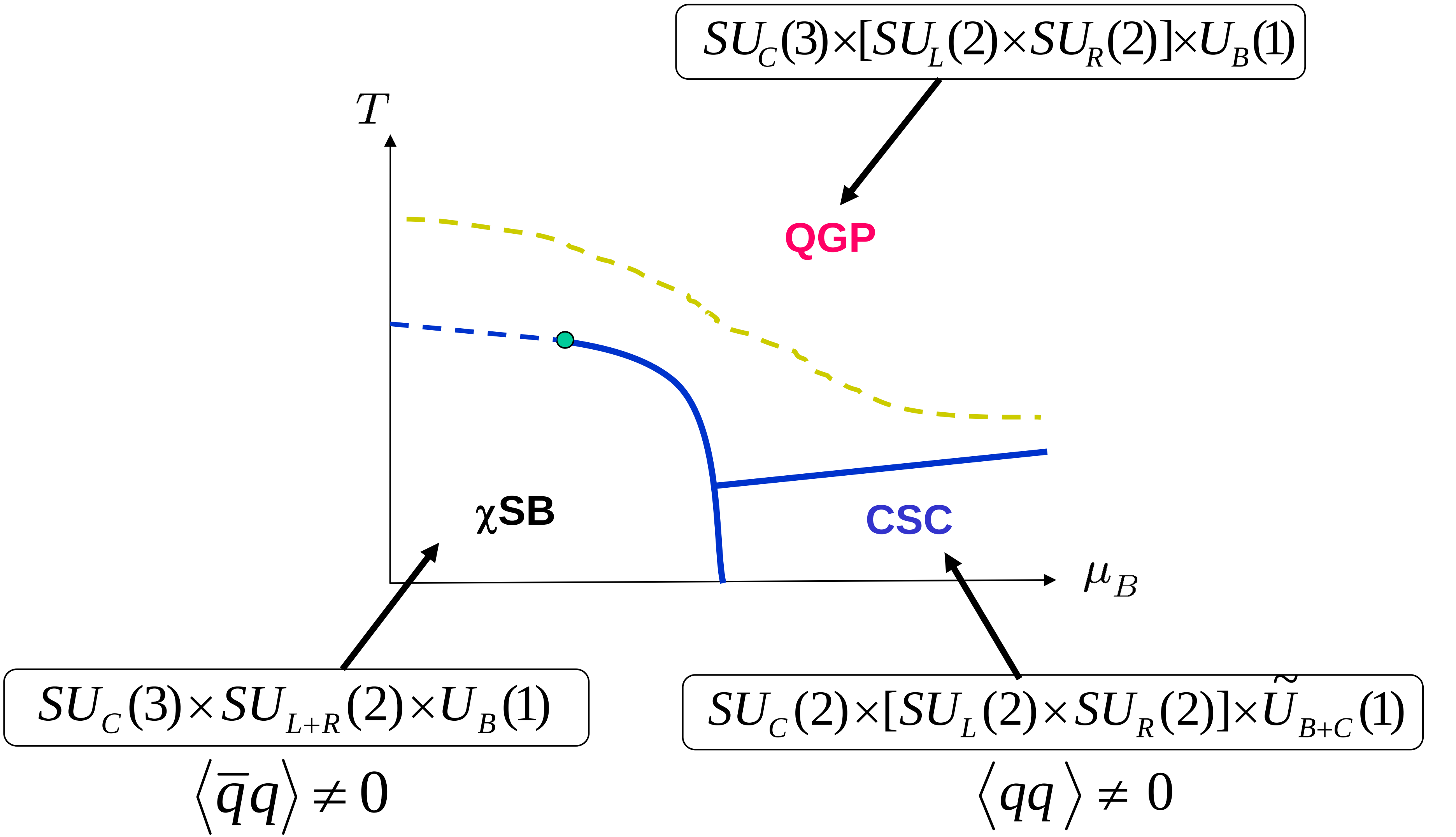
quark-quark pairing
→ **Cooper instability**

Bailin & Love,
Phys.Rep.107 (1984)

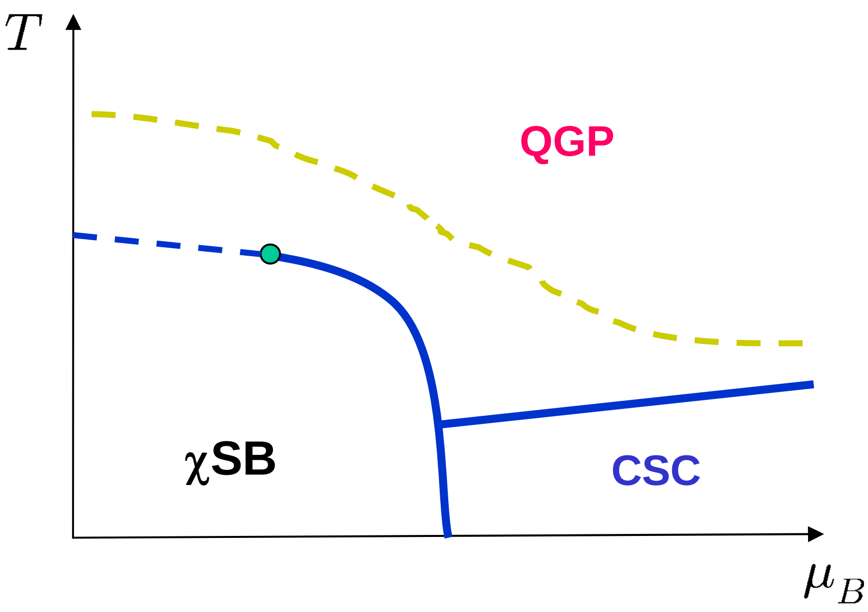
Scale of each "phase"

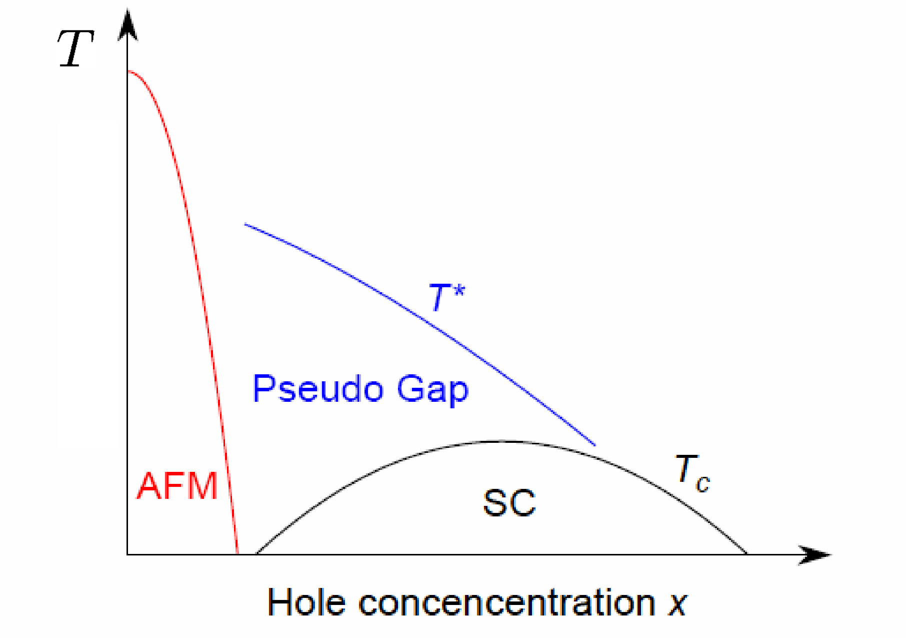


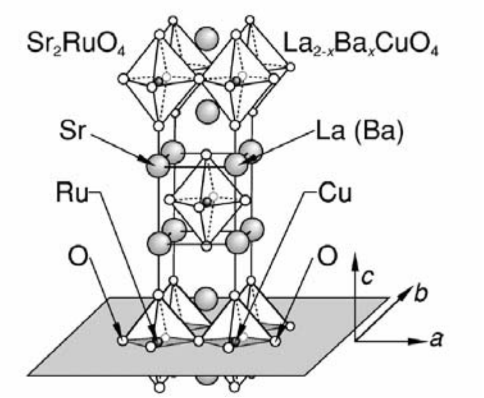
Symmetry of each "phase" (case for small m_{ud} with $m_s=\infty$)



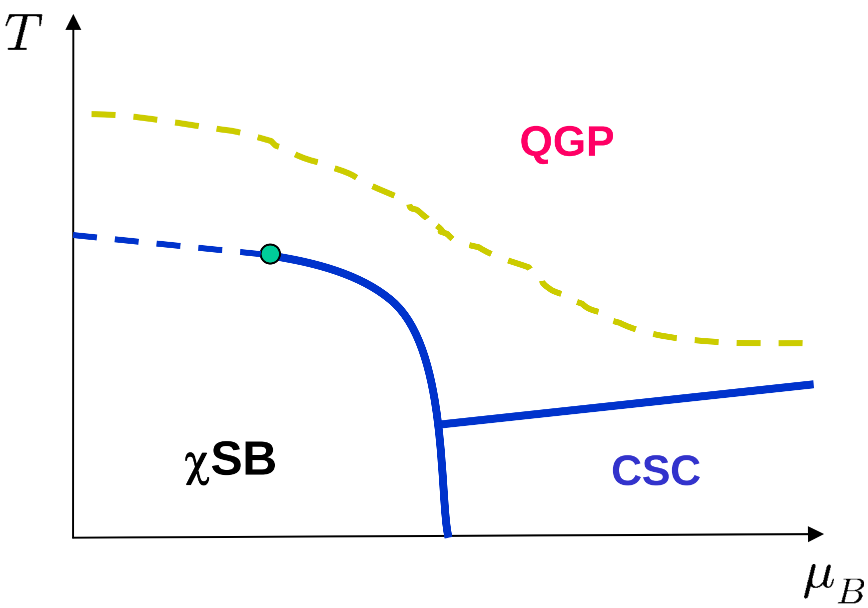
Similarity with high T_c superconductors

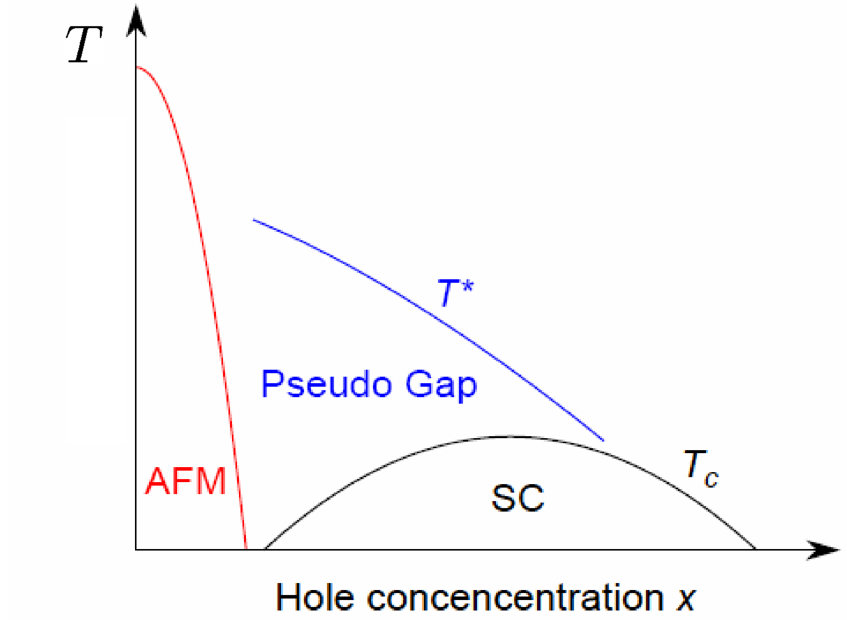




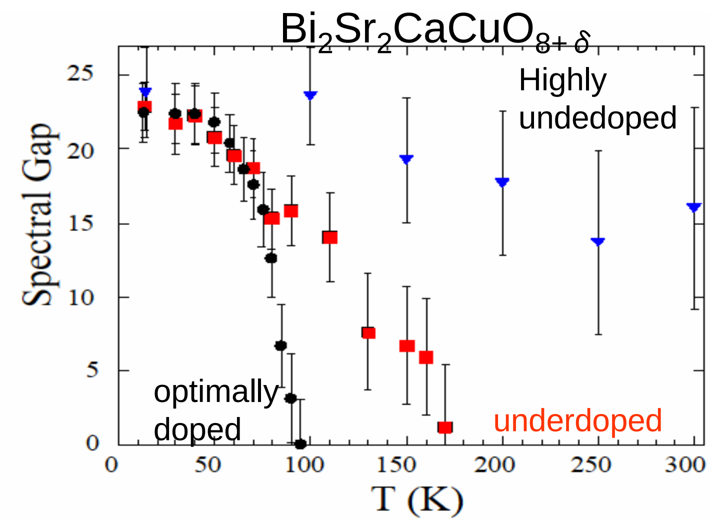


Similarity with high T_c superconductors





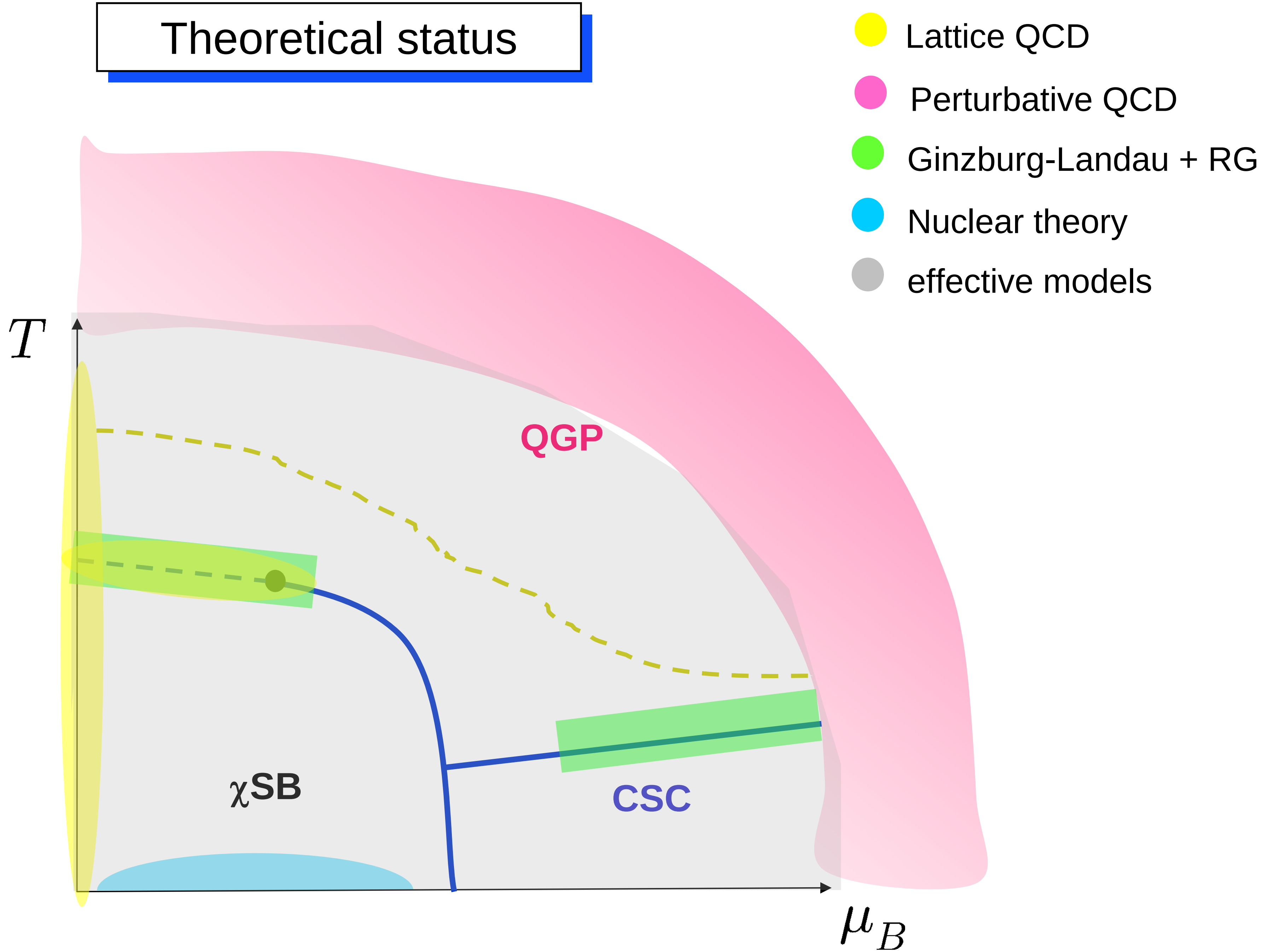
1. insulator – superconductor transition
2. strong coupling → pre-formed pairs?
3. similar physics in "cold-atoms" too



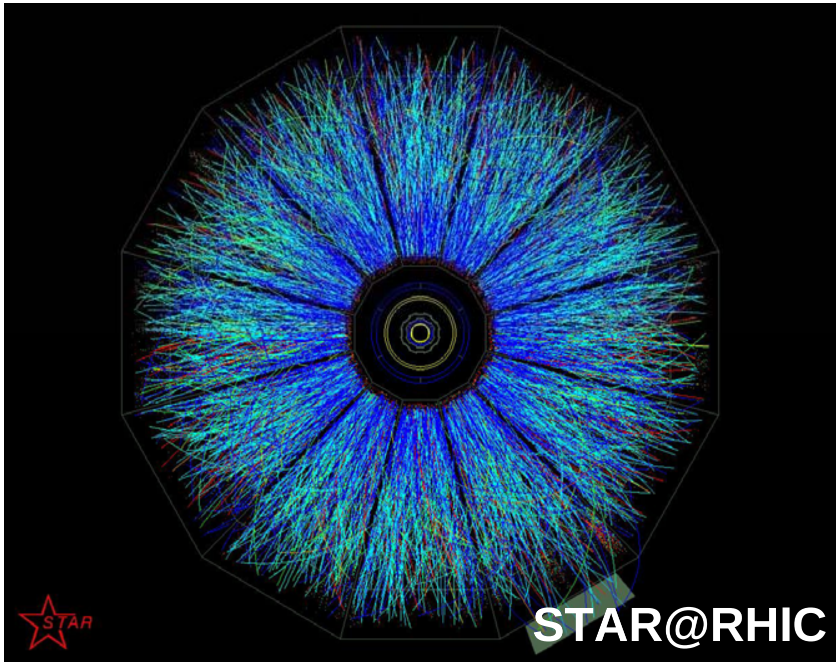
HTS – BEC – QCD connection ?

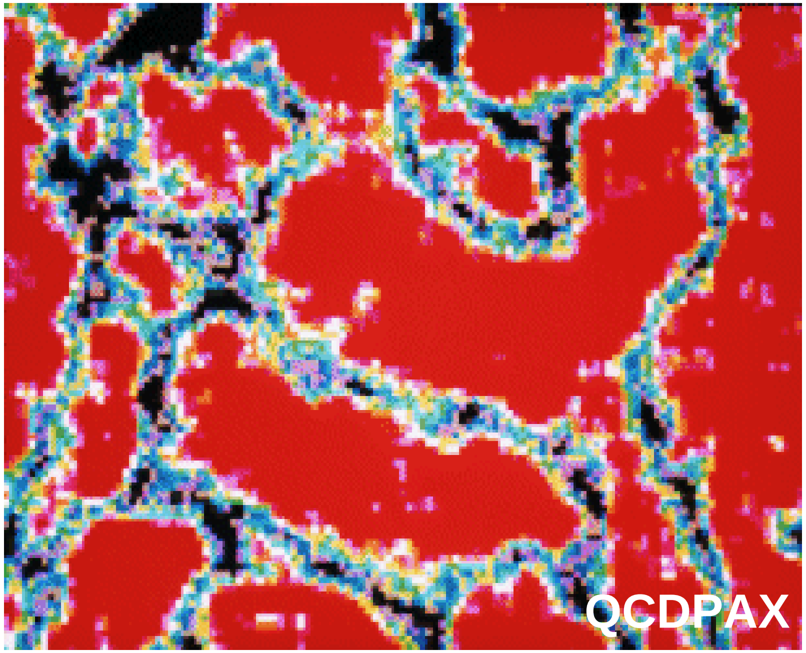
- Babaev, PRD ('00)
- Abuki, Itakura & Hatsuda, PRD ('02)
- Kitazawa, Koide, Kunihiro & Nemoto, PRD ('02)
- Chen, Stajic, Tan & Levin, Phys. Rep. ('05)

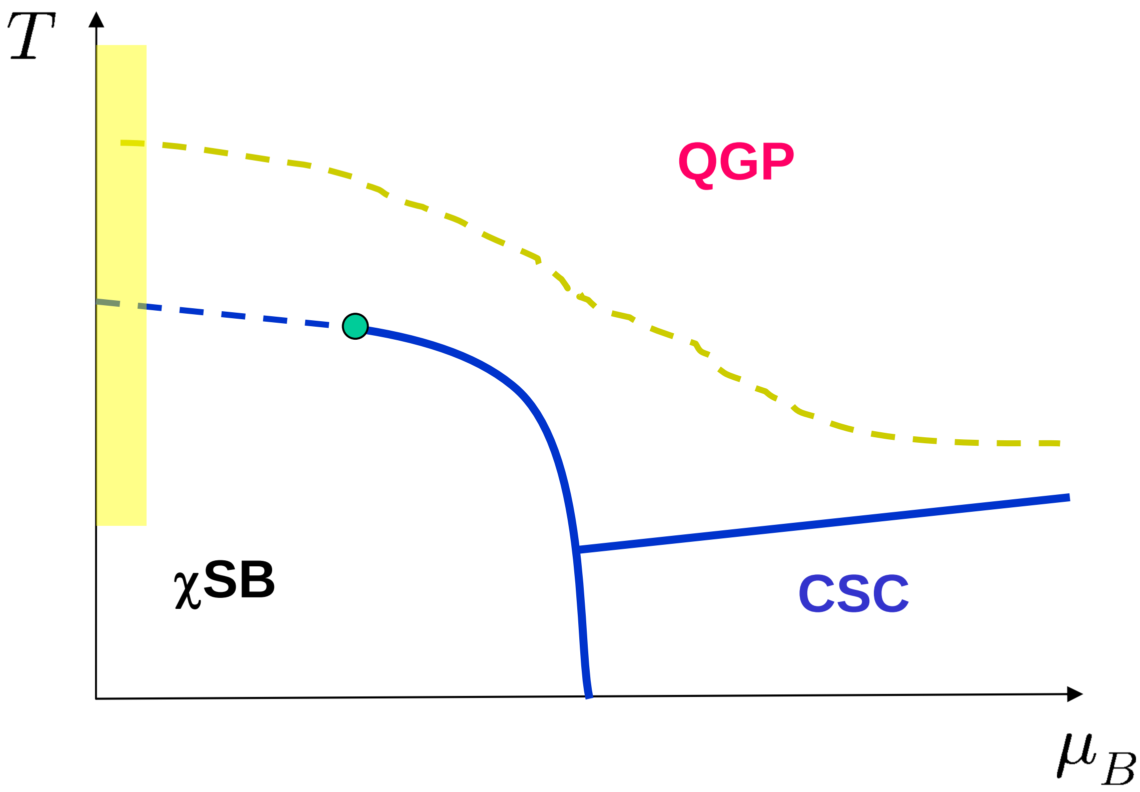
Theoretical status



Phases in hot QCD

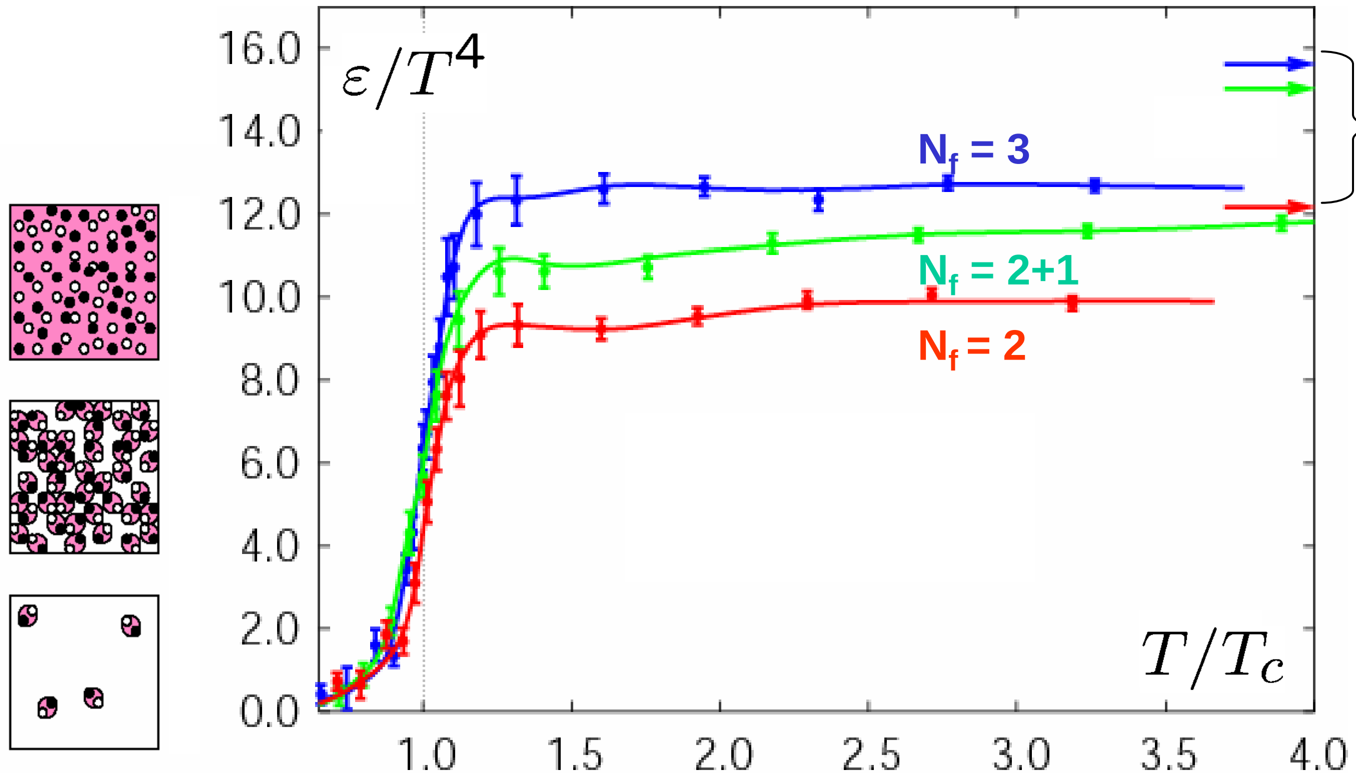






T
QGP
χSB
CSC
μ_B

Equation of State (μ=0)



SB limit

Karsch, Lect.Notes Phys. 583 ('02) 209

T_c = 173$\pm$10 MeV (N_f=2)
= 154$\pm$10 MeV (N_f=3)

Karsch's talk

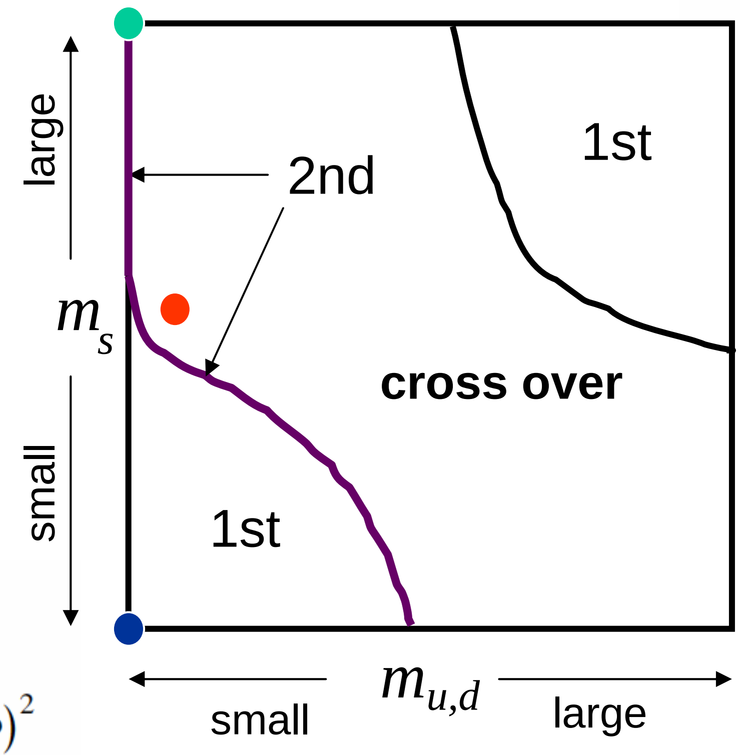
Order of the thermal transition (μ=0)

Svetitsky & Yaffe, NPB210 ('82)

Pisarski and Wilczek, PRD29 ('84)

O(4) GL theory

$$L_{GL} = \frac{1}{2}(\partial\vec{\phi})^2 + \frac{a(m_s,T)}{2}\vec{\phi}^2 + \frac{b(m_s,T)}{4!}(\vec{\phi}^2)^2 + \frac{c}{6!}(\vec{\phi}^2)^3 - h\phi_0$$



$$L_{GL} \quad \frac{1}{2}(\nabla L^*)(\nabla L) + \frac{a}{2}L^*L - \frac{c}{3}\,\mathrm{Re}(L^3) + \frac{b}{4}(L^*L)^2 - h\,\mathrm{Re}(L)$$

Z(3) GL theory

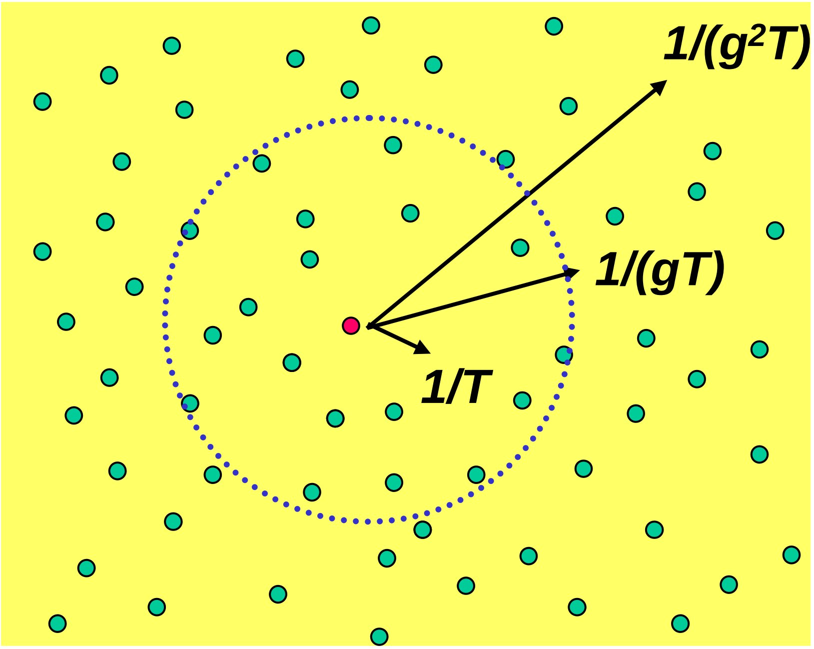
SU$_L$(3)xSU$_R$(3) GL theory

$$L_{GL} = \frac{1}{2}\,\mathrm{tr}\,\partial\Phi^\dagger\partial\Phi + \frac{a}{2}\,\mathrm{tr}\,\Phi^\dagger\Phi + \frac{b_1}{4!}\left(\mathrm{tr}\,\Phi^\dagger\Phi\right)^2 + \frac{b_2}{4!}\,\mathrm{tr}\left(\Phi^\dagger\Phi\right)^2 - \frac{c}{2}\left(\det\Phi + \det\Phi^\dagger\right) - \frac{1}{2}\,\mathrm{tr}\,h(\Phi + \Phi^\dagger).$$

Unified treatment

Weise's talk

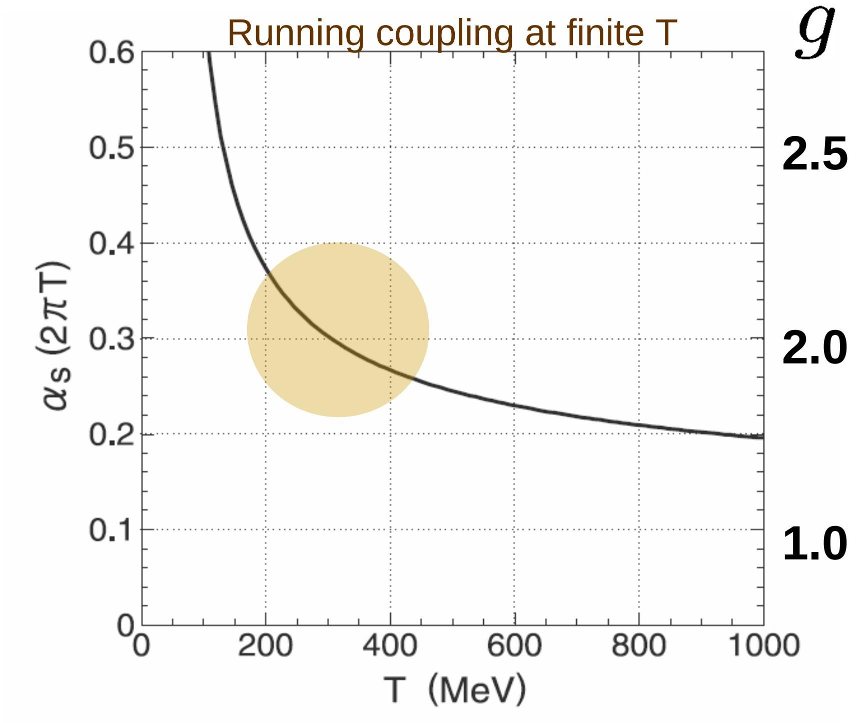
Scale degeneracy near T_c



T^{-1} Inter-particle distance

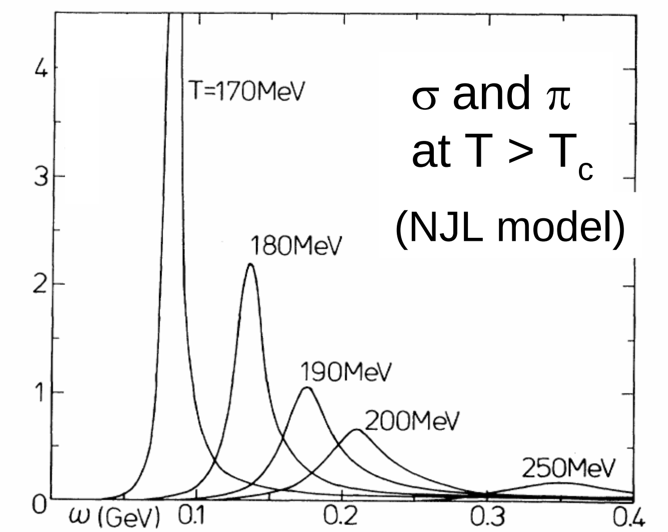
$(gT)^{-1}$ Electric screening length

$(g^2T)^{-1}$ Magnetic screening length

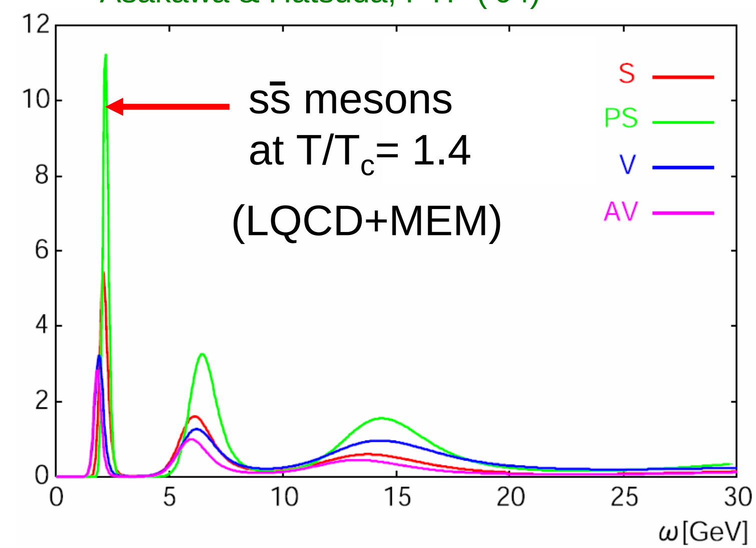


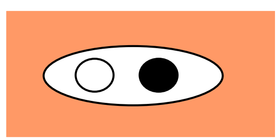
Pre-formed pairs (PFP) for $T_c < T < T^*$

Hatsuda & Kunihiro, PRL ('85)

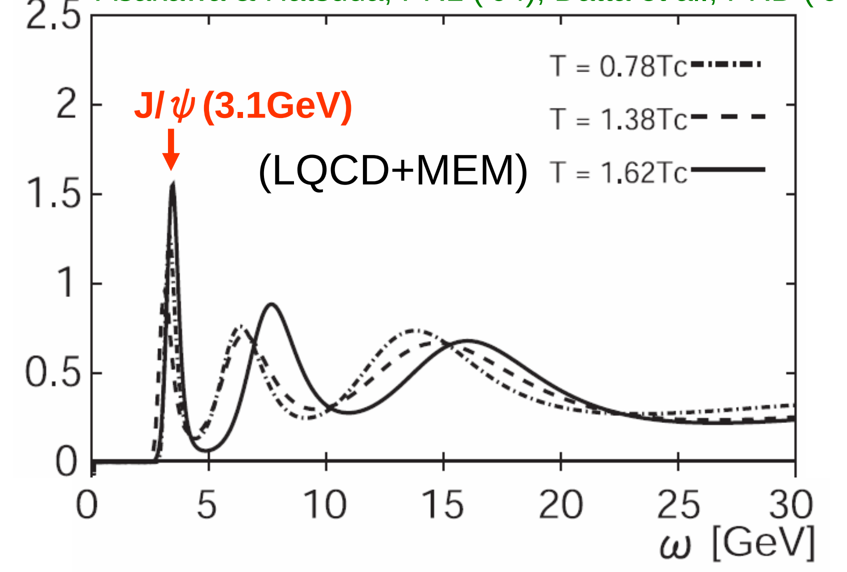


Asakawa & Hatsuda, PTP ('04)





Asakawa & Hatsuda, PRL ('04), Datta et al., PRD ('04)

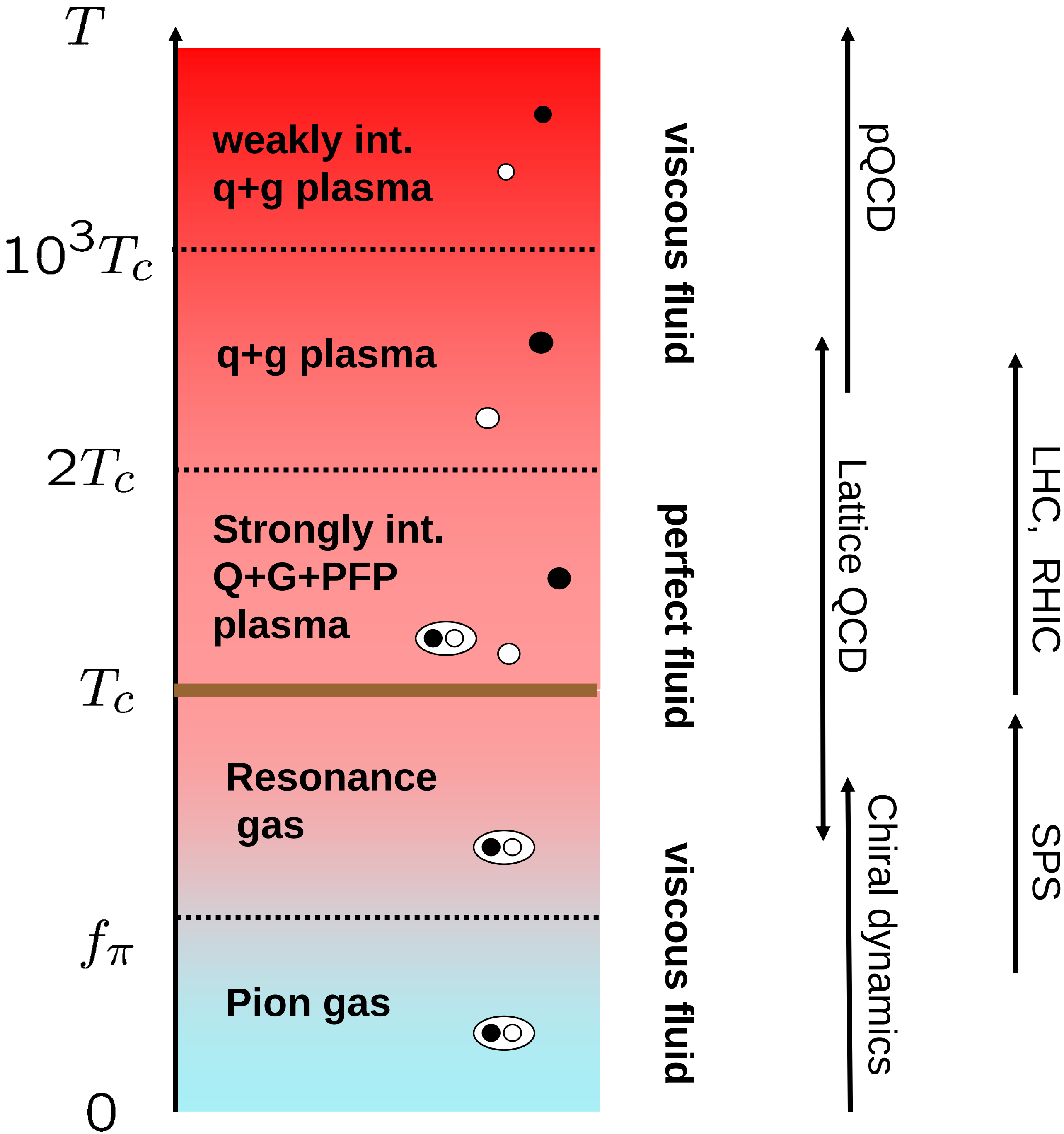


T_c : absence of coherence

T^* : dissociation of PFP

BEC-BCS crossover:

Leggett ('80), Nozieres & Schimitt-Rink ('85)



A modern
"picture"
of hot QCD

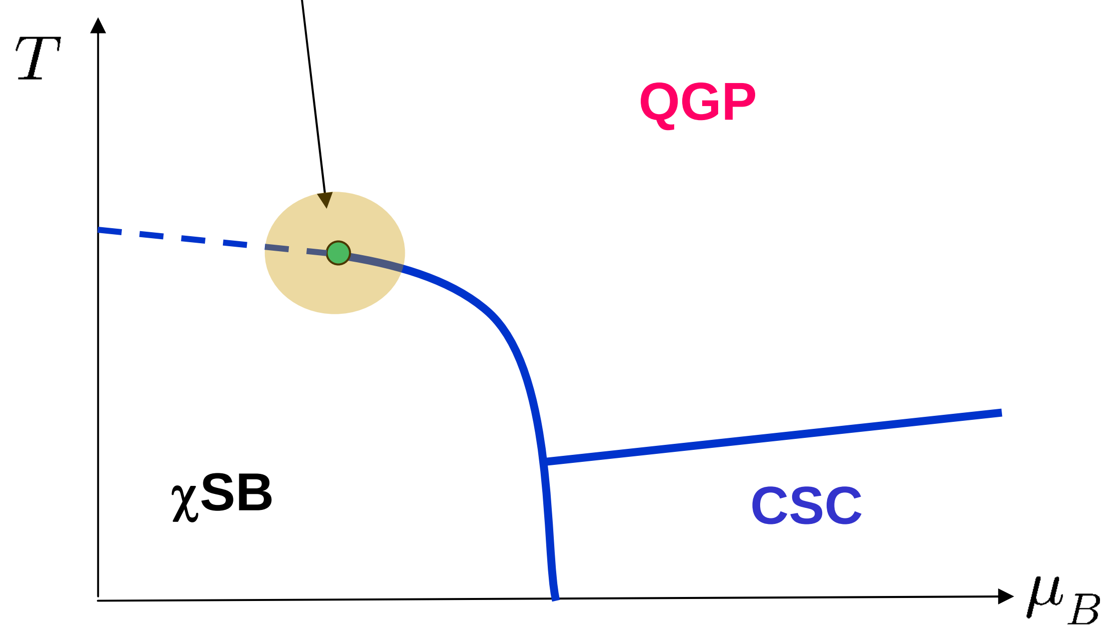
Critical end point at finite μ

- First evidence in some models: Asakawa & Yazaki, NPA ('89), Barducci et al., PLB ('89)
  See however, Klimt, Lutz and Weise, PLB ('90)
- General properties in Ginzburg-Landau+RG
  Halasz et al., PRD ('98), Hatta and Ikeda, PRD ('03)

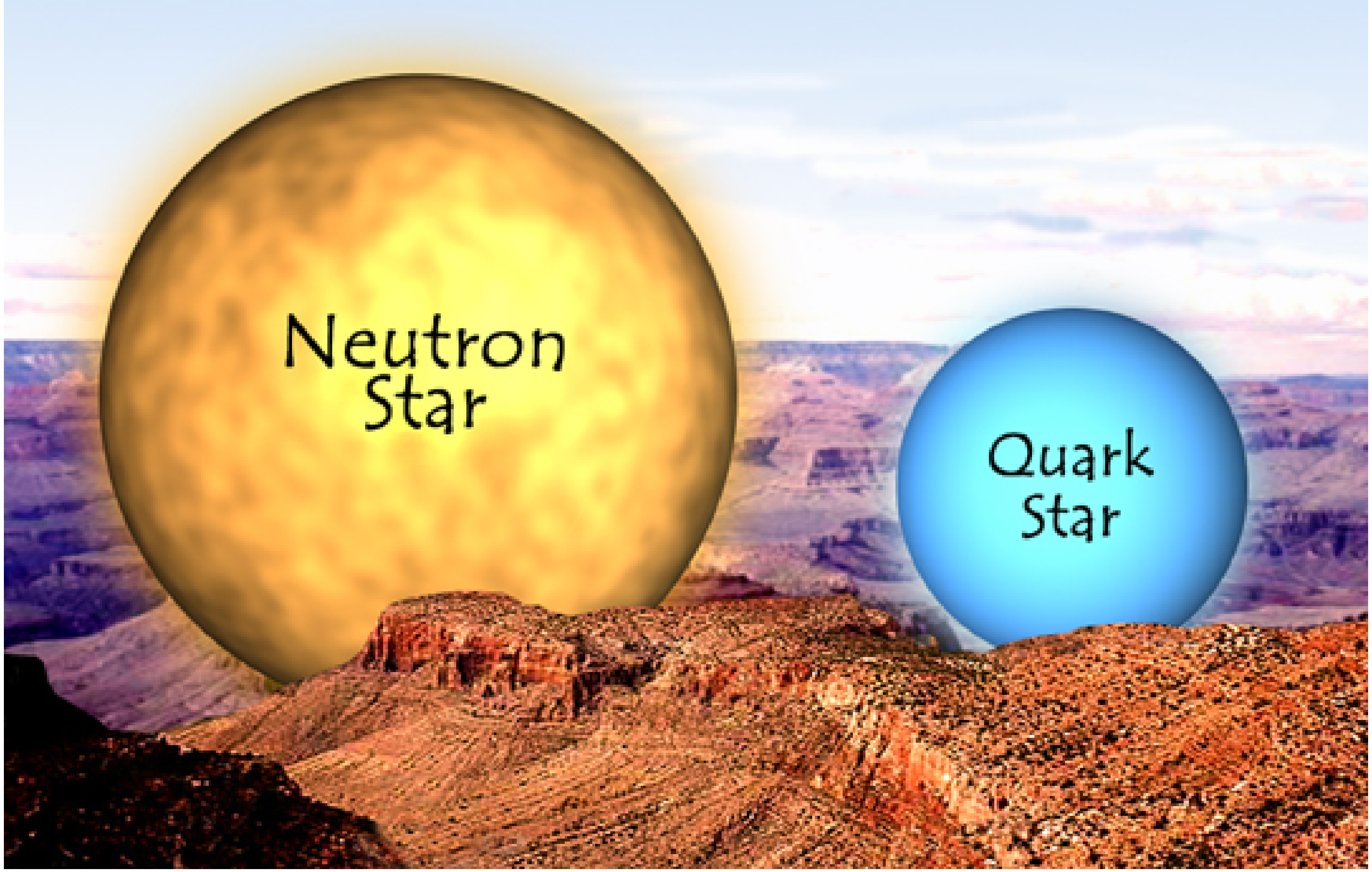
$$L_{GL} = \frac{1}{2}(\partial\vec{\phi})^2 + \frac{a(\mu,T)}{2}\vec{\phi}^2 + \frac{b(\mu,T)}{4!}(\vec{\phi}^2)^2 + \frac{c}{6!}(\vec{\phi}^2)^3 - h\phi_0$$

- Lattice QCD study

Karsch's talk
Fodor's talk

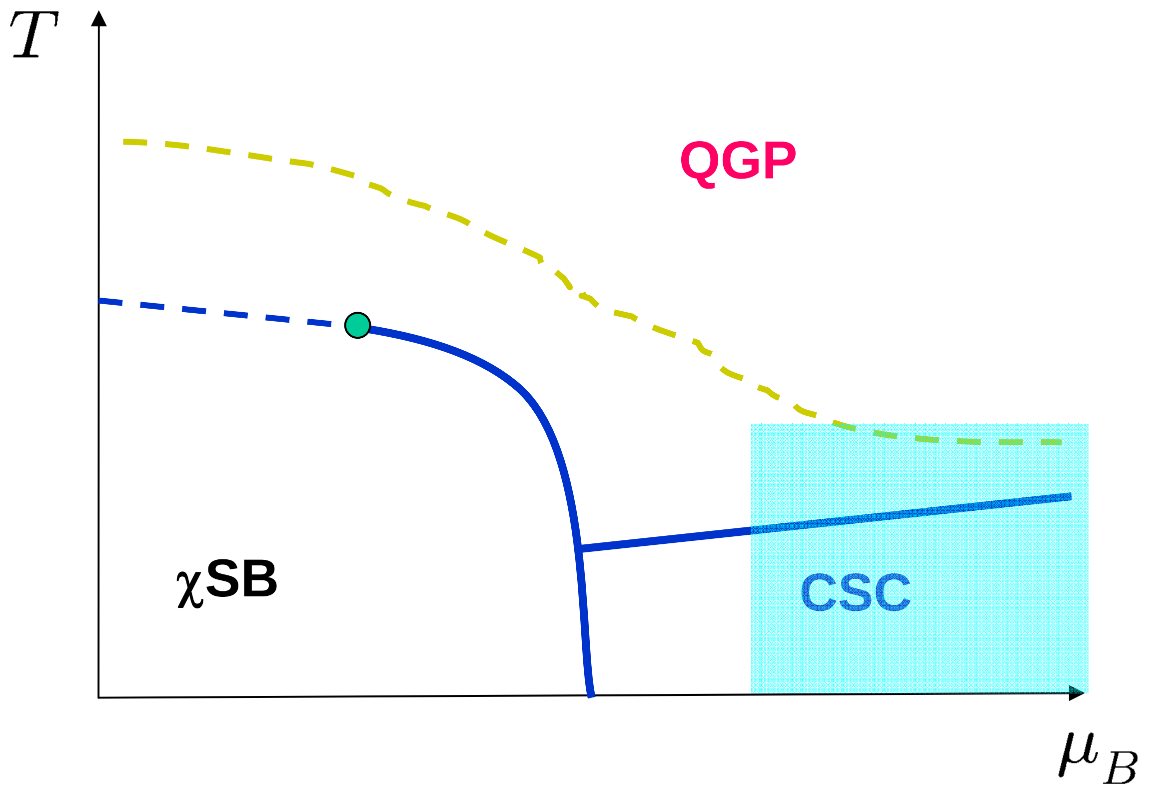


Phases in dense QCD



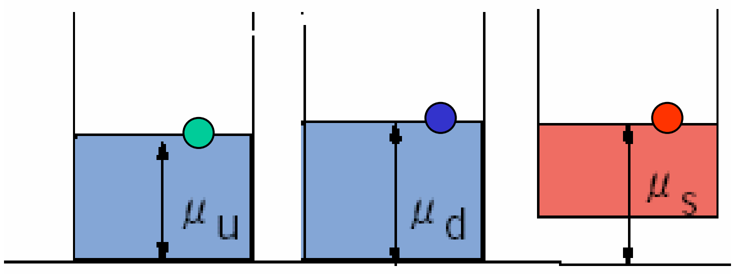
Baade-Zwicky ('34) **N. Itoh ('70), E. Witten ('84)**

http://chandra.harvard.edu/resources/illustrations/neutronStars.html



Bailin & Love, Phys. Rep. 107 (1984)
Iwasaki & Iwado, PL B350 (1995)
Alford, Rajagopal & Wilczek, PL B422 (1998)
Rapp, Schafer, Shuryak & Velkovsky, PRL81 (1998)

Origin of Color Superconductivity (CSC)



$$\Delta_{i\alpha} = \epsilon_{ijk}\epsilon_{\alpha\beta\gamma}\langle q_{j,\beta} C\gamma_5 q_{k,\gamma}\rangle$$

flavor (i)   color (α)

Major differences from BCS

1. Highly **relativistic**
   Long range **magnetic int.**

$$|\Delta| \sim \varepsilon_F \; e^{-c/\sqrt{\alpha_s}}$$

→ **High Tc superconductor**
$T_c/\varepsilon_F \sim 0.1$
Compact Cooper pair
size ~ 1-10 fm

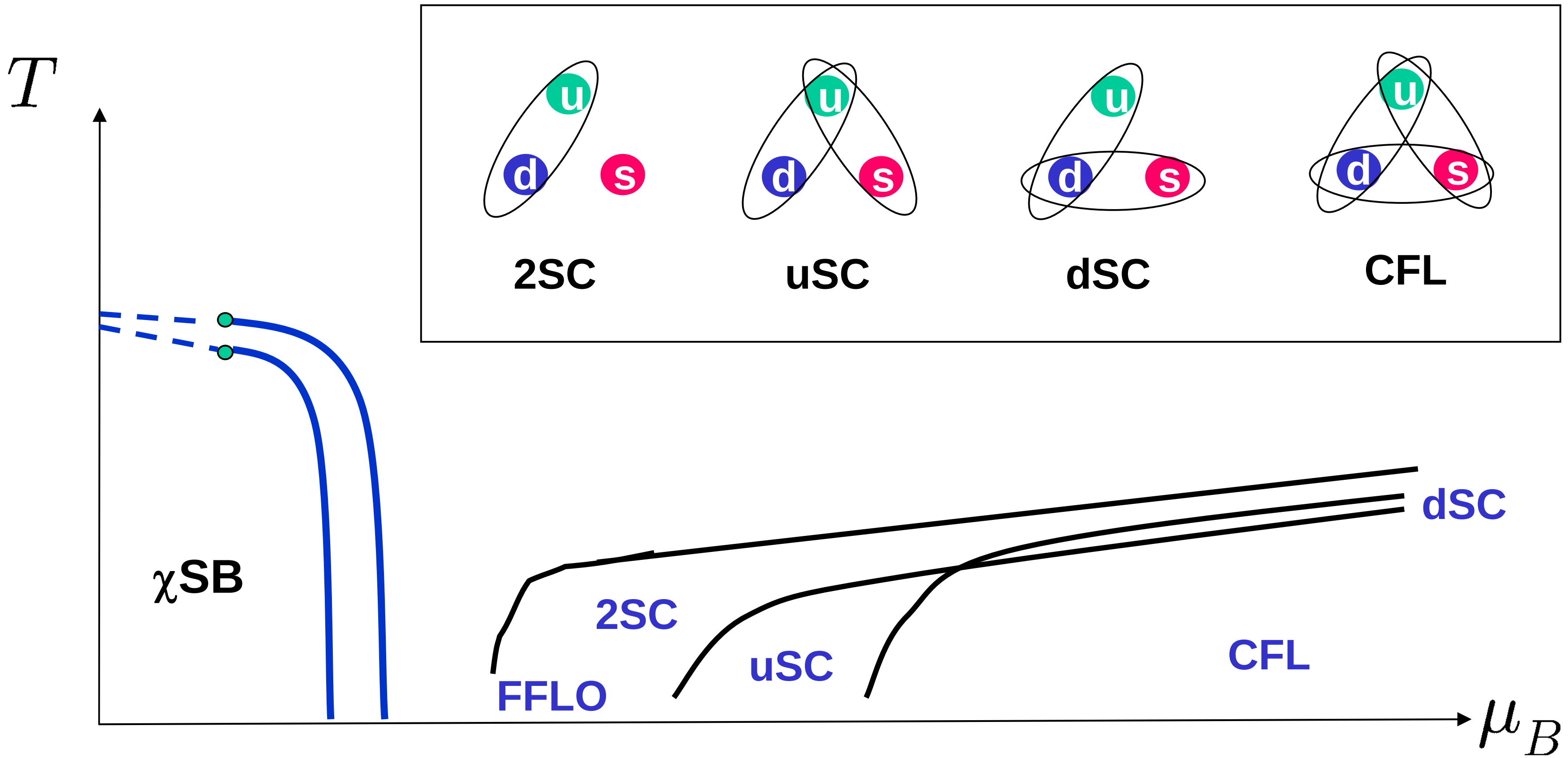
2. Color-flavor **entanglement**

$$\Delta_{i\alpha} = \begin{pmatrix} \Delta_1 & 0 & 0 \\ 0 & \Delta_2 & 0 \\ 0 & 0 & \Delta_3 \end{pmatrix}$$

→ **Variety of phases (such as ice and ^{3}He)**
CFL, 2SC, dSC, uSC, etc

Phase structure relevant to compact stars

with charge-neutrality & β-equilibrium $n_d > n_u > n_s$

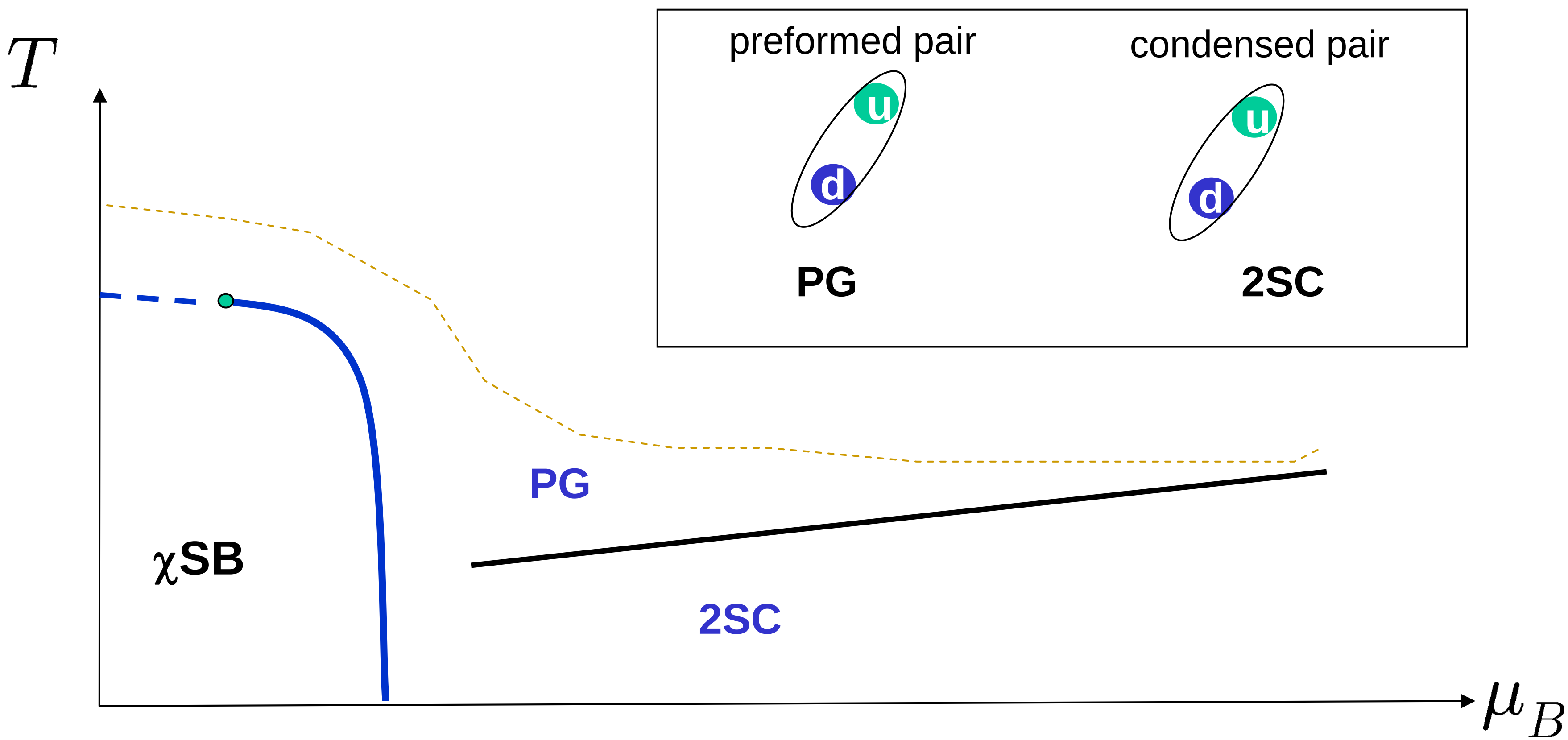


***2SC* :** Bailin and Love, Phys. Rep. ('84)
***CFL* :** Alford, Rajagopal and Wilczek, NPB ('99)
***dSC* :** Iida, Matsuura, Tachibana and Hatsuda, PRL ('04)
***uSC* :** Ruster, Werth, Buballa, Shovkovy and Rischke, PRD ('05)
FFLO, gapless phase, CSL, K-cond. etc

Rischke's talk

Phase structure relevant to heavy ion collisions

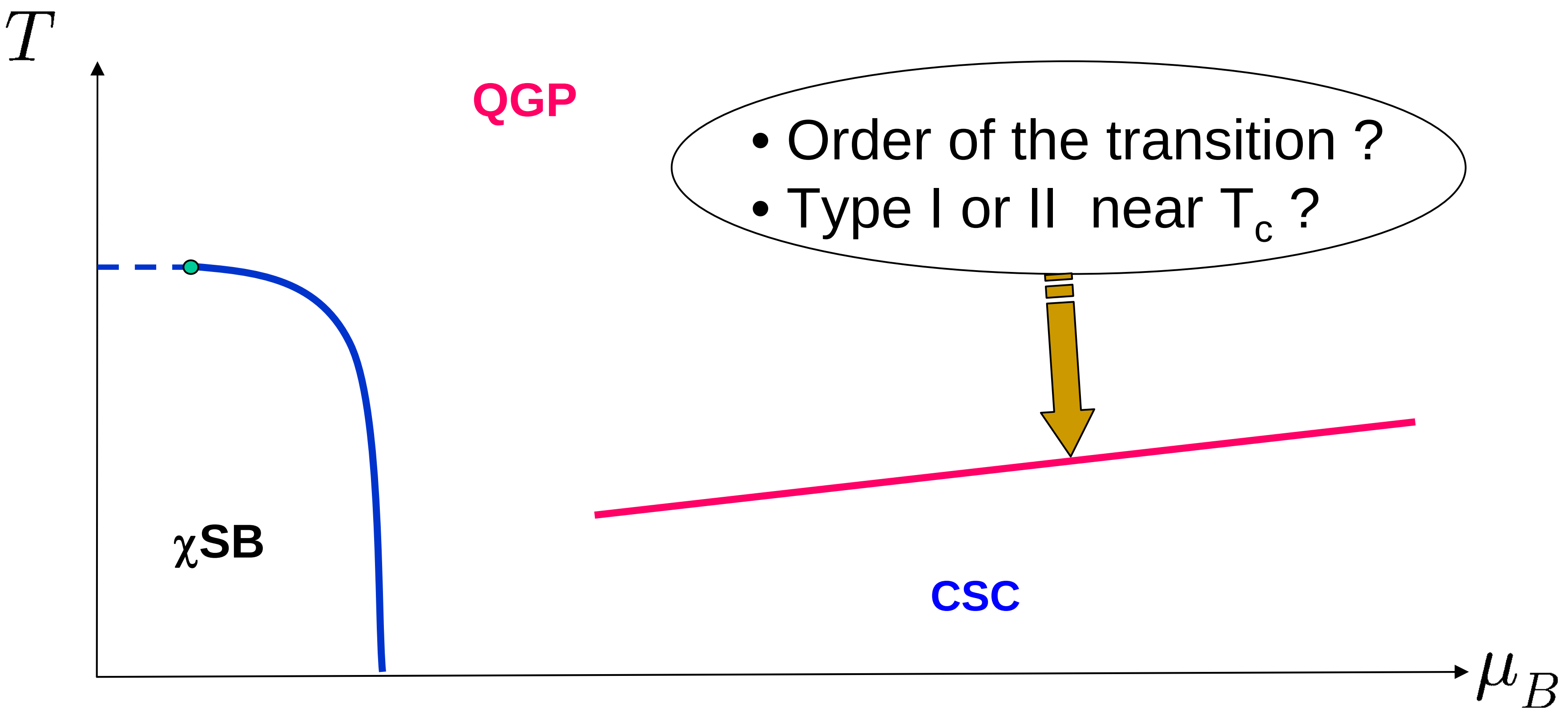
no charge-neutrality & β-equilibrium **$n_d = n_u$, n_s=0**



2SC : Bailin and Love, Phys. Rep. ('84)

PG : Kitazawa, Koide, Kunihiro and Nemoto, PRD ('04)

Thermal phase transition of CSC



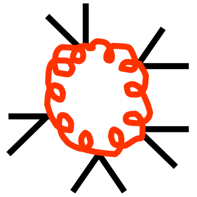
Ginzburg-Landau theory at $T \sim T_c$

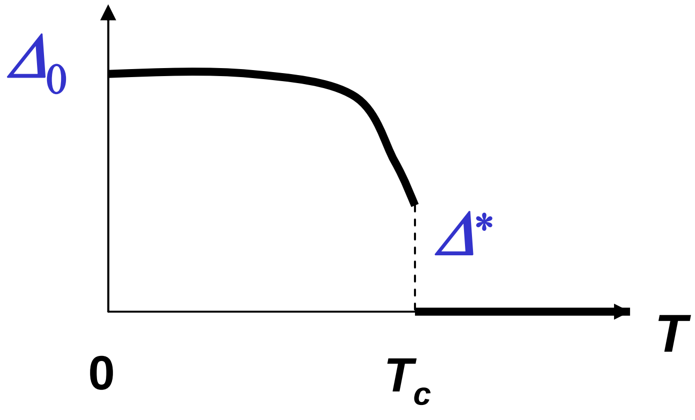
$SU_c(3) \times SU_{L+R}(3)$ gauged Higgs model in 3d : Iida & Baym, PRD63 ('01)

$$A_\mu^a, \quad \Delta_{i\alpha} \quad (= \Delta_{i\alpha}^L = \Delta_{i\alpha}^R)$$

- Weak coupling analyses — Matsuura, Iida, Hatsuda & Baym, PRD 69 ('04); Giannakis, Hou, Ren & Rischke, PRL 93 ('04)
- Lattice simulations : Digal, Hatsuda & Ohtani, hep-lat/0511018

First order transition at high density : Coleman-Weinberg type



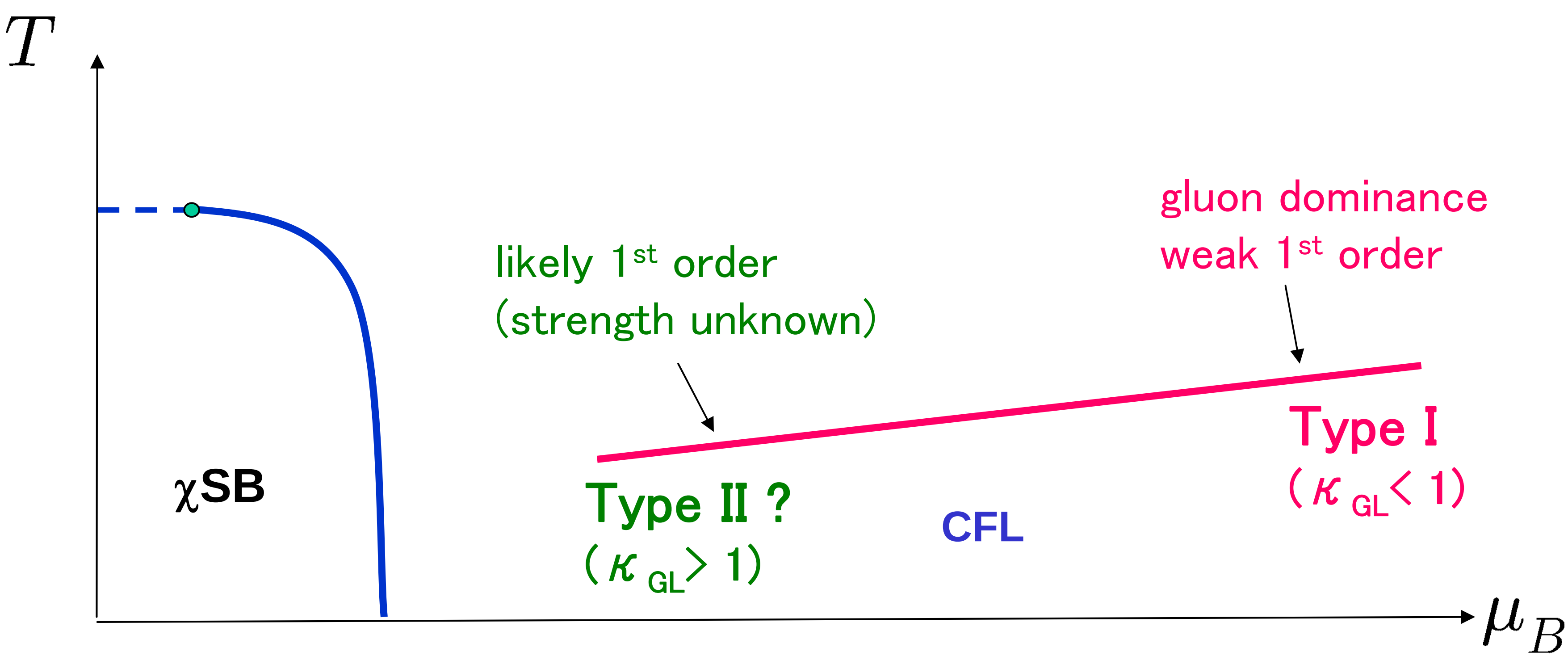


$$\left.\frac{\Delta^*}{\Delta_0}\right|_{WC} \sim \frac{g}{4}$$

Thermal transition : CFL → normal

Ginzburg-Landau parameter ::

$$\kappa_{\rm GL} = \frac{\text{color penetration depth}}{\text{color coherence length}} = \frac{m_\Delta}{m_A} \sim \frac{1}{\sqrt{\alpha_s}}\left(\frac{T_c}{\mu_B}\right)$$

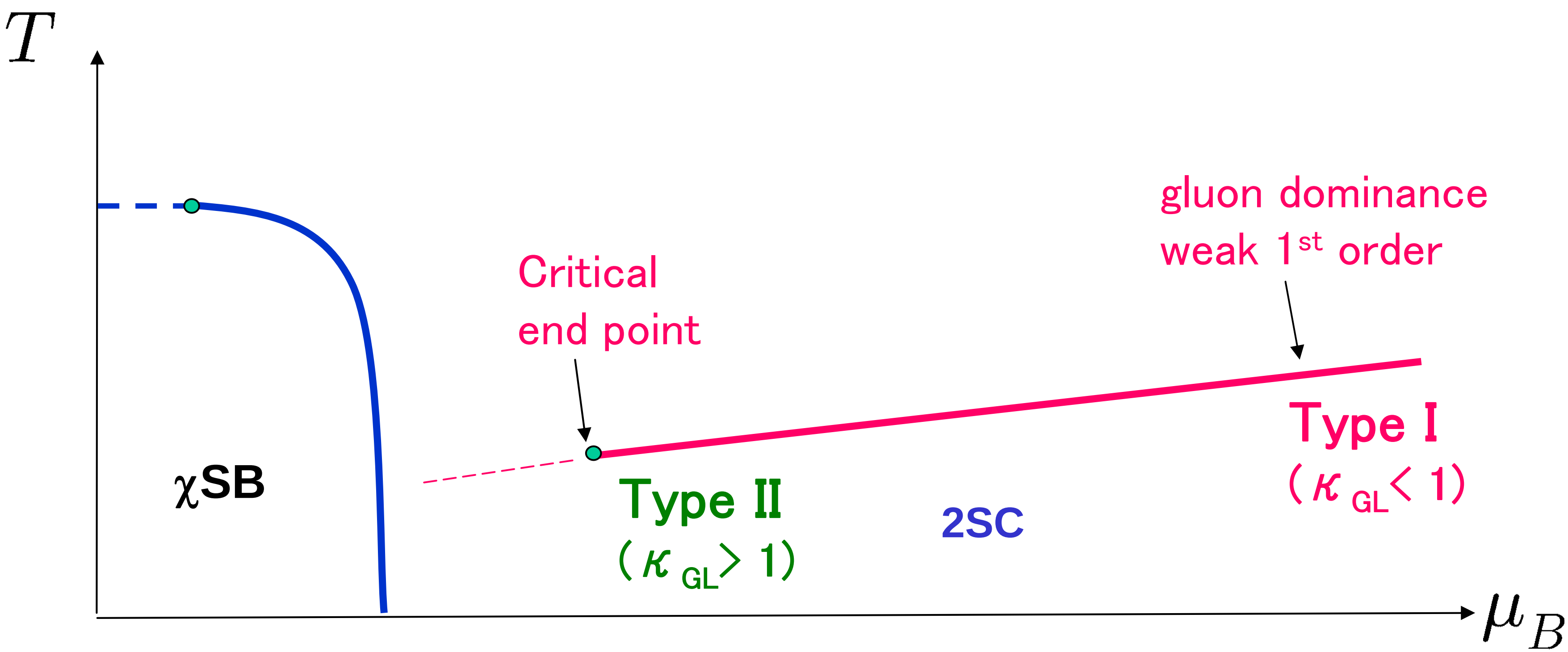


Case for m_{uds}=0

Thermal transition : 2SC → normal

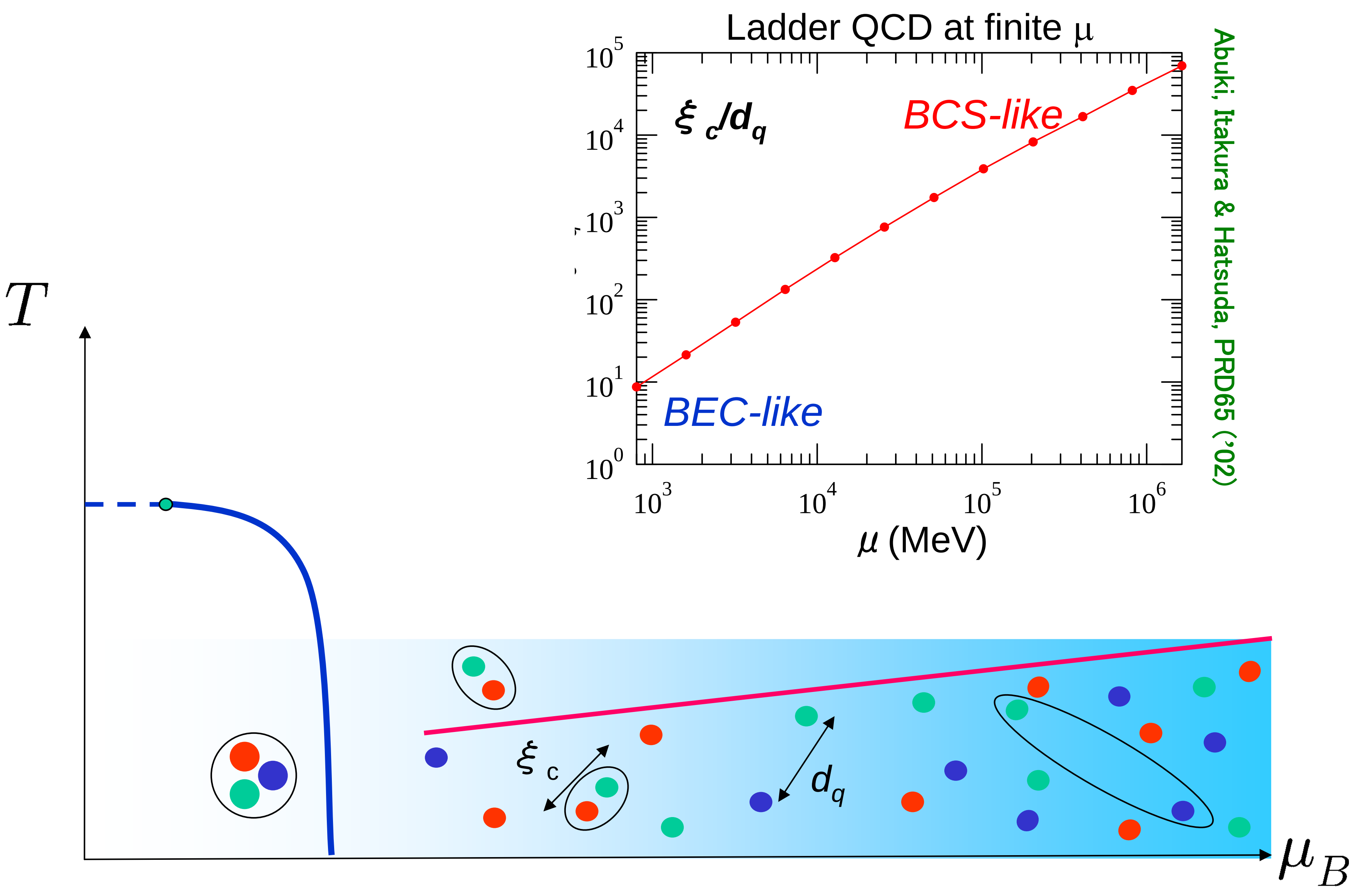
Ginzburg-Landau parameter ::

$$\kappa_{\mathrm{GL}} = \frac{\text{color penetration depth}}{\text{color coherence length}} = \frac{m_\Delta}{m_A} \sim \frac{1}{\sqrt{\alpha_s}} \left(\frac{T_c}{\mu_B} \right)$$

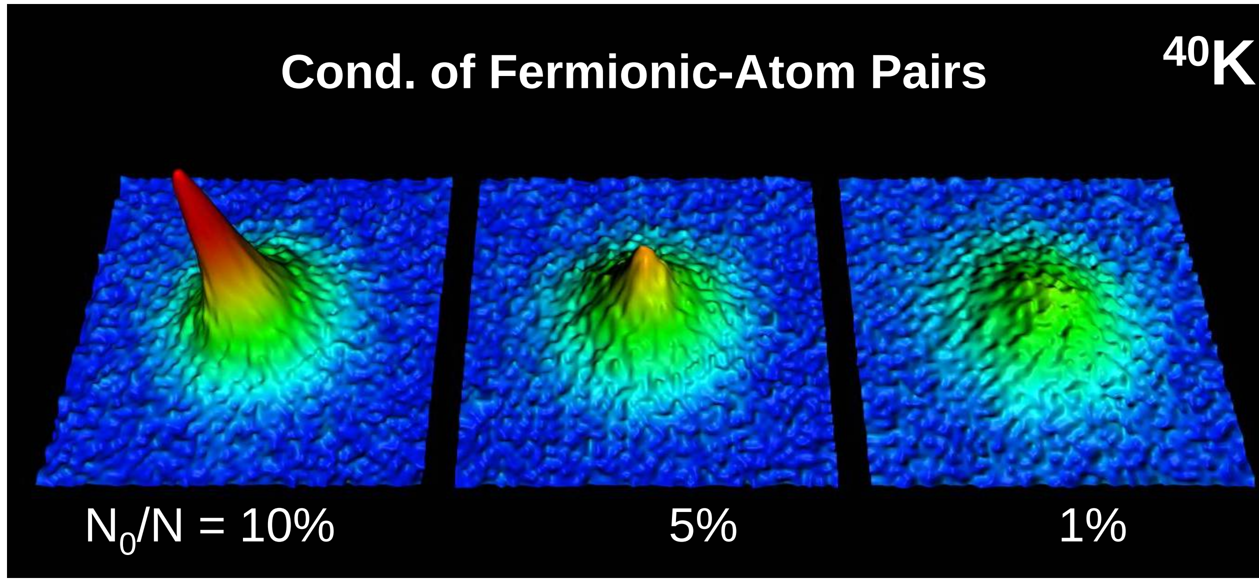


Case for $m_s = \infty$

BCS-BEC crossover ?



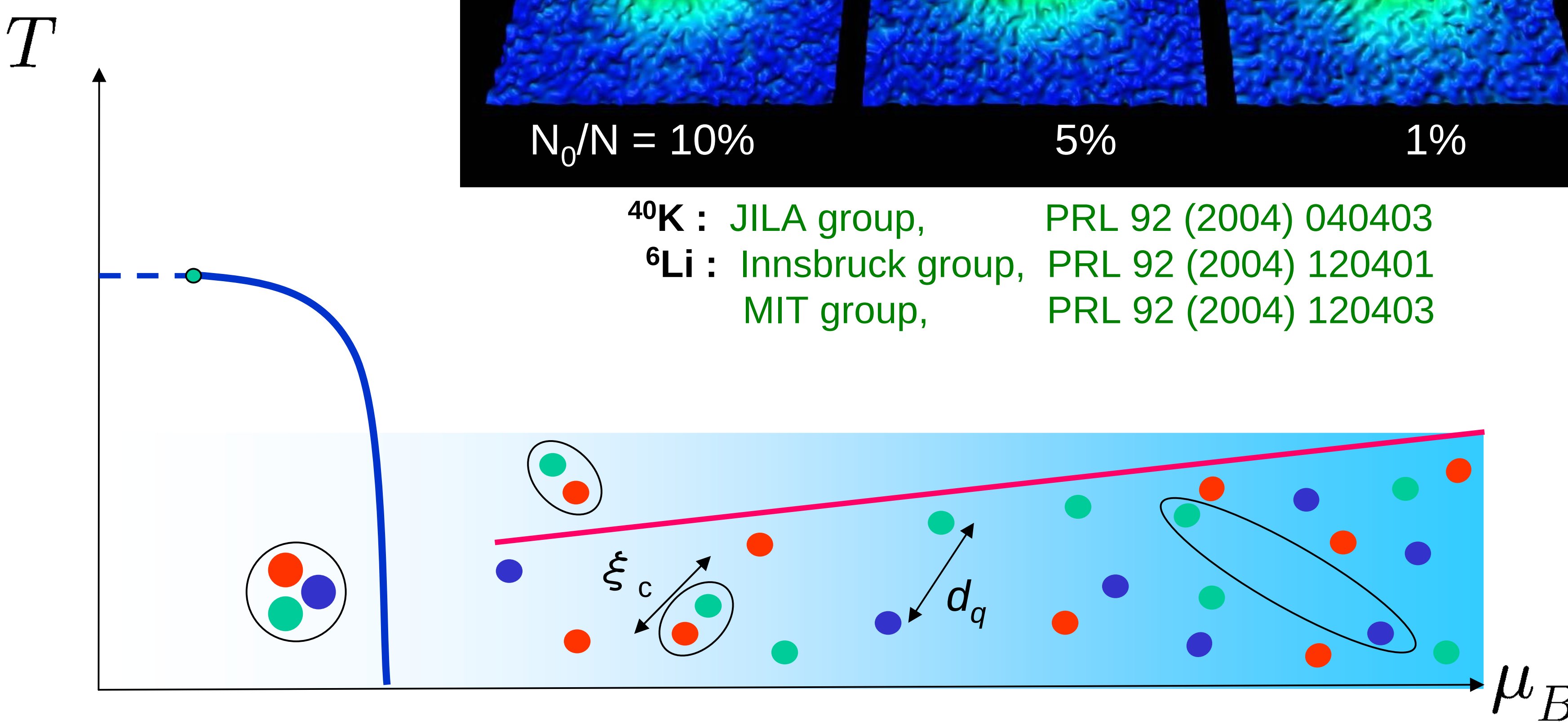
BCS-BEC crossover ?



^{40}**K :** JILA group, PRL 92 (2004) 040403

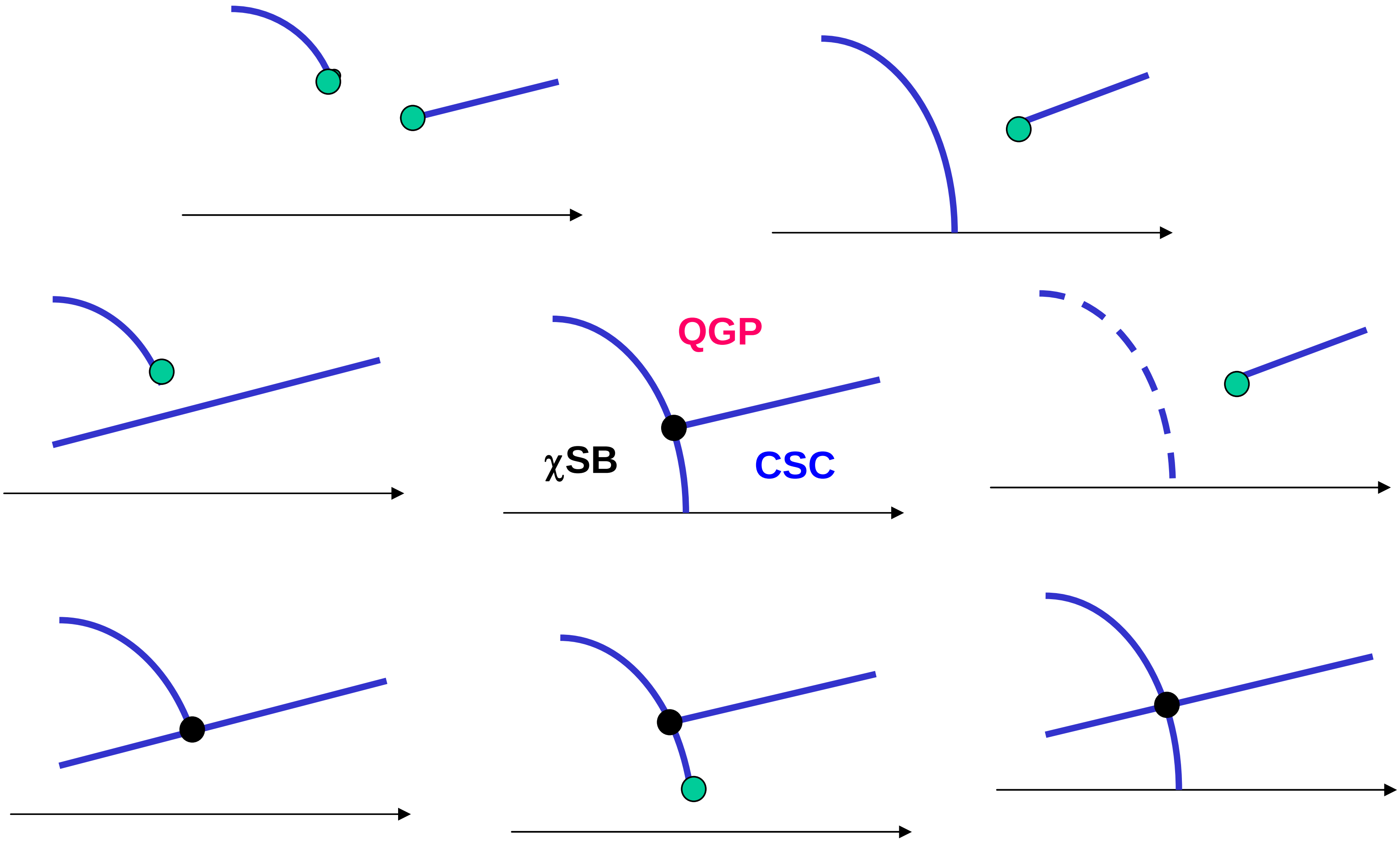
^{6}**Li :** Innsbruck group, PRL 92 (2004) 120401

MIT group, PRL 92 (2004) 120403



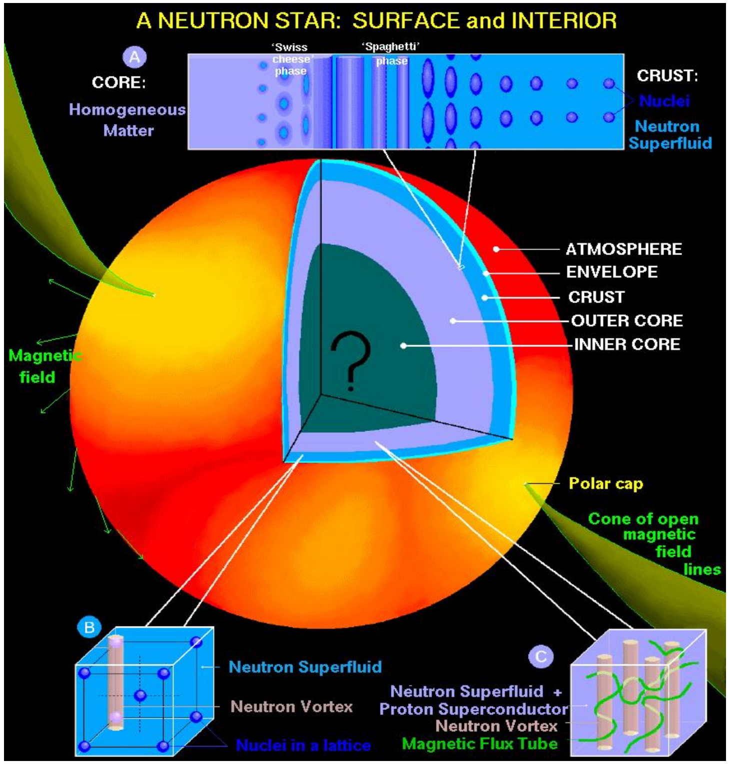
Possible phase structure

$n_d = n_u$, $n_s=0$



See Kitazawa, Koide, Kunihiro & Nemoto, PTP108 ('02)

Probing Dense QCD



J-PARC

➡ **Weber's talk**

SIS100/300

Future Experimental Facilities for hot/dense QCD

LHC (2008-)

2.8 TeV/A

- Hottest matter
- Precision QGP

J-PARC (2008-)

50 GeV PS

Phase I
- Dense mesic nuclei
- Exotic hadrons

Phase II
- Primary beam phys.

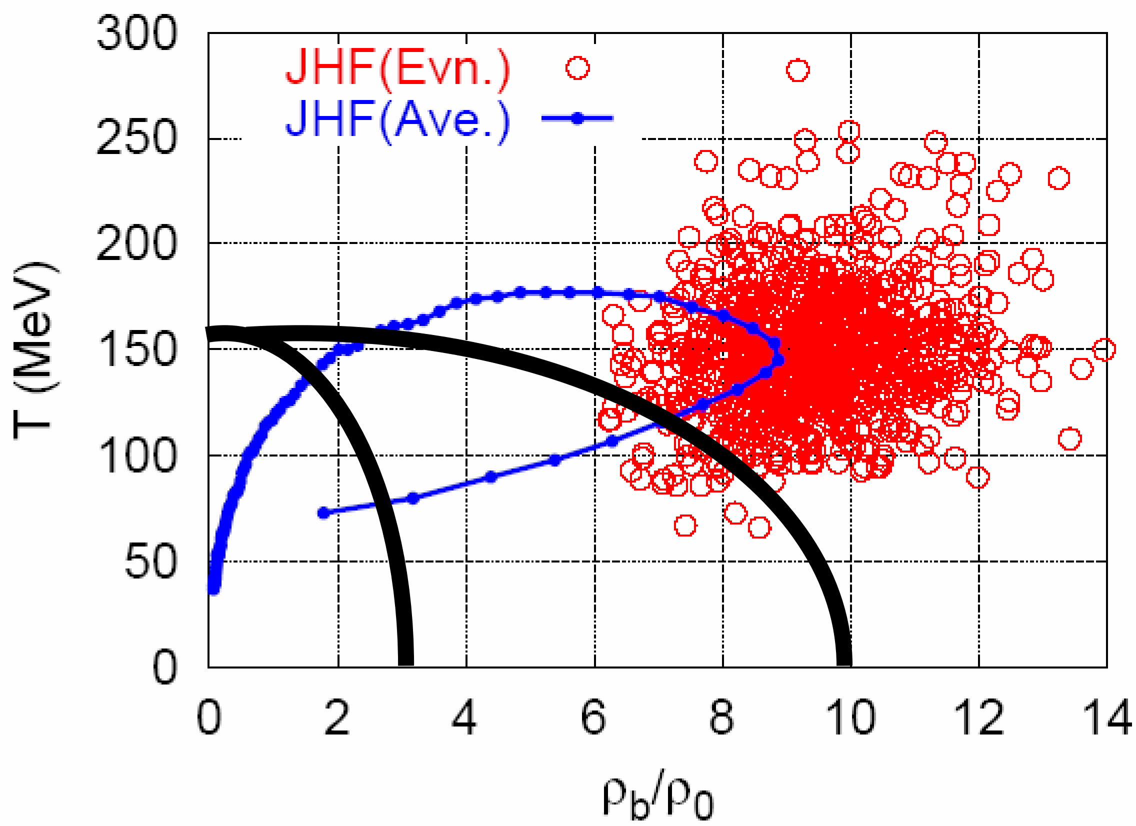
SIS100/300 (201? -)

90 GeV PS

- Densest matter
- In-medium hadrons

Heavy ion collision at J-PARC & SIS energies

[25A GeV Au] +Au



JAM
(Hadronic cascade model)
Y. Nara et al, PRC61 (2000)

$\rho_B > 6\ \rho_0$

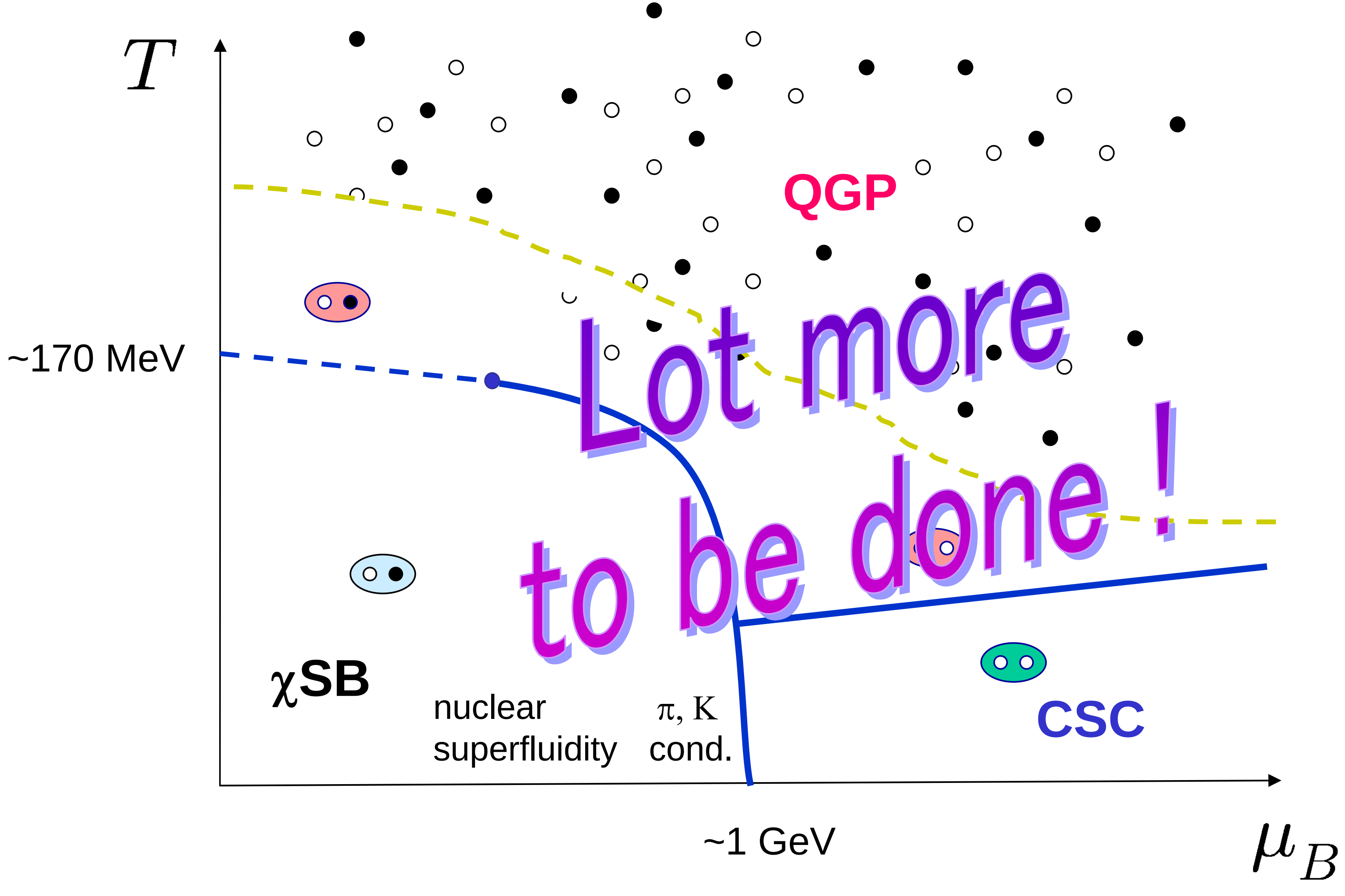
for about 3 fm/c

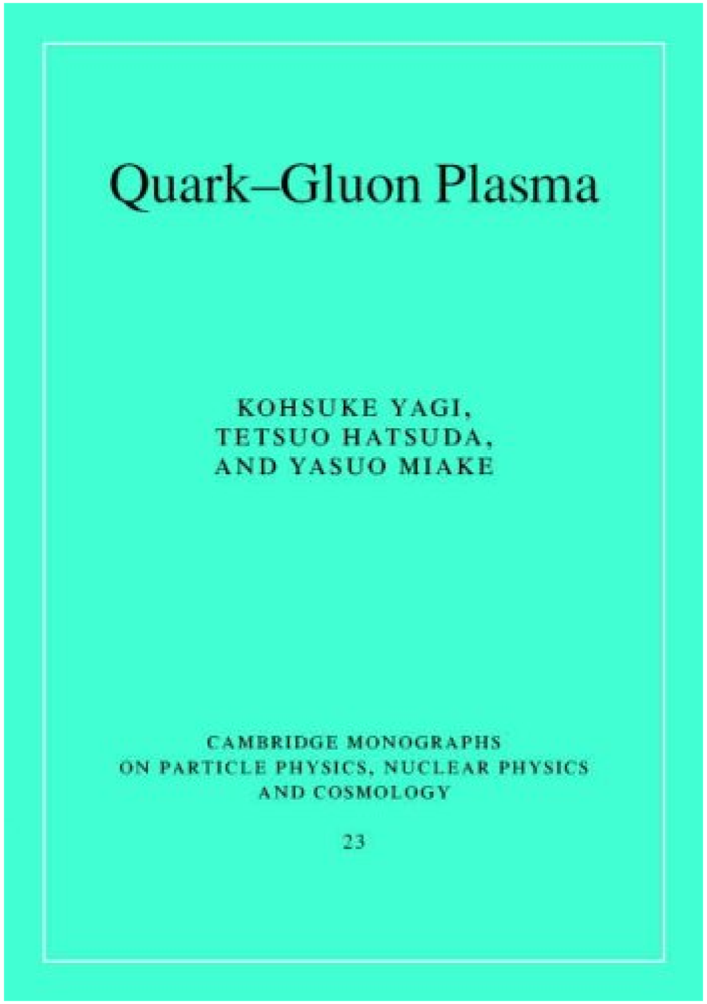
➡ **Ivanov's talk**

Figure taken from JHF report (2002) by A.Ohnishi

Summary

“phase”	theory	exp./obs.
χSB (low T & low μ)	Mature (precision physics) lattice QCD effective theories	variety of data
QGP (high T)	Developing lattice QCD effective theories	data accumulation RHIC → LHC
QM and CSC (low T & high μ)	Developing effective theories Need lattice inputs	• Neutron stars (M-R) • SIS, J-PARC, Nuclotron
“PG” (intermediate T & μ)	Not- fully explored Interesting connection to HTS, cold atoms	Relevant region to RHIC, SIS, J-PARC, Nuclotron ?


T
~170 MeV
QGP
Lot more
to be done !
χSB
nuclear
superfluidity
π, K
cond.
CSC
~1 GeV
μ_B



published, Dec. 15, 2005

1. What is quark-gluon plasma

Part I. Basic Concept of Quark-Gluon Plasma:

2. Introduction to QCD
3. Physics of quark-hadron phase transition
4. Field theory at finite temperature
5. Lattice gauge approach to QCD phase transitions
6. Chiral phase transition
7. Hadronic states in hot environment

Part II. QGP in Astrophysics:

8. QGP in the early universe
9. Compact stars

Part III. QGP in Relativistic Heavy Ion Collisions:

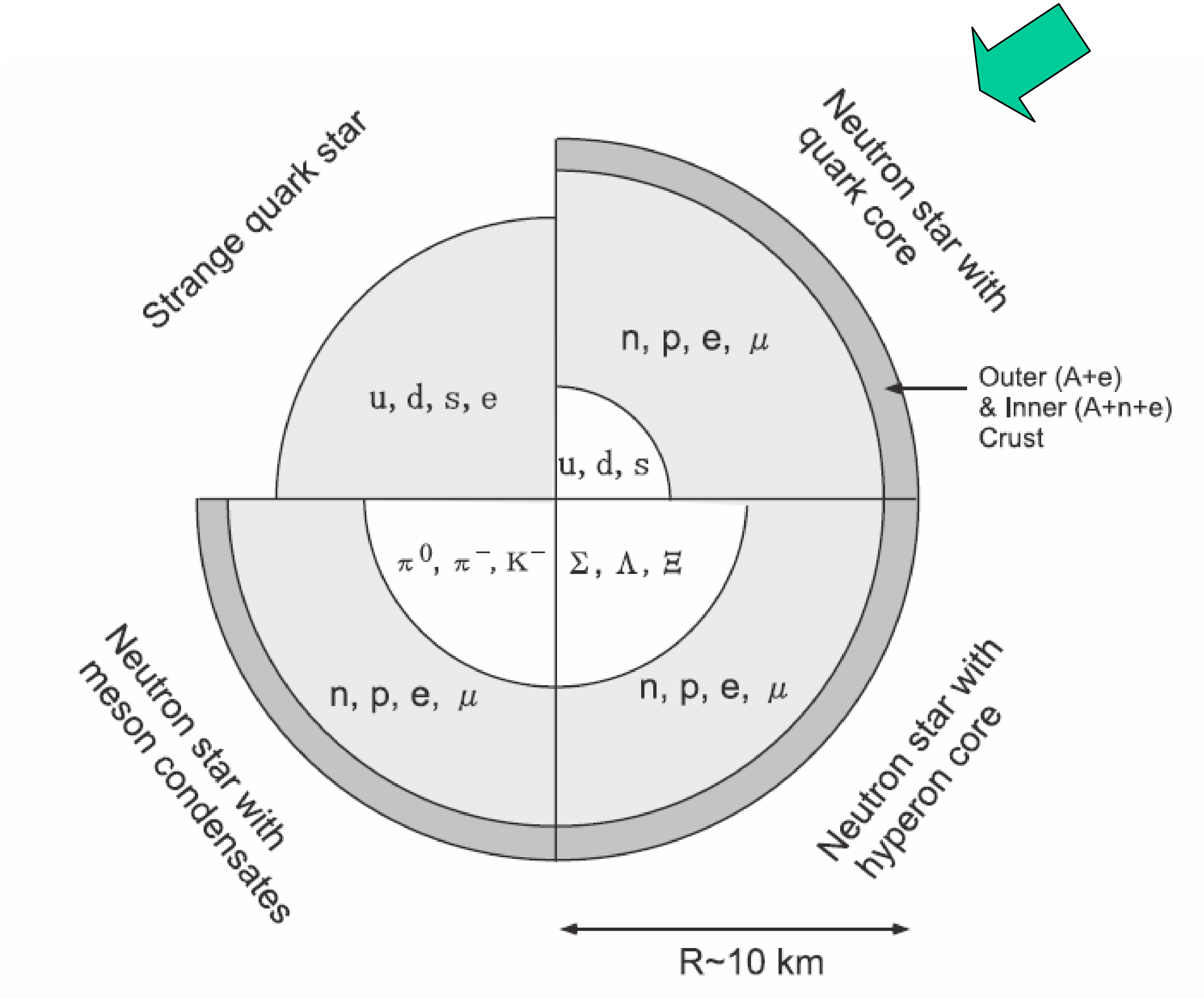
10. Introduction to relativistic heavy ion collisions
11. Relativistic hydrodynamics for heavy ion collisions
12. Transport theory for pre-equilibrium process
13. Formation and evolution of QGP
14. Fundamentals of QGP diagnostics
15. Results from CERN-SPS experiments
16. First results from BNL-RHIC
17. Detectors in relativistic heavy ion experiments

http://utkhii.px.tsukuba.ac.jp/cupbook/index.html

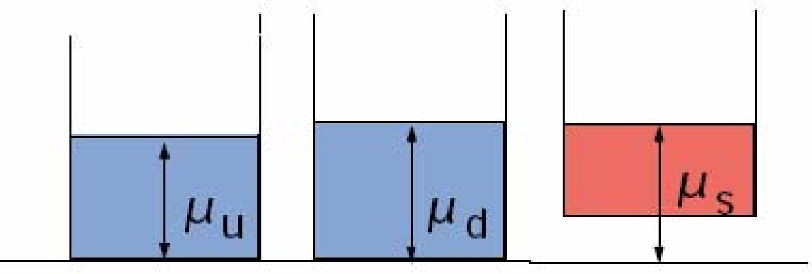
Appendices A-H:
120 Exercises

Back up slides

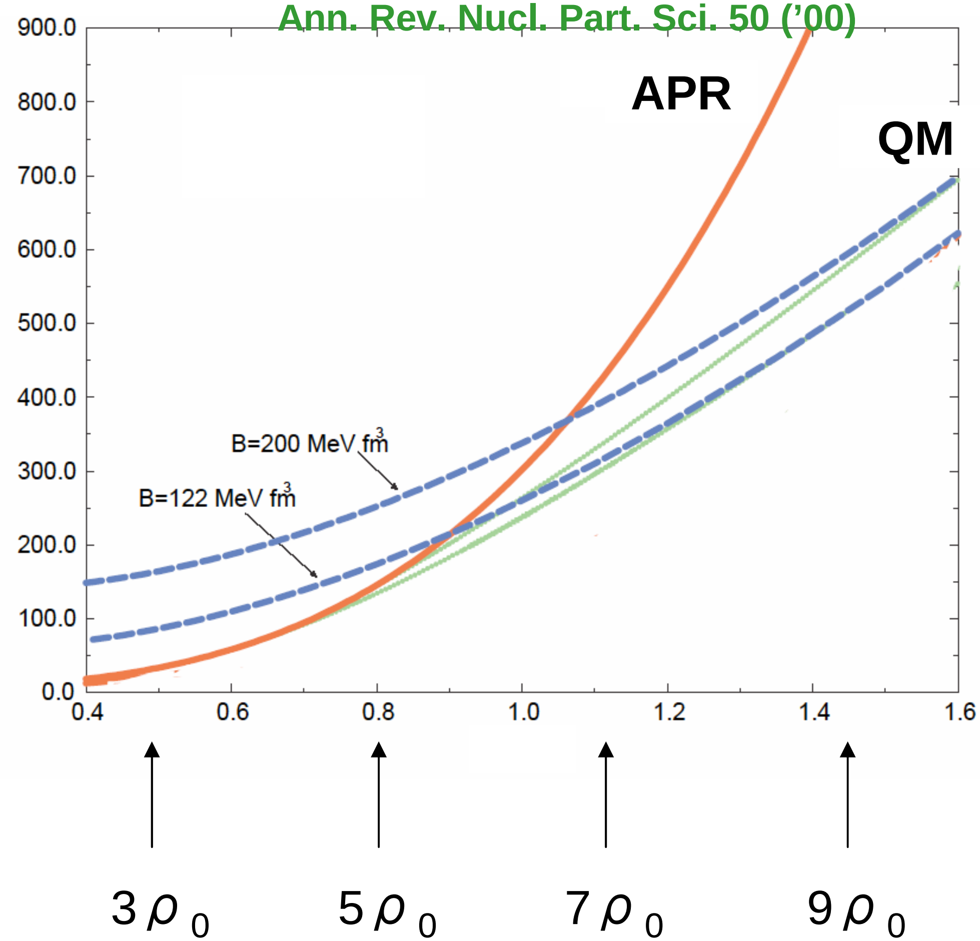
Neutron Star Structure



Quark matter : u, d, s, e^- with $d \rightleftarrows u + e^-$, $d \rightleftarrows u + e^-$, $s \rightleftarrows d$



Heiselberg & Pandharipande,
Ann. Rev. Nucl. Part. Sci. 50 ('00)

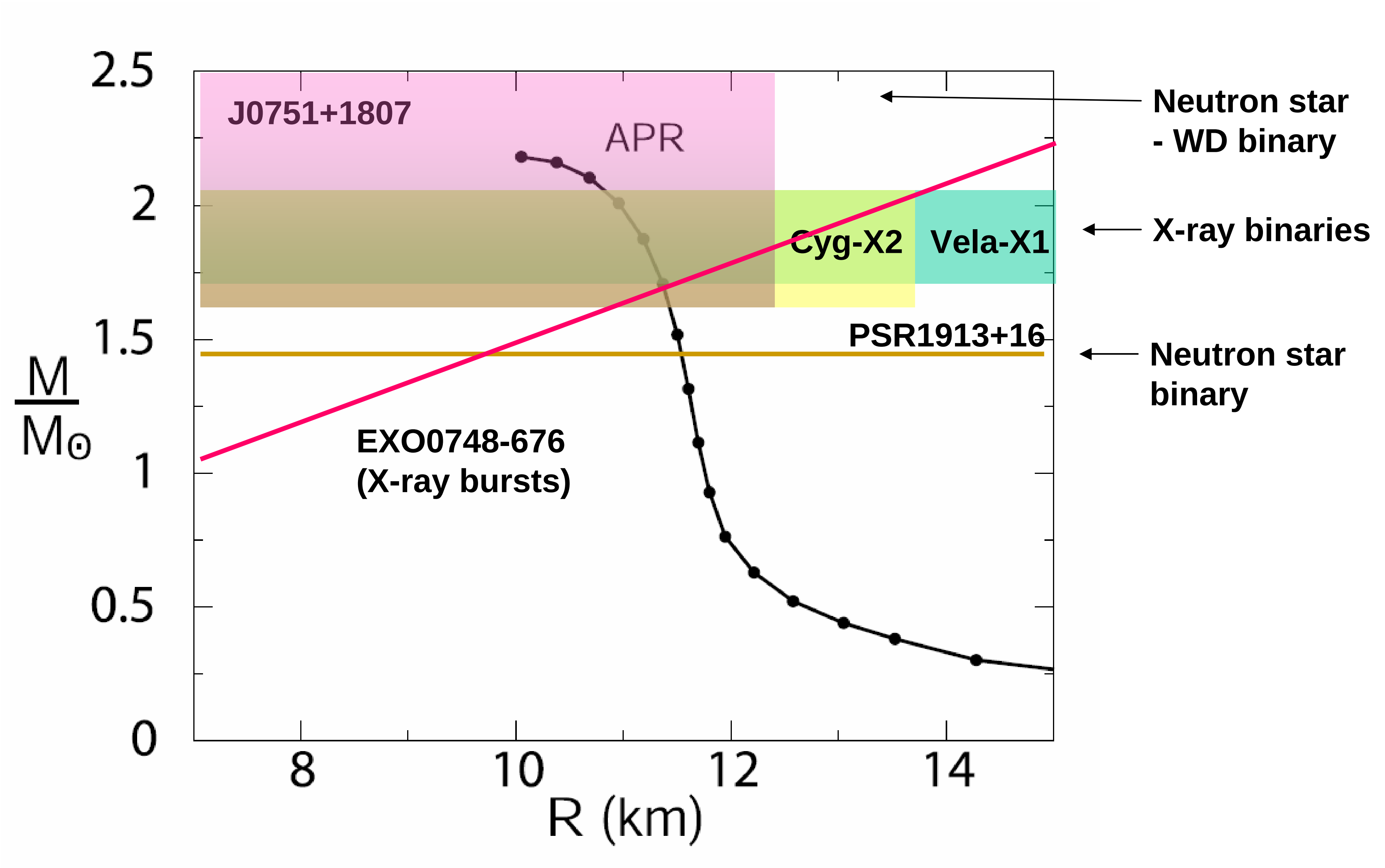


Remarks

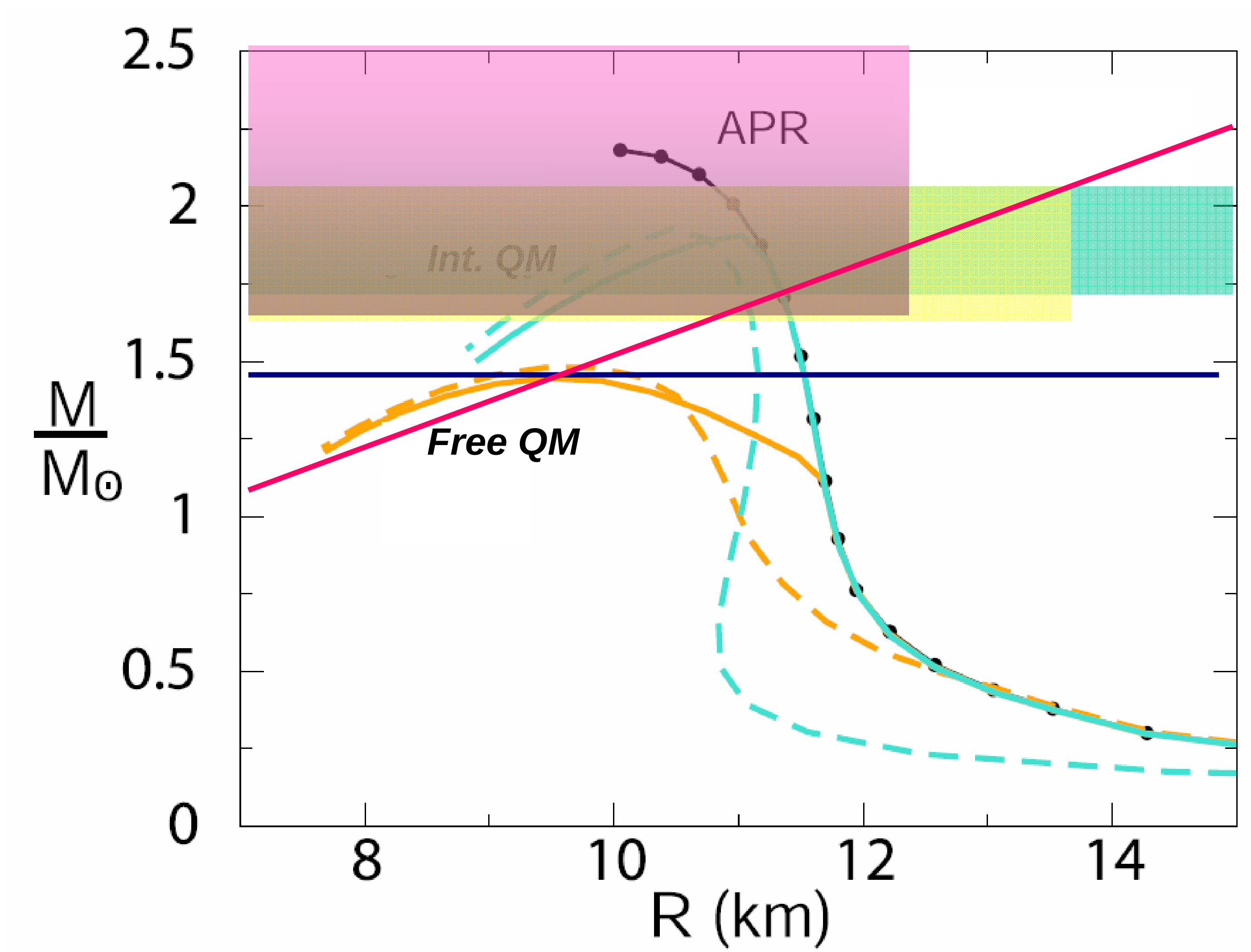
- Mixed phase may start even at ~ 3 ρ_0
- sensitive to quark matter EOS

M-R relation in APR EoS

($\rho_{max} \sim 6\rho_0$)



M-R relation in APR EoS + CFL quark matter



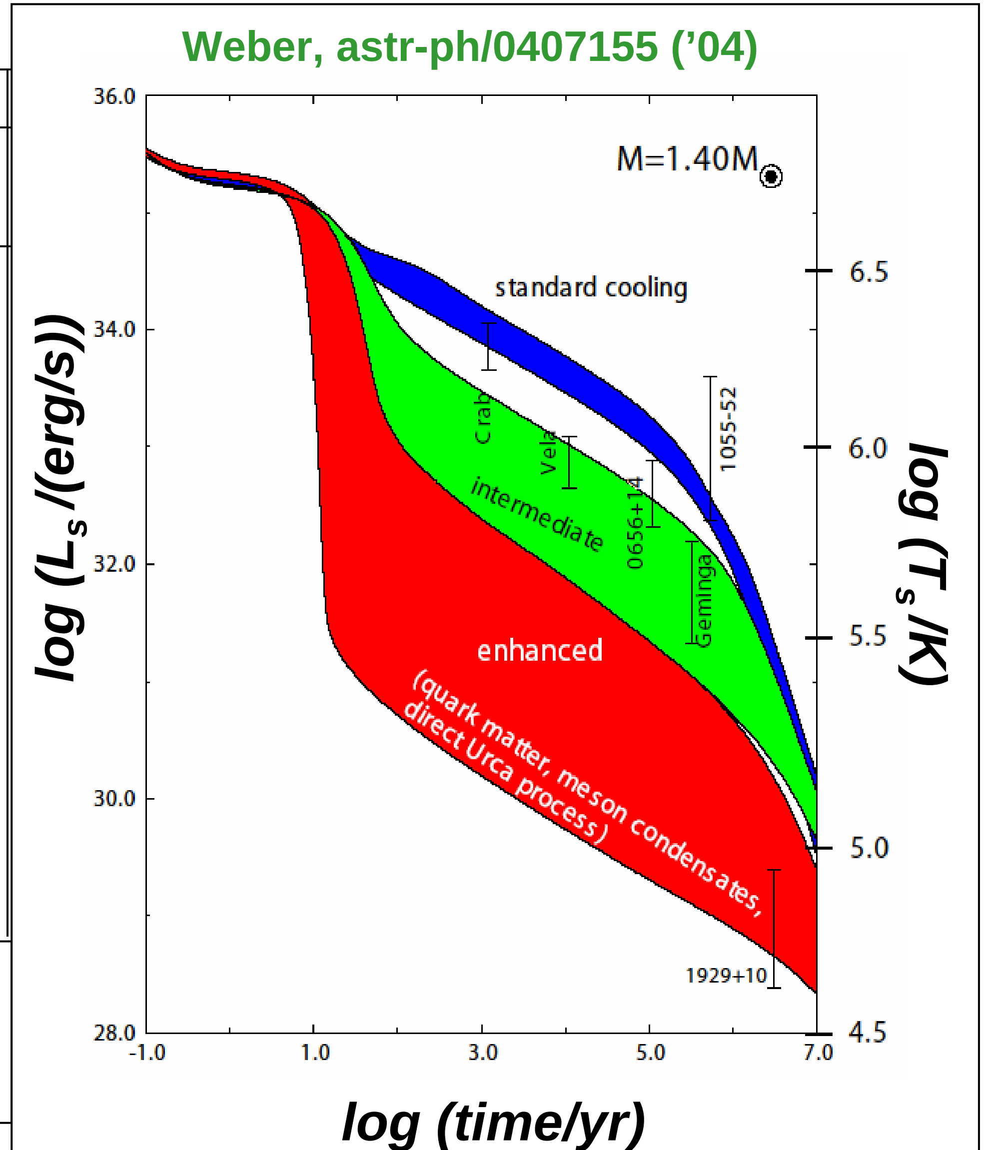
Alford, Braby, Paris & Reddy, ApJ 629 (2005)

Cooling of neutron stars

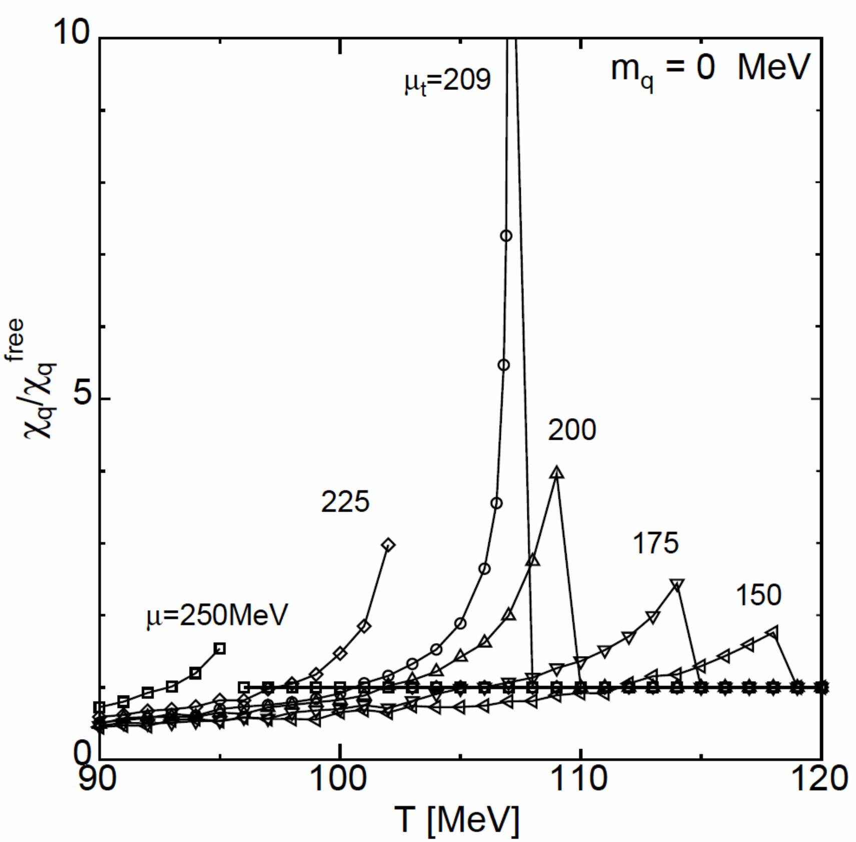
	Name	Processes	Emissivity
Standard	Modified Urca	$n+n\rightarrow n+p+e^-+\bar{\nu}_e$ $n+p+e^-\rightarrow n+n+\nu_e$	$\sim 10^{20}T_9^8$
	Direct Urca	$n\rightarrow p+e^-+\bar{\nu}_e$ $p+e^-\rightarrow n+\nu_e$	$\sim 10^{27}T_9^6$
Exotic	Quark modified Urca	$d+u+e^-\rightarrow d+d+\nu_e$ $u+u+e^-\rightarrow u+d+\nu_e$ $d+u+e^-\rightarrow d+s+\nu_e$ $u+u+e^-\rightarrow u+s+\nu_e$	$\sim 10^{20}T_9^8$
	Quark direct Urca	$d\rightarrow u+e^-+\bar{\nu}_e$ $u+e^-\rightarrow d+\nu_e$ $s\rightarrow u+e^-+\bar{\nu}_e$ $u+e^-\rightarrow s+\nu_e$	$\sim 10^{26}T_9^6$
	π^- condensate	$n+<\pi^->\rightarrow n+e^-+\bar{\nu}_e$	$\sim 10^{26}T_9^6$
	K^- condensate	$n+<K^->\rightarrow n+e^-+\bar{\nu}_e$	$\sim 10^{26}T_9^6$
quenching	***n superfluidity*** ***Q color super***	**exp(-Δ/T)**	

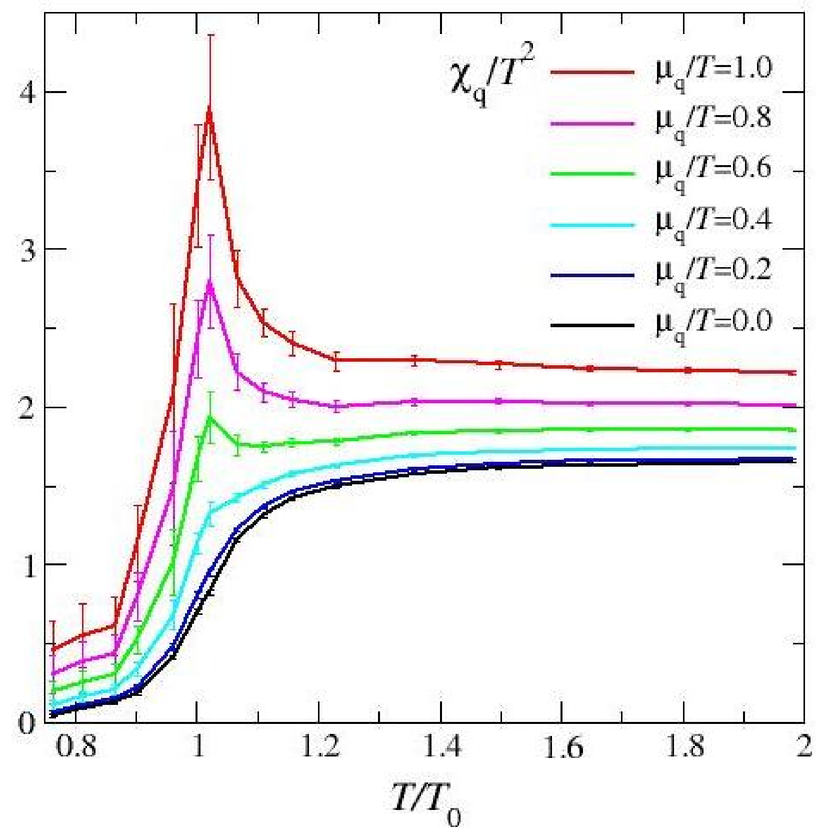
Cooling of neutron stars

	Name
Standard	Modified Urca
	Direct Urca
Exotic	Quark modified Urca
	Quark direct Urca
	π^- condensate
	K^- condensate
quenching	***n superfluidity***
	Q color super



Quark number susceptibility





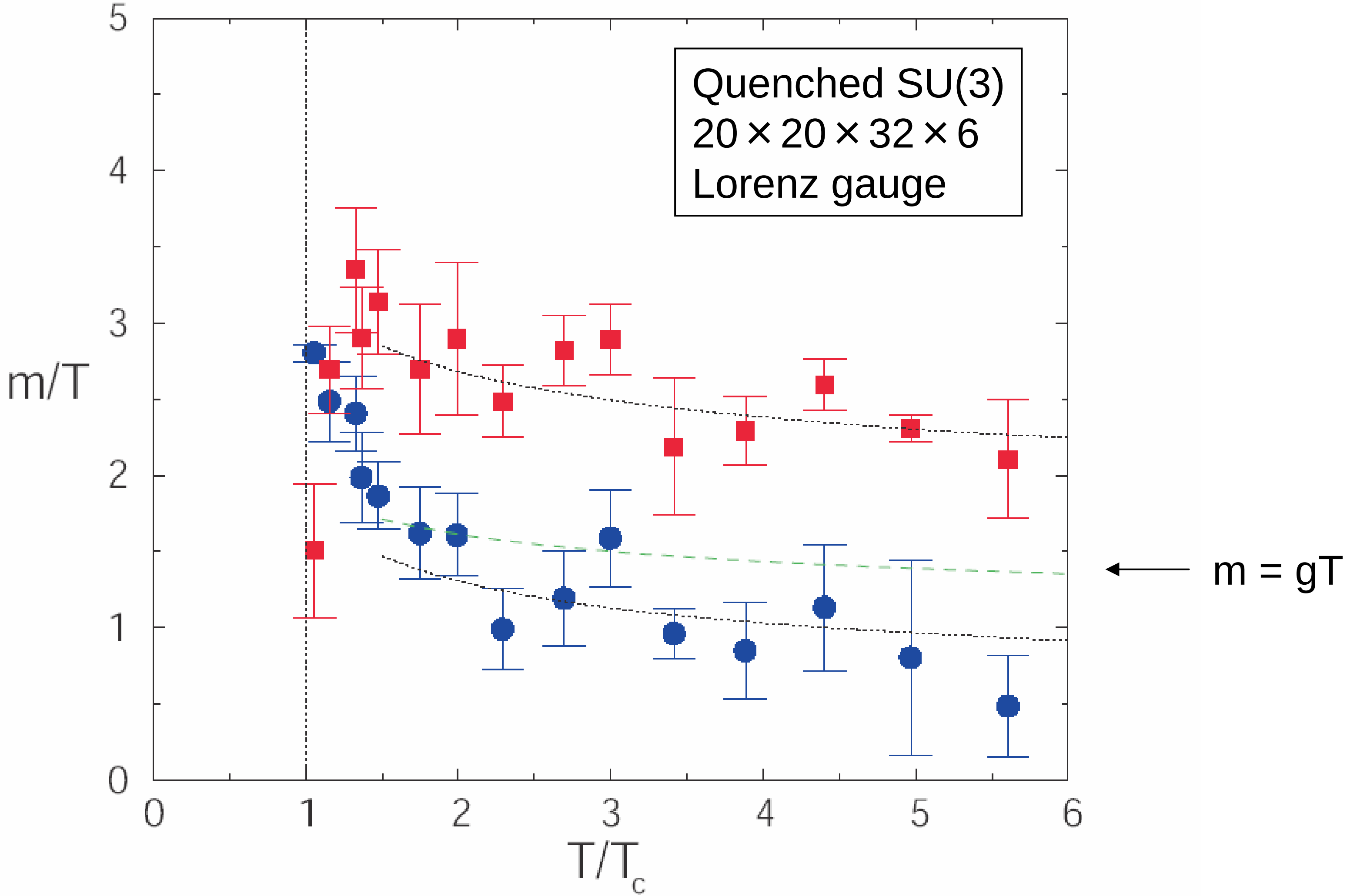
$$\frac{\chi_q}{T^4}(\mu_q) = +2c_2 + 12c_4\left(\frac{\mu_q}{T}\right)^2 + O\left(\mu_q^4\right)$$

Kunihiro, Phys. Lett. B271 ('92) 395
Hatta-Ikeda, Phys.Rev.D67 ('03) 014028

Ejiri et al. (Bielefeld-Swansea Coll.)

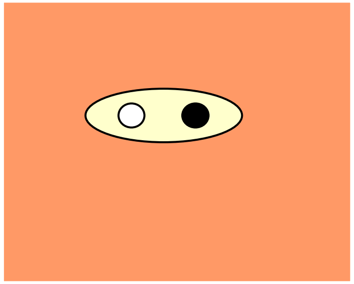
Screening masses at T>T_c on the lattice

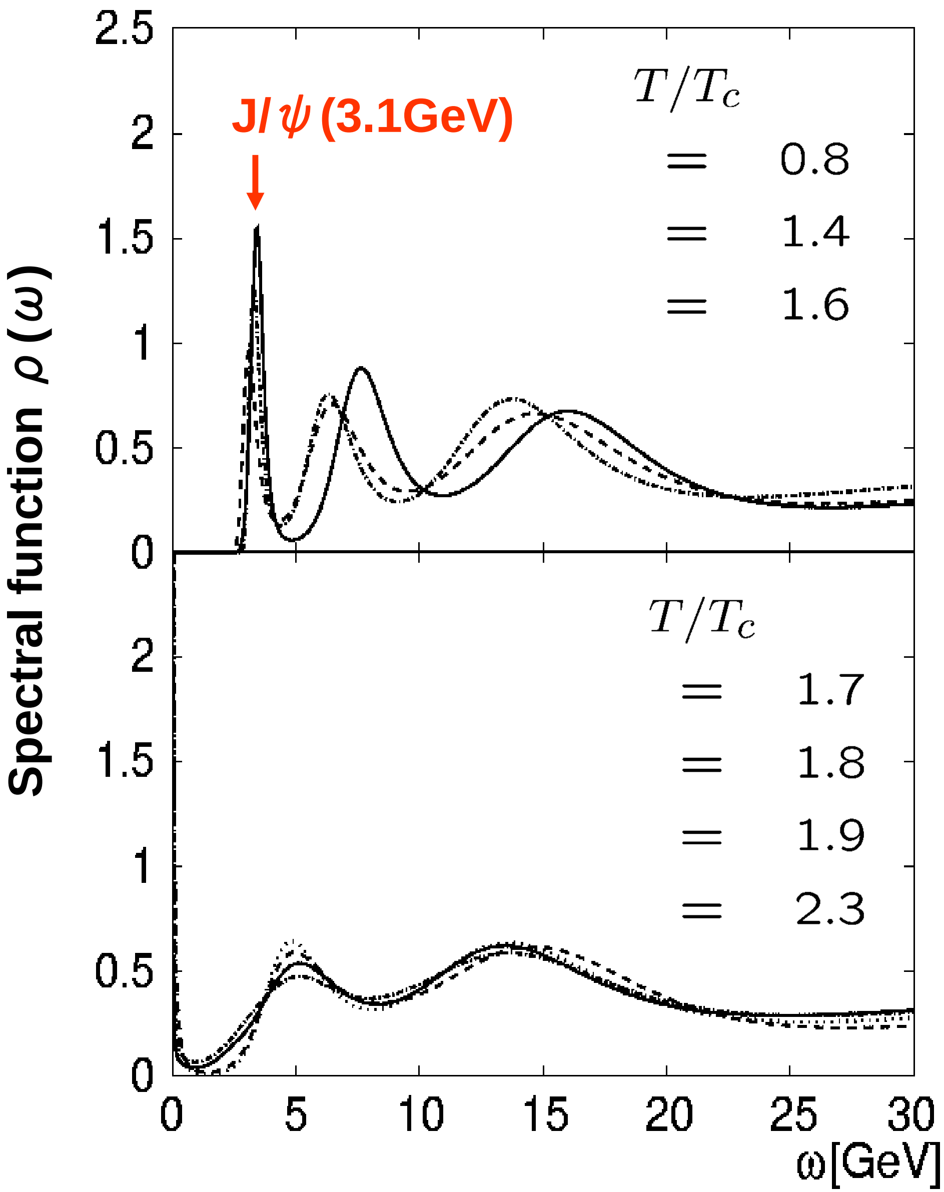
$$\langle A_\mu(\mathbf{x}) A_\nu(\mathbf{0}) \rangle \sim e^{-m|\mathbf{x}|}$$



Nakamura, Saito & Sakai, Phys.Rev.D69 ('04) 014506

$c\bar{c}$ bound state above T_c (quenched)





1. J/ψ survives up to 1.6 T_c

2. J/ψ disappears in 1.6 T_c < T < 1.7 T_c

Asakawa & T.H., PRL 92 ('04) 012001

see also,
Umeda et al, hep-lat/0401010
Datta et al., PRD 69 ('04) 094507