QCD phase diagram in heavy-ion collisions and compact stars

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Colloquium @ Nagoya University, Dec. 6, 2011

- **Introduction: QCD phase diagram**
- **Phase diagram study in HIC and compact stars**
  - **Phase transition at small densities**
  - **Critical point search**
  - **Phase structure in dense matter**
- **Recent progress in strong coupling lattice QCD**
- **Summary**

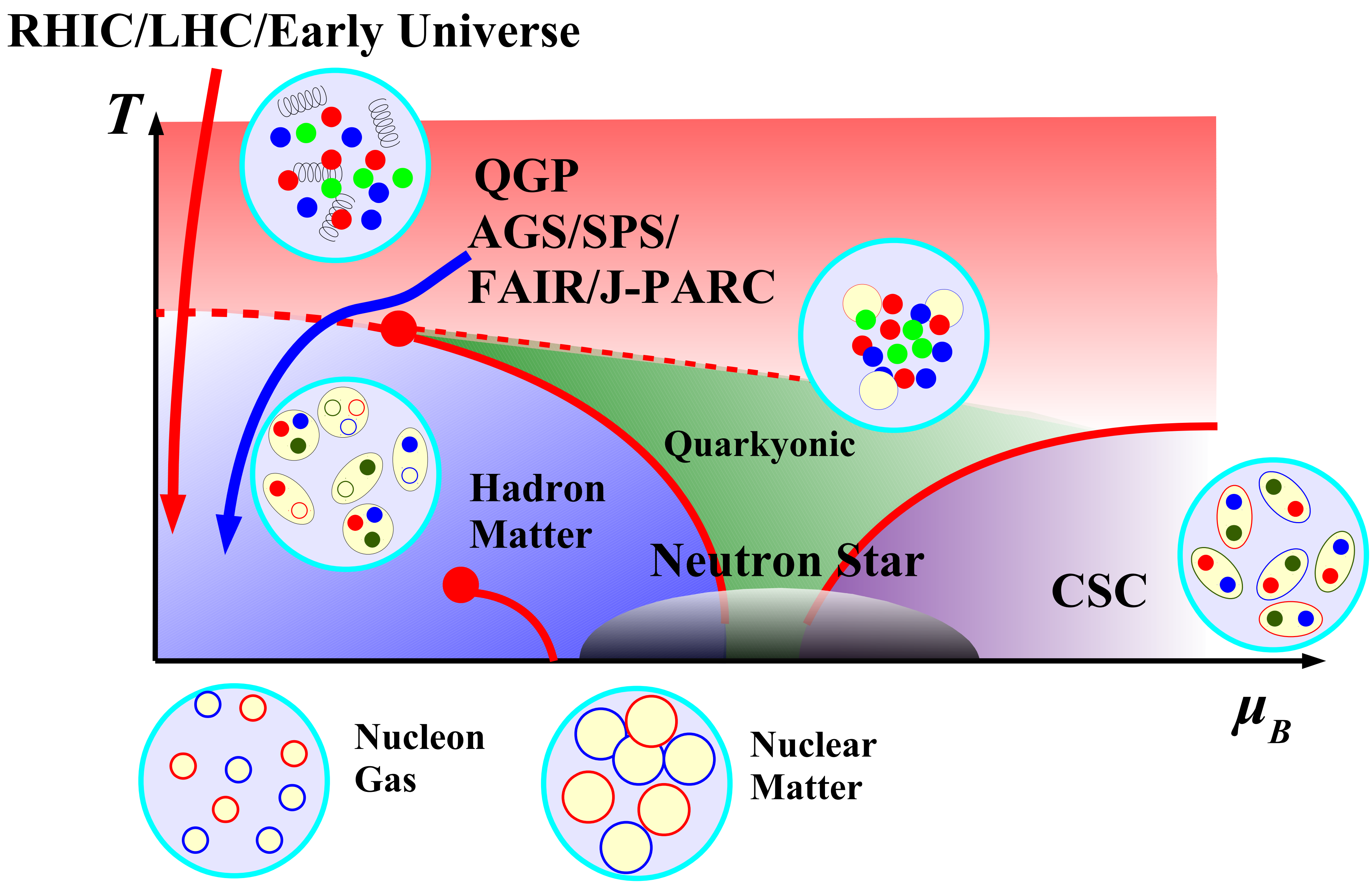
AO, Proc. ISMD 2011, arXiv:1112.XXXX

Abstract

QCD phase transition from hadronic to quark-gluon matter is attracting much attention in recent years. High-energy heavy-ion experiments at RHIC and LHC have shown the formation of strongly interacting matter with very high energy density. Theoretical arguments and experimental data suggest that this matter is a strongly coupled quark-gluon plasma (sQGP) at small baryon density. Lower energy heavy-ion experiments at RHIC and SPS are expected to probe higher baryon density region, where we may find the QCD critical point, which connects the cross over transition at low density and the first order transition at high density. The transition to quark matter at high density also has an impact on compact astrophysical phenomena, such as neutron stars, supernovae, and black hole formation processes.

In this talk, I review our current understanding of the QCD phase diagram in lattice QCD and QCD effective models in connection with experimental observations. I also discuss recent theoretical attempts to describe QCD phase transition at high density in terms of strong coupling lattice QCD.

QCD Phase Diagram

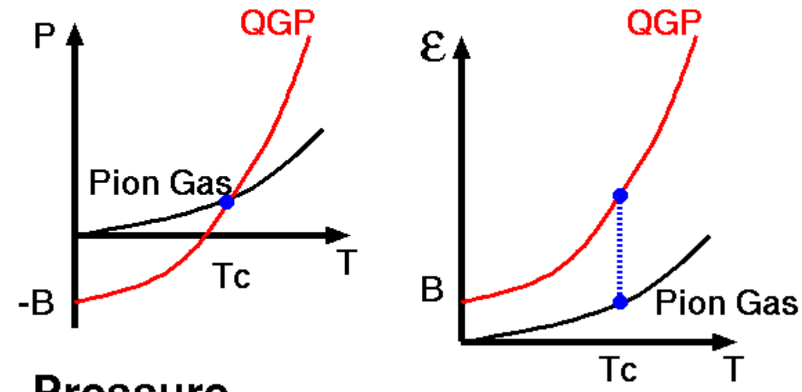


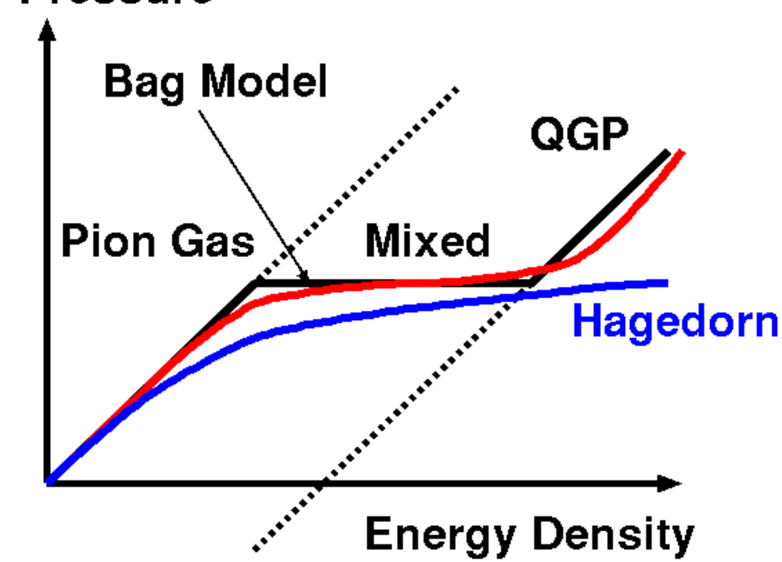
Why does QCD phase transition take place?

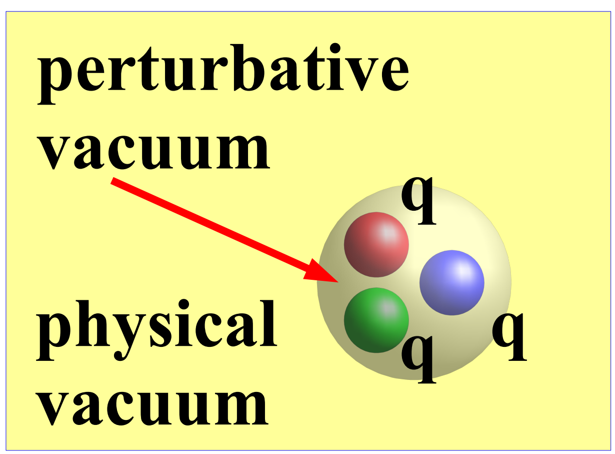
- **Fundamental dof in QCD = Quarks & Gluons**
  "Elementary particle" in our world = Nucleons + electrons
- **Bag model EOS**
  - **dof change from hadrons to q & g**
  - **Free pion gas → Free q & g gas**

$$P_H = 3\,P_{SB}\,,\quad P_{QGP} = 37\,P_{SB} - B$$
$$\rightarrow\quad T_c = (45\,B / 17\,\pi^2)^{1/4} \sim 0.72\,B^{1/4}$$
$$\sim (105\text{-}220)\ \mathrm{MeV}$$

  - $P_{SB} = \pi^2 T^4 / 90$ **(Stephan-Boltzmann)**
  - $B^{1/4}$**=(Bag constant)**$^{1/4} \sim$ **(145-300) MeV**







Why does QCD phase transition take place?

- **Energy gain from Spontaneous chiral Symmetry Breaking (χSSB)**
  - **Fermion contribution to free energy density ~ - log (fermion det.)**

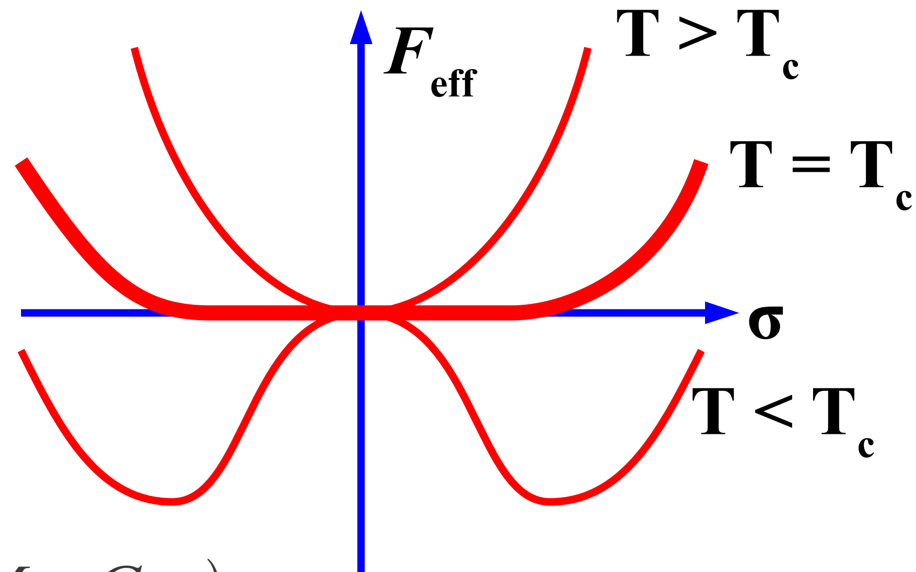
$$F_{\rm eff}^{(F)} = -\frac{d_f}{2}\int \frac{d^3k}{(2\pi)^3}\left[\underbrace{E^*}_{\text{Zero E.}} + \underbrace{T\log\left(1+e^{-(E^*-\mu^*)/T}\right)}_{\text{particle}} + \underbrace{T\log\left(1+e^{-(E^*+\mu^*)/T}\right)}_{\text{anti particle}}\right]$$

$$= d_f\left[-P_{SB}^F - \frac{M^2\Lambda^2}{16\pi^2} + \frac{M^2\mu^2}{16\pi^2} + \frac{M^2T^2}{48}\right] + \text{const.} + O(M^4)$$

  - **With quark mass ∝ σ, and with quadratic σ contribution, 2nd order transition can take place at finite T and/or μ,**

$$F_{\rm eff} = F_{\rm eff}^{(F)} + \frac{1}{2}m_0^2\sigma^2$$

$$\to T^2 + \frac{\mu_B^2}{3\pi^2} = T_c^2 \quad \left(T_c^2 = \frac{3\Lambda^2}{\pi^2} - \frac{24m_0^2}{G^2},\ M = G\sigma\right)$$



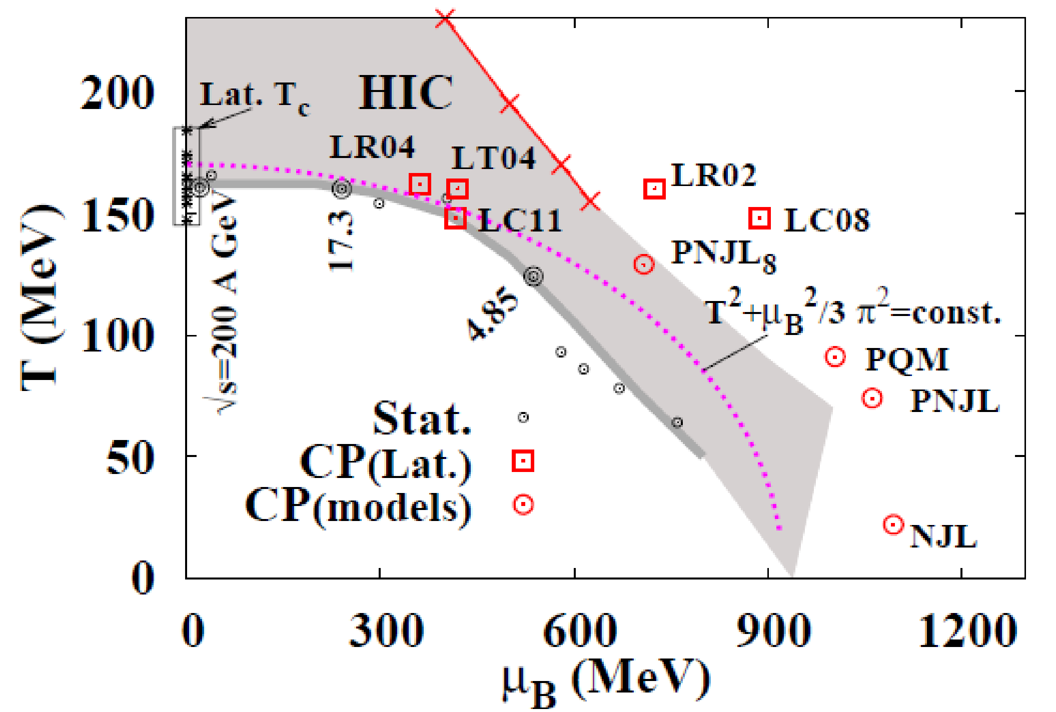
Why does QCD phase transition take place?

- **Simple guess of μ_c from T_c.**

$$\mu_c(T=0) \simeq \sqrt{3\pi^2}\, T_c(\mu=0) \simeq 5.44\, T_c(\mu=0)$$

Tc=170 MeV → μc ~ 925 MeV

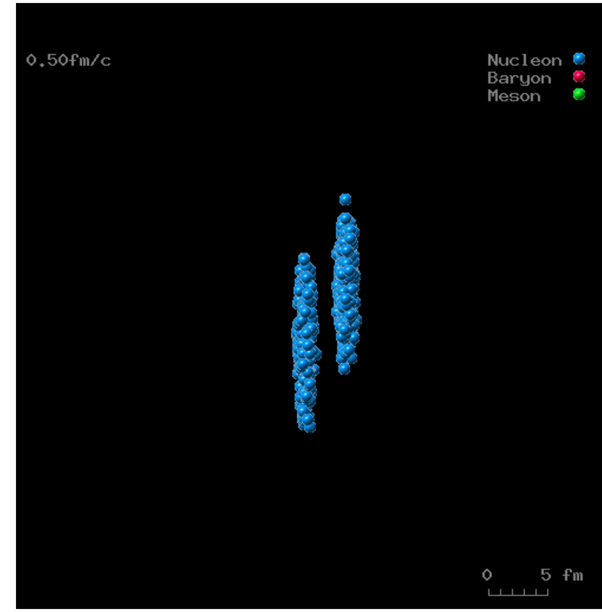
- **Simple models based on deconfinement / chiral transition predict QCD phase transition at T_c ~ (100-200) MeV, $\mu_c \sim M_N$**
  - **How to observe the phase transition ?**
  - **How can we observe the phase transition at high density ?**
  - **How can we fix the position of CP ?**



We need data on
hot and/or dense matter
→ High Energy
Heavy-Ion Collisions

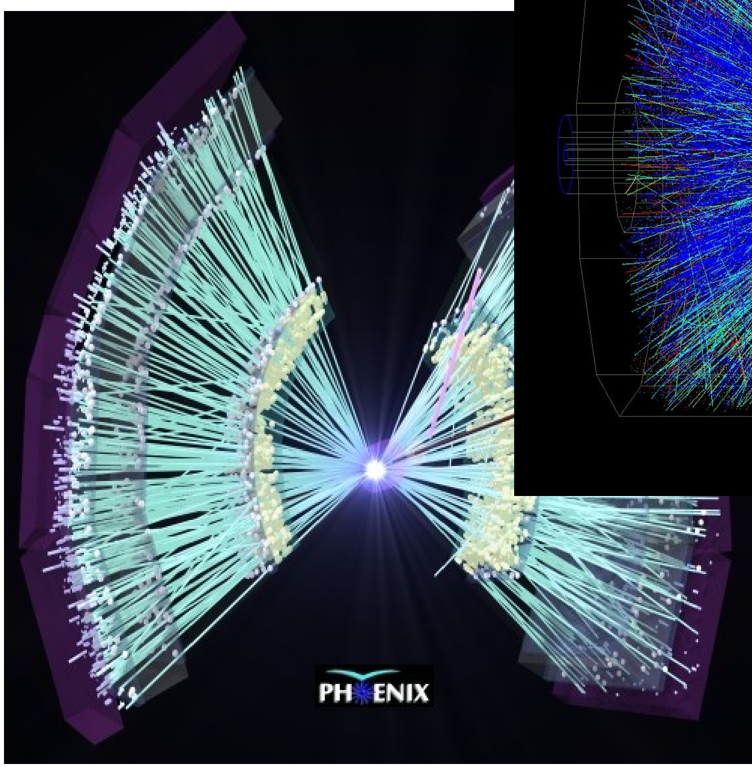
High-Energy Heavy-Ion Collisions

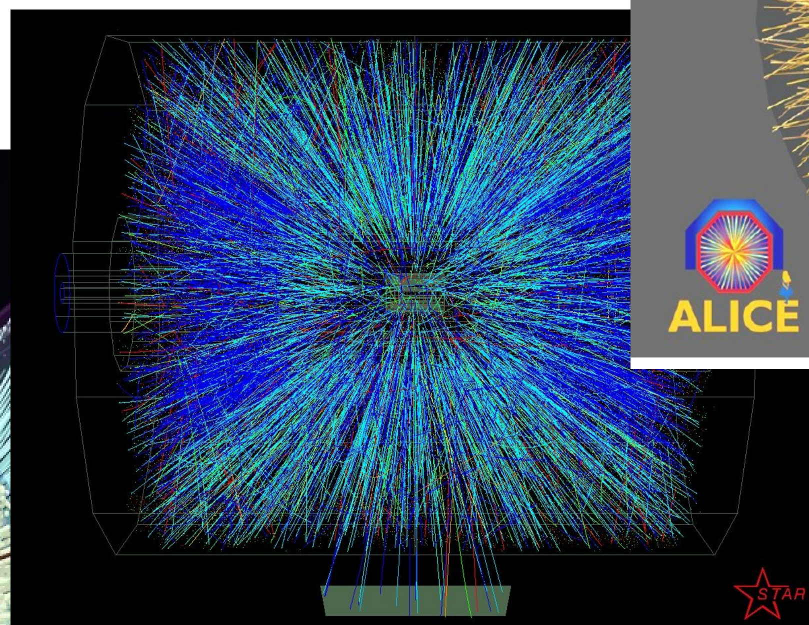
- **Nuclear physicists wanted to make QGPfor a long time....**
  - **Bevalac: ~ 800 A MeV**
  - **AGS: 10.6 A GeV ($\sqrt{s_{NN}}$ ~ 5 GeV)**
  - **SPS: 158 A GeV ($\sqrt{s_{NN}}$ ~ 17 GeV)**
  - **RHIC: 100 + 100 A GeV ($\sqrt{s_{NN}}$ ~ 200 GeV)**
  - **LHC: $\sqrt{s_{NN}}$ = 2.76 TeV**
    (Design energy: 7+7 TeV for p+p)

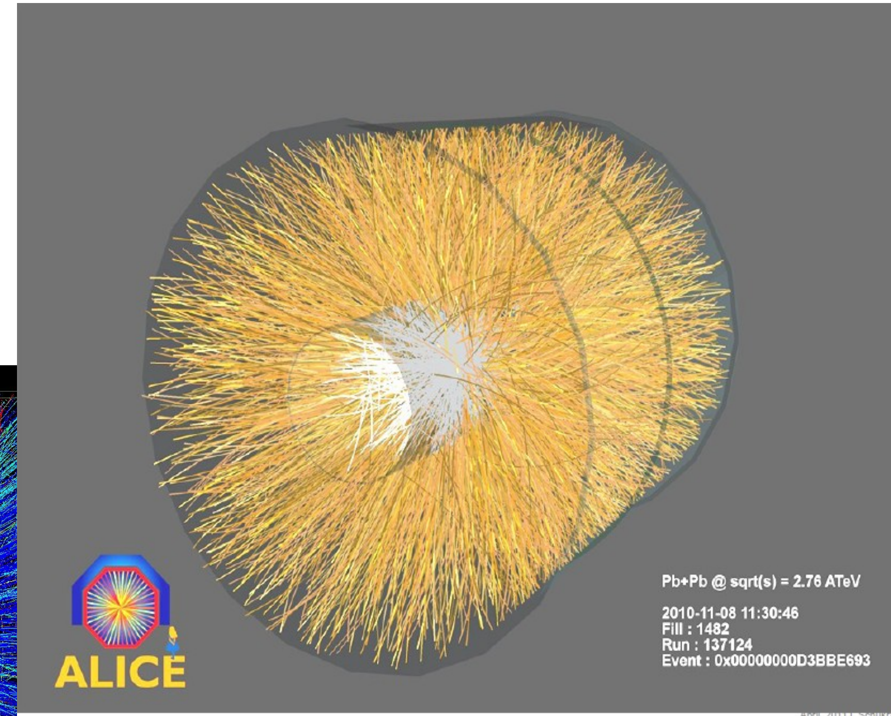


Formation experiments of QGP in laboartory = Little Bang

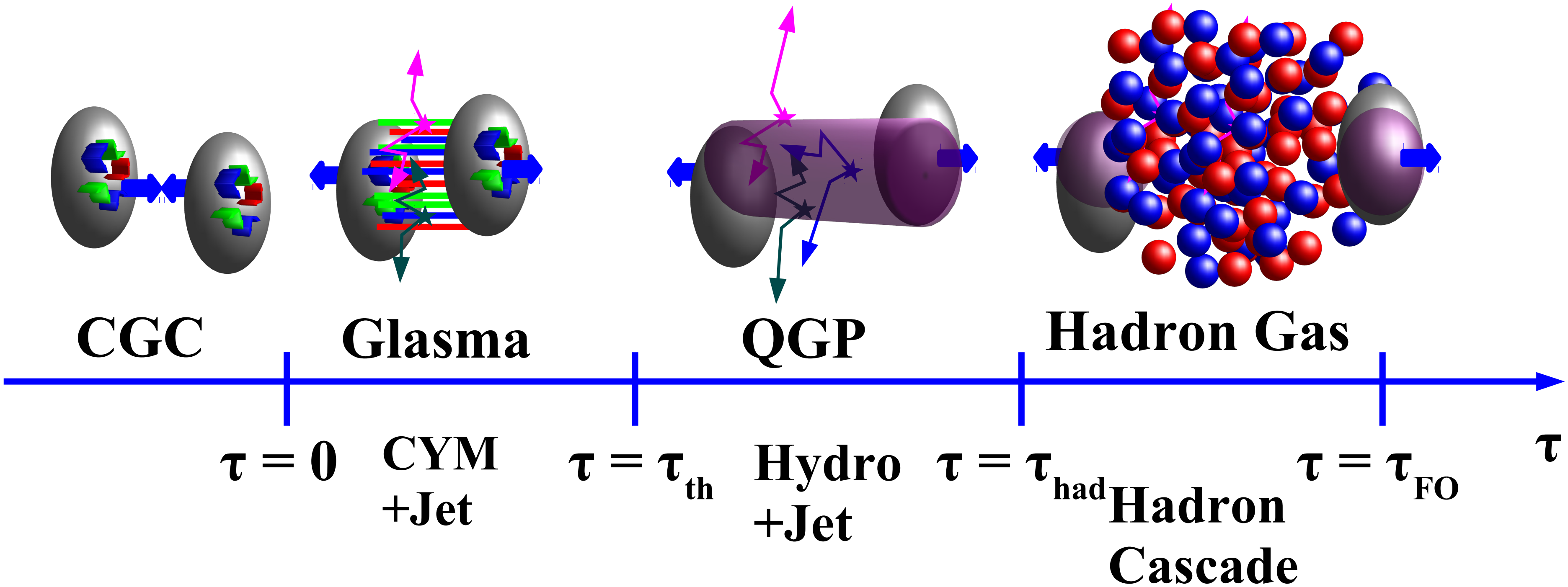
Actual view of collisions....





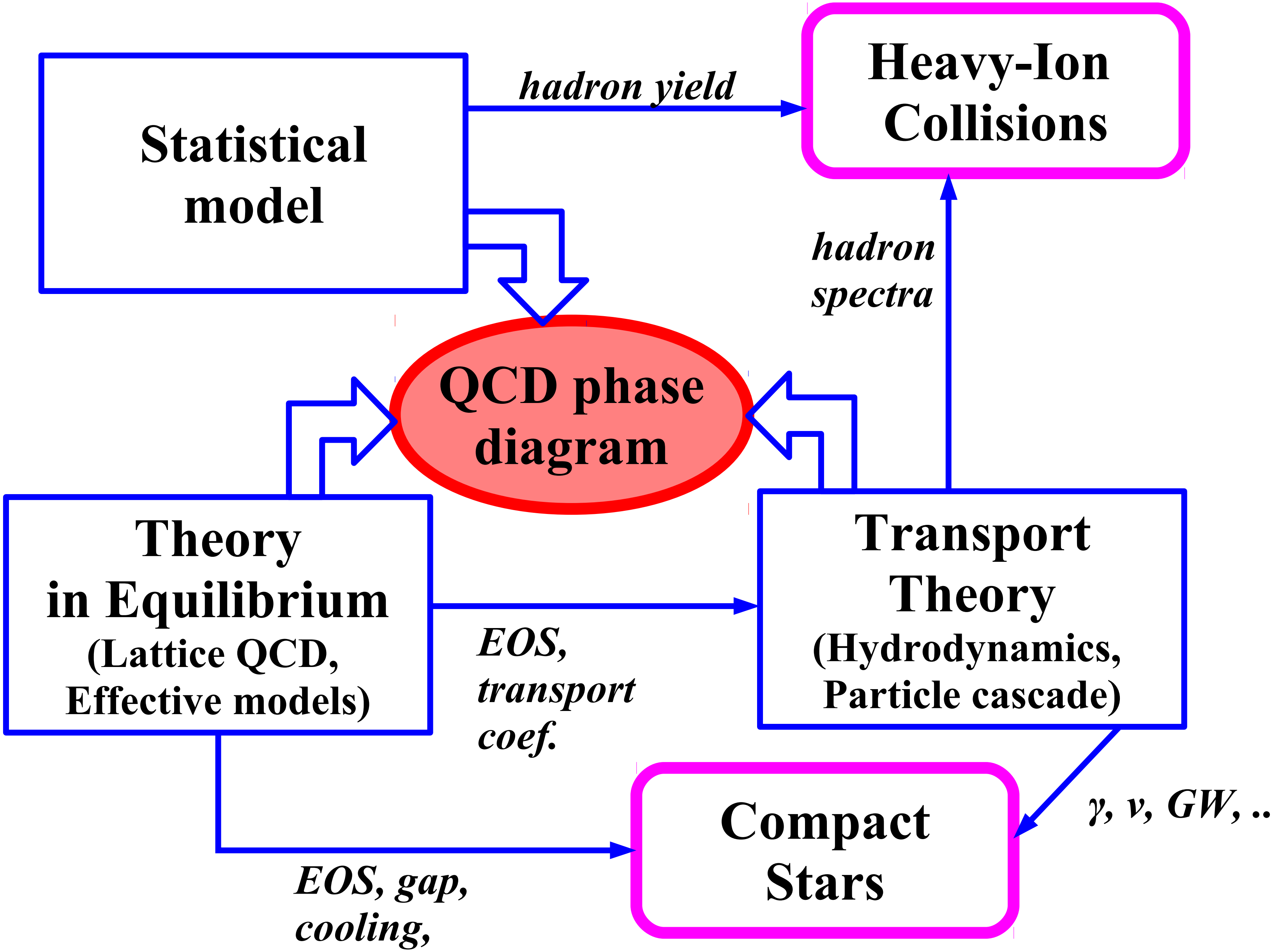


High Energy Heavy-Ion Collisions

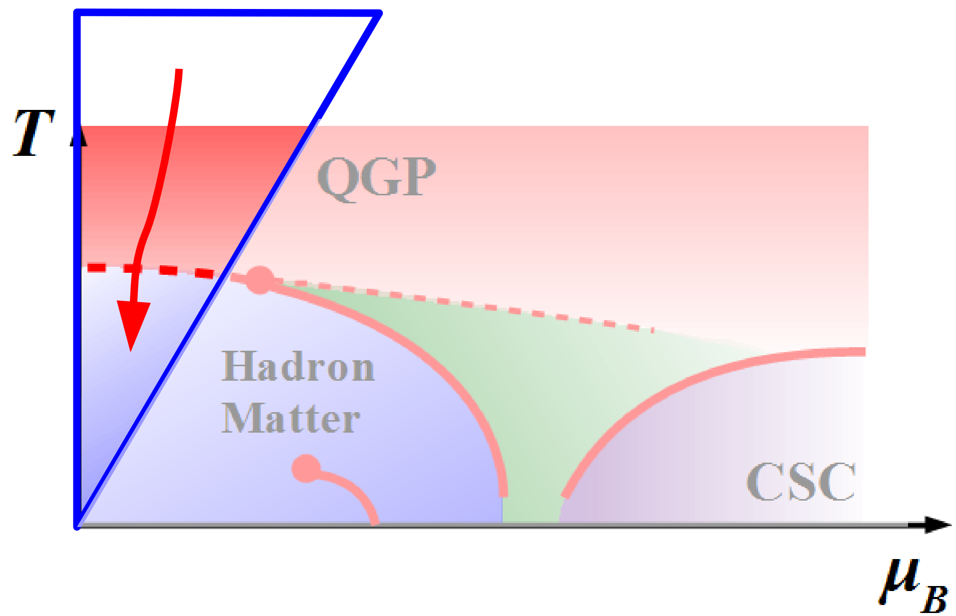


- **Initial condition: Color Glass Condensate or Hadron Gas**
- **Preequilibrium Stage: Glasma (CYM + Jet + ?)**
- **Quark Gluon Plasma (QGP): Hydro + Jet**
- **Hadron Gas: Hadron Cascade**

Sites and Tools for QCD phase diagram

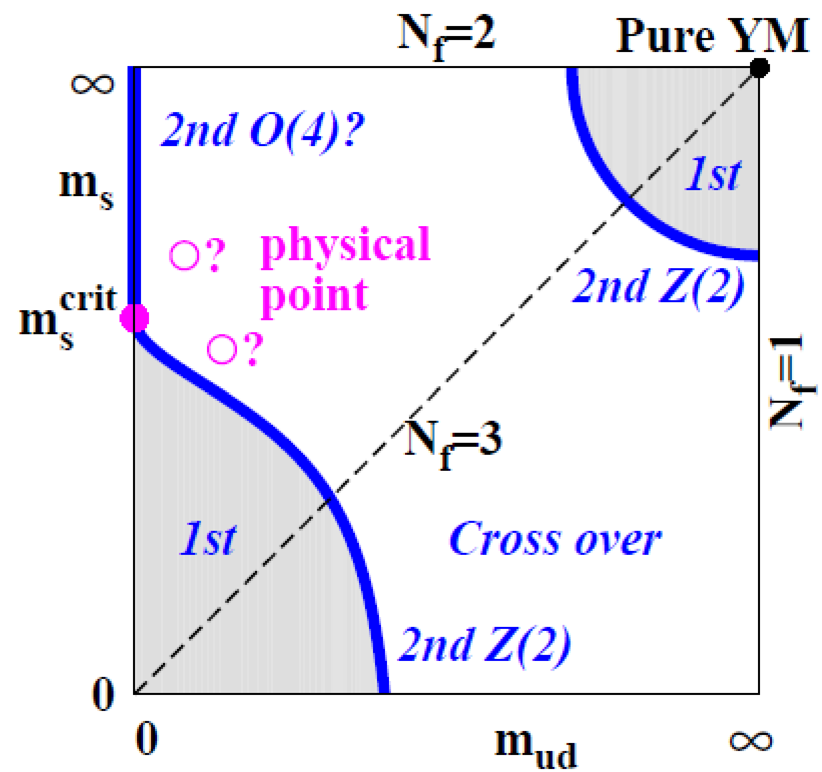


High Temperature Phase Transition



Order and Critical Temperature in Lattice QCD

- **Order of the phase transition depends on the quark masses**
  - **N_f=0: 1st order (No light quarks)**
  - **N_f=1: cross over**
  - **N_f=2: 2nd order (~ 3d O(4) ising)**
  - **N_f=3: 1st order (σ^3 from det. int.)**



- **Order of the phase transition at μ=0 → Cross over at physical point**

  E.g. Y. Aoki et al., Nature 443('06) 675

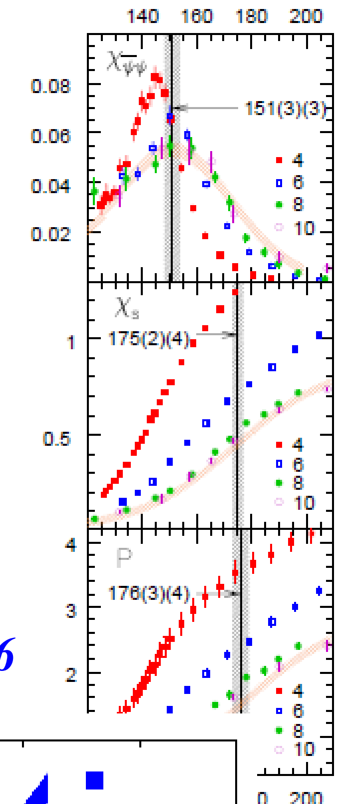
- **Scaling at $m_{u,d} \to 0$: 2nd or 1st ?**

  Kaczmarek et al., PRD83('11)014504 (scaling behavior at $m_{ud} \to 0$, i.e. $m_s > m_s^{crit}$);

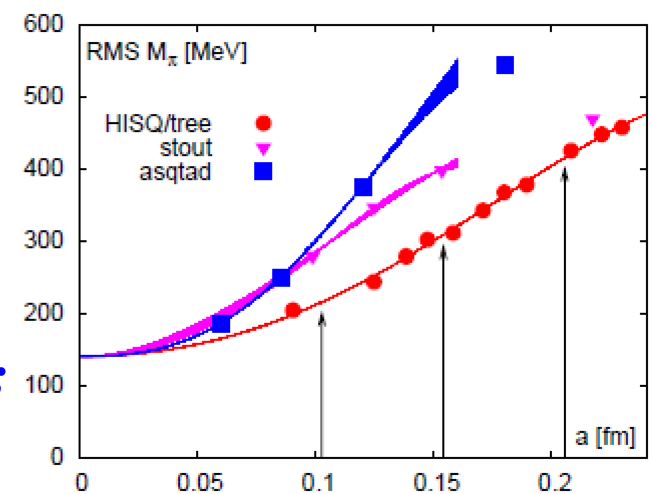
  de Forcrand, Philipsen, PoS(LAT08)208 ($m_s < m_s^{crit}$).

Order and Critical Temperature in Lattice QCD

- **Tc value from lattice QCD: Tc=(145-185) MeV**
  K. Kanaya, PoS LATTICE2010 ('10) 012
- **Staggered Fermion: Tc=(145-165) MeV**
  - **stout: Tc(χ_σ)=151(3)(3) MeV**
    Y. Aoki, Z. Fodor, S. D. Katz, K. K. Szabo,
    Phys. Lett. B 643 (2006) 46 (Budapest, Wuppertal).
  - **asqtad (+HISQ/tree): Tc(O(N))=157 ± 6 MeV**
    A. Bazavov et al. [HotQCD Collaboration],
    J. Phys. G 38 (2011) 124099.
  - **Previous HotQCD result: Tc= 192 MeV**
    M. Cheng et al., Phys. Rev. D 77 (2008) 014511.
    Problem = "Heavy" pion contamination.
- **Other Fermions: Tc=160-184 MeV**
  DW(2+1): Cheng et al. (DW,2+1, HotQCD)0911.3450;
  Wilson(N_F=2): Bornyakov (QCDSF-DIK) 0910.2392;
  Ejiri et al. (WHOT) 0909.2121.



Aoki et al. (BW) 2006



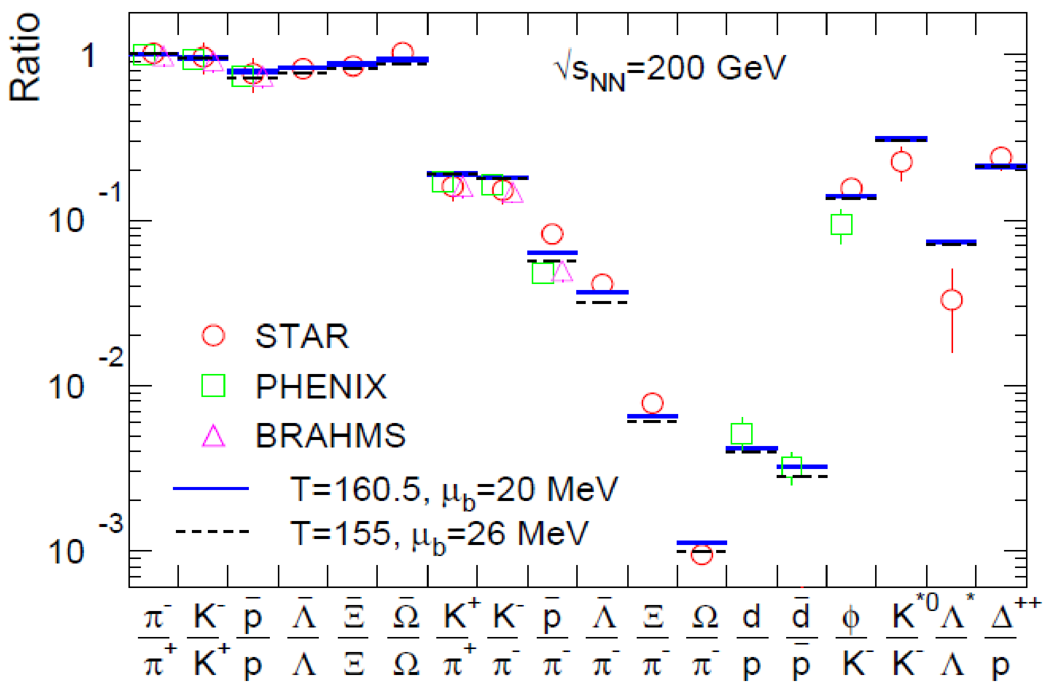
A. Bazavov, et al., 1111.1710 [hep-lat]

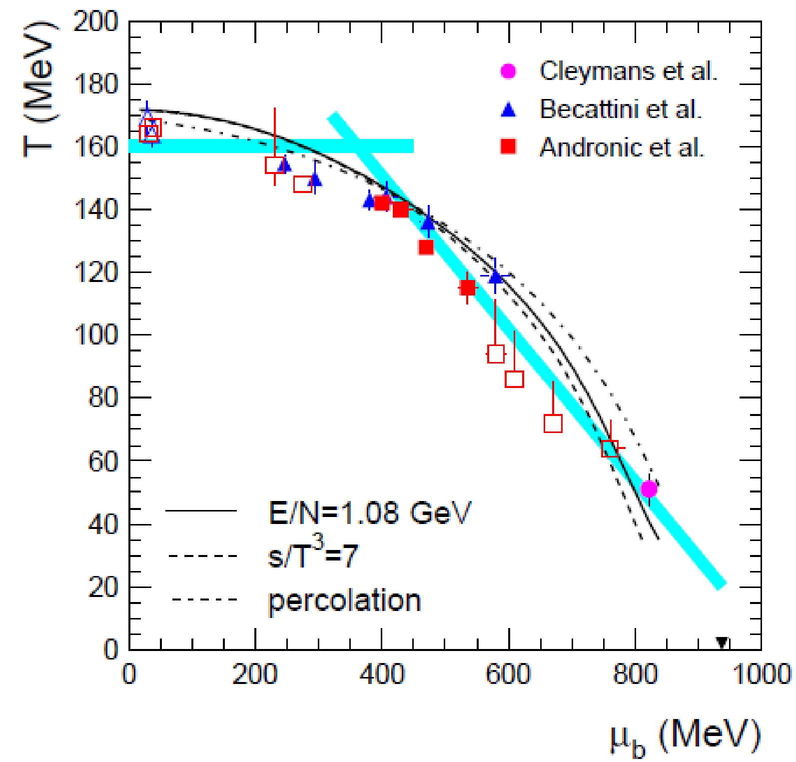
Statistical Model

- **Statistical model**

$$N_h^{stat} = V_H \frac{g_h}{2\pi^2} \int_0^\infty \frac{p^2\,dp}{\gamma_h^{-1} \exp(E_h/T_H) \pm 1} \quad (\gamma_h : \text{fugacity})$$

  - **Successful explanation of hadron yields at RHIC**
  - **Chem. Freeze-out line may reflect the phase boundary**

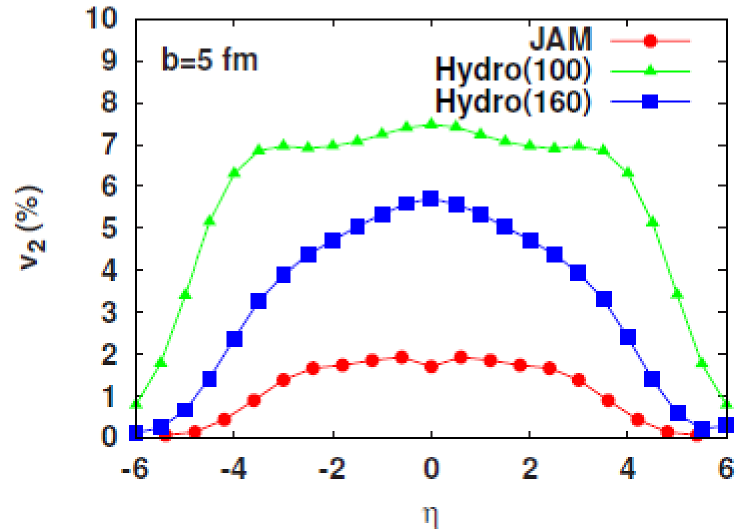




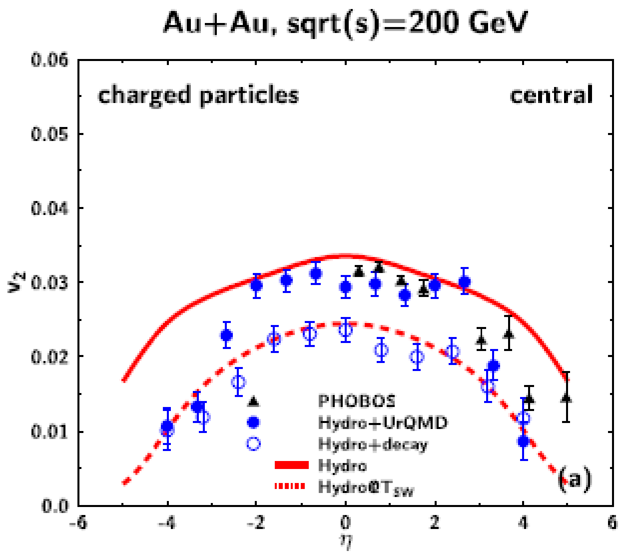
A. Andronic, P. Braun-Munzinger, J. Stachel, NPA772('06)167.

Elliptic flow at RHIC

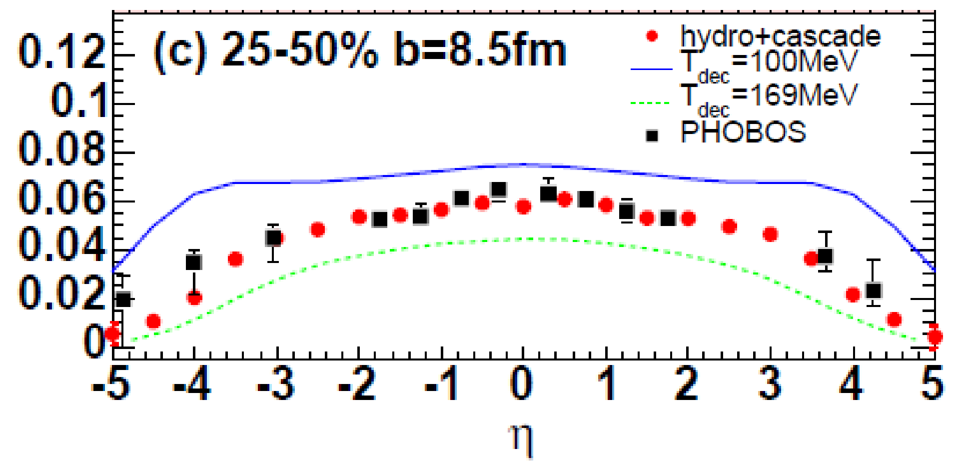
- Chemical freeze-out temperature (T_{CFO}) and critical temperature (Tc) are close.
  - Why are they close ?
    Is it consistent with other data ?
  - Hydro+Cascade results: T_{sw} = Tc – ε
  - Elastic scat. dominate in hadronic phase, and particle ratio does not change very much.



T.Hirano, M.Isse, Y.Nara, A.Ohnishi, K.Yoshino, PRC72('05)041901(R)



C.Nonaka, S.A.Bass, PRC75 ('07) 014902

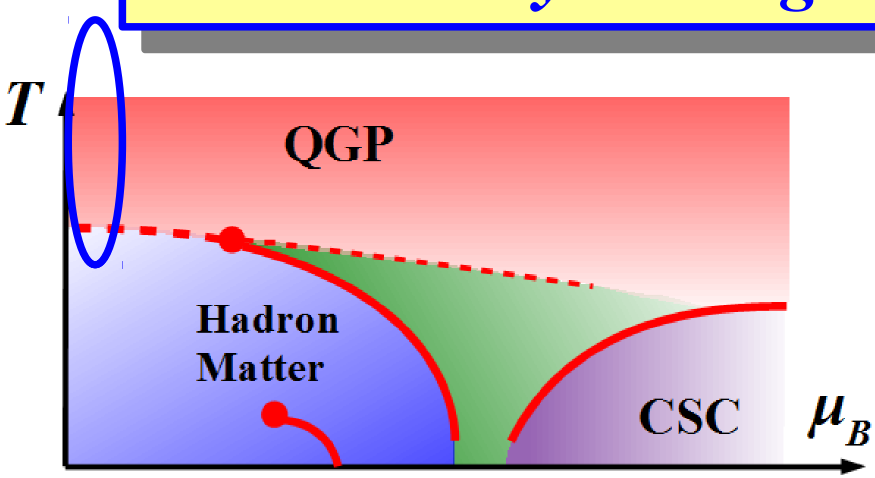


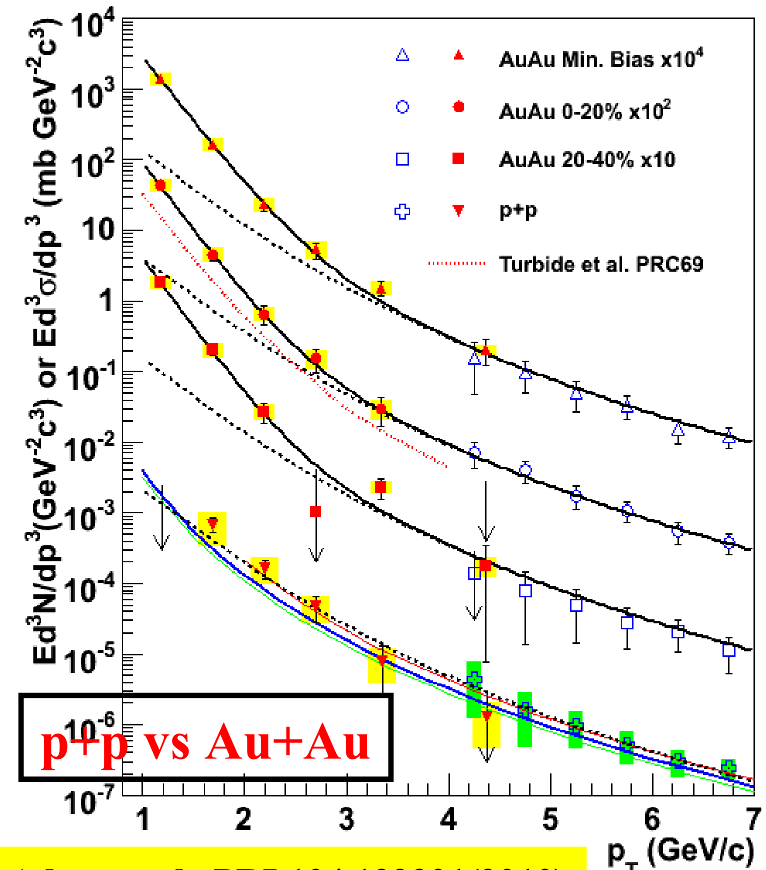
T.Hirano, U.W.Heinz, D.Kharzeev, R.Lacey, Y. Nara, PLB636('06)299

Can we measure QGP temperature ?

- **Temperature measured via hadrons < Tc**
  → How can we measure QGP temperature ?
- **Direct photon spectrum in Au+Au at RHIC**
  - **Significant excess in p_T<3GeV/c**
  - **Exponential fit (Central): T = 221 MeV**
  - **Initial temperature: T_i =(300-600) MeV (depending on thermalization time)**

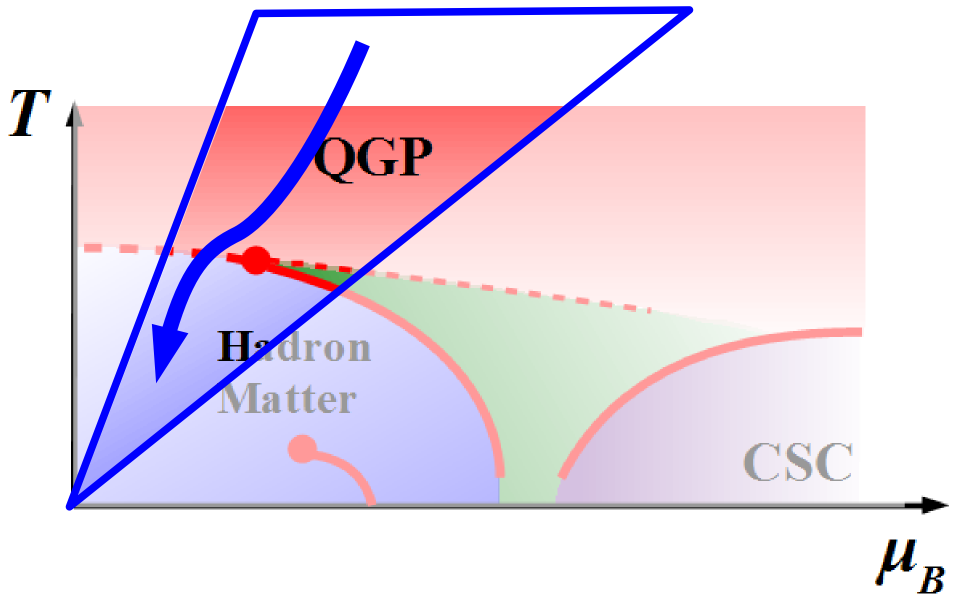
T_{photon}, T_i > T_c (LQCD)
We are really looking at QGP !





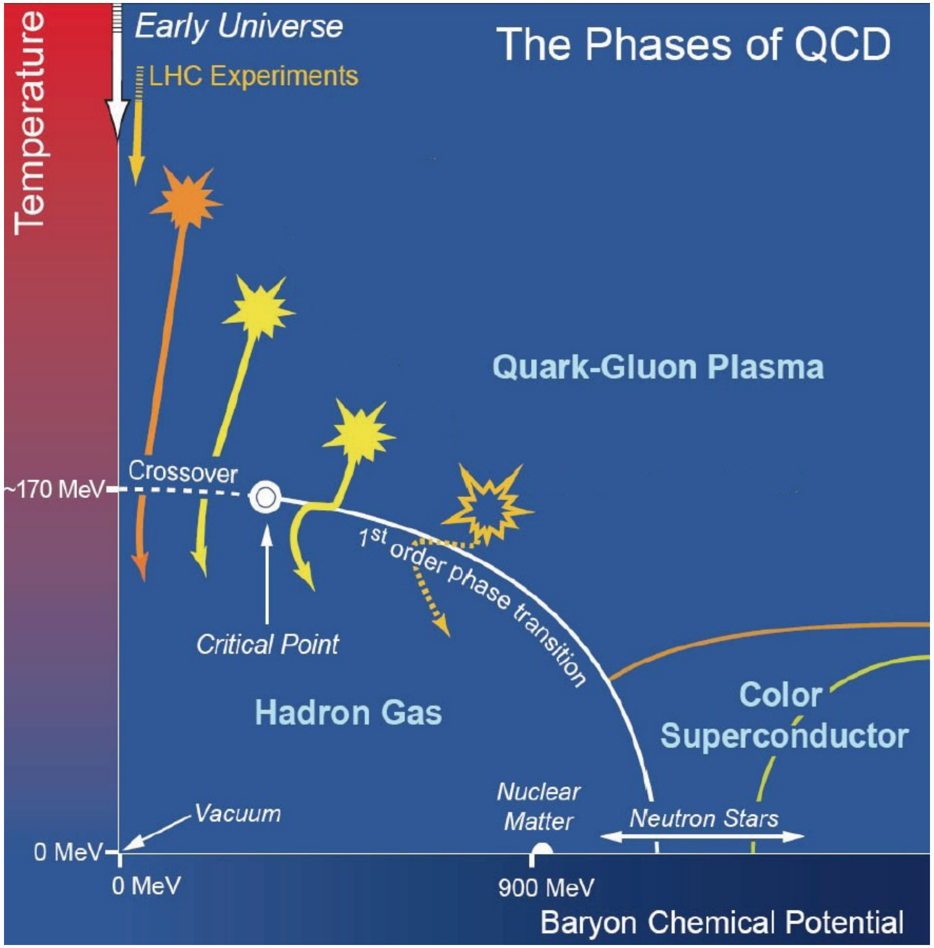
A. Adare et al., PRL104,132301(2010)

QCD Critical Point



QCD Critical Point

- **We do not observe real (1st or 2nd order) phase transition at top energy of RHIC and LHC. How can we observe it ?**
- **Critical Point (CP) connects cross over at small μ (lattice QCD) and 1st order transition at low T.**
  Asakawa, Yazaki ('89)



- **Questions**
  - **Where is CP ?**
  - **How can we observe CP ?**
  - **How many CPs exist ?**
  - **Where does the 1st order phase transition take place ?**
  - **What is the signal of 1st ord. p.t. ?**
- **Basic idea**
  → Go to lower energy HIC
  BES @ RHIC, SPS, FAIR, (and J-PARC)

Where is CP ? Lattice MC results

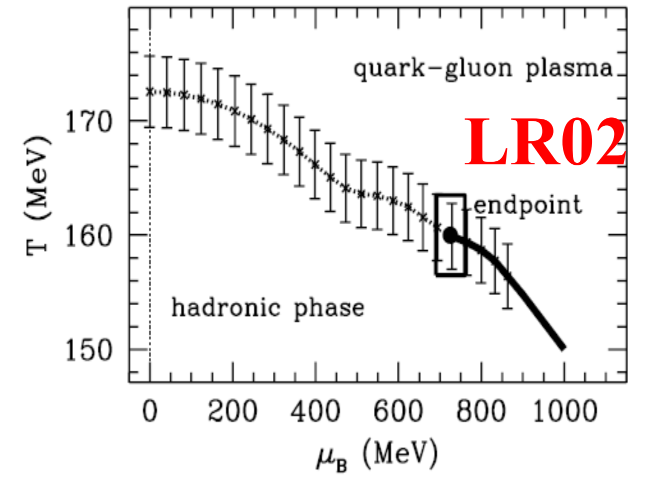
- **Sign problem at finite μ: Fermion det. D*(μ) = D(-μ)**
- **Reweighting**

  (T_{CP}, μ_{CP})=(162 MeV, 360 MeV) (LR04)

  c.f. (T_{CP}, μ_{CP})=(160 MeV, 725 MeV) (LR02)

  Z.Fodor, S.D.Katz, JHEP 0203 ('02) 014.

  JHEP 0404 ('04)050 (smaller mass, larger size).



- **Canonical ensemble**

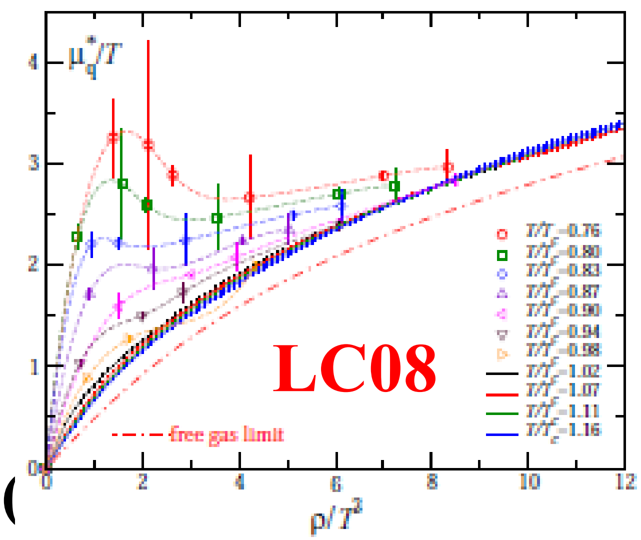
  (T_{CP}, μ_{CP})=(0.87 Tc, 6 T) (LC08) (m/T ~ 0.4)

  (T_{CP}, μ_{CP})=(0.927 Tc, 2.60 Tc) (LC11)

  (m_{ud} ~ m_s)

  S.Ejiri, PRD78 ('08) 074507;

  A.Li, A.Alexandru, K. -F.Liu, PRD 84 ('11) 071503.



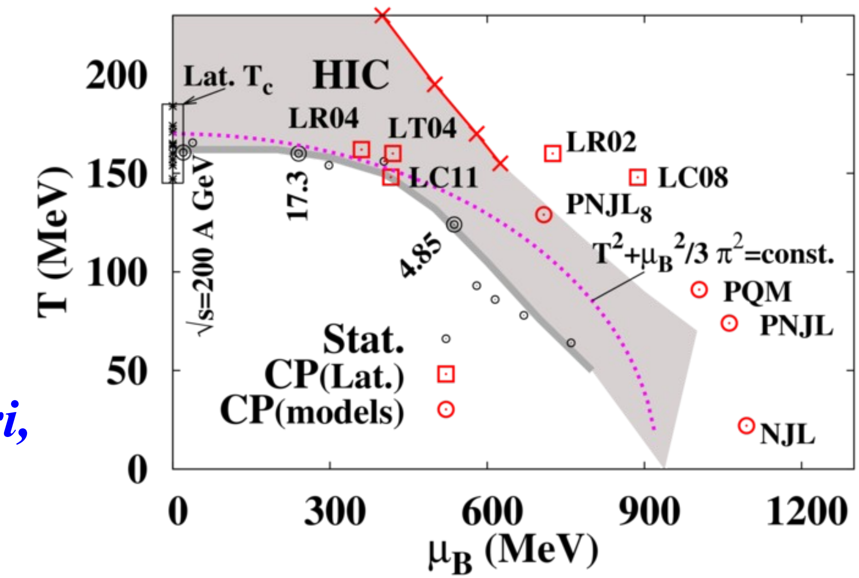
- **Taylor expansion + reweighting: μ_{CP}= 420 MeV (**

  S. Ejiri et al., PTPS 153 ('04) 118

- **No CP ?** *P.de Forcrand, O.Philipsen, JHEP 0701 ('07) 077; 0811 ('08) 012.*

Where is CP ? Effective model predictions

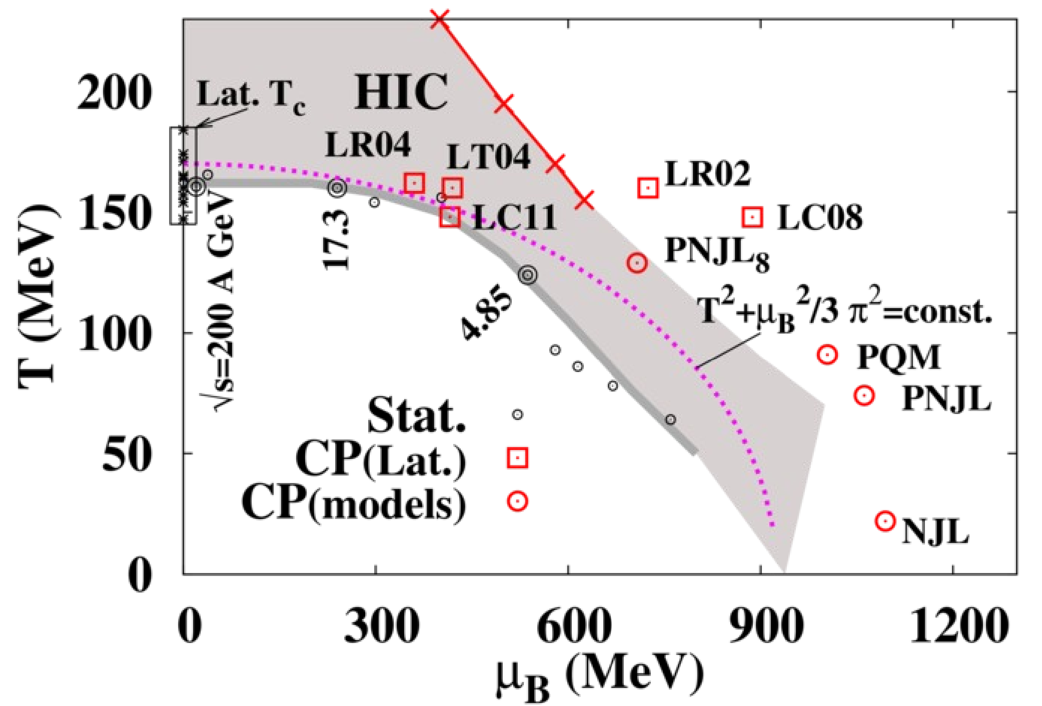
- **Chiral Effecitve models of QCD**
  - **Nambu-Jona-Lasinio (NJL) model: $(T_{CP}, \mu_{CP}) = (22\ \mathrm{MeV}, 1095\ \mathrm{MeV})$**
    Y. Nambu and G. Jona-Lasinio, PR122('61)345; PR124 ('61) 246;
    T.Hatsuda, T.Kunihiro, PRep 247 (1994) 221.
  - **Polyakov loop extended NJL (PNJL): $(T_{CP}, \mu_{CP}) = (74\ \mathrm{MeV}, 1062\ \mathrm{MeV})$**
    K.Fukushima, PLB591('04)277; S.Roessner, C.Ratti, W.Weise, PRD75('07)034007.
  - **PNJL with 8-quark int.: $(T_{CP}, \mu_{CP}) = (129\ \mathrm{MeV}, 708\ \mathrm{MeV})$**
    K.Kashiwa, H.Kouno, M.Matsuzaki, M.Yahiro, PLB 662 ('08) 26;
  - **Polyakov loop extended Quark Meson (PQM): $(T_{CP}, \mu_{CP}) = (91\ \mathrm{MeV}, 1005\ \mathrm{MeV})$**
    B.-J.Schaefer, J.M.Pawlowski, J.Wambach, PRD76('07)074023; V.Skokov, B.Friman, E.Nakano, K.Redlich, B.-J.Schaefer, PRD82('10)034029.



CP locations: AO, H.Ueda, T.Z.Nakano, M.Ruggieri, K.Sumiyoshi, PLB704 ('11) 284.
AO, ISMD proc., submitted to PTPS.

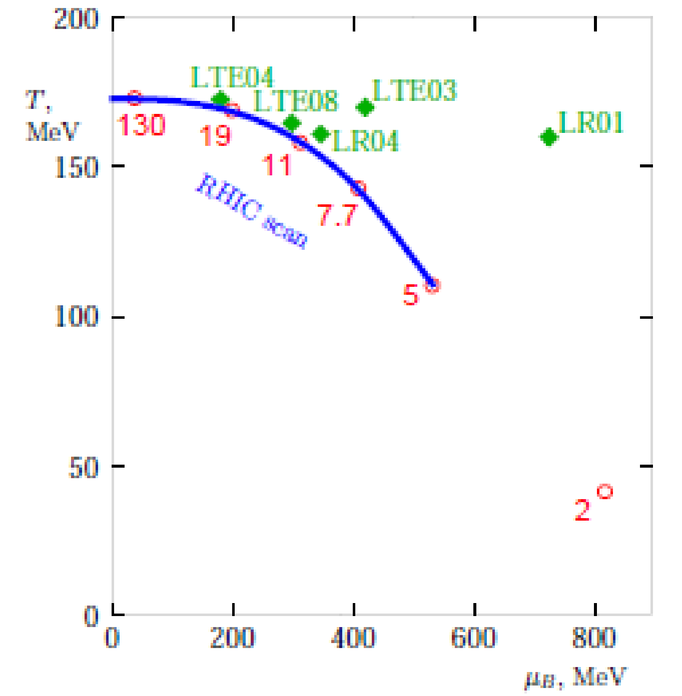
Where is CP ?

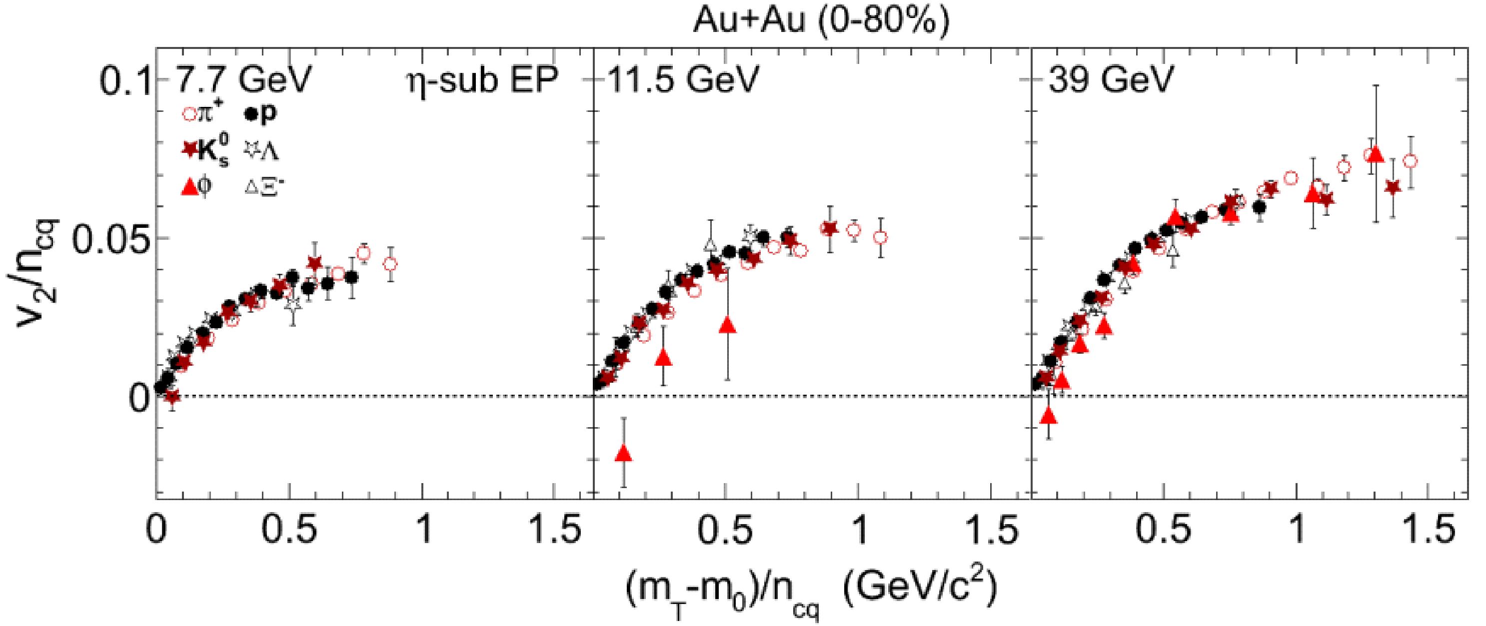
- Lattice QCD MC results seems to predict
  $T_{CP} > 0.85\ Tc(\mu=0)$, $\mu_{CP} < 500$ MeV
  - Correct predictions ? Lattice artefact ?
    imaginary chem. potential, RW critical point at $\mu_q/T = \pi/3$
    P. de Forcrand, O.Philipsen, NPB 642 ('02)290; M.D'Elia and M.-P. Lombardo, PRD 67 ('03) 014505;T.Sasaki, Y.Sakai, H.Kouno, M.Yahiro, PR84 ('11) 091901; K.Morita, V. Skokov, B.Friman, K.Redlich, PRD84 ('11) 076009
- Reachable in HIC ?
  - Statistical model fit results
    → CFO line is close to CP
- Effective models predict
  smaller T_{CP}, larger μ_{CP}
  than Lattice MC
  - Based on fermion zero point E and thermal quark pressure.
  - Polyakov loop → larger T_{CP}



Critical Point Search at RHIC

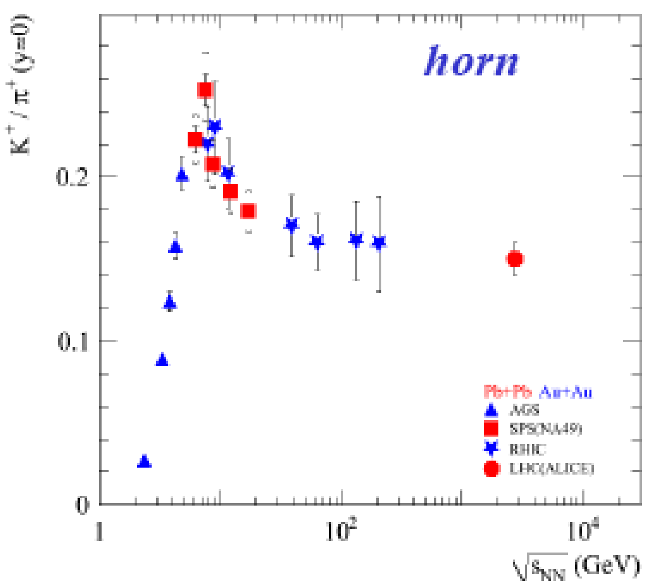
- **Beam Energy Scan (BES) program at RHIC**
  E.g. G. Odyniec, Acta Phys. Polon. B40 ('09) 1237
  - **$\sqrt{s_{NN}}$ = 5-200 GeV**
    → μ_B < 500 MeV at Chemical Freeze-out
  - **First stage results of BES @ RHIC**
    → Quark number scaling of v_2 works and $v_2(p_T)$ saturates for $\sqrt{s_{NN}}$ > 39 GeV

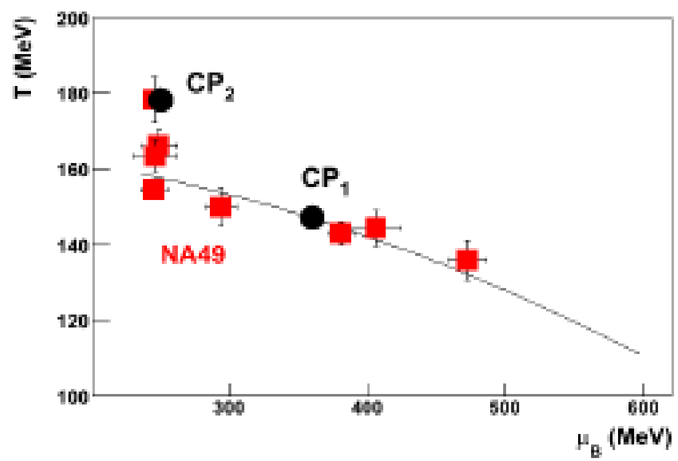


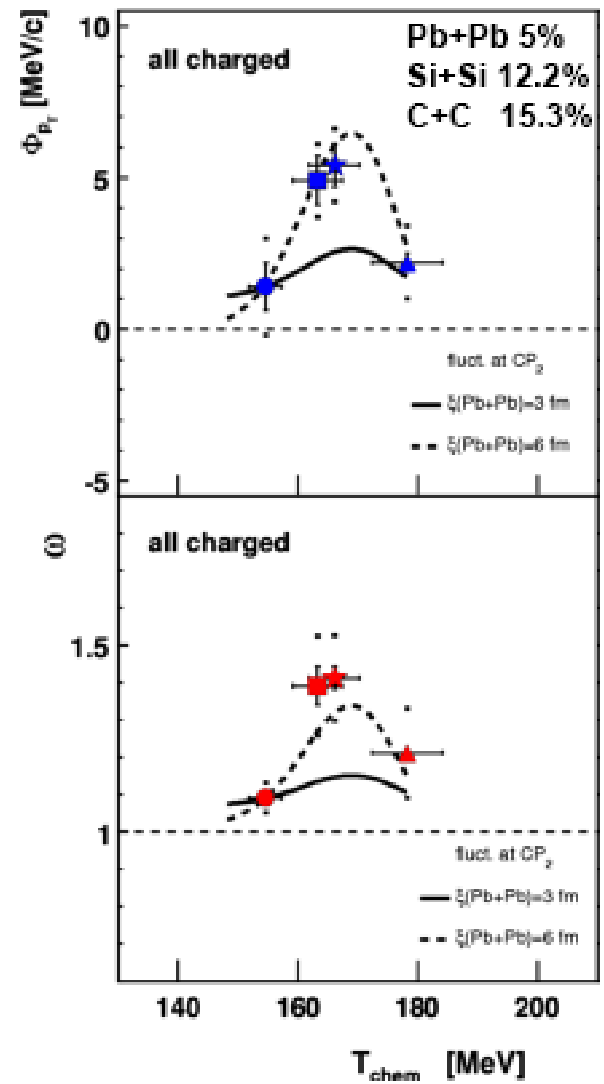


Critical Point / Onset of Deconfinement Search at SPS

- **Non-monotonic incident energy dependence at lower SPS energies**
  → Horn, Step, and Dale around $\sqrt{s_{NN}}$ = 8 GeV
  S. V. Afanasiev et al. [NA49 Collab.], PRC66 ('02) 054902.
  Theory: M. Gazdzicki, M. I. Gorenstein,
  Acta Phys. Polon. B30 ('99) 2705.
- **Incident energy / System size scan @ SPS**
  → Enhanced fluctuations in Si+Si collisions
  at E = 158 *A* GeV
- **What do these signals imply ?**



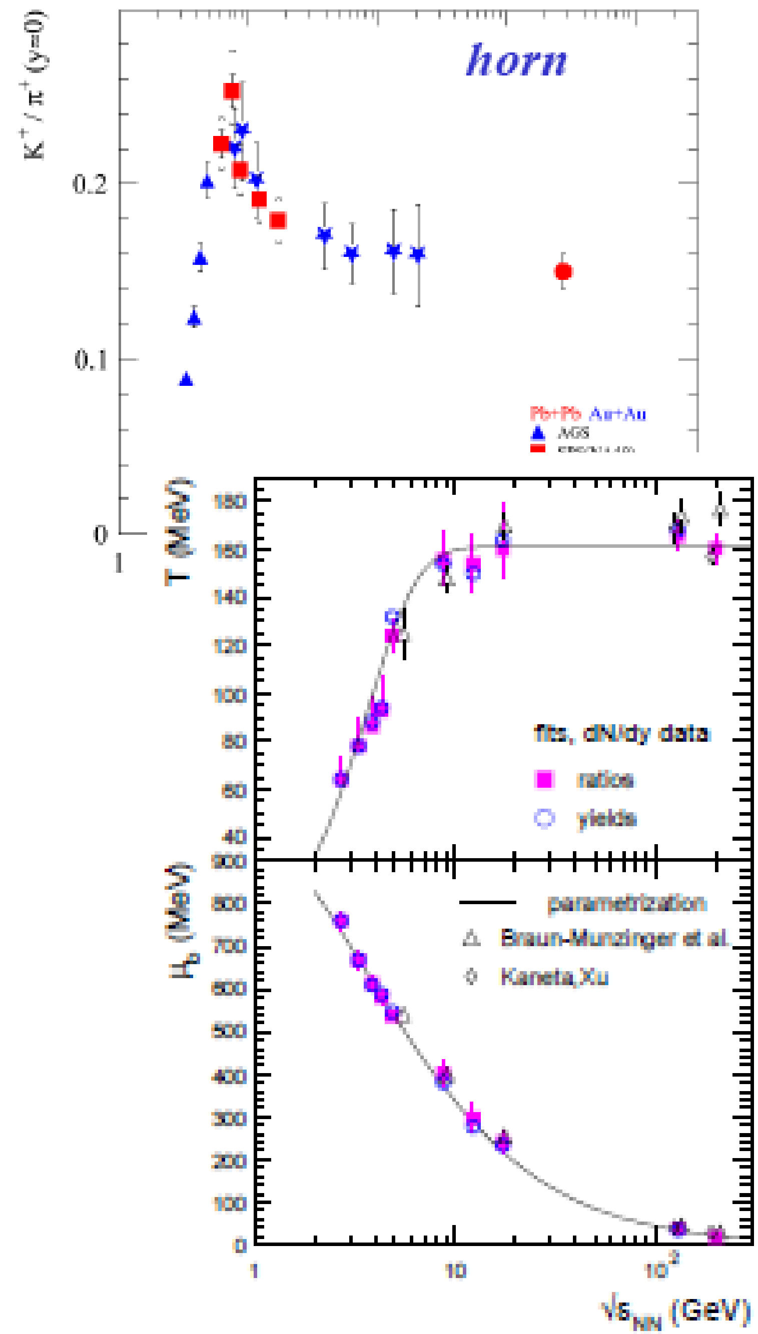




NA49, NA61/SHINE

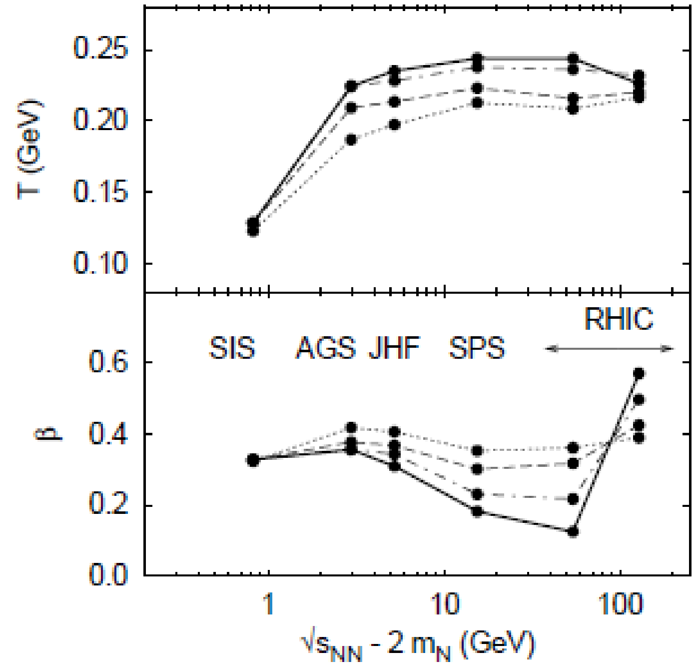
Horn structure

- **Horn = Sharp peak of $K^+/\pi+$ ratio observed at around $\sqrt{s_{NN}} = 8$ GeV (Einc=(20-30) A GeV)**
  S. V. Afanasiev et al. [NA49 Collab.], PRC66 ('02) 054902.
- **Theoretical Prediction**
  - **Assumption: Strange hadron production is frequent enough in initial NN collisions, larger than equil. yield in QGP.**
    M. Gazdzicki, M. I. Gorenstein, Acta Phys. Polon. B30 ('99) 2705.
  - **Statistical model analysis**
    Andronic et al. ('06)
    Saturated T_{CFO} ('step')
    + decreasing μ_{CFO} at around $\sqrt{s_{NN}} = 8$ GeV
    $\rightarrow$ K+ is unfavored at $\sqrt{s_{NN}} > 8$ GeV

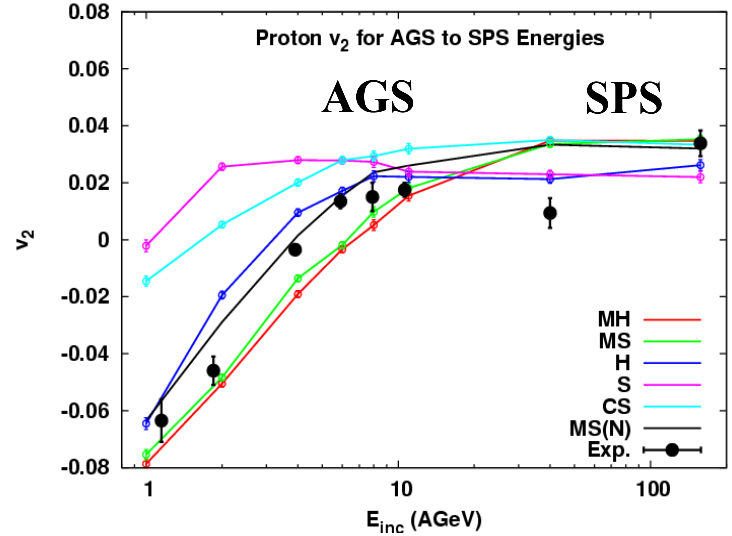


Does the Horn signal QGP formation ?

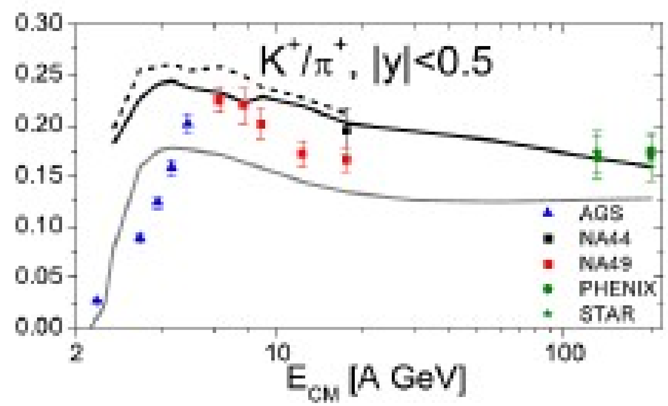
- **Objection ! Hadron-string cascade explain the hadron spectra and flow at AGS and SPS energies.**
  - **String decay dominance→ *'Step'***
    P.K.Sahu, N.Otuka, M.Isse, Y.Nara, AO, Pramana 66 ('06) 809 [nucl-th/0102051]
  - **Momentum dep. mean field**
    → v2 at 2-158 A GeV (AGS, SPS)
    M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72 ('05)064908



- **Yes(?): UrQMD+Hydro at lower SPS**
  Nahrgang et al. arXiv:1103.0753

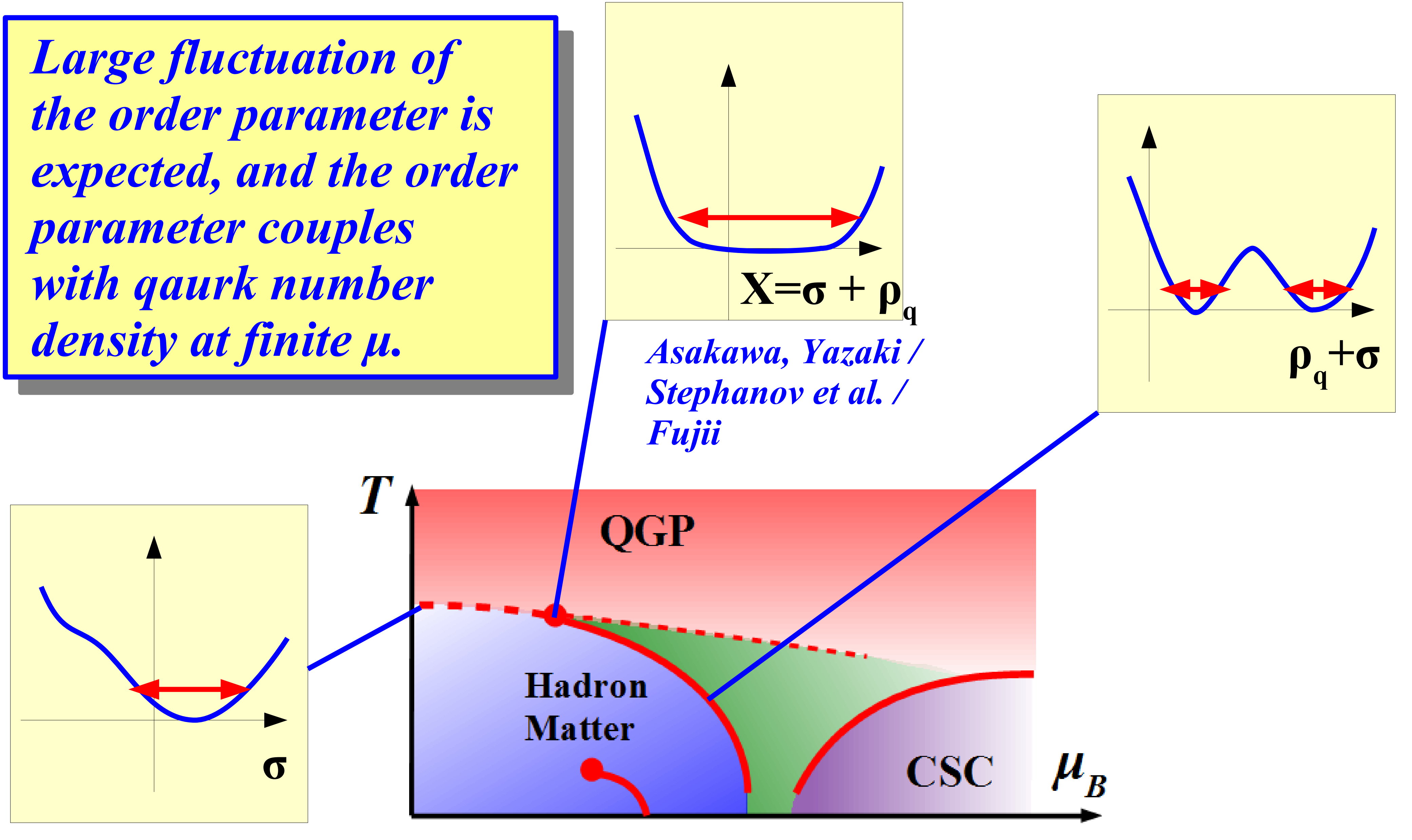


Further studies are necessary → NA61/SHINE



QCD Critical Point

Large fluctuation of the order parameter is expected, and the order parameter couples with qaurk number density at finite μ.

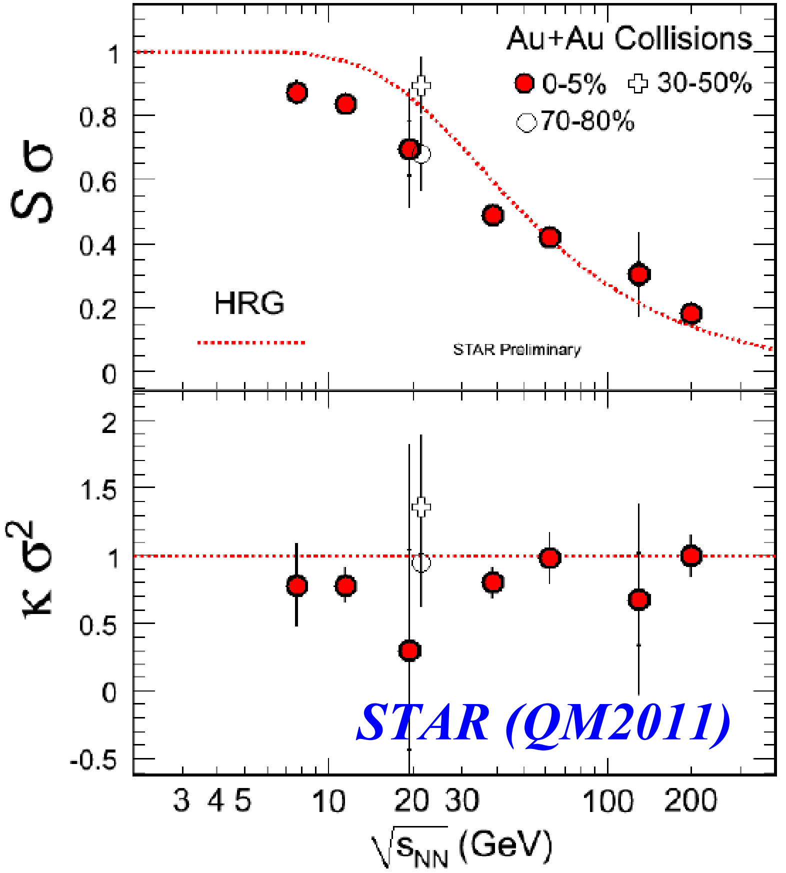


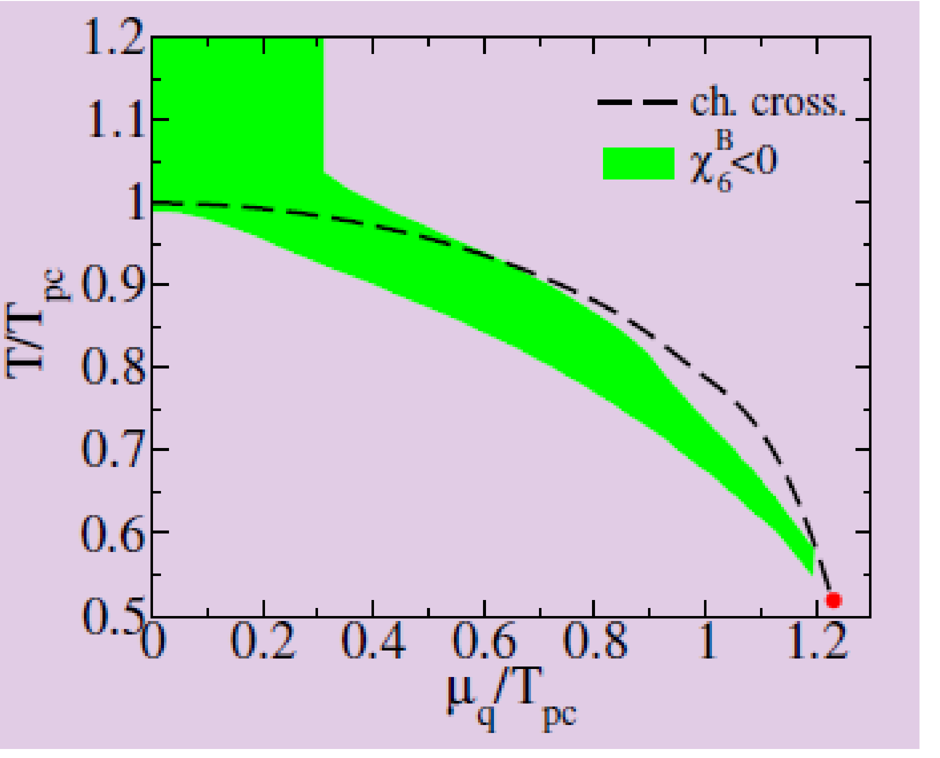
What is the signal of CP ?

- **Skewness sign ?**

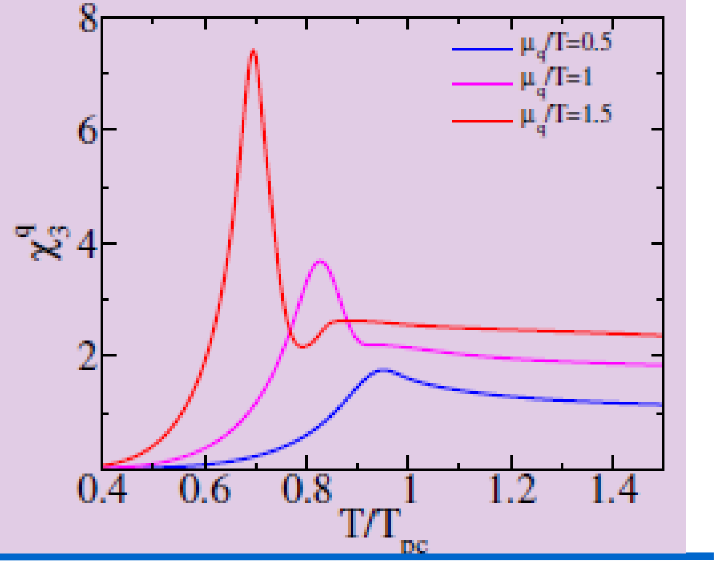
$$\frac{\partial \chi_B}{\partial \mu_B} = -\frac{1}{V}\frac{\partial^3 \Omega}{\partial \mu_B^3} = \frac{\langle (\delta N_B)^3 \rangle}{VT^2}$$

- **Negative Kurtosis (4-th order) ?**
- **6-th order correlation ?**





V. Skokov

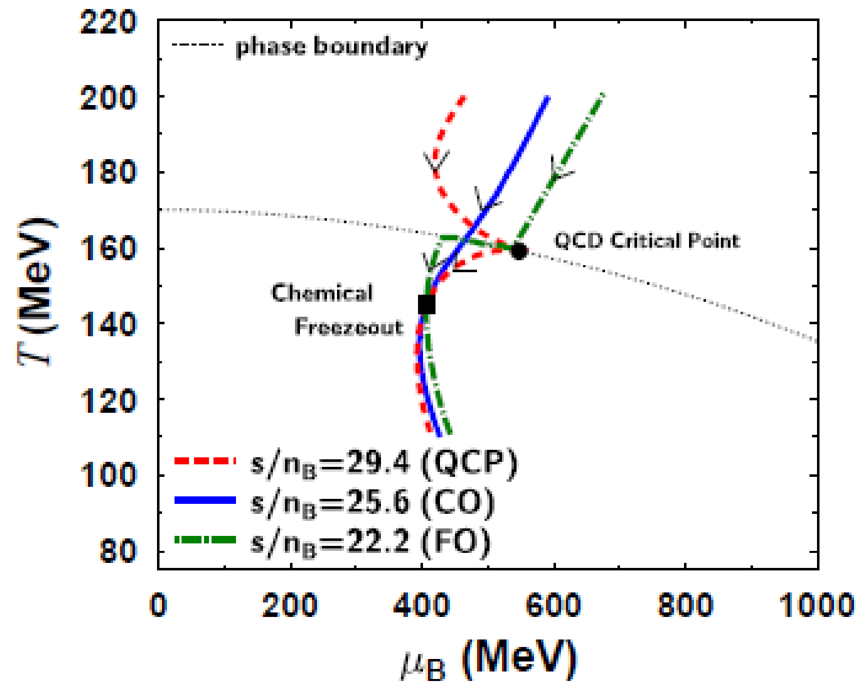


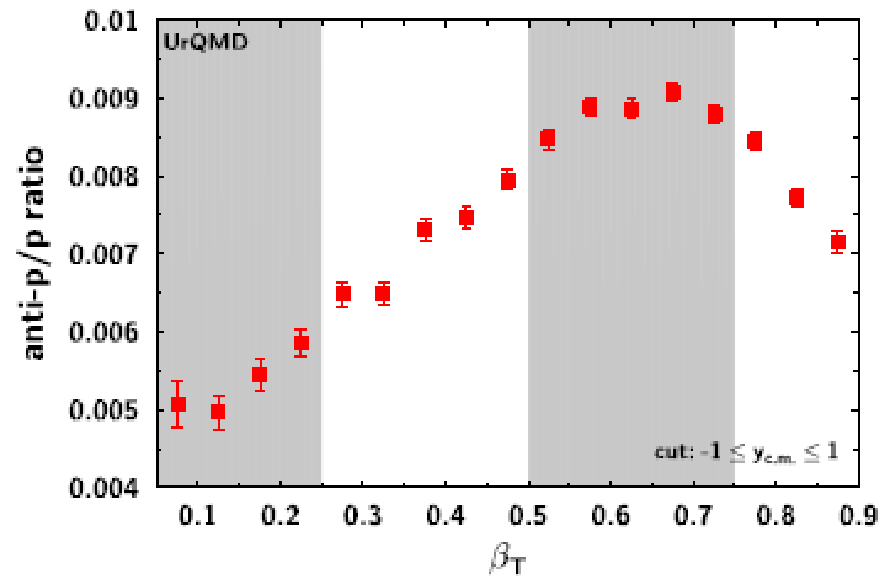
Change of thermal trajectory

- **Another proposed signal.**
  Change of trajectory
  in the vicinity of CP
  → Unusual βT dependence of $\bar{p}/p$
  ratio in a narrow incident
  energy region.

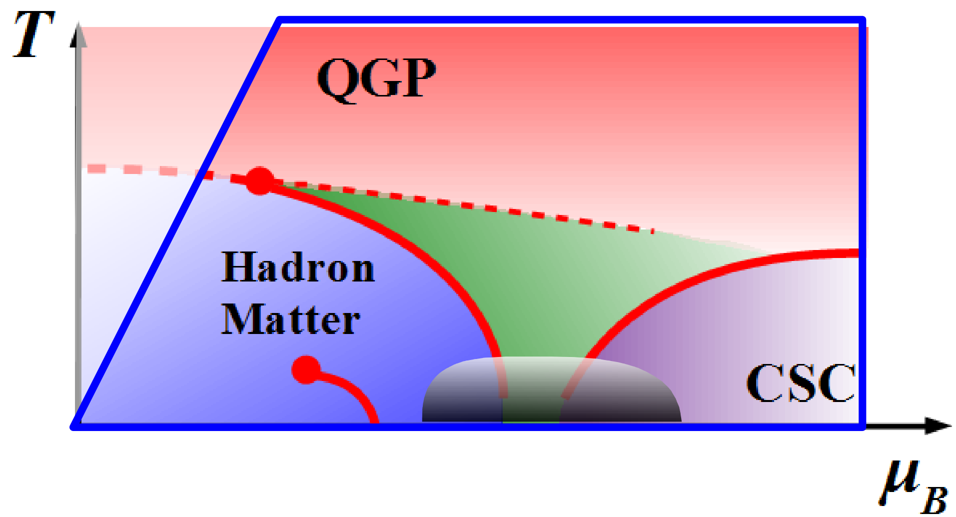
  M. Asakawa, S.A.Bass, B.Muller,
  C.Nonaka, PRL101('08)122302.

  → Ask Chiho !



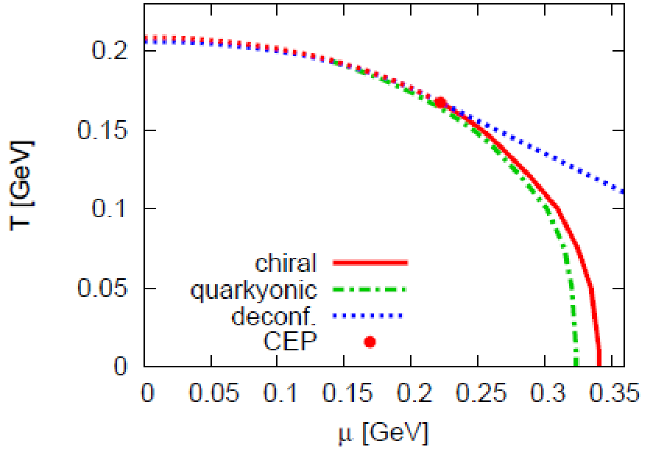


Phase structure in dense matter

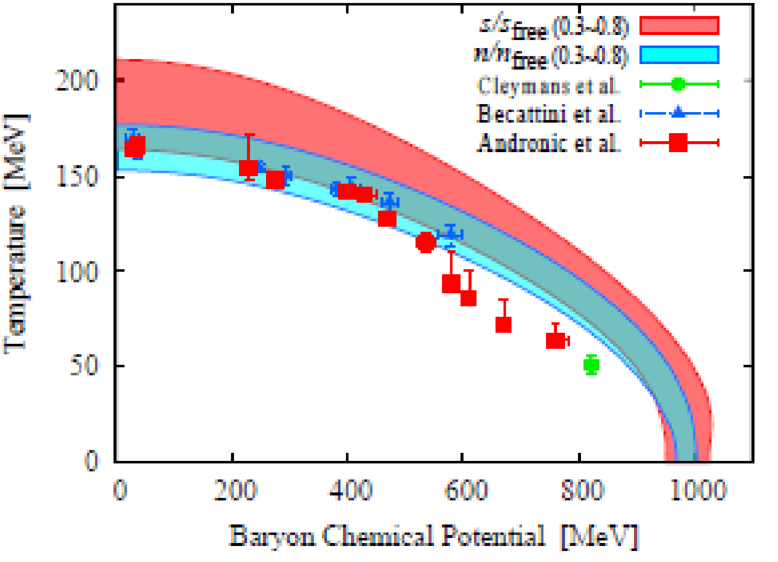


Phase diagram structure

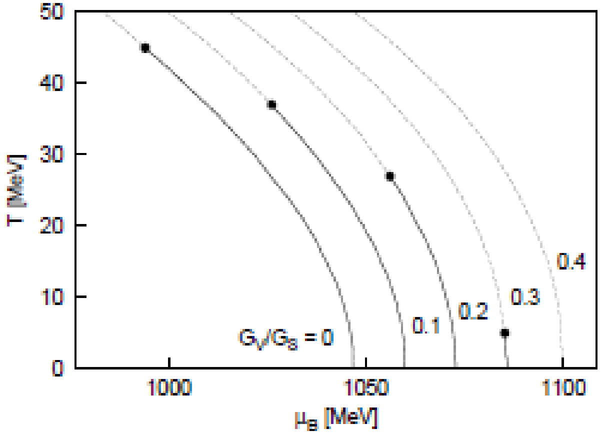
Polyakov loop extended NJL
McLerran, Redlich, Sasaki ('09)
Large Nc: McLerran, Pisarski, NPA796 ('07)83



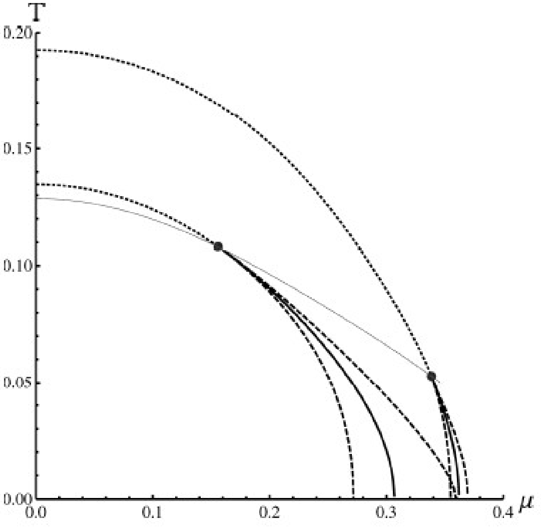
PNJL+Stat.:
K.Fukushima, PLB 695('11)387



NJL with vector int.
Kitazawa,Kunihiro,Nemoto ('02)

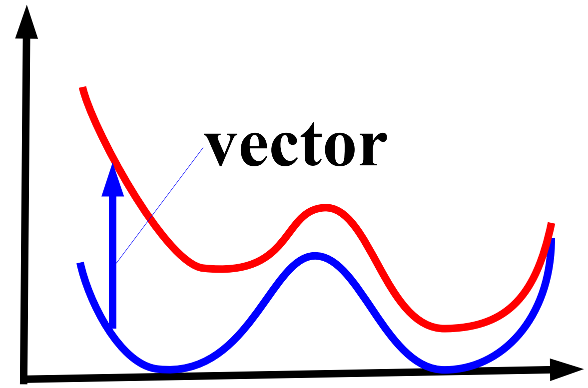


NJL+8q int., Hiller et al.

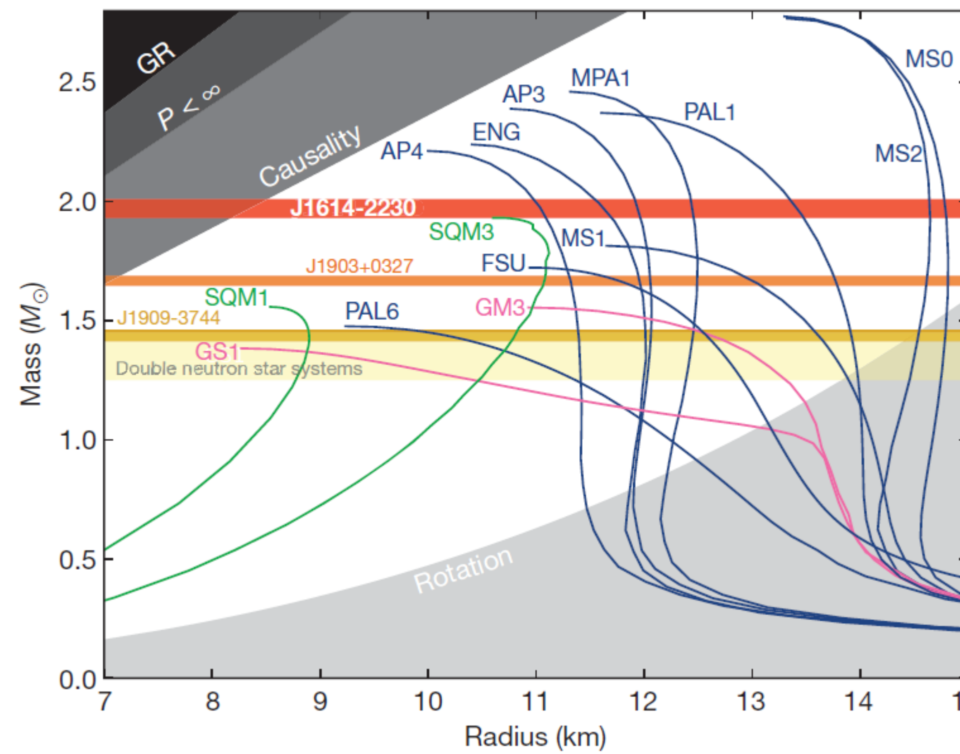


Phase diagram structure (cont.)

- Phase diagram structure is sensitive to interaction
  - Vector interaction → larger μ_{CP}, smaller T_{CP}
  - 8 quark interaction → shaper transition
    μ also make p.t. shaper → smaller μ_{CP}
  - Number of CPs is also sensitive to interaction and CSC.



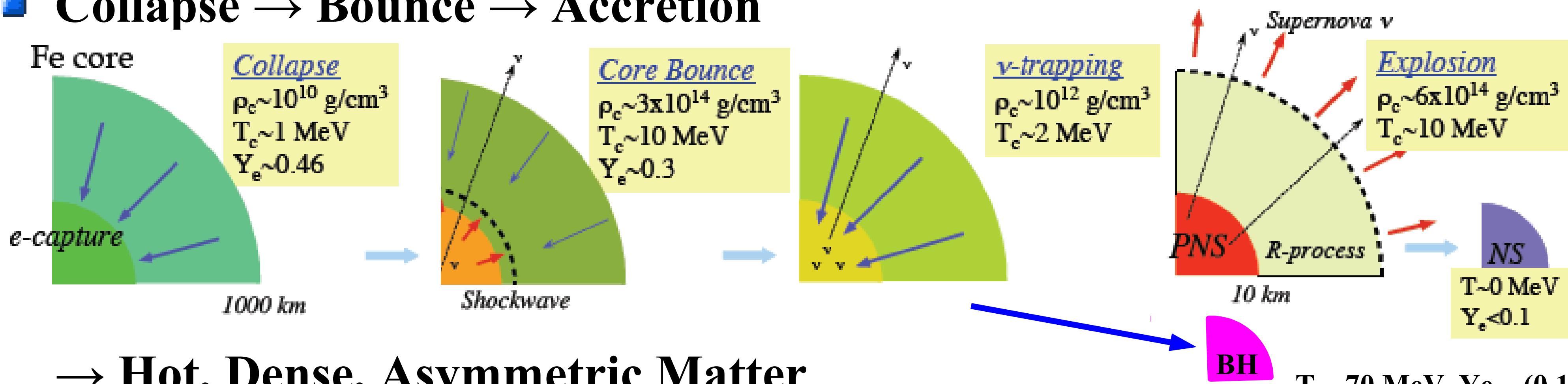
- Are these academic problems ?
  → No
  - When CP is probed in HIC, quarkyonic matter properties affects observables.
  - Recently observed 1.97 Msun neutron star would have quark matter core.
  - Hot and dense region may be reachable in black hole formation.



Demorest et al., Nature 467 (2010) 1081

Dynamical Black Hole Formation

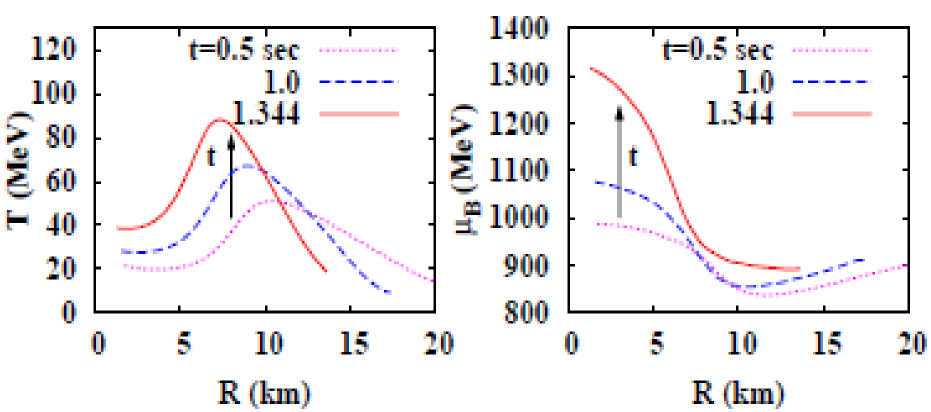
- Collapse → Bounce → Accretion

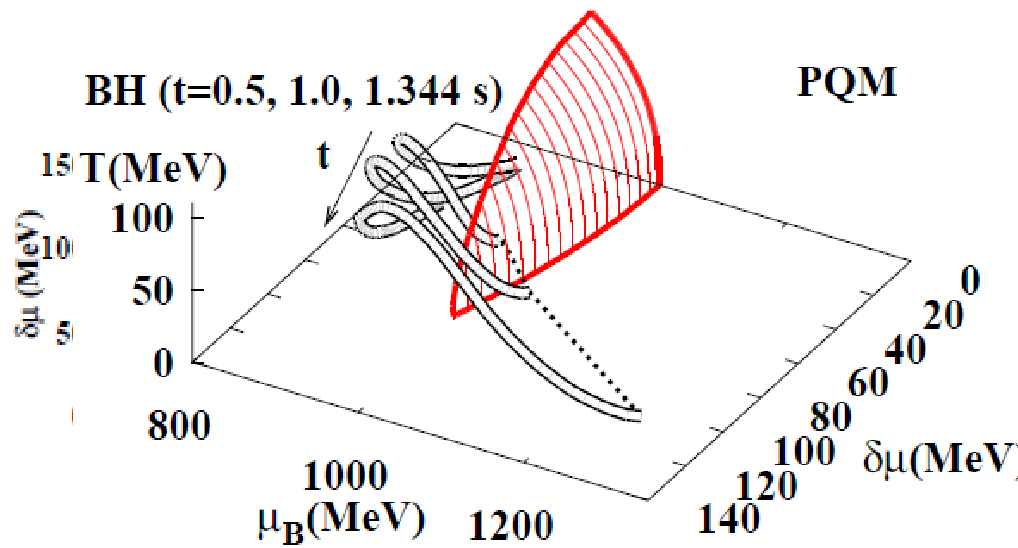


→ Hot, Dense, Asymmetric Matter

$T \sim 70$ MeV, $\mu_B \sim 1300$ MeV, $\delta\mu=\mu_e/2 \sim 130$ MeV

→ CP may be reachable



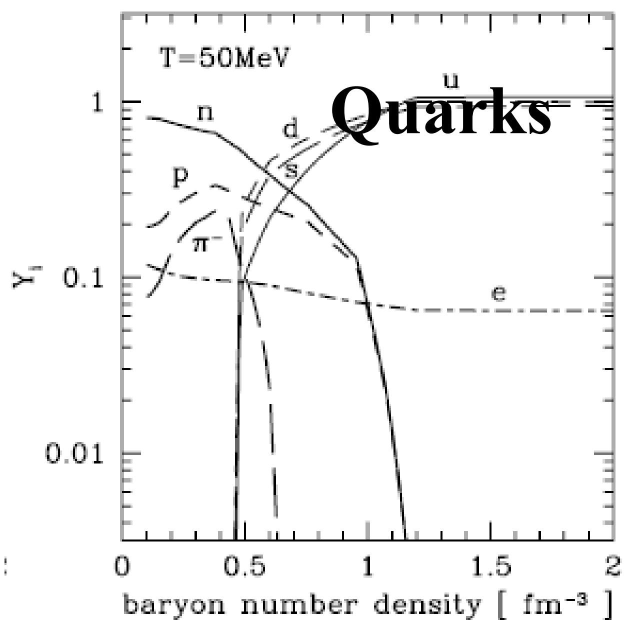


K. Sumiyoshi, et al.,('06); K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki ('09)
AO, H.Ueda, T.Z.Nakano, M. Ruggieri, K. Sumiyoshi, PLB704 ('11) 284.

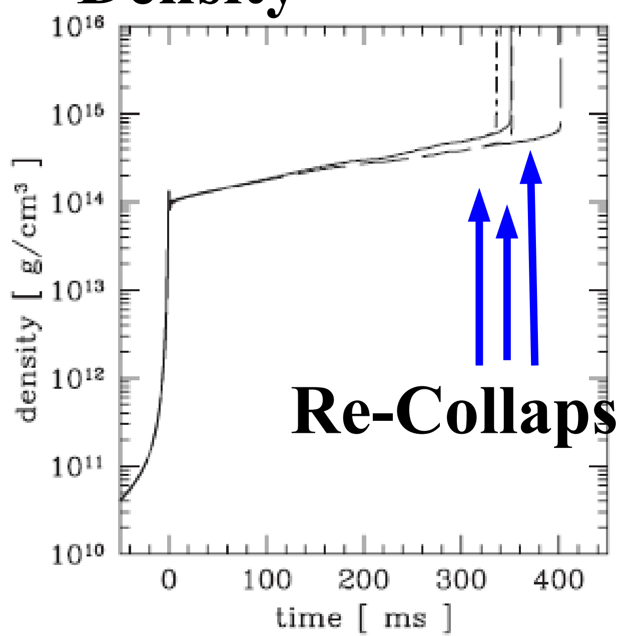
Can we detect Quark Matter ?

- **Supernova EOS with Quark-Hadron Coexistence**
  - **Quark matter=Bag model, Hadronic matter= RMF with free pions**
    → Earlier Collapse to Black Hole *(Nakazato, Sumiyoshi, Yamada, 2008)*
  - **Transition to Strange Quark Star → Second Shock**
    (Hatsuda, 1987; Sagert et al., 2009)

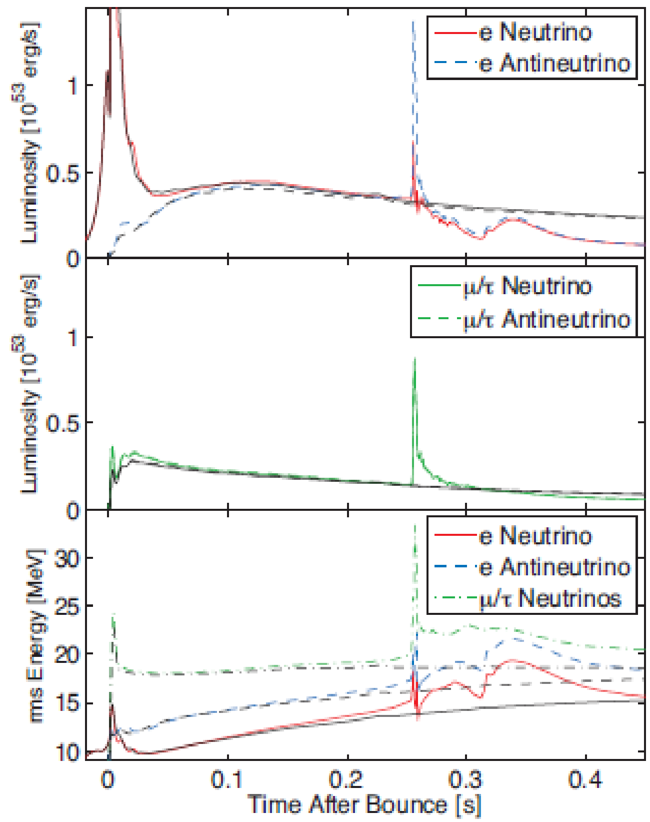
Fraction



Density



Density *Nakazato, Sumiyoshi, Yamada* **Time**

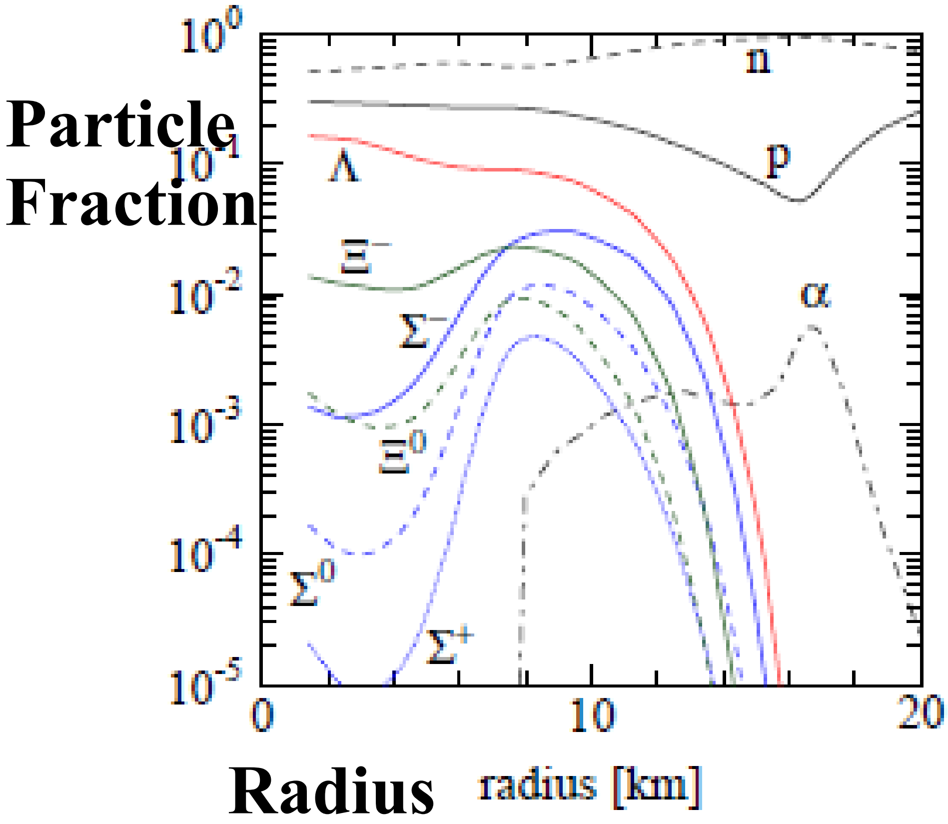


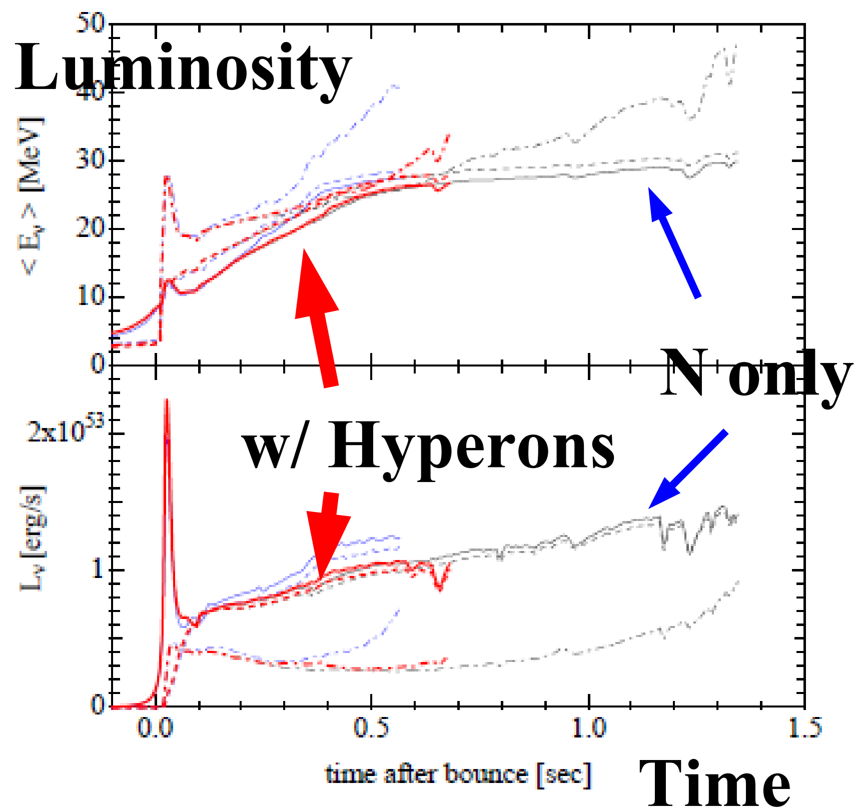
Sagert et al., 2009

Black Hole Formation (Failed Supernova)

- **High T during BH formation**
  → Abundant hyperons → Soft EOS → Earlier Collapse to BH

Short ν emission may be the signal of Hyperon Admixture at high density and/or temperature

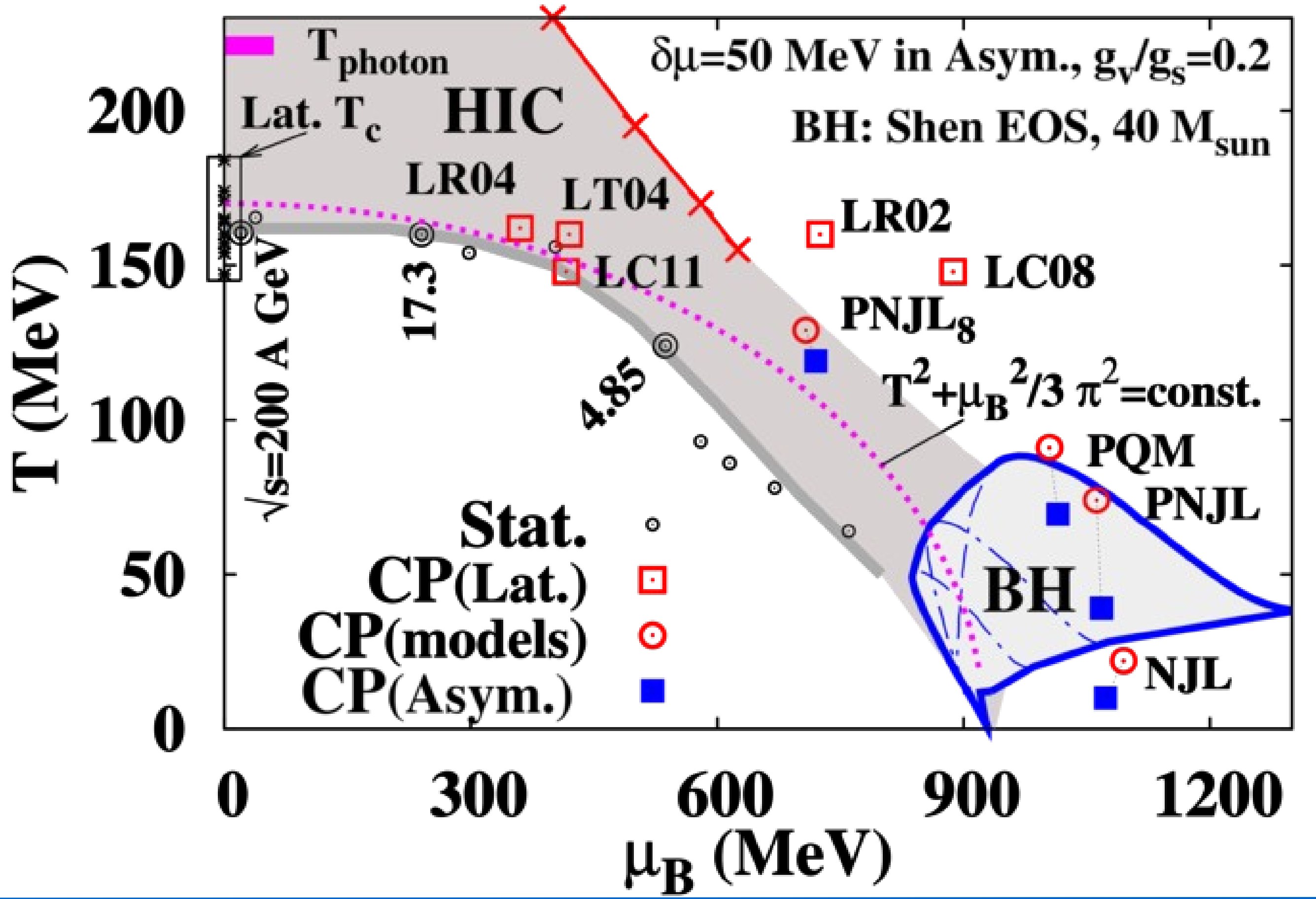




Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009

Critical Point Search in HIC and BH

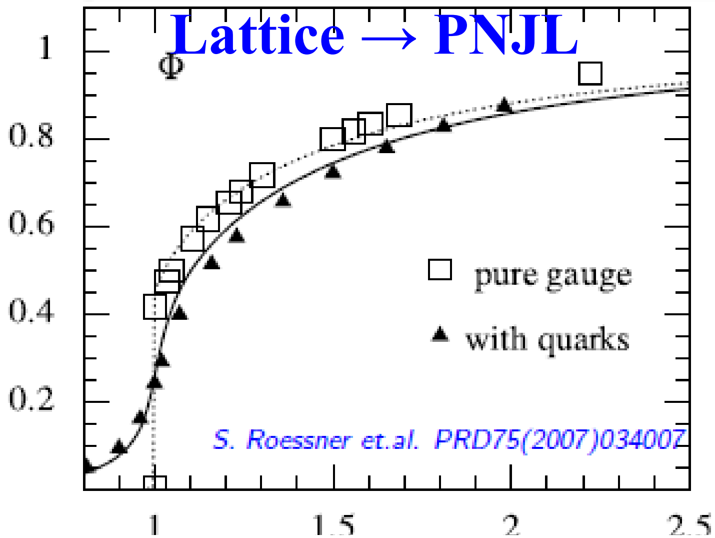
- How can we probe dense matter, μ > 600 MeV ?
- Neutron Star: $\mu_B \sim 1650$ MeV in the core (TM1)
- Candidate = Black hole formation process !
  K.Sumiyoshi, et al.,('06); K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki ('09); AO, H.Ueda, T.Z.Nakano, M. Ruggieri, K. Sumiyoshi, PLB704 ('11) 284.



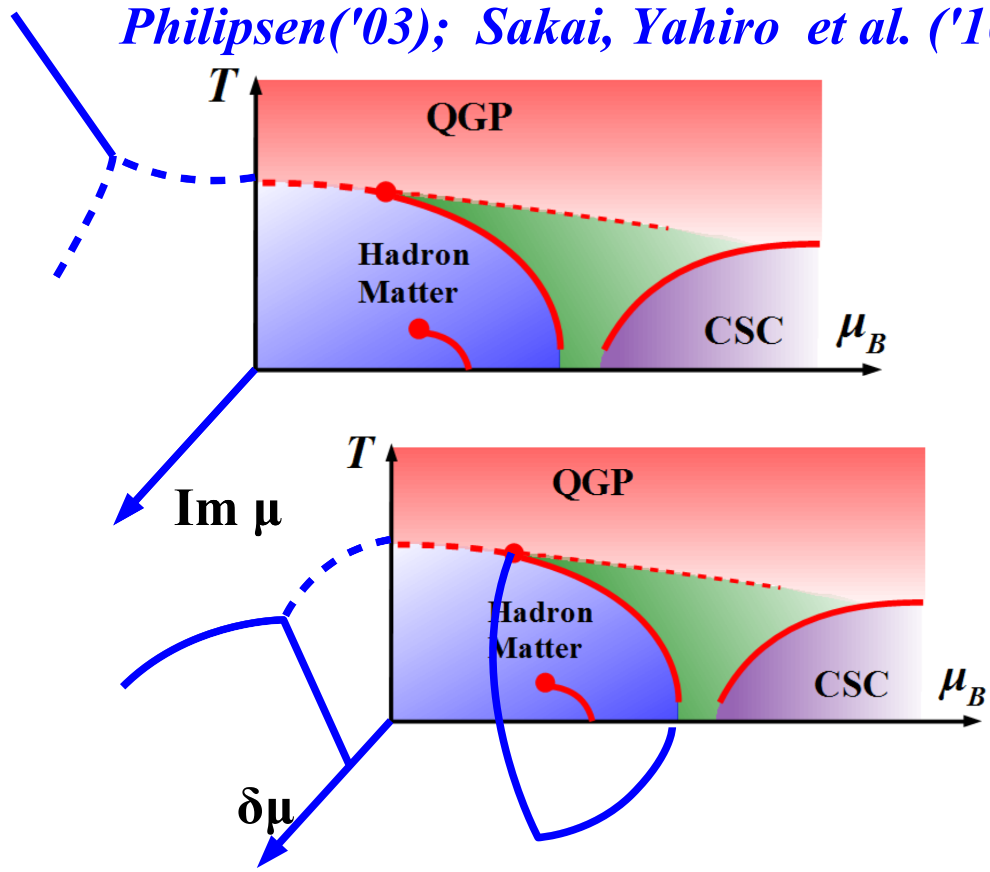
How can we fix model parameters ?

- **Vacuum hadron properties + finite T (μ=0) lattice data**

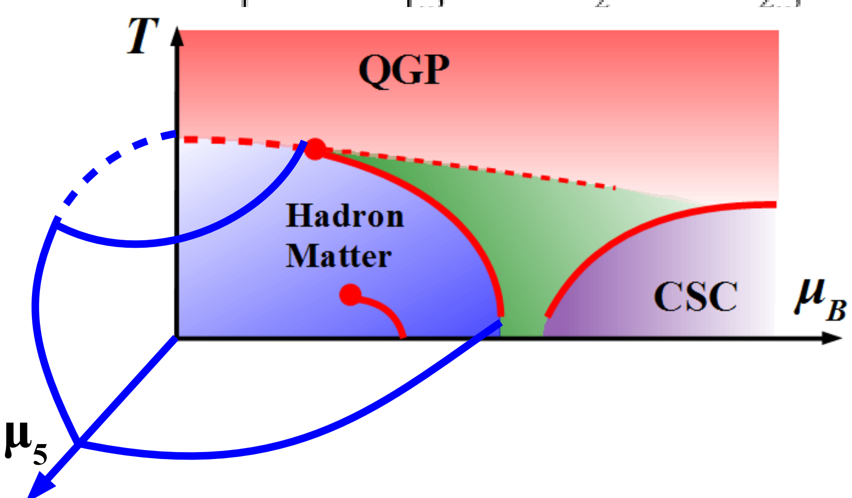
  + 3D phase diagram !



D'Elia, Lombardo('03); de Forcrand, Philipsen('03); Sakai, Yahiro et al. ('10),



Kogut, Sinclair ('04); Sakai et al.('10); AO, Ueda, Nakano, Ruggieri, Sumiyoshi ('11)



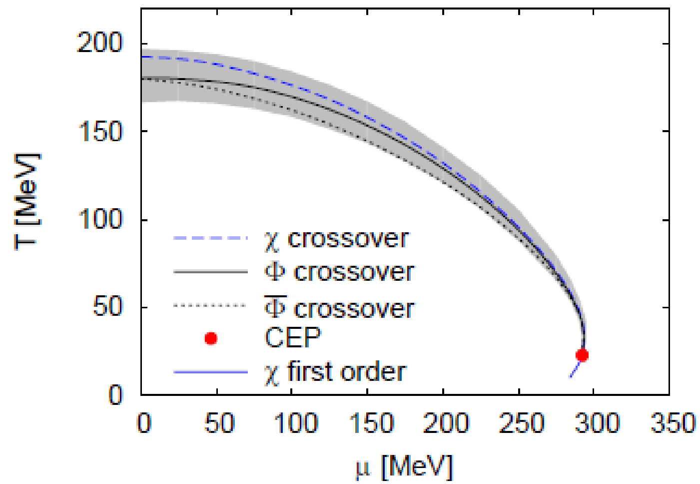
Fukushima et al.('08); Fukushima,Ruggieri,Gatto('10), Ruggieri ('10);Yamamoto('11); Nakano,AO (in prep.)

No sign prob. at μ_B=0

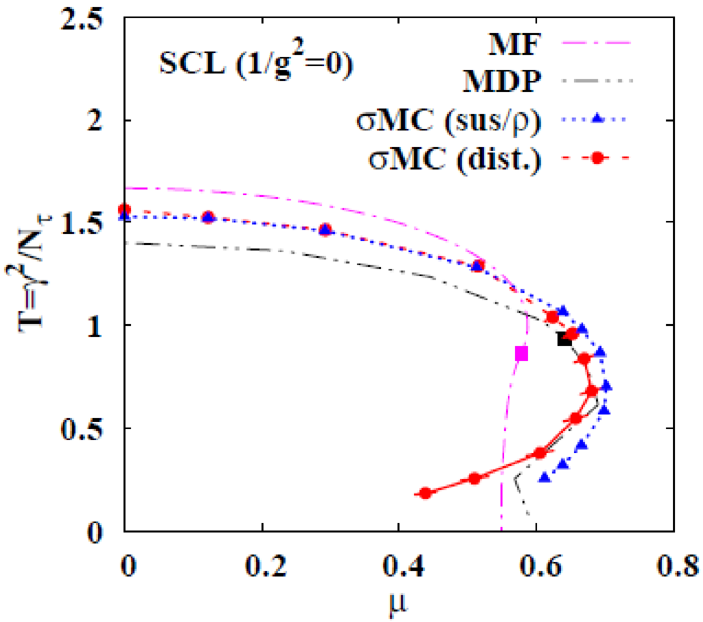
Phase diagram study in Strong Couling Lattice QCD

"First Principle" Approaches

- **Functional RG method**
  Herbst, Pawlowski, Schafer ('11)
- **Canonical approach in LQCD**
  Ejiri ('08); Nagata, Nakamura('10)
- **Strong Coupling Lattice QCD**
  de Forcrand, Fromm ('09); de Forcrand, Unger ('11) ; Miura,Nakano, AO('11), AO, Nakano, in prep.

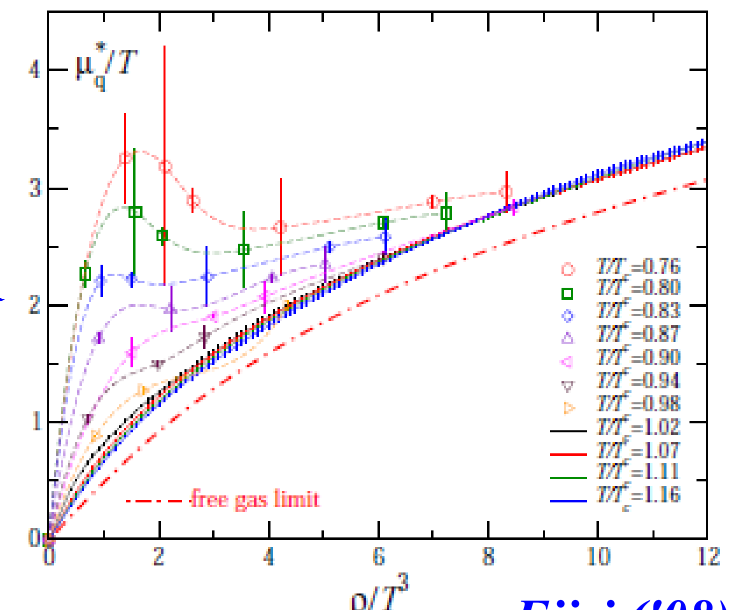


Herbst, Pawlowski, Schafer, ('11)



AO, Nakano

CP ?



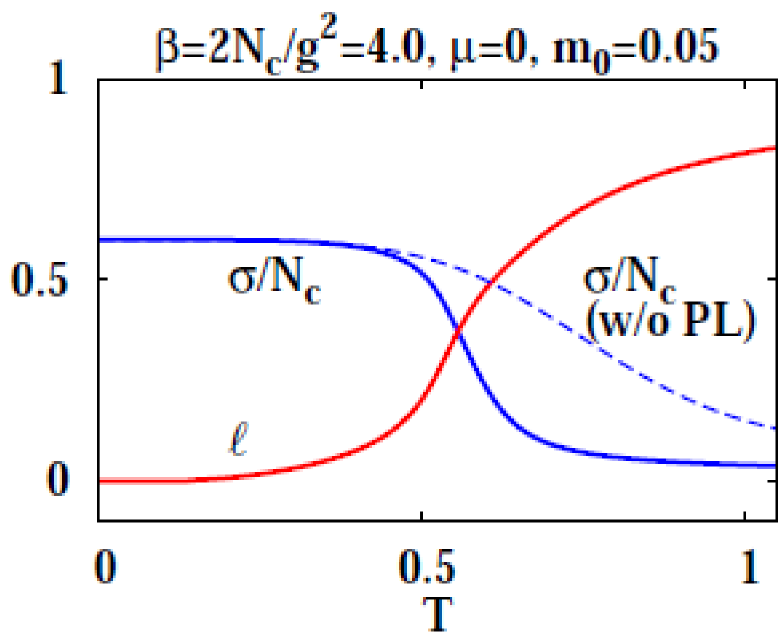
Ejiri ('08)

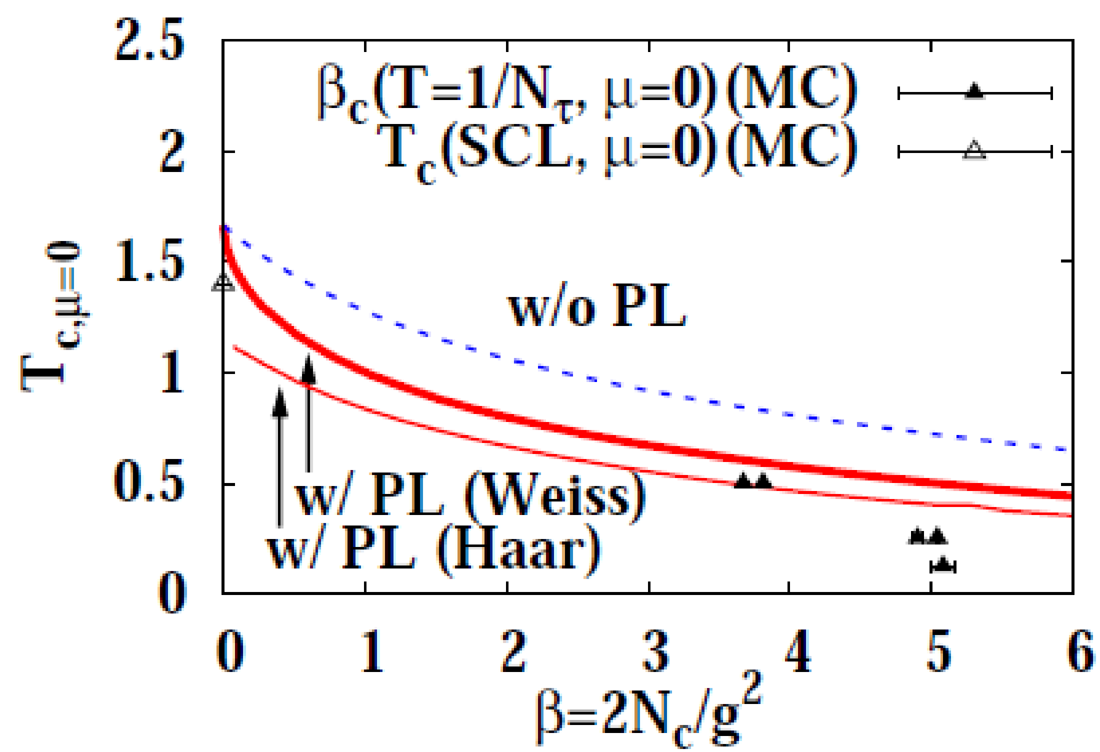
Polyakov loop extended Strong Coupling Lattice QCD

T. Z. Nakano, K. Miura, AO, PRD 83 (2011), 016014 [arXiv:1009.1518 [hep-lat]]

- **P-SC-LQCD reproduces $T_c(\mu=0)$ in the strong coupling region ($\beta= 2N_c/g^2 \leq 4$)**

  MC data: SCL (Karsch et al. (MDP), de Forcrand, Fromm (MDP)), N_τ =2 (de Forcrand, private), N_τ=4 (Gottlieb et al.('87), Fodor-Katz ('02)), N_τ =8 (Gavai et al.('90))



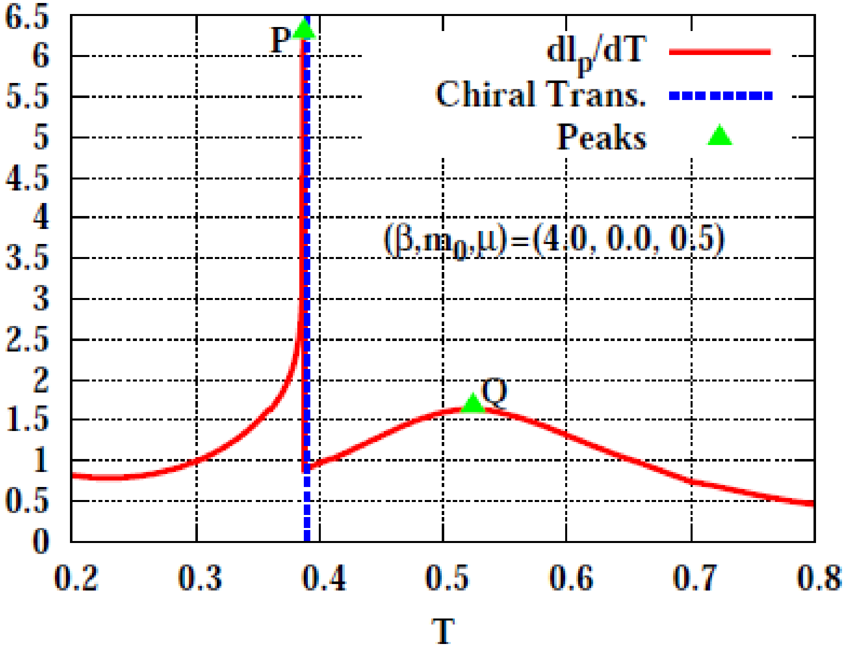


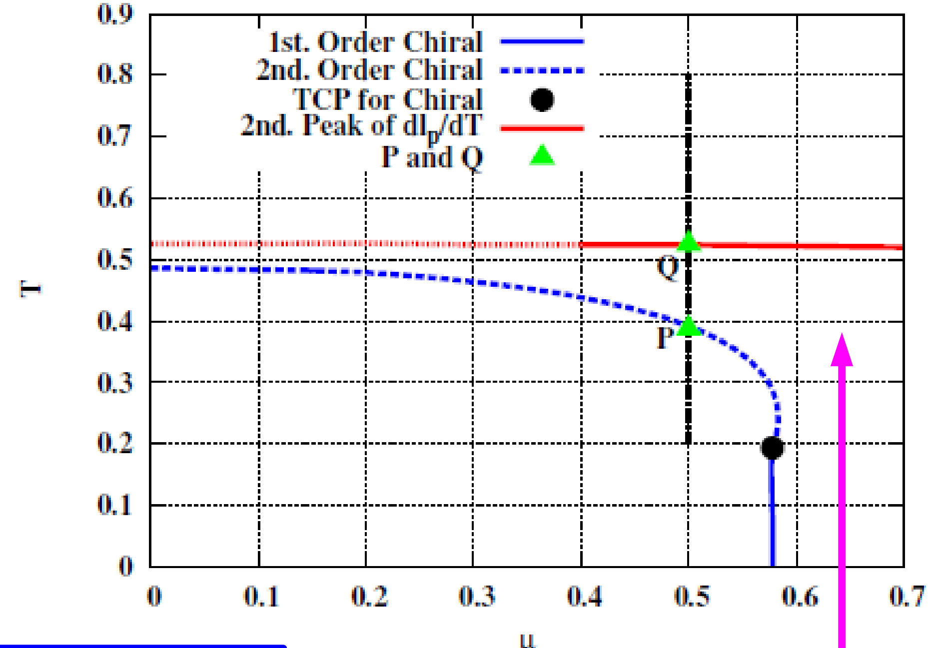
Lattice Unit

Phase diagram in P-SC-LQCD

K. Miura, T.Z. Nakano, AO, N. Kawamoto,
PoS LATTICE2010 (2010), 202 [arXiv:1012.1509 [hep-lat]] ; in prep.

- **and predicts the existence of the "Quarkyonic-like" matter**
  - **dl_p/dT has two peaks: Chiral-induced & Z_{Nc}-induced.**
    (c.f. Lattice MC predict $T_{deconf} > T_{chiral}$!)



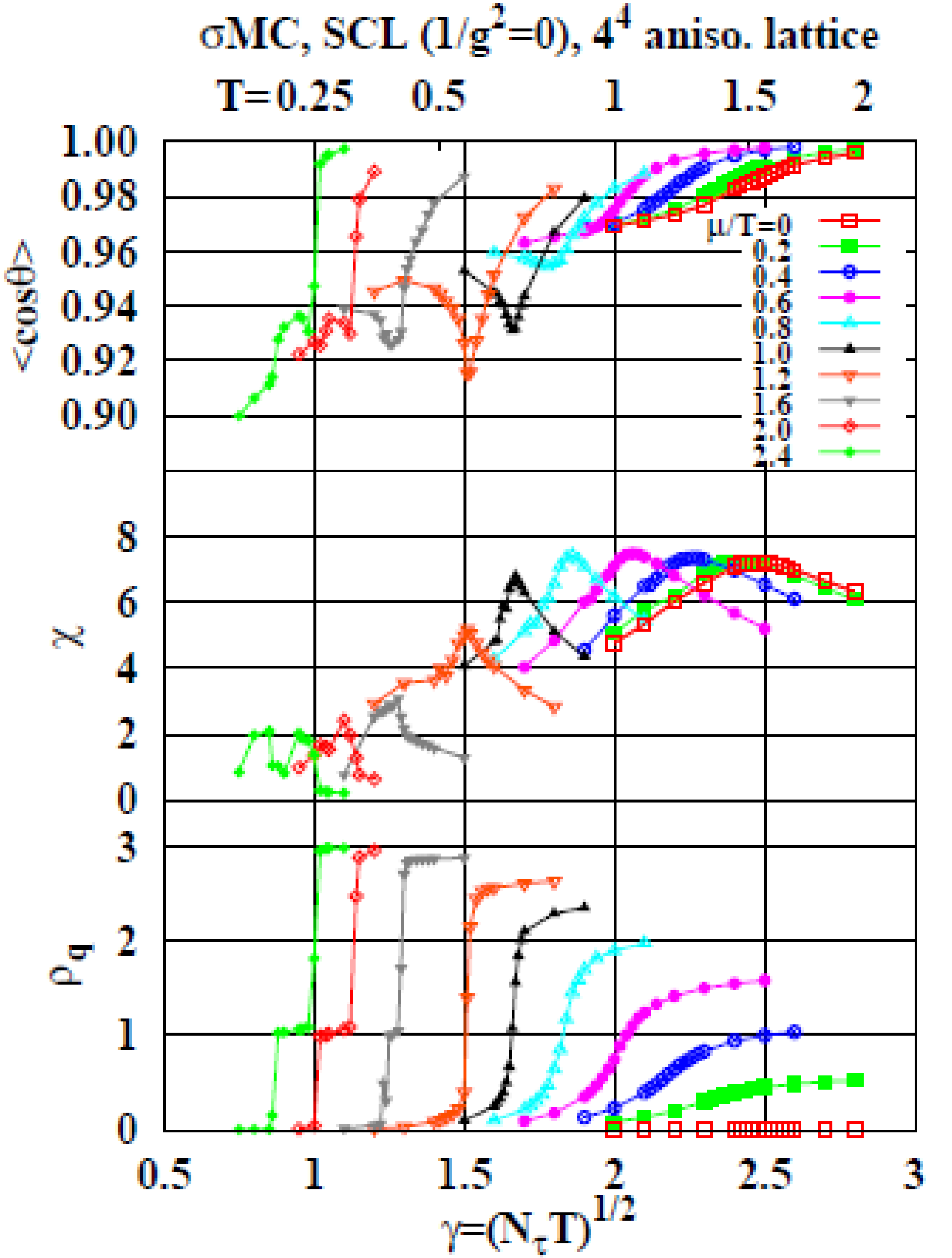


"Q" depends only weakly on μ and m_0 .
→ Z_{Nc}-induced peak

Quarkyonic-like
(χ restored,
Pol. loop suppressed.)

Fluctuation Effects

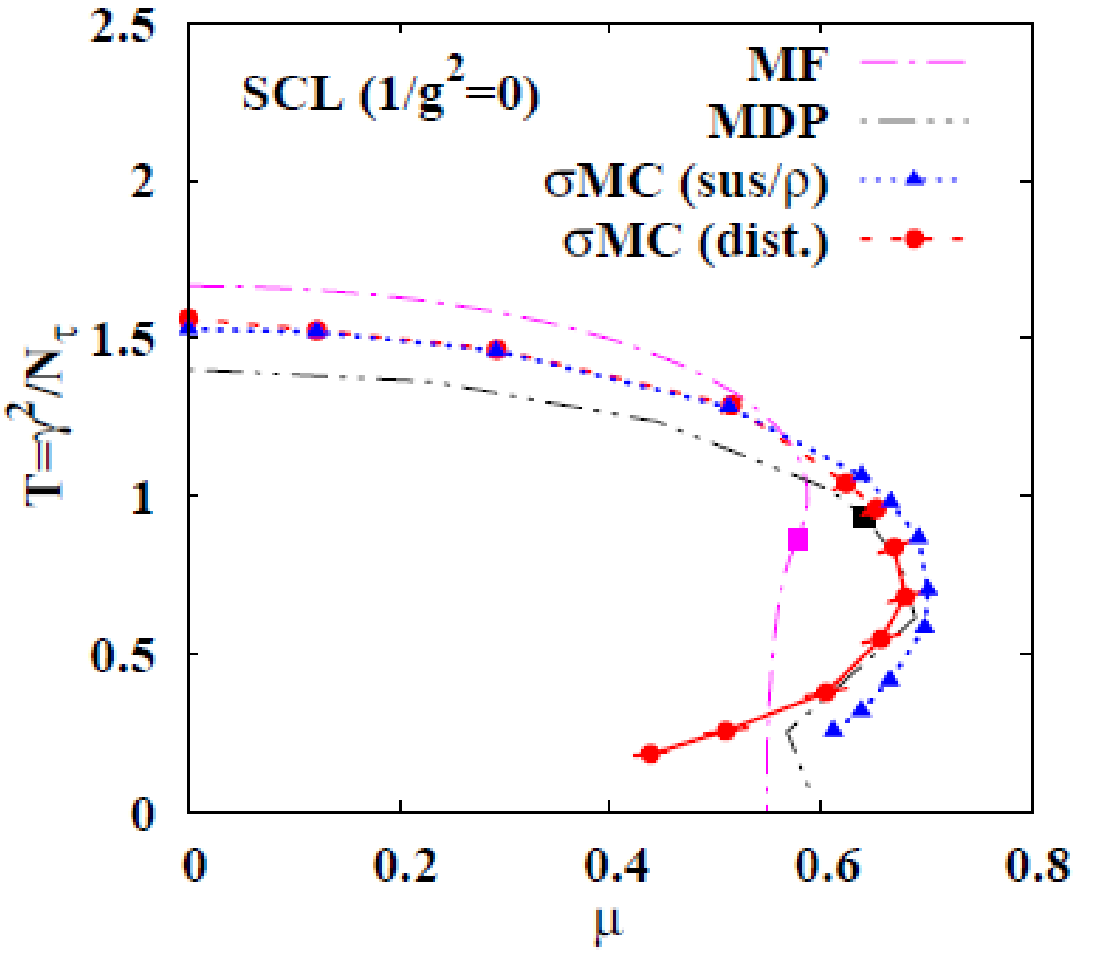
- **Mean-field results = no fluc. in the auxiliary fields → What happens when we include the fluctuation ?**
  AO, Nakano, in prep.
- **Small lattice result (4^4 lattice) in the strong coupling limit.**
  - **Sign problem is weak. <cos θ> > 0.9**
  - **Chiral susceptibility shows smooth peak at small μ/T and sharp peak at large μ/T**
  - **Quark number density shows smooth increase at small μ/T and sharp increase at large μ/T (finite size → two step increase)**



Phase diagram in the strong coupling limit

- **Definitions of phase boundary**
  - **$\phi^2 = \sigma^2 + \pi^2$ dist. peak: finite or zero (red curve)**
  - **Chiral susceptibility peak (blue)**
- **Fluctuation effect**
  - **Reduction of T_c at μ=0**
  - **Enlarged hadron phase at medium T**

→ Consistent with MDP
de Forcrand, Fromm ('09); de Forcrand, Unger ('11)



Summary

- ***High T phase transition: Successful example !***
  - **All of Lattice MC, Statistical model analyses of data, Dyanmical approach suggest the same conclusion. QGP is formed !**
  - **Question: $T_c(\chi_\sigma) < T_{CFO}$? Then what is the partial restoration effects ?**
- ***QCD critical point = cornerstone of the phase diagram.***
  - **Recent lattice MC & chem. freeze-out line suggest CP may be probed in HIC. CP predicted in effective models is accessible during BH formation.**
  - **Question: Which is true ? What is the real signal ?**
- ***Phase structure at high densities is a challenge in HIC and Astrophysics.***
  - **Experimental / Observational results are essential to understand the phase structure at high densities. How can we observe quark matter ?**
- ***Ab initio approaches are desired, and there are some promising attempts !***
  - **Various approaches in finite density lattice QCD, Func. RG methods, ...**
- ***Exotic hadron nature may be studied in HIC.***

Thank you for your attention !

- **Coalescence model**

$$N_h^{\text{coal}} \simeq g_h \int \left[\prod_{i=1}^{n} \frac{d^3x\, d^3p}{(2\pi)^3} \boxed{f(x_i, p_i)} \right] \times \boxed{f^W(x_1, x_2, \ldots x_n; p_1, p_2, \ldots p_n)}$$

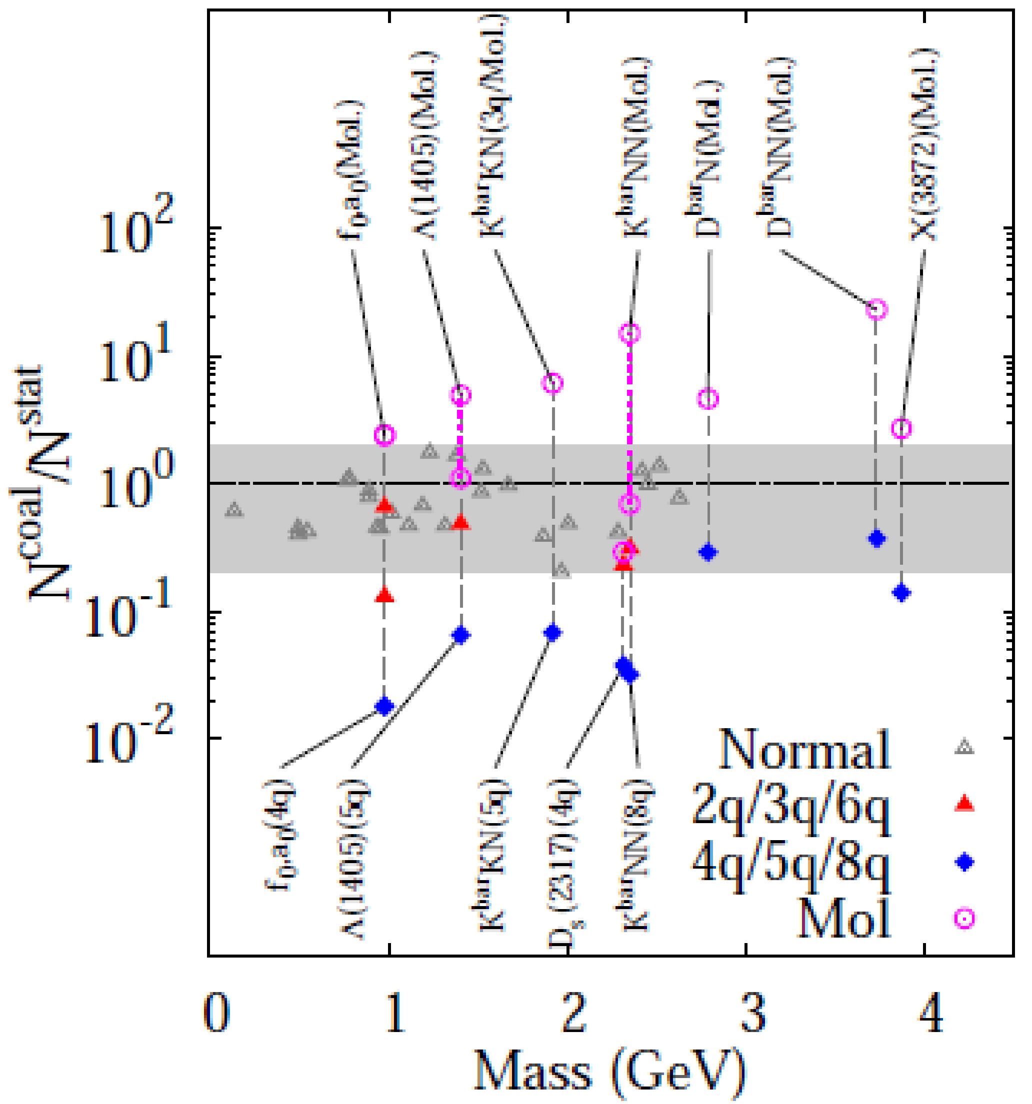
Dist. of const.

Intrinsic Wigner func.

  - **Successful in explaining baryon enhancement, quark number scaling of v_2, .**

- **Assuming that coalescence formation is dominant, we can utilize *Hadron Yield in HIC as a ruler of hadron size*.**

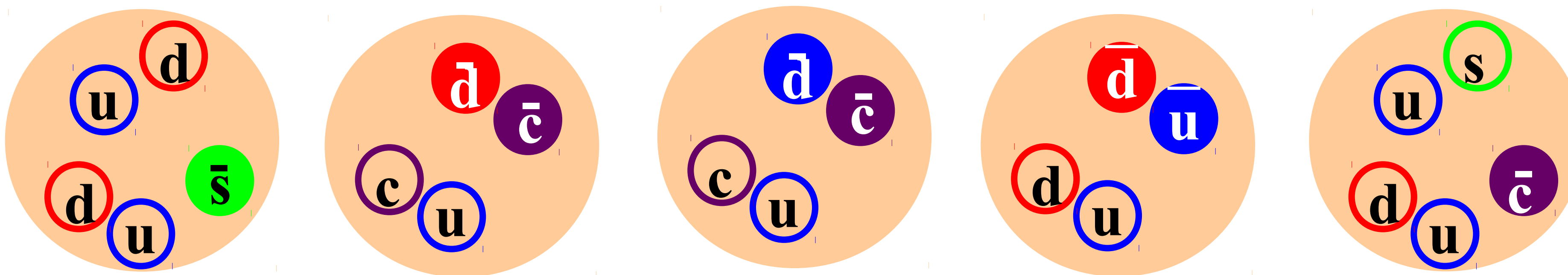
Coal. / Stat. ratio at RHIC



Cho, Furumoto, Hyodo, Jido, Ko, Lee, Nielsen, AO, Sekihara, Yasui, Yazaki (ExHIC Collab.), PRL('11)212001; arXiv:t:1107.1302

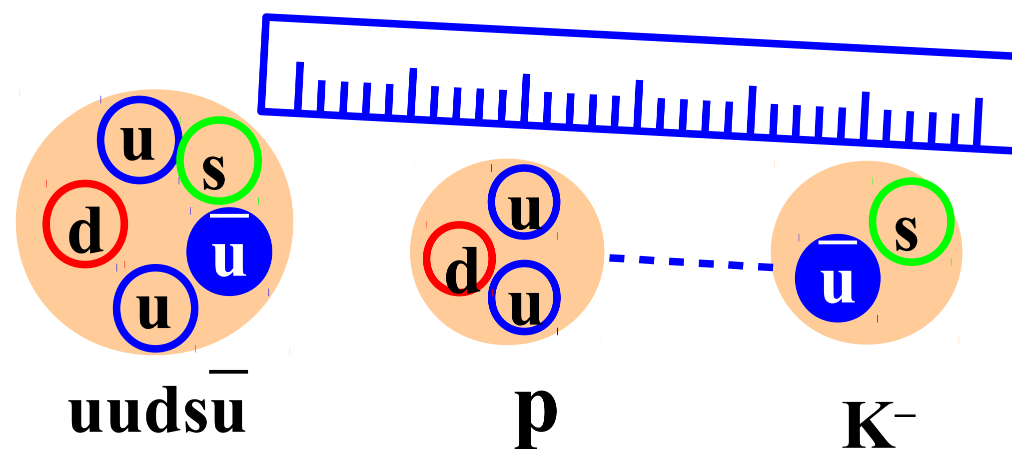
Related Topics: Exotic Hadrons

- **Exotic hadrons**
  → Θ⁺, Z, X, Y, ... Discovered/Proposed at LEPS, Belle, BaBar,...



Θ^+ | Z(4430) | X(3872) | f_0 | Θ^+_{cs}

- **X, Y, Z particles from Belle**
  Talk by S. Olsen (Sep.26, 15:35-)
- **Relation to HICs**
  Can we distinguishi various pictures (Di-quark, Hadronic molecule, Tetraquark) ?
  → Production Yields in HIC.



Λ (1405)