Probing the QCD Critical Point in Core Collapsing Compact Stars

Akira Ohnishi (YITP)

in collaboration with H. Ueda, T.Z.Nakano (Kyoto U.), M. Ruggieri (YITP → Catania), K. Sumiyoshi (Numazu CT)

7th Int. workshop on

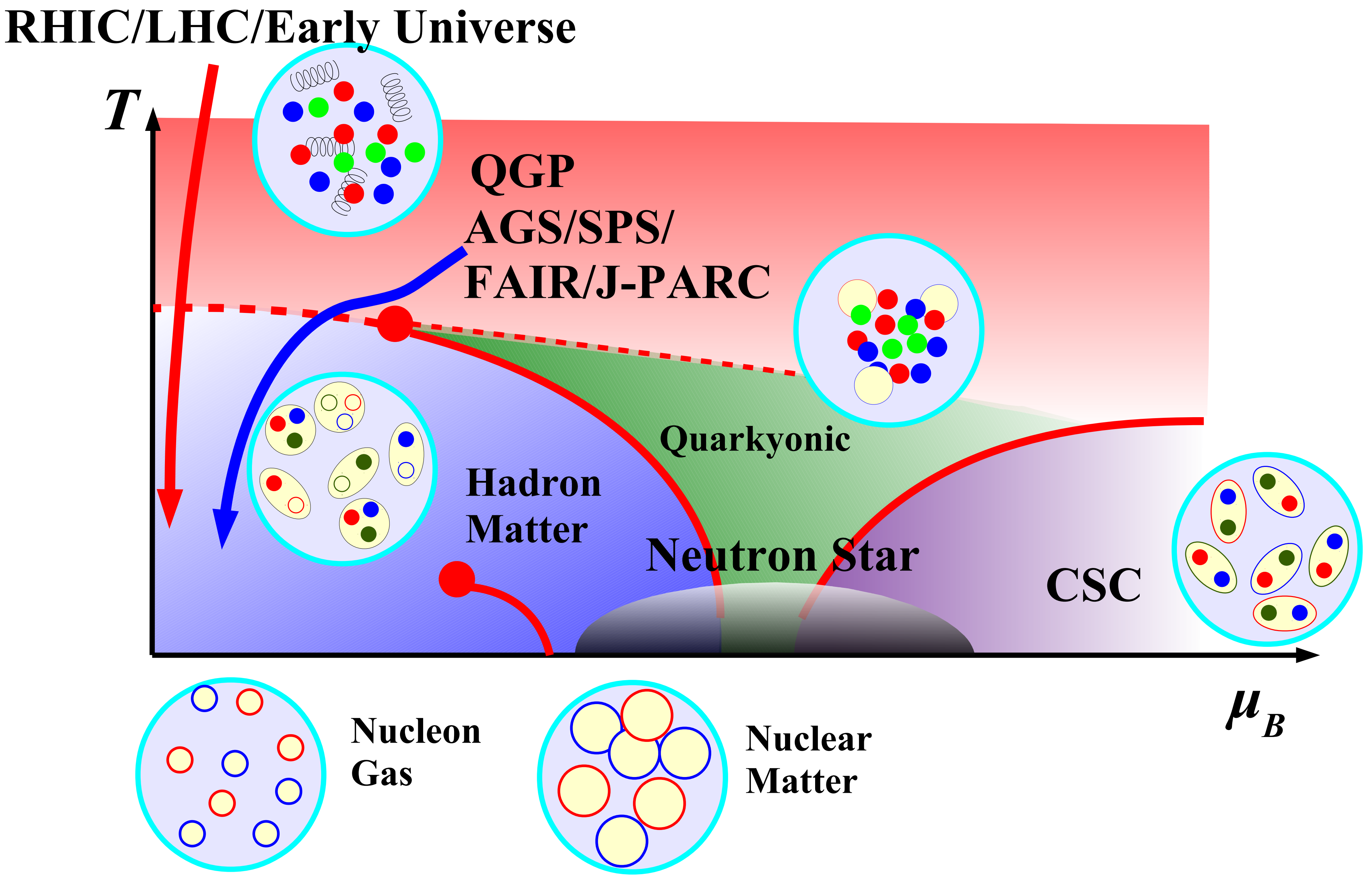
"Critical Point and Onset of Deconfinement"

CCNU, Wuhan, China, Nov.7-11, 2011

- **Introduction**
- **QCD phase diagram in asymmetric nuclear matter**
- **Critical Point sweep during black hole formation**
- **Summary**

AO, H. Ueda, T.Z.Nakano, M. Ruggieri, K. Sumiyoshi, PLB 704 ('11)284 [arXiv:1102.3753].

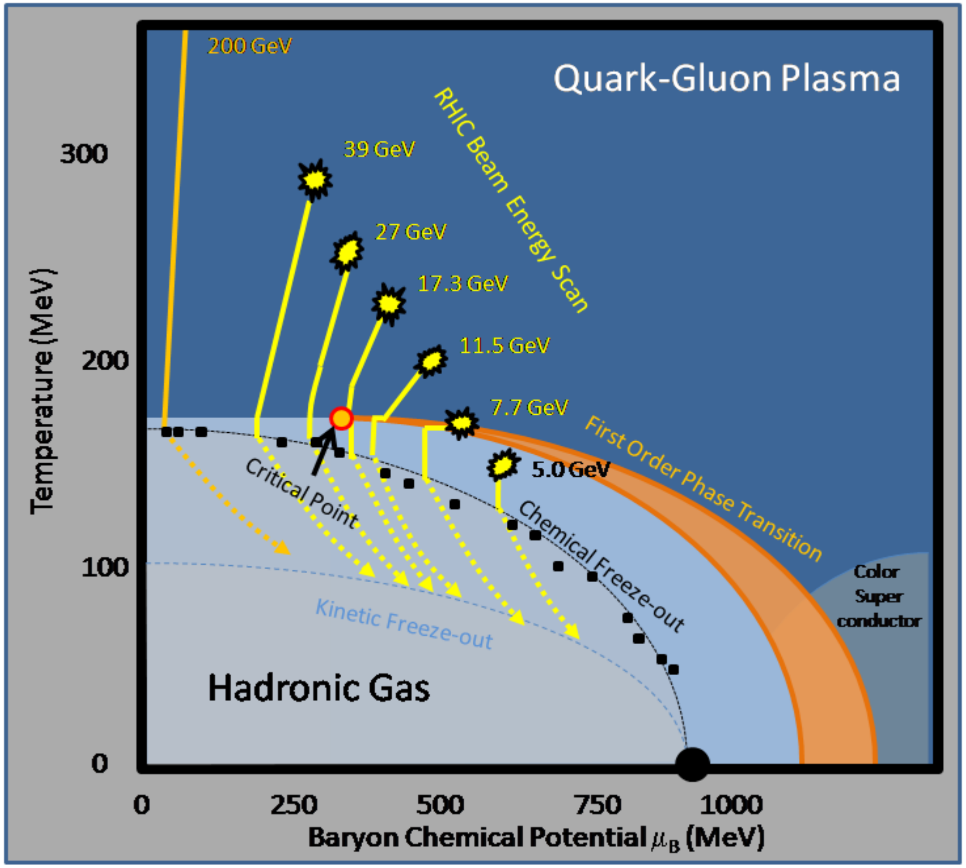
QCD Phase Diagram



Critical Point Search

- **Physics of QCD phase diagram connects the birth of our universe and the final form of materials, and is probed in laboratory.**
- **Critical Point is a Corner Stone of the phase diagram, and is accessible if μ_{CP} < 500 MeV.**

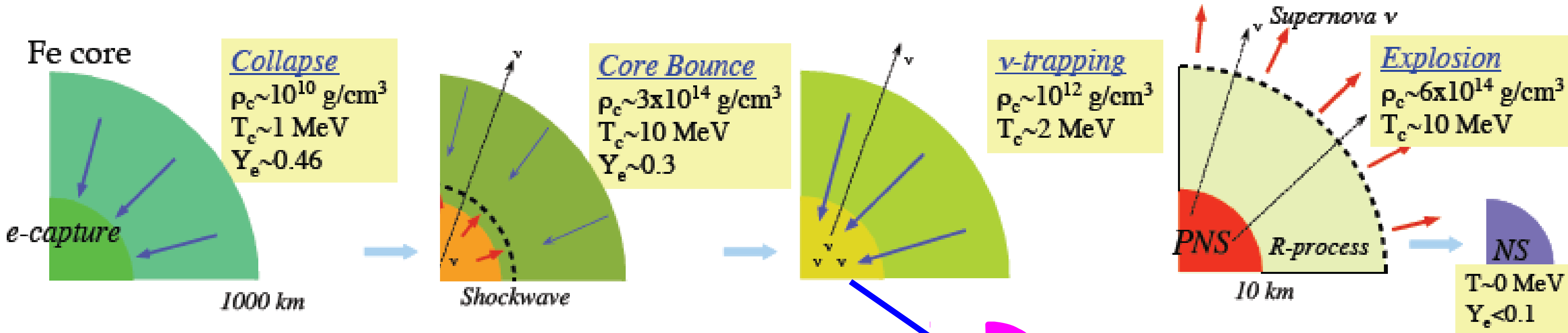
Are there any other sites where Hot and Dense matter is formed ?
→ Compact Astrophysical Phenomena !

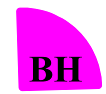


Quark Matter in Compact Stars

- **Neutron Star**
  E.g. N. Glendenning, "Compact Stars";F. Weber, Prog.Part.Nucl.Phys.54('05)193
  - **Cold (T~0), Dense (ρ_B~5 ρ_0), Highly Asymmetric (Y_p ~ (0.1-0.2))**
- **Supernovae** *T. Hatsuda, MPLA2('87)805; I. Sagert et al., PRL102 ('09) 081101.*
  - **Warm (T~20 MeV), Dense (ρ_B~1.8 ρ_0), mildly asym. (Y_p~ (0.3-0.4))**
- **Neutron star merger**
  - **Very dense, warm (T~(10-20) MeV)**
- ***Dynamical black hole formation***
  K. Sumiyoshi, et al., PRL97('06) 091101;
  K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki, ApJL690('09),L43
  - **Hot (T~(70-90)MeV), Dense(ρ_B~(4-5)ρ_0), and Asymmetric (Y_p ~ (0.1-0.3))**

Gravitational Collapse of Heavy Star





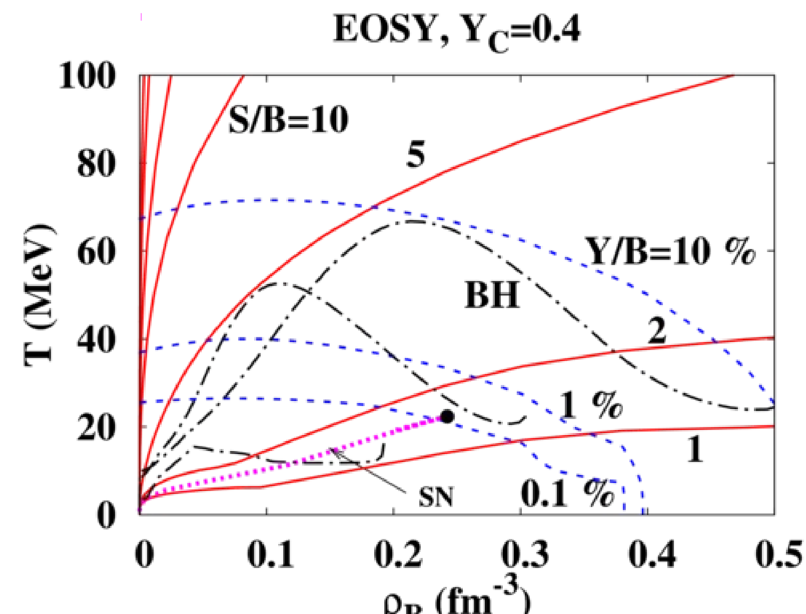
T ~ (70-90) MeV
Ye ~ (0.1-0.3)

- **Core collapse supernova (type II)**
  Fe core collapse → Core bounce
  → ν trapping
  → proto-neutron star
  + explosion of envelope

- **or → Black Hole formation**
  + Failed Supernova

  M. Liebendorfer et al., ApJS 150('04)263
  K. Sumiyoshi et al., PRL 97('06)091101

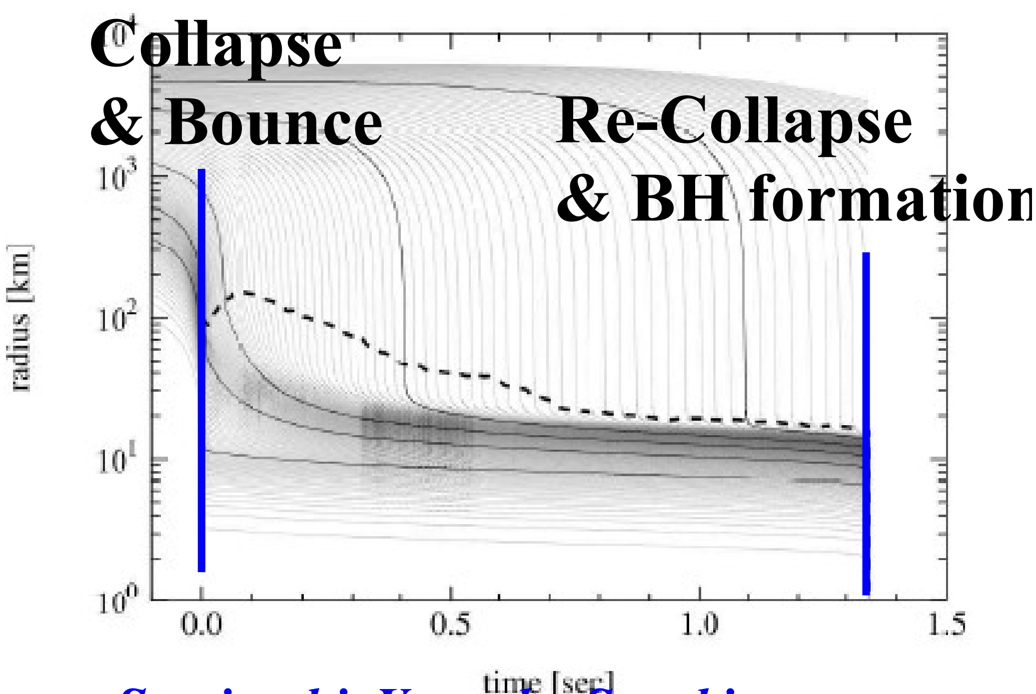
  - **Dynamical collapse with accretion.**
  - **Hot and Dense nuclear matter is formed**
    $T \sim (70\text{-}90)$ MeV, $\rho_B = 4\,\rho_0$



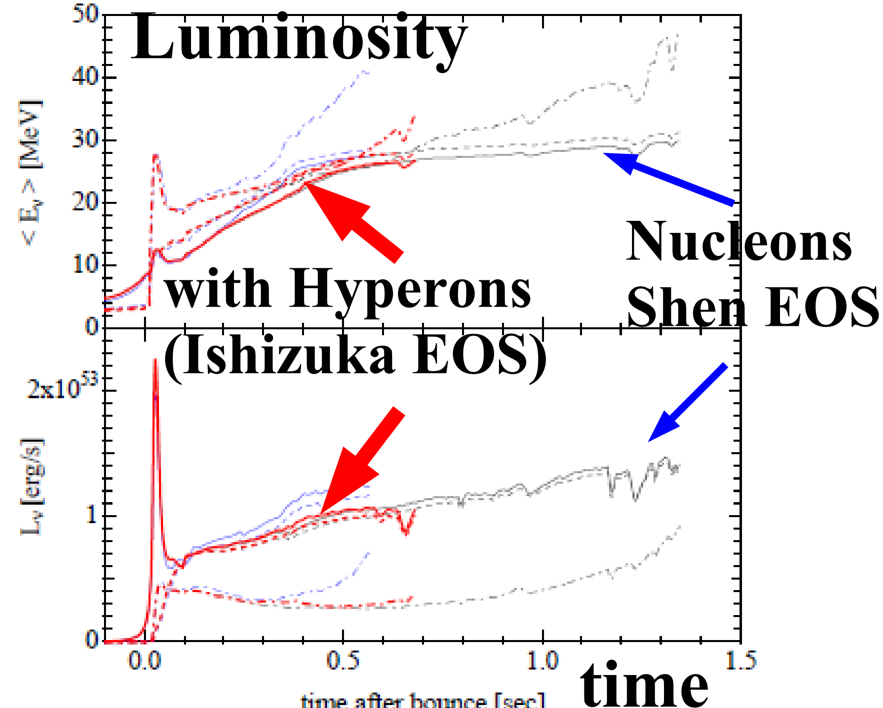
C.Ishizuka,AO,K.Tsubakihara, K. Sumiyoshi, S.Yamada, JPG 35('08) 085201;AO et al., NPA 835('10) 374.

Dynamical Black Hole Formation

- **Gravitational collapse of heavy (e.g. 40 $M_\odot$) progenitor would lead to BH formation.**
  - **Shock stalls, and heating by ν is not enough to take over strong accretion. → failed supernova**
  - **ν emission time ~ (1-2) sec w/o exotic matter.**
  - **emission time is shortened by exotic dof (quarks, hyperons, pions).**



Sumiyoshi, Yamada, Suzuki, Chiba, PRL 97('06)091101.

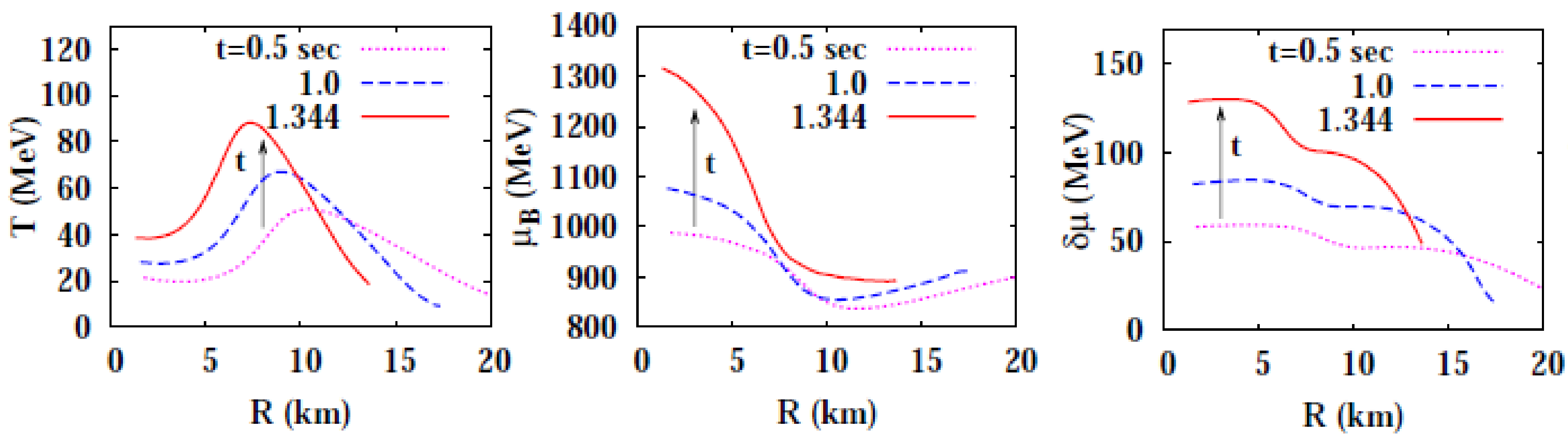


Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, ApJL 690('09)43.

Thermal Condition during BH formation

- **Quark-hadron and nuclear physicists are interested in (T, μ) !**
  - **Maximum T ~ 90 MeV (off-center)**
    (Heated by shock propagation)
  - **Maximum μ_B ~ 1300 MeV (center)**
  - **Maximum $\delta\mu = (\mu_n - \mu_p)/2$ ~ 130 MeV (center)**

Can we reach CP ? What is the effects of δμ ?



Nucleon+leptons+photon (Shen EOS), 40 Msun

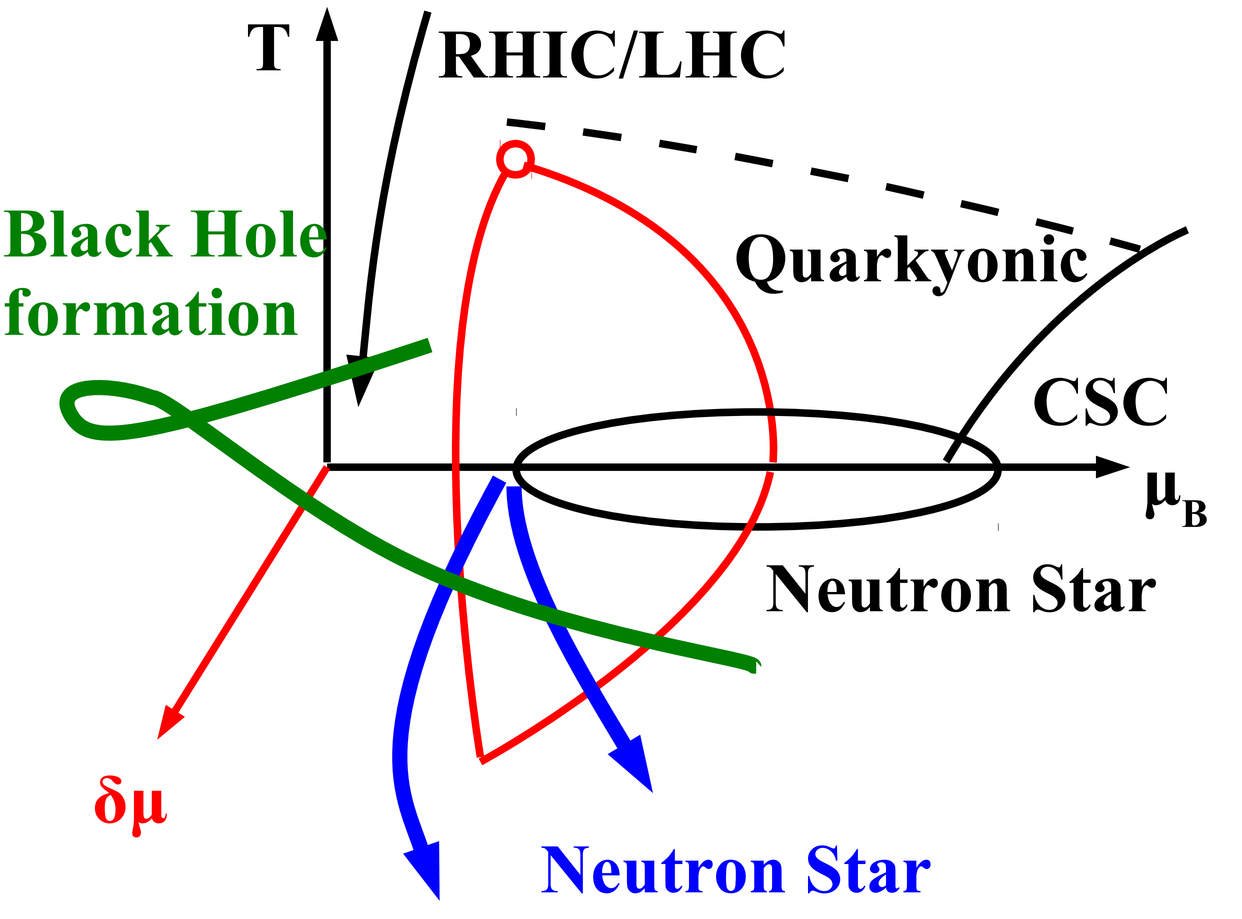
AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284

QCD phase diagram in Compact Astrophys. Phen.

- **Phase diagram probed in High-Energy Heavy-Ion Collisions**
  - **Hot & Dense *Symmetric* matter**
- **Phase diagram probed in Compact Astrophysical Phenomena**
  - **Hot and/or Dense *Asymmetric* matter**

→ 3D phase diagram must be considered !
(c.f. P. Zhuang)

We compare the 3D phase diagram in effective models and thermal condition in Compact Stars



Model Details

- **BH formation calculation**

  Sumiyoshi, Yamada, Suzuki, Chiba, PRL 97('06)091101.

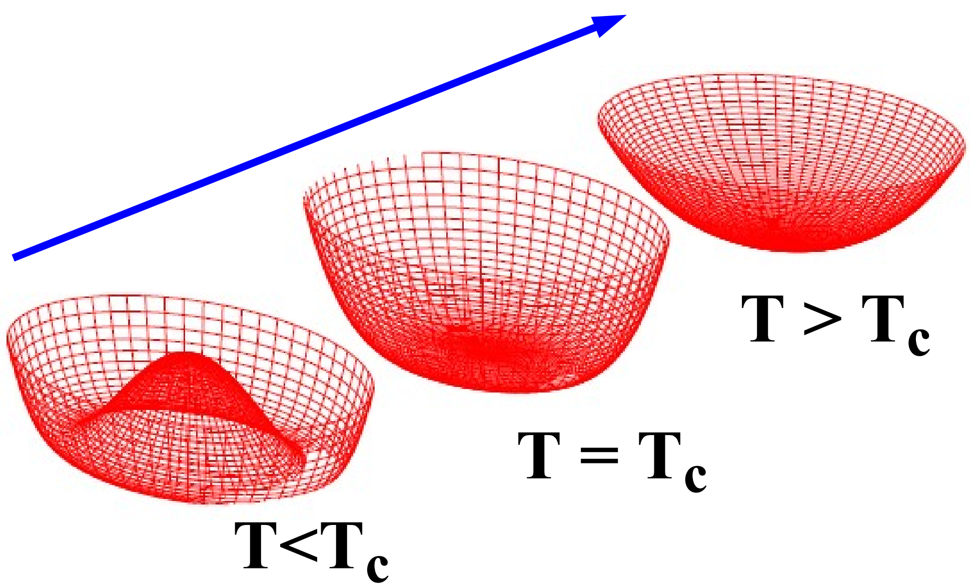
  - **ν radiation 1D (spherical) Hydrodynamics**
  - **ν transport is calculated exactly by solving the Boltzmann eq.**
  - **Gravitational collapse of 40 $M_\odot$ star**
  - **Initial condition: WW95**

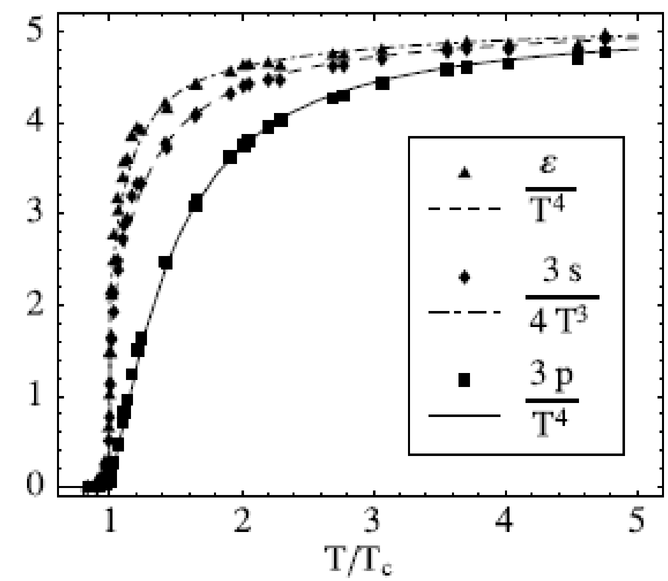
    S.E.Woosley, T.A.Weaver, ApJS 101 ('95) 181
  - **Shen EOS (npeμ)**
- **QCD effective models**
  - **NJL, PNJL, PNJL with 8 quark int., PQM**
  - **N_f=2**
  - **Vector coupling → G_V/G_S (g_V/g_S in PQM)=0, 0.2**

Phase diagram in (Isospin) Asymmetric Matter

Chiral Effective Models

- **Approaches to Phase Diagram**
  - **Lattice QCD:**
    Reliable at small μ (μ << T), but has the sign problem at large μ
  - **Chiral Effective models: NJL, PNJL, PQM**
    Nambu, Jona-Lasinio ('61), Fukushima('03), Ratti, Thaler, Weise ('06), B.J.Schafer, Pawlowski, Wambach ('07); Skokov, Friman, E.Nakano, Redlich('10)
    Spontaneous breaking & restoration of chiral symmetry
    Polyakov loop extension → Deconf. transitions





Roessner et al.('07)

Chiral Effective Models (N_f=2)

- **Lagrangian (PQM, as an example)**

$$L=\bar{q}\left[i\gamma^\mu \underline{D_\mu} - g_\sigma \underline{(\sigma+i\gamma_5 \boldsymbol{\tau}\cdot\boldsymbol{\pi})}\right]q+\frac{1}{2}\partial^\mu\sigma\,\partial_\mu\sigma+\frac{1}{2}\partial^\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}$$

q-Pol. **quark-meson**

$$-\underline{U_\sigma(\sigma,\pi)}-\underline{U_\Phi(\Phi,\bar{\Phi})}$$

chiral **Polyakov**

$$F_{\text{eff}}\equiv\Omega/V=U_\sigma(\sigma,\pi=0)+U_\Phi(\Phi,\bar{\Phi})+\underline{F_{\text{therm}}}+\underline{U_{\text{vac}}(\sigma,\Phi,\bar{\Phi})}$$

particle exc. **q zero point**

- **Polyakov loop effective potential from Haar measure**

  U_Φ ~ -log (Haar Measure) **(Fit lattice data to fix parameters).**

- **Vector coupling is not known well → Comparison of g_V/g_S=0, 0.2**

$$L_V=-g_v\bar{q}\gamma_\mu(\omega^\mu+\boldsymbol{\tau}\cdot\boldsymbol{R}^\mu)q-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu}-\frac{1}{4}\boldsymbol{R}_{\mu\nu}\cdot\boldsymbol{R}^{\mu\nu}+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu+\frac{1}{2}m_\rho^2 R_\mu R^\mu$$

- **8 Fermi interaction**

T. Sasaki, Y. Sakai, H. Kouno, M. Yahiro ('10)

$$G_{\sigma 8}\left[(\bar{q}q)^2+(\bar{q}i\gamma_5\boldsymbol{\tau}q)^2\right]^2$$

Isospin chemical potential

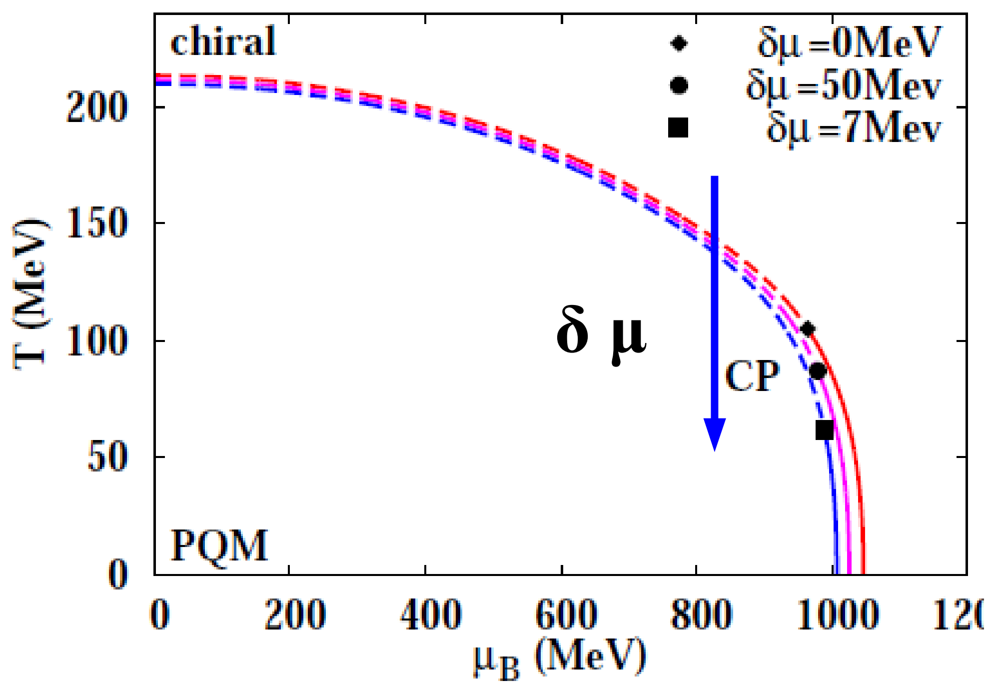
- **Isospin chemical potential $\delta\mu$**

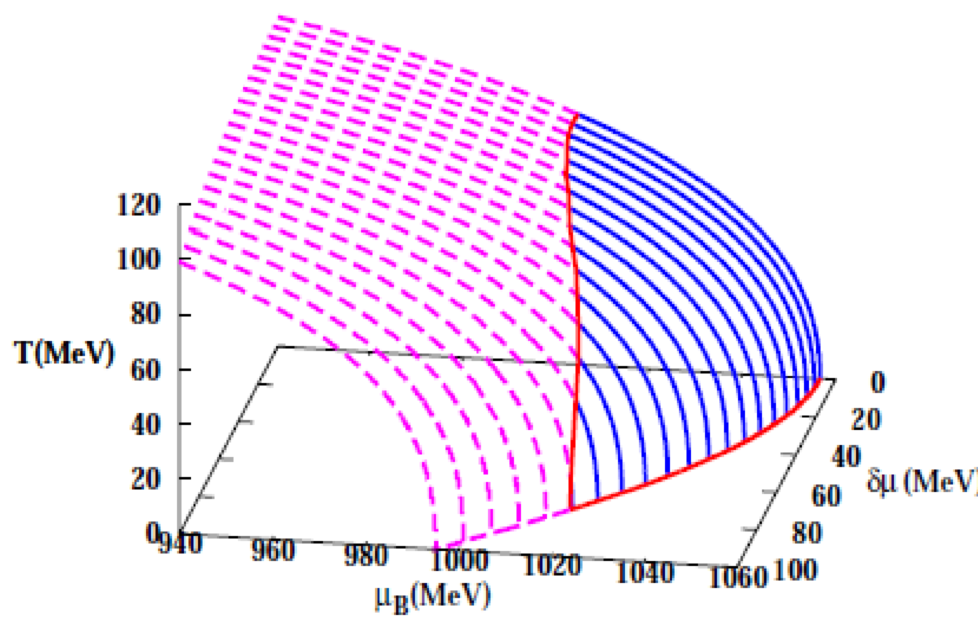
  $$\delta\mu = (\mu_d - \mu_u)/2 = (\mu_n - \mu_p)/2 \rightarrow \mu_d = \mu_q + \delta\mu,\ \ \mu_u = \mu_q - \delta\mu$$

  - **Finite $\delta\mu$ → (Isospin) Asymmetric matter $N_u \neq N_d$**

    → Smaller "Effective" number of flavors

    → Weaker phase transition → smaller T_{CP}



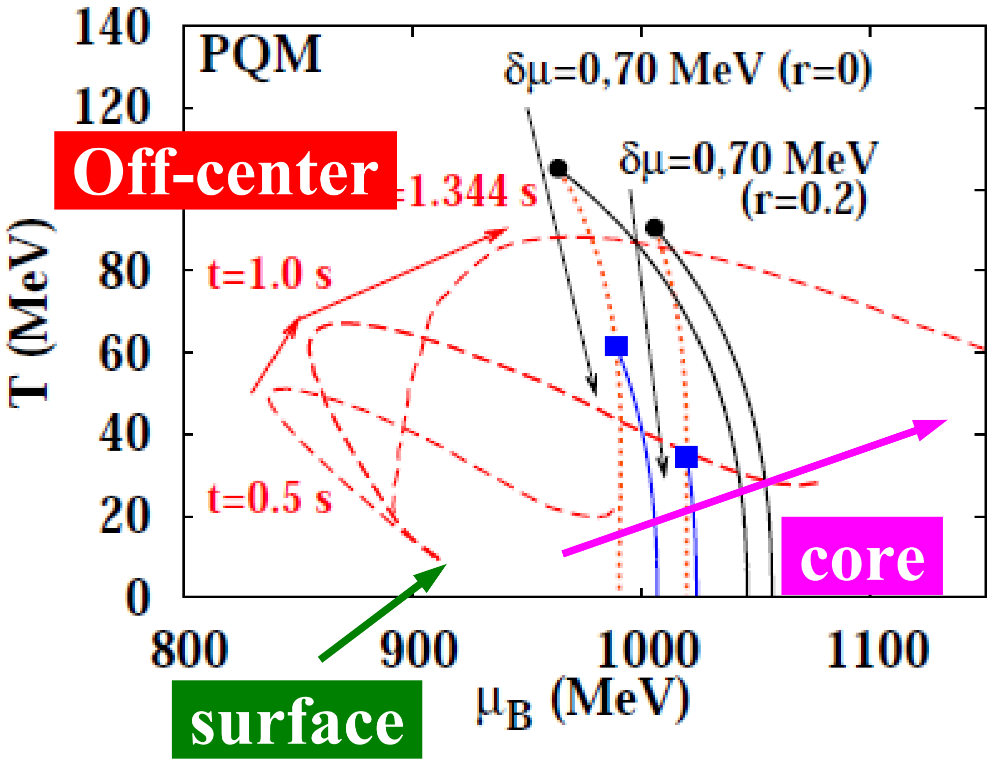


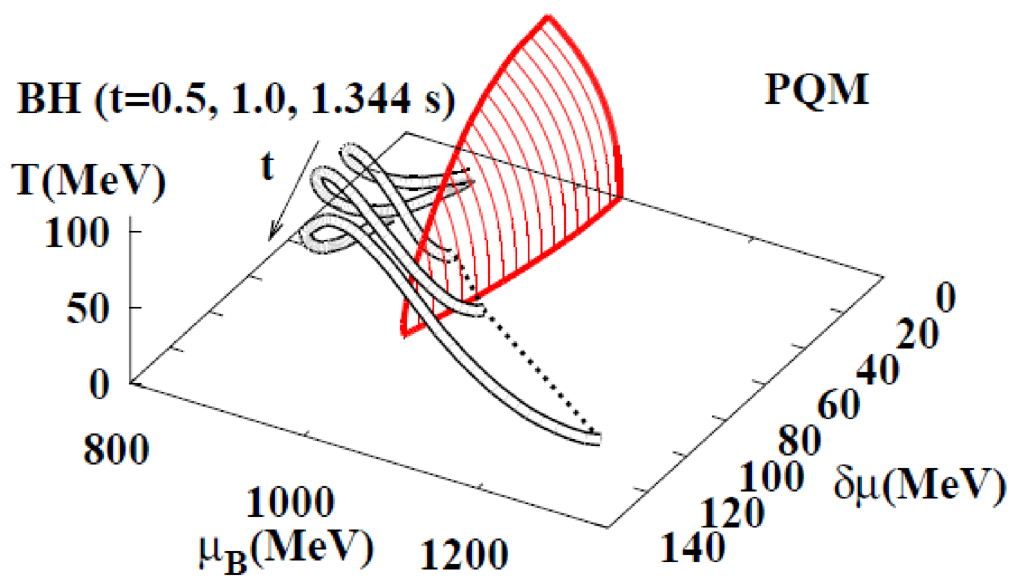
H. Ueda, et al, in preparation

Critical Point sweep during black hole formation

How is quark matter formed during BH formation ?

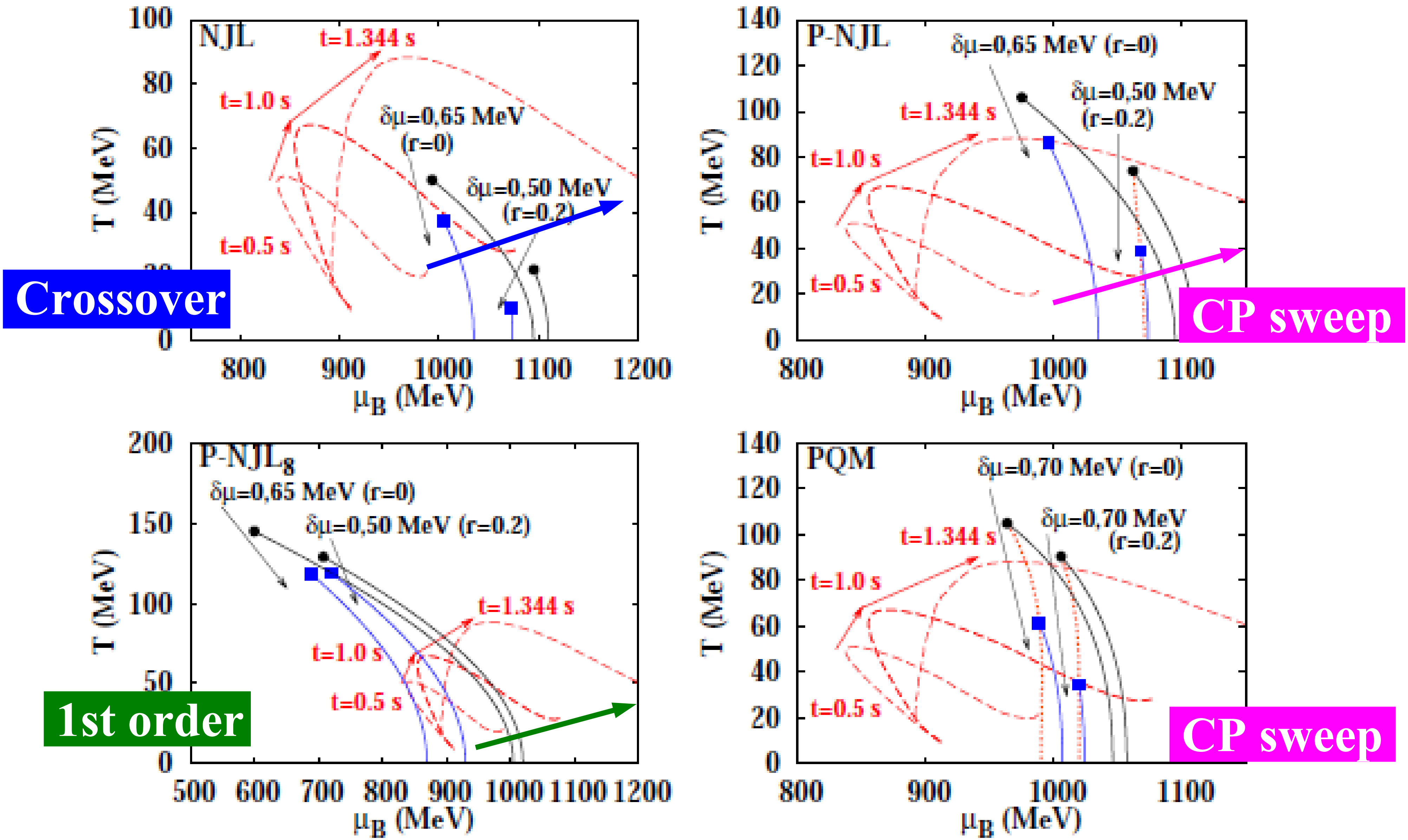
- Highest μ_B just before horizon formation ~ 1300 MeV
  > QCD transition μ (1000-1100 MeV)
  → *Quark matter is formed before BH formation*
- Core evolves below CP, Off-center goes above CP
  → *CP sweep*





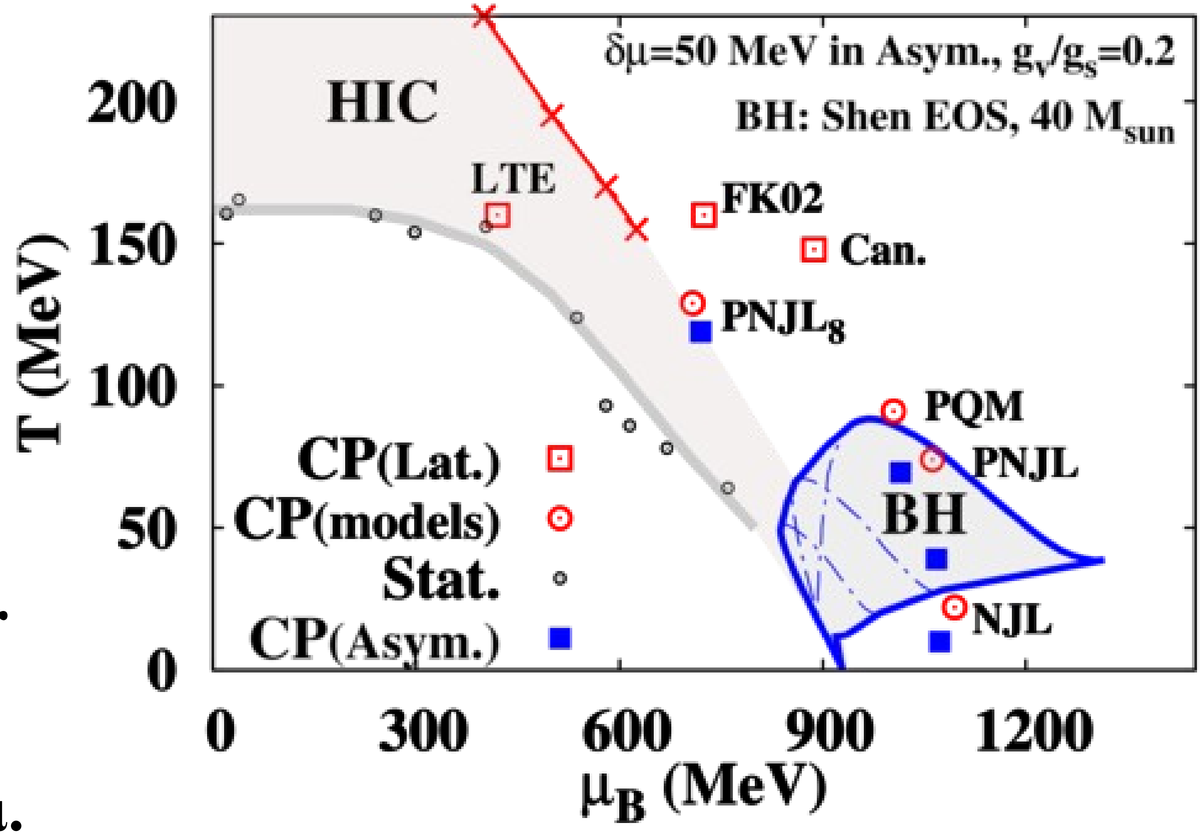
How is quark matter formed during BH formation ?

- **Model dependence to form quark matter → Three ways**



Swept Region of Phase Diagram during BH formation

- **CP location in Symmetric Matter**
  - **Lattice QCD**
    μ_{CP}=(400-900) MeV
  - **Effecitve models**
    μ_{CP}=(700-1050) MeV
- **CP in Asymmetric Matter (E.g. $\delta\mu$=50 MeV)**
  - **T_{CP} decreases at finite $\delta\mu$.**
    → Accessible (T, μ_B) region during BH formation

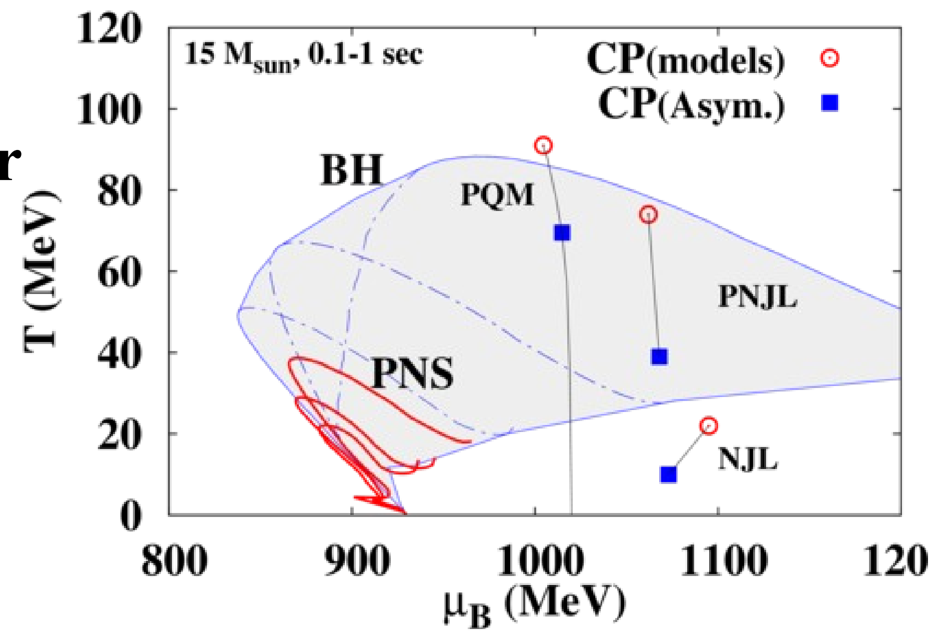


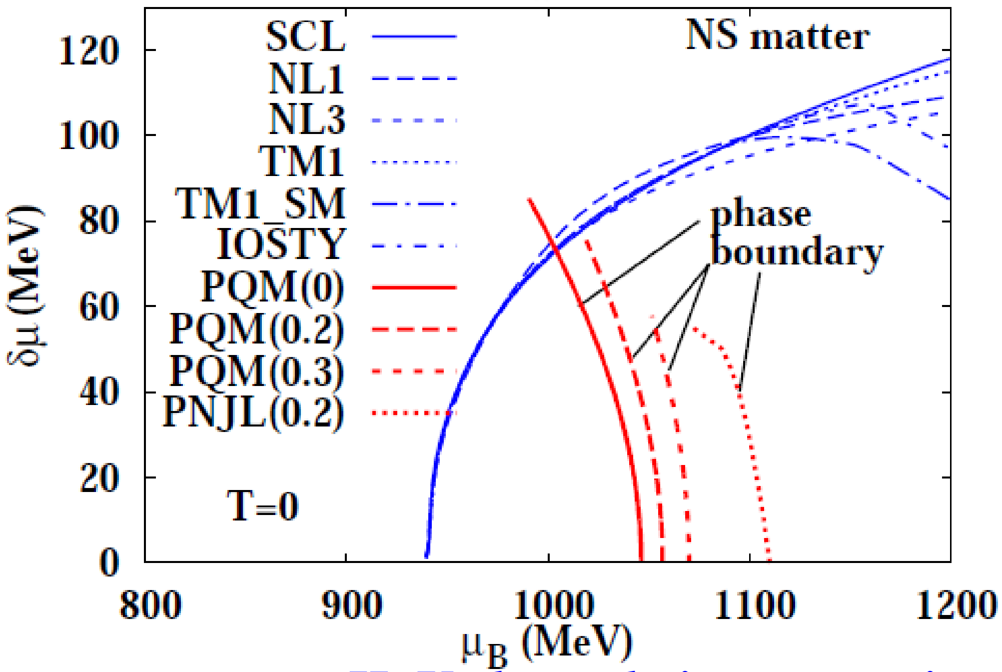
(Stephanov plot)

M.A.Stephanov, Prog.Theor.Phys.Suppl.153 ('04)139;
FK02:Z. Fodor, S.D.Katz, JHEP 0203 (2002) 014
LTE:S. Ejiri et al., Prog.Theor.Phys.Suppl. 153 (2004) 118;
Can: S. Ejiri, PRD78 (2008) 074507
Stat.:A. Andronic et al., NPA 772('06)167

How about Neutron Stars ?

- **Contraction of Proto-Neutron Star**
  - **(T, μ_B) are not enough at 1 sec after bounce of 15 $M_\odot$ star collapse**
  - **Larger (T, μ_B) is expected in long time evolution (~20 sec) or heavier proto-neutron stars.**
    K. Sumiyoshi et al. ApJ 629 ('05) 922;
    J. A. Pons et al., ApJ 513 ('99)780;
    J. A. Pons et al., ApJ 553 ('01) 382.
- **Cold Neutron Star**
  - **max. $\delta\mu$~ 100 MeV**
  - **Possibility of cross over in NS**

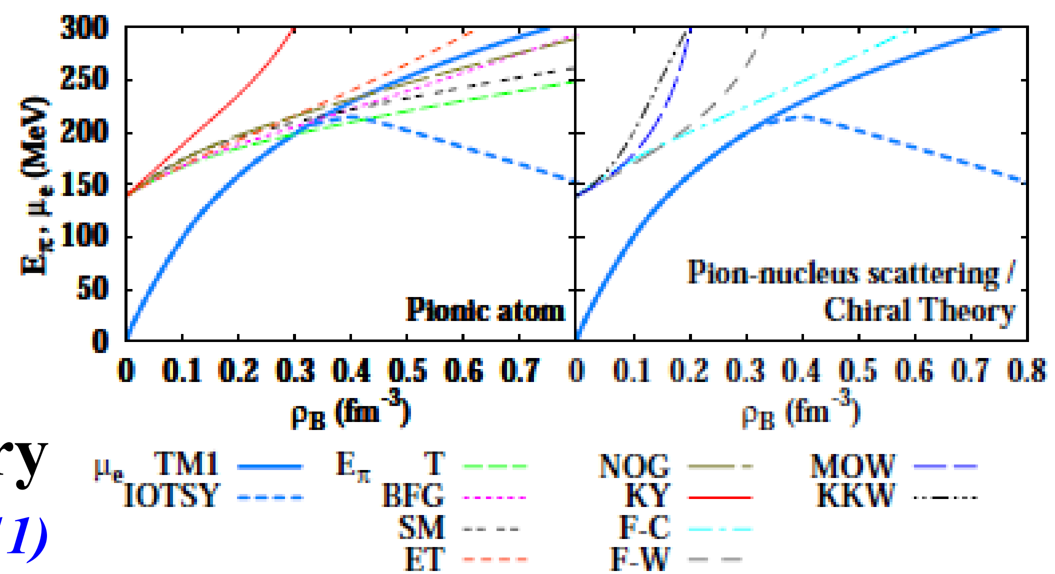




H. Ueda et al., in preparation

Discussion

- **How can we observe the phase transition signal ?**
  - **ν spectrum ? Gravitational waves ?**
    Supernova: Second peak in ν & $\bar{\nu}$ emission
    Hatsuda('87), Sagert et al.('09)
- **How frequent do dynamical BH formation take place ?**
  - **Less frequent than SN (< 20 $M_\odot$), but should be in collapse of heavy stars (>40 $M_\odot$).**
    C.L.Fryer, ApJ 522('99)413; E.O'Connor, C.D.Ott, ApJ 730('11)70
- **Strangeness may reduce δμ in hadronic / quark matter**
  - **No s-wave π cond. in NS**
    AO, D. Jido, T. Sekihara,
    K. Tsubakihara, PRC80('09)038202.
- **Hadron-Quark EOS is necessary**
  E.g. Steinheimer,Schramm,Stocker('11)



Summary and Discussion

- **Critical Point temperature is expected to be reduced in asymmetric nuclear matter.**
- **Black hole formation processes produce hot (~90 MeV) and dense (μ_B ~ 1300 MeV) matter, and we expect the formation of baryon rich quark matter.**
- **Since the temperature and asymmetry (δμ~130 MeV) are high, we have a possibility that CP is swept during BH formation.**
- **Construction of Hadron-Quark matter EOS with CP and its application to BH formation are desired. (c.f. J. Steinheimer; D. Blaschke)**

Thank you for your attention !

Collaborators

T.Z.Nakano (Kyoto U./YITP),
H. Ueda (Kyoto U.), M. Ruggieri (YITP)
K. Sumiyoshi (Numazu), K. Tsubakihara (Hokkaido U.),
C. Ishizuka (Tokyo U. of Sci.),
S. Yamada (Waseda), H. Suzuki (Tokyo U. Sci.),

Questions and Conclusion

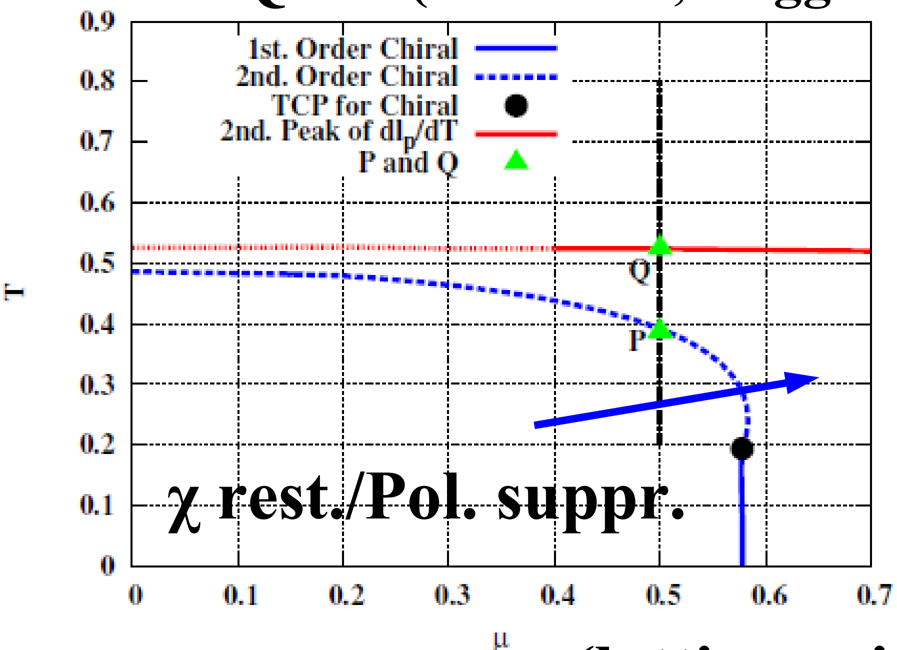
- ***Does Quarkyonic matter exist in QCD with N_c=3 ?***

  → **There is χ restored & Polyakov loop suppressed region at low T and large μ in Strong Coupling Lattice QCD**

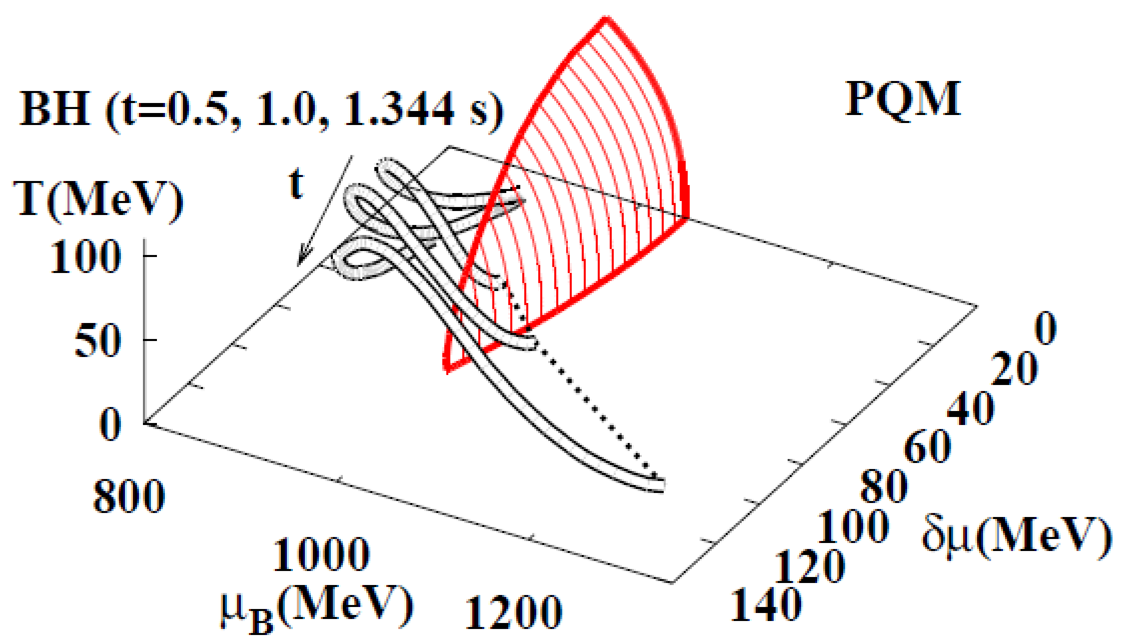
- ***Is there any site where Quarkyonic matter is formed ?***

  → **During the dynamical black hole formation, CP may be swept and quarkyonic matter may be formed.**

P-SC-LQCD (NLO+LO, staggered)

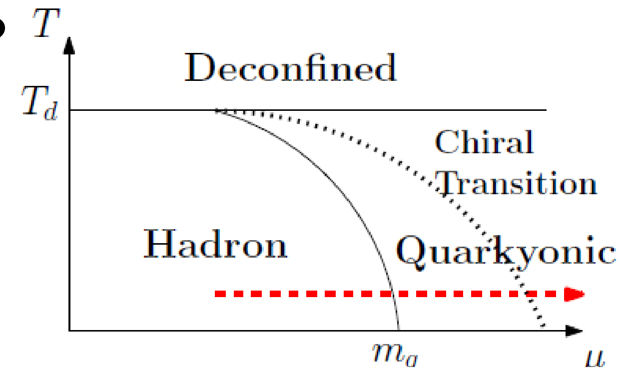


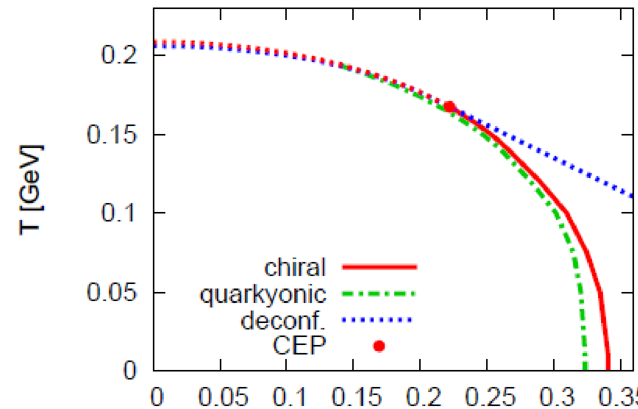
(lattice unit)



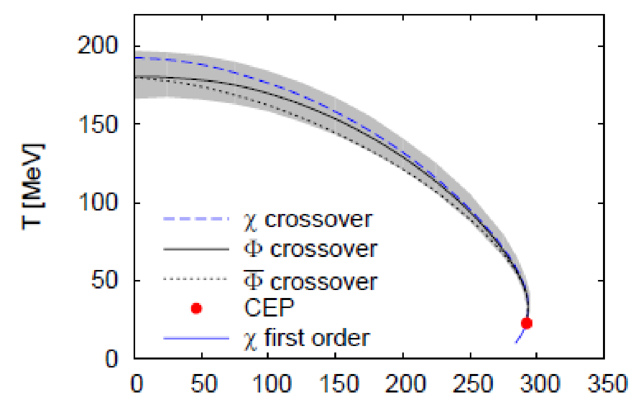
Quarkyonic matter

- **Do χ and Z_{N_c} transitions deviate at large μ ?**
  - **Large Nc: Yes**
    L. McLerran, R. D. Pisarski, NPA796 ('07)83
  - **Effective Models: Yes and No**
    - **Yes, in PNJL with some parameter set**
      L.McLerran, K.Redlich, C.Sasaki,NPA824('09) 86; H. Abuki et al.('08); Y.Sakai et al.,('10); D. Blaschke et al.('11)
    - **No, with FRG or phen. inputs**
      T. K. Herbst, J. M. Pawlowski, B. J. Schaefer, PLB 696 ('11)58 (PQM-FRG), K.Fukushima, PLB 695('11)387 (PNJL+Stat.)
- **QCD with Nc=3: Difficult**
  - **AC, Taylor expansion, … → μ/T<1**
  - **QCD-FRG: Not yet**
  - ***SC-LQCD: This work***





McLerran, Redlich, Sasaki ('09)



Herbst, Pawlowski, Schafer, ('11)

Strong Coupling Lattice QCD

- **SC-LQCD has been a successful tool from the beginning of the lattice QCD formulation !**
  - **Pure Yang-Mills theory → *Confinement***

    Area Law (Wilson ('74)), S.C. Expansion (Munster ('81)), ...,
    Finite T Pol. loop eff. action (Langelage, Münster, Philipsen ('08)), ..
  - **With fermion → *SSB and restoration of Chiral Symmetry***

    SSB [Kawamoto, Smit ('81)]
    meson mass [Kluberg-Stern, Morel, Petersson ('83)],
    Chiral restoration [Damgaard, Kawamoto, Shigemoto('84)],
    phase diagram [Bilic, Karsch, Redlich ('92), Fukushima ('04),
    Kawamoto, Miura, AO, Ohnuma ('07), de Forcrand, Fromm ('10)],
    Finite coupling [Miura, Nakano, AO, Kawamoto ('09-'11)]
  - **Combination → *Chiral and Polyakov loop dynamics***

    Chiral Polyakov Dynamics [Ilgenfritz, Kripfganz ('85),
    Gocksch, Ogilvie ('85), Fukkushima('03), Nakano, Miura, AO('11),
    Miura, Nakano, AO, Kawamoto('11)]

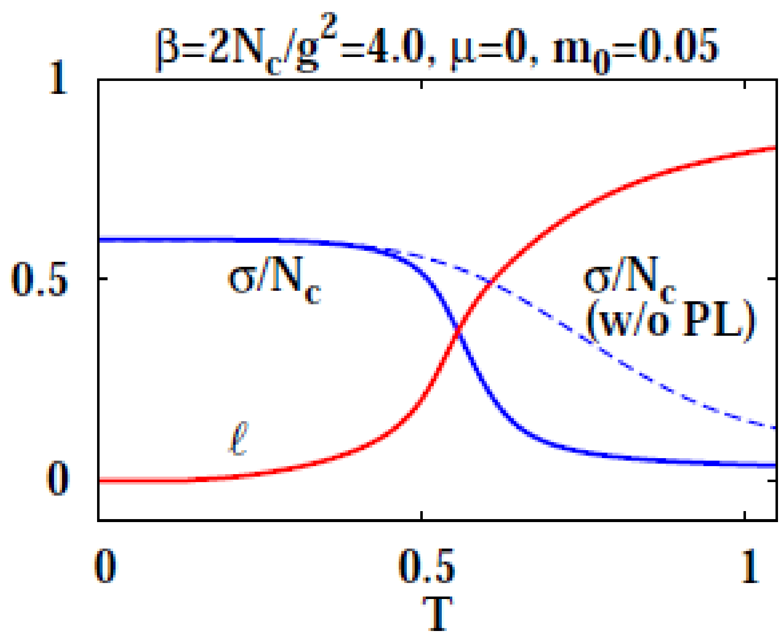
Does SC-LQCD show quarkyonic matter ?

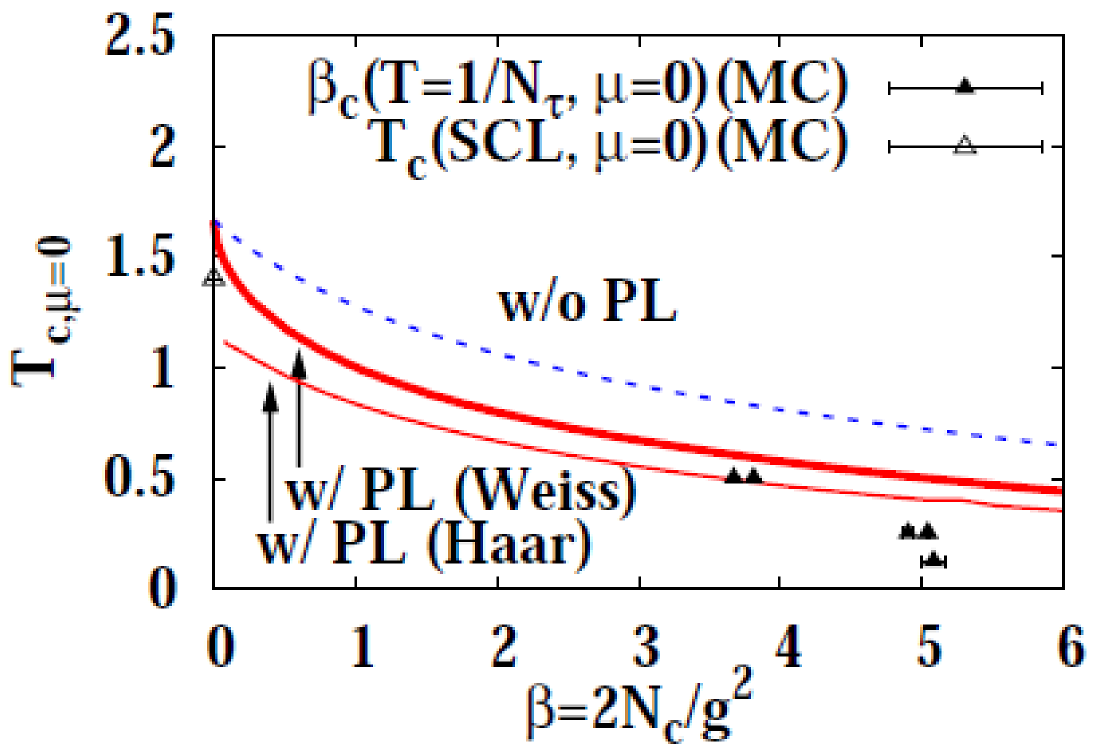
P-SC-LQCD at μ=0

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))



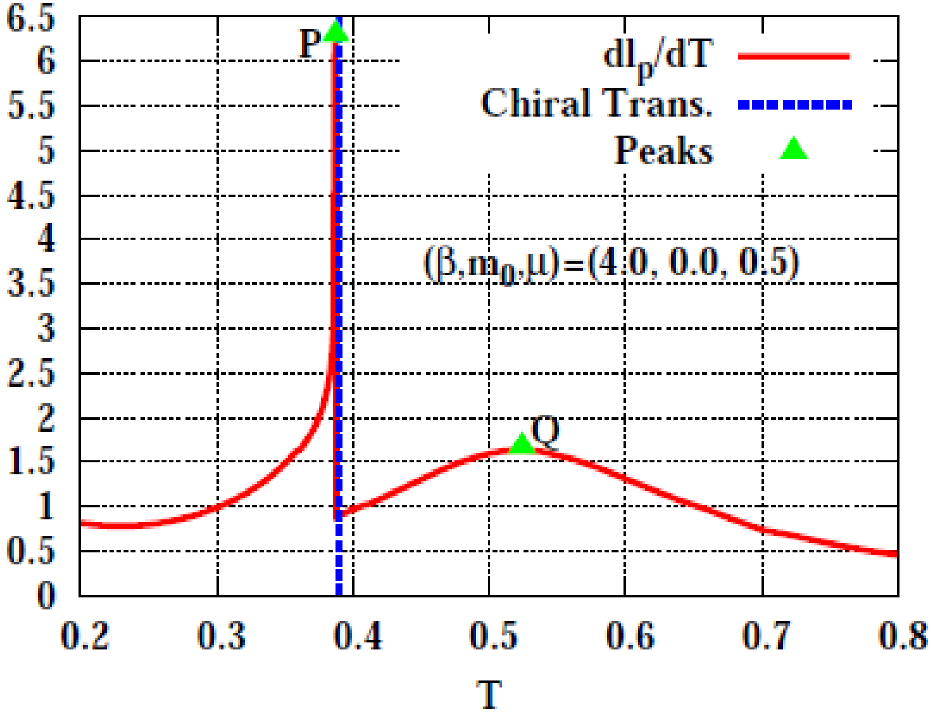


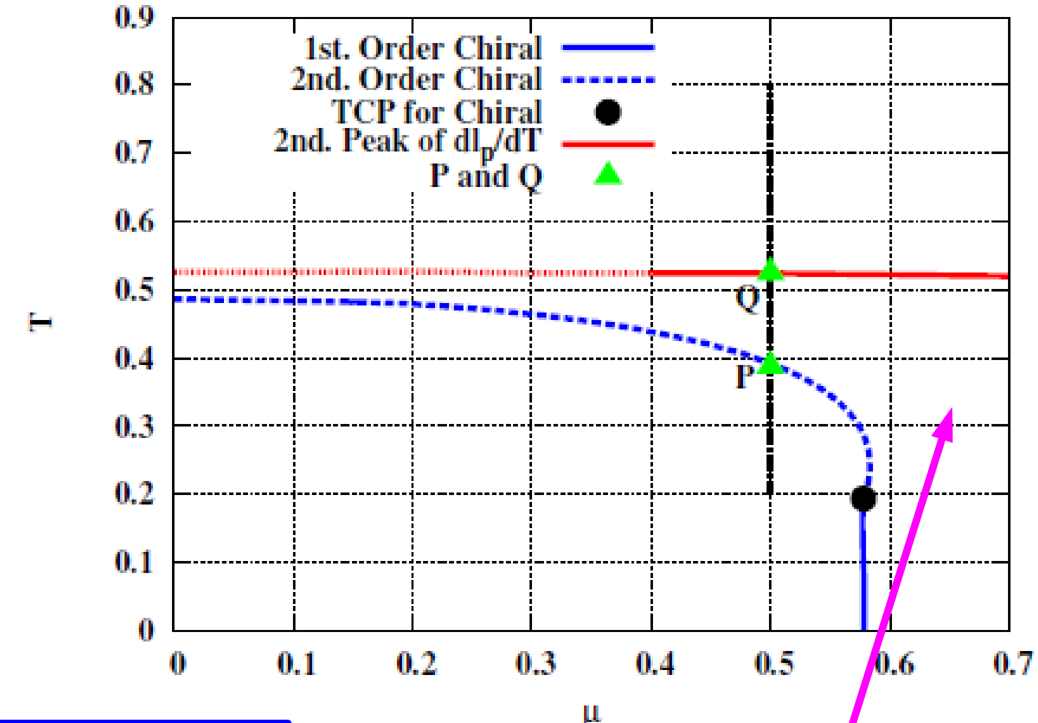
Lattice Unit

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.**





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

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