QCD critical point in the strong coupling lattice QCD and during black hole formation

Akira Ohnishi (YITP)

HIC for FAIR workshop & 28th Max Born Symposium

Three days on Quarkyonic Island, Wroclaw

- **Questions & Conclusion**
- **QCD phase diagram in strong coupling lattice QCD**
  K. Miura, T. Z. Nakano,AO, PTP 122('09)1045.
  K. Miura, T. Z. Nakano, AO, N. Kawamoto, PRD 80 (2009), 074034; PoS LAT2010 (2010), 202; in prep.
  T. Z. Nakano, K. Miura, AO, PTP 123('10)825; PRD 83('11)016014.
- **Critical Point sweep during black hole formation**
  AO, H. Ueda, T.Z.Nakano, M. Ruggieri, K. Sumiyoshi, arXiv:1102.3753.
  K. Sumiyoshi, C. Ishizuka, AO, S. Yamada, H. Suzuki , ApJL690('09),L43.
- **Summary**

Questions and Conclusion

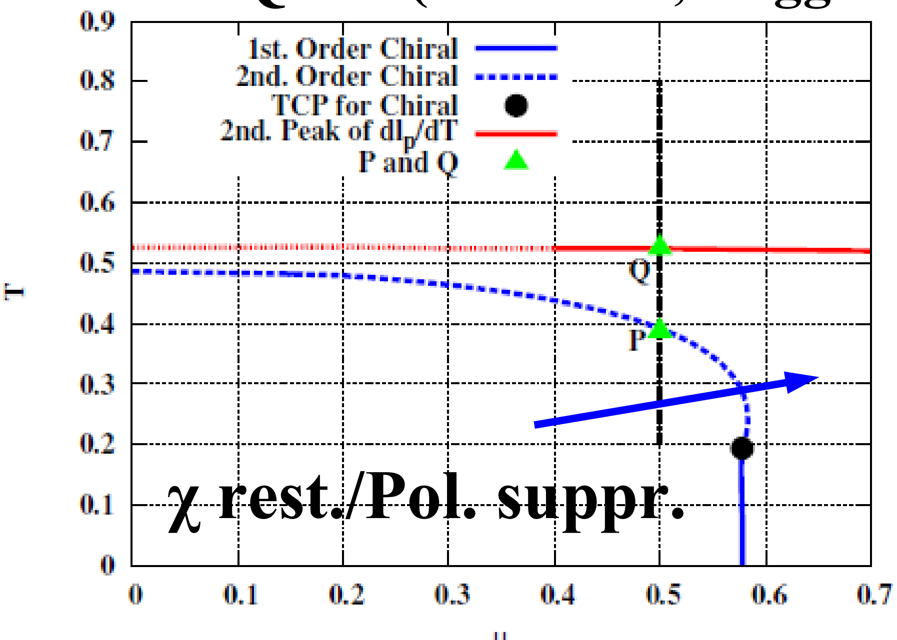
- ***Does Quarkyonic matter exist in QCD with N_c=3 ?***

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

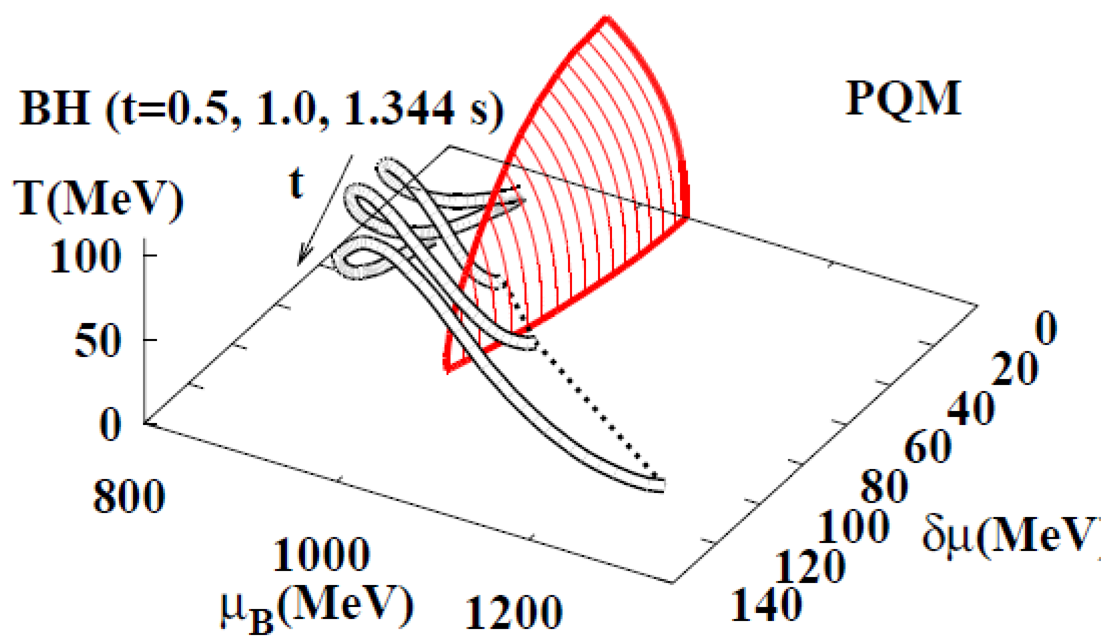
- ***Is there any site where Quarkyonic matter is formed ?***

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

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



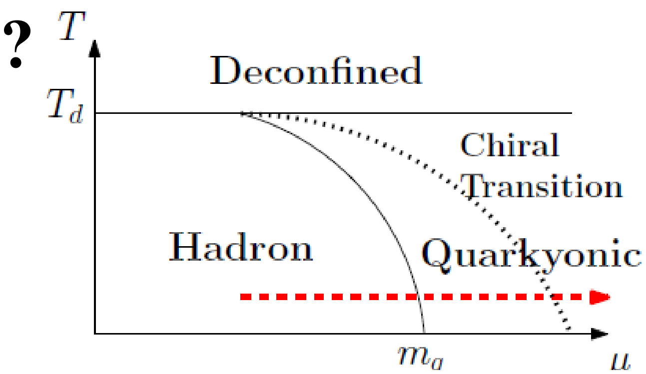
(lattice unit)

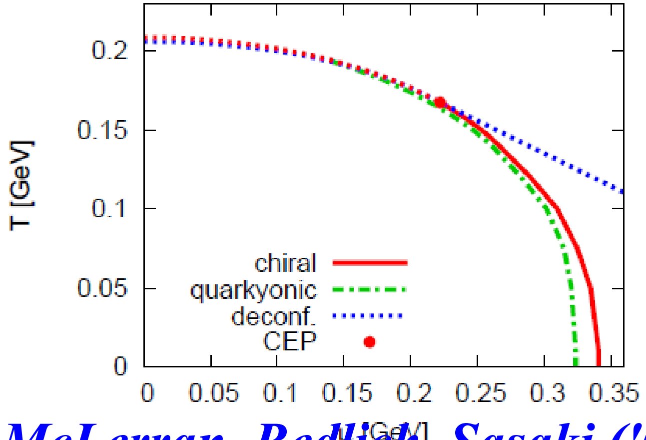


Phase diagram in strong coupling lattice QCD with Polyakov loop effects (P-SC-LQCD)

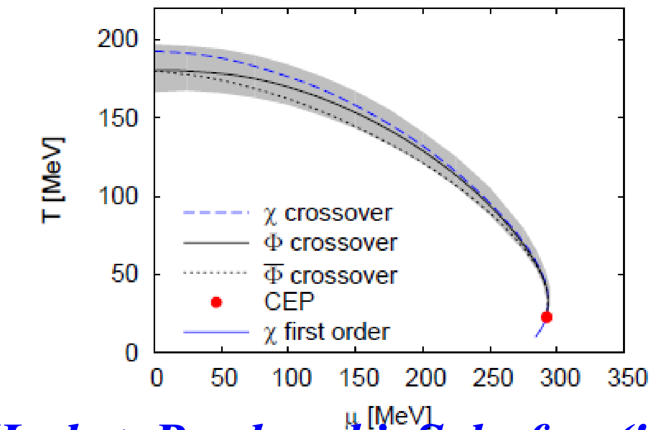
Quarkyonic matter

- Do χ and Z_{Nc} 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

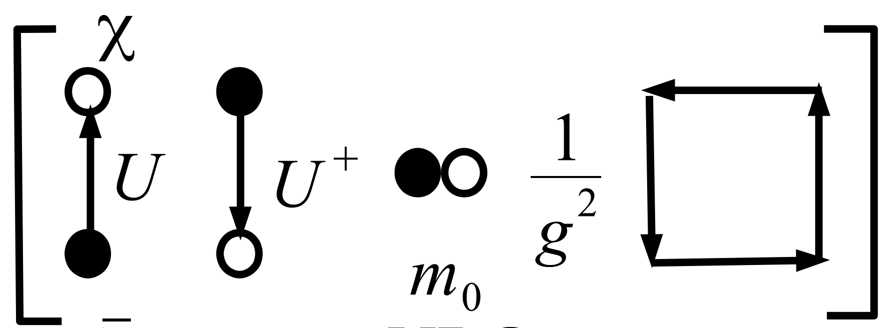
- **SC-LQCD has been a successful tool from the beginning of the lattice QCD formulation !**
  - **Pure Yang-Mills theory → *Confinement***
    Area Law (Wilson ('74)), S.C. Expansion (Munster ('81)), ...,
    Finite T Pol. loop eff. action (Langelage, Münster, Philipsen ('08)), ..
  - **With fermion → *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 ?

SC-LQCD with Fermions & Polyakov loop (1)

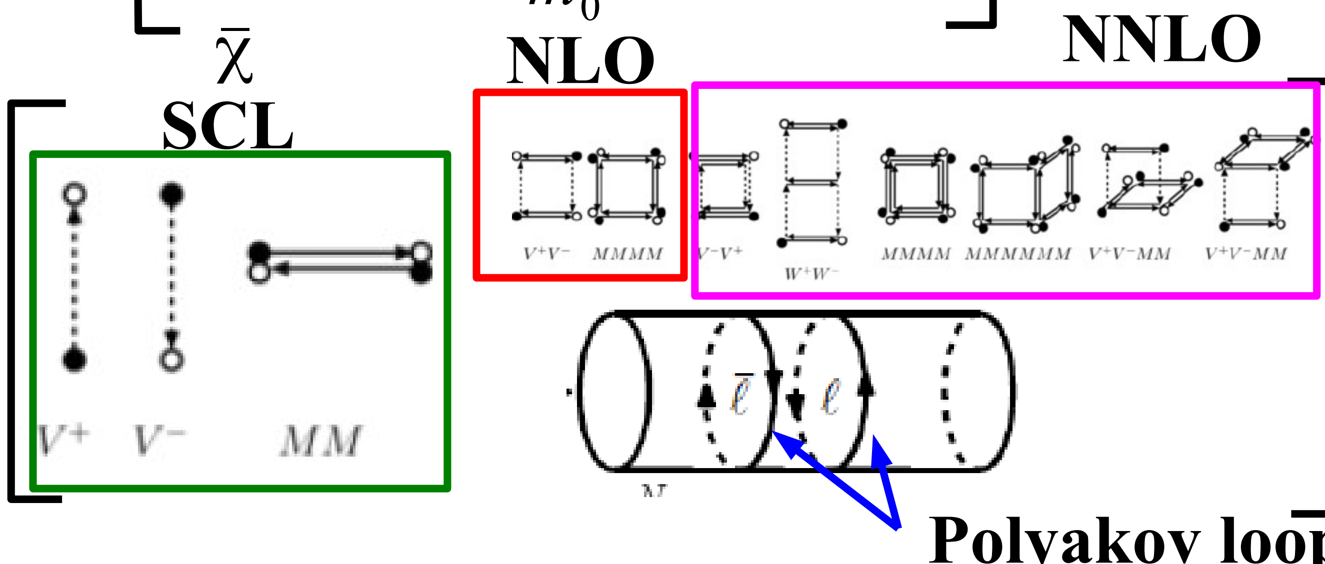
- **Effective Action & Effective Potential (free energy density)**

$$Z=\int D[\chi,\bar{\chi},U_0,U_j]\exp$$



Spatial link integral

$$=\int D[\chi,\bar{\chi},U_0]\exp$$



Bosonization

$$\approx\int D[\chi,\bar{\chi},U_0]\exp\left(-S_{\text{eff}}[\chi,\bar{\chi},U_{0,}\Phi_{\text{stat.}}]\right)$$

$$\approx\exp\left(-V\,F_{\text{eff}}(\Phi;T,\mu)/T\right)\qquad(\text{fermion}+U_0\,\text{integral})$$

SC-LQCD with Fermions & Polyakov loop (2)

- **Effective potential [free energy density, NLO + LO(Pol. loop)]**

$$\mathcal{F}_{\rm eff}(\Phi;T,\mu) \equiv -(T\log \mathcal{Z}_{\rm LQCD})/N_s^d = \mathcal{F}_{\rm eff}^{\chi} + \mathcal{F}_{\rm eff}^{\rm Pol}$$

$$\mathcal{F}_{\rm eff}^{\chi} \simeq \left(\frac{d}{4N_c}+\beta_s\varphi_s\right)\sigma^2 + \frac{\beta_s\varphi_s^2}{2} + \frac{\beta_\tau}{2}(\varphi_\tau^2-\omega_\tau^2) - N_c\log Z_\chi - N_c E_q - T(\log \mathcal{R}_q(T,\mu) + \log \mathcal{R}_{\bar{q}}(T,\mu))$$

aux. fields
w.f. ren.
zero point E.
thermal

$$\mathcal{R}_q(T,\mu) \equiv 1 + e^{-N_c(E_q-\tilde{\mu})/T} + N_c\left(L_{p,\mathbf{x}}e^{-(E_q-\tilde{\mu})/T} + \bar{L}_{p,\mathbf{x}}e^{-2(E_q-\tilde{\mu})/T}\right)$$

$$\mathcal{F}_{\rm eff}^{\rm Pol} \simeq -2TdN_c^2\left(\frac{1}{g^2N_c}\right)^{1/T}\bar{\ell}_p\ell_p - T\log \mathcal{M}_{\rm Haar}(\ell_p,\bar{\ell}_p)$$

quad. coef.
Haar measure

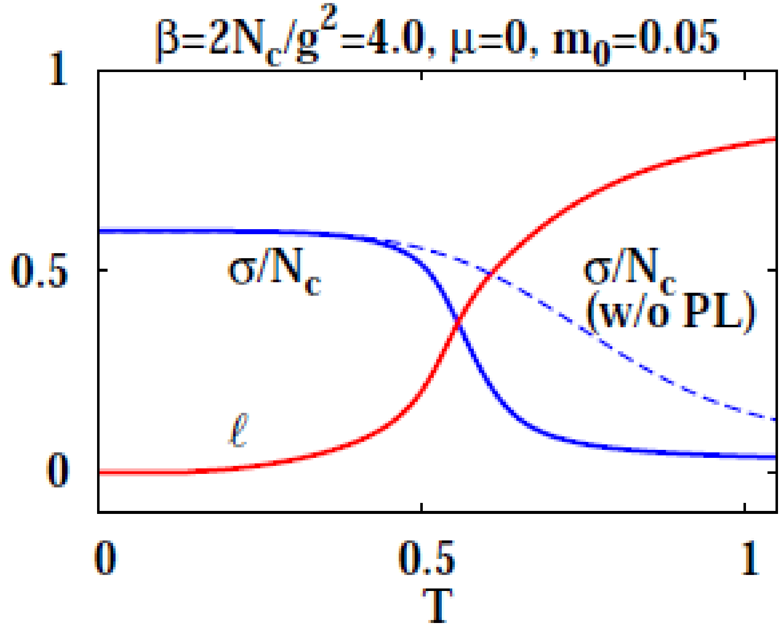
- **Strong coupling lattice QCD with Polyakov loop (P-SC-LQCD)**
  = Polyakov loop extended Nambu-Jona-Lasino (PNJL) model
  (Haar measure method, quadratic term fixed)
  + higher order terms in aux. fields
  - quark momentum integral

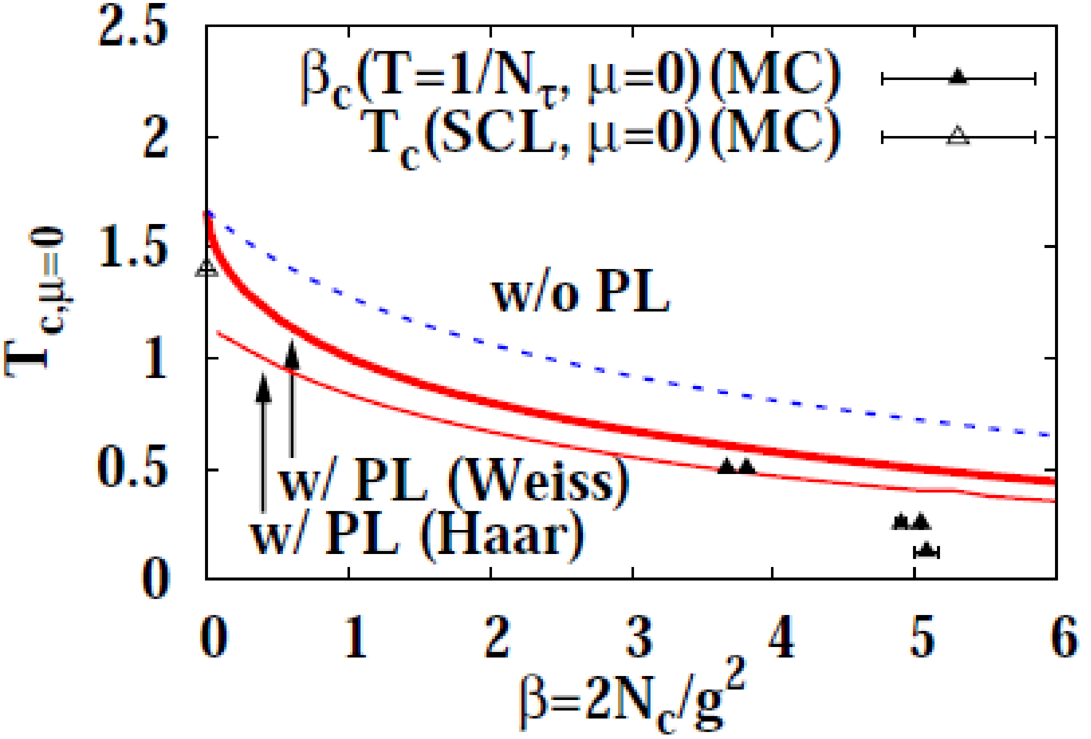
P-SC-LQCD at μ=0

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)), $N_\tau=2$ (de Forcrand, private), $N_\tau=4$ (Gottlieb et al.('87), Fodor-Katz ('02)), $N_\tau=8$ (Gavai et al.('90))



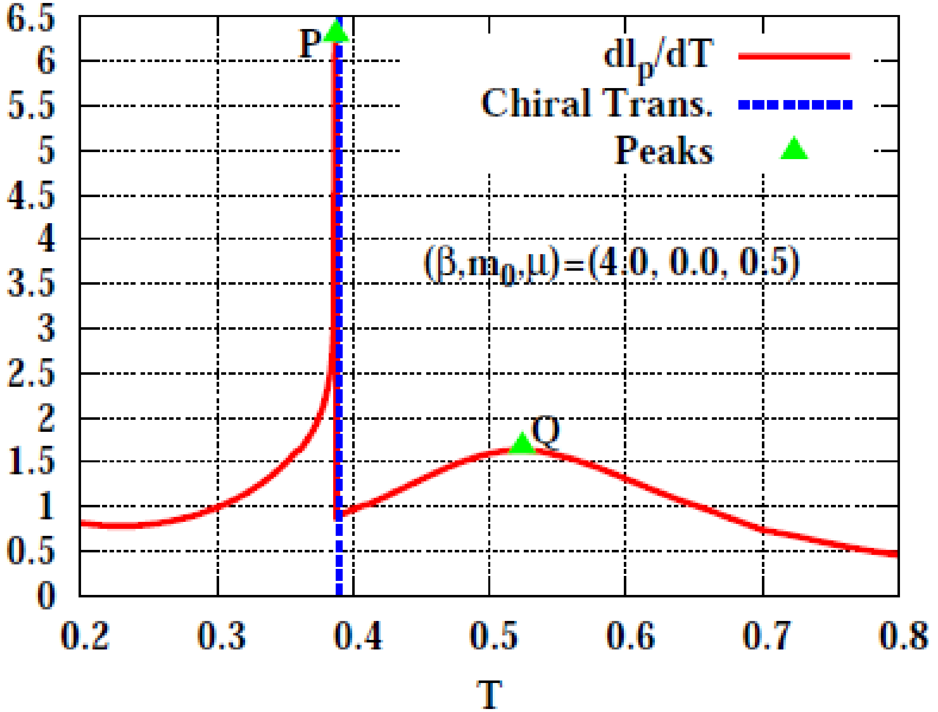


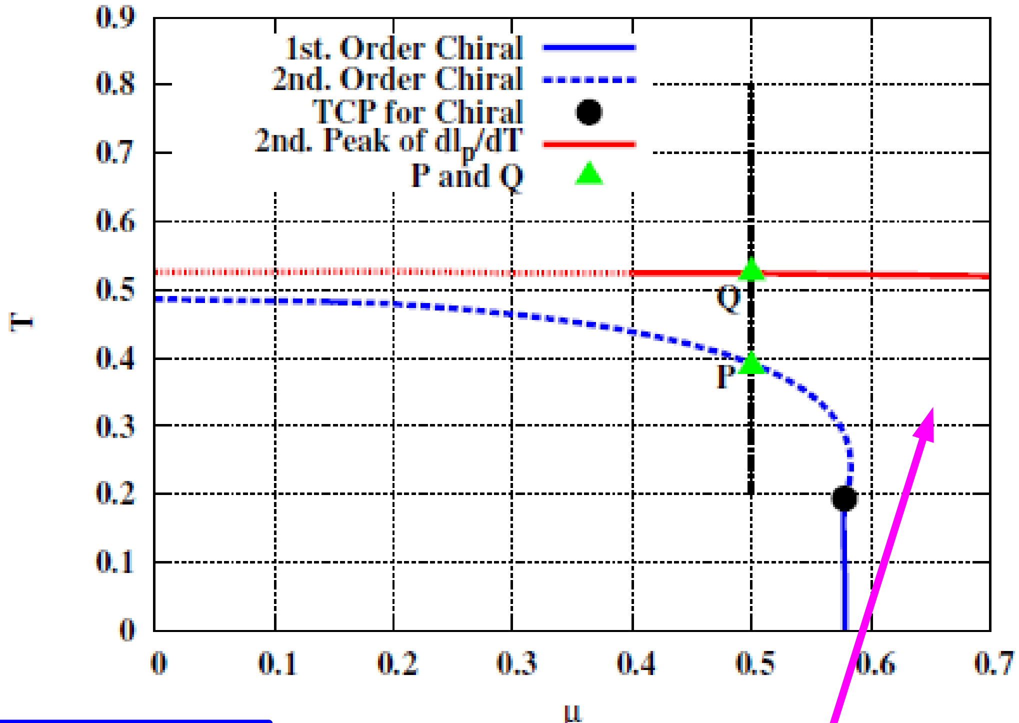
Lattice Unit

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.)

Discussions

- **Disclaimer**
  - **Unrooted staggered fermion (N_f=4 @ cont.)**
  - **NLO/NNLO & LO in quark & Polyakov loop effective actions (strong coupling ($1/g^2$) expansion)**
  - **LO in 1/d expansion, mean field (min. # of quarks for a given plaq. config.)**
- **Followings may modify the present conclusion.**
  - **μ dependent coef. in Polyakov loop effective action, or χ-Pol. entanglement**

$$\mathcal{U}(\Phi) = (aT^4 + b\mu^2T^2 + c\mu^4)\Phi^2 + a_2T_0^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$

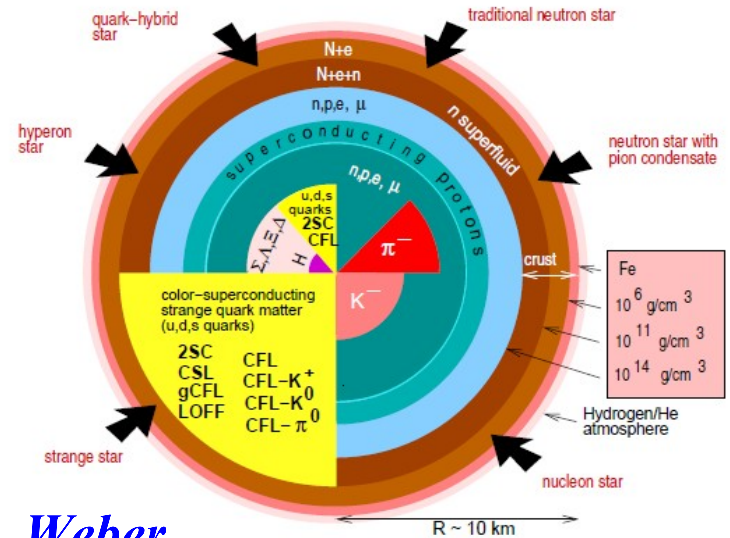
Dexheimer, Schramm, NPB(PS)199('10)319; Blaschke et al., PTPS186('10)81; Sakai, Sasaki, Kouno, Yahiro, PRD82('10)076003.

  - **Different fermion, e.g. (Staggered-)Wilson Fermion**
  - **With higher order corrections, …..**

Critical Point sweep during black hole formation

Compact Astrophysical Phenomena

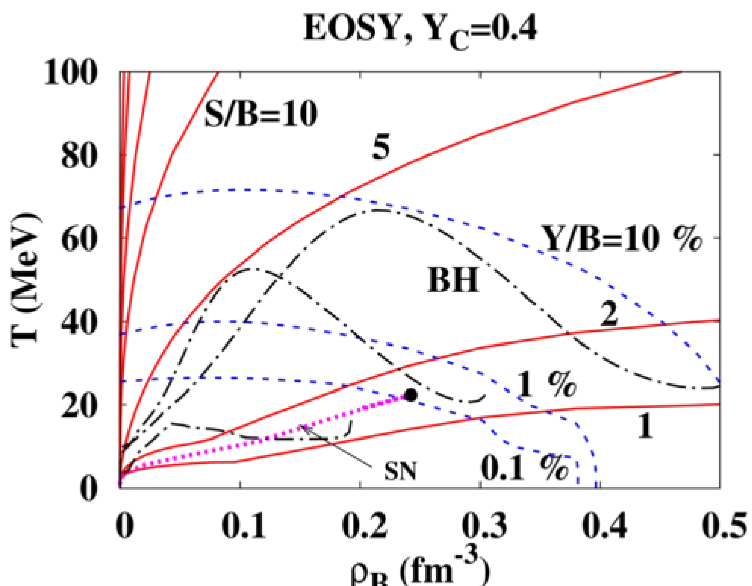
- Neutron Star
  - Cold (T ~ 0), Dense ($\rho_B \sim 5\ \rho_0$)
    Highly Asymmetric ($Y_p \sim$ (10-20) %)



F. Weber, Prog.Part.Nucl.Phys.54('05) 193

- Supernovae
  - Warm (T ~ 20 MeV), Dense ($\rho_B \sim 1.8\ \rho_0$)
    mildly asymmetric ($Y_p \sim$ (30-40) %)
  - QCD phase transition ?
    T. Hatsuda, MPLA2('87)805; I. Sagert et al., PRL102 ('09) 081101.

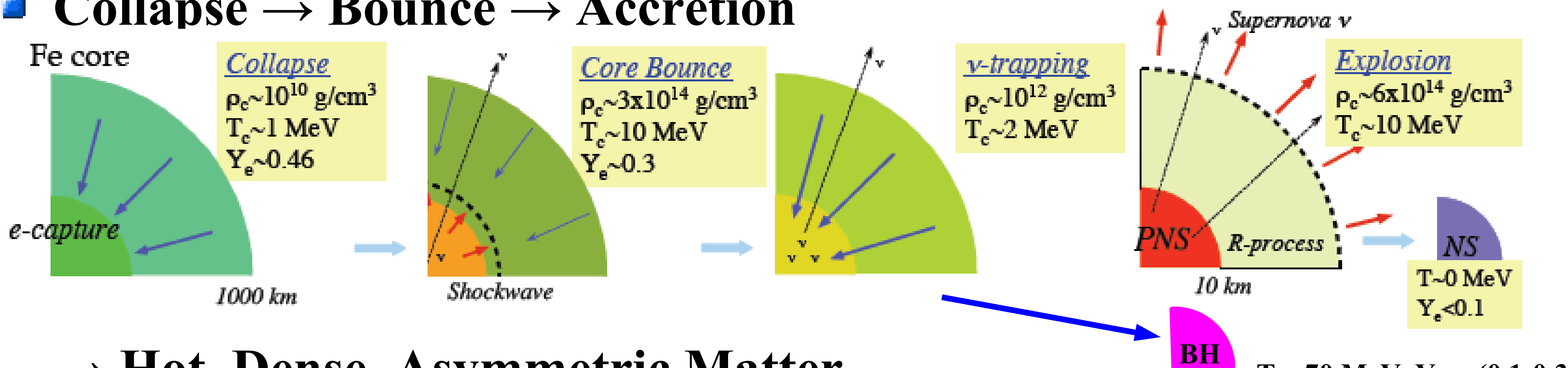
- *Dynamical black hole formation*
  - *Hot (T ~ 70 MeV), Dense ($\rho_B \sim 5\ \rho_0$)*
    Asymmetric ($Y_p \sim$ (10-30) %)
    K. Sumiyoshi, et al., PRL97('06) 091101.
    K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki, ApJL690('09),L43



C.Ishizuka,AO,K.Tsubakihara,K.Sumiyoshi, S.Yamada, JPG 35('08)085201

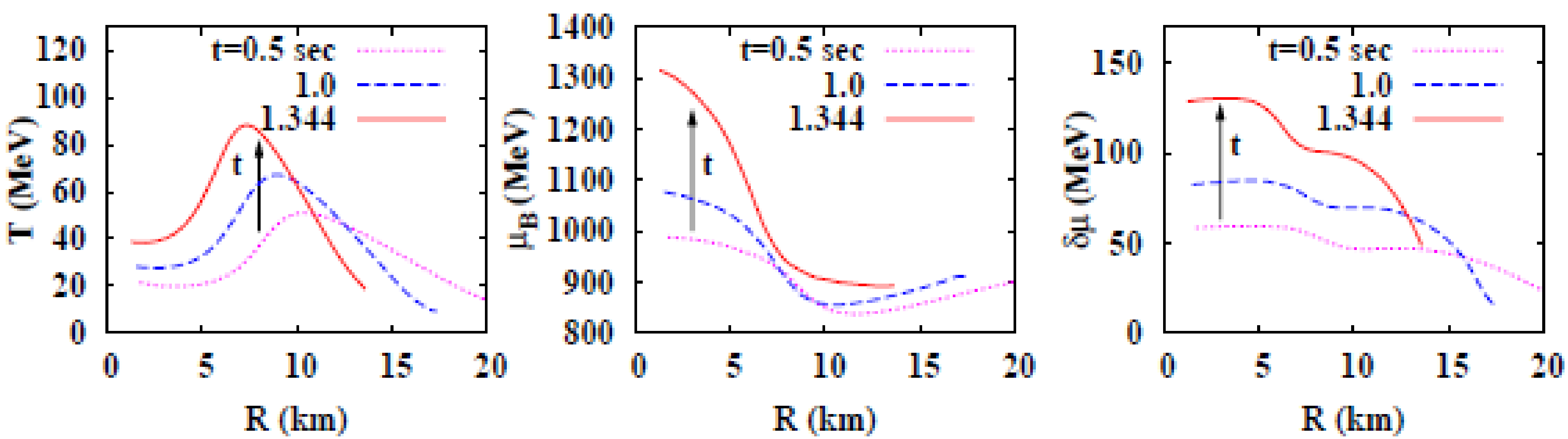
Dynamical Black Hole Formation

- **Collapse → Bounce → Accretion**



→ Hot, Dense, Asymmetric Matter

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



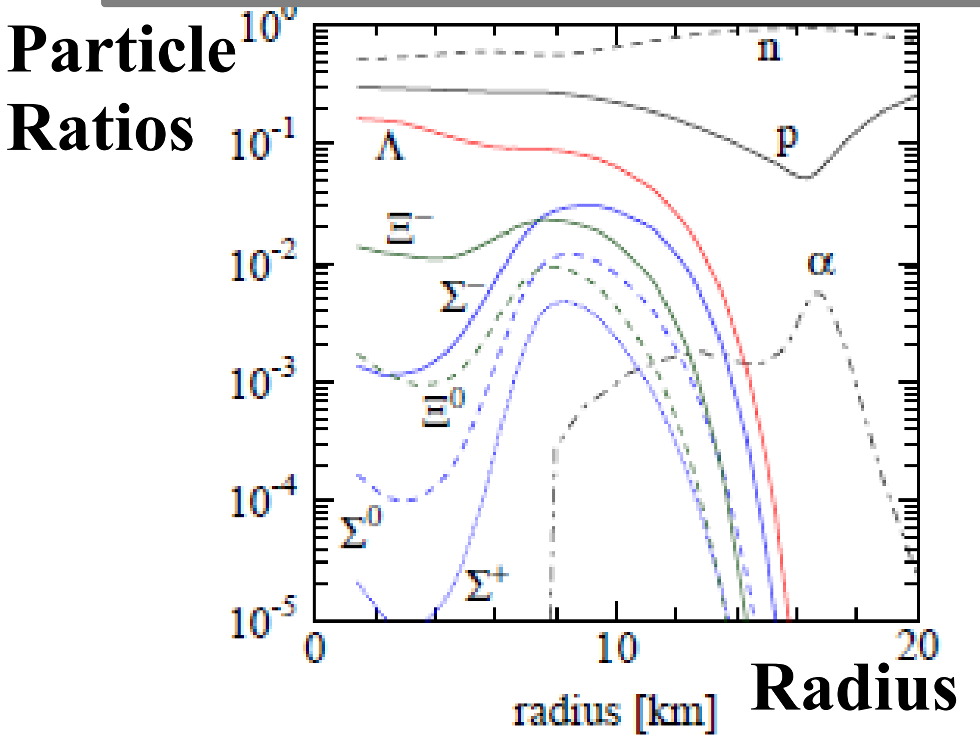
→ Black Hole

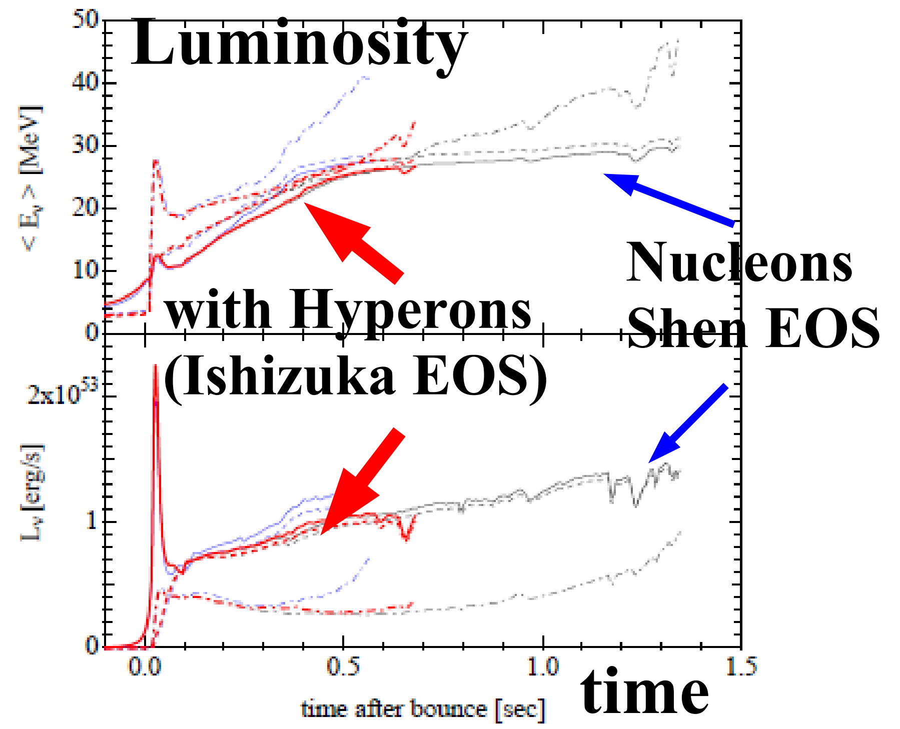
K. Sumiyoshi, et al.,('06); K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki ('09)

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



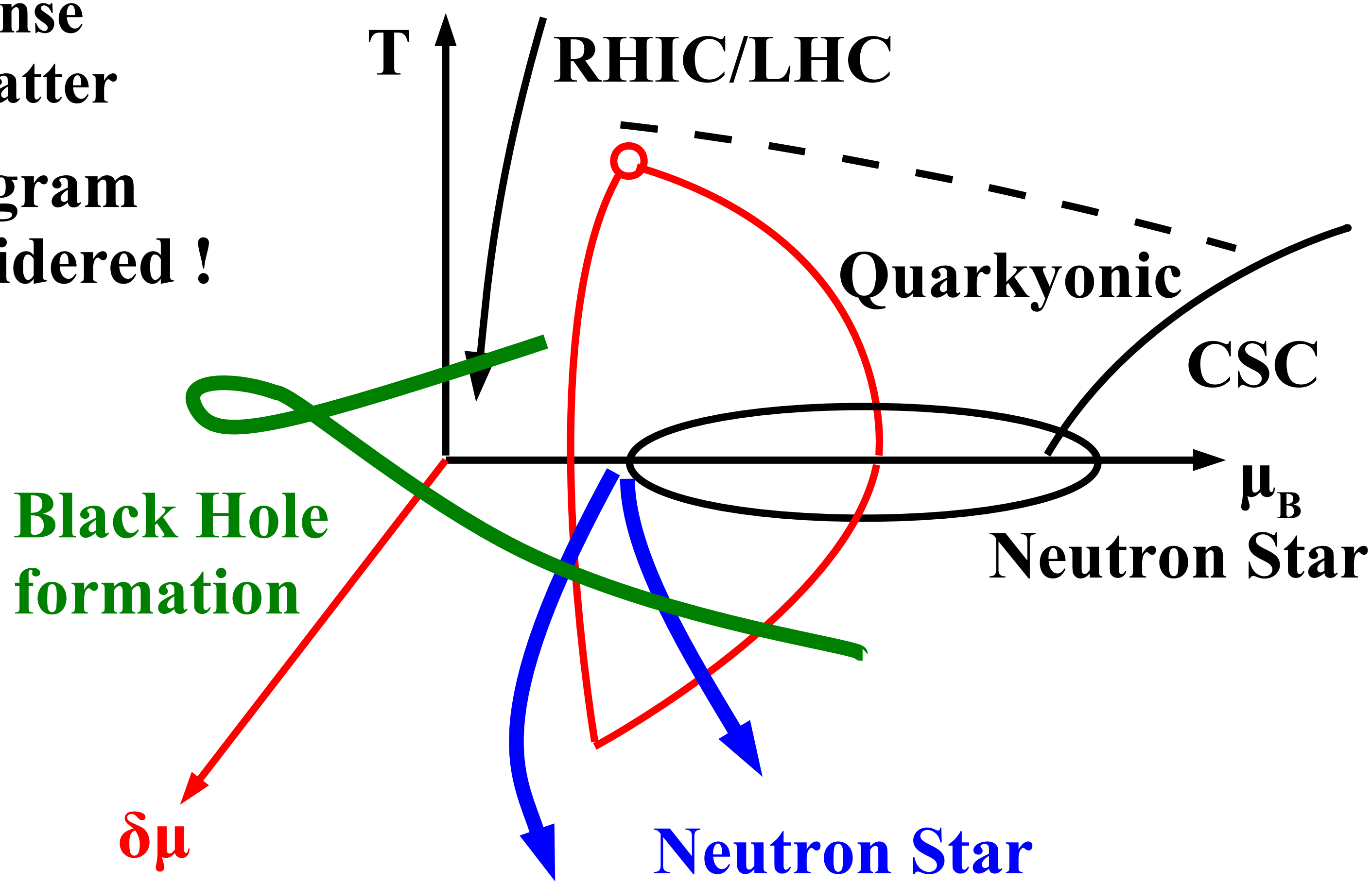


K. Sumiyoshi, C. Ishizuka, AO, S. Yamada, H. Suzuki, ApJL 690('09)L43
C. Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S. Yamada, JPG 35 ('08)085201

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 !



Chiral Effective Models (1)

- **Chiral Effective models**
  - **Spontaneous breaking of chiral sym. → const. quark mass**
  - **Polyakov loop extension → chiral & deconf. transitions**
- **NJL model** *Nambu, Jona-Lasinio ('61)*
- **PNJL** *Fukushima('03), Ratti, Thaler, Weise ('06), Sakai et al. ('08)*
- **PQM model**

B.J.Schafer, Pawlowski, Wambach ('07), Skokov, Friman, E.Nakano, Redlich ('10)

$$\mathcal{L}_{PQM} = \bar{q}\left(i\,\not{D} - g(\sigma + i\gamma_5\vec{\tau}\vec{\pi})\right)q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\pi)^2 - U(\sigma,\vec{\pi}) - \mathcal{U}(\Phi,\bar{\Phi})$$

$$\Omega_{PQM}(\Phi,\bar{\Phi},\sigma) = \Omega_{\bar{q}q}(\Phi,\bar{\Phi},\sigma) + U_{vac}(\sigma) + U(\sigma) + \mathcal{U}(\Phi,\bar{\Phi})$$

$$\Omega_{q\bar{q}}^{u,d} = -2T\int\frac{d^3k}{(2\pi)^3}[\ln\left(1 + 3\Phi e^{-(E_k-\mu_{u,d})/T} + 3\bar{\Phi}e^{-2(E_k-\mu_{u,d})/T} + e^{-3(E_k-\mu_{u,d})/T}\right)$$

$$U_{vac} = -2N_fN_c\int\frac{d^3k}{(2\pi)^3}E_k\theta(\Lambda^2-k^2) \qquad U(\sigma) = U(\sigma,\vec{\pi}=0) = \frac{\lambda}{4}(\sigma^2-v^2)^2 - c\sigma$$

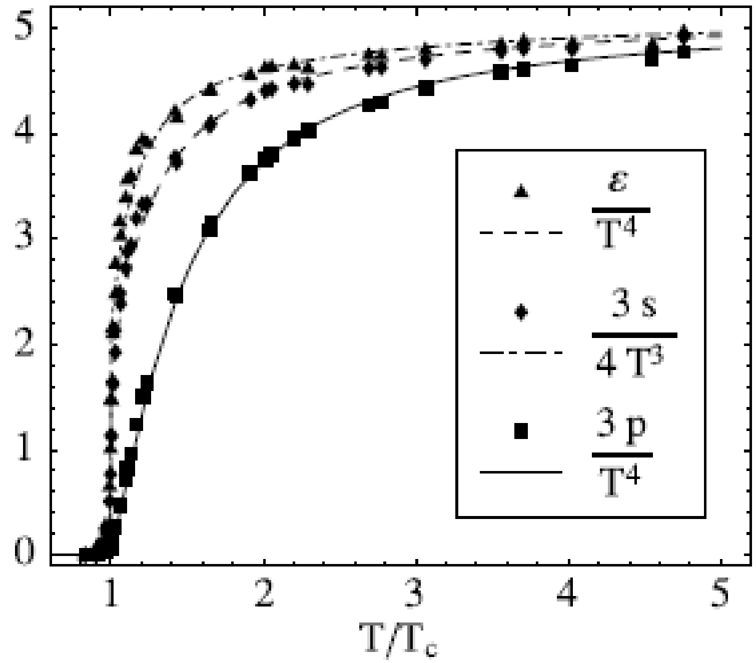
$$\frac{\mathcal{U}(\Phi,\bar{\Phi})}{T^4} = -\frac{a(T)}{2}\Phi\bar{\Phi} + b(T)\log[1 - 6\Phi\bar{\Phi} - 3(\Phi\bar{\Phi})^2 + 4(\Phi^3+\bar{\Phi}^3)]$$

Chiral Effective Models (2)

- **Polyakov loop effective potential**
  - **log (Haar measure) type**
    Lattice data → coef. (a(T), b(T))
- **Vector-Vector coupling**

$$-G_\rho\left[(\bar{q}\gamma^\mu\boldsymbol{\tau}q)^2+(\bar{q}i\gamma_5\gamma^\mu\boldsymbol{\tau}q)^2\right]-G_\omega(\bar{q}\gamma^\mu q)^2$$

  - **Modifies chem. pot. effectively.**
  - **Compare the results with G_v/G_s= 0, 0.2**



Roessner et al.('07)

- **8 Fermi interaction**
  T. Sasaki, Y. Sakai, H. Kouno, M. Yahiro ('10)

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

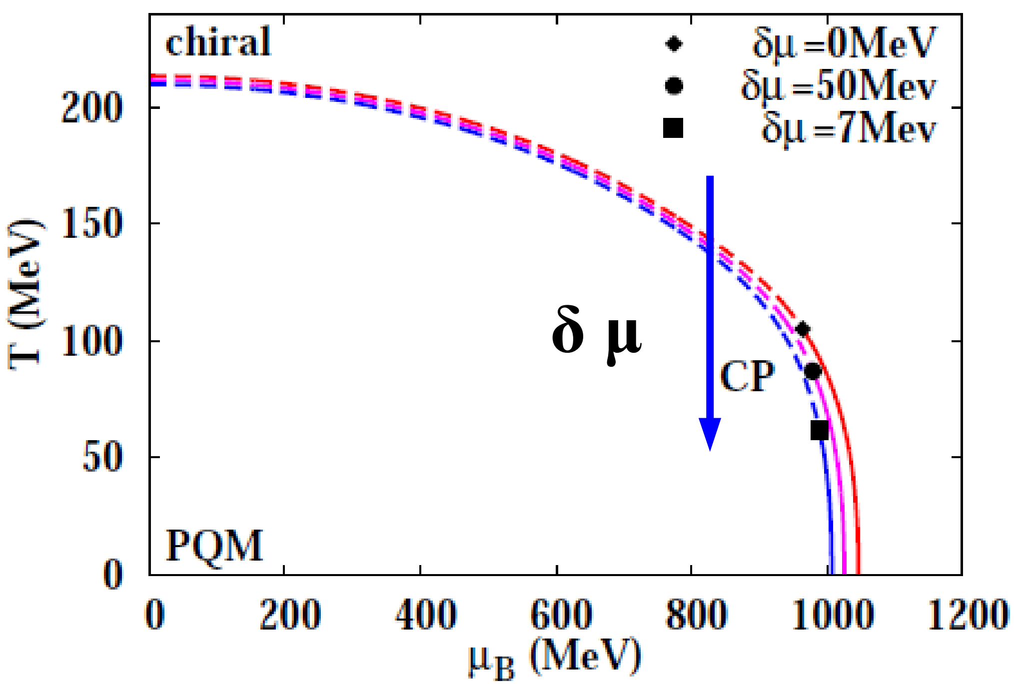
  - **modifies quark masses in vacuum**

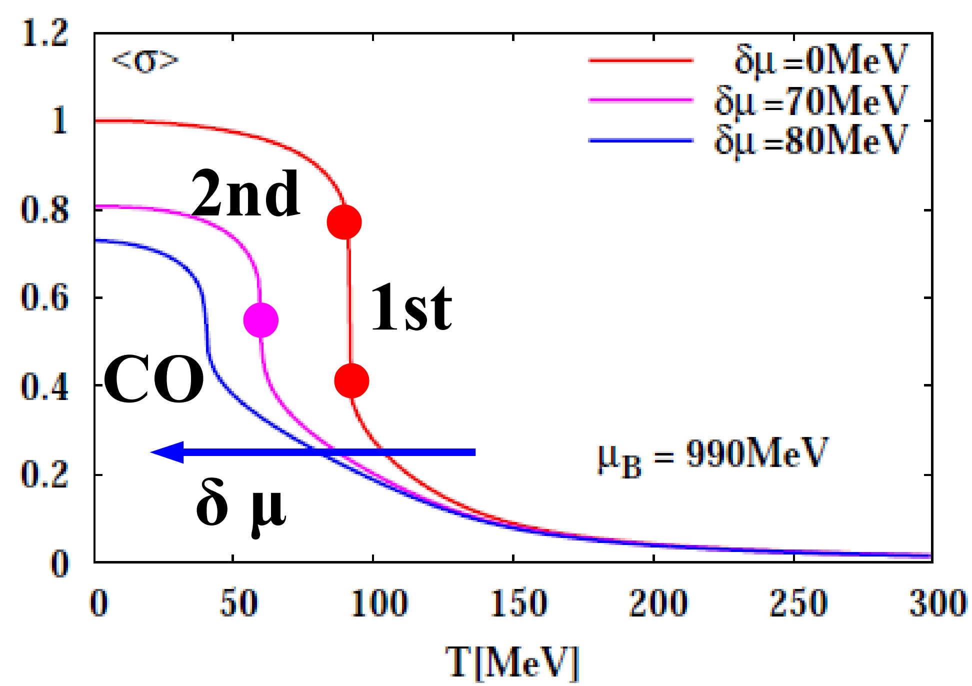
We compare the phase diagram in NJL, PNJL, PNJL8, PQM with ν-radiation Hydro. results.

Isospin chemical potential

- **Isospin chemical potential**
  $\delta\mu = (\mu_d - \mu_u)/2 = (\mu_n - \mu_p)/2 \rightarrow \mu_d = \mu_q + \delta\mu,\ \ \mu_u = \mu_q - \delta\mu$
- **(Iso)Asymmetric matter** $N_u \neq N_d$
  - **Finite δμ → "Effective" number of flavors** $1 \leq N_f \leq 2$
  - **large** k_F **(for a given** ρ_B**) → smaller E gain in NG phase → small transition T, small** T_{CP}

H. Ueda, M. thesis

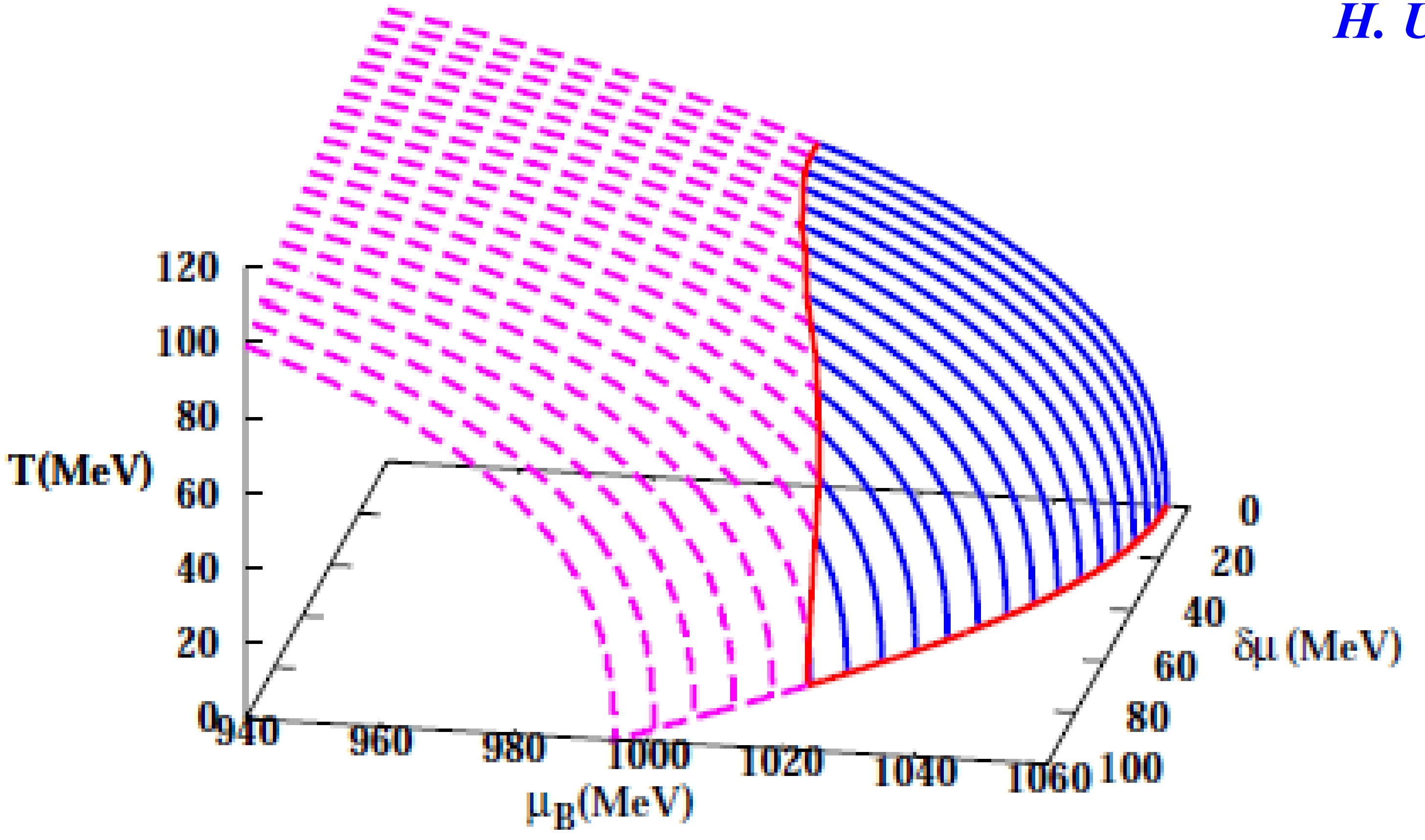




3D phase diagram in PQM

- **Phase diagram in (T, μ, δμ) space** $\delta\mu = (\mu_d - \mu_u)/2$

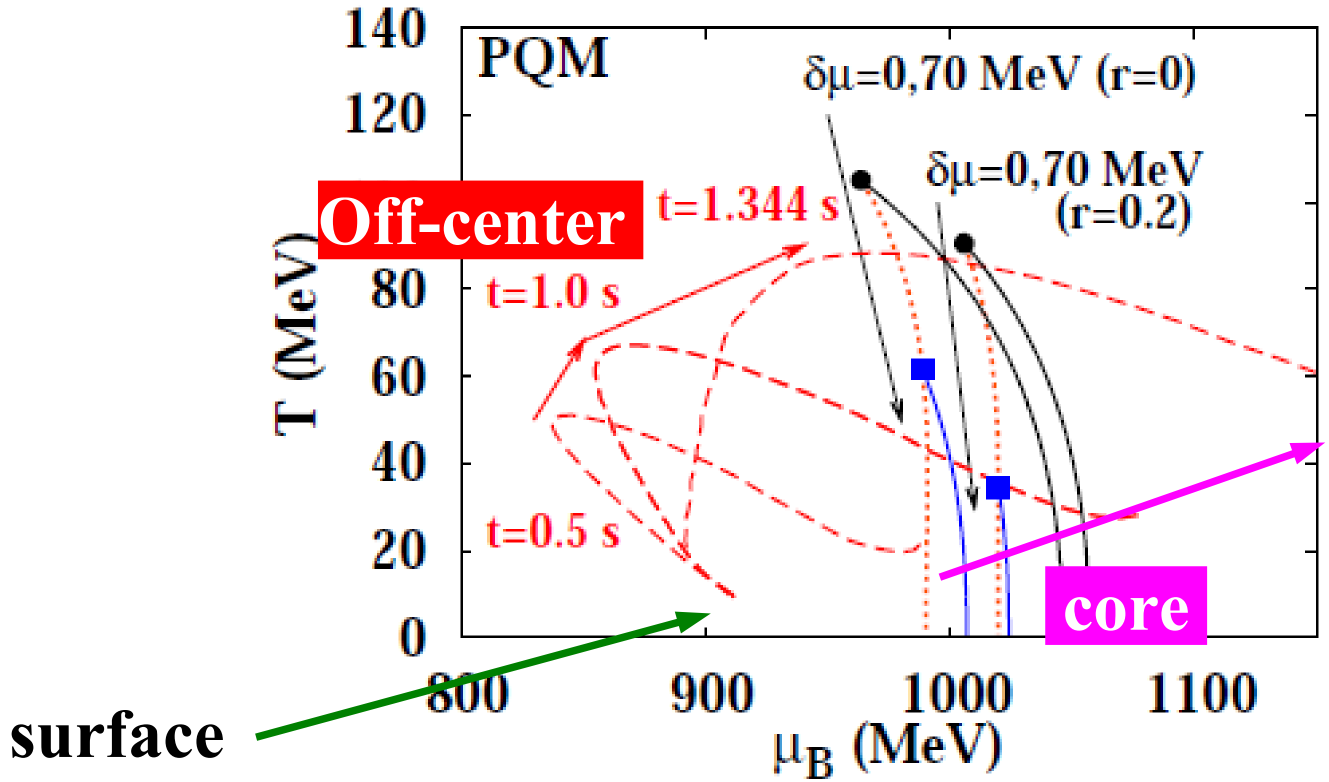
H. Ueda, M. thesis



CP temperague goes down at finite δμ in the range reachable during BH formation.

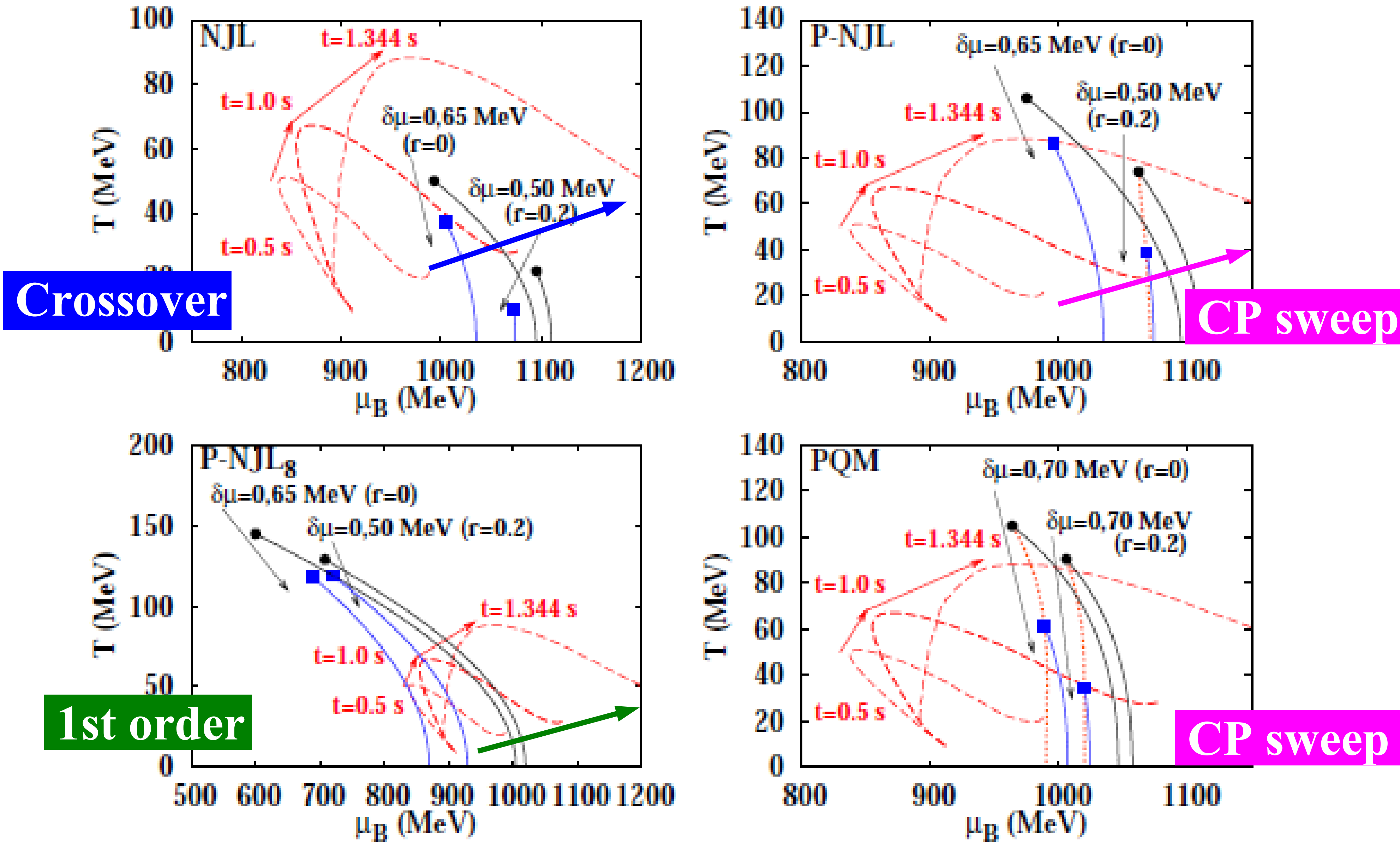
How is quark matter formed during BH formation ?

- **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



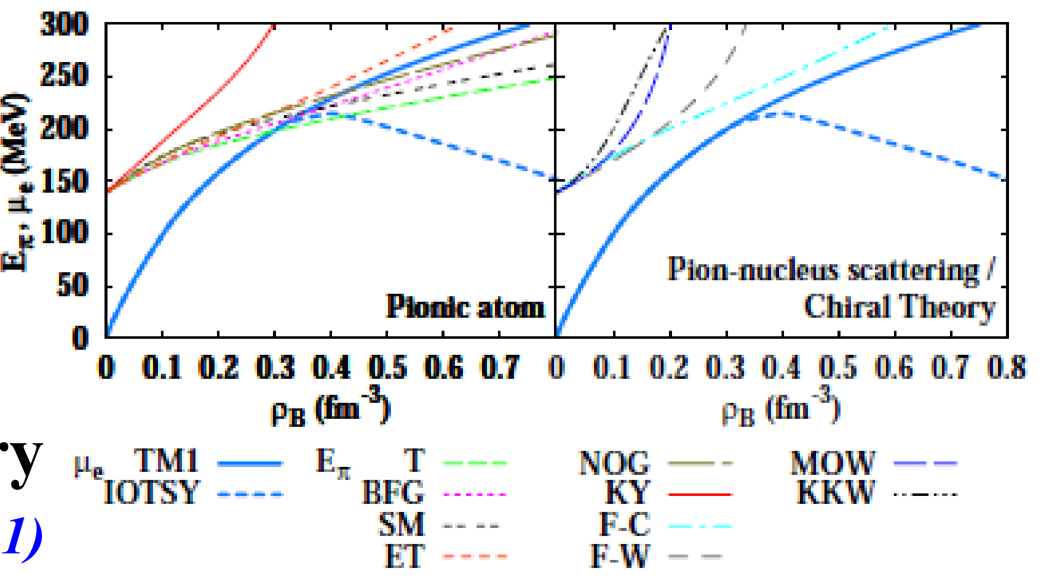
How is quark matter formed during BH formation ?

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



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)
- Large δμ in hadronic EOS comes from strong vector coupling.
  - $g_\omega / g_\sigma > 1$ in RMF → Large sym. E & large δ μ
  - Gv/Gs < 0.3 in PNJL or no CP (c.f. Poster by Blaschke)
- 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)

Questions and Conclusion

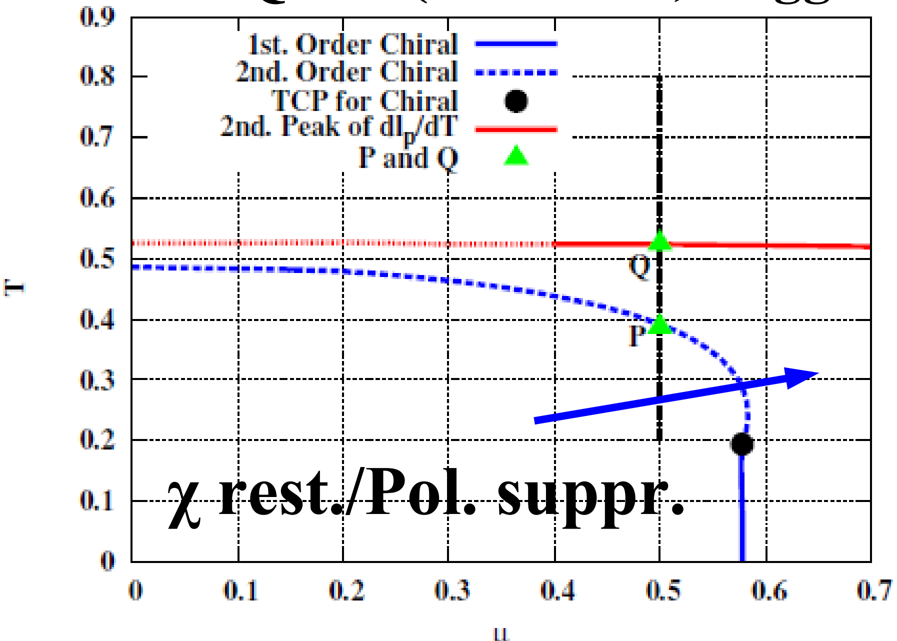
- *Does Quarkyonic matter exist in QCD with N_c=3 ?*

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

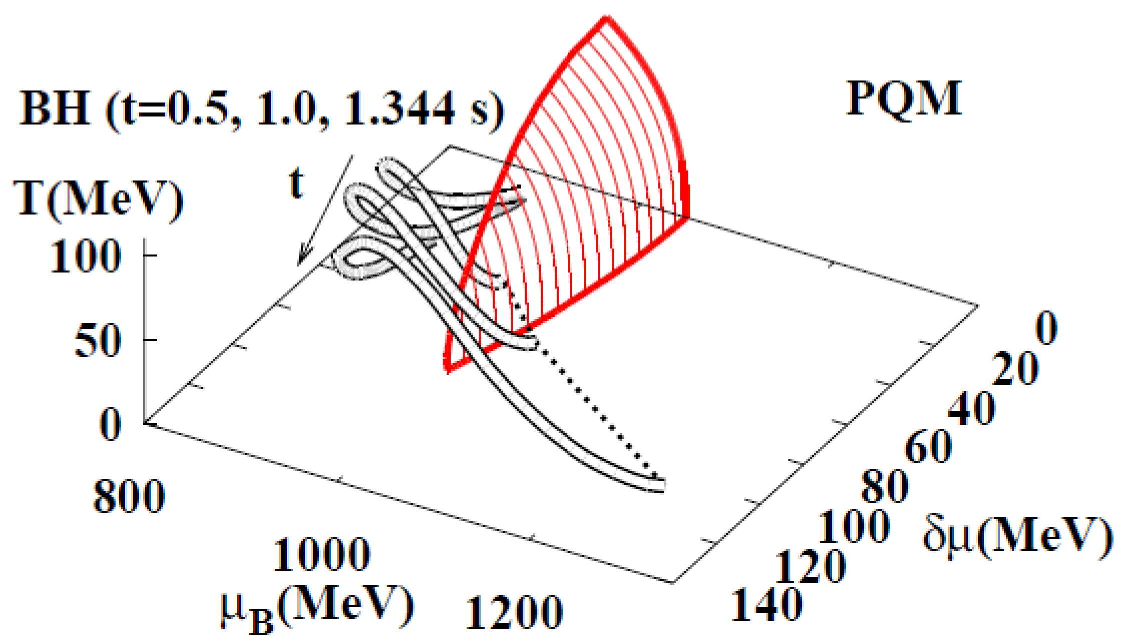
- *Is there any site where Quarkyonic matter is formed ?*

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

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



(lattice unit)



Summary and Discussion

- **P-SC-LQCD reproduces MC results of T_c at μ=0, and predicts *Quarkyonic-like state in cold-dense matter*.**
  - **P-SC-LQCD: Strong coupling lattice QCD with Polyakov loop**
  - **Quarkyonic-like = χ restored & Polyakov loop suppressed matter**
- **Comparison of χ effective models & ν-radiation hydrodynamics suggests *the possibility of CP sweep during BH formation*.**
  - **TCP decreases with increasing δμ.**
  - **Hadronic EOS favors large isospin chemical potential (δμ).**

    (cf. neutral constraint in χ eff. models predicts smaller δμ.)
- ***Construction of Hadron-Quark matter EOS with CP and its application to BH formation are desired.***

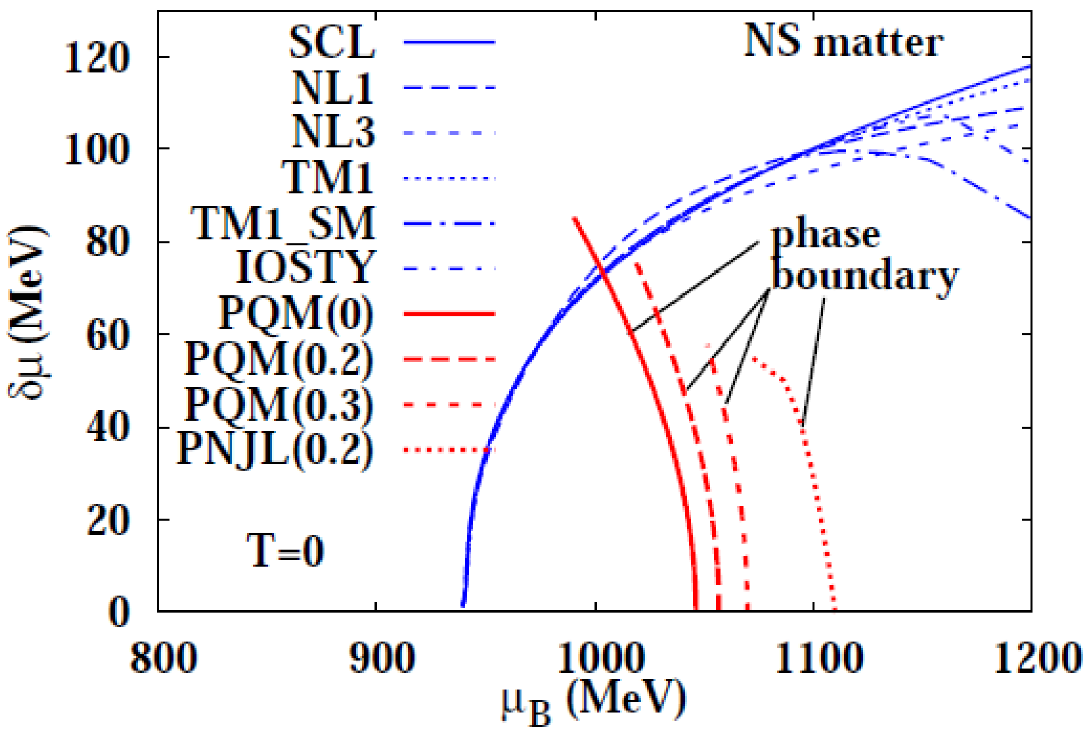
Thank you for your attention !

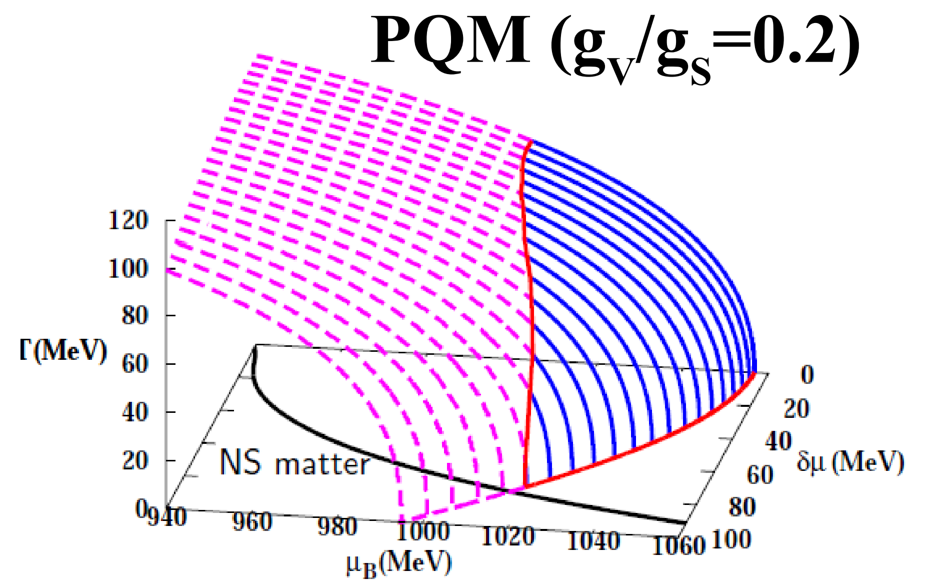
Collaborators

K. Miura (Frascati), T.Z.Nakano (Kyoto U./YITP),
N. Kawamoto (Hokkaido U.)
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.),

Crossover in Neutron Star Matter ?

- **1st order phase transition disappears at $\delta\mu$ = (60-80) MeV**
  → There may be no 1st order transition in NS.
  - **General trend of TCP decrease as a function of $\delta\mu$ is confirmed by using GL analysis (M. Ruggieri et al., in prep.) and in FRG analysis (K.Kamikado, in prep.)**





H. Ueda, M. thesis