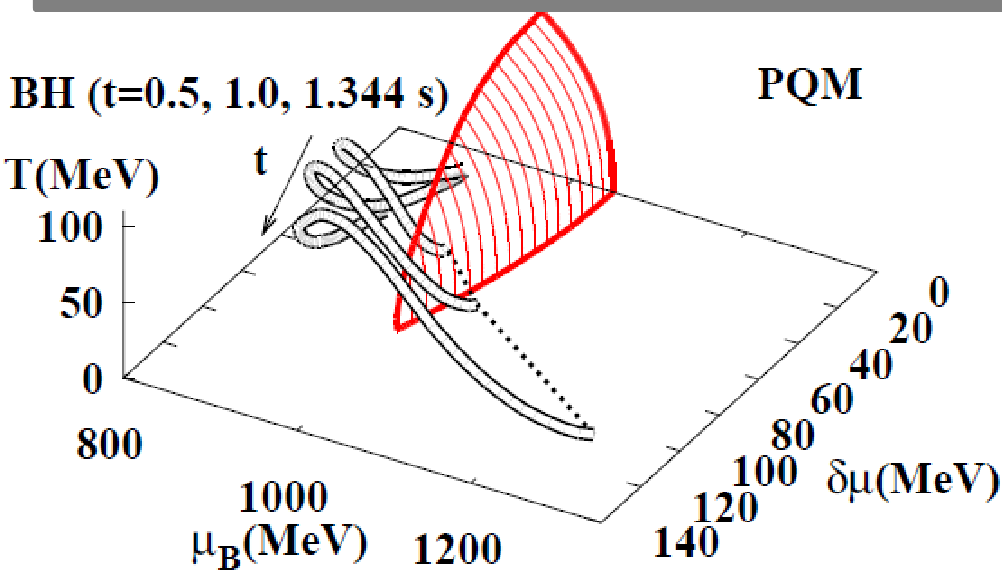
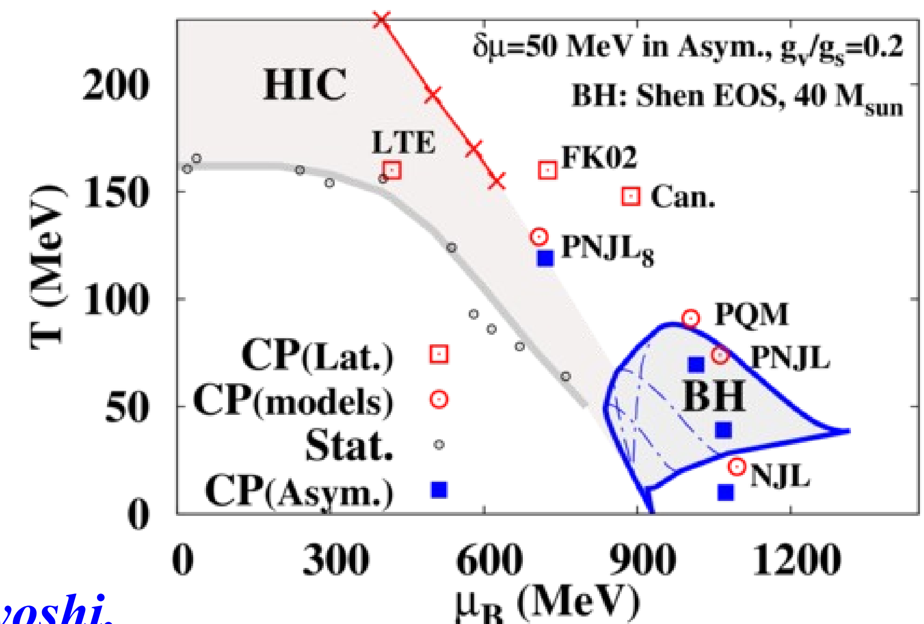
QCD critical point sweep during black hole formation

A. Ohnishi[1], H. Ueda[2], T. Z. Nakano[1,2], M. Ruggieri[1], K. Sumiyoshi[3]

1. YITP, Kyoto U., 2. Kyoto U., 3. Numazu CT

It may be possible to probe the QCD critical point in hot and dense matter formed during black hole formation.

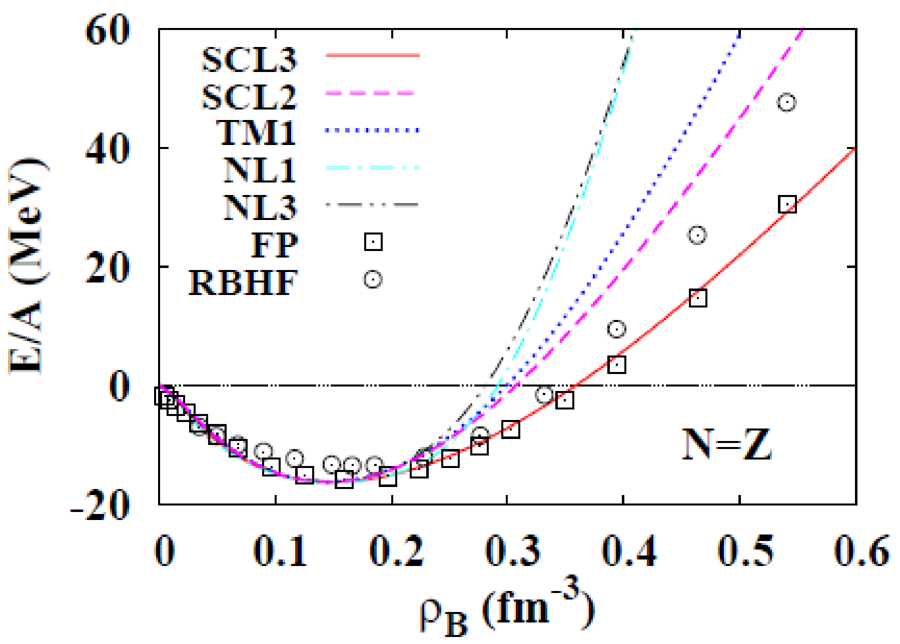


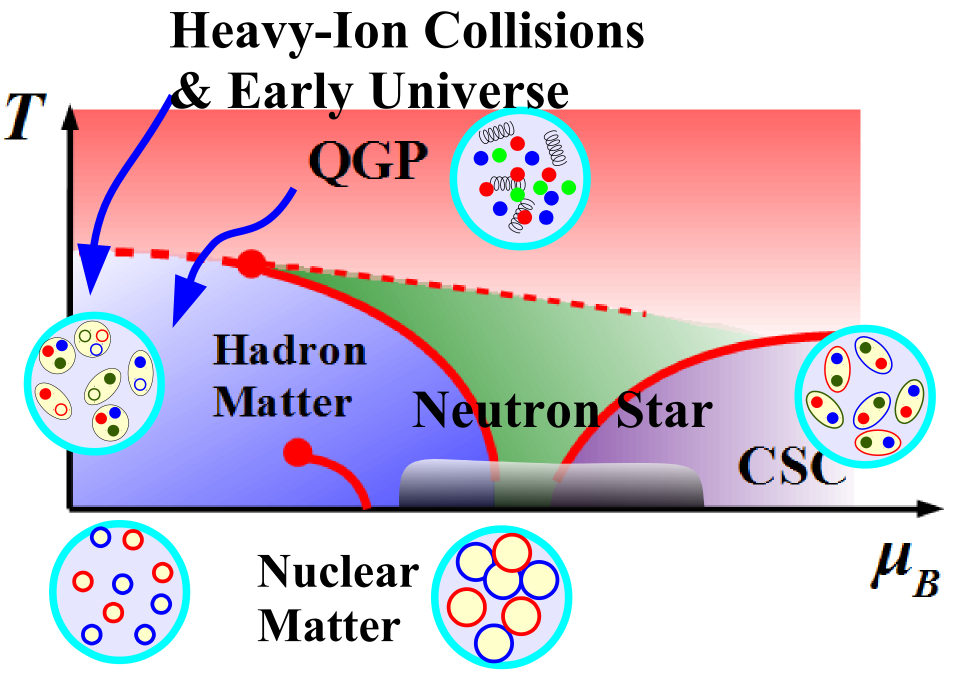


AO, H.Ueda, T.Z.Nakano, M.Ruggieri, K.Sumiyoshi, Phys. Lett. B 704 ('11)284 [arXiv:1102.3753 [nucl-th]].

Dense Matter EOS and QCD Phase diagram

- **Two important aspects of Nuclear Matter**
  - **Dense matter EOS is important in compact Astrophysics.**
    → Neutron star, Supernova, Black hole formation, NS merger, ...
  - **QCD phase diagram structure is roughly determined,**
    if the existence & location of the Critical Point (CP) is known.
    (CP connects cross over & 1st order phase boudnary.)



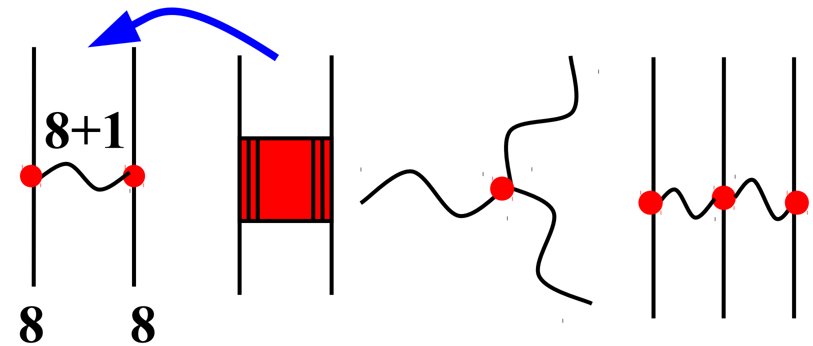


From Supernova Matter EOS to Phase Diagram

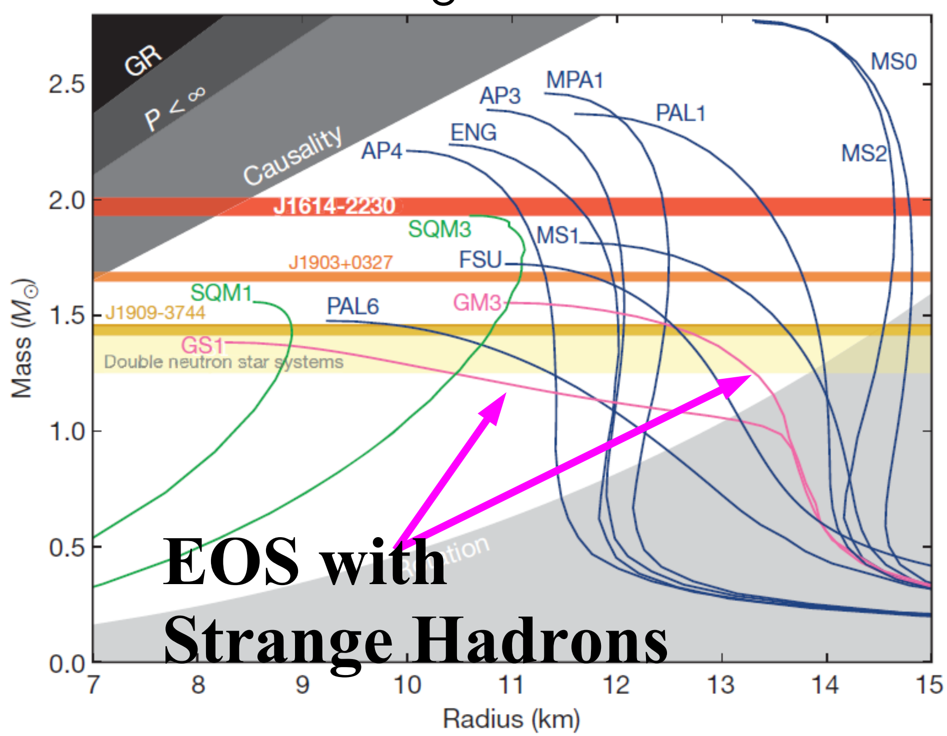
- **Supernova matter EOS**
  - **Lattimer-Swesty EOS (Skyrme-type int. + Droplet)**
    J.M.Lattimer, F.D.Swesty, NPA535('91)331.
  - **Shen EOS (Relativistic Mean Field + Thomas Fermi)**
    H.Shen et al., NPA637('98)435;PTP100('98)1013.
  - **Ishizuka EOS (Shen EOS + Hyperons)**
    C. Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada, JPG 35 ('08)085201.
- **Does quark matter exist in compact stars ?**
  - **Suggested in Supernovae: Warm(~20 MeV), mildely dense (~1.8 ρ_0)**
    T. Hatsuda, MPLA2('87)805; I. Sagert et al., PRL102 ('09) 081101.
  - **Probable in Neutron Stars: Cold (T~0), Dense (ρ_B~5 ρ_0)**
    E.g. N. Glendenning, "Compact Stars";F. Weber, Prog.Part.Nucl.Phys.54('05)193

$1.97 \pm 0.04\ M_\odot$ Neutron Star and Hyperons

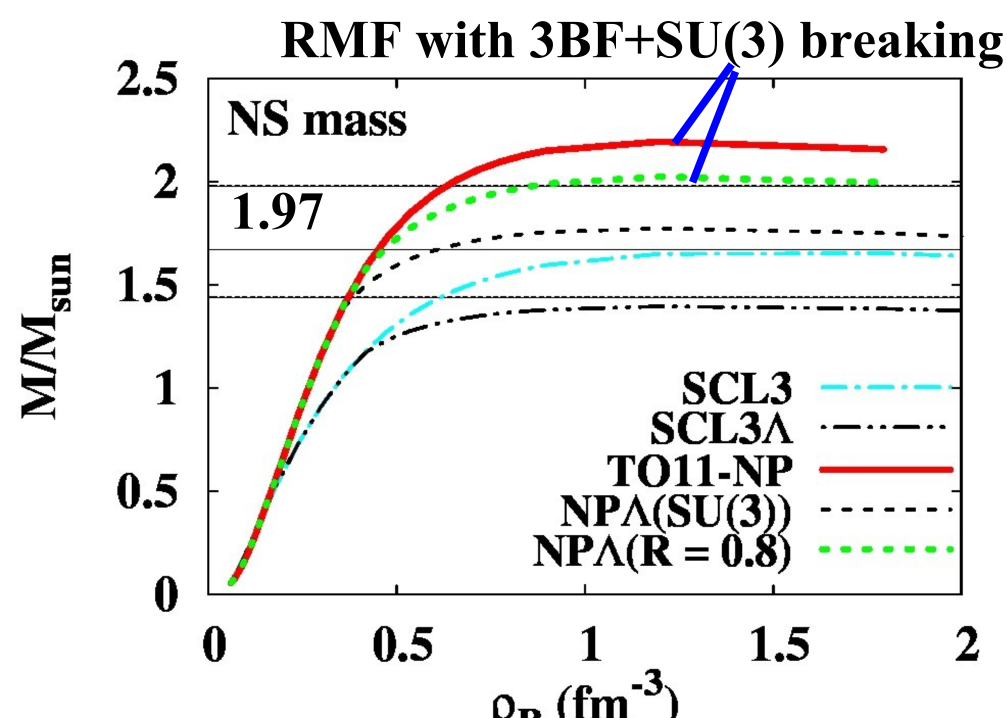
- **Discovery of 2 $M_\odot$ Neutron Star**
  → Reject EOS including hyperons with ~ SU(3) BBM coupling
- **Three-body force and "apparent" SU(3) sym. breaking helps to support 2 $M_\odot$ NS even with hyperons.**



Nishizaki, Takatsuka, Yamamoto, PTP108('02)703; Schulze, Polls, Ramos, Vidana, PRC73('06),058801.



Demorest et al., Nature 467 (2010) 1081.

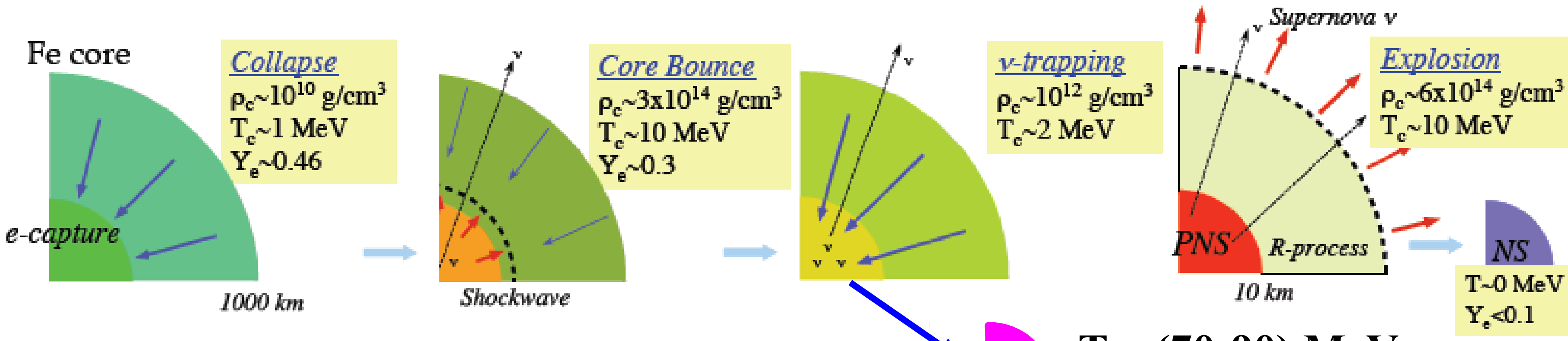


Tsubakihara, AO, in prep.

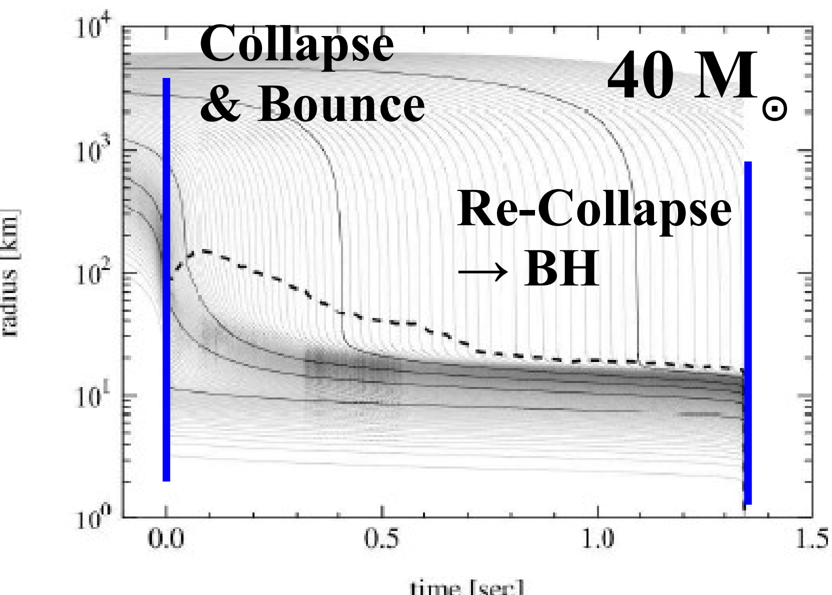
From Supernova Matter EOS to Phase Diagram

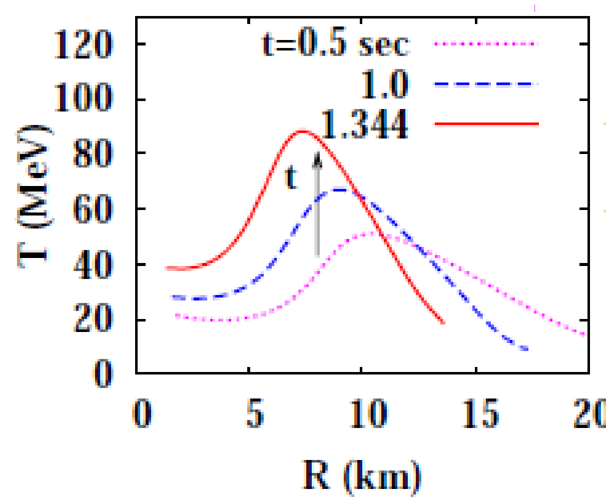
- **Supernova matter EOS**
  - **Lattimer-Swesty EOS (Skyrme-type int. + Droplet)**
    J.M.Lattimer, F.D.Swesty, NPA535('91)331.
  - **Shen EOS (Relativistic Mean Field + Thomas Fermi)**
    H.Shen et al., NPA637('98)435;PTP100('98)1013.
  - **Ishizuka EOS (Shen EOS + Hyperons)**
    C. Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada, JPG 35 ('08)085201.
- **Does quark matter exist in compact stars ?**
  - **Suggested in Supernovae: Warm(~20 MeV), mildely dense (~1.8 ρ_0)**
    T. Hatsuda, MPLA2('87)805; I. Sagert et al., PRL102 ('09) 081101; Nishimura talk.
  - **Probable in Neutron Stars: Cold (T~0), Dense (ρ_B~5 ρ_0)**
    E.g. N. Glendenning, "Compact Stars";F. Weber, Prog.Part.Nucl.Phys.54('05)193
  - ***How about Black hole formation ?***
    M. Liebendorfer et al., ApJS 150('04)263; K. Sumiyoshi et al., PRL97('06) 091101; K.Sumiyoshi, C.Ishizuka, AO, S.Yamada, H.Suzuki, ApJL690('09),L43; K.Nakazato et al., ApJ, to appear [arXiv:1111.2900] (Nakazato, Poster)

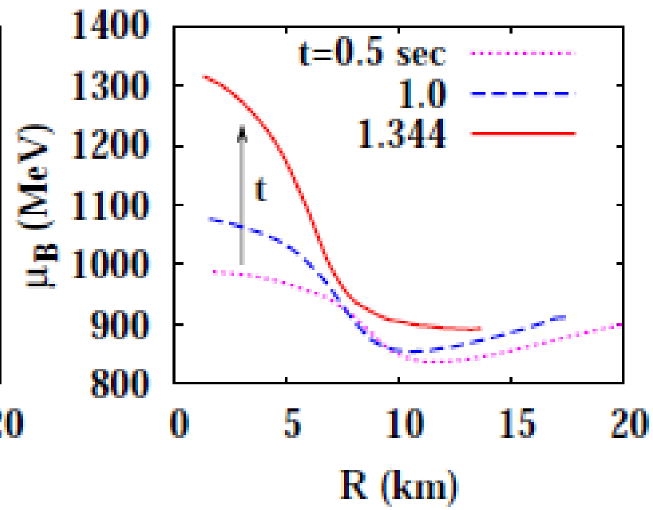
Dynamical Black Hole Formation



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







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

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

Very Hot (~90 MeV), dense(~5ρ0), Asym. (Yp~ (0.1-0.3))
→ Is the Critical Point probed during BH formation ?

Purpose and Methods

- ***We compare (T, μ_B) during BH formation and QCD phase transition boundary by using***
  - **ν radiation Hydrodynamics (1D) for BH formation**
    Sumiyoshi et al.,PRL97('06)091101;
    - **Shen EOS (npeμ)** *Shen et al., NPA637('98)435;PTP100('98)1013*
    - **Grav. collapse of 40 M_{sun} star with WW95 initial condition.**
      S.E.Woosley, T.A.Weaver, ApJS 101 ('95) 181.
  - **Chiral Effective Models for phase boundary and Critical Point**
    - **NJL (Nambu, Jona-Lasinio), PNJL (Polyakov loop extended NJL), PNJL with 8 quark int., PQM (Pol. loop ext. quark meson) models**
      Nambu, Jona-Lasinio('61); Hatsuda, Kunihiro('94), Fukushima('04); Ratti, Thaler, Weise('06); Roessner et al.('07); Kashiwa, Kouno, Matsuzaki, Yahiro('08), Schaefer, Pawlowski, Wambach ('07), Skokov et al. ('10).
    - **Vector coupling: unknown → compare results with G_v/G_s=0, 0.2**
    - **Flavor SU(2) models are considered.**

and discuss how quark matter is formed !

Chiral Effective Models

- **NJL, PNJL, PQM, ...**
  = Quark models with chiral symmetric interaction

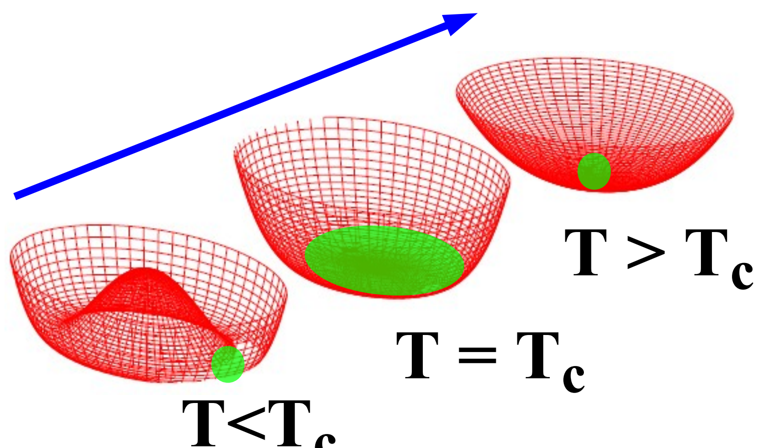
$$L=\bar{q}\left[i\gamma^{\mu}\underline{D_{\mu}}-g_{\sigma}\underline{(\sigma+i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})}\right]q+\frac{1}{2}\partial^{\mu}\sigma\,\partial_{\mu}\sigma+\frac{1}{2}\partial^{\mu}\boldsymbol{\pi}\cdot\partial_{\mu}\boldsymbol{\pi}-\underline{U_{\sigma}(\sigma,\pi)}-\underline{U_{\Phi}(\Phi,\bar{\Phi})}$$

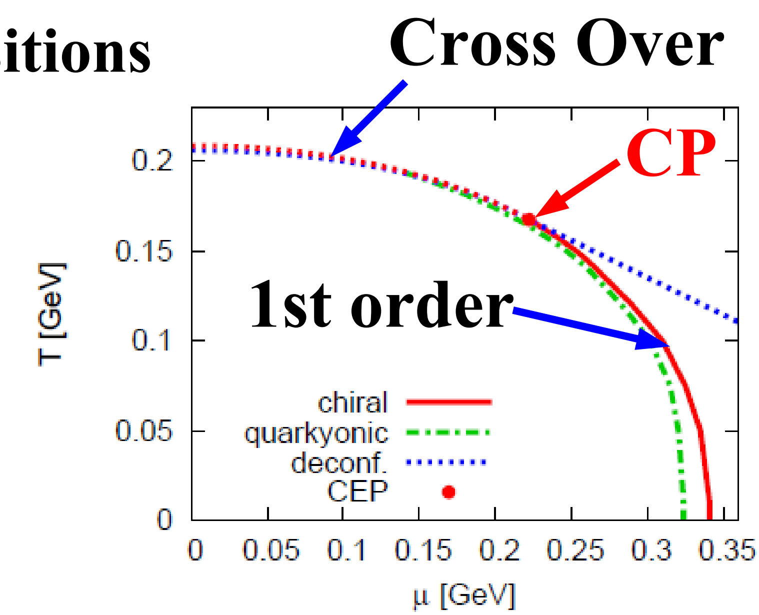
q-Pol. **quark-meson** **chiral** **Polyakov**

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

particle exc. **q zero point** **(PQM)**

- **Spontaneous breaking & restoration of chiral symmetry**
- **Polyakov loop extension → Deconf. transitions**
- **Phase diagram with critical point (CP)**



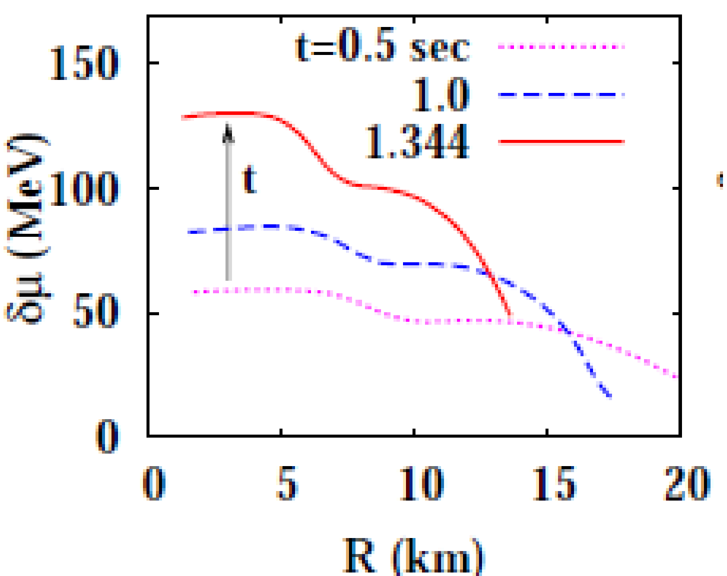


McLerran, Redlich, Sasaki ('09)

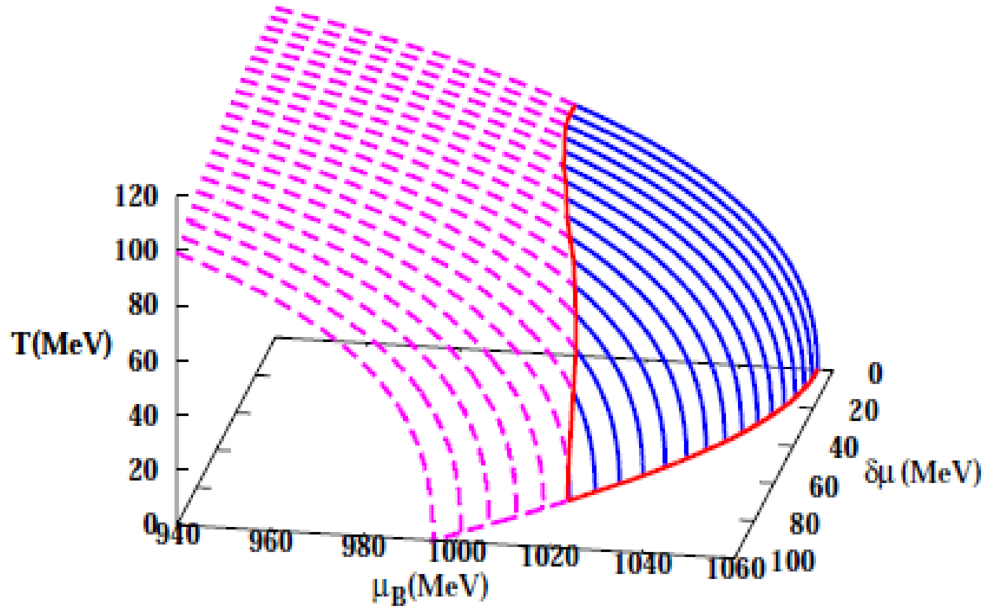
QCD phase diagram in Asymmetric Matter

- **Characteristic features of Compact Star Matter**
  - **Hot and/or Dense**
  - ***Unbalanced n and p yields (Isospin Asymmetric Matter)***

    Isospin chemical potential $\delta\mu = (\mu_n - \mu_p)/2 = (\mu_d - \mu_u)/2 > 0$
- **T_{CP} (critical point T) decreases at finite $\delta\mu$**
  - **Decrease of effective number of flavors**



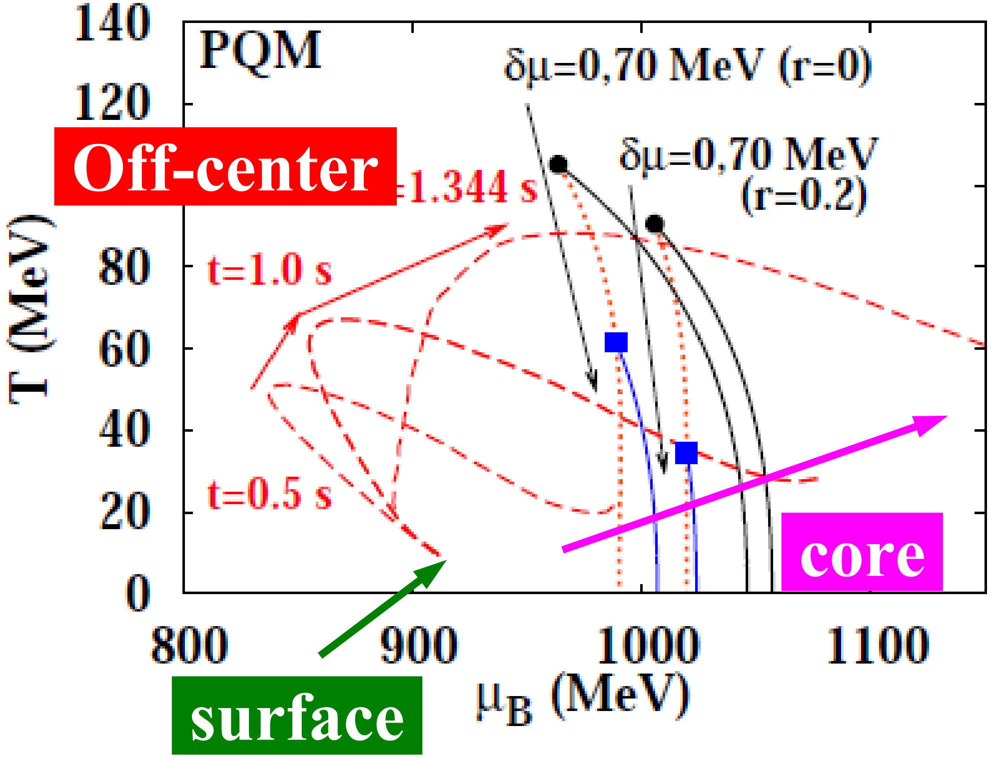
AO, Ueda, Nakano, Ruggieri, Sumiyoshi ('11)

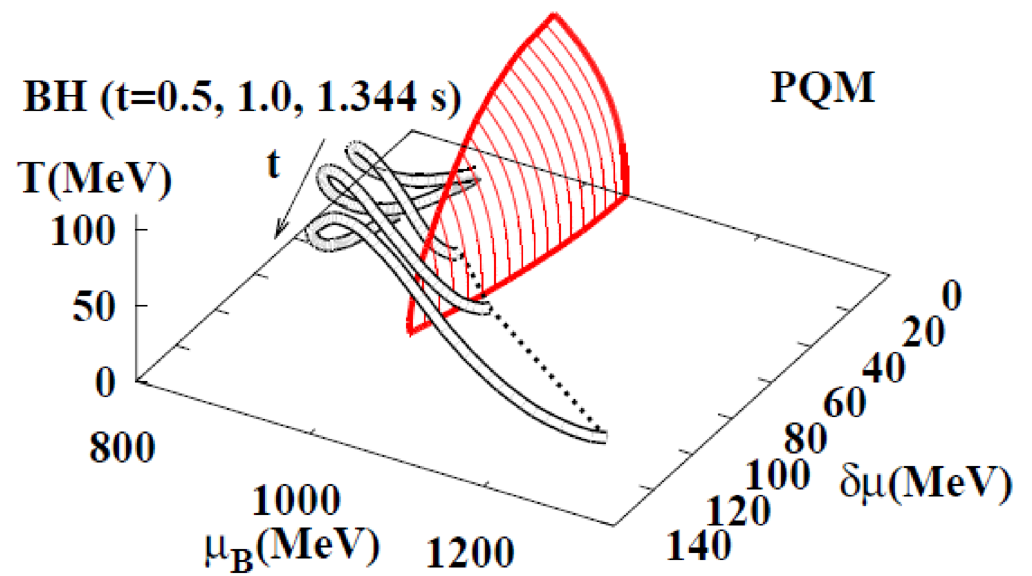


Ueda et al, in preparation

How is quark matter formed during BH formation ?

- Highest $\mu_B \sim 1300$ MeV > μ_c (1000-1100 MeV in eff. models)
  → *Quark matter is formed before BH formation*
- Highest T ~ 90 MeV > T_{CP} (at $\delta\mu$~50 MeV)
  Core evolves below CP, Off-center goes above CP → *CP sweep*
- Convenient to consider 3D phase diagram (T, μ_B, $\delta\mu$)

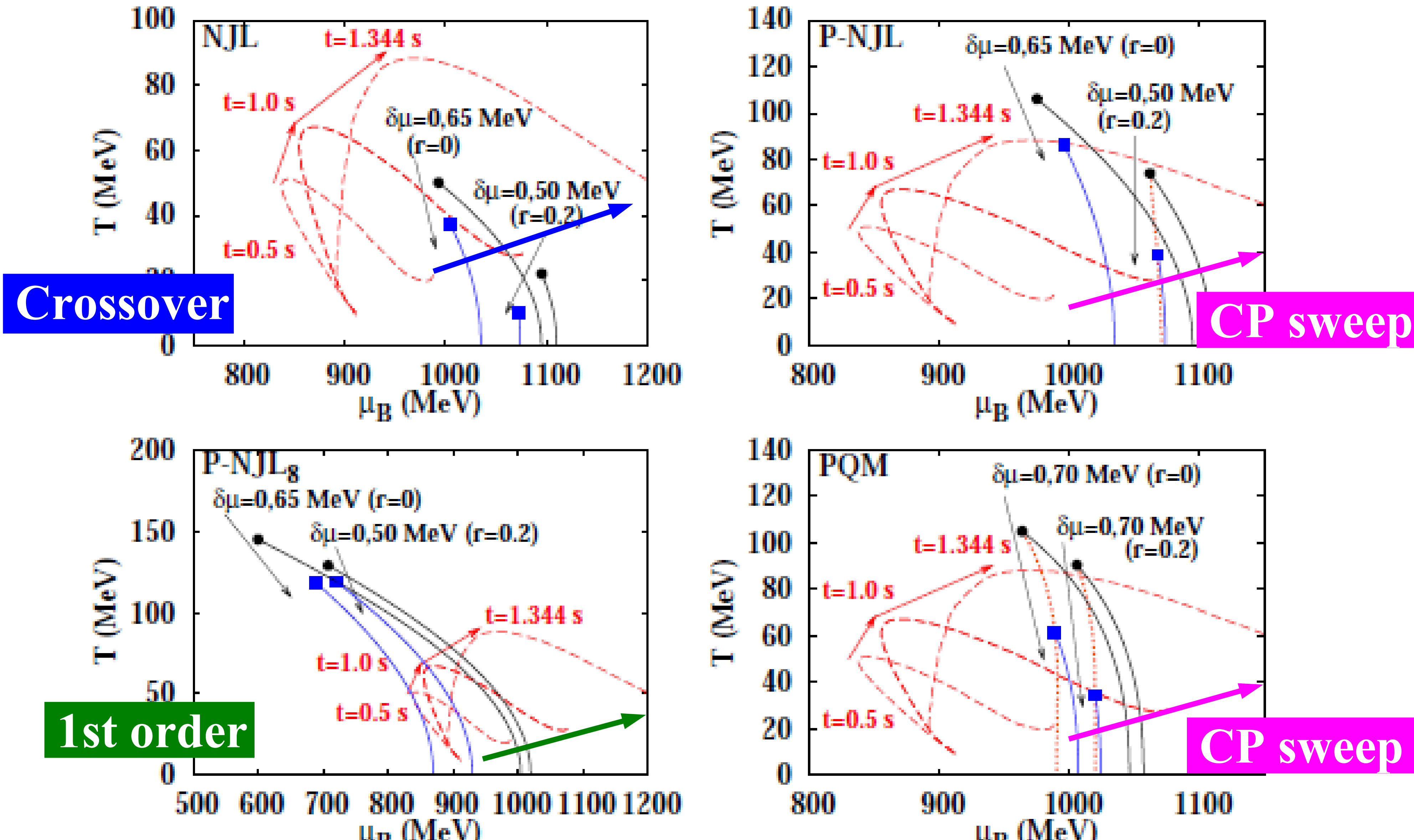




1.344 s = Just before BH formation

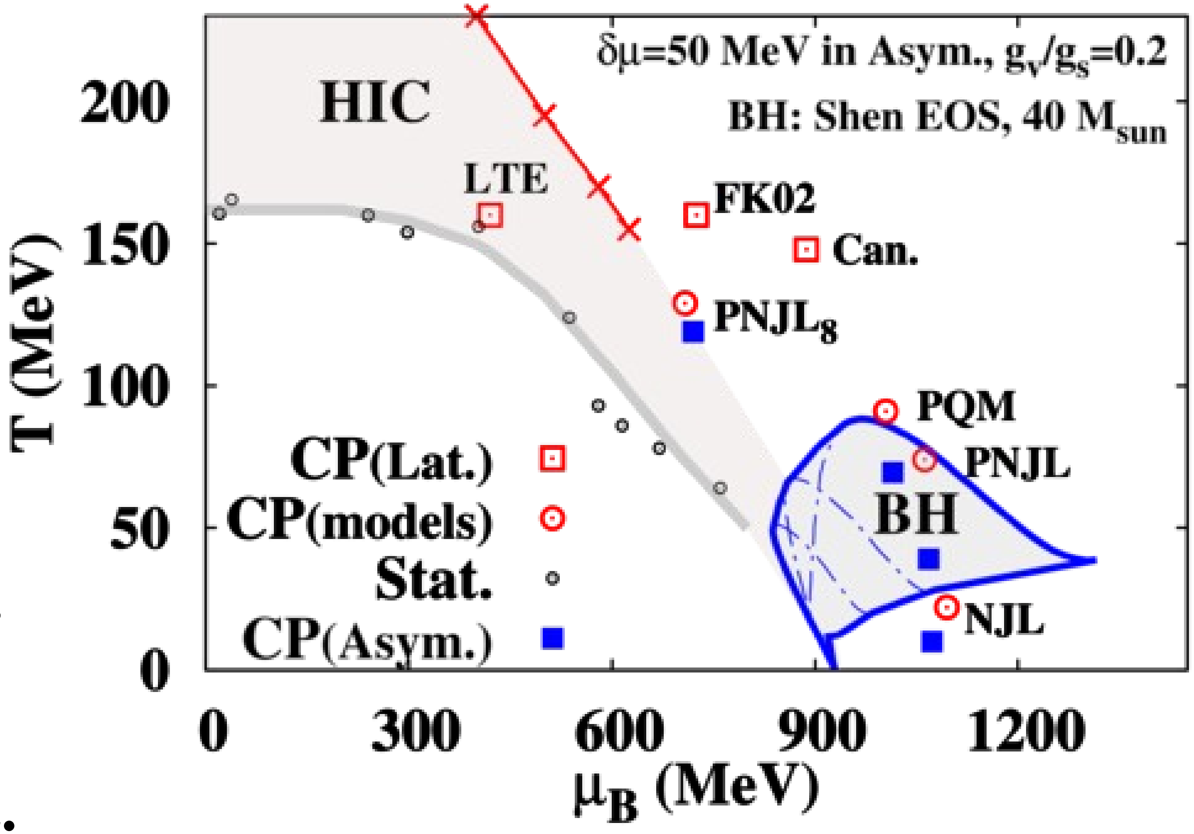
How is quark matter formed during BH formation ?

- Model dependence to form quark matter → Three ways



Swept Region of Phase Diagram during BH formation

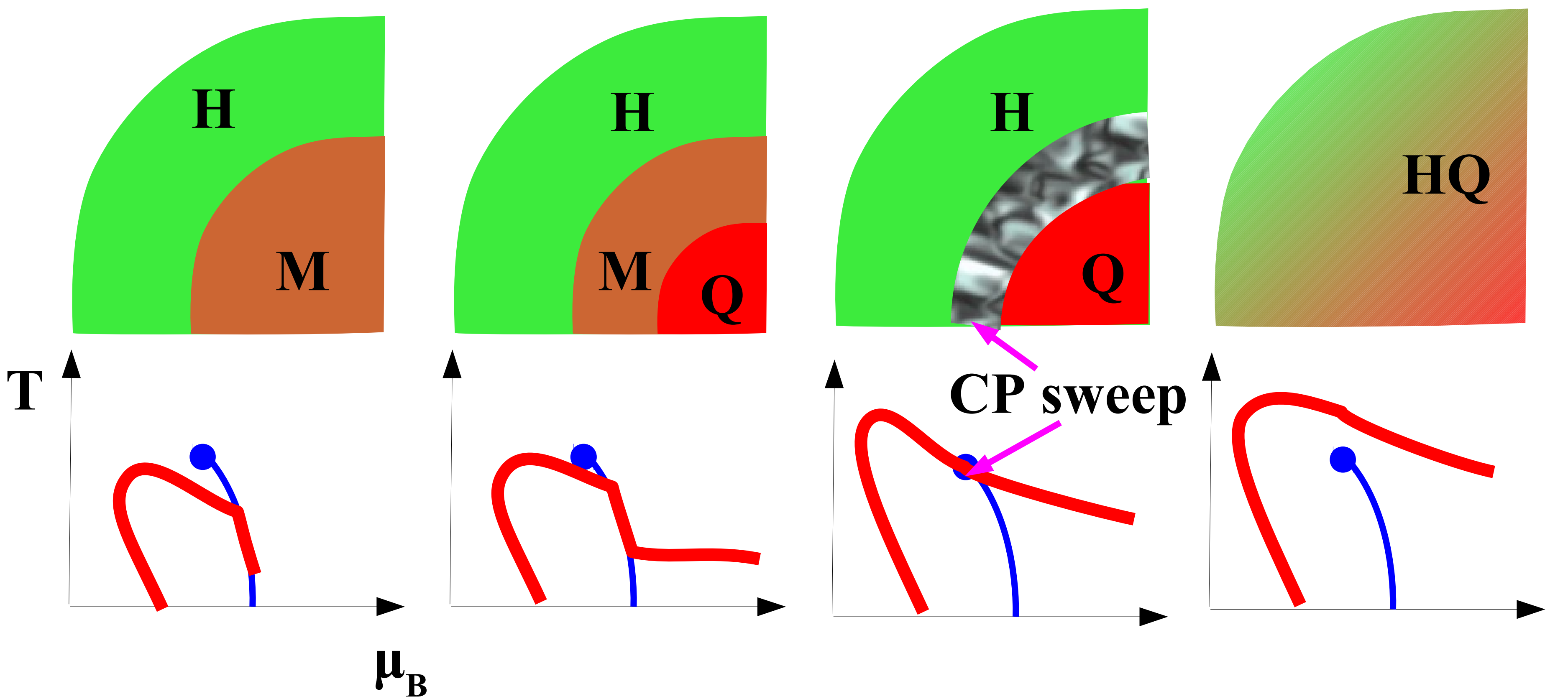
- CP location in Symmetric Matter
  - Lattice QCD
    μ_{CP}=(400-900) MeV
  - Effecitve models
    μ_{CP}=(700-1050) MeV
- CP in Asymmetric Matter (E.g. $\delta\mu$=50 MeV)
  - T_{CP} decreases at finite $\delta\mu$.
    → Accessible (T, μ_B) region during BH formation



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

What happens at CP sweep ?

- Large density fluctuation is expected around CP.
- Three layers (hadron, mixed, quark) merges to be one at a time.



What kind of signal do we expect ? I would like to have your idea ....

Summary

- **Dynamical BH formation would form**
  Hot(T~90 MeV), Dense(ρ_B~5ρ_0), Asymmetric(Y_C~(0.1-0.3)) matter,
  which provides a *Unique* opportunity to probe right-upper region of the QCD phase diagram.
  - **High μ_B~1300 MeV→ *baryon rich QGP formation.***
  - **High δμ~120 MeV → lower T_{CP}**
    → *CP sweep* , Cross over, or 1st order
- **Comparison of hadronic EOS hydro. results and effective model phase diagram is relevant, since hybrid EOS should be consistent with the hadronic EOS at low T and low ρ_B.**
- **What is the signal ?**
  - **No clear signal is proposed. (ν curve ? GW ? sound mode ?)**
  - **Hadron-Quark matter EOS with CP is necessary.**

    J. Steinheimer et al., PRC84 ('11)045208; D. Blaschke et al., PTPS 186 ('10)81.

Thank you for your attention !

Collaborators

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

CP sweep:
A.Ohnishi, H.Ueda, T.Z.Nakano, M.Ruggieri, K.Sumiyoshi,
Phys. Lett. B 704 ('11)284 [arXiv:1102.3753 [nucl-th]].

EOS with Hyperons:
C. Ishizuka, AO, K.Tsubakihara, K.Sumiyoshi, S.Yamada,
J. Phys. G 35 ('08)085201.
K. Tsubakihara, H. Maekawa, H. Matsumiya, A. Ohnishi,
Phys. Rev. C 81 (2010), 065206.

Hyperons in BH formation:
K. Sumiyoshi, C. Ishizuka, A. Ohnishi, S. Yamada, H. Suzuki,
Astrophys. J. Lett. 690 (2009), L43
K. Nakazato, S. Furusawa, K. Sumiyoshi, A. Ohnishi, S. Yamada, H. Suzuki,
Astrophys. J., to appear [arXiv:1111.2900 [astro-ph.HE]].