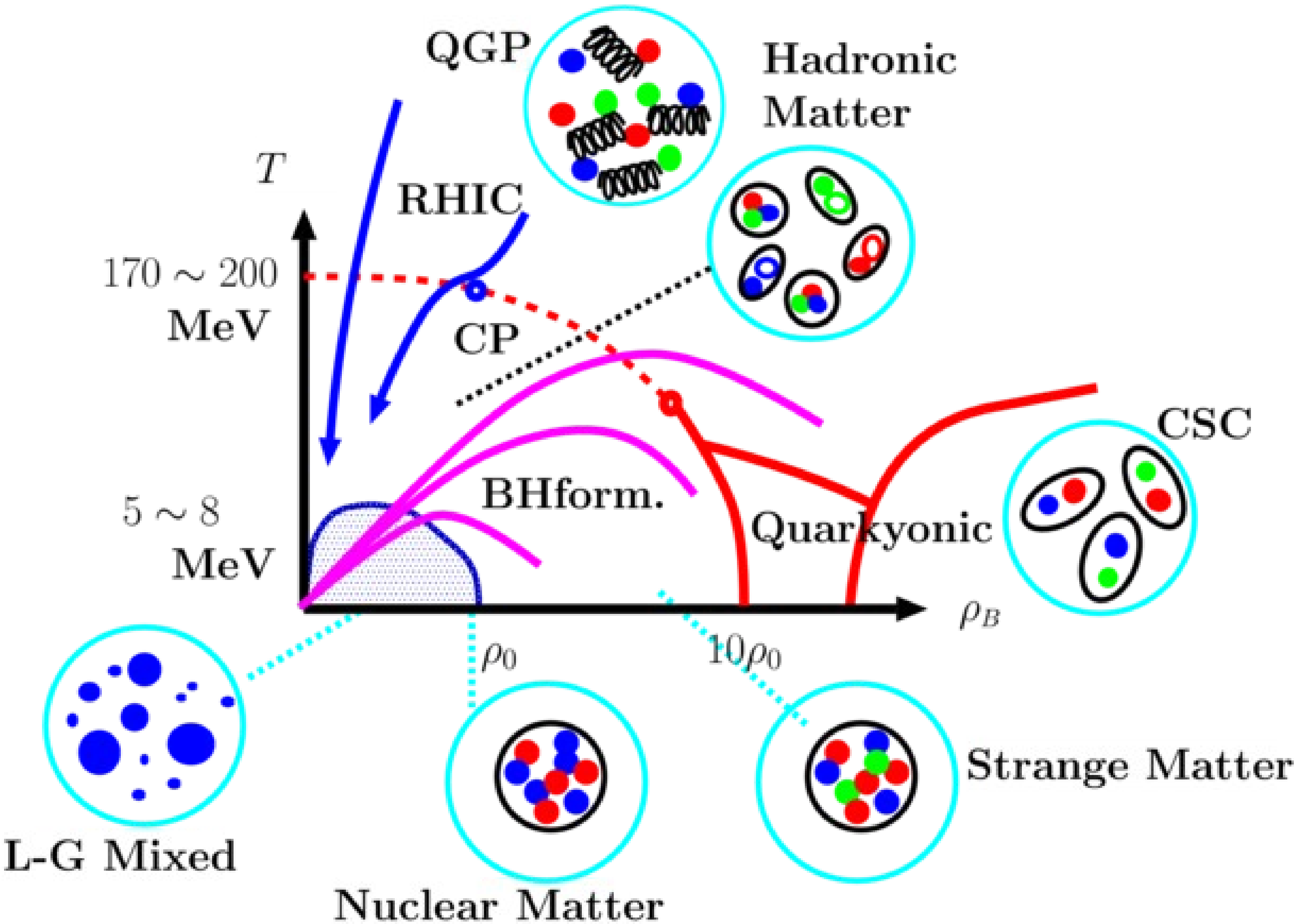
QCD phase diagram and dense matter EOS

Akira Ohnishi (YITP, Kyoto Univ.)

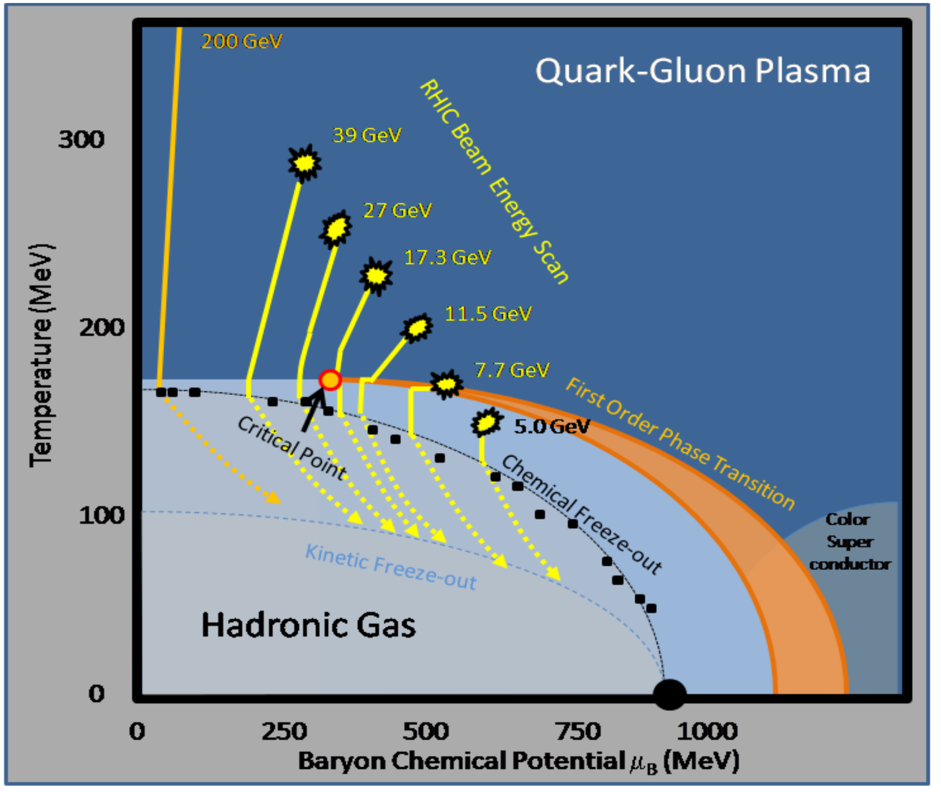
- **QCD phase diagram --- How can we observe it ?**
- **Phase diagram and in Strong coupling lattice QCD**
  - *Miura, Nakano, AO, Prog. Theor. Phys.,122(09),1045 [arXiv:0806.3357]*
  - *Miura, Nakano, AO, Kawamoto, PRD80(09),074034 [arXiv:0907.4245]*
  - *Nakano, Miura, AO, arXiv:0911.3453 [hep-lat]*
- **EOS of dense hyperonic matter and its application to black hole formation**
  - *Ishizuka, AO, Tsubakihara, Sumiyoshi,Yamada, JPG35(08)085201.*
  - *Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, ApJ690(09)L43.*
  - *Tsubakihara, Maekawa, Matsumiya, AO, arXiv:0909.5058.*
- **Summary**

QCD Phase diagram



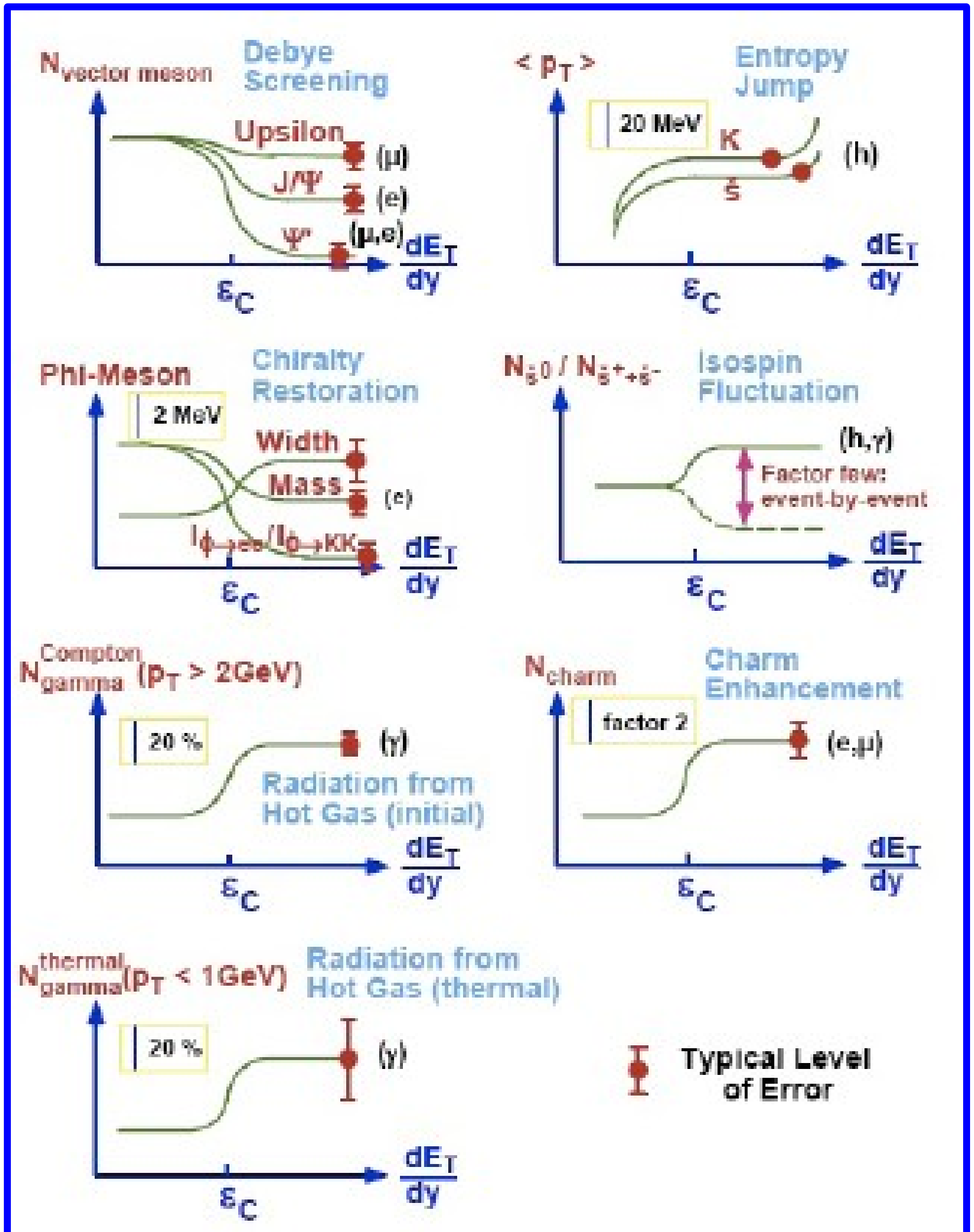
Critical Point Search at RHIC

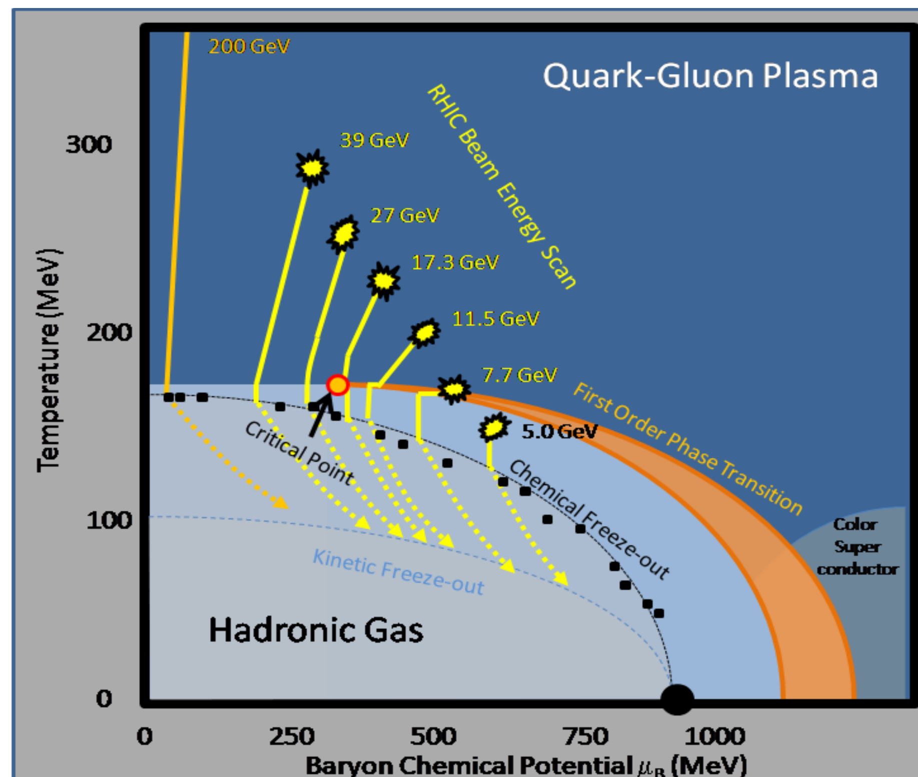
- Critical Point Search
  = One of the main goals in Low-E progs. at RHIC
- √s= 200 A GeV (RHIC top energy): Cross Over
  → √s = 5 A GeV (Injector (AGS) energy): Hadron phase
  We may observe "first order phase transition"
  and the QCD critical point in the range, √s= 5-200 A GeV



「相転移」をどうやって見つけるか？

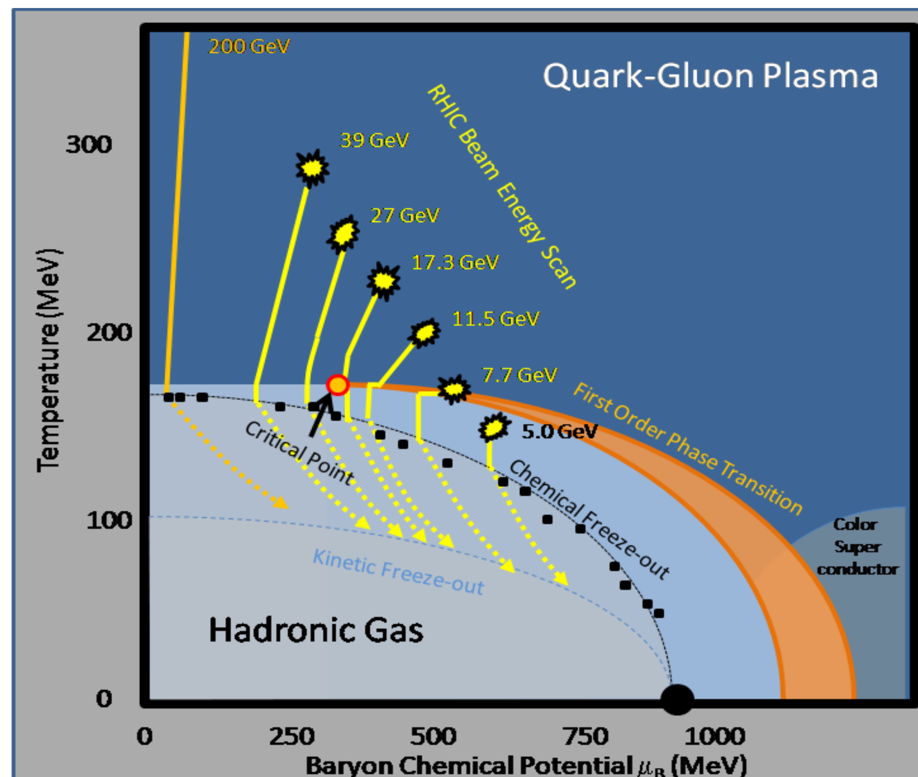
- 永宮 Method→ 様々な観測量の変化を同時測定





「相転移」をどうやって見つけるか？

- **永宮 Method→ 様々な観測量の変化を同時測定**
- **Critical Point (CP) or 1st order P.T.**
  - **Critical Point 近辺で期待されること**
    - **Fluctuation の増大 , Non-Gaussian 揺らぎ (Stephanov, Rajagopal, Shuryak)**
    - **軌道の focusing とそれにともなう粒子分布の変化 (Ejiri, Karsch, Laermann, Schmidt; Asakawa, Bass, Muller, Nonaka)**
    - **音波の消失 → Mach Cone の消失 (Minami, Kunihiro)**
  - **1st order phase transition での期待**
    - **密度揺らぎをもつ相転移後の状態からのハドロン化 (Mishustin; Randrup; Koch, Majumber, ...)**



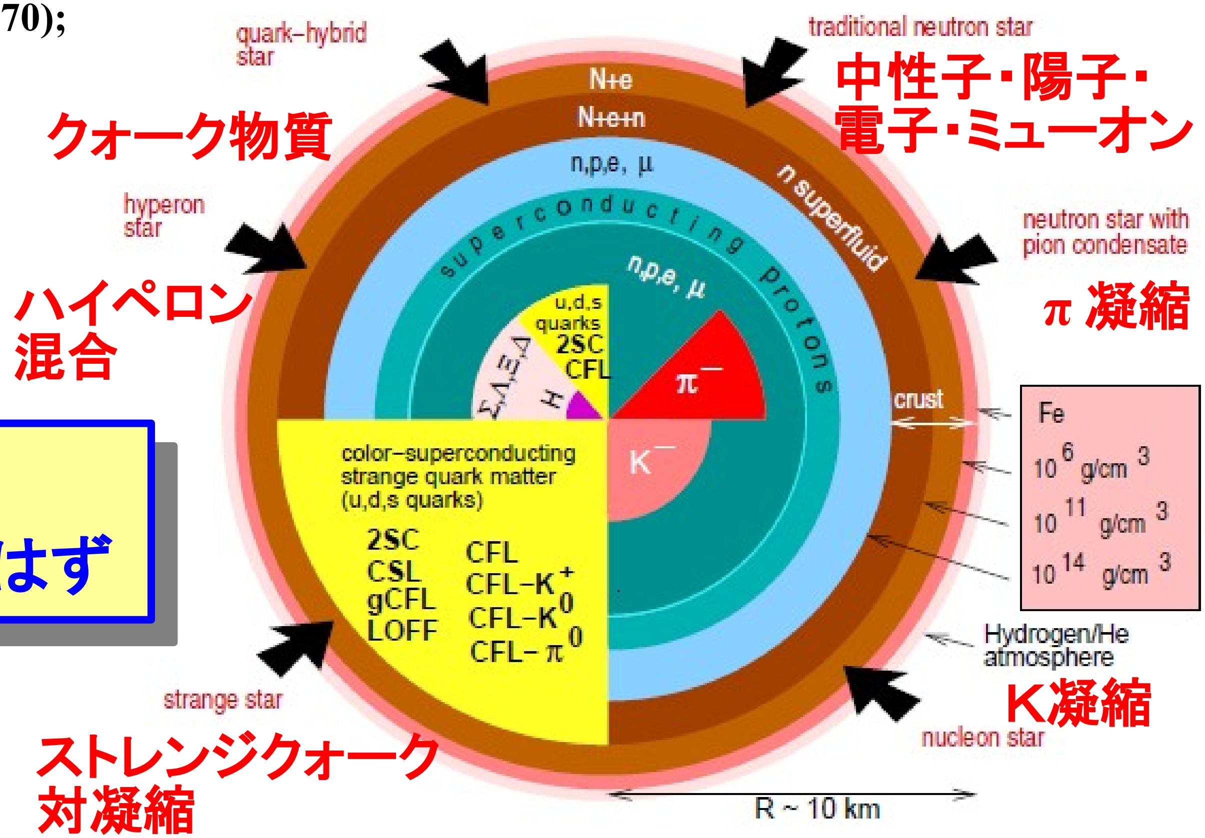
まだまだシグナル候補は未確定
→ 多くのアイデアが必要

Neutron Stars

- **高密度物質はどのような状態か？**
  - **核子の超流動状態 ($^3S_1$, $^3P_2$)**
  - **π 凝縮、K 凝縮、QGP 、カラー超伝導、Quarkyonic 物質、....**
  - **ハイペロン混合**

Tsuruta, Cameron (66); Langer, Rosen (70);
Pandharipande (71); Itoh(75);
Glendenning; Weber, Weigel;
Sugahara, Toki; Schaffner, Mishustin;
Balberg, Gal; Baldo et al.;Vidana et al.;
Nishizaki,Yamamoto, Takatsuka;
Kohno,Fujiwara et al.; Sahu,AO;
Ishizuka, AO, Tsubakihara,
Sumiyoshi, Yamada; ...

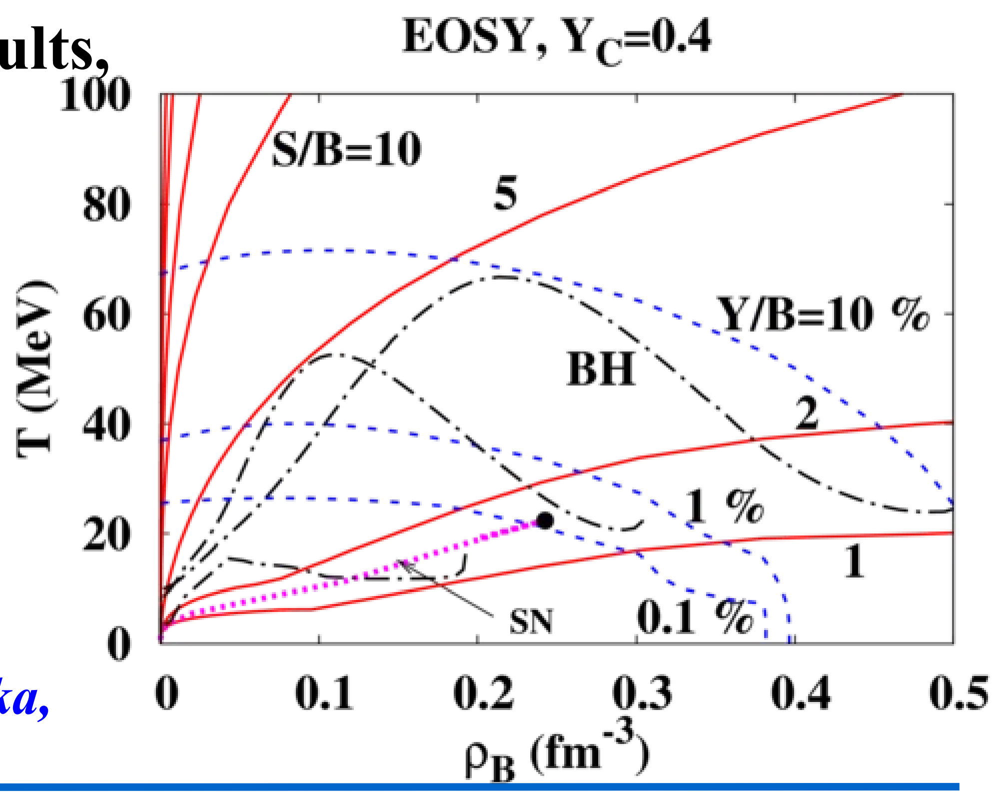
重い *Neutron star* では、
***strangeness* が現れているはず**



F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193

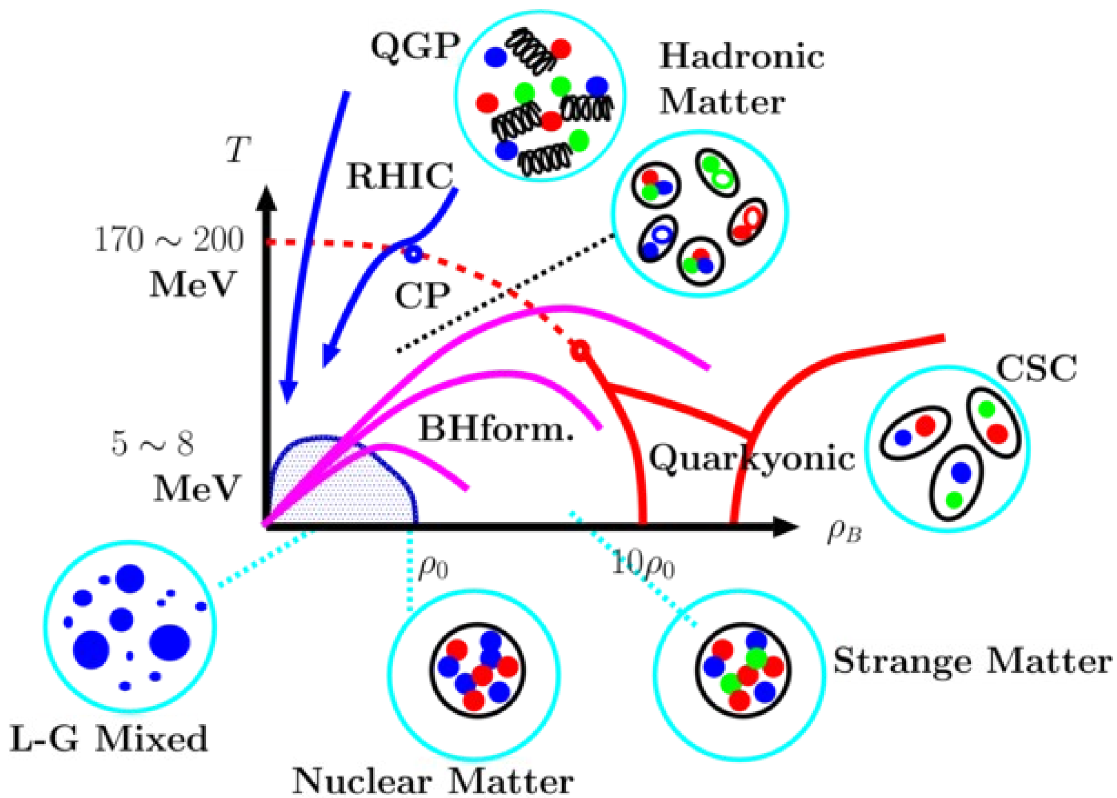
Core Collapse processes

- Numerical Simulation = ν radiation hydrodynamics
  - Baryons, Electons, Photons (Hydro) + neutrinos (Boltzmann)
- Supernova
  - 1-dim. (Spherical Sym.) → Exact ν transport, Explosion fails
    Sumiyoshi, Yamada, Suzuki, Shen, Chiba, Toki, 2005
  - 2-dim. Hydrodynamics
    → Some successful explosion results,
    but not yet conclusive
    Janka et al. (02); Kitaura et al. (06), Marek, Janka (08)
  - Second Shock due to QCD p.t. ?
    (Hatsuda, 1987; Sagert et al., 2009)
- Black hole formation
  - Hot and dense matter is formed
    Sumiyoshi et al. (05), Sumiyoshi, Ishizuka, AO, Yamada, Suzuki (09)



QCD Phase diagram

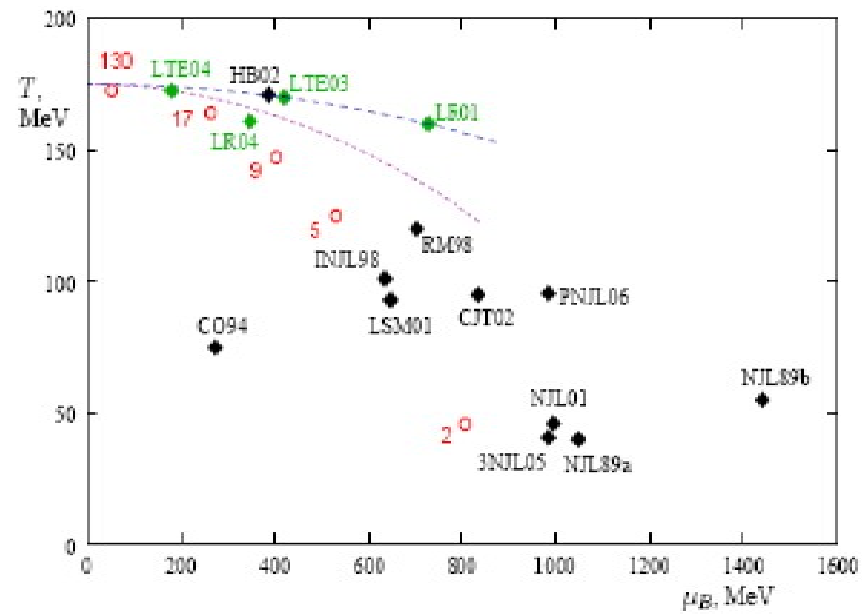
- **Phase transition at high T → Lattice MC & RHIC**
- **High μ transition has rich physics**
  → Various phases, CEP, Astrophysical applications, ...



QCD phase diagram is not only an academic subject, but also to be observed in near future !

Theoretical Approaches

- **Sign problem**
  → Important sampling in Lattice MC does not work precisely.
- **Models & Approximate Approaches**
  - **Lattice MC for small μ (Tayler, AC, DOS, Canonical, …)**
    → Consistent in small μ (μ/T < 1)
  - **Monomer-Dimer-Polymer sim. in the Strong Coupling Limit**
    Karsch, Mutter ('89), de Forcrand, Fromm ('09)
  - **Eff. Models:**
    - **NJL, PNJL (c.f. Sakai's talk)**
      Nambu, Jona-Lasino ('61), Hatsuda, Kunihiro('94), Fukushima ('03)
    - **PLSM (Linear σ model with Pol.)**
  - **Approximations:**
    - **Large Nc**
      E.g. Hidaka, McLerran, Pisarski (08)
    - **Strong coupling lattice QCD**



Phase diagram in Strong-Coupling Lattice QCD

Strong Coupling Lattice QCD: Pure Gauge

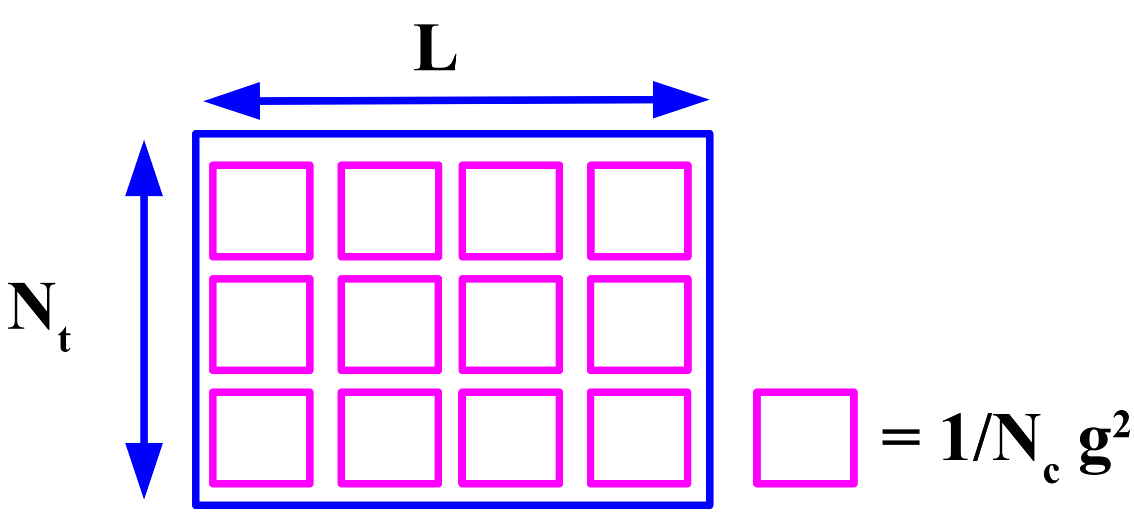
- **Quarks are confined in Strong Coupling QCD**

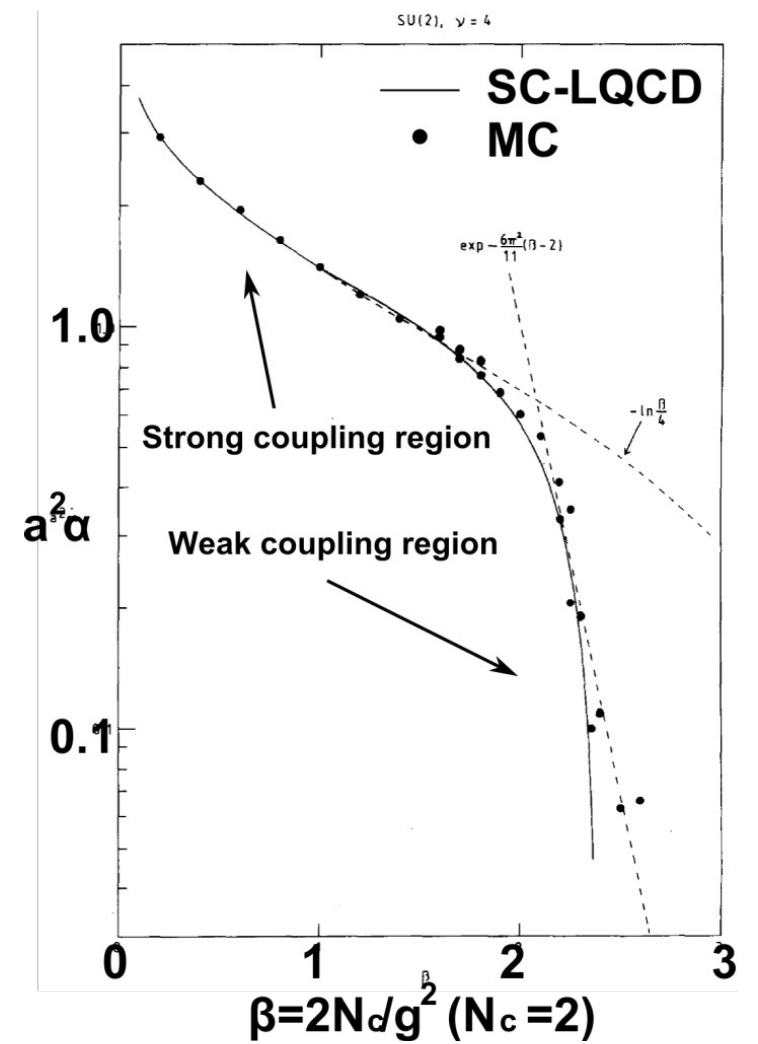
K. G. Wilson, PRD10(1974),2445
M. Creutz, PRD21(1980), 2308.
G. Munster, 1981

  - **Strong Coupling Limit (SCL)**
    → Fill Wilson Loop with Min. # of Plaquettes
    → Area Law (Wilson, 1974)

$$S_{\rm LQCD} = -\frac{1}{g^2}\sum_{\Box} {\rm tr}\left[U_\Box + U_\Box^\dagger\right]$$

  - **Smooth Transition from SCL to pQCD in MC (Creutz, 1980)**





Munster, '81

NLO & NNLO SC-LQCD: Setups & Disclaimer

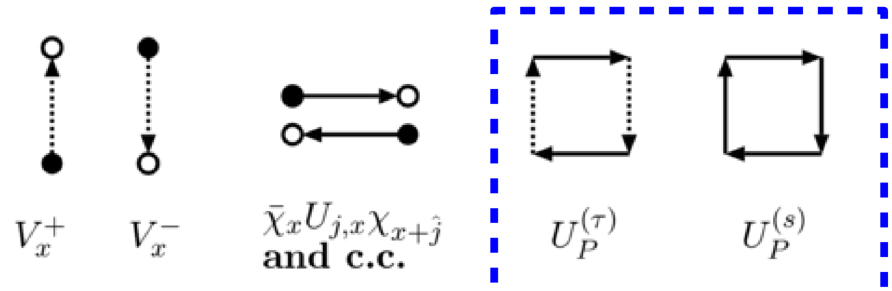
- **We investigate the phase diagram and try to understand nuclear matter based on the strong-coupling lattice QCD (SC-LQCD).**
  - **Effective potential (free E. density) → phase boundary & EOS**
  - **Setups & Disclaimer**
    - **Effective action in SCL ($1/g^0$), NLO ($1/g^2$), NNLO ($1/g^4$) terms**
      NLO: Faldt-Petersson ('86), Bilic-Karsch-Redlich ('92)
      Conversion radius > 6 in pure YM ? Osterwalder-Seiler ('78)
    - **One species of unrooted staggered fermion (N_f=4 in continuum limit)**
      Moderate N_f deps. of phase boundary: BKR92, Nishida('04), D'Elia-Lombardo ('03)
    - **Leading order in 1/d expansion (d=3=space dim.)**
      → Min. # of quarks for a given plaquette configurations, no spatial B prop.
    - **Effective potential is obtained in mean field approximation**
    - **Polyakov loop effects are not included (No Deconfinement).**
    - **Different from "strong couling" in "large N_c"**

Still far from "Realistic", but SC-LQCD would tell us useful qualitative features of the phase diagram and EOS.

Effective Potential in SC-LQCD with Fermions

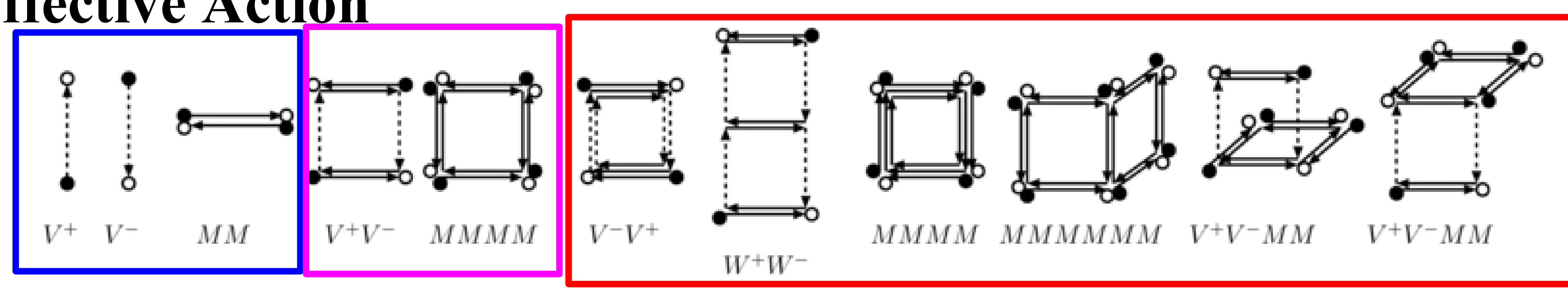
- **Lattice QCD partition function**
  → Effective action of fermion and U_0 (U_j integral)
  → Linearized eff. Action (Bosonization)
  → Eff. potential (fermion & U_0 integral)

- **Lattice Action = fermion x link + plaq.**



$1/g^2$

- **Effective Action**



SCL (Kawamoto-Smit, '81) *NLO (Faldt-Petersson, '86)* *NNLO (Nakano, Miura, AO, '09)*

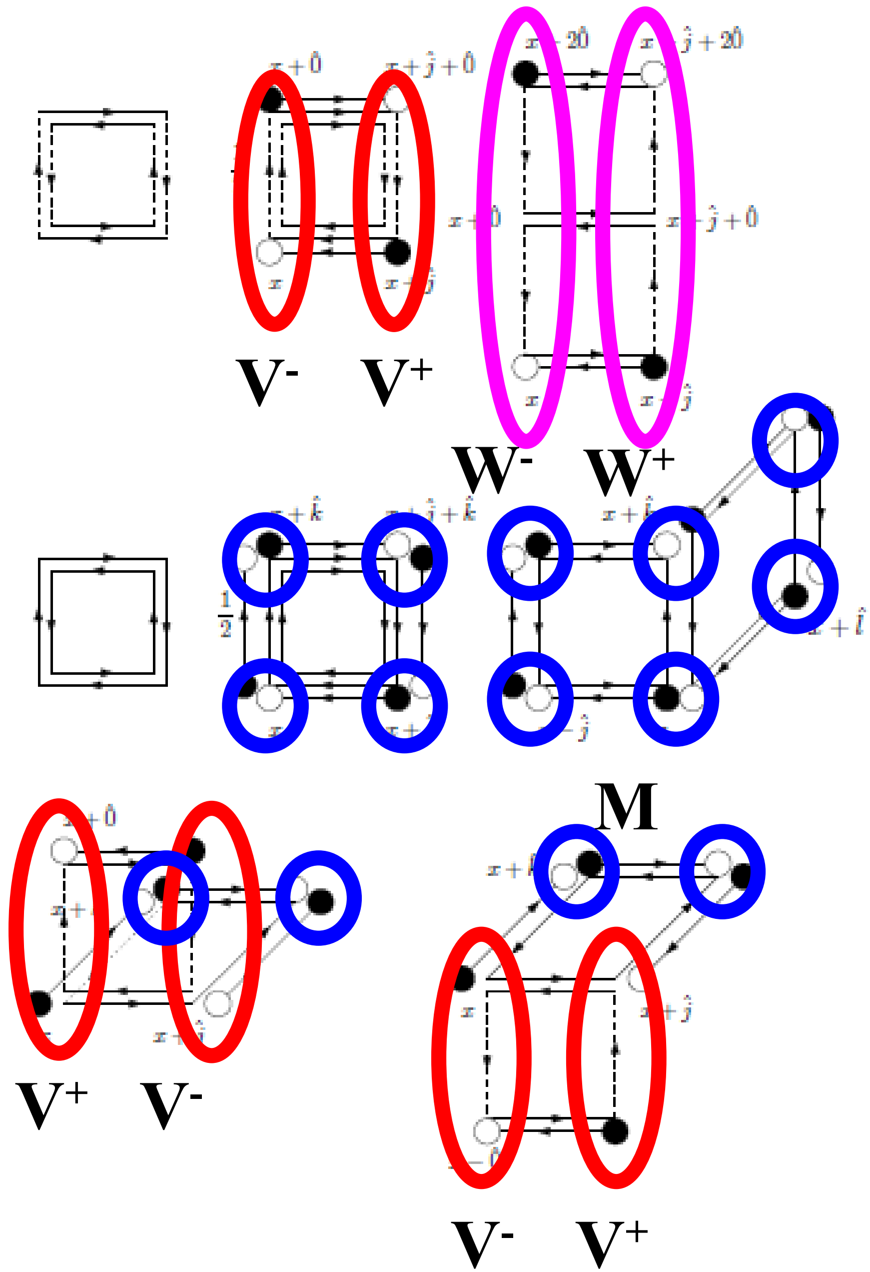
NNLO Effective Action

- **Cumulants of two plaquettes**
  = Correlation part of connected two plaquettes
  - **Uncorr. & Normalization part are suppressed in 1/d power**
  - **Effective Action consists of**

$$V^- V^+, W^- W^+, MMMM, MMMMMM, V^- V^+ MM$$

  - **New type of Composite**
    = next-to-nearest neighboring site coupling in τ direction

$$W_x^+ = \chi_x U_{0,x} U_{0,x+\hat{0}} \bar{\chi}_{x+2\hat{0}}$$



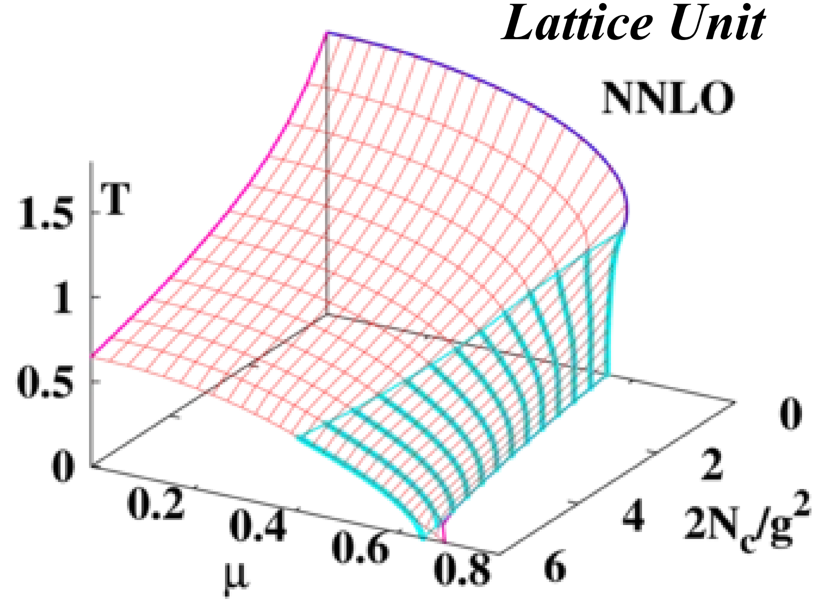
Effective Potential and Phase Diagram

- **Effective Potential in NLO/NNLO SC-LQCD**
  - **Suppression of const. quark mass → Smaller Tc**
  - **Vector potential from temporal plaq. → Chem. Pot. is shifted**

→ σω model of quarks with non-linear couplings !

- **Phase diagram evolution with β**
  → Miura's talk
  - **Shape of the phase diagram is compressed in T direction with β**
  - **Critical Point moves in lower μ direction in NNLO.**
    EPisarski-Wilczek ''84), Ejiri, ('08), Aoki et al.(WHOT,'08), Allton et al., ('03,'05)

Lattice Unit

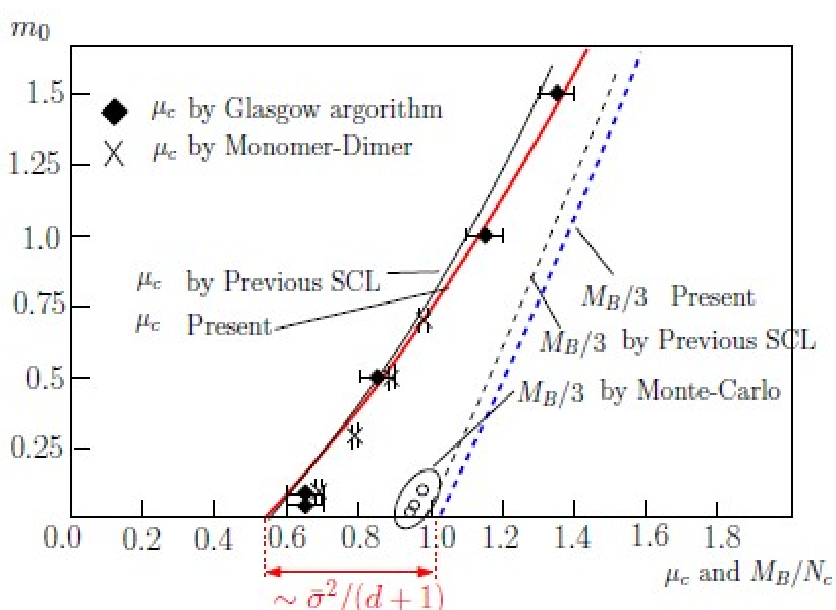


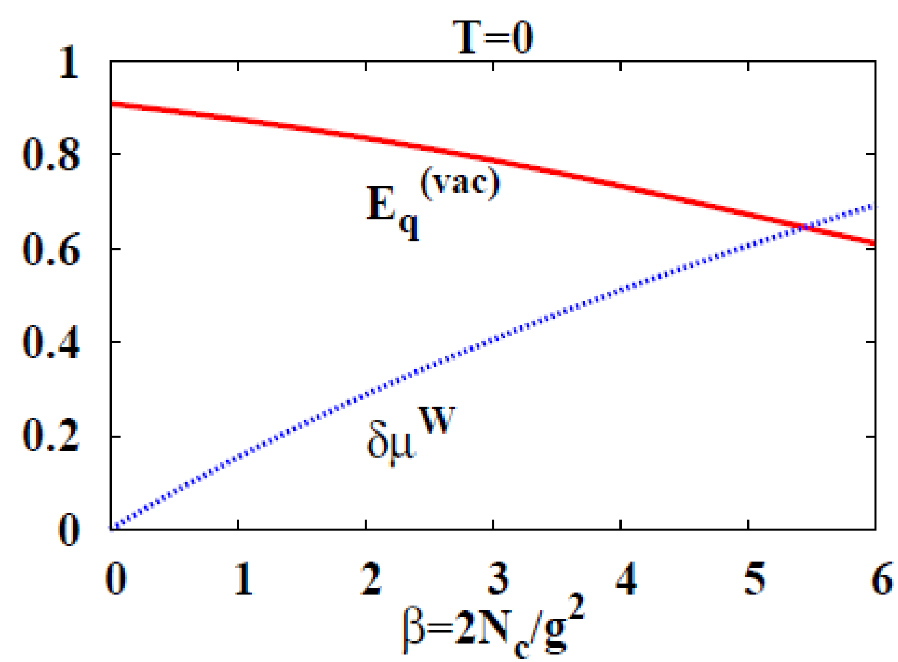
NLO/NNLO improves the shape of the phase diagram, but effects are not enough to explain the real world.

Cold Nuclear Matter on the Lattice

- **Baryon mass puzzle in SCL-LQCD: $N_c\mu_c < M_B$**
  → QCD phase transition takes place before baryons appear.
  Kluberg-Stern, Morel, Petersson ('83), Damgaard, Hochberg,Kawamoto ('85), Karsch, Mutter ('89), Barbour et al.('97), Bringoltz('07), Miura, Kawamoto, AO ('07)

- **Finite coupling effects: Decrease of quark mass.**
  → Const. quark mass (~ E_q) becomes smaller than μ_c for β > 5.5 in NNLO SC-LQCD.

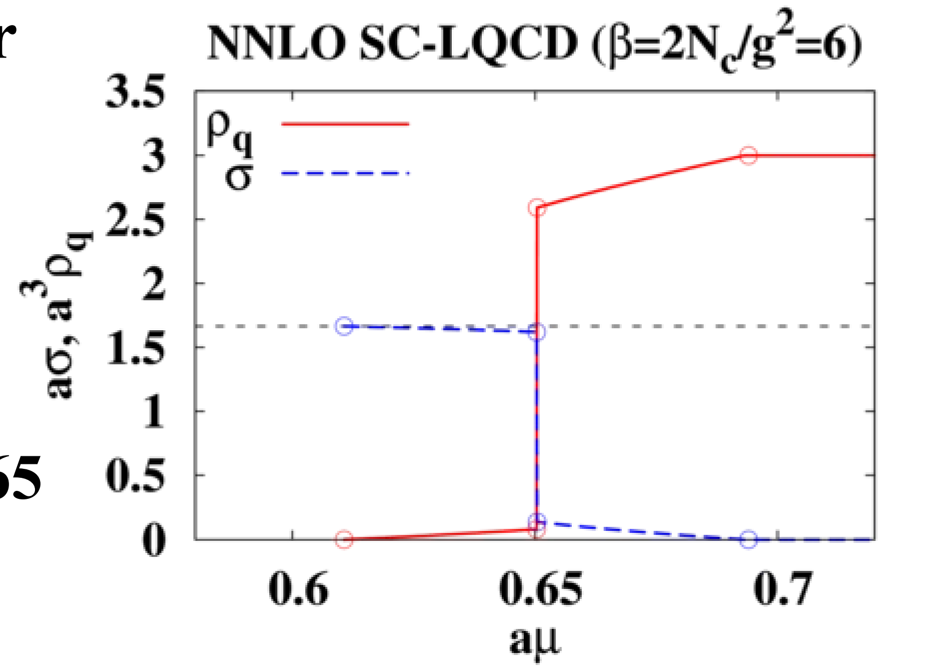




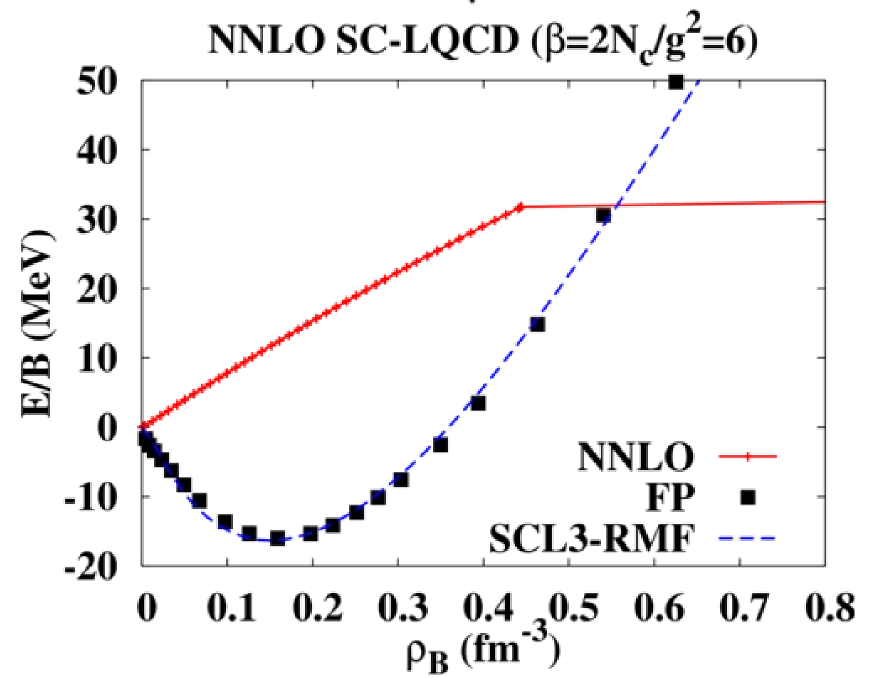
Miura, Kawamoto, AO ('07)

Cold Nuclear Matter on the Lattice

- **Do we observe finite density matter before 1st order phase transition ?**
  → Yes !
  - **$E_q(\mu=0, T=0, \beta=6)=0.61$**
    $\mu_c^{(1st)}(T=0, \beta=6)=0.65$
    → "Nuclear matter" in $0.61<\mu<0.65$



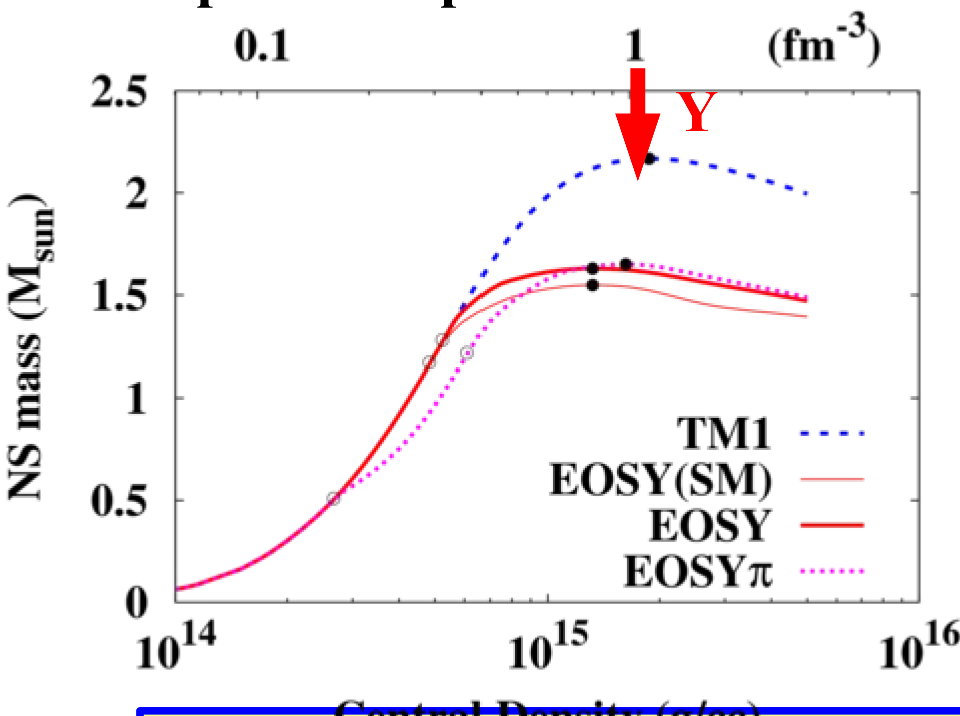
- **EOS of "Nuclear matter"**
  - **$a^{-1} \approx 500$ MeV**
    Bilic, Demeterfi, Petersson ('92)
    → Density in the order of ρ_0
  - **No saturation**
  - **1st order transition at $\rho_B \approx 0.4\ \mathrm{fm}^{-1}$.**

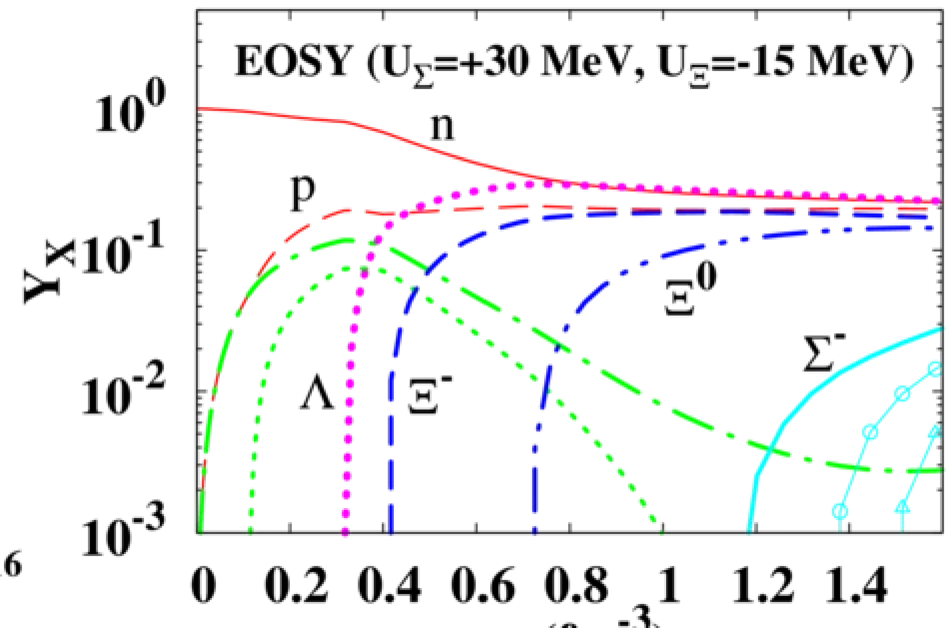


EOS of Dense Hyperonic Matter and Its Applicatoin to Black Hole Formation

Neutron Stars

- **RMF with Hyperons**
  - **Hyperon Potential: U_Λ = -30 MeV, U_Σ = +30 MeV, U_Ξ = -15 MeV**
  - **Neutron Star: (ρ_B,T,Y_e) ~ (5ρ_0, 0 MeV, 0.2) → Hyperon fraction ~ 50 %**
  - **Reduction of max. mass of NS**
  - **Repulsive Σ pot. → Ξ will be the next hyperon to Λ !**



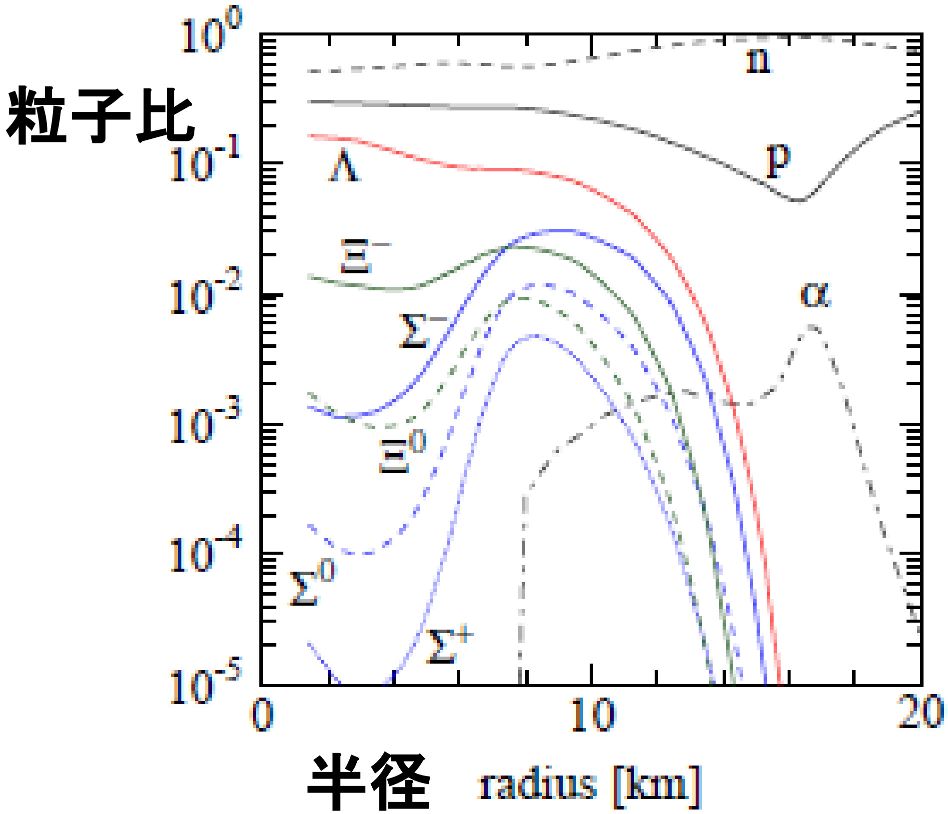


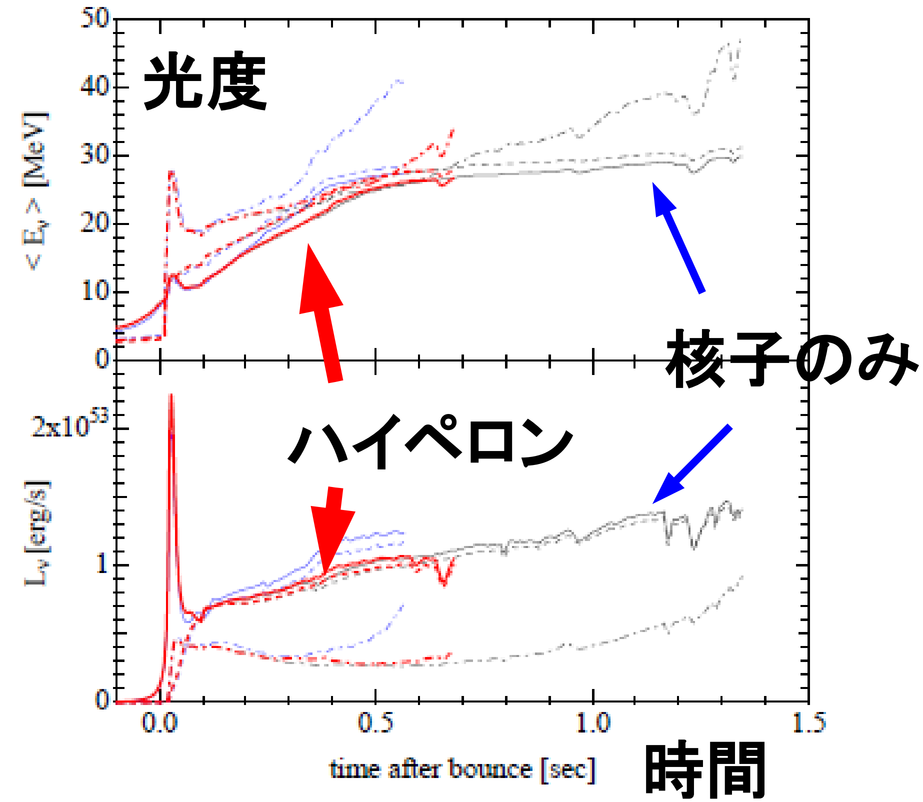
Neutron Star can be understood as Hyperon Star !

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***

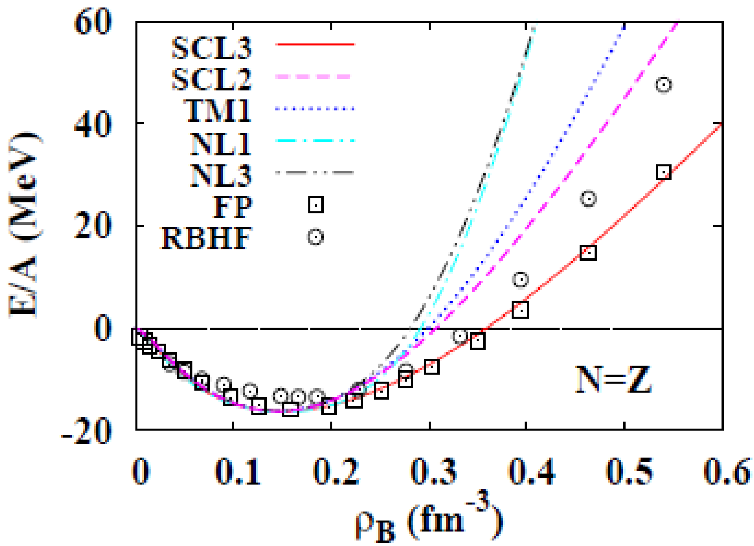


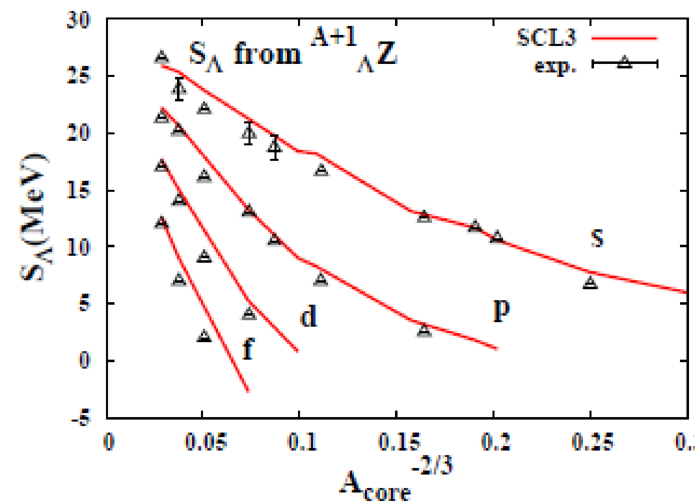


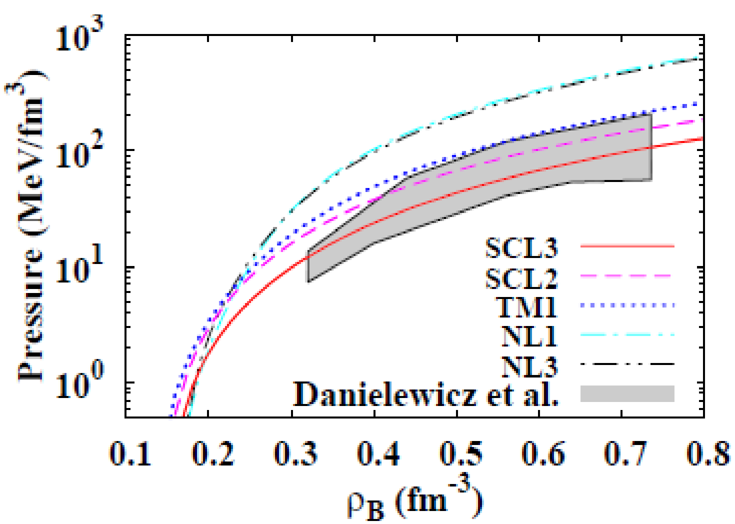
Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009

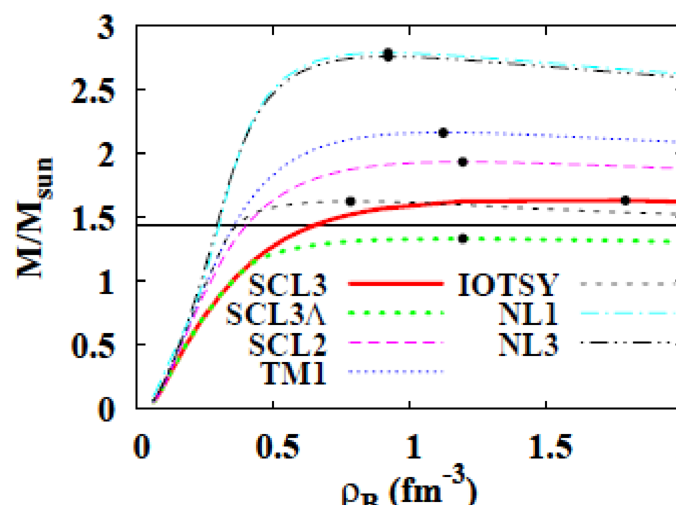
Chiral SU(3) RMF with a Logarithmic σ potential

- **Nuclear matter EOS is important in**
  - **Nuclear B.E., HIC, Neutron Stars, Supernova, BH formation, ...**
    → Chiral symmetry may be as important as flavor SU(3) sym.









Tsubakihara et al., arXiv:0909.5058

Summary

- QCD phase diagram at finite μ or ρ_B may be probed in near future experiments (RHIC/FAIR) and observations (ν/GW), in addition to the current study in the μ=0 region.
- Due to the sign problem, approximate/effective model studies are needed to understand finite density matter.
- We have derived the effective potential with NLO ($1/g^2$) and NNLO($1/g^4$) effects in strong coupling lattice QCD.
  - finite coupling → smaller quark mass, repulsive vector pot.
  - Phase diagram shape is improved, while the effects are not enough.
  - Baryon mass puzzle is solved (at least weakened) with finite coupling.

Nuclear matter on the lattice may not be too far (?)

Thank you !

- Collaborators
  - Strong coupling lattice QCD: K. Miura (YITP), T.Z. Nakano (Kyoto U.), N.Kawamoto (Hokkaido U.)
  - Hyperonic EOS for Supernovae: K. Sumiyoshi (Numazu), K. Tsubakihara (Hokkaido), C. Ishizuka (Keele), S. Yamada (Waseda), H. Suzuki (Tokyo Sci. U.)
  - Chiral RMF / Hyperon production reactions: K. Tsubakihara, H. Maekawa, H. Matsumiya (Hokkaido), P.K. Sahu (India)

  Not mentioned....

  - Ξ and Λ hypernuclei in AMD: M. Isaka, H. Matsumiya, M. Kimura (Hokkaido), A. Dote (KEK)
  - pions in neutron star: D. Jido (YITP), T. Sekihara (Kyoto U.), K. Tsubakihara (Hokkaido)
  - Heavy-Ion Collisions: Isse, Nara, Hirano, Kunihiro, Schafer, Muller