Symmetry energy in dense matter and its relation to phase boundary

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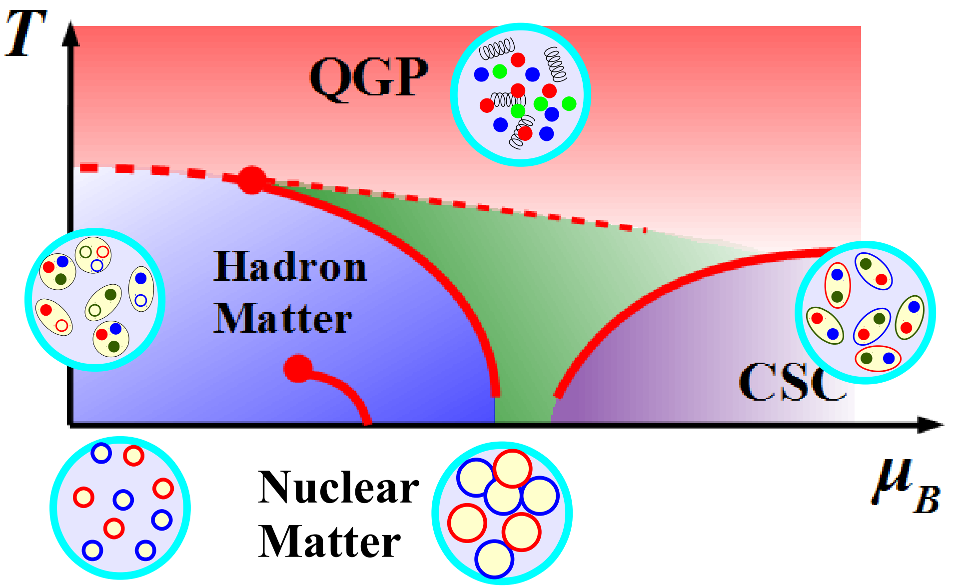
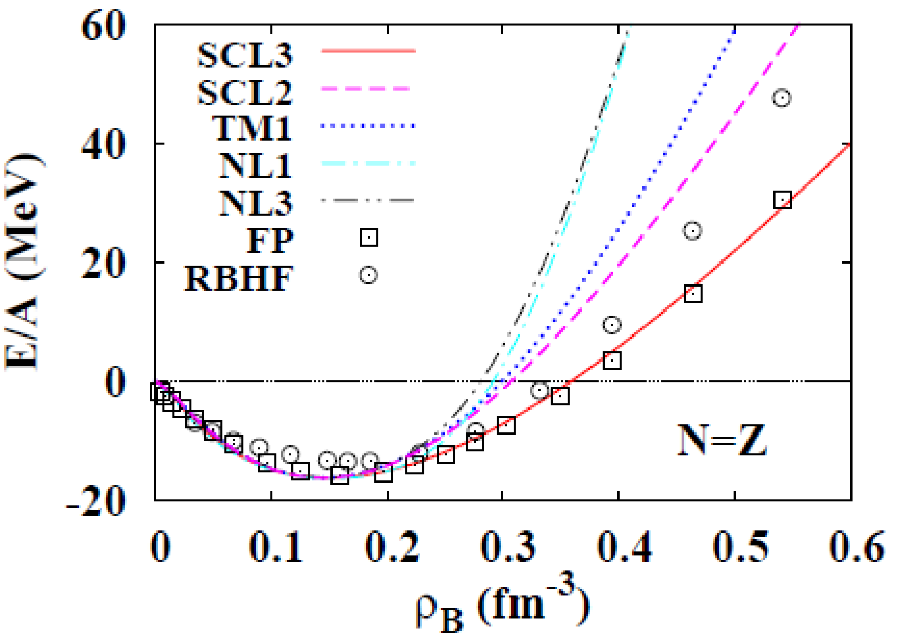
**Symmetry Energy workshop,
Nov. 10-12, 2011, Kyoto, Japan**

- **Introduction**
- **QCD phase diagram in asymmetric nuclear matter and black hole formation**
- **Symmetry energy dependence of dense matter EOS**
- **Summary**

QCD Phase diagram and Nuclear Matter EOS

- **Phase diagram and EOS**
  = Two important aspects of Nuclear Matter
- **Dense nuclear matter has rich physics**
  → Many-body theory, Exotic compositions, CEP, Astrophysical applications, ...





Nuclear matter EOS
= Subjects in Nuclear, Quark-Hadron, Particle, Astro, and Condensed Matter Physics !

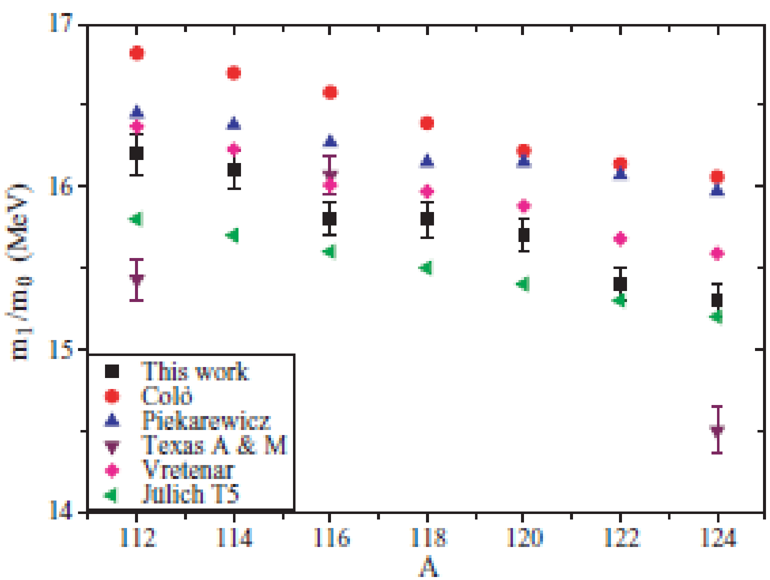
Symmetry Energy

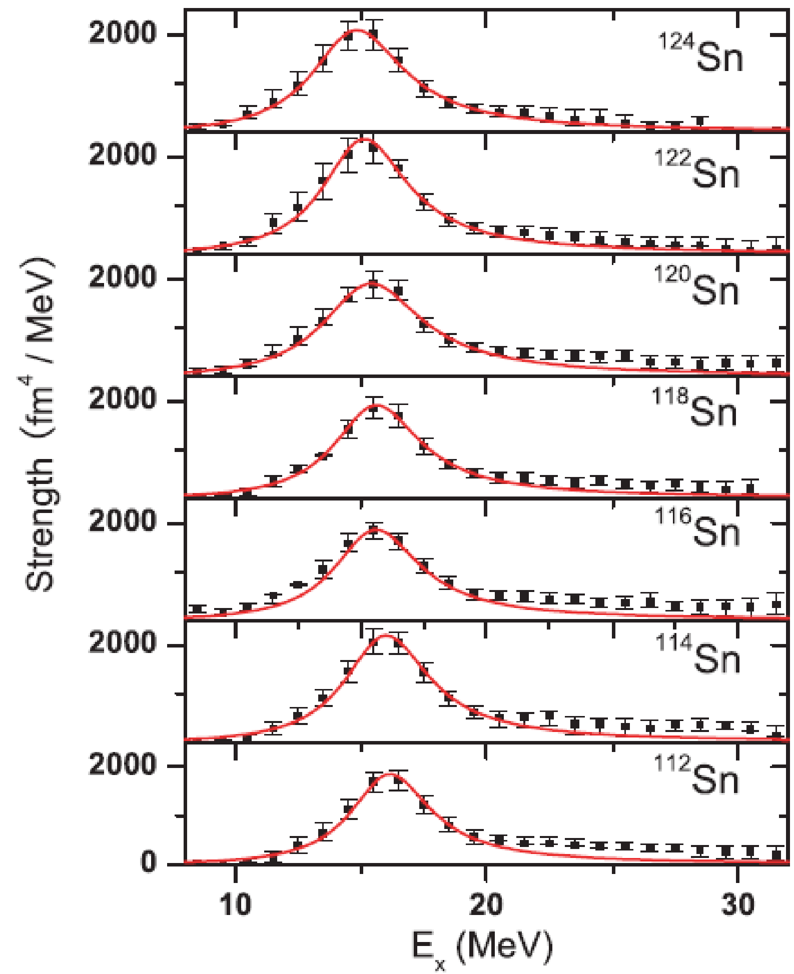
- **Recent data suggest that EOS becomes softer in asymmetric nuclear matter.**

$$K = K_{sym} + K_{asy}\,\delta^2, \quad K_{asy} \sim -550\,\mathrm{MeV}$$

$$E_{sym} \simeq 31.6\,(\rho/\rho_0)^{1.05}$$

- **Isoscalar Giant Monopole Resonance (ISGMR) of Sn isotopes**
  - **ISGMR in Isotope chain (^{112}Sn ~ ^{124}Sn) is systematically studied.**





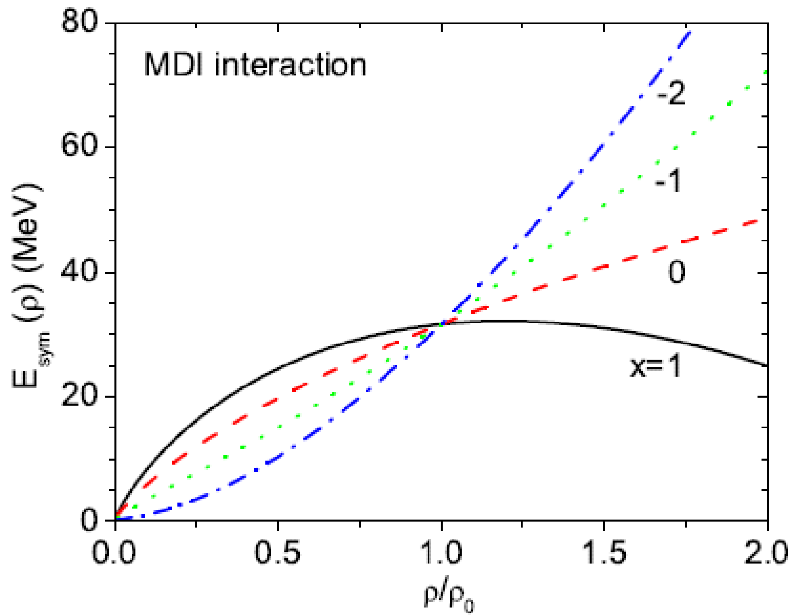
T. Li, U. Garg, et al., PRC81('10), 034309.

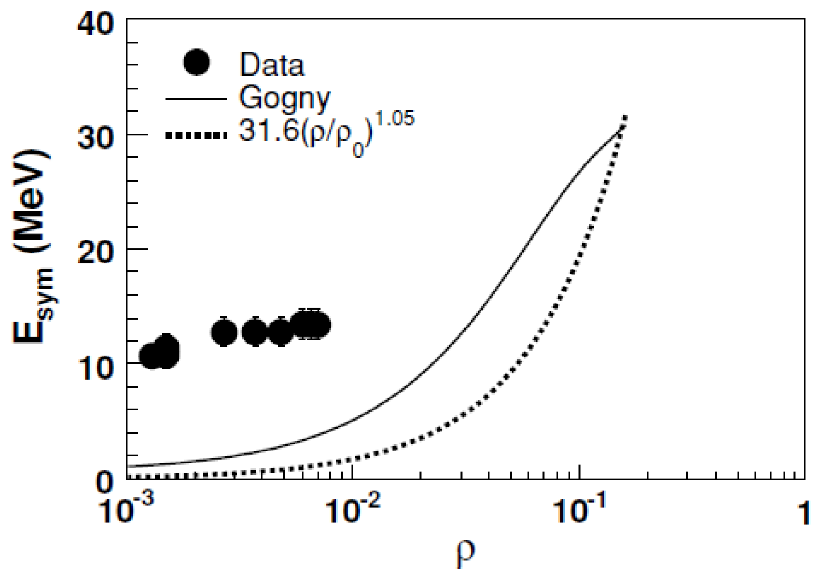
Symmetry Energy

- **Symmetry energy in HIC**
  - **Isospin diffusion → K_{asy} ~ -550 MeV**

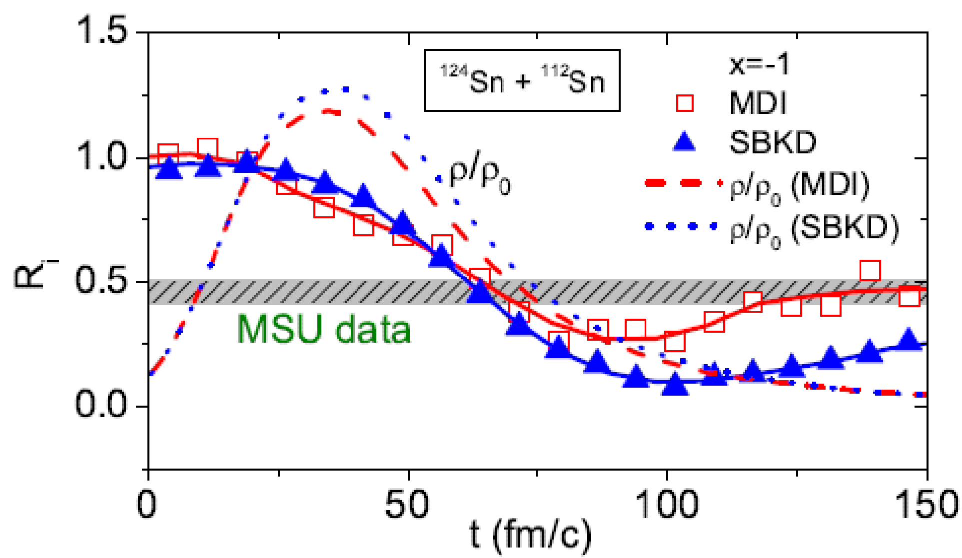
$$R_i = \frac{2X_{^{124}Sn+^{112}Sn} - X_{^{124}Sn+^{124}Sn} - X_{^{112}Sn+^{112}Sn}}{X_{^{124}Sn+^{124}Sn} - X_{^{112}Sn+^{112}Sn}}$$

  - **Light frag. dist.**
    → Larger Sym. E at low ρ



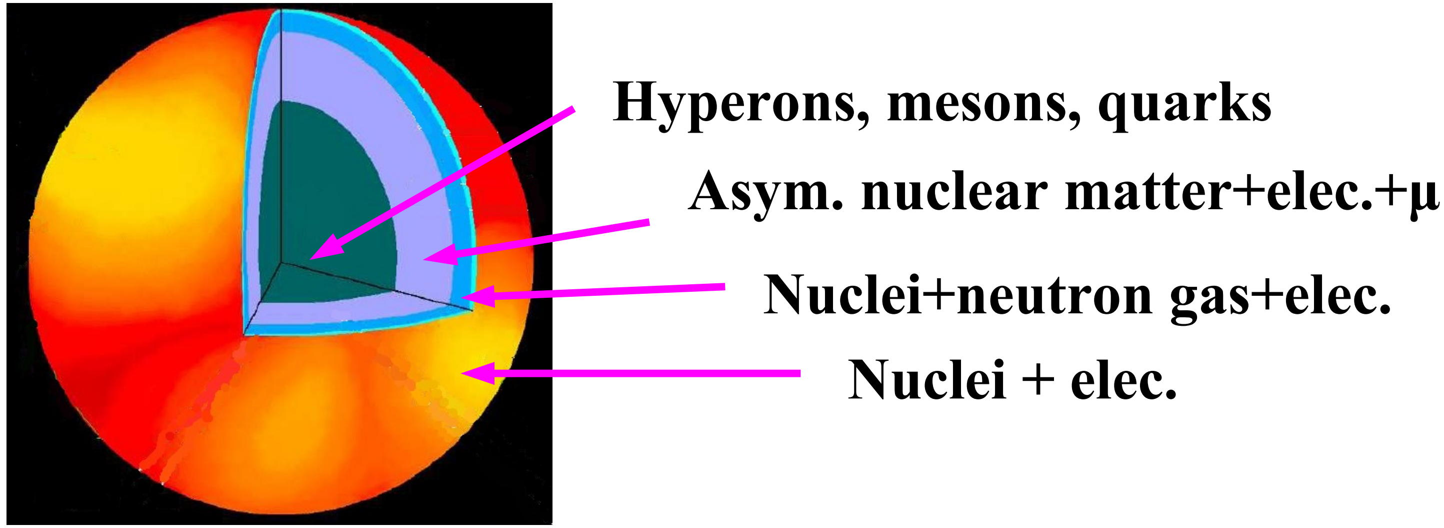


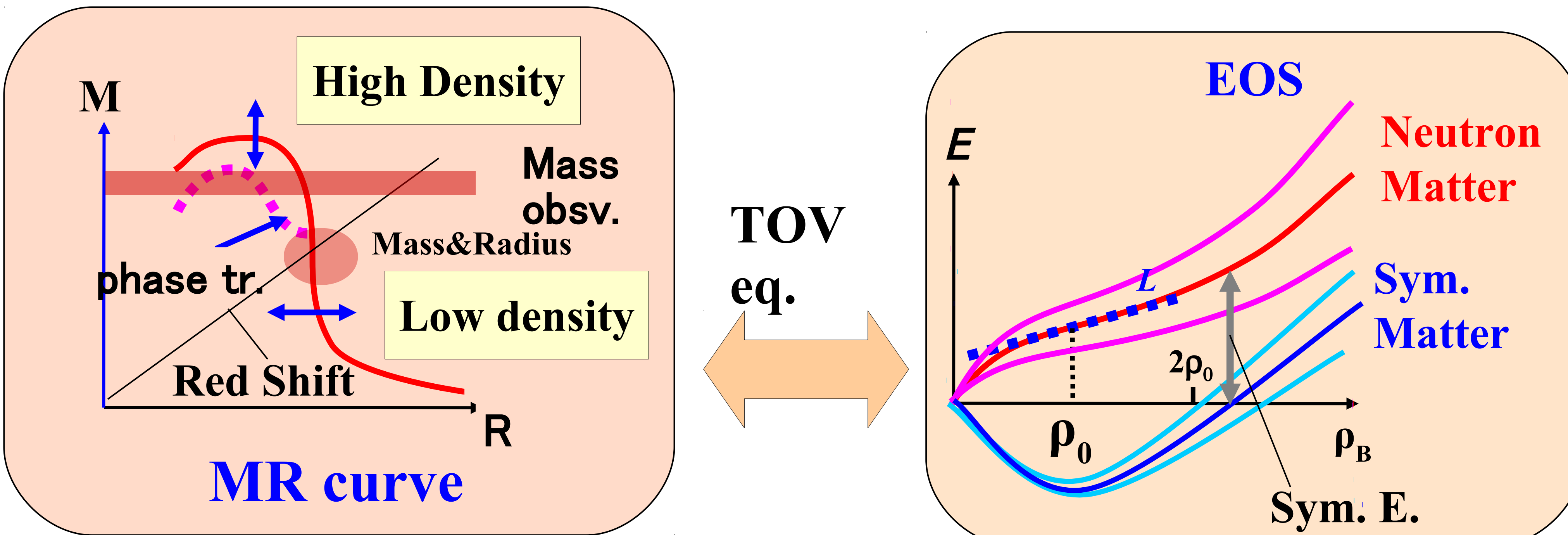
S. Kowalski, ..., A. Ono, PRC75('07)014601



L.W.Chen, C.M.Ko, B.A.Li, PRL94('05),032701.

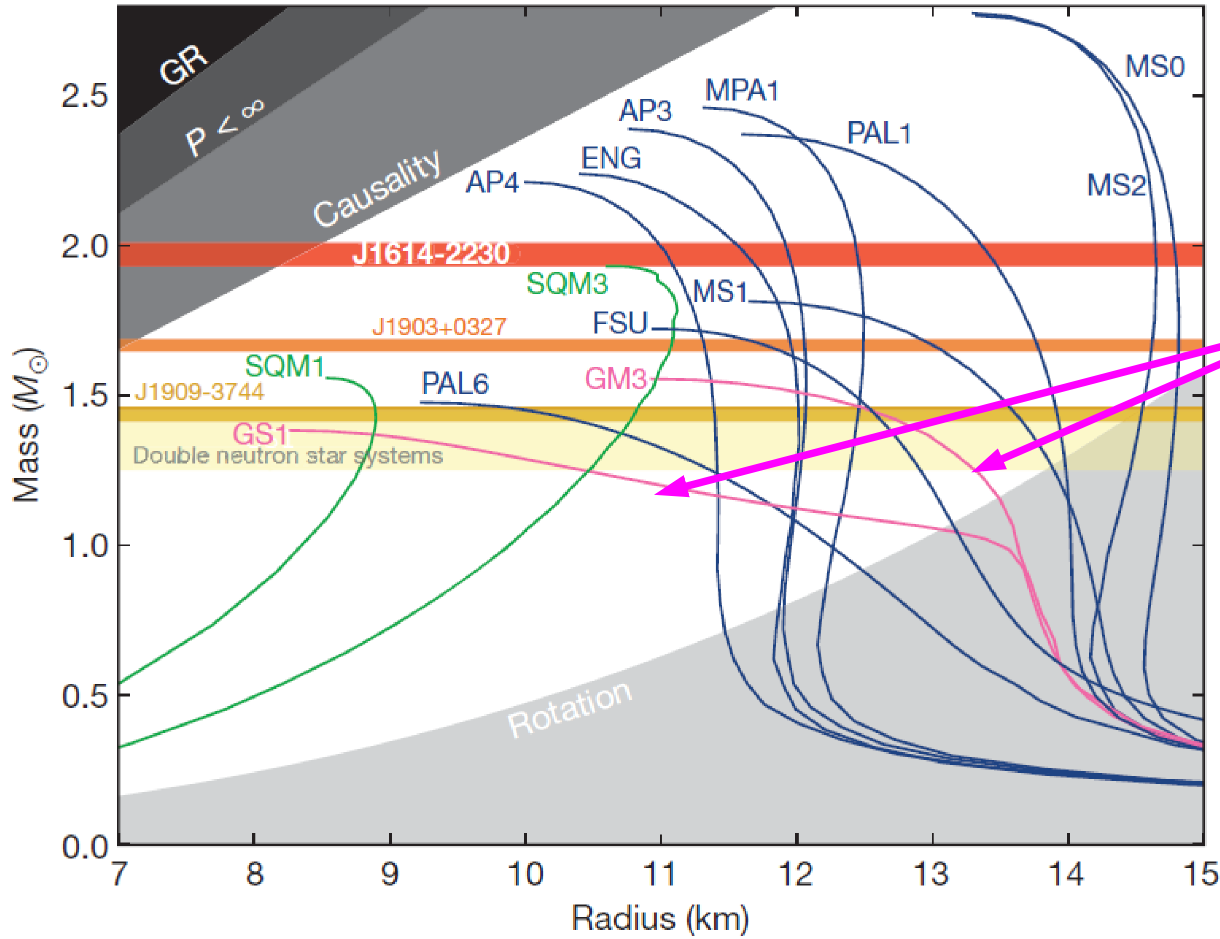
Neutron Star Composition





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

Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



EOS with Strange Hadrons

signature. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_\odot$, which rules out almost all currently proposed[2–5] hyperon or boson condensate equations of state ($M_\odot$, solar mass). Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not 'free' quarks[12].

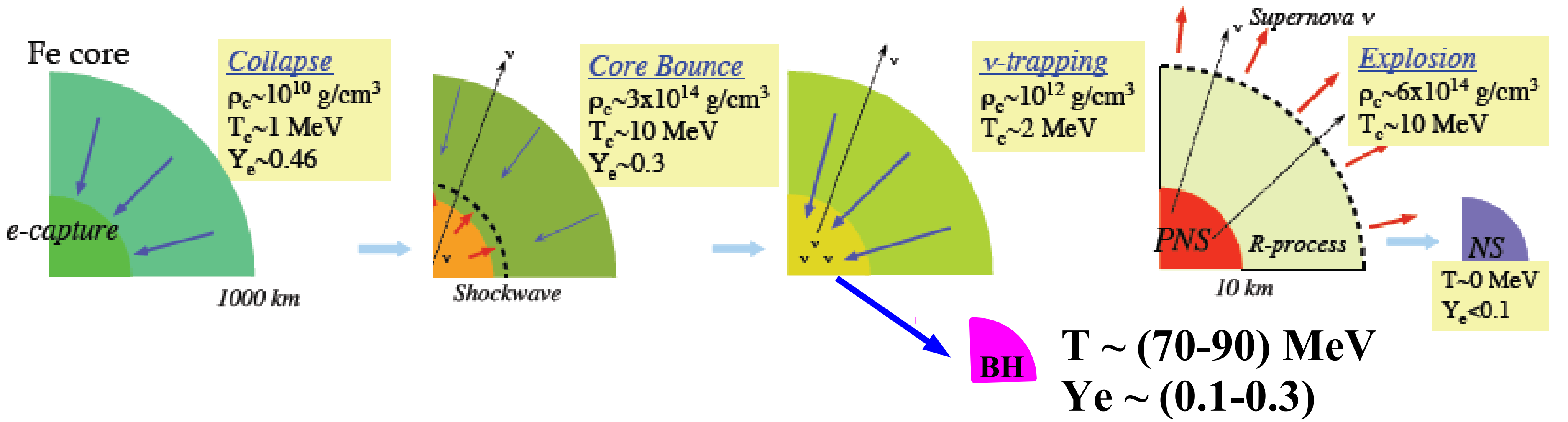
Symmetry Energy at High Density

- **Symmetric matter pressure is zero at ρ_0.**
  → A large part of pressure in neutron star matter at ~ ρ_0 comes from symmetry energy.
- **Symmetry energy helps to enhance electron chemical potential.**
  → How does it affect to pion condensation and transition to quark matter ?
- **In this work, we study the role of symmetry energy at high density from the comparison of**
  the hadronic EOS (Relativistic Mean Field; RMF)
  and
  chiral effective model (NJL, PNJL, PQM, …)
  results.

Let me advertize our recent work on ...

**Black Hole Formation
and
Phase diagram
in (Isospin) Asymmetric Matter**

Quark Matter in Compact Stars



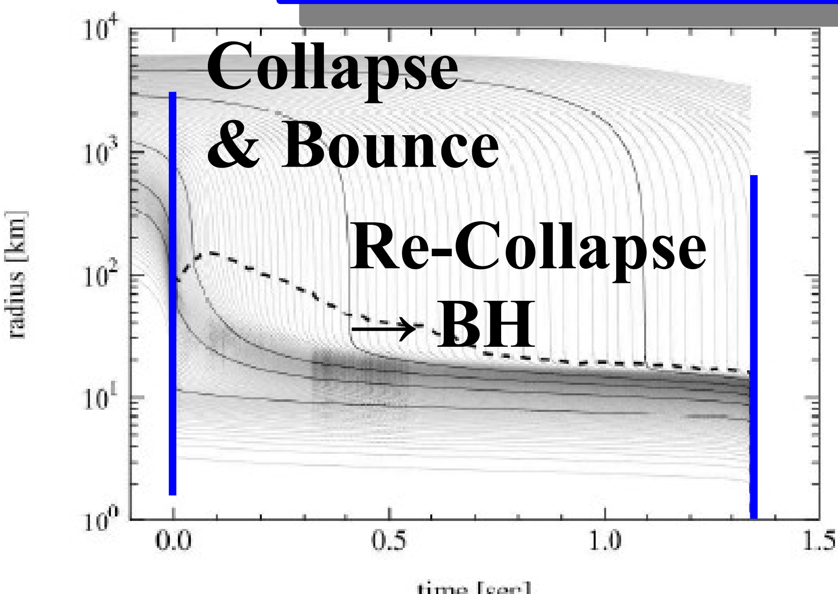
- **Probable in Neutron Star (Cold, dense, asymmetric)**
  E.g. N. Glendenning, "Compact Stars";F. Weber, Prog.Part.Nucl.Phys.54('05)193
- **Suggestions in Supernovae (Warm, mildely dense (~1.8 ρ_0))**
  T. Hatsuda, MPLA2('87)805; I. Sagert et al., PRL102 ('09) 081101.
- **May be in Neutron star merger (Very dense)**
- ***How about Dynamical black hole formation***
  → Very Hot (~90 MeV), dense(~5ρ_0), Asym. (Y_p~ (0.1-0.3))
  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

Dynamical Black Hole Formation

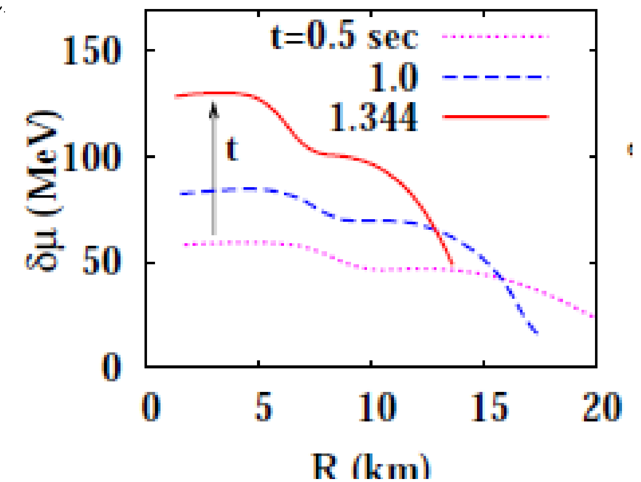
- **Gravitational collapse of heavy (e.g. 40 $M_\odot$) progenitor → BH**
  - **ν heating is not enough → failed supernova**
  - **Hot and Dense → exotic dof → shorter ν durat**

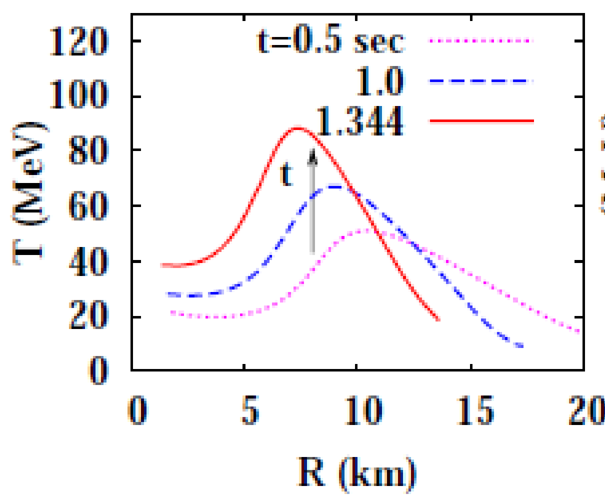
Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, ApJL690('09)L43

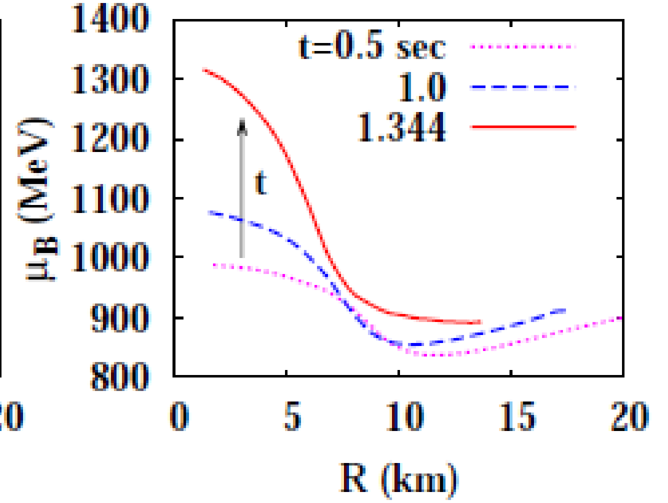
Is quark matter formed ?
Is the Critical Point probed ?



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







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

Model Details

- **BH formation calculation**

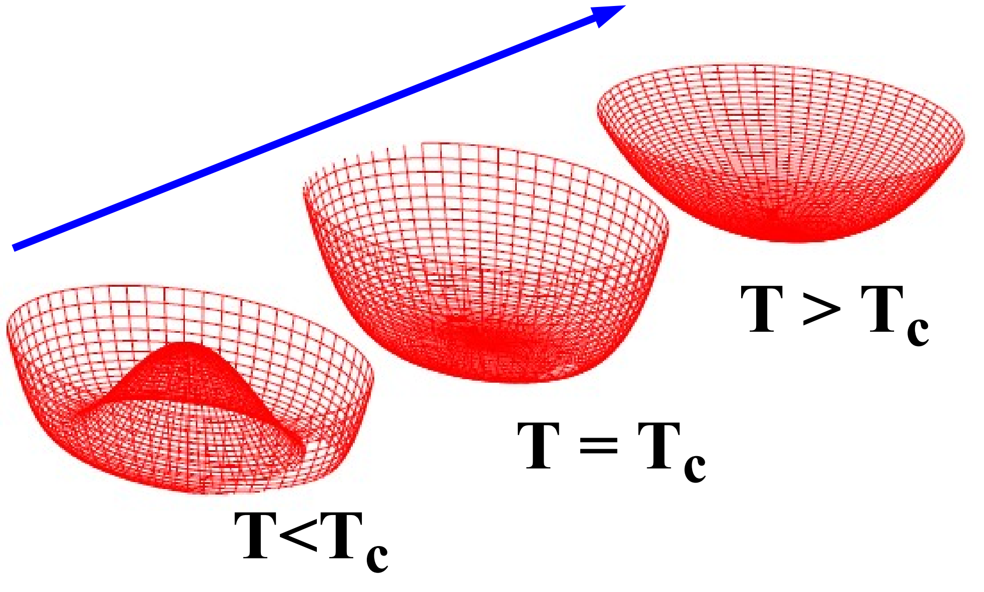
  Sumiyoshi, Yamada, Suzuki, Chiba, PRL 97('06)091101.

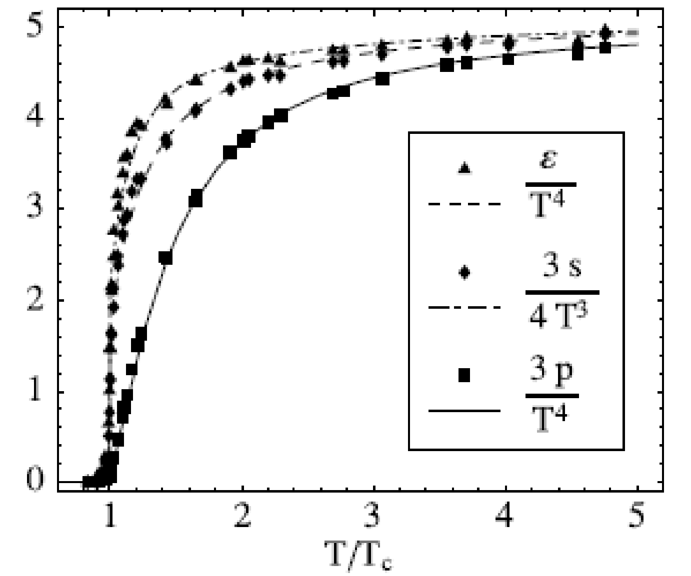
  - **ν radiation 1D (spherical) Hydrodynamics**
  - **ν transport is calculated exactly by solving the Boltzmann eq.**
  - **Gravitational collapse of 40 $M_\odot$ star**
  - **Initial condition: WW95**

    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**

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)**

$$L=\bar{q}\left[i\gamma^\mu \underbrace{D_\mu}_{\text{q-Pol.}} - g_\sigma \underbrace{(\sigma + i\gamma_5 \boldsymbol{\tau}\cdot\boldsymbol{\pi})}_{\text{quark-meson}}\right]q + \frac{1}{2}\partial^\mu\sigma\,\partial_\mu\sigma + \frac{1}{2}\partial^\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi} - \underbrace{U_\sigma(\sigma,\pi)}_{\text{chiral}} - \underbrace{U_\Phi(\Phi,\bar{\Phi})}_{\text{Polyakov}}$$

$$F_{\text{eff}} \equiv \Omega/V = U_\sigma(\sigma,\pi=0) + U_\Phi(\Phi,\bar{\Phi}) + \underbrace{F_{\text{therm}}}_{\text{particle exc.}} + \underbrace{U_{\text{vac}}(\sigma,\Phi,\bar{\Phi})}_{\text{q zero point}}$$

  - **$U_\sigma \sim \varphi^4$ theory, $U_\Phi \sim$ -log (Haar Measure)**
  - **Parameters are fixed by fitting vacuum hadron masses (U_σ) and lattice data ($\Phi(T) \to U_\Phi$)**
  - **Vector coupling is not known well → Comparison of g_V/g_s=0, 0.2**

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

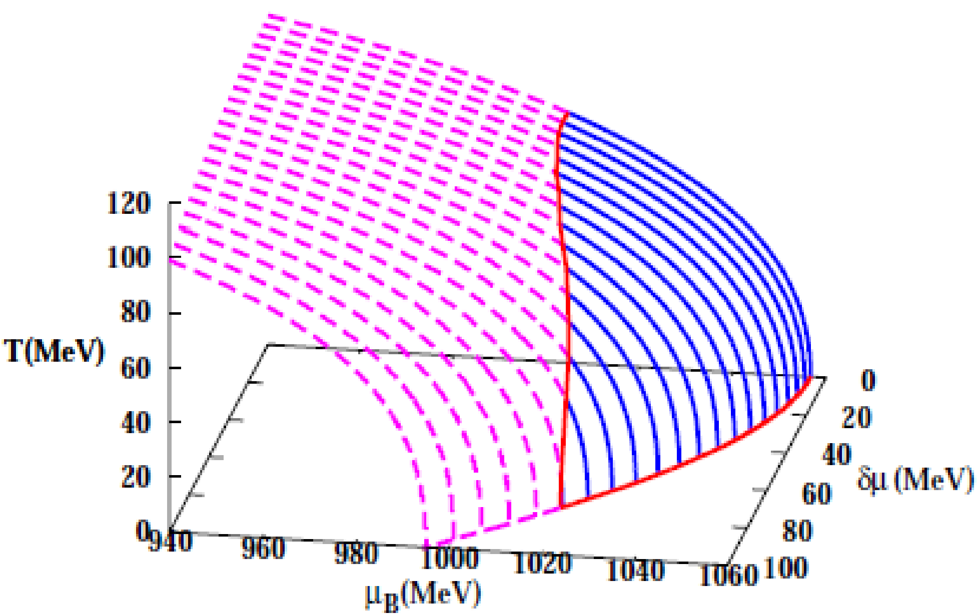
  - **8 Fermi interaction**

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

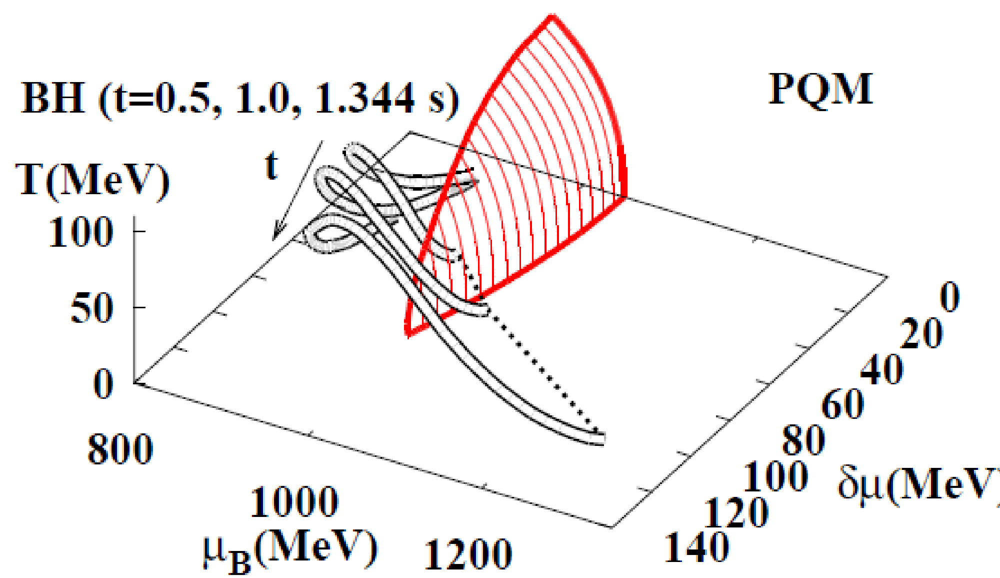
$$G_{\sigma 8}\left[(\bar{q}q)^2 + (\bar{q}i\gamma_5\boldsymbol{\tau}q)^2\right]^2$$

3D phase diagram and BH formation

- Isospin chemical potential $\delta\mu = (\mu_d - \mu_u)/2 = (\mu_n - \mu_p)/2$
  - Smaller "Effective" number of flavors → smaller T_{CP}
- BH formation process → Quark matter formation & CP sweep
  - Highest μ_B just ~ 1300 MeV > μ_c (1000-1100 MeV in eff. models)
  - Highest T ~ 90 MeV > T_{CP} (at $\delta\mu$~50 MeV)



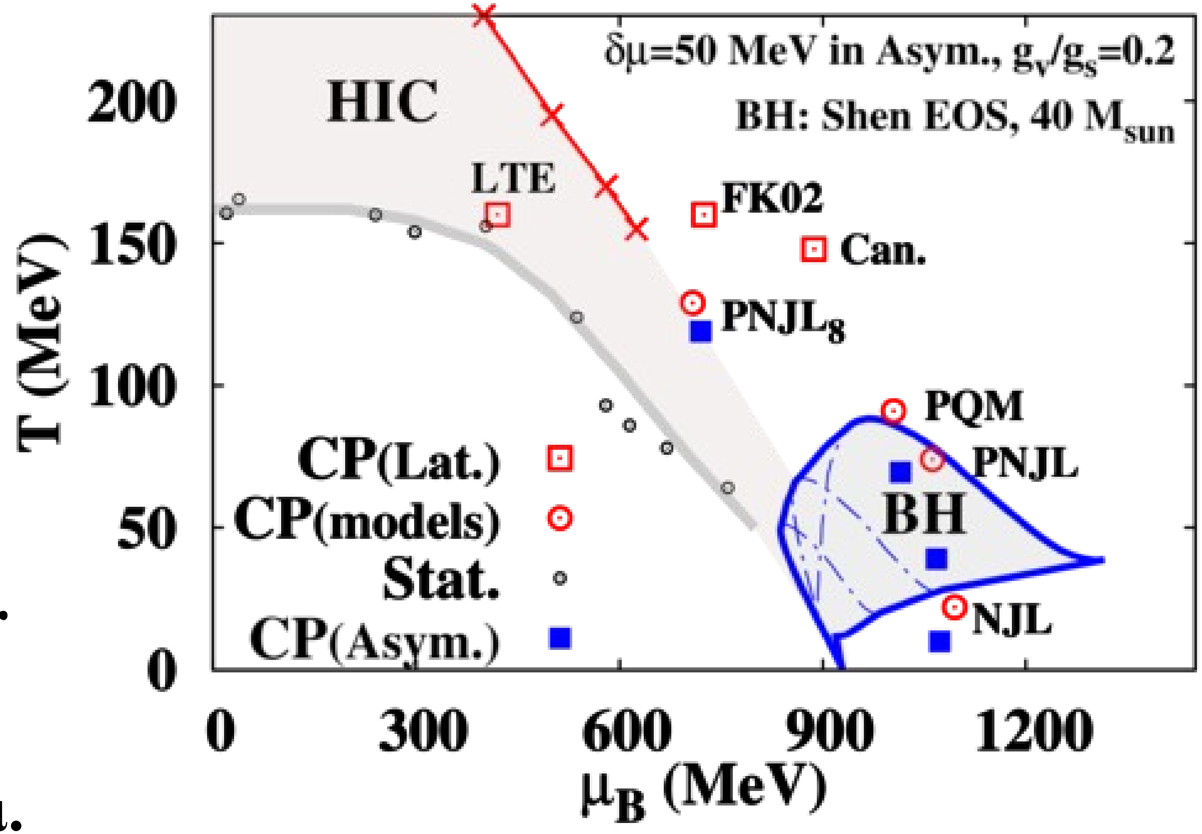
H. Ueda, et al, in preparation



AO, H.Ueda, T.Z.Nakano, M.Ruggieri, K.Sumiyoshi, PLB 704 ('11)284.

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



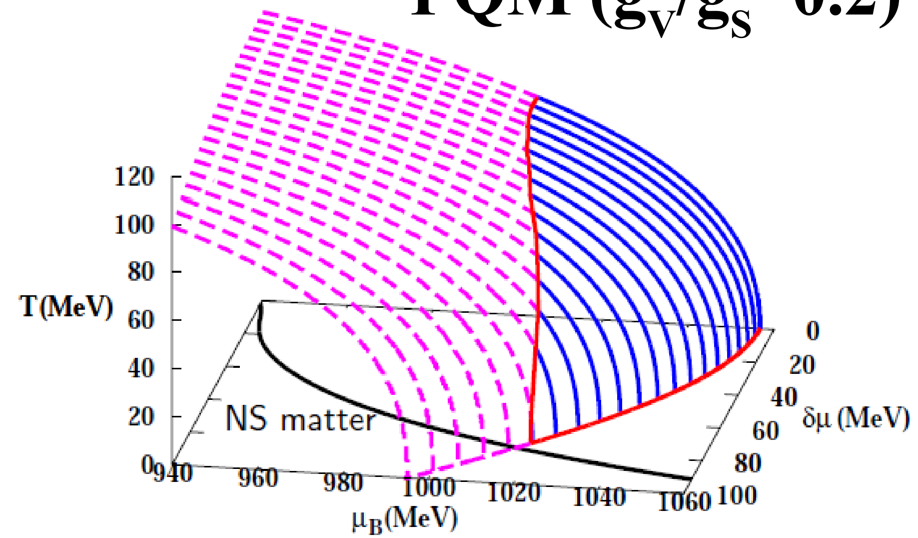
M.A.Stephanov, Prog.Theor.Phys.Suppl.153 ('04)139;
FK02:Z. Fodor, S.D.Katz, JHEP 0203 (2002) 014
LTE:S. Ejiri et al., Prog.Theor.Phys.Suppl. 153 (2004) 118;
Can: S. Ejiri, PRD78 (2008) 074507
Stat.:A. Andronic et al., NPA 772('06)167

Phase diagram in (μ_B, $\delta\mu$) plane (T=0) and Nuclear Symmetry Energy at High Density

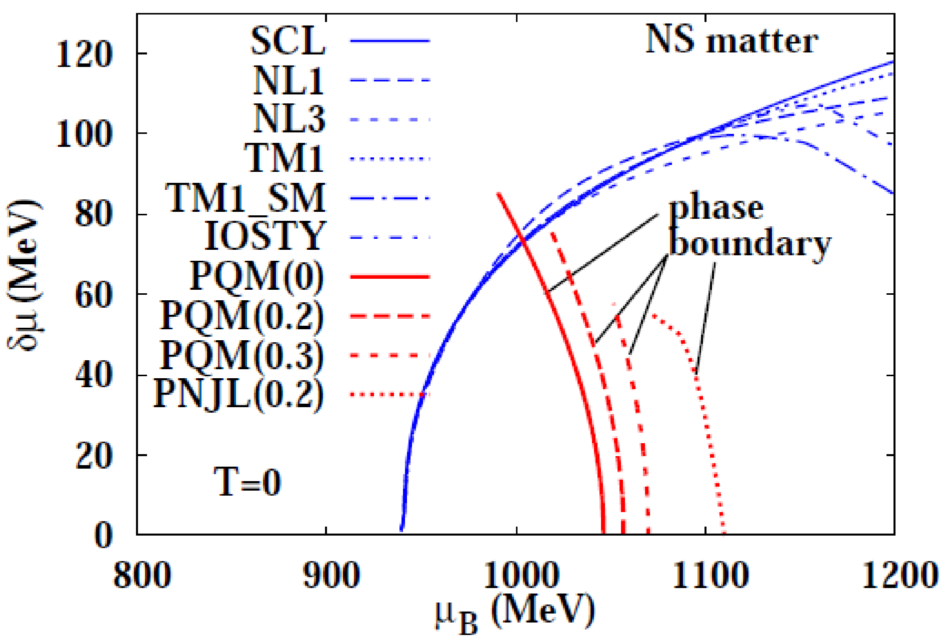
How about Neutron Stars ?

- **Neutron Star matter in RMF**
  - **Solve equilibrium condition at T=0**
    $\delta\mu=\mu_e/2$, $\rho_c=0$ (ν less, no charge)
  - **Various RMFs predict similar δμ values**
  - **max. δμ ~ 100 MeV**

PQM (g_V/g_S=0.2)



- **Phase boundary at T=0 in eff. models**
  - **First order phase transition disappears at δμ = (60-80) MeV**
    → Possibility of cross over in NS

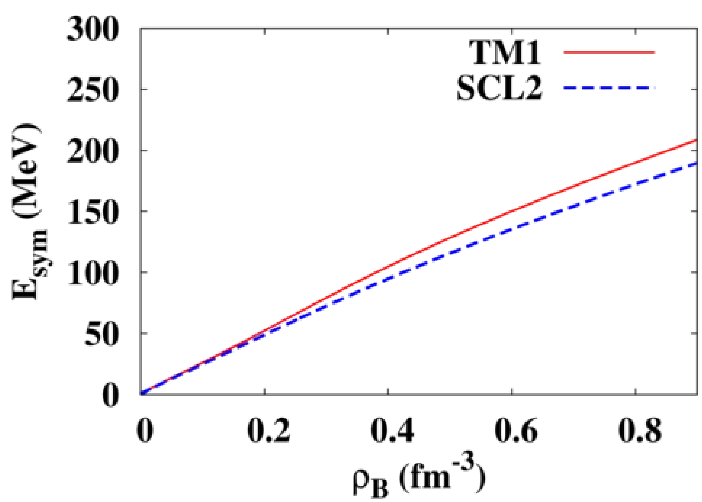


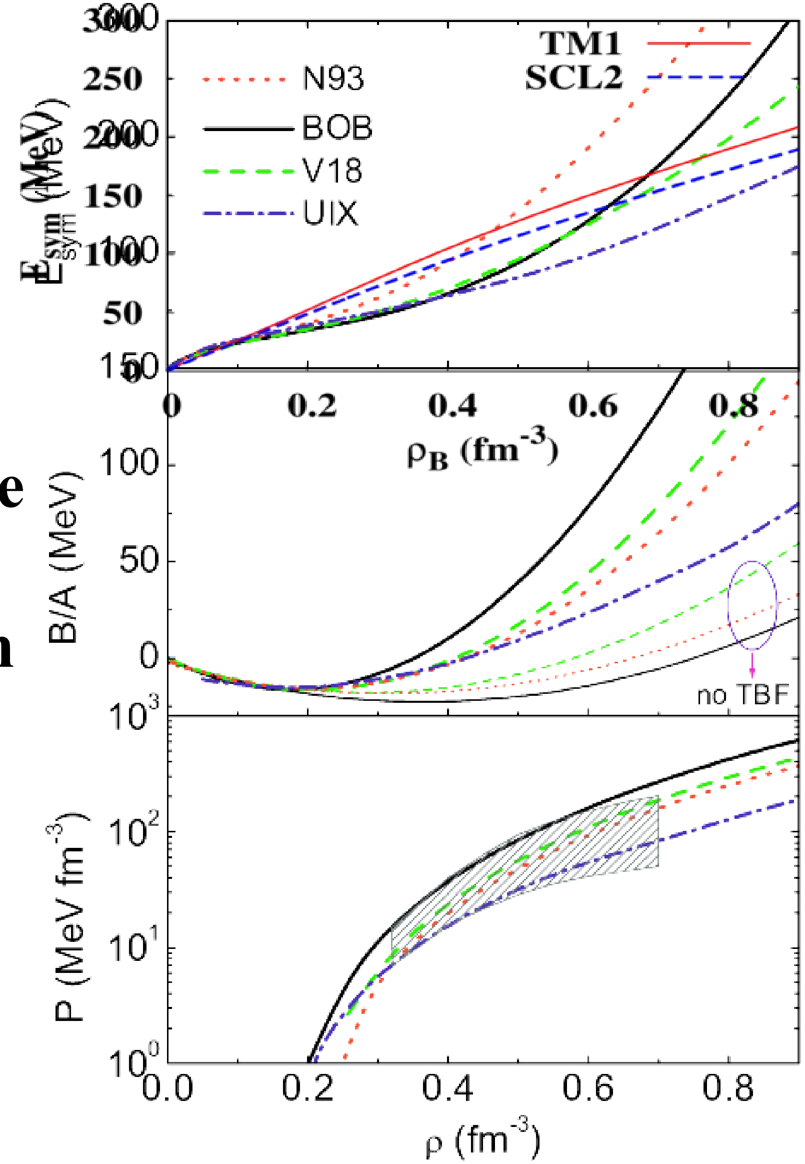
H. Ueda et al., in preparation

Density dependence of Symmetry Energy

- **RMFs have small ambiguity in Esym. Is it true ?**
  - **RMF Esym is determined to fit finite nuclear BE, thus reflects average values in the $\rho_B < \rho_0$ region.**
  - **Nuclear effective potential (g-matrix) suggests S-curve behavior of Esym, while RMF gives Esym almost linear in ρ_B.**

    → RMF may overestimate Esym at high density.

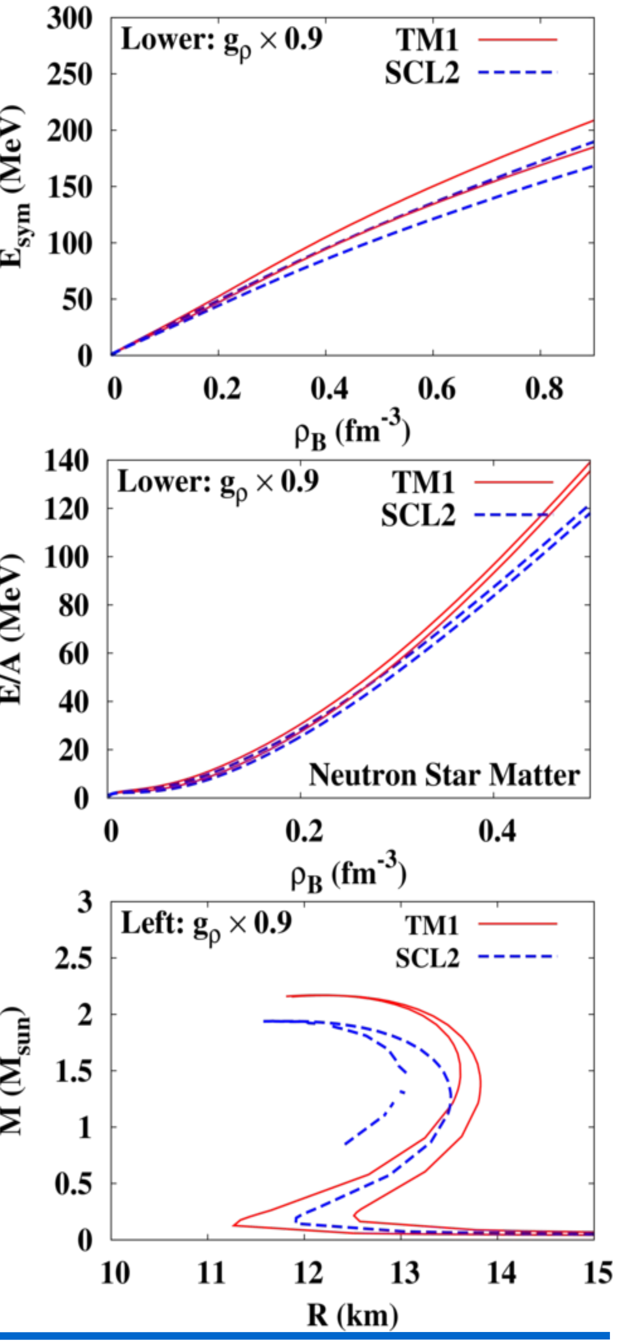




Lombardo, DCEN slide

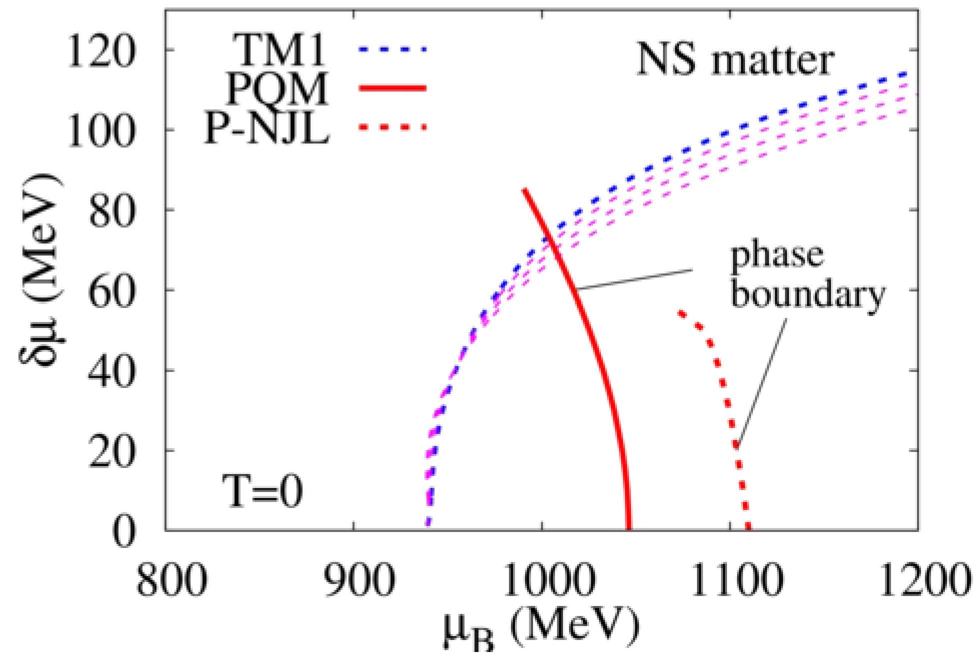
Effects of Symmetry Energy Change on Phase Transition

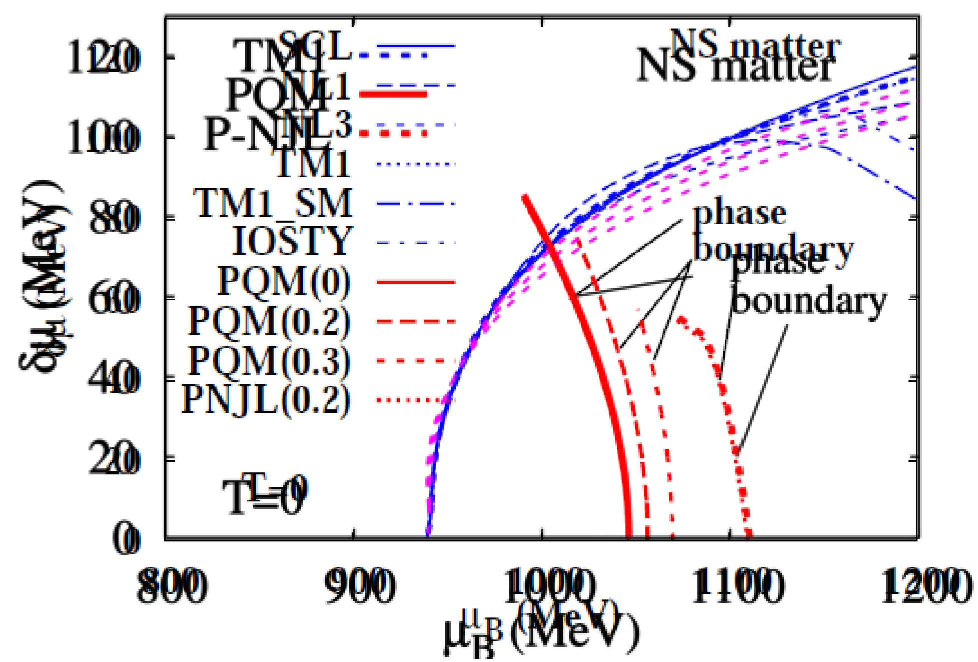
- **Simple try: Reduce g_ρ (ρ-N coupling) by a factor 0.9.**
  - **No re-fit of nuclear BE**
  - **Not connected to low-density (nuclear mixed) EOS (i.e. Do not believe the results.)**
- **Light neutron star radii sensitively depends on the symmetry energy strength.**
  - **Pressure at around ρ_0 is dominated by symmetry energy.**



Phase transition with reduced Nuclear Sym. Energy

- **Isospin chemical potential**
  - **Smaller Esym leads to smaller δμ.**
  - **Dependence is not large, but moves in the region of gv/gs=0-0.2.**





Summary

- **Critical point temperature would decrease at finite isospin chemical potential, $\delta\mu=(\mu_d - \mu_u)/2$.**
  - **Quark matter formation and critical point sweep are expected in black hole formation processes.**
  - **There is also a possibility for the first order phase boundary to disappear in neutron stars because of large δμ.**
- **Symmetry energy strength at high density is relevant in low-mass neutron star radius (already known) and phase transition.**
  - **Reduced SymE → Smaller δμ in NS**
    → Possibility of transition order change.
- **There are many subjects to be discussed**
  - **Construction of Hadron-Quark matter EOS with CP (c.f. J. Steinheimer; D. Blaschke), and its application.**
  - **S-shape dep. of symmetry energy, 1.97 $M_\odot$ neutron star, …**

Thank you for your attention !

Collaborators

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