

核物質の状態方程式とコンパクト天体現象

京大基研 大西 明

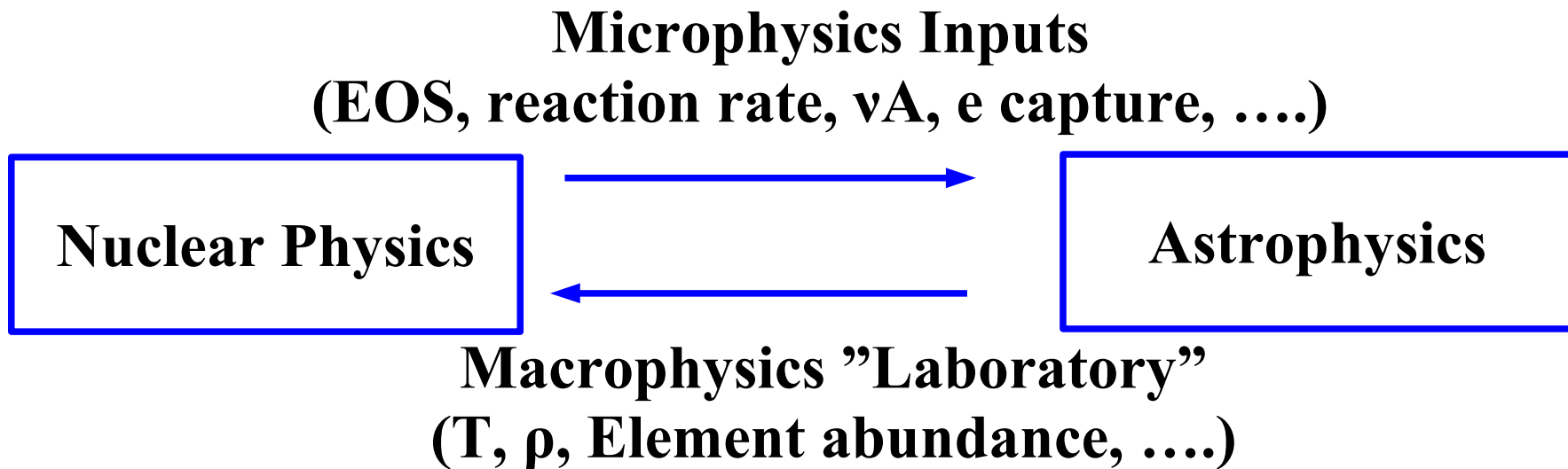
基研研究会「超新星爆発と数値シミュレーション」、2011年12月26-28日

- Introduction: 高密度天体現象における核物理・天体物理
- Nuclear matter EOS for compact astrophysical phenomena
 - 対称エネルギー
 - ハイペロンを含む状態方程式
 - QCD 相転移の可能性
- Summary



原子核物理と宇宙物理

- Nuclear physicists think that
“Astrophysics is a laboratory of nuclear physics”.
- Astrophysicists think that
“Nuclear physics gives us inputs of Astrophysics”.
- Both of them are true, and hopefully we can keep win-win relation.



コンパクト天体現象

■ 中性子星

- Cold -dense ($\sim 5 \rho_0$) matter (static, v-less)
- Many new forms of matter have been proposed !

■ 超新星

- Warm ($T \sim 20$ MeV), dense ($\sim 1.6 \rho_0$), dynamical, non-eq. v
- Important site of nucleosynthesis

■ ブラックホール形成過程

- Hot ($T \sim 90$ MeV), dense ($\sim 5 \rho_0$), dynamical, non-eq. v
- QCD critical point may be reached

■ BH-BH, NS-BH, NS-NS 融合

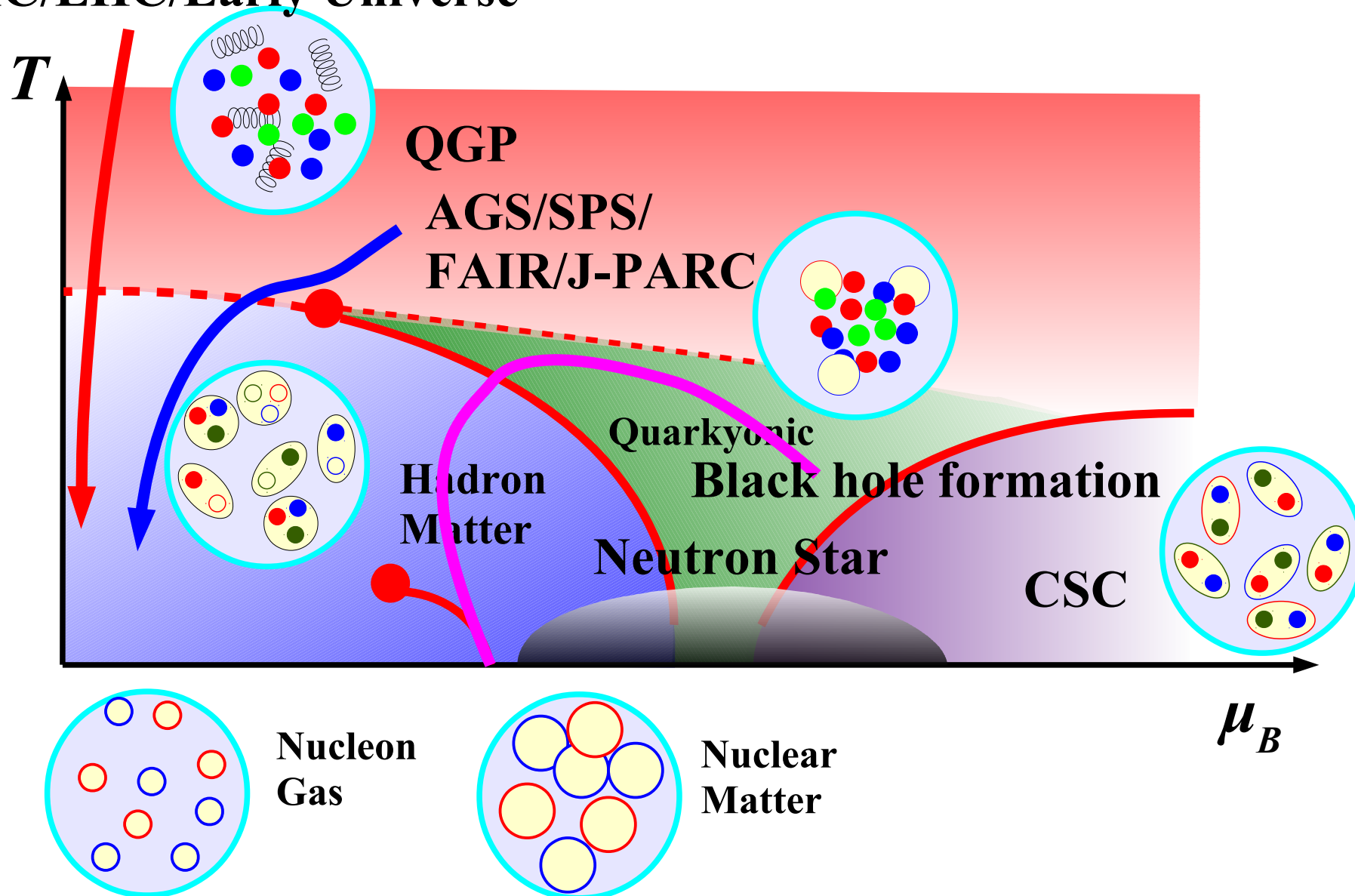
- Very dense matter is formed.

様々な温度・密度の核物質が作られる！

→ QCD 相図探索に使えるのでは（核物理屋の期待）？

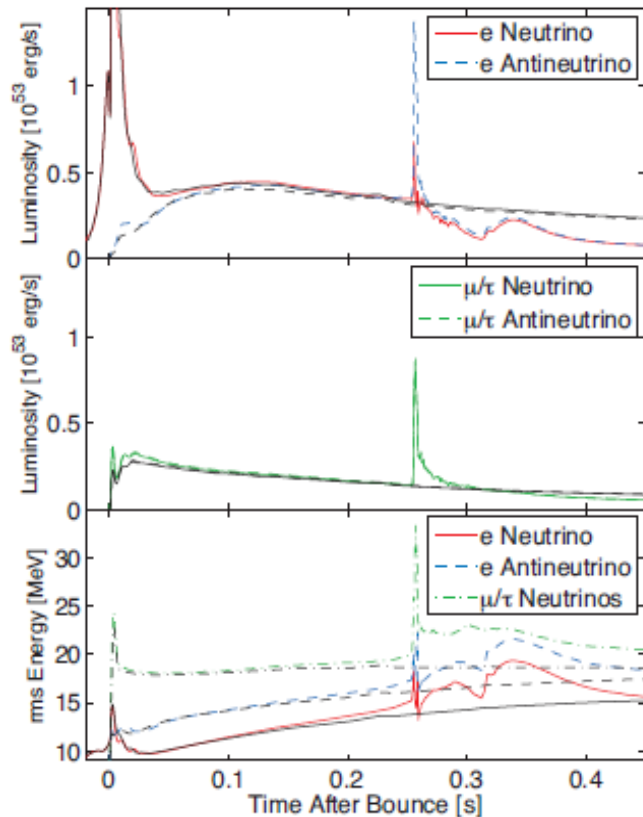
QCD Phase Diagram

RHIC/LHC/Early Universe



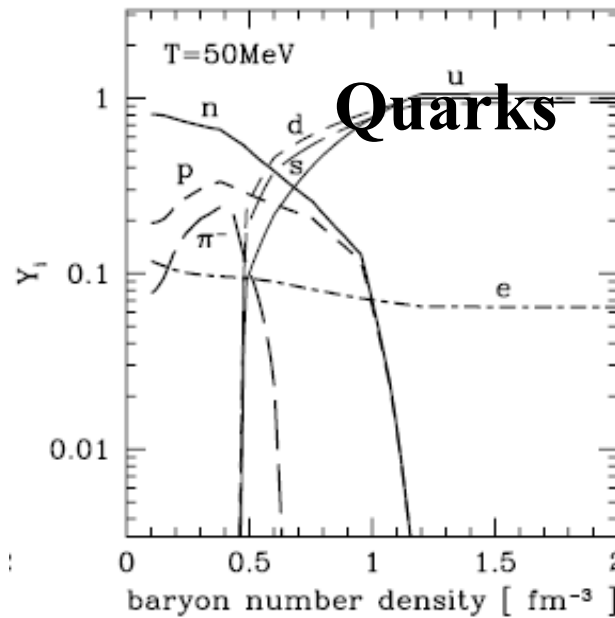
Can we detect Quark Matter ?

- Transition to Strange Quark Star during Supernovae → Second Shock (*Hatsuda, 1987; Sagert et al., 2009*)
- Earlier Collapse to Black Hole with Quark-Hadron Coexistence (*Nakazato, Sumiyoshi, Yamada, 2008*)



Sagert et al., 2009

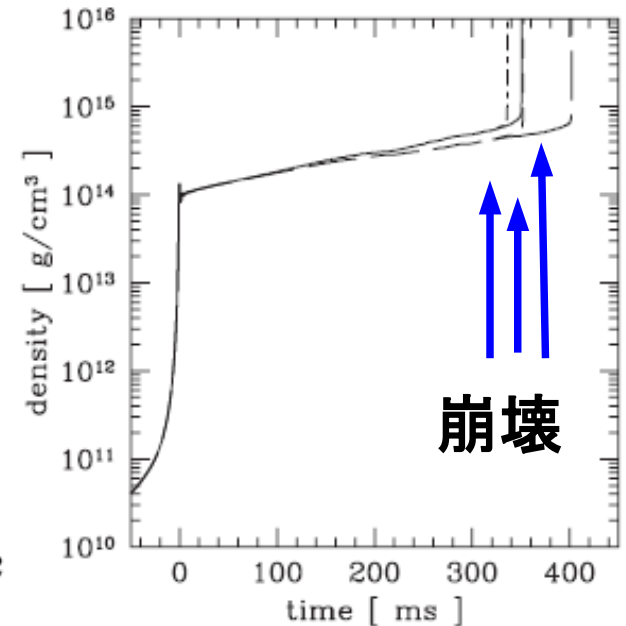
粒子比



密度

Nakazato, Sumiyoshi, Yamada

密度

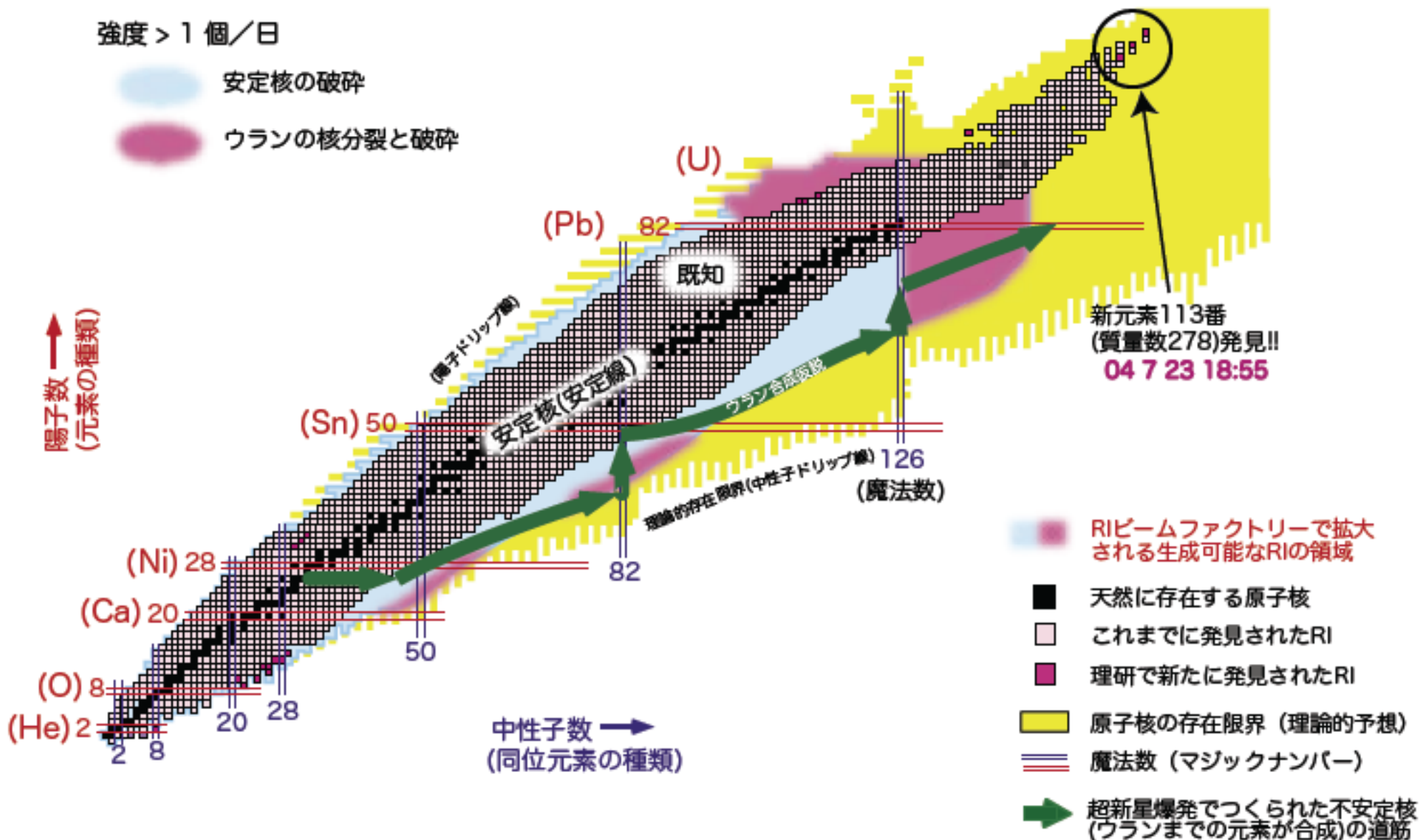


崩壊

時間

原子核の存在領域の拡大

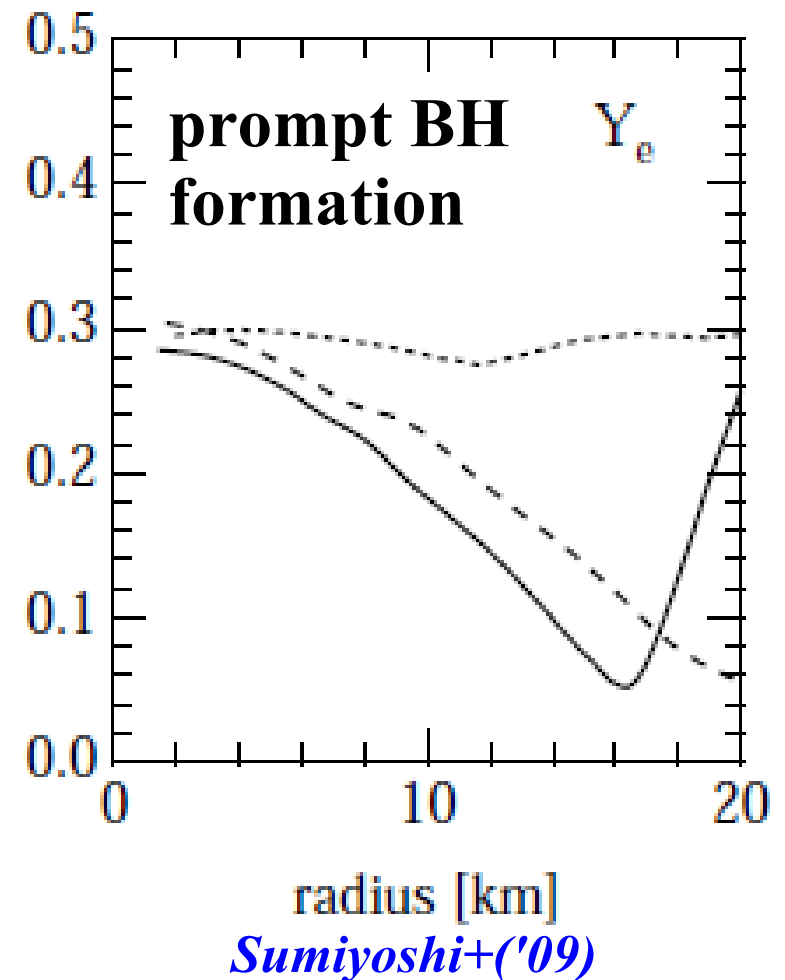
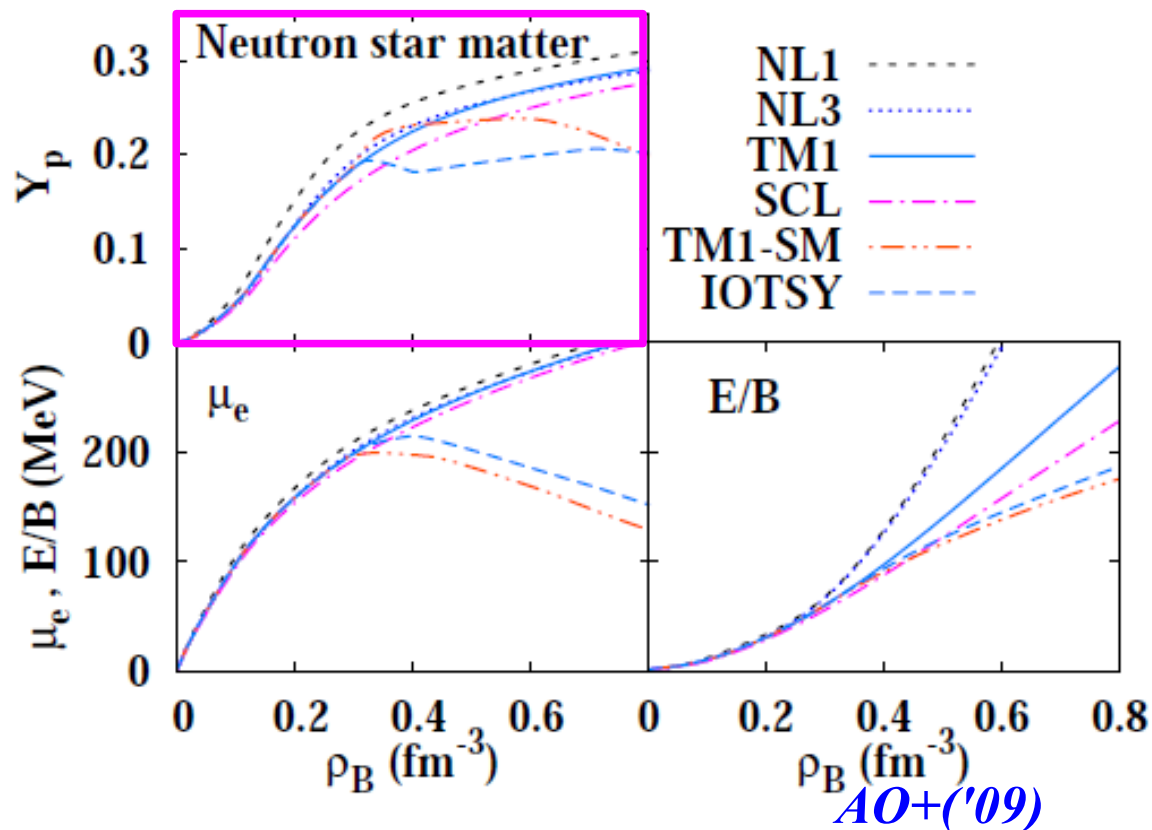
Nishina Center RIBF Pamph.



Compact Star Matter is Neutron Rich

■ Proton fraction in Compact Stars

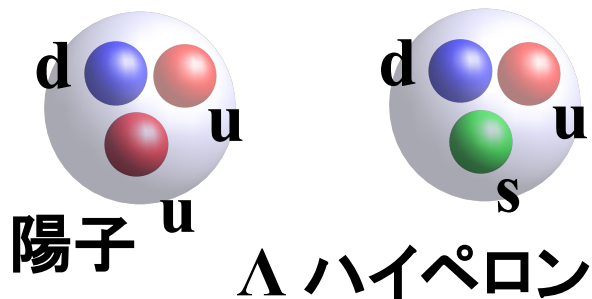
- Neutron star $Y_p \sim 0.1$ ($\rho_B \sim \rho_0$)
- Supernova $Y_p \sim 0.3$ (bounce) (c.f. H. Suzuki's talk)
- Black hole formation $Y_p \sim (0.1-0.3)$



中性子星コアの状態

■ コア領域では様々な可能性

- ストレンジクォークを含むバリオン (ハイペロン) を含む物質

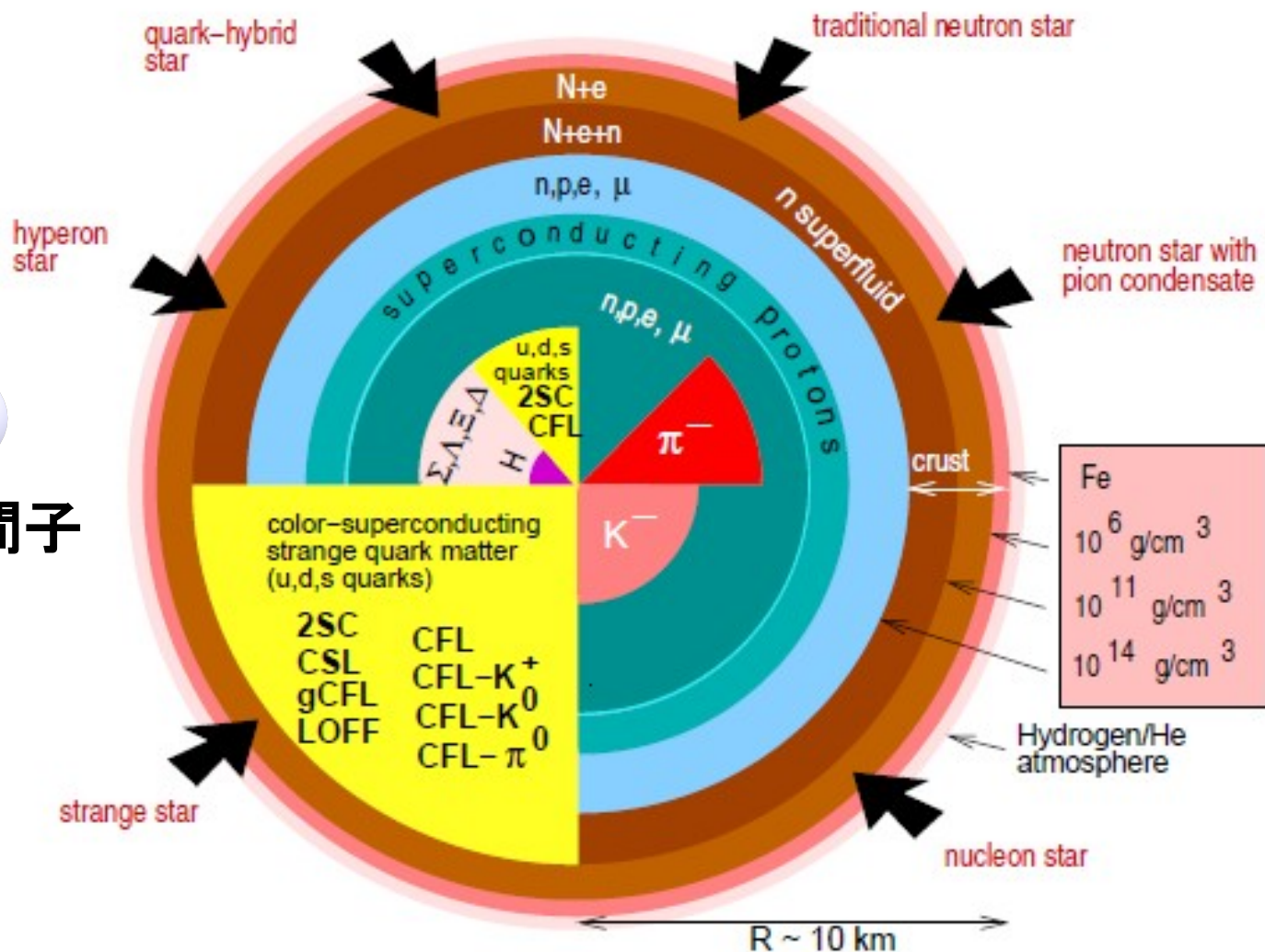


- 中間子凝縮 (K, π)



π 中間子 (反)K 中間子

- クォーク物質
- クォーク対凝縮状態 (カラー超伝導)



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

重い中性子星ショック....

■ 2010年のビッグニュース

「 $1.97 \pm 0.04 M_{\odot}$ の質量をもつ中性子星が発見された」

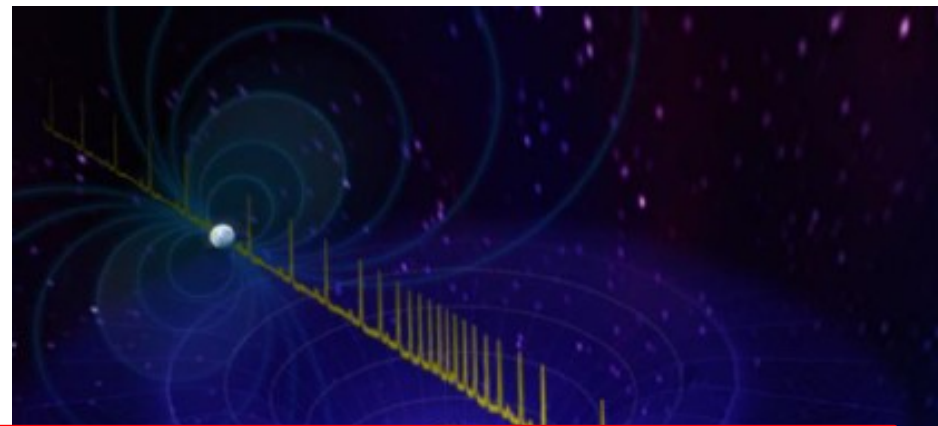
Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).

● 一般相対論に基づく観測

「パルサー(中性子星)からくる光が伴星(白色矮星)の近くを通り、時間が遅れる(Shapiro delay)。」

論文での主張

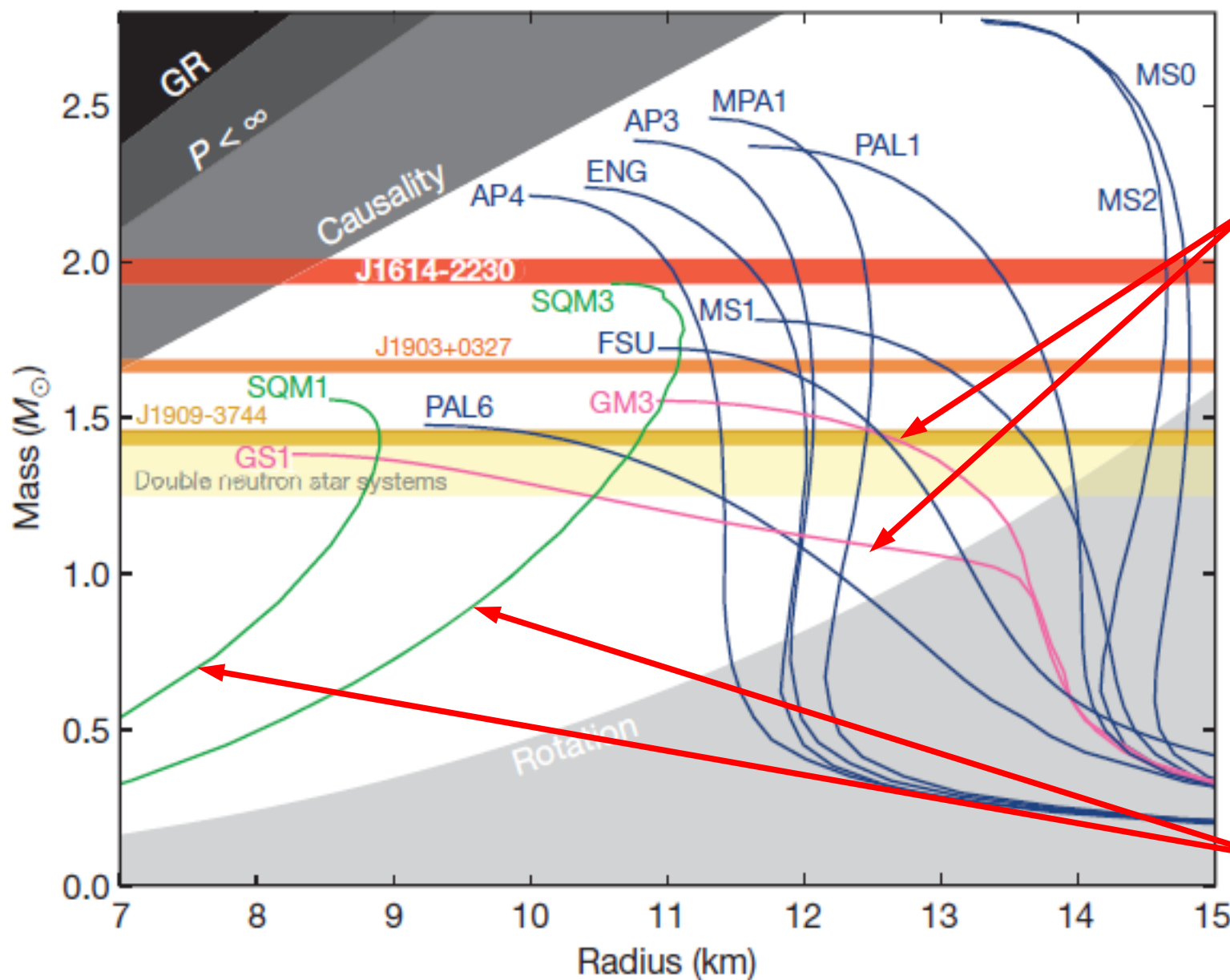
$(1.97 \pm 0.04) M_{\odot}$ の中性子星は、ハイペロン、中間子凝縮を含む状態方程式では支えられない。クォーク物質でも強い相互作用が必要である。



signature. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_{\odot}$, which rules out almost all currently proposed²⁻⁵ 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' quarks¹².

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

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



ハイペロンを含む EOS

クォーク物質のみの EOS

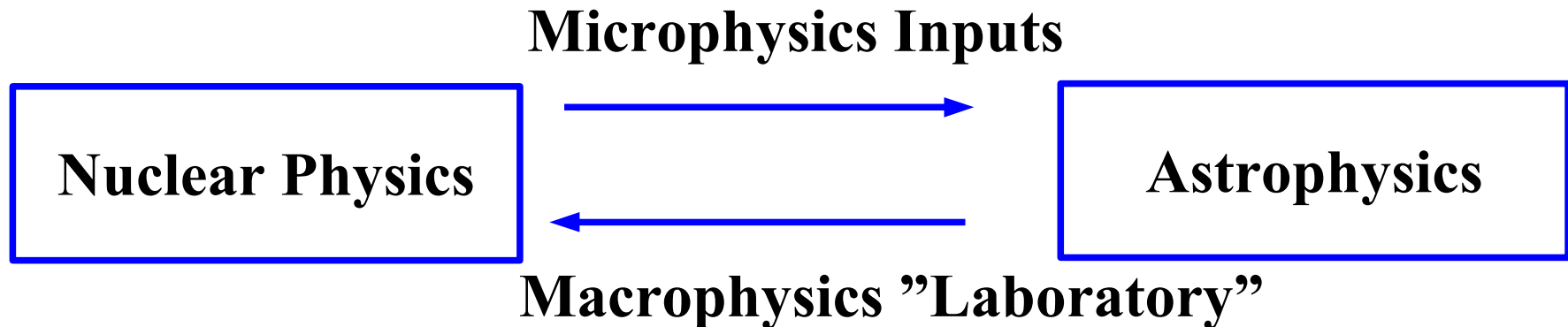
核物質のEOSとコンパクト天体現象

■ 核物理の立場からの興味

- 低温～中程度の温度、高（バリオン）密度、非対称物質 ($n > p$)
→ 高エネルギー重イオン衝突（高温・低バリオン密度）と異なる環境
- 不定性のある高密度物質・非常に非対称な物質の状態方程式を決められるか？
- Exotic な物質・相を見つけられるか？

■ 天体物理からの興味（要請）

- 知られている全ての観測・データと無矛盾な状態方程式を用意せよ！



中性子過剰核（対称エネルギー）、ハイパー核、クォーク物質における最近の話題について議論します。

*Nuclear Matter EOS
for Compact Astrophysical Phenomena*

コンパクト天体現象に用いる核物質状態方程式

- 超新星爆発計算 = v 輸送を取り入れた流体模型
 - 時間スケール \sim 数100 msec = v 以外は熱・化学平衡
 - 状態方程式：核子，電子，光子，**原子核**，**ハイペロン**， π , K, クォーク ...
 - 輸送方程式 (Boltzmann) : v -A 断面積、e- 捕獲率
- 状態方程式 \rightarrow 有限温度効果、広い密度・ Y_p 範囲、公開
 - パラメトライズされた状態方程式 (Sato, Takahara)
 - 第一原理計算 (LQCD, GFMC, Variational, DBHF, G-matrix)
 \rightarrow 飽和性の説明には現象論的 3 体力などが必要

($L \cdot \sigma_i \cdot \sigma_j$), and a MS part with operators ($L \cdot S$)_{ij}, $L_{ij}^2 \cdot \sigma_i \cdot \sigma_j L_{ij}^2$ and $(L \cdot S)_{ij}^2$. The UIX model of V_{ijk} contains two static terms; the two-pion exchange Fujita-Miyazawa interaction, $V_{ijk}^{2\pi}$, and a phenomenological, intermediate range repulsion V_{ijk}^R . The strength of the $V_{ijk}^{2\pi}$ interaction was determined by reproducing the binding energy of the triton via Green's-function Monte Carlo (GFMC) calculations [20], while that of V_{ijk}^R was adjusted to reproduce the saturation density of SNM.

(Akmal, Pandharipande, Ravenhall)

コンパクト天体現象に用いる核物質状態方程式

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 - 状態方程式: 核子, 電子, 光子, 原子核, ハイペロン, π , K, クォーク ...
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 \rightarrow 飽和性の説明には現象論的 3 体力が必要
 - Variational EOS (Kanzawa+('07)) でも現象論的 3 体力が必要。
 - Lattimer-Swesty (LS) EOS (*J. M. Lattimer, F.D. Swesty, NPA535('91)331*)
 - ◆ 一様物質 \rightarrow スキルム力 (密度依存ゼロレンジ力) での平均場
 - ◆ 非一様効果 \rightarrow 圧縮性液滴
 - Shen EOS (*Shen, Toki, Oyamatsu, Sumiyoshi, NPA637('98)435*)
 - ◆ 一様物質 \rightarrow Relativistic Mean Field (RMF, TM1)
 - ◆ 非一様効果 \rightarrow Thomas-Fermi 近似 + 排除体積効果を取り入れた α

Relativistic Mean Field

- Effective Lagrangian of Baryons and Mesons + Mean Field App.
B.D.Serot, J.D.Walecka, Adv.Nucl.Phys.16 ('86), 1

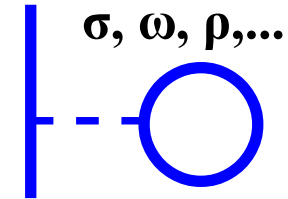
$$L = L_B^{\text{free}} + L_M^{\text{free}} + L_{BM} + L_M^{\text{Int}}$$

$$L_M^{\text{Int}} = -U_\sigma(\sigma) + \frac{1}{4} c_\omega (\omega_\mu \omega^\mu)^2 + \dots$$

$$L_{BM} = -\sum_{B,S} g_{BS} \bar{\Psi}_B \varphi_S \Psi_B - \sum_{B,V} g_{BV} \bar{\Psi}_B \gamma^\mu V_\mu \Psi_B$$

$$L_B^{\text{free}} = \bar{\Psi}_B (i \gamma^\mu \partial_\mu - M_B) \Psi_B$$

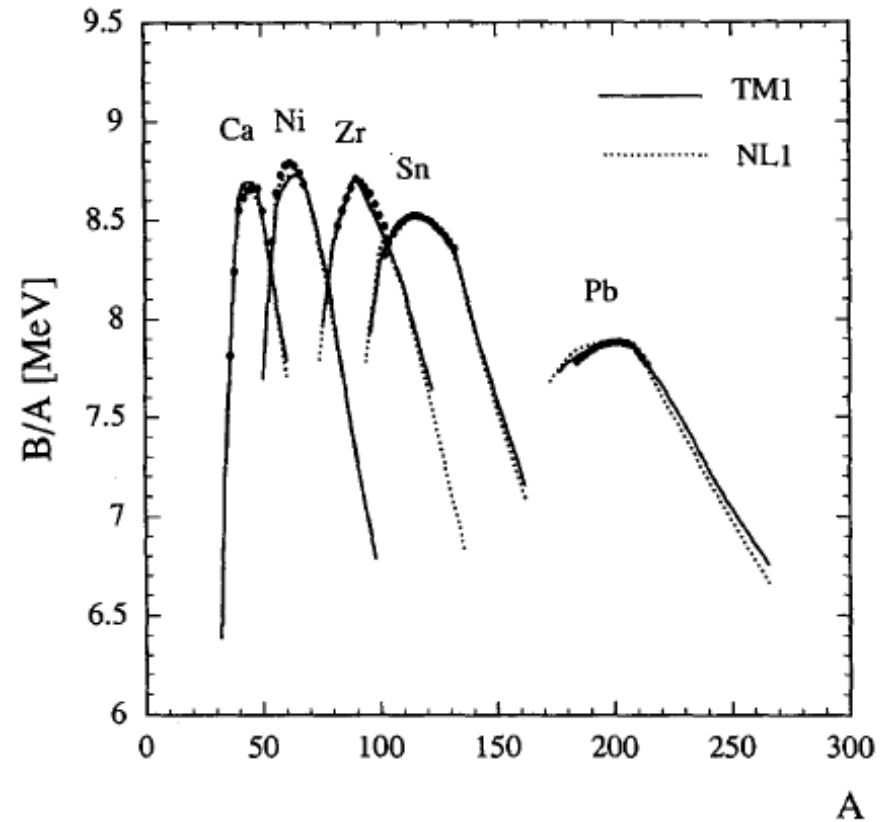
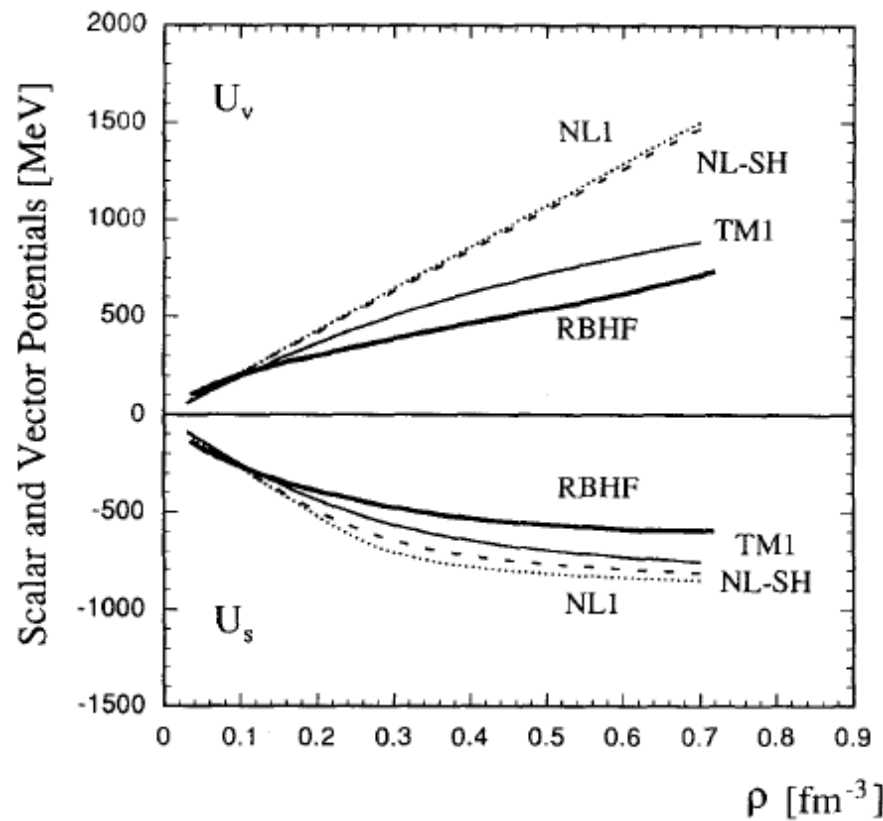
$$L_M^{\text{free}} = \sum_S \left[\frac{1}{2} \partial^\mu \varphi_S \partial_\mu \varphi_S - \frac{1}{2} m_S^2 \varphi_S^2 \right] + \sum_V \left[-\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} V_\mu V^\mu \right]$$



- スカラー中間子からの強い引力とベクトル中間子からの強い斥力により適度な中心力と強いLS力を記述。
 - 相対論的理論 → causality を破らない。
 - 中間子・バリオン結合にフレーバー SU(3) 対称性などの導入が容易。
- 高密度物質の状態方程式を記述する標準的な理論の一つ。

RMF with meson self-interaction

- 最も単純な RMF ($\sigma\omega$ 模型) では EOS が硬すぎる ($K > 600$ MeV)
- Self-interaction term of mesons
 - ω^4 の導入 \rightarrow 第一原理計算 (DBHF) のベクトル・ポテンシャルを模倣
 - σ^3, σ^4 の導入 \rightarrow 柔らかい状態方程式が可能

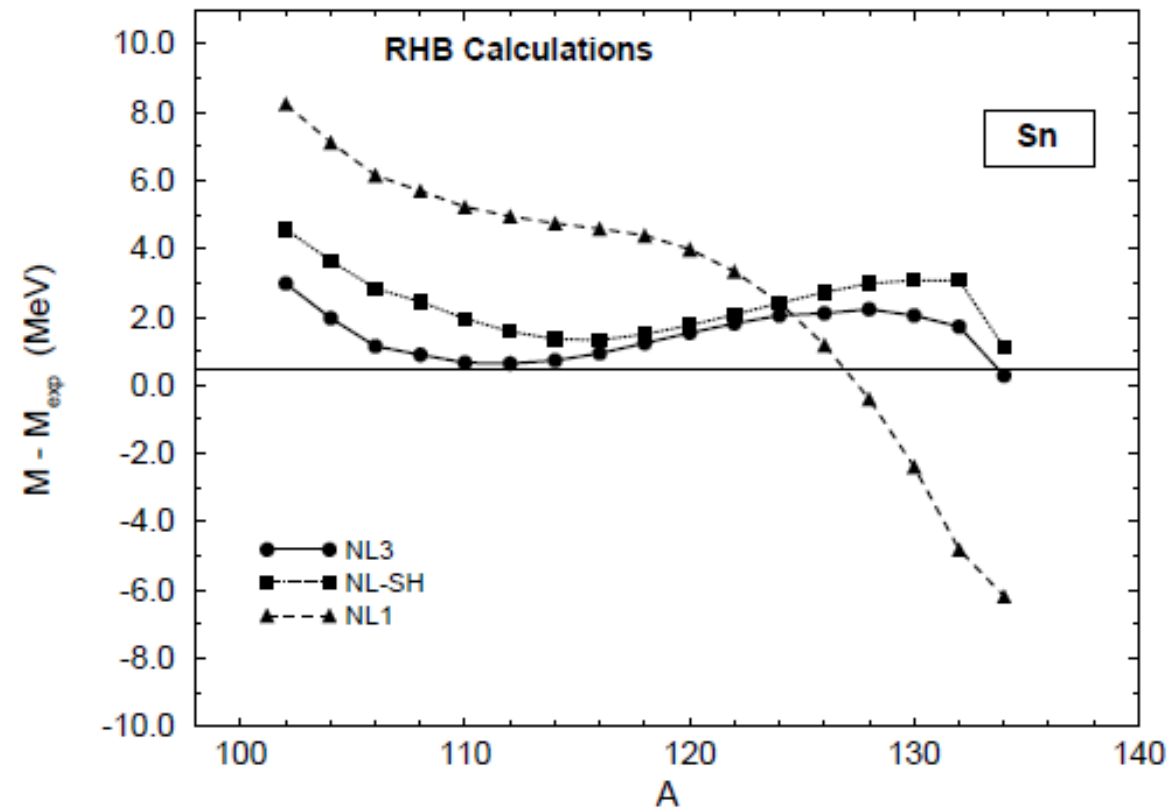
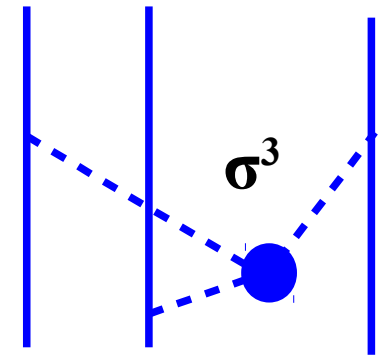


TM1: Sugahara, Toki ('94)

High Quality RMF models

- いくつかの RMF パラメータによる計算は、「質量公式」に迫る精度で原子核質量を記述！
→ High Quality RMF models.
TM, NL1, NL3,

- 全質量で 1, 2 MeV の誤差 (NL3)
- Linear coupling (σN , ωN , ρN), self-energy in σ , ω
- 場合によっては結合定数の密度依存性を導入。



NL3: Lalazissis, Konig, Ring, PRC55 ('97)540

対称エネルギー：最近の進展

Symmetry Energy

■ 核子あたりのエネルギー(一様物質)

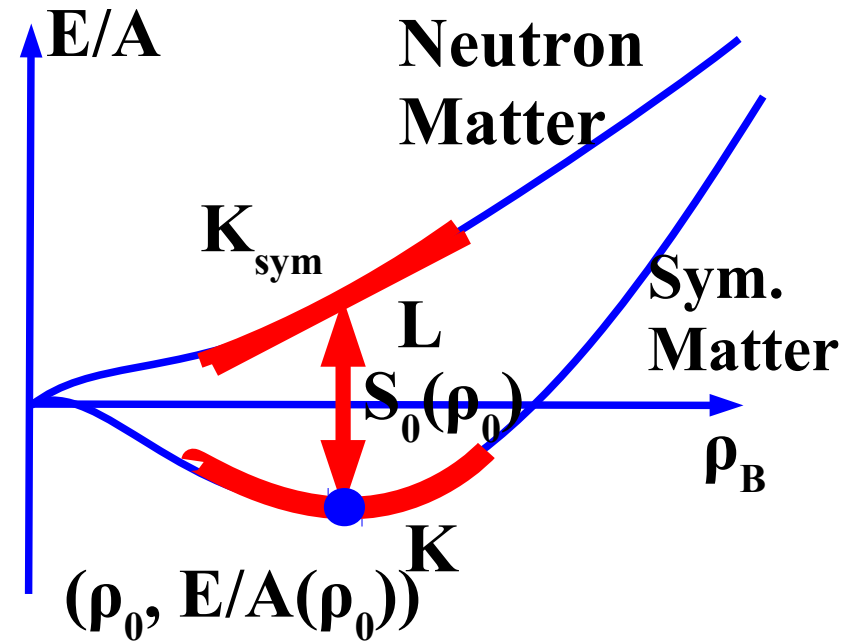
- 原子核の質量公式、半径
→ 飽和密度、体積エネルギー、
対称エネルギー

$$(\rho_0, E/A(\rho_0)) = (0.15 \text{ fm}^{-3}, -16 \text{ MeV})$$

$$S_0 \sim 30 \text{ MeV}$$

- 対称エネルギーの密度依存性 (L)、
非圧縮率 (K)

→ 大きな不定性



$$E/A(\rho, \delta) = \varepsilon(\rho) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4)$$

Symmetric Matter

$$\varepsilon(\rho) = \varepsilon(\rho_0) + \frac{K(\rho - \rho_0)^2}{18\rho_0^2} + O((\rho - \rho_0)^3)$$

Symmetry Energy ($\delta = (N - Z)/A = 1 - 2Y_p$)

$$E_{\text{sym}}(\rho) = S_0 + \frac{L(\rho - \rho_0)}{3\rho_0} + \frac{K_{\text{sym}}(\rho - \rho_0)^2}{18\rho_0^2} + O((\rho - \rho_0)^3)$$

Symmetry Energy

■ Summary of Nuclear Symmetry Energy workshop

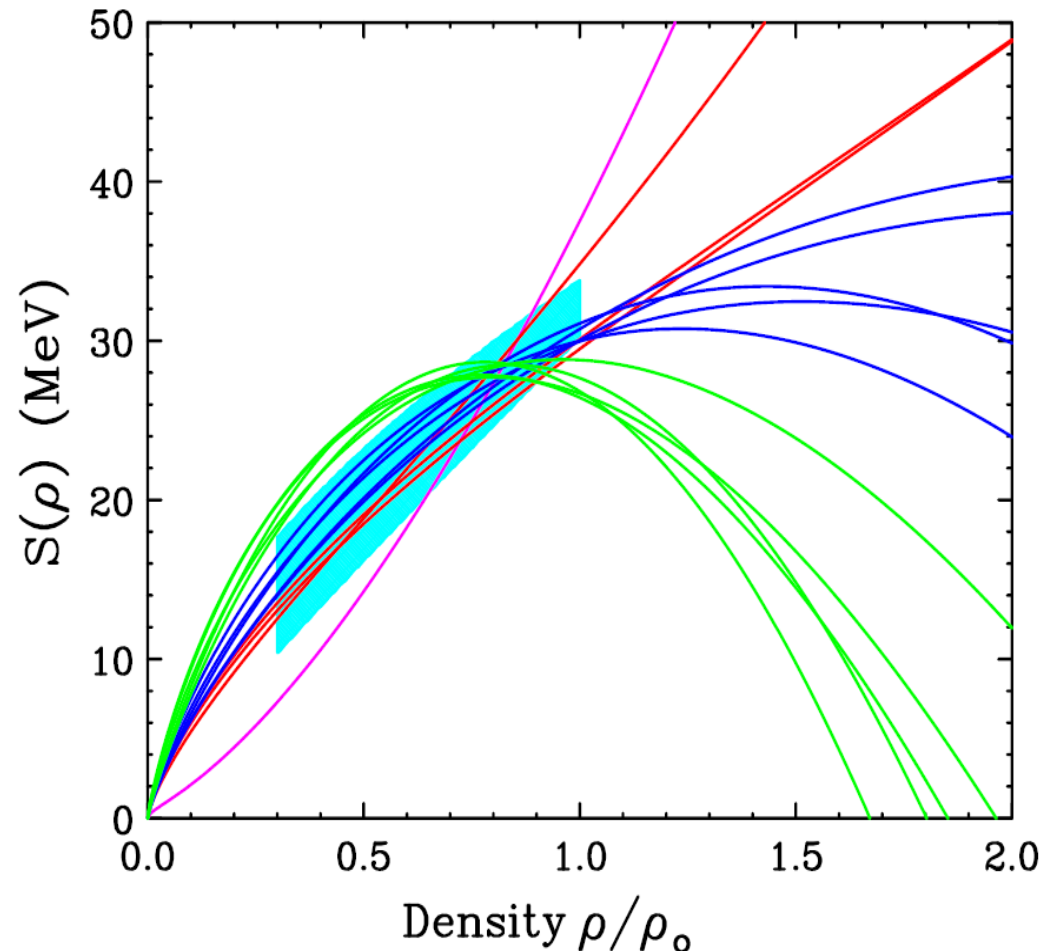
NuSym11 <http://www.smith.edu/nusym11>

$$E_{\text{sym}}(\rho_0) = 31\text{-}34 \text{ MeV}, L = 50\text{-}110 \text{ MeV}$$

extracted from various observations.

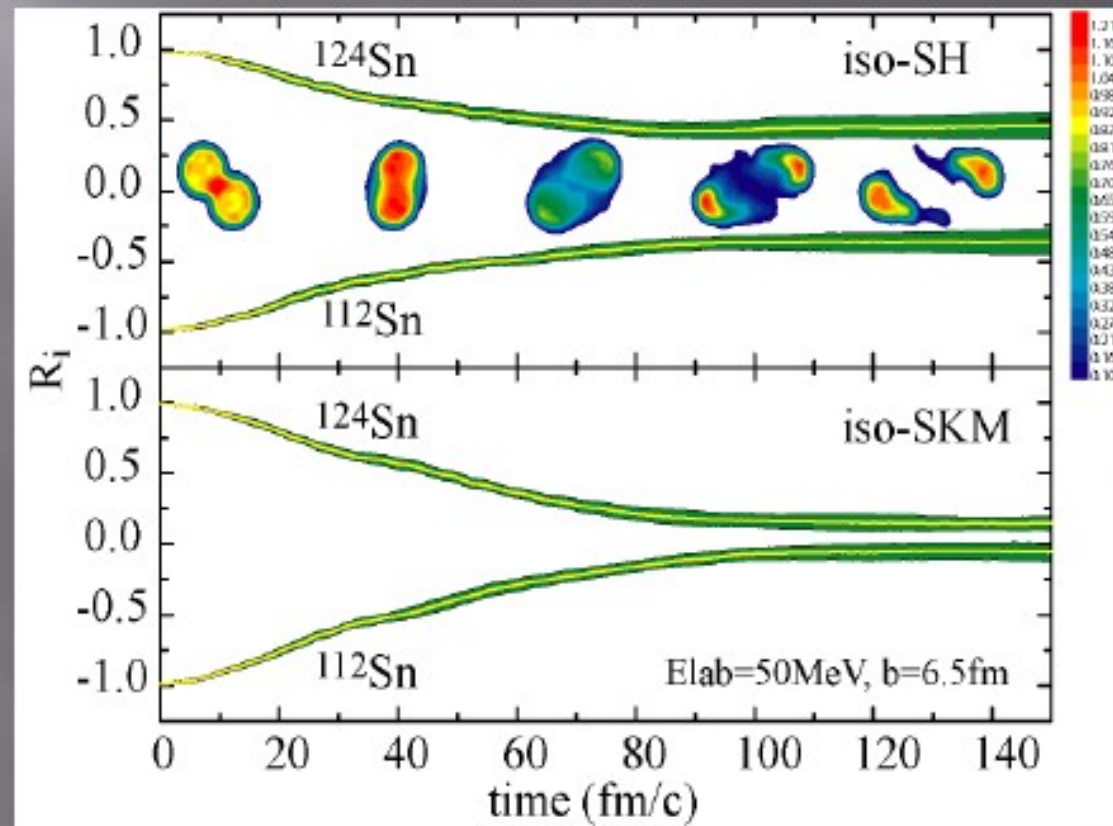
- Mass formula Moller ('10)
- Isobaric Analog State
Danielewicz, Lee ('11)
- Pygmy Dipole Resonance
Carbone+ ('10)
- Isospin Diffusion
NSCL/MSU group
- Neutron Skin thickness
J.Zenihiro+ ('10)

■ 注意:これらは全て ρ_0 以下の密度での E_{sym} に敏感。



From Heavy Ion Collisions compared to transport theory calculation NSCL/MSU group

- Isospin diffusion in peripheral collisions



- Yield ratio of neutron and proton

Symmetry Energy

■ Summary of Nuclear Symmetry Energy workshop

NuSym11 <http://www.smith.edu/nusym11>

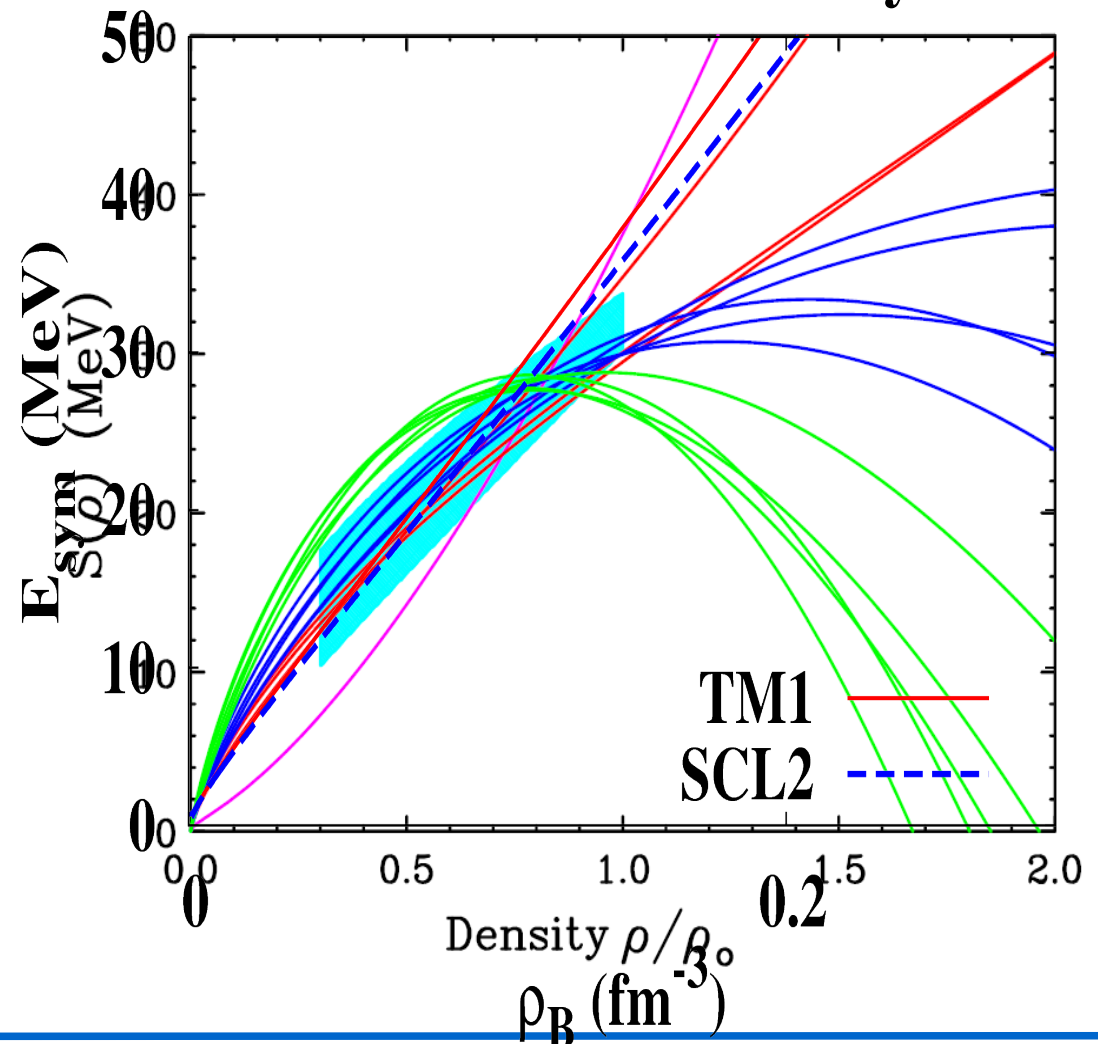
$$E_{\text{sym}}(\rho_0) = 31\text{-}34 \text{ MeV}, L = 50\text{-}110 \text{ MeV}$$

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TM1: barely OK

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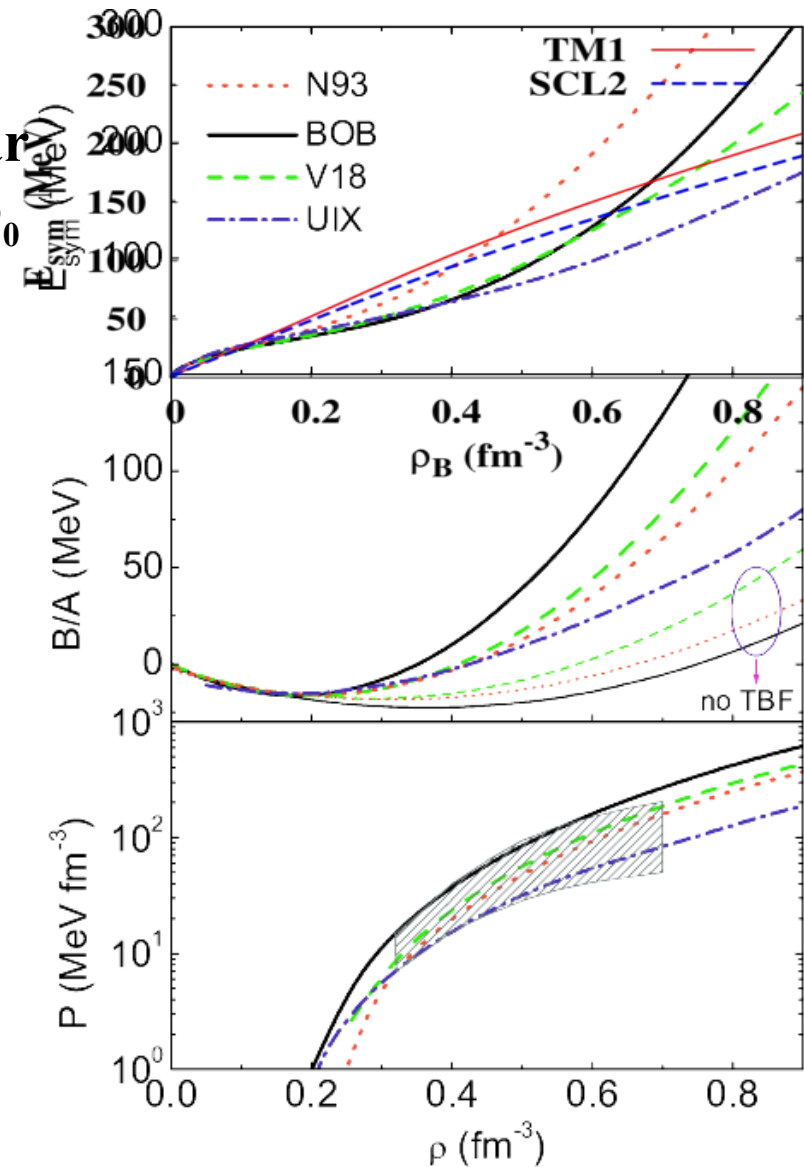
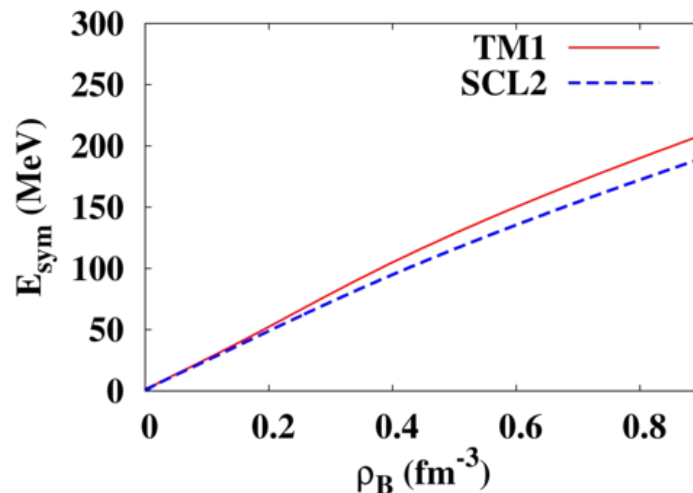


Density dependence of Symmetry Energy

■ RMFs have small ambiguity in E_{sym} .

Is it true ?

- RMF E_{sym} 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 E_{sym} , while RMF gives E_{sym} almost linear in ρ_B .
 → RMF may overestimate E_{sym} at high density.



Lombardo, DCEN slide

Symmetry Energy

■ Isoscalar Giant Monopole Resonance (ISGMR) of Sn isotopes

- ISGMR in Isotope chain ($^{112}\text{Sn} \sim ^{124}\text{Sn}$) is systematically studied (RCNP experiment).

- Resonance $E. \propto K$ (nuclei)

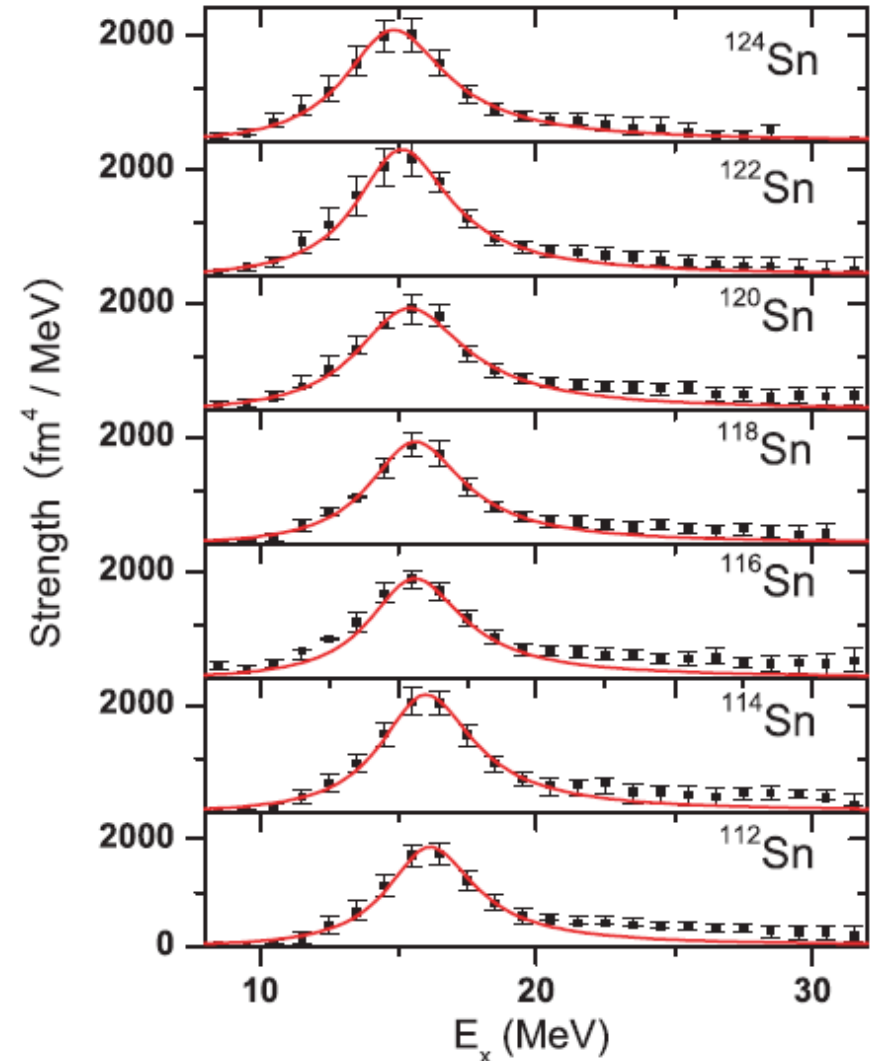
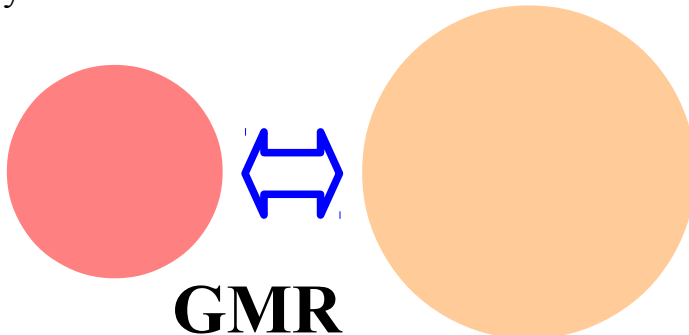
$$K_{A,Z} = K(1 + c A^{-1/3}) + K_{\text{sym}} \delta^2 + O(\delta^4)$$

- Data suggest that EOS becomes softer in asym. nuclear matter.

$$K(\delta) = K + K_{\text{sym}} \delta^2$$

$$K = 240 \pm 10 \text{ MeV}$$

$$K_{\text{sym}} = -550 \pm 100 \text{ MeV}$$



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

ハイペロンを含む状態方程式と $2 M_{\odot}$ 中性子星

RMF へのハイペロンの導入 (1)

■ 中間子・ハイペロン結合

- フレーバー・スピン (SU(6)) 対称性
 ~ クォーク数カウンティング

Glendenning ('81)

$$x_{\sigma\Lambda} \equiv g_{\sigma\Lambda} / g_{\sigma N} = 2/3$$

$$x_{\omega\Lambda} \equiv g_{\omega\Lambda} / g_{\omega N} = 2/3$$

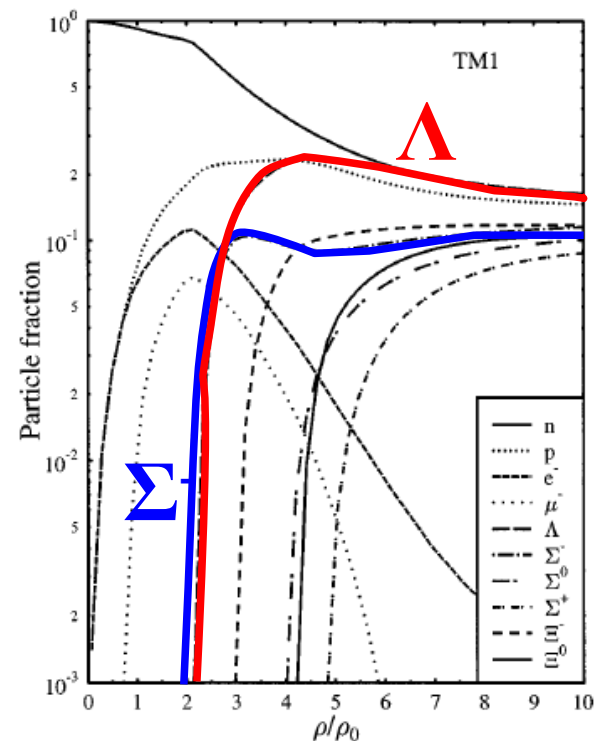
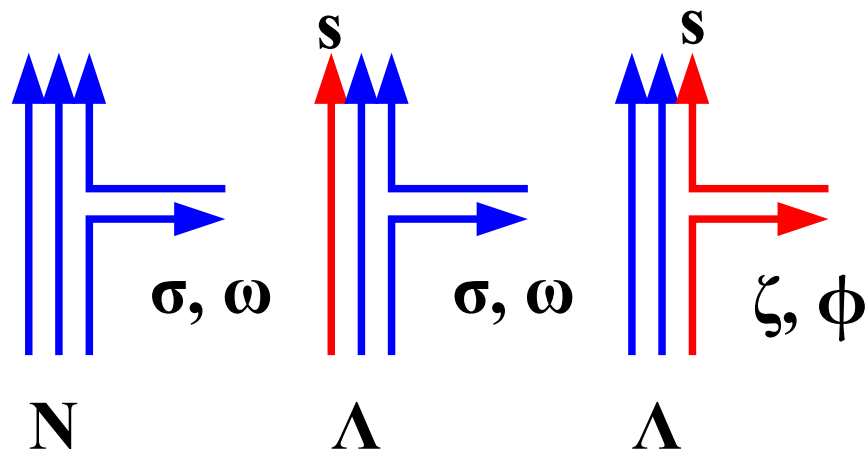
→ 核物質中のポテンシャルの比
 ($U_{\Lambda} \sim 2/3 U_N$) と対応。

c.f. π 交換をもとに考えると $x_{\sigma\Lambda} \sim 1/3$

Brockmann, Weise ('77)

- $s\bar{s}$ からなるスカラー、ベクトル中間子
 (ζ, ϕ) との結合を導入

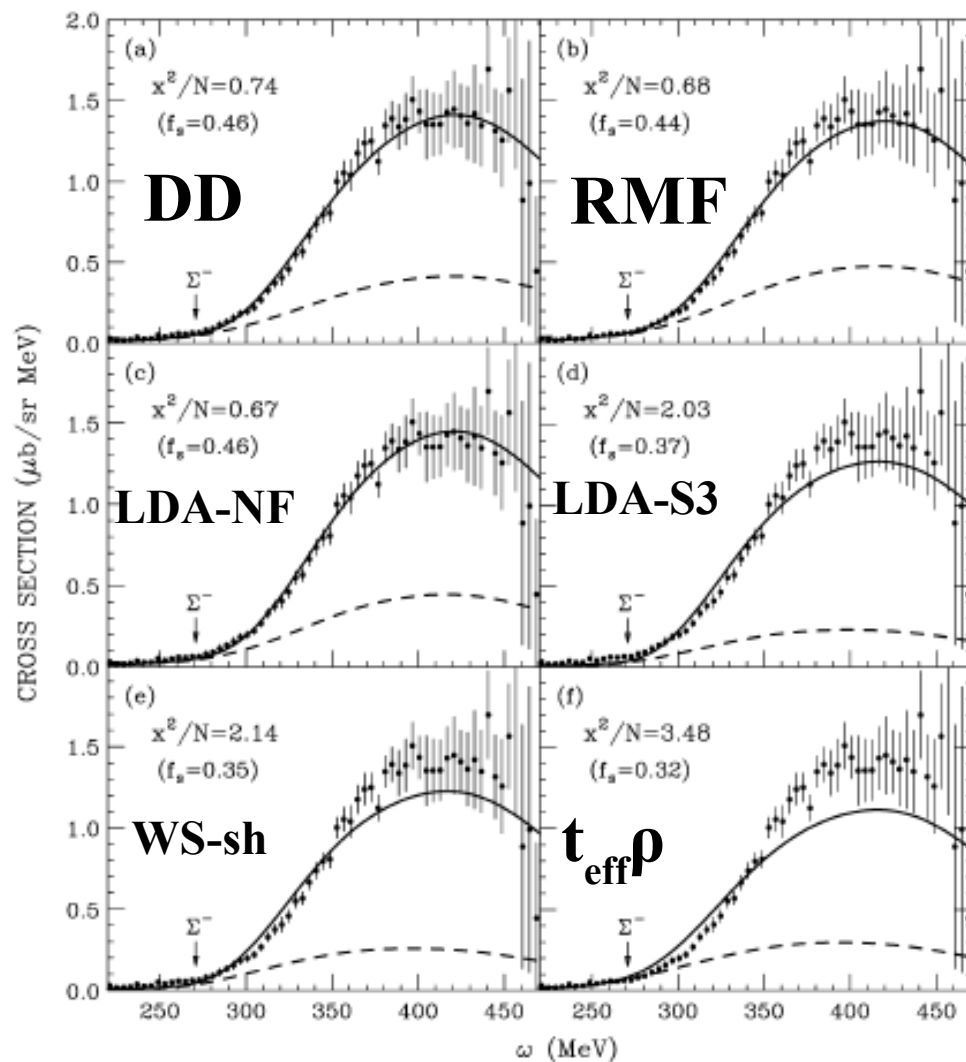
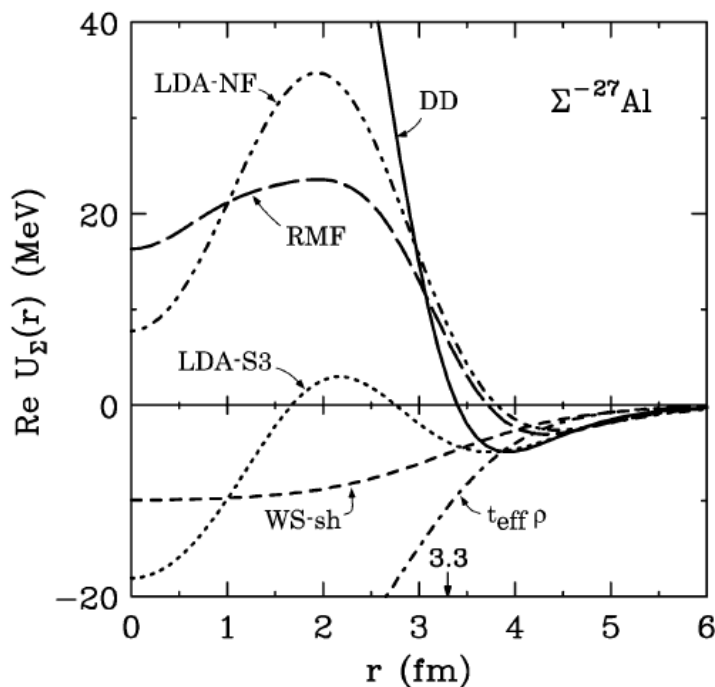
- 高密度物質中の大きなフェルミエネルギー、
 弱い斥力により、(2-4) ρ_0 でハイペロンが出現



*J. Schaffner, I. N. Mishustin,
 PRC 53('96)1416*

RMF へのハイペロンの導入 (2)

- クォーク数カウンティングに従うと、
 $U_{\Sigma} \sim U_{\Lambda} \sim 2/3 U_N \sim -30 \text{ MeV}$
 のはず。
- Σ バリオン生成反応データを
 分析すると、 $U_{\Sigma} > 0$ (斥力)



Harada, Hirabayashi ('05)

Relativistic EOS of Supernova Matter with Hyperons

- Extention of the Relativistic (Shen) EOS to $SU_f(3)$ with updated Hyperon Potentials in Nuclear Matter (*Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, J. Phys. G35(08),085201*)
 - Relativistic (Shen) EOS (*Shen, Toki, Oyamatsu, Sumiyoshi, PTP 100('98), 1013*)
Rel. Mean Field (RMF) + Local Density Approx. (Nuclear Formation)
 - $SU_f(3)$ Extention of RMF (*Schaffner, Mishustin, PRC53 (1996), 1416*)

$$\mathcal{L} = \mathcal{L}_{Free}(B, \sigma, \omega_\mu, \vec{R}_\mu, \zeta, \phi_\mu) - U_\sigma(\sigma) + \frac{1}{4} c_\omega (\omega^\mu \omega_\mu)^2 - \sum_B \bar{\Psi}_B \left(g_{\sigma B} \sigma + g_{\omega B} \omega + g_{\rho B} \vec{R} \cdot \vec{T}_B + g_{\zeta B} \zeta - g_{\phi B} \gamma^\mu \phi_\mu \right) \Psi_B$$

Coupling ~ Quark Number Counting

- $g_{\sigma Y}$ is tuned to fit Hyperon Potential in Nuclear Matter
 $U_\Lambda = -30 \text{ MeV}, U_\Sigma = +30 \text{ MeV}, U_\Xi = -15 \text{ MeV}$
(*SU(6) breaking in scalar coupling*).
- Nuclear Formation is included using Shen EOS table

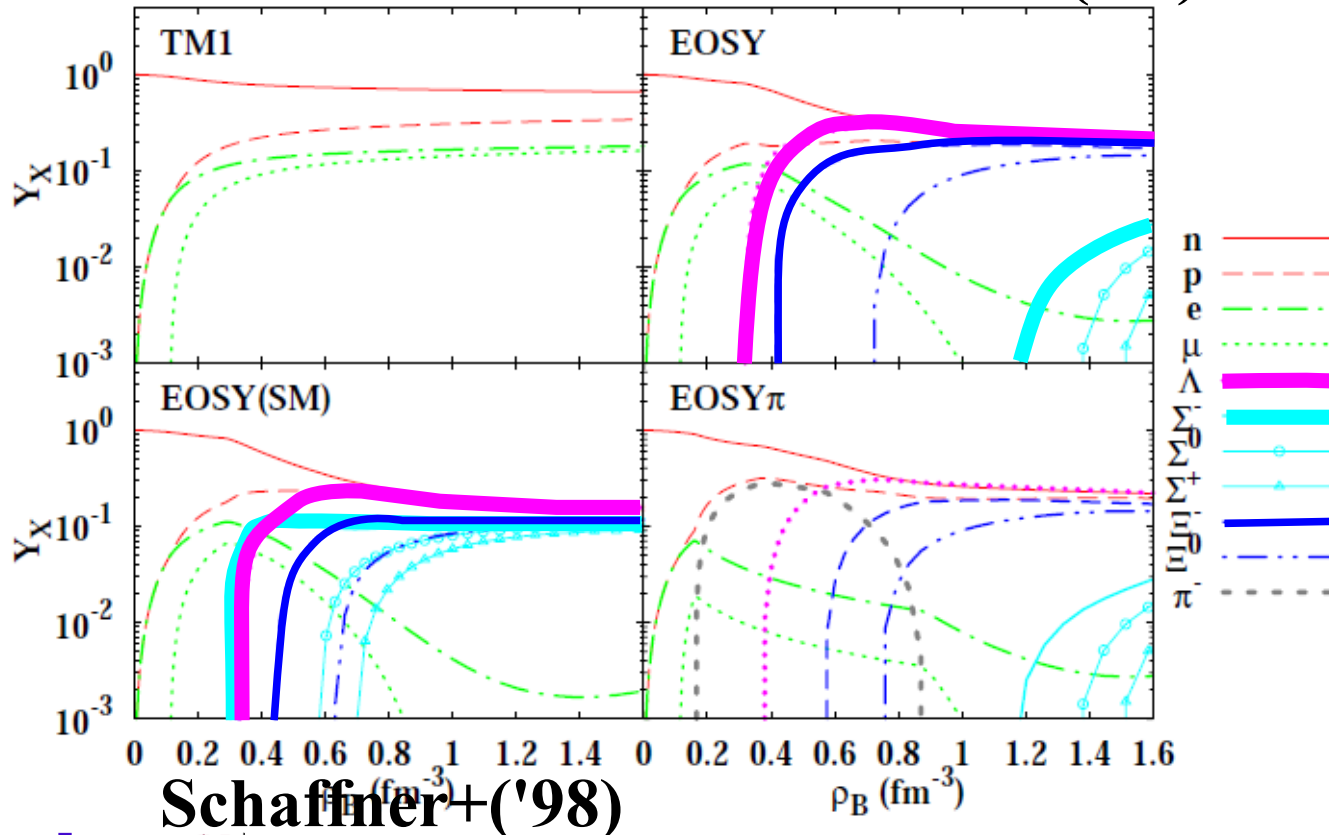
Neutron Star

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, *J. Phys. G35(08),085201*

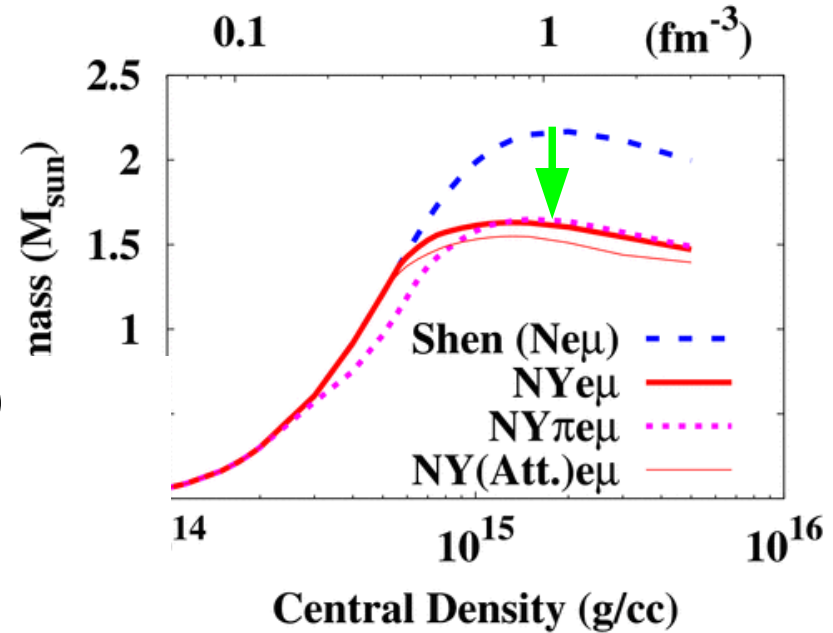
Hyperon Effect is DRASTIC

- $M_{\text{max}} = 2.1 M_{\odot} \rightarrow 1.56 M_{\odot}$
- Composition $Y_{\Lambda} \sim Y_n$
- Large fraction of Ξ

Neutron Star Matter **Ishizuka+('08)**



Schaffner+('98)



c.f. H. Shen+('09)
 $\rightarrow n, p, \Lambda$ EOS

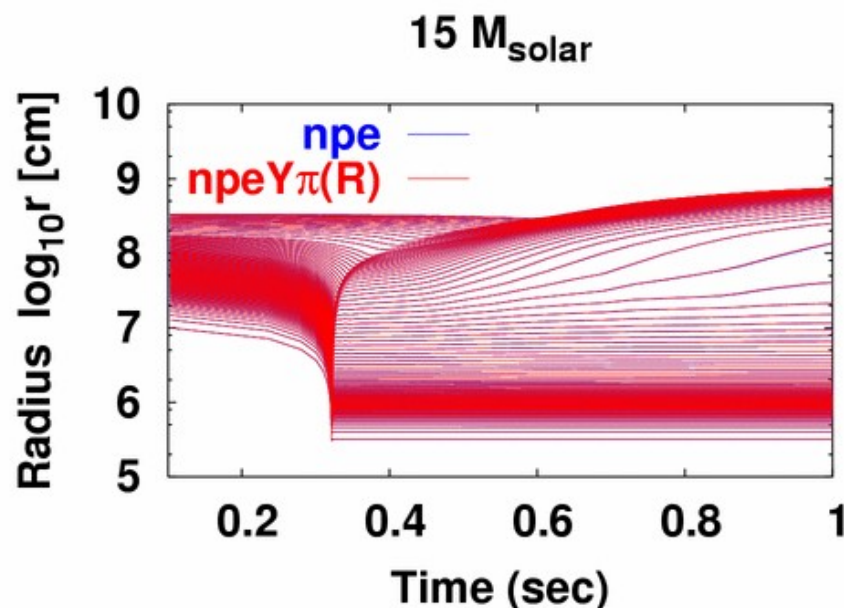
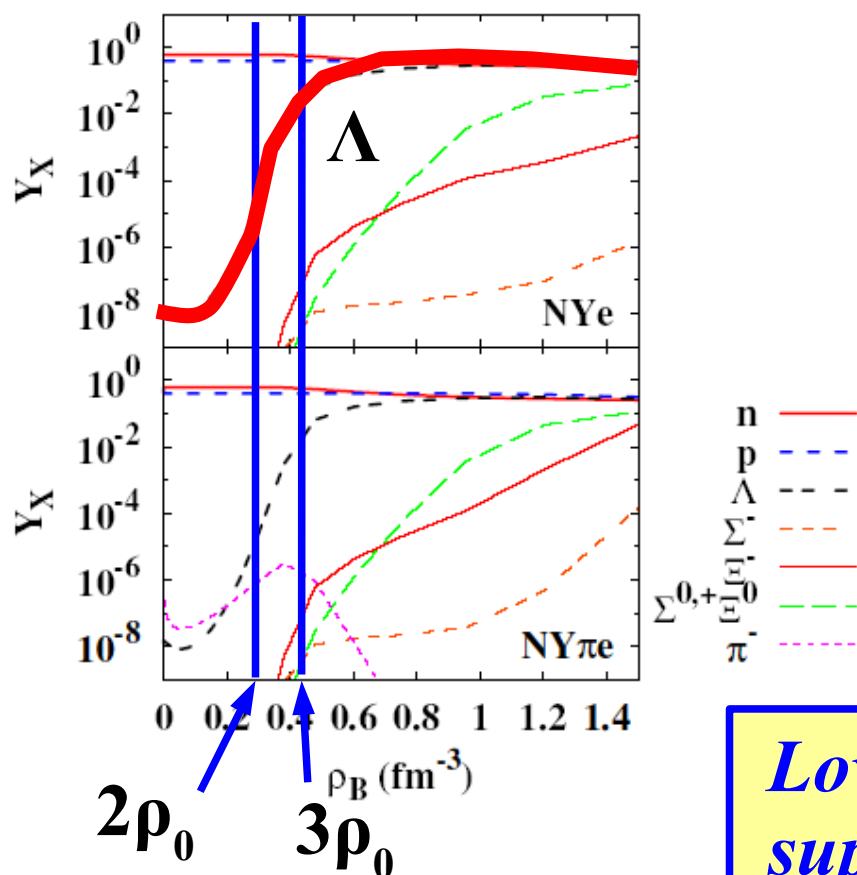
Finite Temperature and Supernova

Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, *J. Phys. G35(08),085201*

- **Example: $T=10$ MeV, $Y_e = 0.4$**
 - Λ starts to increase at $\rho \sim 2\rho_0$, becomes significant at $\rho \sim 3\rho_0$.

- **Prompt explosion (without ν transport) \rightarrow Almost no change (Expl. E. increase $\sim (0.1-0.5 \%)$)**

$T=10$ MeV, $Y_C=0.4$

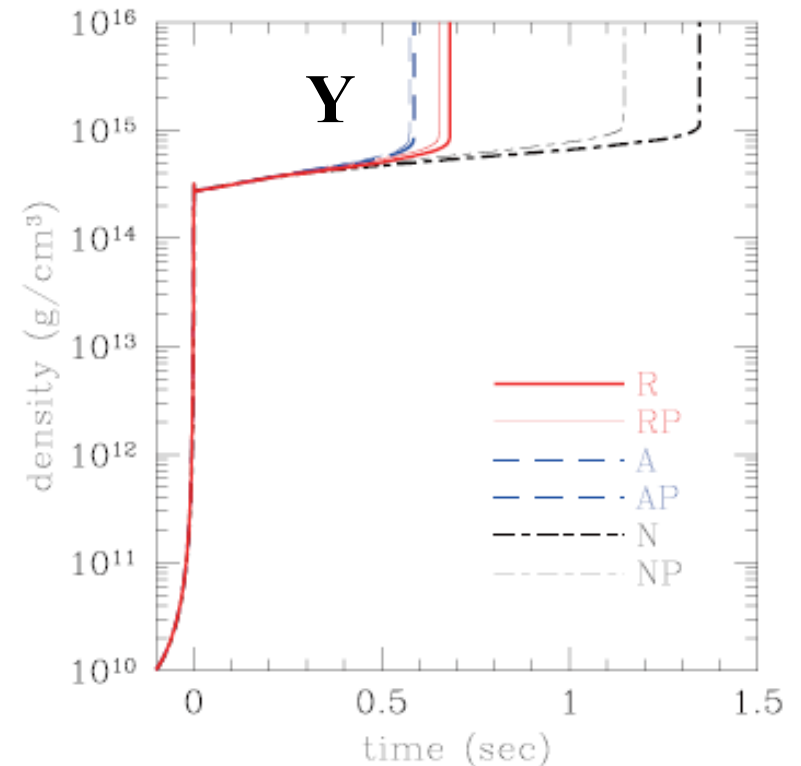
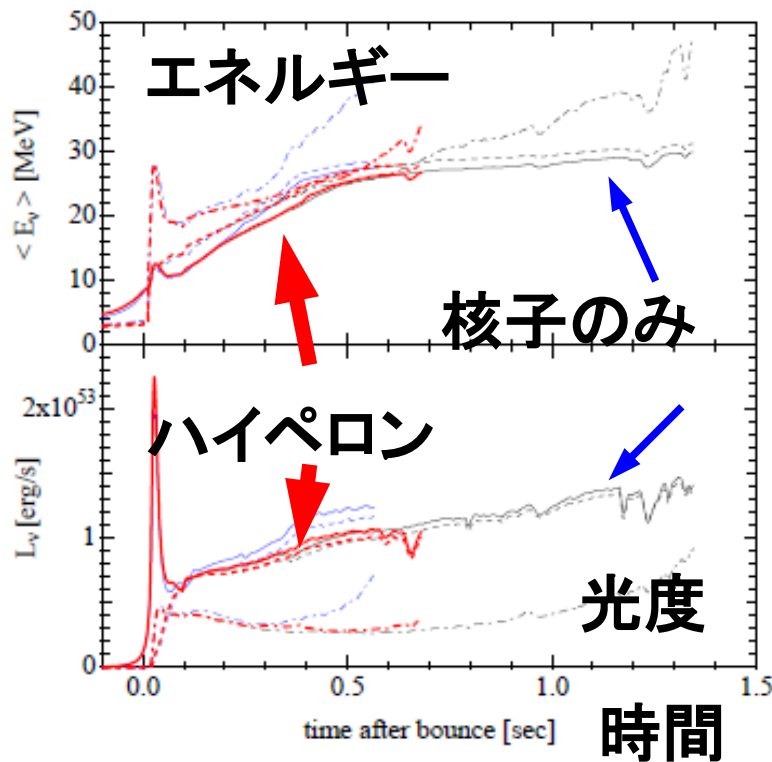


WW95 + 1 Dim. Hydro. (Sumiyoshi, Yamada)

Low density and High Y_e suppresses Hyperons in the Early Stage

Black Hole Formation (Failed Supernova)

- “Hot” and “Dense” matter in BH formation process !
 - $T_{\max} \sim 90$ MeV (Nucleon), 70 MeV (w/ Hyperon), $\rho_{\text{Bmax}} \sim 4 \rho_0$
- ν spectrum is sensitive to dense matter EOS (stiffness, hyperon, quark, ...)



Sumiyoshi, Ishizuka, AO, Yamada, Suzuki, 2009

Nakazato, Furusawa, Sumiyoshi, AO,
Yamada, Suzuki, *ApJ*, to appear

RMF は現象論的な「模型」である！

- 「模型」、あるいは密度汎関数としての RMF
 - 中間子・バリオン結合は 2 体散乱を再現しない。
 - バリオンの 1 ループ (Hartree) のみを考えている。
 - 結合定数・self-energy の形と係数を適切に選べば原子核をうまく記述。
- 実験データ・第一原理計算結果を再現するように Lagrangian を与える。
 - Saturation point (ρ_0 and $E/A(\rho_0)$) from mass formula, Nuclear binding energies, U_v and U_s from DBHF results, $P(\rho_B)$ from heavy-ion data
 - Λ and $\Lambda\Lambda$ separation energies from hypernuclear data, Σ atomic shift, Σ and Ξ potential depth from quasi-free production data
 - Pure neutron matter EOS from ab initio calculations (not used here)
 - Neutron Star Max. Mass $> 1.44 M_\odot$.

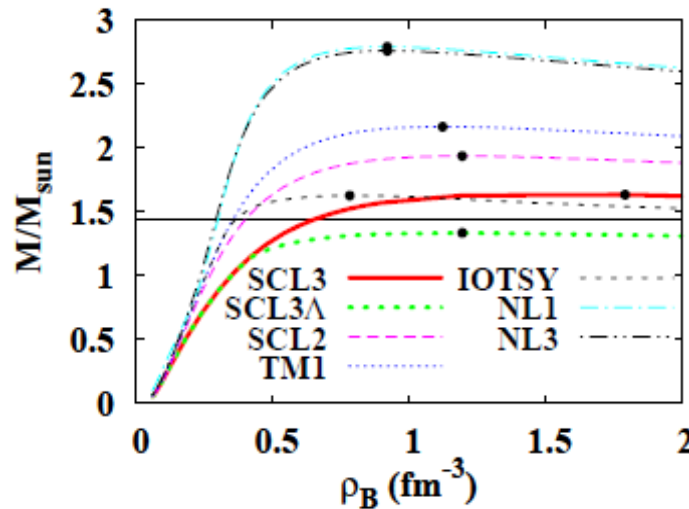
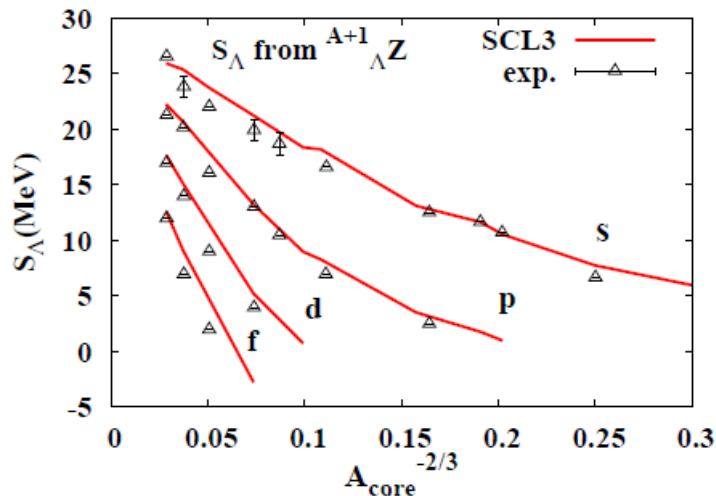
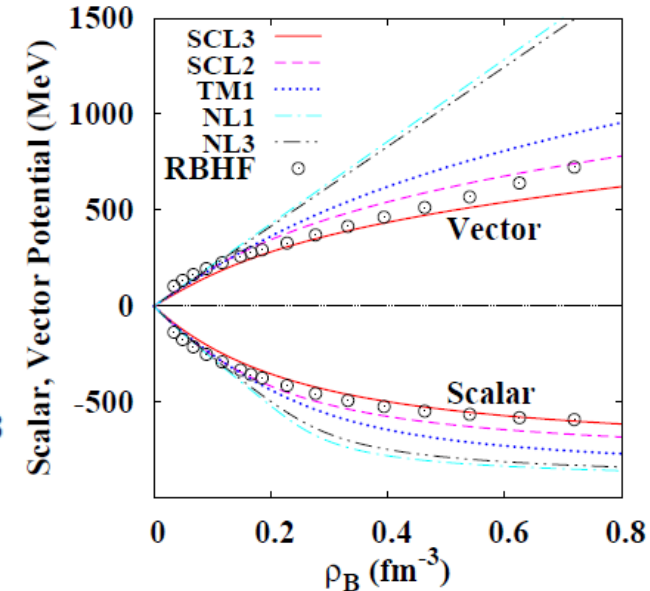
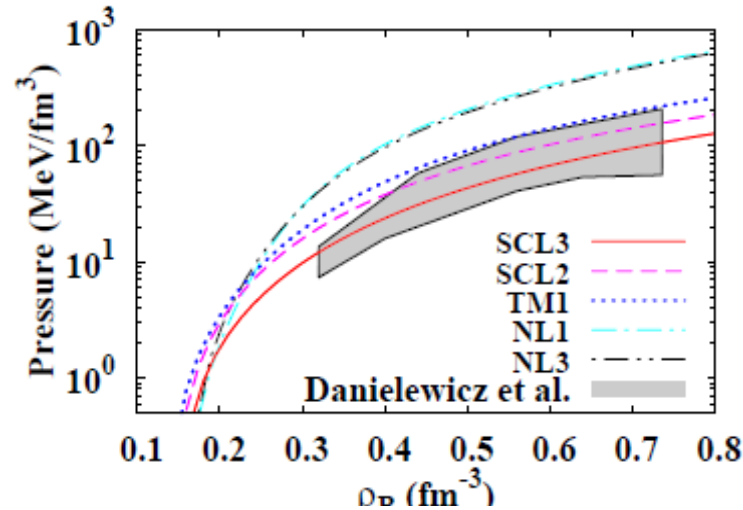
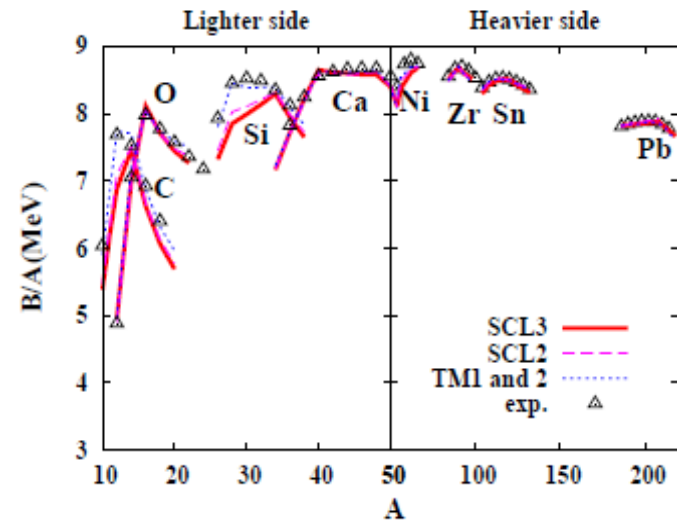
Not considered in Ishizuka EOS

現象論としてのRMF

Fit as many as known observables

K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

- EOS, Nuclear B.E., High density EOS from HIC, Vector potential in DBHF, Hypernuclear Separation Energy, Neutron Star, ...



*P. Danielewicz et al.,
Science 298('02)1592.
R. Brockmann,
R. Machleidt,
PRC 42('90)1965.*

RMF は現象論的な「模型」である！

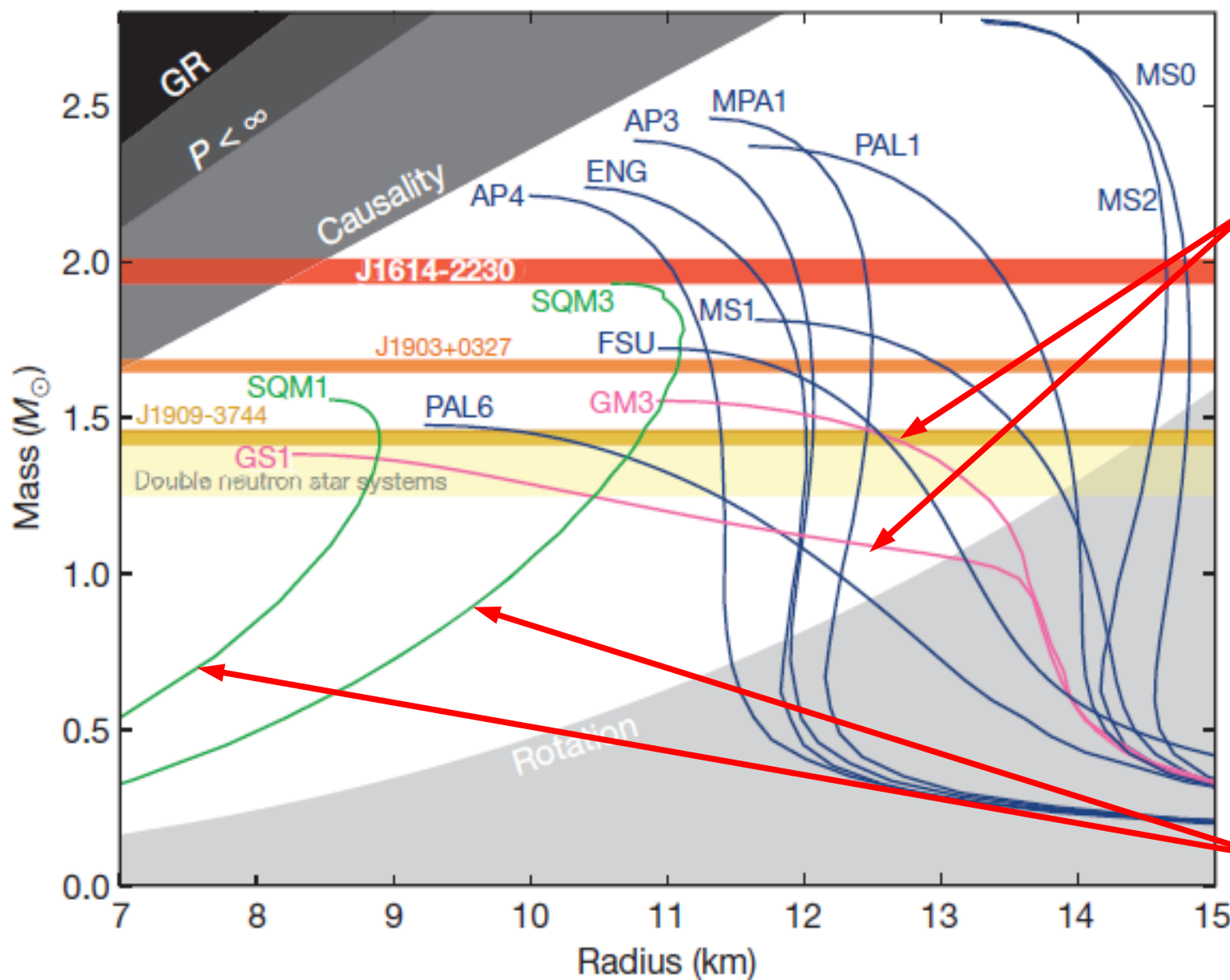
- 「模型」、あるいは密度汎関数としての RMF
 - 中間子・バリオン結合は 2 体散乱を再現しない。
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 - ● Saturation point (ρ_0 and $E/A(\rho_0)$) from mass formula, Nuclear binding energies, U_v and U_s from DBHF results, $P(\rho_B)$ from heavy-ion data
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 - ? ● Pure neutron matter EOS from ab initio calculations (not used here)
 - ▲ ● Neutron Star Max. Mass $> 1.44 M_\odot$.

K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

The Judgement Day, Oct. 28, 2010.

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

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



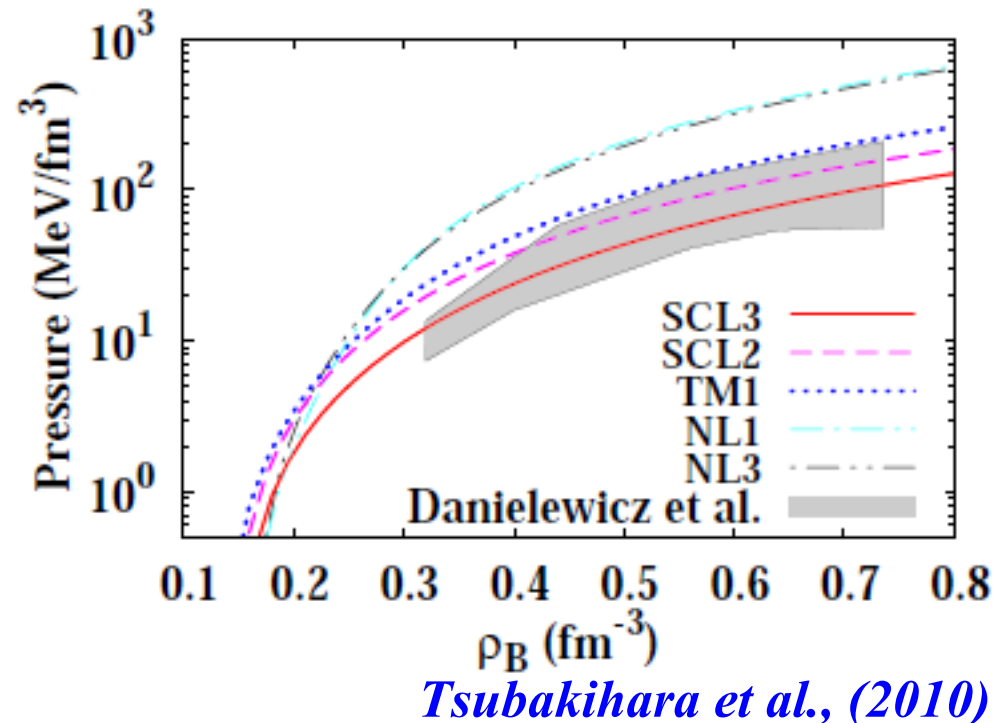
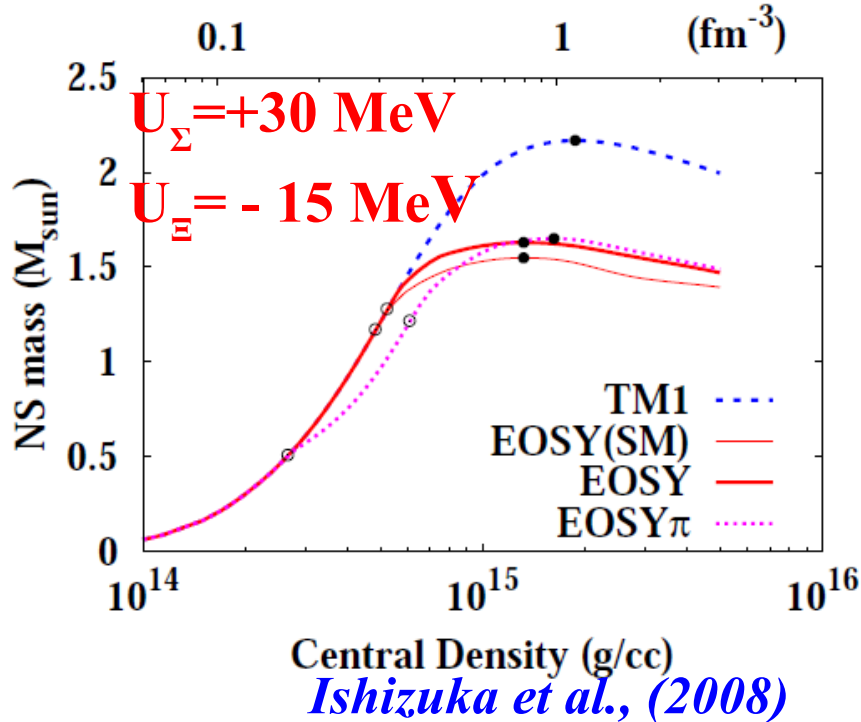
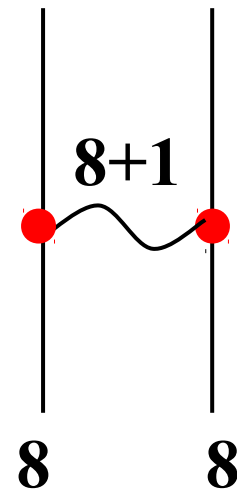
ハイペロンを
含む EOS

クォーク物質
のみの EOS

Which type of EOSs are rejected ?

Rejected Hyperonic Matter EOS

- Relativistic Mean Field model
 - GM3: Glendenning & Moszkowski (1991)(npY)
 - GS1: Glendenning & Schaffner-Bielich (1999)(npK)
- Coupling \sim Quark Counting ($g_{\omega Y}/g_{\omega N} \sim 2/3$)
- Even with rel. effects, we cannot support $1.97M_{\odot}$ as long as we respect hypernuclear & HIC data.



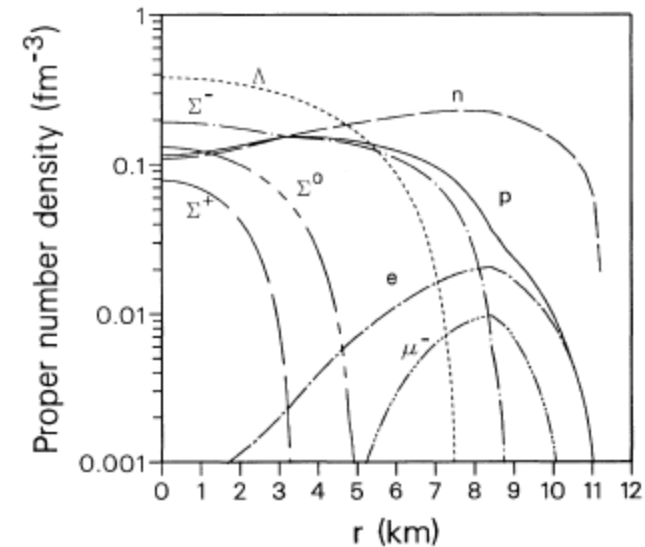
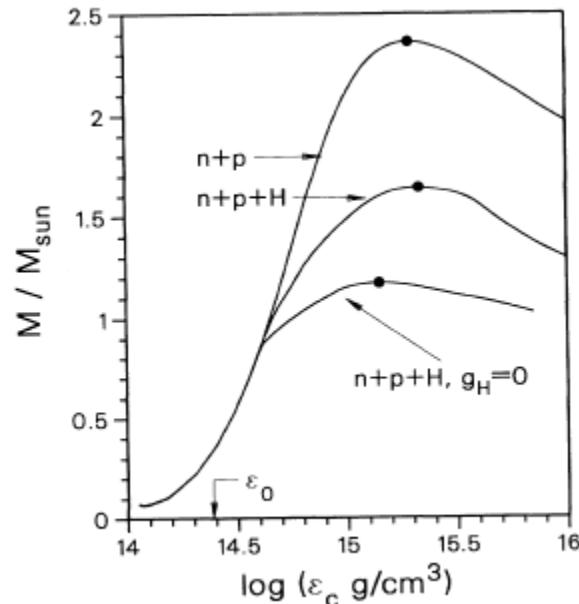
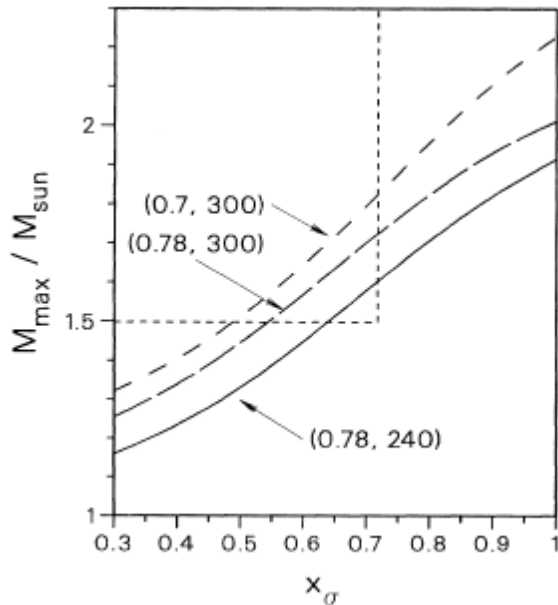
Glendenning & Moszkowski (1991)

■ RMF with hyperons

- $n, p, Y, \sigma, \omega, \rho / \sigma^3, \sigma^4$
- Give $x_\sigma = g_{\sigma Y} / g_{\sigma N}$ and fix $x_\omega = g_{\omega Y} / g_{\omega N}$ to fit Λ separation energy.
- $x_\sigma = 0.6 \rightarrow m^*/m=0.7, x_\omega=0.653$
(similar to quark number counting result, $x=2/3$)
 $\rightarrow M_{\max} \sim 1.6 M_\odot$

TABLE I. Values of the hyperon-to-nucleon scalar and vector coupling that are compatible with the binding of -28 MeV for Λ hyperons in nuclear matter for two values of the nucleon (Dirac) effective mass at saturation density.

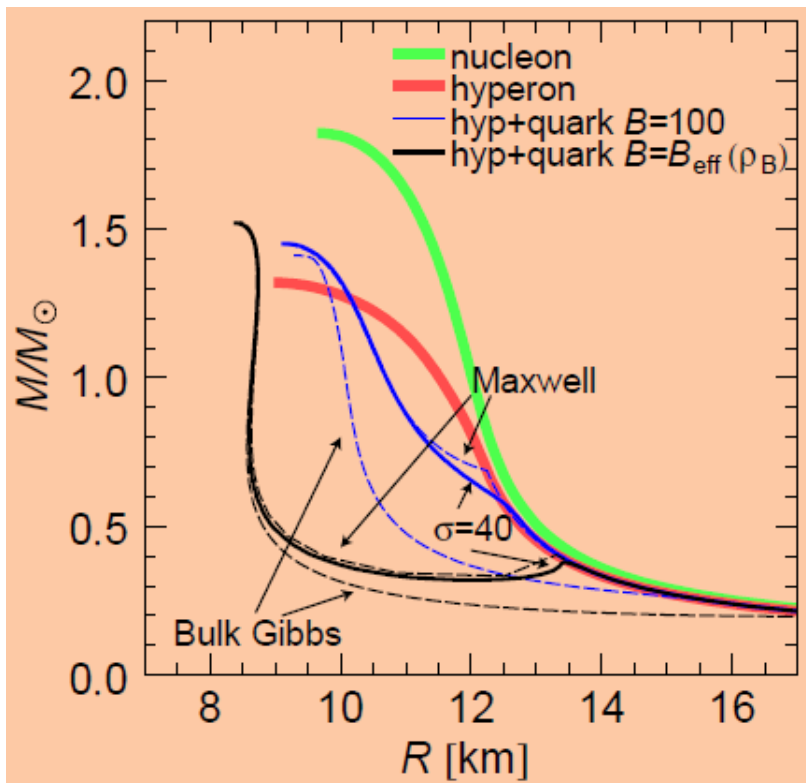
x_σ	x_ω	$m^*/m=0.7$	$m^*/m=0.78$
0.2		0.131	0.091
0.3		0.261	0.233
0.4		0.392	0.375
0.5		0.522	0.517
0.6		0.653	0.568
0.7		0.783	0.800
0.8		0.913	0.942
0.9		1.04	1.08
1		1.17	1.23



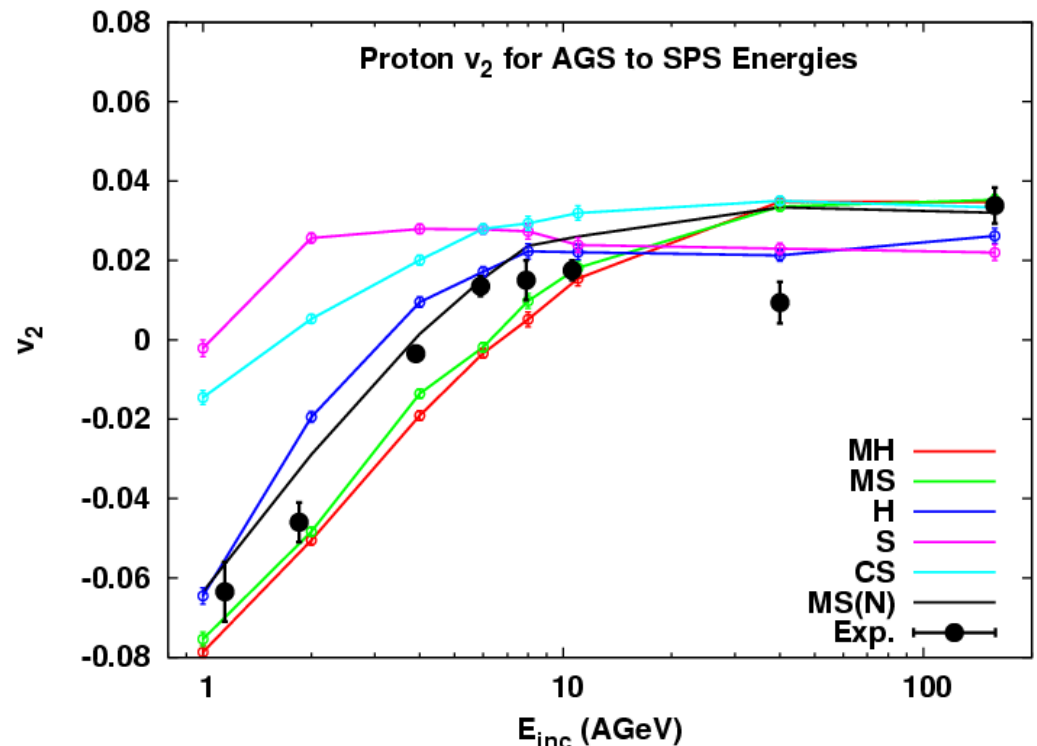
N.K.Glendenning, S.A.Moszkowski, PRL67('91)2414

How can we solve it ?

- No Hyperons, No Kaons → How can it be consistent with YN int ? (μ_B in NS ~ 1650 MeV in core in TM1)
- Stiff nuclear matter EOS + transition to quark matter at small ρ_B → How can it be consistent with HIC data at AGS-SPS energies ?
- Three-body force for baryons, quarks, ...



H.-J. Schulze, NFQCD10



M. Isse, A.O., N. Otuka, P. K. Sahu,
Y. Nara, PRC72 ('05)064908

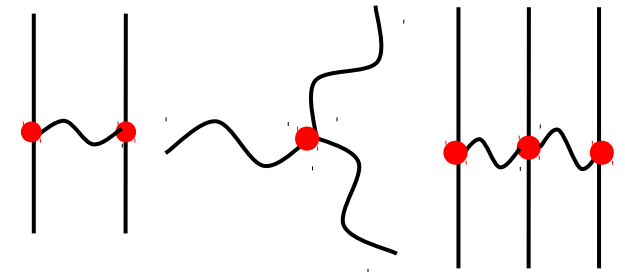
■ Three-baryon coupling term

$$L = L_B^{\text{free}} + L_M^{\text{free}} + L_{BM} + L_M^{\text{Int}} + \delta L$$

$$\delta L = -U_\sigma(\sigma) - \frac{1}{2} c_{\sigma\omega} \sigma \omega_\mu \omega^\mu - \frac{1}{4} c_{\omega\omega} (\omega_\mu \omega^\mu)^2$$

$$- \sum_B \bar{\Psi}_B \left[g_{\sigma\sigma B} \sigma^2 + g_{\sigma\omega B} \sigma \omega_\mu \gamma^\mu + g_{\omega\omega B} \omega_\mu \omega^\mu \right] \Psi_B$$

$\mathbf{v} = 3$ terms



- BBMM terms are ignored in standard RMF.

(They can be absorbed in other terms by field re-definitions.)

R.D.Furnstahl, B.D.Serot, H.-B. Tang, NPA615 ('97)441

- But field re-definition modifies the order of NDA.

Naïve dimensional analysis (NDA)

$$\mathbf{v} = \mathbf{B}/2 + \mathbf{M} + \mathbf{d}$$

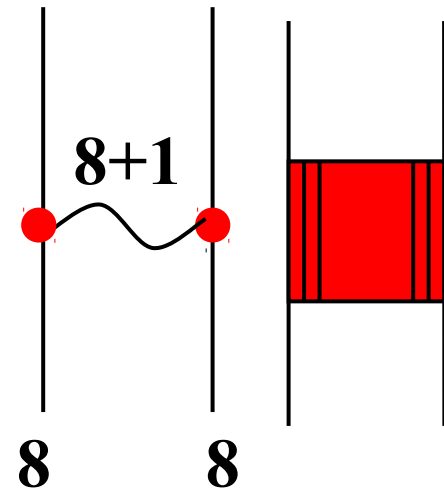
(B, M, d=# of baryon and non-NG boson field, derivatives to NG fields)

- Higher \mathbf{v} terms are found to be suppressed at $\rho \sim \rho_0$, but they will contribute more at high densities.

- c.f. σ polarizability in QMC *T.Miyatsu, K.Saito, PTP 122 ('10) 1035*

$SU(3)_f$ “violating” coupling

- Naïve RMF assumption = BM coupling follows $SU(3)_f$.
- Short range BB interaction comes from quark Pauli blocking + one-gluon exch.
Oka, Yazaki; Faessler et al.; Fujiwara et al.; HAL QCD collab.
- Short-range BB repulsion is sensitive to (S,T) in the s-channel. When we include those interactions in the bosonized form, BM coupling violates $SU(3)_f$.

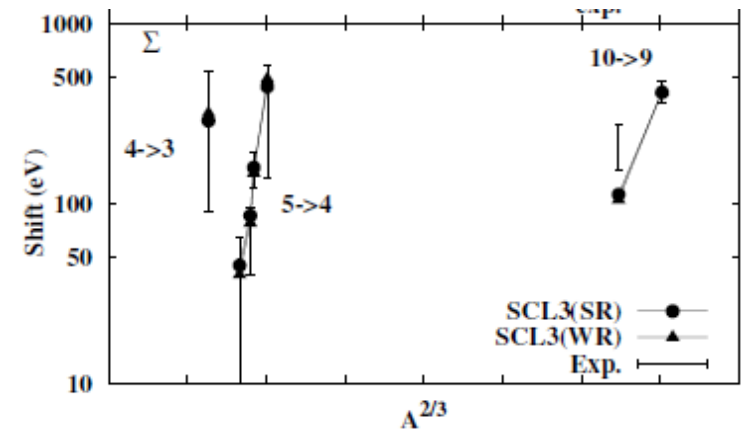


$$V = \sum_{\alpha, \beta} (\bar{\Psi} \bar{\Psi})_{\alpha} \Gamma_{\alpha\beta} (\Psi \Psi)_{\beta} \rightarrow -\frac{1}{2} \sum_{\alpha} m_{\alpha}^2 \omega_{\alpha}^2 + \sum_{\alpha} g_{\alpha} \omega_{\alpha} (\Psi \Gamma \Psi)_{\alpha}$$

E.g., Σ atomic shift

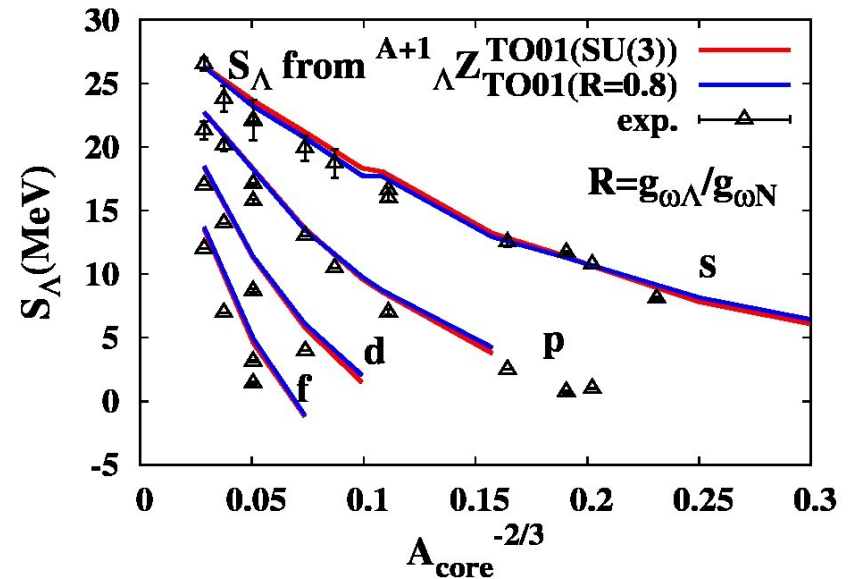
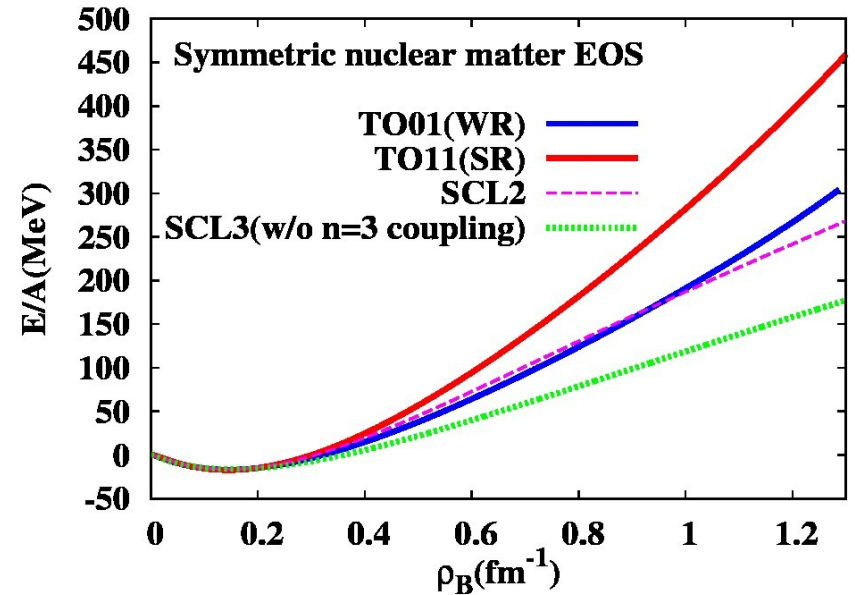
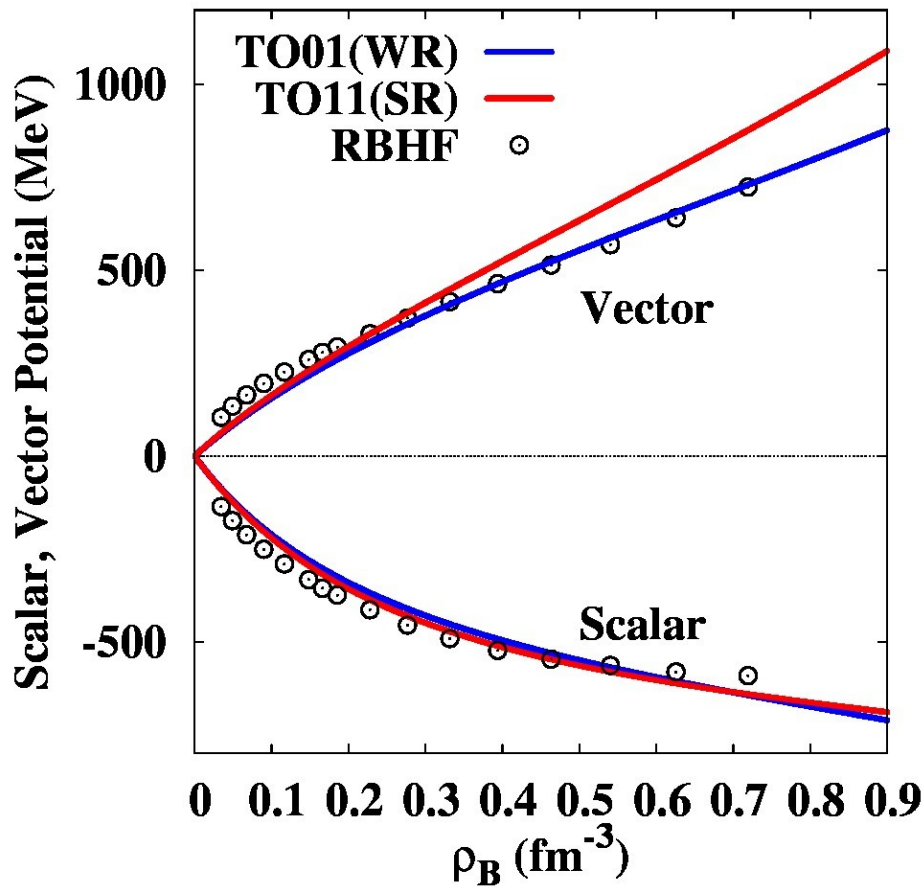
$\rightarrow g_{\sigma\Sigma} \sim g_{\sigma\Sigma} (SU(3)) \times (0.2-0.3)$

- Finite size of baryons would lead to excluded volume effects $\rightarrow \mu - \nu P$
(flavor singlet vector-like effects)



Tsubakihara et al., (2010)

- Nucleon vector potential $U_V(\rho)$ in DBHF: Non-linear behavior in ρ_B .
 → EOS becomes gradually stiffer



RMF with 3BF + SU(3)_f “violation”

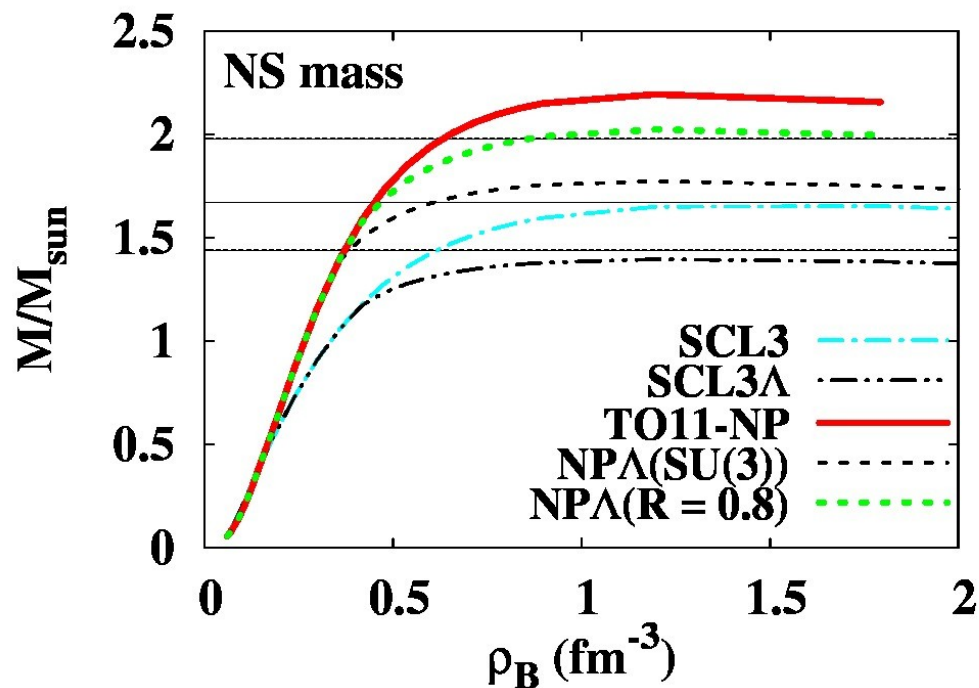
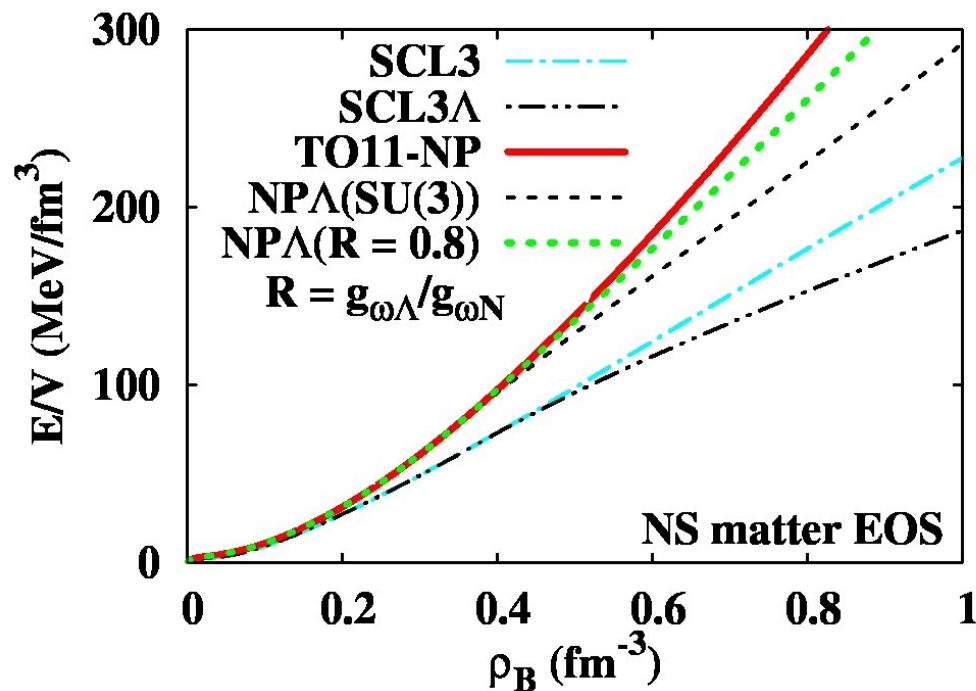
■ Two types of modification

Tsubakihara, AO, in prep.

- 3-baryon repulsion → EOS becomes stiff gradually at high density.
(Fitting meson mass (E325) and U_v in RBHF)

- $R = g_{\omega\Lambda} / g_{\omega N} \sim 0.8$ ($\sim 2/3$ (SU(3)))

→ $M_{\max} \sim 2.02 M_{\odot}$ with hyperons ($\sim 1.4 M_{\odot}$ w/o 3BF, violation)

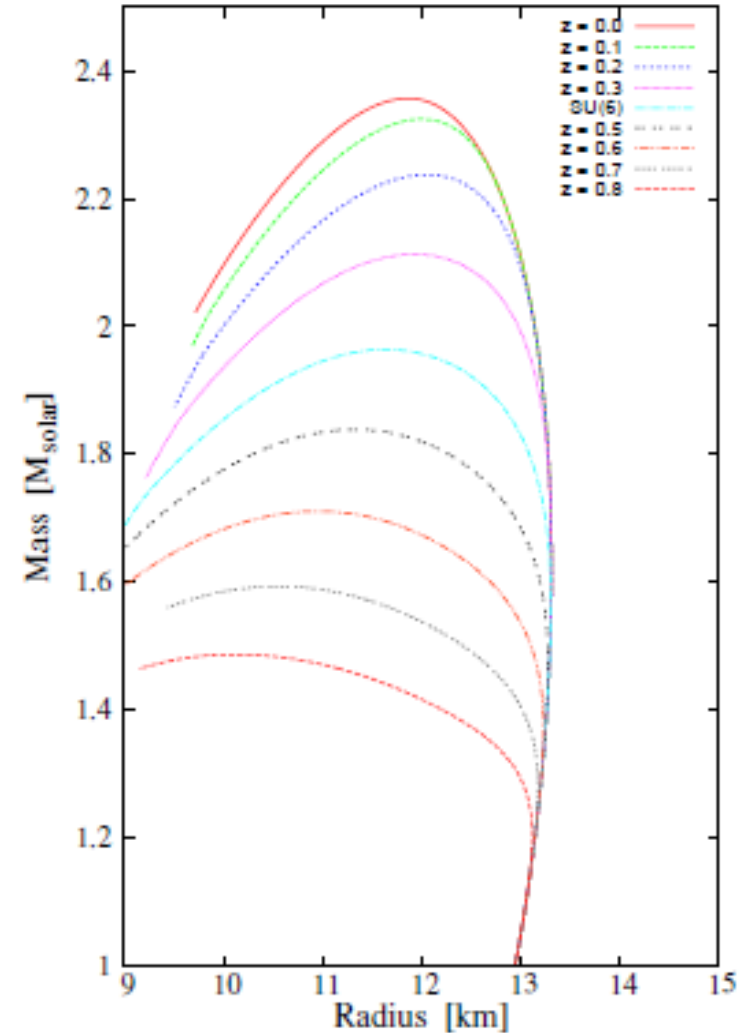
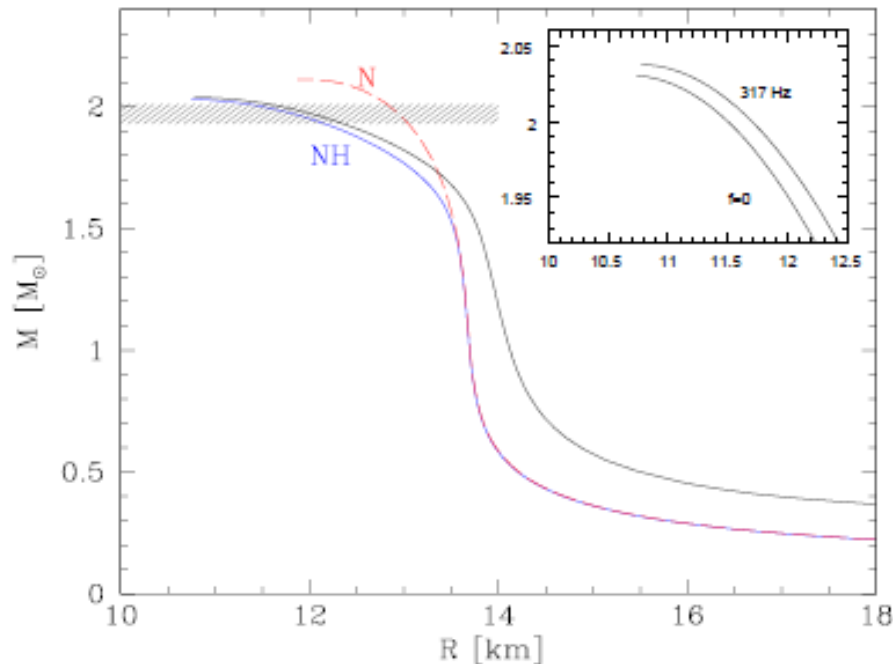


他の解決方法

■ Hidden strange meson の4次

- $\zeta^4, \zeta^2(\omega^2 + \rho^2)$ を導入
- Λ 間の引力を小さく見積もる
- SU(6) 関係式は保持

■ Vector 結合に SU(6) の破れを導入



*Weisenborn, Chatterjee,
Schaffner-Bielich ('11)*

Bednarek, Haensel et al. ('11)

*Critical Point Sweep
during Black Hole Formation*

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), mildly dense ($\sim 1.8 \rho_0$)
T. Hatsuda, MPLA2('87)805; I. Sagert et al., PRL102 ('09) 081101; Nishimura talk.
- Probable in Neutron Stars: Cold ($T \sim 0$), Dense ($\rho_B \sim 5 \rho_0$)
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)

Purpose and Methods

- *We compare (T, μ_B) during BH formation and QCD phase transition boundary by using*
 - **v radiation Hydrodynamics (1D) for BH formation**
Sumiyoshi et al., PRL97('06)091101;
 - ◆ Shen EOS (npe μ) *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 \rightarrow 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

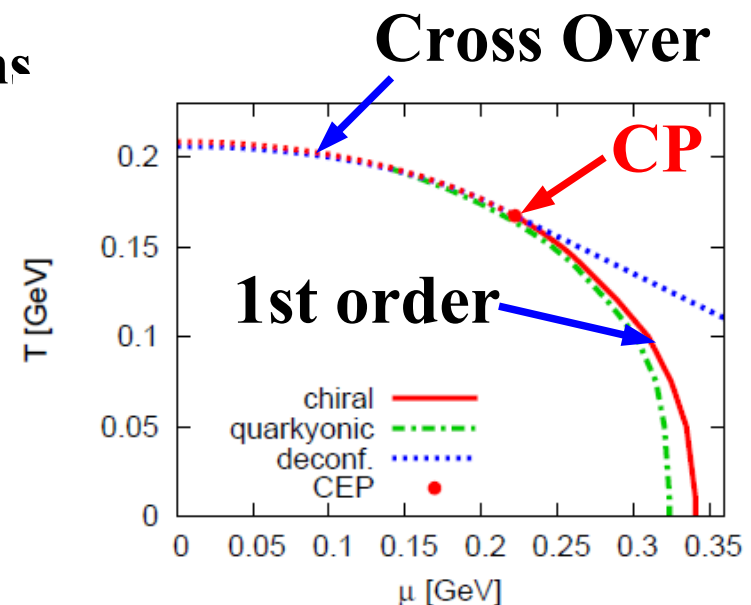
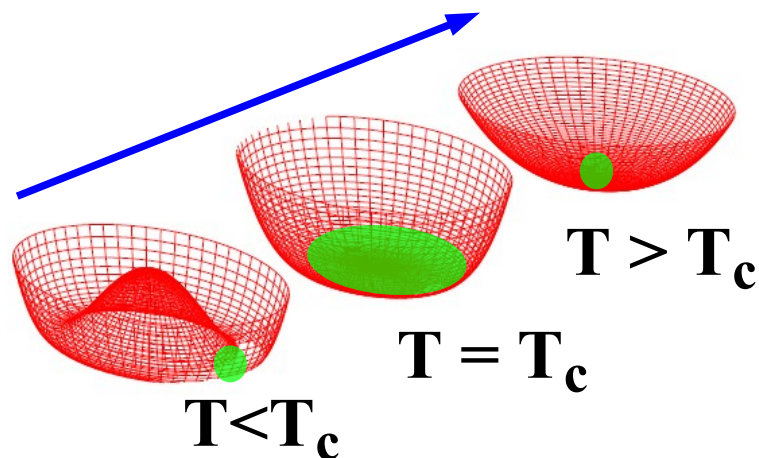
$$L = \bar{q} \left[i \gamma^\mu \underline{D}_\mu - g_\sigma (\sigma + i \gamma_5 \underline{\tau} \cdot \underline{\pi}) \right] q + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} \partial^\mu \underline{\pi} \cdot \partial_\mu \underline{\pi} - \underline{U}_\sigma(\sigma, \underline{\pi})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

q-Pol.
quark-meson
chiral
Polyakov

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

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

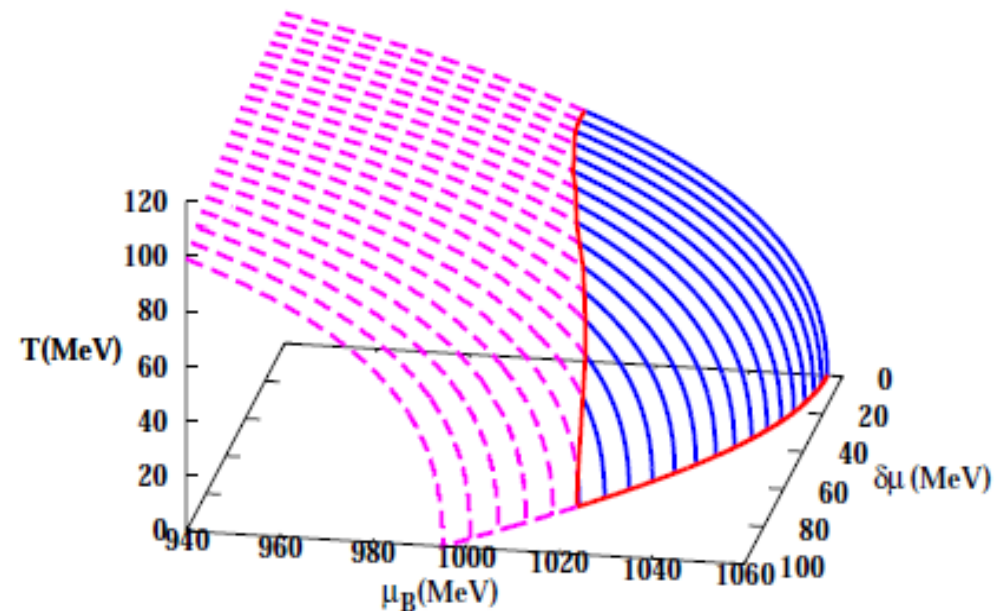
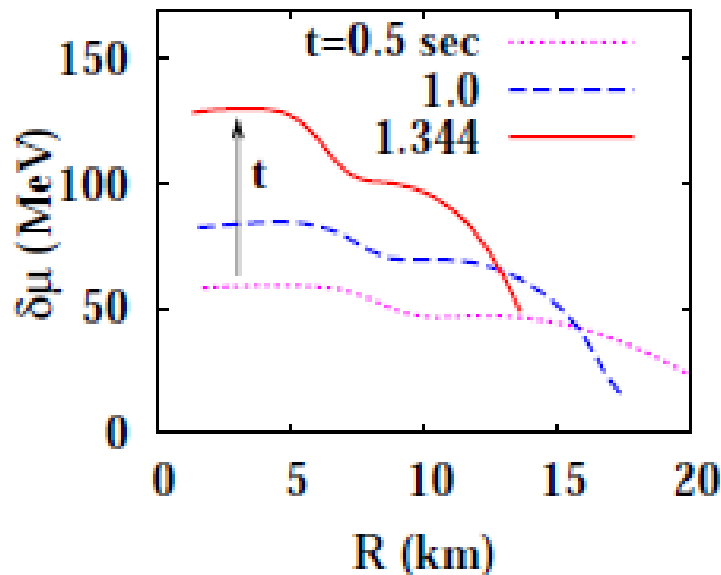
■ Characteristic features of Compact Star Matter

- Hot and/or Dense
- Unbalanced n and p yields (*Isospin Asymmetric Matter*)

$$\text{Isospin chemical potential } \delta\mu = (\mu_n - \mu_p)/2 = (\mu_d - \mu_u)/2 > 0$$

■ T_{CP} (critical point T) decreases at finite $\delta\mu$

- Decrease of effective number of flavors

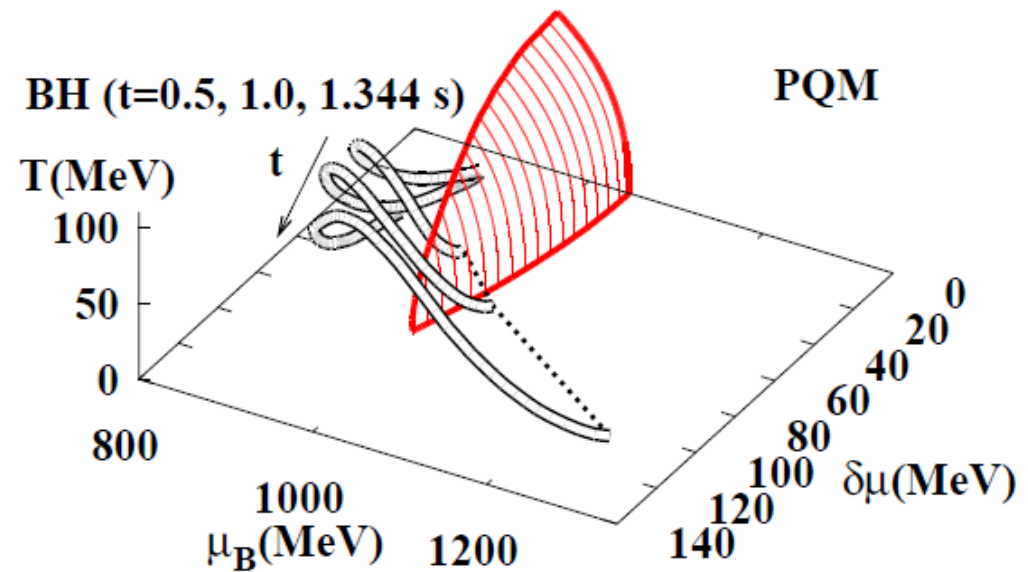
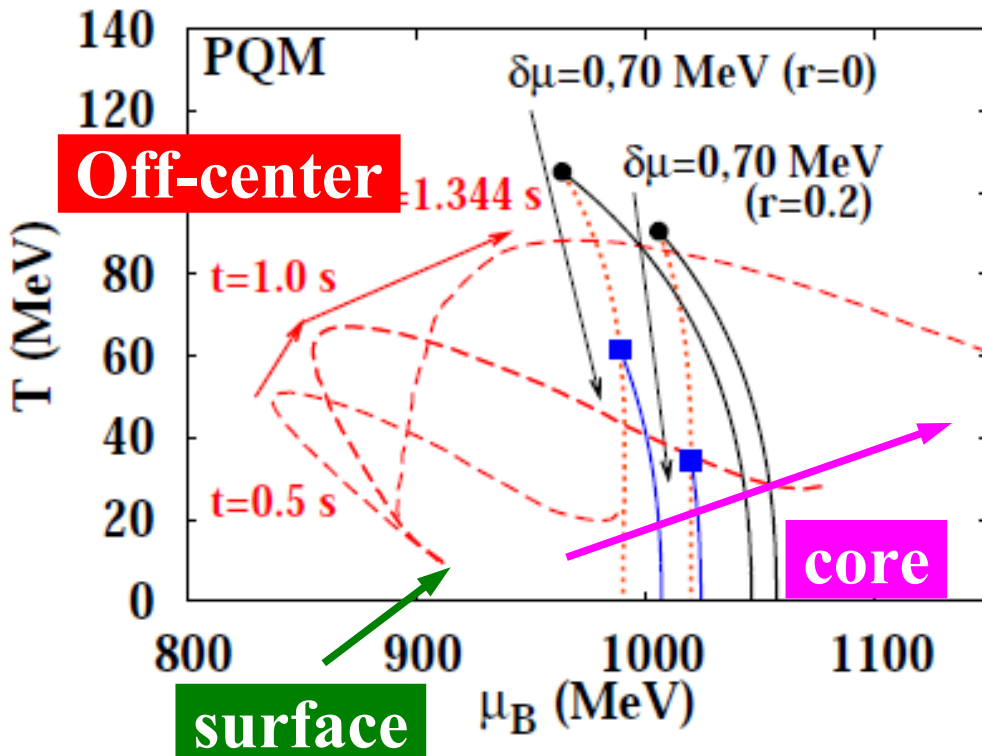


Ueda et al, in preparation

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

How is quark matter formed during BH formation ?

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



1.344 s = Just before BH formation

Swept Region of Phase Diagram during BH formation

■ CP location in Symmetric Matter

- Lattice QCD

$$\mu_{CP} = (400-900) \text{ MeV}$$

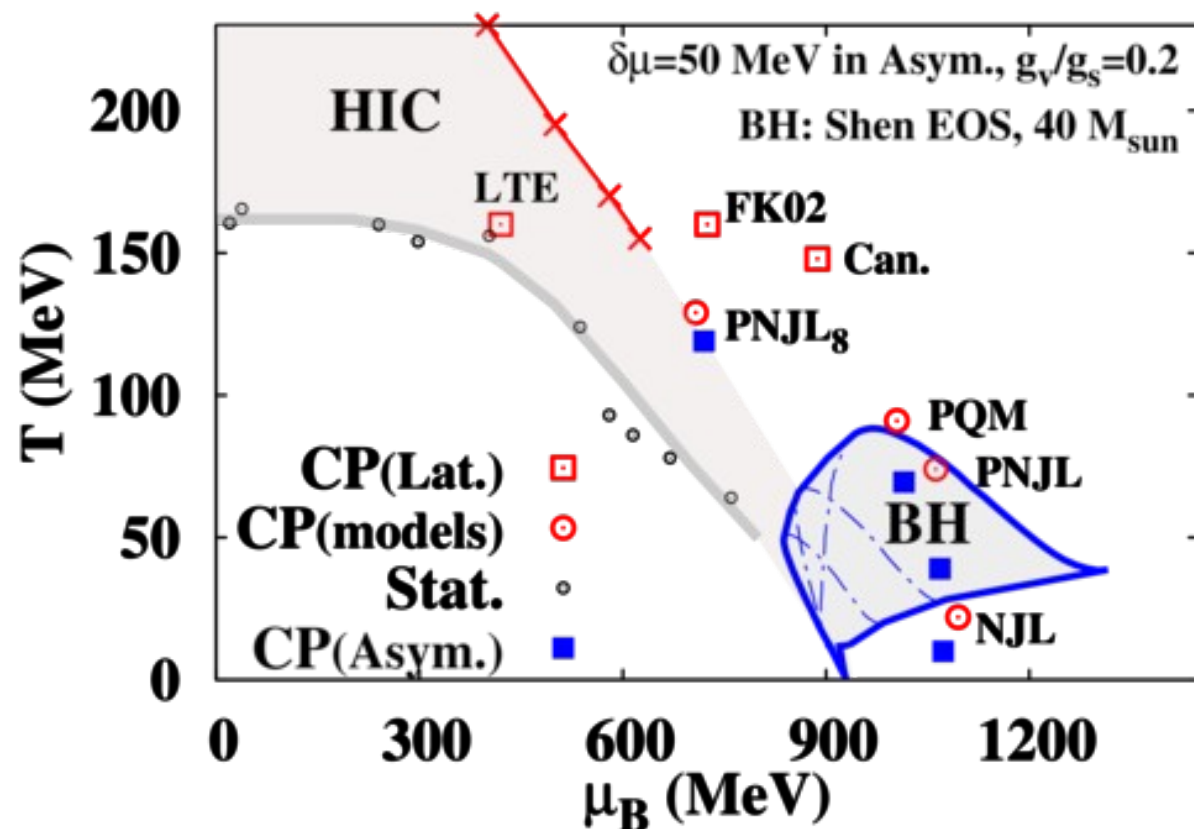
- Effective models

$$\mu_{CP} = (700-1050) \text{ MeV}$$

■ CP in Asymmetric Matter (E.g. $\delta\mu=50 \text{ MeV}$)

- T_{CP} decreases at finite $\delta\mu$.

→ Accessible (T, μ_B) region during BH formation



M.A.Stepanov, Prog.Theor.Phys.Suppl.153 ('04)139;

FK02:Z. Fodor, S.D.Katz, JHEP 0203 (2002) 014

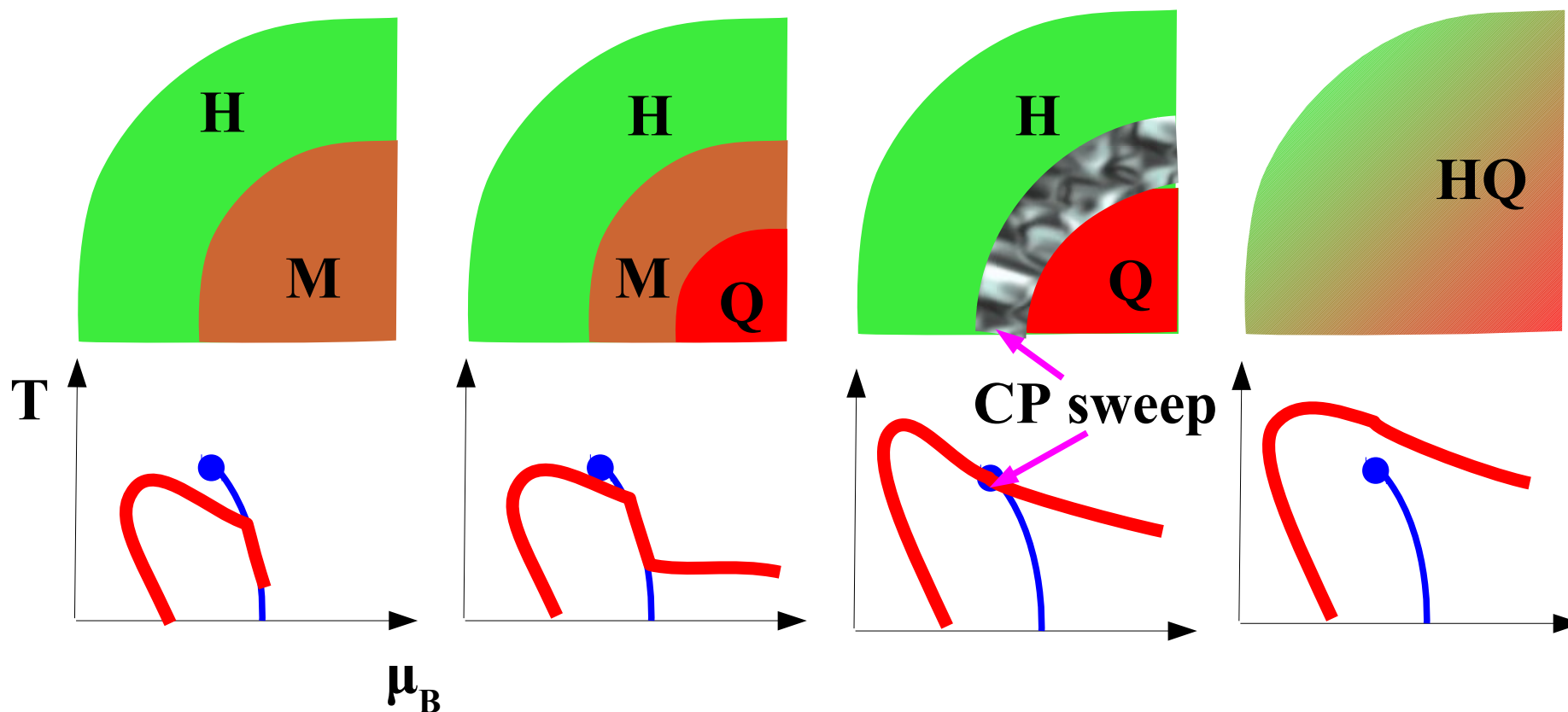
LTE:S. Ejiri et al., Prog.Theor.Phys.Suppl. 153 (2004) 118;

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

- コンパクト天体現象は原子核物理学にとっても興味深い対象。
 - 重イオン衝突で届かない高密度物質の物性、相転移の探索
 - 状態方程式 (密度汎関数) の作成自体が核物理の重要なテーマ
- 中性子過剰核・ハイパー核における最近の進展
 - 対称エネルギーの密度依存性が決まりつつある ($\rho_B < \rho_0$)
 - 単純なフレーバー SU(3) RMF 描像が崩れている。
(核物質中の Σ のポテンシャル、 $1.97 M_\odot$ 中性子星)
- 多体力、 π の効果を導入した RMF に基づく状態方程式へ！
- 中性子星コア、ブラックホール形成、中性子星合体過程ではクォーク物質への相転移を起こしている可能性が十分ある。
- 今後の課題:「実験・観測・理論」
 - (低密度)核物質の第一原理計算 \leftrightarrow 中性子過剰核の性質, ρ_0 以上の密度での対称エネルギー \rightarrow RIBF
 - Λ, Σ, Ξ と核物質の相互作用、 $\Lambda\Lambda$ 相互作用 \rightarrow J-PARC
 - 中性子星の半径測定 \rightarrow Astro-H

Thank you for your attention !

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■ 触れたかったが触れられなかった話題

- 飽和密度以下でのパスタ、NSE、比熱、液相気相相転移、....
- Nuclear Matter on the Lattice への取り組み (有限密度格子 QCD)
- ...