Three-body coupling effects in relativistic mean field for dense matter EOS

A. Ohnishi (YITP), K. Tsubakihara (Hokkaido Univ.)

YIPQS Molecule-type workshop on
"Nuclear equation of state and hypernuclear physics"
Jan.4-31, 2013, YITP, Kyoto, Japan

- Introduciton: Massive Neutron Star Puzzle
- Three-body coupling in Relativistic Mean Field
- Effects on Neutron Star Matter EOS
- Summary

K. Tsubakihara, AO, arXiv:1211.7208

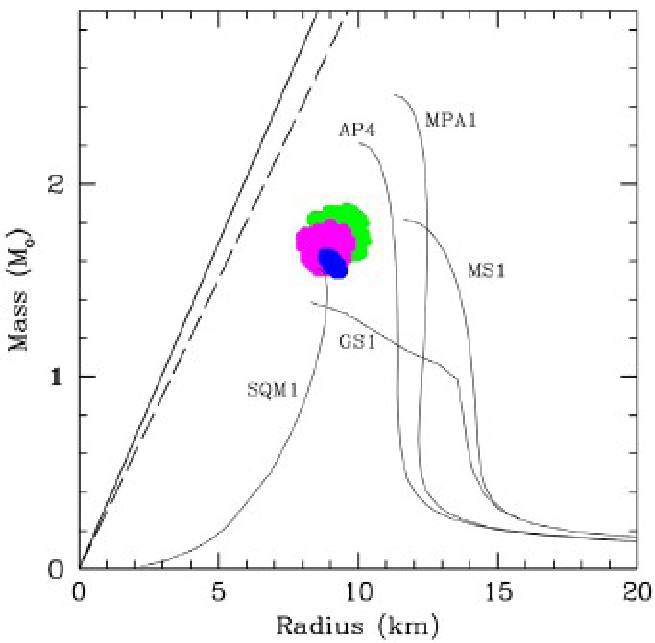
NFQCD 2010 Group photo (Jan.26) in the Astro part

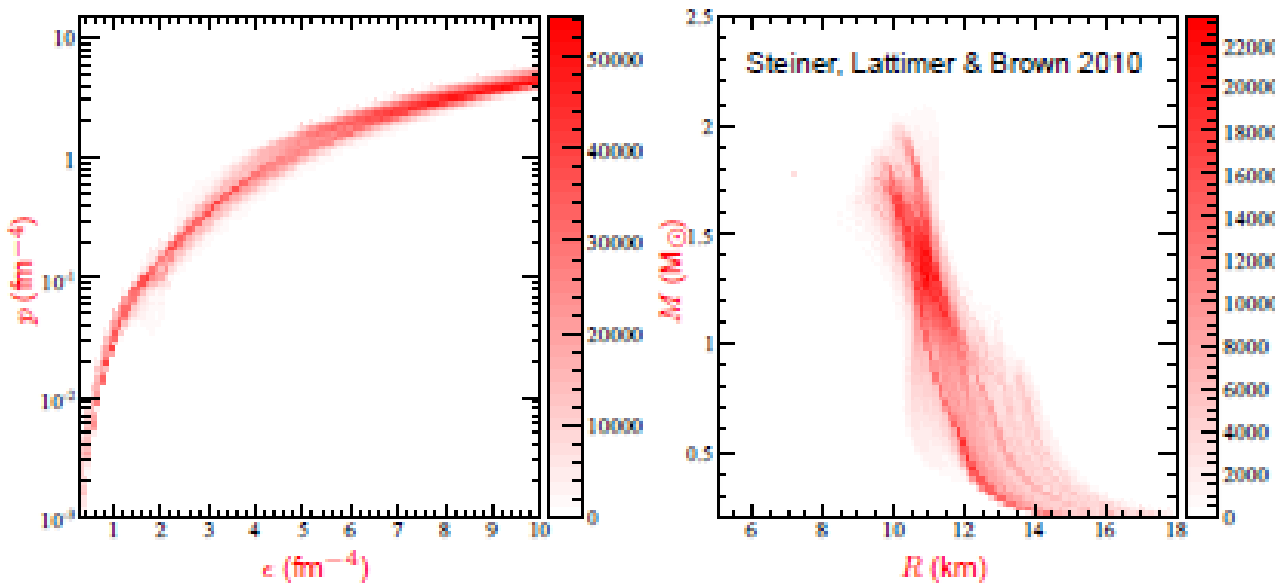
NFQCD 2010, Jan.18-Mar.19, 2010, Kyoto, Japan
http://www2.yukawa.kyoto-u.ac.jp/~nfqcd10/
(Group photo at the Mini-Symposium on Nuclear Astrophysics, Jan.26, 2010)

Observational Neutron Star Physics

- **We may have information both of M and R**
→ Strong constraint on NSmatter EOS

- **Two important papers are published just after NFQCD2010.**



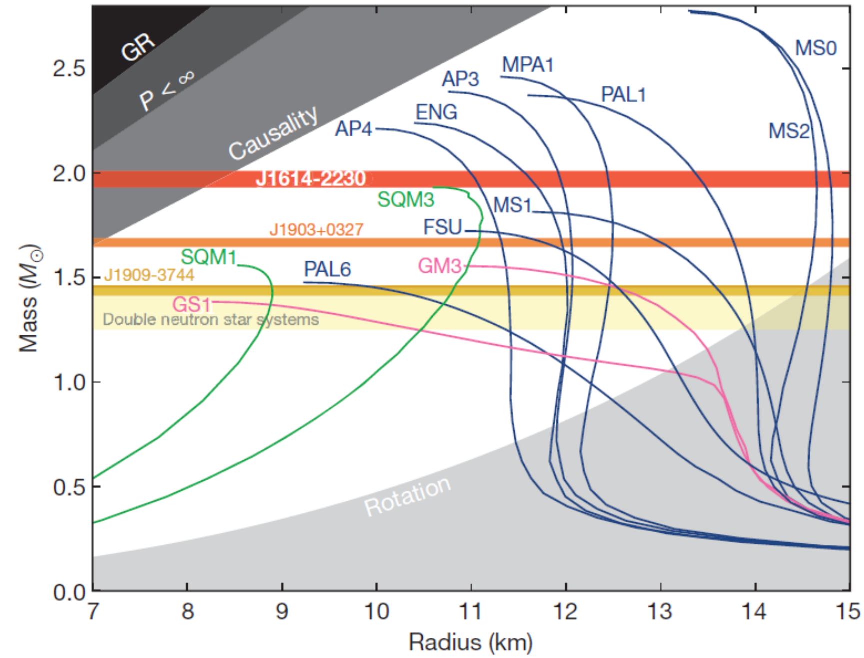


Ozel, Baym & Guver, PRD82('10)101301 [arXiv: 1002.3153]

Steiner, Lattimer, Brown, ApJ 722 (2010) 33 [arXiv:1005.0811]

Massive Neutron Star Puzzle

- **Discovery of Massive Neutron Star 1.97 ± 0.04 $M_\odot$** *Demorest+ (2010)*
- **Naïve RMF-EOS with strange hadrons cannot support 2 $M_\odot$ neutron star.**
- **G-matrix EOSs also have difficulty.**
- **Proposed solutions**
- **Almost no hyperons or kaons in neutron stars.**
  Weissenborn+ (2011)
  → Needs consistency check with hypernuclear physics
- **"Universal" Three-baryon repulsion**
  Nishizaki, Takatsuka, Yamamoto (2002)
  Tsubakihara, AO, arXiv:1211.7208
- **Crossover transition to quark matter**
  Masuda+ (2012) ;
  Burgio, Baldo, Sahu, Schulze (2002)



We consider three-body forces (couplings) in Relativstic Mean Field.

Three-body couplings in Relativistic Mean Field

Many-body coupling in RMF (1)

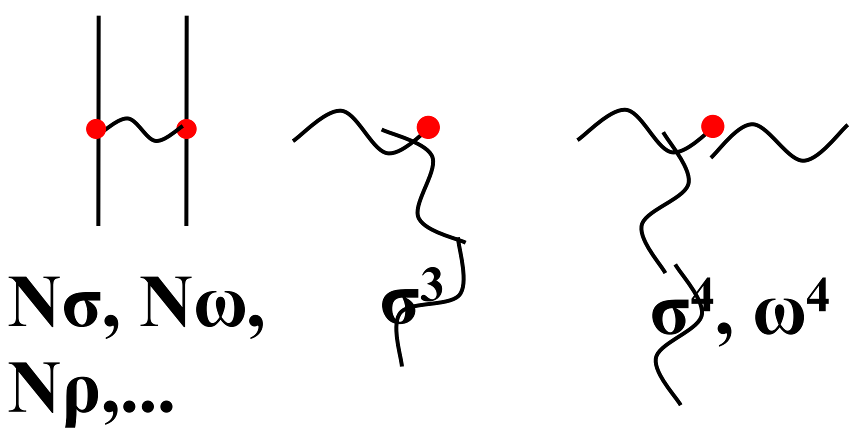
- **σω model** *Serot, Walecka ('79, '86)*
  - **Strong attraction (σ) and repulsion (ω) → Saturation + Strong LS**
  - **EOS is too stiff (K ~ 700 MeV)**
- **Non-linear (higher order) terms of σ**

Boguta, Bodmer ('77), NL1: Reinhardt+('86), NL3: Lalazissis+('97)

  - **Softer EOS, High precision nuclear binding energies**
- **Non-linear term of ω**

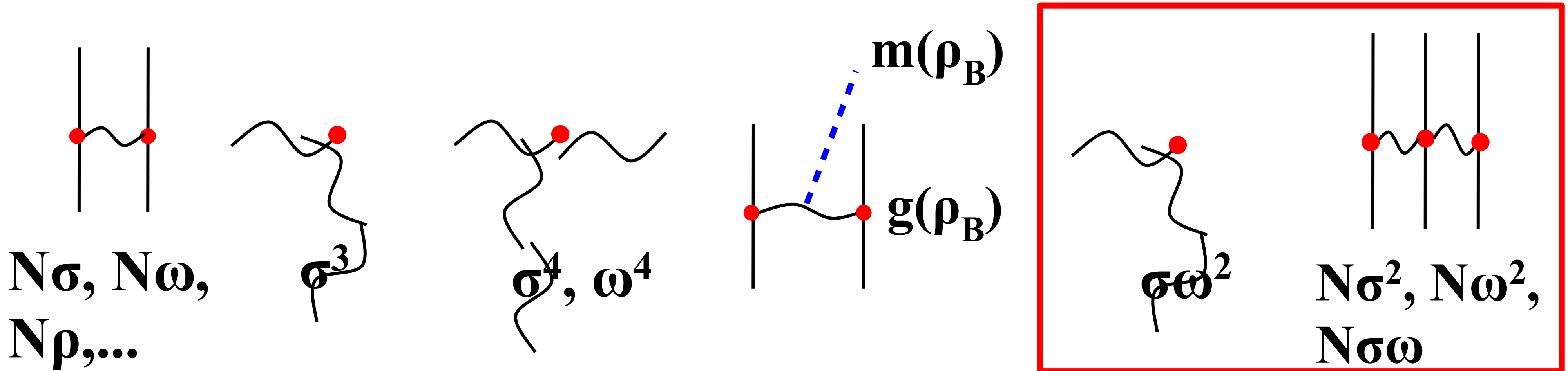
Brockmann, Toki ('92), TM: Sugahara, Toki ('94).

  - **Simulates Dirac-Bruckner-Hartree-Fock results of vector potential**



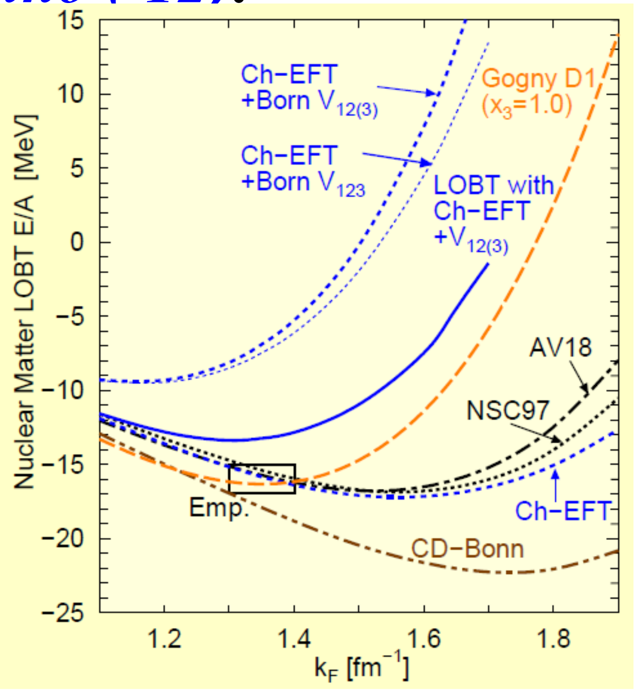
Many-body coupling in RMF (2)

- **Three-body force from vector mass modification**
  Furumoto, Sakuragi, Yamamoto ('09)
- **Effects on Nucleus-Nucleus Elastic Scattering**
- **Density-dependent couping** *E.g. Roca-Maza+('11)*
- **Softer EOS, High precision nuclear binding energies**
- **Three-body coupling terms** *Tsubakihara, AO ('12)*
- **Simulate both of ρ_B dependent meson masses & ρ_B depdendent coupling**

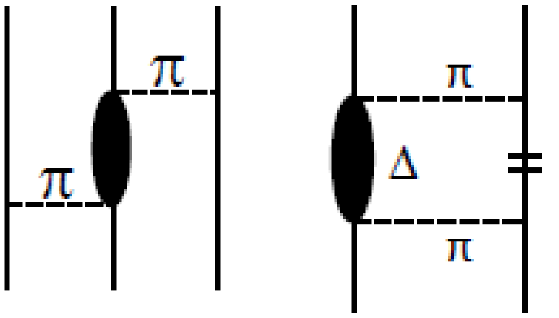


Why do we have in-medium mod. of coupling ?

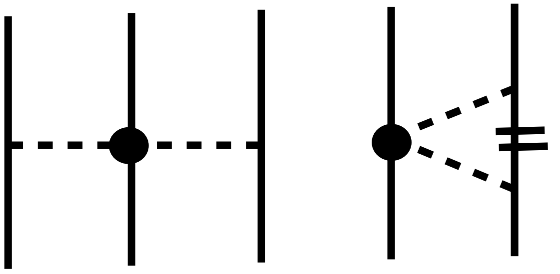
- **Three-body force and ρ_B dep. coupling**
- **3NF from Δ is known to be important to explain ^{3}H and ^{3}He B.E.**
- **2NF from the same coupling will suffer from Pauli blocking, generating strong density dep. repulsion, and explains nuclear matter saturation. *Kohno ('12)*.**



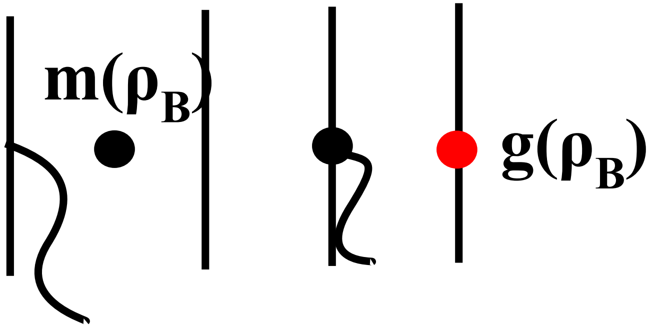
Physical Picture



χ EFT



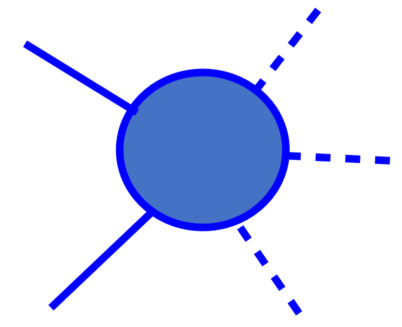
RMF



Criteria for higher order terms in Effective Lagrangian

- **RMF = Effective theory to give density functional**
- **No need of renormalizability → How to constrain higher order terms ?**

$$\mathcal{L}_{\rm int} \sim \sum_{l,m,n,p} \frac{C_{lmnp}}{m!n!p!} \left(\frac{\bar\psi\Gamma\psi}{f_\pi^2\Lambda}\right)^l \left(\frac{\varphi}{f_\pi}\right)^m \left(\frac{\omega}{f_\pi}\right)^n \left(\frac{\rho}{f_\pi}\right)^p (f_\pi\Lambda)^2$$



- **Naive dimensional analysis (NDA) and Naturalness**

Manohar, Georgi ('84); Furnstahl, Serot, Tang ('97)

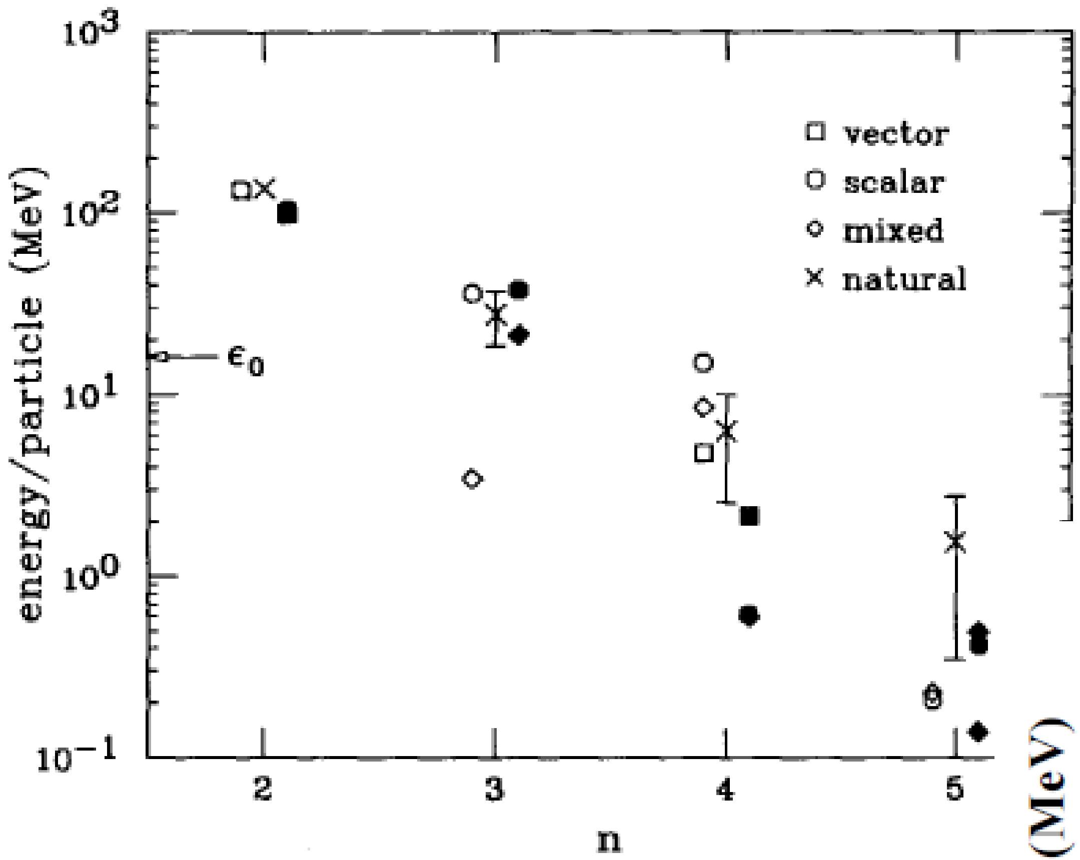
- **Eff. Lag. is natural when $C_{lmnp} \sim O(1)$**
- **Assumption: Vertex appears from quark & gluon diagrams, and there is no gluon internal line (perturbative).**
- ***We should NOT request naturalness for U(σ), because SSB of χ-sym. is NOT described perturbatively.***
- **Field redefinition: No need to introduce Nσσ coupling ?**

$$\bar N(g_{\sigma N}\sigma - g_{\sigma\sigma N}\sigma^2 - g_{\omega\omega N}\omega_\mu\omega^\mu)N = \bar N g'_{\sigma N}\sigma N$$

Furnstahl, Serot, Tang ('97)

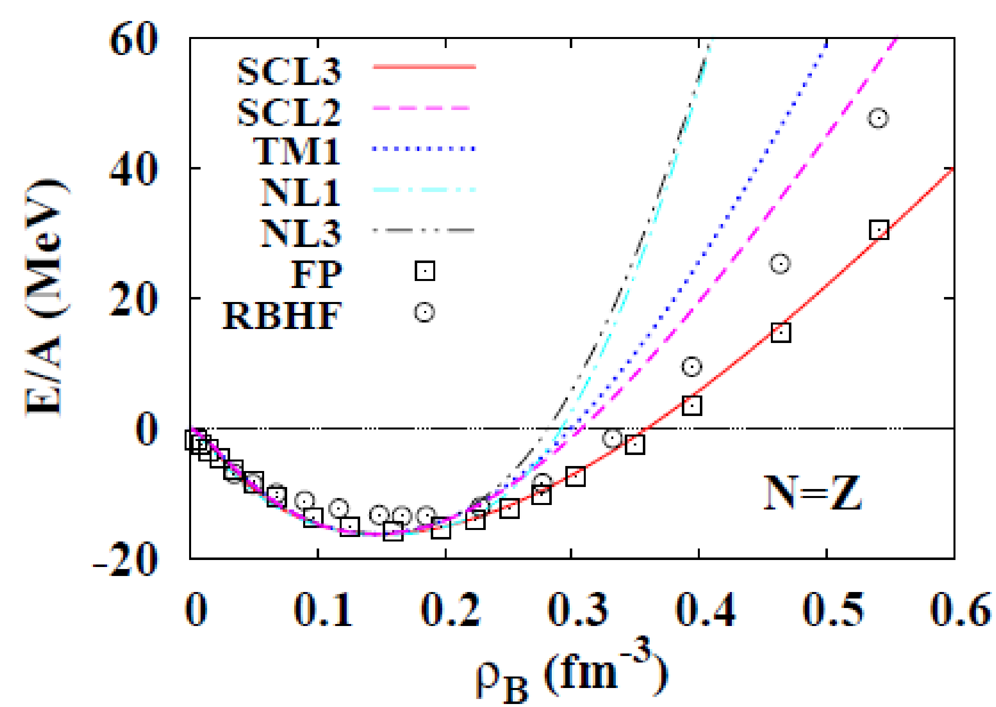
- ***Field redefinition generate higher l+m+n+p terms and affect dense EOS***

Many-body coupling effects



Furnstahl, Serot, Tang ('97)

Higher n couplings give smaller contributions at ρ_0, but significant differences are found at higher density.



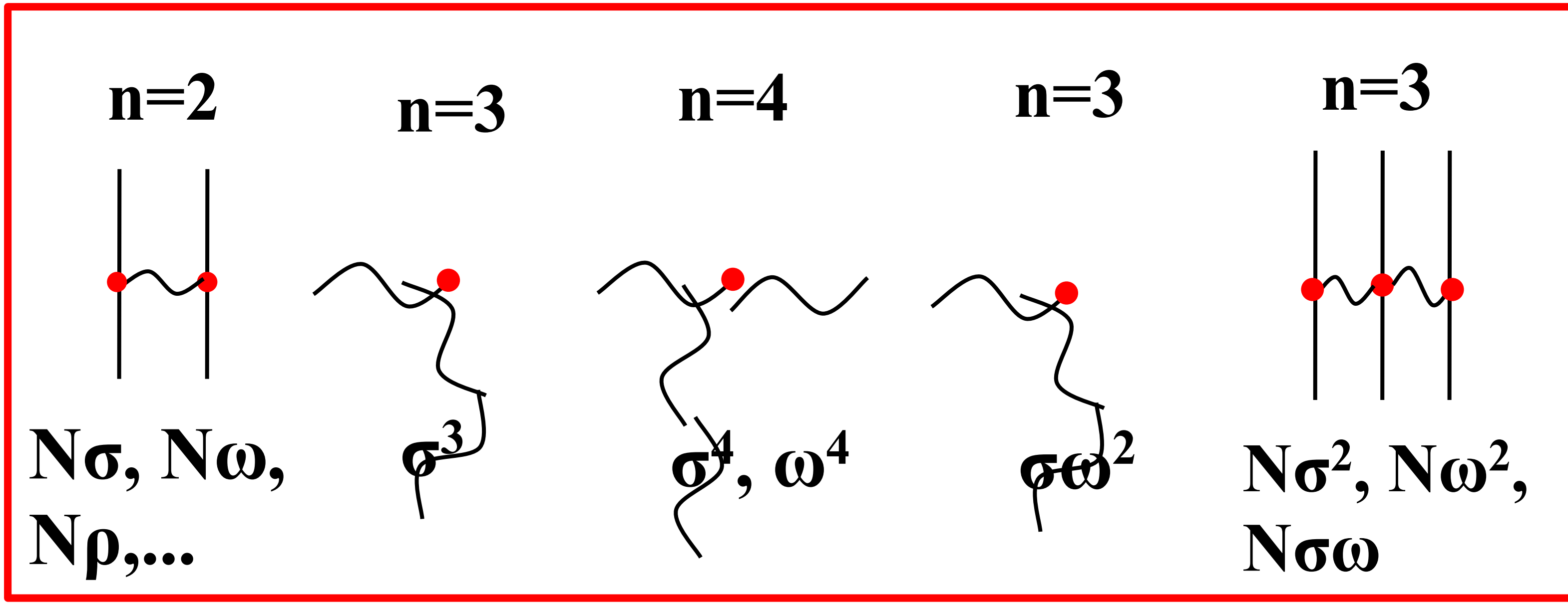
Effects of Three-body couplings in Nuclear & Neutron Star matter EOS

RMF with Three-Body couplings

- Definition of "three-body" coupling : "n=3" terms where

  n = B/2 + M + D

(B: # of baryon fields, M: # of non-NG meson fields, D: # of derivatives)



- Three-body coupling terms relevant to symmetric matter

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

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

ω mass mod.

BMM couplings

Symmetric Nuclear Matter in TB-RMF

- **Two parameter sets:**
  - **TB-a (Weakly repulsive 3BC)**
  - **TB-b (Stroger repulsion)**

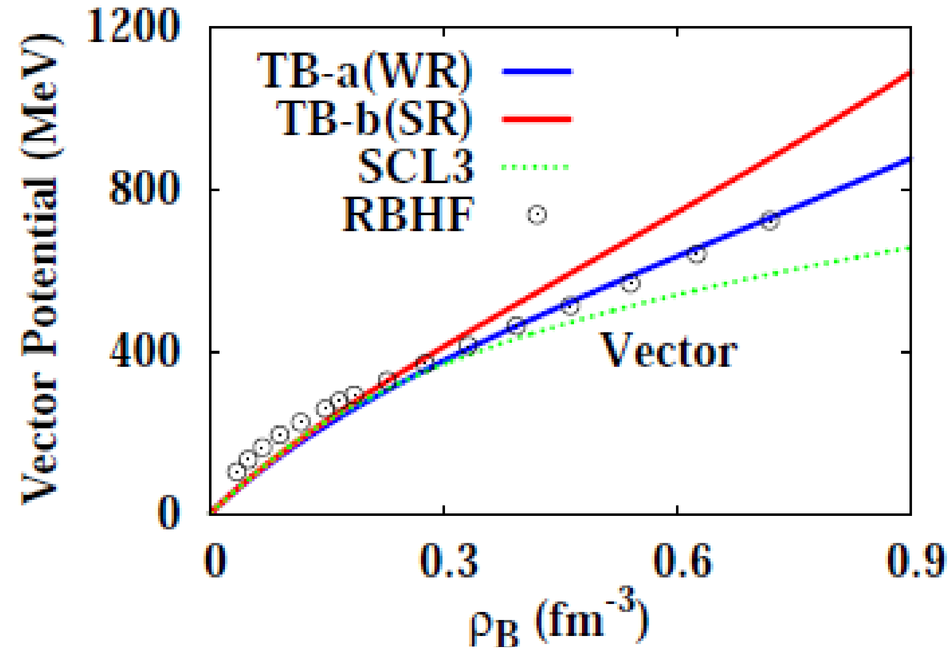
Results are compared with
  - **SCL3 (No 3BC)**

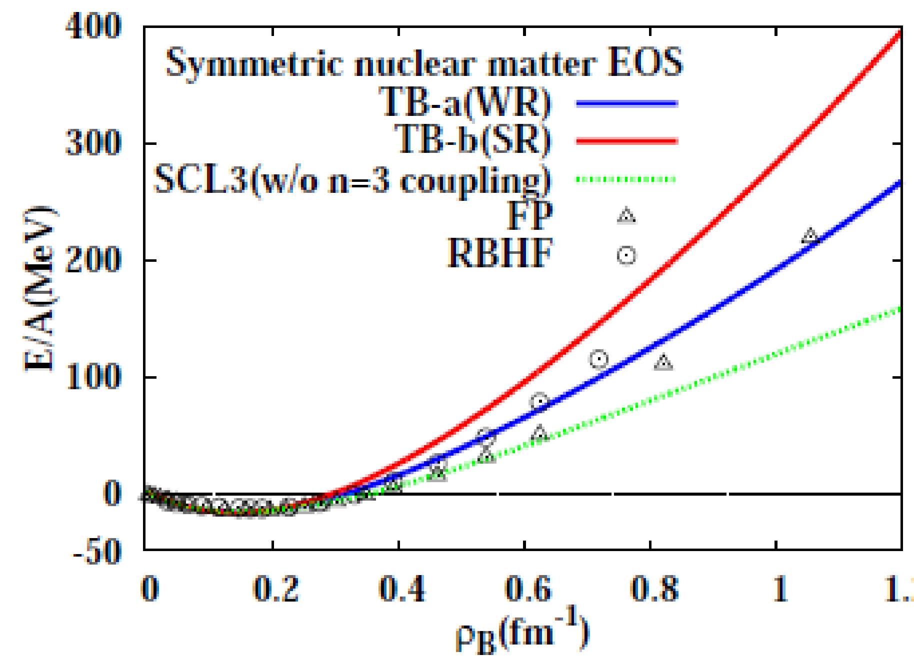
Tsubakihara+('10)

- **Density dep. of vector potential in relativistic BHF (RBHF) is simulated in**
  - **ω^4, $\sigma\omega\omega$, $B\sigma\omega$**

terms.

- **Symmetric Matter EOS**
  - **SCL3 ~ FP**
  - **TB-a ~ RBHF**
  - **TB-b > RBHF**





Tsubakihara, AO ('12)

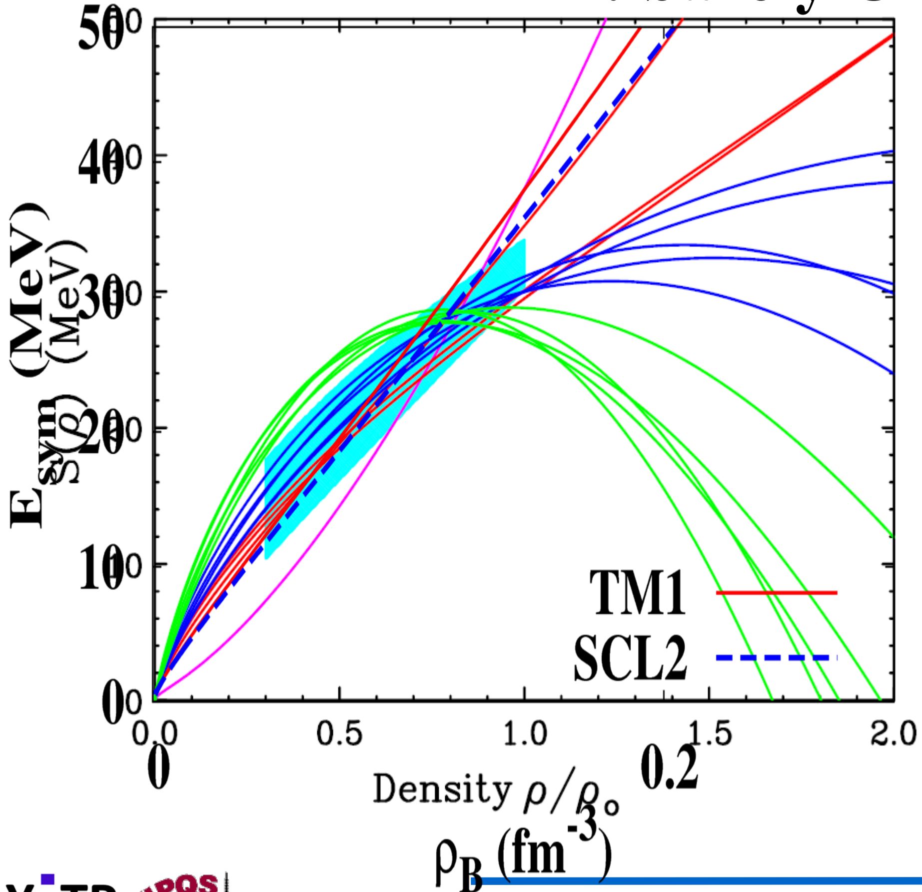
Symmetry Energy in 3BC-RMF

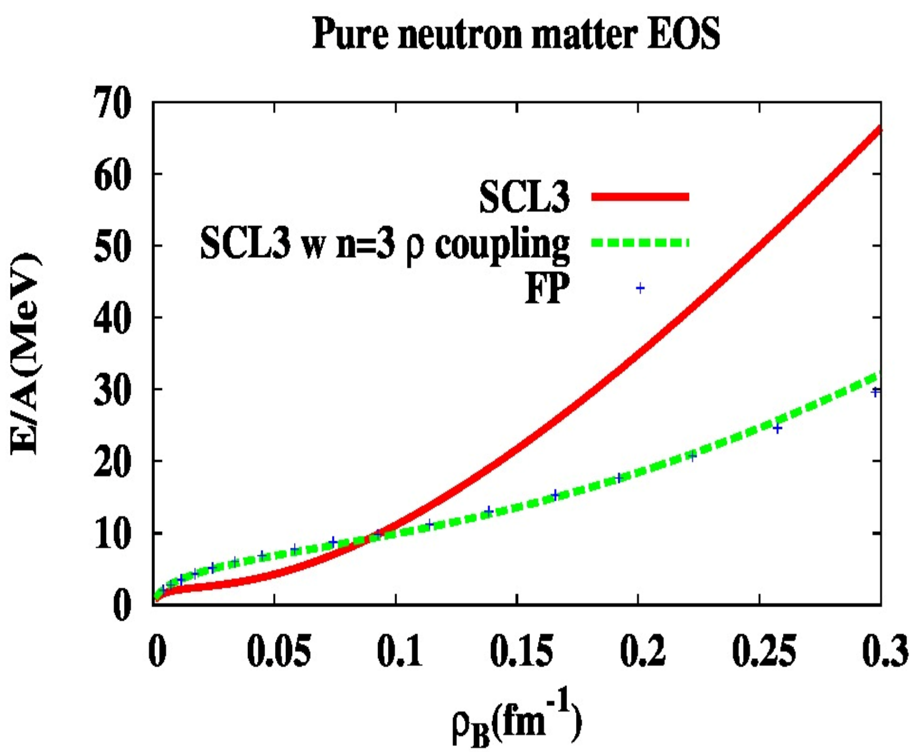
- Only with n=2 terms, Symmetry energy is almost linear in density,
→ L=3 S, High Sym. E at high density (c.f. Hu's question 2 years ago)

- 3BC with ρ mesons → We CAN control ρ_B dependence of Sym. E.

$$\delta L = -\frac{1}{2} c_{\sigma\omega} \sigma \rho^a_\mu \rho^\mu_a - \sum_B \bar{\psi}_B \left[g_{\sigma\rho B} \sigma \rho^a_\mu \tau_a \gamma^\mu \right] \psi_B$$

TM1: barely OK





Tsubakihara et al., in prep.
FP: Friedman, Pandharipande ('81)

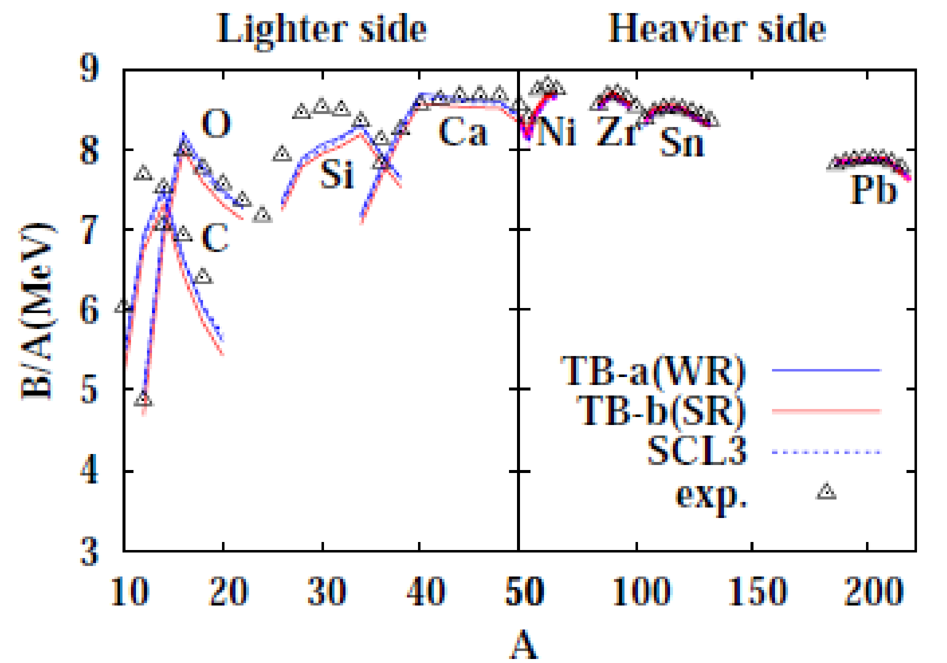
Normal Nuclei and Hypernuclei

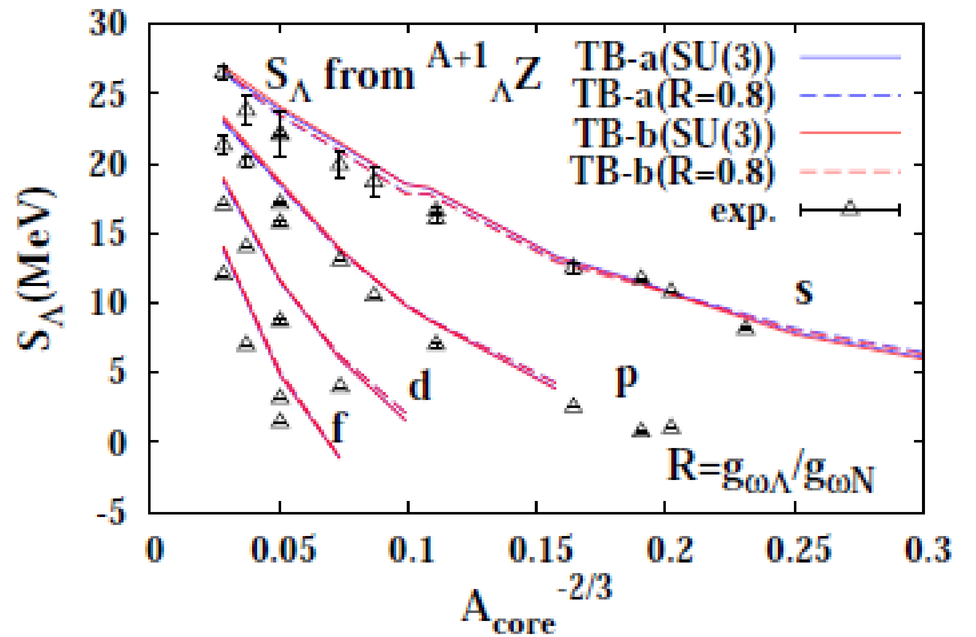
- Normal nuclei (n, p)
  - B.E./A is well reproduced, especially in the large mass region.
  - Both TB-a and TB-b underestimate the LS strength. (We may need to prepare parameter sets for lighter nuclei. e.g. TM1 and TM2)
- Hypernuclei
  - Λω coupling is modified from SU(6) value,

$$R = g_{\omega\Lambda} / g_{\omega N} \sim 2/3 \ (SU(6)) \sim 0.8 \ (present)$$

  - S_Λ is more sensitive to R rather than to 3BC.

Tsubakihara, AO ('12)

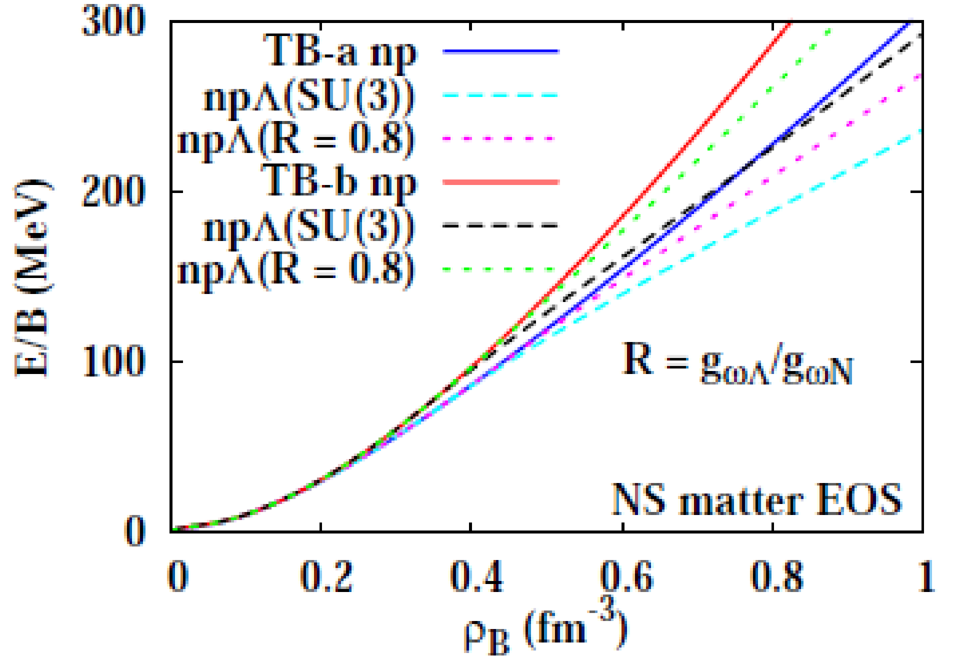


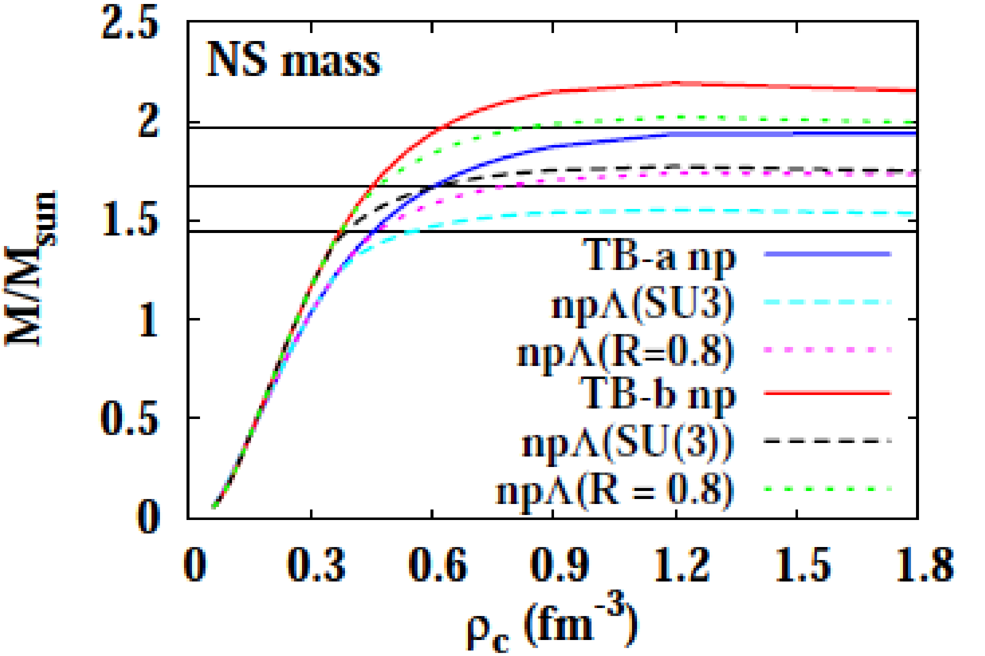


Neutron Star matter EOS

- **Neutron star matter**
  = Cold (T=0), Charge neutral,
  β equilibrium, ν-less matter
- **Large effects of 3BC terms at high density.**
- **With R ~ 0.8, we can support 2 M⊙ neutron star with hyperons included.**

→ We have (at least several) solutions of the massive neutron star puzzle.



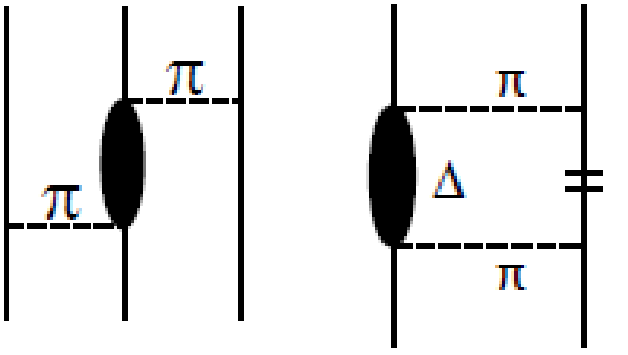


Tsubakihara, AO ('12)

How can we fix 3BC terms ?

- Many *free* parameters in 3BC-RMF. How can we fix it ?

→ We need *ab initio* evaluation !



- One idea: Pauli blocking

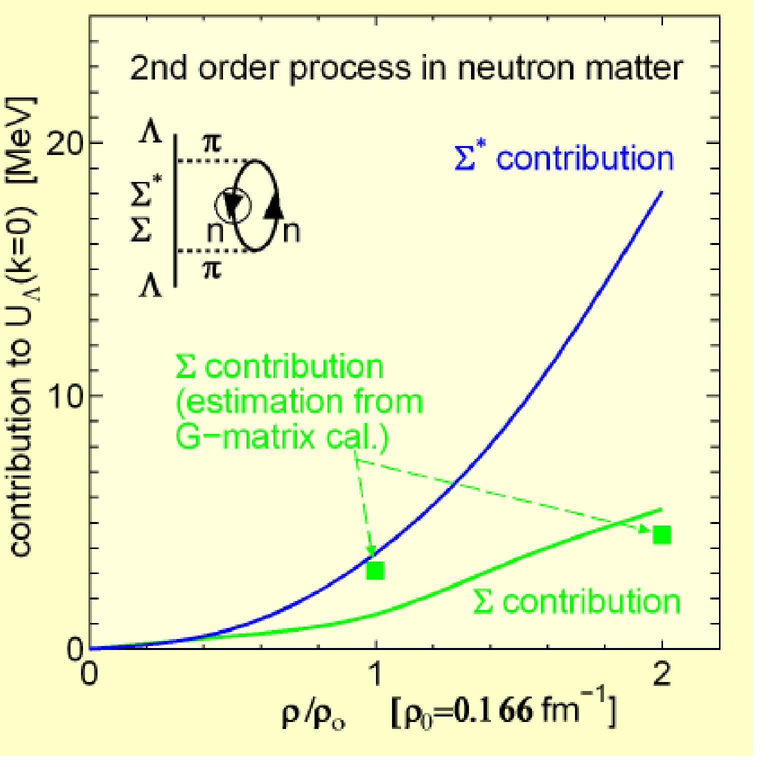
  σ in RMF includes

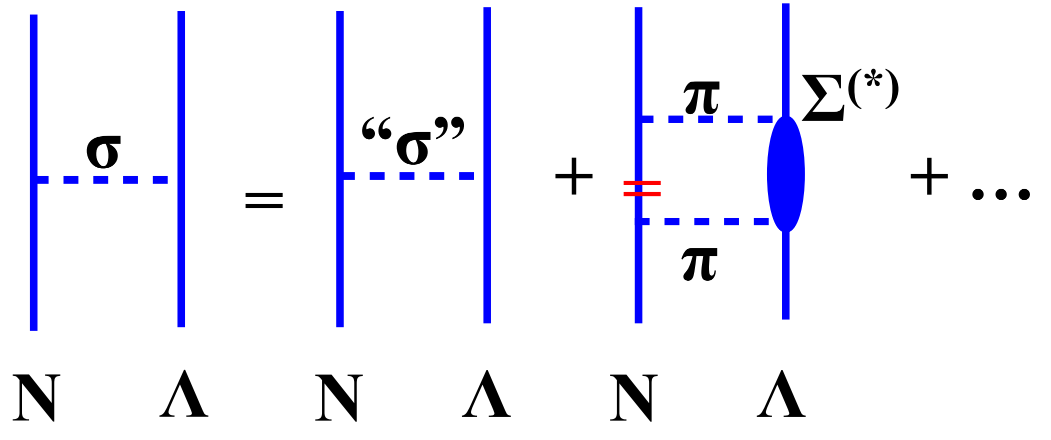
  2π exchange contributions !

→ $g_{\sigma B}$ coupling should be suppressed

  from Pauli blocking.

  (Ueda, AO, Schulze started working ...)





by Kohno (Kick-off meeting)

Summary

- **Three-body coupling terms are introduced in relativistic mean field (RMF) model, and their effects are considered.**

- **Effects on finite nuclei are not large,**
but large effects at high density are expected and found.

- **We have some solutions of the massive neutron star puzzle:**
We can parametrize hyperonic matter EOS which is stiff enough to support 2 $M_\odot$ neutron star AND consistent with finite nuclear data.

- **In order to fix parameters,**
we need experiments and ab initio calculations

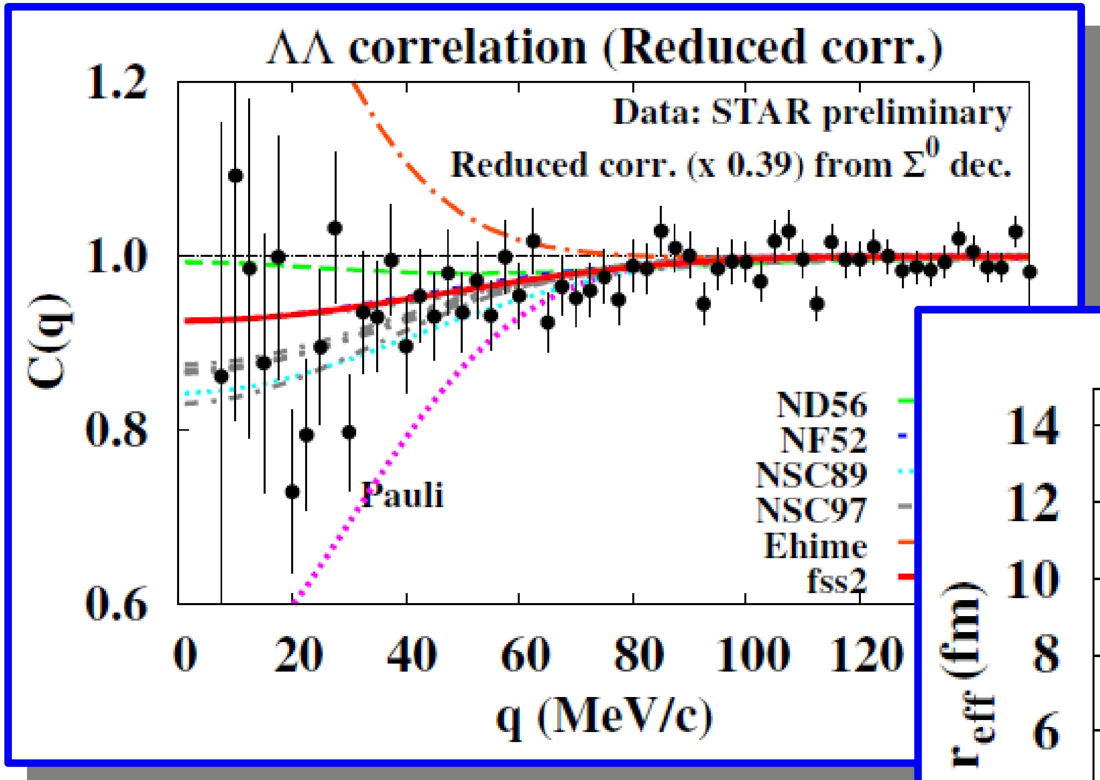
- **BB interactions: J-PARC, GSI-FAIR, RHIC/LHC, Lattice QCD**

- **2 pion exchange force related to Fujita-Miyazawa type three-body force + Pauli blocking → density dependent coupling in RMF.**

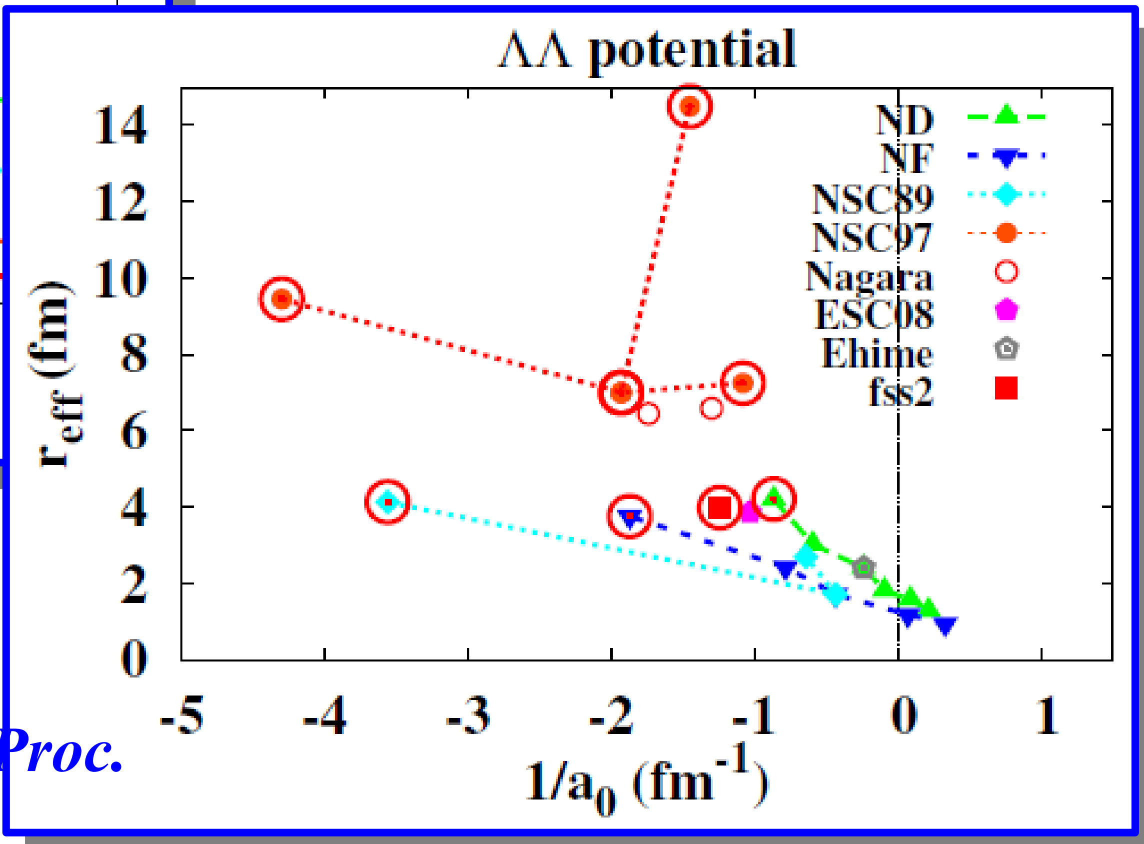
Preferred ΛΛ Interaction

- **STAR data choose some of the ΛΛ interaction**

→ $1/a_0 < -0.8\ \mathrm{fm}^{-1}$ ($-1.2\ \mathrm{fm} < a_0 < 0$), $r_{eff} > 3$ fm seems to be preferred.



Nijmegen (Rijken), Fujiwara+, Ueda+, Filikhin-Gal; Hiyama+



AO+ (ExHIC collab.), Hyp 2012 Proc. /AO, Furumoto, Morita, in prep.

Summary

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- BB interactions: J-PARC, GSI-FAIR, RHIC/LHC, Lattice QCD
- 2 pion exchange force related to Fujita-Miyazawa type three-body force + Pauli blocking → density dependent coupling in RMF.
- Researches by using Grant-in-Aid for Scientific Research on Innovative Area, "Neutron Star matter EOS",
will be (should be!) useful !

Thank you for your attention !

RMF with three-body coupling

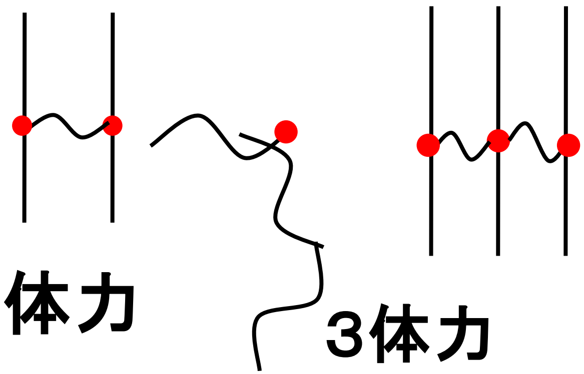
- RMFにおける陽な3体結合の導入

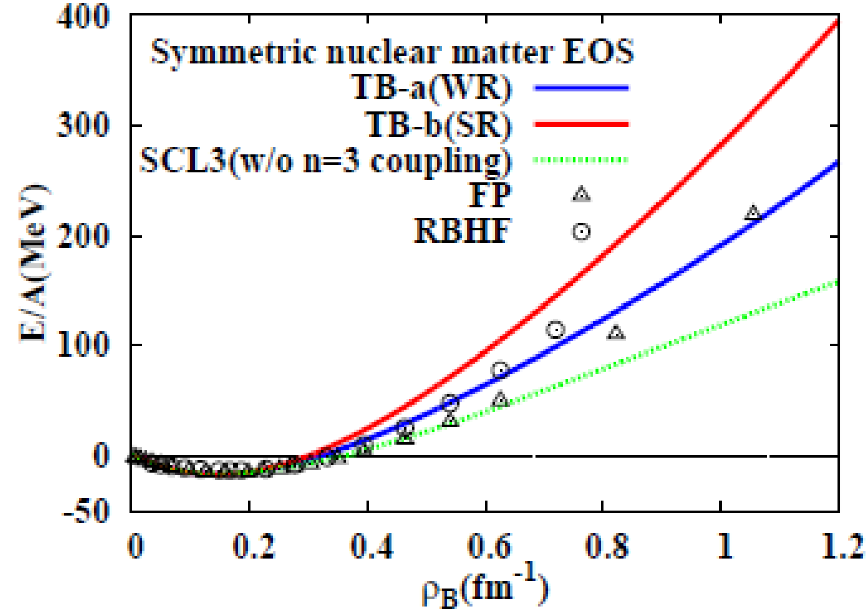
→ 斥力の増大

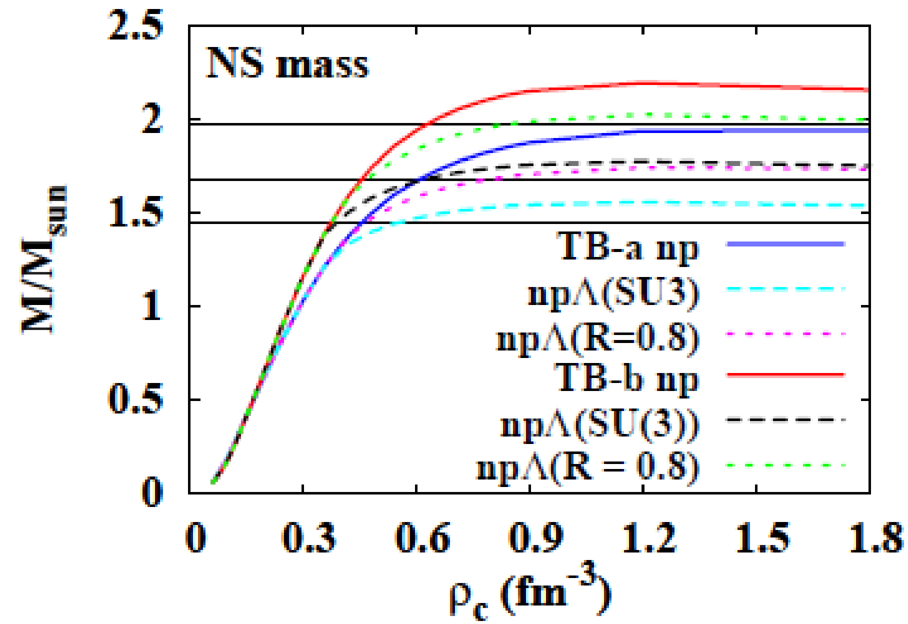
→ 2 $M_\odot$ の中性子星を支えられる

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

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





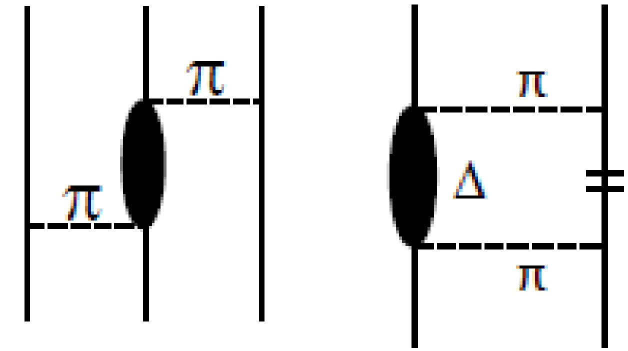


結合定数はどのように与えるか？

3体結合と飽和性

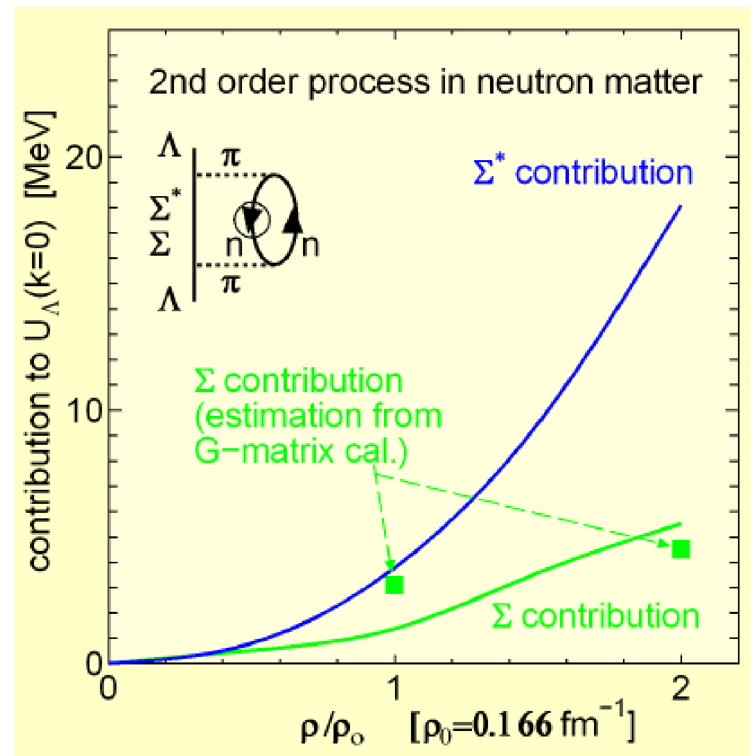
- 飽和性を出す機構の新しい提案

M. Kohno, 2012



- Δ 経由の3体力と同じ結合から現れる2体力
→ 媒質中では Pauli blocking を受ける
→ 強い「斥力」効果

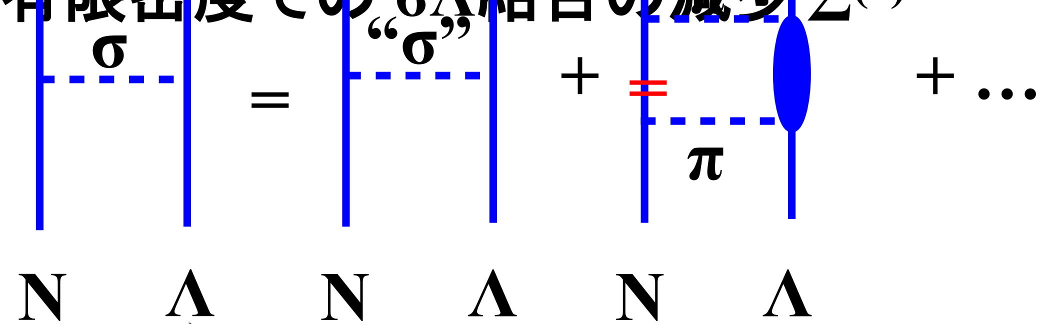
斥力を加える → 引力を減らす



- Hyperon を含む場合はΣ、Σ* 経由の2体力が減少

- RMFにおける現象論的解釈

- Δ 経由2 π交換力~ σ交換の主要項
→ 有限密度での σΛ結合の減少 $\Sigma^{(*)}$



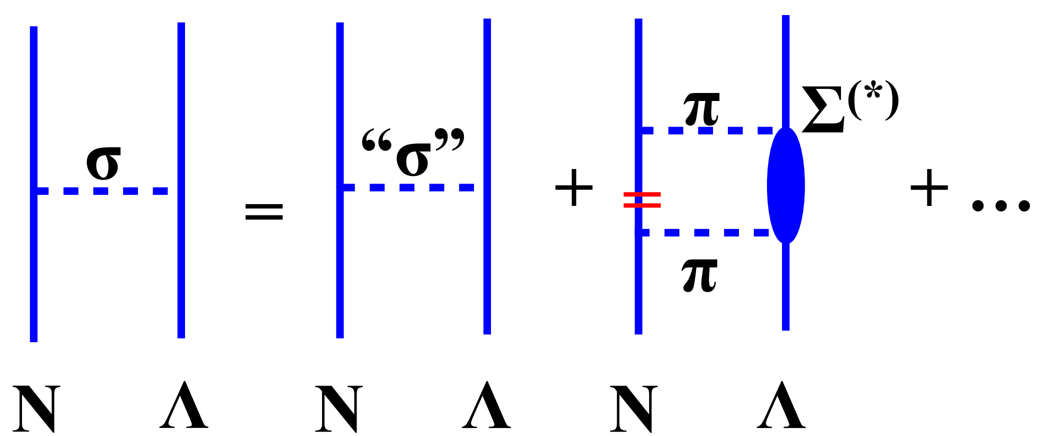
by Kohno (Kick-off meeting)

提案:g-matrix でEOSのΛσ結合定数依存性を調べる

- Catania group のg-matrix 計算(Nijmegen, Bonn, Paris, ...)において
Λσ結合定数が数10%変化した場合に、
Λの一粒子エネルギー、ハイペロンを含む物質のEOS
の変化を調べる。

- Nijmegen模型のσ交換がB*(decuplet)経由2 π交換力を含むなら
媒質中にて抑制を受けるはず。
(Σ 経由は既にg-matrix計算に含まれる)

- 飽和性、バリオン間力の実体論、高密度での斥力、
→ 同じ起源かもしれない。



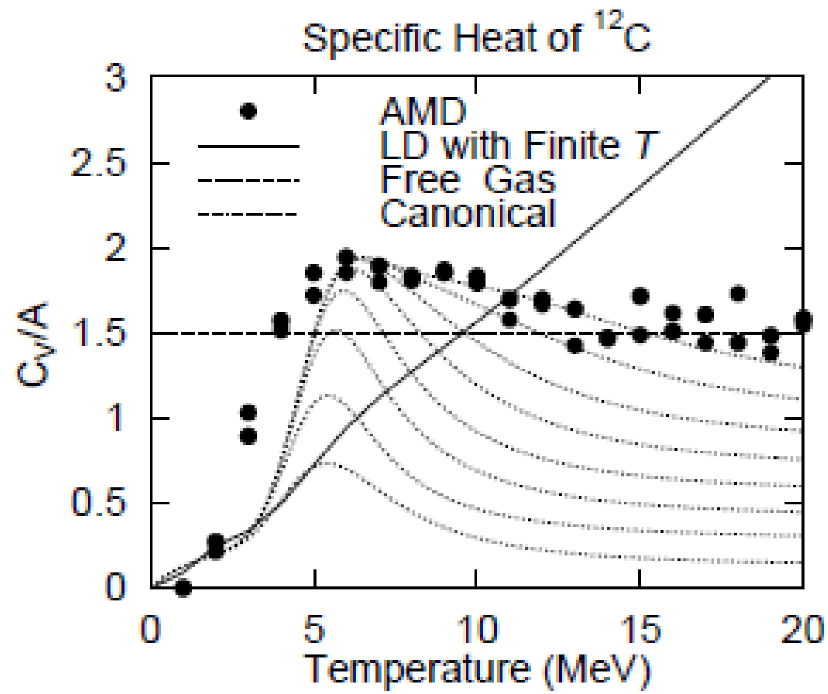
Ueda, AO, Schulze, ...

有限温度EOSについて

- 超新星物質EOSにおいて温度はどのように扱われているか？
- Shen EOS → 有限温度 RMF の結果を利用
- 平均場的取扱いでは、低温での励起が小さい

  $E^* \sim AT^2 / 16$ (Fermi gas), $E^* \sim AT^2 / 8$ (empirical)
- collective modeの存在により、低励起状態における状態密度は Fermi gas に比べて大きい

宇宙の方の計算結果について
聞いていると、
低温でのEOSの振る舞いを変えると、
それなりの影響があるような
気がします。



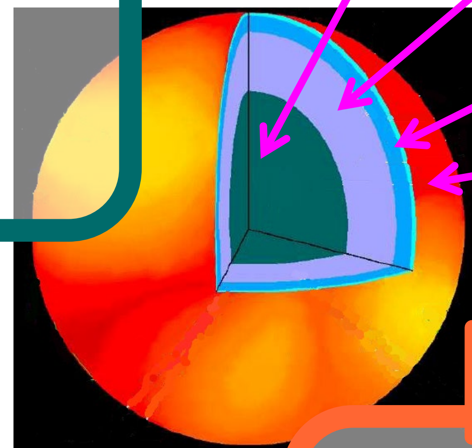
AO, Randrup ('94)

実験と観測で解き明かす中性子星の核物質

高密度領域

ハイパー核、K中間子核、
YN, YY 相互作用、
有効相互作用、
(重イオン衝突)、

J-PARC



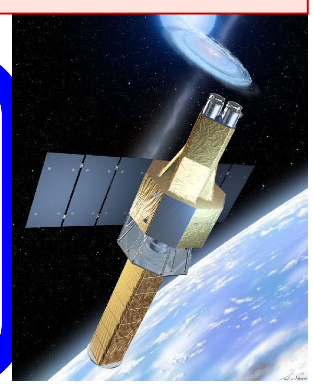
低密度領域

対称エネルギー、
対相関ギャップ、
BEC-BEC cross over、
冷却原子系とのつながり、

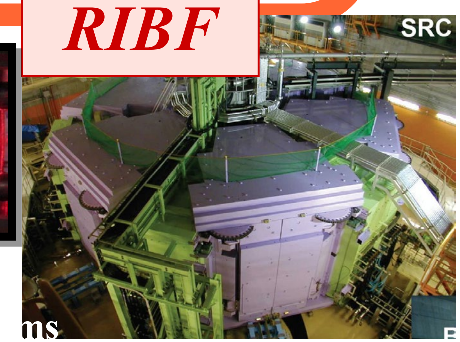
天体現象

半径、質量、
温度(時間依存性)、
星震、パスタ、

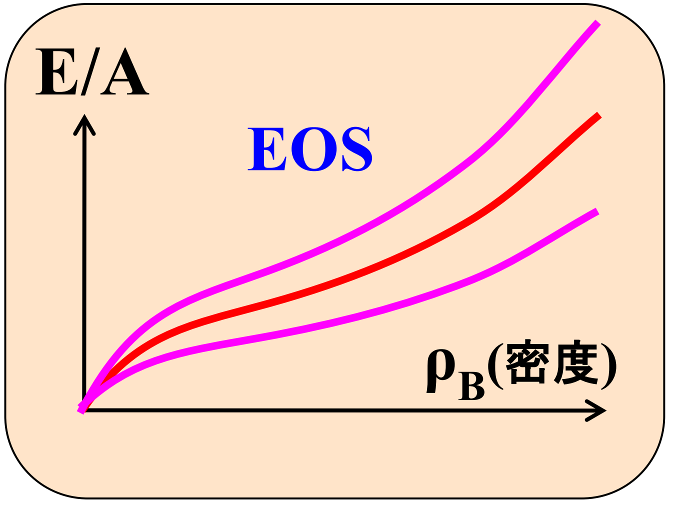
ASTRO-H



RIBF



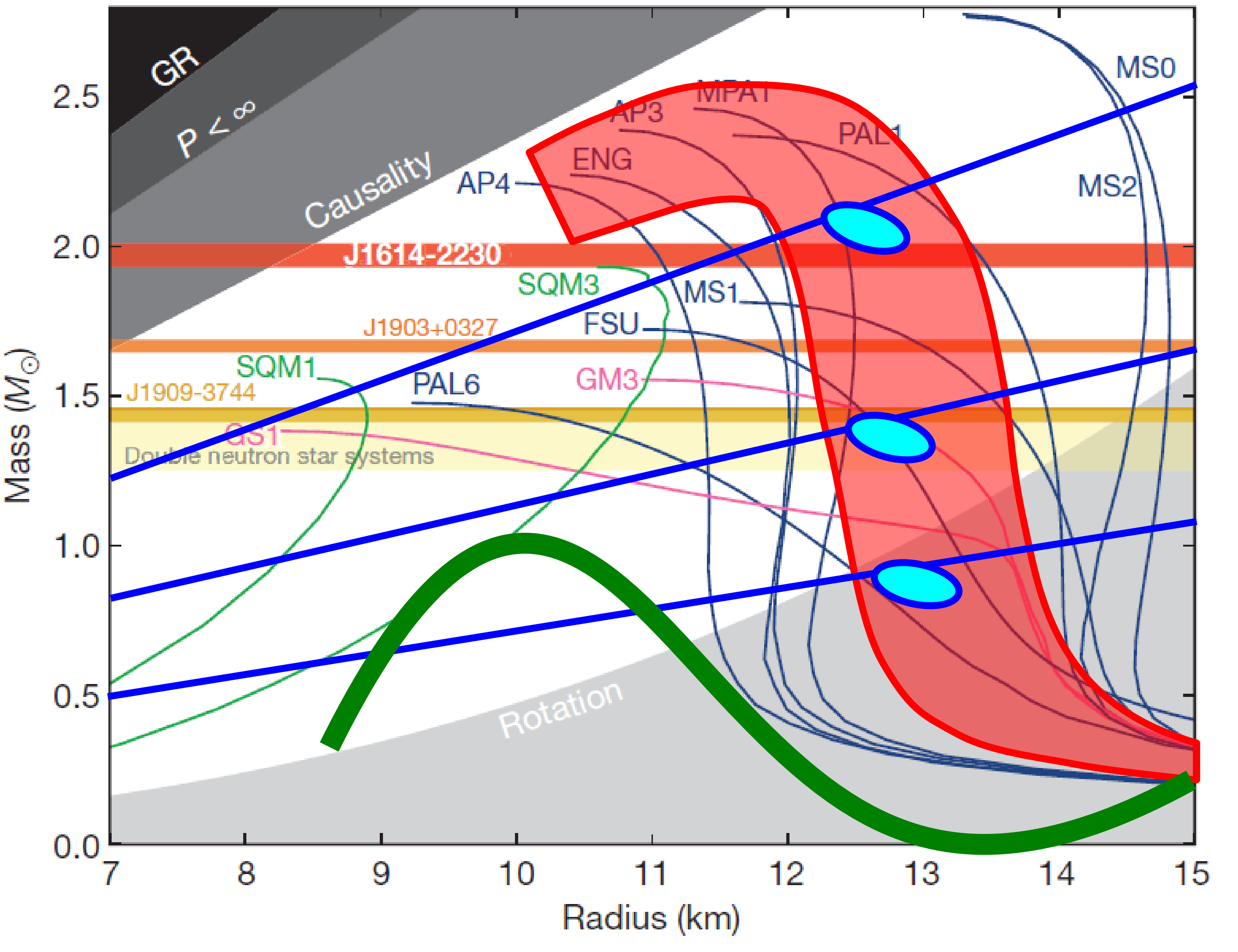
中性子星の質量と半径



ASTRO-H

Red shift (line)から
M/Rを決定

静水圧平衡(TOV方程式)



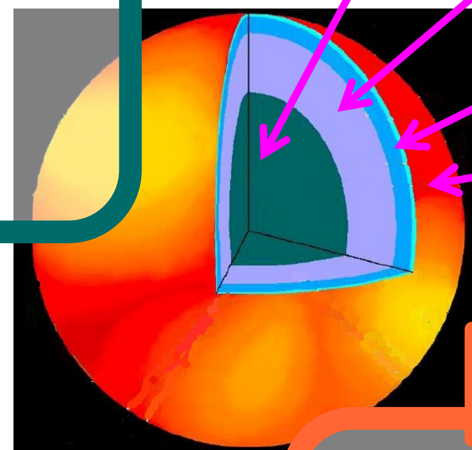
Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).

中性子星と核物質の理論研究(理論計画班)

高密度領域

原田(Prod.)、
木村(Structure)、
土手(Kaon Nucl.)

J-PARC



Hyperons, mesons, quarks

Asym. nuclear matter
+elec.+μ

Nuclei+neutron gas+elec.

Nuclei + elec.

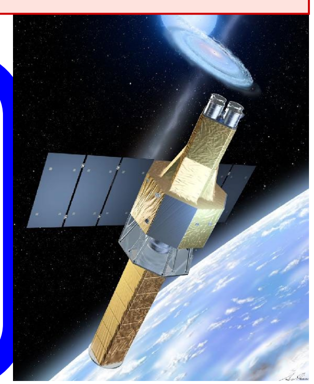
低密度領域

中田(Sym.E)、
松尾(EOS)、
小野(HIC)、

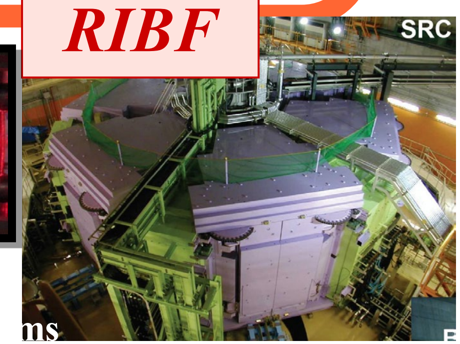
天体現象

飯田(Phen.)、
巽(Quark)、
中里(Pasta)

ASTRO-H



RIBF



連携:国広、西崎、親松、丸山、阿武木、大橋、柴崎、中務(C)

高密度物質状態方程式と
中性子星最大質量

1.97 ± 0.04 $M_\odot$ Neutron Star

- 重い中性子星(2倍の太陽質量)の観測

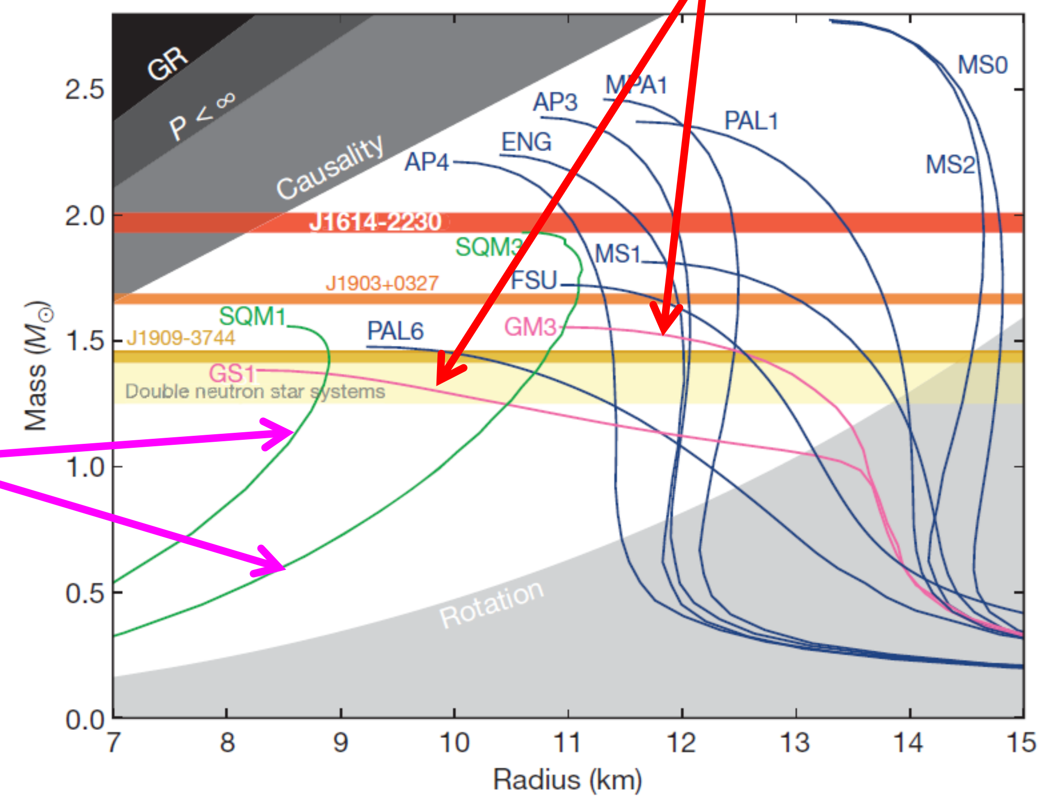
Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).

PSR J1614-2230 (NS-WD binary), 1.97 ± 0.04 Msun

- 一般相対性理論(Shapiro delay)に基づく質量決定
- 幸運な公転面の向き+美しい観測結果
- 高密度状態方程式(EOS)に強い制限
- Strange Hadron (ハイペロン・K中間子) 凝縮を含むEOSは棄却(?)
- クォーク物質でも相互作用に制限

Strange Hadron を含むEOS

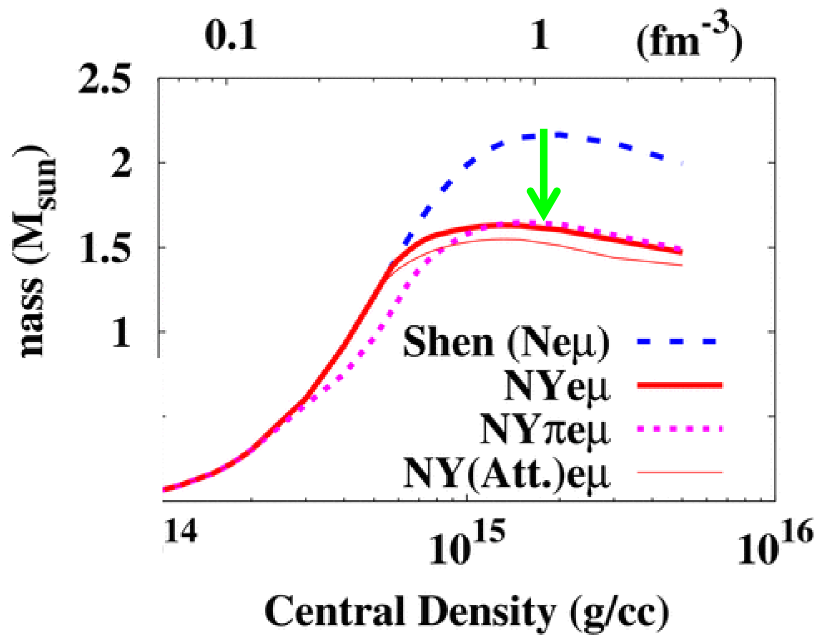
クォーク物質のEOS

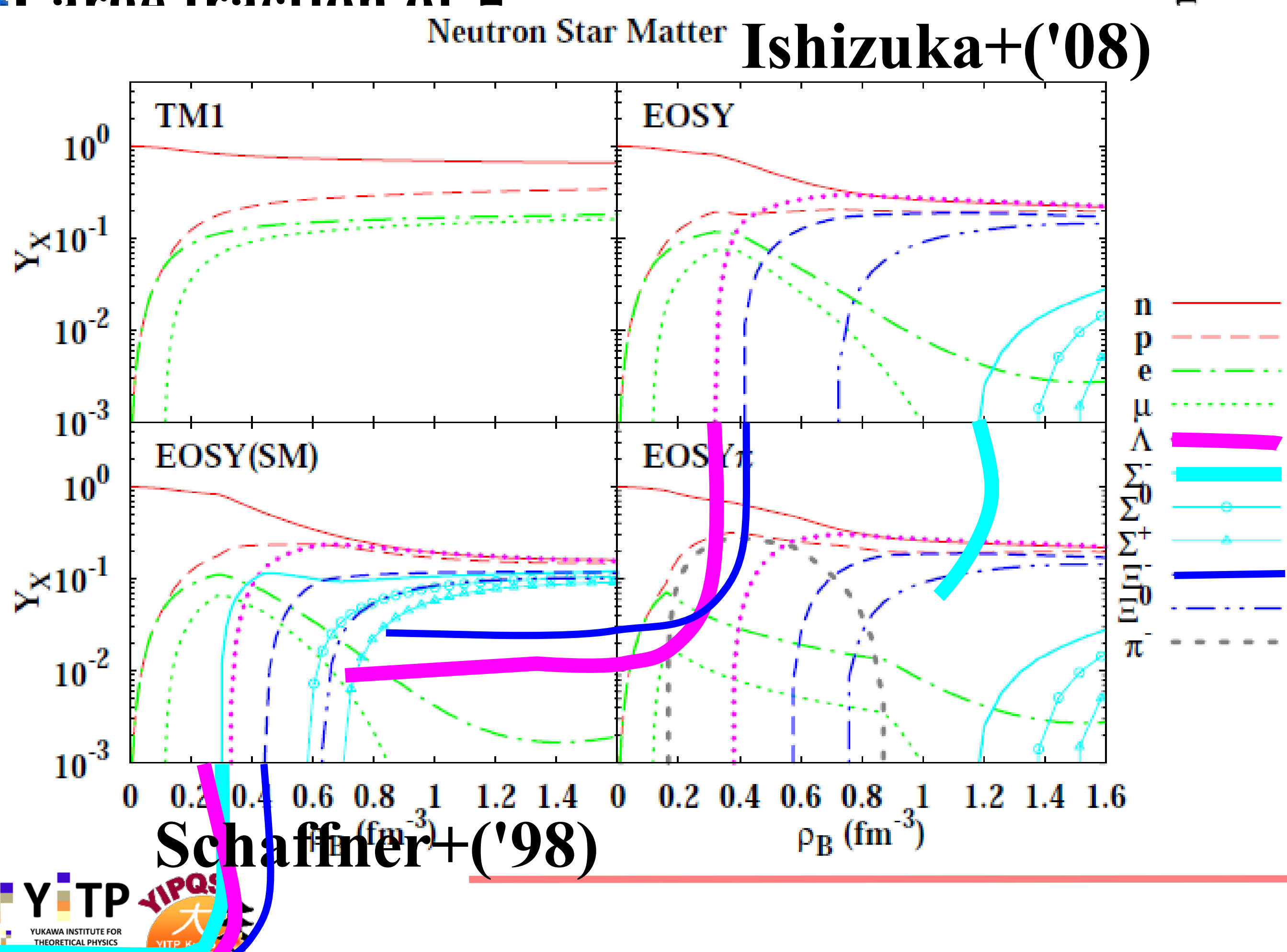


ハイペロンを含むRMFの例(1)

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

- Hyperon Effect is DRASTIC
- Mmax=2.1 $M_\odot \rightarrow$ 1.56 $M_\odot$
- Composition $Y_\Lambda \sim Y_n$
- Large fraction of Ξ





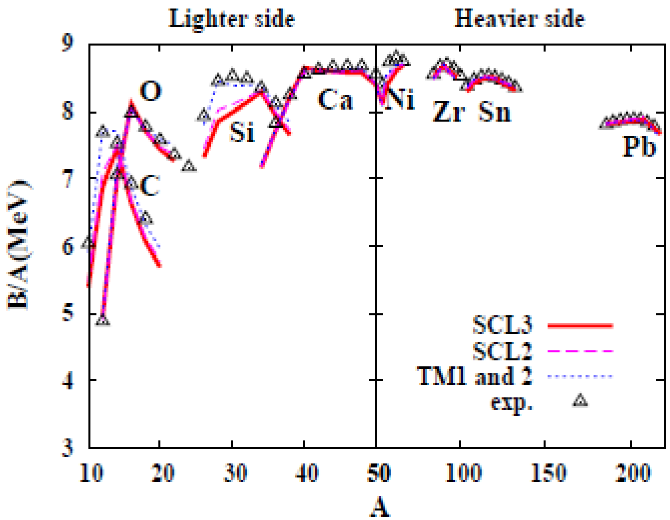
c.f. H.Shen+('09)
→ n, p, Λ EOS

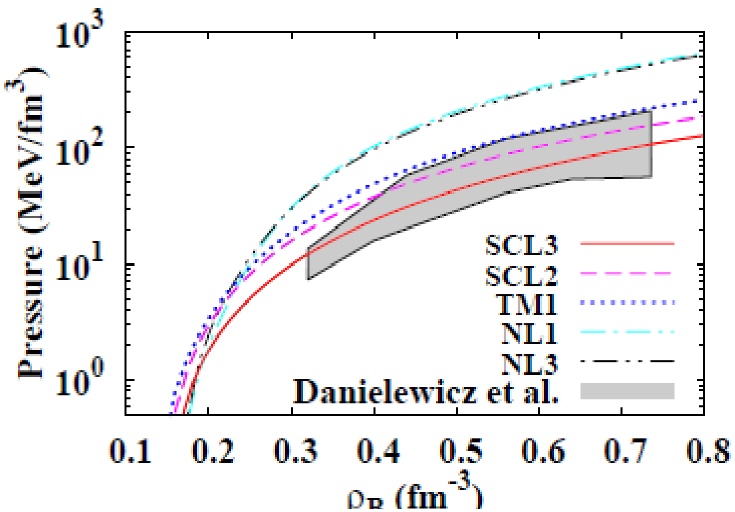
ハイペロンを含むRMFの例(2)

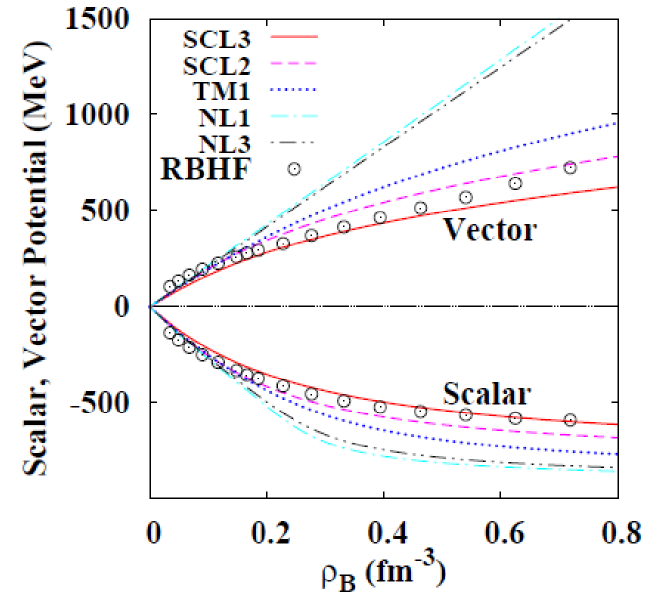
- **Fit as many as known observables**

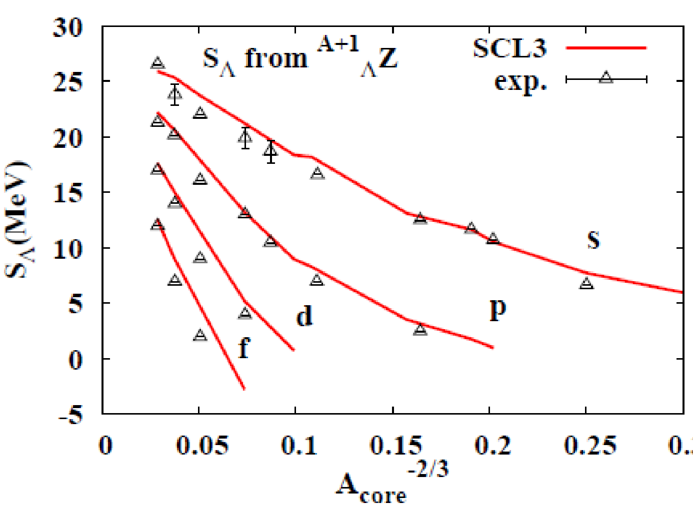
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

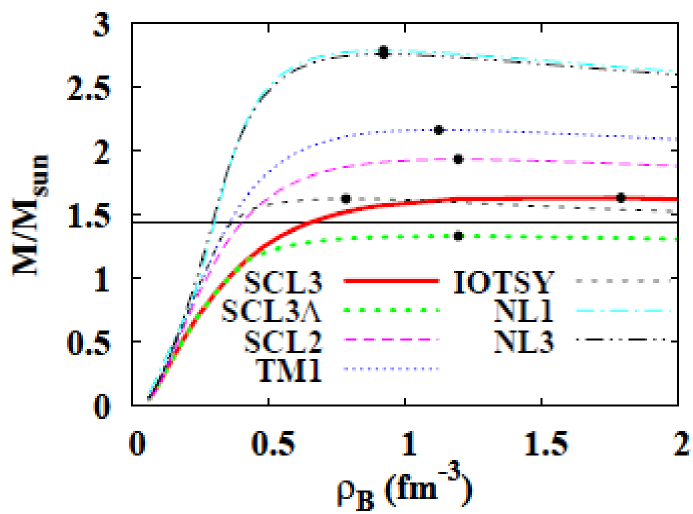
- **EOS, Nuclear B.E., High density EOS from HIC, Vector potential in DRHF, Hypernuclear Separation Energy, Neutron Star, ...**







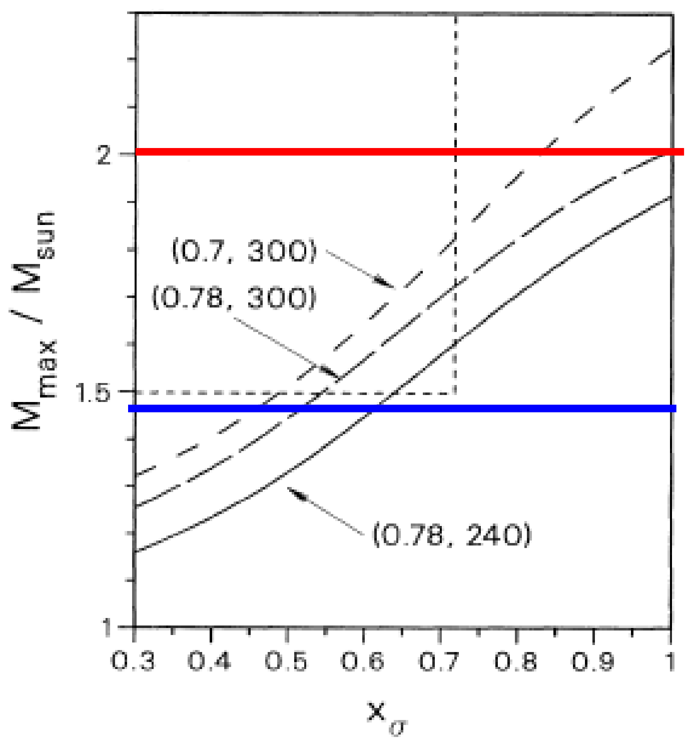


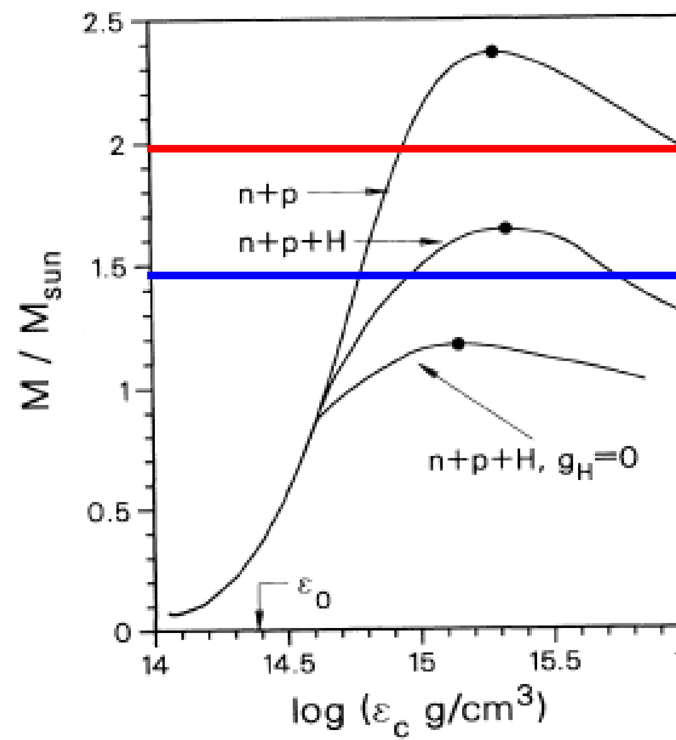


P. Danielewicz et al., Science298('02)1592.
R. Brockmann, R. Machleidt, PRC42('90)1965.

ハイペロンと重い中性子星

- 中性子星における One of the Two Serious Problems (高塚)
- 「柔らかいEOSは否定されたが、exoticな構成粒子が否定されたわけではない。」(Lattimer)
- 否定されたハイペロン・K中間子を含むEOS
= 相対論的平均場理論(RMF)において結合定数をほぼSU(6)にしたがって選んだもの ($g_{\sigma\Lambda}$ / $g_{\sigma N}$ ~ 2/3)



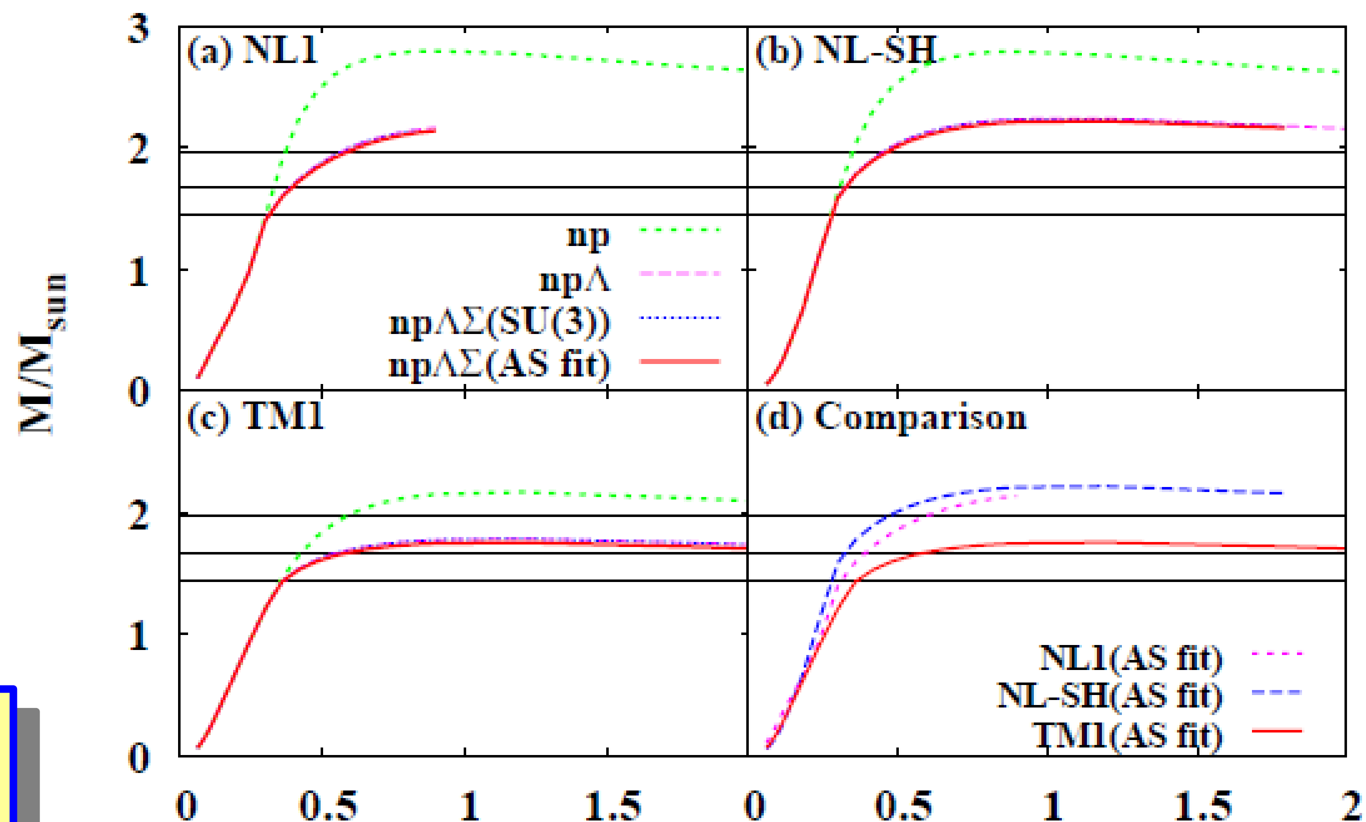


N.K.Glendenning, S.A.Moszkowski, PRL67('91)2414

ハイペロンと重い中性子星

- ハイペロンを含み、重い中性子星を支えるRMF
- ハイパー核情報を尊重：Λの一粒子エネルギー、ダブルハイパー核の相互作用エネルギー、Σ-原子のatomic shift
- NL1, NL-SH 等のRMFパラメーターではハイペロンを含んでも中性子星最大質量は2 $M_\odot$ を越える！
- TM1を基にした場合、最大質量は1.7$M_\odot$ 程度

Calculated Neutron Star Mass



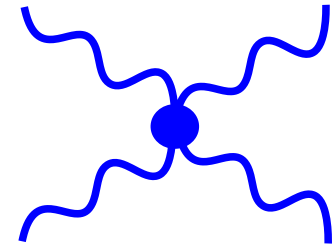
その違いは？
→ *meson self-energy*

Tsubakihara, AO, to be submitted

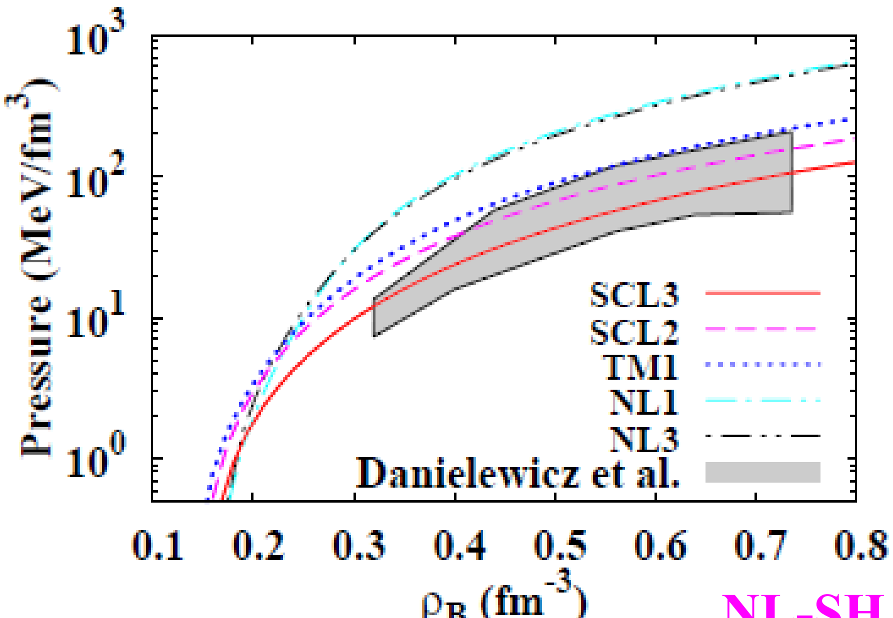
Meson self-energy 効果

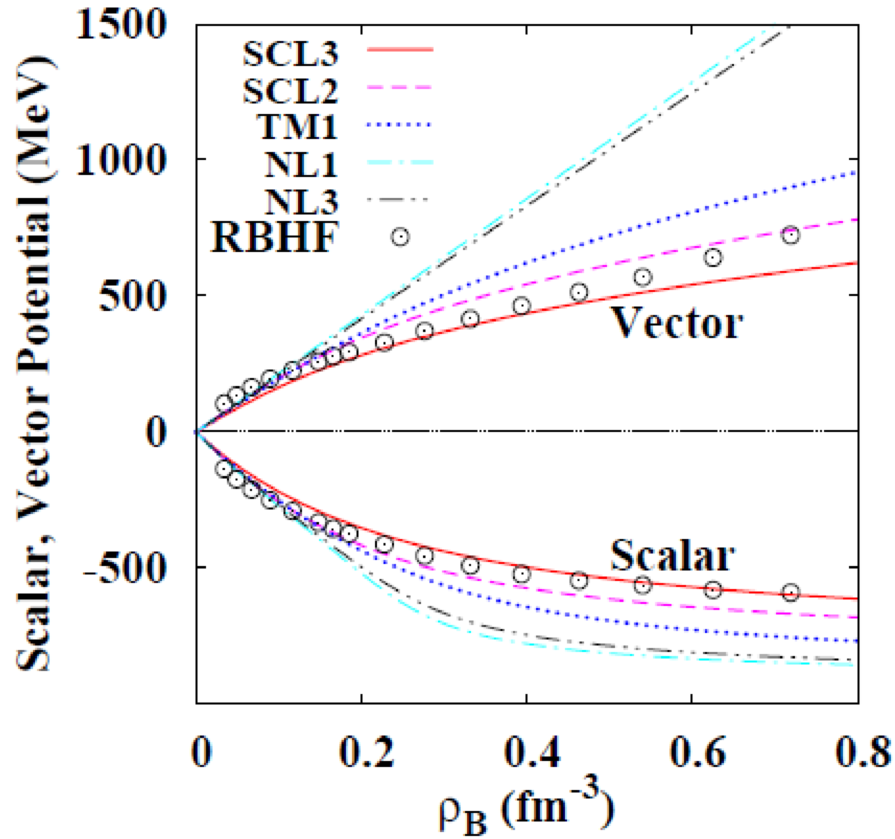
- ベクトル中間子の自己エネルギー項

$$L_\omega = \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}c_\omega\left(\omega_\mu\omega^\mu\right)^2$$



- 第一原理計算(RBHF)、重イオン衝突からの制限のクリアに必要だが NL1, NL-SH には含まれていない。





NL-SH ~ NL3

P. Danielewicz et al., Science298('02)1592;
R. Brockmann, R. Machleidt, PRC42('90)1965.
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206

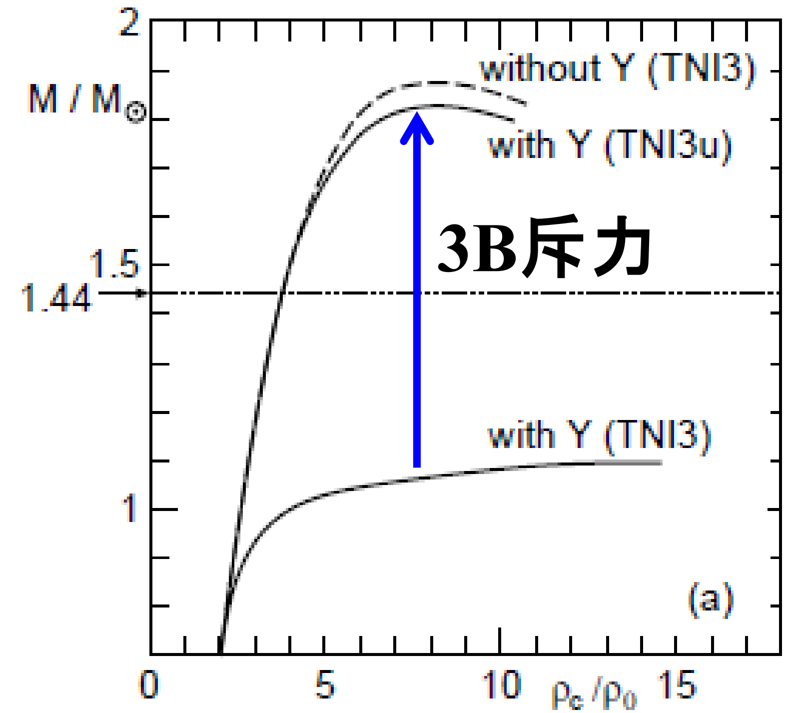
Short Summary

問題点

- Demorest et al. (2010) では核子以外の自由度による
EOSの軟化の問題を指摘。

- 非相対論的理論ではハイペロンを含むUniversalな斥力が必要。

- 相対論的平均場(RMF)では
相対論効果から現れるUniversalな
斥力が存在するので問題はややまし。
しかし第一原理計算の結果や
重イオン衝突からの制限を課すと、
2 M⊙を支えるには
同様にハイペロンを含む
"Extra Repulsion" が必要。



S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

- → ３体力(多体力)を含むEOS理論へ！

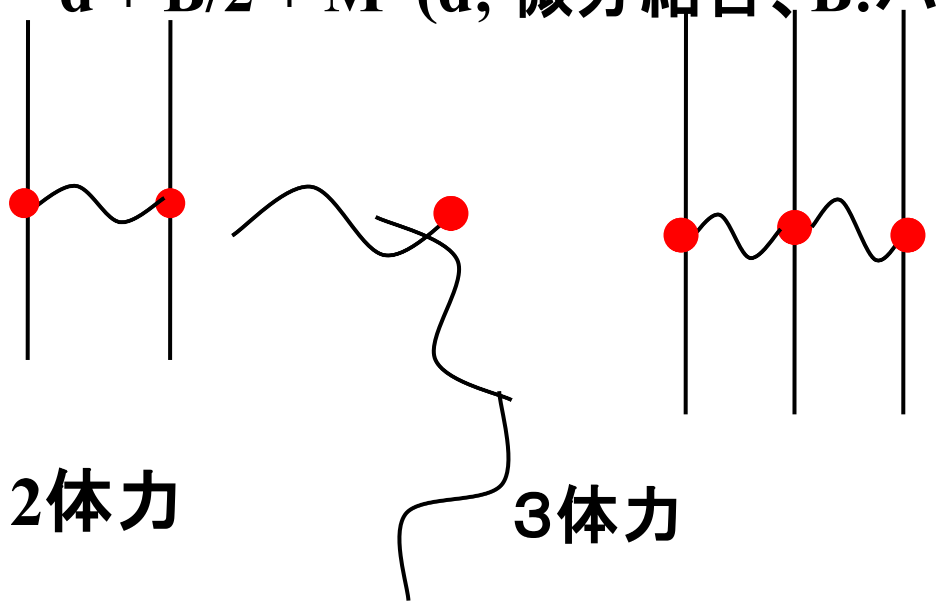
３体力を含む相対論的平均場理論
(Progress Report)

3体力を含むRMF

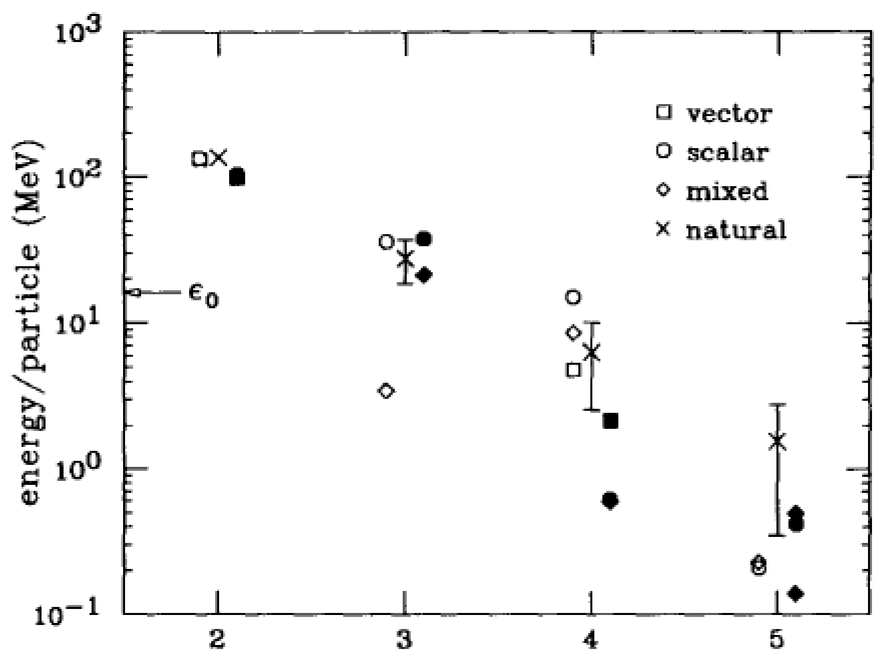
3体力を含む相互作用項

$$\delta L = -\frac{1}{2} c_{\sigma\omega} \sigma \omega_\mu \omega^\mu - \sum_B \bar{\psi}_B \left[g_{\sigma\sigma B} \sigma^2 + g_{\sigma\omega B} \sigma \omega_\mu \gamma^\mu + g_{\omega\omega B} \omega_\mu \omega^\mu \right] \psi_B$$

- **BBMM相互作用項は標準的なRMFでは無視**
(場の再定義により他の項に吸収可能) *Furnstahl, Serot, Tang ('97)*
しかし場の再定義はNaïve dimensional analysis (NDA)の次数を変え、高密度ではn体力が重要な役割を果たす。
n = d + B/2 + M (d; 微分結合、B:バリオ



2体力 **3体力**



Furnstahl, Serot, Tang ('97)

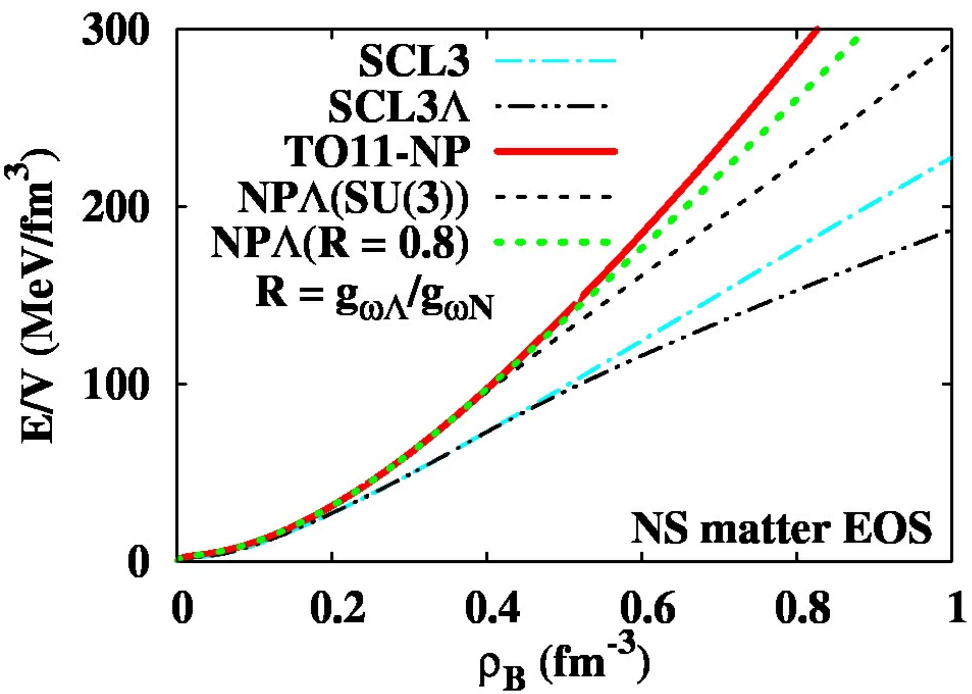
RMF with 3BF + $SU(3)_f$ "violation"

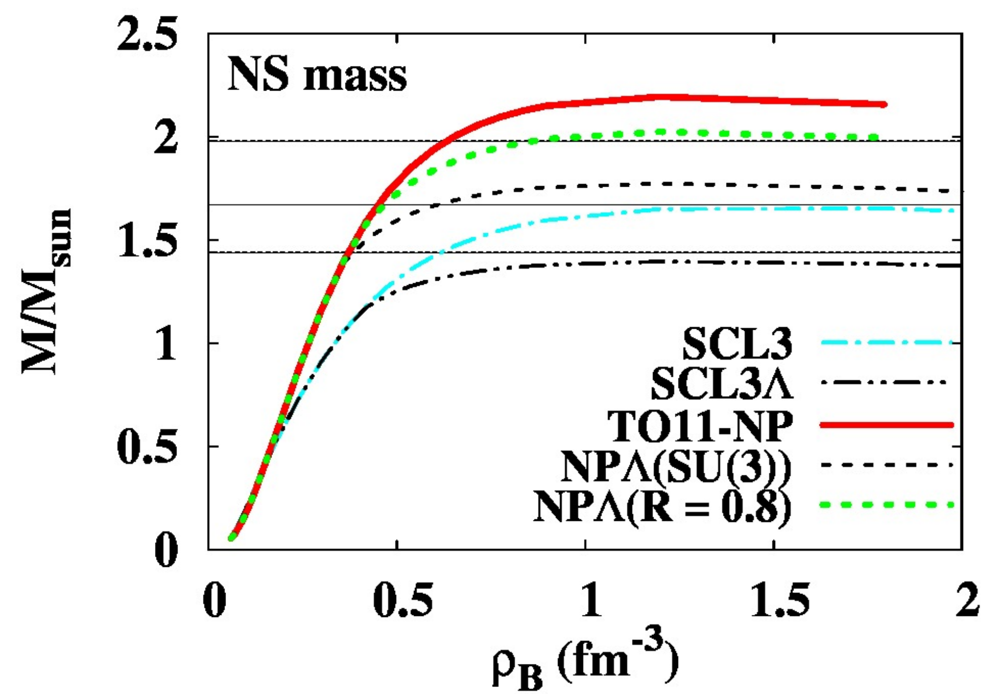
- **Two types of modification** *Tsubakihara et al., in prep.*

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

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

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





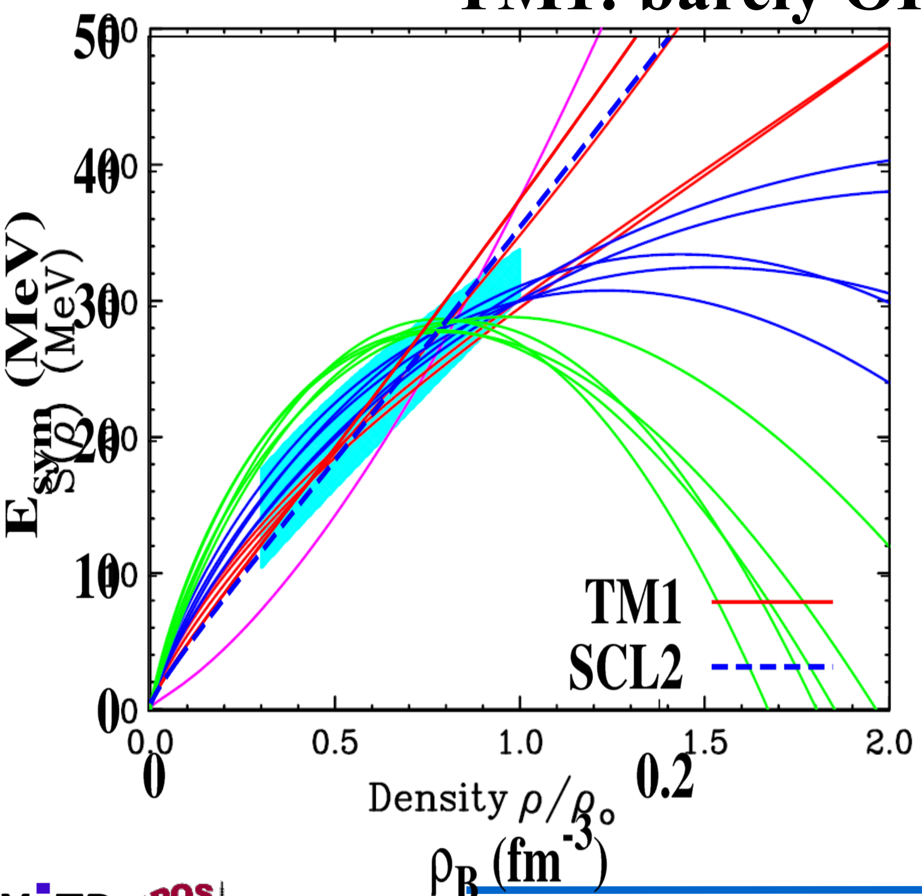
Symmetry Energy in 3BC-RMF

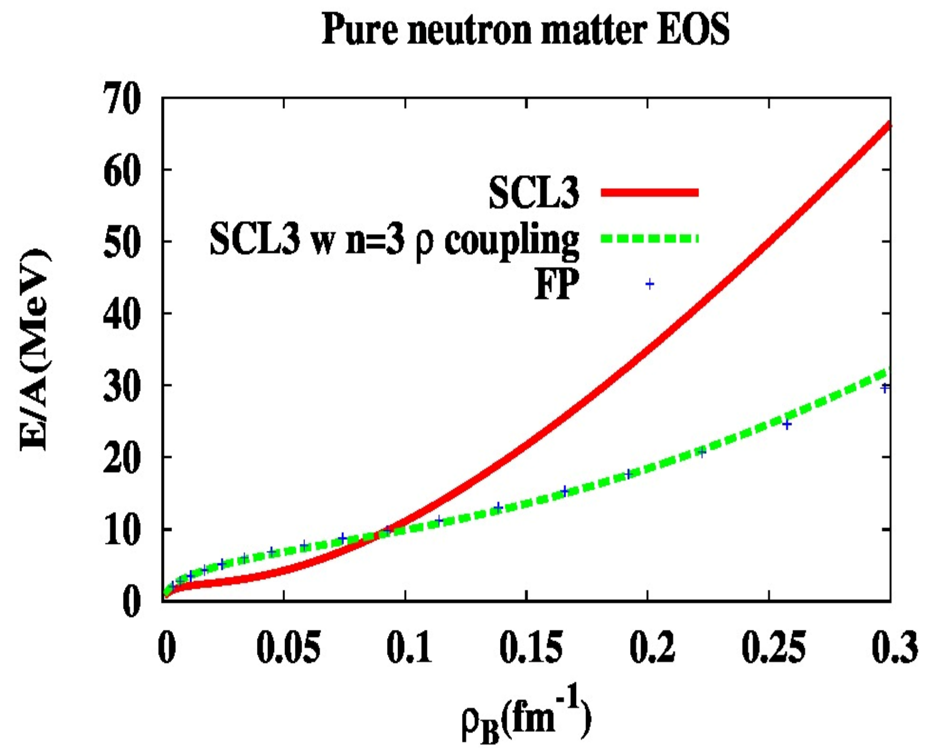
- **Only with n=2 terms, Symmetry energy is almost linear in density,**
→ L=3 S, High Sym. E at high density

- **3BC with ρ mesons → We CAN control ρ_B dependence of Sym. E.**

$$\delta L = -\frac{1}{2} c_{\sigma\omega} \sigma \rho^a_\mu \rho^\mu_a - \sum_B \bar{\psi}_B \left[g_{\sigma\rho B} \sigma \rho^a_\mu \tau_a \gamma^\mu \right] \psi_B$$

TM1: barely OK





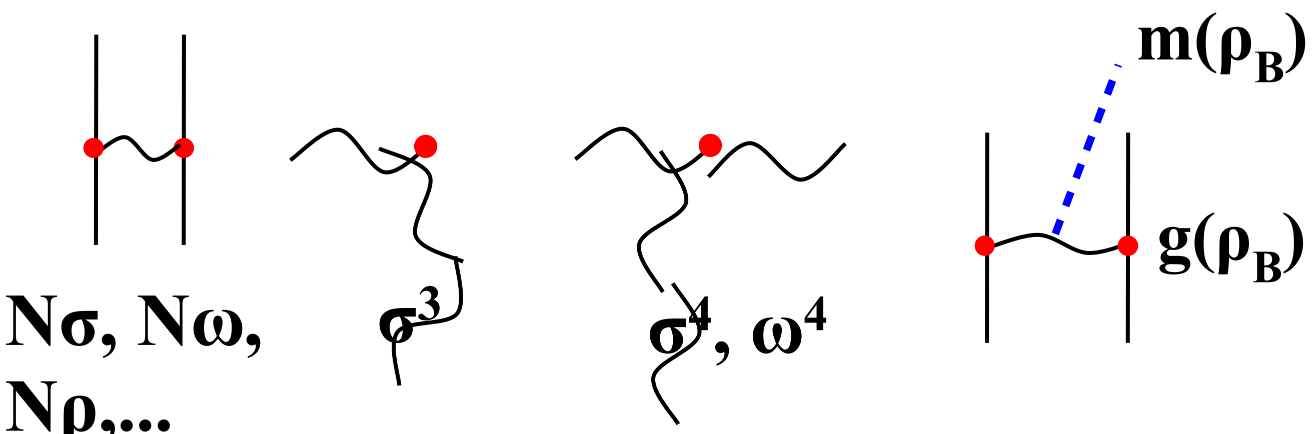
Tsubakihara et al., in prep.
FP: Friedman, Pandharipande ('81)

Summary

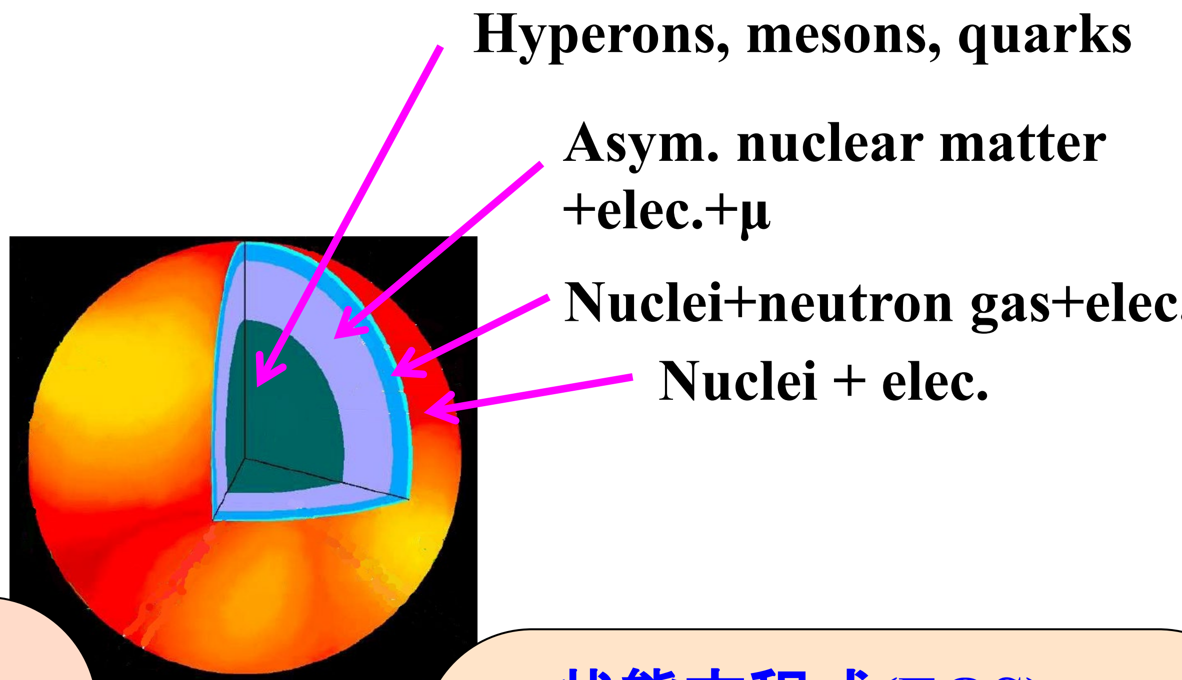
- 新学術領域「実験と観測で解き明かす中性子星の核物質」
  - 低密度核物理、高密度核物理、天体物理の協力により中性子星の性質を明らかに！
  - 理論班: 実験・観測に対応してEOS情報を引き出す体制
  - 冷却、磁場、QCD相転移、格子QCD等、多くの課題がカバー出来ていません。→ 公募研究への応募、よろしくお願いします。
- ハイペロンを含む状態方程式と重い中性子星
  - ハイペロンを含み、2倍の太陽質量を越える中性子星を支える模型は存在しうる。
  - 他の実験データとconsistentであるためには、単純な相対論効果を越える何らかの3体力(多体力)効果が必要。
  - 3体力を含む相対論的平均場理論では重い中性子星を支えるとともに、対称エネルギーの密度依存性をコントロールできる。
  - 実験・観測・第一原理計算からどのように決められるか？

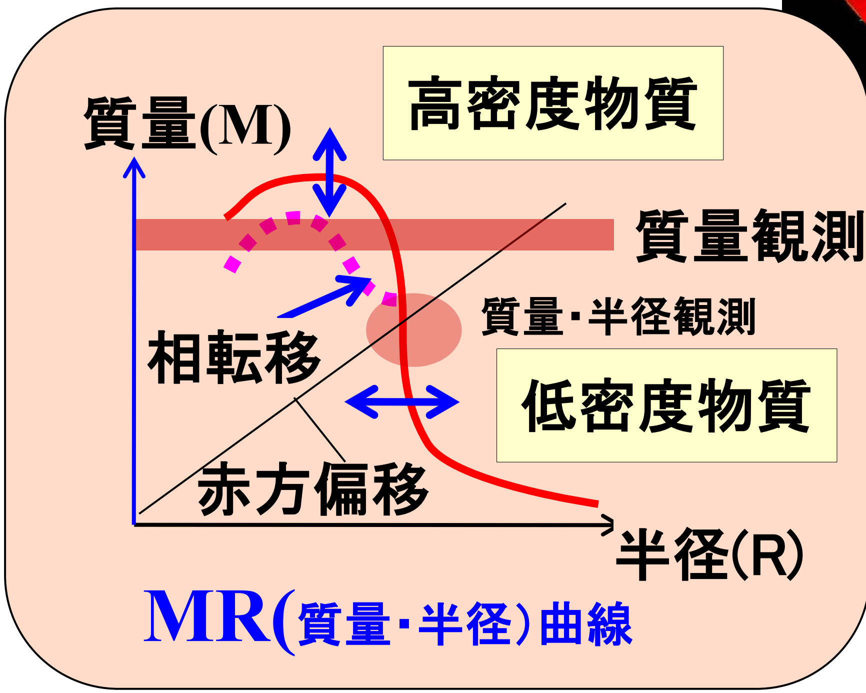
Many-body coupling in RMF (2)

- **Three-body force from vector mass modification**
  Furumoto, Sakuragi, Yamamoto ('09)
- **Effects on Nucleus-Nucleus Elastic Scattering**
- **Density-dependent couping** *E.g. Roca-Maza+('11)*
- **Softer EOS, High precision nuclear binding energies**



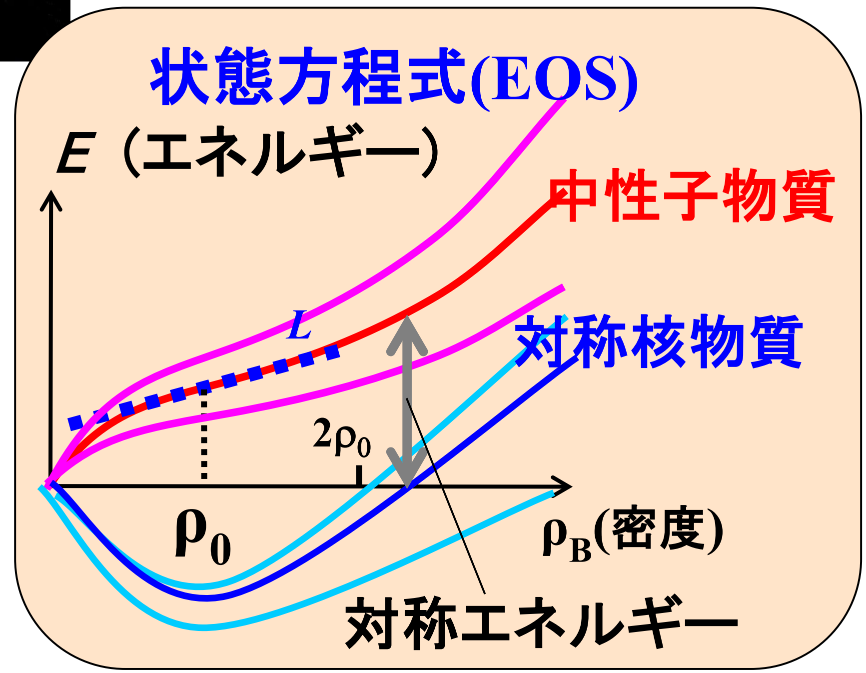
中性子星の組成・MR曲線と状態方程式



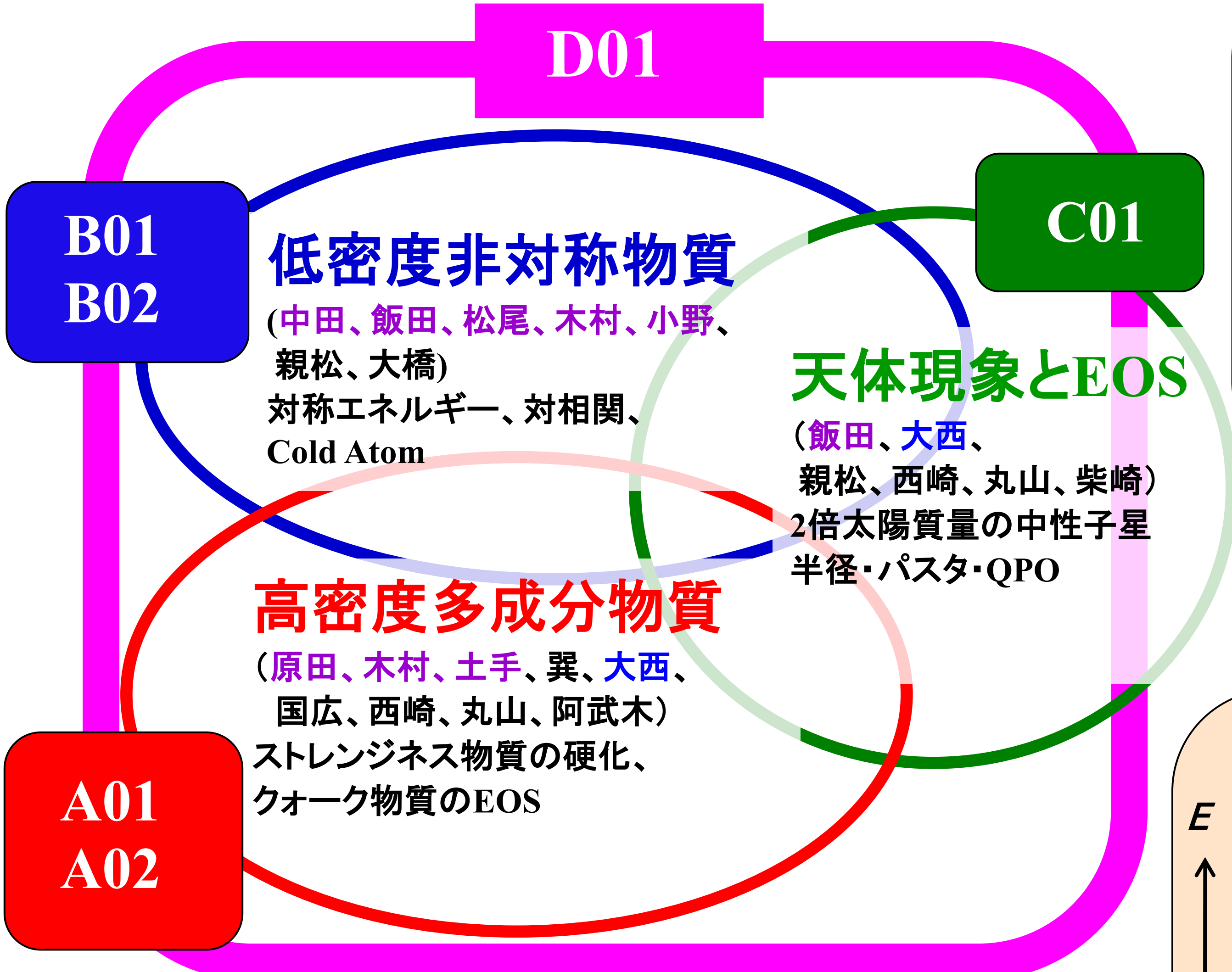


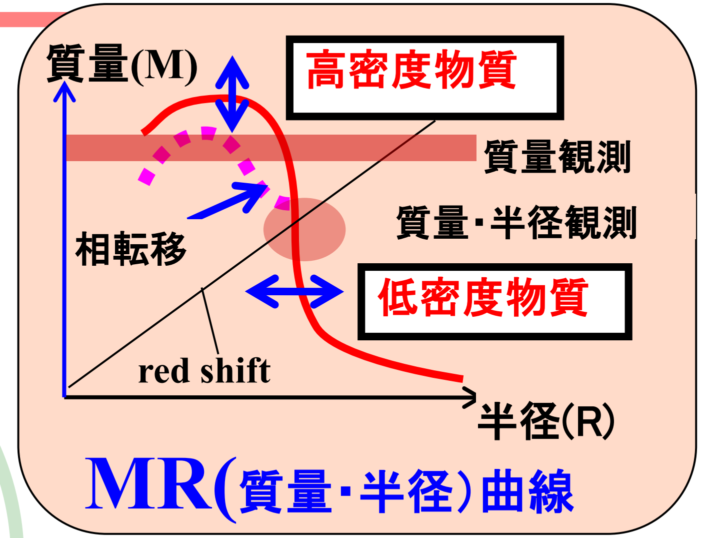
TOV
方程式

重力と
圧力の
釣り合い

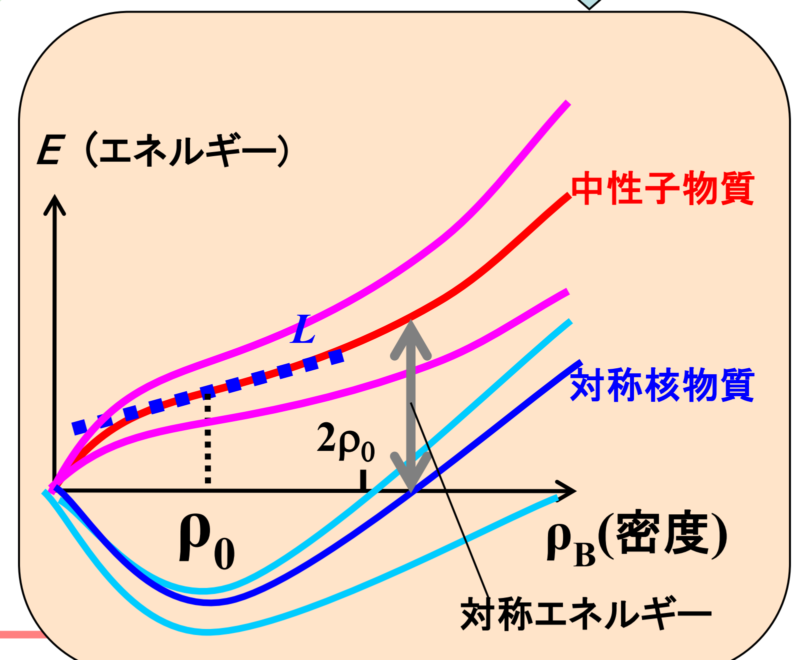


D01: 中性子星と核物質の理論研究



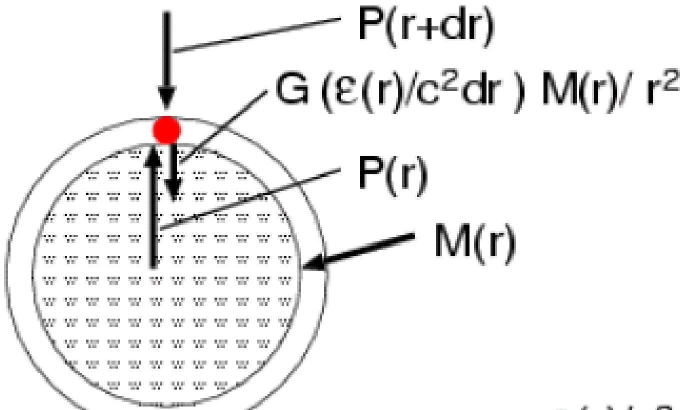


TOV方程式



理論の立場から、
ストレンジネス核物理、中性子過剰核物理、
冷却原子物理、天体物理を結びつけ、
現象に裏付けられた "*The EOS*" を決定する。

Tolman-Oppenheimer-Volkoff equation



Non-Rela. $\frac{dP}{dr} = -G \frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$

$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2 \;, \quad \frac{dP}{dr} = \frac{dP}{d\varepsilon}\frac{d\varepsilon}{dr}$$

$$P = P(\varepsilon) \;, \quad \frac{dP}{d\varepsilon} = \frac{dP}{d\varepsilon}(\varepsilon) \quad \text{(EOS)}$$

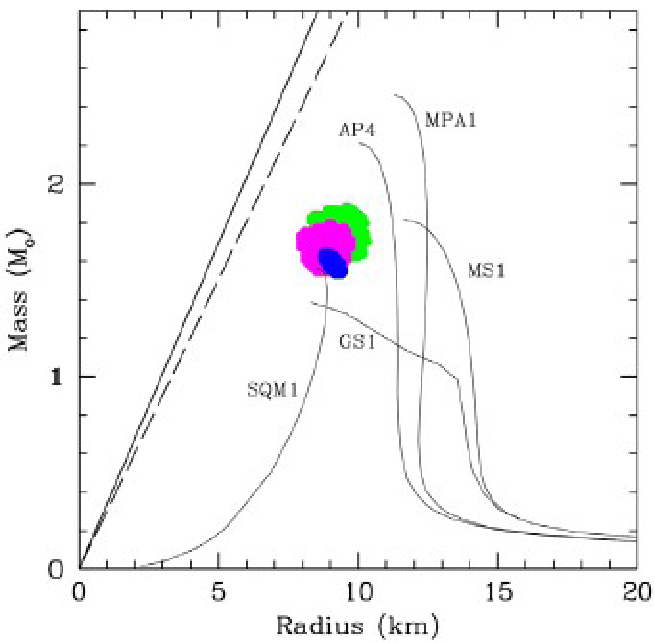
When you make a new EOS, please check the NS mass !

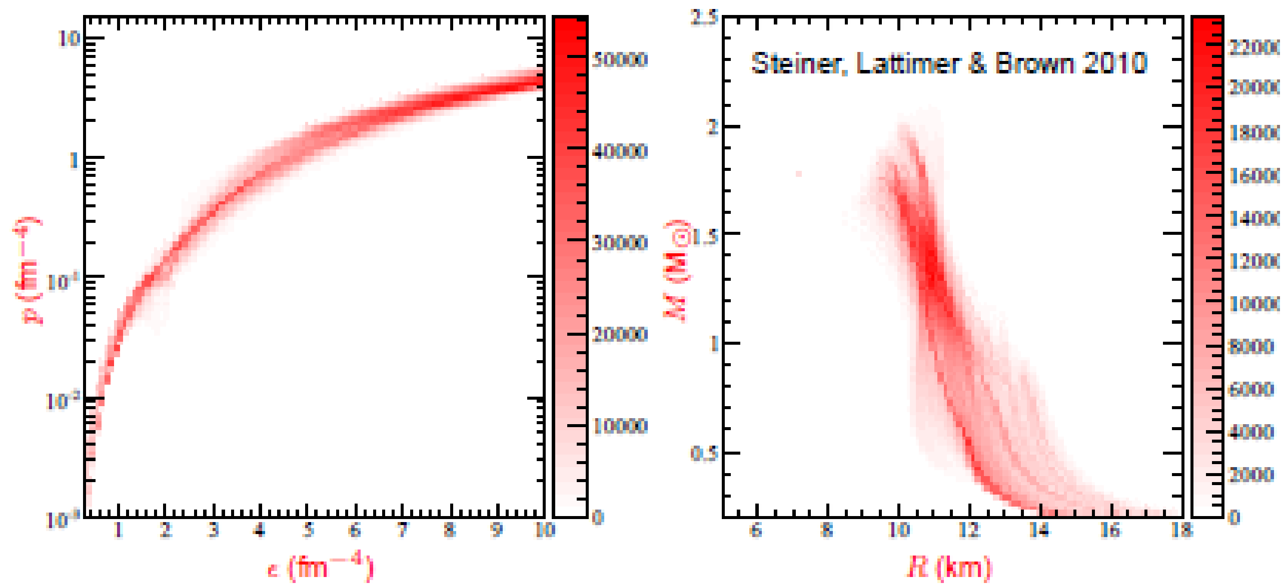
なぜ今、中性子星か？

- 近年の実験の進展が面白い！
  - ストレンジネス核物理の進展 – NY, YY相互作用(高橋(俊))
  - 高エネルギー重イオン衝突による相図探索(坂口)
  - 中性子過剰核---対称エネルギー・対相関(中村)
  - 高エネルギー重イオン衝突におけるΛΛ相関とΛΛ力
- 近年の理論の進展が面白い！
  - 格子QCDバリオン間力(根村)
  - 中性子星物質中の対相関・対称エネルギー・パスタ(飯田)
- 最近の天体観測結果が面白い！
  - 1.97 $M_\odot$ 中性子星の発見 (Demorest+, 2010)
  - 半径の測定 (高橋(忠))
  - 速い冷却の発見 (Page+, 2011)
- 分野間のつながりが面白い！

最近の中性子星観測の話題

- 中性子星の質量・半径同時測定
- TOV方程式を使うと M(質量)-R(半径)関係式と EOS は1対1対応
- M, Rが同時に決まると、EOS に非常に強い制限
[観測された(M, R) の”点”を通る必要がある！]
- X線バースト観測 → 半径(+質量)の情報





Ozel, Baym & Guver, PRD82('10)101301 [arXiv: 1002.3153]

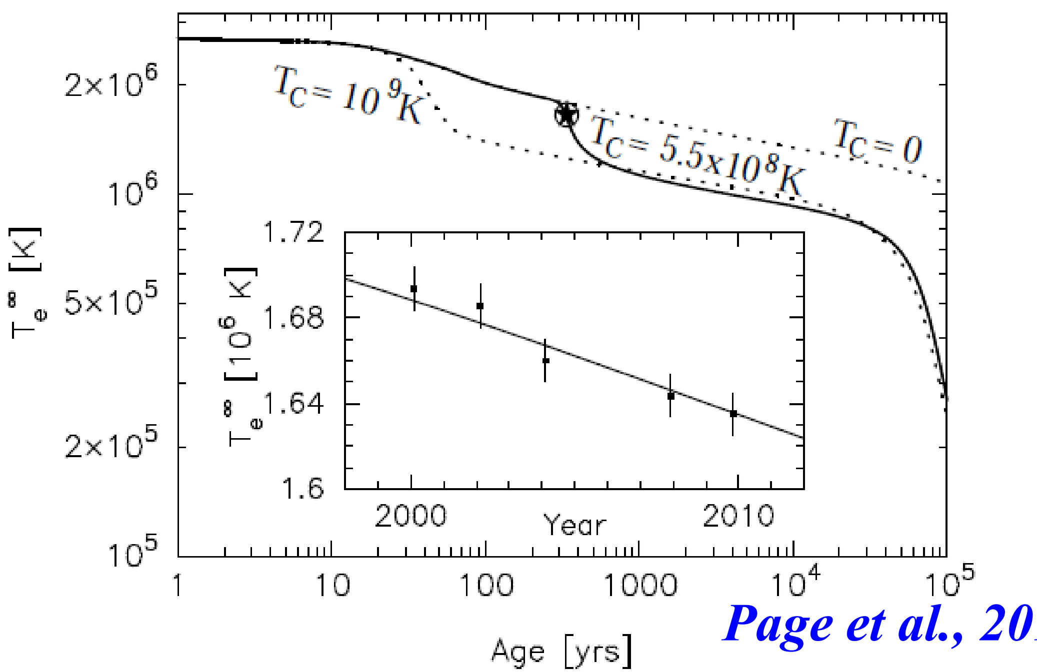
Steiner, Lattimer, Brown, ApJ 722 (2010) 33 [arXiv:1005.0811]

核子超伝導状態と冷却曲線

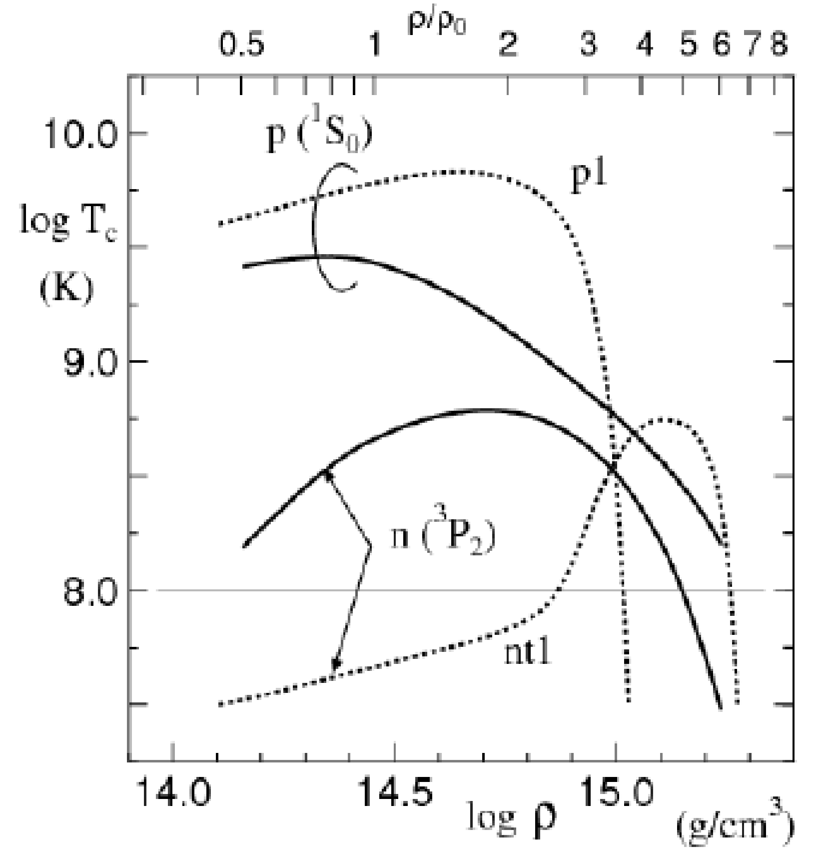
- 表面温度測定と冷却曲線
- 超伝導状態 → ギャップ → ν 放出の抑制
- Cas A の正確な温度測定と冷却率の測定

Heinke, Ho, ApJ 719('10) L167 [arXiv:1007.4719]
Page et al., PRL 106 ('11) 081101 [arXiv:1011.6142]

- neutron pair のbreaking & formation
- 核物理への宿題：$5\rho_0$程度までのギャップを正確



Page et al., 2011



Takatsuka

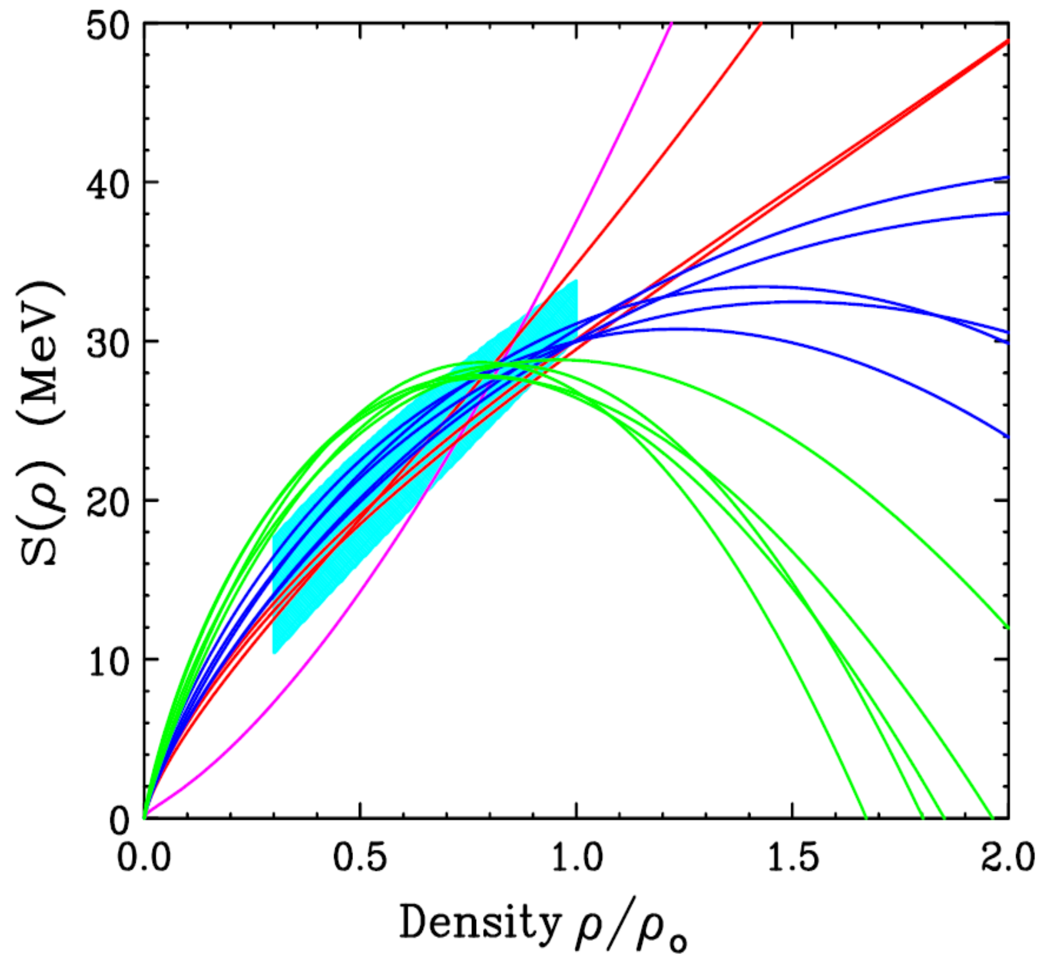
Symmetry Energy(対称エネルギー)

- **Summary of Nuclear Symmetry Energy workshop NuSym11 http://www.smith.edu/nusym11**

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

  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 Esym に敏感。**

  →高密度側では？

中性子星核物質状態方程式

- 第一原理的計算

Akmal, Pandharipande, Ravenhall ('98), Kanzawa, Oyamatsu, Sumiyoshi, Takano ('07)
Brockmann, Machleidt ('90), Schulze, Polls, Ramos, Vidana ('06),
Nishizaki, Takatsuka, Yamamoto ('02), …

- 現実的な核力から出発して、多体問題を直接解く(GFMC, Variational) あるいは有効相互作用を導出(DBHF, G-matrix)
- 飽和性の説明には一般に現象論的3体力・密度依存斥力などが必要
- ハイペロンを導入するとさらに軟化 → Universal 3B Repulsion (NTY)

- 非相対論的平均場模型 *E.g. Lattimer, Swesty ('91), Nakada ('08)*
  - 密度依存力(Skyrme力、M3Y)平均場＋圧縮性液滴
- 相対論的平均場模型

Muller, Serot ('96), Glendenning, Moszkowski ('91), Shen, Toki, Oyamatsu, Sumiyoshi, ('98), Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada('08)

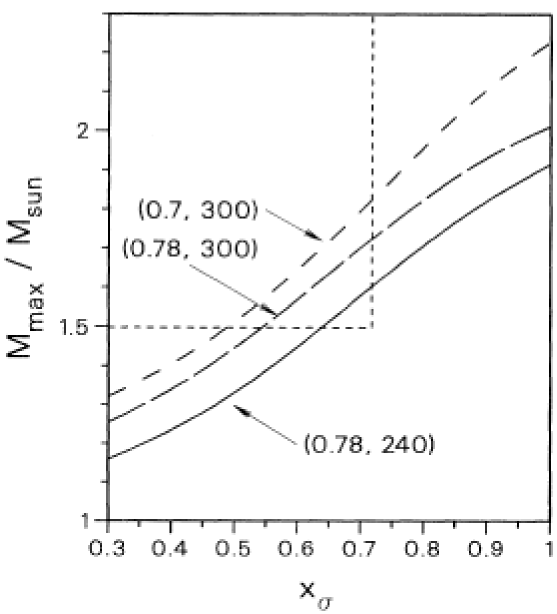
- 相対論的平均場(RMF)+非一様性(Thomas-Fermi近似)
- 相対論効果による斥力
  → ハイペロンを導入しても1.5 $M_\odot$程度の中性子星を支える

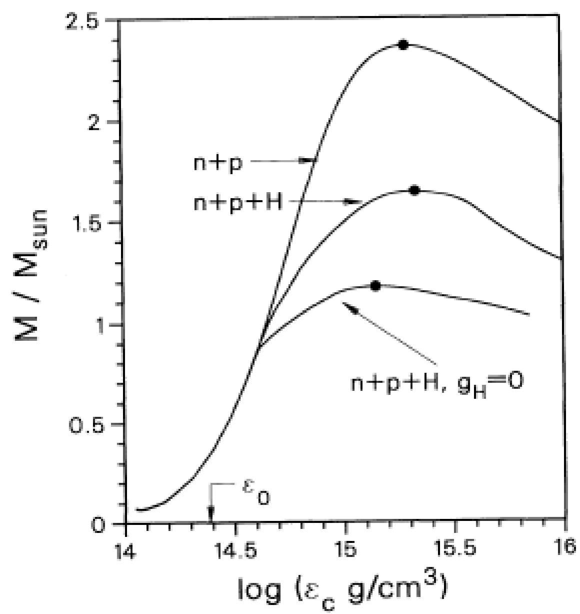
Glendenning & Moszkowski (1991)

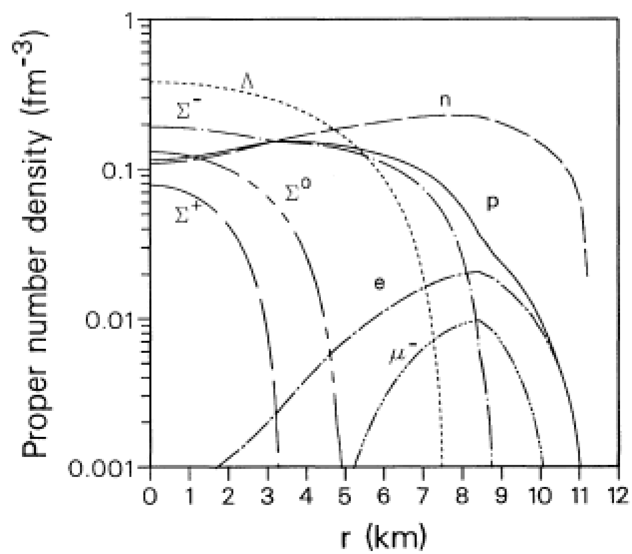
- **RMF with hyperons**
- **n, p, Y, σ, ω, ρ / σ^3, σ^4**
- **Give $x_\sigma = g_{\sigma Y}/g_{\sigma N}$ and fix $x_\omega = g_{\omega Y}/g_{\omega N}$ to fit Λ separation energy.**
- **x_σ = 0.6 → m*/m=0.7, x_ω=0.653 (similar to quark number counting result, x=2/3)**
  → M 1.6 M

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_ω	
x_σ	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





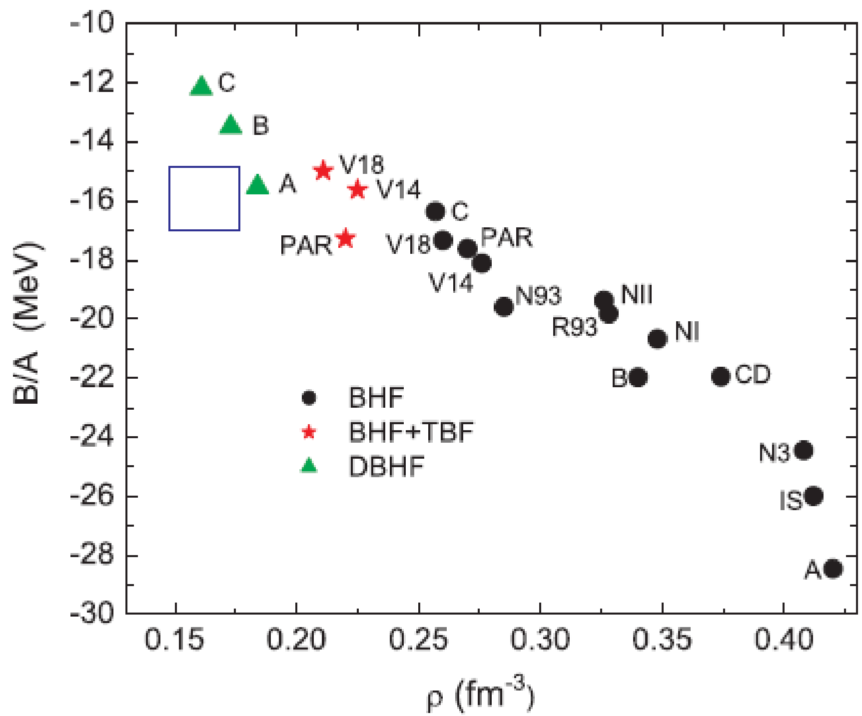


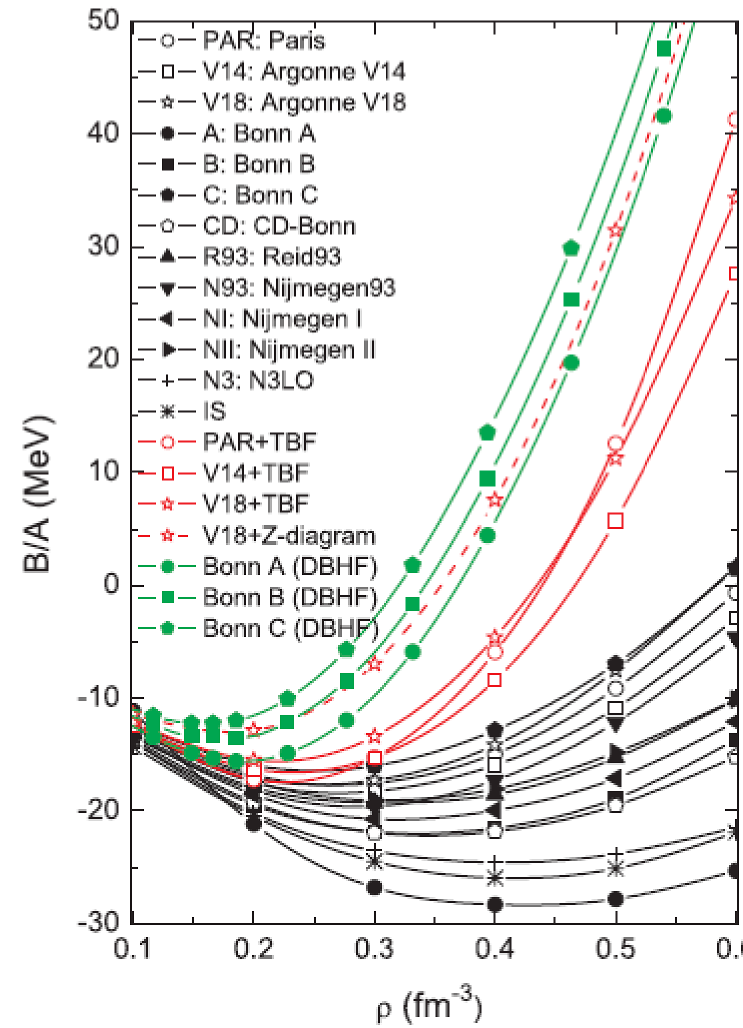
N.K.Glendenning, S.A.Moszkowski, PRL67('91)2414

Bruckner-Hartree-Fock理論

- 現実的核力からスタートして、
  有効相互作用(G-matrix)と一粒子エネルギー
  をself-consistentに決定。

- 飽和点を再現するには、3体力が必要。
  → 藤田・宮沢タイプ(バリオン共鳴経由)の
  3体力(2 π交換)
  ＋現象論的3体力(or 相対論効果)





Z.H.Li, U. Lombardo, H.-J. Schulze, W. Zuo, L. W. Chen, H. R. Ma, PRC74('06)047304.

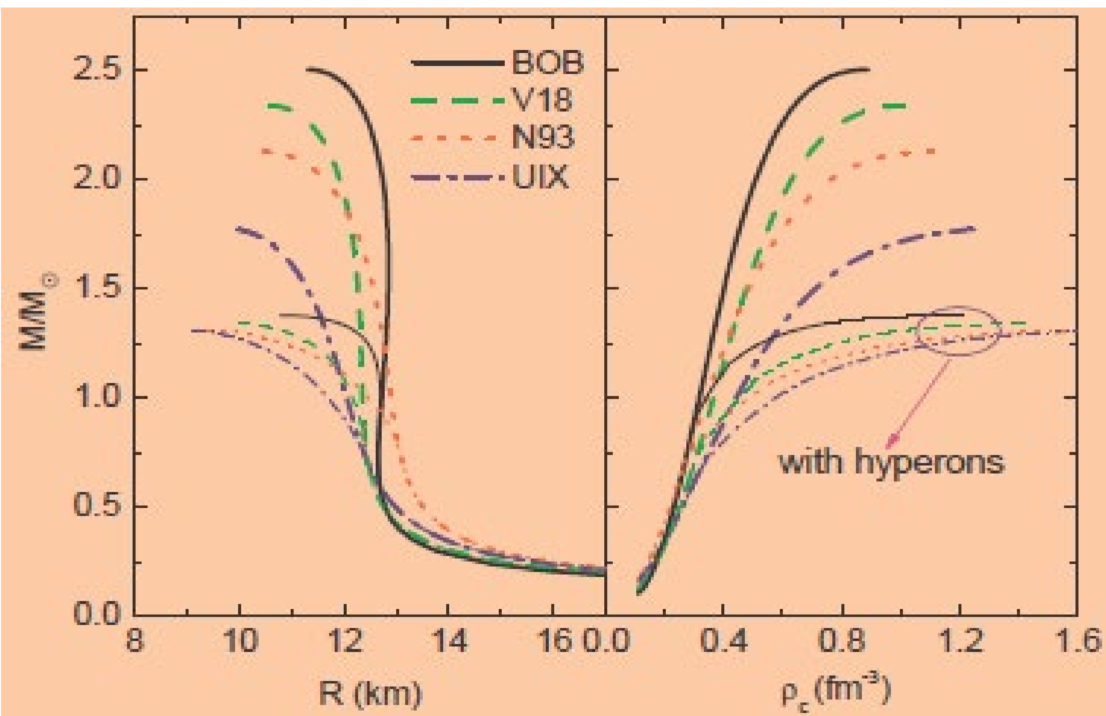
BHF with Hyperons

- 現実的NN, NY 力から構成した有効相互作用(微視的有効相互作用)
*3体力(現象論を含む)

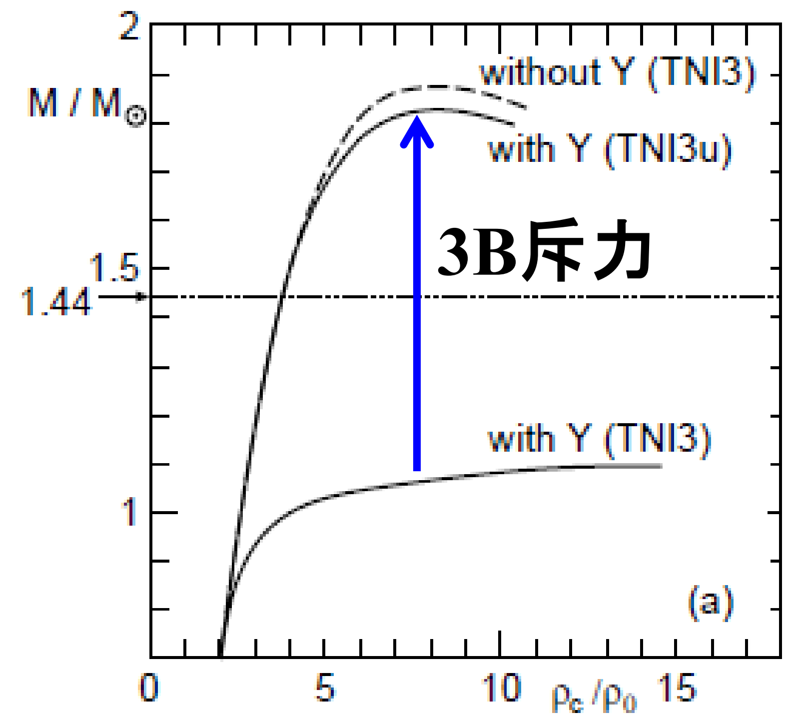
- 相互作用依存性 (V18, N93, ...) 大 → ハイパー核情報が必要。

E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / H.Tamura et al.

- 3B力を入れないと中性子星はつぶれる。



H.J.Schulze, A.Polls, A.Ramos, I.Vidana, PRC73('06),058801.

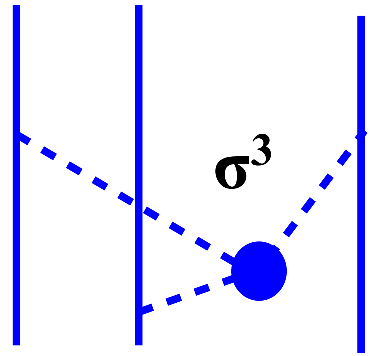


S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

相対論的平均場理論(Relativistic Mean Field)

- RMFのパラメータ

→ MB 結合定数、中間子質量、非線形結合



- 原子核の性質

→ σN, ωN, ρN 結合定数は確立

- σ^3 and σ^4 項 → EOS のソフト化

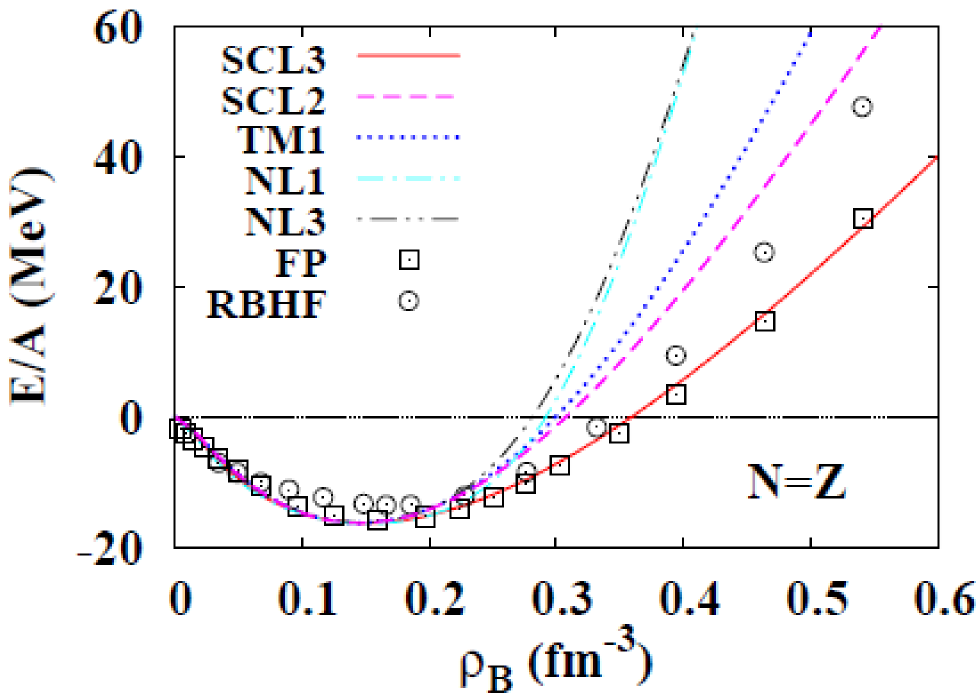
J. Boguta, A.R.Bodmer NPA292('77)413,
NL1:P.-G.Reinhardt, M.Rufa, J.Maruhn, W.Greiner, J.Friedrich, ZPA323('86)13.
NL3: G.A.Lalazissis, J.Konig, P.Ring, PRC55('97)540.

- ω^4 項 → DBHFの結果をsimulate

TM: Y. Sugahara, H. Toki, NPA579('94)557;
R. Brockmann, H. Toki, PRL68('92)3408.

-

→ 高密度領域では大きな違い



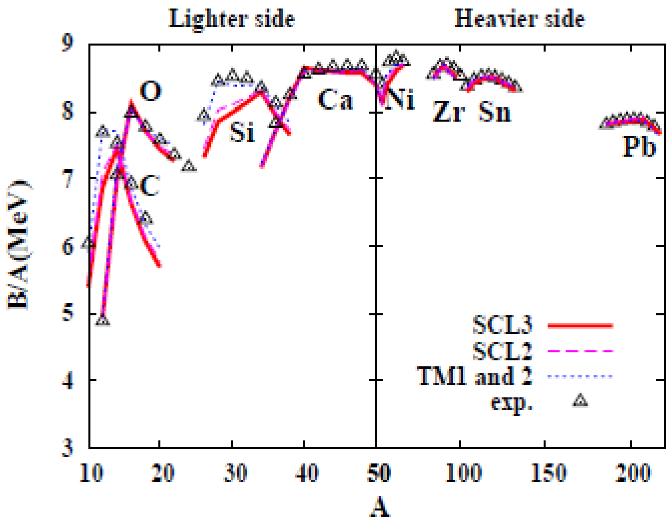
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

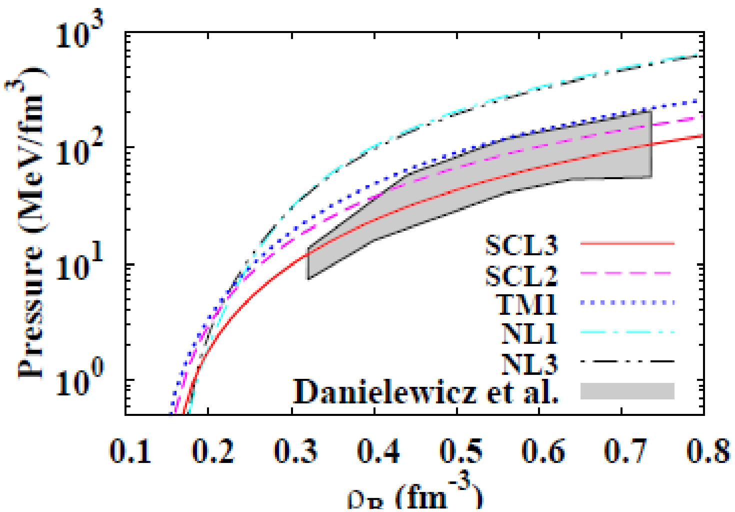
現象論としてのRMF

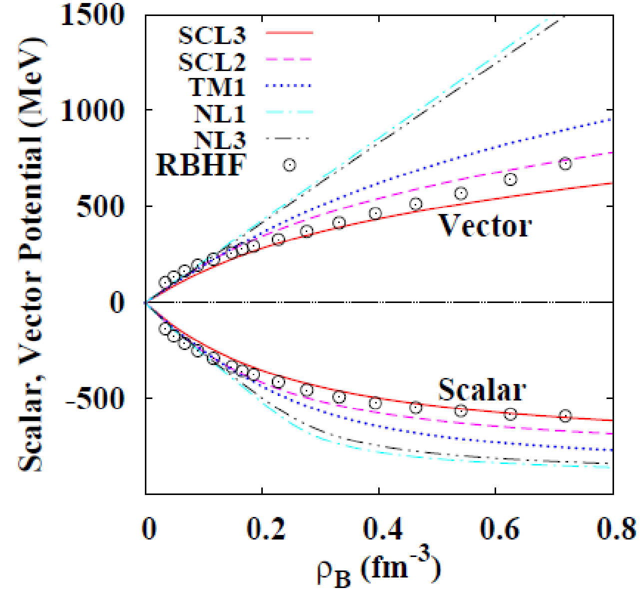
- **Fit as many as known observables**

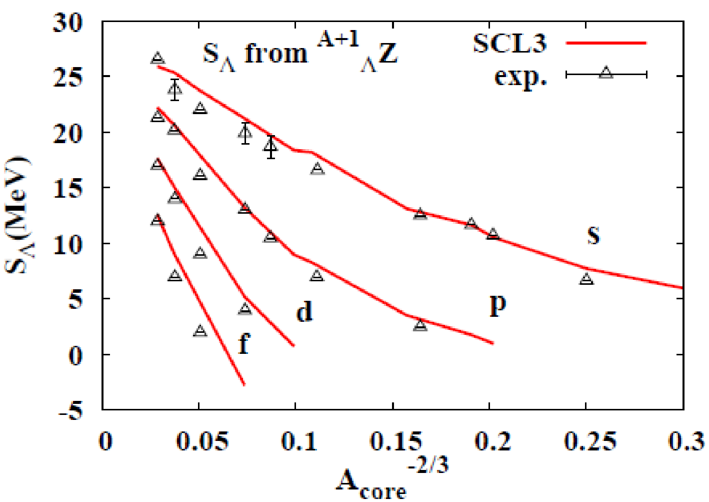
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

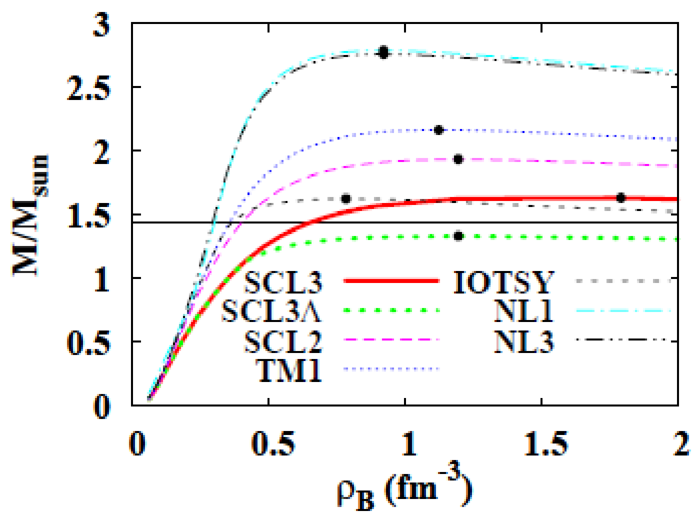
- **EOS, Nuclear B.E., High density EOS from HIC, Vector potential in DRHF, Hypernuclear Separation Energy, Neutron Star, ...**







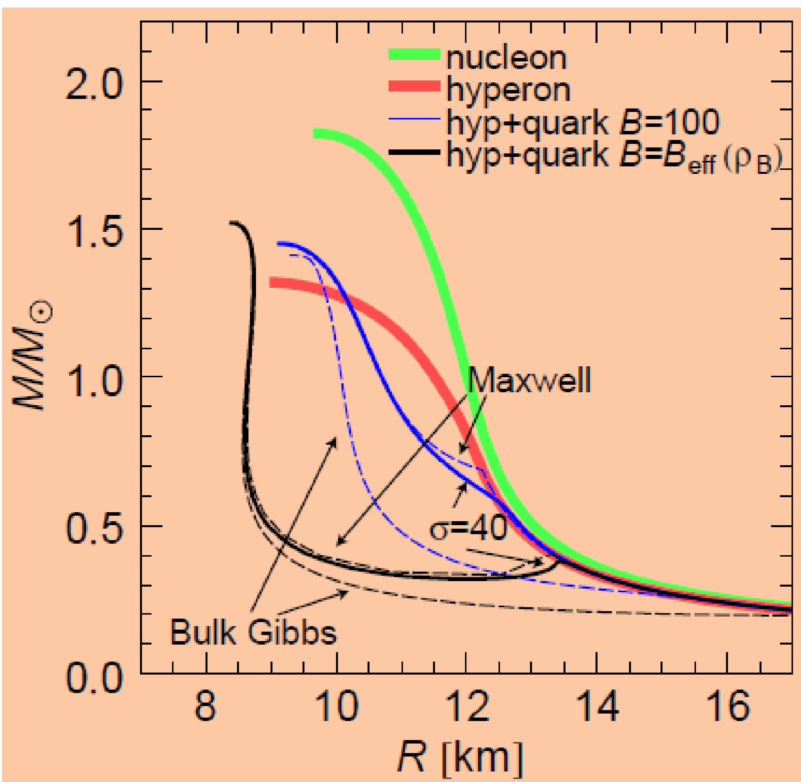




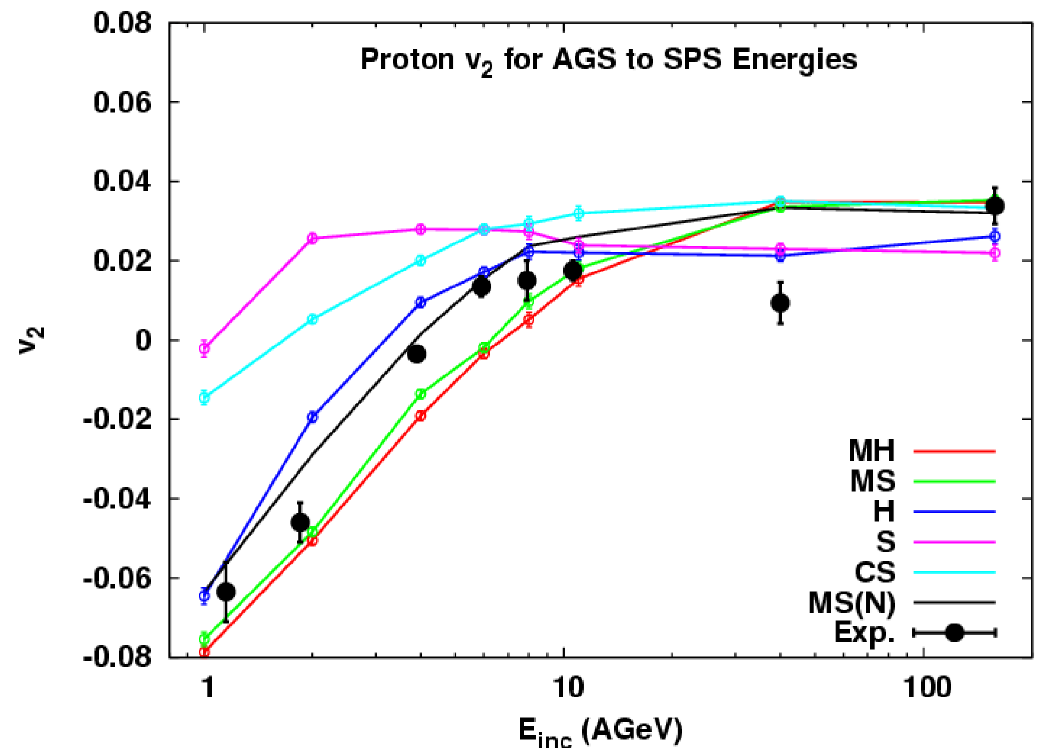
P. Danielewicz et al., Science298('02)1592.
R. Brockmann, R. Machleidt, PRC42('90)1965.

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

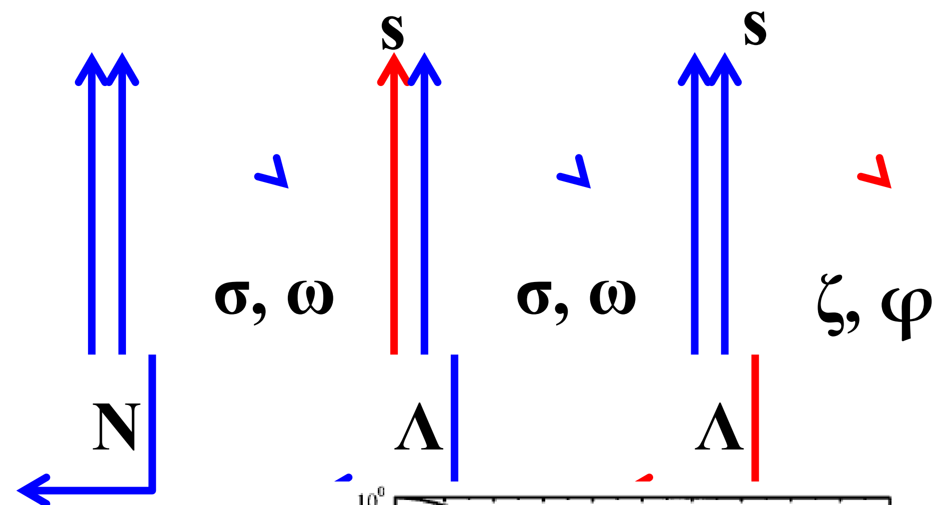


M.Isse, AO, N.Otuka, P. K.Sahu, Y.Nara, PRC72 ('05)064908

RMFへのハイペロンの導入

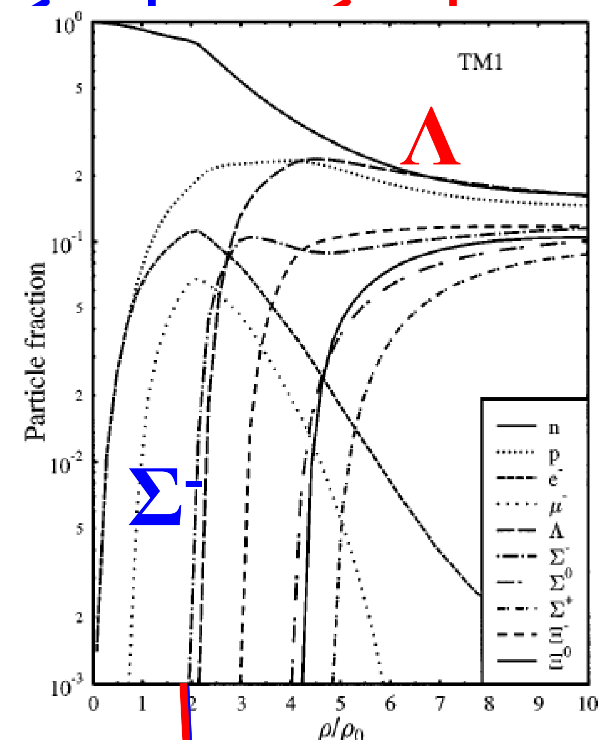
- 中間子・ハイペロン結合
- フレーバー・スピン(SU(6))対称性
～　クォーク数カウンティング
Glendenning ('81)

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



→ 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)

- ss からなるスカラー、ベクトル中間子
(ζ, φ)との結合を導入



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

- 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

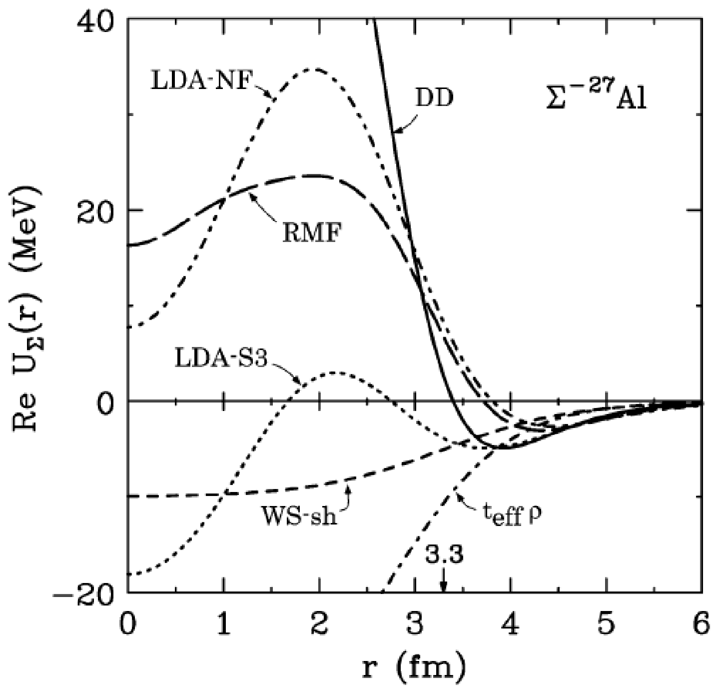
RMFへのハイペロンの導入

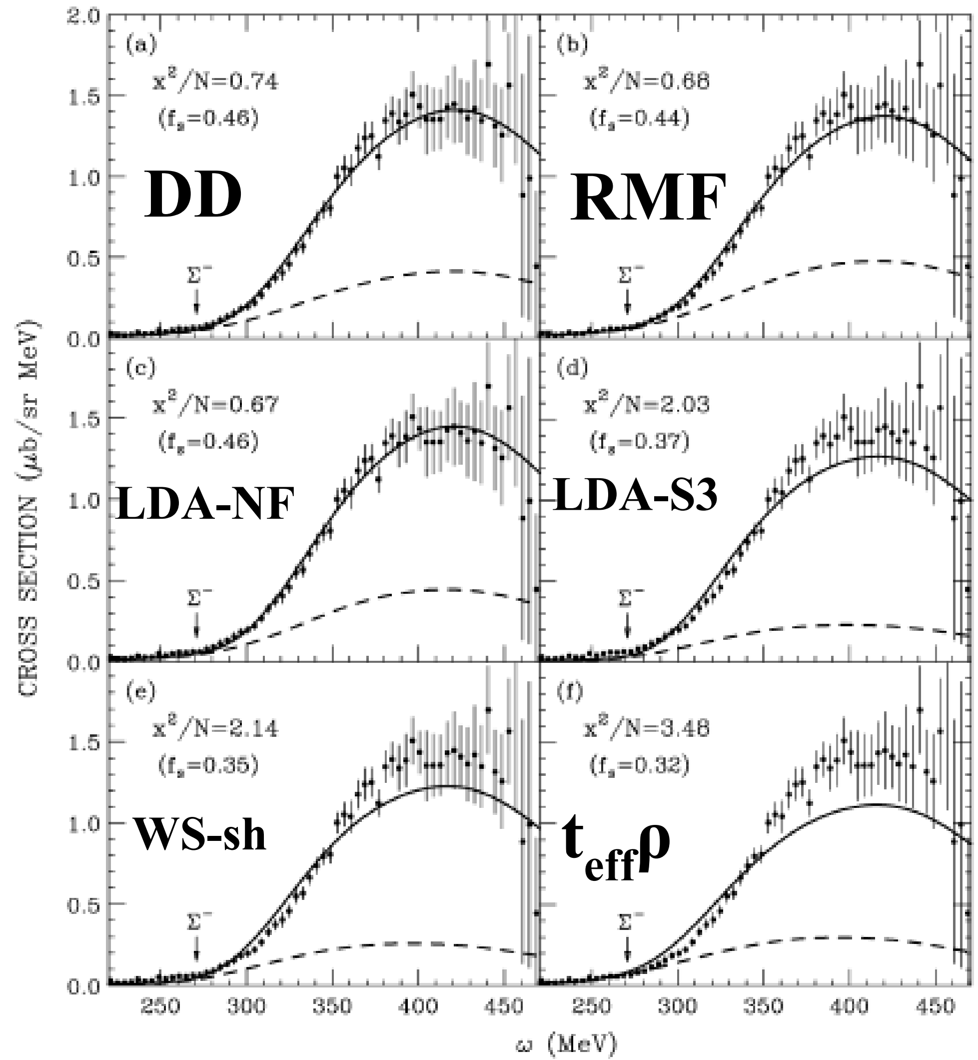
- クォーク数カウンティングに従うと、

$$U_\Sigma \sim U_\Lambda \sim 2/3\ U_N \sim -30\ \mathrm{MeV}$$

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)

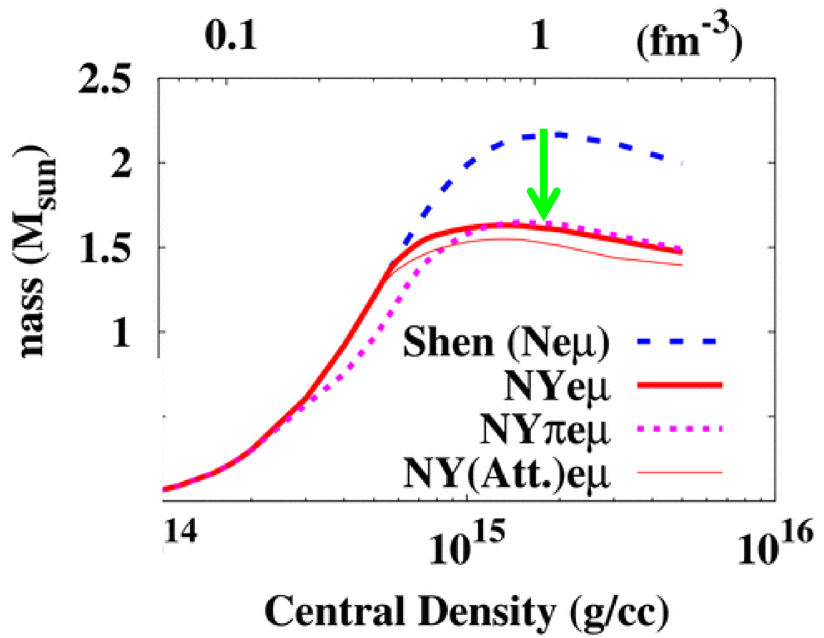




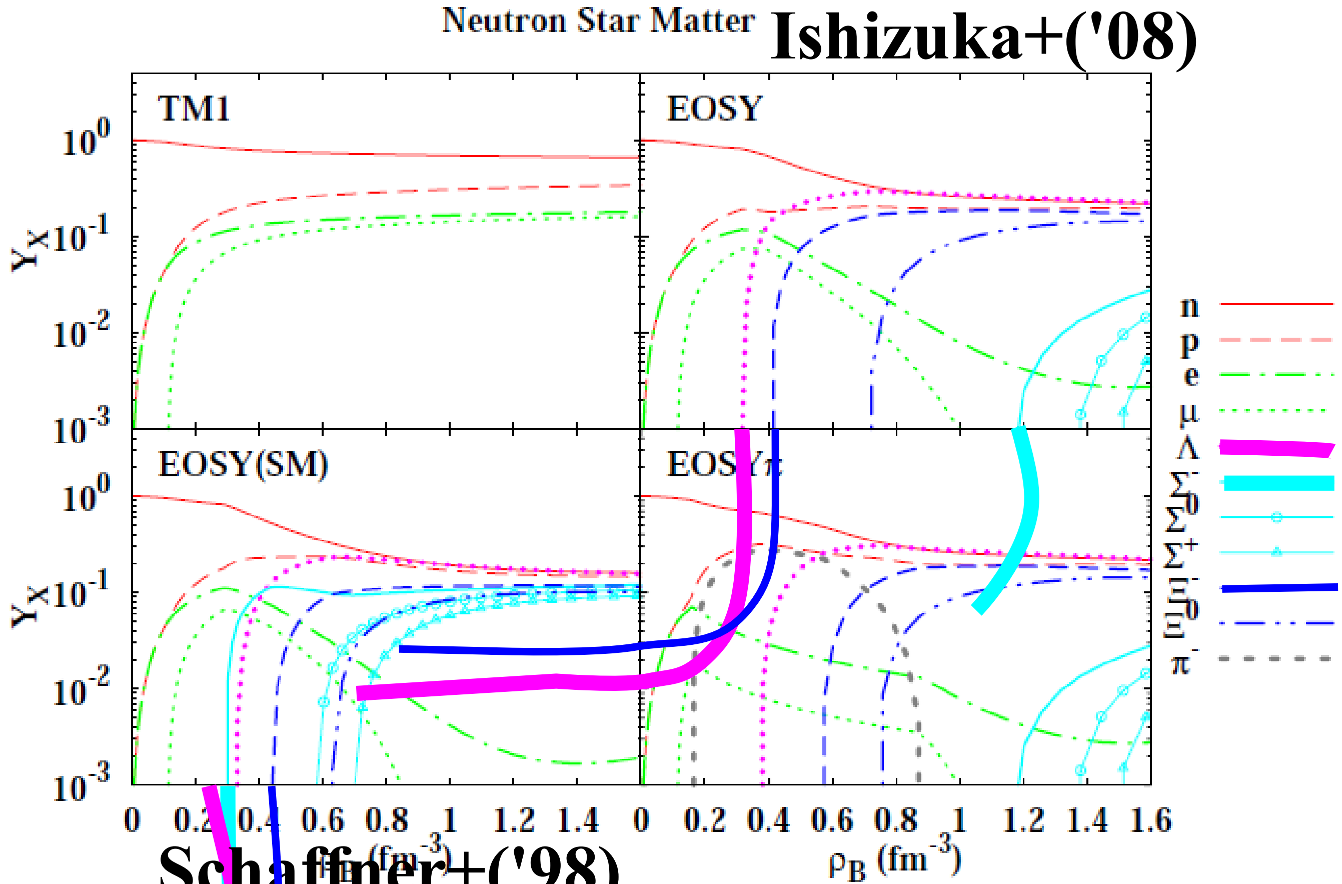
Harada, Hirabayashi ('05)

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

- **Hyperon Effect is DRASTIC**
- **Mmax=2.1 M$_\odot$ → 1.56 M$_\odot$**
- **Composition $Y_\Lambda \sim Y_n$**
- **Large fraction of Ξ**



Ishizuka+('08)

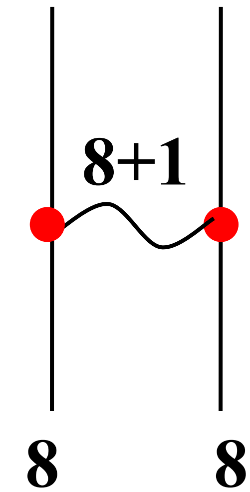


Schaffner+('98)

c.f. H.Shen+('09)
→ n, p, Λ EOS

何が中性子星を支えるのか？

■棄却されたEOS
＝　SU(3) (or SU(6))対称性に基づく中間子交換起源の2体斥力による平均場的状態方程式
Glendenning, Moszkowski ('91)



●相対論効果を含めても、ωΛ 結合 ~ (ωN 結合) x (2/3) とすると、1.97 $M_\odot$は支えられない。
→ ベクトル中間子交換以外の起源の斥力がある！

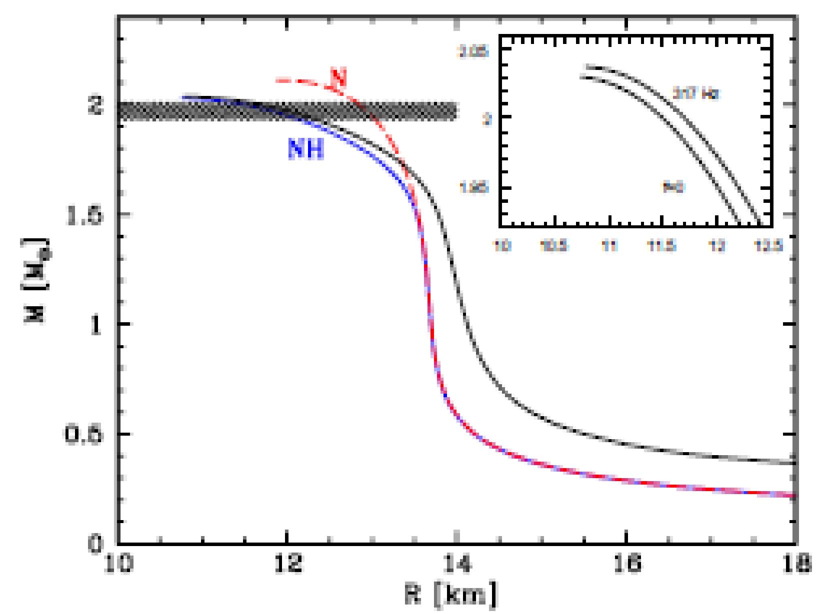
■高密度での斥力の起源は？

●3体斥力の導入
Nishizaki, Takatsuka, Yamamoto ('02)

●高次項の導入*Bednarek, Haensel et al.('11)*

●Vector 結合にSU(6)の破れを導入
Weisenborn, Chatterjee, Schaffner-Bielich ('11)

●クォーク物質への相転移
この学会での講演5件！
(高塚、益田、山崎、李、上田)



Bednarek, Haensel et al.('11)

3体力を含むRMF

- **3体力を含む相互作用項**

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

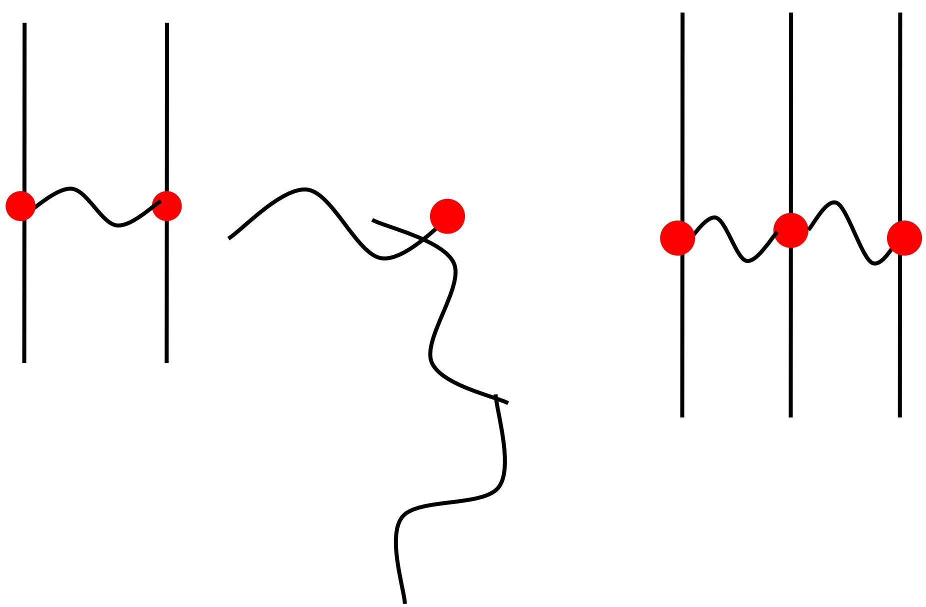
$$- \sum_B \bar{\psi}_B \left[g_{\sigma\sigma B} \sigma^2 + g_{\sigma\omega B} \sigma \omega_\mu \gamma^\mu + g_{\omega\omega B} \omega_\mu \omega^\mu \right] \psi_B$$

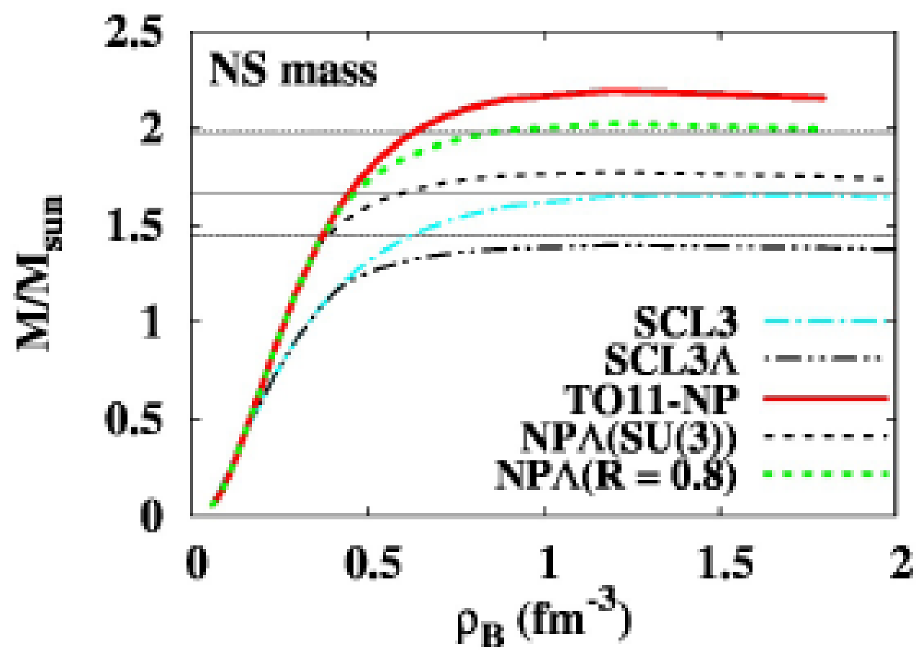
- **BBMM相互作用項は標準的なRMFでは無視**

(場の再定義により他の項に吸収可能) *Furnstahl, Serot, Tang ('97)*

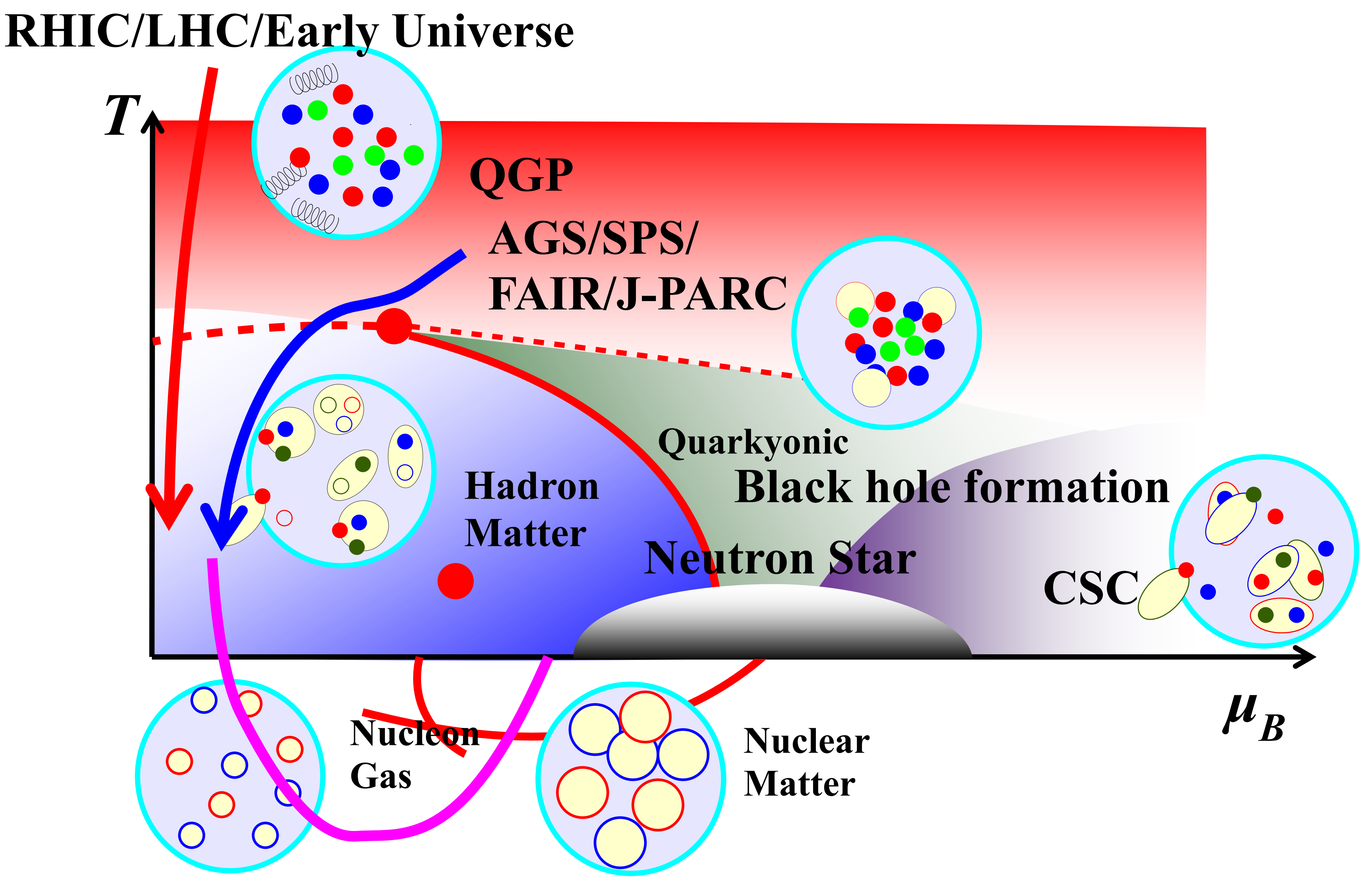
しかし場の再定義はNaïve dimensional analysis (NDA)の次数を変える

n = B/2 + M



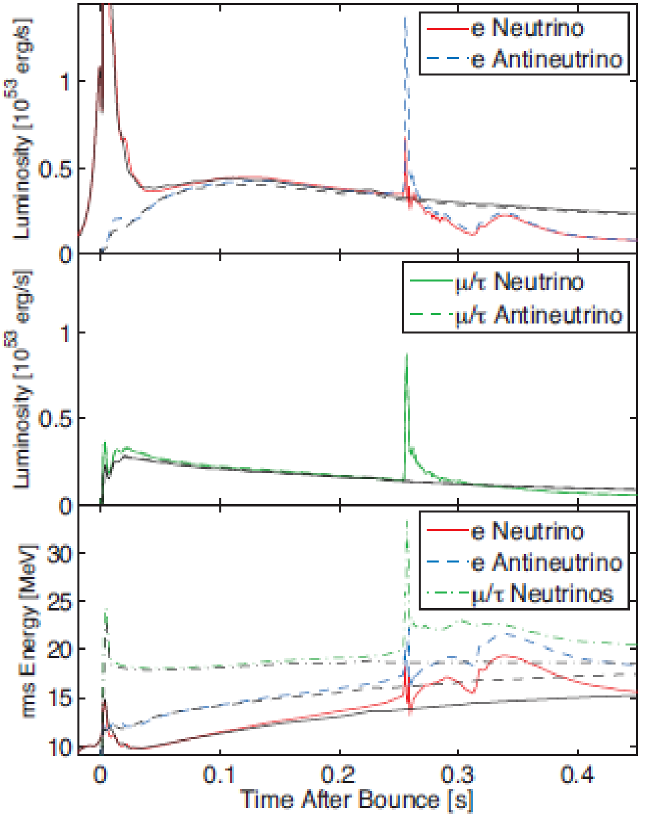


Tsubakihara, AO, in prep.

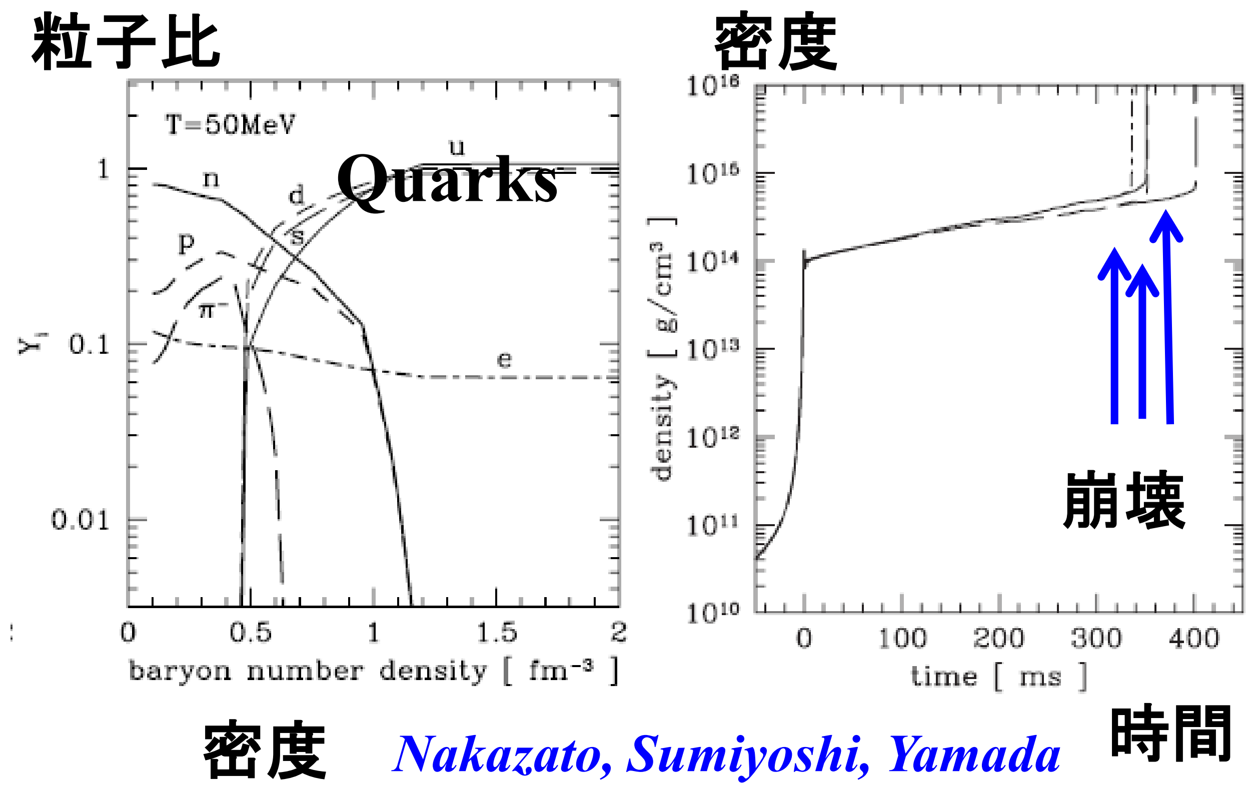

RHIC/LHC/Early Universe
T
QGP
AGS/SPS/
FAIR/J-PARC
Quarkyonic
Black hole formation
Hadron
Matter
Neutron Star
CSC
μ B
Nucleon
Gas
Nuclear
Matter

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)



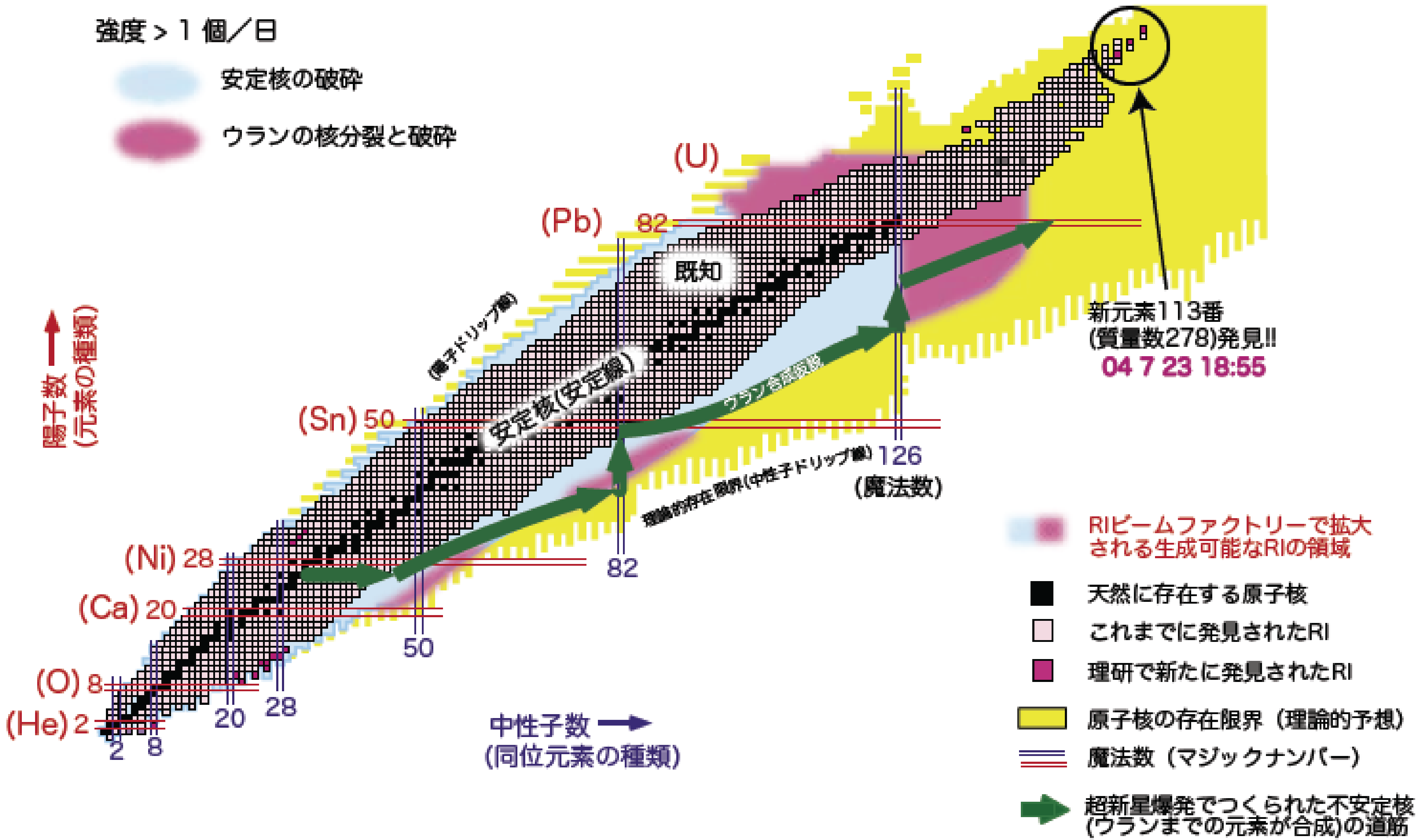
Sagert et al., 2009



Nakazato, Sumiyoshi, Yamada

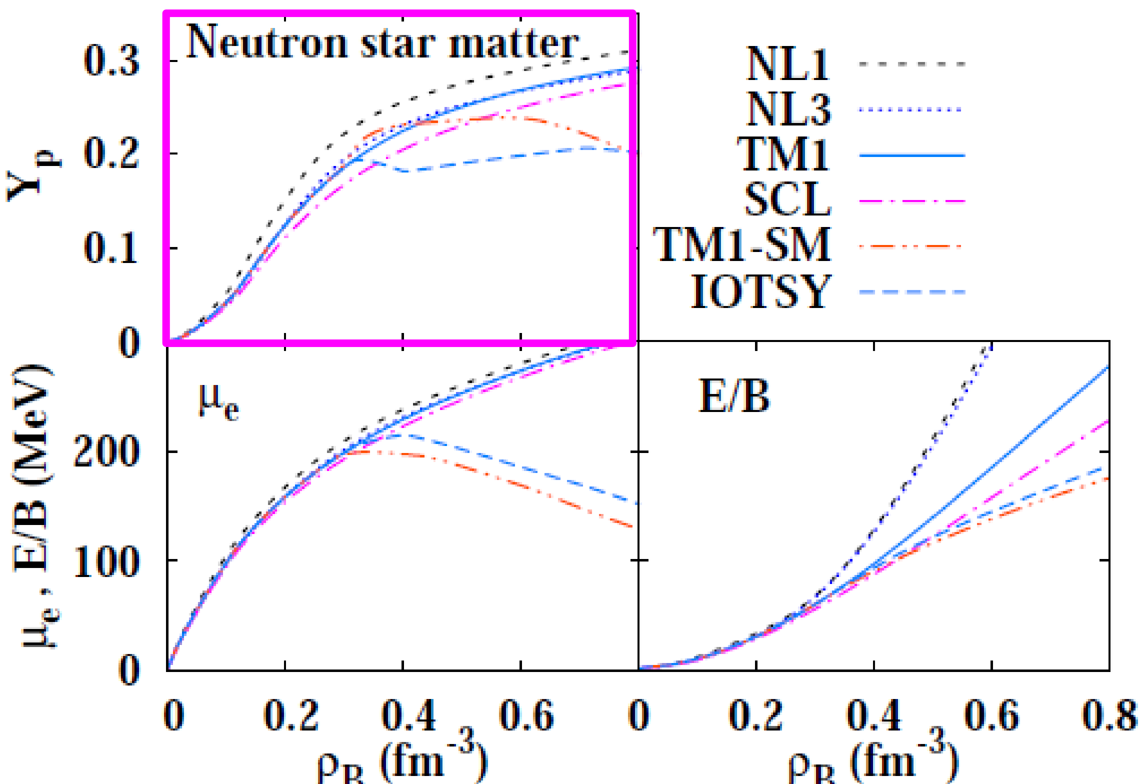
原子核の存在領域の拡大

Nishina Center RIBF Pamph.

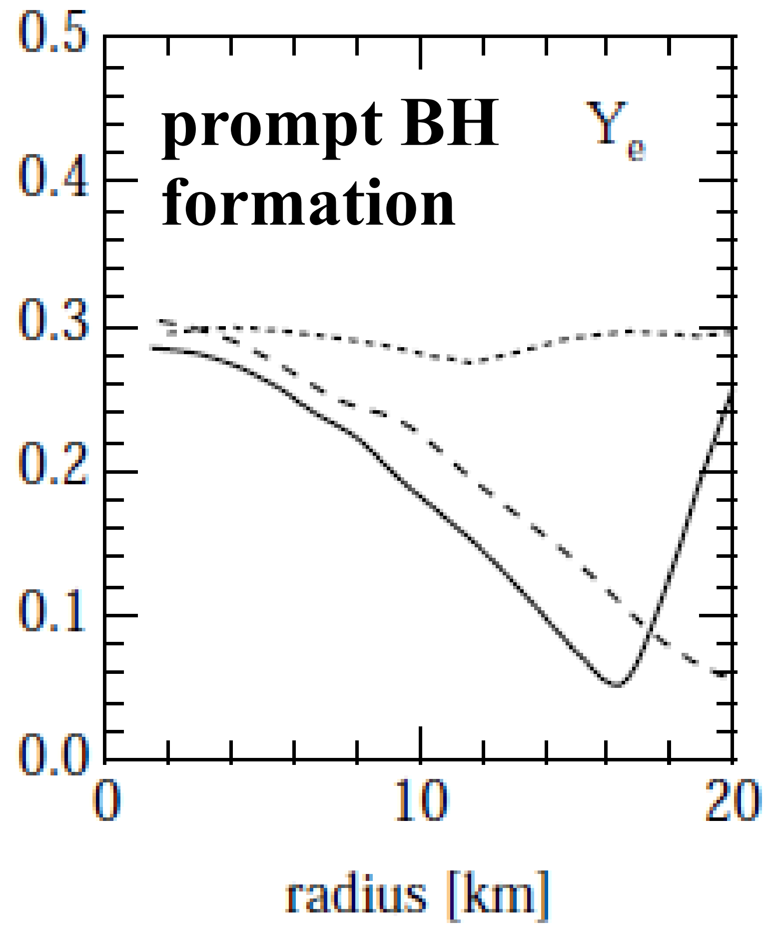


Compact Star Matter is Neutron Rich

- **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 $Y_p \sim (0.1\text{-}0.3)$**



AO+('09)



Sumiyoshi+('09)

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

d u u 陽子

d u s Λハイペロン

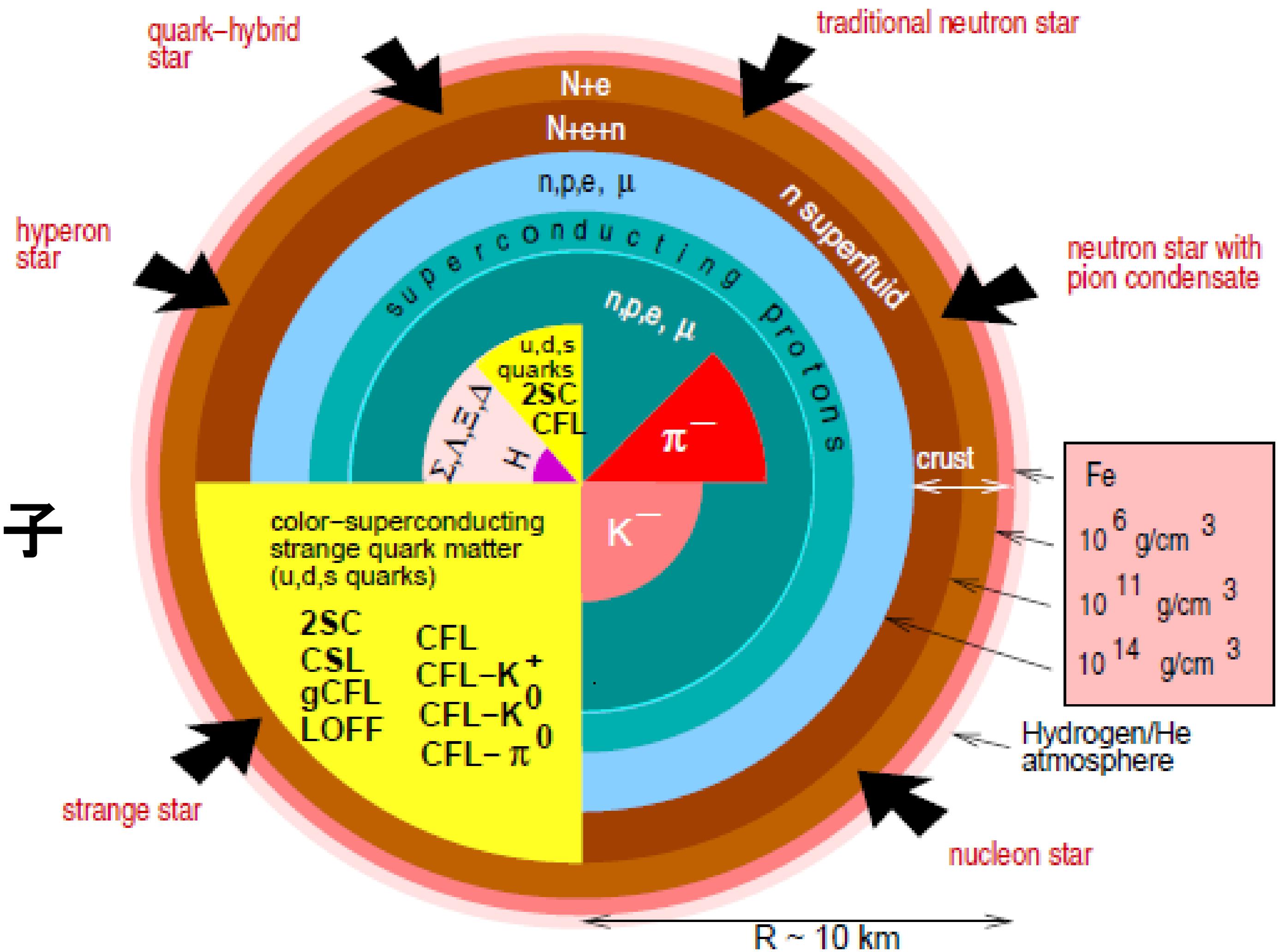
- 中間子凝縮(K, π)

d u π 中間子

u s (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)

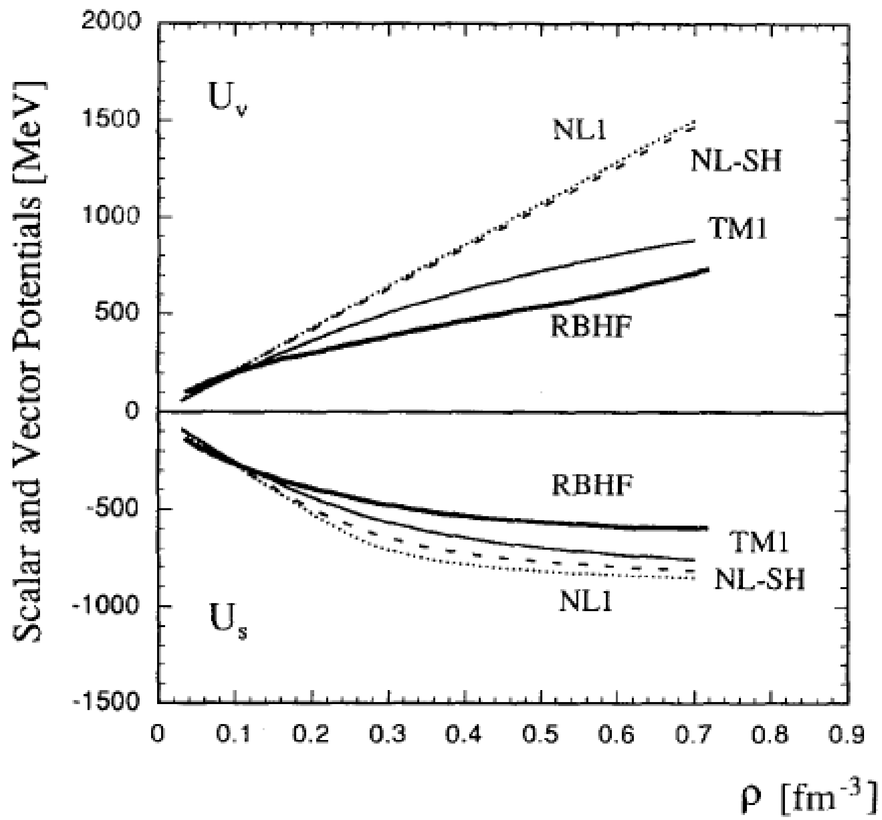
d 2SC

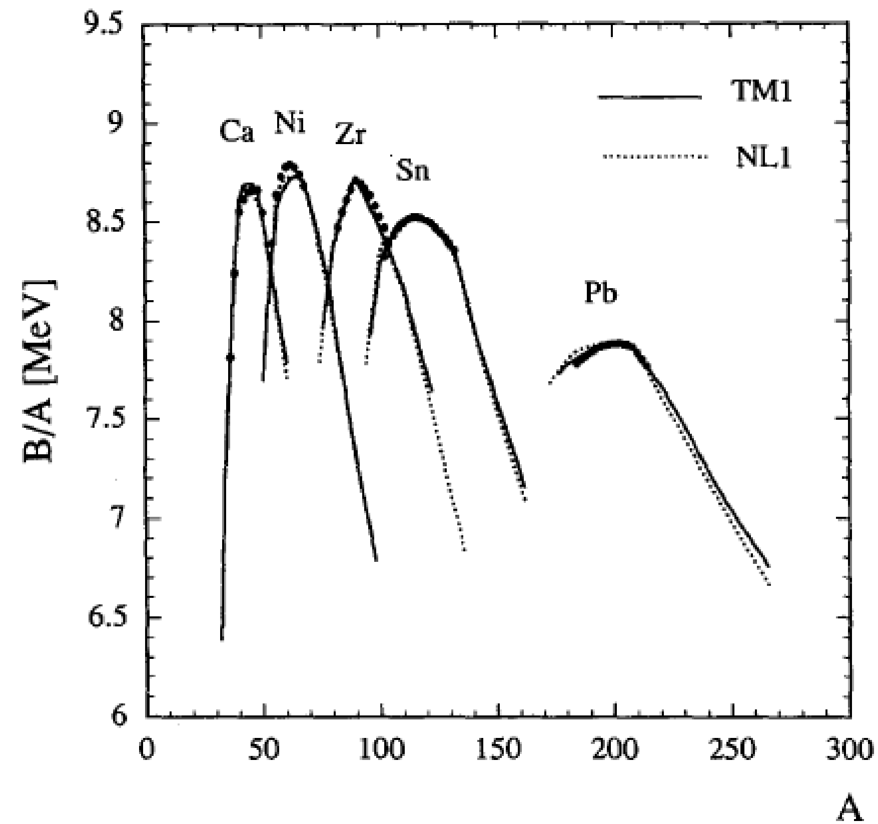


F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193

RMF with meson self-interaction

- 最も単純な RMF (σω模型) ではEOSが硬すぎる(K > 600 MeV)
- Self-interaction term of mesons
- ω^4 の導入 → 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 → 柔らかい状態方程式が可能

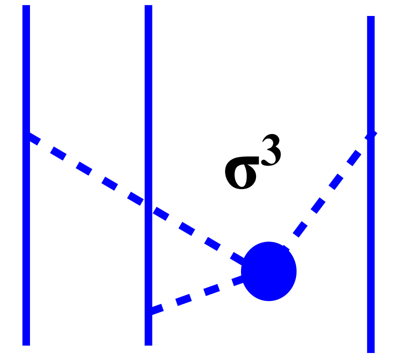




TM1: Sugahara, Toki ('94)

High Quality RMF models

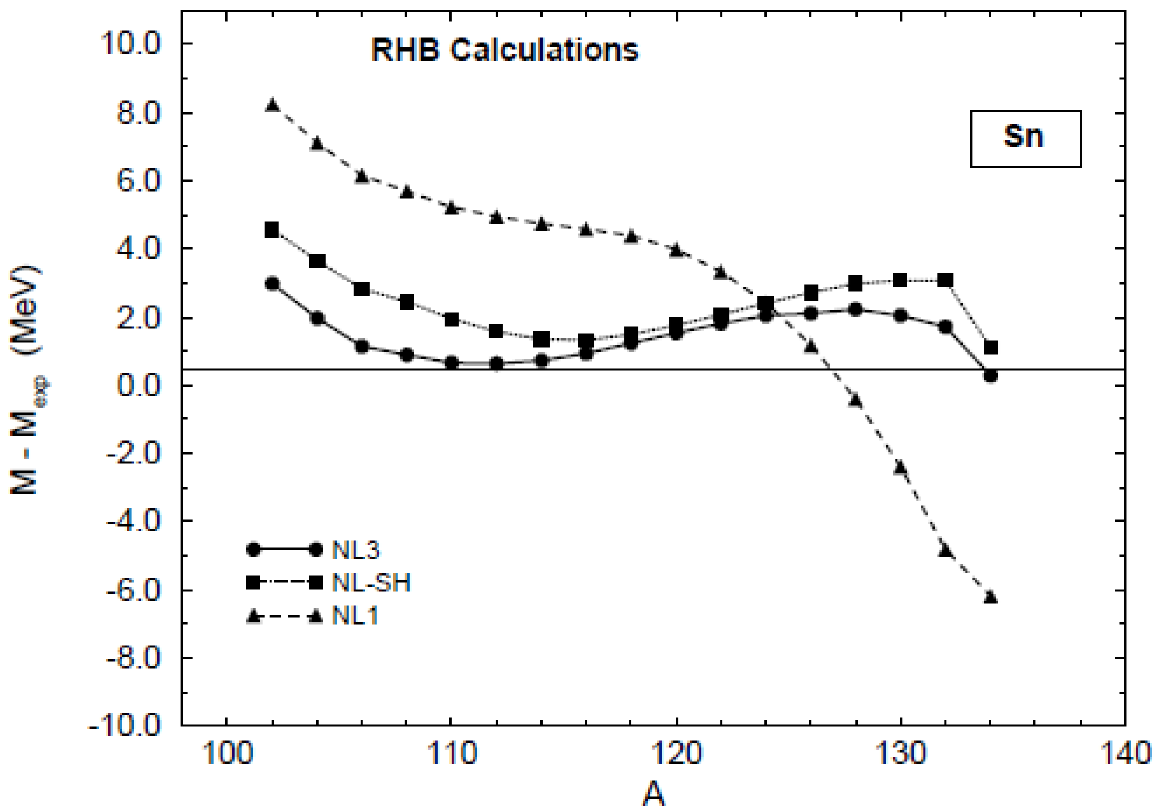
- いくつかのRMFパラメータによる計算は、「質量公式」に迫る精度で原子核質量を記述！
→ High Quality RMF models.
TM, NL1, NL3, ….



- 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

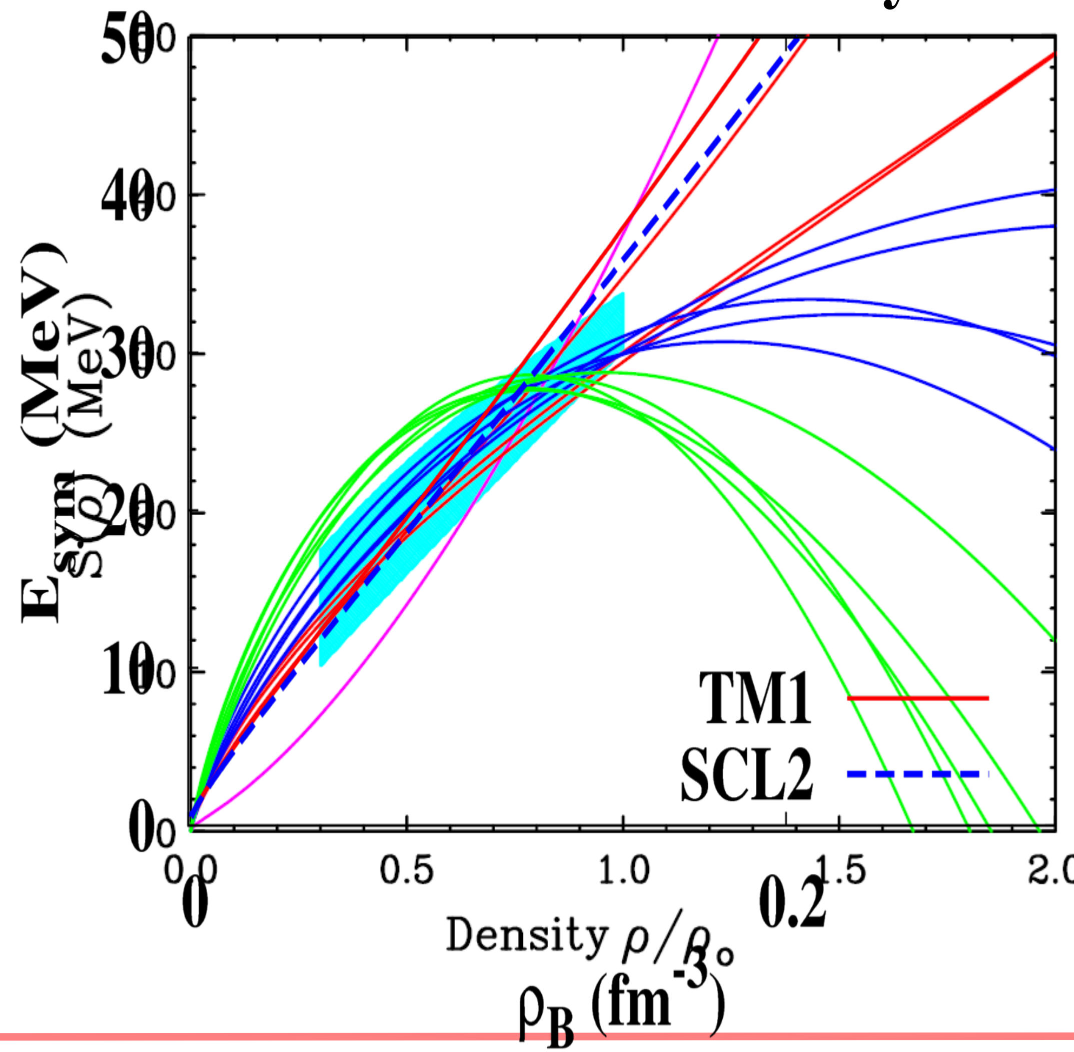
Symmetry Energy

- Summary of Nuclear Symmetry Energy workshop NuSym11 http://www.smith.edu/nusym11

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

extracted from various observations.

TM1: barely OK



- 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 Esym に敏感。

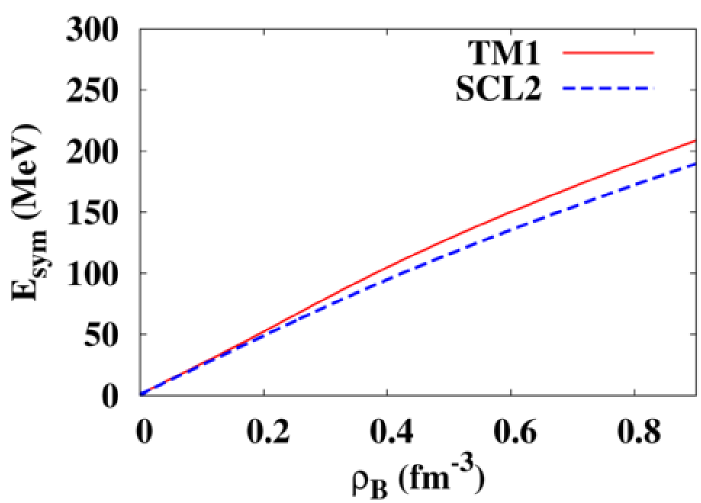
- RMFs have small ambiguity in Esym.

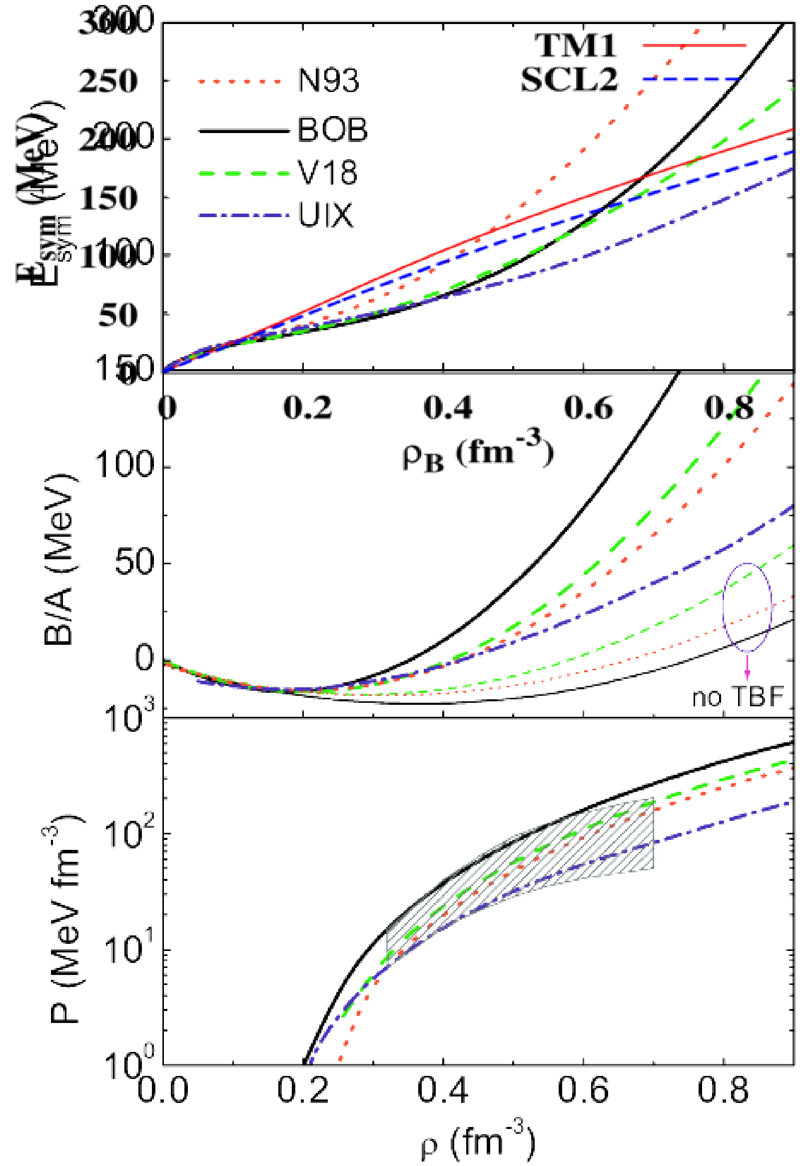
Is it true ?

- 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

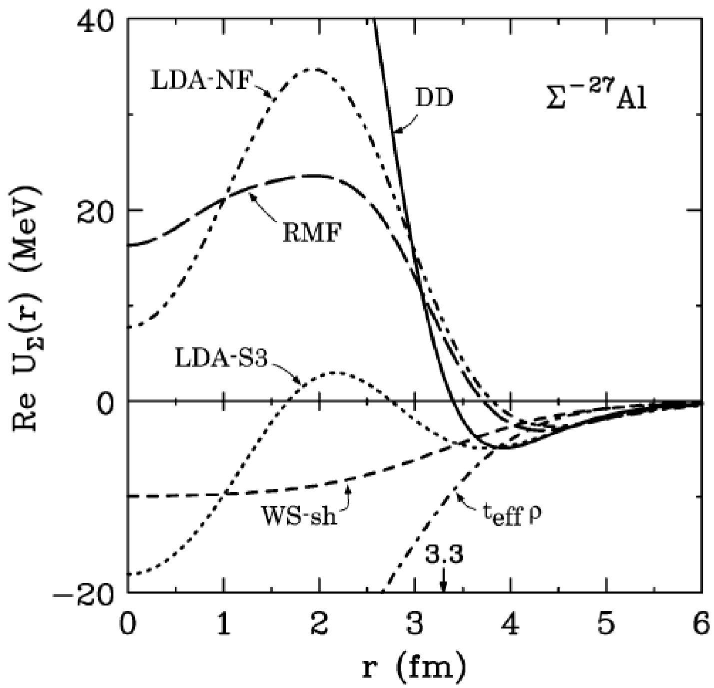
RMFへのハイペロンの導入(2)

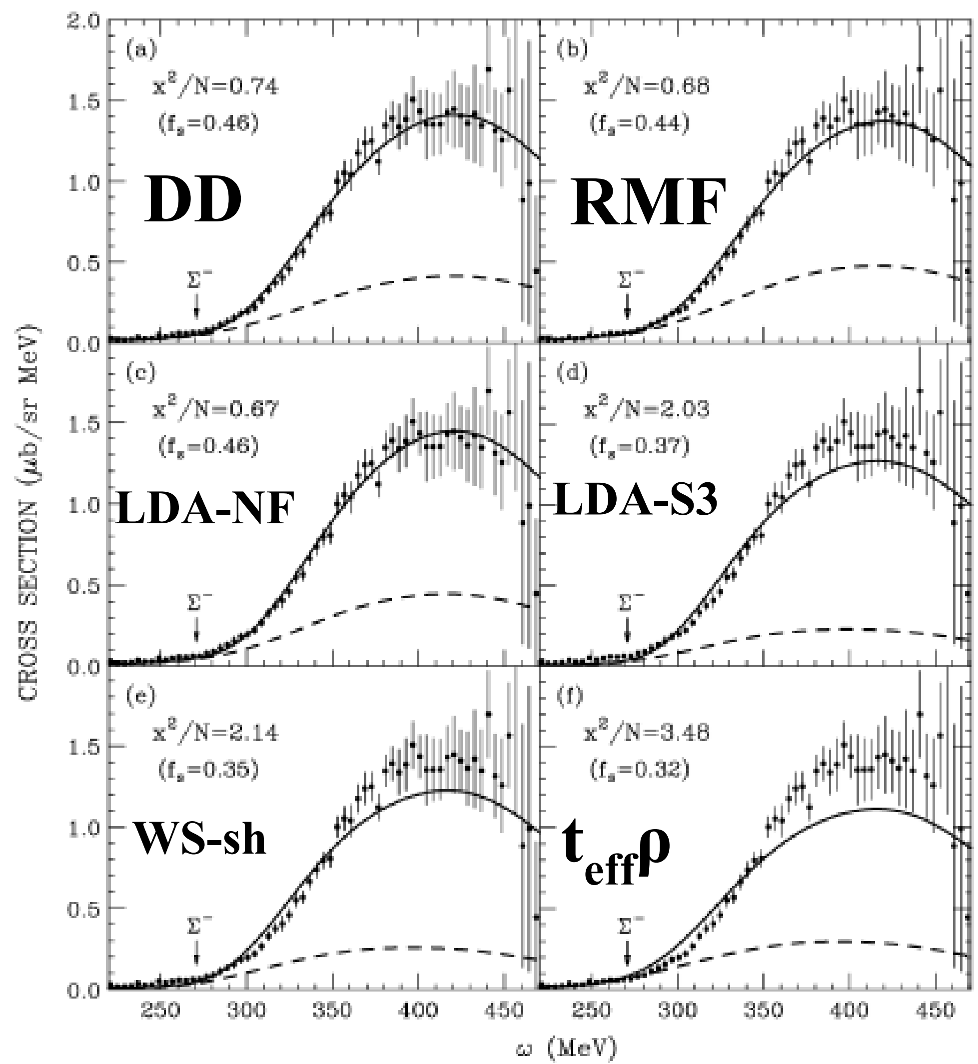
- クォーク数カウンティングに従うと、

$$U_\Sigma \sim U_\Lambda \sim 2/3\ U_N \sim -30\ \mathrm{MeV}$$

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)

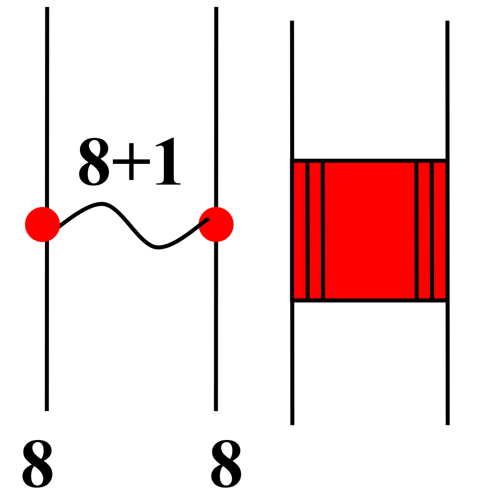




Harada, Hirabayashi ('05)

$SU(3)_f$ "violating" coupling

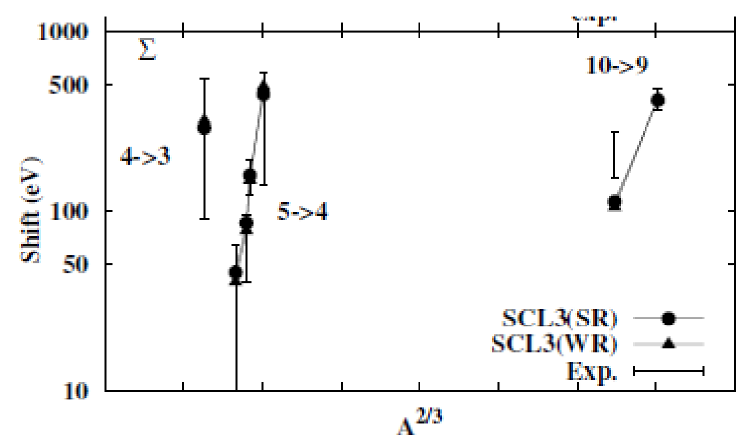
- Naïve RMF assumption = BM coupling follows $SU(3)_f$.
- Short range BB interaction comes from quark Pauli blocking + one-gluon exch.
  Oka, Yazaki; Faessler et al.; Fujiwara et al.; HAL QCD collab.
- Short-range BB repulsion is sensitive to (S,T) in the s-channel. When we include those interactions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



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

E.g., Σ atomic shift
$\to g_{\sigma\Sigma} \sim g_{\sigma\Sigma}$ (SU(3)) x (0.2-0.3)

- Finite size of baryons would lead to excluded volume effects → μ – vP
  (flavor singlet vector-like effects)

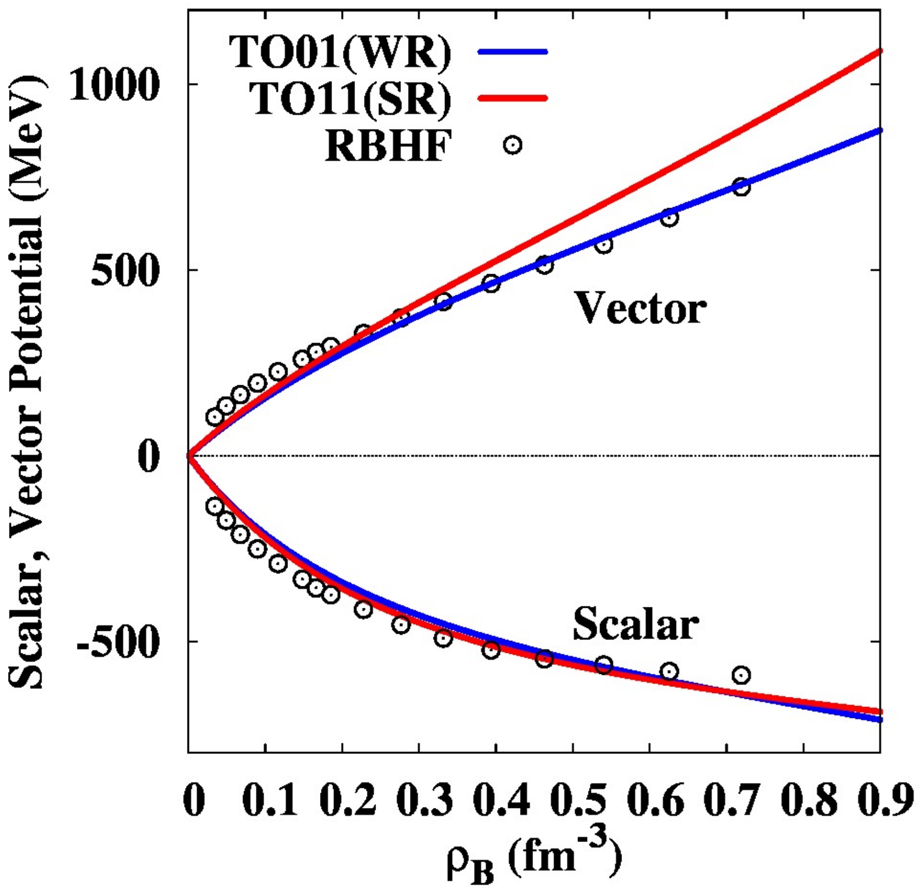


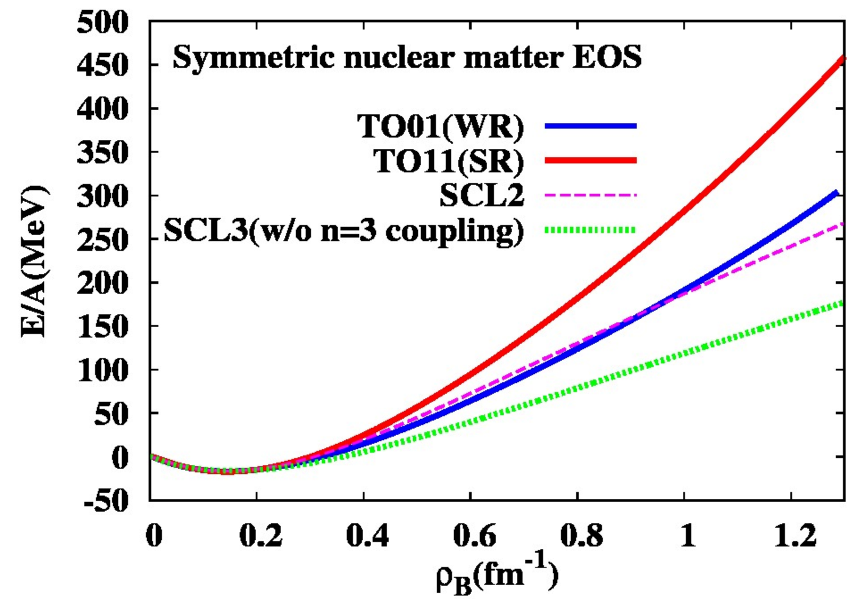
Tsubakihara et al., (2010)

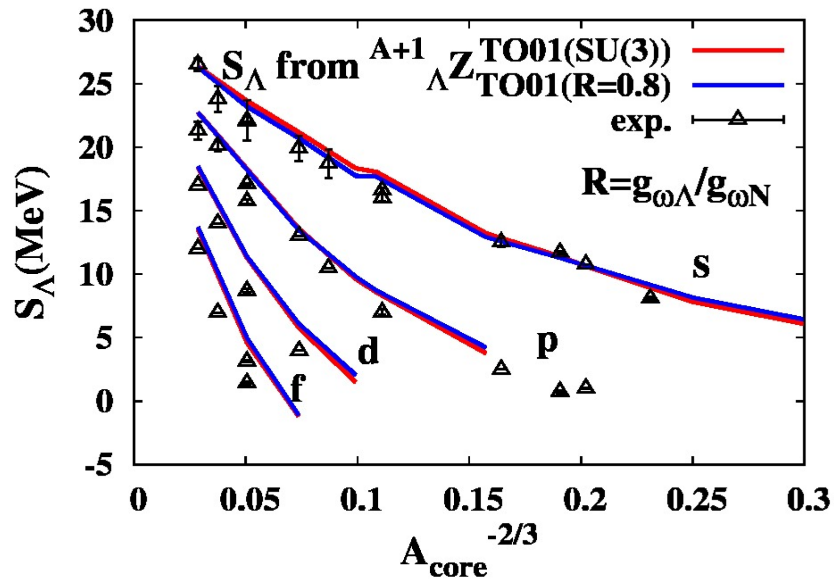
RMF with 3BF

Tsubakihara, AO, in prep.

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



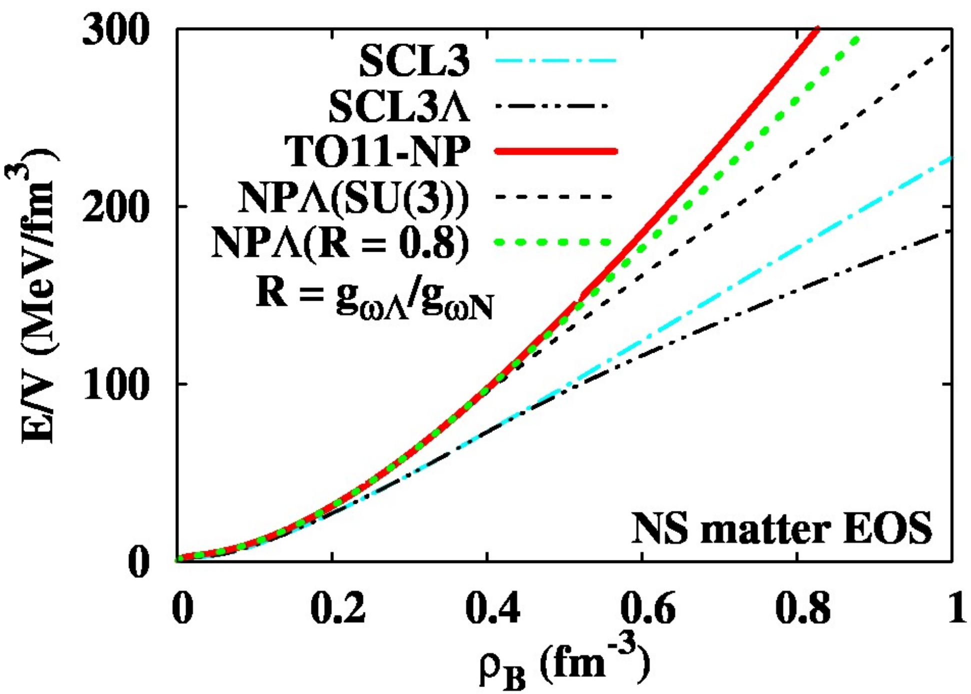


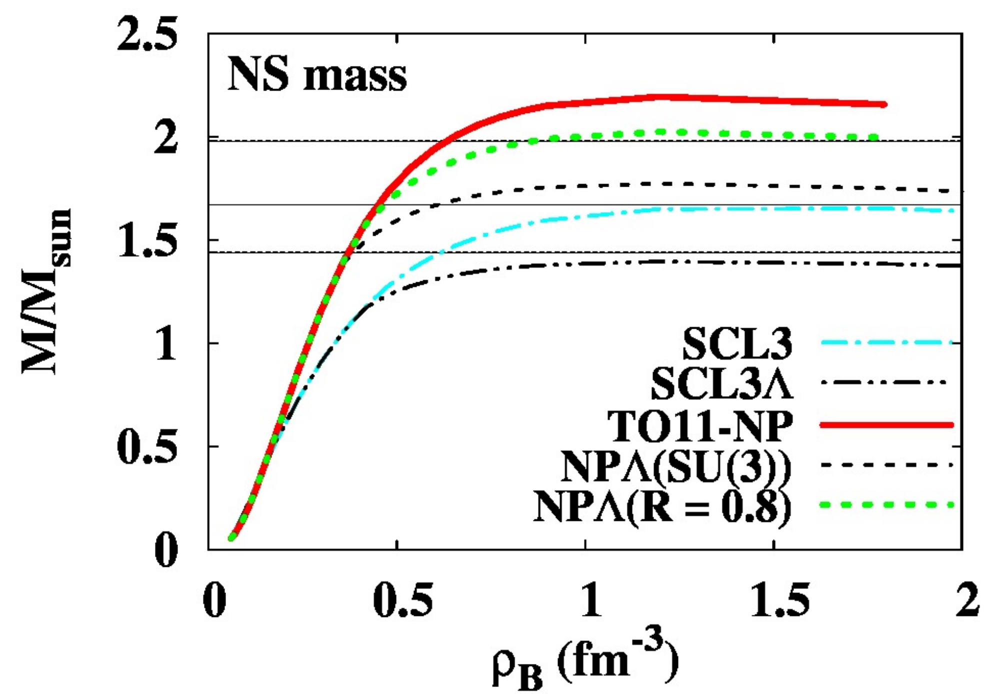


RMF with 3BF + $SU(3)_f$ "violation"

Tsubakihara et al., in prep.

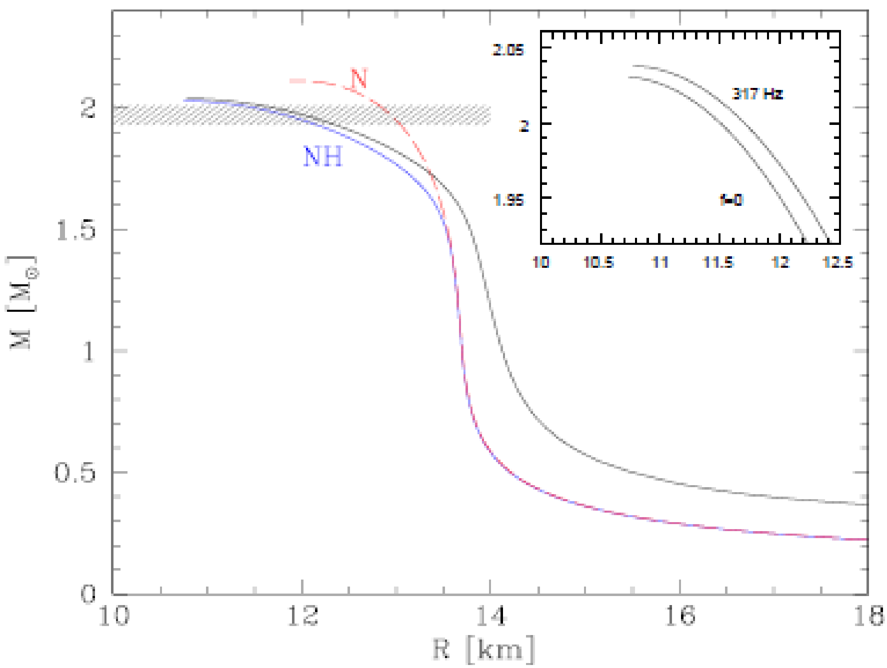
- **Two types of modification**
- **3-baryon repulsion → EOS becomes stiff gradually at high density. (Fitting meson mass (E325) and Uv in RBHF)**
- **$R = g_{\omega\Lambda} / g_{\omega N} \sim 0.8$ (> 2/3 (SU(3))**
- **→ $M_{max} \sim 2.02\ M_{\odot}$ with hyperons (~ 1.4 $M_{\odot}$ w/o 3BF, violation)**



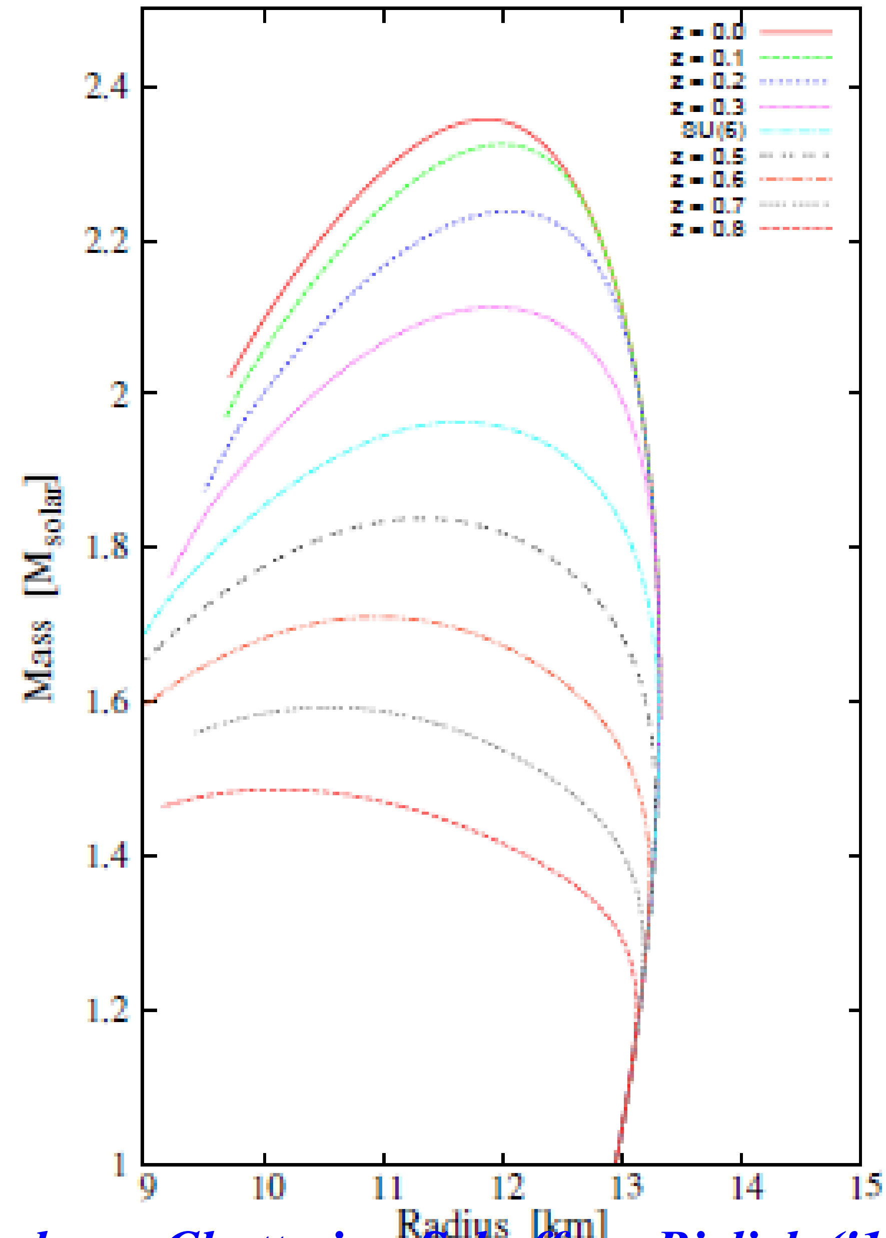


他の解決方法

- Hidden strange meson の4次
  - ζ^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



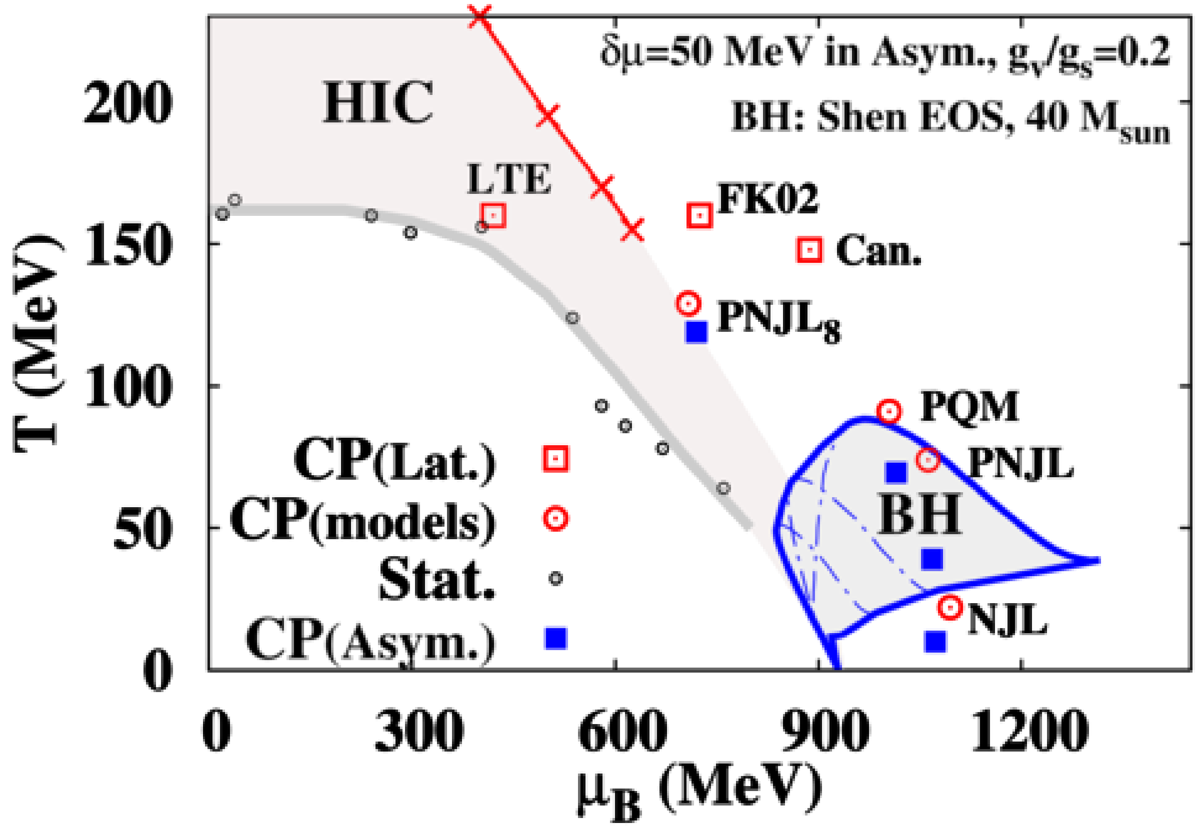
Bednarek, Haensel at al.('11)



Weisenborn, Chatterjee, Schaffner-Bielich ('11)

Swept Region of Phase Diagram during BH formation

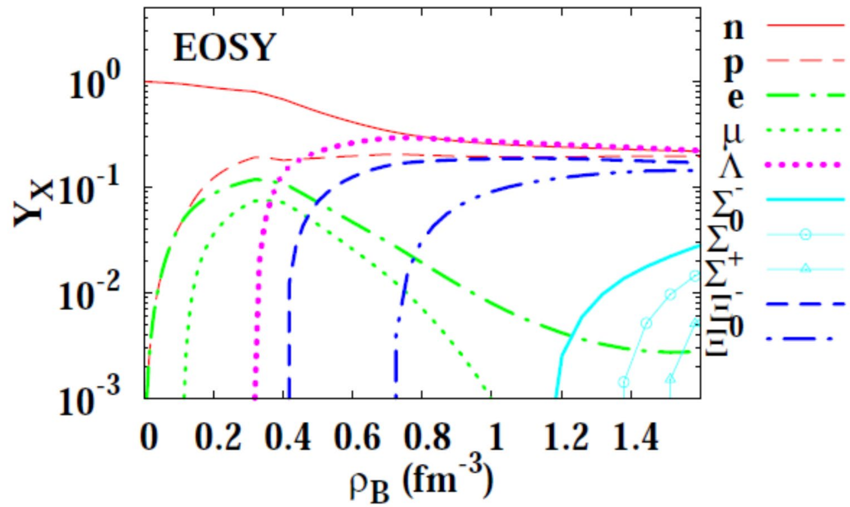
- CP location
in Symmetric Matter
- Lattice QCD
  μ_{CP}=(400-900) MeV
- Effecitve models
  μ_{CP}=(700-1050) MeV
- CP in Asymmetric Matter
(E.g. $\delta\mu$=50 MeV)
- T_{CP} decreases at finite $\delta\mu$.
→ Accessible (T, μ_B) region during BH formation



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

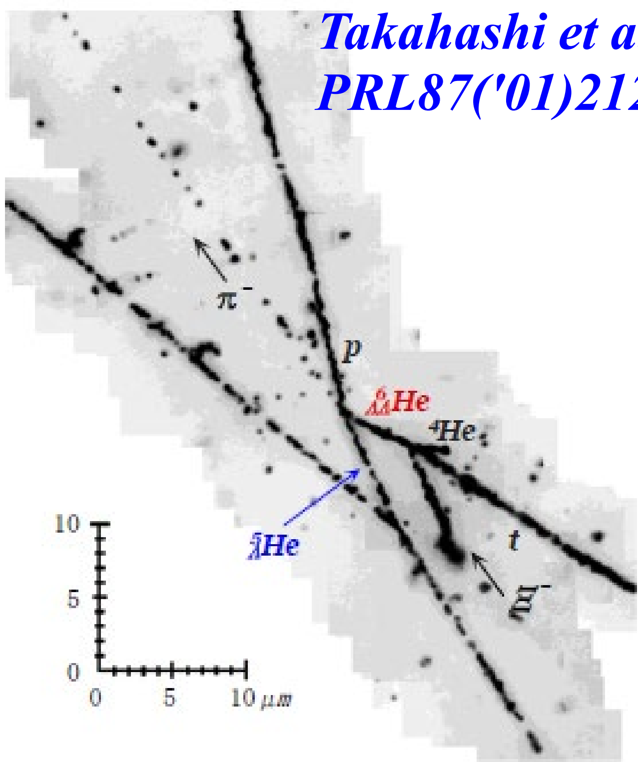
ハイペロン-ハイペロン相互作用

- 中性子星のハイペロン
- コア領域での化学ポテンシャル
  $\mu_B \sim 1650$ MeV >> M_Λ (Shen EOS)
  → ハイペロンが出てくるのが自然

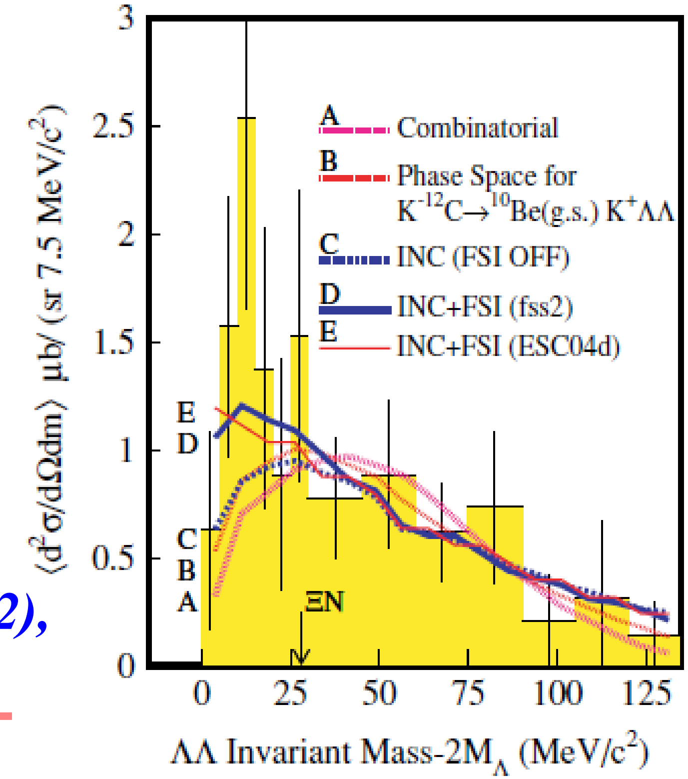


Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, JPG35('08)085201

- ΛΛ 相互作用は？
  … ダブル Λ ハイパー核、ΛΛ corr.



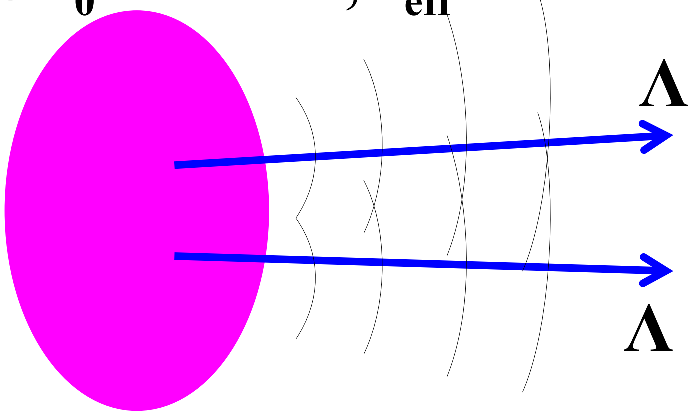
Takahashi et al.(KEK-E373), PRL87('01)212502

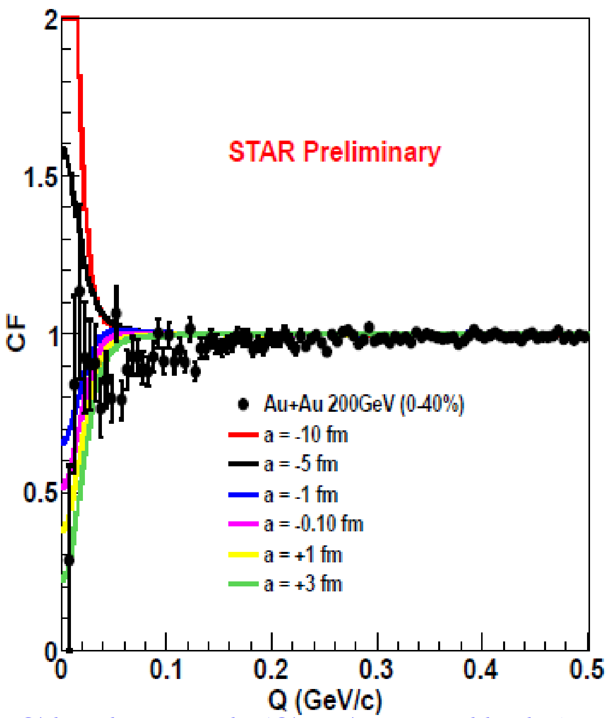


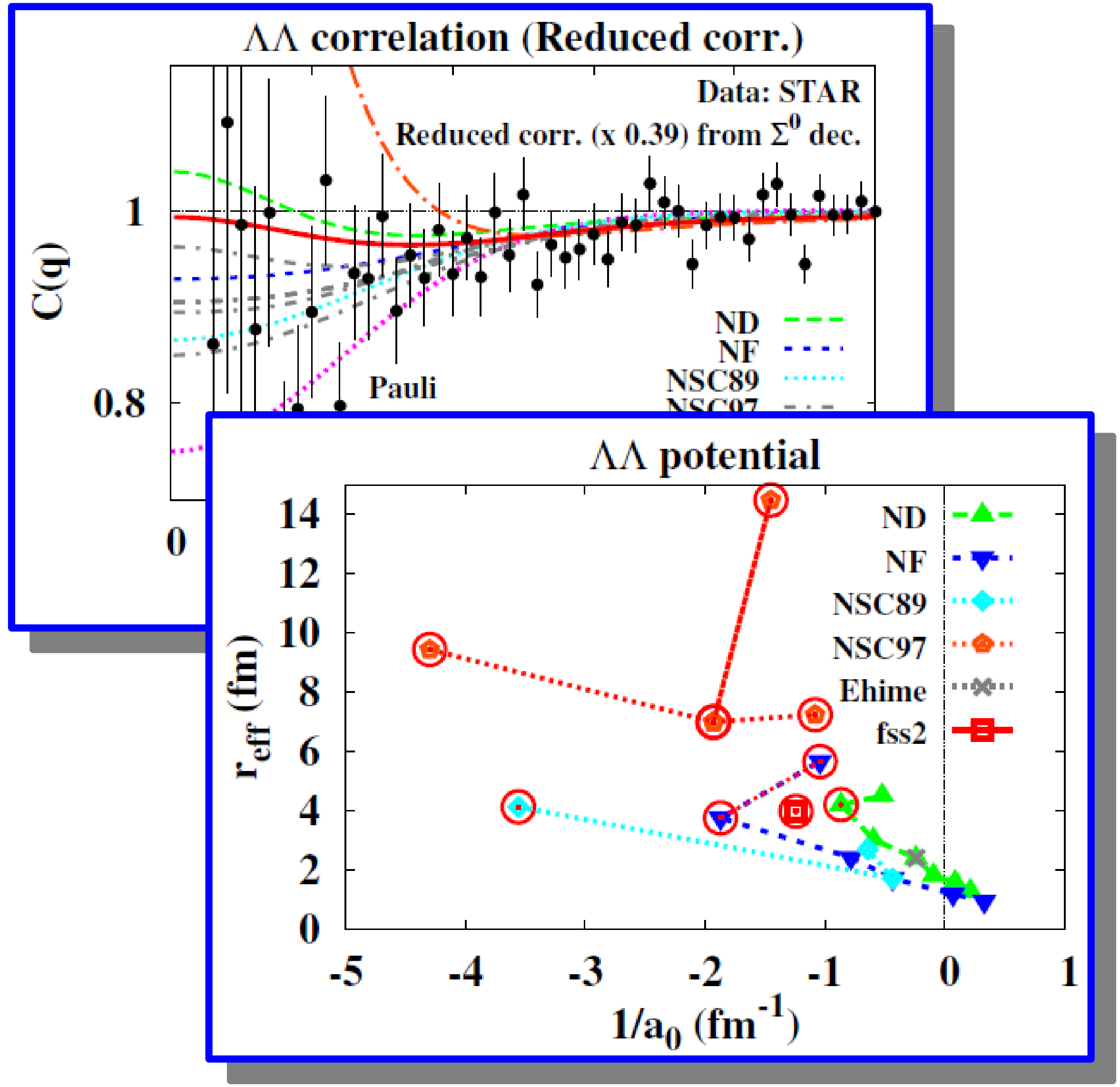
C.J.Yoon et al., (KEK-E522), PRC75 (2007) 022201(R)

- **RHIC-STAR measured ΛΛ correlation !**

→ $1/a_0 < -1\ \mathrm{fm}^{-1}$, $r_{eff} > 3$ fm







Shah et al.(STAR collab.), arXiv:1112.0590

AO, Furumoto, HHI workshop @ BNL