高密度物質と中性子星の物理
Physics of Neutron Star Matter

京大基研　大西　明
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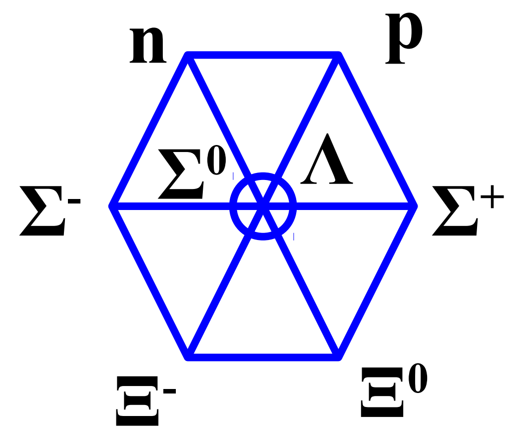
- 中性子星の基本的性質
- 状態方程式を記述する理論模型
- 対称エネルギーと非対称核物質の状態方程式
- ハイパー核物理と高密度核物質の状態方程式
- 中性子星におけるエキゾチック自由度
- Supplementary Contents
  - 実験・観測・理論で解き明かす中性子星物質状態方程式
  - 重イオン衝突とハイパー核から中性子星へ

大阪大学集中講義　7/30-8/1

Hyperons (Baryons with Strangeness)

- **Ground state baryon $SU(3)_f$ octet (J^π=1/2+)**

Baryon	M(Mev)	S	Comp.
n	940	0	udd
p	938	0	uud
Λ	1116	-1	$(uds-dus)/\sqrt{2}$
Σ^+	1189	-1	uus
Σ^0	1193	-1	$(uds+dus)/\sqrt{2}$
Σ^-	1197	-1	dds
Ξ^0	1315	-2	uss
Ξ^-	1321	-2	dss



$SU(3)_f$ transformation

- **Fundamental triplet $(u,d,s)^T = q \to q'=U\,q\ (U \in SU(3))$**
- **Diquark $D_i = \varepsilon_{ijk}\, q_j\, q_k \to D' = D\, U^+$**
- **Baryon octet $B_{ij} = D_j\, q_i \to B'=UBU^+$**

$$\begin{pmatrix} [ds]u & [su]u & [ud]u \\ [ds]d & [su]d & [ud]d \\ [ds]s & [su]s & [ud]s \end{pmatrix} = \begin{pmatrix} \frac{\Lambda}{\sqrt{6}}+\frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}}-\frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

$SU(3)_f$ transformation

- **Fundamental triplet $(u,d,s)^T = q \to q' = U q$ ($U \in SU(3)$)**
- **Anti-quark $\bar{q} \to \bar{q}' = \bar{q}\, U^+$**
- **Meson octet $M_{ij} = \bar{q}_j q_i \to M' = UMU^+$**

$$\begin{pmatrix} \bar{u}u & \bar{d}u & \bar{s}u \\ \bar{u}d & \bar{d}d & \bar{s}d \\ \bar{u}s & \bar{d}s & \bar{s}s \end{pmatrix} = \begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} = P$$

$$S = \begin{pmatrix} \frac{\sigma}{\sqrt{2}} + \frac{a_0}{\sqrt{2}} & a_0^+ & \kappa^+ \\ a_0^- & \frac{\sigma}{\sqrt{2}} - \frac{a_0}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & \zeta \end{pmatrix} \qquad V = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

$SU(3)_f$ invariant coupling

- **Baryon-Meson coupling**

$$\mathcal{L}_{\rm BV} = \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\,(\bar{B}B) + g_D\,{\rm tr}\,(\bar{B}\,\{M_v, B\}) + g_F\,{\rm tr}\,(\bar{B}\,[M_v, B])\}$$
$$= \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\,(\bar{B}B) + g_1\,{\rm tr}\,(\bar{B}M_vB) + g_2\,{\rm tr}\,(\bar{B}BM_v)\}$$

- **Assumption**
  - **BM coupling is SU(3) invariant**
  - **N does not couple with $s\bar{s}$ vector meson**

$$g_{\omega\Lambda} = \frac{5}{6}g_{\omega N} - \frac{1}{2}g_{\rho N}\,,\quad g_{\phi\Lambda} = \frac{\sqrt{2}}{6}\left(g_{\omega N} + 3g_{\rho N}\right)$$

- **Further simplification: $g_{\rho N} = g_{\omega N}/3$ (quark counting)**

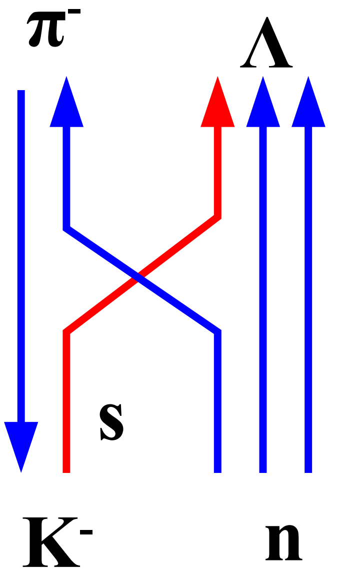
$$g_{\omega N} = g_v\,,\quad g_{\rho N} = g_v/3\,,\quad g_{\omega\Lambda} = 2g_v/3\,,\quad g_{\phi\Lambda} = \sqrt{2}\,g_v/3$$

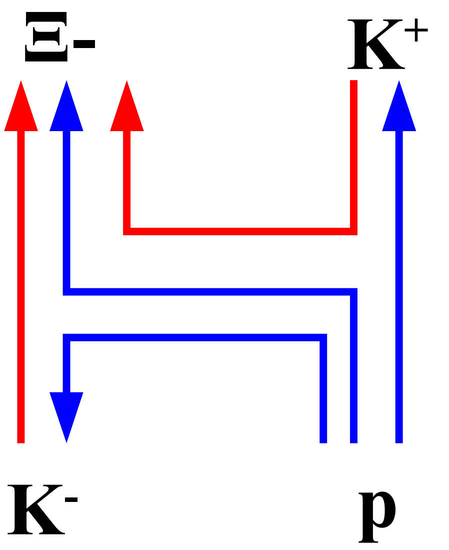
Hypernuclear Formation

Hypernuclear formation

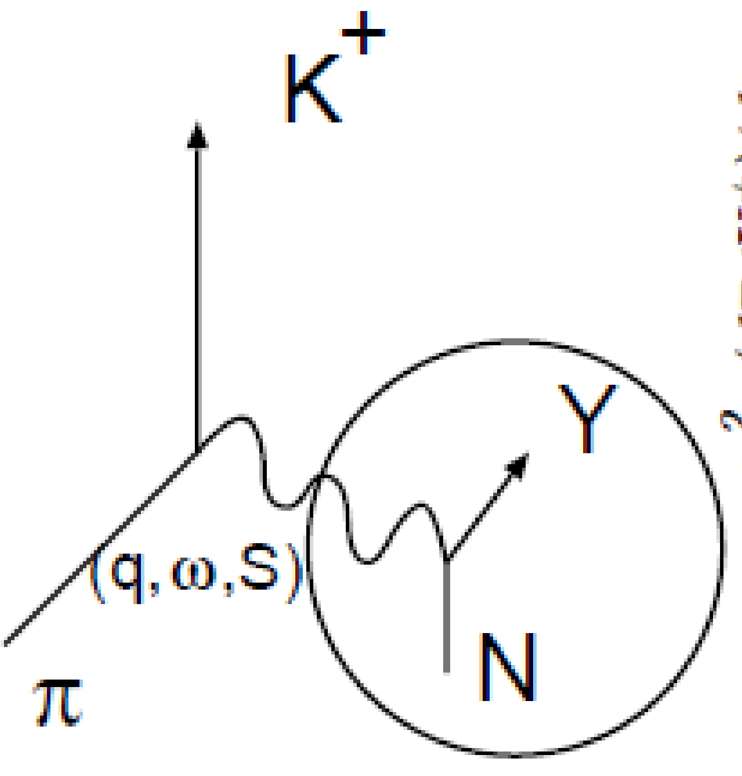
- **(K^-, π), (π, K^+), and (K^-,K^+) reactions on nuclei → Hypernuclei**

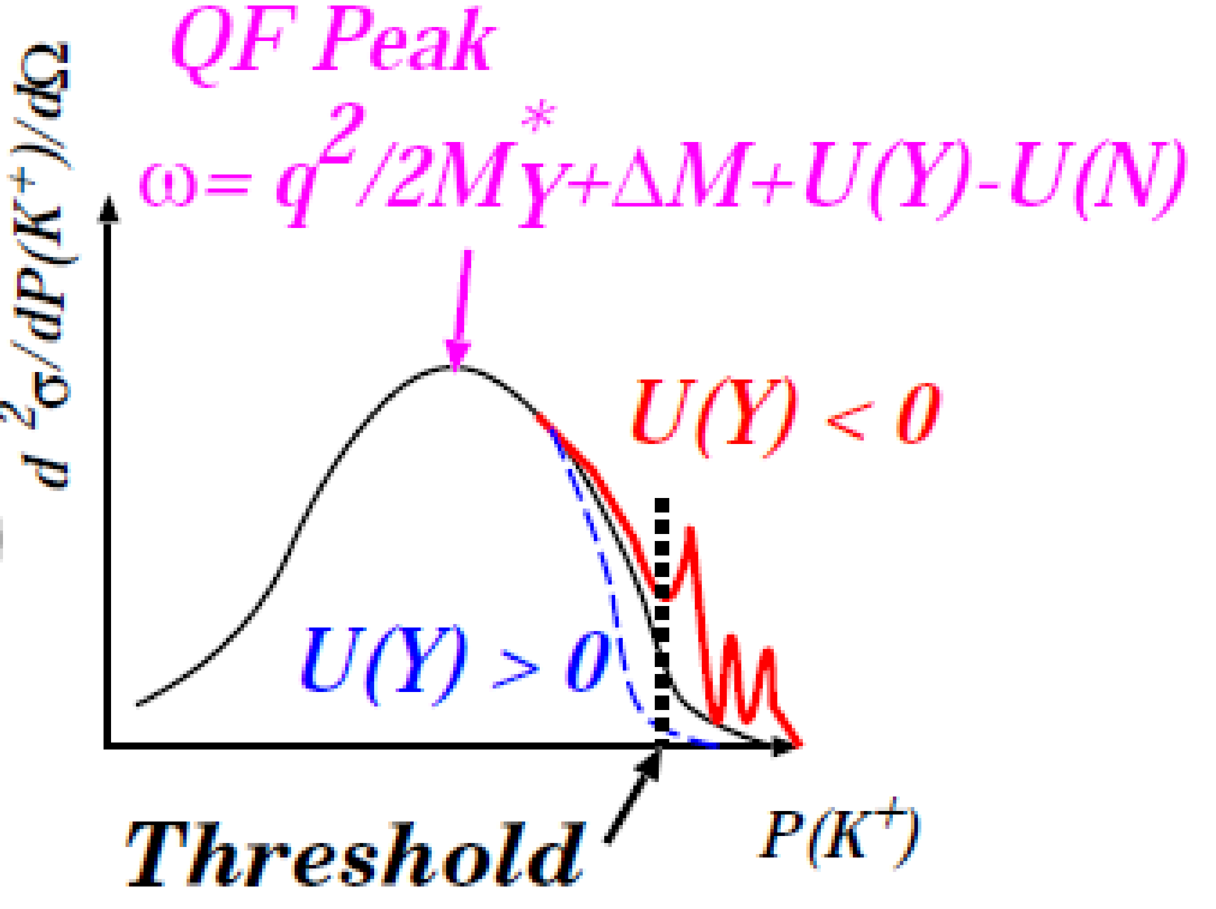
Reaction	Elementary Processes Main Process	Other Processes
(K^-,π^-)	$K^-n \to \pi^-\Lambda$,	$K^-n \to \pi^-\Sigma^0$, $K^-p \to \pi^-\Sigma^+$
(K^-,π^+)	$K^-p \to \pi^+\Sigma^-$,	$K^-pp \to \pi^+\Lambda n$ (n-rich hypernuclear formation)
(π^+,K^+)	$\pi^+n \to K^+\Lambda$,	$\pi^+n \to K^+\Sigma^0$, $\pi^+p \to K^+\Sigma^+$
(π^-,K^+)	$\pi^-p \to K^+\Sigma^-$,	$\pi^-pp \to K^+\Lambda n$ (n-rich hypernuclear formation)
(K^-,K^+)	$K^-p \to K^+\Xi^-$,	$K^-pp \to K^+\Lambda\Lambda$





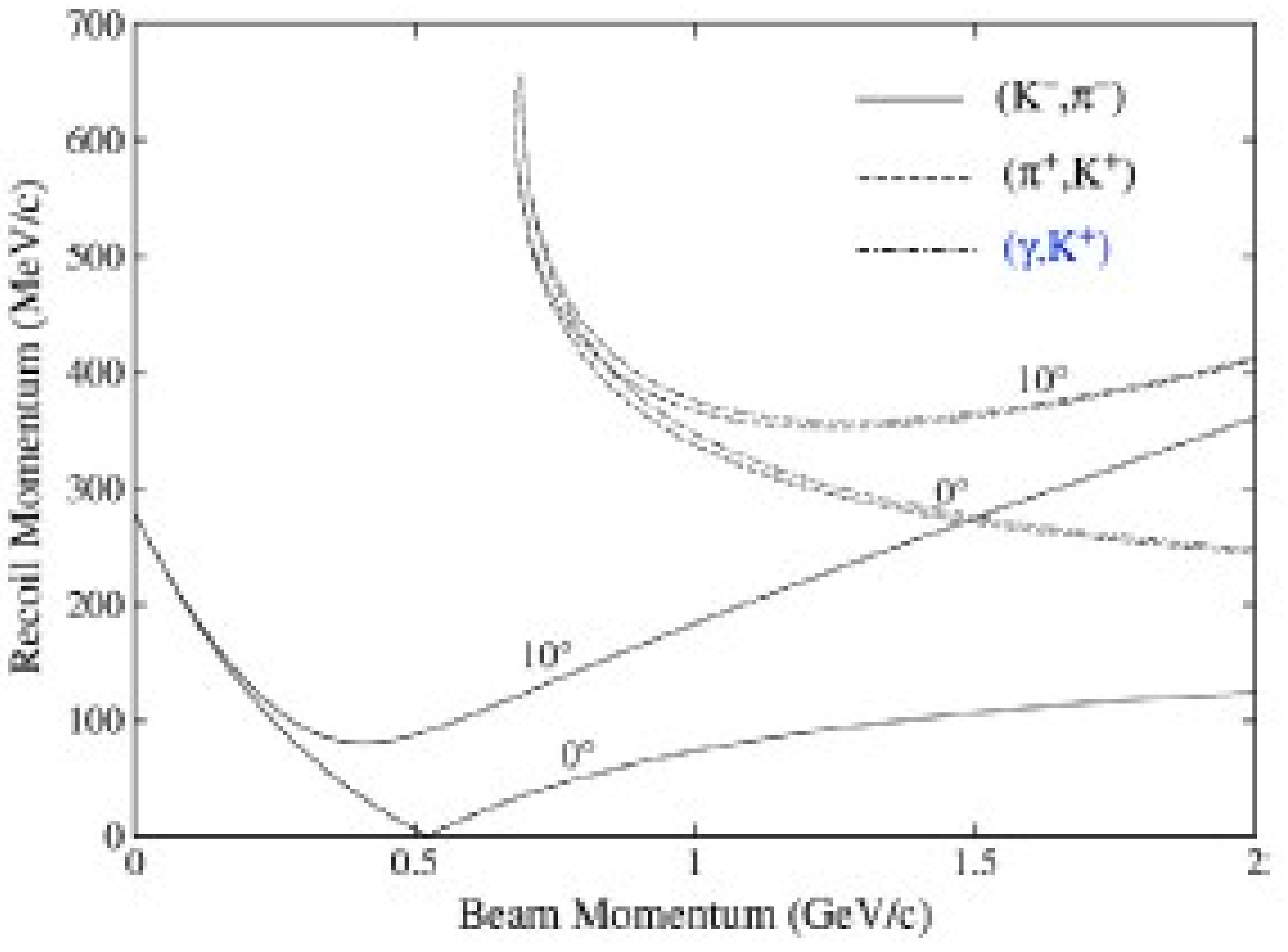
Hypernuclear formation





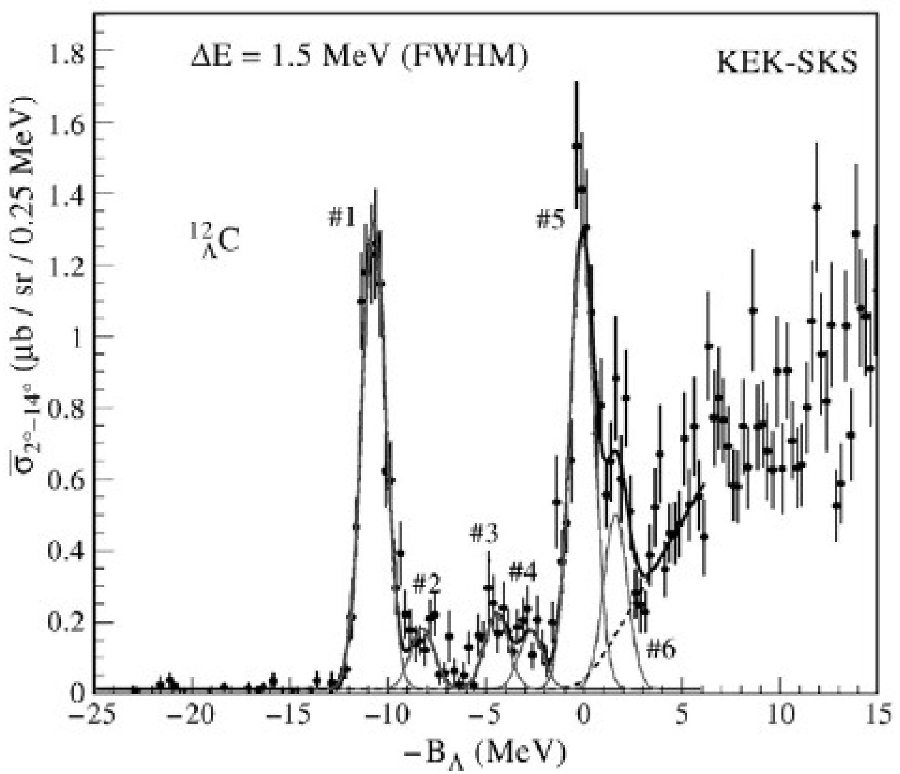
Hypernuclear formation

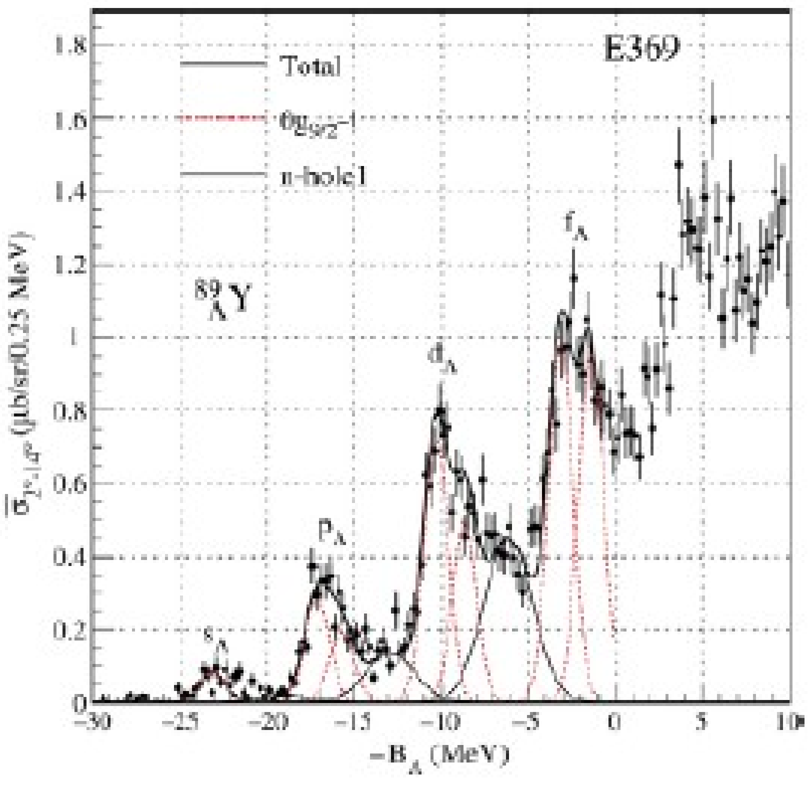
- **(K⁻, π⁻): Q>0, Small momentum transfer → substitutional reaction**
- **(π, K⁺): Q<0, Momentum transfer ~ 300 MeV/c ~ k_F**



Λ hypernuclear formation

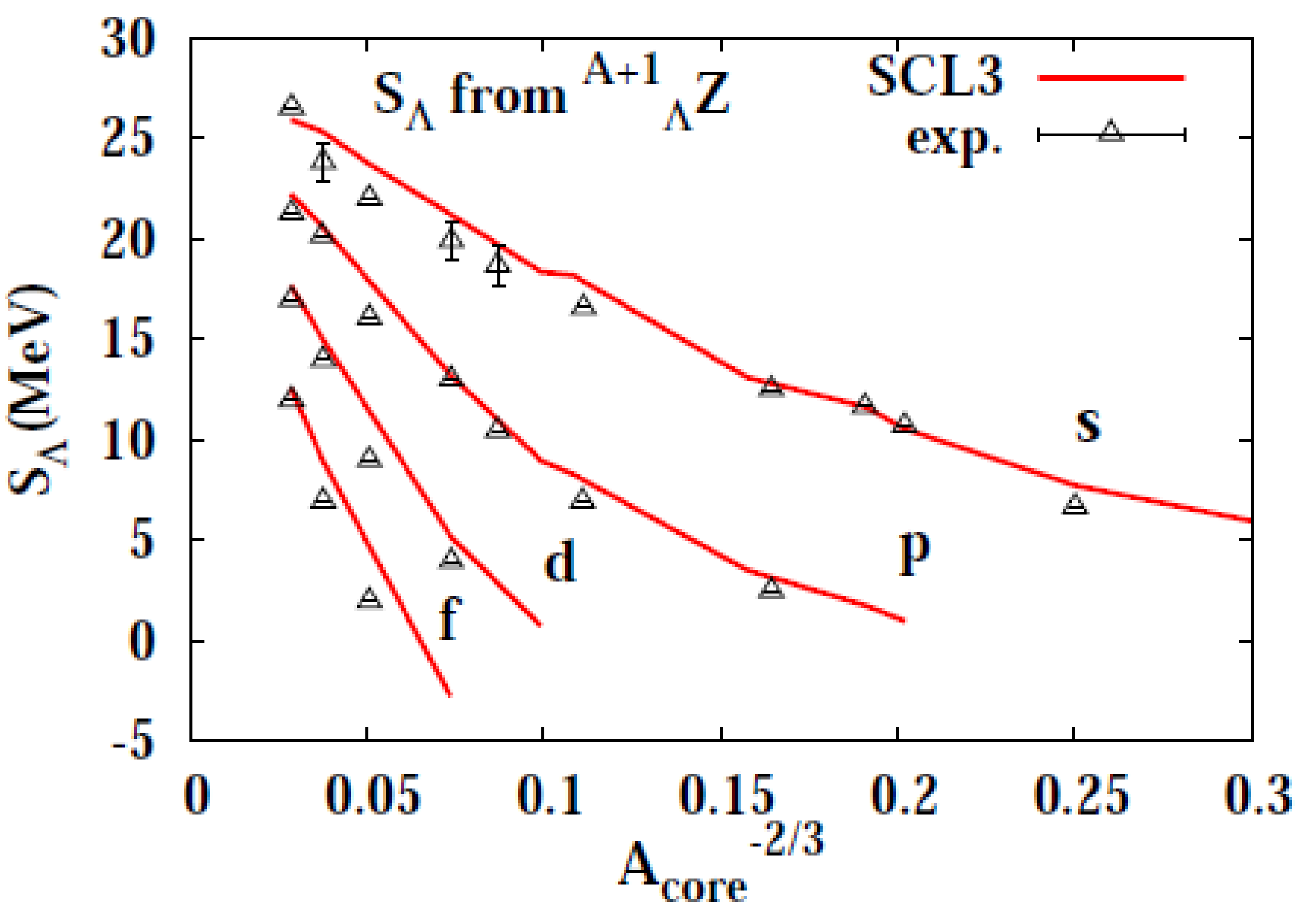
- (π^+, K^+) reactions on nuclei
  - $q \sim k_F \rightarrow$ various s.p. states of Λ are populated

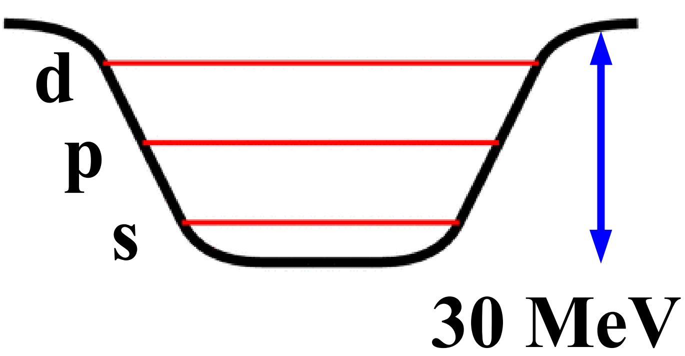




Single particles states of Λ in nuclei

- **Single particle potential depth of Λ is around -30 MeV**
  - **s, p, d, f, … states are clearly seen**
  - **$A_{core}^{-2/3} \propto R^{-2} \propto$ K.E. of Λ**





Σ production in nuclei

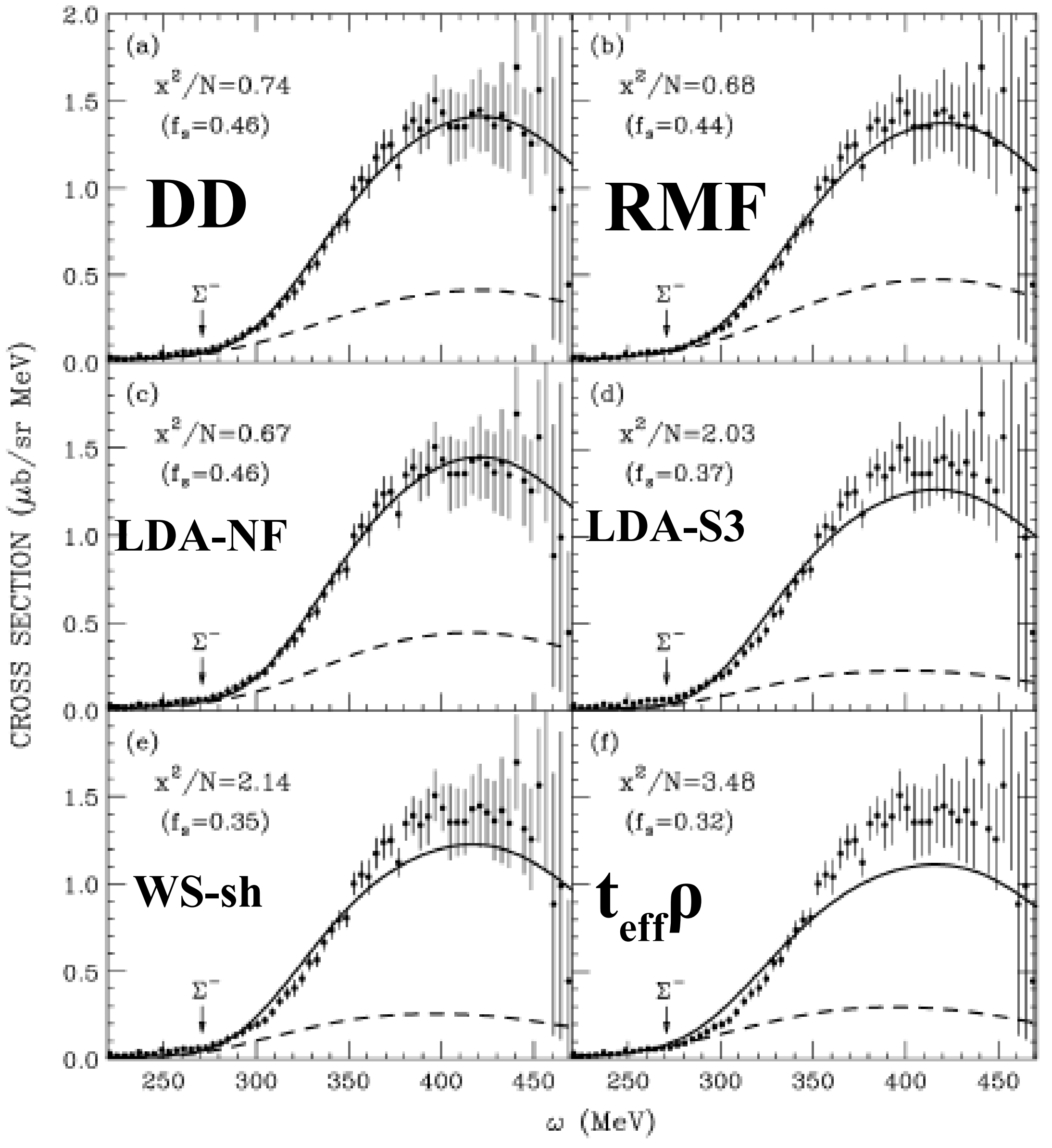
- Only one bound state ${}^4_\Sigma$He (Too light !)
  → Continuum (Quasi-Free) Spectroscopy is necessary
- Cont. Spec. Theory = Distorted Wave Impulse Approx. (DWIA)

$$\frac{d^2\sigma}{dE_K\, d\Omega_K} = \beta \left(\frac{d\sigma}{d\Omega}\right)^{Elem.}_{N\pi\to KY} S(E, \boldsymbol{q})$$

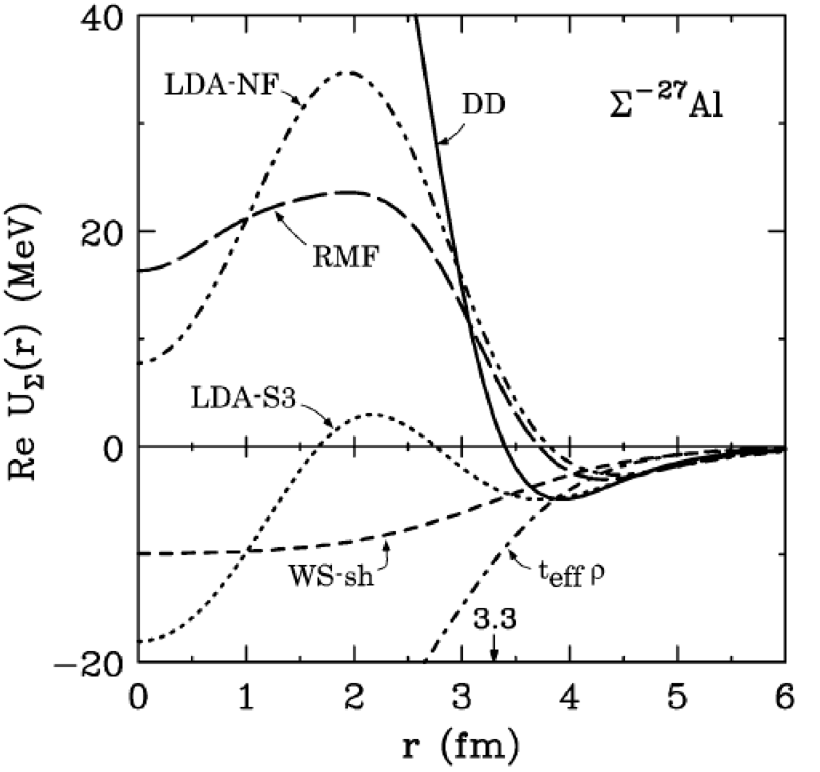
Kinematical Factor (β), Elem. Cross Sec. ($\left(\frac{d\sigma}{d\Omega}\right)^{Elem.}_{N\pi\to KY}$), Strength Func. ($S(E, \boldsymbol{q})$)

  - Large (ω, q) range → Important to respect On-Shell Kinematics
- Another way: Σ^- atomic shift
  - Atomic shift of Σ^- with O, Mg, Al, S, Si, W, Pb core are measured
- Σ potential in nuclei
  - Isoscalar part: 15-35 MeV repulsion
  - Isovector part: 20-30 % of SU(3) value

Σ production in nuclei

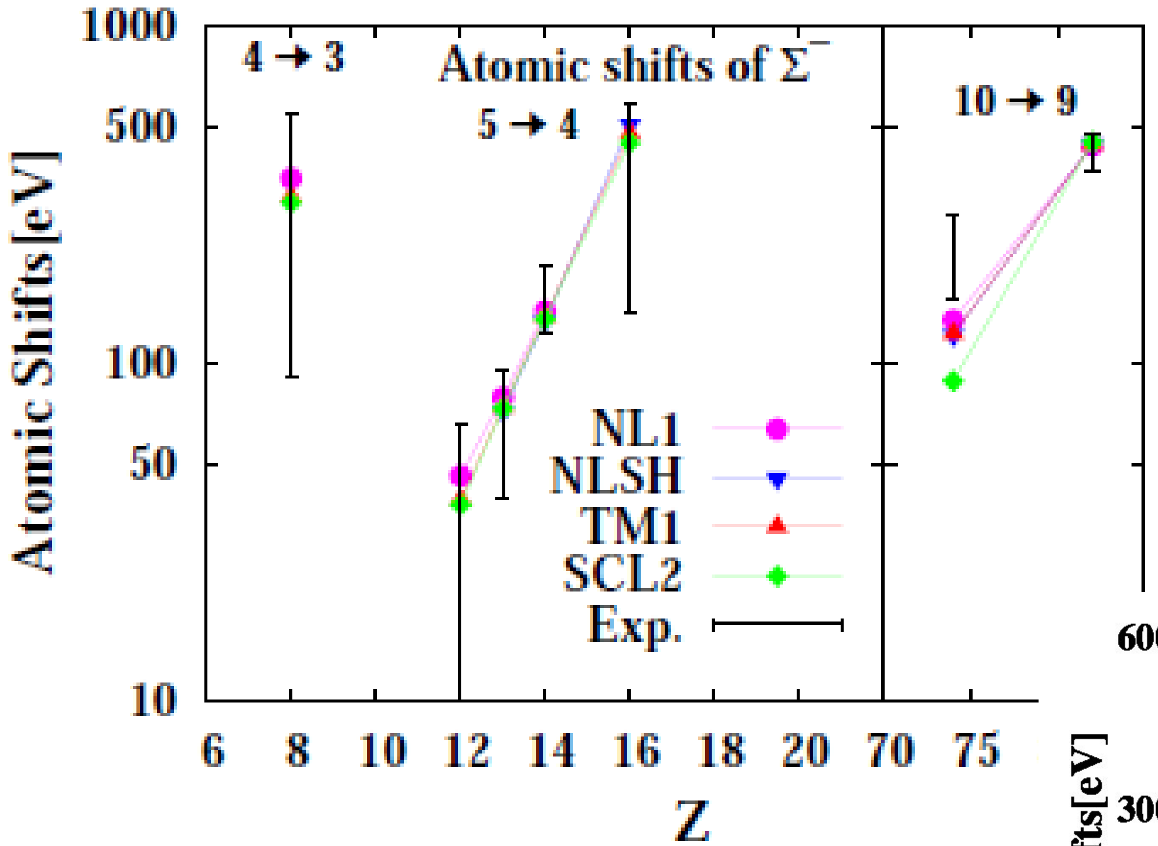


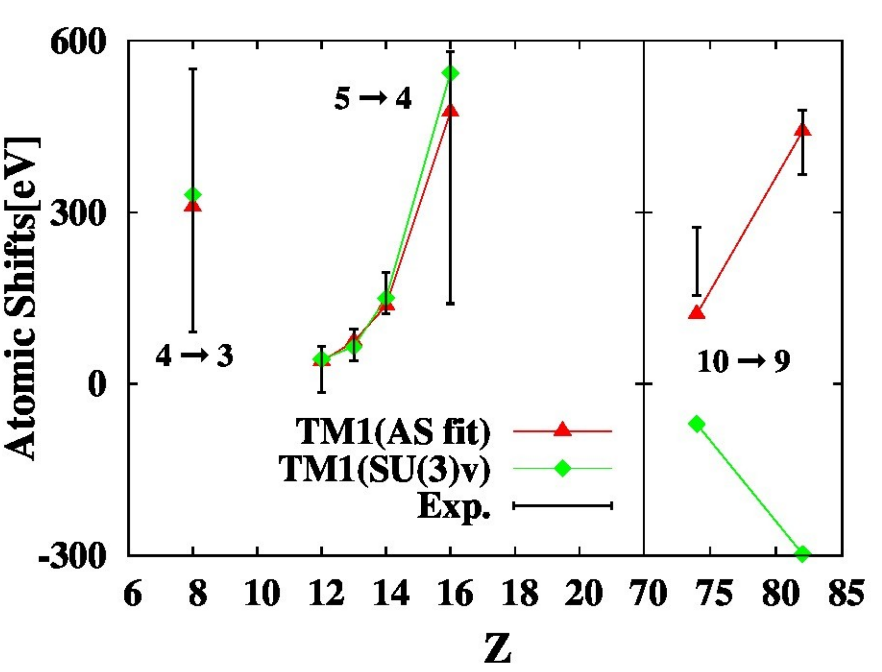
^{28}Si(π^-, K^+)



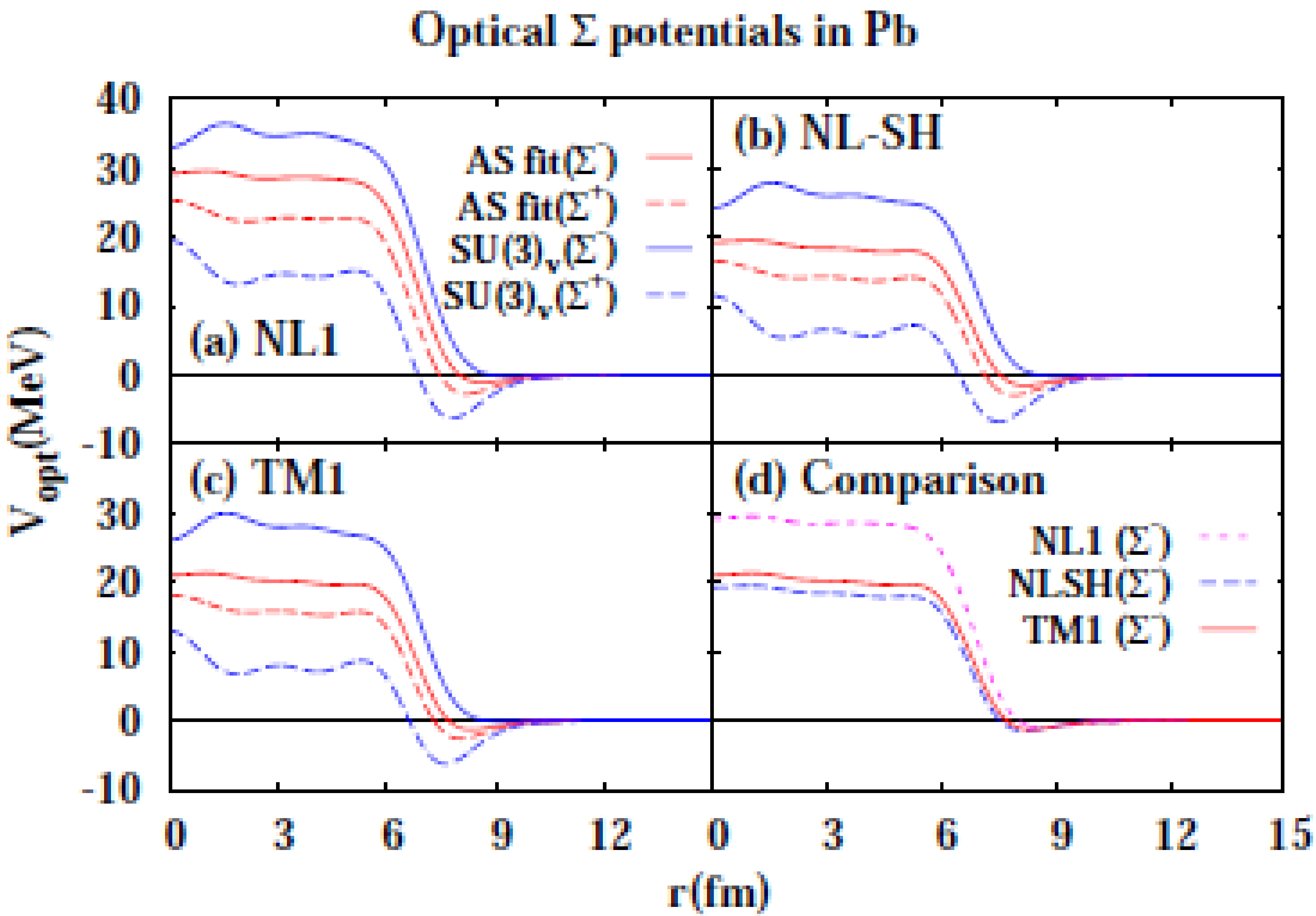
Harada, Hirabayashi ('05)

Σ- atomic shift





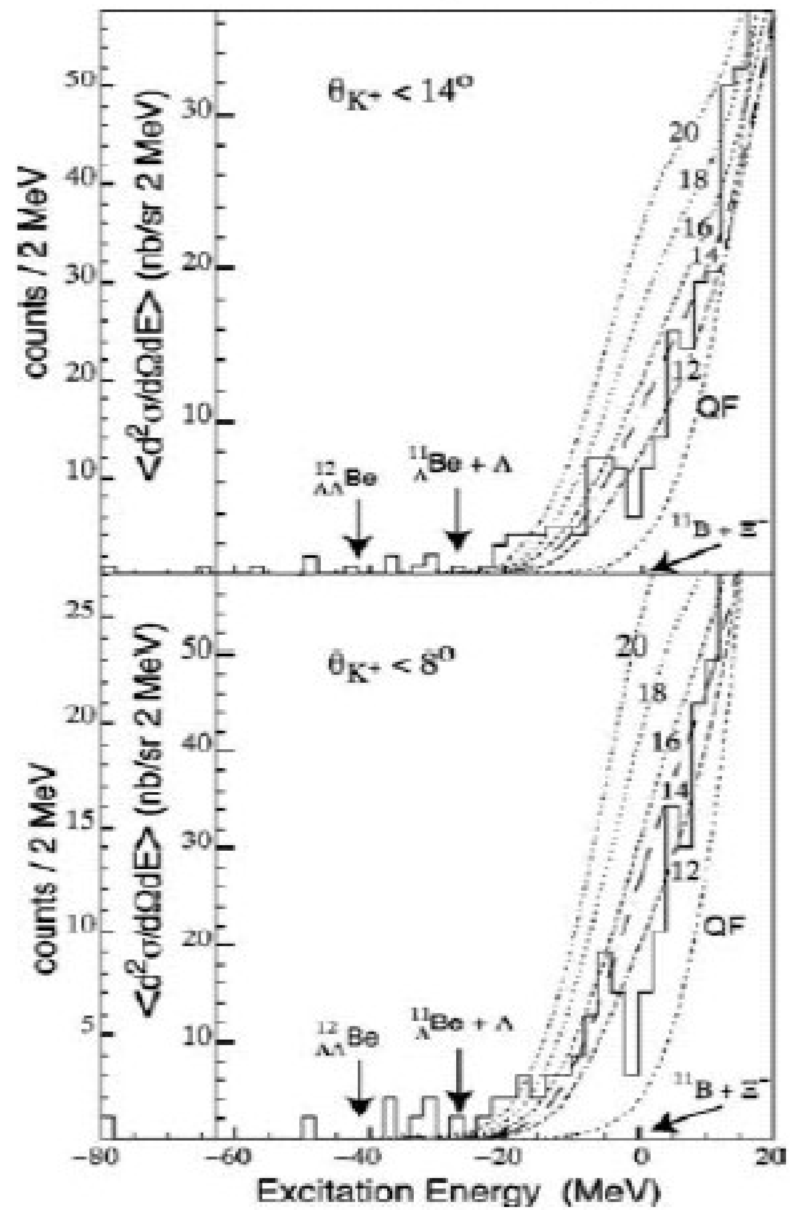
Σ potential in nuclei



Ξ hypernuclear formation

- **Missing mass spectroscopy**
  BNL E885 $^{12}C(K^-,K^+)$
  Fukuda et al. PRC58('98),1306;
  Khaustov et al. PRC61('00), 054603.
  - **No clear bound states found**
- **Twin hypernuclear formation**
  Aoki et al. PLB355('95),45.
- **Potential depth**
  $U_\Xi \sim -14$ **MeV**

E885 (BNL)



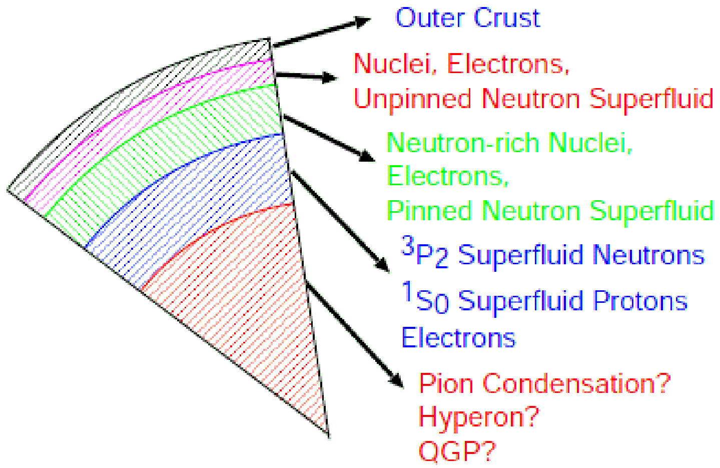
"Stars" of Hyperon Potentials (A la Michelin)

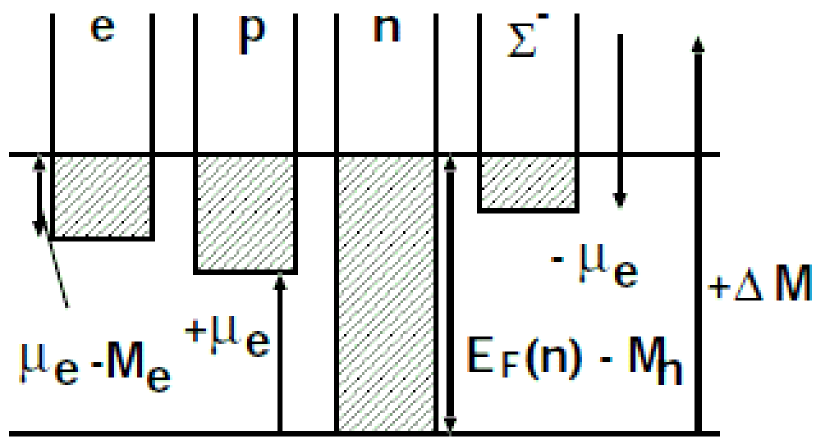
- **$U_\Lambda(\rho_0) \sim -30$ MeV**
  - ***Bound State Spectroscopy + Continuum Spectroscopy***
- **$U_\Sigma(\rho_0) > +15$ MeV**
  - **Continuum (Quasi-Free) spectroscopy**
  - **Atomic shift data (attractive at surface) should be respected.**
- **$U_\Xi(\rho_0) \sim -14$ MeV**
  - **No confirmed bound state, No atomic data,
High mom. transf., ... → Small Potential Deps.**
  - **Continuum low-res. spectrum shape → – 14 MeV**

Hyperons in Neutron Stars

Hyperons in Dense Matter

- **What appears at high density ?**
  - **Nucleon superfluid ($^3S_1$, $^3P_2$), Pion condensation, Kaon condensation, Baryon Rich QGP, Color SuperConductor (CSC), Quarkyonic Matter, ...**
  - **Hyperons**
    Tsuruta, Cameron (66); Langer, Rosen (70); Pandharipande (71); Itoh(75); Glendenning; Weber, Weigel; Sugahara, Toki; Schaffner, Mishustin; Balberg, Gal; Baldo et al.; Vidana et al.; Nishizaki,Yamamoto, Takatsuka; Kohno,Fujiwara et al.; Sahu,Ohnishi; Ishizuka, Ohnishi, Sumiyoshi, Yamada; ...



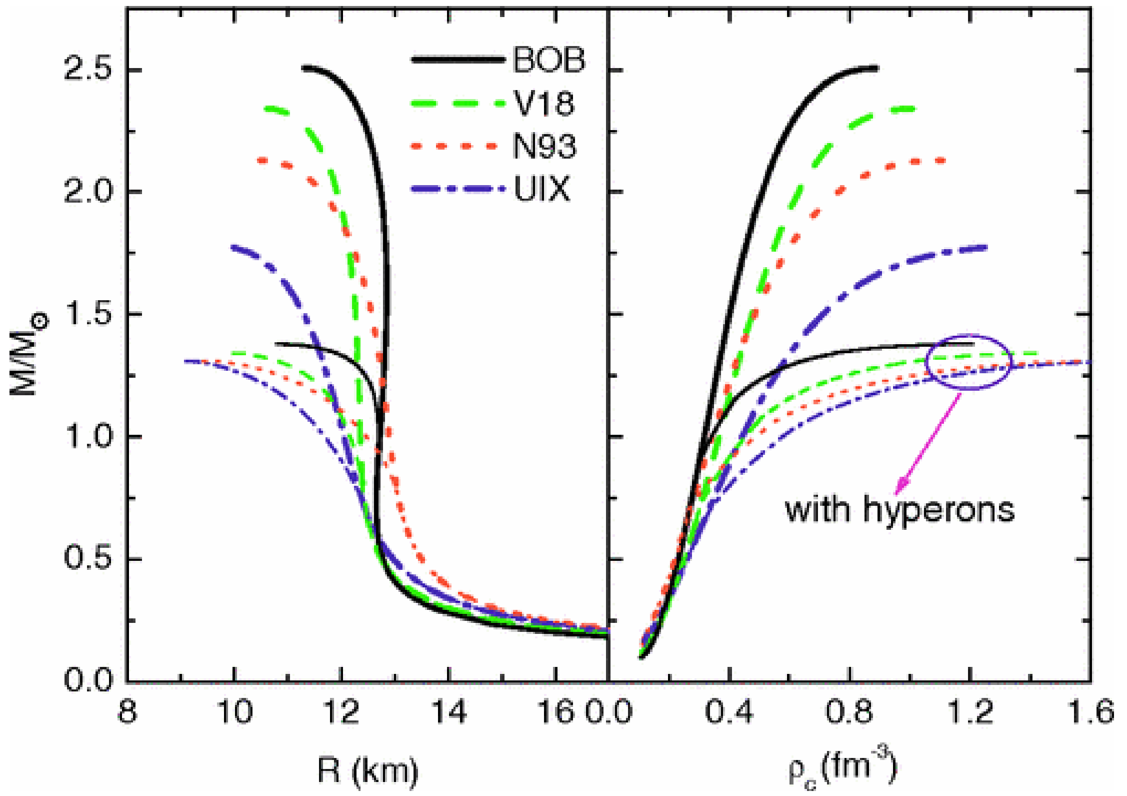


Nobody says "Hyperons cannot appear in neutron star core" !

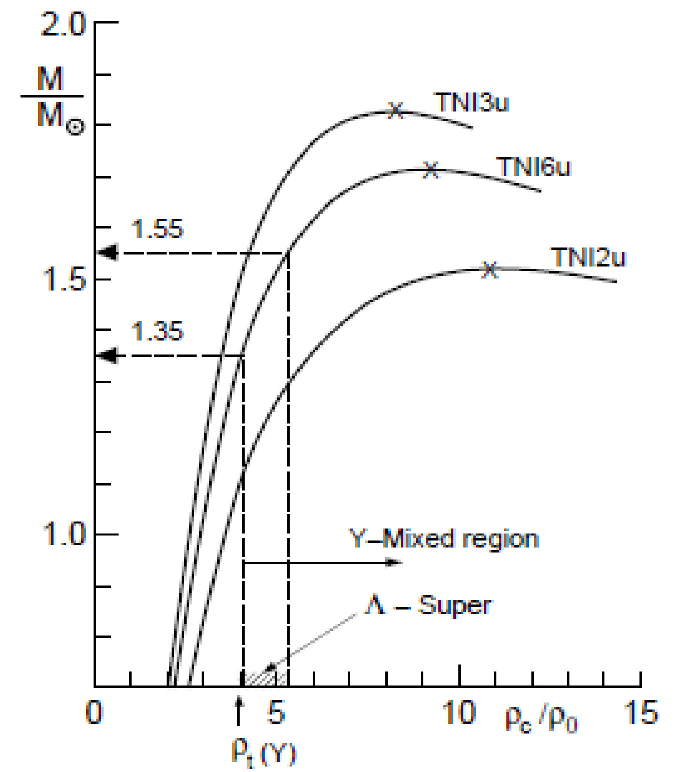
Y appears when $\mu_B = E_F(n) + U(n) \geq M(Y) + U(Y) + Q_Y \mu_e$

Bruckner-Hartree-Fock theory with Hyperons

- **Microscopic G-matrix calculation with realistic NN, YN potential and microscopic (or phen.) 3N force (or 3B force).**
  - **Interaction dep. (V18, N93, ...) is large → Need finite nuclear info.**
    E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / M.Tamura et al.
  - **NS collapses with hyperons w/o 3BF.**



Z.H.Li, H.-J.Schulze,PRC78('08),028801.



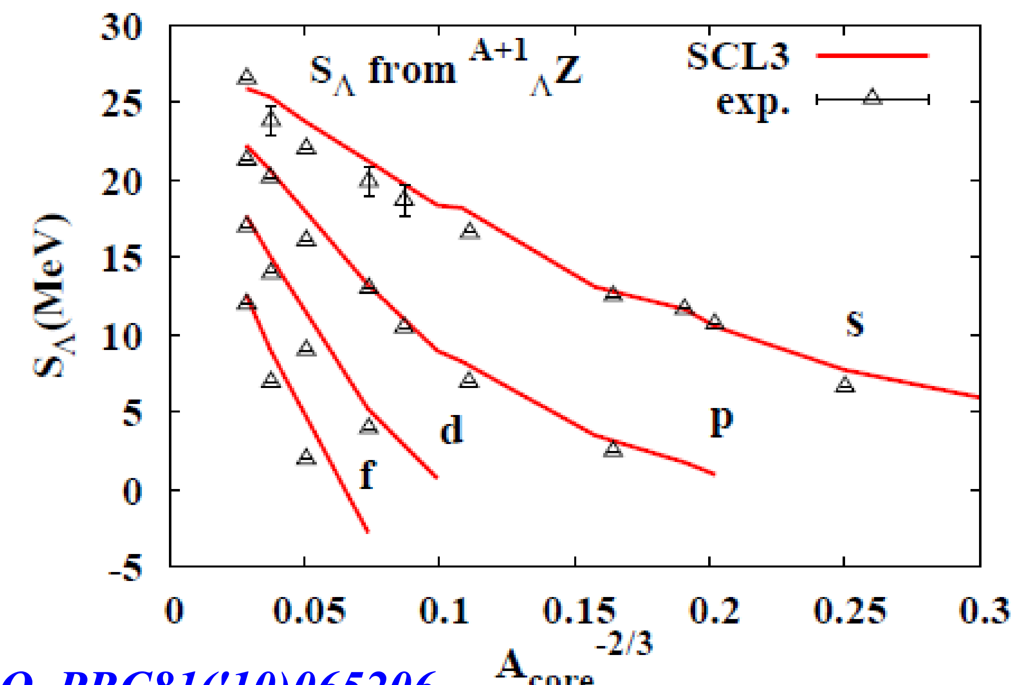
S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

RMF with Hyperons (Single Λ hypernuclei)

RMF for Λ hypernuclei

x ~ 1/3: R. Brockmann, W. Weise, PLB69('77)167; J. Boguta and S. Bohrmann, PLB102('81)93.
x ~ 2/3: N. K. Glendenning, PRC23('81)2757, PLB114('82)392;
Tensor: Y. Sugahara, H. Toki, PTP92('94)803; H. Shen, F. Yang, H. Toki, PTP115('06)325; J. Mares, B. K. Jennings, PRC49('94)2472.
ρ-dep. coupling: H. Lenske, Lect. Notes Phys. 641('04)147; C. M. Keil, F. Hofmann, H. Lenske, PRC 61('00)064309.
SU(3) or SU(6) (ς, φ): J. Schaffner, C. B. Dover, A. Gal, C. Greiner, H. Stoecker,PRL71('93)1328; Schaffner et al., Ann.Phys.235('94)35; J. Schaffner, I. N. Mishustin, PRC 53('96)1416.
Chiral SU(3) RMF: K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

- Sep. E. of Λ is well fitted by $U_\Lambda \sim -30$ MeV $\sim 2/3\, U_N$
- Coupling with mesons
  $x_M = g_{M\Lambda}/g_{MN}$
  quark counting: $x_\sigma \sim 2/3$
  π exchanges: $x_\sigma \sim 1/3$
  → Which is true ?

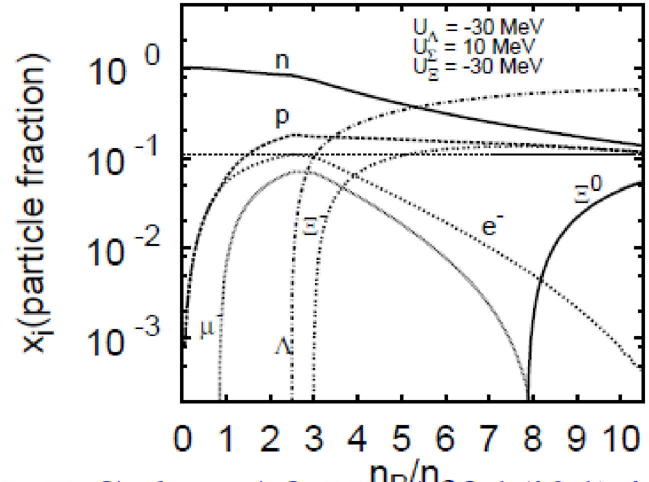


K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

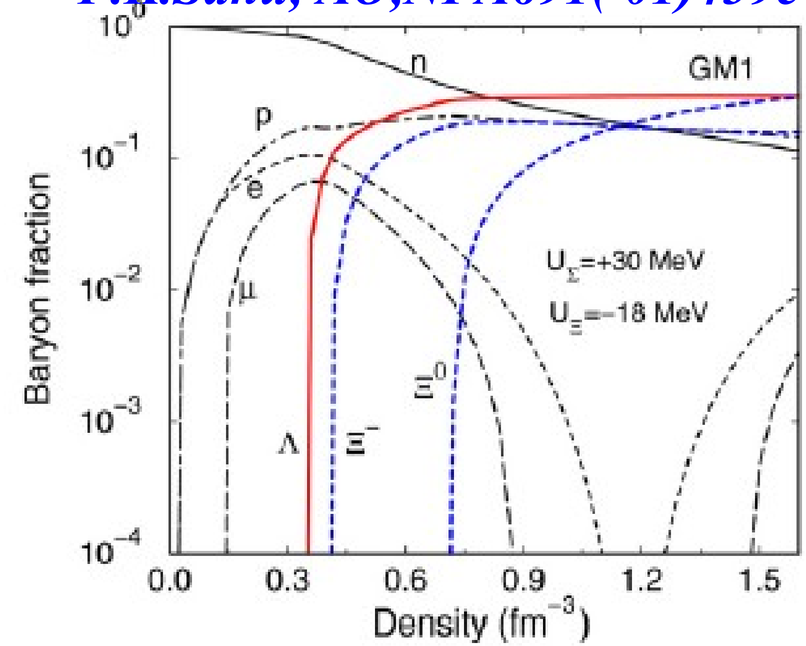
Hyperon Composition in Dense Matter

- Hyperon start to emerge at (2-3)ρ_0 in Neutron Star Matter !

- Hyperon composition in NS is sensitive to Hyperon potential.
  - $U_\Lambda \sim$ -30 MeV: Well-known
  - $U_\Xi \sim$ -(12-15) MeV
    (K^-,K^+) reaction, twin hypernuclei
    P. Khaustov et al. (E885),PRC61('00)054603;
    S. Aoki et al., PLB355('95)45.
  - $U_\Sigma \sim$ -30 MeV (Old conjecture)
    → Σ- appears prior to Λ
  - U_Σ > 0 (repulsive) → No Σ in NS
    Σ atom (phen. fit), QF prod.
    S. Balberg, A. Gal, NPA625('97)435;
    H. Noumi et al., PRL89('02)072301;
    T. Harada, Y. Hirabayashi, NPA759('05)143;
    M. Kohno et al. PRC74('06)064613.



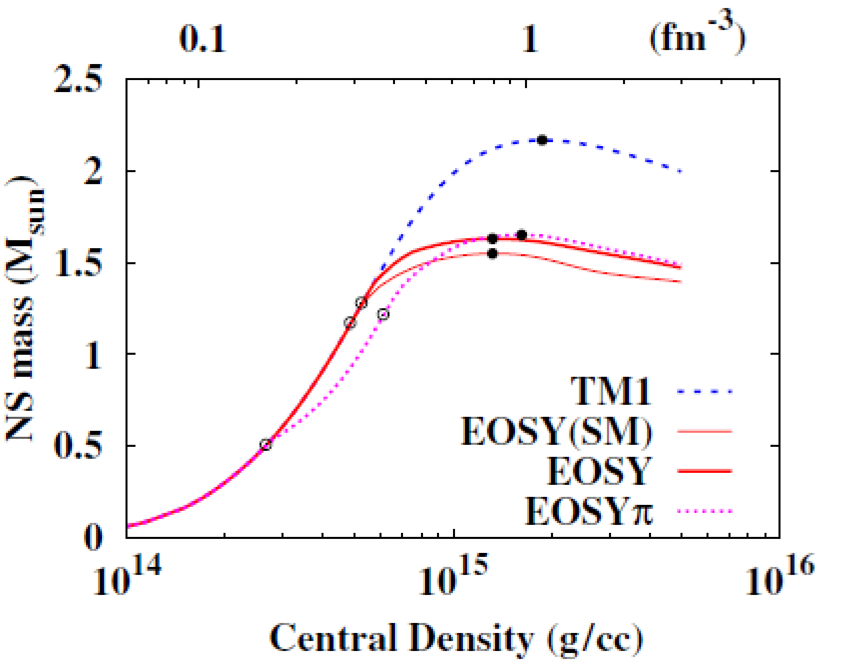
P.K.Sahu, AO,NPA691('01)439c



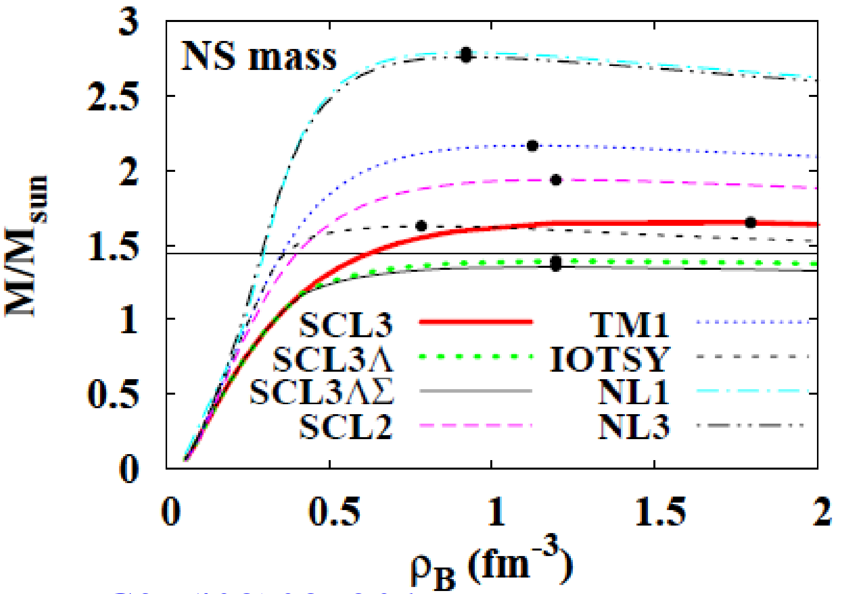
J. Schaffner-Bielich, NPA804('08)309.

Neutron Star Mass

- Large fraction of hyperons softenes EOS at $\rho_B > (0.3\text{-}0.4)\ \mathrm{fm}^{-3}$
  - NS star max. mass red. ~ 1 M_{sun}.
  - RMF generally predicts stiff EOS at high density.
    (Scalar attraction saturation,
    or Z-graph in NR view.)
  - Some of RMF with Y do not support 1.44 M_{sun}.



- Additional Repulsion at high ρ ?
  - Vector mass mod.
    → stronger repulsion at high ρ.
    M. Naruki et al., PRL96('06)092301.
  - Another term such as NNωσ.



C. Ishizuka, AO, K. Tsubakihara, K. Sumiyoshi, S. Yamada, JPG35('08)085201.
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

RMF with hyperons (1)

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

- **Lagrangian including hyperons**

$$\mathcal{L} = \sum_B \bar{\Psi}_B \left(i\partial\!\!\!/ - M_B \right) \Psi_B + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - U_\sigma(\sigma)$$
$$- \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{R}^\mu\cdot\vec{R}_\mu$$
$$- \sum_B \bar{\Psi}_B \left(g_{\sigma B}\sigma + g_{\omega B}\omega\!\!\!/ + g_{\rho B}\vec{R\!\!\!/}\cdot\vec{t}_B \right) \Psi_B + \frac{1}{4}c_\omega(\omega^\mu\omega_\mu)^2 + \mathcal{L}^{YY} ,$$

$$U_\sigma(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{g_3}{3}\sigma^3 + \frac{g_4}{4}\sigma^4 ,$$

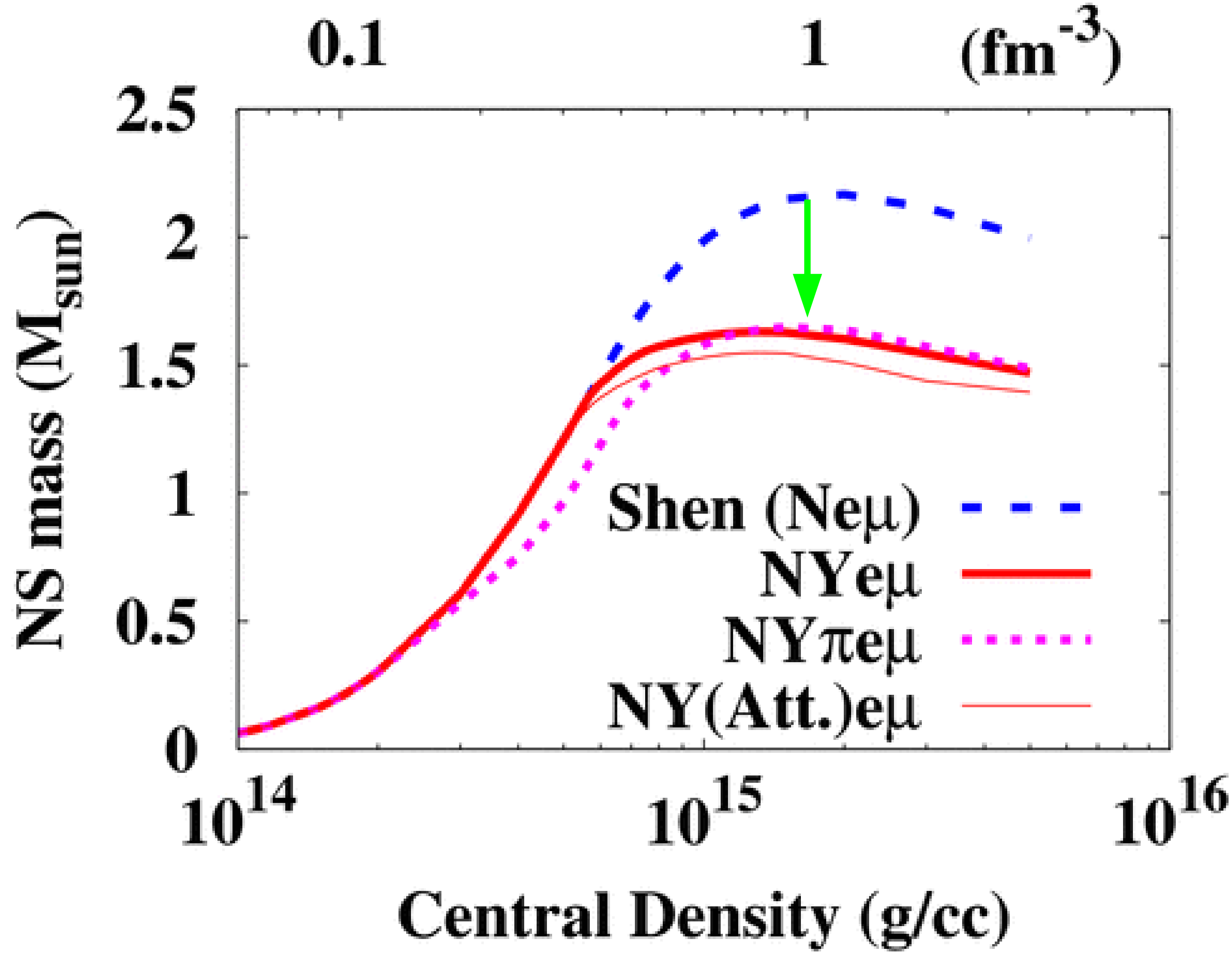
$$\mathcal{L}^{YY} = \frac{1}{2}\partial_\nu\zeta\partial^\nu\zeta - \frac{1}{2}m_\zeta^2\zeta^2 - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu$$
$$- \sum_B \bar{\Psi}_B \left(g_{\zeta B}\zeta + g_{\phi B}\gamma^\mu\phi_\mu \right) \Psi_B ,$$

  - **Nucleon part = TM1**
  - **Vector coupling = Quark counting (SU(6))**
  - **Scalar couplings are chosen to reproduce hyperon potentials in NM**

$$U_\Sigma^{(N)}(\rho_0) \simeq +30\ \text{MeV} , \quad U_\Xi^{(N)}(\rho_0) \simeq -15\ \text{MeV} .$$

ハイペロンを含むRMF での中性子星

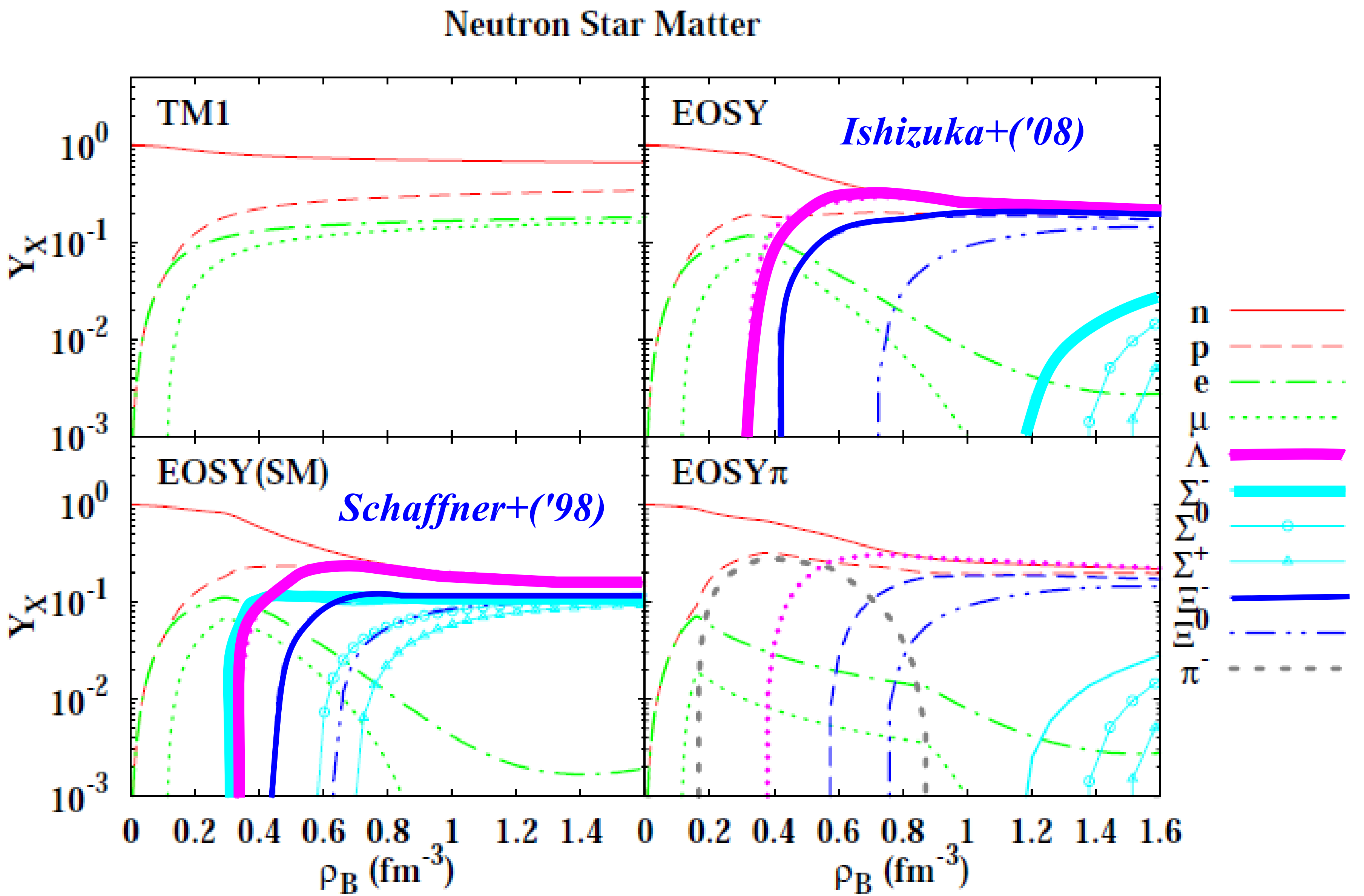
Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, J. Phys. G35(08), 085201



c.f. H.Shen+('09) → n, p, Λ EOS

ハイペロンを含むRMFでの中性子星

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



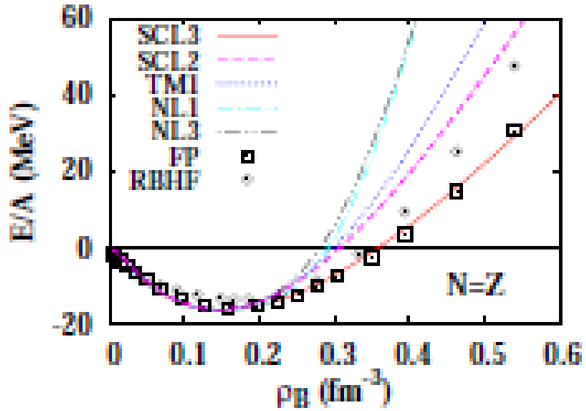
RMF with Hyperons (SCL3)

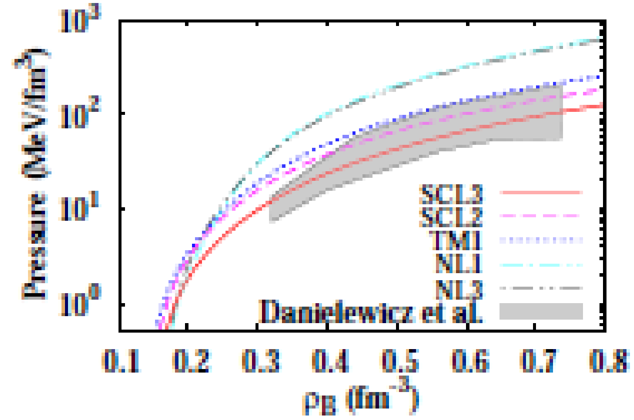
K. Tsubakihara, H. Maekawa, H. Matsumiya, A. Ohnishi, PRC81 (2010), 065206.

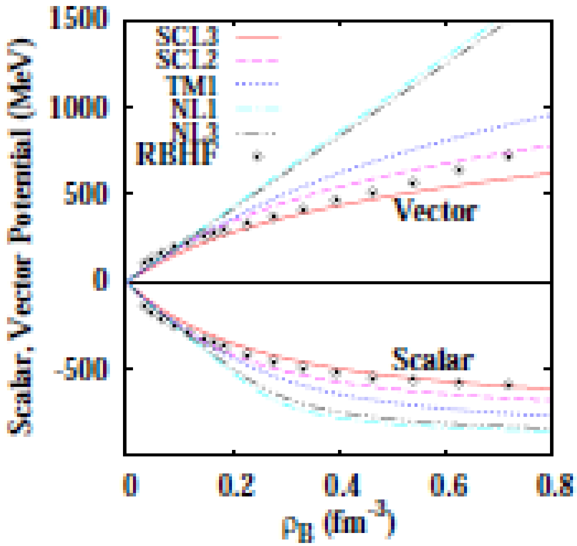
- **Fit available data as much as possible**
  - **BE of normal nuclei, EOS (incompressibility), Pressure suggested from HIC, and Vector potential in RBHF.**
  - **Single Λ single particle energies, Double Λ bond energy, Σ- atomic shift, Ξ potential depth**
- **Non-linear terms**
  - **Logrithmic chiral symmetric σ potential suggested by the strong coupling limit of lattice QCD**
  - **ω^4 term as in TM1**
  - **$U(1)_A$ breaking term (Kobayashi-Masukawa-'t Hooft)**
- **Published on June 22, 2010.**

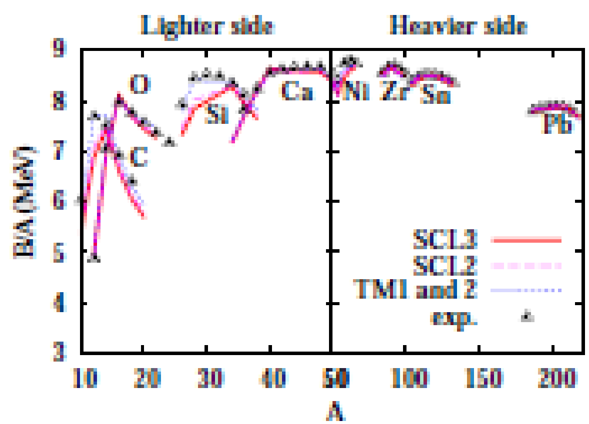
EOS related data

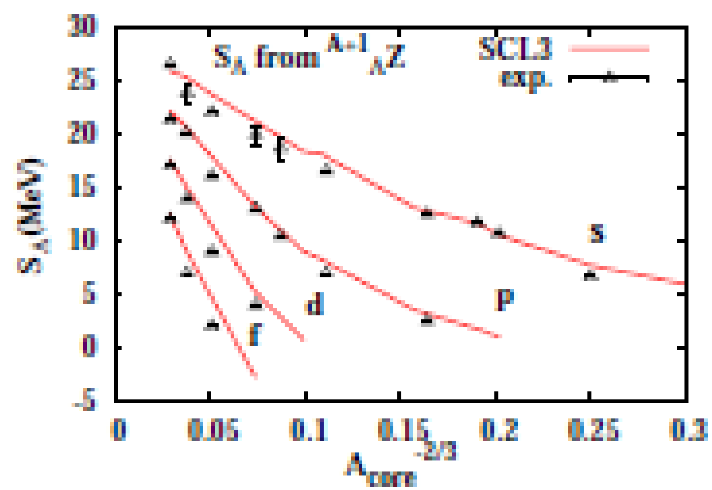
K. Tsubakihara, H. Maekawa, H. Matsumiya, A. Ohnishi, PRC81 (2010), 065206.





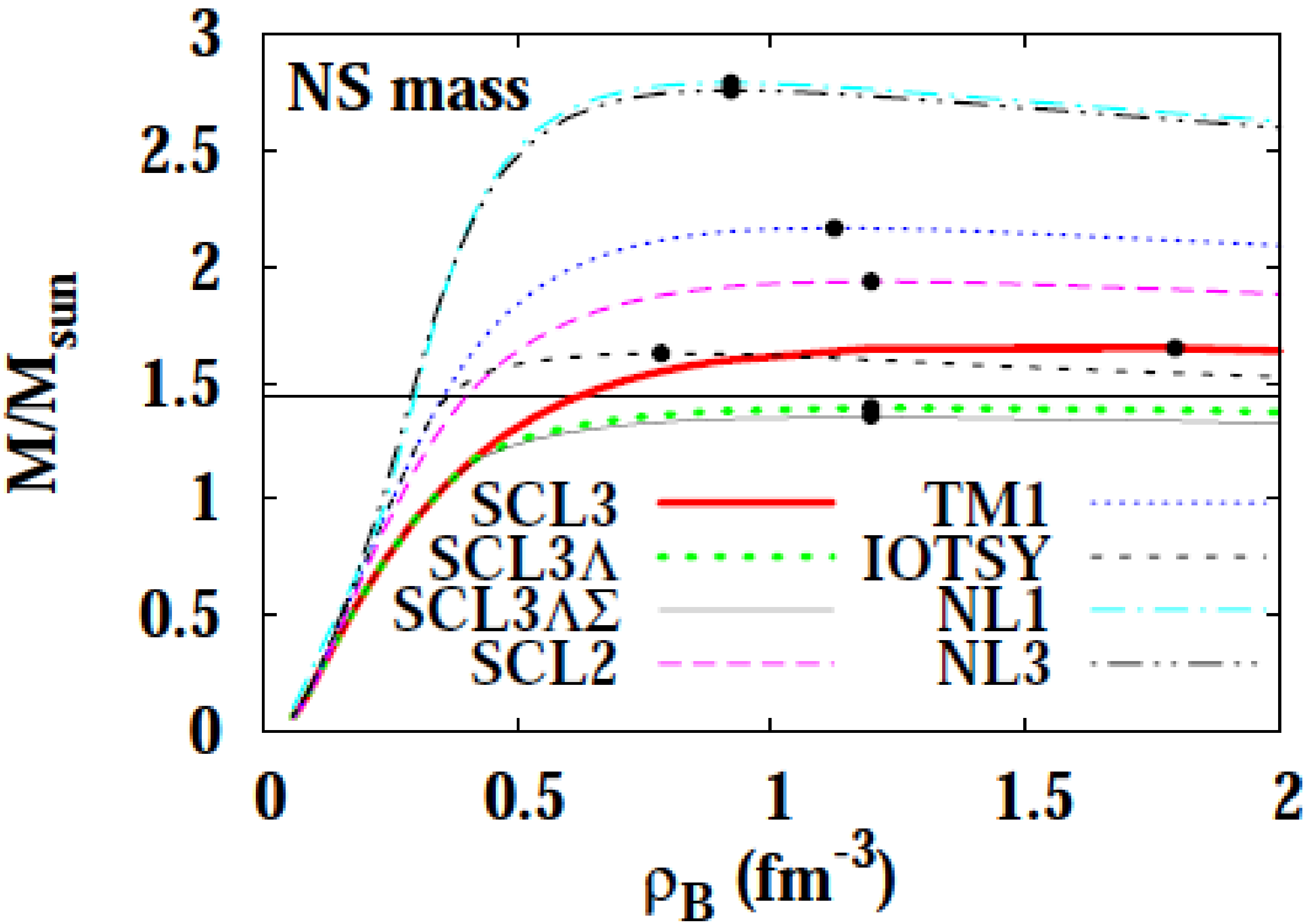






Neutron Star Mass

K. Tsubakihara, H. Maekawa, H. Matsumiya, A. Ohnishi, PRC81 (2010), 065206.



Mmax < 1.44 $M_\odot$ with hyperons

RMF as a phenomenological MODEL !

- **Baryon one-loop approximation (Hartree approximation) makes RMF a phenomenological model.**
  → We need DATA and AB INITIO results.

- **Saturation point (ρ_0 and E/A(ρ_0)) from mass formula**
- **Nuclear binding energies**
- **U_v and U_s from DBHF results**
- **P(ρ_B) from heavy-ion data**
- **Λ separation energy from single Λ hypernuclear data**
- **ΛΛ bond energy from double Λ 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 ~ 1.40 $M_\odot$, a little smaller 1.44 $M_\odot$.**

The Judgement Day, Oct. 28, 2010. 1.97 $M_\odot$

Massive Neutron Star Puzzle

Massive Neutron Star Puzzle

- **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).

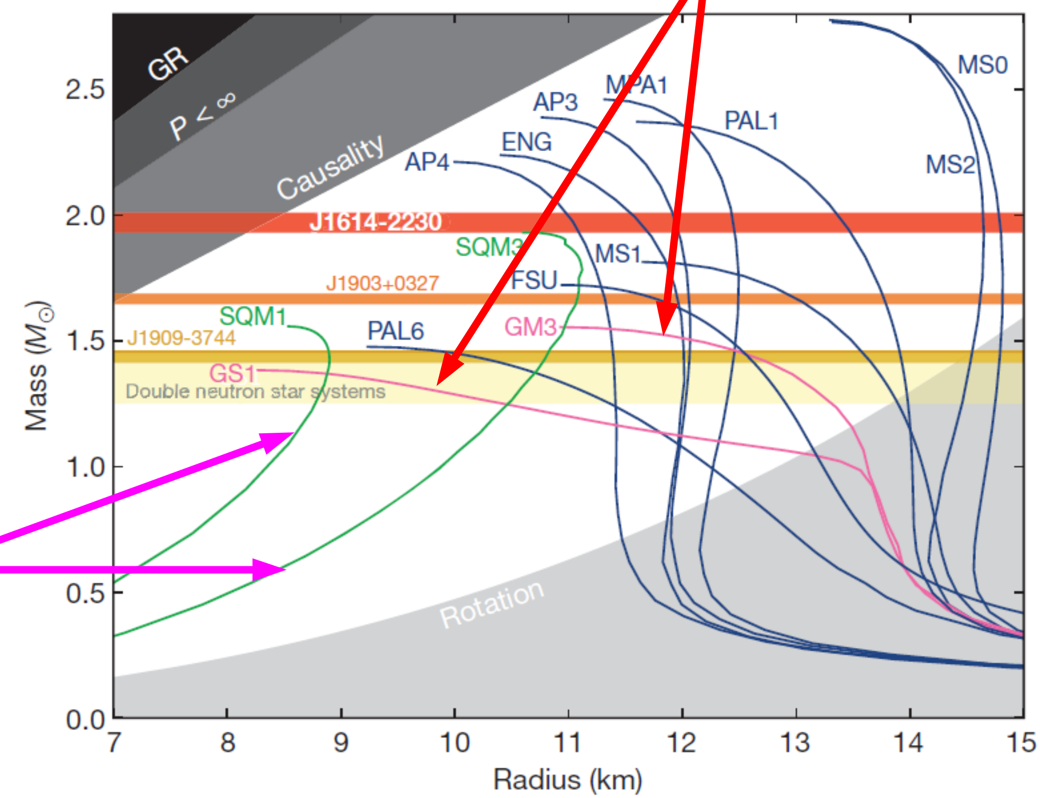
  PSR J1614-2230 (NS-WD binary), 1.97 ± 0.04 $M_\odot$

  - **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**

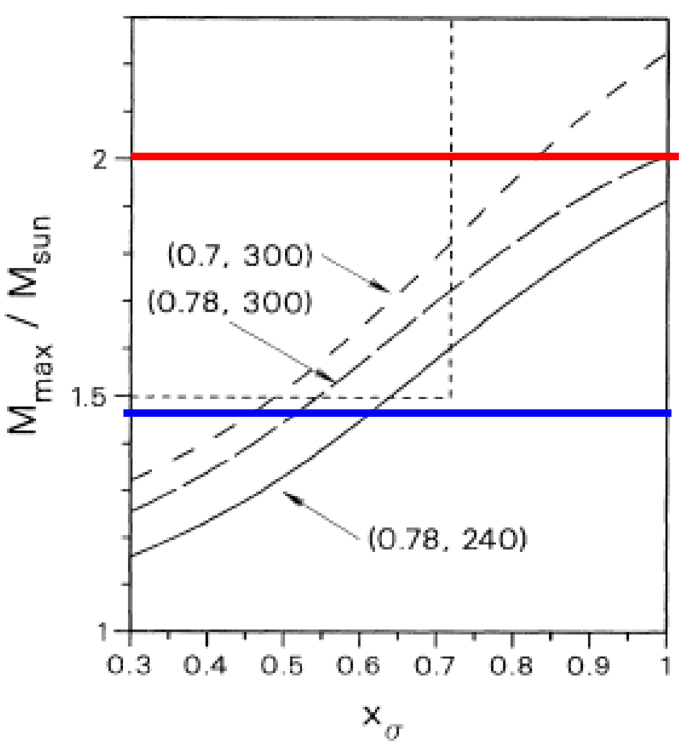
**Strange Hadron
を含む EOS**

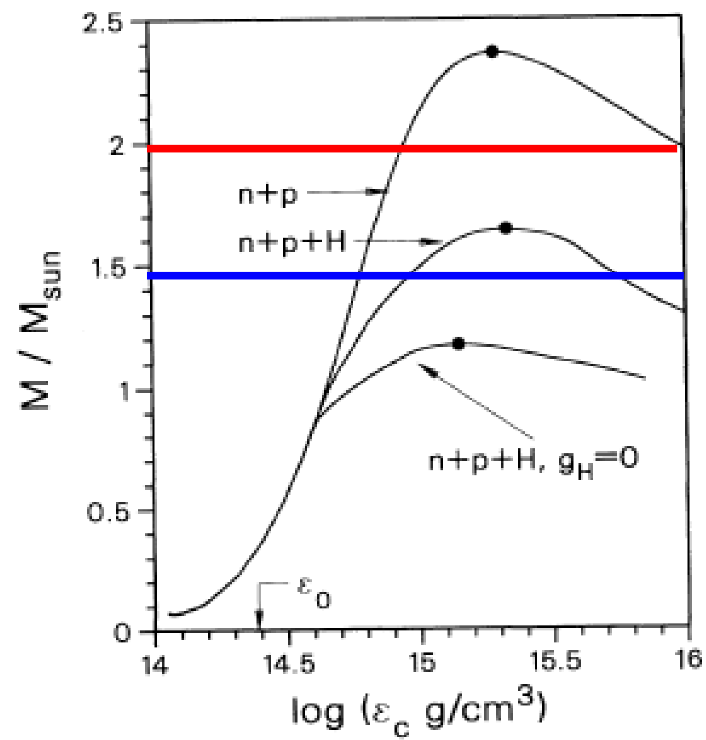
**クォーク物質
の EOS**



ハイペロンと重い中性子星

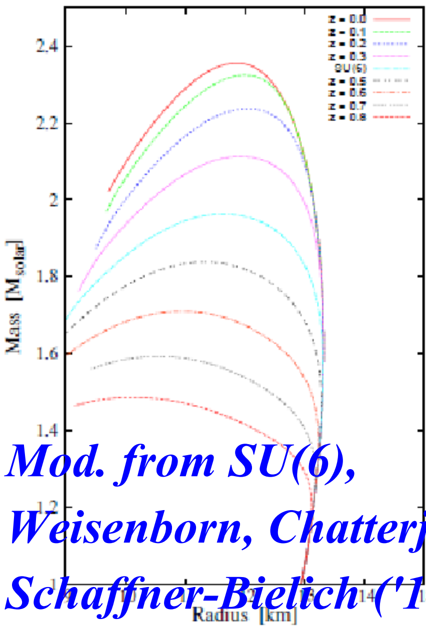
- 「柔らかい EOS は否定されたが、exotic な構成粒子が否定されたわけではない。」(Lattimer)
  - 否定されたハイペロン・K 中間子を含む EOS
    = 相対論的平均場理論 (RMF) において結合定数をほぼ SU(6) にしたがって選んだもの ($g_{\sigma\Lambda} / g_{\sigma N} \sim 2/3$)



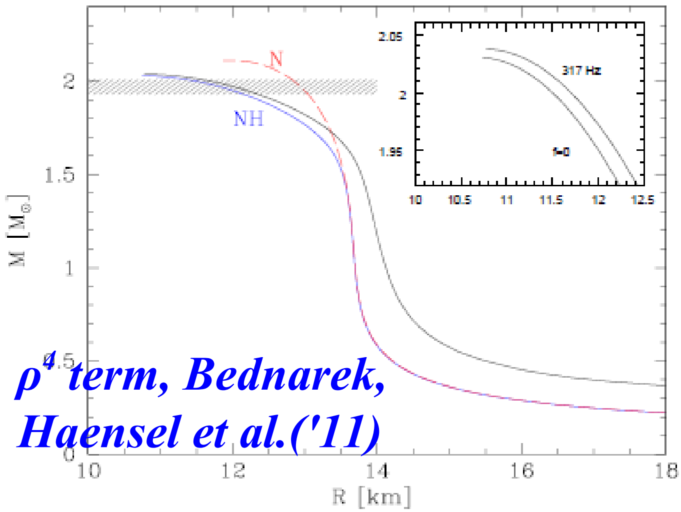


N.K.Glendenning, S.A.Moszkowski, PRL67('91)2414

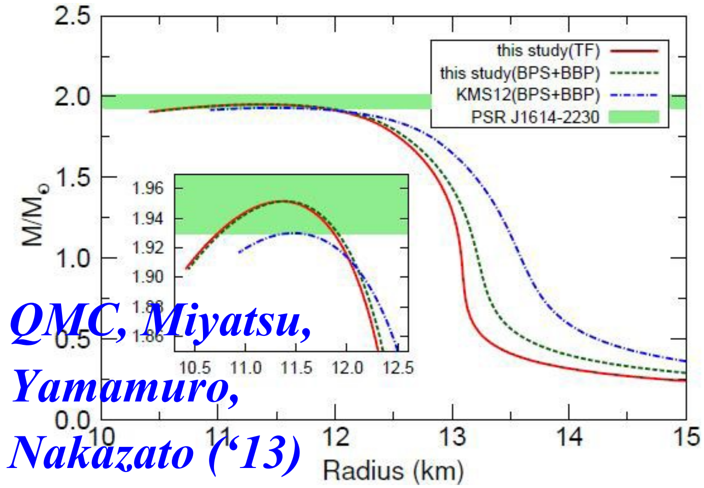
Massive Neutron Star with Hyperons



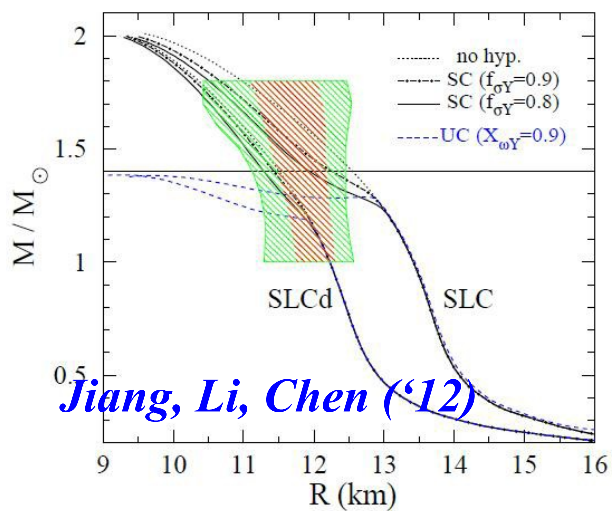
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



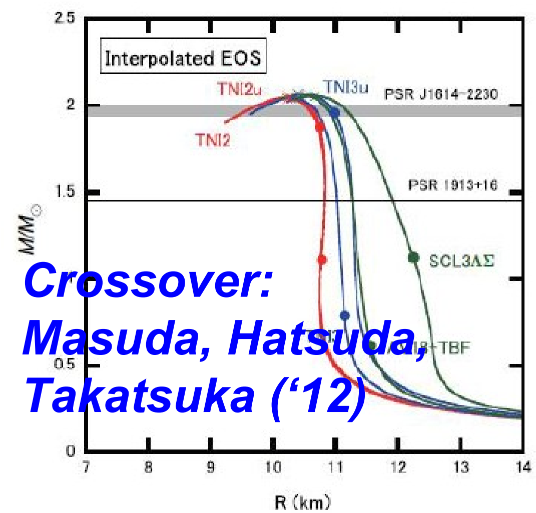
ρ^4 term, Bednarek, Haensel et al.('11)



QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

RMF with many-body coupling

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

  Manohar, Georgi ('84)

  The vertex is called "natural" if C ~ 1.

$$L_{\rm int} \sim (f_\pi \Lambda)^2 \sum_{l,m,n,p} \frac{C_{lmnp}}{m!\,n!\,p!} \left(\frac{\bar\psi \Gamma \psi}{f_\pi^2 \Lambda}\right)^l \left(\frac{\sigma}{f_\pi}\right)^m \left(\frac{\omega}{f_\pi}\right)^n \left(\frac{R}{f_\pi}\right)^p$$

  → Consistent with the idea that the vertex is generated by loop diagrams under the assumption that the QCD coupling is small.

- **FST truncation**

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

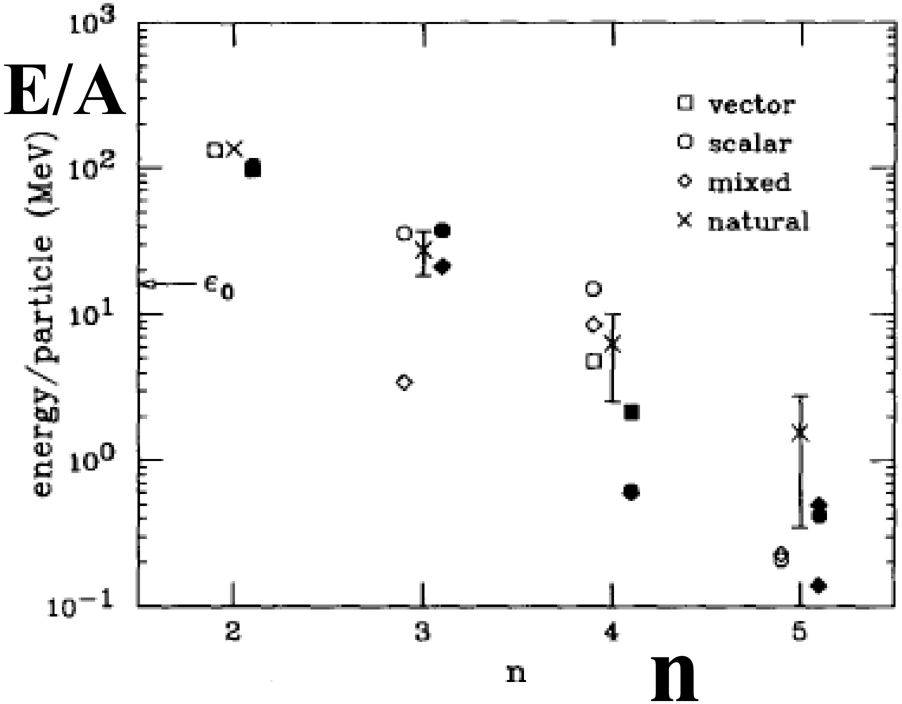
  At a given density, we can truncate the Lagrangian by the index

  n = B/2 + M + D

  (B: baryon field, M: Non NG boson, D: derivatives)

  Naturalness → V ~ $\rho^n/n!$

  → small for large n

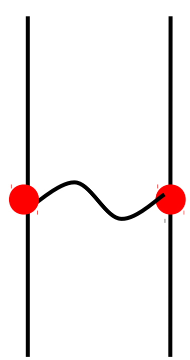


3 体力を含む RMF

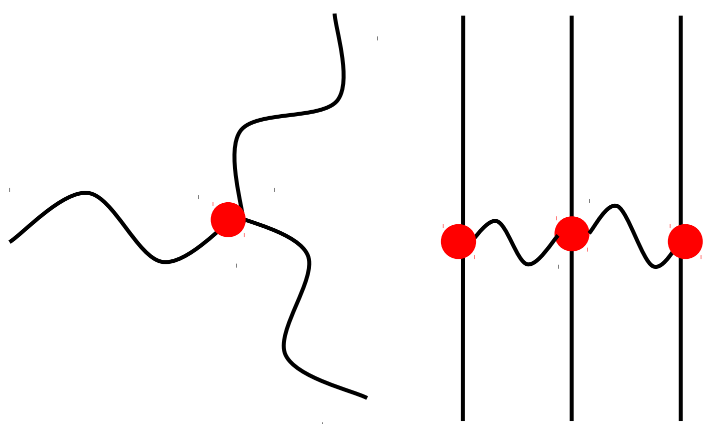
- **3 体力を含む相互作用項**

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

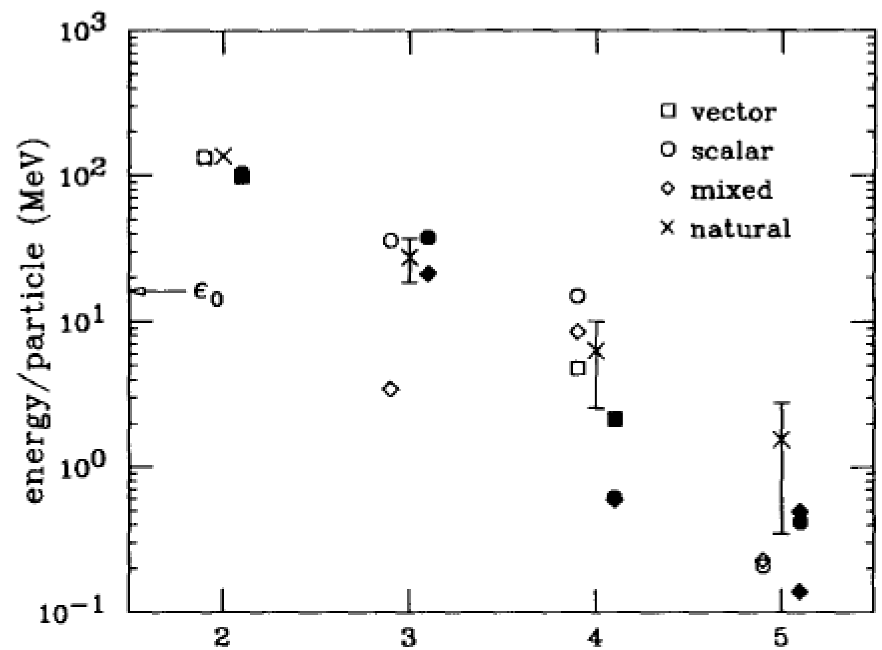
  - **BBMM 項は通常無視 (場の再定義で吸収可能)**
    しかし場の再定義は Naïve dimensional analysis (NDA) の次数を変え、高密度では n 体力が重要な役割を果たす。
    n = d + B/2 + M (d; 微分結合、B: バリオン場、M: non-NG ボソン)



2 体力



3体力

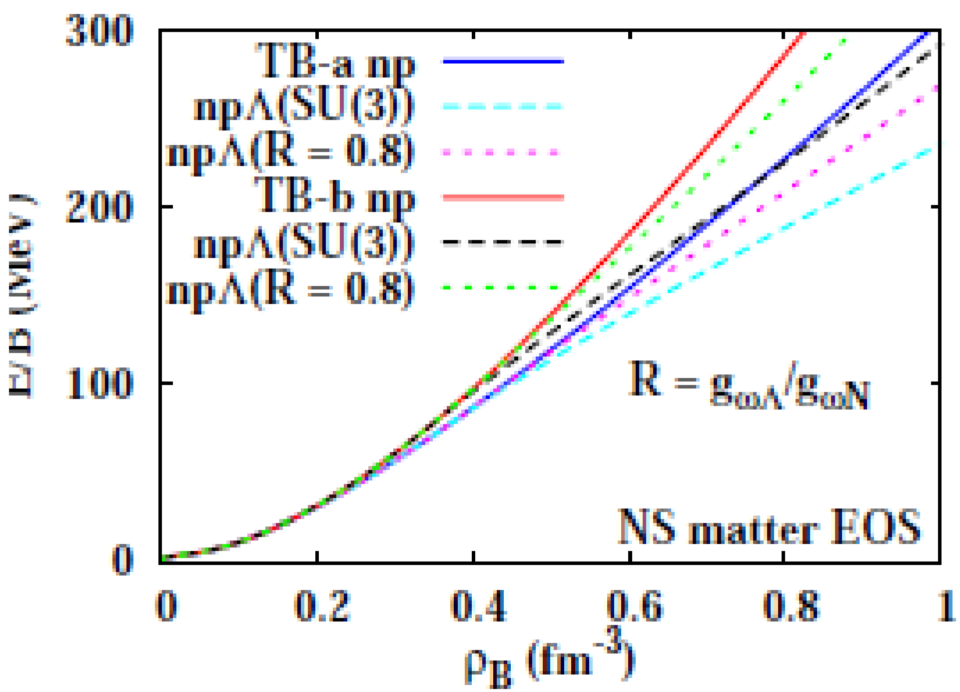


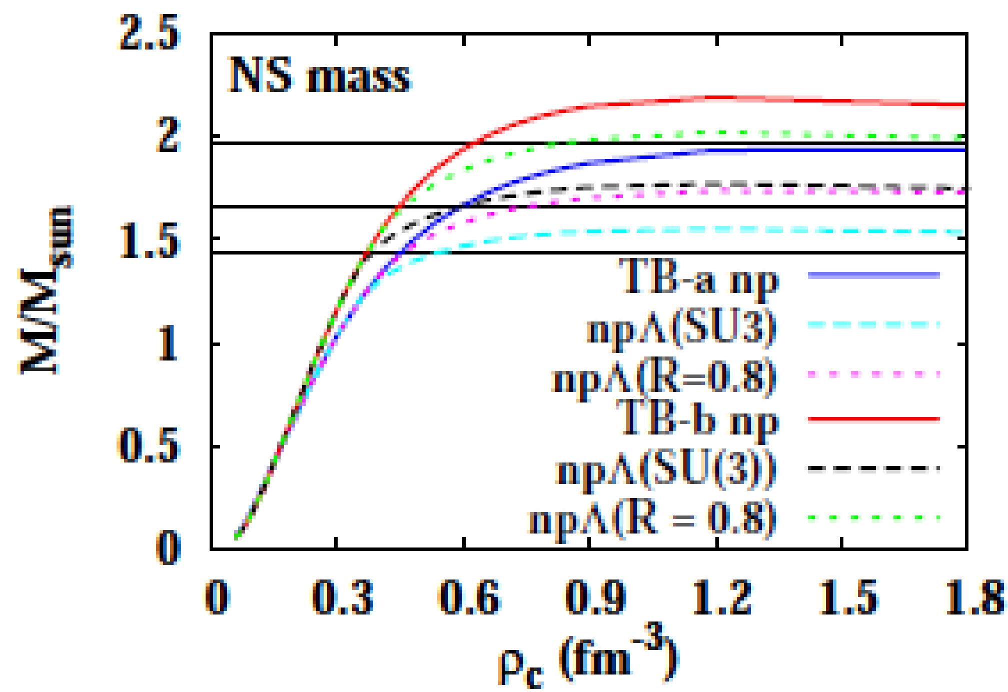
Furnstahl, Serot, Tang ('97)

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

- **Two types of modification**
  - **3-baryon repulsion → EOS becomes stiff gradually at high density. (Fitting meson mass (E325) and Uv in RBHF)**
  - **R= $g_{\omega\Lambda}$ / $g_{\omega N}$ ~ 0.8 (> 2/3 (SU(3))**

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

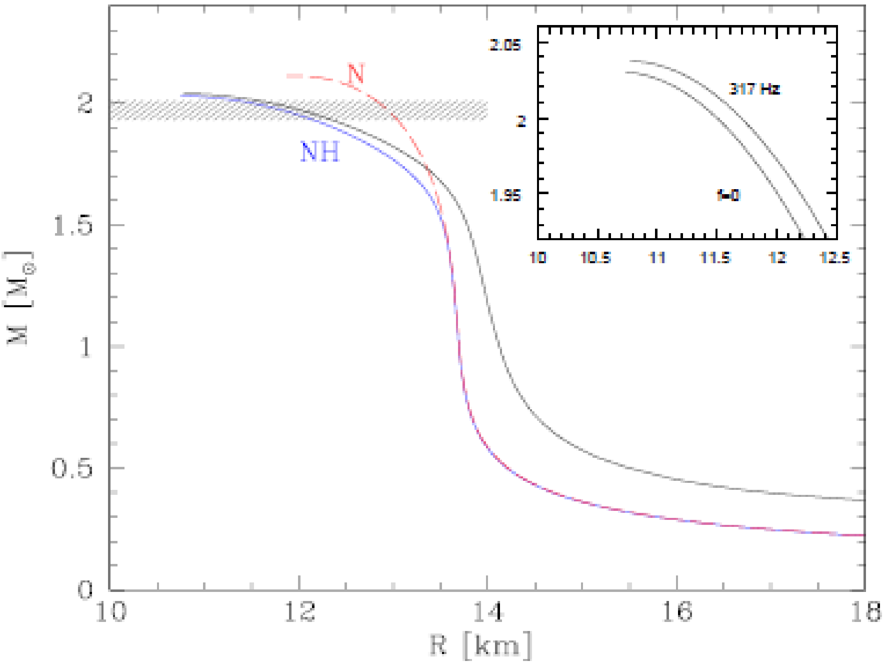




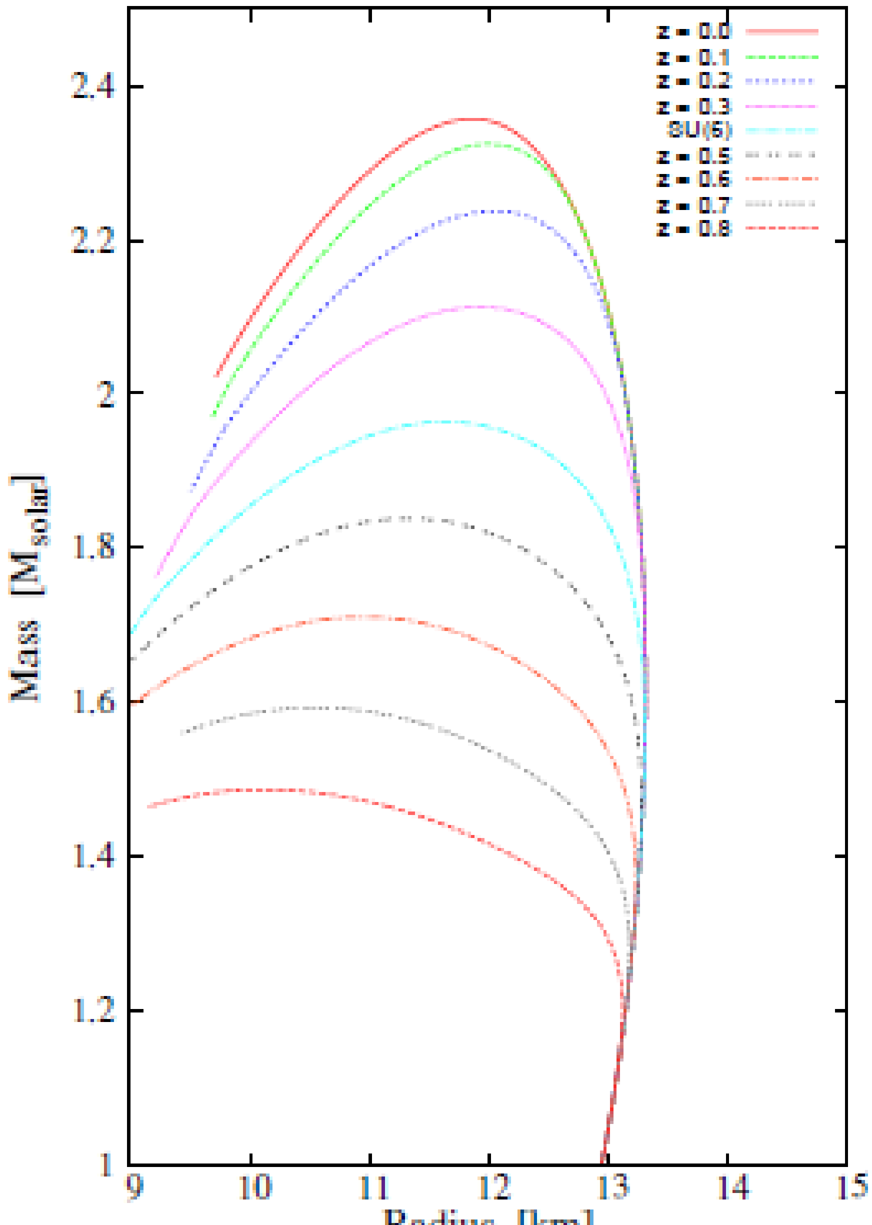
Tsubakihara, AO, NPA914 ('13)438.

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)

Summary of Lecture 4

- ハイパー核物理の進展により、核物質中でのハイペロン・ポテンシャルの深さについて理解が進んでいる。
  $U_\Lambda \sim -30$ MeV, $U_\Sigma \sim +30$ MeV, $U_\Xi \sim -15$ MeV
- 重い中性子星パズルは現象論的には解決可能。
  - SU(6) or SU(3) の破れ、現象論的 3 体力、Quark-meson coupling 、Quark matter への crossover transition 、...
- しかしながらこれらの扱いには実験的に確認できていないパラメータ・仮定を含んでおり、第一原理計算・実験データによる検証が必要。

Hyperons in neutron stars: to be continued

Thank you !