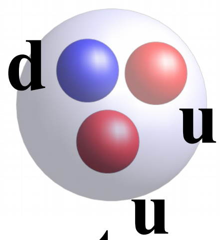
物理学特論I（中性子星と原子核物理）

1. 序論：中性子星とは
2. 中性子星の質量と半径
3. 中性子星に関連する原子核・ハドロン物理学１
   – 原子核の大きさと散乱の量子力学
4. 中性子星に関連する原子核・ハドロン物理学２
   – 原子核の質量と核物質状態方程式
5. 中性子星に関連する原子核・ハドロン物理学３
   – クォークとハドロン
6. 中性子星核物質の状態方程式
7. 中性子星の最近の話題と課題 – 中性子星の最大質量とハイペロンパズル

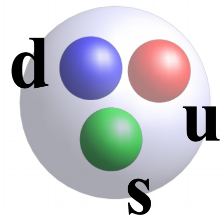
- セミナー：最適化問題としての符号問題

中性子星コアの組成

- 中性子星コアでは様々な粒子・相が現れると期待される！
  - Strange Hadrons

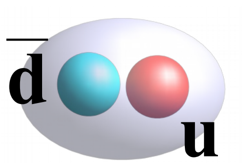


proton

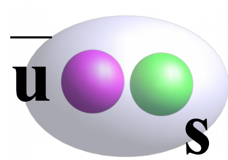


Λ hyperon

  - Meson condensate (K, π)

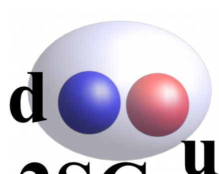


π

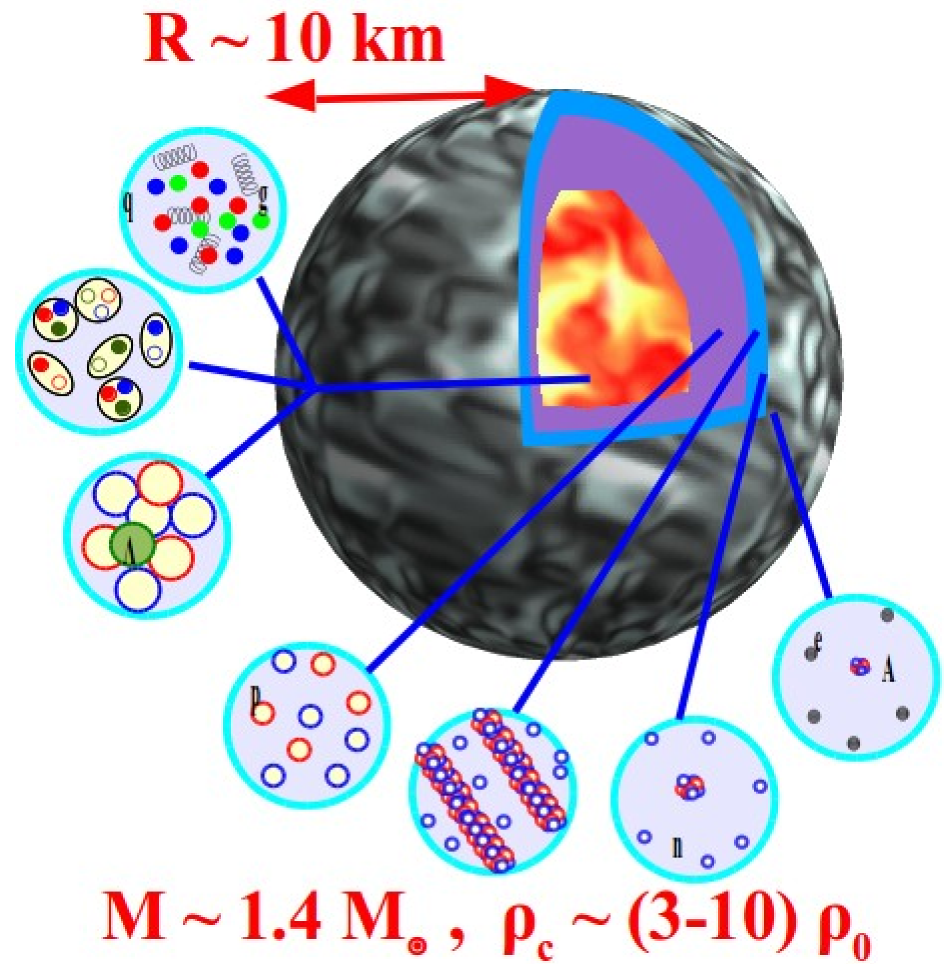


anti kaon

  - Quark matter
  - Quark pair condensate (Color superconductor)



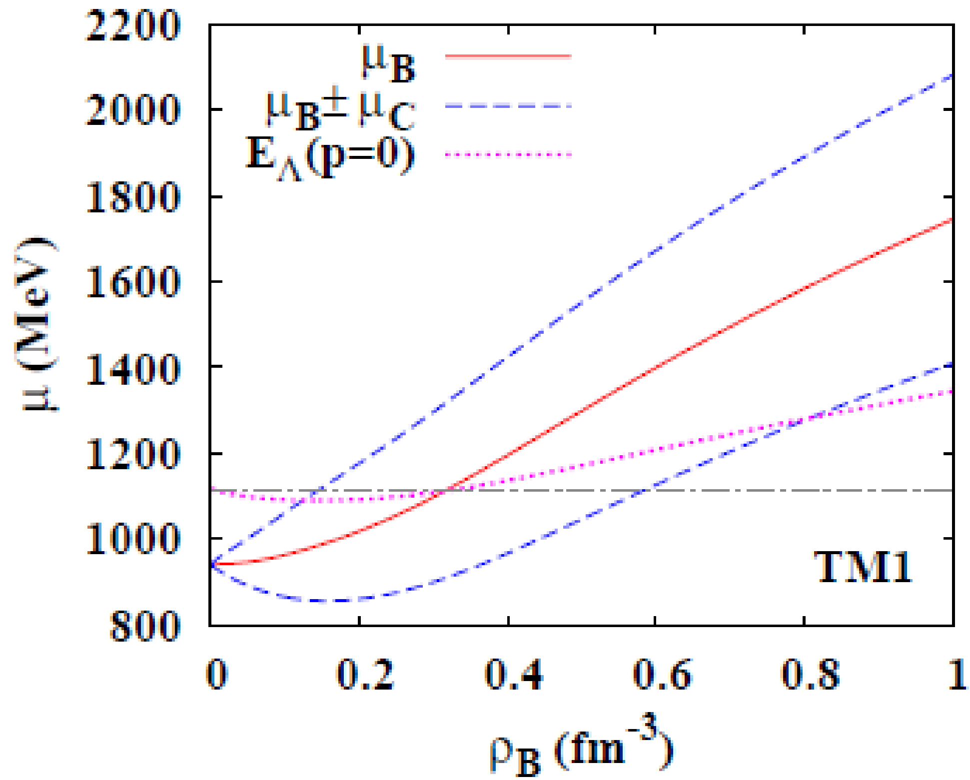
2SC



高密度物質におけるハイペロン

- 高密度→大きな中性子フェルミエネルギー
→様々な粒子・状態
  - 核子超流動 ($^3S_1$, $^3P_2$), π 中間子凝縮 , K 中間子凝縮 , クォーク･グルーオン･プラズマ , カラー超伝導 , ハイペロン混合 , …
  - 特に負電荷をもつバリオンは現れやすい

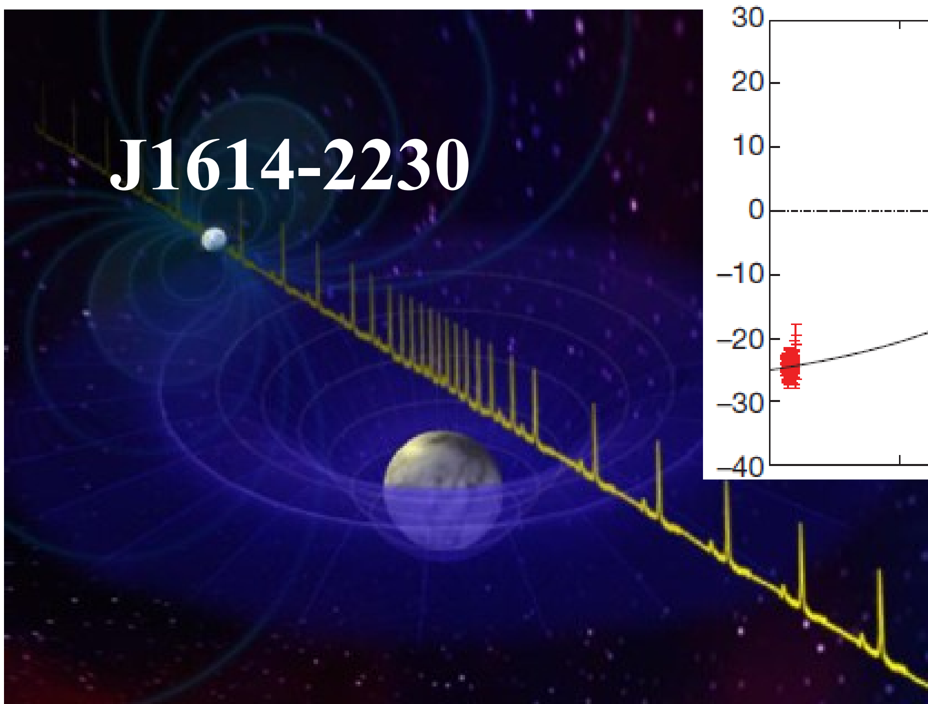
$$\mu_h = \mu_n B_h - \mu_e Q_h$$

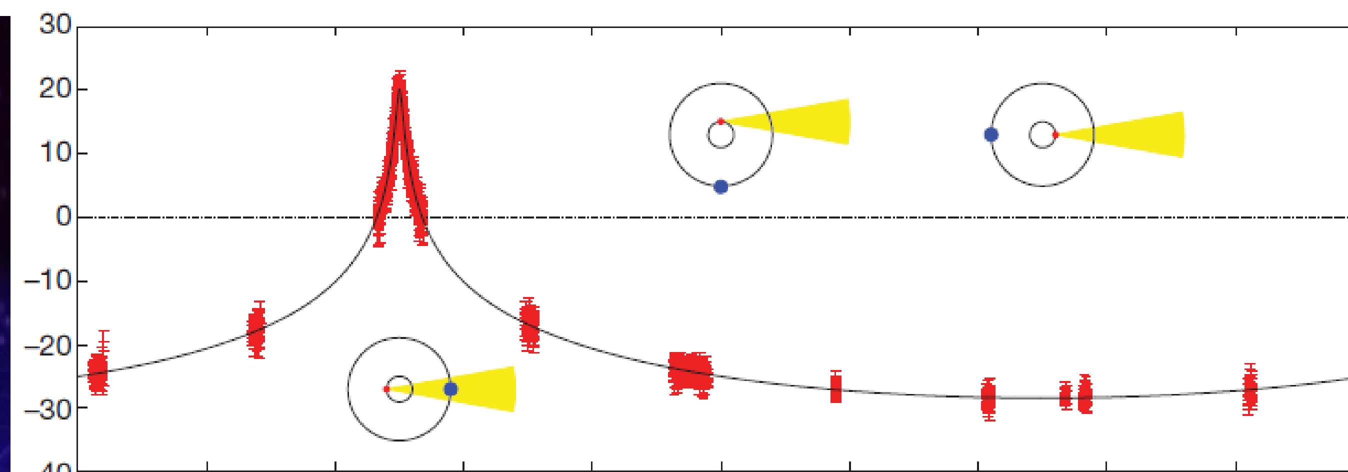


Chemical potential overtakes Λ energy at p=0 → appearance of Λ

重い中性子星 $(M \sim 2\,M_\odot)$

- 一般相対論効果による Time delay
  - Einstein delay : パルサーの運動による遅れ
  - Shapiro delay : 伴星の重力場による遅れ
- 重い中性子星の発見 (J1614-2230)
  - Shapiro delay による質量の評価 $M = 1.97 \pm 0.04\ M_\odot$
    Demorest et al. (2010)

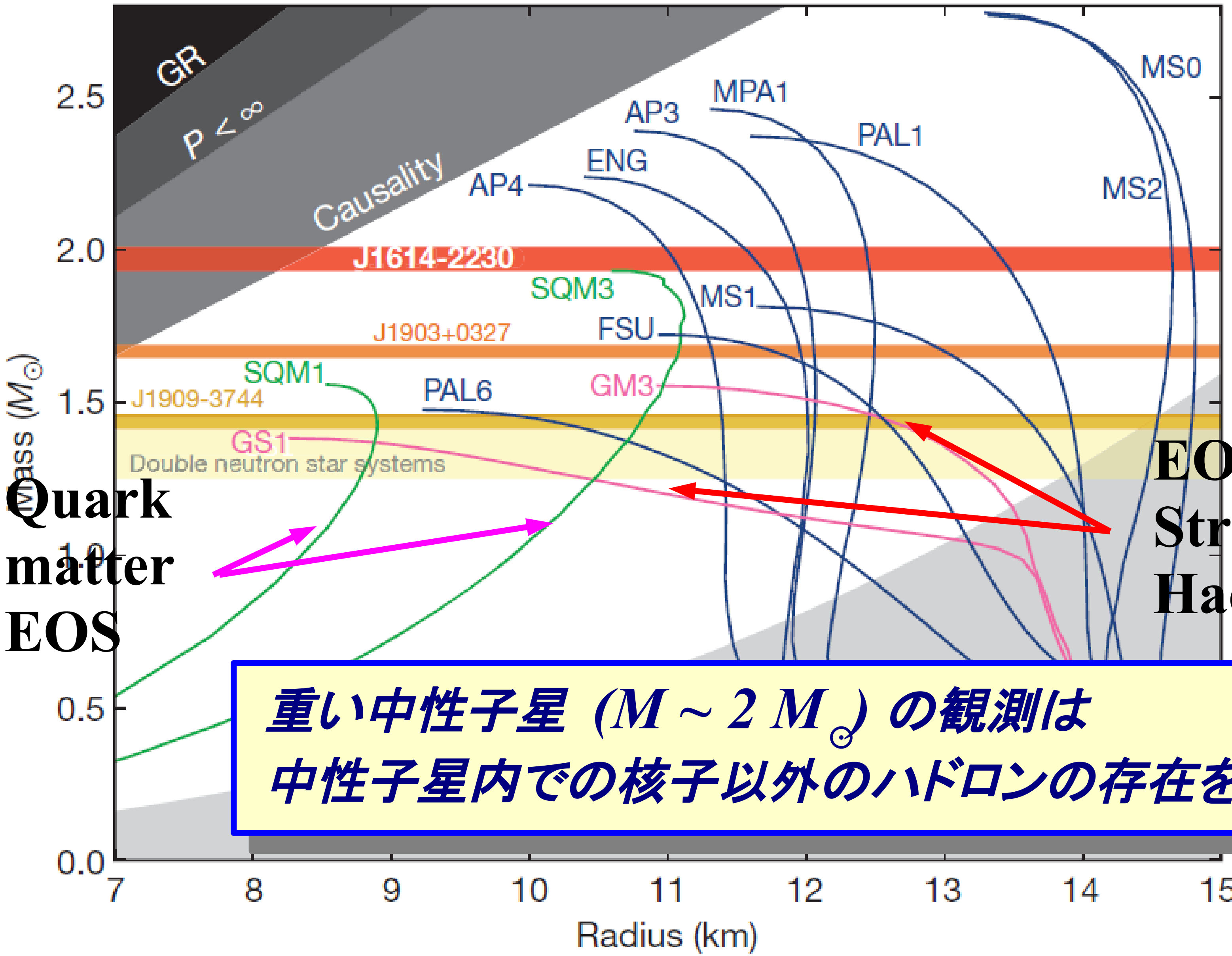




$$\Delta_S = -2m\left[\ln\frac{r}{a} + \ln\left(1 - \sin i \sin\phi\right)\right]$$

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

ハイペロン・パズル



Quark matter EOS

EOS w/ Strange Hadrons

重い中性子星 ($M \sim 2\,M_\odot$) の観測は
中性子星内での核子以外のハドロンの存在を否定する？

PSR J1614-2230: 1.97 ± 0.04 $M_\odot$ *Demorest et al., Nature 467('10)1081 (Oct.28, 2010).*

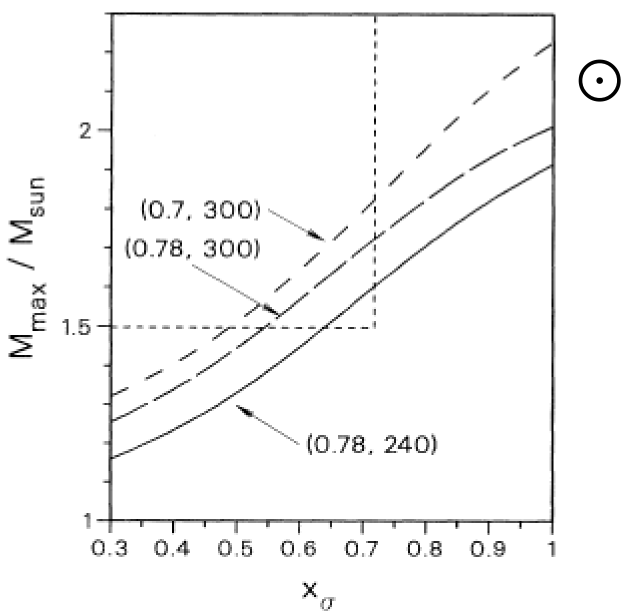
PSR J0348+0432: 2.01 ± 0.04 $M_\odot$ *Antoniadis et al., Science 340('13)1233232.*

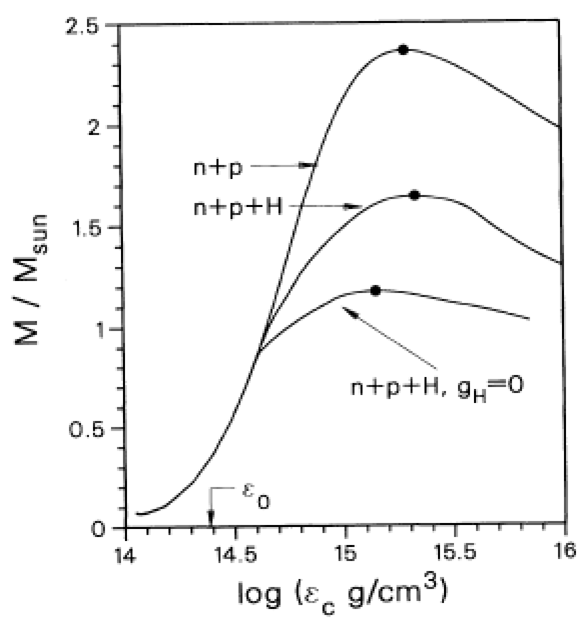
Glendenning & Moszkowski (1991)

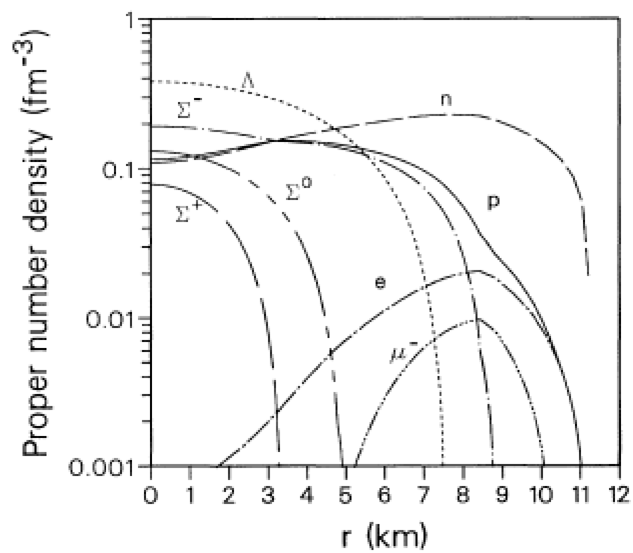
- **RMF with hyperons**
  - **n, p, Y, σ, ω, ρ / σ^3, σ^4**
  - **Give $x_\sigma = g_{\sigma Y}/g_{\sigma N}$ and fix $x_\omega = g_{\omega Y}/g_{\omega N}$ to fit Λ separation energy.**
  - **$x_\sigma = 0.6 \rightarrow m^*/m = 0.7$, $x_\omega = 0.653$ (similar to quark number counting result, x=2/3)**

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

Relativistic Mean Field

- **Mean Field treatment of meson field operator**
  = Meson ield operator is replaced with its expectation value
  $$\varphi(r) \rightarrow \langle\varphi(r)\rangle$$
  Ignoring fluctuations compared with the expectation value may be a good approximation at strong condensate.

- **Which Hadrons should be included in RMF ?**
  - **Baryons (1/2+)** p, n, Λ, Σ, Ξ, Δ, ...
  - **Scalar Mesons (0+)** σ(600), f_0(980), a_0(980), ...
  - **Vector Mesons (1-)** ω(783), ρ(770), ϕ(1020), ...
  - **Pseuso Scalar (0-)** π , K, η, η', ...
  - **Axial Vector (1+)** a_1, ...

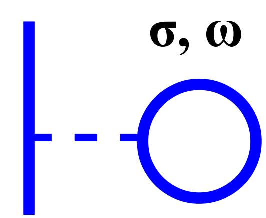
  We require that the meson field can have uniform expectation values in nuclear matter.
  → Scalar and Time-Component of Vector Mesons (σ , ω, ρ, ...)

σω Model

Serot, Walecka, Adv.Nucl.Phys.16 (1986),1

- **Consider only σ and ω mesons**
- **Lagrangian**

$$L=\bar{\psi}(i\gamma^\mu\partial_\mu - M + g_s\sigma - g_v\gamma^\mu\omega_\mu)\psi$$
$$+\frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma - \frac{1}{2}m_s^2\sigma^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_v^2\omega_\mu\omega^\mu$$
$$(F_{\mu\nu}=\partial_\mu\omega_\nu - \partial_\nu\omega_\mu)$$



- **Equation of Motion**
  - **Euler-Lagrange Equation**

$$\frac{\partial}{\partial x^\mu}\left[\frac{\partial L}{\partial(\partial_\mu\phi_i)}\right] - \frac{\partial L}{\partial\phi_i} = 0$$

$$\sigma : \left[\partial_\mu\partial^\mu + m_s^2\right]\sigma = g_s\bar{\psi}\psi$$

$$\omega : \partial_\mu F^{\mu\nu} + m_v^2\omega^\nu = g_v\bar{\psi}\gamma^\nu\psi \quad \rightarrow \quad \left[\partial_\mu\partial^\mu + m_v^2\right]\omega^\nu = g_v\bar{\psi}\gamma^\nu\psi$$

$$\psi : \left[\gamma^\mu\left(i\partial_\mu - g_v V_\mu\right) - (M - g_s\sigma)\right]\psi = 0$$

EOM of ω (for beginners)

- **Euler-Lagrange Eq.**

$$\partial_\mu F^{\mu\nu} + m_v^2 \omega^\nu = g_v \bar{\psi} \gamma^\nu \psi$$

- **Divergence of LHS and RHS**

$$\partial_\nu \partial_\mu F^{\mu\nu} + m_v^2 (\partial_\nu \omega^\nu) = m_v^2 (\partial_\nu \omega^\nu) = g_v (\partial_\nu \bar{\psi} \gamma^\nu \psi) = 0$$

LHS: derivatives are sym. and $F_{\mu\nu}$ is anti-sym.

RHS: Baryon Current = Conserved Current

- **Put it in the Euler-Lagrange Eq.**

$$\partial_\mu F^{\mu\nu} = \partial_\mu (\partial^\mu \omega^\nu - \partial^\nu \omega^\mu) = \partial_\mu \partial^\mu \omega^\nu - \partial^\nu (\partial_\mu \omega^\mu) = \partial_\mu \partial^\mu \omega^\nu$$

Schroedinger Eq. for Upper Component

- **Dirac Equation for Nucleons**

$$\left(i\gamma\partial - \gamma^0 U_v - M - U_s\right)\psi = 0 \quad , \quad U_v = g_\omega \omega \quad , \quad U_s = -g_\sigma \sigma$$

- **Decompose 4 spinor into Upper and Lower Components**

$$\begin{pmatrix} E - U_v - M - U_s & i\sigma\cdot\nabla \\ -i\sigma\cdot\nabla & -E + U_v - M - U_s \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix} = 0$$

$$g = \frac{-i}{E + M + U_s - U_V}(\sigma\cdot\nabla) f$$

$$(E - M - U_v - U_s) f = -i(\sigma\cdot\nabla) g$$

- **Erase Lower Component (assuming spherical sym.)**

$$-i(\sigma\cdot\nabla) g = -(\sigma\cdot\nabla)\frac{1}{X}(\sigma\cdot\nabla) f = -\frac{1}{X}\nabla^2 f - \frac{1}{r}\left[\frac{d}{dr}\frac{1}{X}\right](\sigma\cdot r)(\sigma\cdot\nabla) f = -\nabla\frac{1}{X}\nabla f + \frac{1}{r}\left[\frac{d}{dr}\frac{1}{X}\right](\sigma\cdot l) f$$

$$(\sigma\cdot r)(\sigma\cdot\nabla) = (r\cdot\nabla) + i\sigma\cdot(r\times\nabla) = r\cdot\nabla - \sigma\cdot l$$

- **"Schroedinger-like" Eq. for Upper Component**

$$-\nabla\frac{1}{E + M + U_s - U_v}\nabla f + \left(U_s + U_v + U_{LS}(\sigma\cdot l)\right) f = (E - M) f$$

$$U_{LS} = \frac{1}{r}\left[\frac{d}{dr}\frac{1}{E + M + U_s - U_v}\right] < 0$$ on surface

(Us,Uv)~ (-350 MeV,280 MeV)

→Small Central(Us+Uv), Large LS (Us-Uv)

Nuclear Matter in σω Model

Serot, Walecka, Adv.Nucl.Phys.16 (1986),1

- **Uniform Nuclear Matter**

$$E/V = \gamma_N \int^{P_F} \frac{d^3 p}{(2\pi)^2} E^* + \frac{1}{2} m_s^2 \sigma^2 - \frac{1}{2} m_v^2 \omega^2 + g_v \rho_B \omega$$

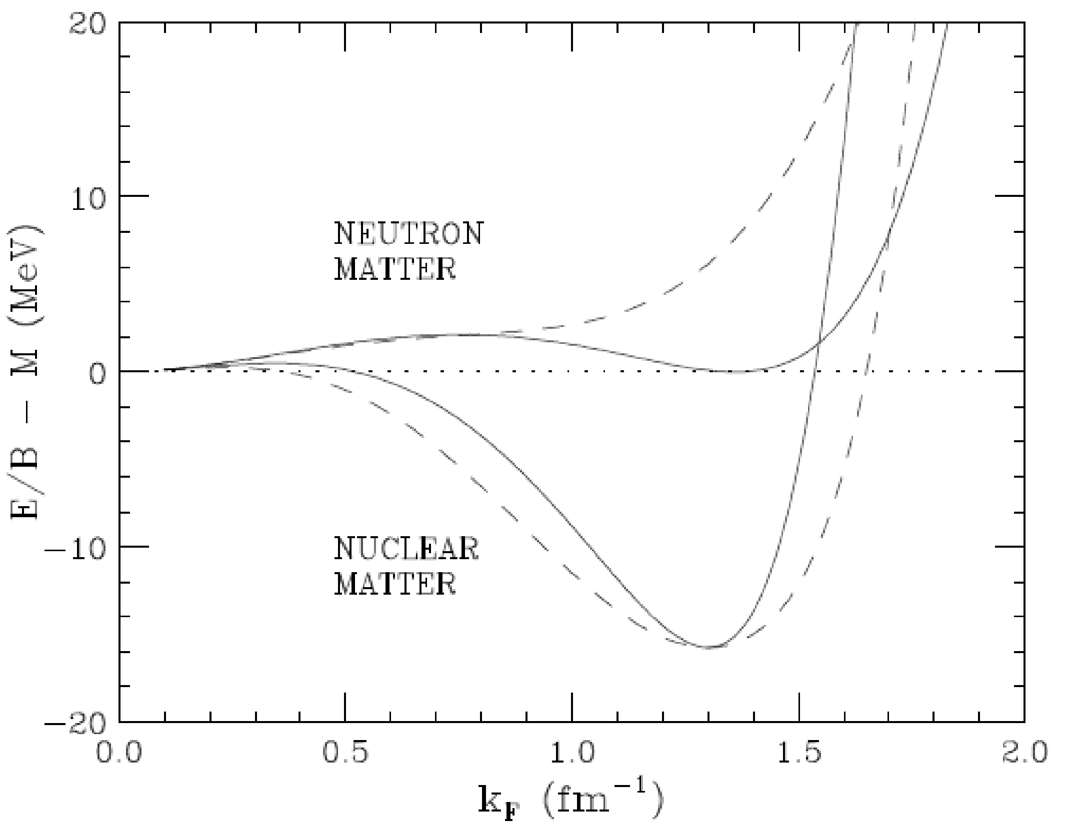
$$\sigma = \frac{g_s}{m_s^2} \rho_s = \gamma_N \frac{g_s}{m_s^2} \int^{P_F} \frac{d^3 p}{(2\pi)^2} \frac{M^*}{E^*} \qquad (M^* = M + U_s = M - g_s \sigma, \quad E^* = \sqrt{p^2 + M^{*2}})$$

$$\omega = \frac{g_v}{m_v^2} \rho_B = \gamma_N \frac{g_v}{m_v^2} \int^{P_F} \frac{d^3 p}{(2\pi)^3}$$

γ_N = Nucleon degeneracy

(=4 in sym. nuclear matte

Problem: EOS is too stiff
K ~ (500-600) MeV !
→ How can we solve ?

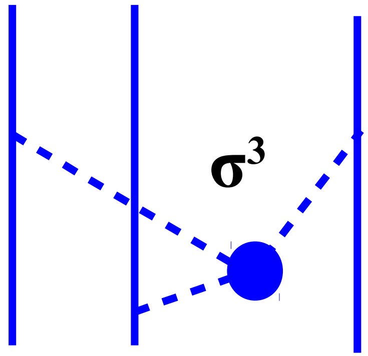


σ ω model --- pros and cons

- **Pros (merit)**
  - **Foundation is clear: based on the success of Dirac phen. and DBHF.**
  - **Simple description of scalar and vector potential in σ and ω mesons.**
  - **Saturation is well described in two parameters.**
  - **Natural explanation of large LS potential in nuclei.**
- **Cons (shortcomings)**
  - **Relation with the bare NN interaction is not clear.**
  - **Especially, pion effects are not included.**
  - **Symmetry energy is too small.**
  - **Incompressibility is too large (K ~ 600-700 MeV)**
    (c.f. Empirical value K ~ (200-300) MeV)
  - **Chiral symmetry is not respected.**

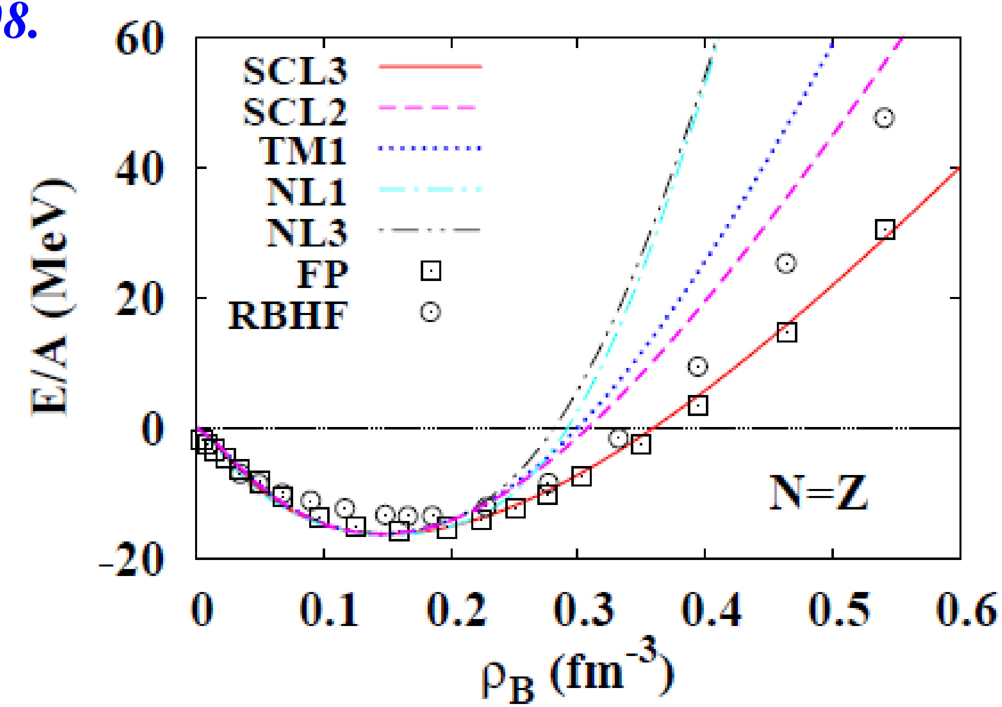
High Quality RMF models

- **Variety of the RMF models**
  → MB couplings, meson masses, meson self-energies



  - ***σN*, *ωN*, *ρN* couplings are well determined**
    → almost no model deps. in Sym. N.M. at low ρ
  - **ω^4 term is introduced to simulate DBHF results of vector pot.**
    TM: Y. Sugahara, H. Toki, NPA579('94)557;
    R. Brockmann, H. Toki, PRL68('92)3408.
  - **σ^3 and σ^4 terms are introduced to soften EOS at ρ_0.**
    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.

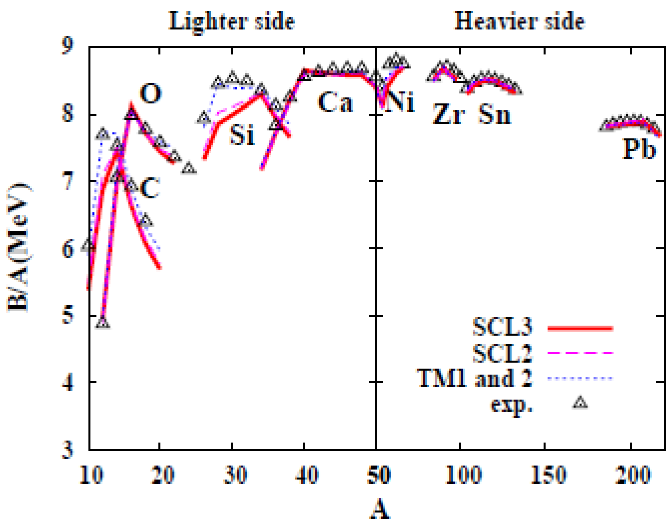
→ Large differences are found at high ρ

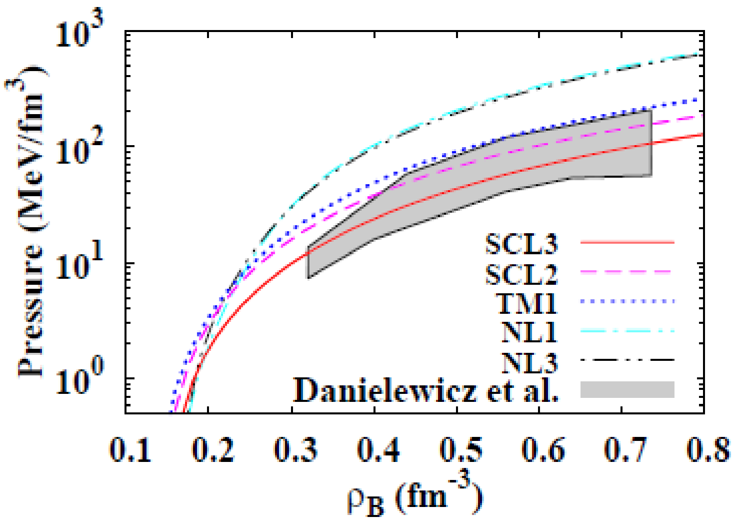


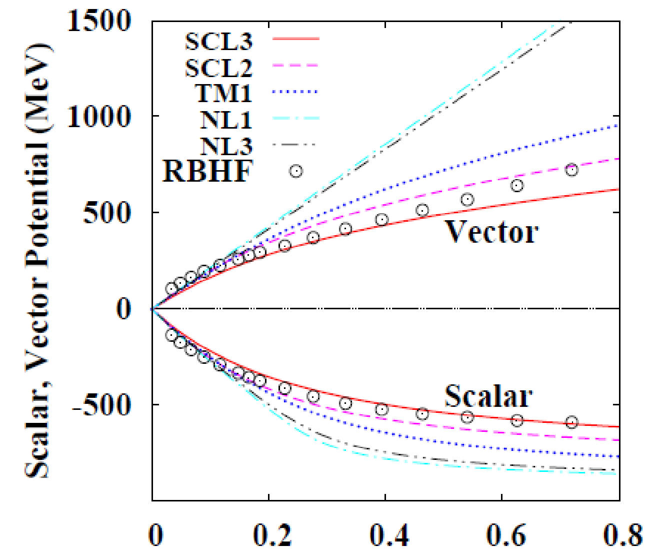
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

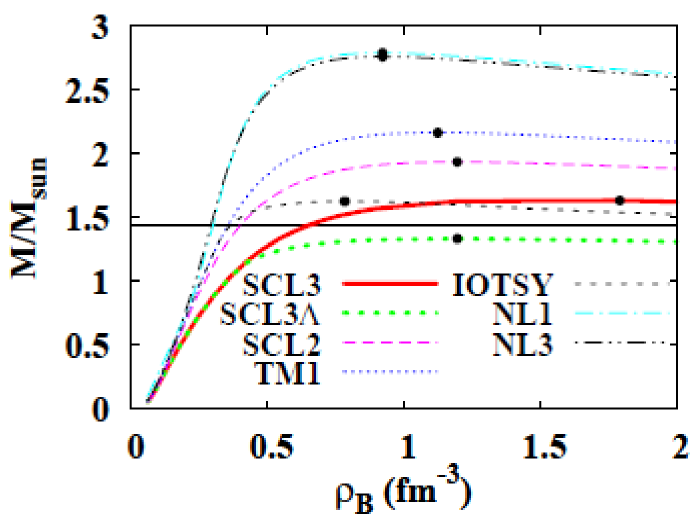
How to determine Non-Linear terms ?

- **Method 1: Fit as many as known observables**
  - **EOS, Nuclear B.E., High density EOS from HIC, Vector potential in DBHF, Neutron Star, ...**









高密度でのハイペロンの性質についてはデータがなく、考慮していない！

P. Danielewicz, R. Lacey,W. G. Lynch, Science298('02)1592.
R. Brockmann, R. Machleidt, PRC42('90)1965.
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO,PRC81('10)065206.

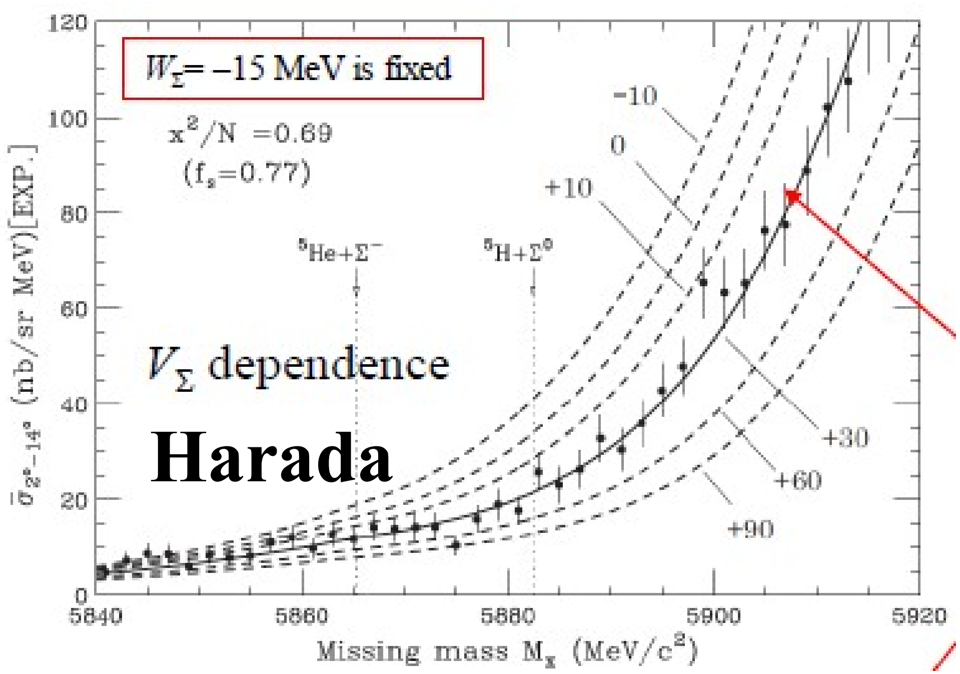
これまでに見落としがあったのか？

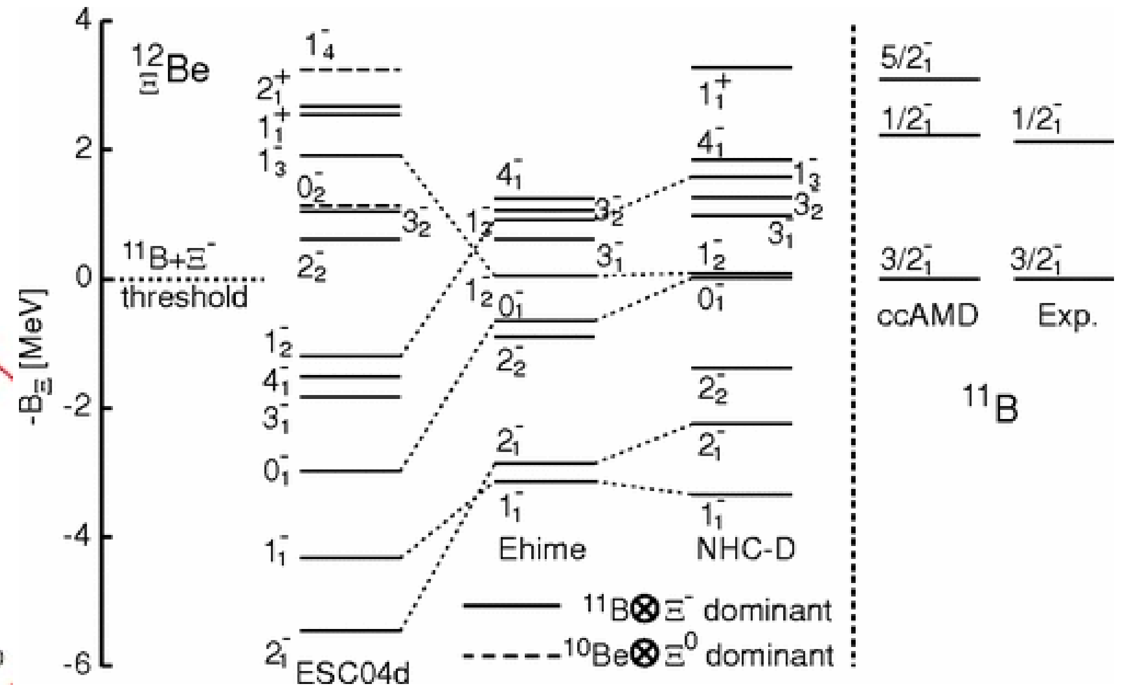
- 核物質中のハイペロン･ポテンシャル ?
  - $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV
- ハイペロン･ハイペロン相互作用？
  - Nagara event → ΛΛ ポテンシャルは弱い引力。
  - 高密度で斥力的となる？
- 反 K 中間子と原子核のポテンシャル ?

- Three-baryon (3B) interaction ?
- Quark matter core ?
- Modified gravity ?

核内でのΣ、Ξ のポテンシャル？

- 新しいΣ 生成実験 : ^{6}Li (π^-, K$^+$) $\Sigma^- {}^5$He と理論分析 (A02, Harada)
  → $U_\Sigma \sim +30$ MeV (consistent)
- Ξ ハイパー核生成実験 → B.E. = 9 MeV & (4 or 1) MeV
  → これまで想定されていたポテンシャル (U~ -14 MeV) よりも深い

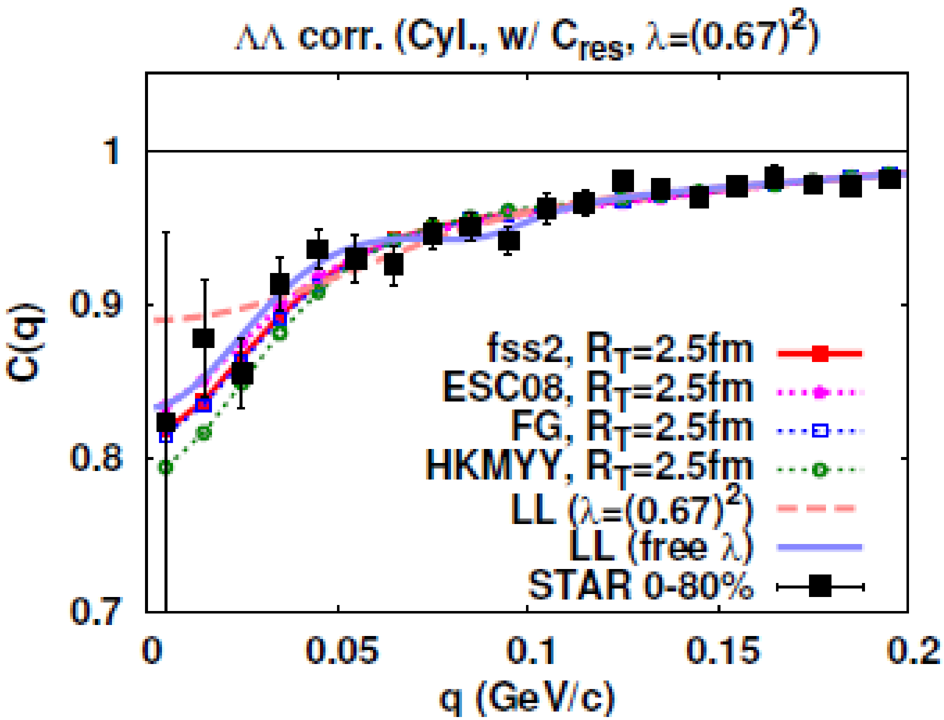


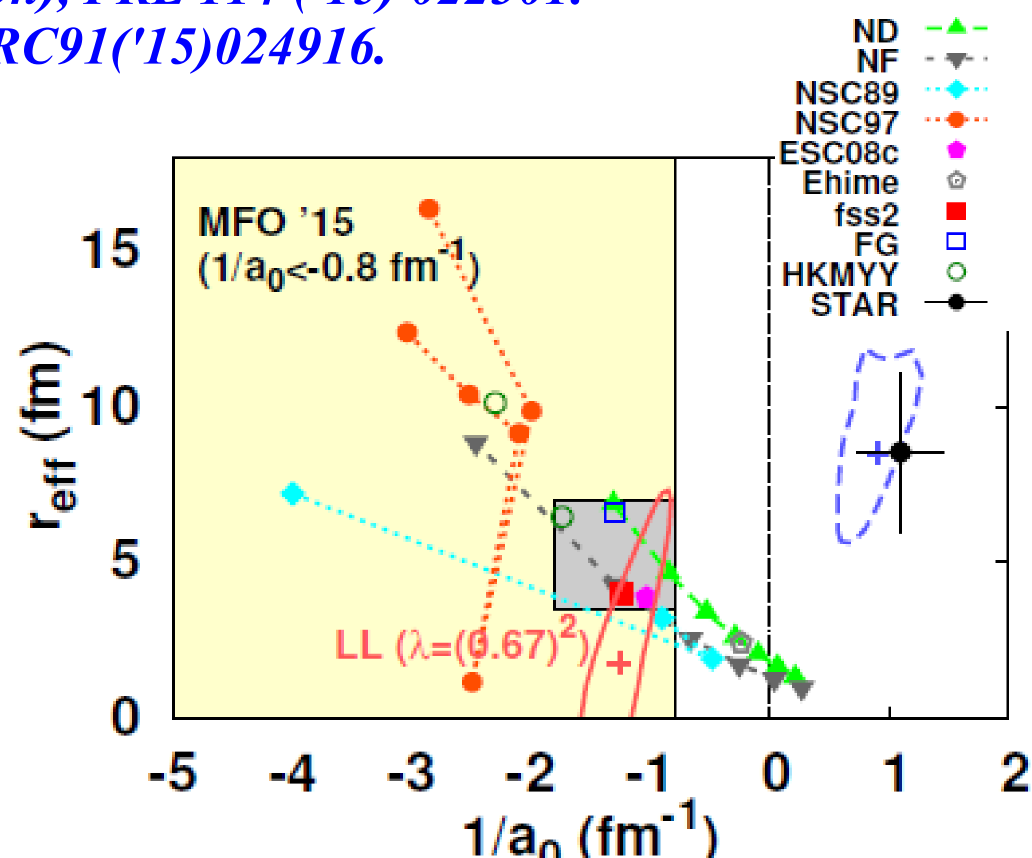


Matsumiya, Tsubakihara, Kimura, Dote, AO ('11)

ΛΛ ポテンシャル？

- Nagara Event → $a_0(\Lambda\Lambda)$= - 0.575 fm or - 0.77 fm
  Hiyama, Kamimura, Motoba, Yamada, Yamamoto ('02), Filikhin, Gal ('02)
- 新しい観測量 : ΛΛ correlation from HIC (Morita)
  → -1.25 fm < $a_0(\Lambda\Lambda)$ < 0 (Consistent with Nagara)
  Exp: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  Theor.:Morita et al., T.Furumoto, AO, PRC91('15)024916.





これまでに見落としがあったのか？

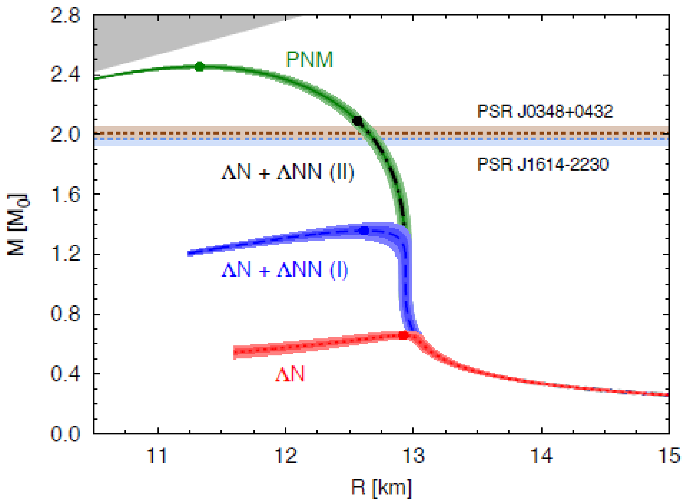
- 核物質中のハイペロン・ポテンシャル？ **($U_\Sigma \sim +30$ MeV)**
  - $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV
  - **($U < -14$ MeV)**
- ハイペロン・ハイペロン相互作用？
  - Nagara event → ΛΛ ポテンシャルは弱い引力。**OK**
  - 高密度で斥力的となる？
- 反 K 中間子と原子核のポテンシャル？

- Three-baryon (3B) interaction ?
- Quark matter core ?
- Modified gravity ?

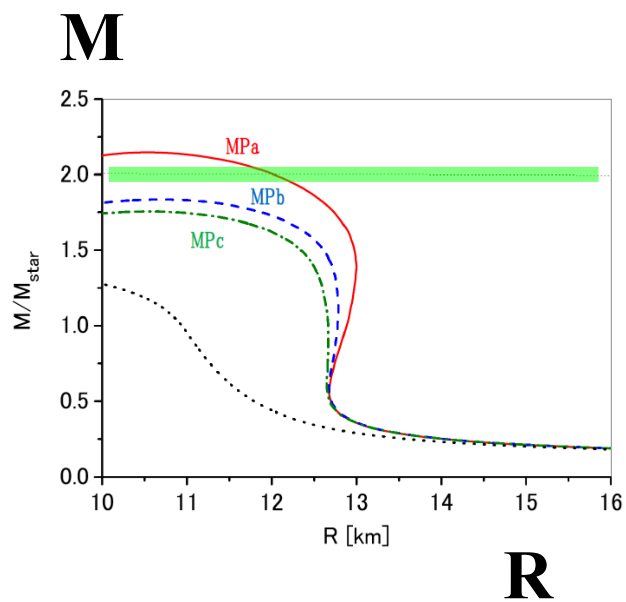
残る解決方法

- **Three-baryon (3B) interaction ?**
  - **“Universal” 3B repulsion**
    Nishizaki, Takatsuka, Yamamoto ('02), Tamagaki ('08), Yamamoto, Furumoto, Yasutake, Rijken ('13)
  - **Repulsive ΛNN potential (or density dep. ΛN pot.)**
    Lonardoni, Lovato, Gandolfi, Pederiva ('15), Togashi, Hiyama, Yamamoto, Takano ('16), Tsubakihara, Harada, AO ('16)
  - **Medium modification of baryons (Quark Meson Coupling model)**
    J.Rikovska-Stone, P.A.M.Guichon, H.H.Matevosyan, A.W.Thomas ('07), Miyatsu, Yamamuro, Nakazato (‘13)
- **Quark matter NS core ?**
  - **First order phase transition**
    L. Bonanno, A. Sedrakian, Astron. Astrophys. 539 (2012) A16; M. Bejger, D. Blaschke, P. Haensel, J. L. Zdunik, M. Fortin, arXiv:1608.07049.
  - **Crossover transition to quark matter** *Masuda, Hatsuda, Takatsuka (‘12)*
- **Modified Gravity** *Astashenok et al. ('14), M.-K. Cheoun's talk*

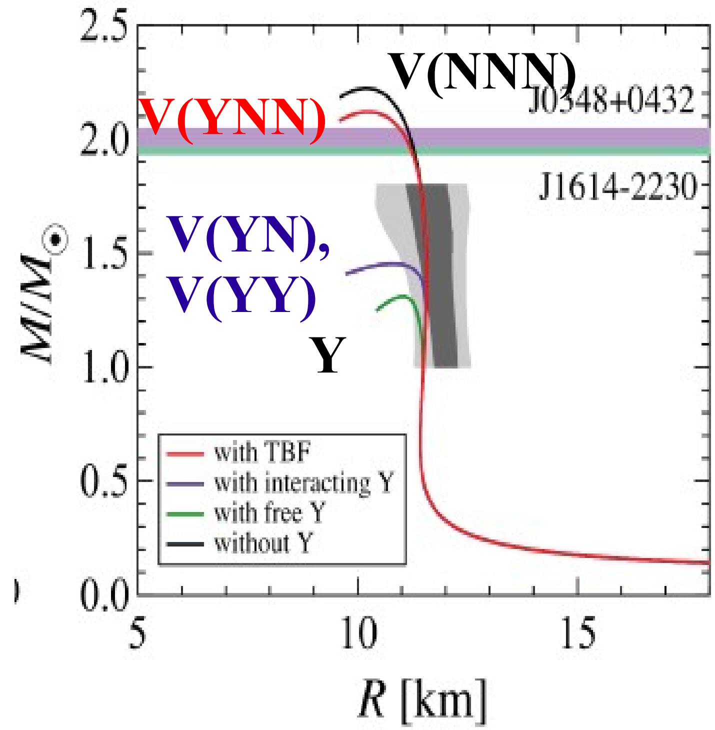
Hyperon Puzzle



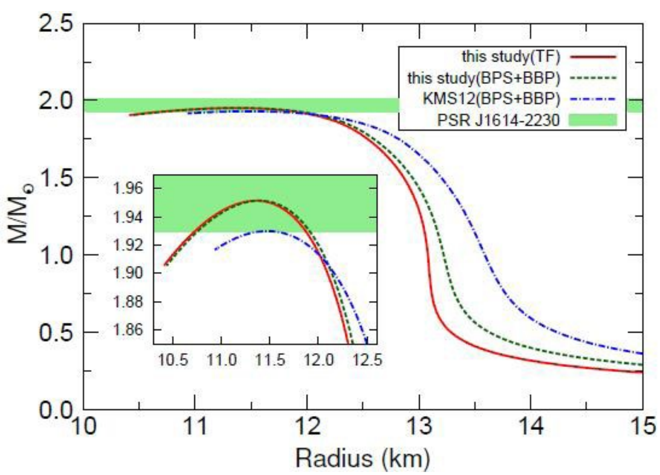
Lonardoni, Lovato, Gandolfi, Pederiva ('15),



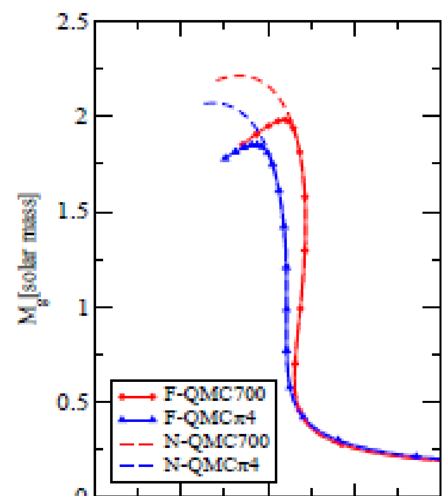
Yamamoto, Furumoto, Yasutake, Rijken ('13)



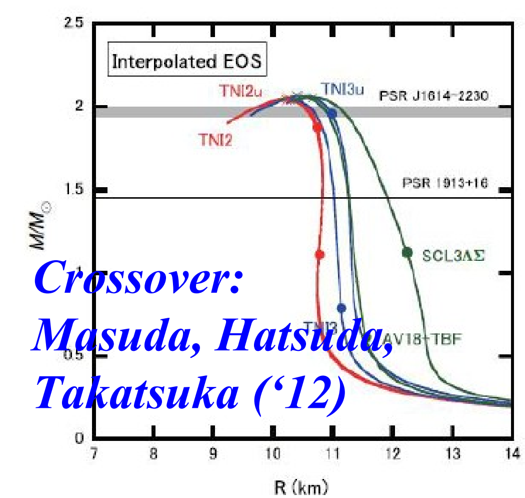
Togashi, Hiyama, Takano, Yamamoto ('16).



QMC, Miyatsu,Yamamuro, Nakazato ('13)



Rikovska-Stone, Guichon, Matevosyan, Thomas ('07),

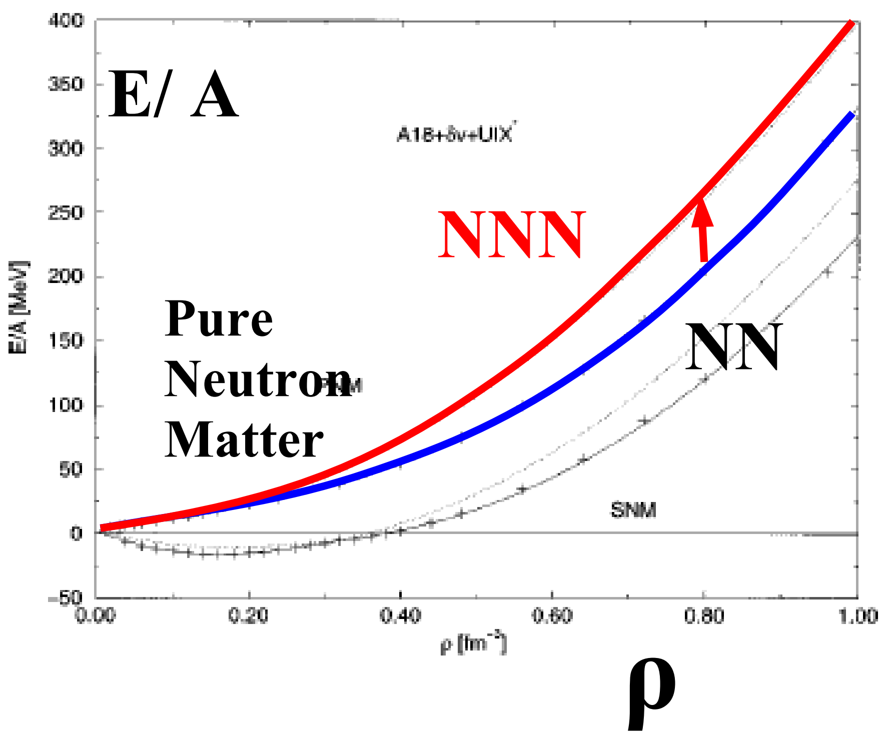


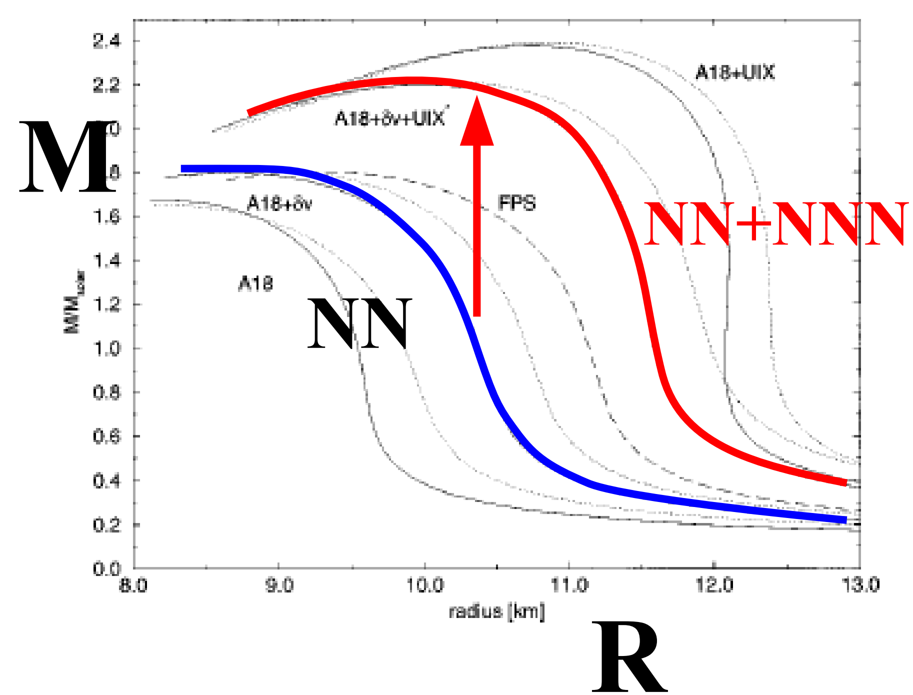
Crossover: Masuda, Hatsuda, Takatsuka ('12)

第一原理計算からの示唆

- 第一原理計算 (核力から出発した近似のない計算)
  - 2 核子間の核力だけでは原子核は支えられない
  - 3 核子間にまたがる力が必要

パズルを解くにはハイペロンを含む 3 体力を考えることが必要

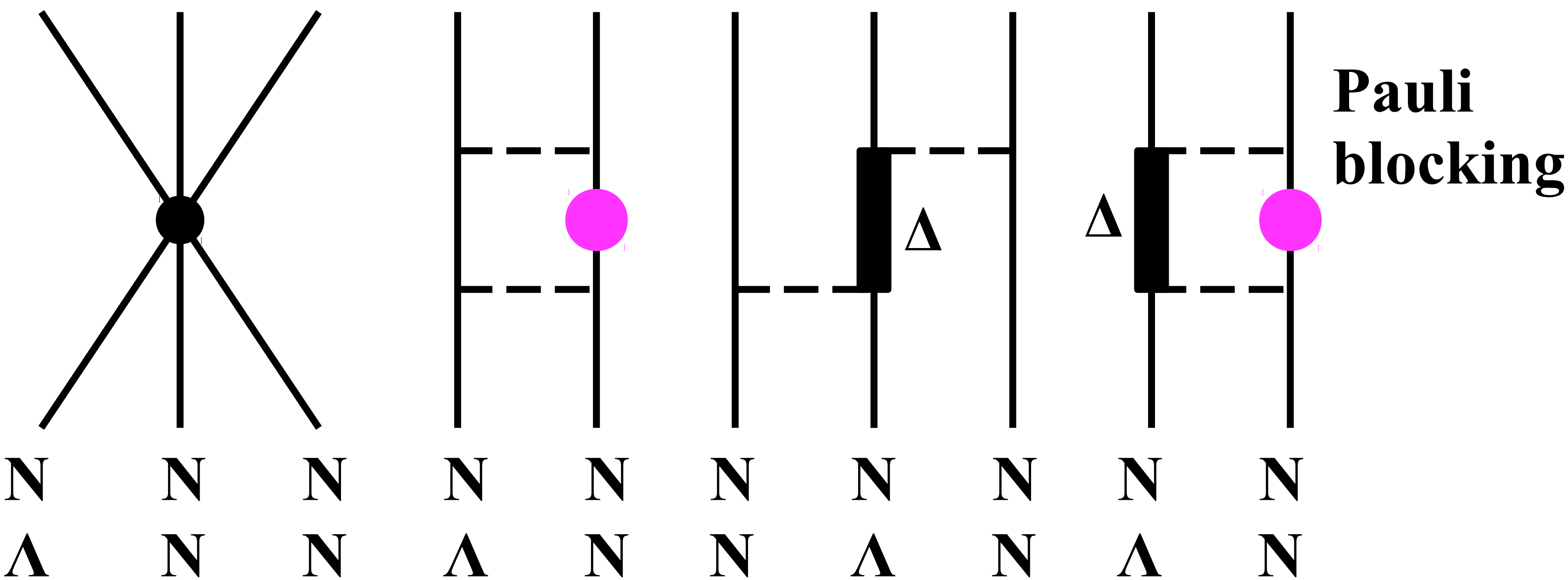




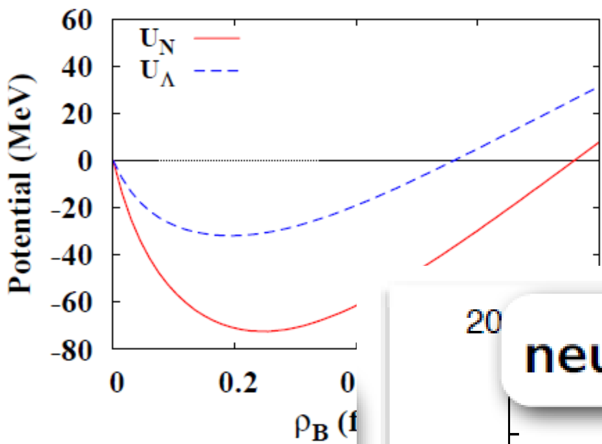
Akmal, Pandharipande, Ravenhall ('98)

3体力 (or 密度依存力) の起源

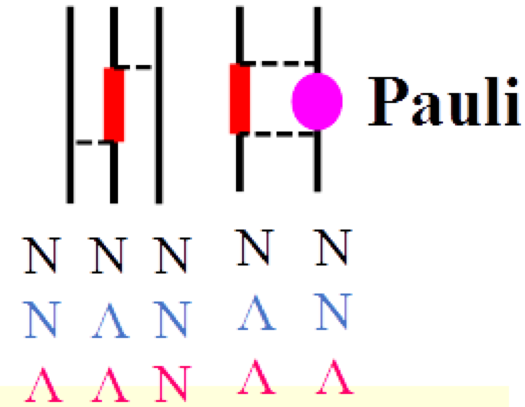
- 生の (bare) 短距離3体力 → クォーク･グルーオン自由度？
- Δ 経由3体力 (藤田･宮沢3体力)
- 2π 交換中間状態におけるパウリ排他率
  → 引力の減少による斥力効果

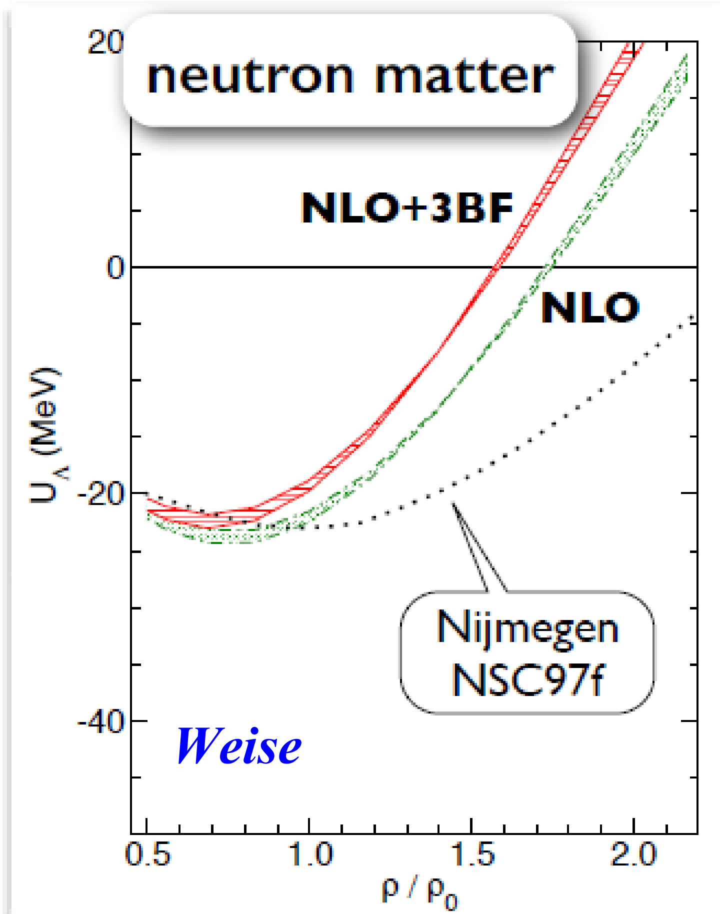


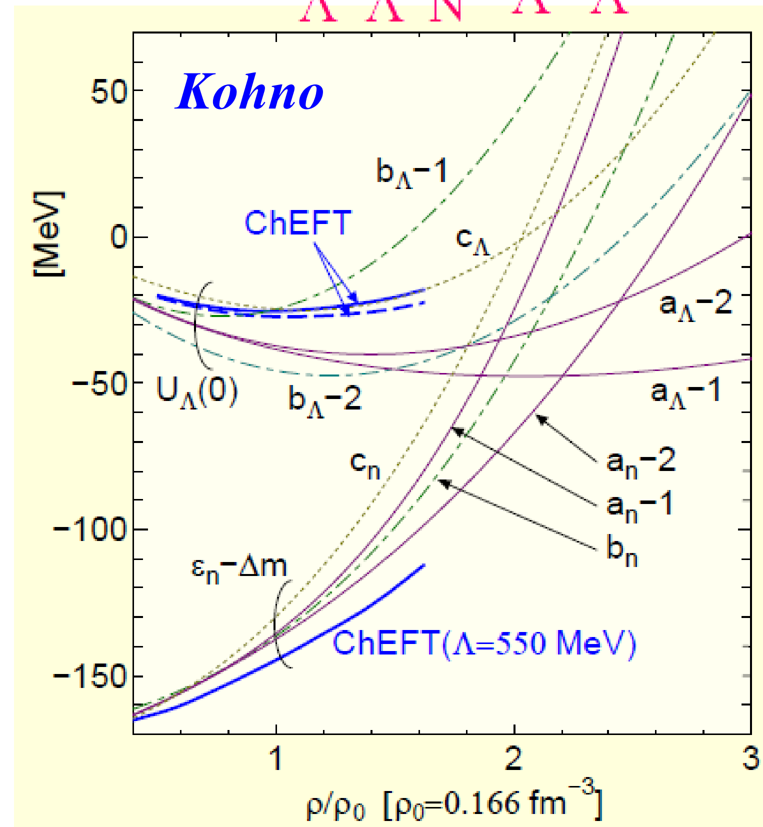
ハイペロン3体力(密度依存性)



Tsubakihara et al. ('10)



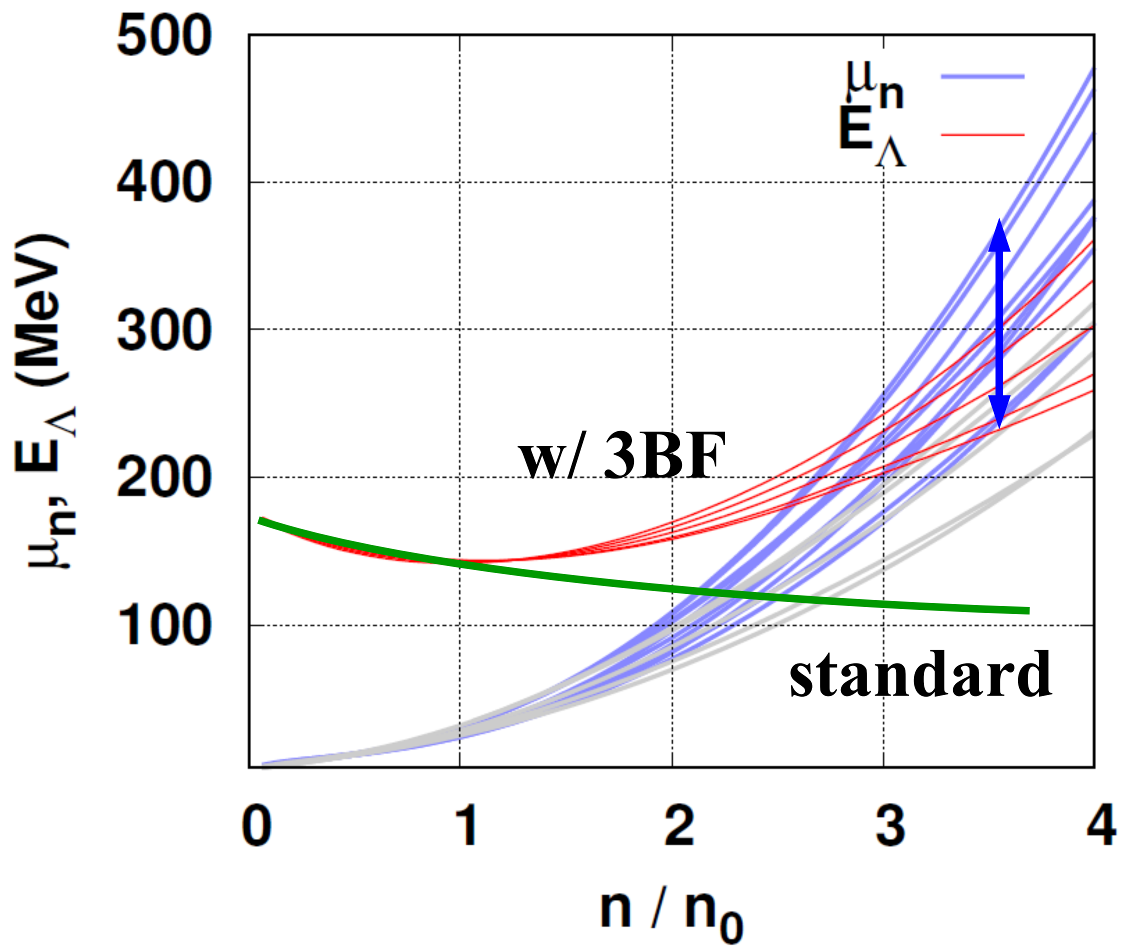




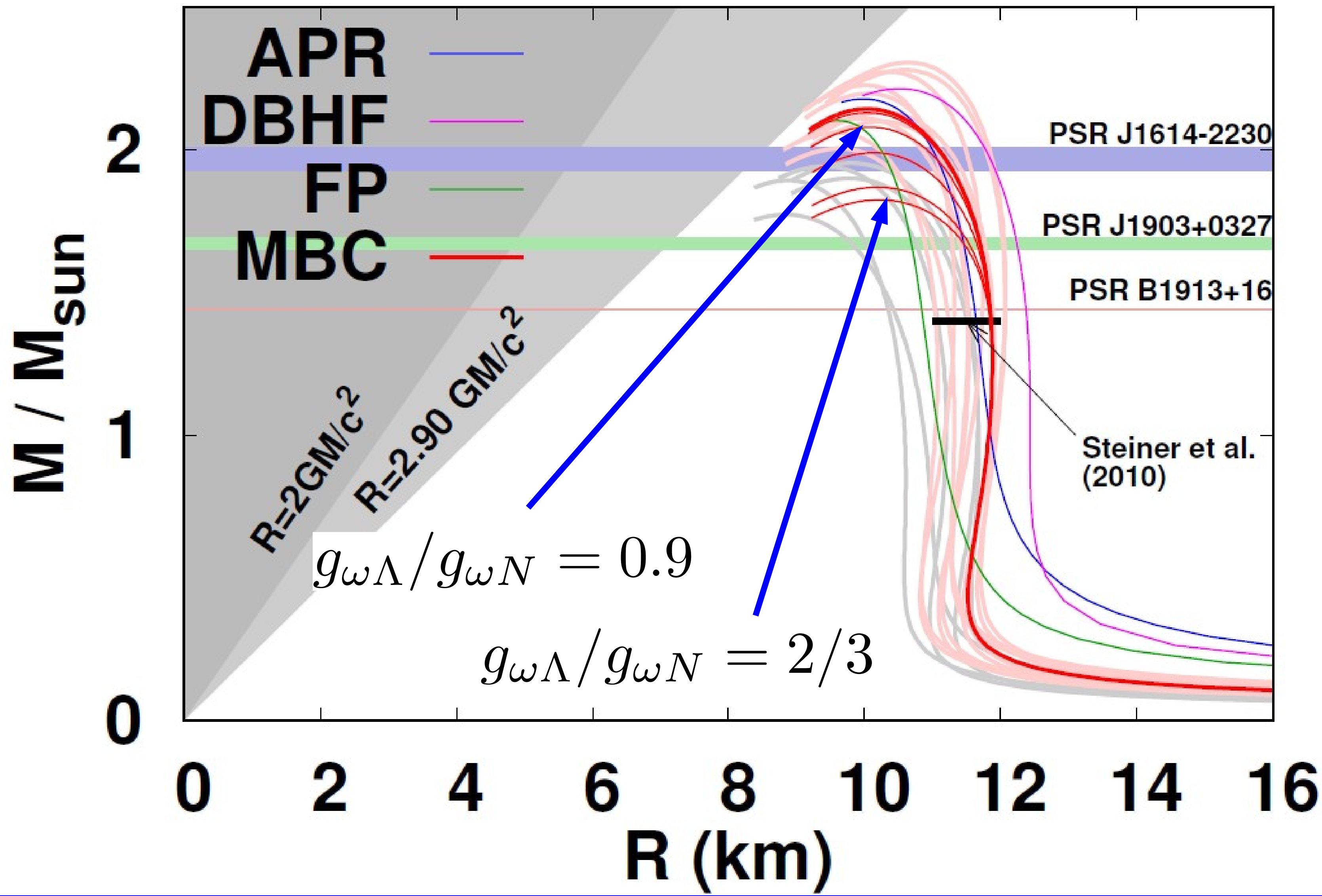
Chiral EFT 等で3体力を考慮 → U_Λ は ρ_0 近辺で上昇へ向かう

ハイペロンは現れるか？

- 新学術研究の成果 → ハイペロンパズルはより深刻に。
  - Ξ 核は束縛 (B.E. > 1 MeV (emulsion), B.E. > 10 MeV? (E07))
  - K 核 (K– pp) も束縛 (B.E. ~ 40 MeV (E15))
  - Σ - 核相互作用は斥力 (UΣ ~ +30 MeV)
- 重い中性子星
  + 対称エネルギーパラメータ
  → μ_n (4n0) > 300 MeV
- ハイペロン発現密度
  $E_\Lambda = \mu_n$
- 高密度対称エネルギーに
  強く依存



ハイペロンを含むEOSでのMR曲線



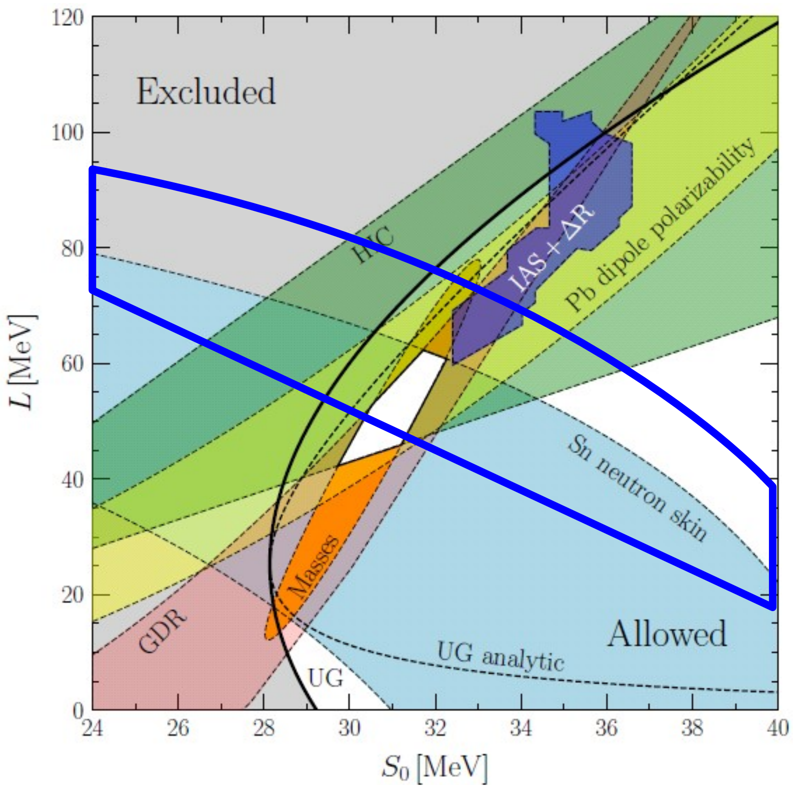
$g_{\omega\Lambda}/g_{\omega N} > 0.8$ であれば、ハイパー核データを説明しつつ、$2\ M_{\odot}$ の中性子星が支えられるようである。

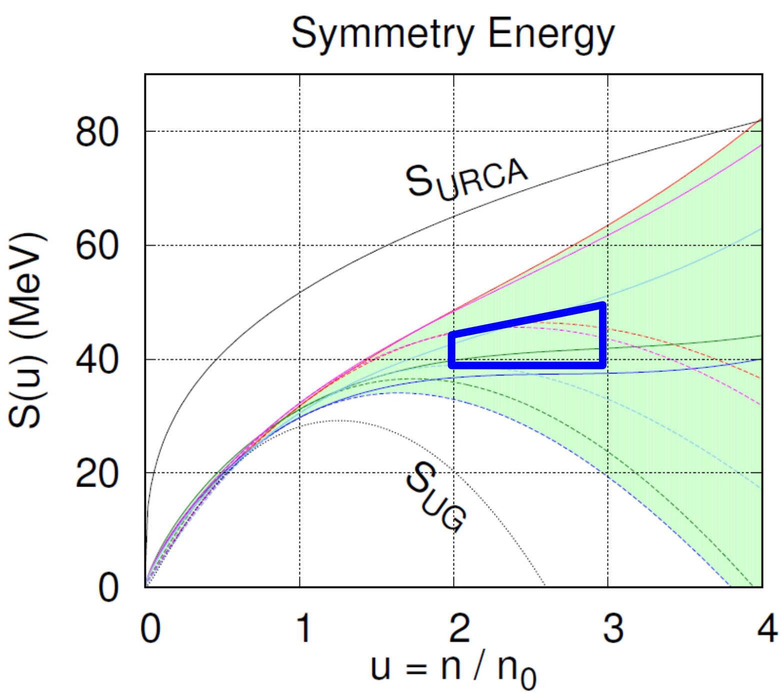
まとめ

- 中性子星の核物質研究
  - 核物理・天体物理・物性物理研究者の連携
    → 原子核と物性 (量子多体問題)
    & 原子核と天体物理 (地上と天上)
- 中性子過剰物質の EOS
  - 5 年間で対称エネルギーパラメータは強く制限された
  - しかし「外挿」、そして中性子星観測量にはまだ大きな不定性
    → to be continued
- ハイペロン・パズル
  - 3 体力 ? クォーク物質 ? 修正重力 ?
  - YN, $\bar{K}$N 相互作用に基づく厳密計算によりデータを定量的 (~ (1-10) MeV の精度) に説明可
  - ハイペロンの発現は対称エネルギーが決定、
    中性子星の最大質量は 3 体力に依存
    → to be continued

展望 (1): 対称エネルギー

- 対称エネルギーパラメータ
  Skin thickness 測定が鍵 (右下がり)→ RIBF 実験
- 高密度での対称エネルギー = 中性子星半径に直接的に重要
  → RIBF 実験
- 分野をまたいで多体問題を解く手法の開発





$$r_{np}^{208}(S_v, L) \simeq a_0 + a_1 S_v + a_2 L + a_3 S_v^2 + a_4 S_v L + a_5 L^2,$$

Chen et al. ('10)

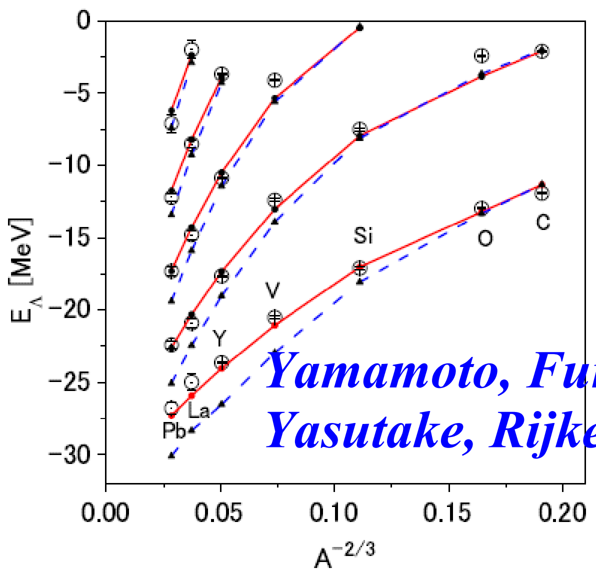
展望 (2): ハイペロンパズル

- 提案されている解決方法: 3 体力、クォーク物質、修正重力
  → 「実験と観測」で決めるには？
- 3 体力効果: Λ 粒子ポテンシャルの「深さ」から「密度依存性」へ
  → 数 100 keV の精度でのハイパー核束縛エネルギー測定

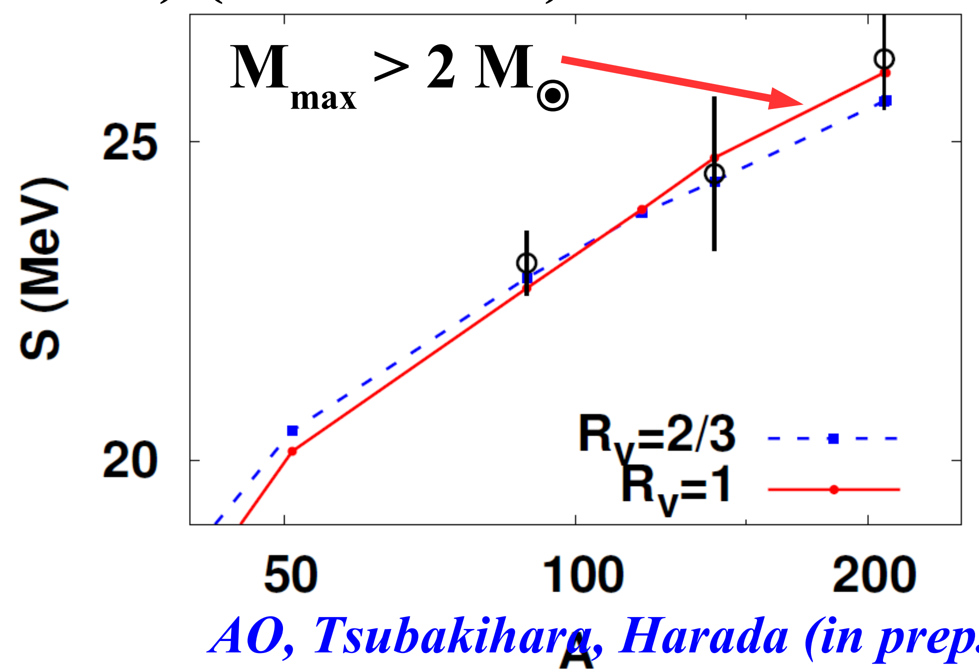
  Kohno ('17), Petschauer, Haidenbauer, Meissner, Kaiser, Weise ('16)
  Isaka, Yamamoto, Rijken('17); Yamamoto, Furumoto, Yasutake, Rijken('17)

$$U_\Lambda(n) = U_\Lambda(n_0) + \frac{L_\Lambda}{3}\frac{n-n_0}{n_0} + \frac{K_\Lambda}{18}\left(\frac{n-n_0}{n_0}\right)^2 + \cdots$$

- Chiral EFT, 格子核力 (含む 3 体力) (+ 重イオン) に期待



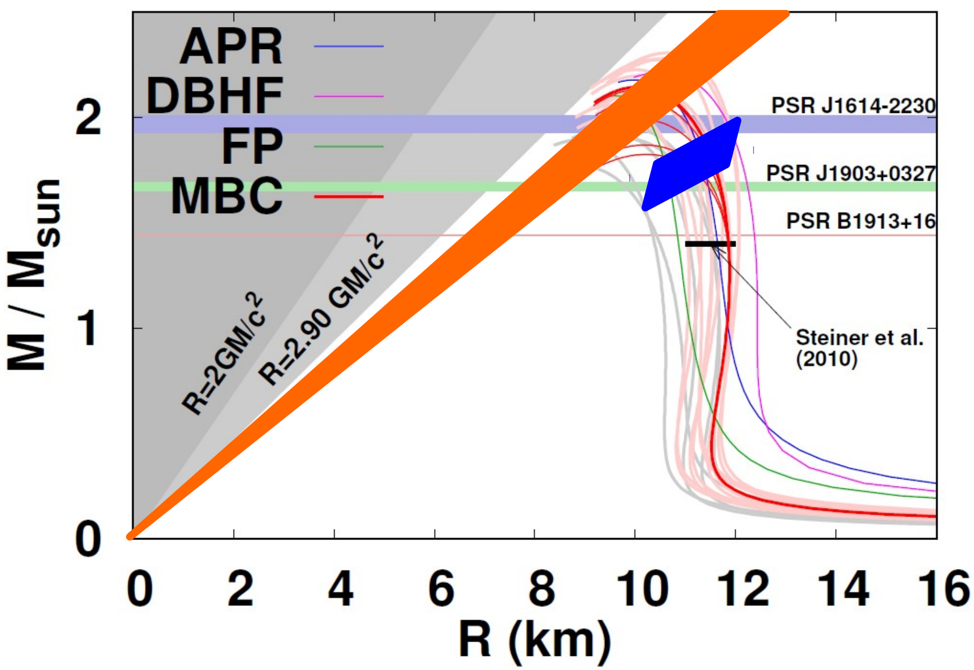
Yamamoto, Furumoto, Yasutake, Rijken ('17)

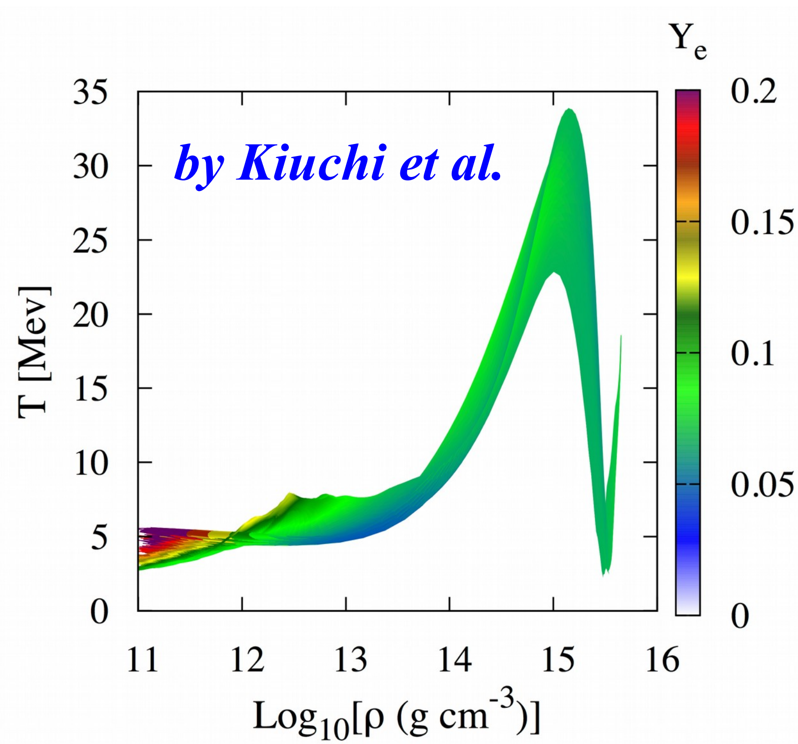


AO, Tsubakihara, Harada (in prep.)

展望 (3): 観測的中性子星物理

- 中性子星半径観測が本格化 Observational NS physics
  - NICER 稼働中 , 2018.09 くらいからデータ公表？
  - XARM (ひとみ後継機)
- Binary Neutron Star Mergers (GW170817 by LIGO/Virgo)
  - 原子核密度の 10 倍程度の高密度物質生成
  - 中性子星の最大質量 ~ (2.15-2.25) $M_\odot$ (Shibata et al., 1710.07579)





Thank you !

A little on NS cooling & Magnetic Field

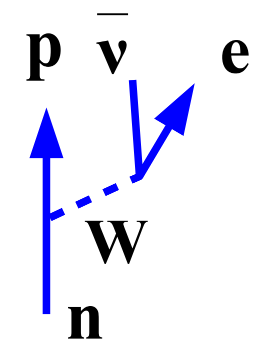
Neutron Star Cooling

Casino de Urca @ Rio

- **Direct URCA process**

$$n \to p + e^- + \bar{\nu}_e \ , \quad e^- + p \to n + \nu_e$$

  - **Dominant at high T (T>10^9 K)**
  - **Suppressed at low T (T < 10^9 K)**

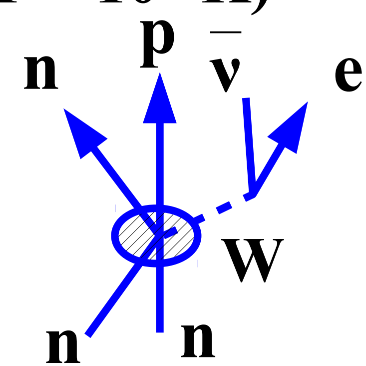


- **Modified URCA process**

$$n + n \to n + p + e^- + \bar{\nu}_e \ , \quad n + p + e^- \to n + n + \nu_e$$

  - **"Standard" cooling process of young NS (t < 10^4 yrs, T > 10^8 K)**

- **Non-standard cooling processes**



  - **Y-URCA**

$$Y \to N + e^- + \bar{\nu}_e \ , \quad e^- + Y \to N + \nu_e$$

  - **π cooling**

$$\pi^- + n \to n + e^- + \bar{\nu}_e \ , \quad n + e^- \to n + \pi^- + \nu_e$$

  - **quark beta decay**

$$d \to u + e^- + \bar{\nu}_e \ , \quad u + e^- \to d + \nu_e$$

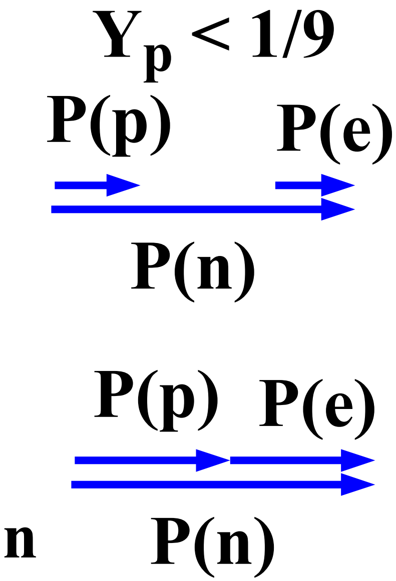
Direct URCA suppression

- **D-URCA is suppressed at $Y_p < 0.11$**
  - **Equilibrium condition: $\mu_n = \mu_p + \mu_e$**

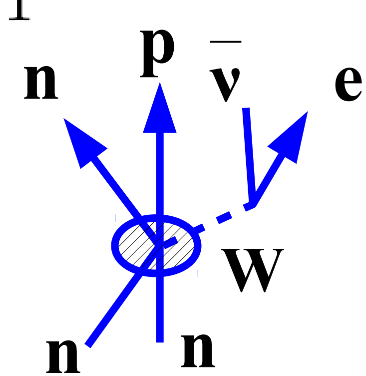
$$\frac{P_F^2(n)}{2M_n} + M_n + U_n = \frac{P_F^2(p)}{2M_p} + M_p + U_p + P_F(e)$$

  - **Charge neutrality: $P_F(p)=P_F(e)$**
  - **Momentum conservation for zero momentum ν emission**

$$P_F(n) = 2P_F(p) \;\rightarrow\; Y_p = Z/(N+Z) = 1/9 = 0.11$$



  - **Y-DURCA and q-DURCA is free from suppression**
- **M-URCA is slow**



$$\Gamma = \frac{(2\pi)^4}{\hbar V}\int \delta(E_f - E_i)\delta^3(\mathbf{p}_f - \mathbf{p}_i)|H_{fi}|^2 f_1 f_2 (1-f_1')(1-f_p)(1-f_e)\prod_i V\frac{d^3p_i}{(2\pi)^3}$$

$$L_\nu^{\rm mURCA} = C\frac{M}{M_\odot}\left(\frac{\rho_0}{\rho}\right)^{1/3}\left(\frac{T}{10^9\ \rm K}\right)^8 \quad (C \simeq (0.8-5)\times 10^{39}{\rm erg/s})$$

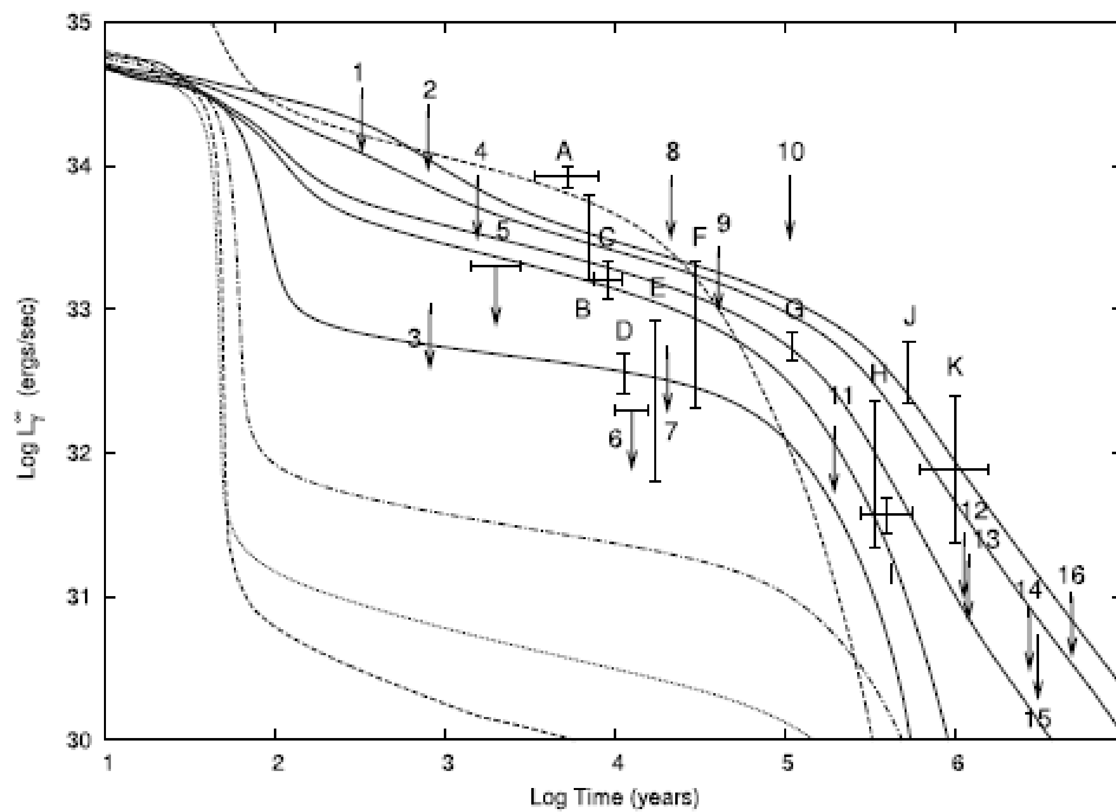
Shapiro texbookt

Neutron Star Cooling (cont.)

- **Many of neutron star temperature observations are consistent with "standard" modified URCA cooling (with some heating).**
- **Some require faster cooling.
Need some exotics.**
- **Exotic cooling is too fast if there is no suppression mechanism. Superfluidity is a promising candidate.**

S. Tsuruta, Grossmann Medalist, 2015

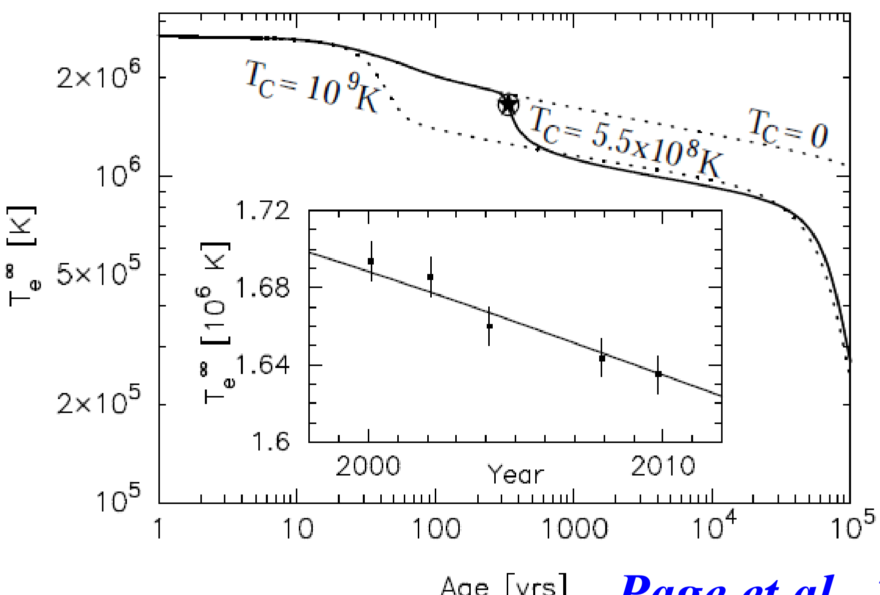
THERMAL EVOLUTION OF HYPERON-MIXED NEUTRON STARS



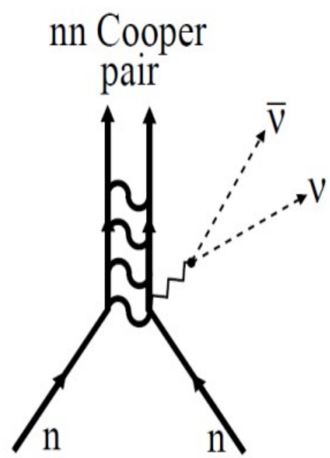
Tsuruta et al., ('09)

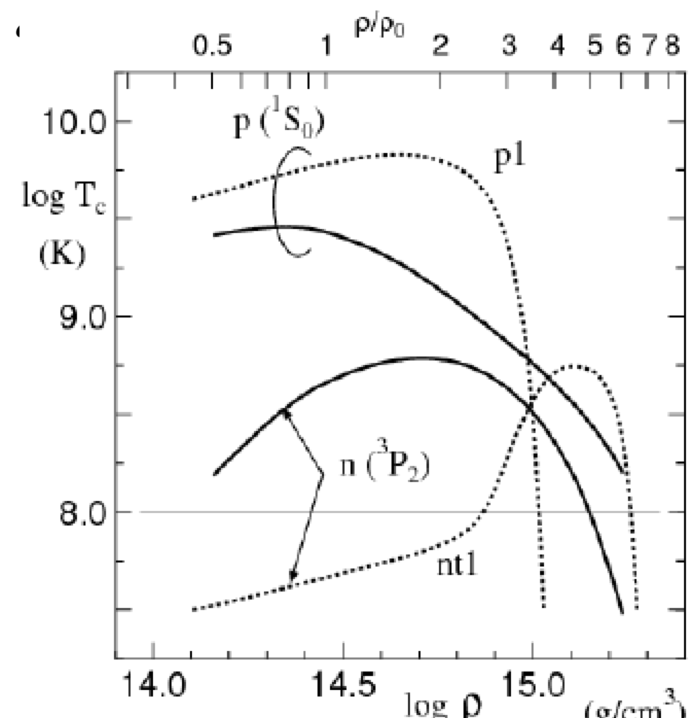
Nuclear Superfluidity and Cooling Curve

- **Surface T measurement and Cooling curve**
  - **Stable superfluid → Gap → Suppression of ν emission**
  - **Onset of superfluidity → Rapid cooling**
  - **Precise T and Cooling rate measurement in Cas A**
    Heinke, Ho, ApJ 719('10) L167 [arXiv:1007.4719]
    Page et al., PRL 106 ('11) 081101 [arXiv:1011.6142]
- **Can we predict the pairing cap around $5\rho_0$**



Page et al., 2011





Takatsuka

Magnetic Field

- **Magnetic Dipole Model**
  (cf. Shapiro, Teukolsky)
  - **Magnetic Dipole Moment**

$$|\mathbf{m}| = \frac{1}{2} B_p R^3 \ ,$$

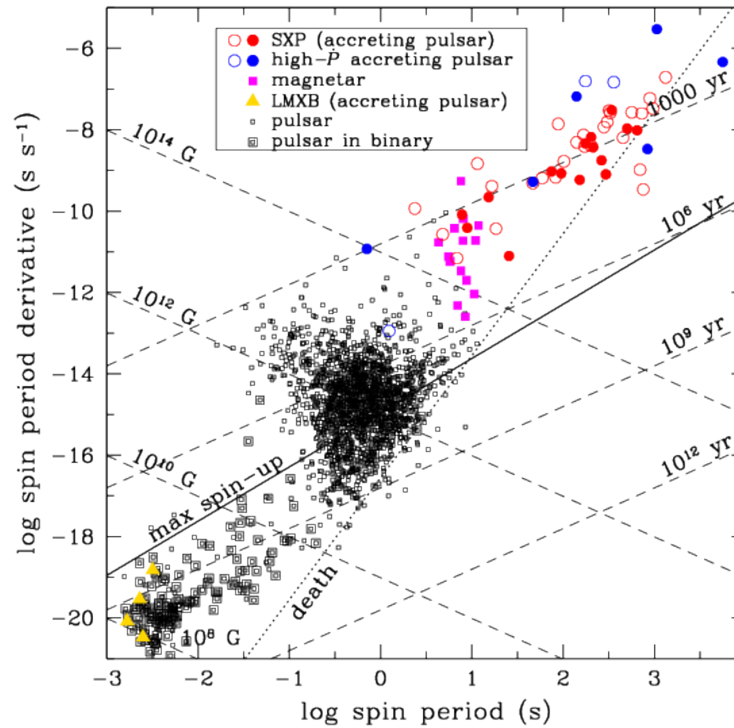
$$\dot{E} = -\frac{2}{3c^3}|\ddot{\mathbf{m}}|^2 = -\frac{B_p^2 R^6 \Omega^4 \sin^2\alpha}{6c^3}$$

  - **Rotation Energy of NS**

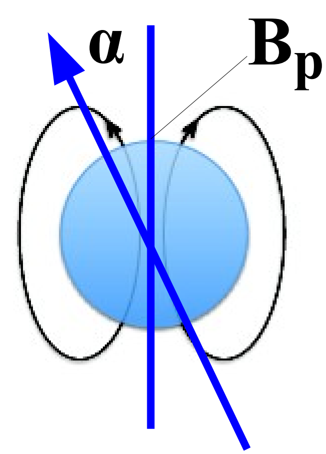
$$E = \frac{1}{2} I\Omega^2 \ , \quad \dot{E} = I\Omega\dot{\Omega} \ ,$$

$$T \equiv -\left(\frac{\Omega}{\dot{\Omega}}\right)_0 = \frac{6Ic^3}{B_p^2 R^6 \sin^2\alpha\,\Omega_0^2} \ ,$$

$$\mathrm{age}: t \simeq T/2$$



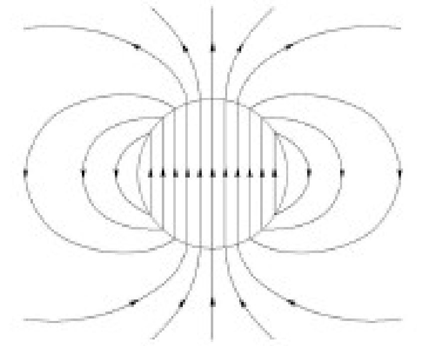
Ho, Klus, Coe, Andersson ('13)

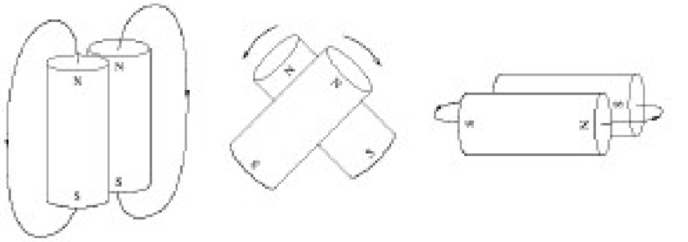


- **Magnetic field in NS B = 10^{12} – 10^{15} G**
  - **From P and dP/dt, we can guess B and t (age) of NS**

Origin of Strong Magnetic Field

- **How can we make strong B ?**
  cf. H. C. Spruit, AIP Conf.Proc.983('08)391.
  - **Fossil field hypothesis (化石磁場)**
    (flux conservation)
  - **Dynamo process in progenitor star evolution**
  - **Ferromagnetism**
    e.g. Yoshiike, Nishiyama, Tatsumi ('15)

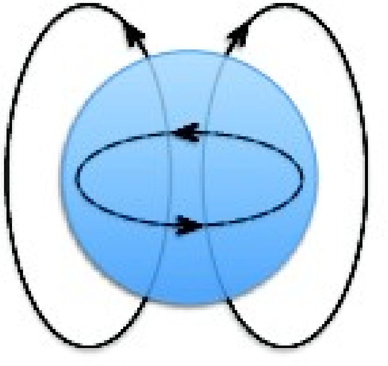




Flowers, Ruderman ('77)

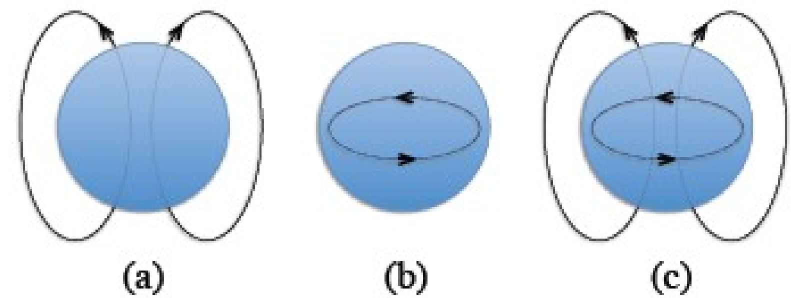
- **How can we keep strong B ?**
  - **Dipole magnetic field is not stable**
    Flowers, Ruderman ('77)
  - **Finite magnetic helicity** $\mathcal{H} = \int dx\, \boldsymbol{A} \cdot \boldsymbol{B}$

    makes magnetic field stable.
    Prendergast ('56); AO, N. Yamamoto, arXiv:1402.4760;
    D. Grabowska, D. B. Kaplan, S. Reddy, PRD('15)085035.



Chiral Plasma Instability ?

- **Chiral Plasma Instability**
  AO, N. Yamamoto, arXiv:1402.4760



  - **Left-handed electrons are eaten in electron capture → chiral chem. pot.**

$$p + e_L^- \to n + \nu_L^e.$$

  - **Chiral plasma instability: N_5 is converted to magnetic helicity**
    Akamatsu, Yamamoto ('13, '14)

$$j_z = \frac{2\alpha}{\pi}\mu_5 B_z. \qquad \frac{d}{dt}\left(N_5 + \frac{\alpha}{\pi}\mathcal{H}\right) = 0, \quad N_5 = \int dx\, n_5$$

  - **Finite magnetic helicity makes magnetic field stable.**

$$\mathcal{H} = \int dx\, A \cdot B$$

  - **Electron Mass may kill the instability.**
    D. Grabowska, D. B. Kaplan, S. Reddy, PRD('15)085035