

# 高密度物質と中性子星の物理：講義の内容

## 1. 中性子星の基本的性質

- 質量・半径測定の概論など

## 2. 状態方程式を記述する理論模型

- 平均場理論、第一原理計算手法、場の理論によるアプローチ

## 3. 対称エネルギーと非対称核物質の状態方程式

- 対称エネルギーを決める実験手法、現在の制限

## 4. QCD 有効模型と高密度核物質の性質

- 有限温度・密度の場の理論入門（松原和・摂動論など）
- NJL 模型による相転移と状態方程式の記述

## 5. ハイパー核物理と中性子星でのハイペロンパズル

- ハイパー核実験の現状、ハイペロンパズルの解決に向けて

## ■ 談話会

Symmetry Parameter Constraints

from a Lower Bound on the Neutron-Matter Energy

# Lec. 5 ハイパー核物理と中性子星でのハイペロンパズル

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- Hypernuclear Physics: Implications from Experiments
- ハイペロン・パズルとは
- ハイペロン・パズルの解決に向けて
- まとめ

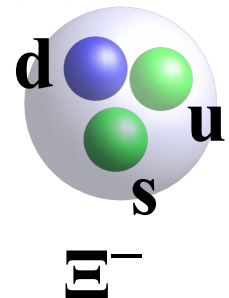
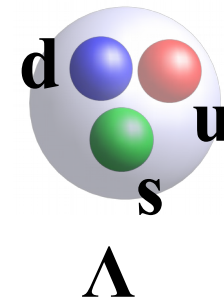
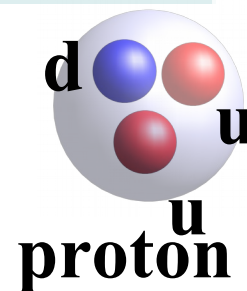
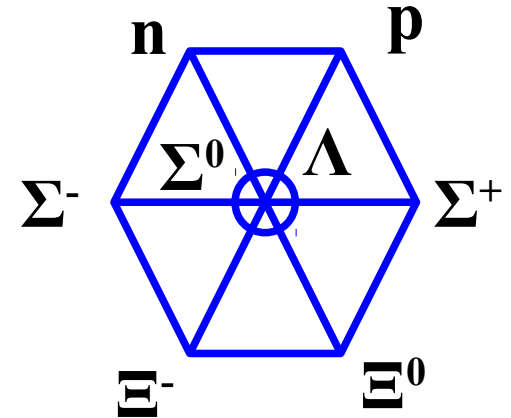
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# *Hypernuclear Physics Implications from Experiments*

# Hyperons (Baryons with Strangeness)

## ■ Ground state baryon $SU(3)_f$ octet ( $J^\pi=1/2^+$ )

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



# $SU(3)_f$ transformation

- Fundamental triplet  $(u,d,s)^T = \mathbf{q} \rightarrow \mathbf{q}' = \mathbf{U} \mathbf{q}$  ( $SU(3)$  transf.)
- Anti-quark  $\bar{\mathbf{q}} \rightarrow \bar{\mathbf{q}}' = \bar{\mathbf{q}} \mathbf{U}^+$
- Meson octet  $\mathbf{M}_{ij} = \bar{\mathbf{q}}_j \mathbf{q}_i \rightarrow \mathbf{M}' = \mathbf{U} \mathbf{M} \mathbf{U}^+$

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

$$S = \begin{pmatrix} \frac{\sigma}{\sqrt{2}} + \frac{a_0}{\sqrt{2}} & a_0^+ & \kappa^+ \\ a_0^- & \frac{\sigma}{\sqrt{2}} - \frac{a_0}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \bar{K}^0 & \zeta \end{pmatrix}$$

$$V = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

# $SU(3)_f$ transformation

- Fundamental triplet  $(u,d,s)^T = \mathbf{q} \rightarrow \mathbf{q}' = \mathbf{U} \mathbf{q}$  ( $SU(3)$  transf.)
- Diquark  $\mathbf{D}_i = \varepsilon_{ijk} \mathbf{q}_j \mathbf{q}_k \rightarrow \mathbf{D}' = \mathbf{D} \mathbf{U}^+$
- Baryon octet  $\mathbf{B}_{ij} = \mathbf{D}_j \mathbf{q}_i \rightarrow \mathbf{B}' = \mathbf{U} \mathbf{B} \mathbf{U}^+$

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

# $SU(3)_f$ invariant coupling

## ■ Baryon-Meson coupling

$$\begin{aligned}\mathcal{L}_{BV} &= \sqrt{2}\{g_s \text{tr}(M_v) \text{tr}(\bar{B}B) + g_D \text{tr}(\bar{B}\{M_v, B\}) + g_F \text{tr}(\bar{B}[M_v, B])\} \\ &= \sqrt{2}\{g_s \text{tr}(M_v) \text{tr}(\bar{B}B) + g_1 \text{tr}(\bar{B}M_v B) + g_2 \text{tr}(BBM_v)\}\end{aligned}$$

## ■ Assumption

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

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

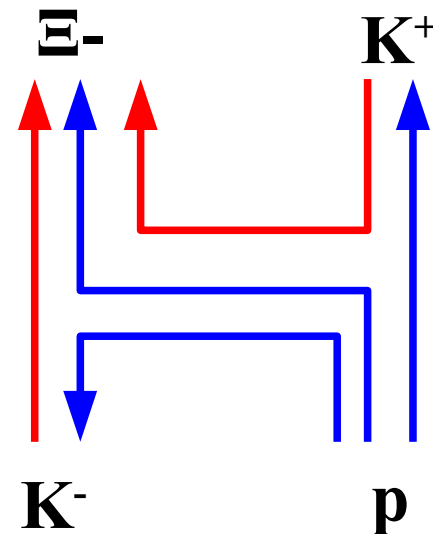
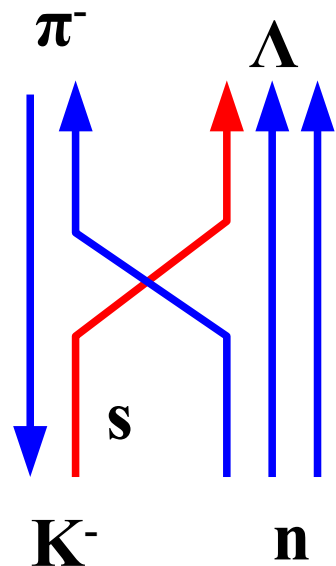
## ■ Further simplification: $g_{\rho N} = g_{\omega N}/3$ (quark counting)

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

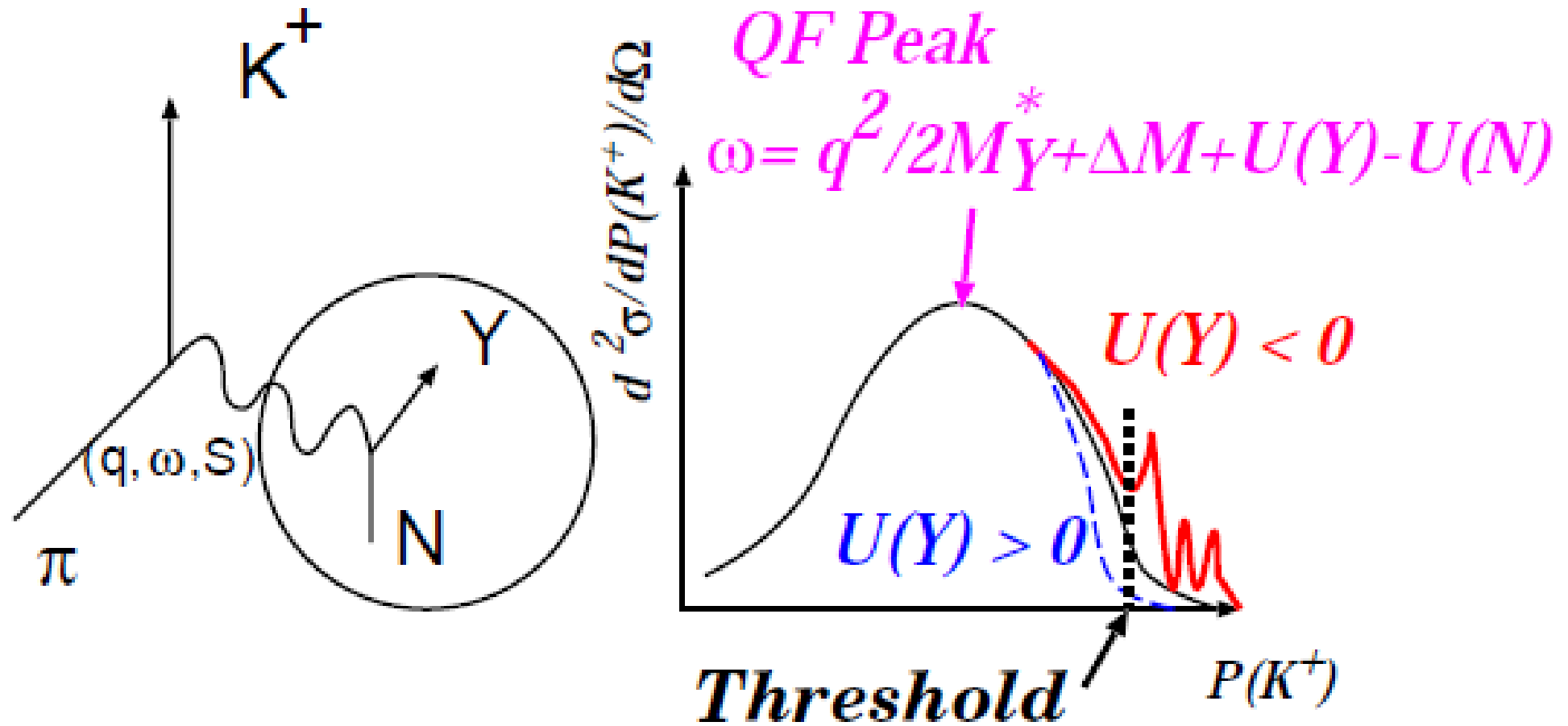
# Hypernuclear formation

- $(K^-, \pi^-)$ ,  $(\pi^-, K^+)$ , and  $(K^-, K^+)$  reactions on nuclei  $\rightarrow$  Hypernuclei

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

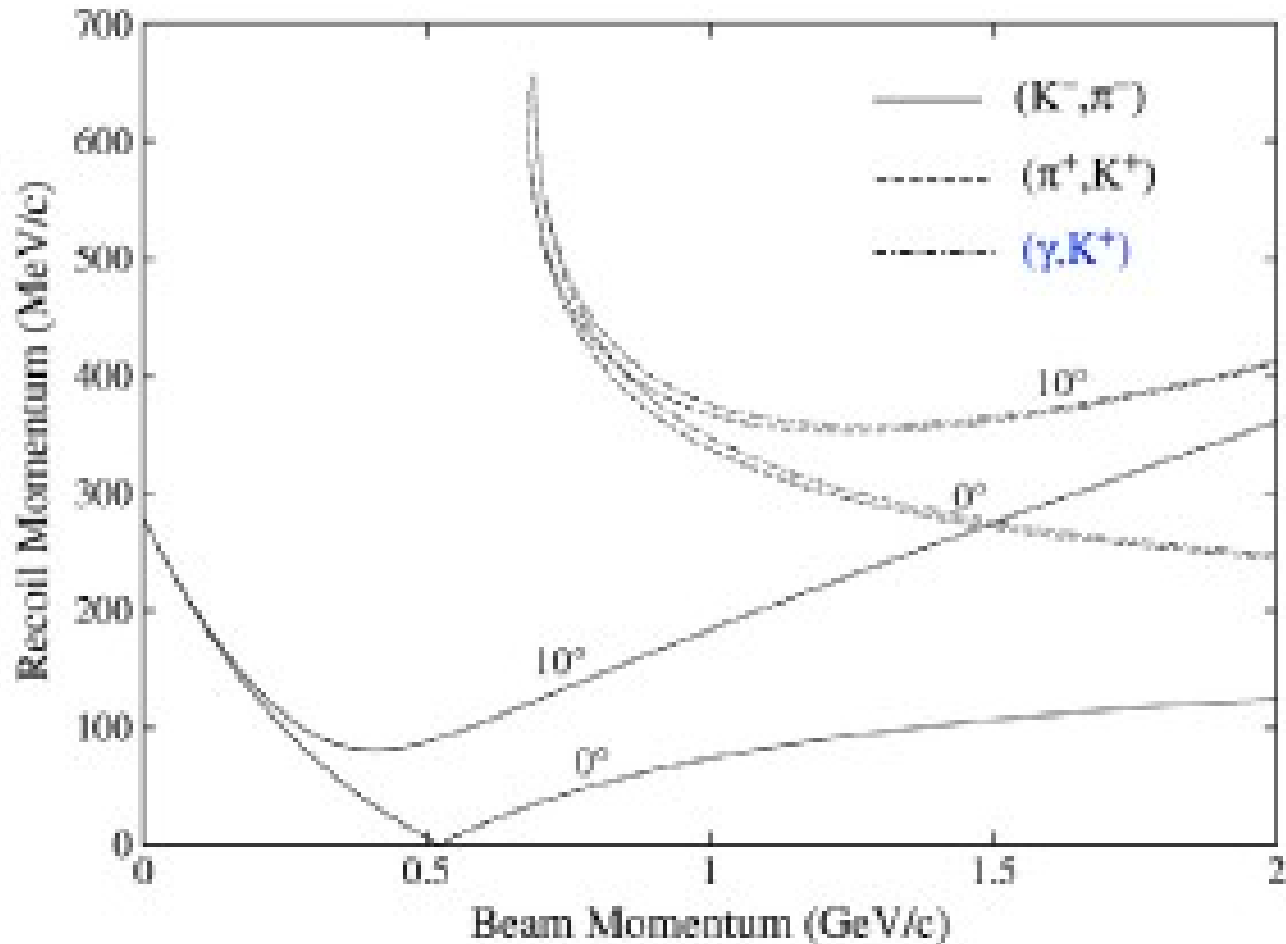


# Hypernuclear formation



# Hypernuclear formation

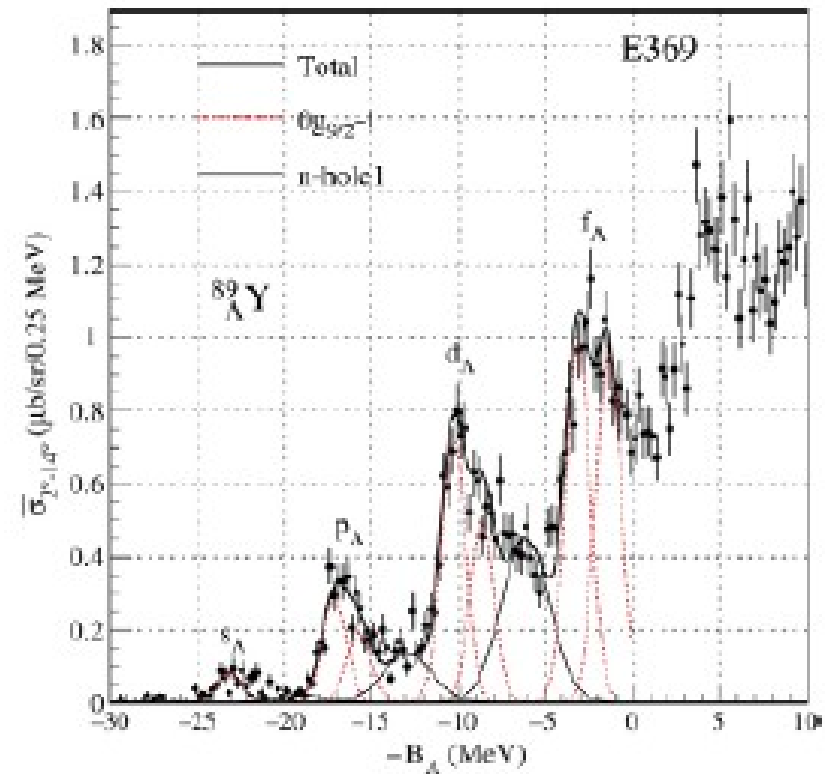
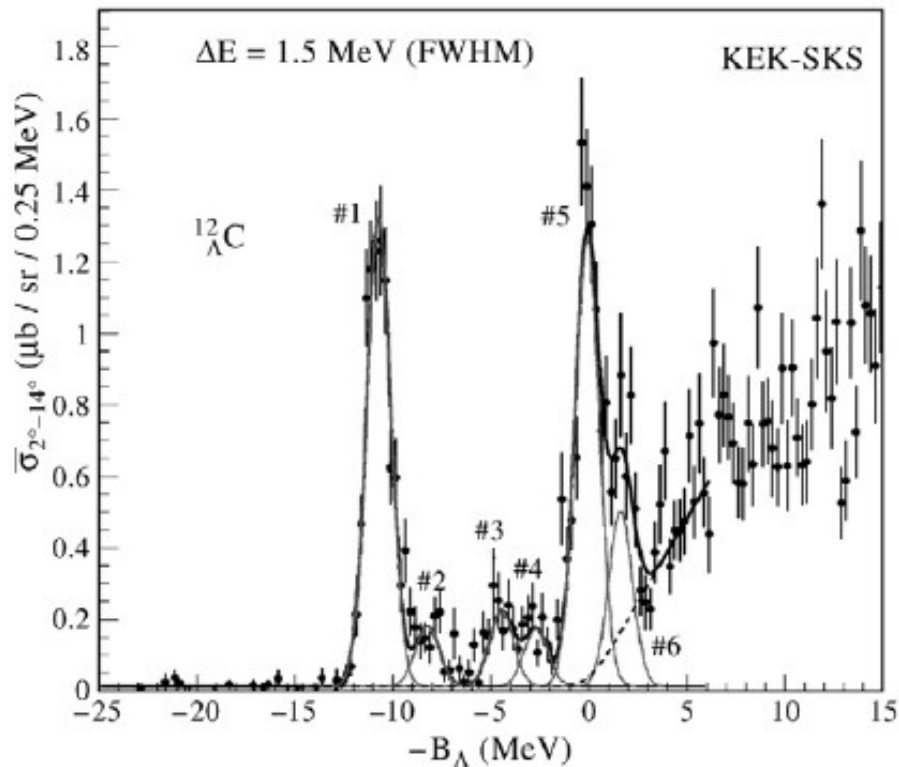
- $(K^-, \pi^-)$ :  $Q > 0$ , Small momentum transfer  $\rightarrow$  substitutional reaction
- $(\pi, K^+)$ :  $Q < 0$ , Momentum transfer  $\sim 300 \text{ MeV}/c \sim k_F$



# $\Lambda$ hypernuclear formation

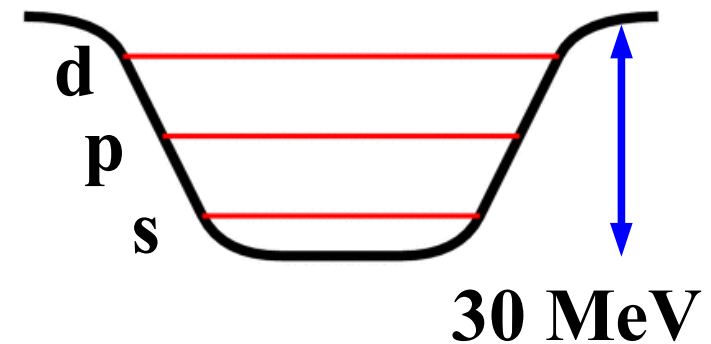
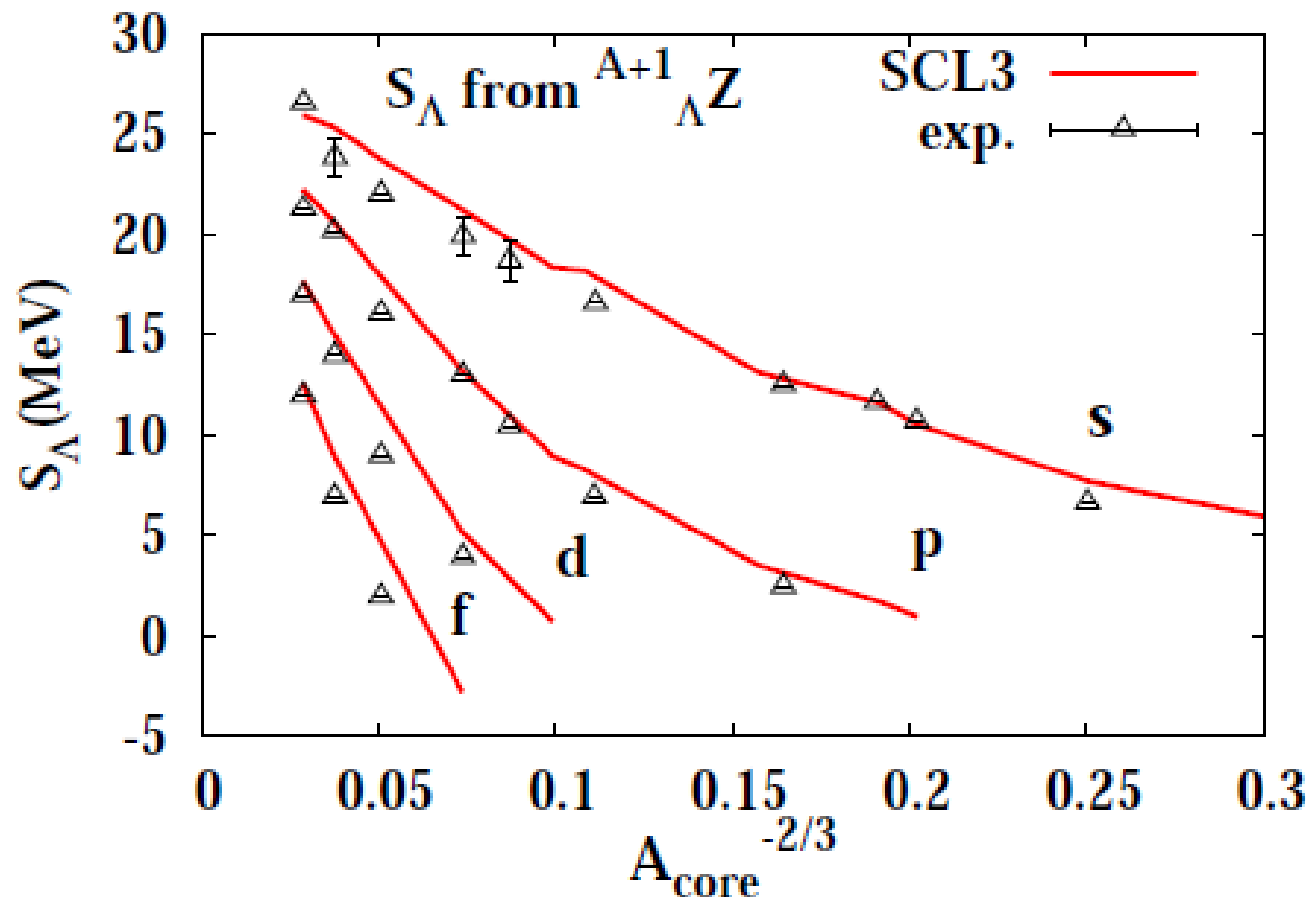
## ■ $(\pi^+, K^+)$ reactions on nuclei

- $q \sim k_F \rightarrow$  various s.p. states of  $\Lambda$  are populated



# Single particles states of $\Lambda$ in nuclei

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



# $\Sigma$ production in nuclei

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

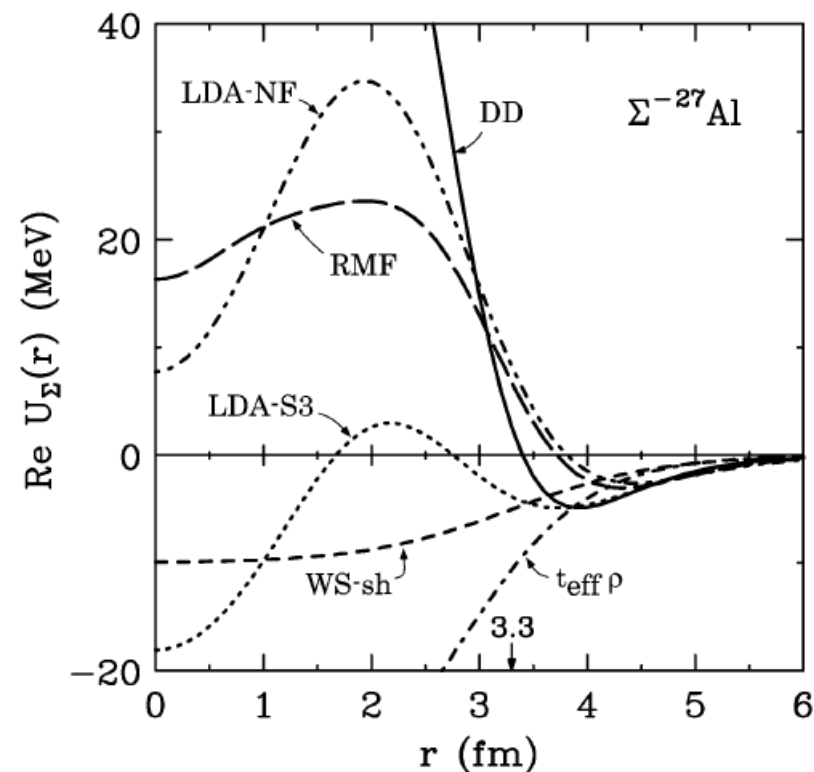
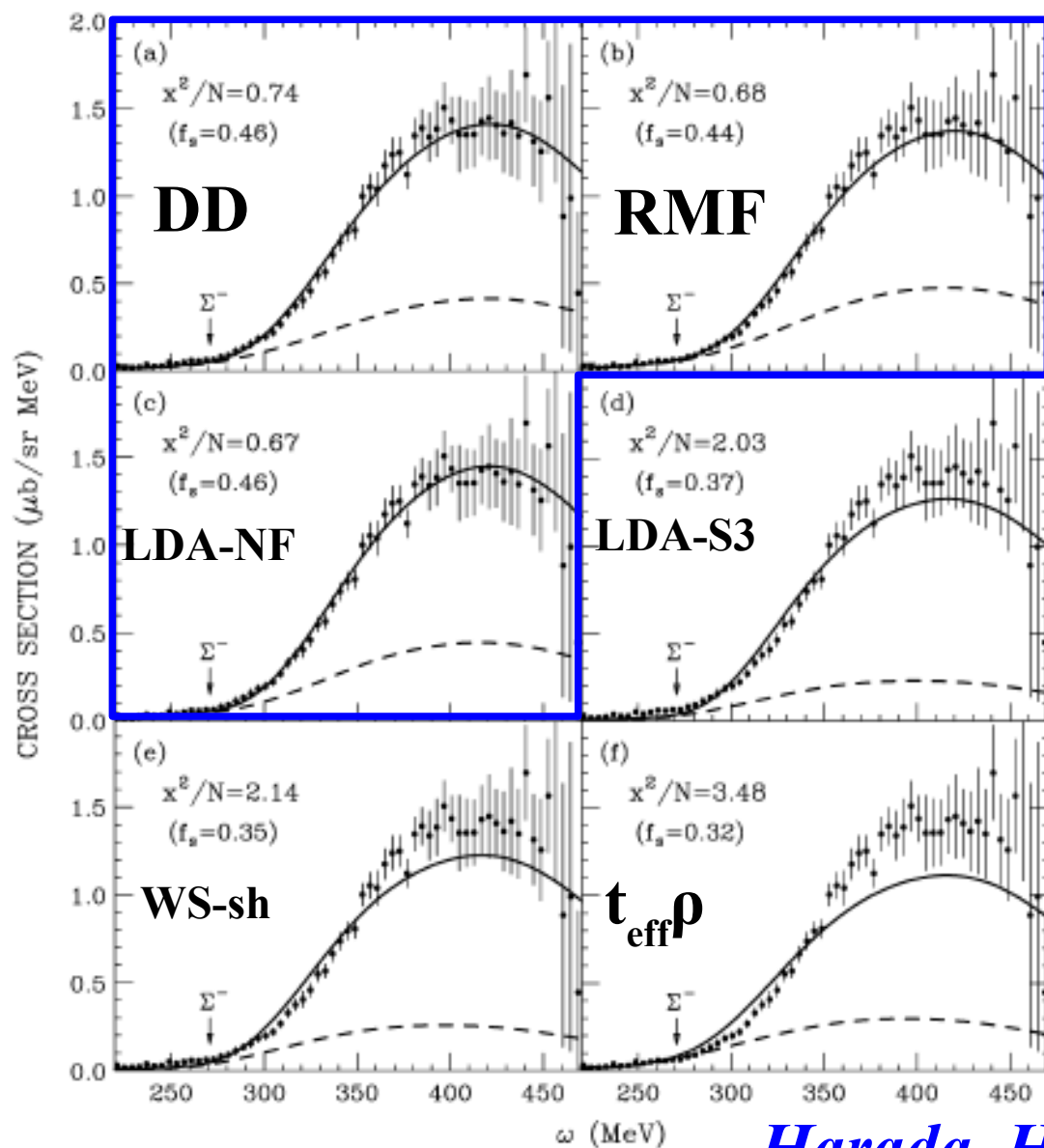
$$\frac{d^2 \sigma}{dE_K d\Omega_K} = \underbrace{\beta}_{\text{Kinematical Factor}} \underbrace{\left( \frac{d\sigma}{d\Omega} \right)^{\text{Elem.}}_{N\pi \rightarrow KY}}_{\text{Elem. Cross Sec.}} \underbrace{S(E, q)}_{\text{Strength Func.}}$$

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

# $\Sigma$ production in nuclei

$\chi^2/\text{DOF} < 1$

$^{28}\text{Si}(\pi^-, K^+)$



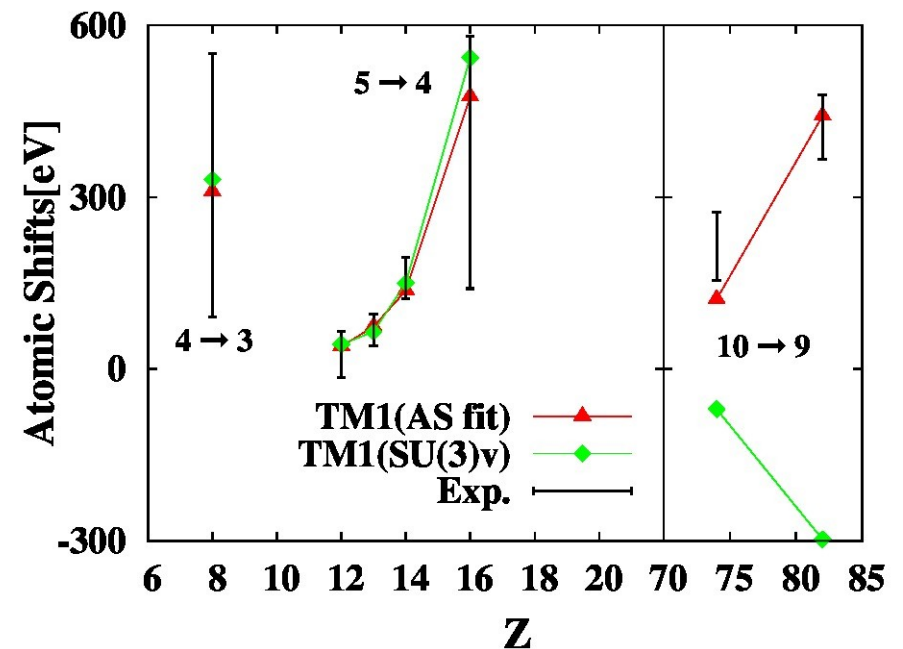
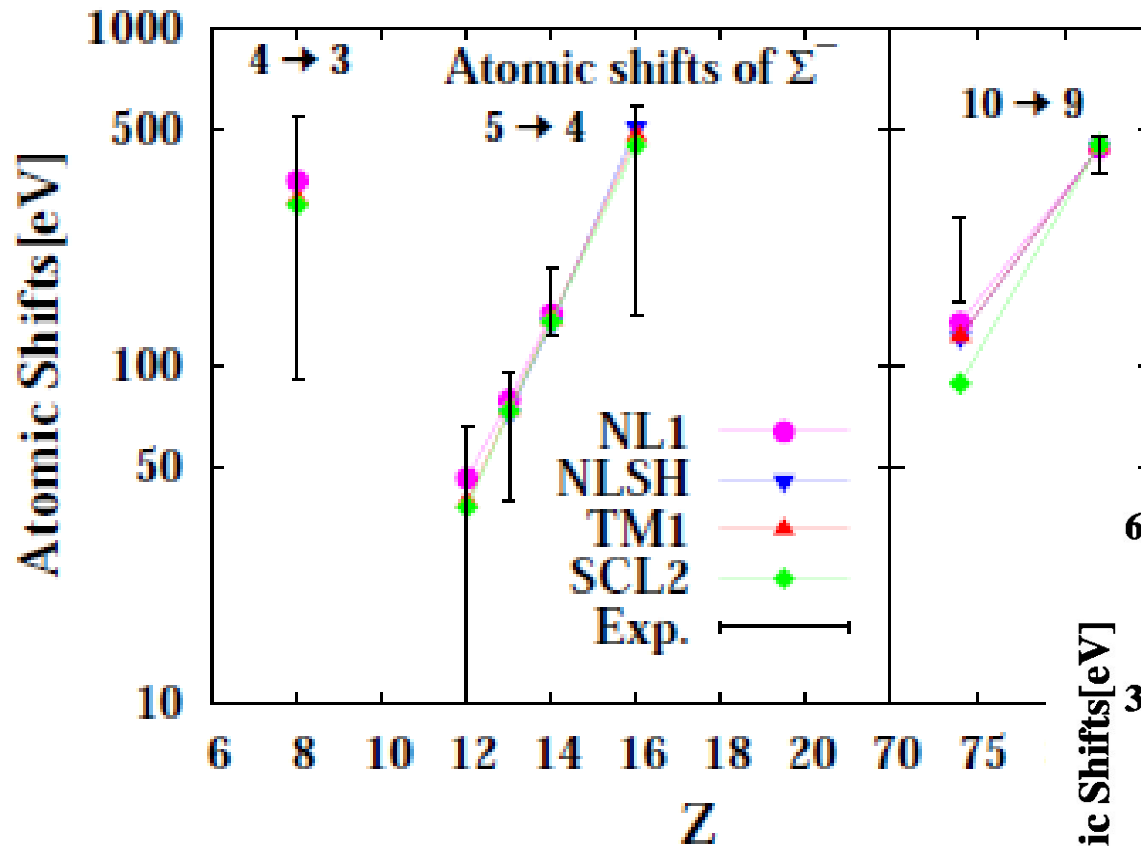
Harada, Hirabayashi ('05)

Data: Noumi et al. ('02); Saha et al. ('04)

A. Ohnishi @ Nagoya U., Dec.4-6, 2018

14

# $\Sigma^-$ atomic shift



Compiled data: Mares, Friedman, Gal, Jennings ('95)  
Calc.: Tsubakihara, Harada, AO: arXiv:1402.0979

# $\Xi$ hypernuclear formation

- Missing mass spectroscopy

BNL E885  $^{12}\text{C}(\text{K}^-, \text{K}^+)$

*Fukuda et al. PRC58('98),1306;*

*Khaustov et al. PRC61('00), 054603.*

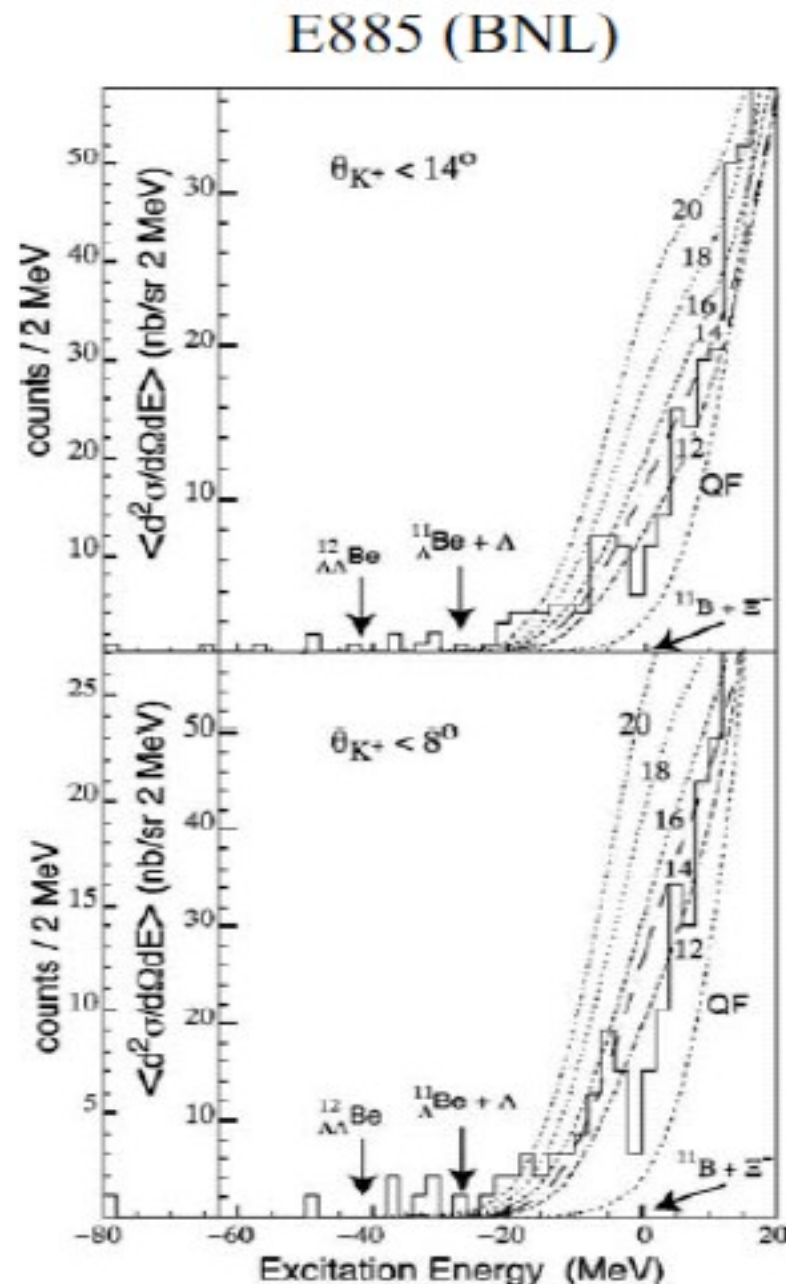
- No clear bound states found

- Twin hypernuclear formation

*Aoki et al. PLB355('95),45.*

- Potential depth

$$U_{\Xi} \sim -14 \text{ MeV}$$



# Hyperon Potential Depth (A la Michelin)

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



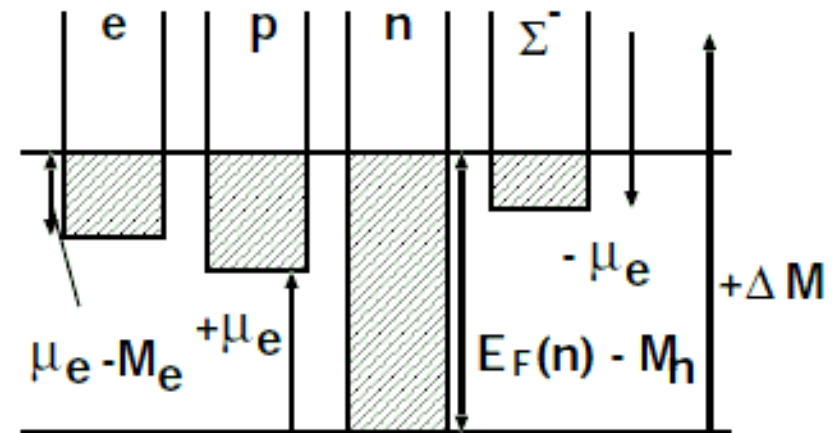
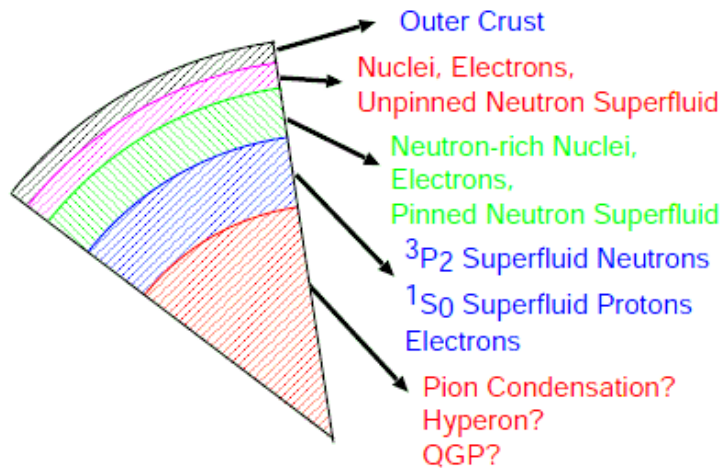
# Hyperons in Dense Matter

## ■ 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; ...

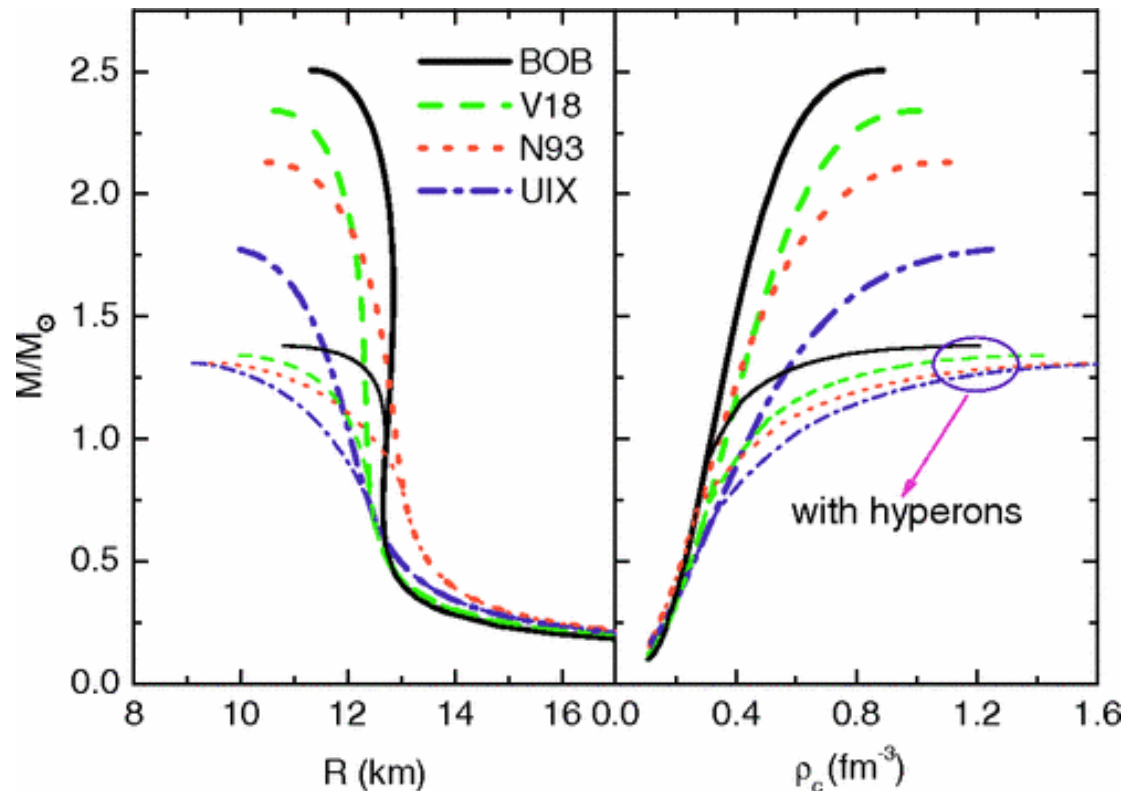


*Nobody says “Hyperons cannot appear in neutron star core” before 2010 !*

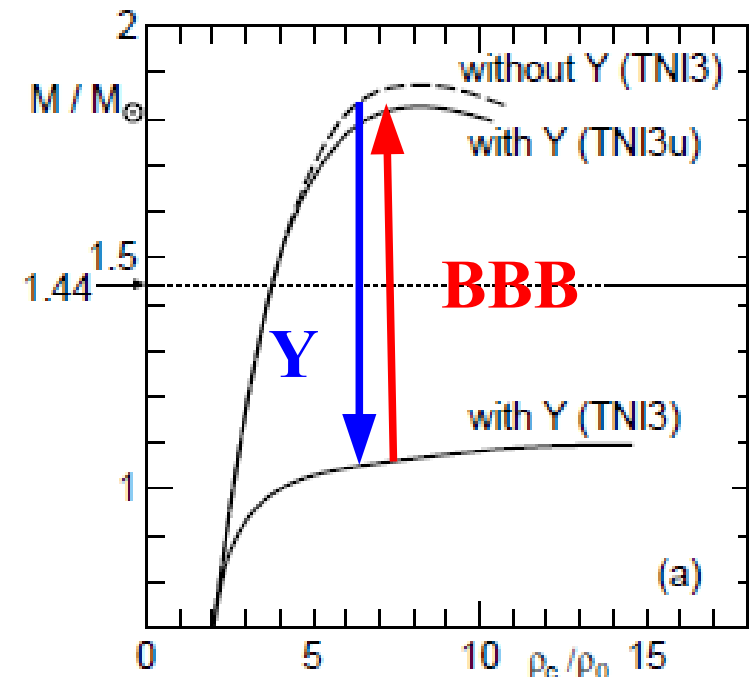
Y appears when  $\mu_B = E_F(n) + U(n) \geq M(Y) + U(Y) + Q_Y \mu_e$

# 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  $\rightarrow$  Need finite nuclear info.  
*E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / M.Tamura et al.*
  - NS collapses with hyperons w/o 3BF.



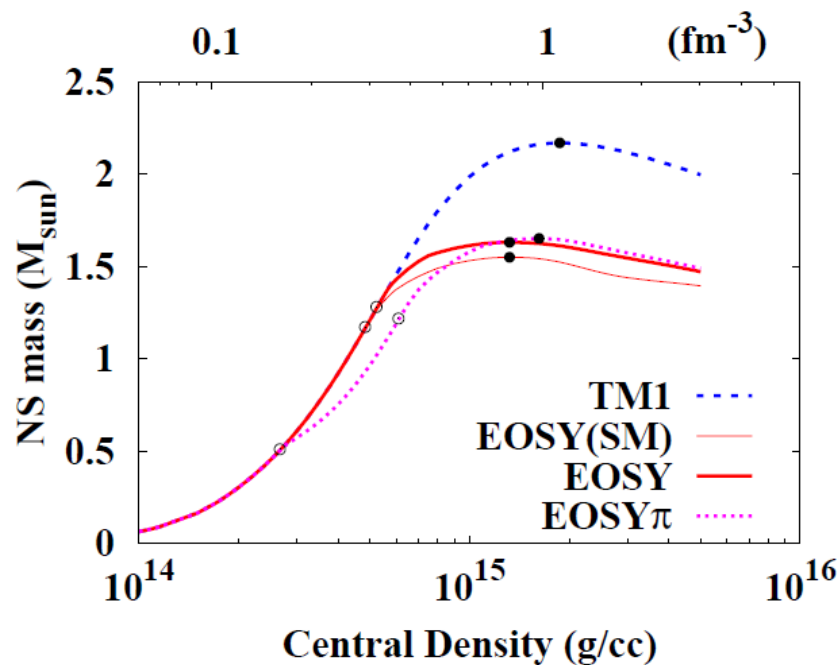
*Z.H.Li, H.-J.Schulze, PRC78('08),028801.*



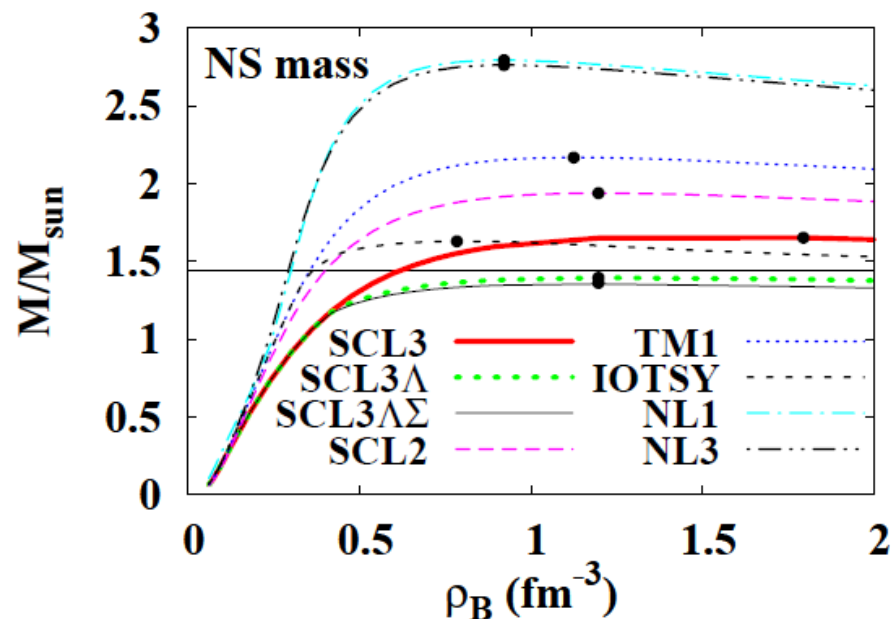
*S. Nishizaki, T. Takatsuka,  
Y. Yamamoto, PTP108('02)703.*

# 中性子星 *with Hyperons (before 2010)*

- 実験データに基づくハイペロン・ポテンシャルの深さを考慮した RMF による中性子星最大質量の推定  $\rightarrow M_{\max} < 1.7 M_{\odot}$
- 推測 (before 2010)
  - ハイペロンは  $(2-4)\rho_0$  で現れる
  - $1.7 M_{\odot}$  を大きく超える中性子星は存在しない。



*Ishizuka+('08)*



*Tsubakihara+('10)*

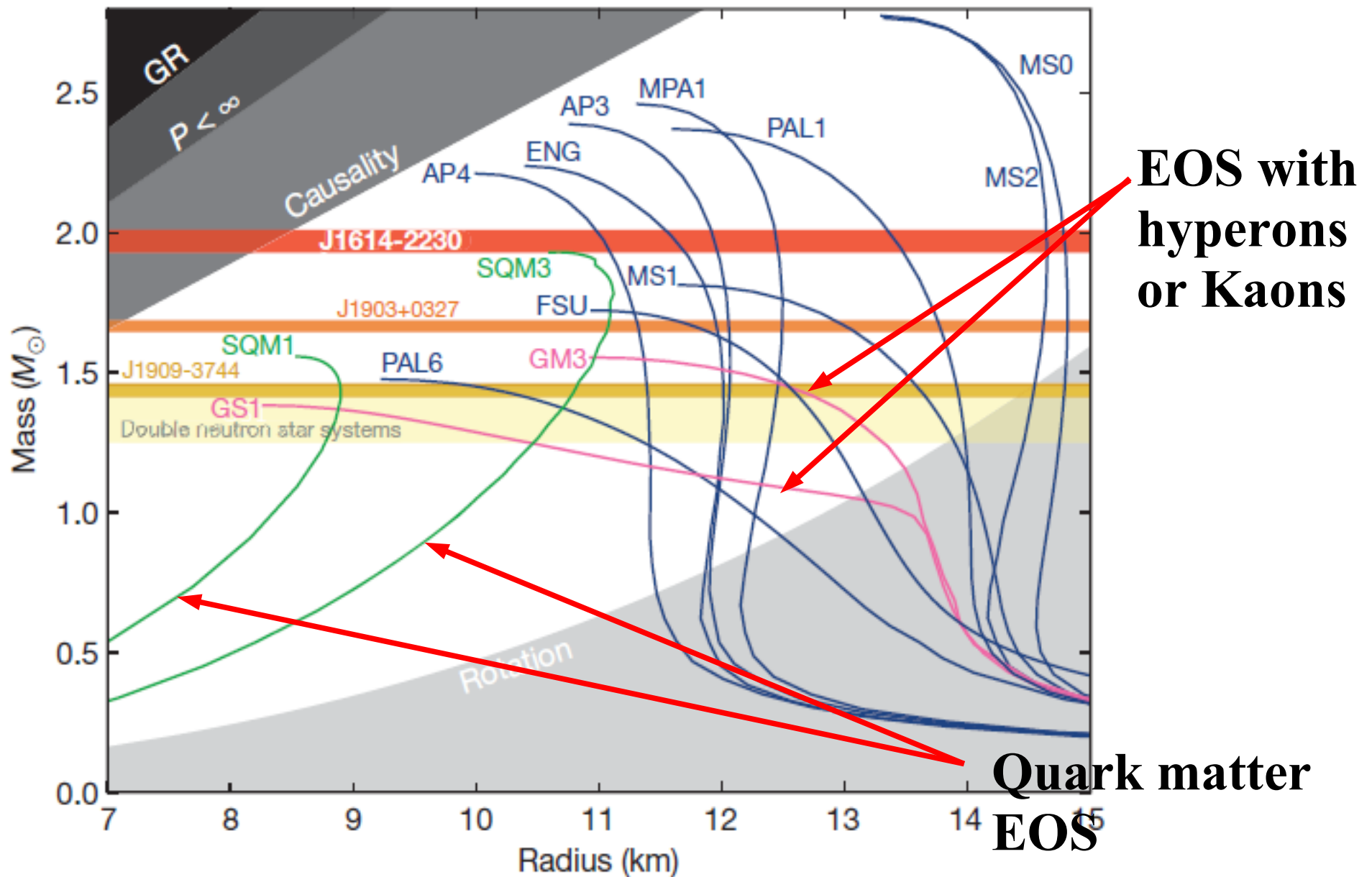
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*Judgement day came ..*

# ハイペロン・パズルとは

# Hyperon Puzzle

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



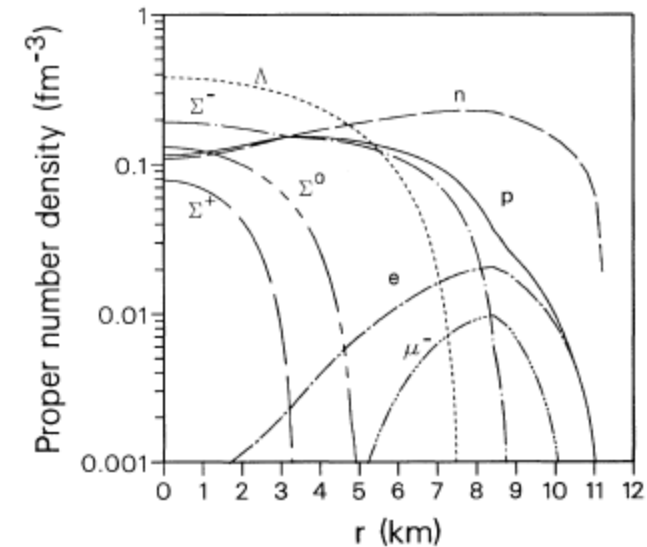
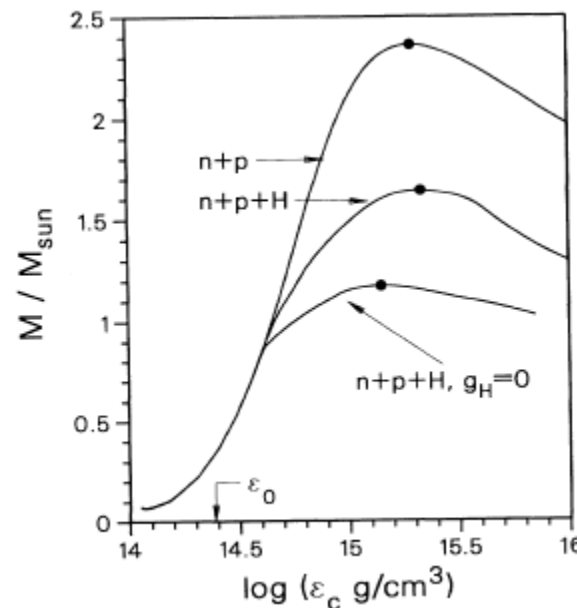
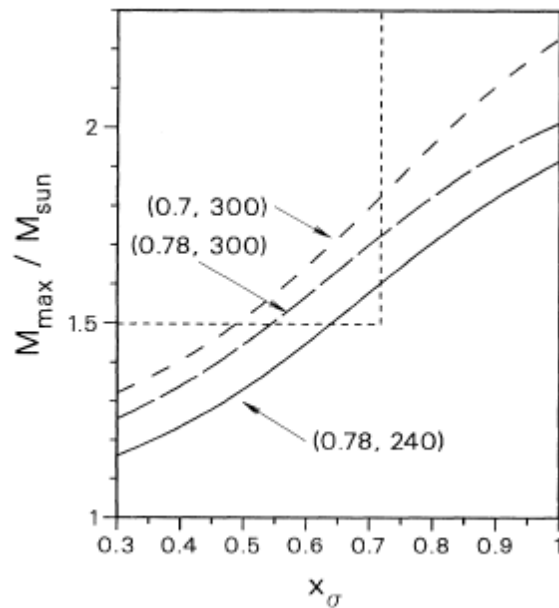
# Glendenning & Moszkowski (1991)

## ■ RMF with hyperons

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

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

| $x_\sigma$ | $x_\omega$ | $m^*/m=0.7$ | $m^*/m=0.78$ |
|------------|------------|-------------|--------------|
| 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         |



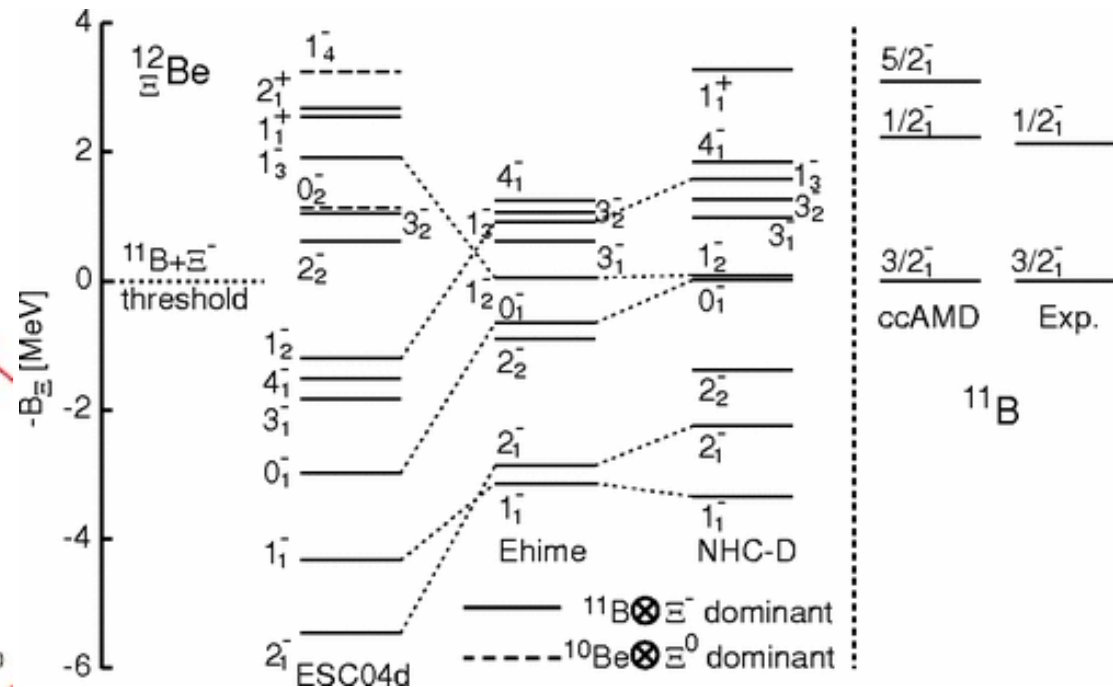
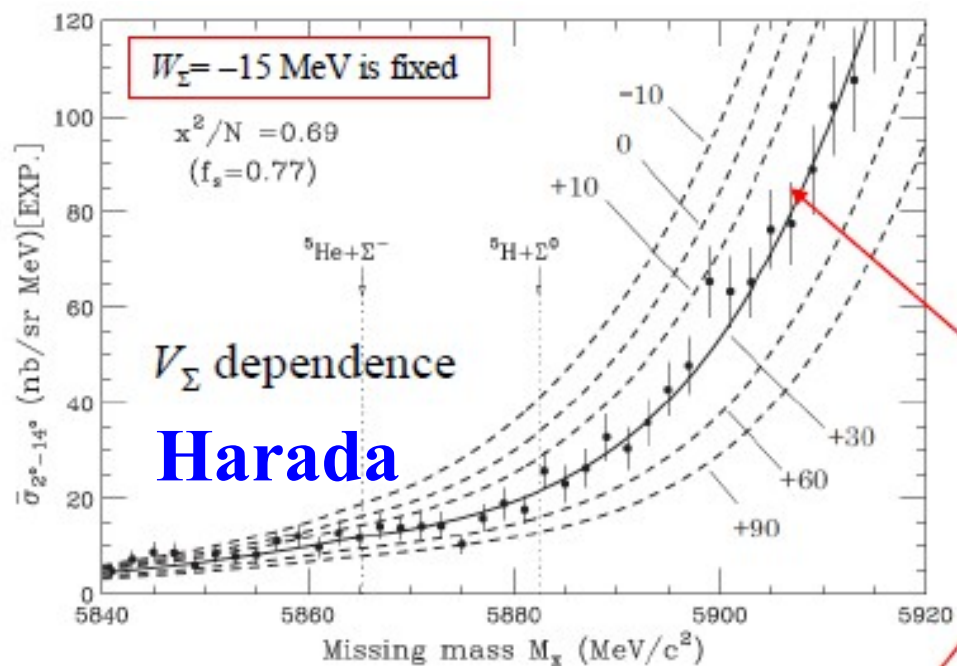
*N.K.Glendenning, S.A.Moszkowski, PRL67('91)2414*

# Hyperon Puzzle

- ハイペロンや反 K 中間子を含む状態方程式、純粋なクォーク物質状態方程式では質量が  $2 M_{\odot}$  の中性子星を支えられない。
- 一方でハイパー核実験データから示唆される  $\Lambda$  粒子のポテンシャル ( $U_{\Lambda}(\rho_0) \sim -30$  MeV) を考慮した理論は、 $(2-4)\rho_0$  においてハイペロンが現れることを预言する。  
(反 K 中間子、クォークは不定性が大きく、パズル (矛盾) とまでは言えない)  
→ *我々は何を見落としているのか？*
- 解決方法・可能性
  - ポテンシャル (e.g.  $U_{\Lambda}(\rho_0) \sim -30$  MeV) が間違っている、
  - 高密度におけるポテンシャルが素直な予測と異なる、
  - クォーク物質がハイペロンより低密度で現れる、
  - 一般相対性理論が間違っている、

# $\Sigma$ or $\Xi$ potential in nuclei ?

- New analysis of  $\Sigma$  production reaction:  ${}^6\text{Li} (\pi^-, K^+) \Sigma^- {}^5\text{He}$   
 $\rightarrow U_\Sigma \sim +30 \text{ MeV}$  (Harada, consistent with previous estimate)
- New  $\Xi$  hypernuclei ?  $\rightarrow \text{B.E.} = \text{■ MeV} \& 1 \text{ MeV}$   
 $\rightarrow \text{Deeper than previous estimate !}$



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

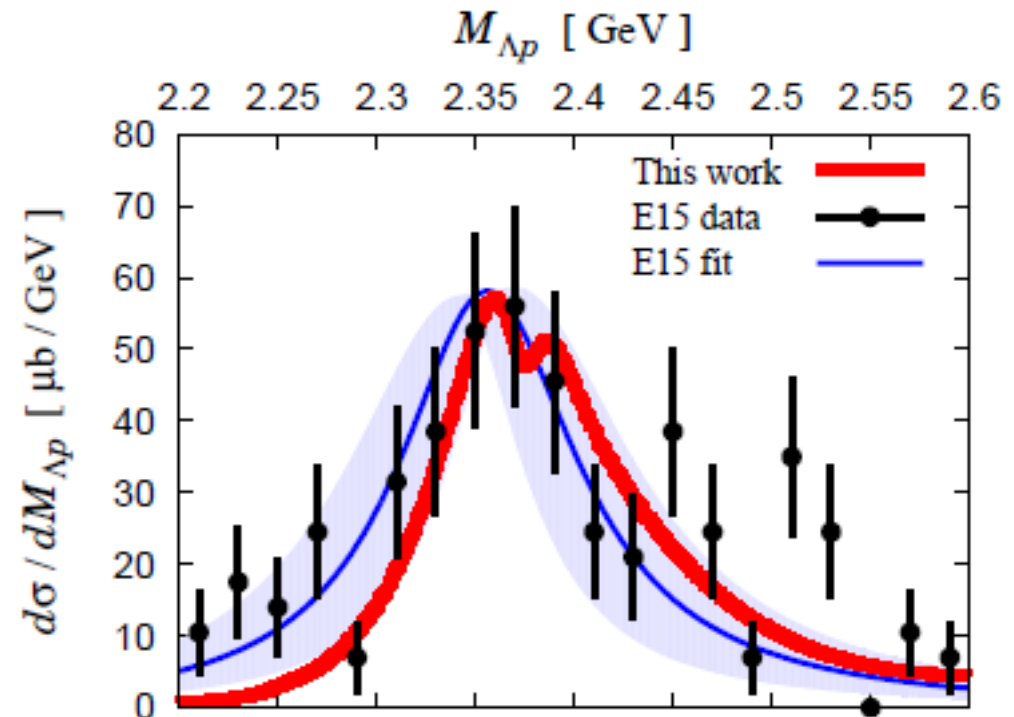
A. Ohnishi @ Nagoya U., Dec.4-6, 2018

# Anti-Kaon potential in Nuclear Matter ?

## ■ $K^-$ pp binding energy (Ohta, Dote)

- E15: One state at B.E.~ (15-30) MeV, Strength at B.E. ~ 100 MeV  
E27: B.E.~100 MeV ?
- Dote: Higher pole B.E.~ 27 MeV, Lower pole B.E.~ 79 MeV (?)  
Akaishi: B.E. ~ 100 MeV (DISTO, FINUDA)  
S.Ohnishi: Saturating B.E. in heavier kaonic nuclei

*We need more work  
to confirm the fate of  
Kaon condensation*



*Sekihara, Oset, Ramos ('16)*

*A. Ohnishi @ Nagoya U., Dec.4-6, 2018*

# Strongly Repulsive $\Lambda\Lambda$ potential ?

- Nagara fit  $\rightarrow a_0(\Lambda\Lambda) = -0.575$  fm or  $-0.77$  fm

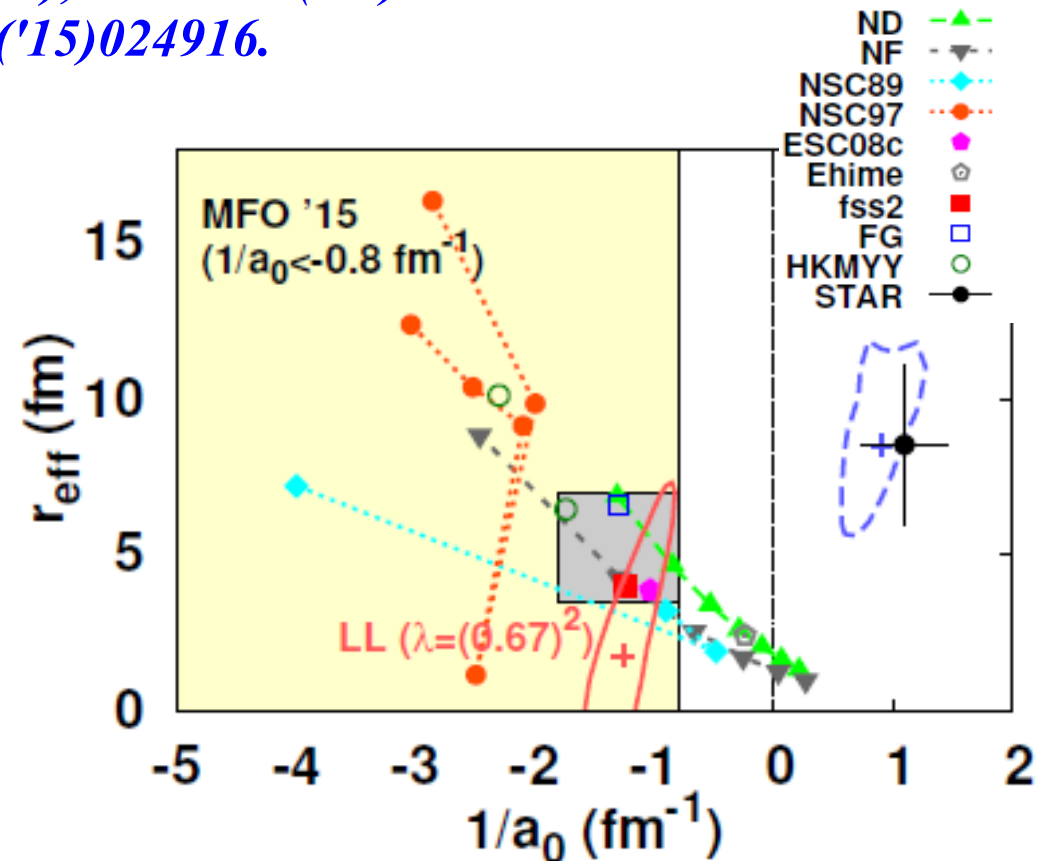
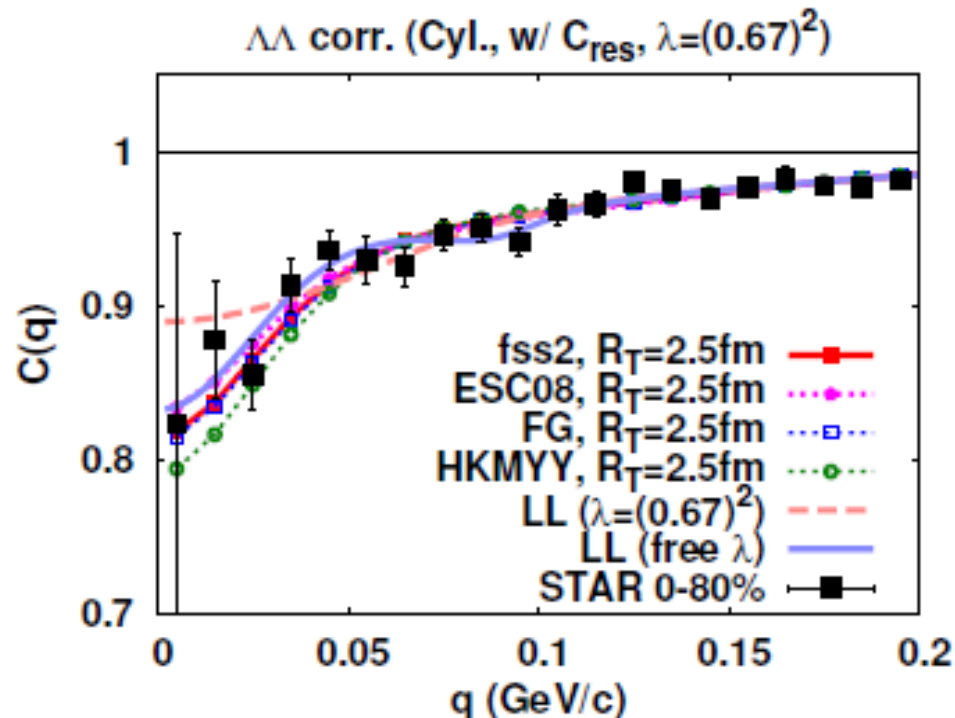
Hiyama, Kamimura, Motoba, Yamada, Yamamoto ('02), Filikhin, Gal ('02)

- New approach:  $\Lambda\Lambda$  correlation from HIC (Morita)

$\rightarrow -1.25$  fm  $< a_0(\Lambda\Lambda) < 0$  (Consistent with Nagara)

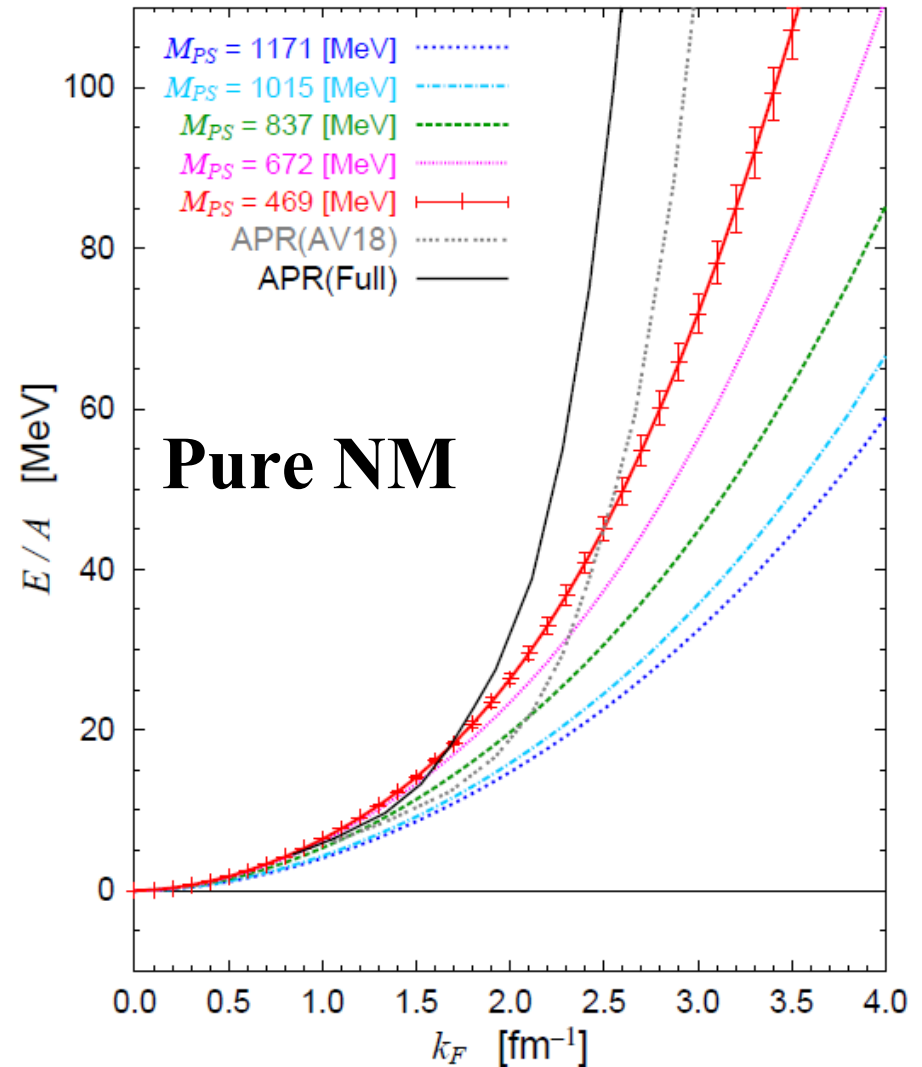
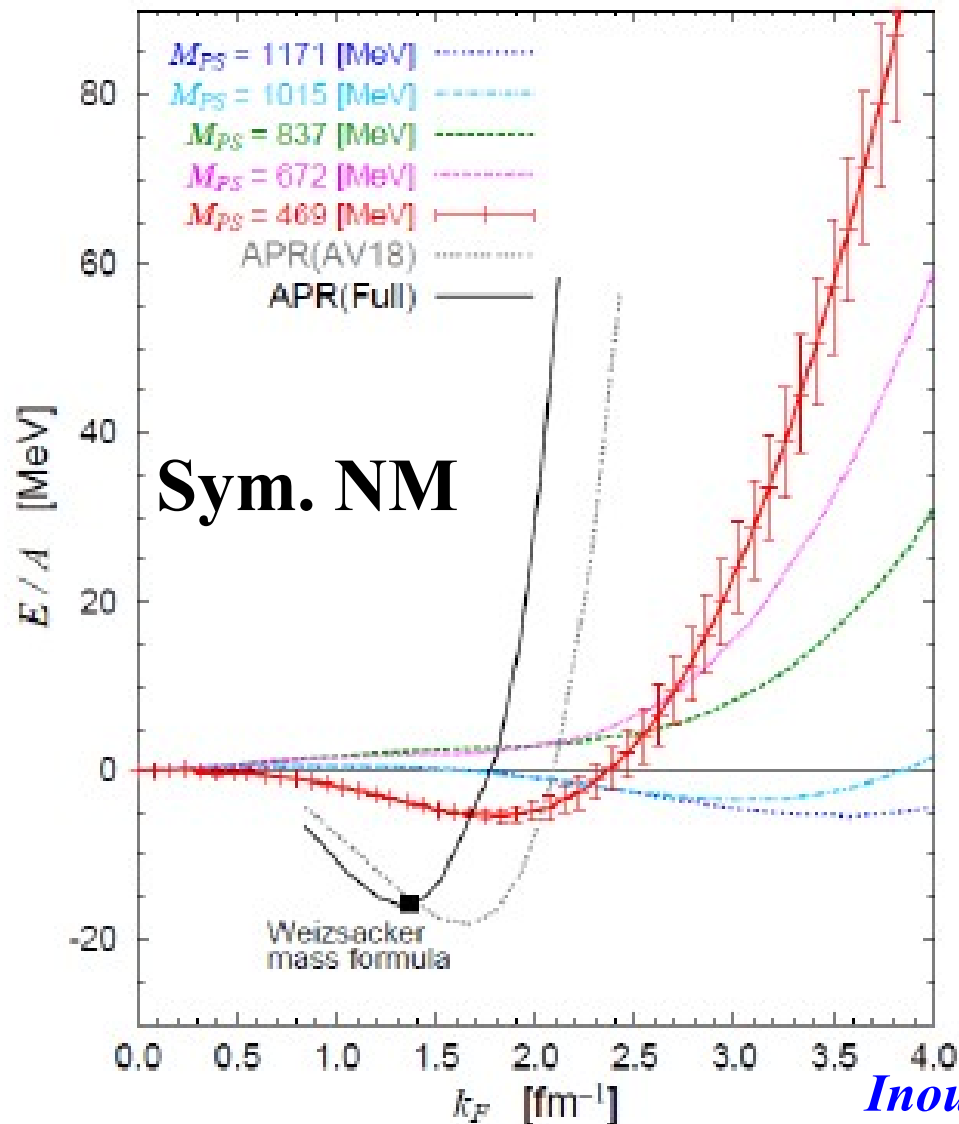
Exp: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.

Theor.: Morita, T. Furumoto, AO, PRC91('15)024916.



# EOS from lattice NN force

- 格子 QCD 核力を用いた高密度状態方程式 (LQCD+BHF)  
NN force:  $^1S_0$ ,  $^3S_1$ ,  $^3D_1$  only



*Inoue et al. (HAL QCD Coll.), PRL111 ('13)112503*

2010 年以降のデータも、  
ハイペロン・パズルを解決する方向への変更はない。  
(むしろ  $\Xi$ ,  $K^-$  については、引力が大きそう。)  
 $U_\Lambda \sim -30 \text{ MeV}$ ,  $U_\Sigma \sim +30 \text{ MeV}$ ,  $U_\Xi < -14 \text{ MeV}$

解決方法は？

# ハイペロン・パズルの 解決に向けて

## ■ Three-baryon (3B) interaction ?

### ● “Universal” 3B repulsion

*Nishizaki, Takatsuka, Yamamoto ('02), Tamagaki ('08),  
Yamamoto, Furumoto, Yasutake, Rijken ('13)*

### ● Repulsive $\Lambda$ NN potential (or density dep. $\Lambda$ N pot.)

*Lonardonì, 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 ?

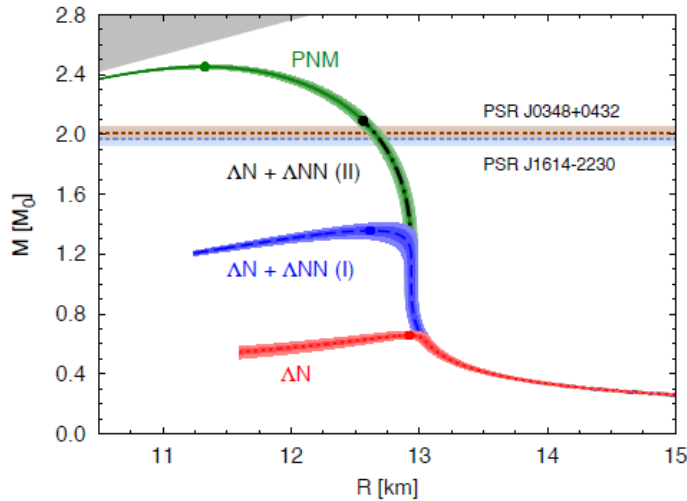
### ● First order phase transition

*L. Bonanno, A. Sedrakian, Astron. Astrophys. 539 (2012) A16; M. Bejger, D. Blaschke, P. Haensel, J. L. Zdunik, M. Fortin, arXiv:1608.07049.*

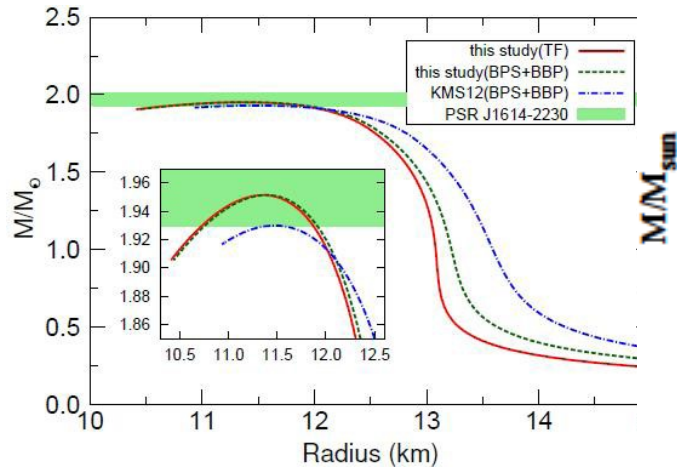
### ● Crossover transition to quark matter *Masuda, Hatsuda, Takatsuka ('12)*

## ■ Modified Gravity *Astashenok et al. ('14), M.-K. Cheoun et al.*

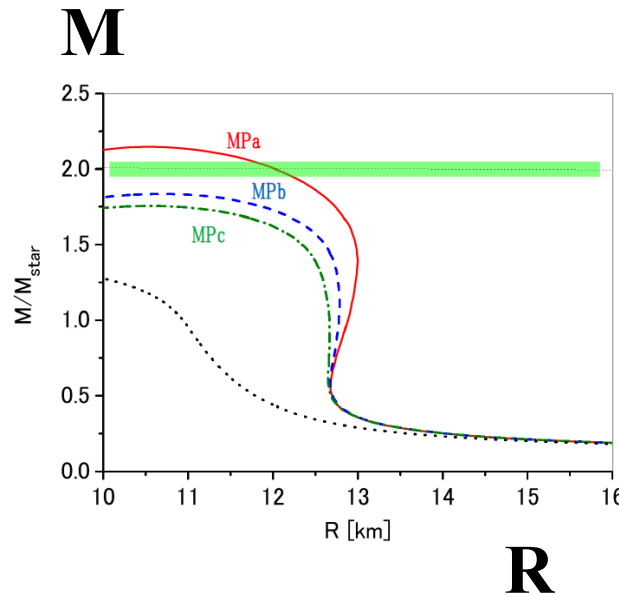
# Possible Solution of Hyperon Puzzle



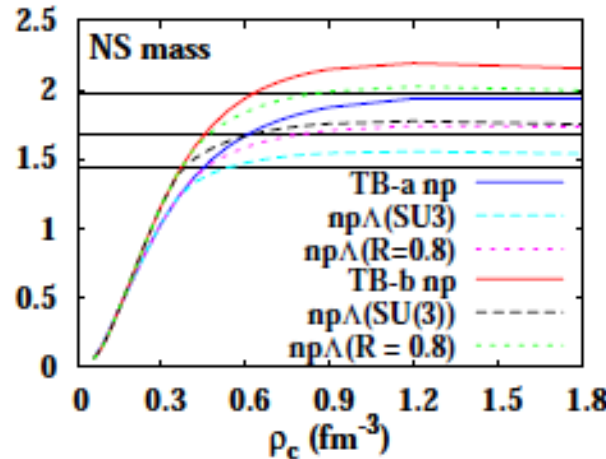
*Lonardonì, Lovato,  
Gandolfi, Pederiva ('15),*



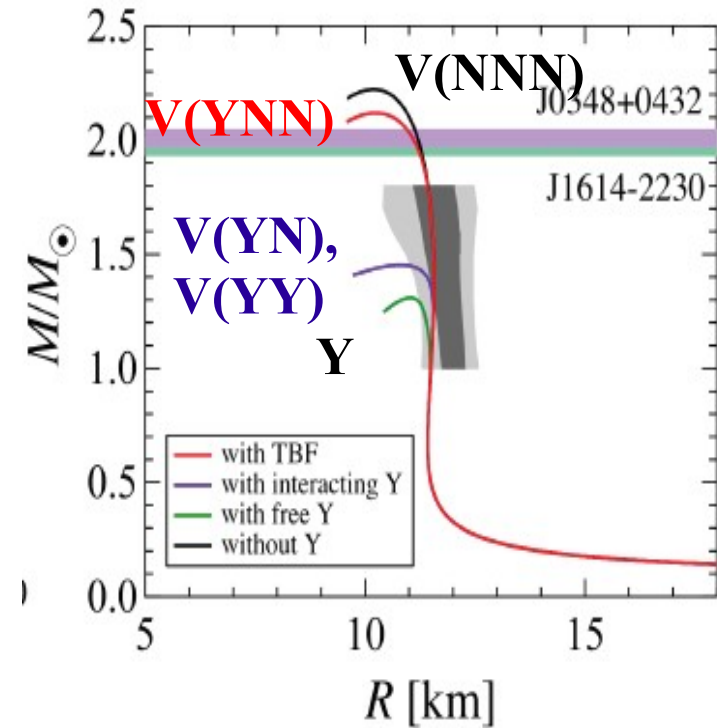
*QMC, Miyatsu, Yamamuro,  
Nakazato ('13)*



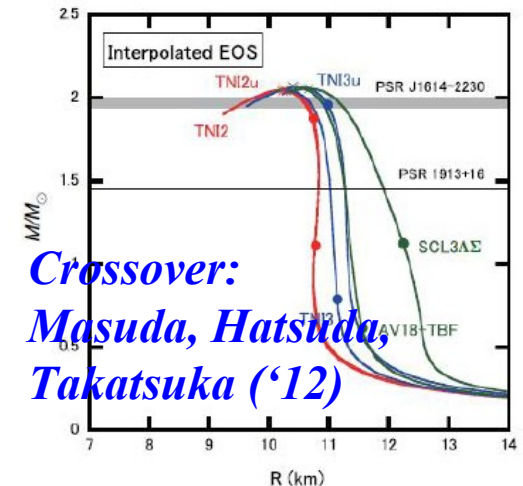
*Yamamoto, Furumoto,  
Yasutake, Rijken ('13)*



*Three-baryon coupling,  
Tsubakihara, AO ('13)*

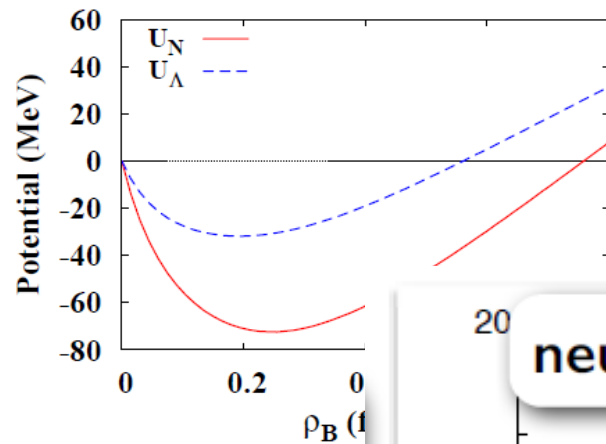


*Togashi, Hiyama, Takano,  
Yamamoto ('16).*

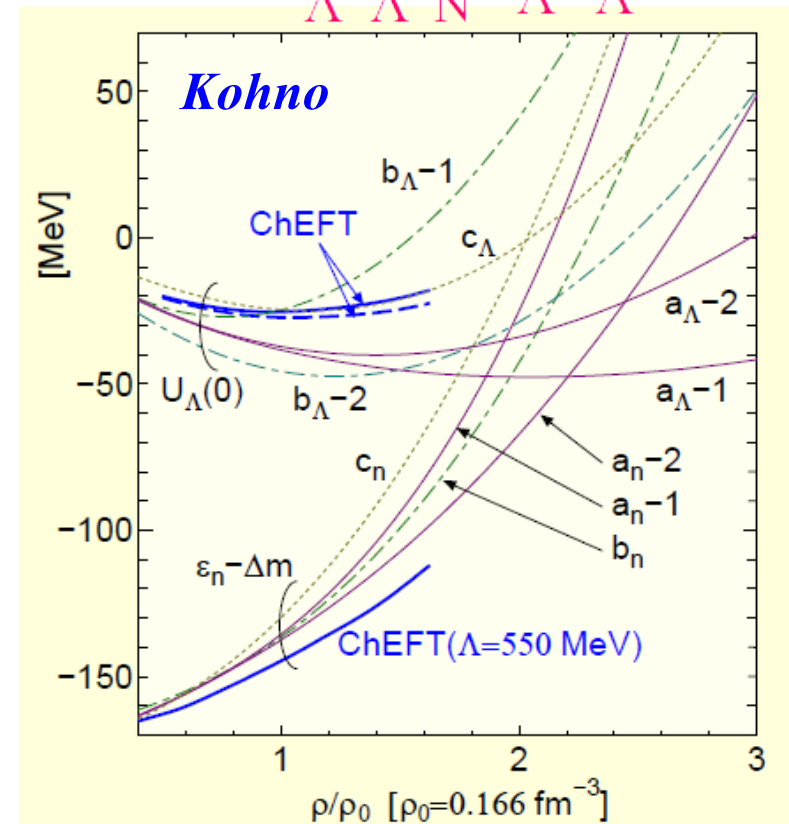
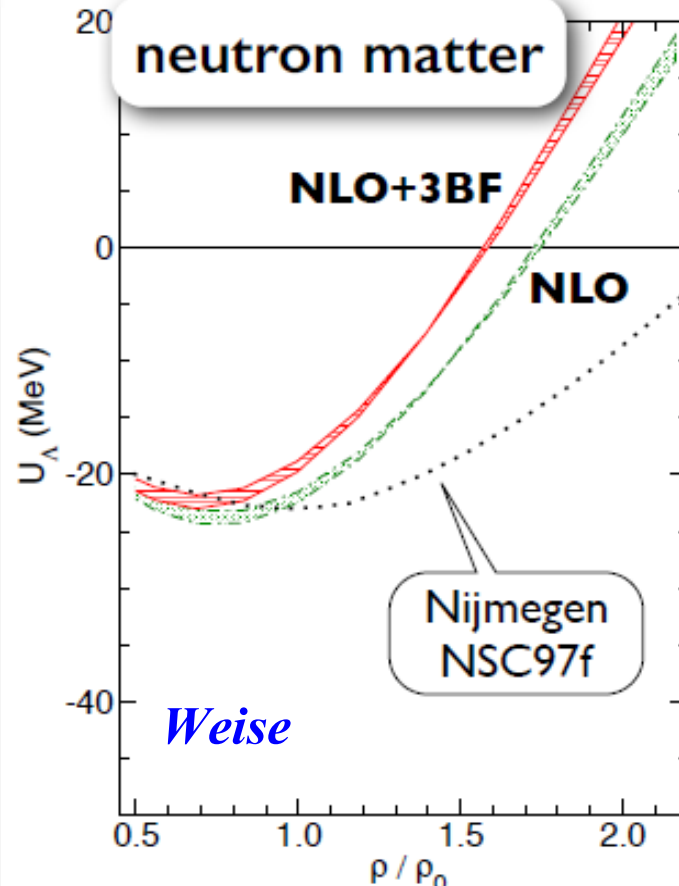
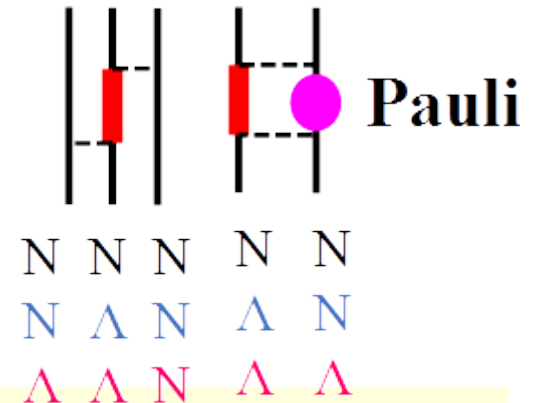


*Crossover:  
Masuda, Hatsuda,  
Takatsuka ('12)*

# ハイペロン3 体力 (密度依存性)



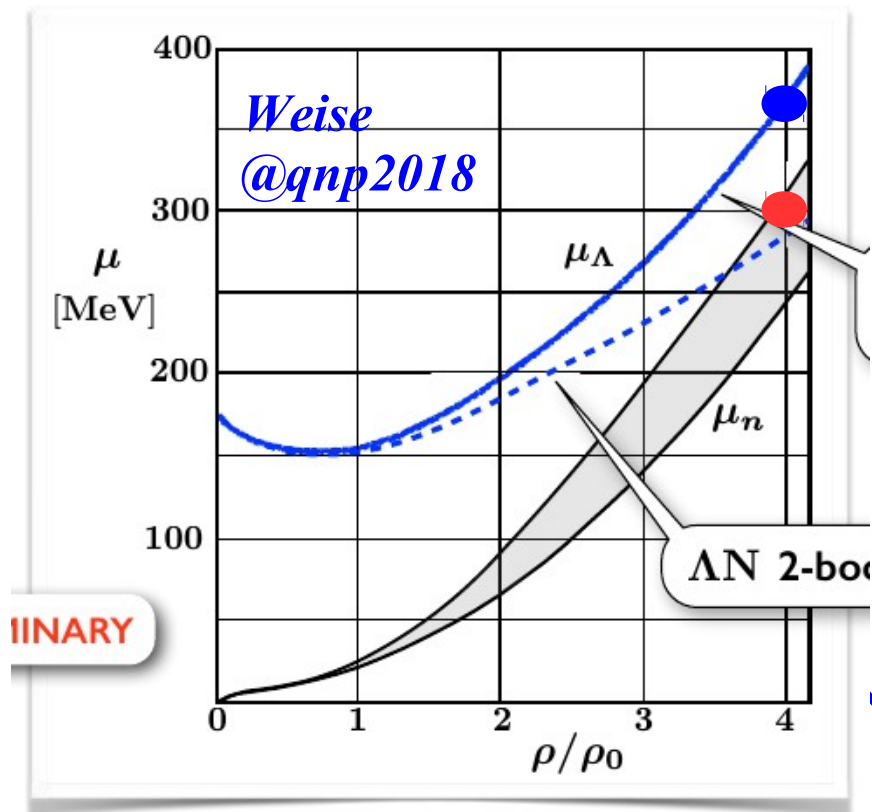
*Tsubakihara et al. ('10)*



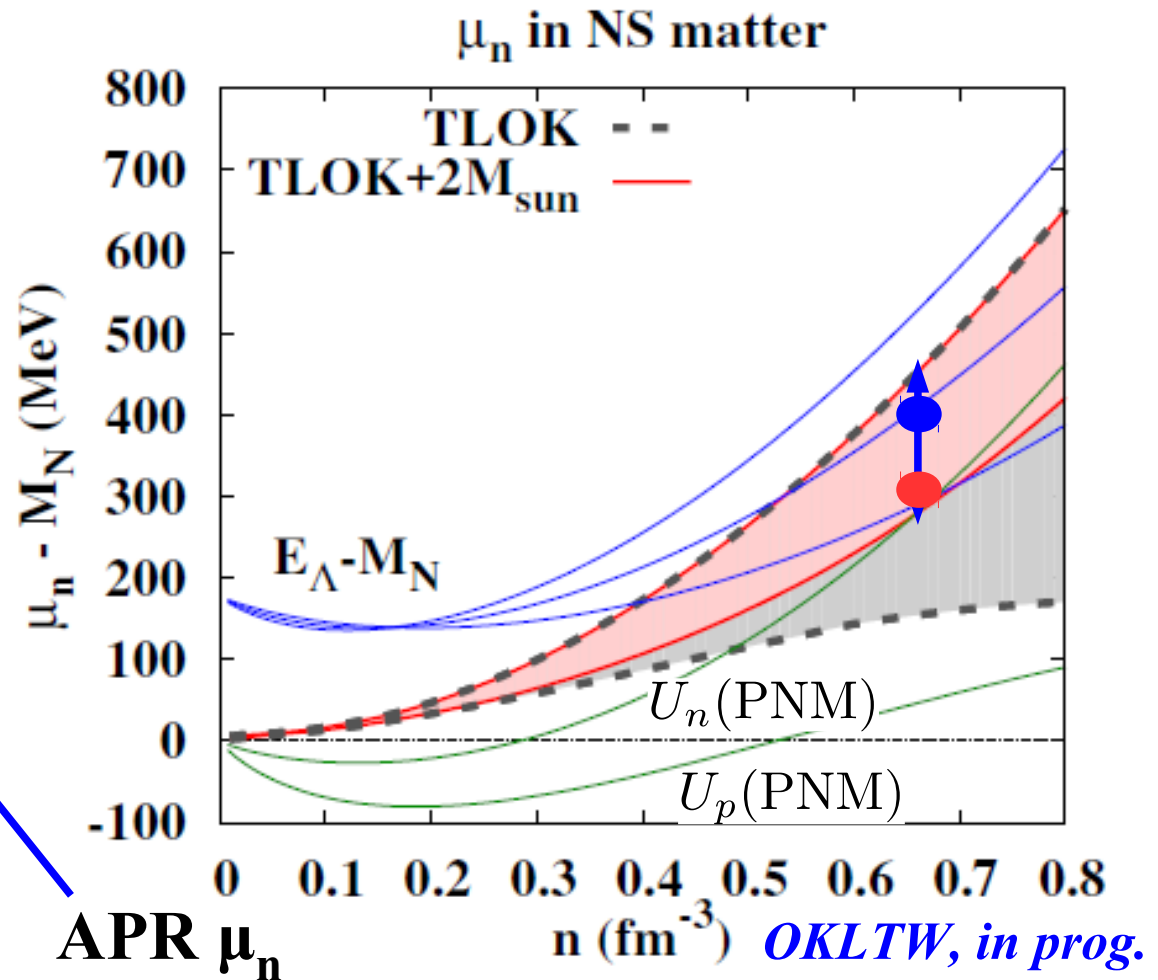
**Chiral EFT 等で3 体力を考慮 →  $U_\Lambda$  は  $\rho_0$  近辺で上昇へ向かう**

# Neutron Chemical Potential in NS

- $\Lambda$  appears in neutron stars if  $E_{\Lambda}(p=0) = M_{\Lambda} + U_{\Lambda} < \mu_n$
- $U_{\Lambda}$  in  $\chi$ EFT (2+3 body) is stiff.
- But  $\mu_n$  is larger with TLOK+2M $_{\odot}$  constraints



W. Weise, NFQCD2018 (2018.06);  
Gerstung, Kaiser, Weise, in prog.



# Neutron Chemical Potential in NS

## ■ Neutron Chemical Potential

$$\mu_n + M_N = \frac{\partial(nE)}{\partial n_n} = E + u \frac{\partial E}{\partial u} + 2\alpha(1 - \alpha)S(u)$$

## ■ Single particle potential

$$U_\Lambda(u) = \frac{\partial(nV)}{\partial n_\Lambda}$$

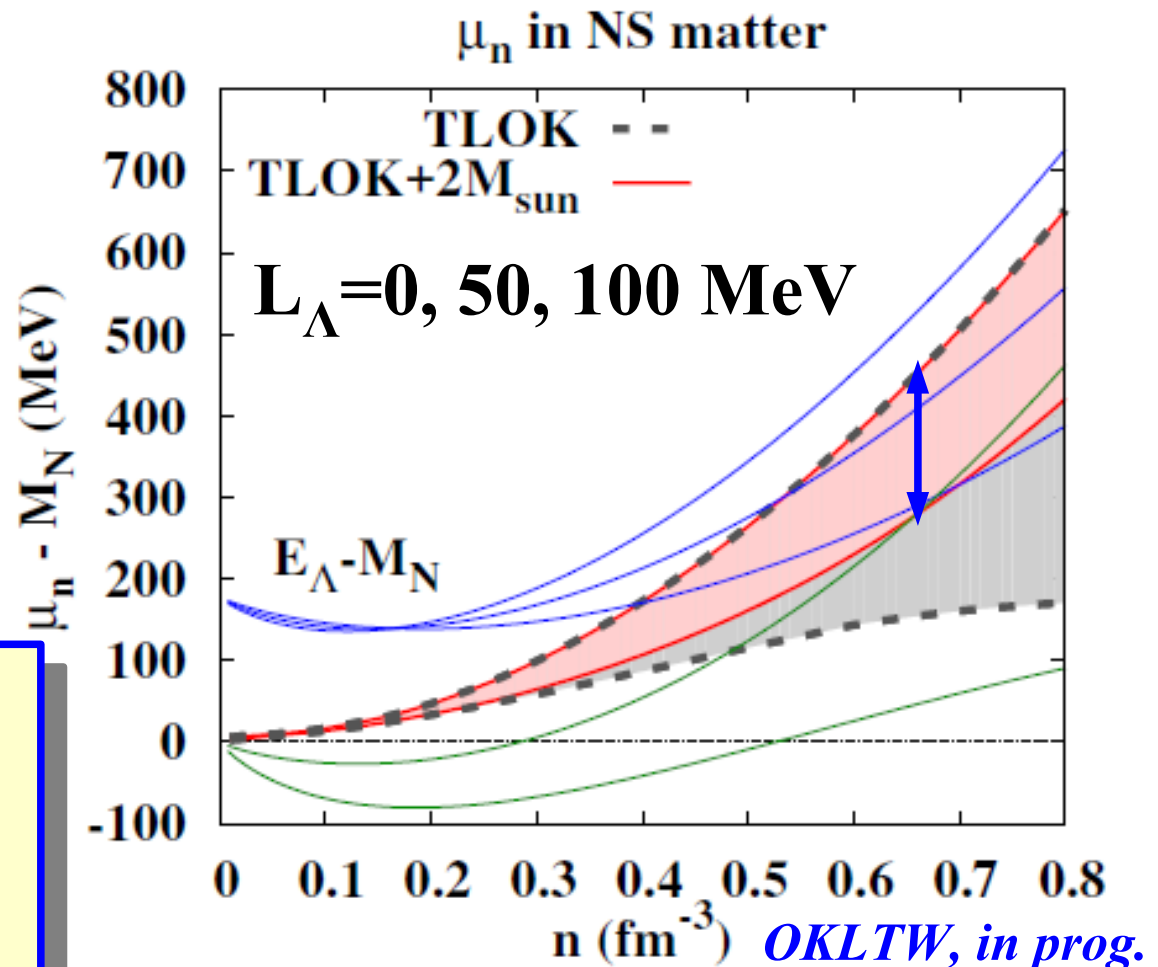
$$\simeq U_{0\Lambda} + \frac{L_\Lambda}{3}(u - 1)$$

$$U_{0\Lambda} \simeq -30 \text{ MeV}$$

$$L_\Lambda = ???$$

( $L_\Lambda < 0$  in most of RMF before 2010)

*Sym.  $E$ . and  $L_\Lambda$  determine the onset density of  $\Lambda$ . (Already mentioned in Millener, Dover, Gal paper)*



# Model calculations of neutron star matter within NJL model

NJL Lagrangian

$$\mathcal{L} = \bar{q}(i\gamma_\mu \partial^\mu - m_q + \mu\gamma_0)q + \mathcal{L}^{(4)} + \mathcal{L}^{(6)}$$

$$\mathcal{L}_\chi^{(4)} = G \sum_{a=0}^8 [(\bar{q}\tau_a q)^2 + (\bar{q}i\gamma_5\tau_a q)^2]$$

chiral interactions

$$\mathcal{L}_d^{(4)} = H \sum_{A,A'=2,5,7} [(\bar{q}i\gamma_5\tau_A\lambda_{A'}C\bar{q}^T)(q^TCi\gamma_5\tau_A\lambda_{A'}q)]$$

BCS pairing interactions

$\mathcal{L}^{(6)}$  = Kobayashi-Maskawa-'t Hooft six quark axial anomaly

plus universal repulsive quark-quark vector coupling

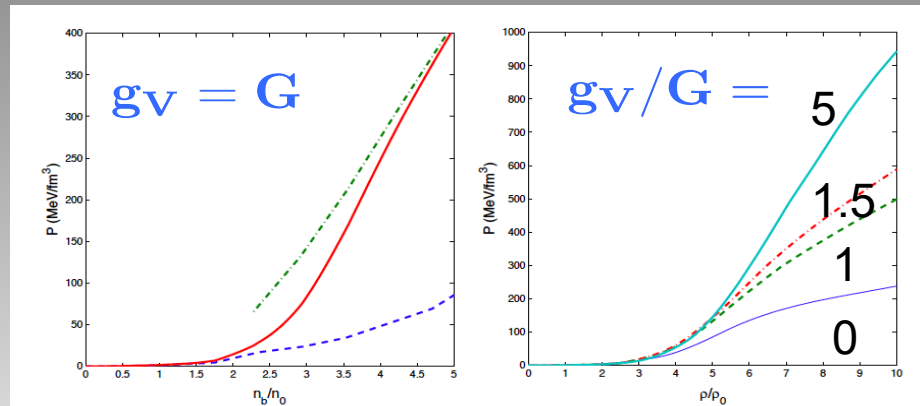
$$\mathcal{L}_V^{(4)} = -g_V (\bar{q}\gamma^\mu q)^2 \quad T. Kunihiro$$

Include u,d, and s quarks

*K. Masuda, T. Hatsuda,  
& T. Takatsuka, Ap. J. 764,  
12 (2013)*

*GB, T. Kojo, T. Hatsuda,  
T. Takatsuka, & Y. Song  
ROPP 81, 056902 (2018)*

pressure



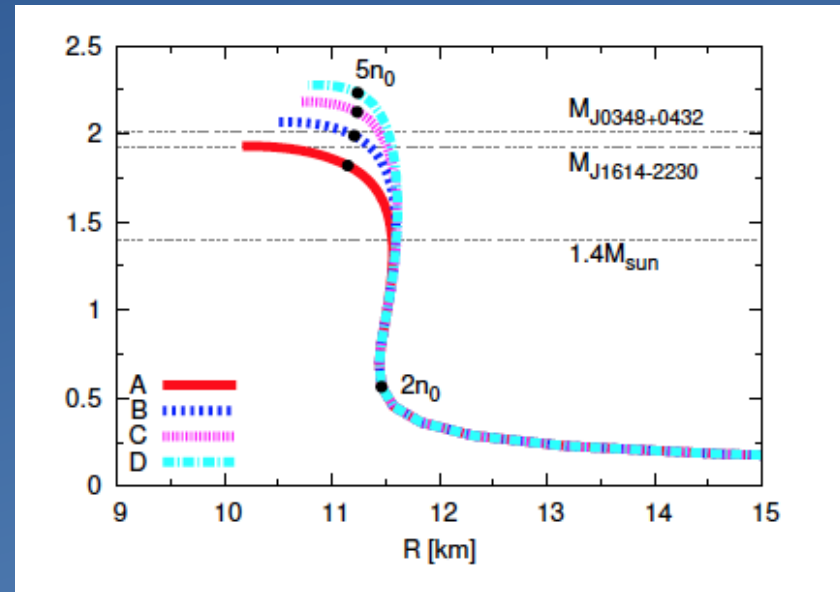
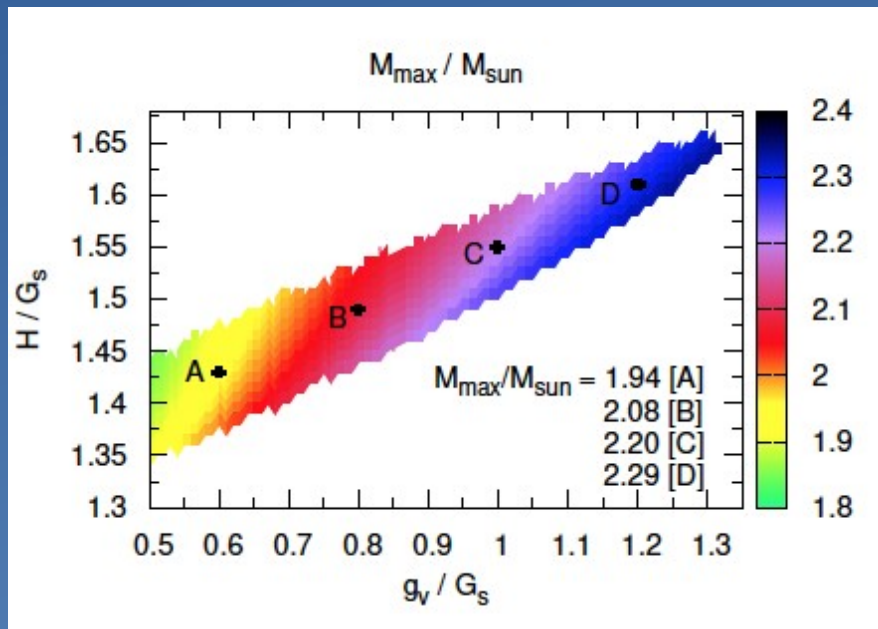
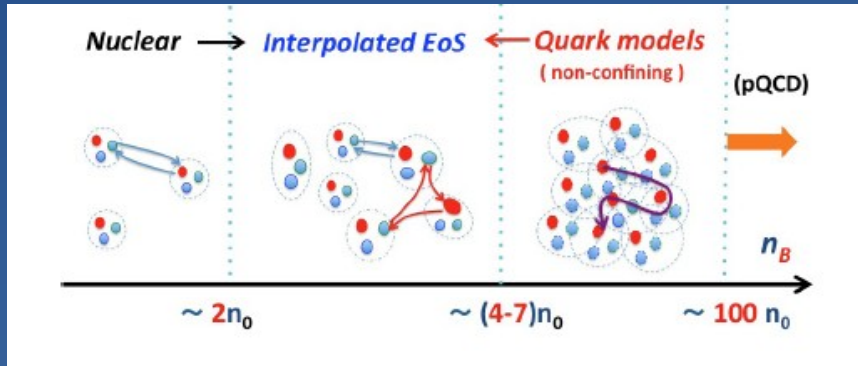
baryon density

mass density

G. Baym

# QHC18 (quark-hadron crossover) equation of state:

*T. Kojo, T. Hatsuda, GB, et al.*



Neutron star radius vs. mass

Maximum mass vs. parameters  $g_v$ ,  $H$

G. Baym

# クォーク物質への相転移

## ■ NJL でのベクトル結合 → クォーク物質での対称エネルギー

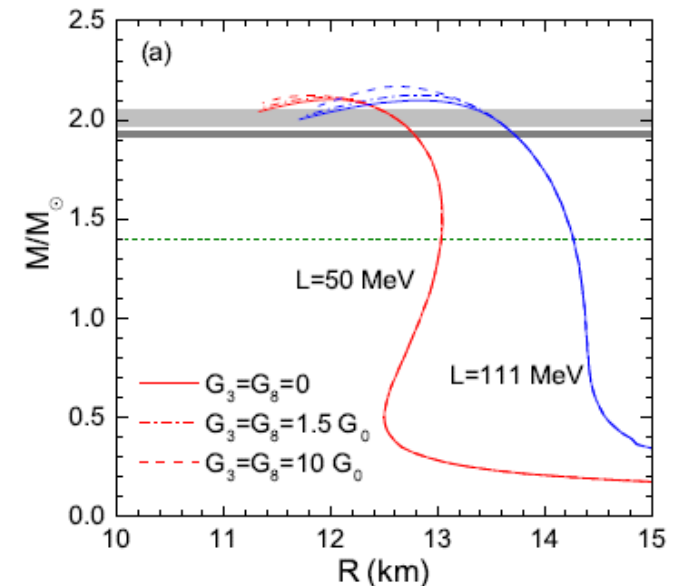
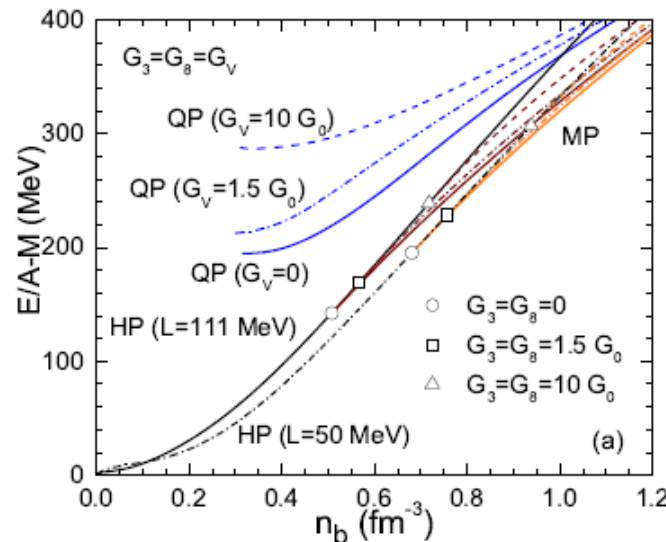
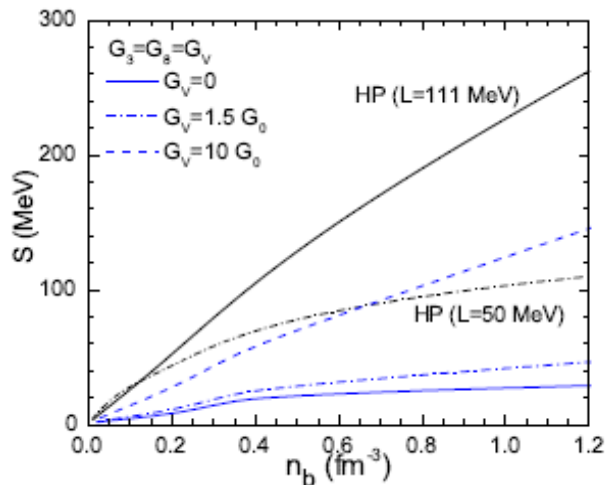
*R.C.Pereira, P. Costa, C. Providencia, PRD94('16)094001*

*X.Wu, AO, H. Shen, PRC98 ('18)065801*

$$\mathcal{L}_v = -G_0(\bar{q}\gamma_\mu q)^2 - G_V \sum_{\alpha} [(\bar{q}\gamma_\mu \lambda_{\alpha} q)^2 + (\bar{q}i\gamma_\mu \gamma_5 \lambda_{\alpha} q)^2]$$

- $G_V=0, G_V=1.5 G_0 (\lambda_0=\sqrt{2}/3)$  の場合にはクォーク物質の対称エネルギーは核物質より非常に小さい。 $G_V=10 G_0$  程度でほぼ同様。

## ■ RMF での L 値の抑制 $\Lambda_v (g_{\omega}^2 \omega_{\mu} \omega^{\mu}) (g_{\rho}^2 \rho_{\mu}^a \rho^{a\mu})$



## Lec. 5 のまとめ

- strangeness を考えることにより、原子核物理はより豊富に！
    - 様々な相互作用の形が現れ、原子核の種類も豊富に！
  - ハイペロンパズルはいまだに大きな問題として残っている
    - ハイペロン・ポテンシャル、反 K 中間子の  $\rho_0$  近辺での深さは、これまでの結果と同程度、あるいはより引力的。  
 $U_{\Lambda} \sim -30 \text{ MeV}, U_{\Sigma} \sim +30 \text{ MeV}, U_{\Xi} < -14 \text{ MeV}$   
→ Hyperon puzzle の解決にはならず、さらに深刻に。
  - 提案されている解決方法
    - ハイペロンを含む 3 体斥力 (YNN, YYN, YYY) or 密度依存性
    - 比較的早い段階でのクォーク物質への転移 (弱い 1 次 or crossover)
    - 強い磁場による EOS の硬化、修正重力、....
- 実験的検証方法は??? → To be continued

- 高密度物質と中性子星の物理: 講義の内容
  1. 中性子星の基本的性質
  2. 状態方程式を記述する理論模型
  3. 対称エネルギーと非対称核物質の状態方程式
  4. QCD 有効模型と高密度核物質の性質
  5. ハイパー核物理と中性子星でのハイペロンパズル
  - 談話会 Symmetry Parameter Constraints from a Lower Bound on the Neutron-Matter Energy
- 中性子星は低密度から高密度にわたる核物質の情報を必要とする興味深い対象。重力波観測も行われ、宇宙物理からの興味も増している。今後も研究していきましょう。