3th Quarks and Compact Stars 2019,
Sep. 26-28, 2019, Hanwha Resort,
Busan, Korea

Hypernuclear Physics and Neutron Stars

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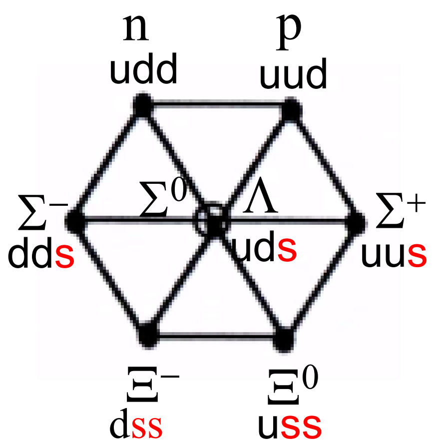
Contents

2019 BUSAN KOREA

■ Keywords

Potential,
Hyperon mixing,
Channel coupling

Hypernuclear Physics



- Hyperon (strangeness) behaves as a probe to explore the nuclear structures
  →can activate strangeness degree of freedom, SU(3) nature in nuclear/hadron physics.

- Hyperon (Λ,Σ,Ξ, …) as an "impurity" in nuclei
  → glue, stabilizer, shrinkage, ….

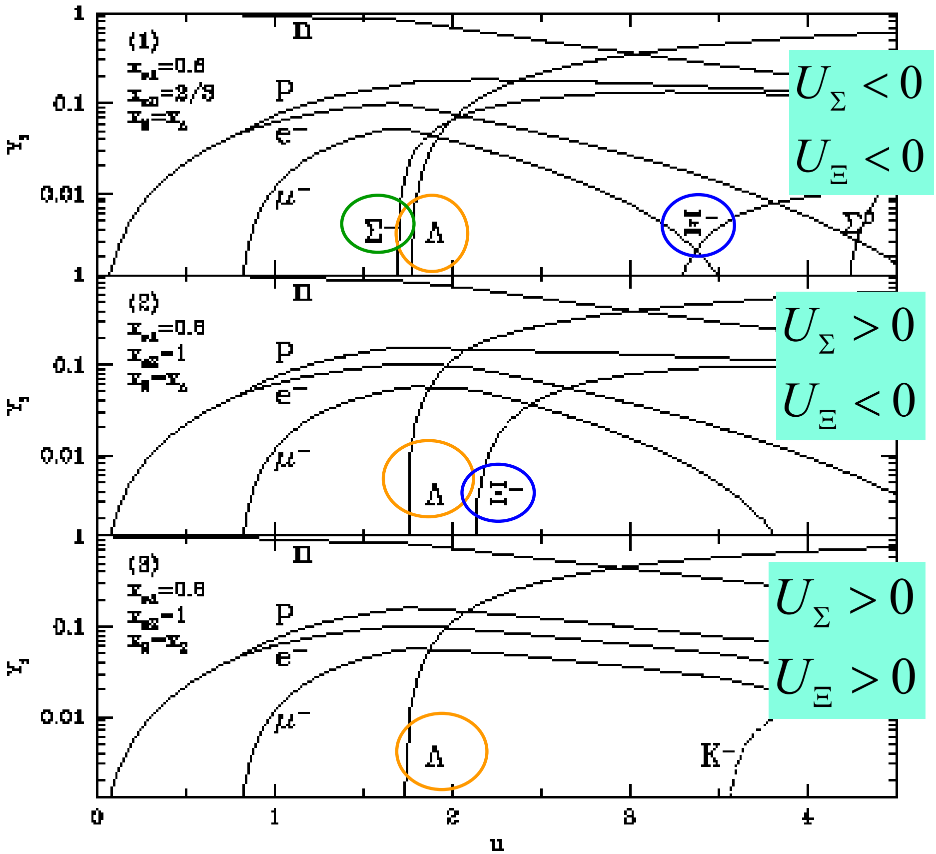
- Doorways to multi-strange hadronic matter, Neutron-star matter, high-dense QCD matter, ….
  → strongly connected with compact stars, EoS, ….
  → YN,YY (spin-isospin, tensor, spin-orbit) force, YNN, YYN,…

- We need to understand YN, YY interactions, together with 3BF in free space and nuclear medium.
  → baryon-baryon interactions based on QCD

Neutron star core

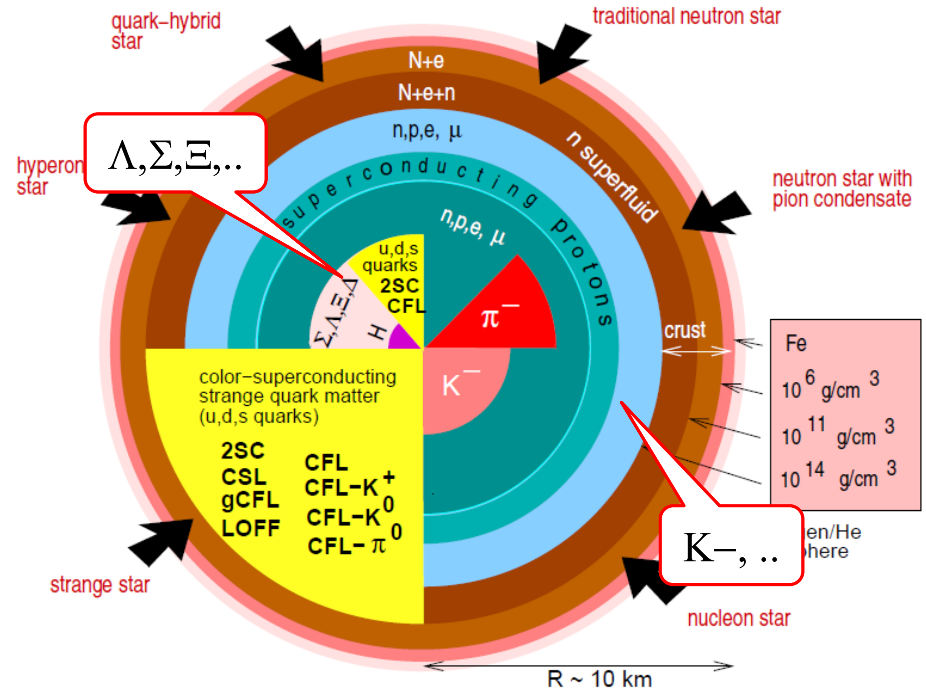
= "An interesting neutron-rich hypernuclear system"

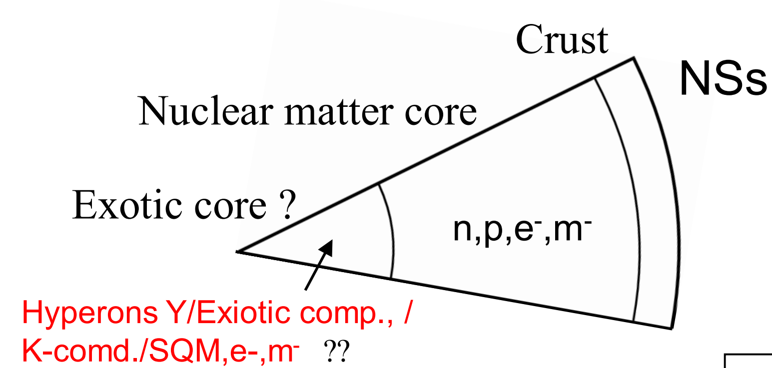
Coupling constant ratio; $x_{iY} = g_{iY}/g_{iN}\ (i=\sigma,\omega,\rho)$



R. Knorren, M. Prakash, P.J.Ellis, PRC52(1995)3470

F. Weber, PPNP 54(2005)193



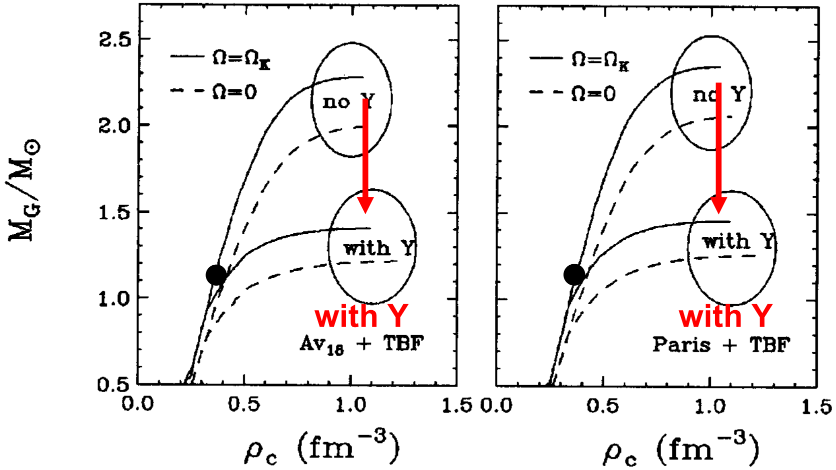


Hyperon-mixing

Equation of States (EoS) with hyperons

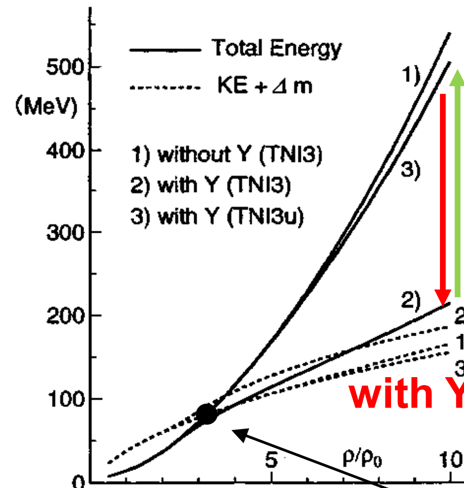
BHF+TBF model+NSC89

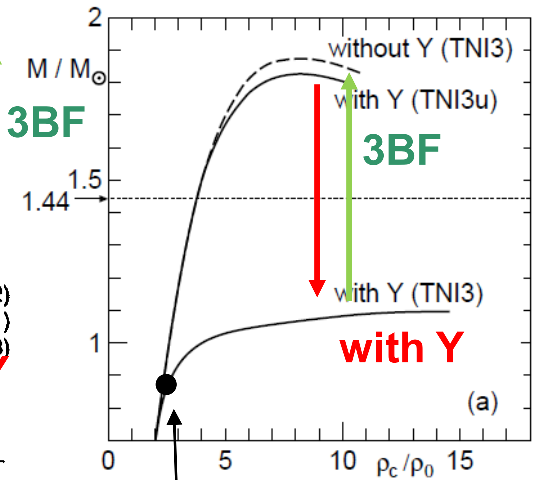
M.Baldo, et al., PRC61(2000)055801



G-matrix model+TNI3u

S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP105(2001)607; 108(2002)703

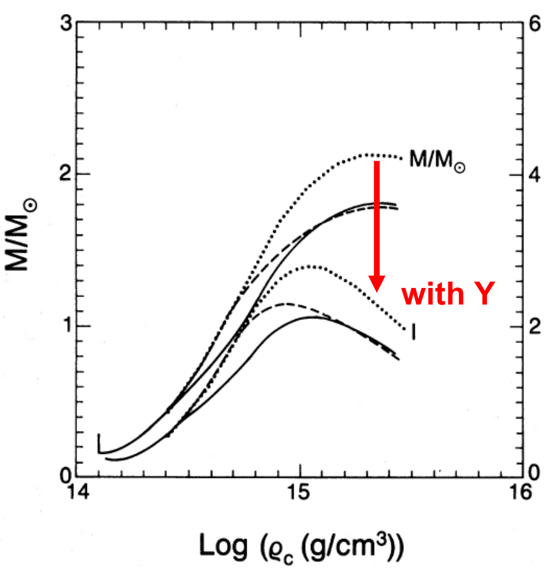




$$\rho_C(Y) \approx (2-3)\rho_0$$

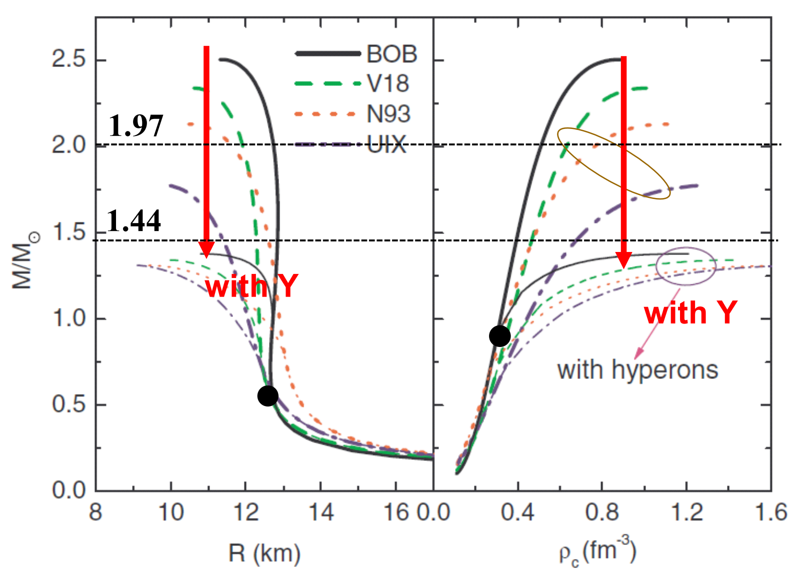
RMF

N.K.Glendenning, AJ293(1985)470



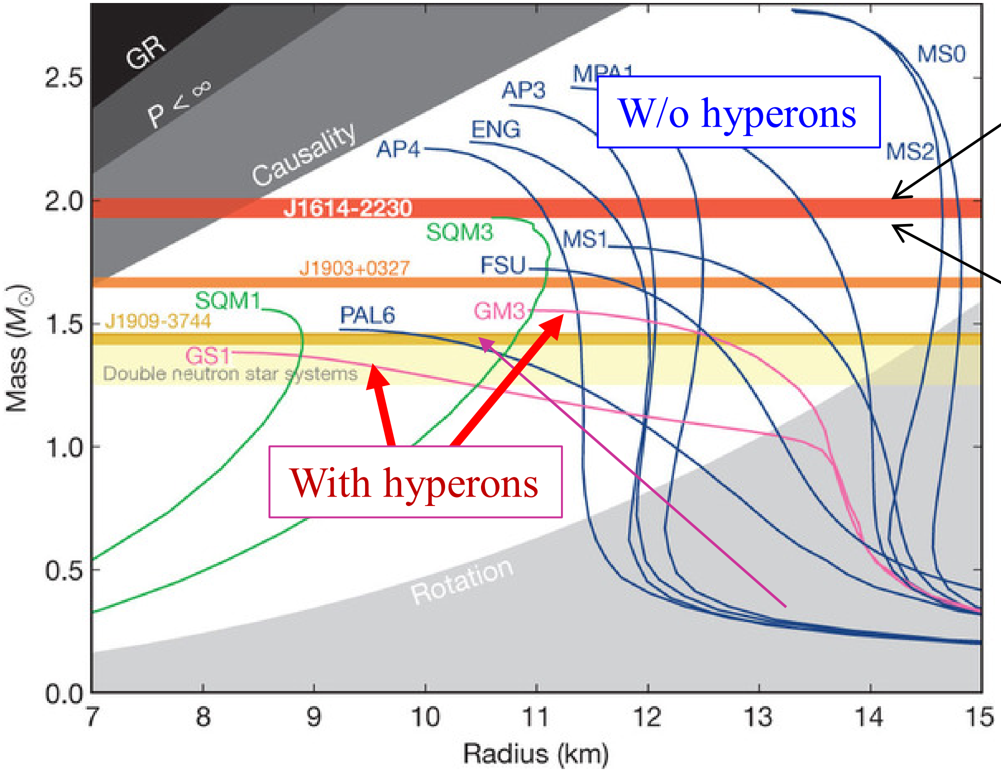
BHF

Z.H.Li, H.-J.Schulze, PRC 78 (2008) 028801



Hyperons (Λ,Ξ,…) appear at $\rho\sim(2\text{-}3)\rho_0$.
→EOS with hyperons must soften.
→Repulsive 3BF is needed ?

"Hyperon Puzzle" in Massive Neutron Stars



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

PSR J1614-2230 M=(1.97 ± 0.04)M_{sun}

(NS:1.97$M_\odot$+WD: 0.50$M_\odot$)

J.Antoniadis et al., Science 340(2013) 6131.

PSR J0348-0432 M=(2.01 ± 0.04)M_{sun}

(NS:2.01$M_\odot$+WD: 0.172$M_\odot$)

EoS
Too-strong softening

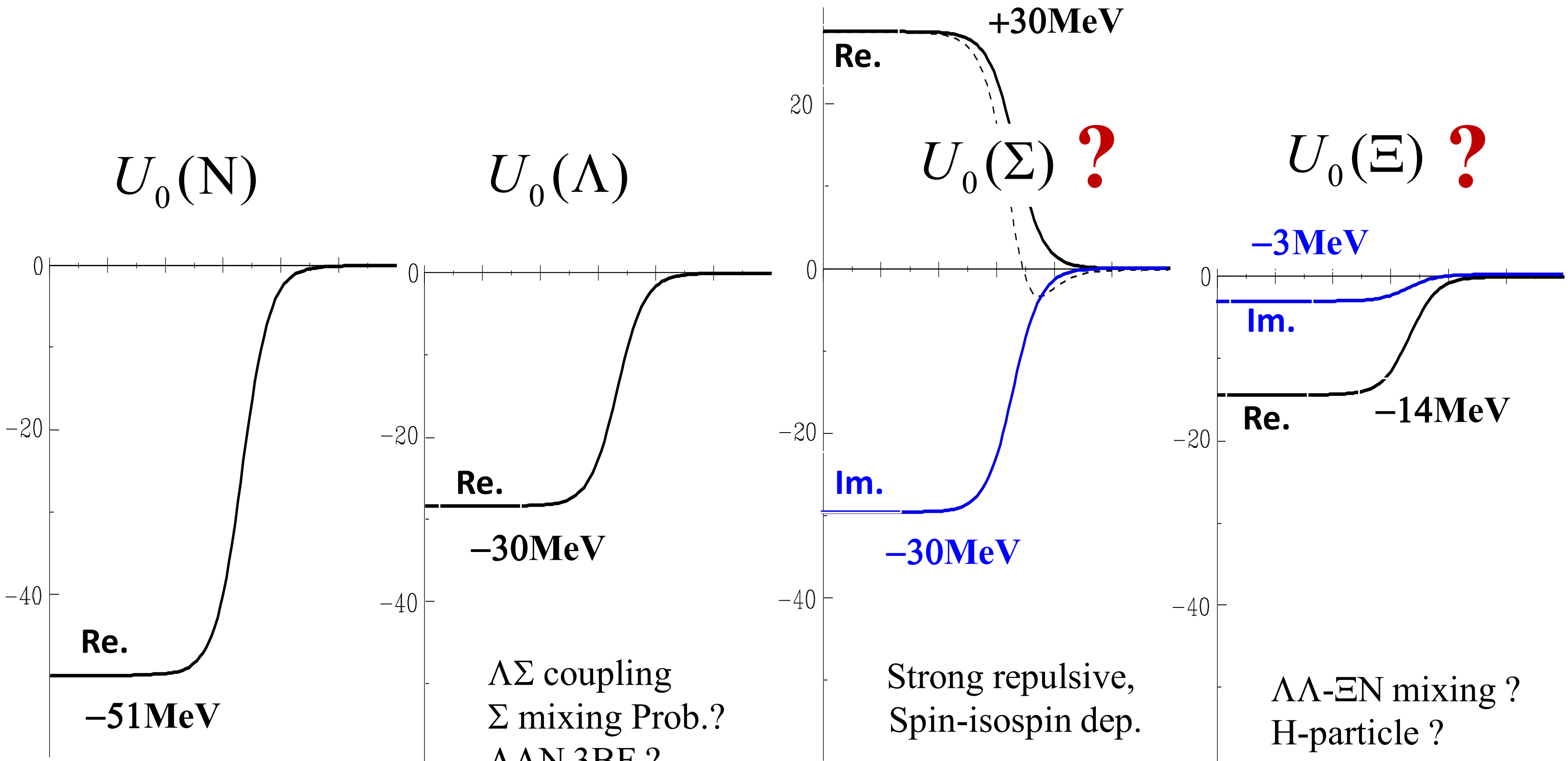
→ EOS with hyperons must be too soft to support massive NSs (> 2$M_\odot$)
→ Collapse of massive NS !?

We need to understand YN, YY interactions with 3BF at high ρ .

- No hyperon in NSs core ?
- Repulsive components in NSs needed at high ρ ?
  → Three-body force: NNN, YNN, YYN, YYY → Universal BBB repulsions ?
- Quark stars ?, Hybrid stars with Hadron-Quark crossover ?

Our understanding of hyperon s.p. potentials

N	Λ	Σ	Ξ



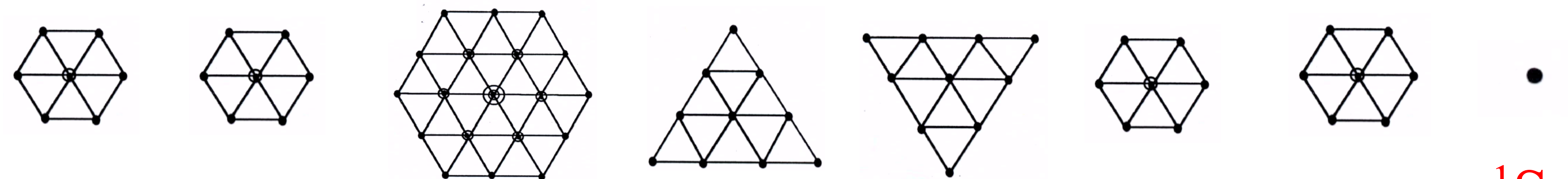
U_0~(−51)MeV	U_0~(−30)MeV	U_0~+30 MeV	U_0~ (−14)MeV?
U_{LS}~ 22 MeV	U_{LS}~ 2 MeV	U_{LS} ?, Σ width ?	Ξ width ?

Bayron-Baryon (NN, YN, YY) interactions

Flavor $SU(3)_f$ symmetry — symmetric — antisymmetric

$$[8] \otimes [8] = [27] \oplus [10^*] \oplus [10] \oplus [8_s] \oplus [8_a] \oplus [1]$$

(1,1) (1,1) (2,2) (3,0) (0.3) (1,1) (1,1) (0,0)



$^1S_0$ (from [27]) $^3S_1$ (from [10*]) $^1S_0$ H?, ΛΛ? (from [1])

S= 0	NN(I=1)	NN(I=0)	NN: 4233 data (T_{lab}<350 MeV)
S= –1	ΣN(3/2),	ΣN-ΛN(1/2)	35 data
S= –2	ΣΣ(2),	ΞN-ΣΛ-ΣΣ(1),	ΞN-ΣΣ-ΛΛ(0)
S= –3	ΞΣ(3/2),	ΞΣ-ΞΛ(1/2)	
S= –4	ΞΞ (1)	ΞΞ(0)	

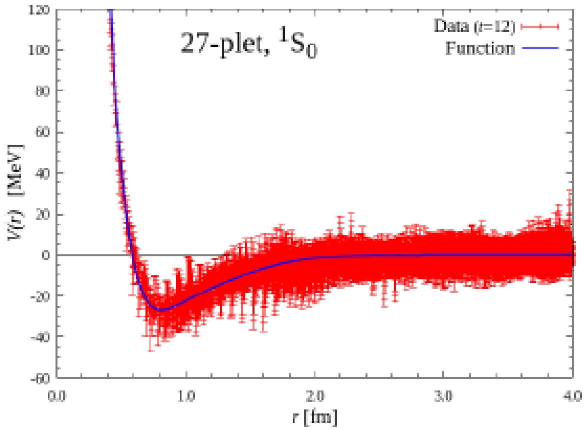
Baryon-Baryon force in SU(3) basis from lattice QCD

T. Inoue, et al., (HAL QCD Collaboration), AIP Conf. 2130 (2019) 020002.

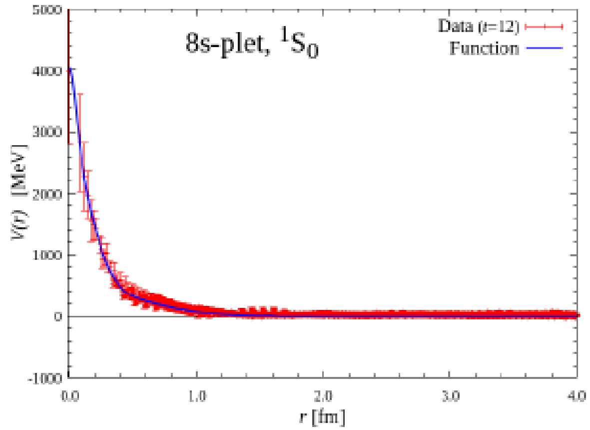
$$[8]\otimes[8]=[27]\oplus[8_s]\oplus[1]\oplus[10^*]\oplus[10]\oplus[8_a]$$

$^1S_0$

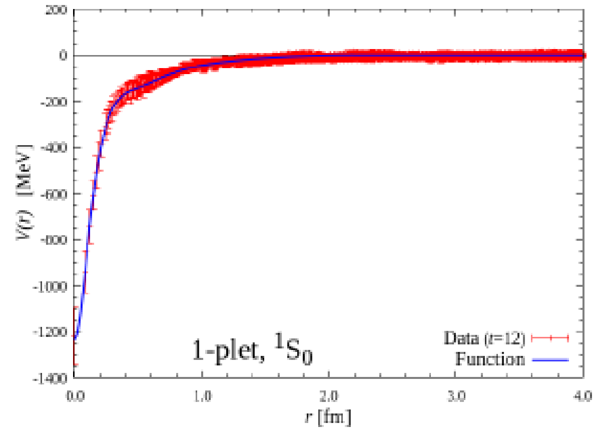
[27]



[8s]

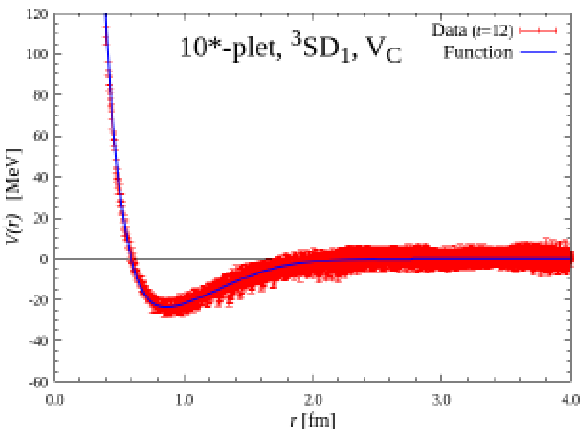


[1]

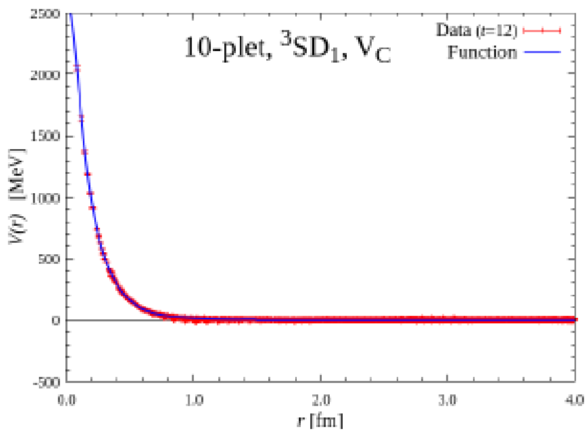


$^3S_1$-$^3D_1$

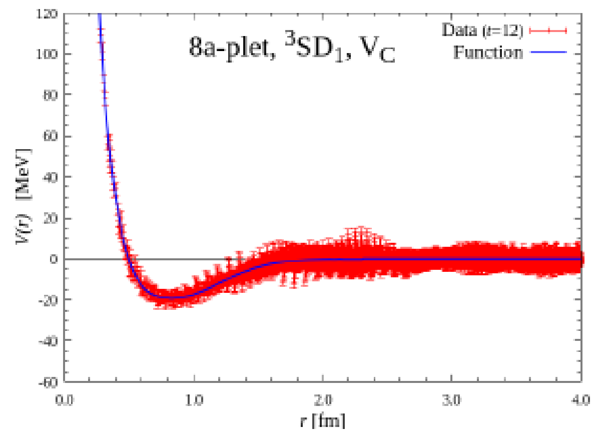
[10*]



[10]



[8a]

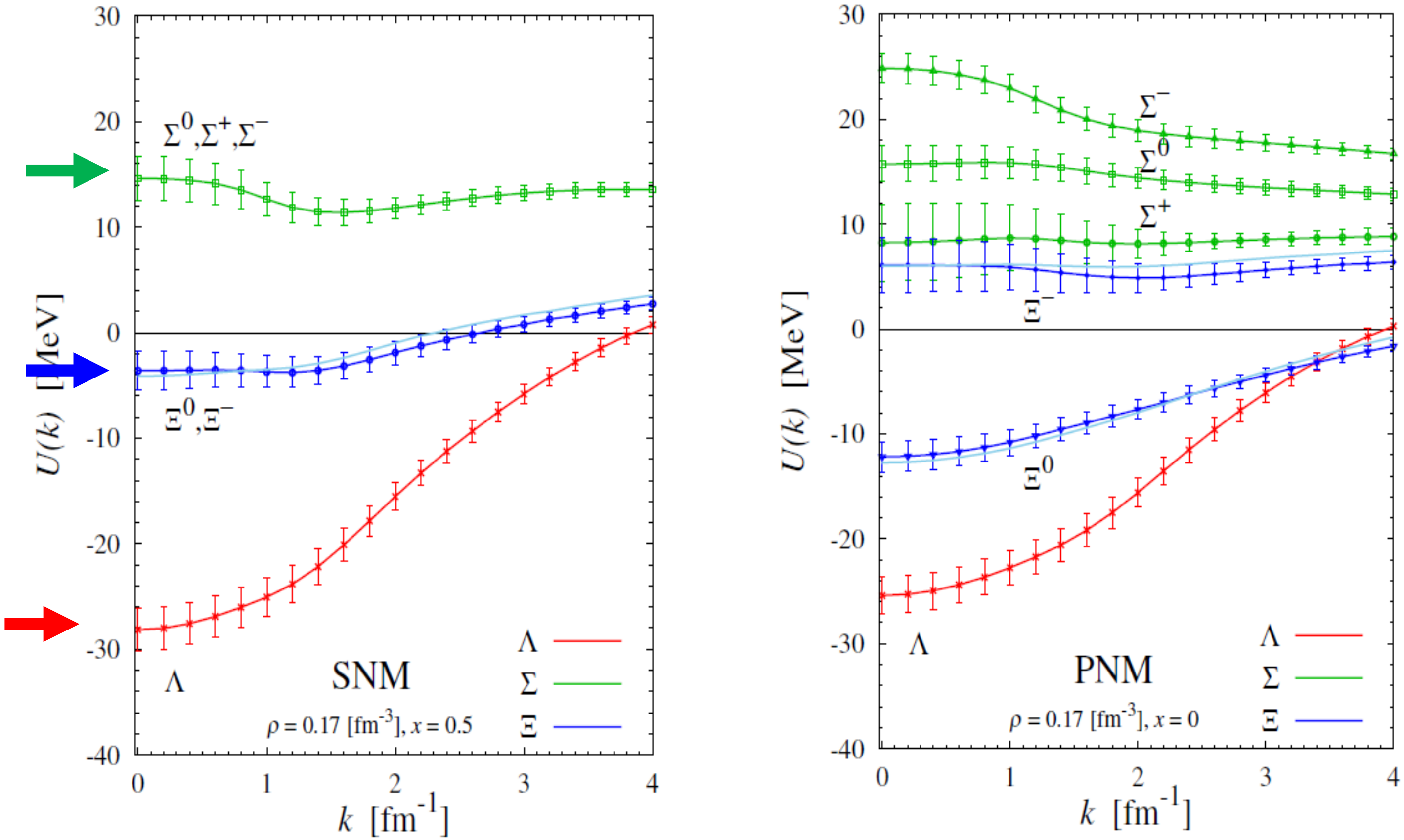


- ➢ $SU(3)_F$ limit corresponding to Mπ =146 MeV, MK = 525 MeV, MN = 958 MeV.

Hyperon s.p. potentials from QCD on lattice

T. Inoue, et al., (HAL QCD Collaboration), AIP Conf. 2130 (2019) 020002.

Bruckner-Hartree-Fock calculations (LOBT)



$U_\Lambda(0) = -\mathbf{28}$ **MeV**
attractive

$U_\Xi(0) = -\mathbf{4}$ **MeV**
weak attractive

$U_\Sigma(0) = +\mathbf{15}$ **MeV**
repulsive

The Lattice calculations support the our understanding of properties of the hyperon potentials at low ρ .

In this talk

Recent theoretical and experimental studies of hypernuclei provide valuable information on properties of strangeness in nuclear matters for overcoming of the "hyperon puzzle".

- From the theoretical point of view, we present the recent status of studies of Λ, Σ, Ξ, and $\Lambda\Lambda$ hypernuclei of which the experimental data have been observed at J-PARC.
- We also discuss properties of Λ, Σ^-, Ξ^-, potentials in nuclei, which are strongly related to the behavior of hyperons in neutron stars and the maximum mass of neutron stars.

Λ Hypernuclei

Recent status of studies of Λ Hypernuclei

- Λ s.p. potential and spin-orbit force
- Glue-like role of Λ hyperon in nuclei

- Precise Λ spectroscopy
  - Λ spectroscopy via (π^+,K^+) reactions@J-PARC
  - Gamma-ray spectroscopy of s, p, sd-shell Λ hypernuclei
    $^{4}_{\Lambda}$He(s); $^{6}_{\Lambda}$Li, $^{9}_{\Lambda}$B, $^{12}_{\Lambda}$C, $^{13}_{\Lambda}$C, $^{15}_{\Lambda}$N, $^{16}_{\Lambda}$O(p); $^{19}_{\Lambda}$F(sd)
  - Λ spectroscopy via (e,e'K^+) reactions@JLAB,MAMI
  - Production and structure of neutron Λ rich hypernuclei

- Overbinding problem on s-shell hypernuclei
- Charge Symmetry Breaking (CSB)

- Weak decays of Λ hypernuclei -- $^{3}_{\Lambda}$H lifetime puzzle

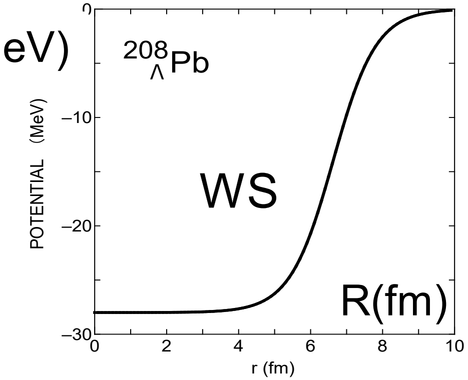
Λ s.p. potential and Λ spin-orbit splitting

$$U_\Lambda = V_0^\Lambda f(r) + V_{LS}^\Lambda \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{\mathrm{d}f(r)}{\mathrm{d}r}\boldsymbol{ls}$$

Woods-Saxon form $f(r) = \dfrac{1}{1+\exp[(r-R)/a]}$

$R = r_0 (A-1)^{1/3}\,\mathrm{fm} \qquad r_0 = 1.165\,\mathrm{fm}$

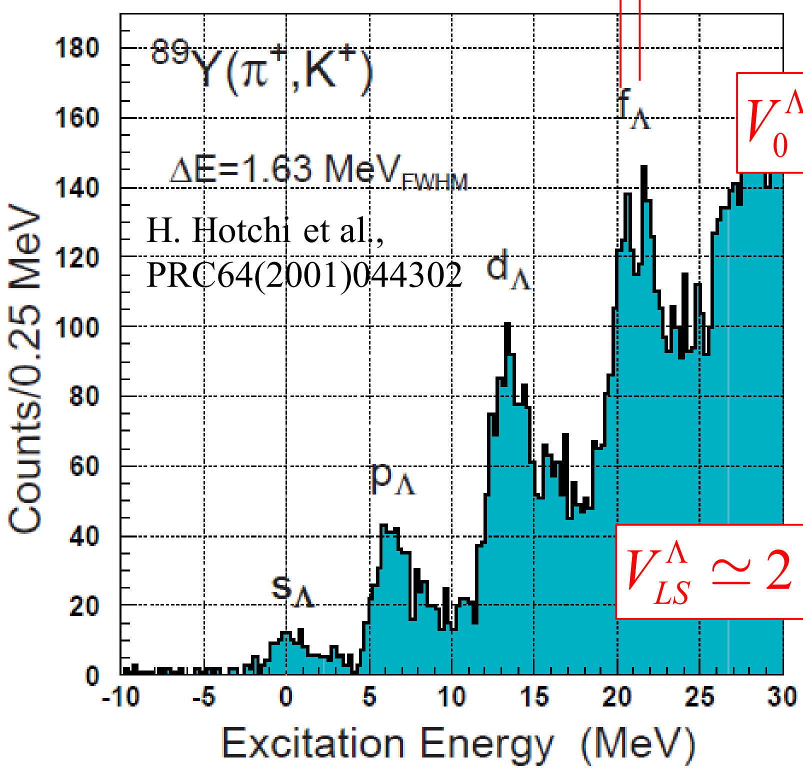
$a = 0.6\ \mathrm{fm}$



A.Gal et al., Rev.Mod.Phys. 88(2016) 035004.

(Exp.) 1.7 MeV

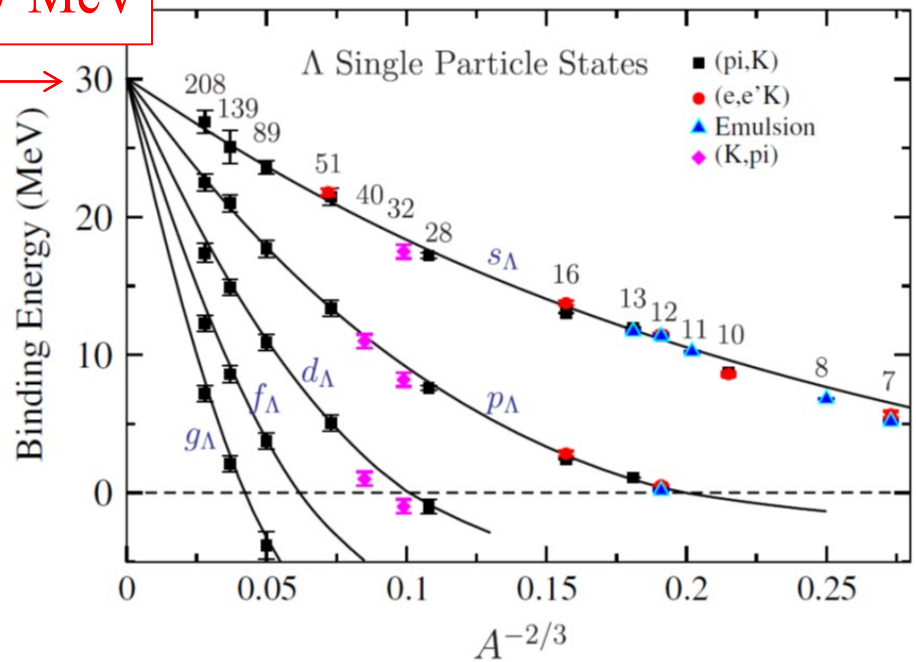
KEK E369



$V_0^\Lambda \simeq -30\ \mathrm{MeV}$

$(A \to \infty)$

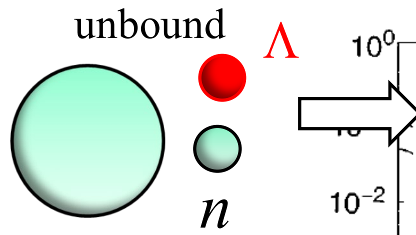
$V_{LS}^\Lambda \simeq 2\ \mathrm{MeV}$



→ **We can confirm the Λ s.p. nature in medium from light to heavy nuclei.**

Glue-like role of the Λ hyperon in nuclei

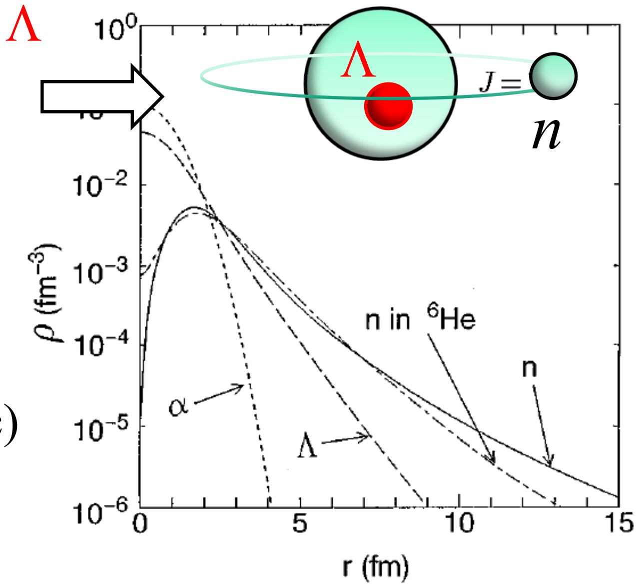
- **"glue"** T. Motoba, et al.,PTP70(1983)189
  E. Hiyama, et al.,PRC59(1999)2351



➢Shrinkage effects (19% for the ^{6}Li core)
➢neutron-skin or neutron halo

E. Hiyama, et al.,PRC59(1999)2351
Tretyakova, Lanskoy, EPJ.A5(1999) 391.

$^{6}_{\Lambda}$He
(α+N+Λ calc)

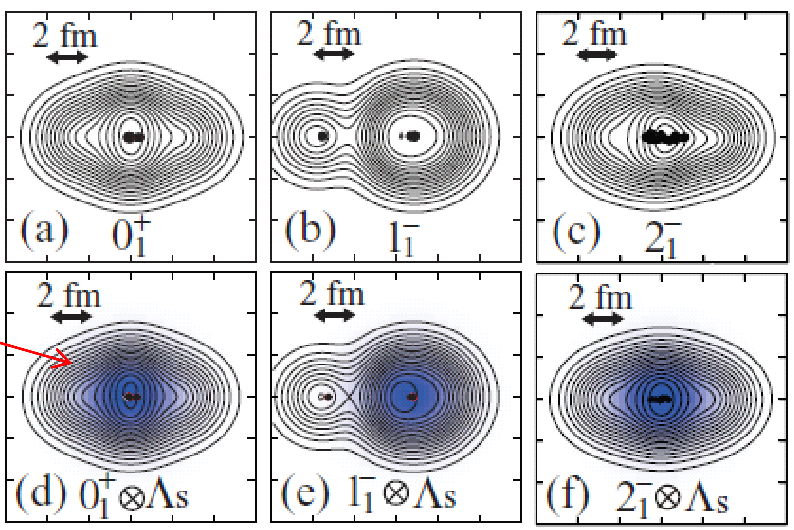


- **"Stabilizing"+"Deformation"**

$^{21}_{\Lambda}$Ne, $^{25}_{\Lambda}$Mg (AMD)

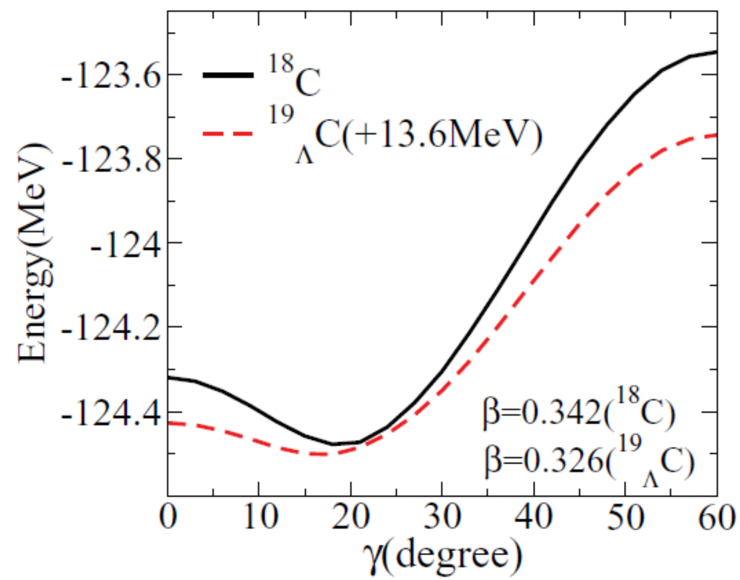
M. Isaka et al, PRC83(2011)054304

g.s.



$^{19}_{\Lambda}$C, $^{29}_{\Lambda}$Si, $^{25}_{\Lambda}$Mg, (CSHF+BCS)

M.T. Win, K.Hagino et al, PRC83 (2011) 014301



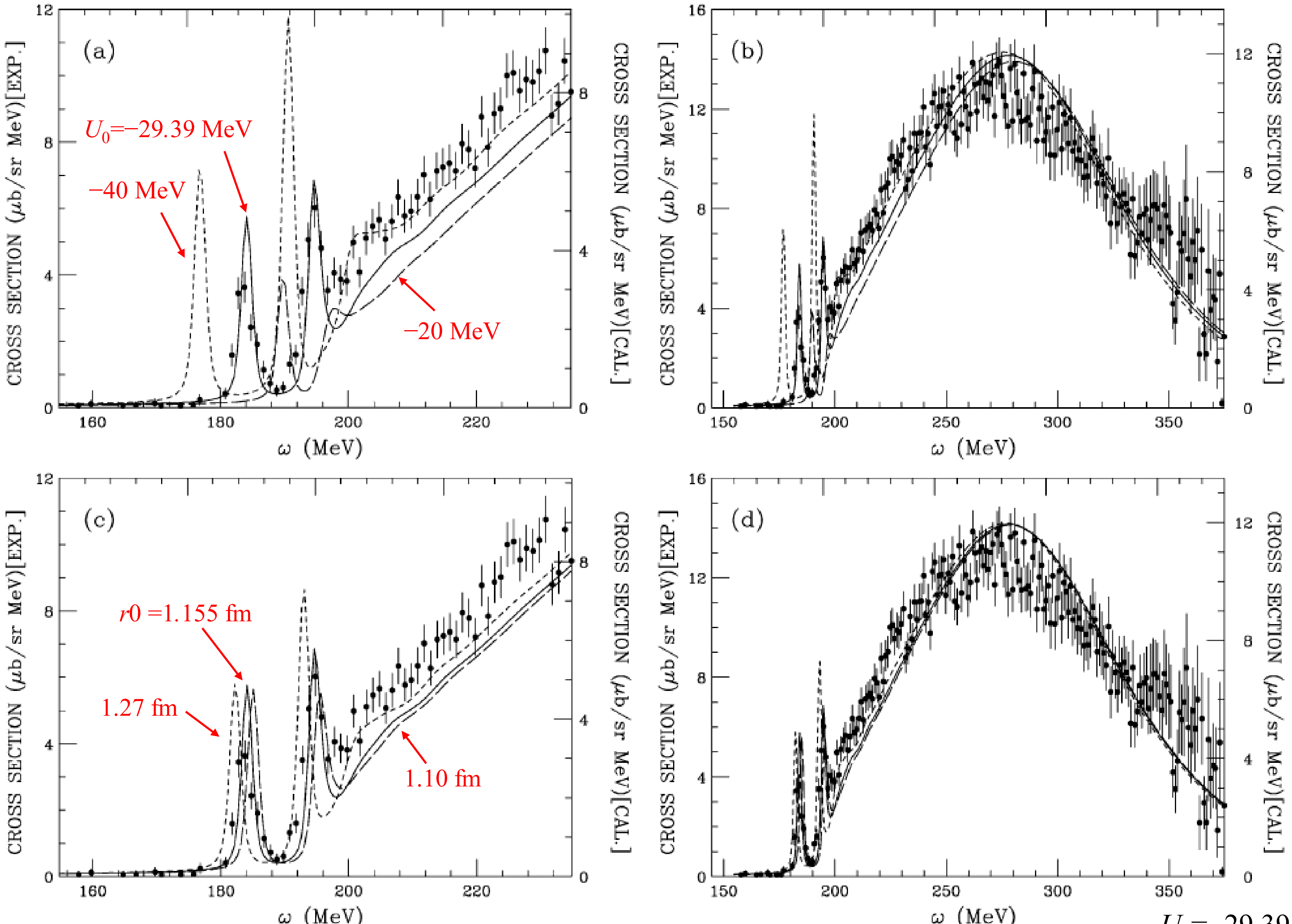
^{12}C

Λ spectrum by (π^+,K^+) reaction at 1.2 GeV/c (6°)

Harada, Hirabayashi, NPA744 (2004) 323.

Sensitivity of the spectrum to the Λ–nucleus potential parameters

r_0 = 1.155 fm



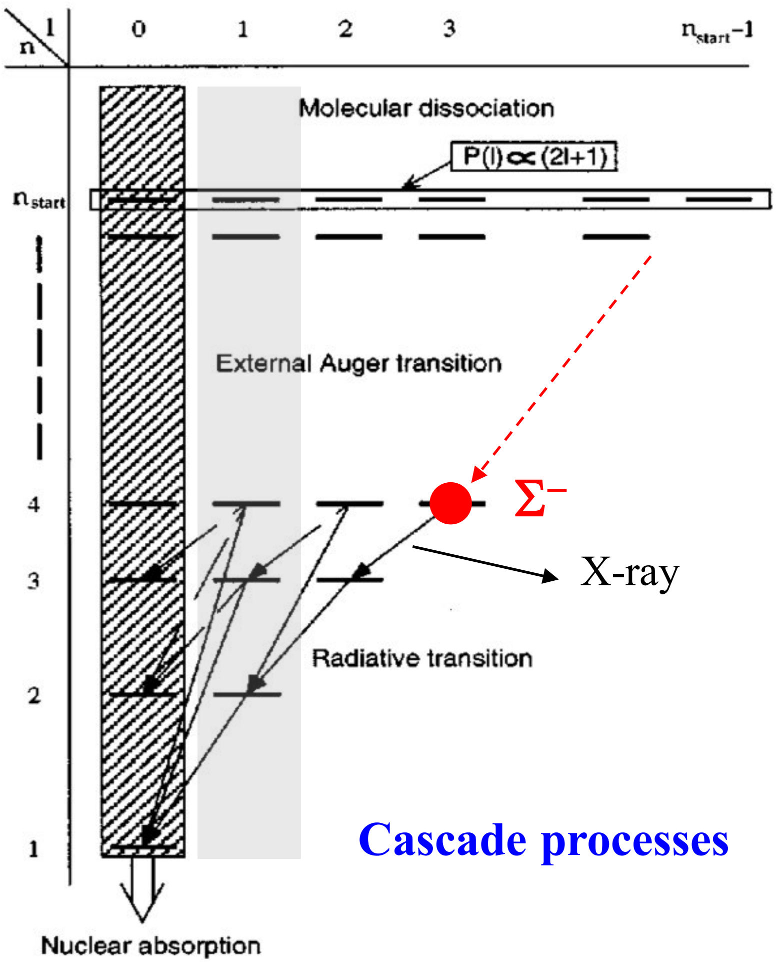
U_0=−29.39 MeV

Σ Hypernuclei

- Σ^- Atomic X-ray measurements
- Σ Hypernuclei via (π^-,K^+) reactions

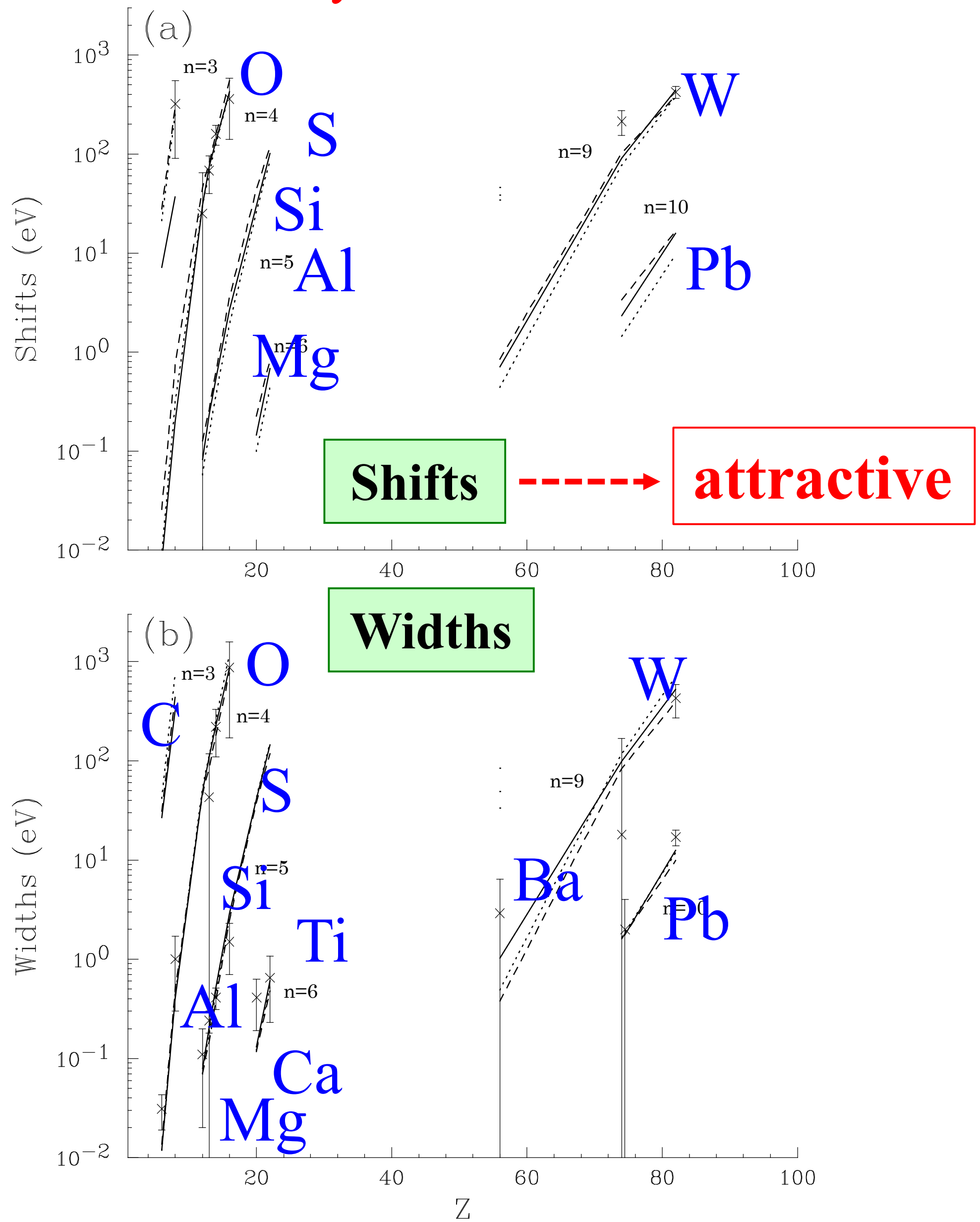
Observation of Σ^- atomic X-ray

G. Backenstoss, et al., Z. Phys. A273(1975)137
C.J. Batty, et al.,Phys.Lett.B 74 (1978) 27
R.J. Powers, et al.,PRC47(1993)1263



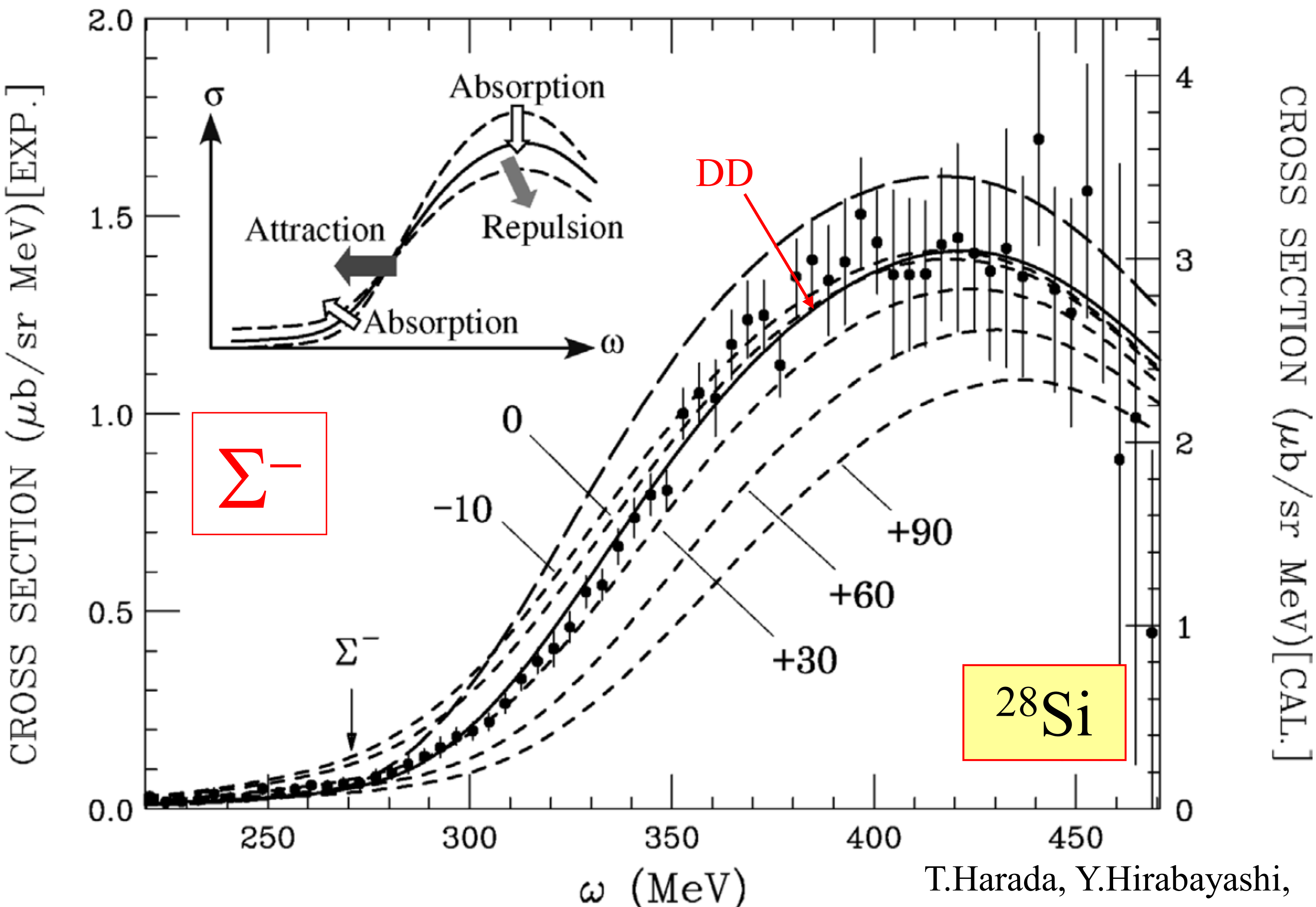
Terada, Hayano PRC55,73(1997)

Only 23 measurements !!



Inclusive spectrum in $^{28}Si(\pi^{-}, K^{+})$ reaction at 1.2GeV/c

Exp. Data from P.K.Saha, H. Noumi, et al., PRC70(2004)044613



T.Harada, Y.Hirabayashi, NPA759 (2005) 143

Σ^- nucleus optical potentials for ^{27}Al

Potential depth for WS potential (V_Σ, W_Σ)

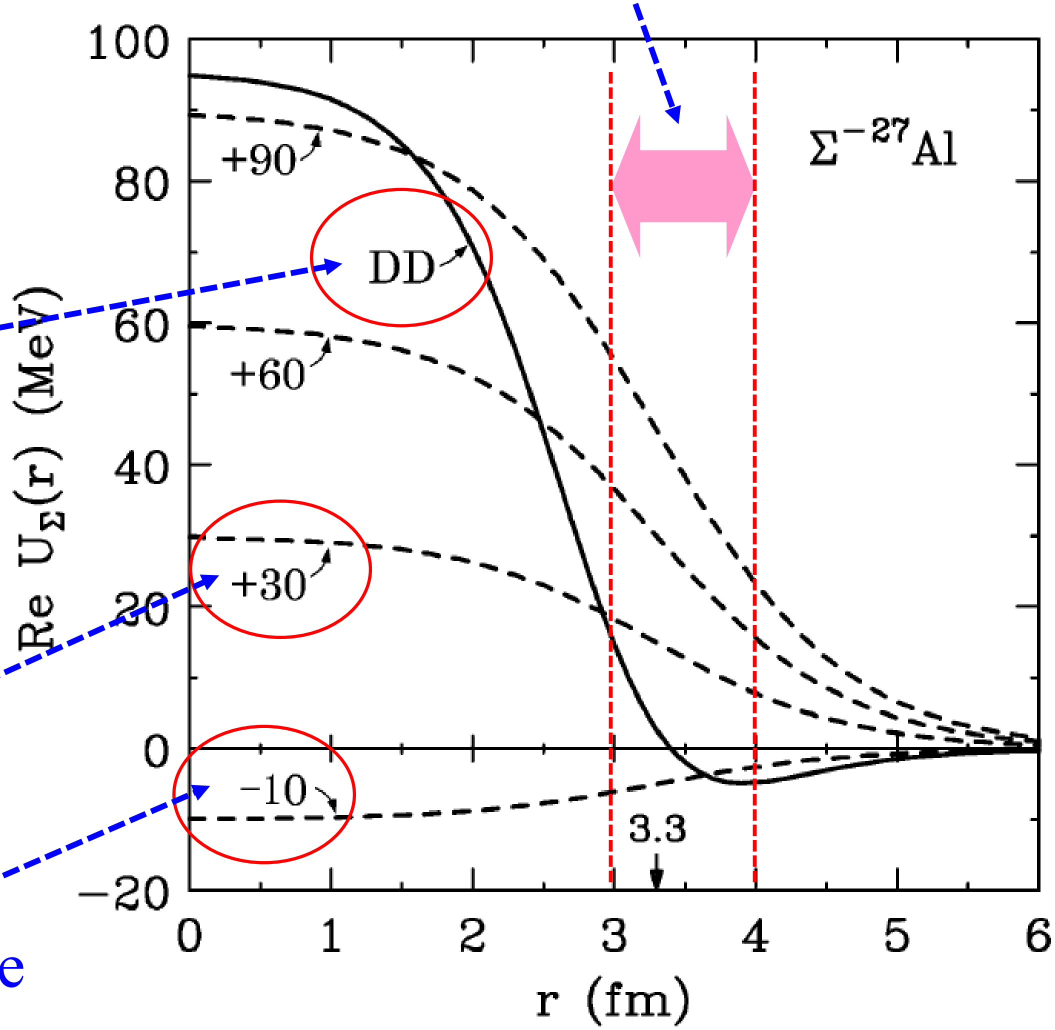
Harada, Hirabayashi,
Nncl. Phys. A767 (2006) 206.

The behavior in the surface region is very sensitive to the atomic X-ray data

DD potential for both the Σ atoms and (π–,K+) spectrum

Repulsive potential for (π–,K+) spectrum

Attractive potential for a fit to Σ-atomic state



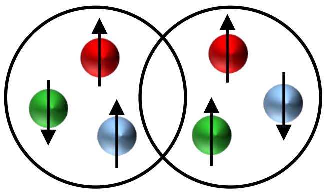
Short-range repulsive core in baryon-baryon interaction

Spin-flavor SU(6) symmetry

Quark Cluster Model

M.Oka,K.Shimizu,K.Yazaki, PLB130(1983)365; NPA464(1987)700

Quark-exchange (anti-symmetrized)



symmetric antisymmetric

$$[3]\otimes[3]=[6]\oplus[42]\oplus[51]\oplus[33]$$

orbital x flavor-spin x color singlet ↓ $L=0$

Pauli forbidden state

1S0 even	[51]	[33]	
1			ΛΛ-ΞN-ΣΣ(I=0), H-dibaryon
8_S	1		$\Sigma N(I=1/2,{}^1S_0)$ ***Pauli forbidden***
27	4/9	5/9	$NN({}^1S_0)$

3S1 even	[51]	[33]	
8_A	5/9	4/9	
10	8/9	1/9	$\Sigma N(I=3/2,{}^3S_1)$ ***almost Pauli forbidden***
10*	4/9	5/9	$NN({}^3S_1)$, ΛN-$\Sigma N(I=1/2,{}^3S_1)$

→ **Strongly spin-isospin dependence are generated by $SU_{SF}(6)$ symm.**

Σ⁻-nucleus optical potentials for ^{27}Al, ^{57}Co, ^{207}Tl

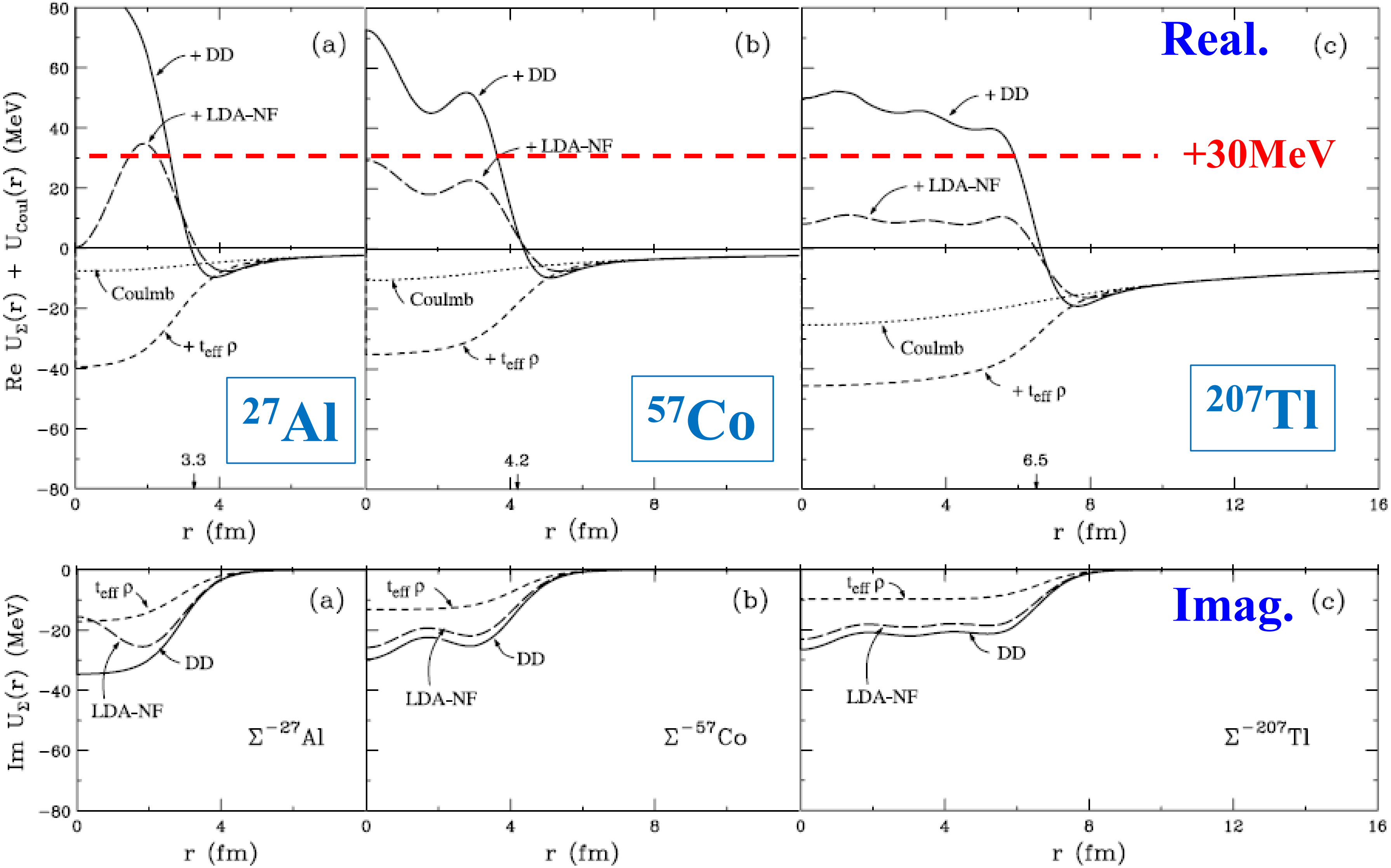


Fig. 2. (Top) Real and (bottom) imaginary parts of the Σ-nucleus potential plus the finite Coulomb potential for (a) Σ^-–^{27}Al, (b) Σ^-–^{57}Co and (c) Σ^-–^{207}Tl. The solid, long-dashed and dashed curves denote the radial distribution of the potentials for DD, LDA-NF and $t_{eff}\rho$, respectively. The strength for the real part includes the finite Coulomb potential. The dotted curves denote only the Coulomb potential for the Σ^--nucleus systems.

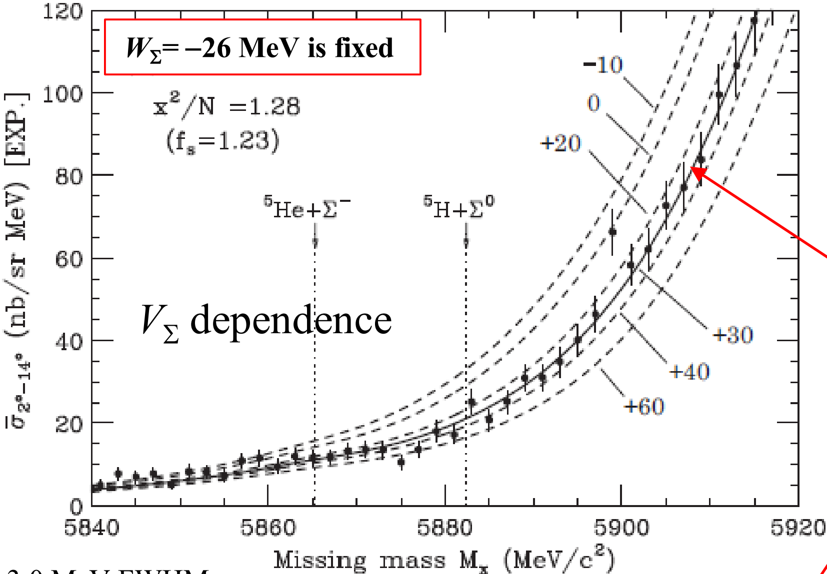
Dependence of calculated spectra for the ^{6}Li(π^-,K^+) reaction

Data: R. Honda, et al., (J-PARC E10)

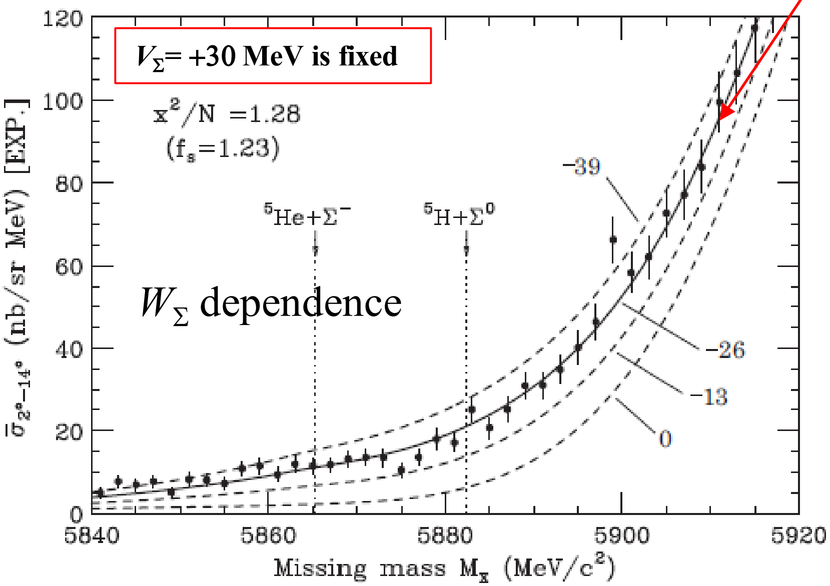
T. Harada et al., PRC97 (2018) 024601.

$p_{\pi-}$ =1.2 GeV/c

WS potential



3.0 MeV FWHM

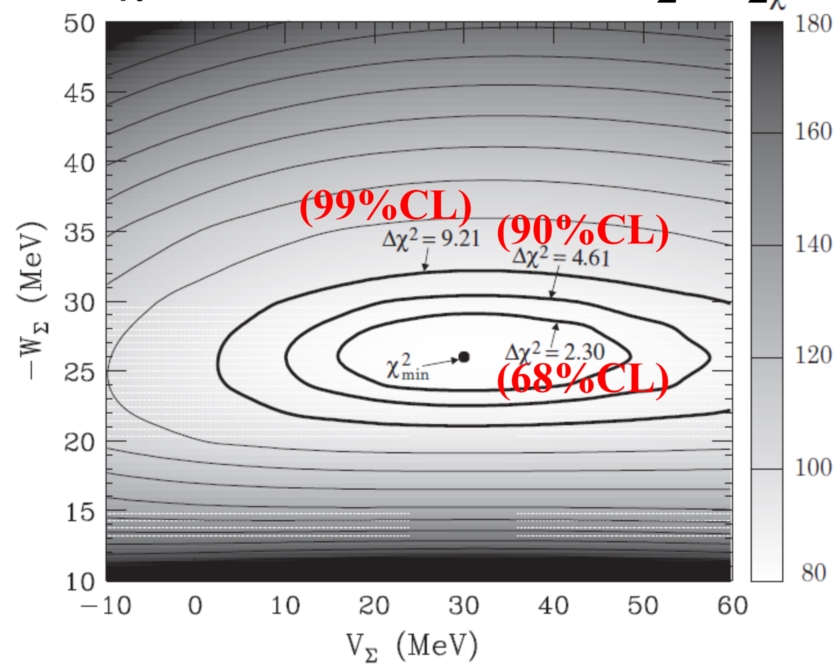


The shape and magnitude of the spectrum are sensitive to the strengths of (V_Σ, W_Σ).

(V_Σ, W_Σ) = (+30, –26) MeV

χ^2/N = 1.28 with f_s (N=66)

The χ^2-value distribution in V_Σ, W_Σ χ^2

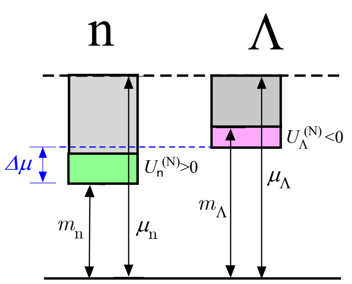


→ **We can confirm the repulsive Σ^- nucleus potential on ^{5}He.**

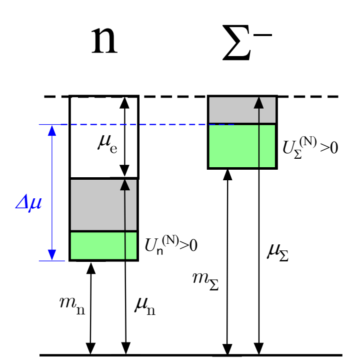
Dependence of the Σ⁻ potential on the baryon fractions in NSs

Calculations based on Balberg, et al., AJ121 (1999) 515

Chemical Equilibrium



$$\mu_n = \mu_\Lambda$$

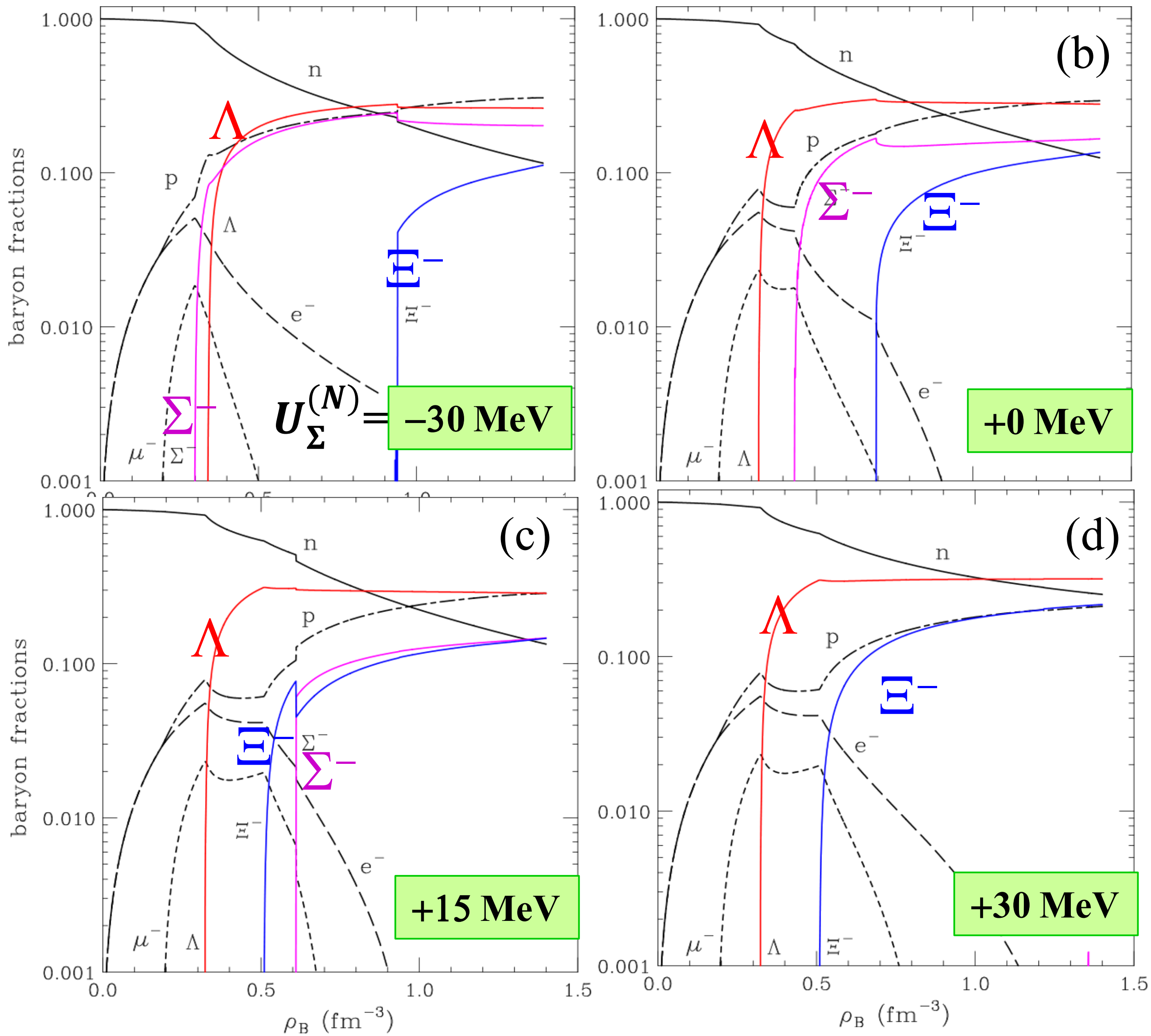


$$\mu_n + \mu_{e-} = \mu_{\Sigma-}$$

$U_\Lambda^{(N)}$= −30 MeV

$U_\Xi^{(N)}$= −14 MeV

fixed

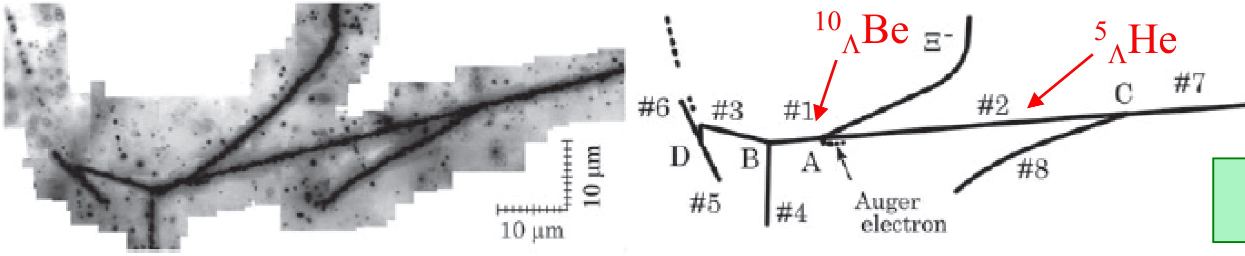


→ The baryon fraction is very sensitive to the hyperon potentials.

Ξ, $\Lambda\Lambda$ Hypernuclei

- Ξ,$\Lambda\Lambda$ Hypernuclei via Hybrid-emulsion
- Ξ^- Atomic X-ray measurements
- Ξ Hypernuclei via (K^-, K^+) reactions

The first evidence of a deeply bound state of Ξ^-–^{14}N system



Nakazawa, et al., PTEP,2015, 033D02

KISO event

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be}(\#1) + {}^{5}_{\Lambda}\mathrm{He}(\#2)$$

State	Hiyama & Yamamoto (cluster model) [28] (MeV)	Expected B_{Ξ^-} (MeV)	Millener (shell model) [29] (MeV)	Expected B_{Ξ^-} (MeV)
g.s.	0 (1^-)	4.38	0 (1^-)	4.378
	0.08 (2^-_1)	4.30	0.110 (2^-)	4.268
1st	2.36 (2^-_2)	2.02	2.482 (2^-)	1.896
	2.41 (3^-)	1.97	2.585 (3^-)	1.793
2nd	3.07 (0^+)	1.31	3.202 (0^-)	1.176
	3.27 (1^+)	1.11	3.228 (1^-)	1.150
3rd	–	–	6.433 (3^-)	Ξ^- unbound
			6.509 (4^-)	

g.s.

Ξ^- 2p absorption Scenario OK ?

$$B_{\Xi^-} = M[(\Xi^- + {}^{14}\mathrm{N})_{\mathrm{atom}}] - M({}^{10}_{\Lambda}\mathrm{Be}) - M({}^{5}_{\Lambda}\mathrm{He})$$

$$M({}^{10}_{\Lambda}\mathrm{Be}) = M({}^{9}\mathrm{Be}) + m_{\Lambda} - B_{\Lambda}({}^{10}_{\Lambda}\mathrm{Be}) \qquad M({}^{5}_{\Lambda}\mathrm{He}) = M({}^{4}\mathrm{He}) + m_{\Lambda} - B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He})$$

$$\mathbf{(1.1 \pm 0.25)MeV} < \boldsymbol{B_{\Xi^-}} < \mathbf{(4.38 \pm 0.25)\ MeV}$$

→ **It suggests that $V_{\Lambda\Lambda}$ is weak attractive in nuclear medium.**

Binding energies and widths on Ξ^- states

$\Xi^{-14}N$

26 Nov. 2017

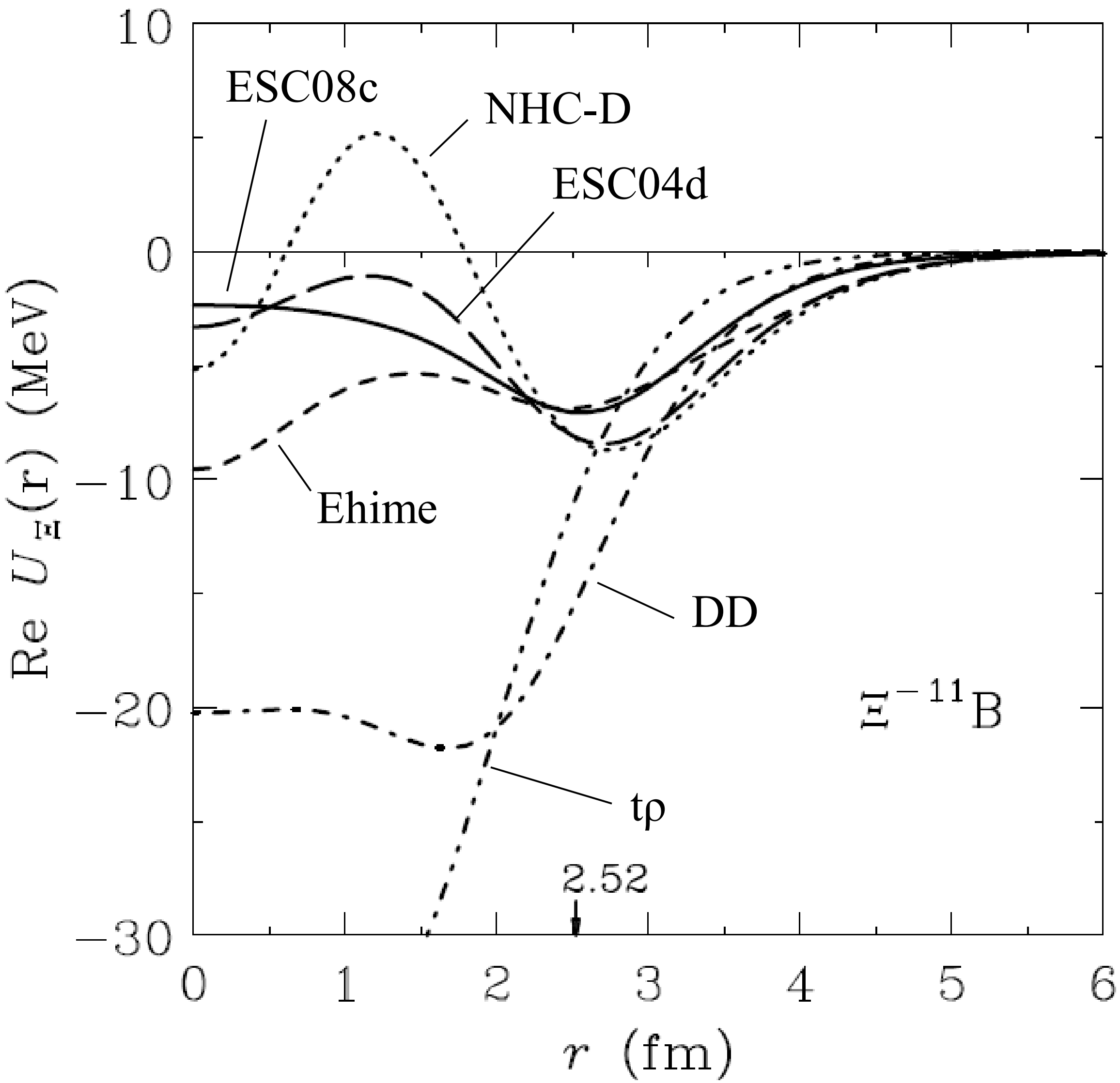
Folding-Model potentials calc.

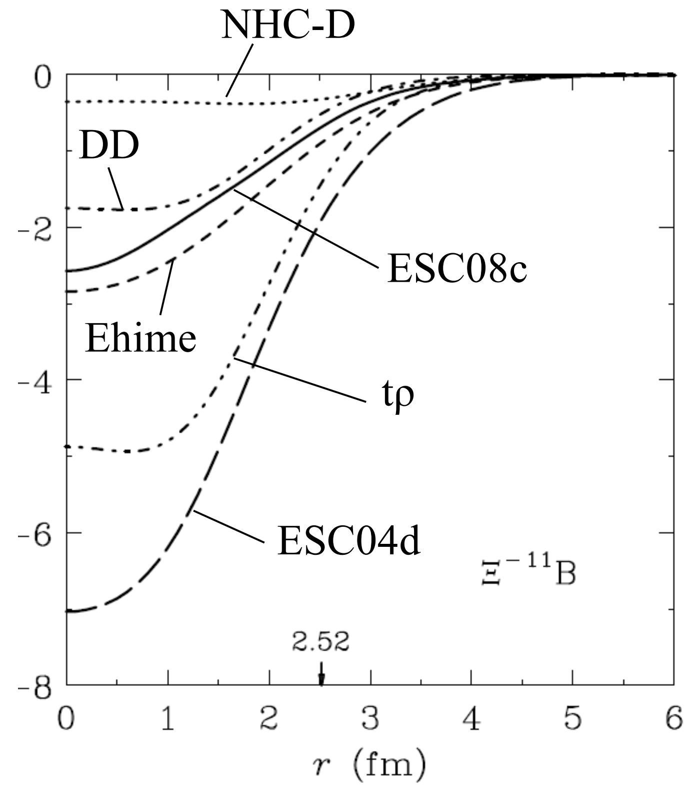
		1s	2p	3d	4f
DD	E	-9.960	-3.056	-0.174	-0.098
	Width	1.719	0.888	0.000	0.000
tρ	E	-20.504	-6.591	-0.174	-0.098
	Width	7.076	4.844	0.000	0.000
NHCD	E	-4.825	-1.355	-0.175	-0.098
	Width	0.459	0.221	0.000	0.000
ESC04d	E	-5.100	-1.298	-0.175	-0.098
	Width	4.151	1.575	0.000	0.000
ESC08c	E	-3.933	-0.639	-0.174	-0.098
	Width	1.414	0.220	0.000	0.000
ESC2017	E	-5.642	-1.022	-0.174	-0.098
	Width	2.717	0.914	0.000	0.000
Ehime	E	-5.533	-1.047	-0.175	-0.098
	Width	2.142	0.544	0.000	0.000

(MeV)

$-U_\Xi > 14$ **MeV in WS pot. (weak attractive)**

Ξ⁻-nucleus optical potentials in $^{11}B+\Xi^-$





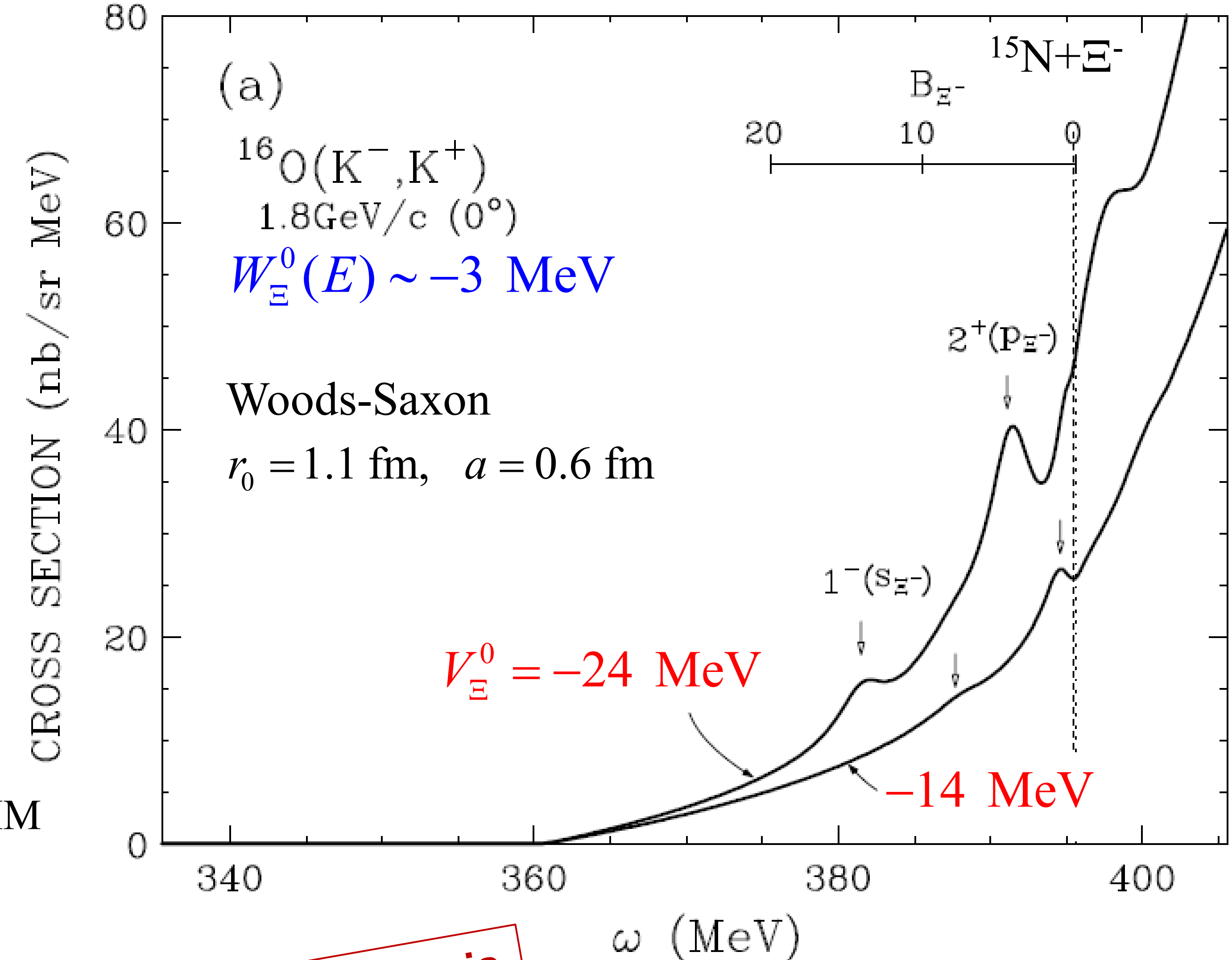
J-PARC E05:
$^{12}C(K^-,K^+)X$ reaction

→ **We need experimental data to determine the most suitable model.**

Ξ^- spectrum in DCX (K$^-$,K$^+$) reactions at 1.8GeV/c

^{16}O

T. Harada, Y. Hirabayashi, A. Umeya, PLB690(2010)363.



1.5MeV FWHM

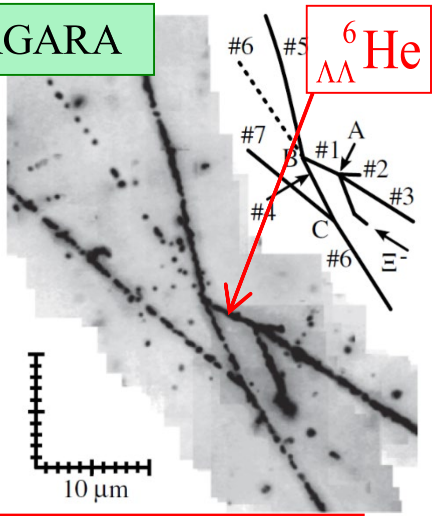
E05@J-PARC

Under analysis

Spectroscopic study of Ξ-hypernucleus, $^{12}_{\Lambda}$Be via the ^{12}C(K-,K+) reaction

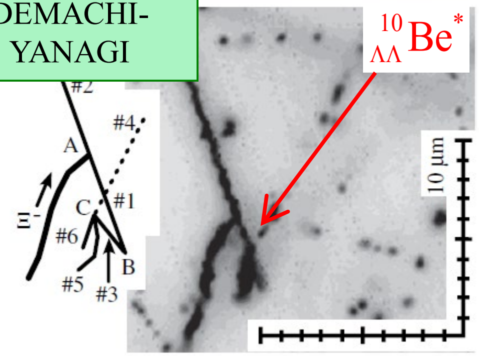
Observation of ΛΛ Hypernuclei in E176/E373 Hybrid Emulsion

NAGARA



$$^{12}C + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$$
$$\hookrightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

DEMACHI-YANAGI

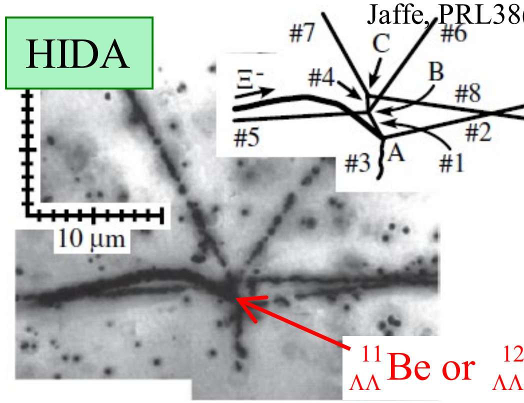


$$2M_\Lambda - B_{\Lambda\Lambda} < M_H$$

H-dibaryon

Jaffe, PRL38(1977)195

HIDA



ΛΛ bound energy

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

event	$^{A}_{\Lambda\Lambda}Z$	Target	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]	Hiyama et al. PRL104(2010)212502 $B^{CM}_{\Lambda\Lambda}$[MeV]	Gal-Millener, PLB701(2011)342 $B^{SM}_{\Lambda\Lambda}$[MeV]
NAGARA	$^{6}_{\Lambda\Lambda}$He	^{12}C	6.91 ± 0.16	0.67 ± 0.17	(6.91)	(6.91)
MIKAGE	$^{6}_{\Lambda\Lambda}$He	^{12}C	10.06 ± 1.72	3.82 ± 1.72		
DEMACHIYANAGI	$^{10}_{\Lambda\Lambda}$Be	^{12}C	11.90 ± 0.13	−1.52 ± 0.15	11.88	
HIDA	$^{11}_{\Lambda\Lambda}$Be	^{16}O	20.49 ± 1.15	2.27 ± 1.23	18.23	18.40
	$^{12}_{\Lambda\Lambda}$Be	^{14}N	22.23 ± 1.15	–		20.27
E176	$^{13}_{\Lambda\Lambda}$B	^{14}N	23.3 ± 0.7	0.6 ± 0.8		23.21
Danysz *et al*[17]	$^{10}_{\Lambda\Lambda}$Be($^{9}_{\Lambda}$Be*)	^{14}N	14.7 ± 0.4	1.3 ± 0.4	14.74 (g.s.)	14.97 (g.s.)

H.Takahashi et al.,PRL87(2001)212502
K.Nakazawa , NPA 835 (2010)207
K.Nakazawa , H.Takahashi,NPA 835 (2010)207

$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) \simeq 4.7 \longrightarrow 1.01 \longrightarrow 0.67\text{MeV}$$

Prowse, 1966 — Nagara,2001 — Ξ mass update

→ $V_{\Lambda\Lambda}$ seems to be weak attractive in nuclear medium.

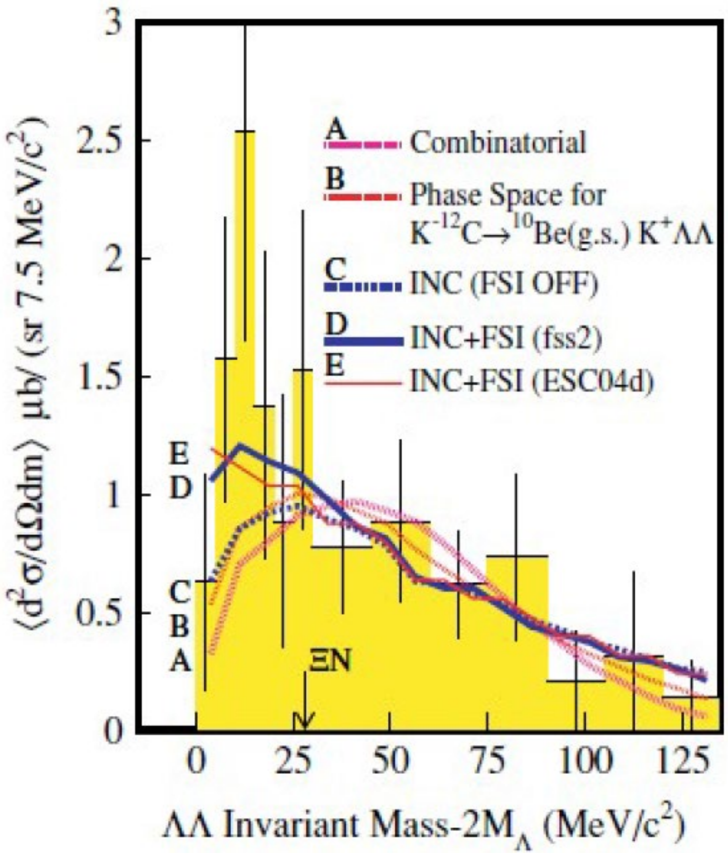
ΛΛ correlation from production nuclei

- **From (K-,K+ΛΛ) reaction**

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

S=-2 dibaryon (uuddss) "H"

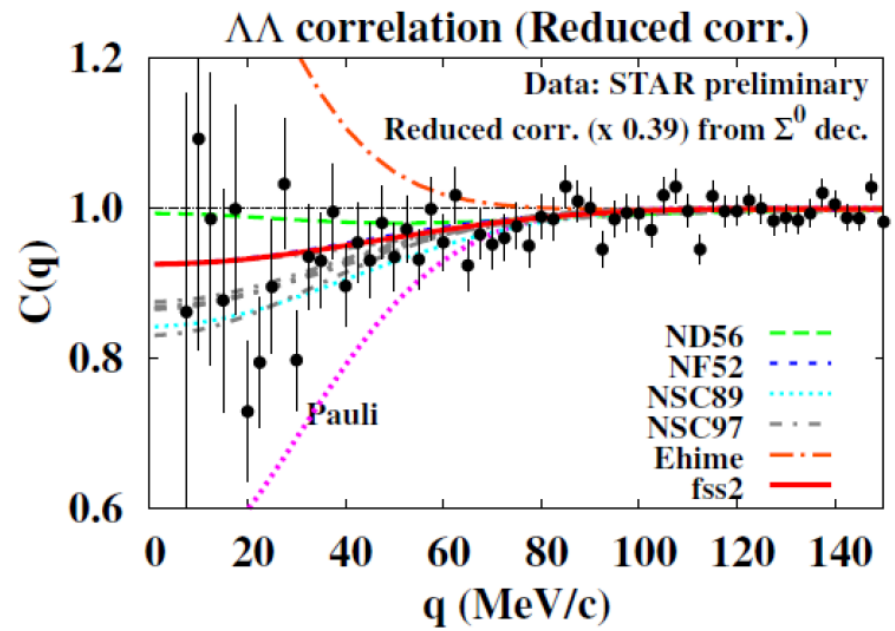
2 σ bump at $E_{\Lambda\Lambda}$ ~ 15 MeV



- **From Heavy-ion Collisions**

A. Ohnishi, T. Furumoto, K. Morita (2012)

Data: N.Shah, et al. (STAR Collab.)



- STAR data clearly show enhanced ΛΛ correlation
- Preferred ΛΛ interactions $1/a_0 < -0.8$ fm-1, $r_{eff} > 3$ fm.

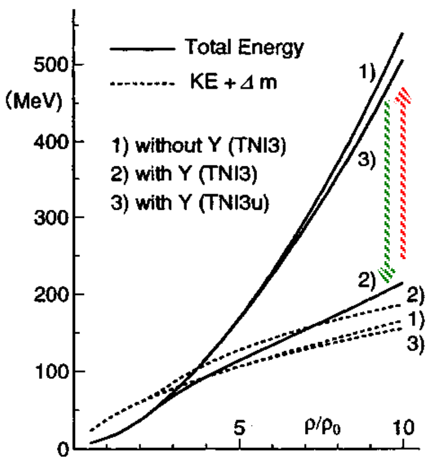
→ **A weak attractive $V_{\Lambda\Lambda}$ is consistent with the ΛΛ correlation data.**

“Hyperon Puzzle” in NSs

Can we solve "Hyperon puzzle" ?

- **YN,YY: extra repulsion TNIu**

  S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP105(2001)607; NPA691(2001)432



Universal repulsive 3BF?

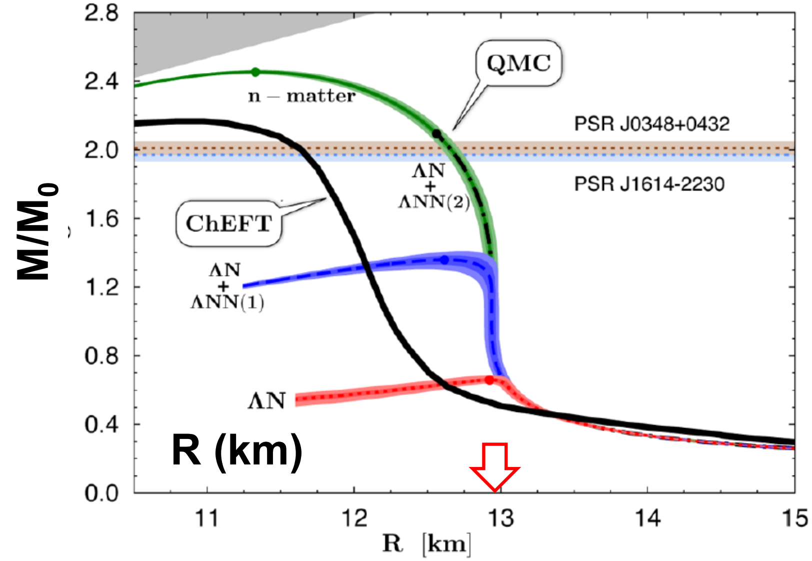
$\rho_C(Y) \approx (4-5)\rho_0$

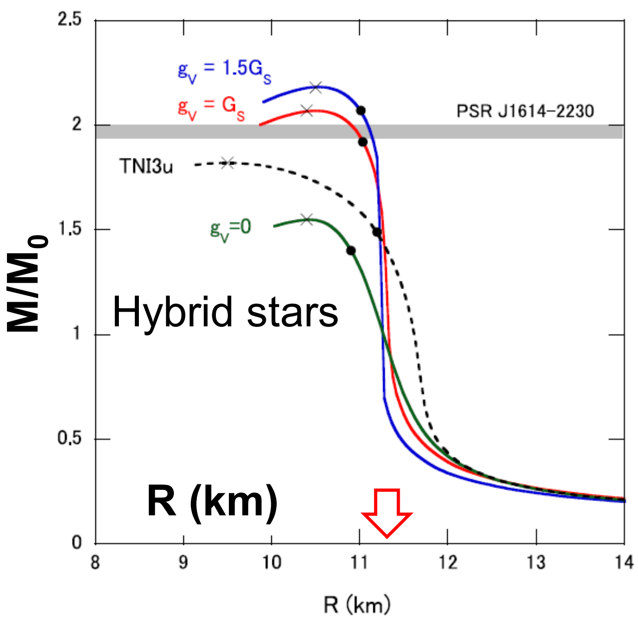
with Y

$\rho_C(Y) \approx (2-3)\rho_0$

- **QMC with ΛN+repulsive ΛNN ρ-dep.**

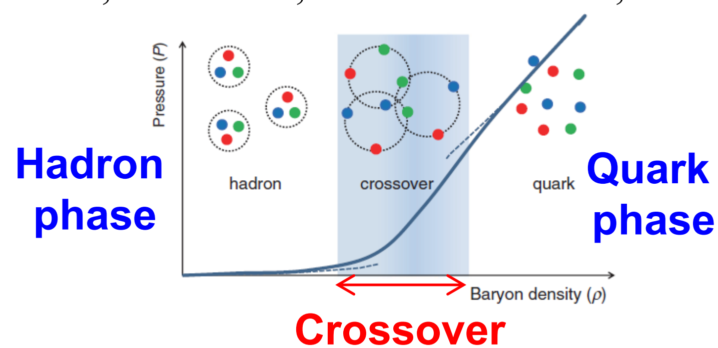
  D. Lonardoni, et al., PRL114(2015),092301.





- **Hadron-Quark crossover in Hybrid Stars**

  K. Masuda, T.Hatsuda, T.Takatsuka et al., AJ764 (2013) 12.



→ **Extra repulsion TNIu?, ΛN+repulsive ΛNN ρ-dep?, H-Q crossover?, …..**

Thermal evolution of neutron stars

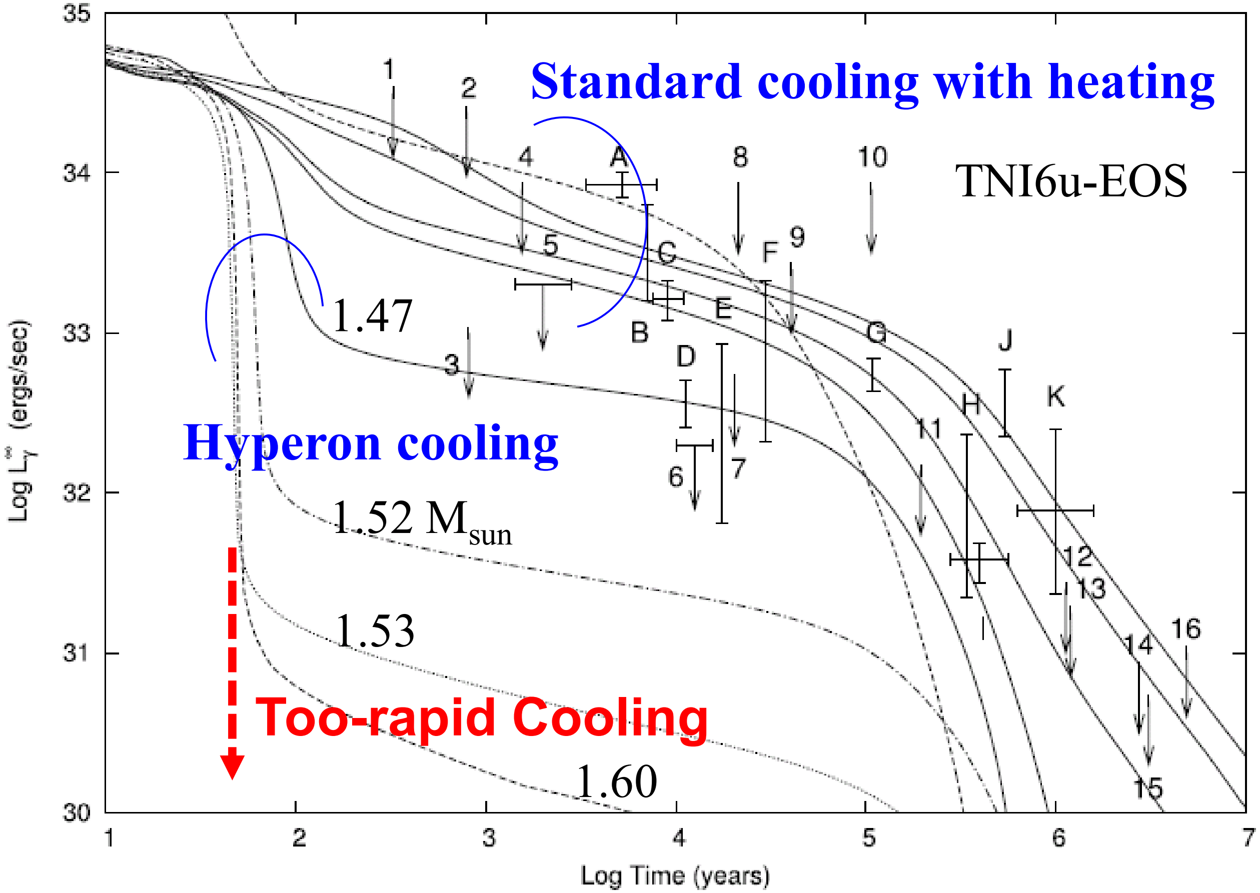
S. Tsuruta et al., AJ 691(2009)621

Rapid neutrino emission via weak processes (Direct/Modified Urca)

$$\Lambda \rightarrow p + e^- + \bar{\nu}_e$$

$$\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e$$

Too-rapid Cooling problem



- Cooper pair
  - $^1S_0$ [inner crust]
  - $^3P_2$-$^3F_2$(n),$^1S_0$(p) [core]
  - → **Standard cooling**
- YY pairing
  - → **Hyperon cooling**
  - Cooling relaxation?

- Hyperon superfluidity v.s.YY intarctions
  - Nagara event $\Delta B_{\Lambda\Lambda}$~0.67 MeV
  - → **no ΛΛ superfluidity ?**

→ The cooling scenario is very sensitive to properties of YN, YY int.

ΛΛ superfluidity vs. less attractive ΛΛ potential

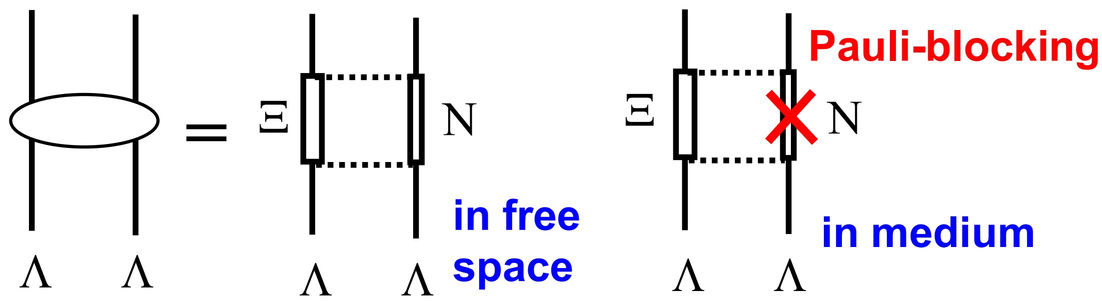
$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) \simeq$ 4.7 ⟶ 1.01 ⟶ 0.67MeV

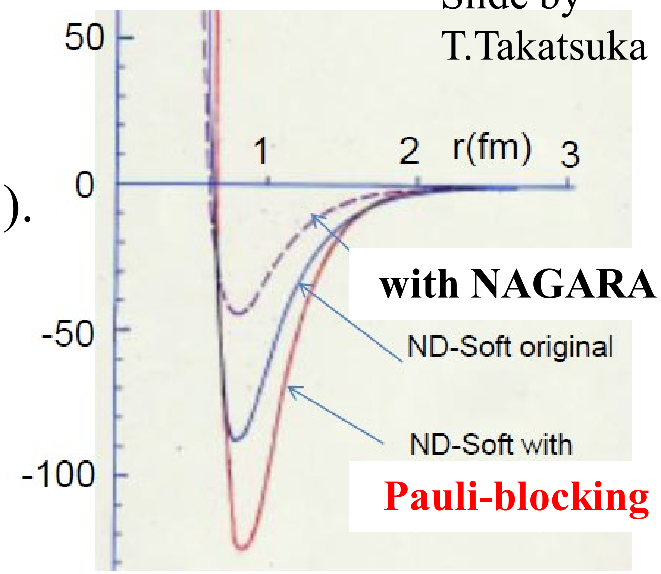
Prowse, 1966 — Nagara,2001 — Ξ mass update

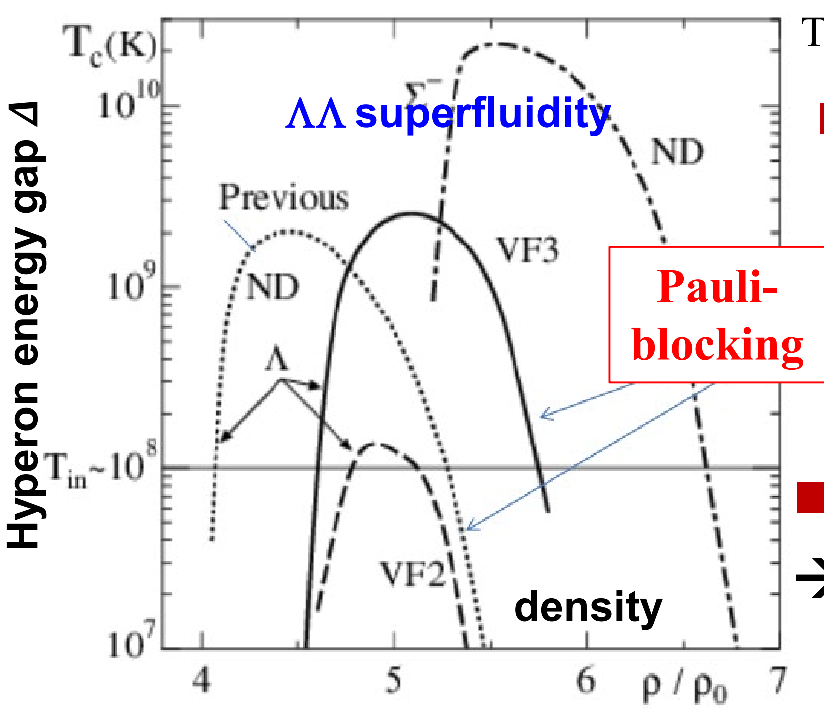
Slide by T.Takatsuka

■ **ΛΛ-ΞN coupling effects in NM**

→$V_{\Lambda\Lambda}$(free) should be more attractive than $V_{\Lambda\Lambda}$(med).



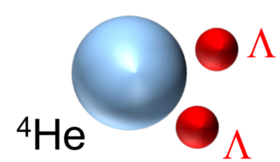




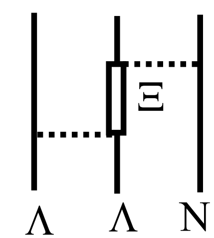
T.Takatsuka, Akaishi et al.

■ **Rearrangement effects on the nucleus**

→ $V_{\Lambda\Lambda}$ should be more attractive in ${}^{6}_{\Lambda\Lambda}$He.



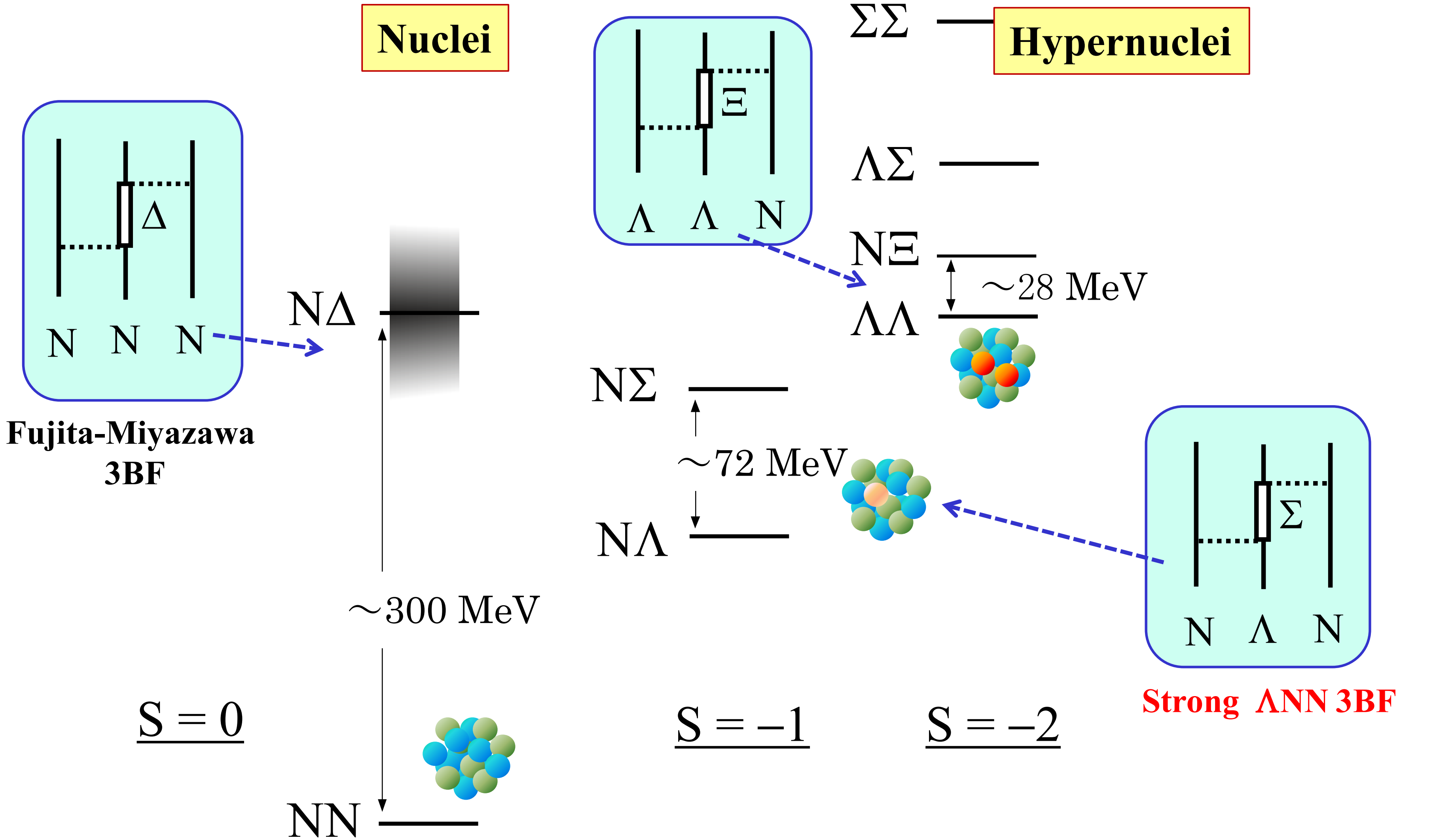
M.Kohno, et al., PRC68(2003)034302



■ **Λ-superfluidity may appear in NSs.**

→This leads to a cooling scenario of NSs consistent with observations.

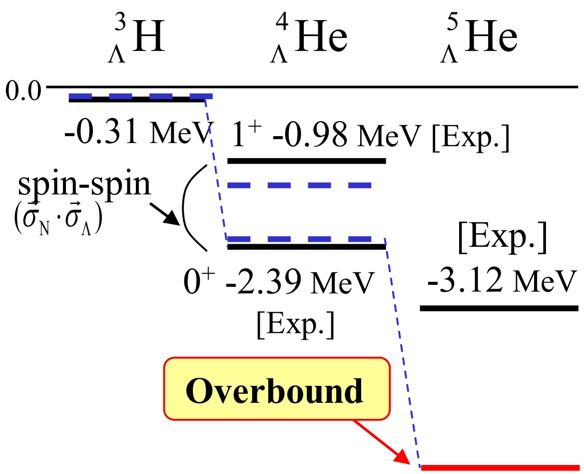
Dynamics in Strangeness Nuclear Systems



- The ΛN-ΣN, ΞN-ΛΛ couplings play important roles in hypernuclei.
  → hyperon mixing probability, production via hyperon doorways
- The coupling effects may be enhanced in asym. NM.

Overbinding Problem on s-Shell Hypernuclei

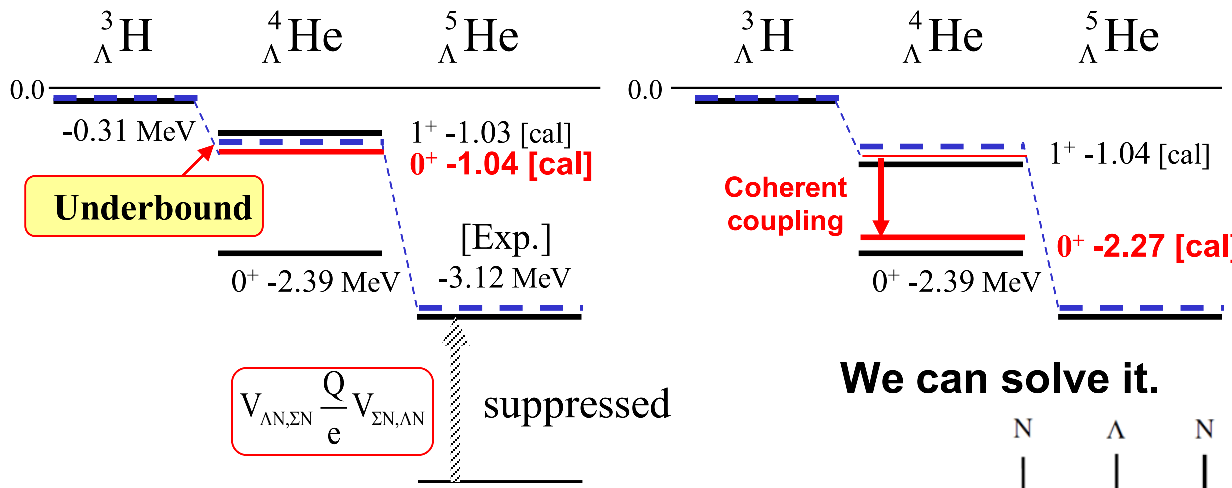
■ Overbinding Problem



ΛN single-channel calc.

Dalitz et al., NP**B47** (1972) 109.

■ Underbinding Problem

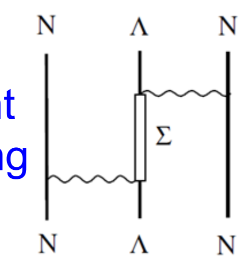


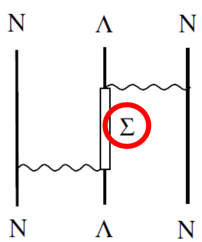
g-matrix calc. with ΛN-ΣN(D2)

Akaishi, Harada et al., PRL **84** (2000) 3539.

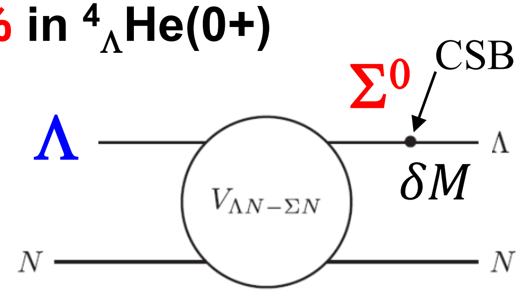
We can solve it.

+ Coherent ΛΣ coupling





- ■ **ΛNN force generated from ΛN-ΣN coupling**
  - **→ Spin-isospin dependence (Λnn≠Λpn) exists**
  - **→ The Σ-mixing probability amounts to 1-2% in $^{4}_{\Lambda}$He(0+)**



- ■ **Charge Symmetry Breaking (CSB) in $^{4}_{\Lambda}$He(0+)-$^{4}_{\Lambda}$H(0+)**
  - **→ The CSB effect is sensitive to the ΛN-ΣN coupling**

A. Gal, PLB744(2015)352: D. Gazda, A. Gal, PRL116 (2016)122501

Summary

- We have presented the recent status of studies of Λ, Σ, Ξ, and ΛΛ hypernuclei of which the experimental data have been observed at J-PARC.
  - Role of hyperon (strangeness) as a probe, impurity, ...
  - ΛN-ΣN, ΞN-ΛΛ couplings are important

- We have discussed properties of Λ, Σ^-, Ξ^-, potentials in nuclei, which are strongly related to the behavior of hyperons in neutron stars and the maximum mass of neutron stars.
  - Attractive: $U_\Lambda = -30\mathrm{MeV}$
  - Repulsive: $U_\Sigma \approx +30\mathrm{MeV}$
  - Weak attractive: $U_\Xi \approx -14\mathrm{MeV}$
  - Repulsive 3BF, H-Q crossover

Keywords

Potential,
Hyperon mixing,
Channel coupling

Thank you very much for your attention.