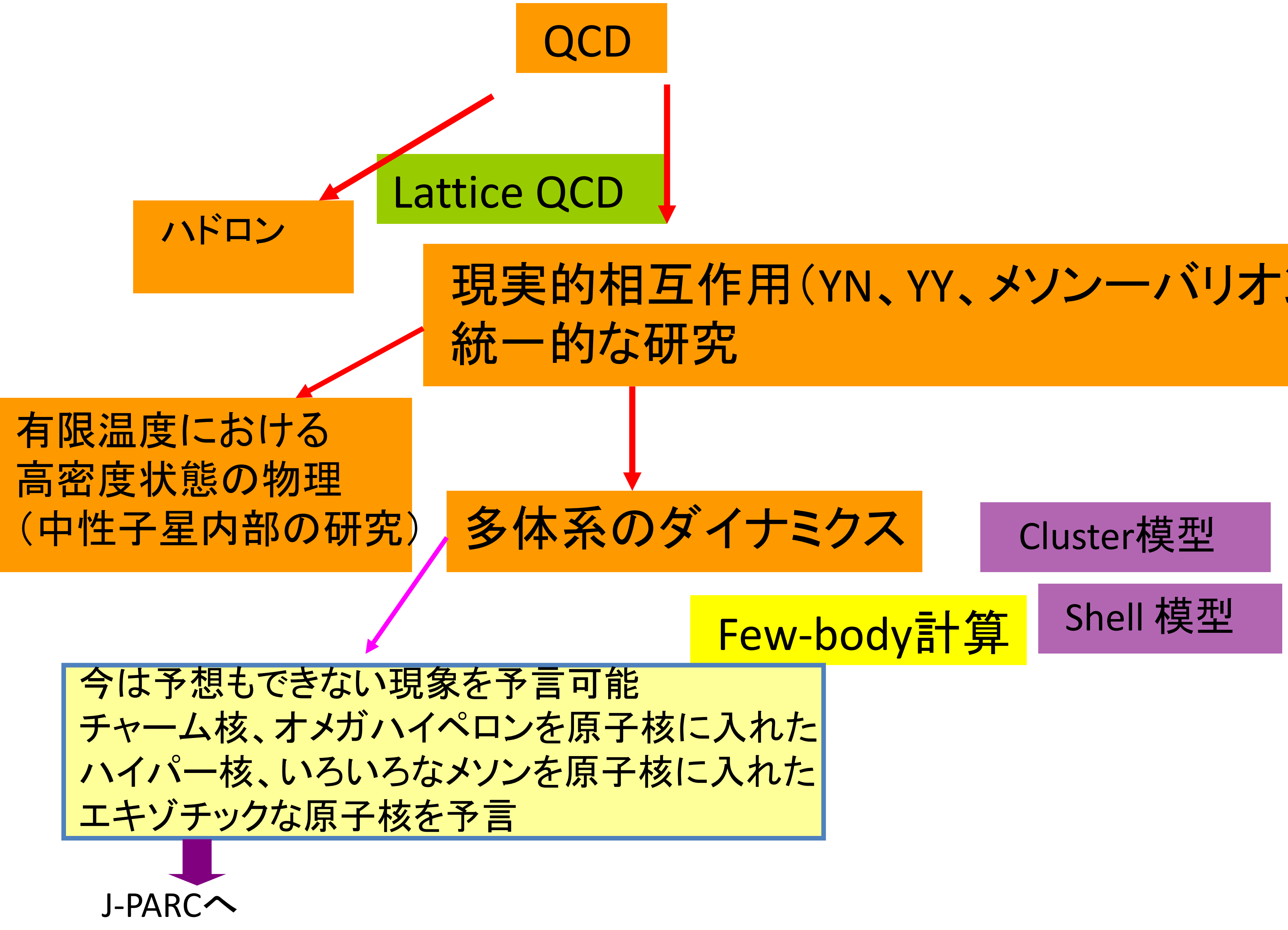
ハイパー核の構造と相互作用

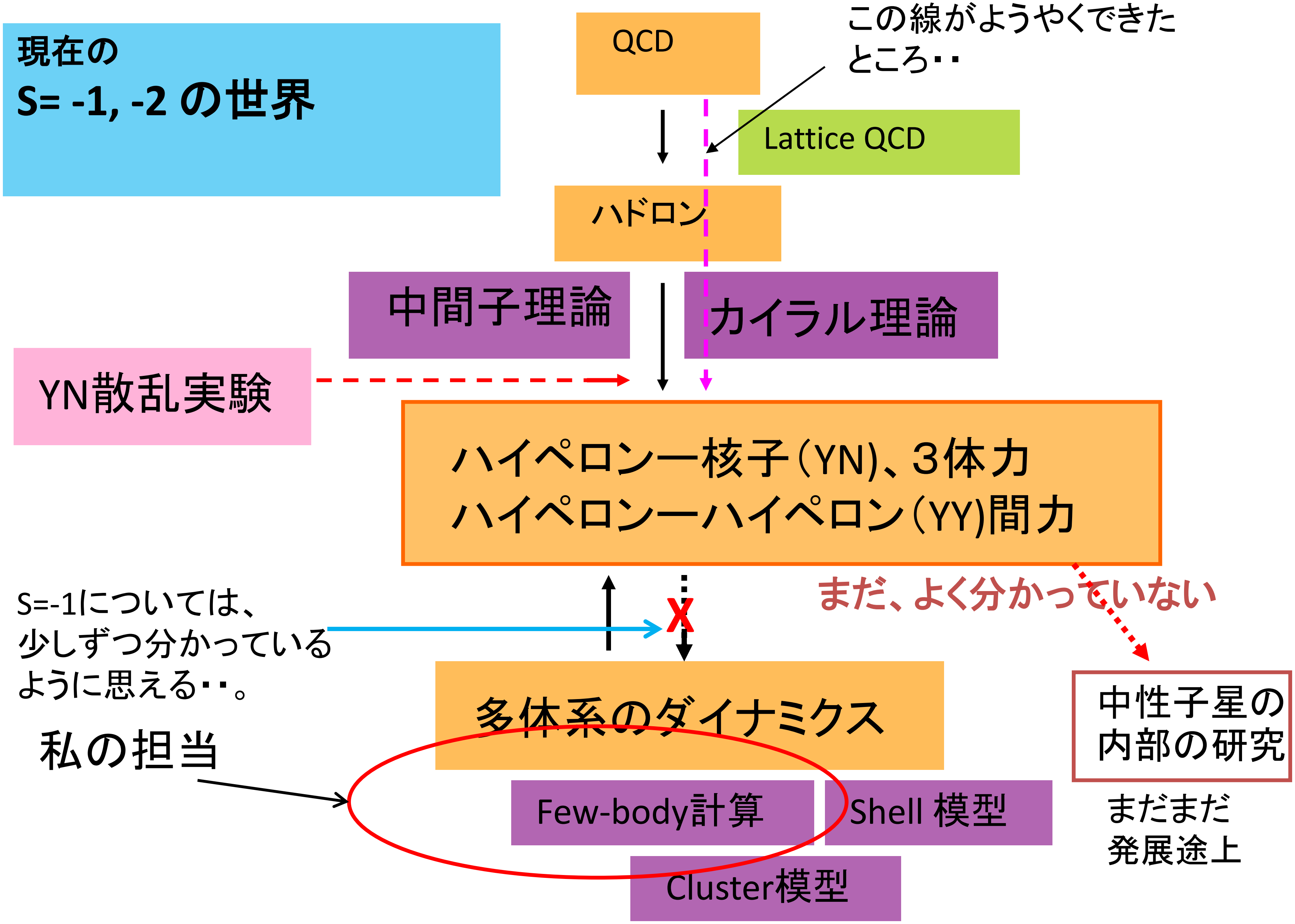
肥山詠美子（東北大/理研）

原子核物理学分野で目指す物理



現在の

S= -1, -2 の世界



構造の研究から、相互作用を決めることがまだ重要であるのが、現状

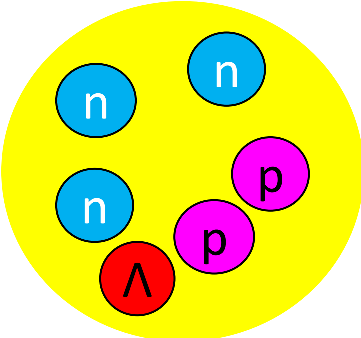
Outline of my talk

- present status in S=-1 hypernuclei and YN interaction

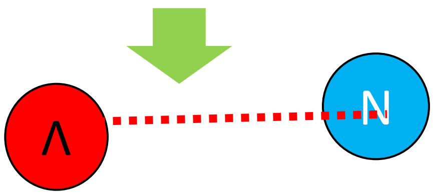
- present status in S=-2 hypernuclei and YY interaction

Hypernuclear γ-ray data (2019)

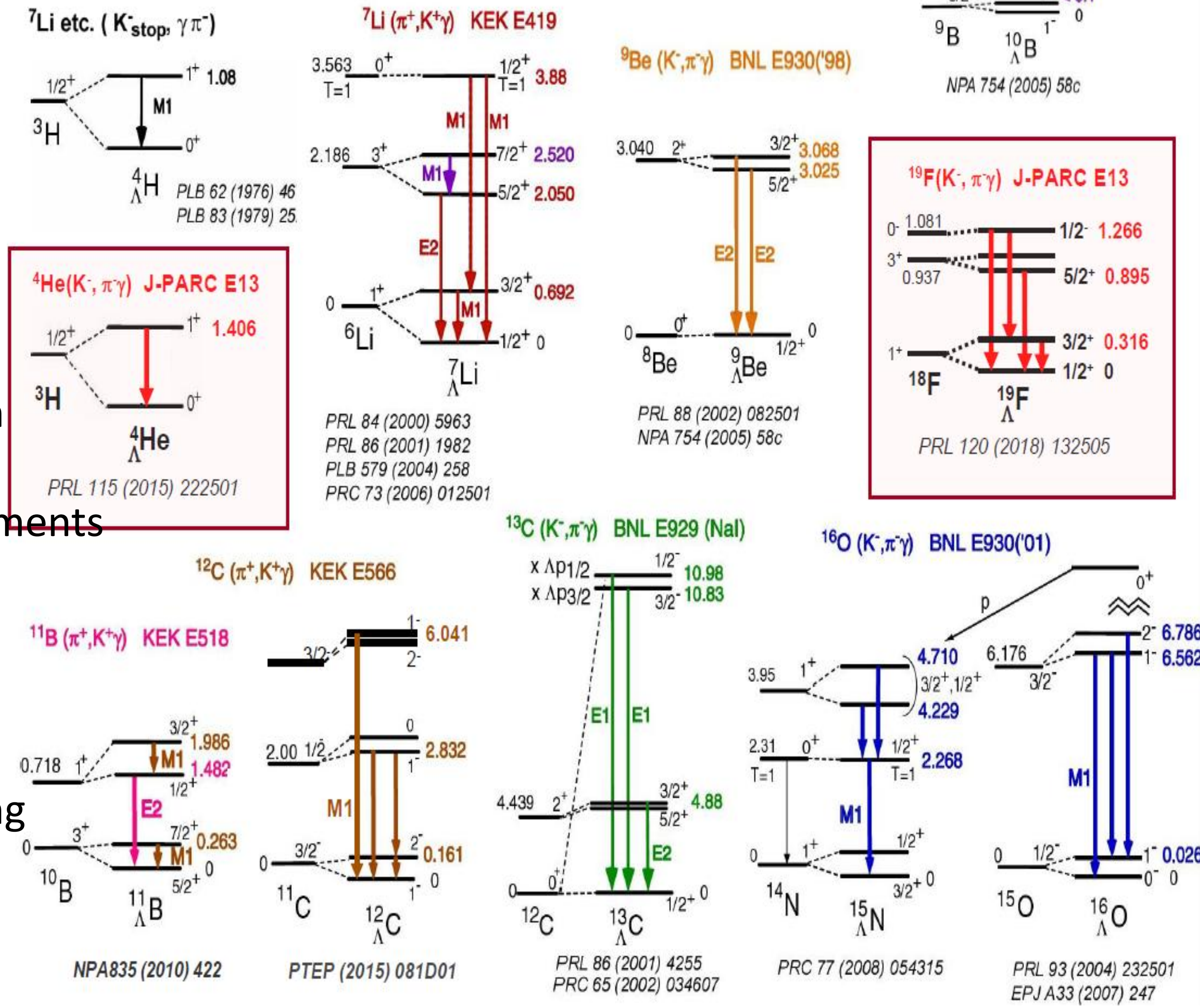
Since 1998



Few-body calculation
Shell model calculation
+
High-resolution experiments



We have been obtaining information on ΛN two-body interaction.

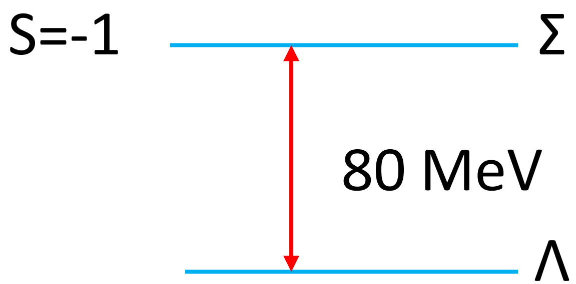


$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N \, V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathbf{s}_\Lambda + \mathbf{s}_N)\, V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathbf{s}_\Lambda - \mathbf{s}_N)\, V_{\mathrm{ALS}} + S_{12}\, V_{\mathrm{tensor}} + \cdots$$

YN相互作用が比較的わかってきたように思えるが、
大きな解くべき問題が生じている。

・ΛNーΣN coupling

$$V_{YN\text{-}YN}=V_{\Lambda N\text{-}\Lambda N}+V_{\Lambda N\text{-}\Sigma N}+V_{\Sigma N\text{-}\Sigma N}$$



Mass is smaller.
It is expected that
Λ-Σ conversion
might affect
in structure of
Λ hypernuclei.

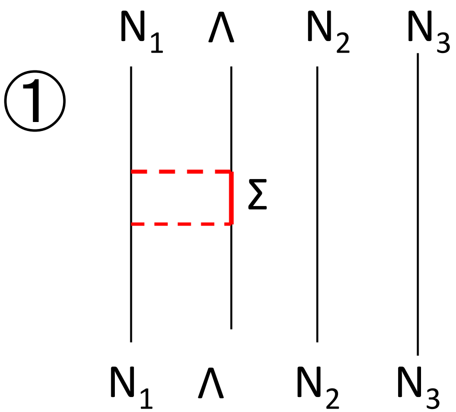
ΛN-ΣN coupling is key issue to construct
YN two-body interaction completely.

Probability of Δ in nuclei is
not large.

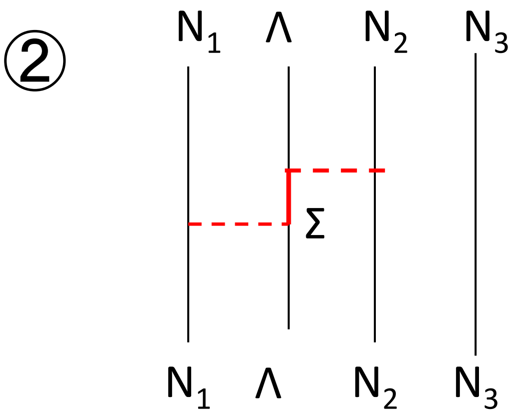
Role of the ΛN-ΣN interaction

- Three-body effect

Question : How large is the Σ-excitation as effective three-body ΛNN force?



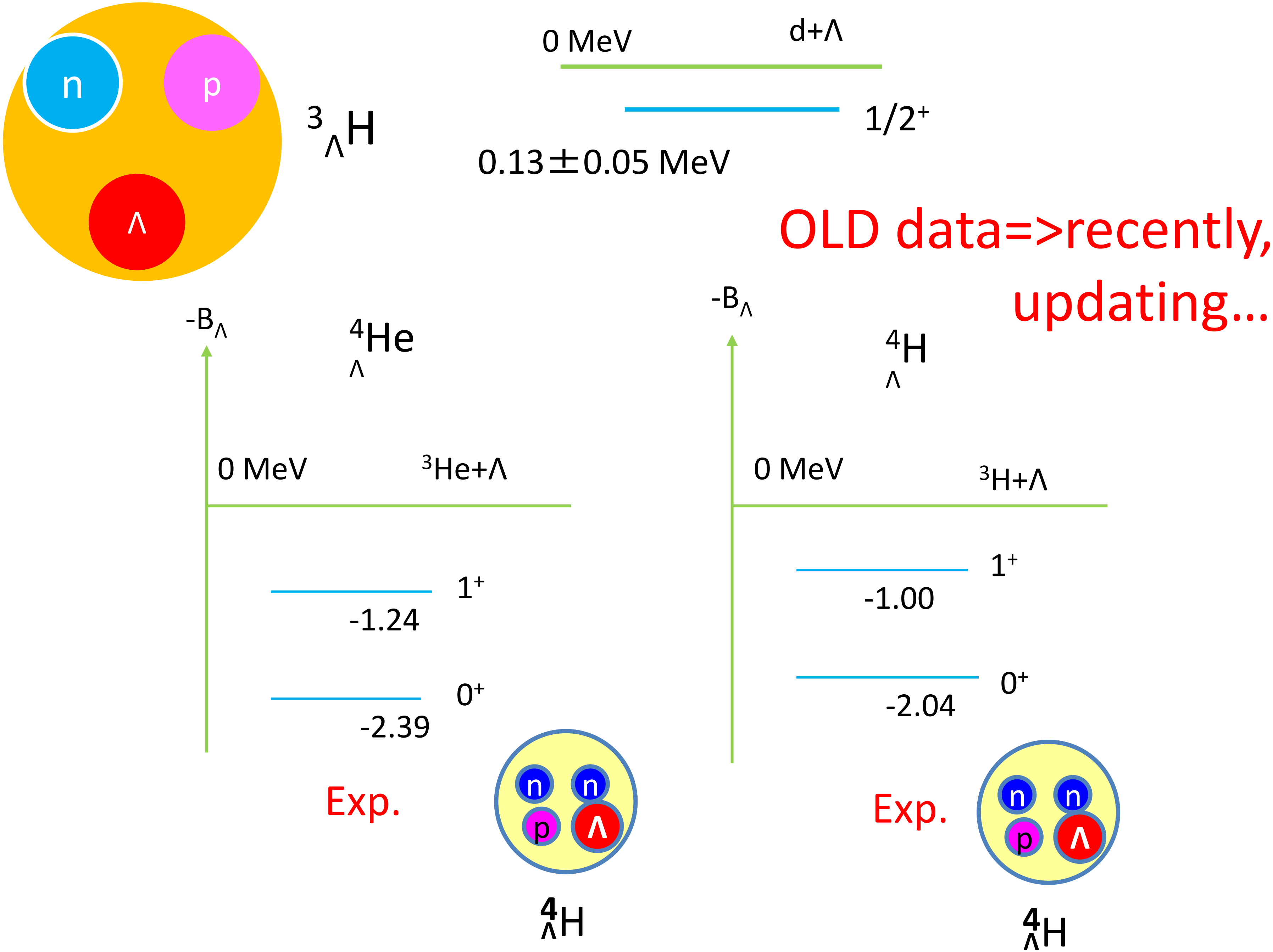
Effective two-body force

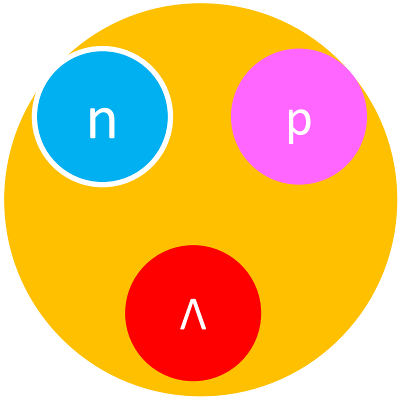


Three-body force

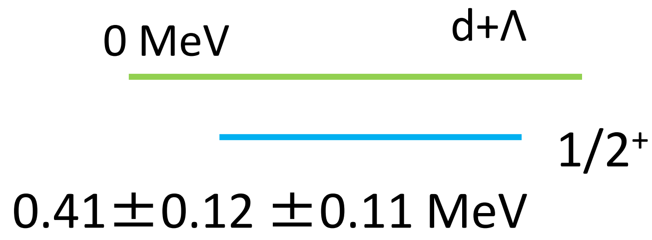
In the neutron matter or neutron star, three-body force might play important role.
This means that the three-body force is a key to solve ‘hyperon puzzle’.

How do we obtain information on ΛN-ΣN coupling ?

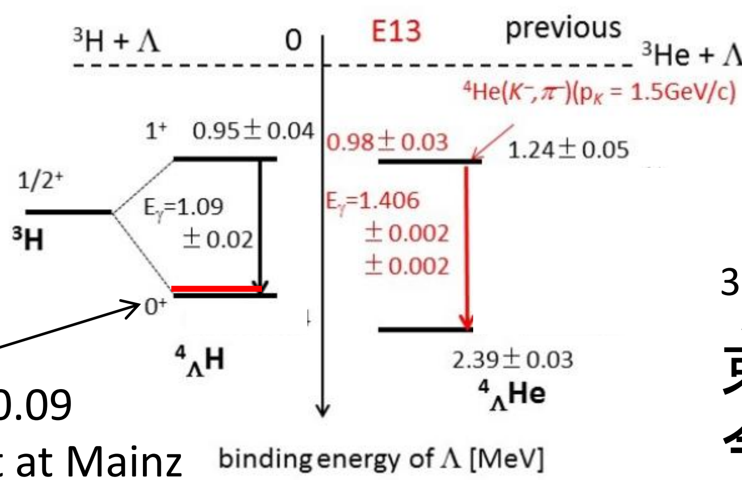

n
p
Λ
$^{3}_{\Lambda}H$
0 MeV
d+Λ
1/2+
0.13±0.05 MeV
OLD data=>recently, updating....
-BΛ
$^{4}_{\Lambda}He$
0 MeV
$^{3}He+\Lambda$
1+
-1.24
0+
-2.39
Exp.
n
n
p
Λ
$^{4}_{\Lambda}H$
-BΛ
$^{4}_{\Lambda}H$
0 MeV
$^{3}H+\Lambda$
1+
-1.00
0+
-2.04
Exp.
n
n
p
Λ
$^{4}_{\Lambda}H$



$^{3}_{\Lambda}H$

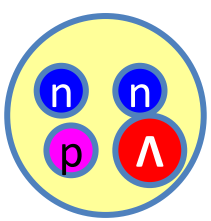


STAR collaboration : Nature Physics 16, 409(2020)

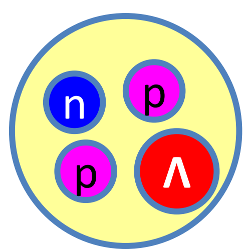


2.12±0.01±0.09
By experiment at Mainz

$^{3}_{\Lambda}H$,A=4Λハイパー核の
束縛エネルギーは
今後変わるかも‥。
今後の実験で確定することを
期待。



$^{4}_{\Lambda}H$

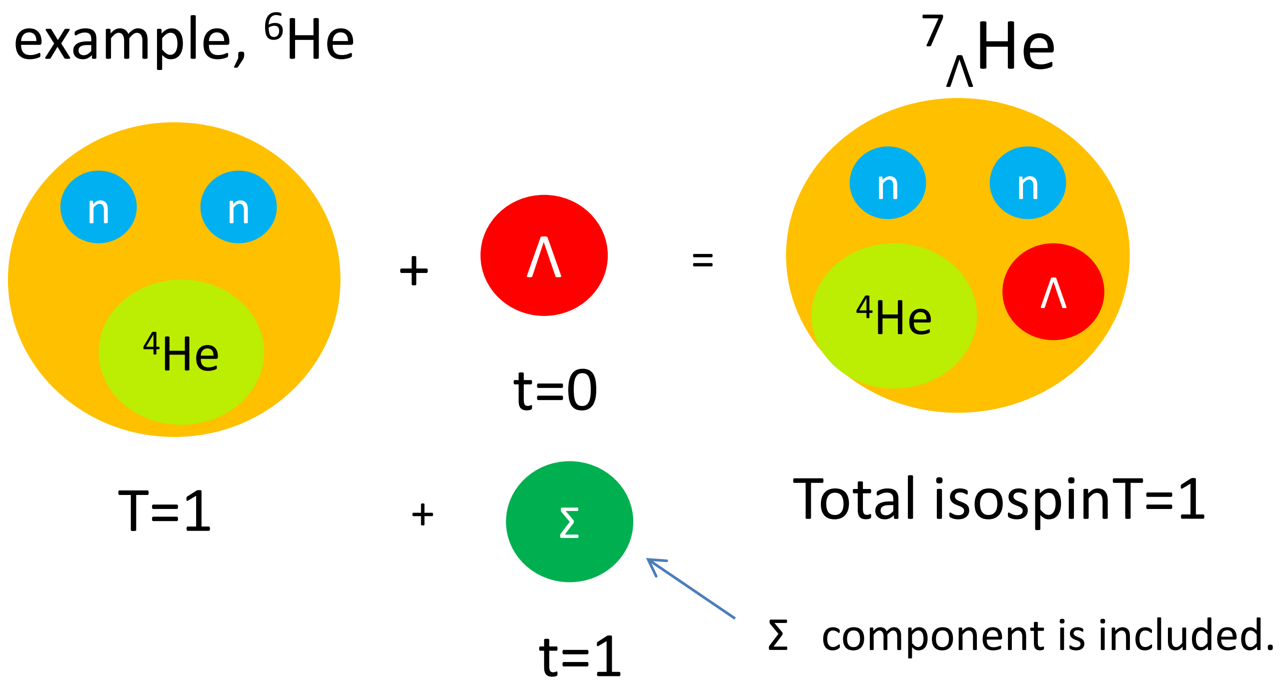


$^{4}_{\Lambda}He$

How do we obtain information on ΛN-ΣN coupling?

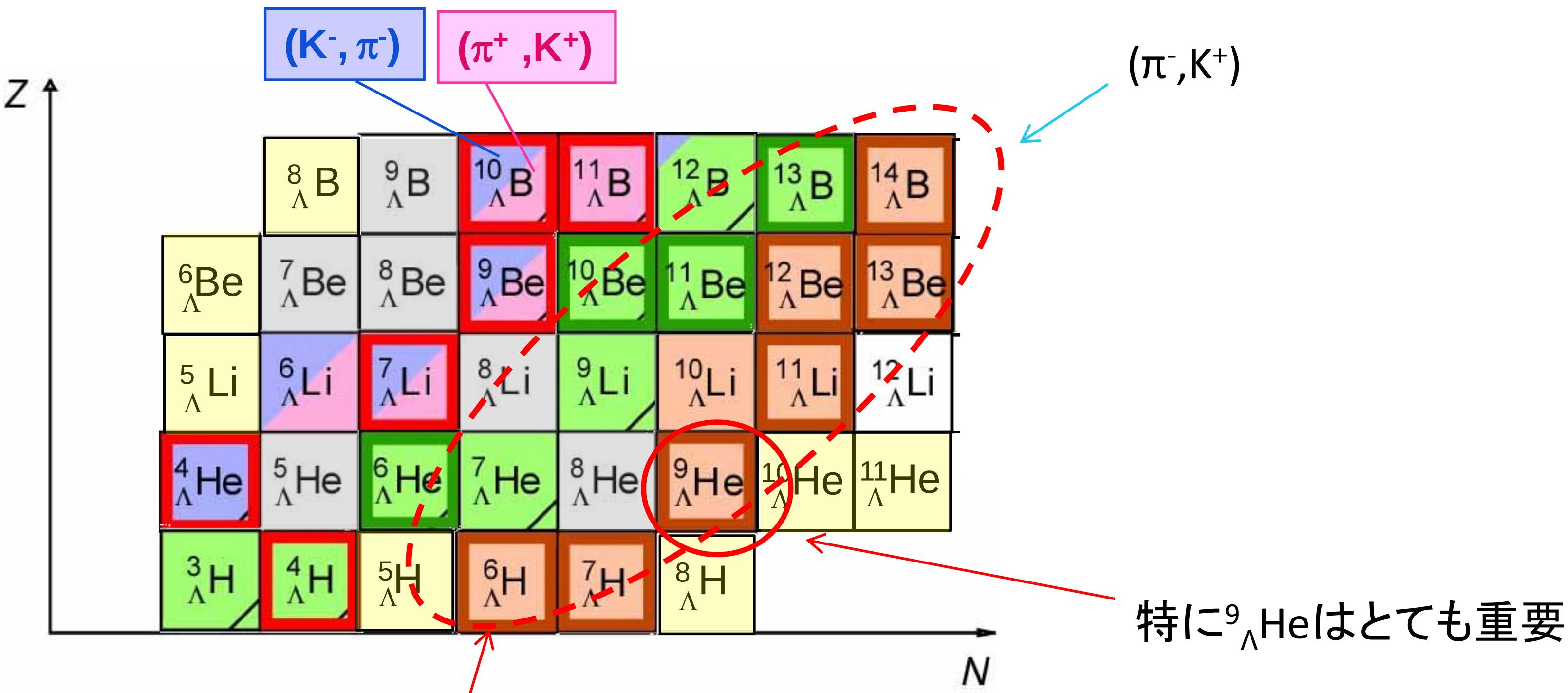
(1)YN scattering experiment, Femtoscopic experiment
(2) To study neutron-rich Λ hypernuclei

Why neutron-rich Λ hypernuclei ?

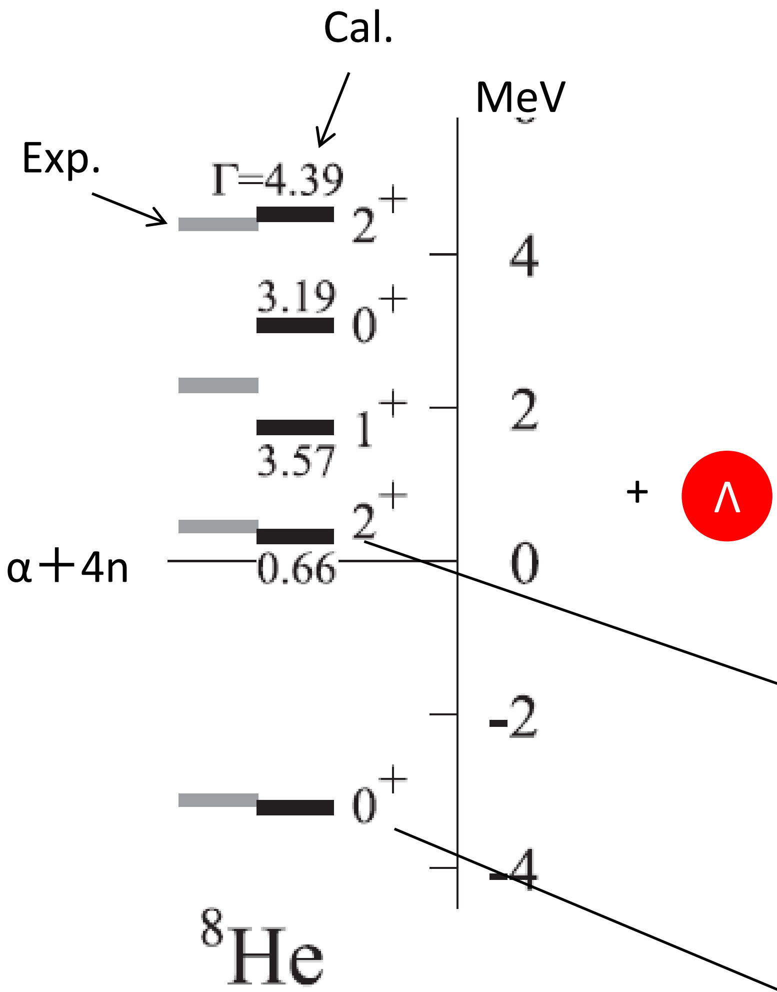


Isospin of neutron-rich core nuclei is large. Then, Σ probability in corresponding Λ hypernuclei would be larger.
Then, Λ neutron-rich hypernuclei are the best suited for study ΛN-ΣN coupling.

ΛN－ΣN結合の情報を得る重要なハイパー核（中性子過剰ラムダハイパー核）



These neutron-rich Λ hypernuclei are important and request to observe them at J-PARC.

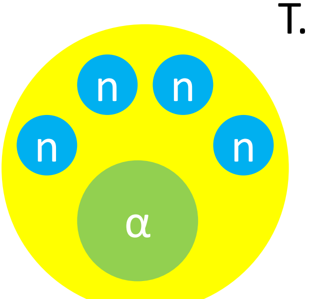


B_Λ ～5－6MeV：共鳴幅があるために、
波動関数がdiluteなので、ΛN相互作用に
よって、そこまでエネルギーを稼がない

B_Λ～7-8MeV

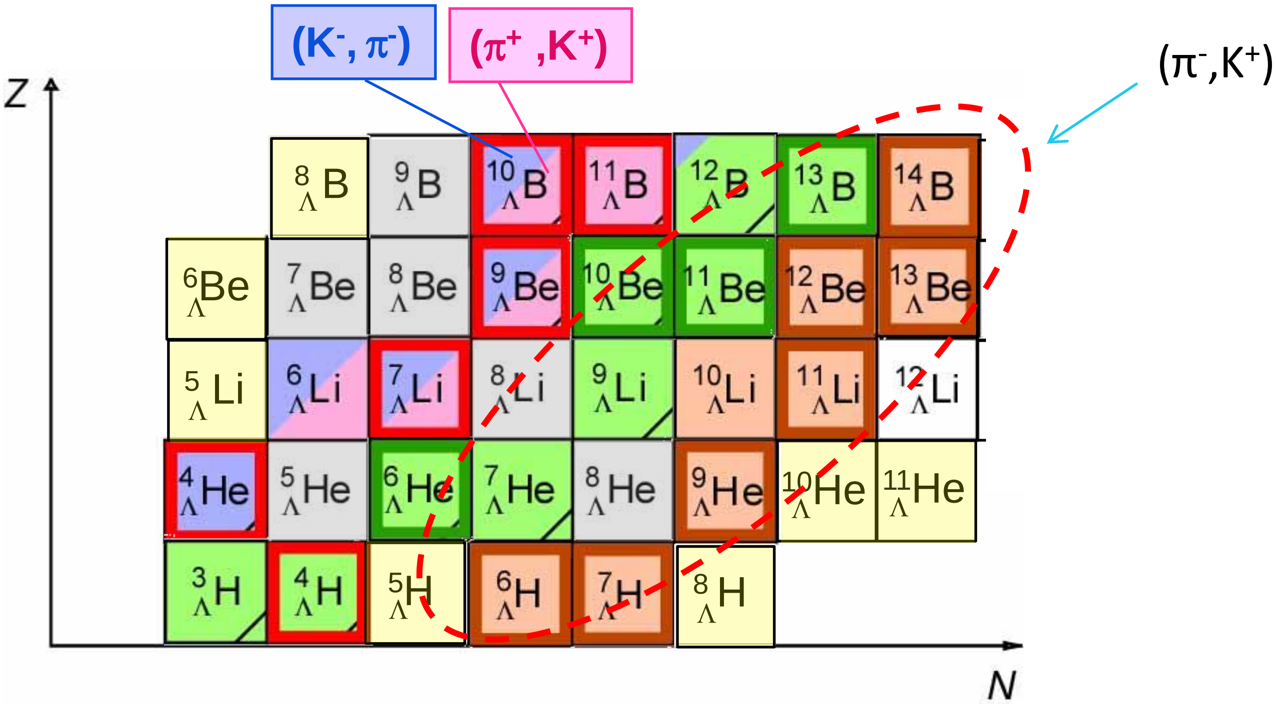
この基底状態を
得ることができるのではないか？
中性子の数が非常に多いので、
${}^{7}_{\Lambda}$HeよりもさらにΛN―ΣN結合についての
情報が得られるであろう。
=>今後の実験に期待

T. Myo et al., PRC104, 044306(2021)



^{8}He

Theory side: Collaboration with T. Myo



軽い中性子過剰ラムダハイパー核から何が得られるか？

By neutron-rich Λ hypernuclei, we could obtain information on long-range tail of ΛN-ΣN coupling. ➡ Long-range part of ΛNN three-body force

Short-range part of ΛN-ΣN coupling=short-range part of ΛNN three-body force

中性子星内部の研究にも重要なところ。＝＞より重いラムダハイパー核の研究が必要　＝＞中村氏による次の講演

S=-1ハイパー核で今後必要な不可欠なこと

・YN散乱実験+Femtoscopic exp. : ある程度YN相互作用の詳細が分かっていたと言っても、
現在は、NN相互作用ほどの詳細は分かっていない。
今後のYN散乱実験は、YN相互作用の根幹でもあるので、是非、実験データが欲しい。

・A=3,4ラムダハイパー核の束縛エネルギー値の確定
現実的YN相互作用＋厳密少数多体系計算
＝＞相互作用の妥当性をチェックのために必要不可欠

・軽い中性子過剰ラムダハイパー核
ΛN一ΣN coupling のlong-range part(ΛNNのlong-range part)

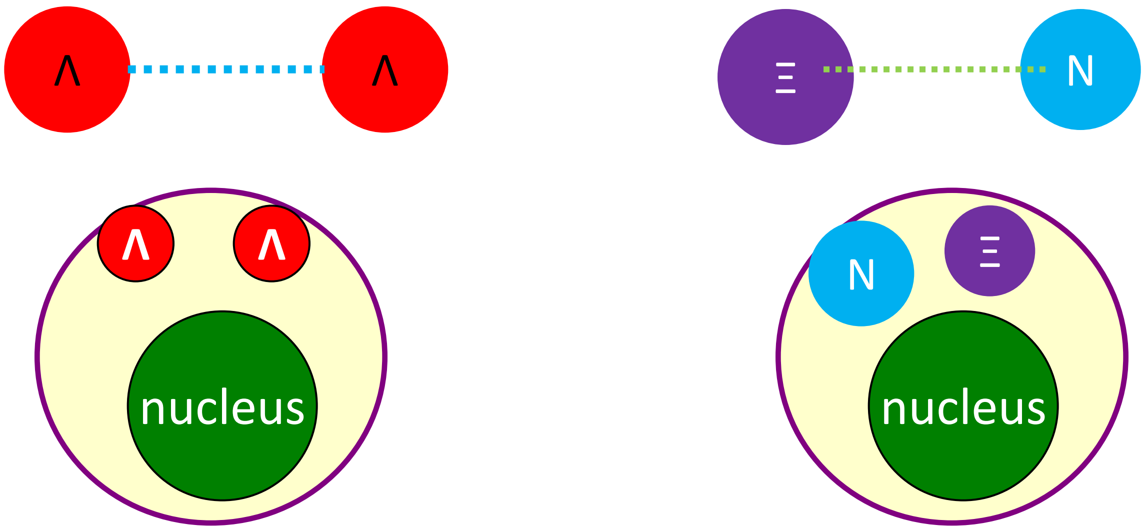
・重いラムダハイパー核
ΛNNのshort-range part

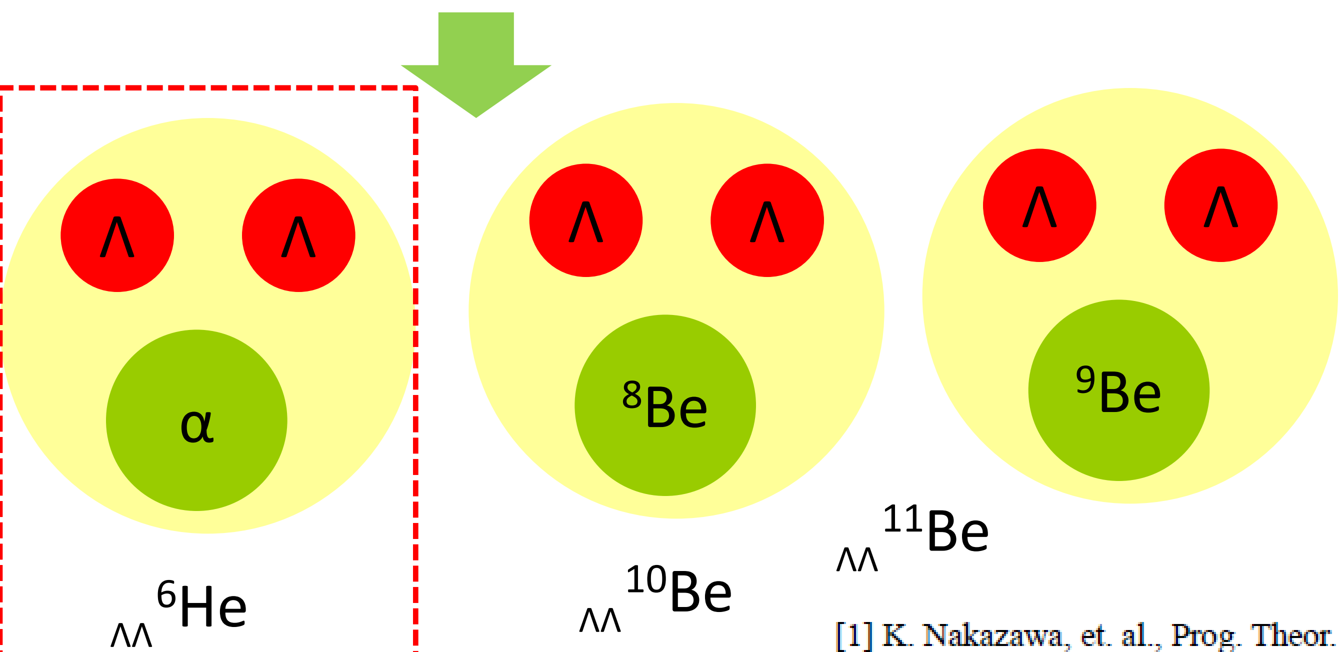
Outline of my talk

- present status in S=-1 hypernuclei and YN interaction

- present status in S=-2 hypernuclei and YY interaction

Next step: S=-2 sector





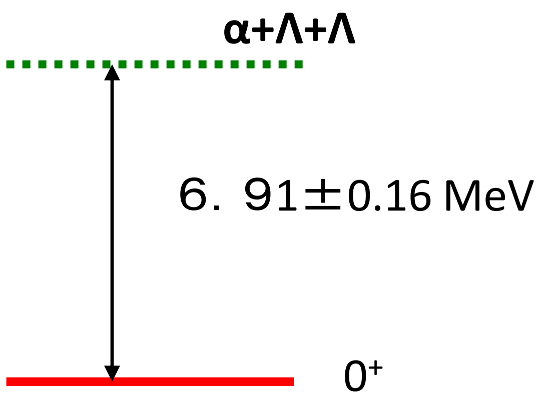
$^1S_0$ of ΛΛ interaction: attractive

[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).

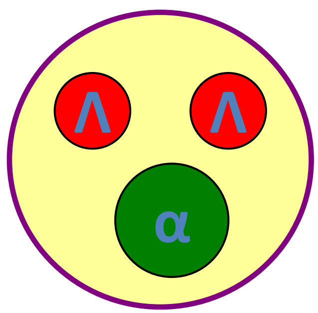
In 2001, the epoch-making data has been reported by the KEK-E373 experiment.

Observation of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$

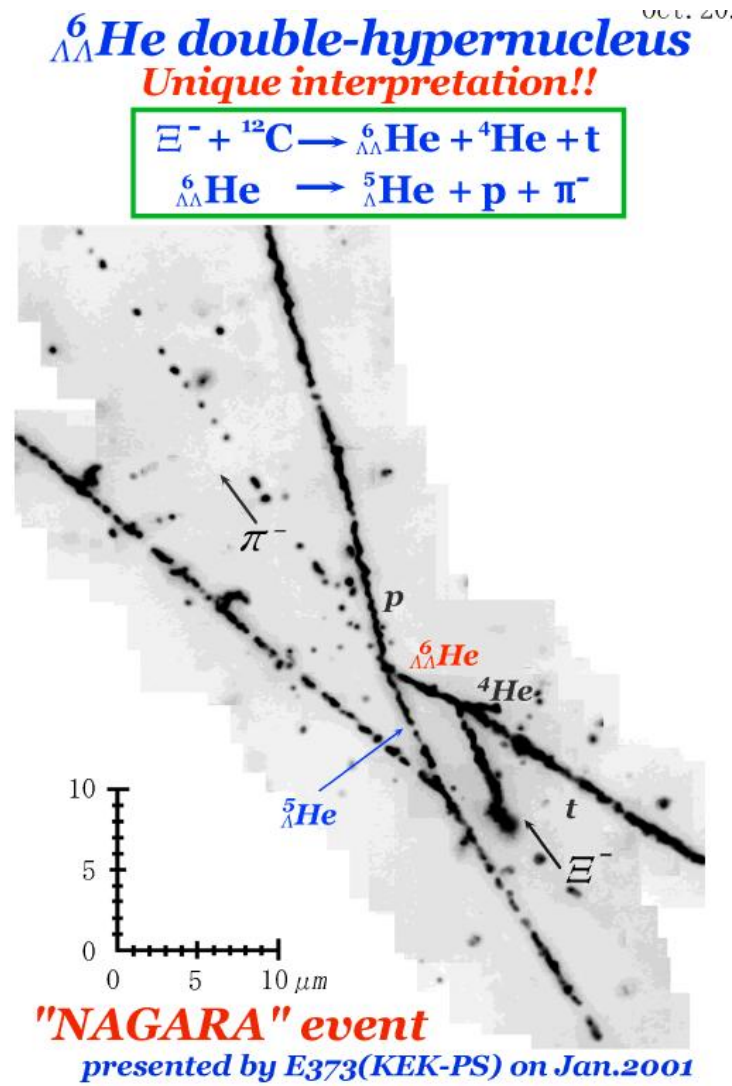
世界初の不定性なく発見された
ダブルラムダハイパー核
この束縛エネルギーからΛΛ相互作用の
${}^{1}S_{0}$の引力の望ましい強さが分かった。



${}^{6}_{\Lambda\Lambda}\mathrm{He}$



${}^{6}_{\Lambda\Lambda}\mathrm{He}$



H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

▪ E07 Approved proposal at J-PARC

"Systematic Study of double strangness systems at J-PARC"

by Nakazawa and his collaborators

E07実験の解析中、続々とデータが出てきている。=>仲澤氏による講演

It is difficult to determine
- (1) spin-parity
- (2) whether the observed state is the ground state or an excited state

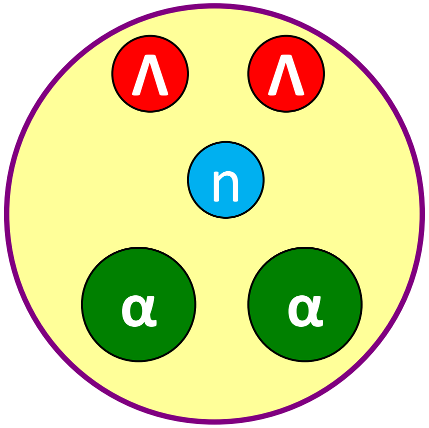
My theoretical contribution using few-body calculation

Emulsion experiment ⟷ (comparison) ⟷ **Theoretical calculation**

input: ΛΛ interaction to reproduce the observed binding energy of $^{6}_{\Lambda\Lambda}$He

↓

the identification of the state



$^{11}_{\Lambda\Lambda}Be$

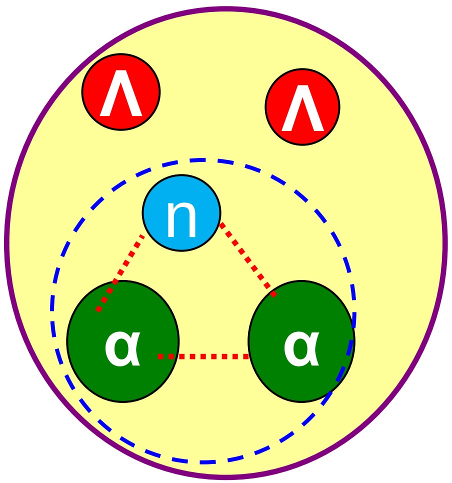
$B_{\Lambda\Lambda}$= 20.83±1.27 MeV(Hida event)

J.K.Ahn, et al., PRC88,014003(2013)

$B_{\Lambda\Lambda}$=19.07±0.11 MeV

H. Ekawa et al., PTEP2019,021D02(2021)

$^{11}_{\Lambda\Lambda}$Be



Core nucleus, ^{9}Be is well described as α +α + n three-cluster model.

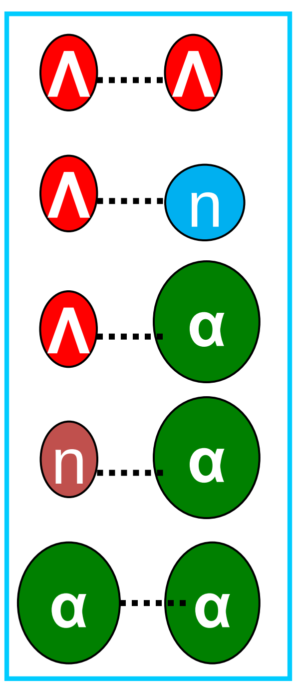
Then, $^{11}_{\Lambda\Lambda}$Be is considered to be suited for studying with α +α + n +Λ +Λ 5-body model.

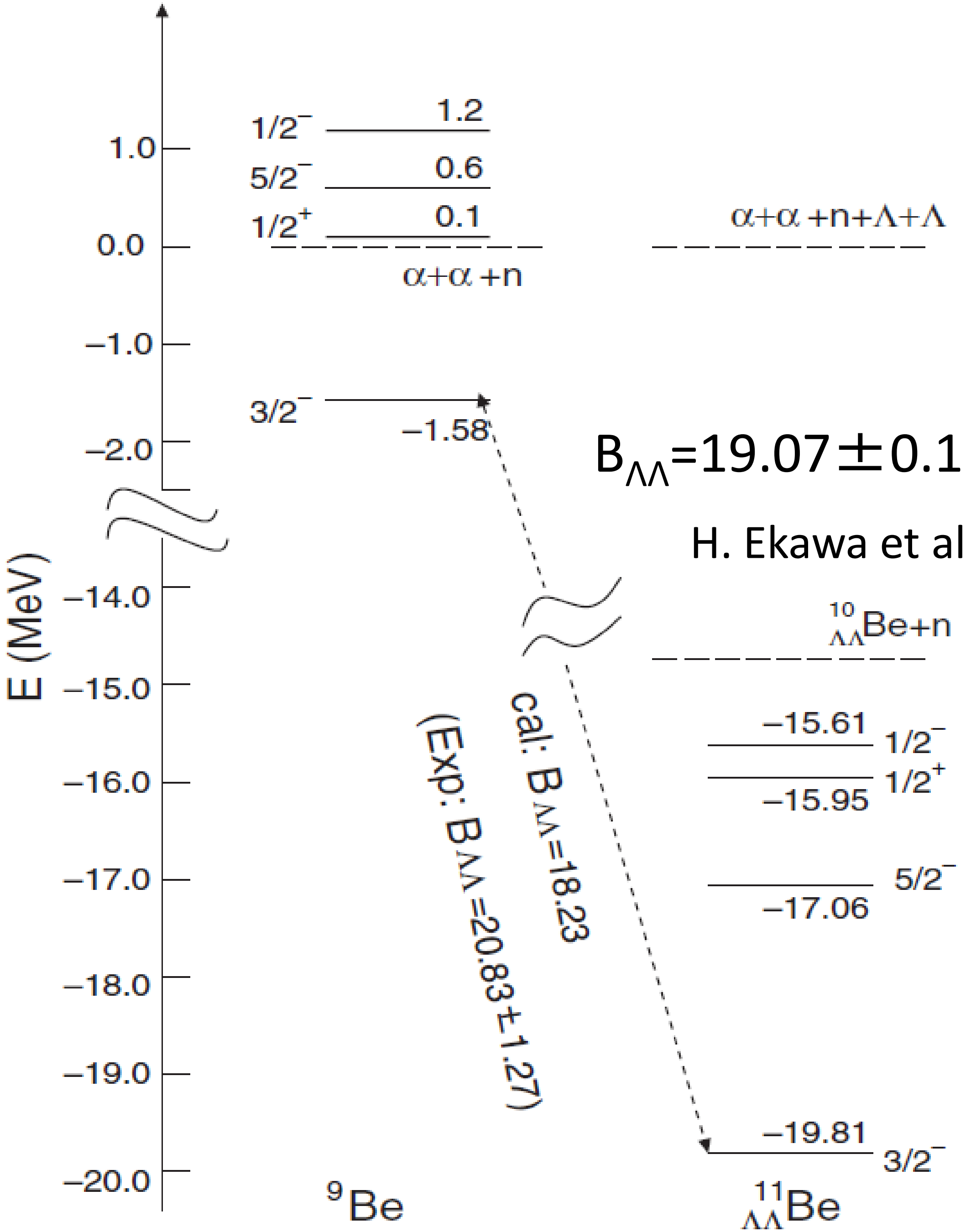
Difficult 5-body calculation:

1) 3 kinds of particles (**α**, Λ, **n**)

2) 5 different kinds of interactions

3) Pauli principle between **α** and **α,** and between **α** and **n**





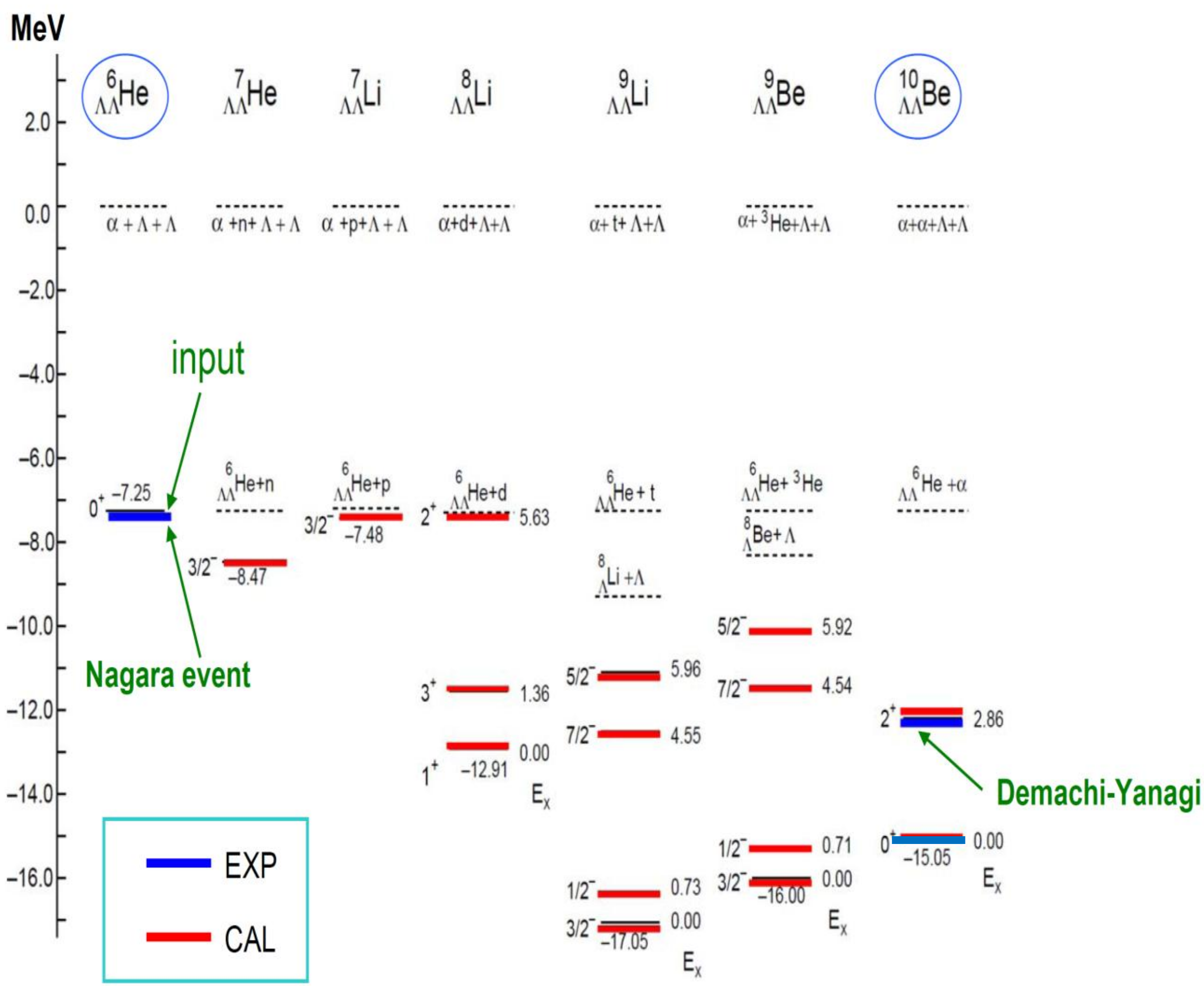
$B_{\Lambda\Lambda}$=19.07±0.11 MeV

H. Ekawa et al., PTEP2019,021D02(2021)

おそらく、$^{11}_{\Lambda\Lambda}$Beの
基底状態だろうと推測される。

Spectroscopy of ΛΛ-hypernuclei

E. Hiyama, M. Kamimura, T.Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002) , 024007



是非、A=7-9のダブルラムダハイパー核のdataが今後出てくることを期待。

2011年以降

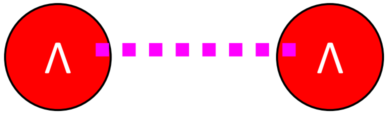
構造研究からΛN相互作用＋そのΛΛ相互作用を使用したEOSの研究へつながりつつある。

しかし、まだ発展途上

理由：ΛΛ相互作用が完全ではないから

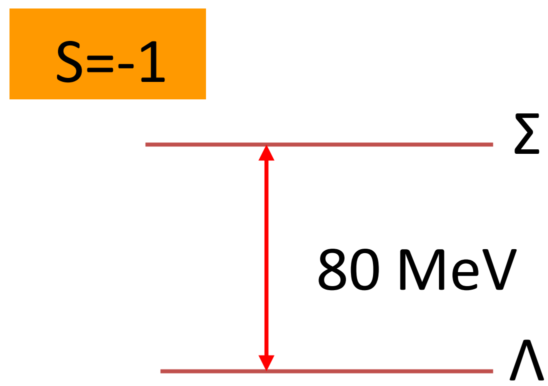
何が必要か？

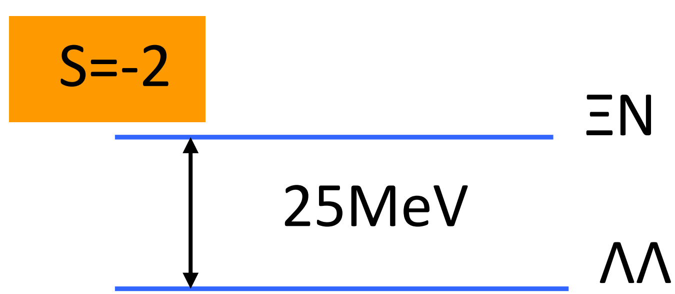
ΛΛ相互作用において、今後必要な部分は？



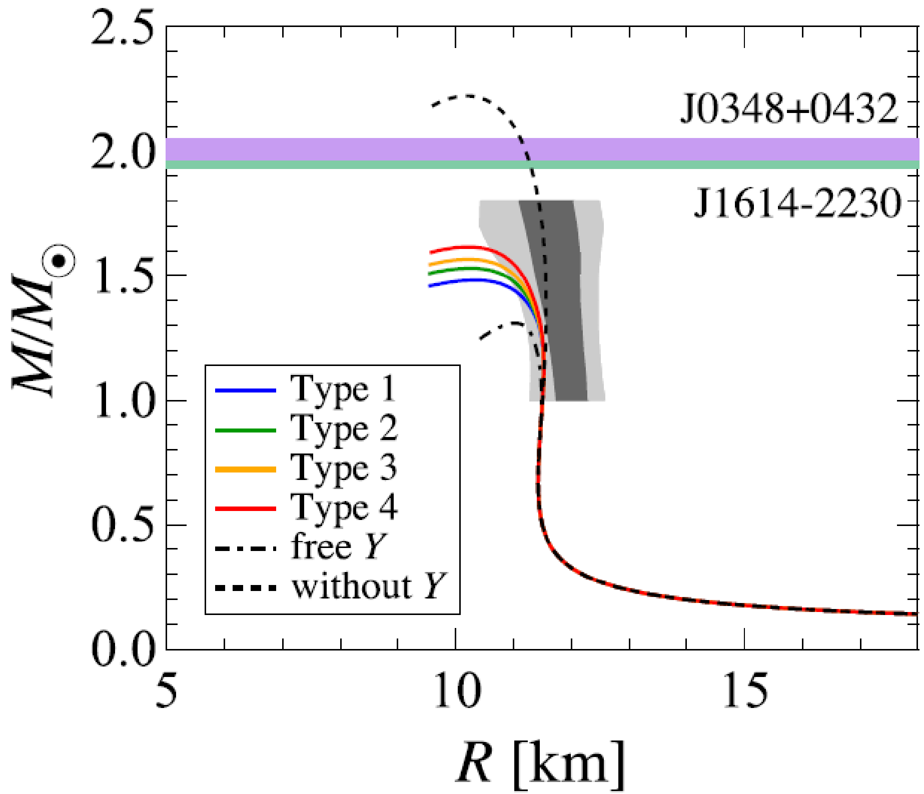
$^1S_0$ → この部分は決まった。

今後：P-波相互作用、ΛΛ-ΞN相互作用の情報が必要





In ΛΛ interaction, what is important to study?
p-wave state of ΛΛ interaction



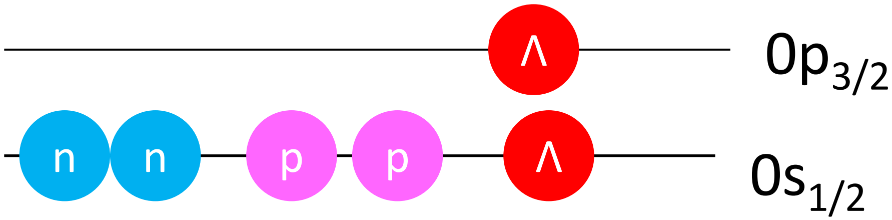
H. Togashi, E.H.,
Y. Yamamoto, and M. Takano,
PRC93, 035808 (2016).

TYPE1:attractive ➡ TYPE2:less attractive ➡ TYPE4:repulsive

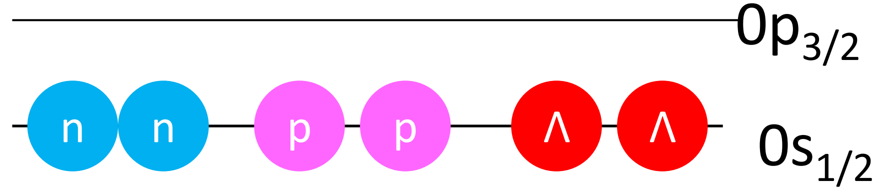
⬇

Similar with odd-state of
ΛN interaction

ΛΛ相互作用のp波で20%ほど中性子星
の最大質量が異なる。



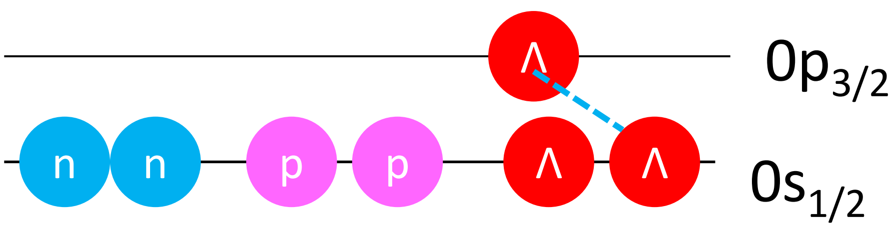
ダブルラムダハイパー核の
励起状態



ダブルラムダハイパー核の
基底状態

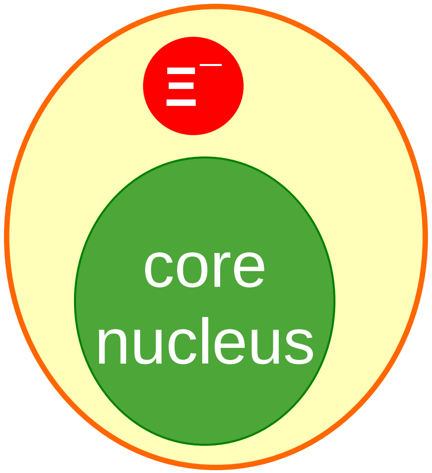
今までこの状態の
ハイパー核が
見つかっている。

今後、このような状態が実験で見つかれば
ΛΛ相互作用のp波の項が決まる。



または、トリプルラムダハイパー核が実験で生成することができるので
あれば、P波が分かる。

グザイハイパー核は？

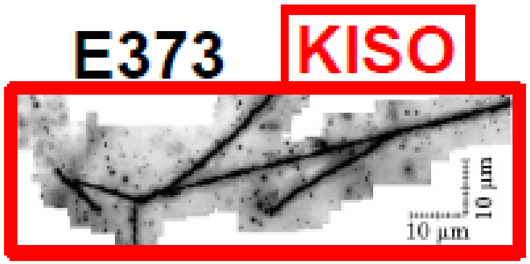


For the study of ΞN interaction, it is important to study the structure of Ξ hypernuclei.

しかし、2015年まで、グザイハイパー核が束縛状態として発見されたことがなかった。

そのため、ΞN相互作用が引力か斥力が分からなかった。

The first measurement of bound Ξ hypernucleus, ^{14}N-Ξ.



^{14}N-Ξ^-

0 MeV

-1.03 ± 0.18 MeV
or
3.87 ± 0.21 MeV

PTEP

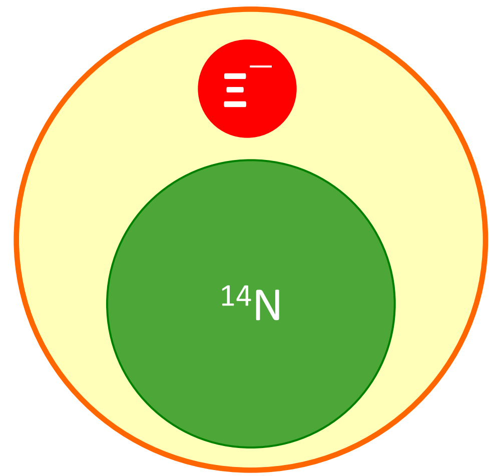
Prog. Theor. Exp. Phys. **2015**, 033D02 (11 pages)
DOI: 10.1093/ptep/ptv008

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

K. Nakazawa[1,*], Y. Endo[1], S. Fukunaga[2], K. Hoshino[1], S. H. Hwang[3], K. Imai[3], H. Ito[1], K. Itonaga[1], T. Kanda[1], M. Kawasaki[1], J. H. Kim[4], S. Kinbara[1], H. Kobayashi[1], A. Mishina[1], S. Ogawa[2], H. Shibuya[2], T. Sugimura[1], M. K. Soe[1], H. Takahashi[5], T. Takahashi[5], K. T. Tint[1], K. Umehara[1], C. S. Yoon[4], and J. Yoshida[1]

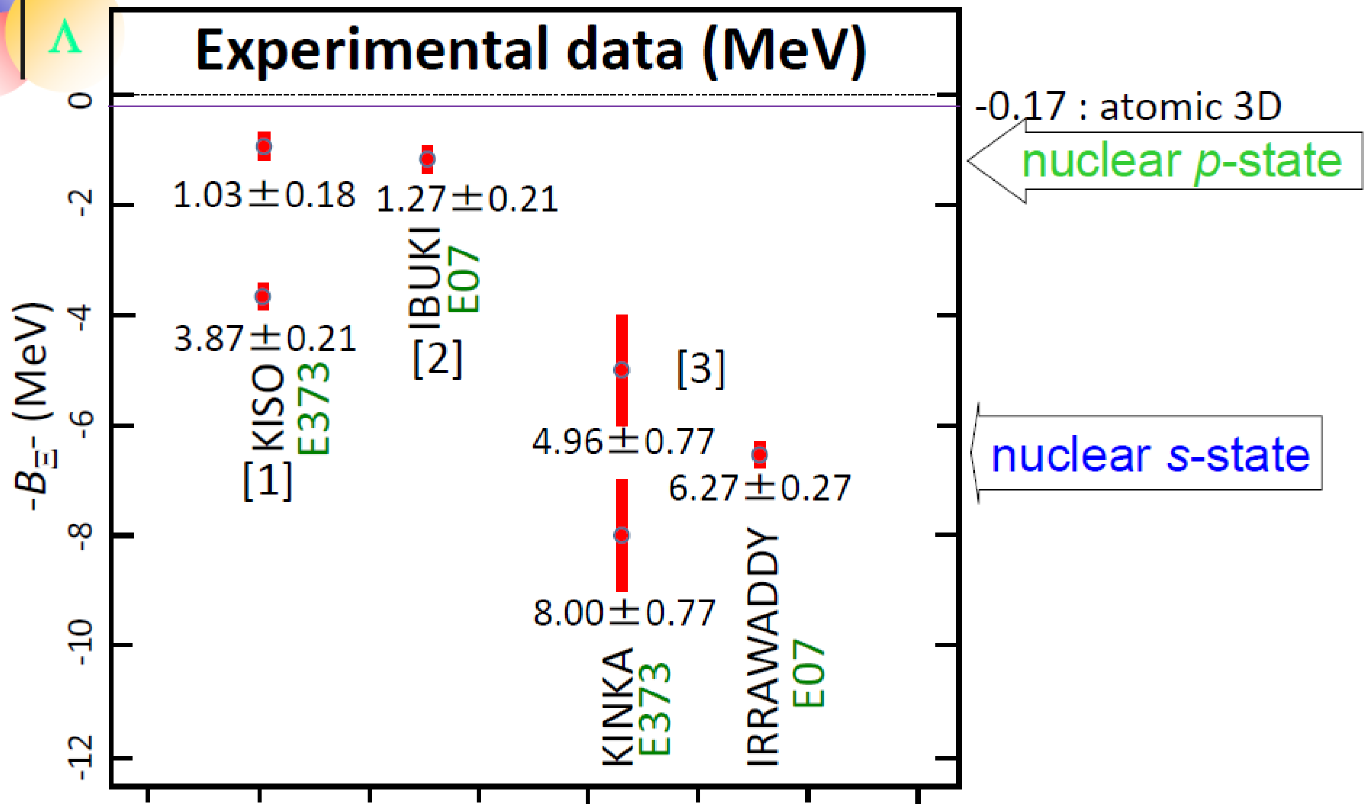
[1] *Physics Department, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan*
[2] *Department of Physics, Toho University, Funabashi 274-8510, Japan*
[3] *Advanced Science Research Center, JAEA, Tokai 319-1195, Japan*
[4] *Department of Physics, Gyeongsang National University, Jinju 660-701, Korea*
[5] *Institute of Particle and Nuclear Studies, KEK, Tsukuba 305-0801, Japan*
[*] E-mail: nakazawa@gifu-u.ac.jp

Received October 27, 2014; Revised December 25, 2014; Accepted January 9, 2015; Published March 5, 2015



We understood Ξ-nuclear potential should be attractive.

Level scheme of Ξ hypernucleus ($^{15}_{\Xi}C$ [Ξ^--^{14}N])



[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

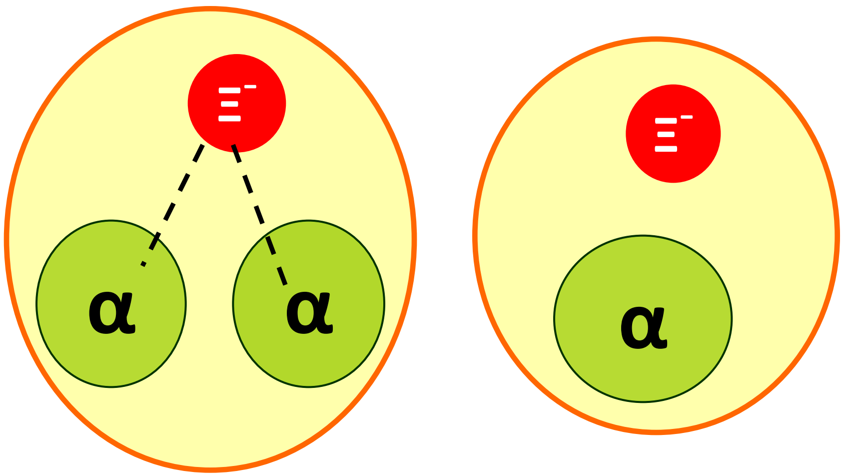
Slide by Nakazawa

After observation of Kiso event, they observed several events of ^{14}N-Ξ hypernucleus.
Some are observed as excited state and
some are observed as ground state.

After observation of ^{11}B-Ξ(J-PARC-E70 exp.), we want to know V_0 term, first.

$$V_{\Xi N} = V_0 + \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}\, V_{\sigma\cdot\sigma} + \boldsymbol{\tau}\cdot\boldsymbol{\tau}\, V_{\tau\cdot\tau} + (\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})\, V_{\sigma\cdot\sigma\ \tau\cdot\tau}$$

the **(σ·σ)**, **(τ·τ)** and **(σ·σ) (τ·τ)** terms of $V_{\Xi N}$ vanish by folding them into the **α**-cluster wave function that are spin-, isospin-satulated.



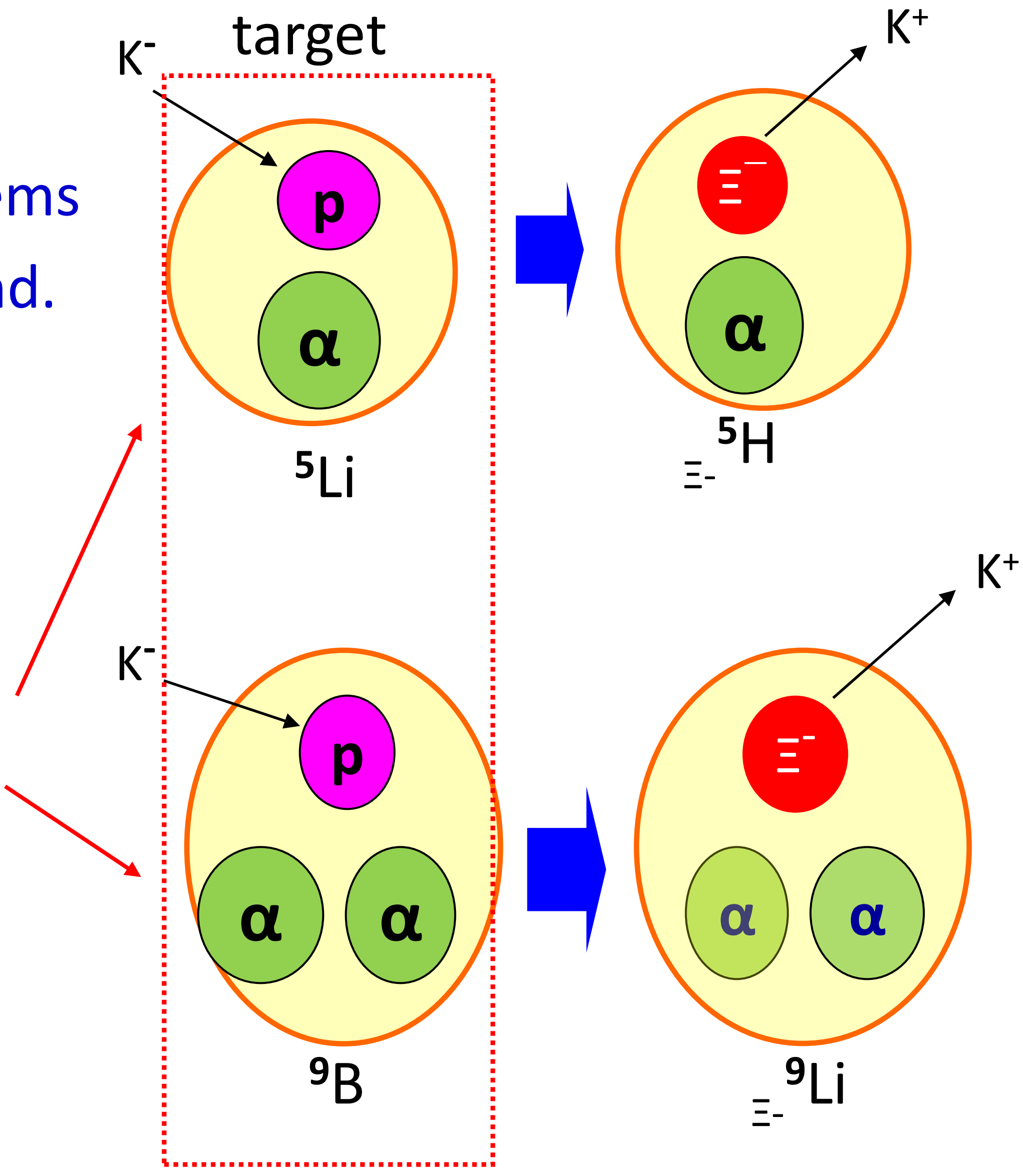
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ･･･

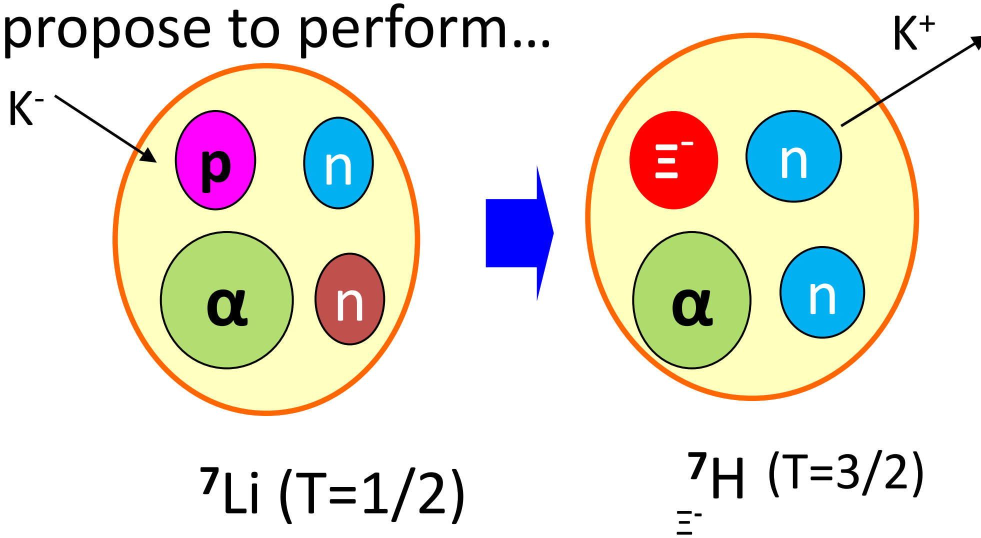
To produce **αΞ⁻** and **ααΞ⁻** systems by (K^-, K^+) reaction,

These systems are unbound.

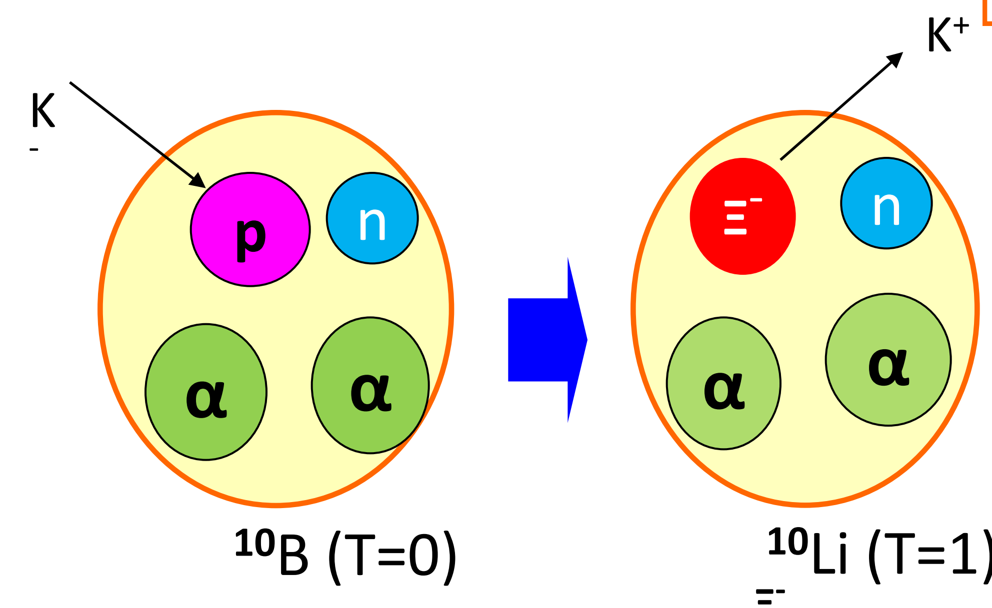
Then, we cannot use them as targets.



As the second best candidates to extract information about the spin-, isospin-independent term V_0, we propose to perform…

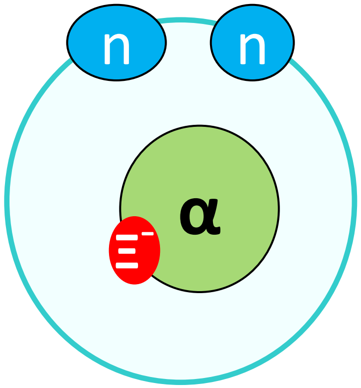


Why they are suited for investigating V_0?



(more realistic illustration)

Core nucleus ^{6}He is known to be halo nucleus. Then, valence neutrons are located far away from α particle.

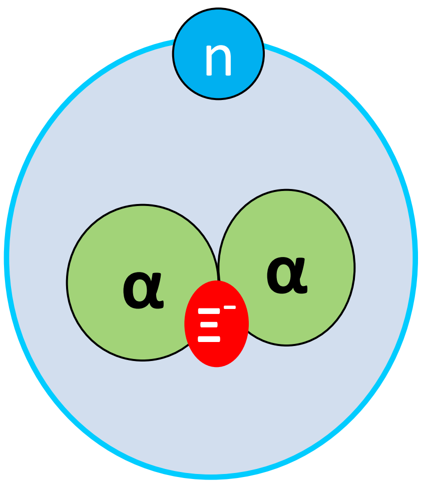


Valence neutrons are located in p-orbit,

whereas Ξ particle located in 0s-orbit.

$^{7}_{\Xi^-}$H (T=3/2)

Then, distance between Ξ and **n** is much larger than the interaction range of Ξ and **n**.



Then, αΞ potential, in which only V_0 term works, plays a dominant role in the binding energies of these system.

$^{10}_{\Xi^-}$Li (T=1)

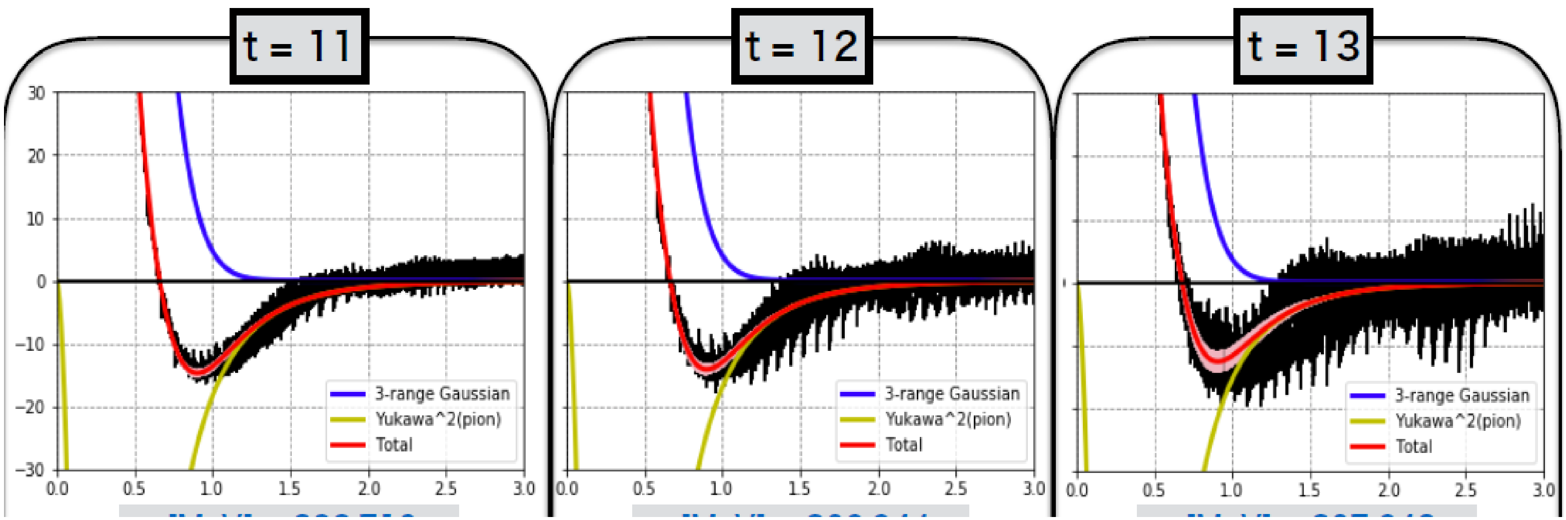
ΞN interaction

Nijmegen potential : Nijmegen model-D(ND),
Extended soft core ’04d

HAL potential(Base on Lattice QCD potential:HAL collaboration)
by K. Sasaki, Miyamoto, T. Doi, T. Hatsuda et al.

$$V_{\Xi N}=V_0(r)+(\sigma_\Xi\cdot\sigma_N)V_s(r)+(\tau_\Xi\cdot\tau_N)V_t(r)+(\sigma_\Xi\cdot\sigma_N)(\tau_\Xi\cdot\tau_N)V_{ts}(r)$$

All terms are central parts only.



Property of the spin- and isospin-components of ESC04, ND,HAL

V(T,S)	ESC04	ND	HAL
T=0, S=1	strongly attractive (a bound state)	weakly attractive	Weakly attractive
T=0, S=0	weakly repulsive		Strongly attractive
T=1, S=1	weakly attractive		Weakly attractive
T=1, S=0	weakly repulsive		Weakly repulsive

Although the spin- and isospin-components of these potentials are very different (due to the different meson contributions),

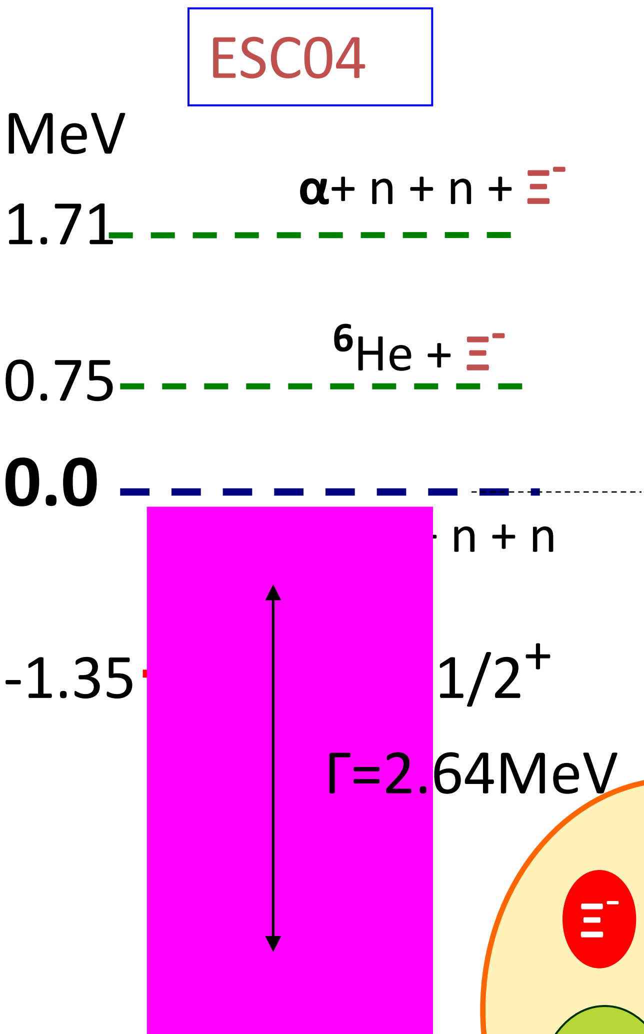
we find that the spin- and isospin-averaged property,

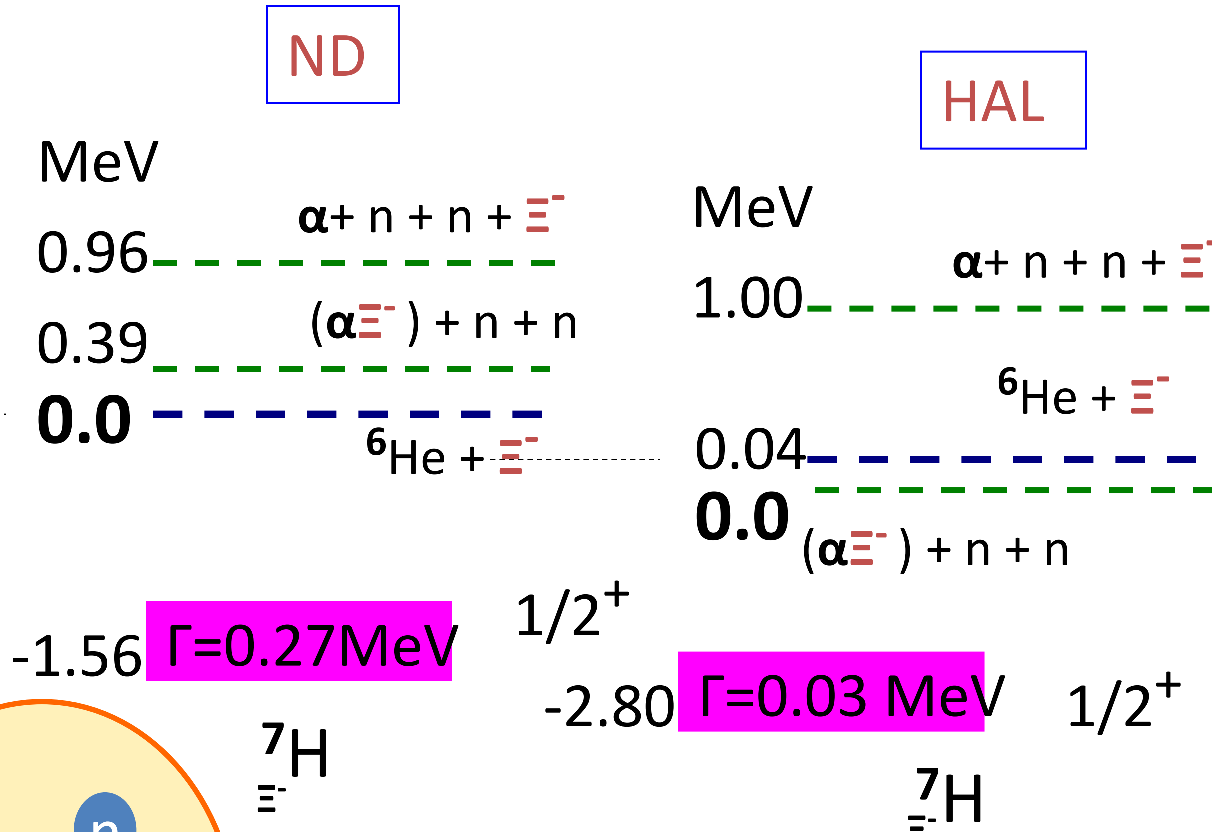
$$V_0 = [V(0,0) + 3V(0,1) + 3V(1,0) + 9V(1,1)] / 16,$$

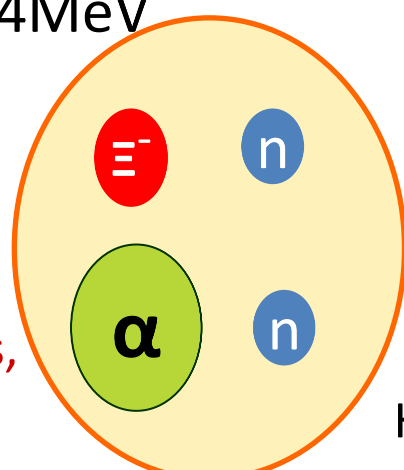
namely, strength of the V_0- term is similar to each other.

4-body calculation of $^{7}_{\Xi^-}H$

E. Hiyama et al.,
PRC**78** (2008) 054316







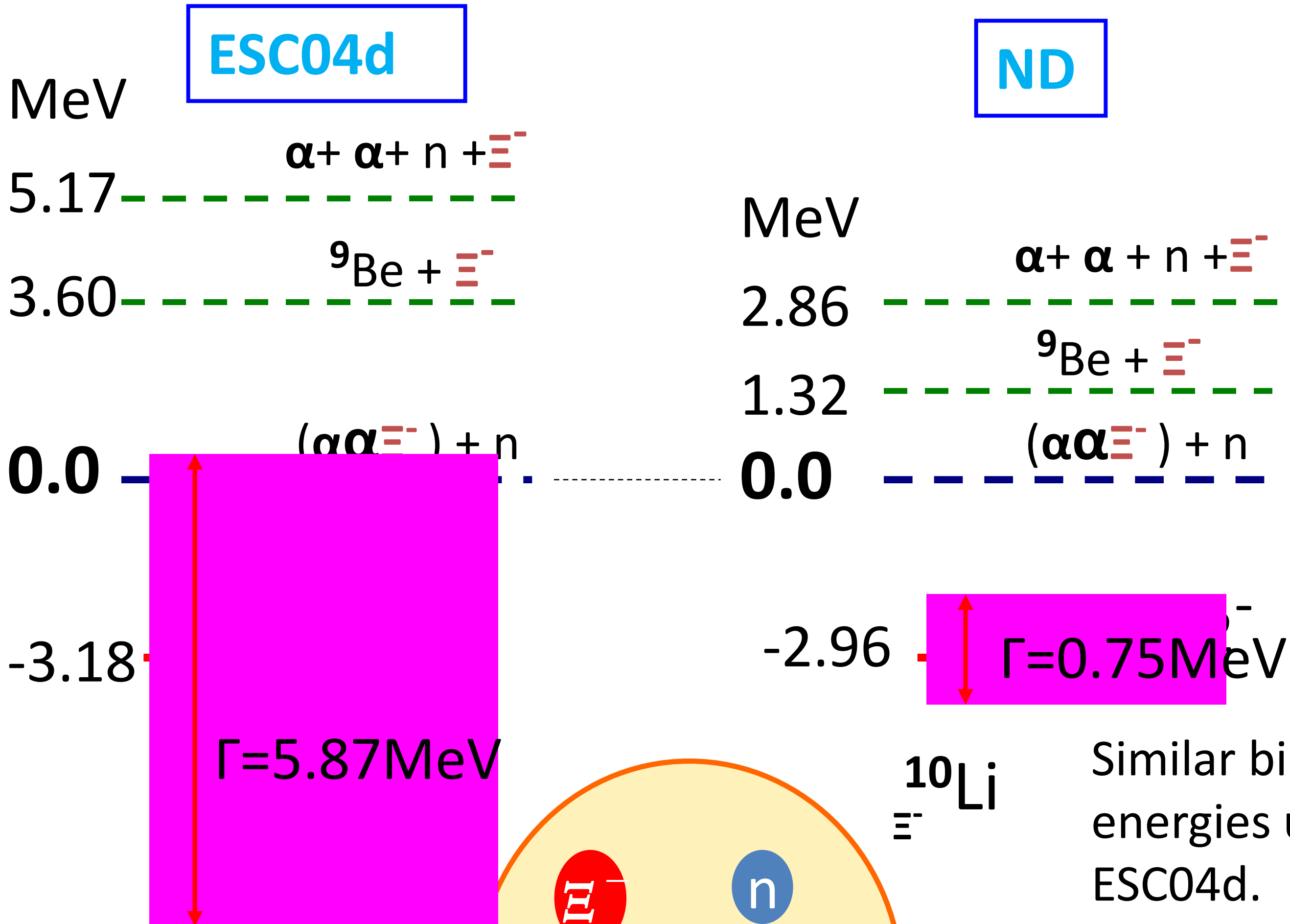
Similar binding energies using ND and ESC04.

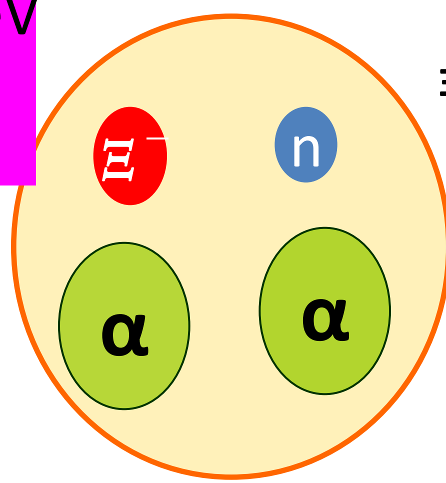
In experiments, we can expect a bound state.

However, decay width is dependent on on employed ΞN potential

4-body calculation of $^{10}_{\Xi^-}\mathrm{Li}$

E. Hiyama et al., PRC**78** (2008) 054316





Similar binding energies using ND and ESC04d.

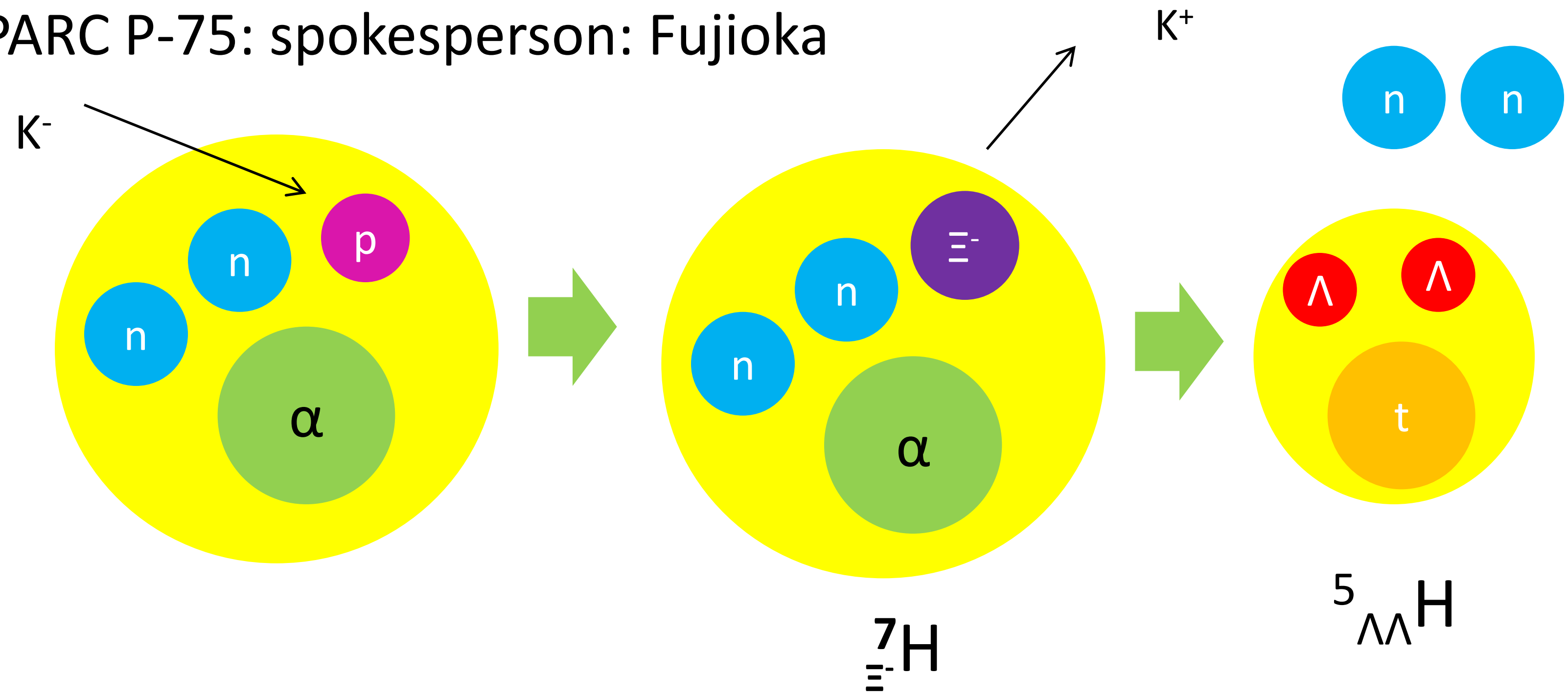
Independent on employed ΞN potential

But, decay width is dependent on employed ΞN interaction.

In experiments, we can expect a bound state.

In this way, the binding energies of Ξ hypernuclei with A=7 and 10 are dominated by αΞ potential, namely, spin-, and iso-spin independent ΞN interaction (V_0).

J-PARC P-75: spokesperson: Fujioka



まとめ

・S=-1 sector

・YN散乱実験+Femtoscopic exp.
・A=3,4ラムダハイパー核の束縛エネルギー値の確定

・軽い中性子過剰ラムダハイパー核

ΛN一ΣN coupling のlong-range part(ΛNNのlong-range part)

・重いラムダハイパー核

ΛNNのshort-range part

・S=-2 sector:
これから多くのハイパー核のdataが必要

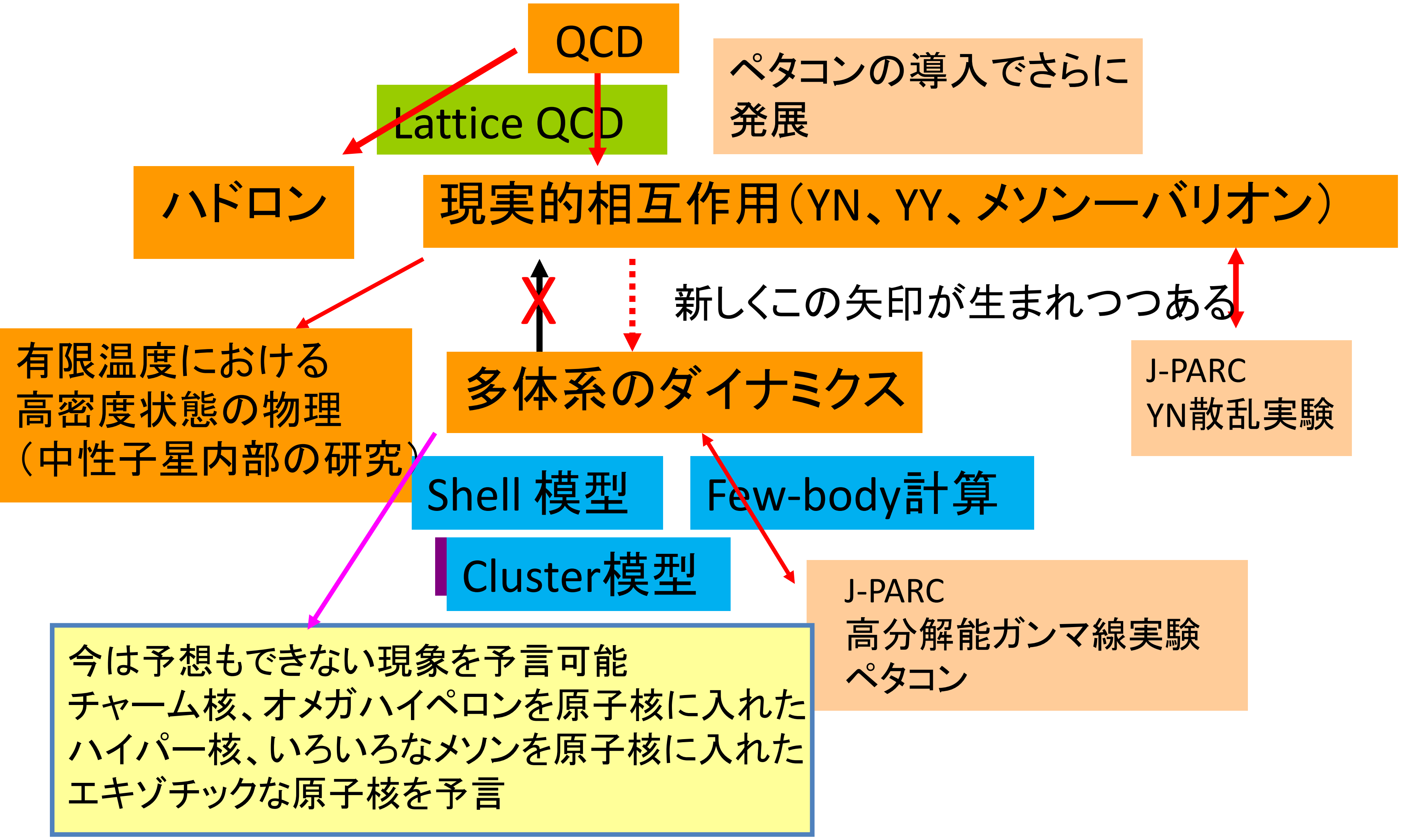
・ΞN散乱

・軽いp殻ダブルラムダハイパー核
・A=4～10グザイハイパー核
・トリプルラムダハイパー核

⇒ S=-2については、
相互作用を固めていくことが先決であり、今後、10年間は集中して進めている必要がありそう。

現在からこれらのS=-1、S=-2の世界

（personal view)



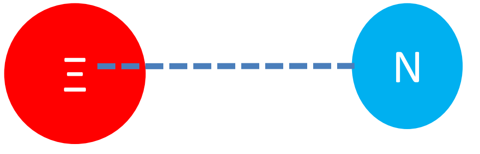
おわり

T S

$V_0 = [\,V(0,0) + 3V(0,1) + 3V(1,0) + 9V(1,1)\,] / 16,$

which partial contribution makes attractive for V_0 **?**

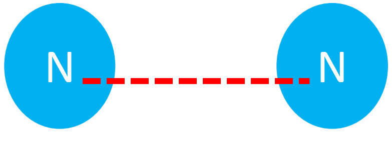
ΞN interaction: T=0, S=0
T=0, S=1
T=1, S=0
T=1, S=1



t=1/2 S=1/2 t=1/2 S=1/2

we have a two-body bound state for ΞN system?
No idea

Cf. NN interaction



T=0, S=0
T=0, S=1
T=1, S=0
T=1,S=1

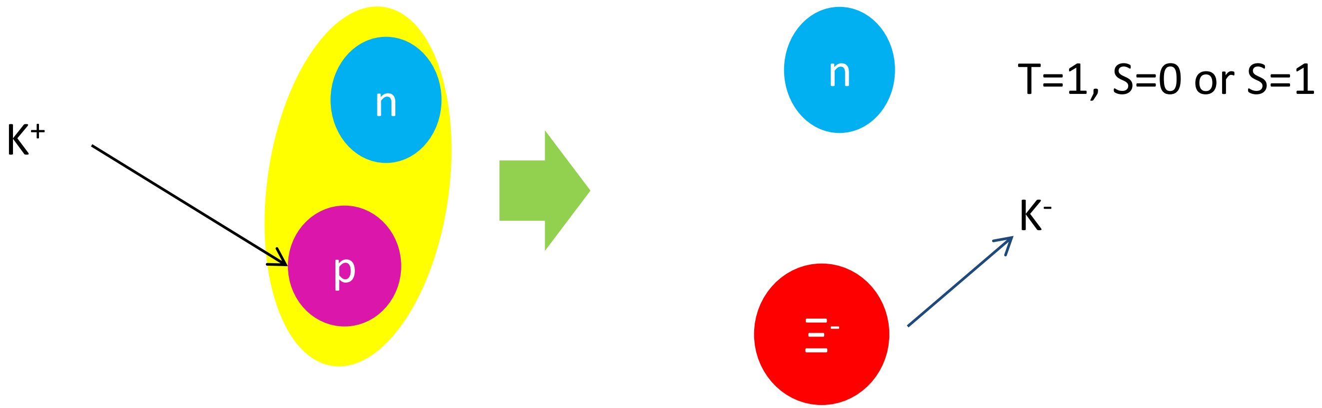
➡ strong attraction to have a bound state as a deuteron

Property of the spin- and isospin-components of ESC08 and HAL

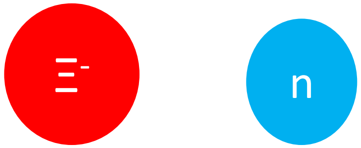
V(T,S)	ESC08c	HAL
T=0, S=1	strongly attractive	Weakly attractive
T=0, S=0	weakly repulsive	Strongly attractive
T=1, S=1	strong attractive	Weakly attractive
T=1, S=0	weakly repulsive	Weakly repulsive

Although the spin- and isospin-components of these two models are very different between them.

To investigate bound state of ΞN system, it might be possible to perform the following experiment:

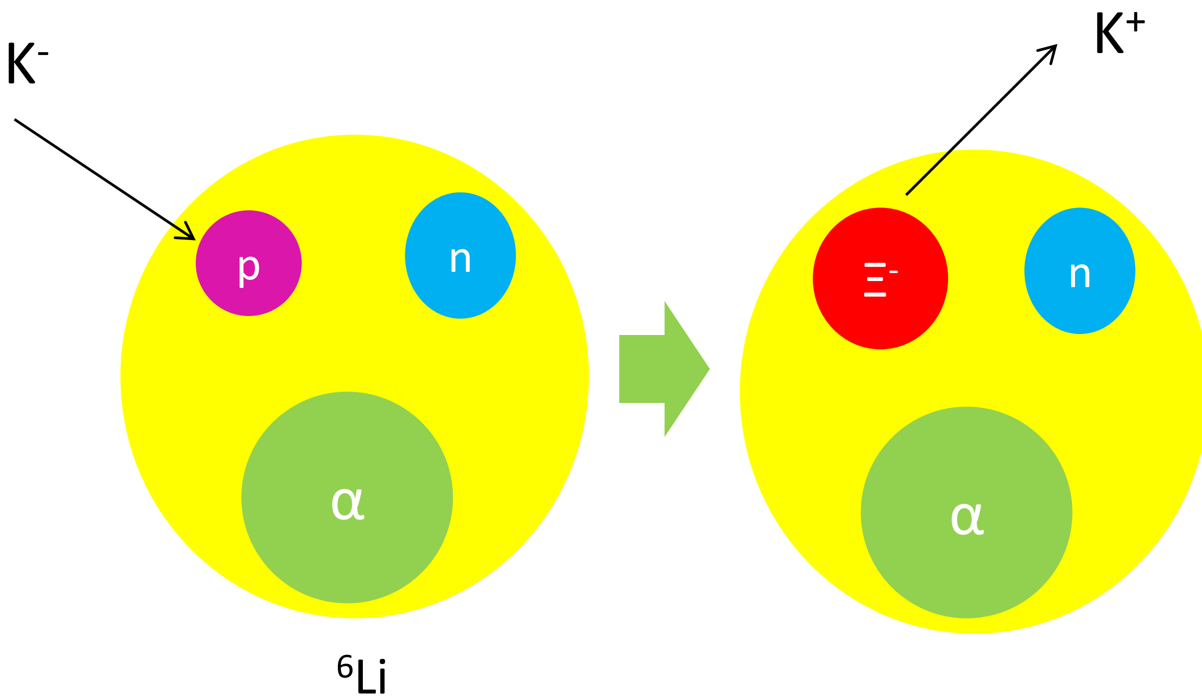


It would be difficult to obtain information on ΞN interaction (T=1,S=0 or 1).
Because, there might be no bound state for this system.



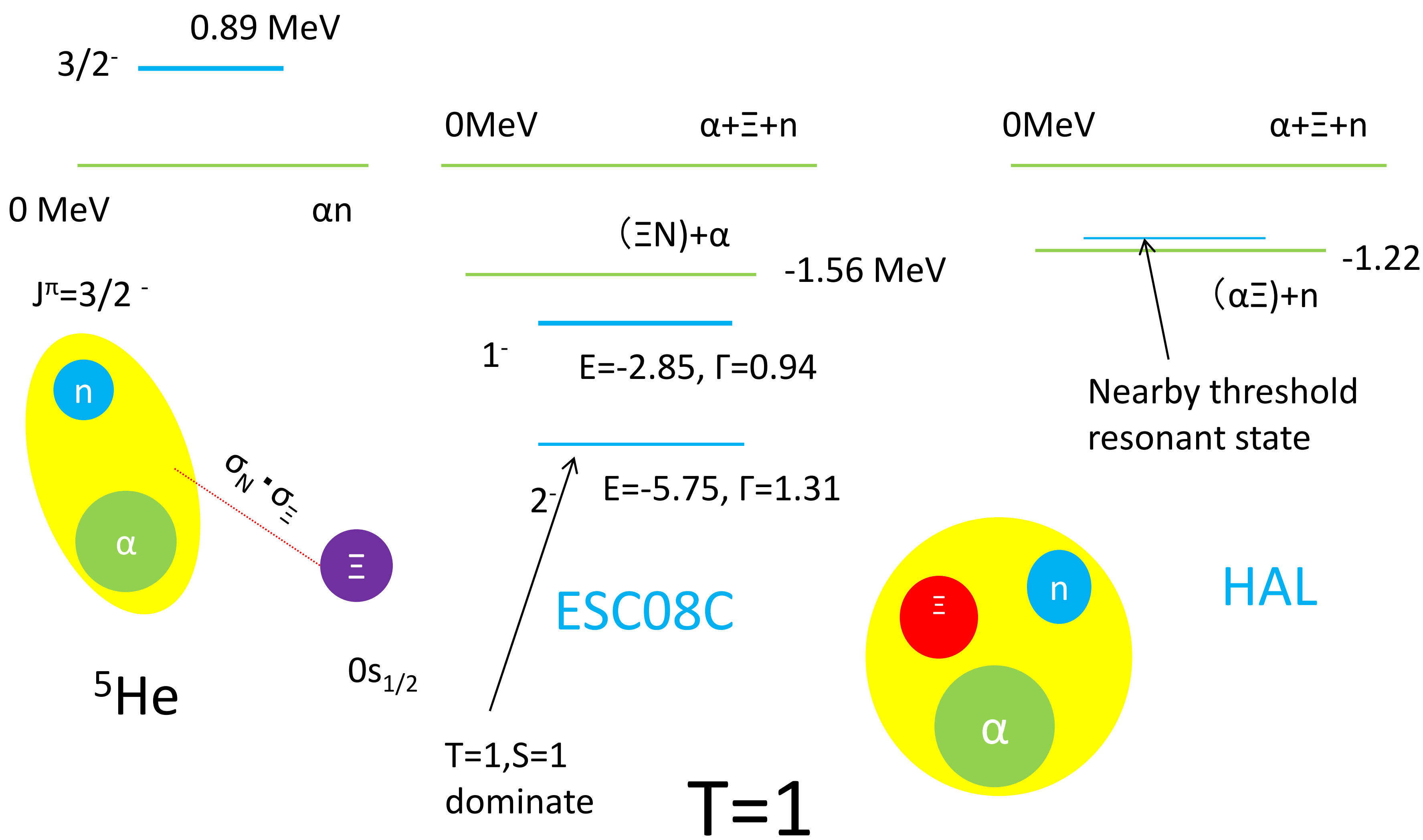
T=1, S=0 or S=1

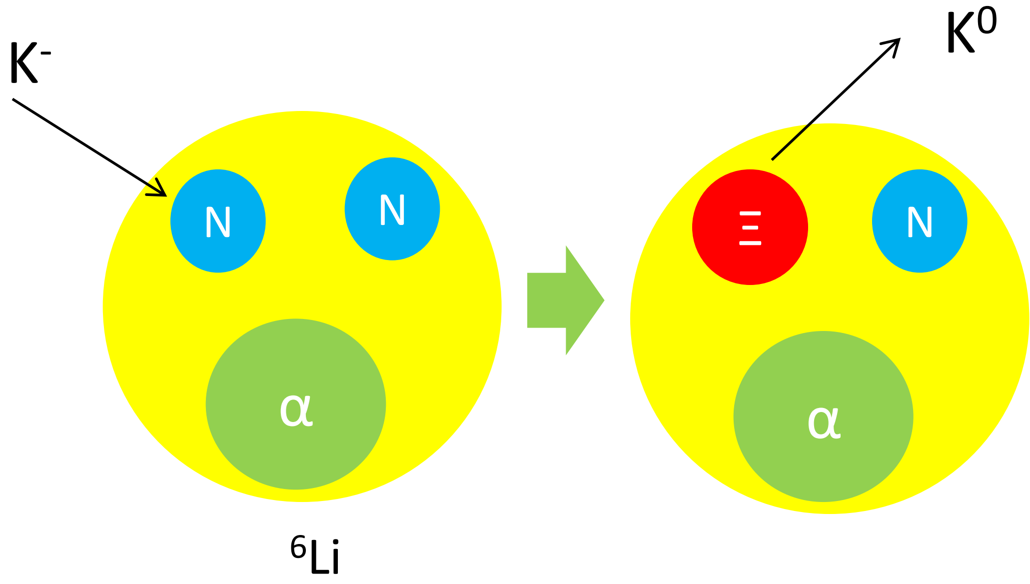
We can add a α.
Due to the attraction of αΞ and αN interactions,
ΞN system might have bound system.



T=1,S=0 or S=1

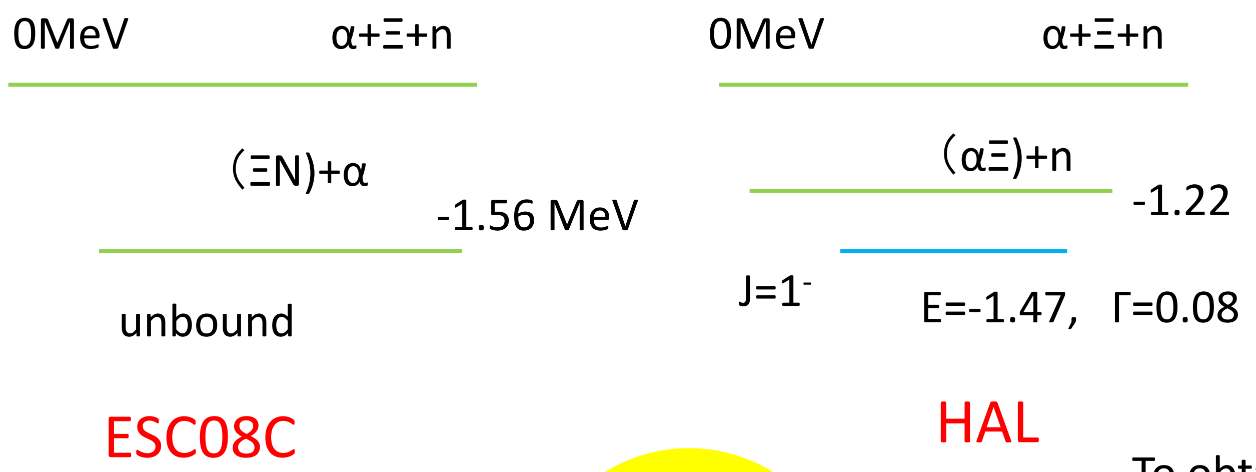
Experimentally,
It is possible to
produce Ξ hypernucleus.


0.89 MeV
3/2⁻
0MeV
α+Ξ+n
0MeV
α+Ξ+n
0 MeV
αn
(ΞN)+α
-1.56 MeV
-1.22
(αΞ)+n
Jπ=3/2 -
1-
E=-2.85, Γ=0.94
Nearby threshold
resonant state
n
$\sigma_N \cdot \sigma_\Xi$
2-
E=-5.75, Γ=1.31
α
Ξ
ESC08C
Ξ
n
HAL
α
^{5}He
$0s_{1/2}$
T=1,S=1
dominate
T=1

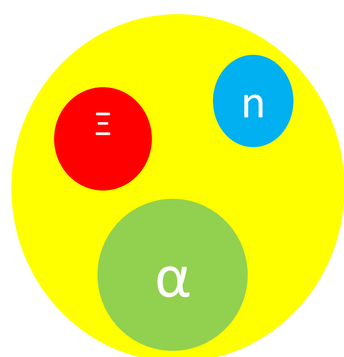


T=0,S=0 or S=1

We can obtain information on T=0, S=0 and S=1 ΞN interaction.



T=0,S=0 of ΞN interaction dominate



To obtain information on two-body ΞN interaction, ^{6}Li target is better.