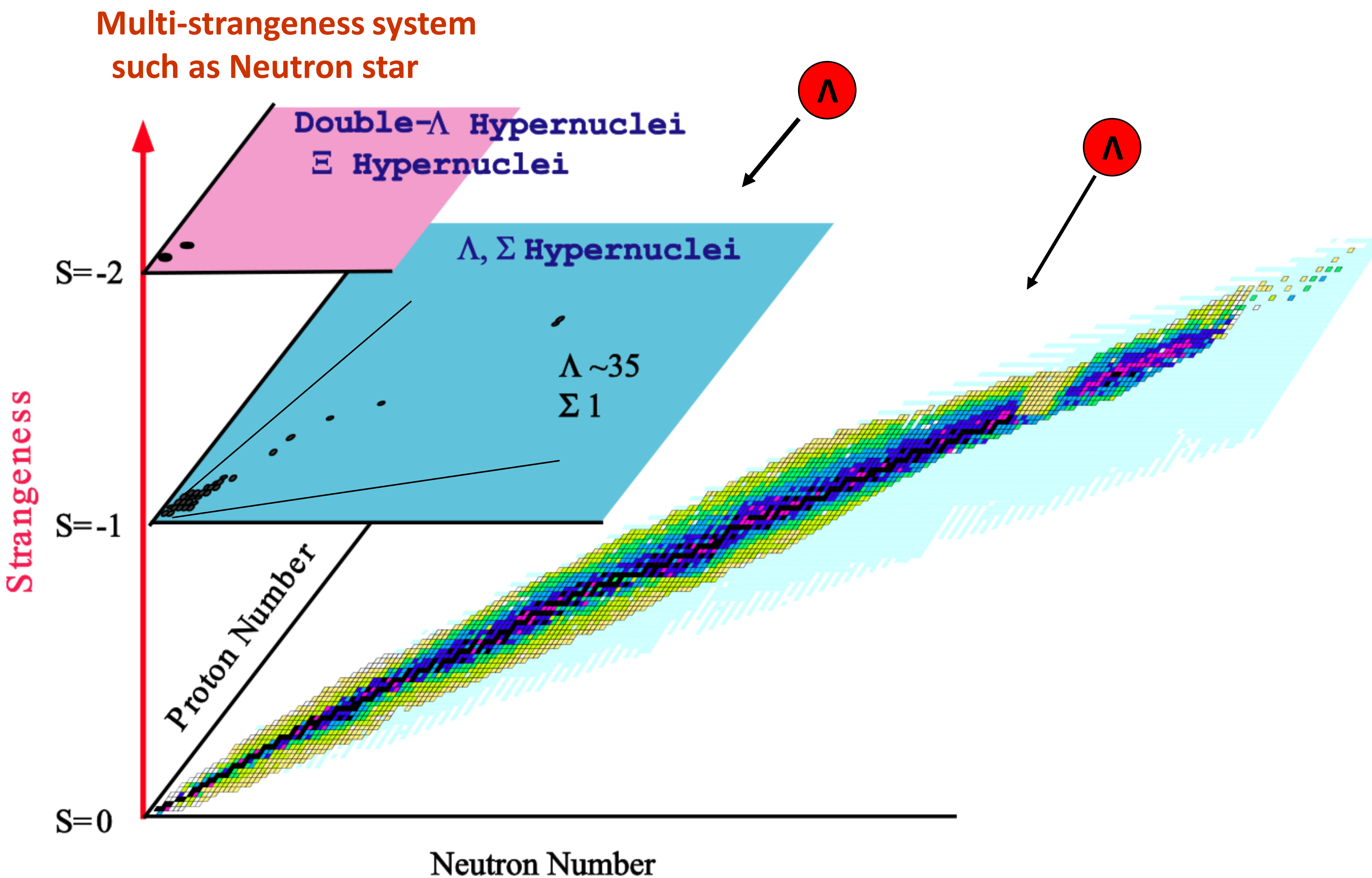
Structure of light Ξ hypernuclei with modern ΞN interaction

Emiko Hiyama (Kyushu Univ./RIKEN)

In 2017, move to Kyushu University from RIKEN
keep my position at RIKEN for 6 years since 2019

Nuclear chart with strangeness



Outline of my talk

- Historical Overview on hypernuclear physics
- What is the hot topics in hypernuclear physics?
  - Ξ hypernuclei

- What is problem? How do we try to solve it?

The major goal of hypernuclear physics

1) To understand baryon-baryon interactions

Fundamental and important for the study of nuclear physics

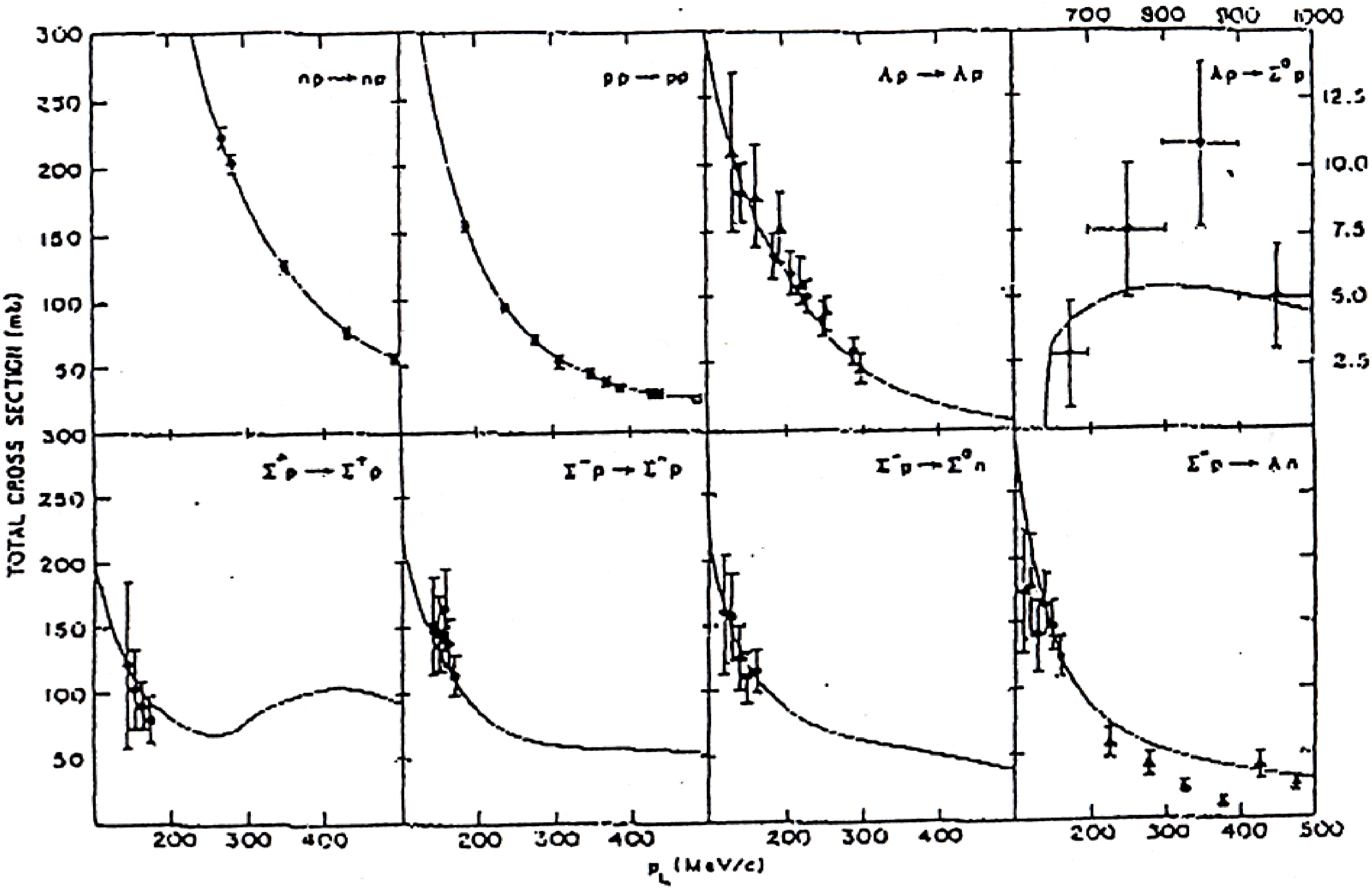
To understand the baryon-baryon interaction, two-body scattering experiment is most useful.

Total number of
Nucleon (N) -Nucleon (N) data: 4, 000

- Total number of differential cross section Hyperon (Y) -Nucleon (N) data: **40**
- **NO** YY scattering data

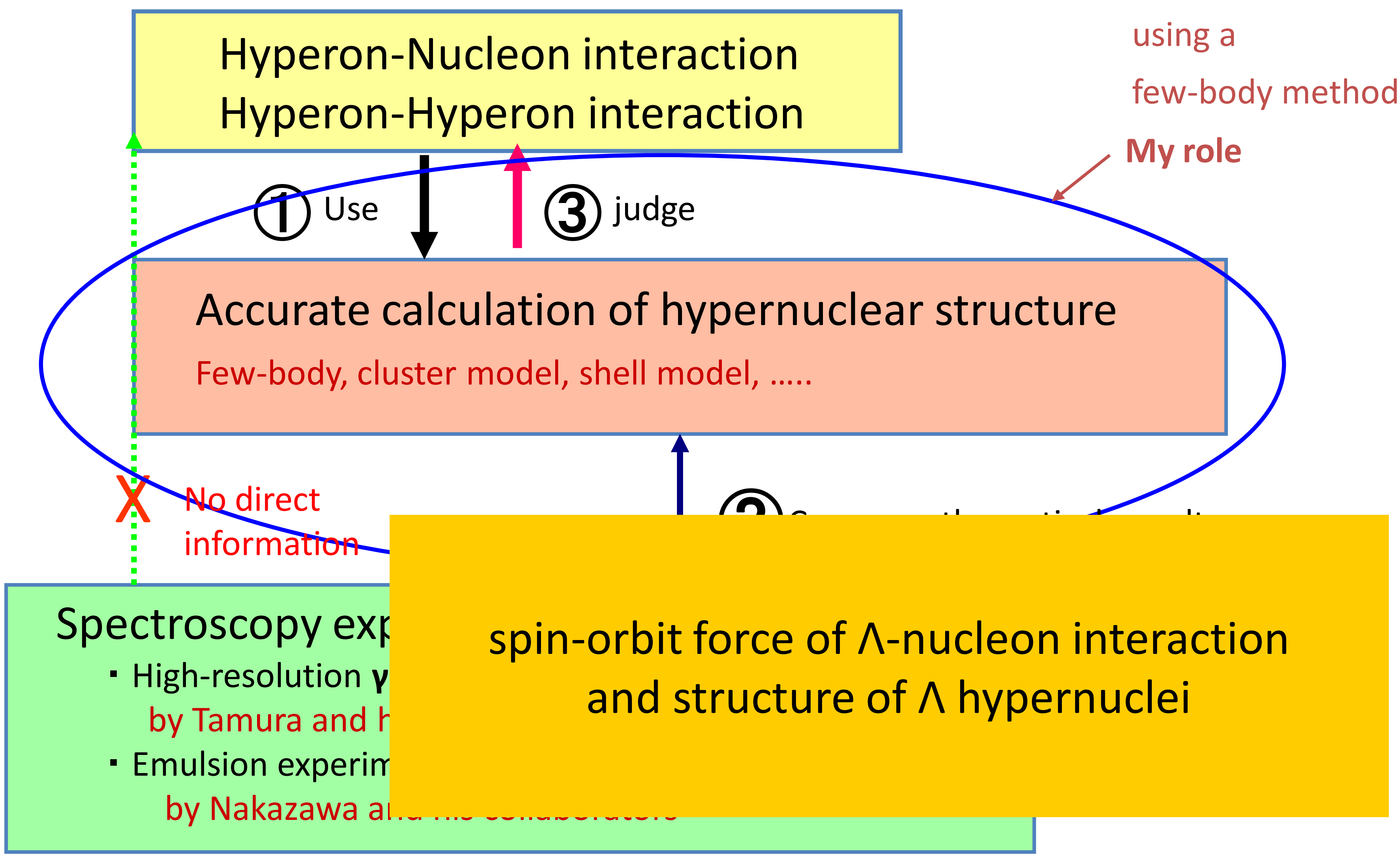
YN and YY potential models so far proposed (ex. Nijmegen, Julich, Kyoto-Niigata) have large ambiguity.

l data of hyperon-nucleon scattering data :40



2.7: バリオン－バリオン相互作用の研究の端緒となった核子－核子散乱の

Strategy to determine Hyperon-Nucleon and Hyperon-Hyperon interactions from the studies of light Hypernuclear structure



Our few-body caluclation method

Gaussian Expansion Method (GEM) , since 1987,

- A variational method using Gaussian basis functions
- Take all the sets of Jacobi coordinates

Developed by Kyushu Univ. Group,
Kamimura and his collaborators.

Review article :
E. Hiyama, M. Kamimura and Y. Kino,
Prog. Part. Nucl. Phys. 51 (2003), 223.

High-precision calculations of various 3- and 4-body systems:

Exotic atoms / molecules ,
3- and 4-nucleon systems,
multi-cluster structure of light nuclei,
Light hypernuclei,
3-quark systems,

In order to solve the **Schrödinger equation, we use Rayleigh-Ritz variational method and we obtain eigen value E and eigen function Ψ.**

$$(\mathbf{H} - \mathbf{E})\,\boldsymbol{\Psi} = \mathbf{0}$$

Here, we expand the total wavefunction in terms of a set of L^2-integrable basis function $\{\Phi_n$:n=1,….,N)}

$$\boldsymbol{\Psi} = \sum_{\mathbf{n}=1}^{\mathbf{N}} \mathbf{C}_{\mathbf{n}}\,\boldsymbol{\Phi}_{\mathbf{n}}$$

The Rayleigh-Ritz variational principle leads to a generalized matrix eigenvalue problem.

$$\langle\, \boldsymbol{\Phi}_{\mathbf{i}} \,|\, \mathbf{H} - \mathbf{E} \,|\, \underbrace{\sum_{\mathbf{n}=1}^{\mathbf{N}} \mathbf{C}_{\mathbf{n}}\,\boldsymbol{\Phi}_{\mathbf{n}}}_{=\ \boldsymbol{\Psi}} \,\rangle = \mathbf{0}\,, \qquad (\mathbf{i} = \mathbf{1}, \ldots, \mathbf{N})$$

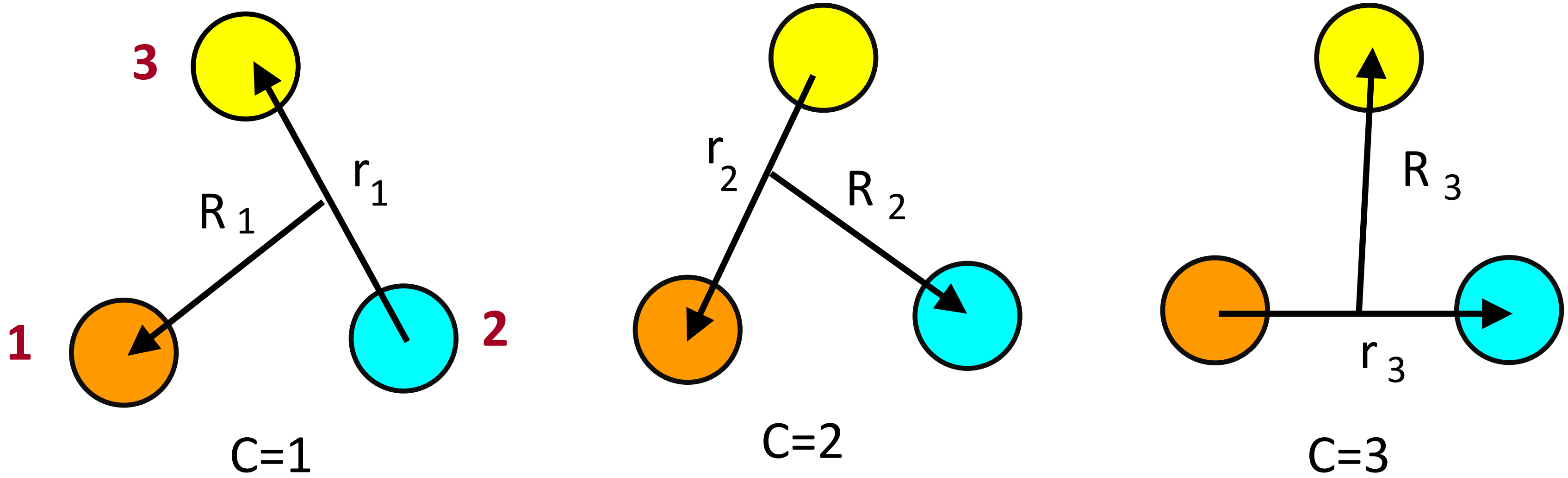
Where the energy and overlap matrix elements are given by

$$H_{in} = \langle \Phi_i \mid H \mid \Phi_n \rangle$$

$$N_{in} = \langle \Phi_i \mid 1 \mid \Phi_n \rangle$$

Next, by solving eigenstate problem, we get eigenenergy E and unknown coefficients C_n .

$$\left[(H_{in}) - E\,(N_{in}) \right] \left[\mathbf{C_n} \right] = 0$$

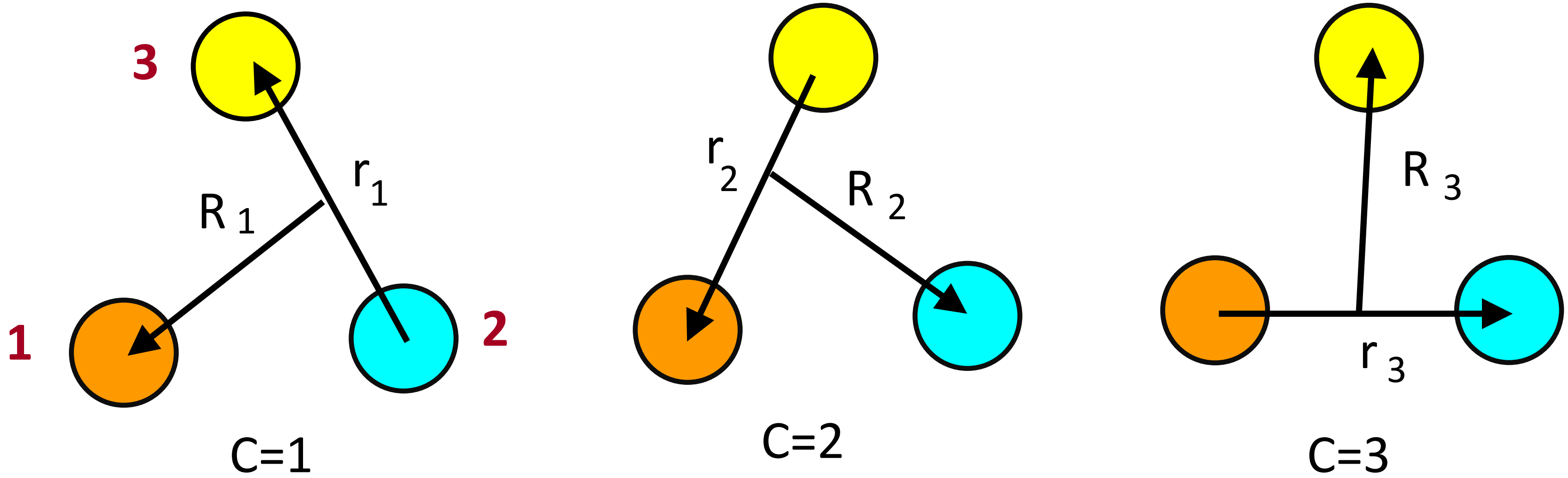


$$(H - E)\Psi_{JM} = 0$$

$$H = T + V_1(r_1) + V_2(r_2) + V_3(r_3)$$

$$T = -\frac{\hbar^2}{2\mu_{r_c}}\nabla^2_{\mathrm{r}_c} - \frac{\hbar^2}{2\mu_{R_c}}\nabla^2_{\mathrm{R}_c} \qquad (c = 1, 2, \text{ or } 3)$$

$$\Psi_{JM} = \Phi^{(1)}_{JM}(\mathrm{r}_1, \mathrm{R}_1) + \Phi^{(2)}_{JM}(\mathrm{r}_2, \mathrm{R}_2) + \Phi^{(3)}_{JM}(\mathrm{r}_3, \mathrm{R}_3)$$



$$\Psi_{JM} = \Phi^{(1)}_{JM}(\mathrm{r}_1, \mathrm{R}_1) + \Phi^{(2)}_{JM}(\mathrm{r}_2, \mathrm{R}_2) + \Phi^{(3)}_{JM}(\mathrm{r}_3, \mathrm{R}_3)$$

Basis functions of each Jacobi coordinate

$$\phi^{(c)}_{nl}(r_c)\, Y_{lm}(\widehat{\mathrm{r}}_c), \quad \psi^{(c)}_{NL}(R_c)\, Y_{LM}(\widehat{\mathrm{R}}_c), \quad (c = 1, 2, 3)$$

(θ, ϕ) (Θ, Φ)

$$\Phi^{(c)}_{JM}(\mathrm{r}_c, \mathrm{R}_c) = \sum_{nl,NL} \underline{A^{(c)}_{nl,NL}}\, \phi^{(c)}_{nl}(r_c)\, \psi^{(c)}_{NL}(R_c) \left[Y_l(\widehat{\mathrm{r}}_c) \otimes Y_L(\widehat{\mathrm{R}}_c) \right]_{JM}$$

Determined by diagonalizing H

Benchmark-test calculation of the 4-nucleon bound state

Good agreement among 7different methods

In the binding energy, r.m.s. radius and wavefunction density

TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies E_b in MeV, and the radius in fm.

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
GEM	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

ours

very different techniques and the complexity of the nuclear force chosen. Except for NCSM and EIHH, the expectation values of T and V also agree within three digits. The NCSM results are, however, still within 1% and EIHH within 1.5% of the others, but note that the EIHH results for T and V are

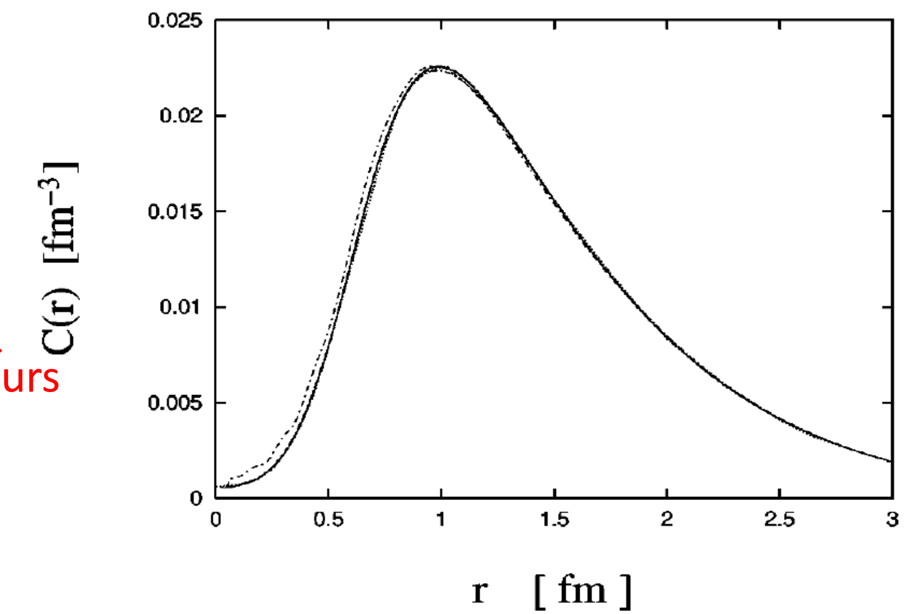
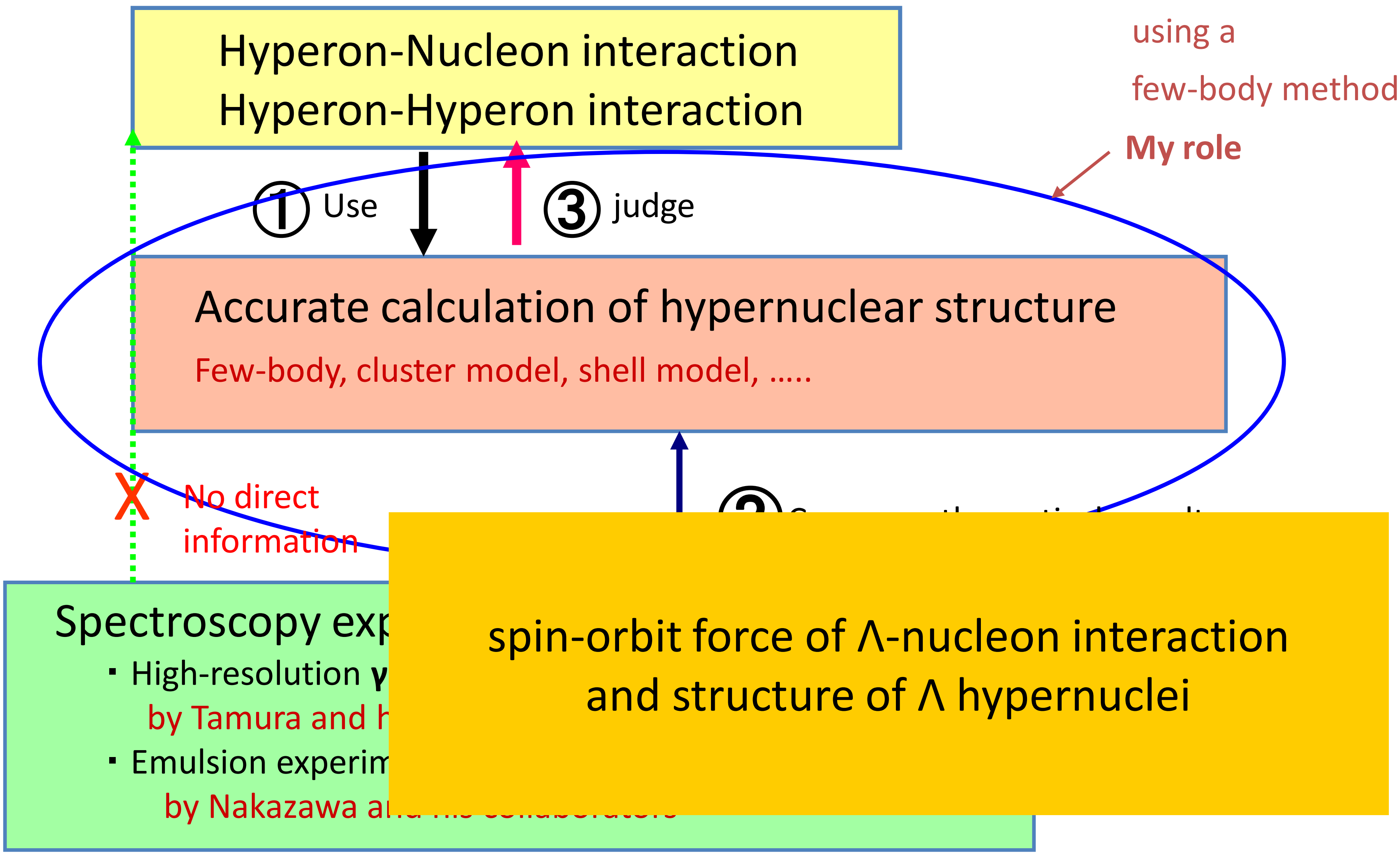


FIG. 1. Correlation functions in the different calculational schemes: EIHH (dashed-dotted curves), FY, CRCGV, SVM, HH, and NCSM (overlapping curves).

Congratulations!! I was very happy

Strategy to determine Hyperon-Nucleon and Hyperon-Hyperon interactions from the studies of light Hypernuclear structure



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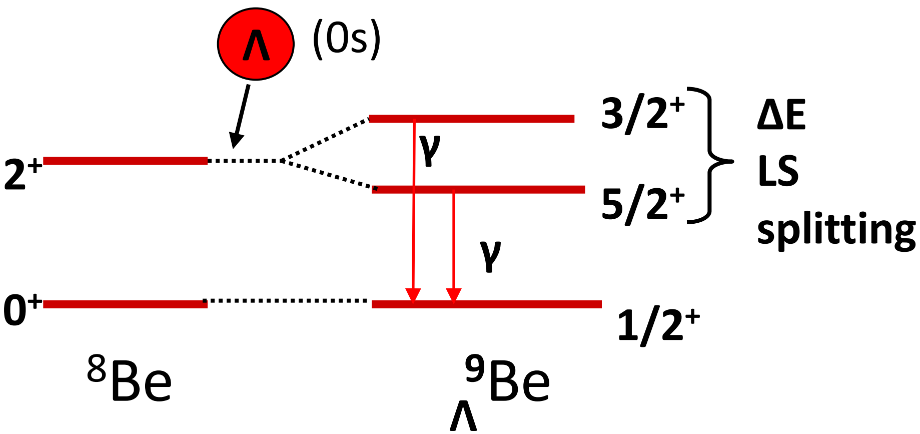

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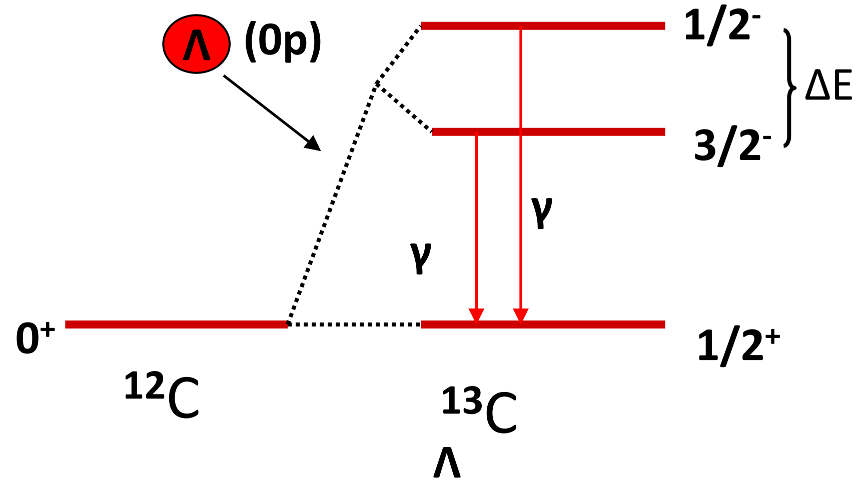
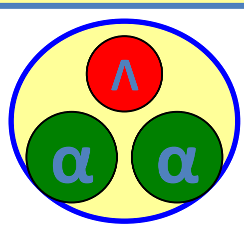
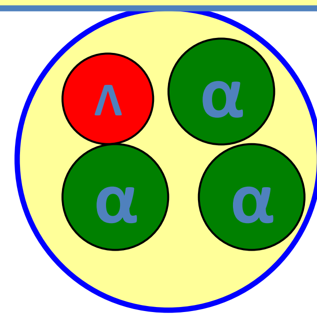


3- and 4-body calculations:
E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. Lett. 85 (2000) 270.



$^{9}_{\Lambda}$Be



$^{13}_{\Lambda}$C

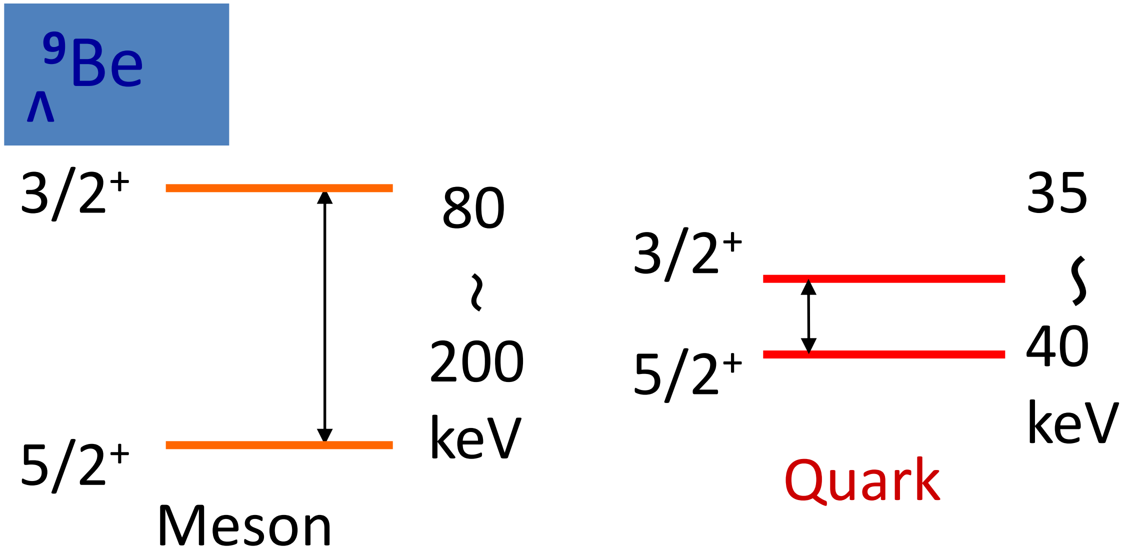
YN LS force

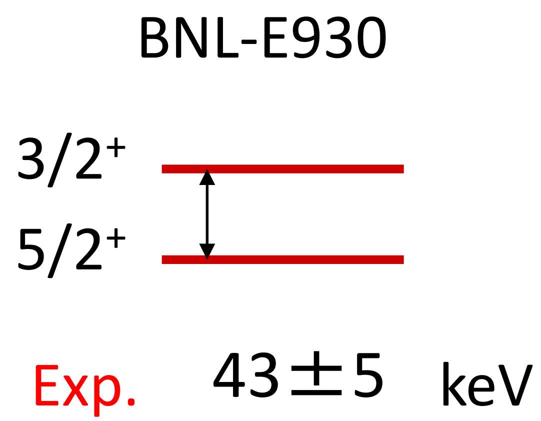
1) Meson theory : Nijmegen Model D, F, soft core'97 a – f.

2) Qurak model : Kyoto-Niigata, FSS

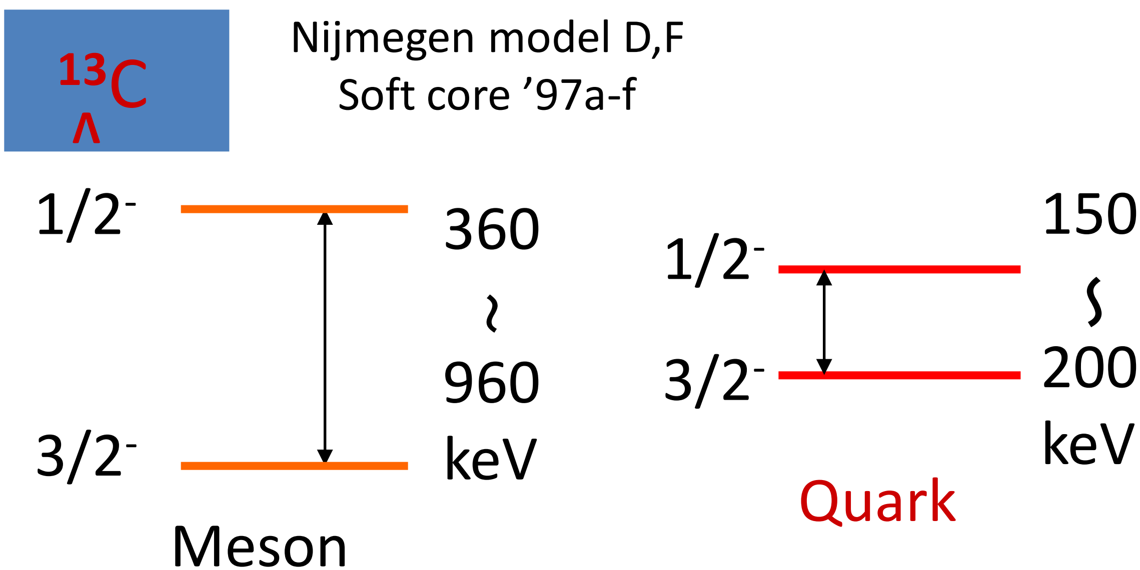
ΛN LS force and $^{9}_{\Lambda}Be$ and $^{13}_{\Lambda}C$

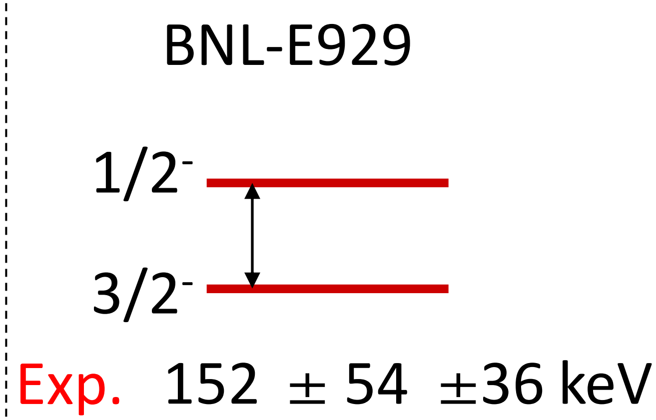
H. Akikawa et al.
Phys. Rev. Lett. **88** (2002) 082501; H. Tamura et al.
Nucl. Phys. A**754** (2005) 58c





Nijmegen model D,F
Soft core ’97a-f





S.Ajimura et al.
Phys. Rev. Lett. 86,(2001) 4255

Strategy to determine Hyperon-Nucleon and Hyperon-Hyperon interactions from the studies of light Hypernuclear structure

ΛN spin-orbit potentials

Meson based :Nijmegen
Quark based :Kyoto-Niigata

① Use

③ ・Quark based interaction gives desirable spin-orbit strength

・suggest to Nijmegen group to improve the spin-orbit strength

Accurate calculation of energy splitting ($^{9}_{\Lambda}$Be and $^{13}_{\Lambda}$C) using the spin-orbit potentials

② comparison

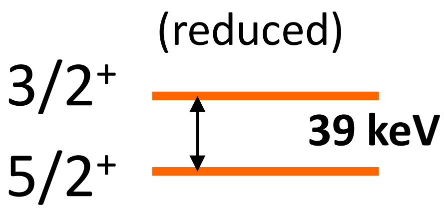
Spectroscopy experiments

High-resolution **γ**-ray spectroscopy experiment in $^{9}_{\Lambda}$Be and $^{13}_{\Lambda}$C
by Tamura and his collaborators
by Kishimoto and his collaborators

LS splitting in $^{9}_{\Lambda}\mathrm{Be}$

Recently, a new spin-orbit ΛN interaction based on meson theory, extended soft core potential 06 (ESC06) by Nijmegen group

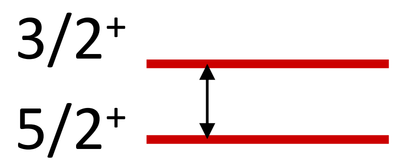
$^{9}_{\Lambda}\mathrm{Be}$



ESC06

Good agreement

BNL-E930



Exp. 43±5 keV

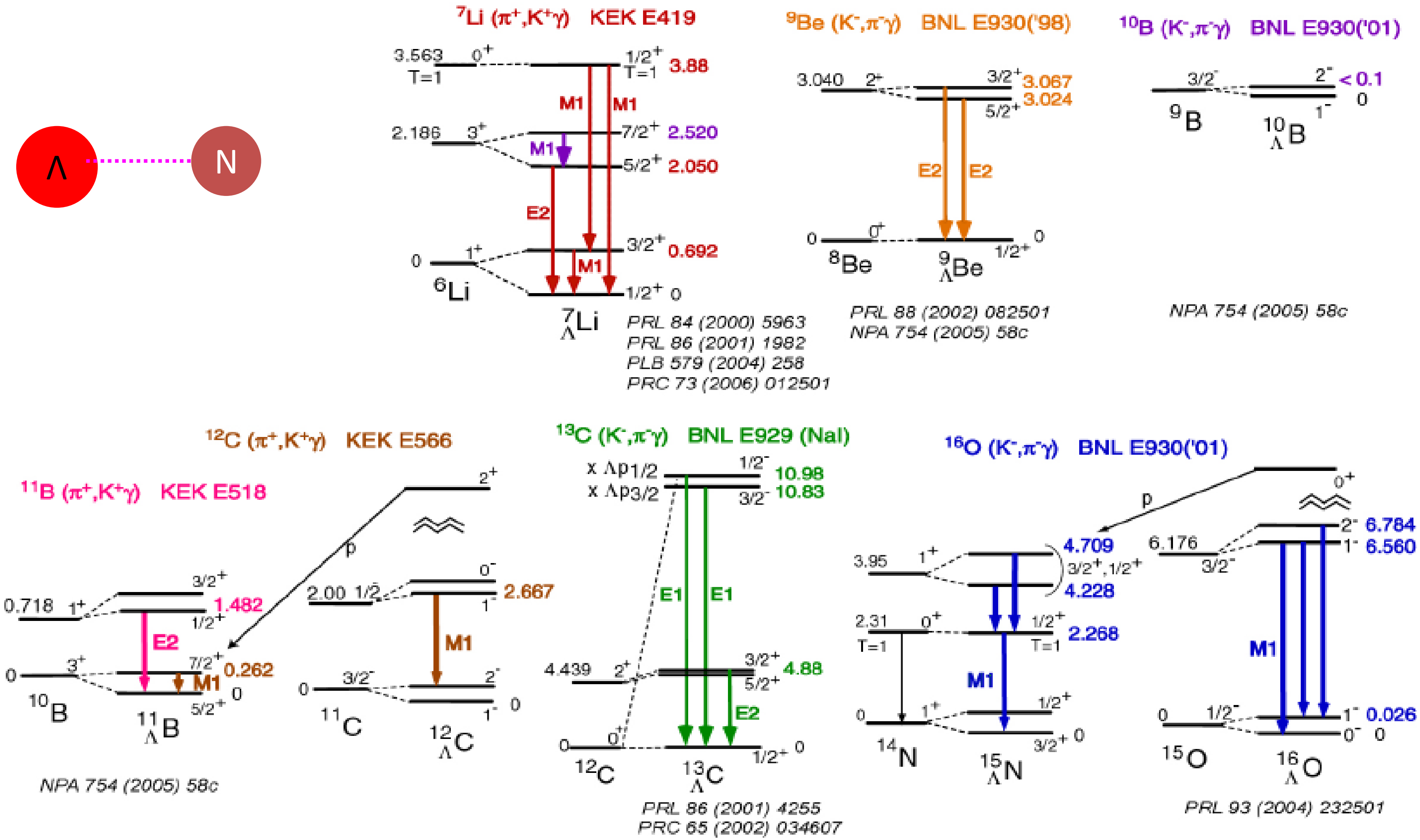
Hiyama (2007)

H. Akikawa et al.
Phys. Rev. Lett. 88,(2002)82501;
H. Tamura et al.
Nucl. Phys. A754,58c(2005)

Desirable strength of ΛN spin-orbit force was determined.

Hypernuclear γ-ray data since 1998

Taken by Tamura



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

- Millener (p-shell model),
- Hiyama (few-body)

In S= -1 sector,
what are the open questions in YN interaction?

(1) Charge symmetry breaking

(2) ΛN—ΣN coupling

SKIP

J-PARC : Day-1 experiment

- E13 "γ-ray spectroscopy of light hypernuclei"
  by Tamura and his collaborators

$^{11}_{\Lambda}B$ $^{4}_{\Lambda}He$

- E10 "Study on Λ-hypernuclei with the doubleCharge-Exchange reaction"
  by Sakaguchi , Fukuda and his collaboratiors

$^{9}_{\Lambda}He$ $^{6}_{\Lambda}H$

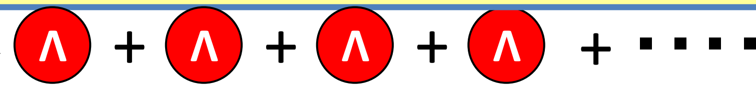
S=-2 hypernuclei

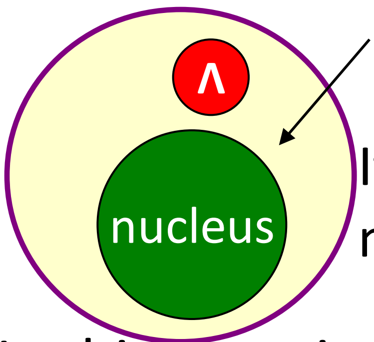
and

YY interaction

So far, we have discussed about single Λ hypernuclei.

What is the structure when one or more Λs are added to a nucleus?





It is conjectured that extreme limit, which includes many Λs in nuclear matter, is the core of a neutron star.

In this meaning, the sector of S=-2 nuclei , double Λ hypernuclei and Ξ hypernuclei is just the entrance to the multi-strangeness world.

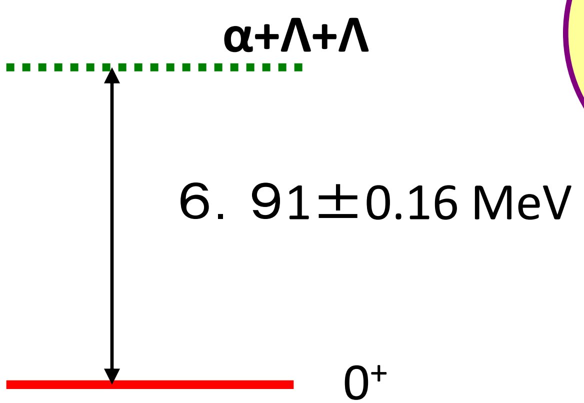
However, we have hardly any knowledge of the YY interaction because there exist no YY scattering data.

Then, in order to understand the YY interaction, it is crucial to study the structure of double Λ hypernuclei and Ξ hypernuclei. But, up to 2000, we have no observed bound double Λ hypernuclei.

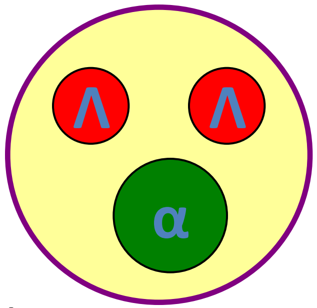
In 2001, the epoch-making data has been reported by the KEK-E373 experiment.

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

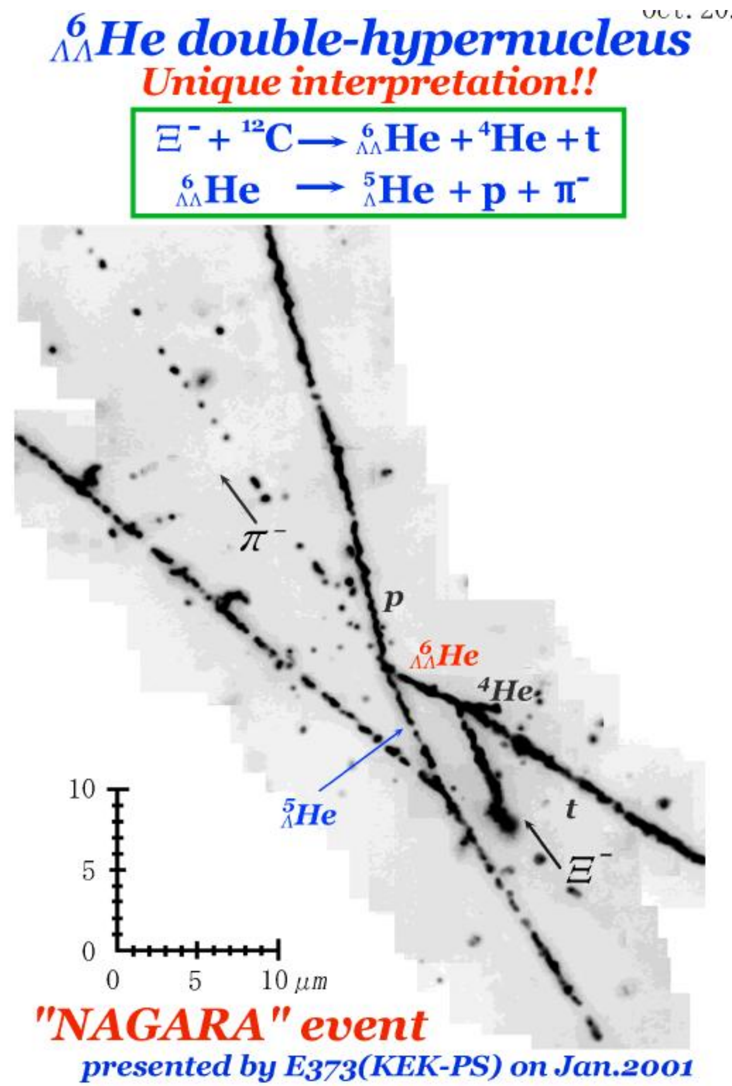
Uniquely identified without ambiguity for the first time



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



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



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

Strategy of how to determine YY interaction from the study of light hypernuclear structure

YY interaction
Nijmegen model D

① use

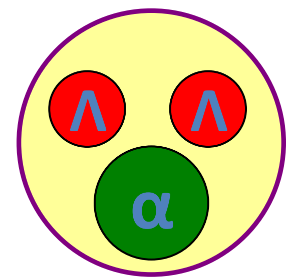
③ Suggest reducing the strength of spin-independent force by half

Accurate structure calculation

② compare between the theoretical result and the experimental data of the biding energy of ${}_{\Lambda\Lambda}^{6}He$

Spectroscopic experiments
Emulsion experiment (KEK-E373)
by Nakazawa and his collaborators

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



④ **prediction of new** double Λ hypernuclei

KEK-E373 experiment analysis is still in progress.

- E07 Approved proposal at J-PARC

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

by Nakazawa and his collaborators

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**

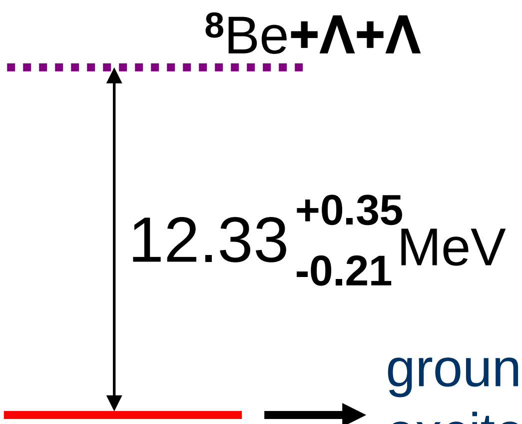
input: ΛΛ interaction to reproduce the observed binding energy of $^{6}He_{\Lambda\Lambda}$

↓

the identification of the state

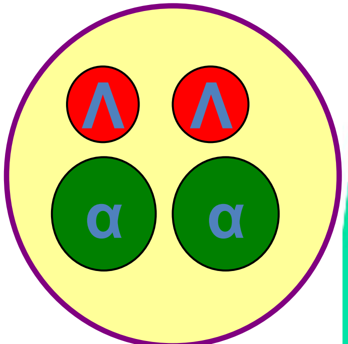
Successful example to determine spin-parity of double Λ hypernucleus --- Demachi-Yanagi event for $^{10}_{\Lambda\Lambda}$Be

Observation of $^{10}_{\Lambda\Lambda}$Be --- KEK-E373 experiment

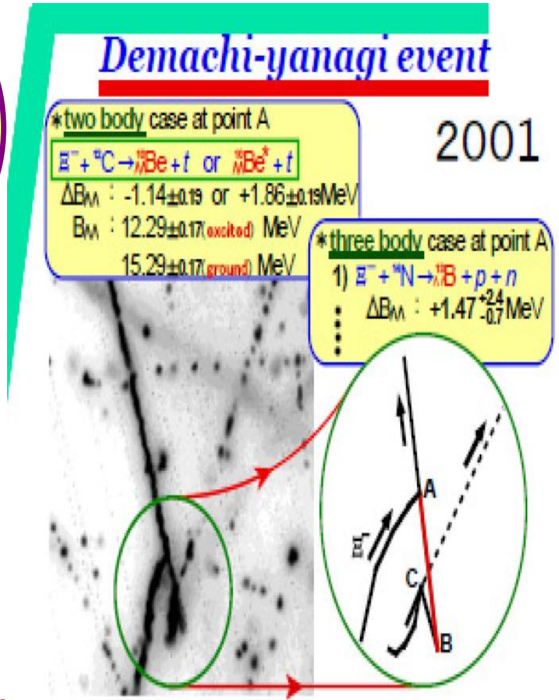


$^{10}_{\Lambda\Lambda}$Be

ground state ?
excited state ?



$^{10}_{\Lambda\Lambda}$Be

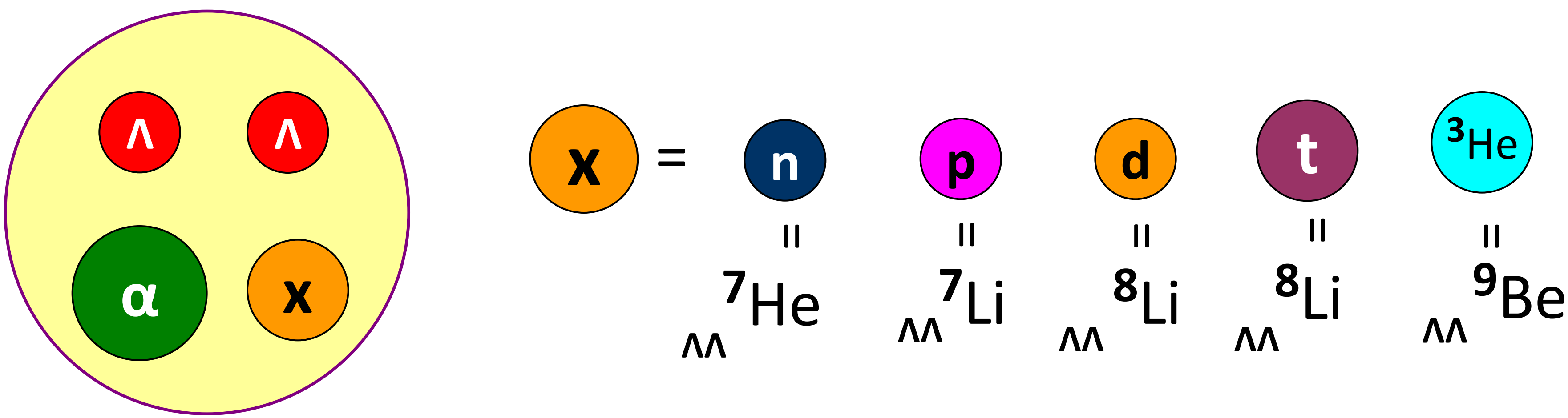


Demachi-Yanagi event

Hoping to observe new double Λ hypernuclei in future experiments, I predicted level structures of these double Λ hypernuclei within the framework of the α+x+Λ+Λ 4-body model.

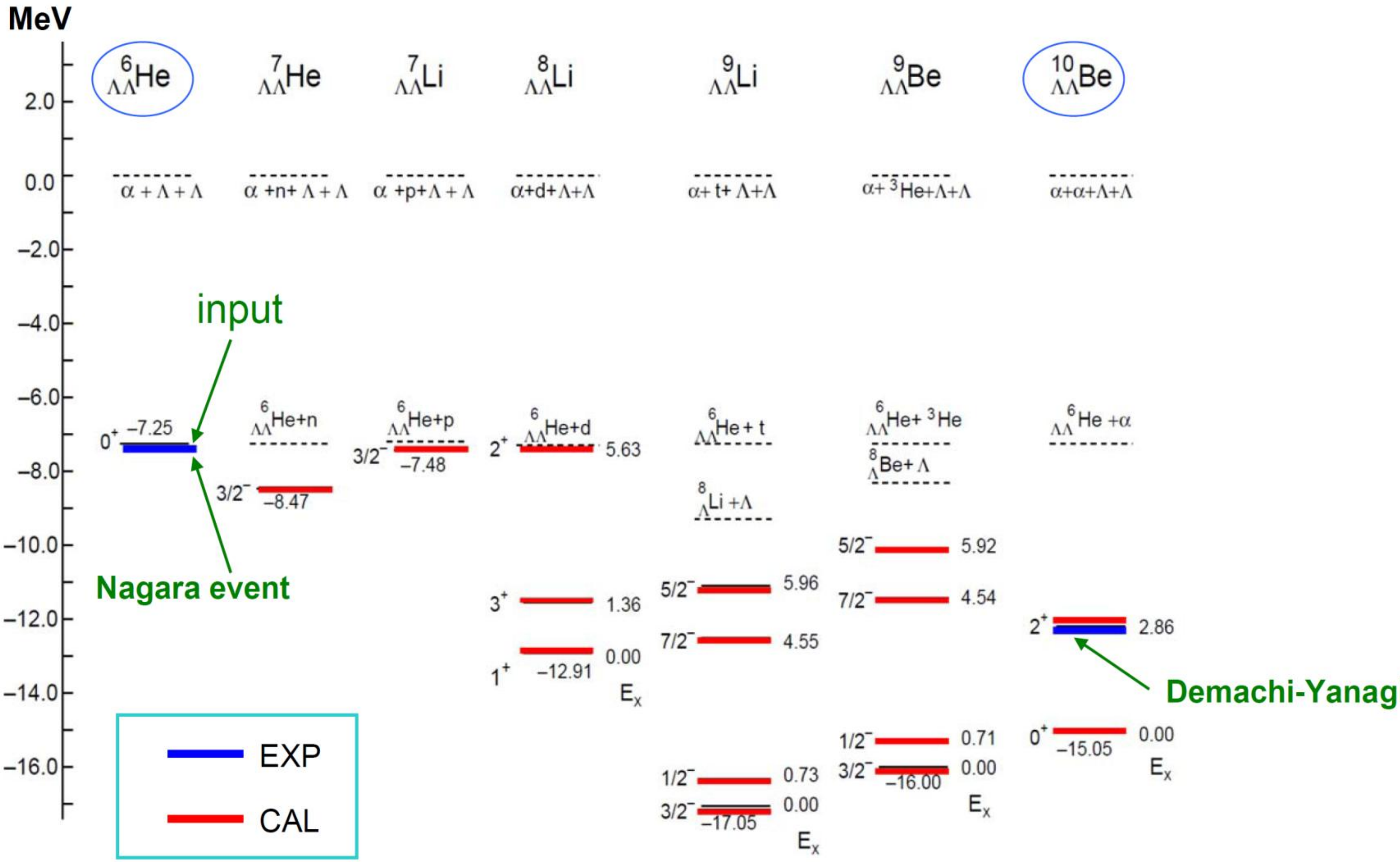
E. Hiyama, M. Kamimura, T. Motoba, T.Yamada and Y. Yamamoto

Phys. Rev. C66, 024007 (2002)



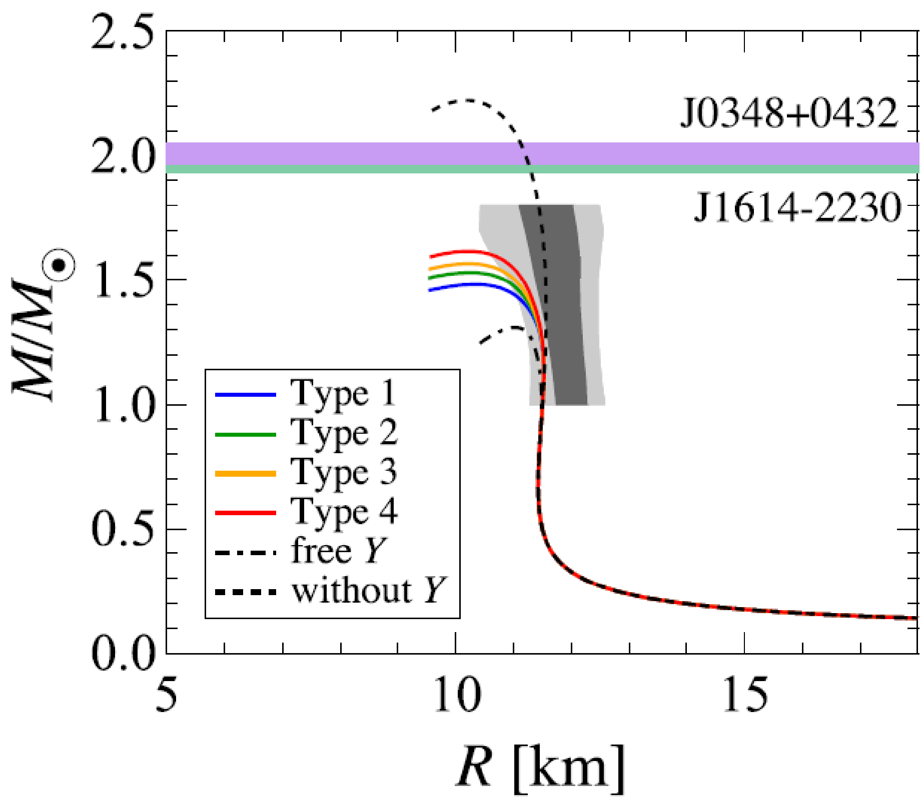
Spectroscopy of ΛΛ-hypernuclei

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



I have been looking forward to having new data in this mass-number region.

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



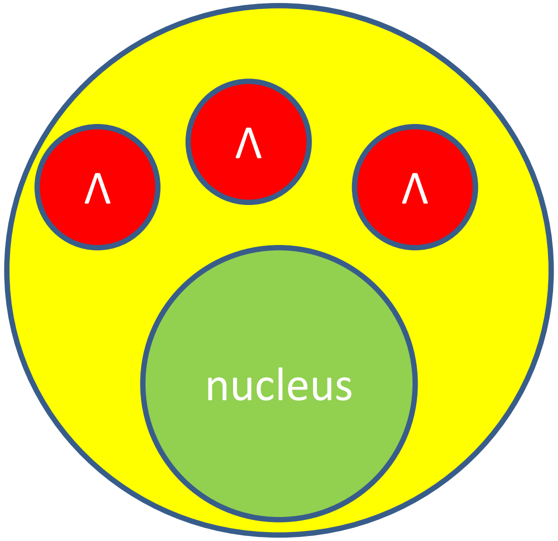
H. Togashi, E.H., Y. Yamamoto, and M. Takano, PRC93, 035808 (2016).

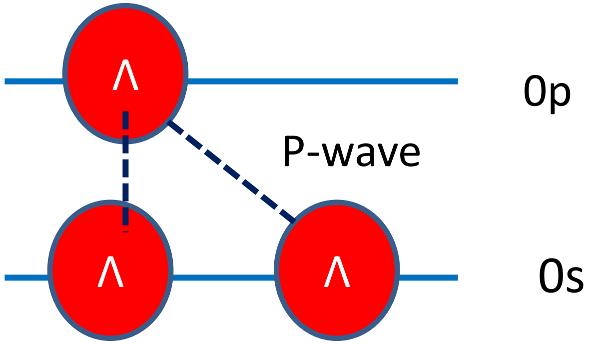
TYPE1:attractive ➡ TYPE2:less attractive ➡ TYPE4:repulsive

⬇

Similar with odd-state of ΛN interaction

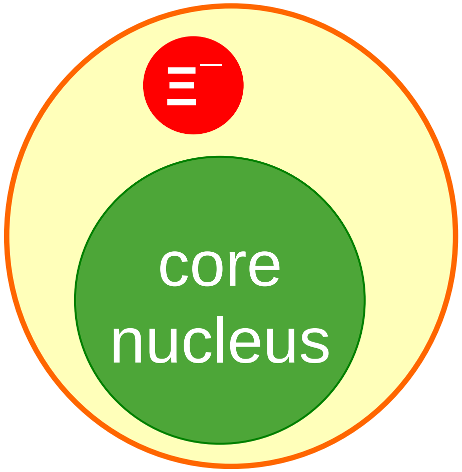
To obtain odd-state (p-wave) interaction of ΛΛ interaction,
I propose you to perform search experiment of triple Λ hypernucleus.





But, I do not know to produce triple Λ hypernuclei currently.

Ξ hypernuclei



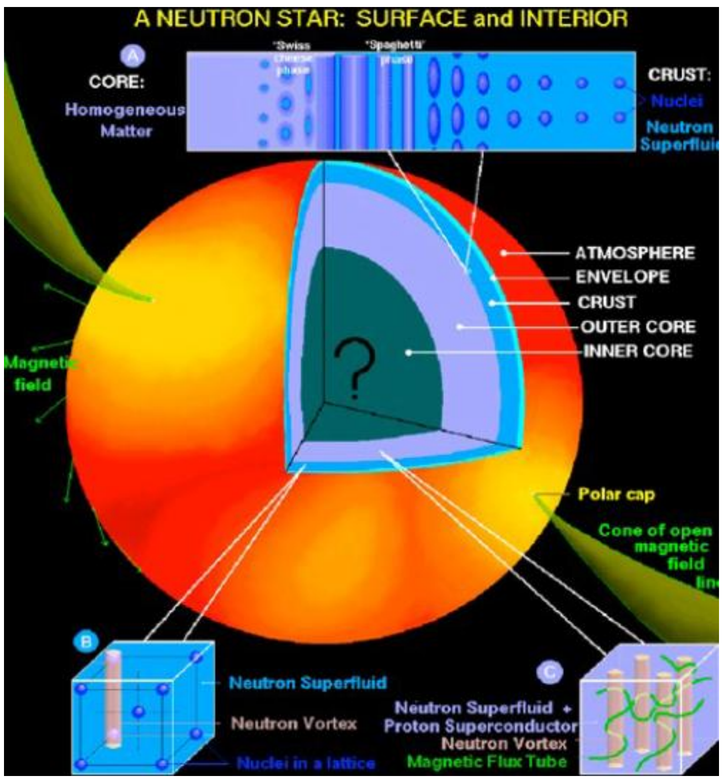
For the study of ΞN interaction, it is important to study the structure of Ξ hypernuclei.

This is related to maximum mass of neutron star.

Major goals of hypernuclear physics

To understand structure of few-body and many-body nuclei (with strangeness) and also life of star

Core of neutron star



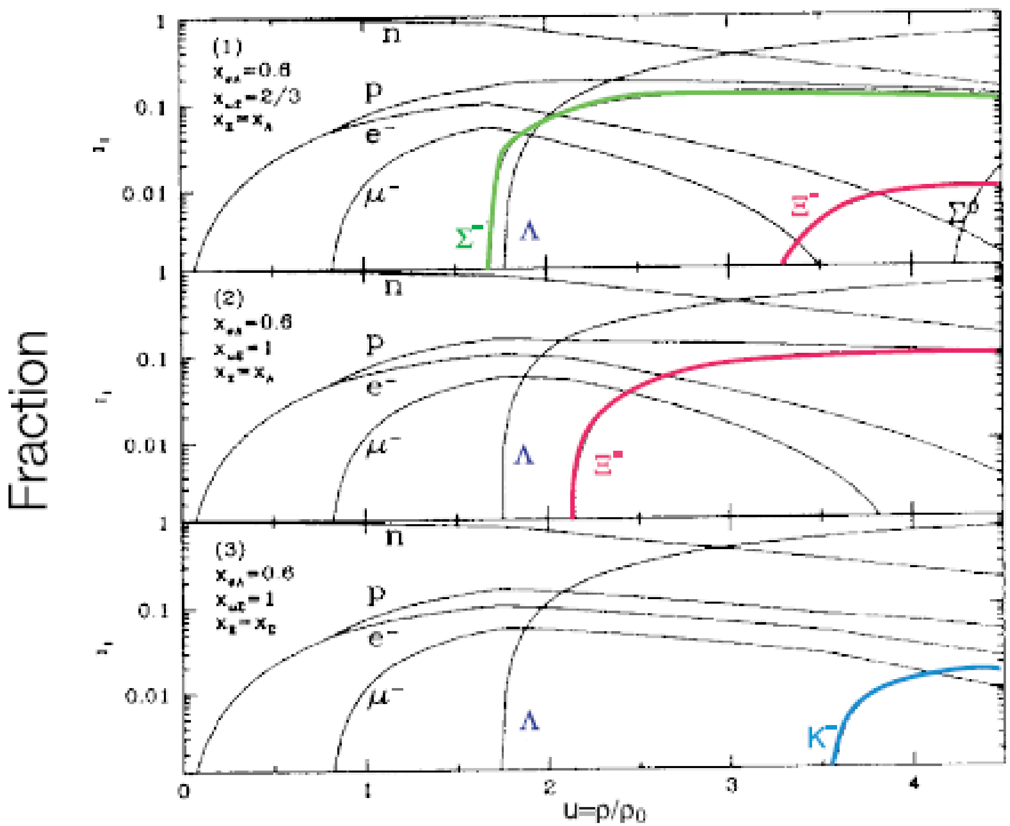
We need to understand 2 solar mass for the maximum of neutron stars. Now, it is one of hot topics in hypernuclear physics.

Question: Ξ particles are included in neutron star?

$V_{\Xi N}$:attractive=>Yes , include
$V_{\Xi N}$:repulsive=>No,

Ξ hypernuclei potential ?

- Λ, Σ^-, Ξ^-, K^- in Neutron Star Core ?
- Chemical Potential: $$\mu_B = m_B + \frac{k_F^{\ 2}}{2m_B} + U(k_F)$$



$U_\Sigma < 0$, $U_\Xi < 0$

$U_\Sigma > 0$, $U_\Xi < 0$

$U_\Sigma > 0$, $U_\Xi > 0$

- So far, we do not know whether ΞN interaction is attractive or repulsive.

It is difficult to perform ΞN scattering data.

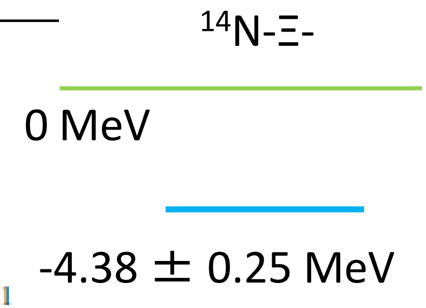
Then, it is important to observe find bound Ξ hypernuclei.

If there is bound Ξ bound hypernuclei.=>Ξ— nucleus potential should be attractive.

So far, there was NO observed bound Ξ hypernucleus.

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]

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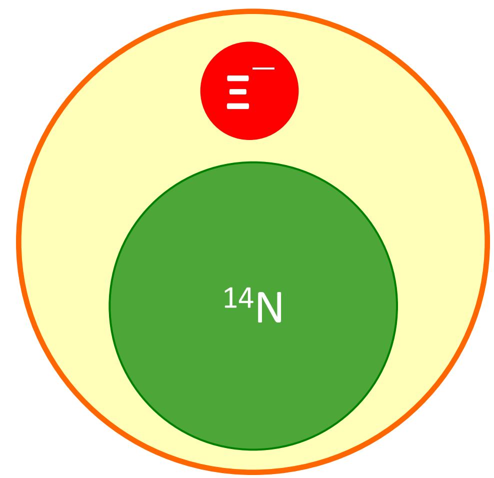
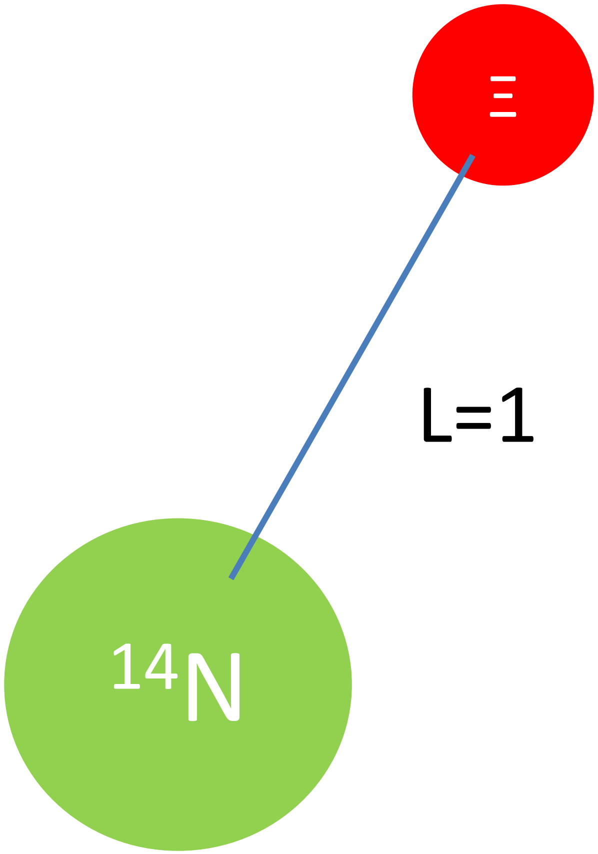
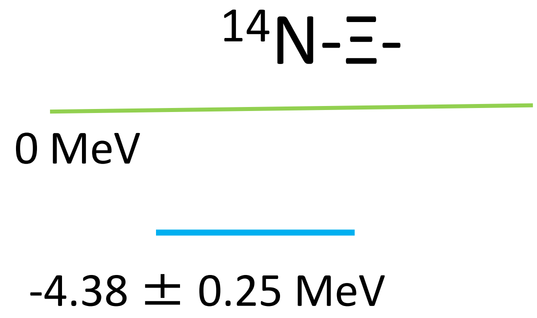
Kiso event



In 2015, we observed bound Ξ hypernucleus, for the first time in the world. Now, we understood that ΞN interaction should be attractive.





From this experimental data, we obtain information on the p-wave state of ΞN interaction.

This is very important information. But, we want to obtain Information on s-wave of ΞN interaction.

In Ξ hypernuclei,

Hot topics is

- What kinds of ΞN interaction, we should extract information on?
- What kinds of Ξ hypernuclei are suited for this purpose?

- How do we produce these Ξ hypernuclei?

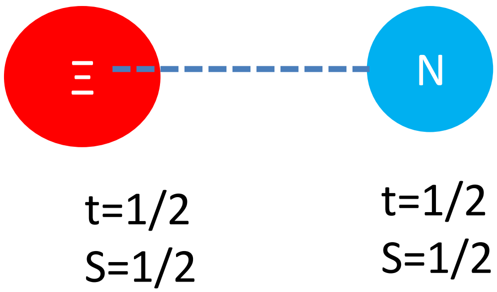
Next, we want to obtain information on s-wave of ΞN interaction.

ΞN interaction: T=0, S=0

T=0, S=1

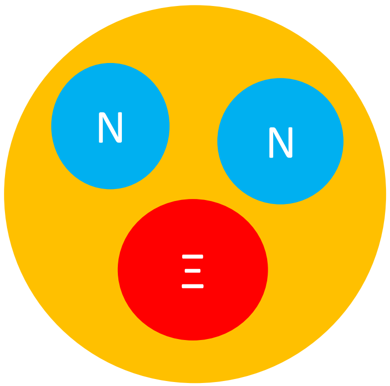
T=1, S=0

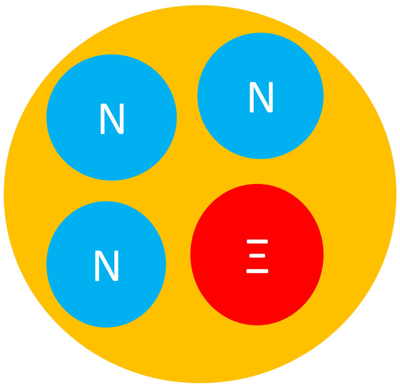
T=1, S=1

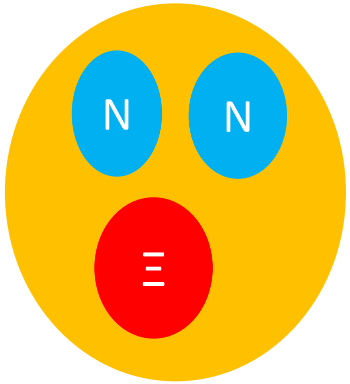


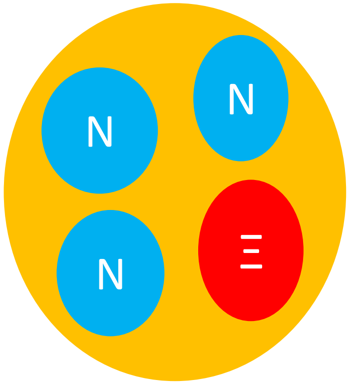
We want to know which partial wave is attractive or repulsive.

The suited systems to study are s-shell Ξ hypernuclei such as $NN\Xi$ and $NNN\Xi$ systems.









I show my new results of these light systems.

NN interaction: AV8 potential

ΞN interaction :

Nijimegen extended soft core potential (ESC08c)

Realistic potential (only ΞN channel)

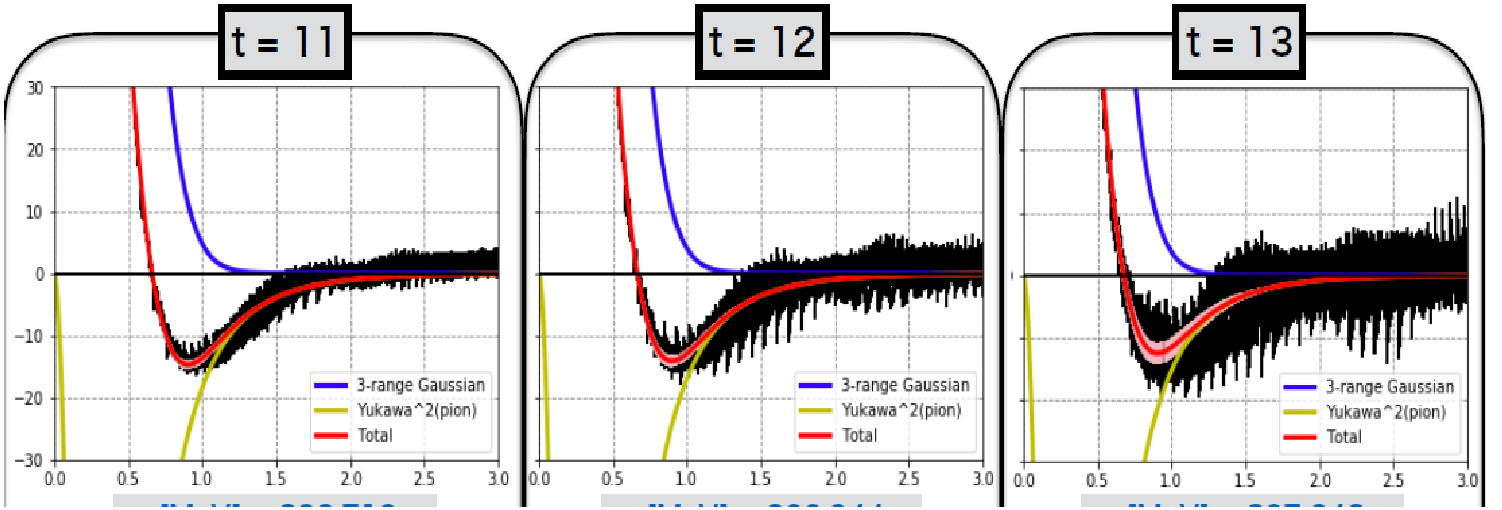
ΞN interaction by HAL collaboration (Lattice QCD calculation)

The potential was made by K. Sasaki and Miyamoto.

HAL potential

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

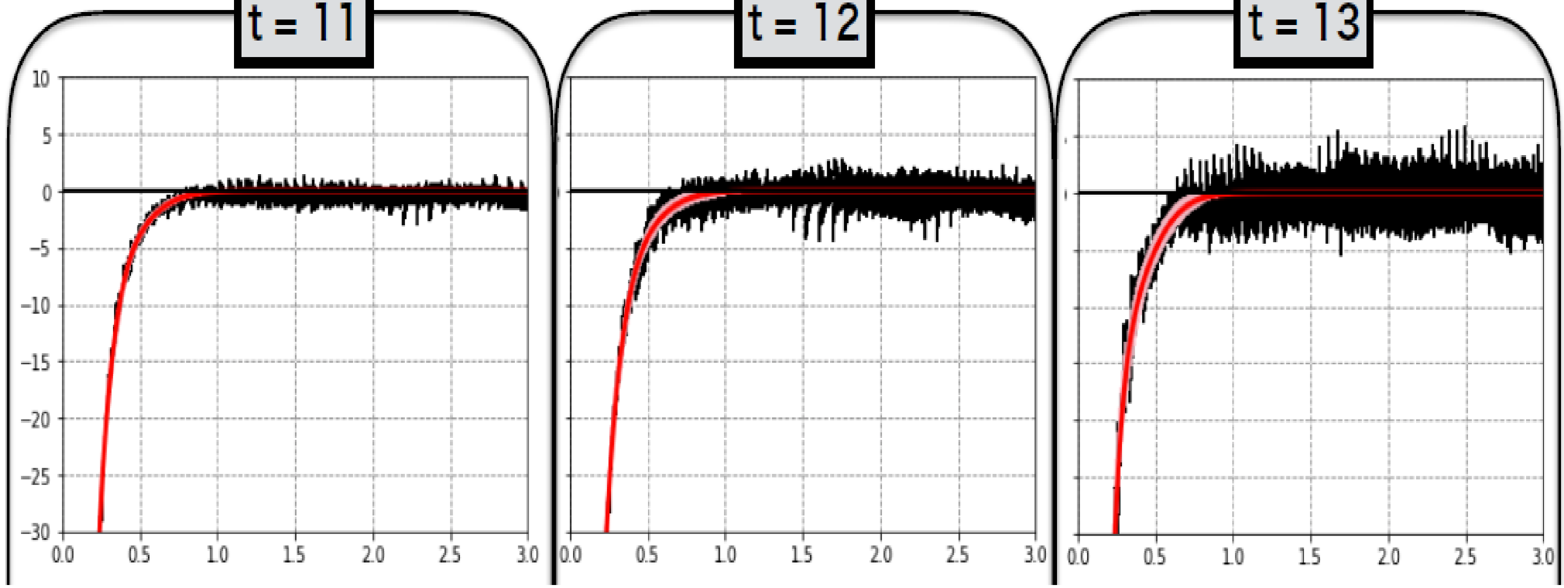
All terms are central parts only.



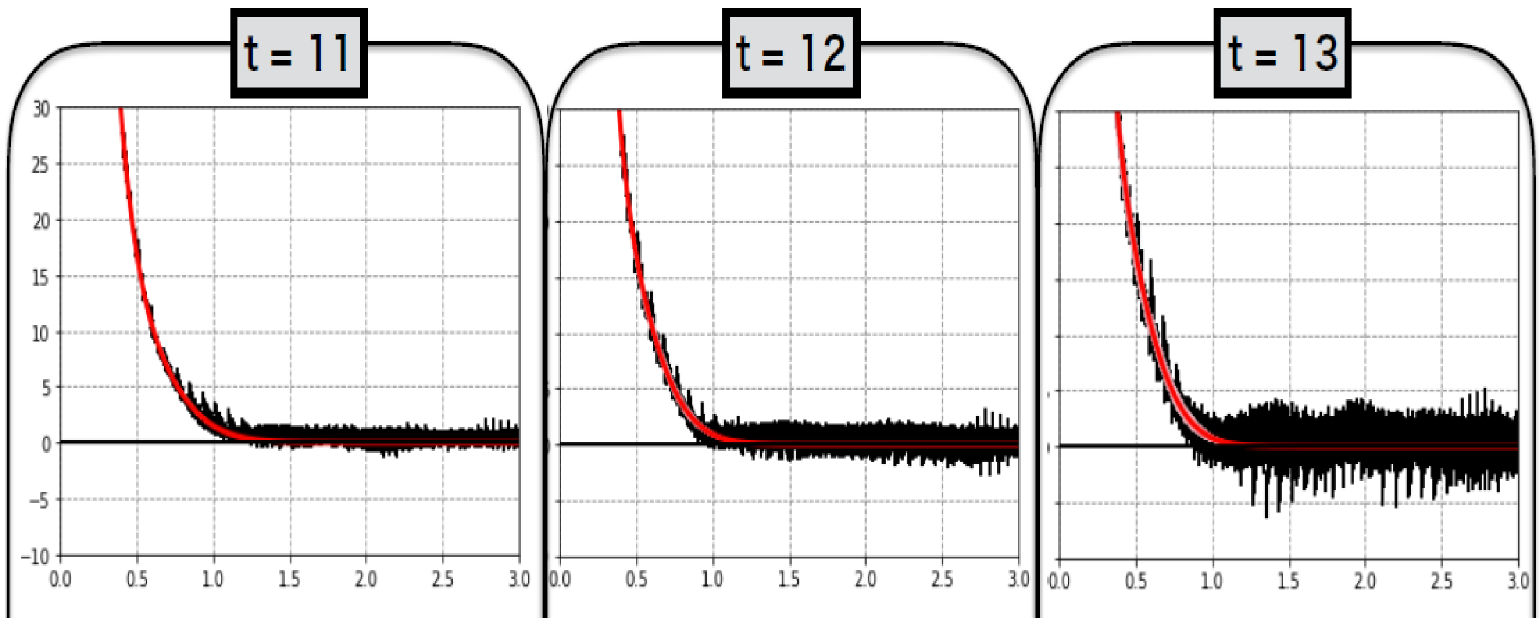
$V_0(r)$

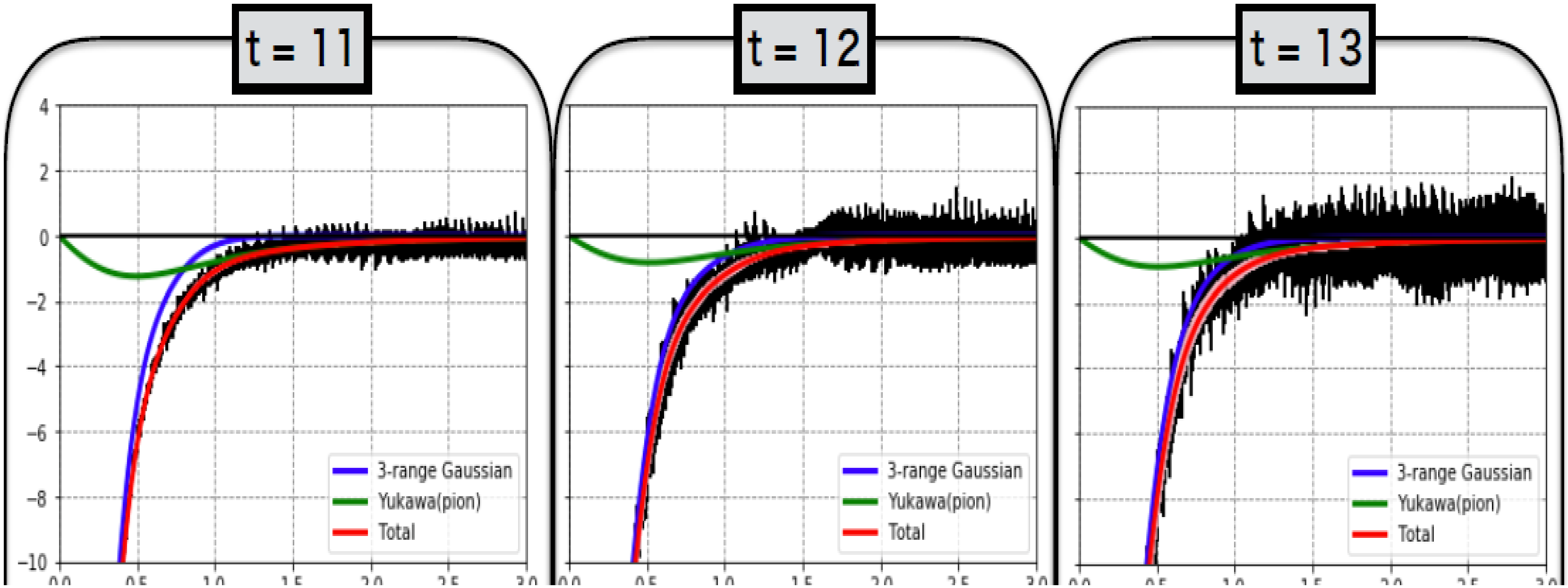
In HAL potential , the statistical errors are NOT included.

$(\sigma_{\Xi} \cdot \sigma_N) V_s(r)$



$(\tau_{\Xi} \cdot \tau_N) V_t(r)$





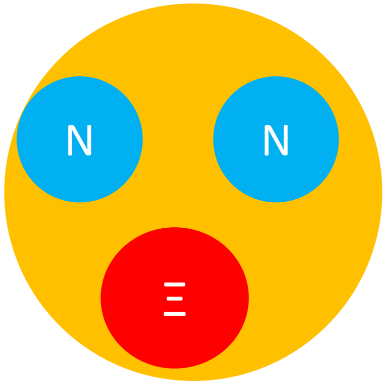
$$(\sigma_{\Xi} \cdot \sigma_N)(\tau_{\Xi} \cdot \tau_N) V_{ts}(r)$$

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

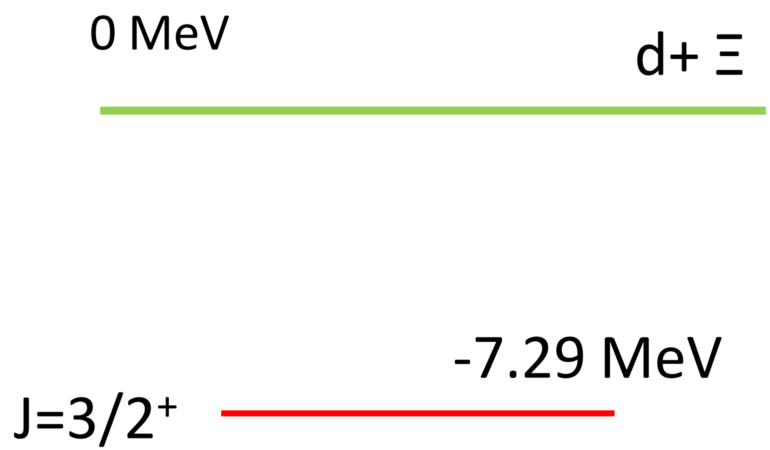
Although the spin- and isospin-components of these two models are very different between them.

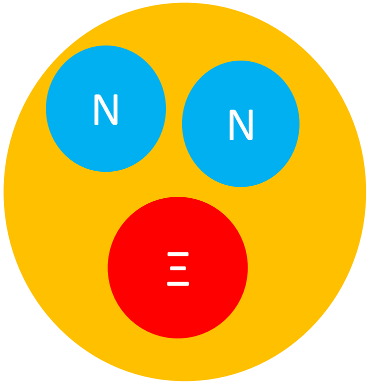
It is interesting to see the difference in the energy spectra in s-shell Ξ hypernuclei.



T=1/2, J=1/2$^+$ and J=3/2$^+$

ESC08c





T=1/2, J=1/2$^+$ and J=3/2$^+$

HAL potential

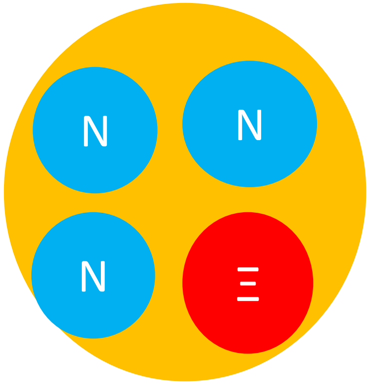
0 MeV d+ Ξ

0 MeV d+ Ξ

J=1/2+

No bound state

J=3/2$^+$



T=1 state

0 MeV 3N+Ξ

-3.54 MeV 0^+

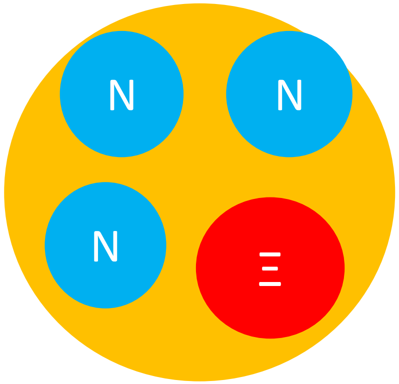
-10.08MeV 1^+

ESC08c

0 MeV 3N+Ξ

No bound state

HAL potential



T=0 state

In HAL potential , the statistical errors are NOT included.

0 MeV 3N+Ξ

-10.18 MeV $J=1^+$

ESC08c

0 MeV 3N+Ξ

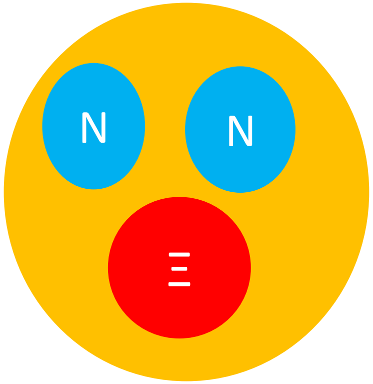
1^+

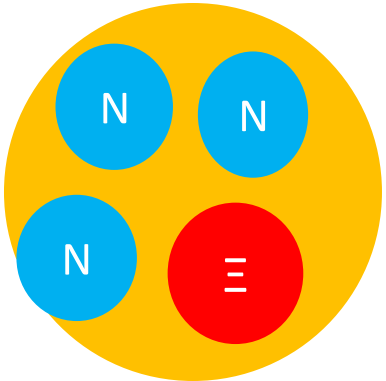
-0.05 MeV～-0.5 MeV

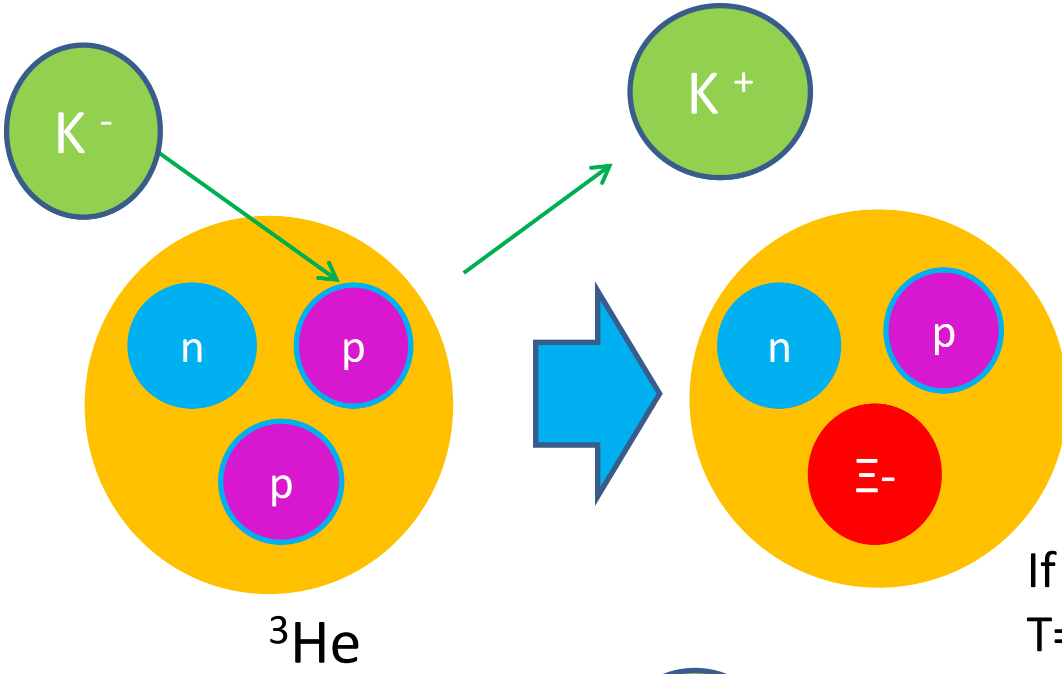
HAL potential

Summary

To investigate spin- isospin dependence on NNΞ and NNNΞ system, we calculated these systems using two types ΞN interactions, ESC08c and HAL potential.
The energies of these systems are strongly dependent on
the ΞN potential employed.
To investigate this fact, I suggest to produce these Ξ hypernuclei using ^{3}He and ^{4}He target by (K^+,K^-) reaction.

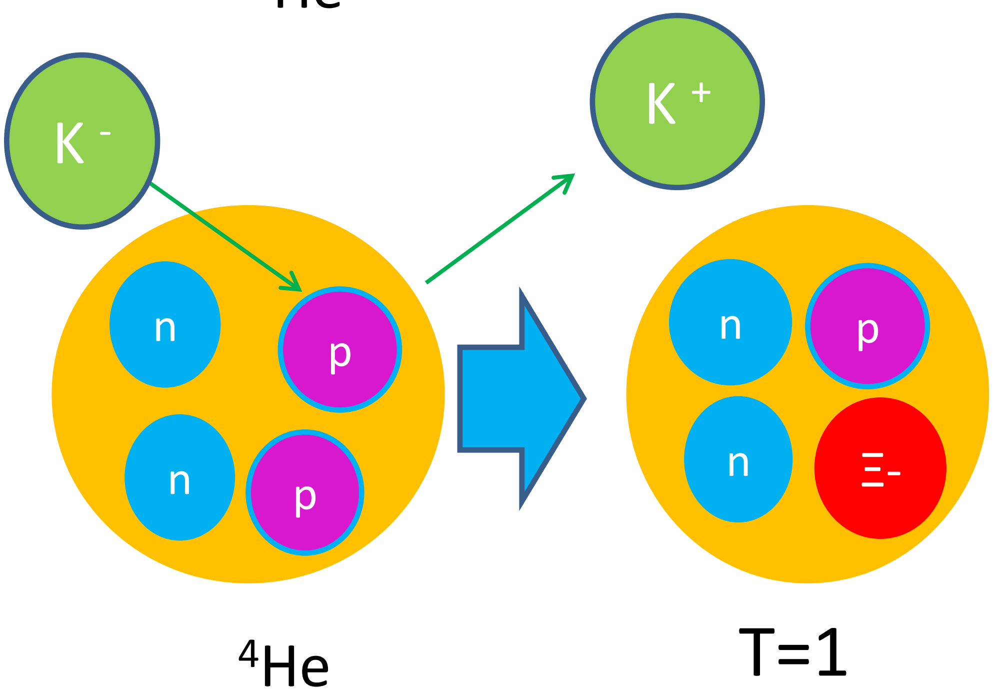






It is possible to produce NNΞ three-body system using 3He target.

T=1/2



If we use Nijimegen potential,
T=1 four-body system
becomes bound state.
But, HAL potential does not
produce bound state in T=1 system,
But produce a bound state for T=0 state.
How do we produce bound state with
T=0?
One possibility is to use heavy ion
collision experiment.

Still, we have a question.

Next, what kinds of ΞN interaction, we should obtain?

P-wave? Spin-orbit, tensor etc.

ΛΛ-ΞN interaction

- Thank you !

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7) Full professor at Kyushu Univ. (September 2017～)