Recent progress of Hypernuclear physics

E. Hiyama (Tohoku Univ./RIKEN)

Major goals of hypernuclear physics

To understand baryon-baryon interactions

Fundamental and important for the study of nuclear physics

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

⇨

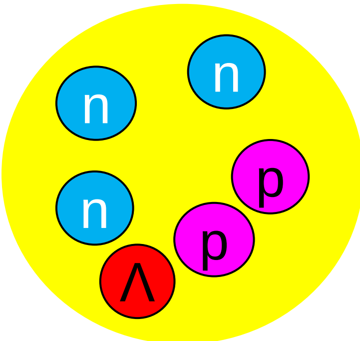
YN and YY potential models so far proposed
(ex. Nijmegen,
Julich, Kyoto-Niigata)
have large ambiguity.

Therefore, for the study of YN and YY interactions, the systematic investigation of the structure of light hypernuclei is one of the important way.

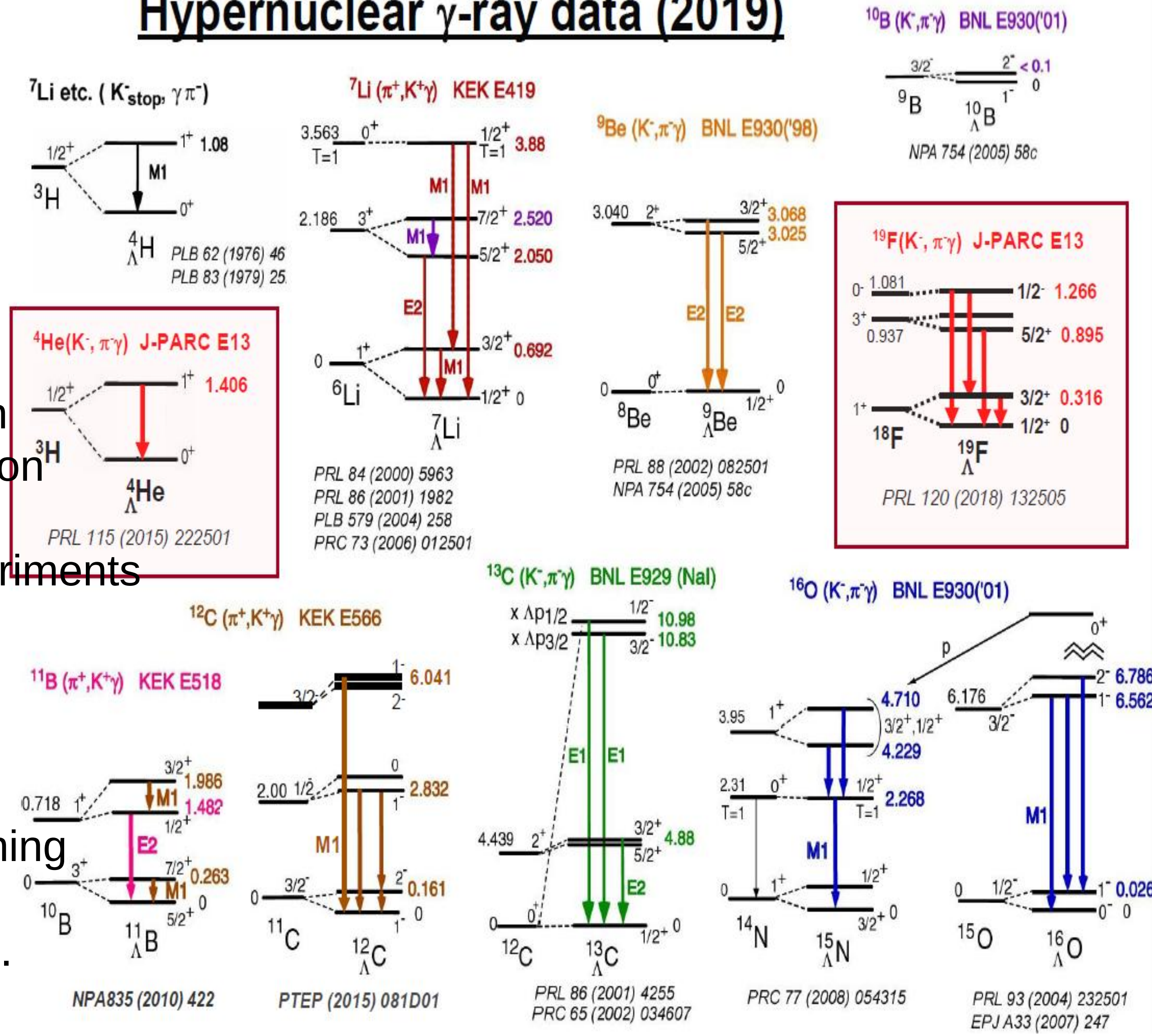
(it is planned to perform YN scattering data at J-PARC.)

Once YN and YY interactions are determined, we can predict interesting phenomena which cannot be imagined so far. In addition, we could study inner part of neutron stars which have been observed.

Since 1998



Hypernuclear γ-ray data (2019)

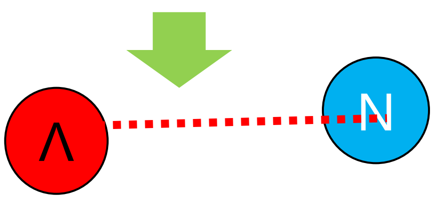


Few-body calculation

Shell model calculation

+

High-resolution experiments

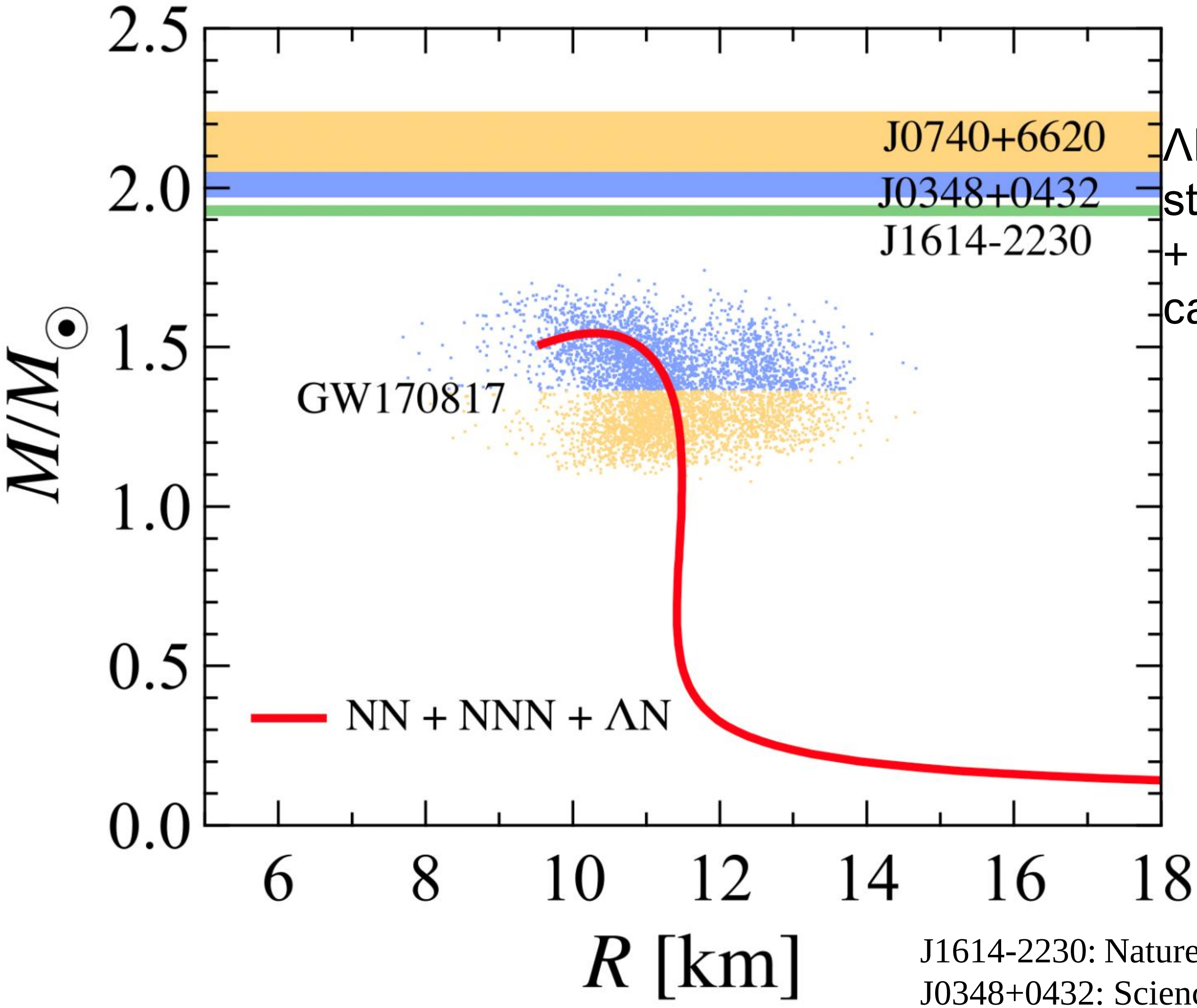


We have been obtaining information on ΛN two-body interaction.

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

Mass-Radius Relation of Neutron Stars

2021



ΛN interaction updated by structure study of Λ hypernuclei + EoS by cluster variational calculation done by Togashi

Still, the maximum mass of neutron star is less than twice of solar mass.

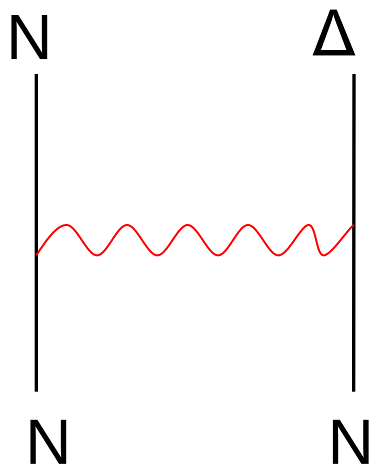
J1614-2230: Nature 467 (2010) 1081, APJ 832 (2016) 167
J0348+0432: Science 340 (2013) 1233232
J0740+6620: Nat. Astron. (2019)
GW170817: PRL 121 (2018) 161101

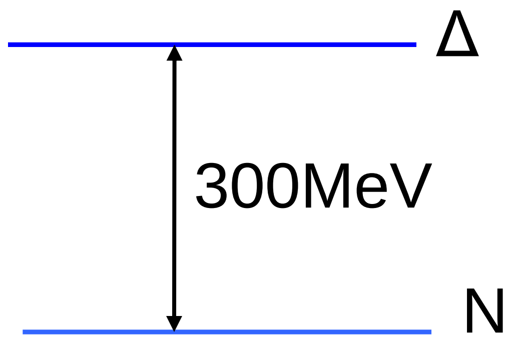
Hyperon puzzle

missing part of YN interaction: ΛN-ΣN coupling

ΛN－ΣN coupling

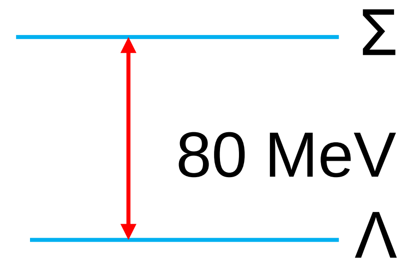
Non-strangeness sector





Probability of Δ in nuclei is not large.

S=-1



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

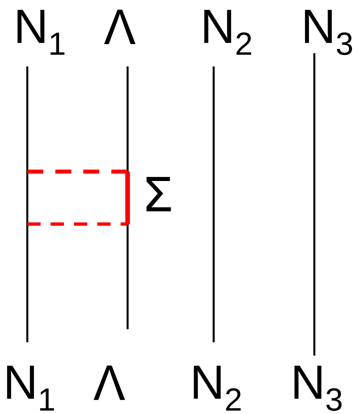
ΛN-ΣN coupling is key issue to construct YN two-body interaction completely.

Role of the ΛN-ΣN interaction

- Three-body effect

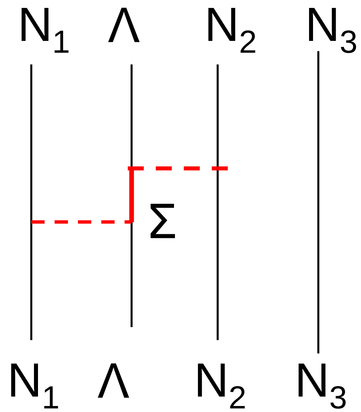
Question : How large is the Σ-excitation as effective three-body ΛNN force?

①



Effective two-body force

②



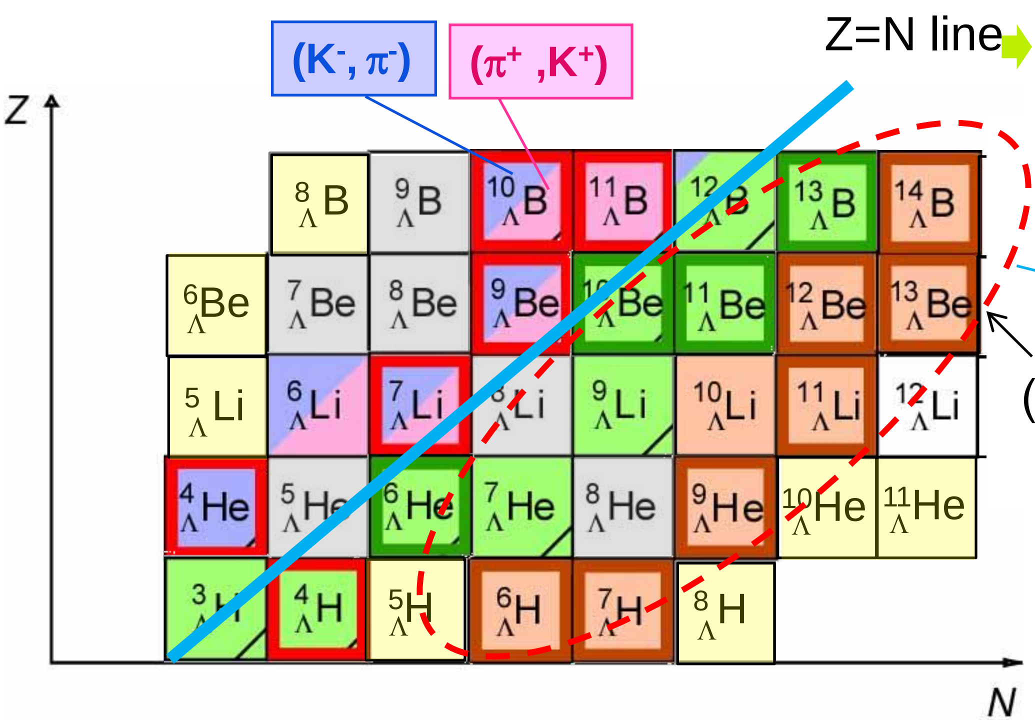
Three-body force

In the neutron matter or neutron star, three-body force might play important role.

How do we obtain information on ΛN-ΣN coupling?

(1)YN scattering experiment at J-PARC, Femtoscopic experiment

(2) To study neutron-rich Λ hypernuclei at J-PARC



difficult to obtain information on
ΛN-ΣN coupling
Total isosopin of core nuclei is small.

Total isospin is larger.
ΛN-ΣN coupling give a great contribut
to binding energy of neutron-rich Λ
hypernuclei.

These neutron-rich Λ hypernuclei are important.

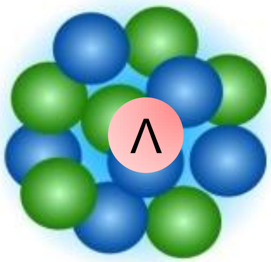
By neutron-rich Λ hypernuclei, we could obtain information on

long-range part of ΛN-ΣN coupling. Long-range part of ΛNN three-body force

Furthermore, we need short-range part of ΛNN three-body force.: important for the study
neutron star

heavier Λ hypernuclei

For example: Pb, Sn, Zr, La, Y etc. Istopes



Density of heavier nuclei is high and then, Λ particle is acting in such high dense matter.=> We could obtain information on the short-range part of ΛNN interaction.

In heavier nuclei, density becomes high.

$^{208}_{\Lambda}$Pb, $^{139}_{\Lambda}$La, $^{89}_{\Lambda}$Y: plan in the project at HIHR

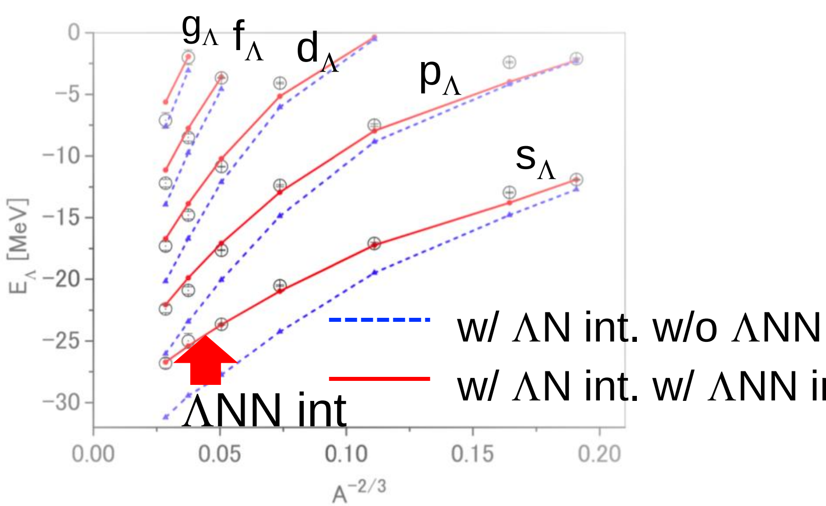
Heavy Λ hypernuclei exp. + theoretical cal.

Isotope dependence of ΛNN three-body force

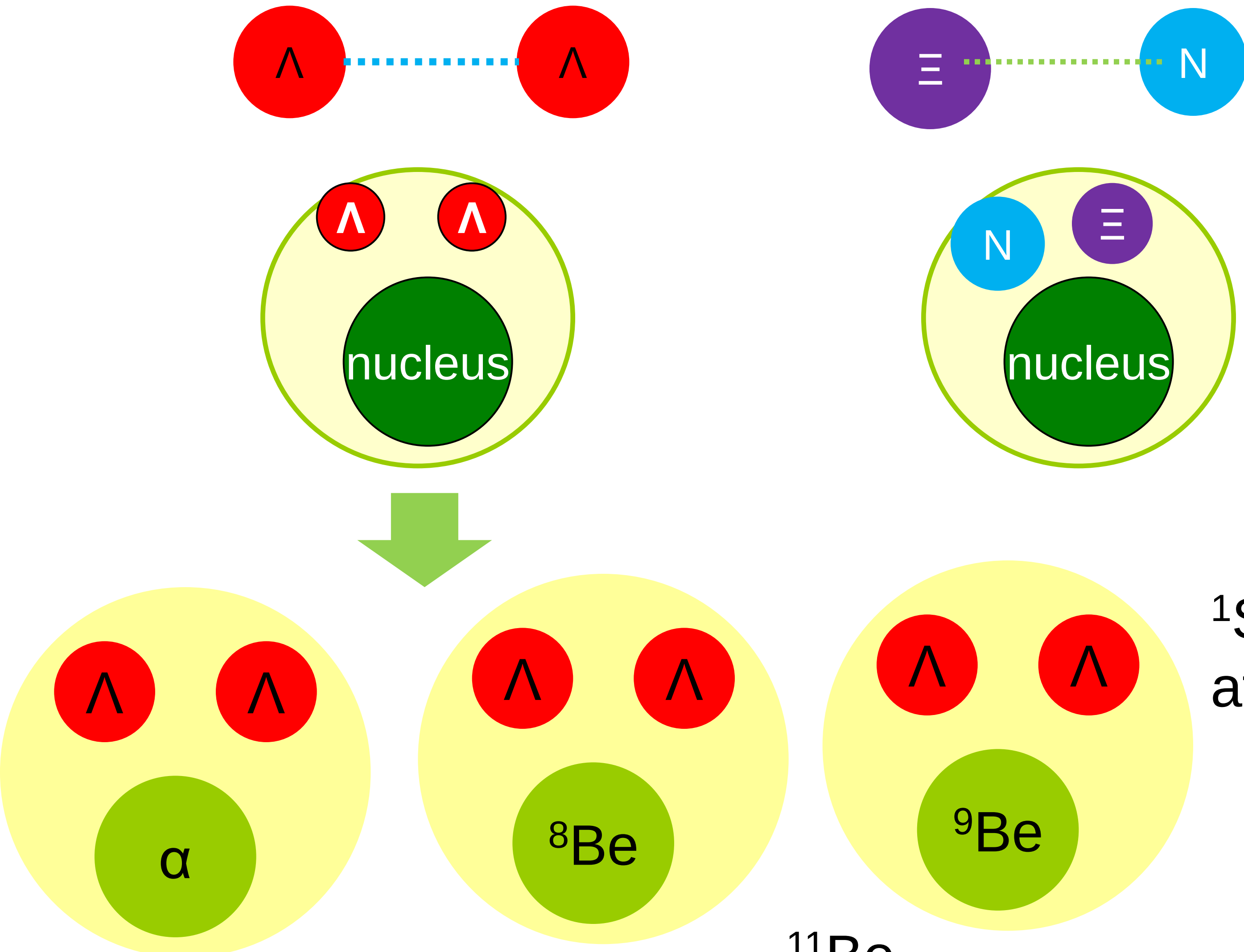
Determine ΛNN interaction

Reliable EOS

Calc. by Nijmegen ESC16 model



Next step: S=-2 sector

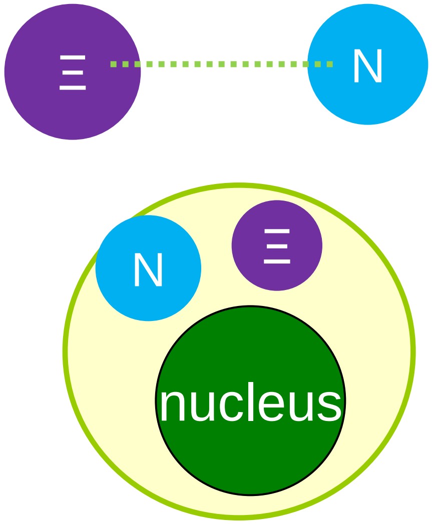


$^1S_0$ of ΛΛ interaction attractive

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

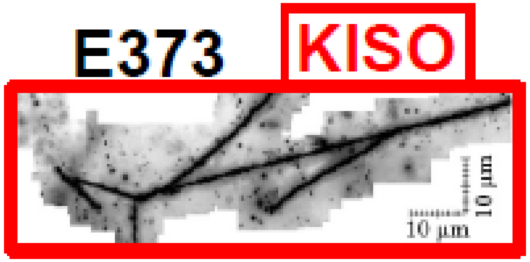
$_{\Lambda\Lambda}^{6}$He $_{\Lambda\Lambda}^{10}$Be

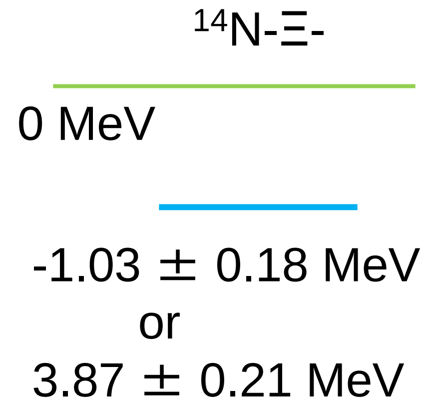
[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).



Before 2015, there was no confirmed bound Ξ hypernucleus. Then, we do not know ΞN potential should be repulsive or attractive?

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





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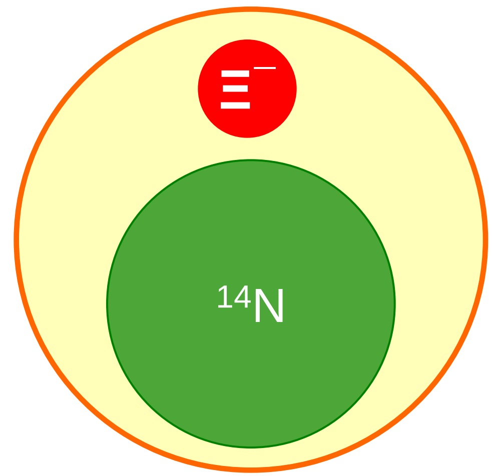
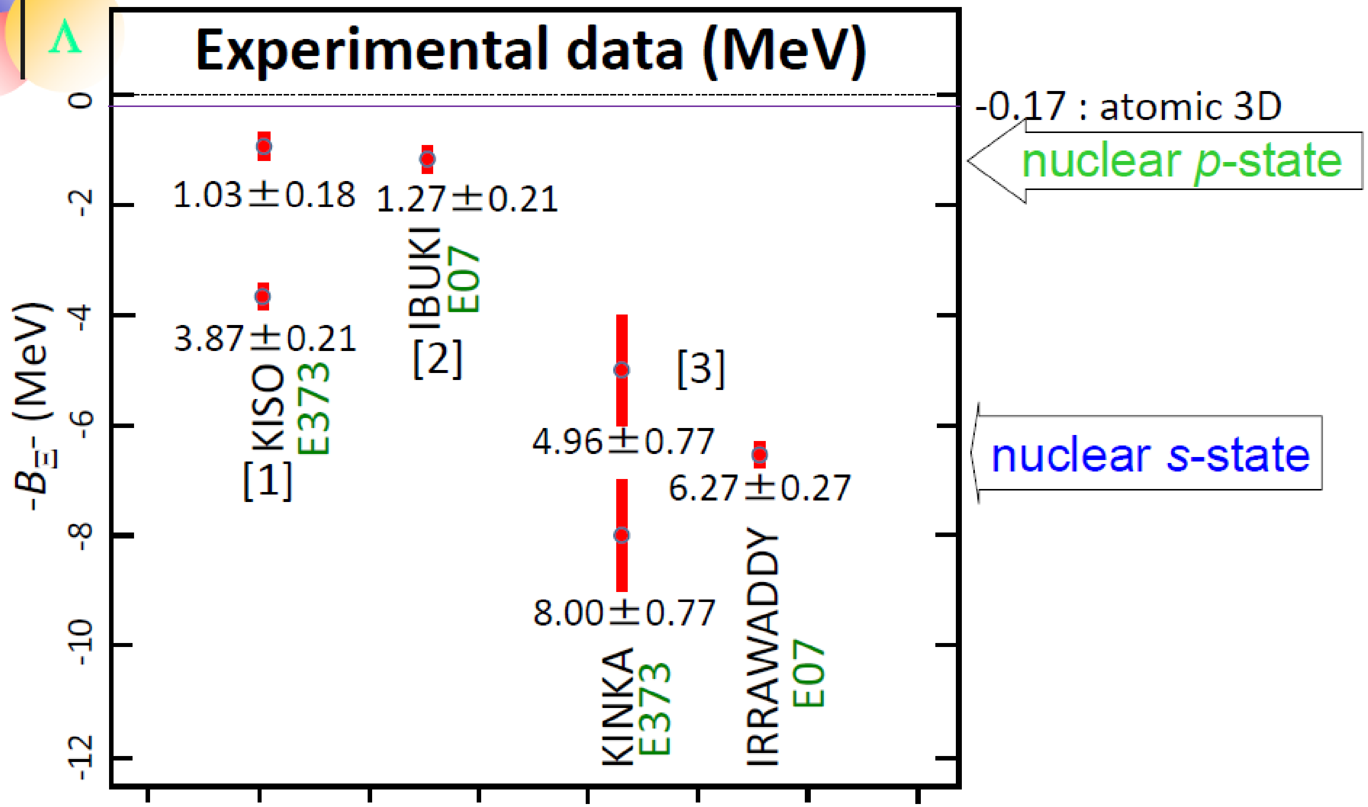
Received October 27, 2014; Revised December 25, 2014; Accepted January 9, 2015; Published March 5, 2015



We understood Ξ-nuclear potential should be attractive.

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



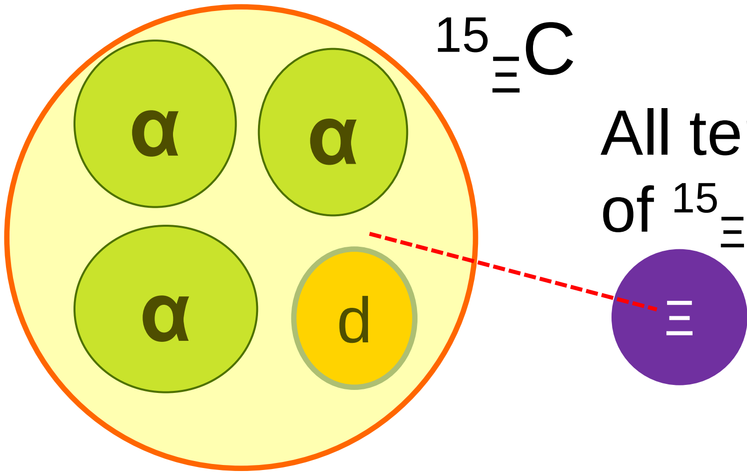
[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

Slide by Nakazawa

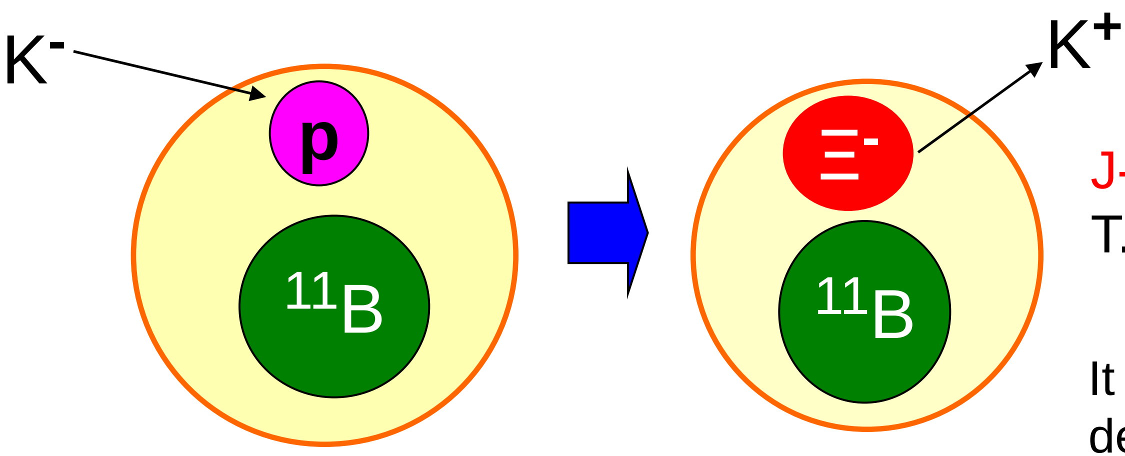
After observation of Kiso event, they observed several events of ^{14}N-Ξ hypernucleus.
Some are observed as excited state and some are observed as ground state.

What parts of ΞN interaction can we obtain?

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



All terms contribute to the binding energies of $^{15}_{\Xi}C$.



^{12}C

Ξ hypernucleus

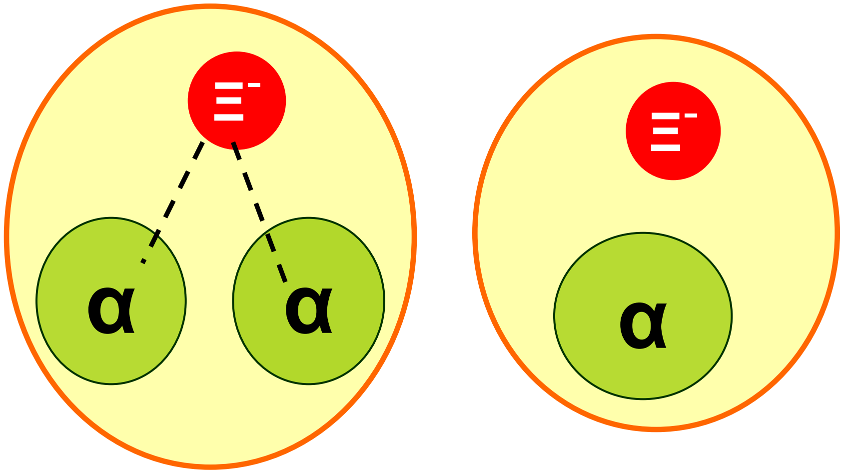
J-PARC: E70: spokesperson T. Nagae

It is possible to observe decay width which corresponds to ΛΛ-ΞN coupling.

After observation of 11B-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 $(\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})$, $(\boldsymbol{\tau}\cdot\boldsymbol{\tau})$ and $(\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})$ terms of $V_{\Xi N}$ vanish by folding them into the **α**-cluster wave function that are spin-, isospin-satulated.



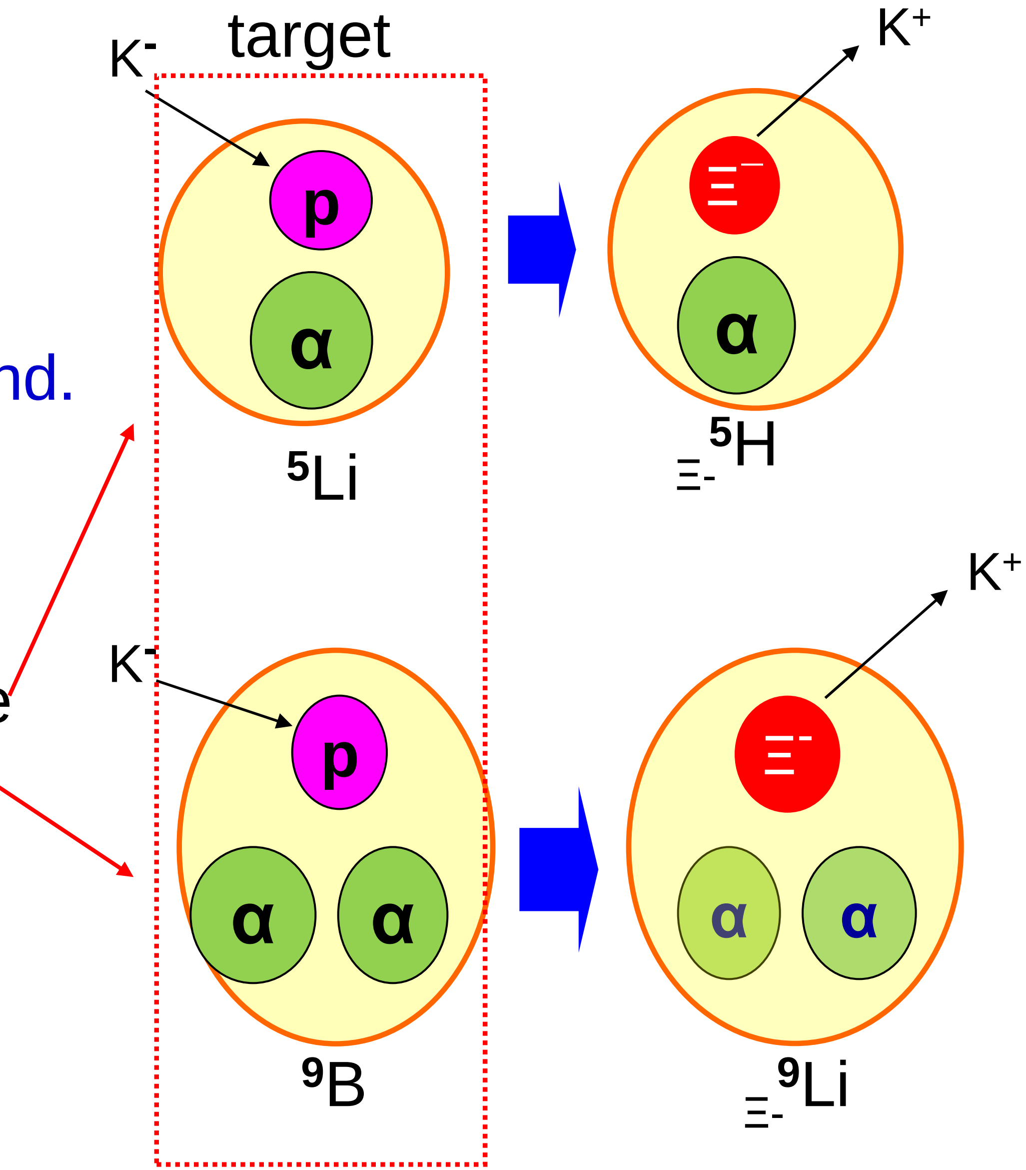
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ･･･

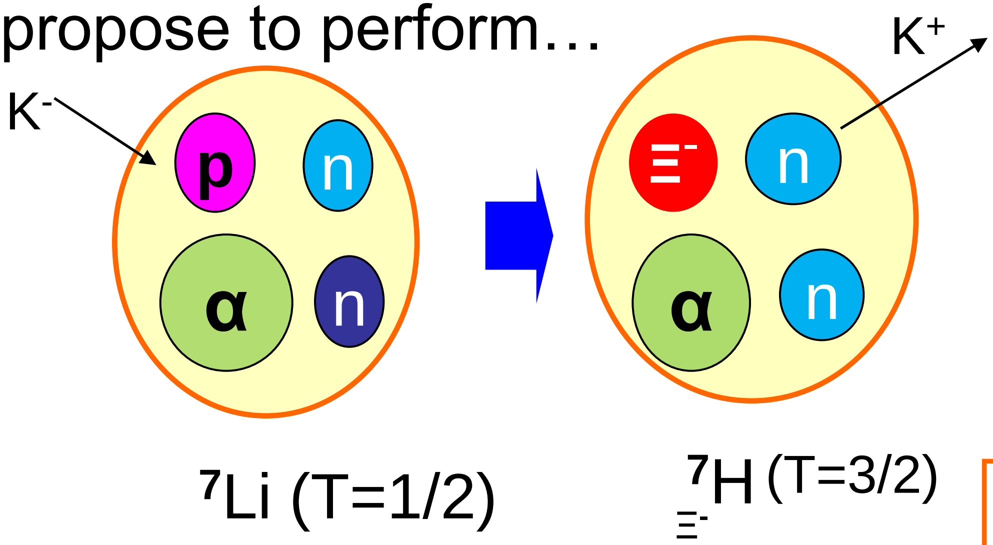
To produce **αΞ⁻** and **ααΞ⁻** systems by (K^-, K^+) reaction,

These systems are unbound.

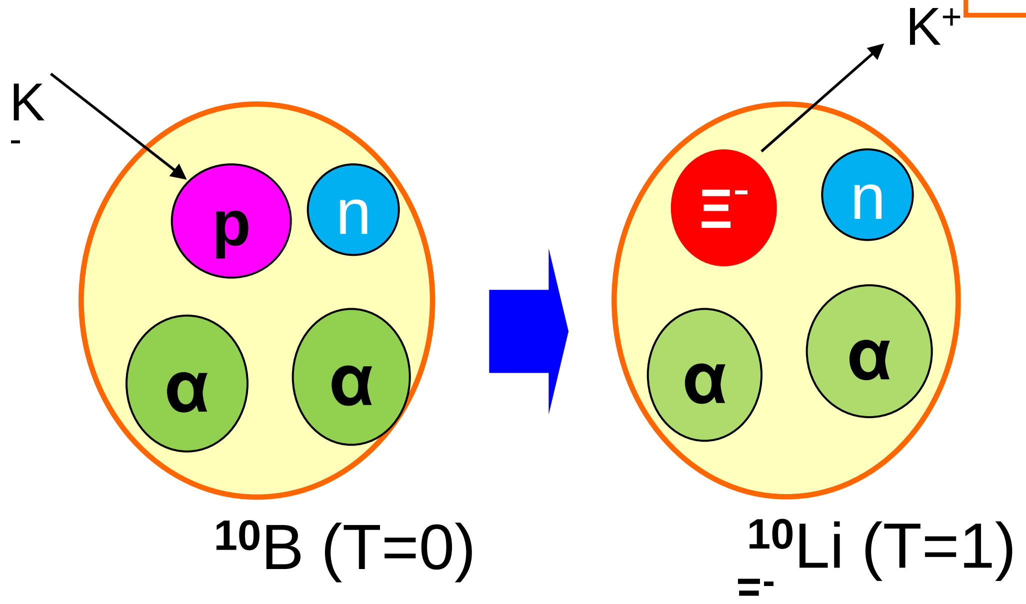
Then, we cannot use them as targets.



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

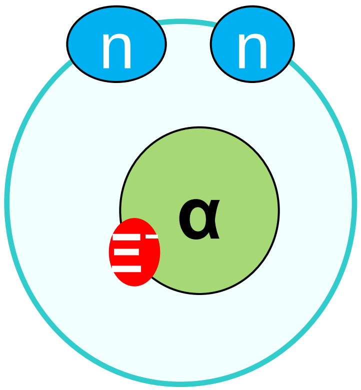


Why they are suited for investigating V_0?



(more realistic illustration)

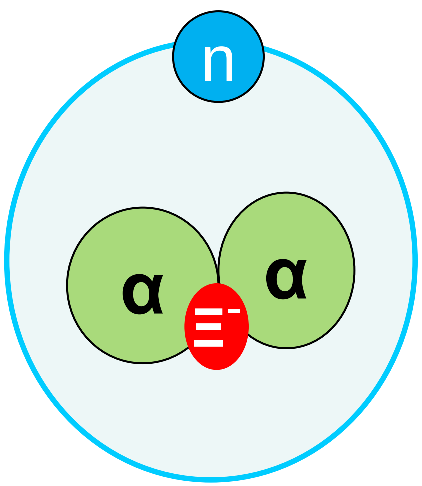
Core nucleus ^{6}He is known to be halo nucleus. Then, valence neutrons are located far away from α particle.



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

Valence neutrons (n) are located in p-orbit, whereas Ξ particle (Ξ-) is located in 0s-orbit.

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



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

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

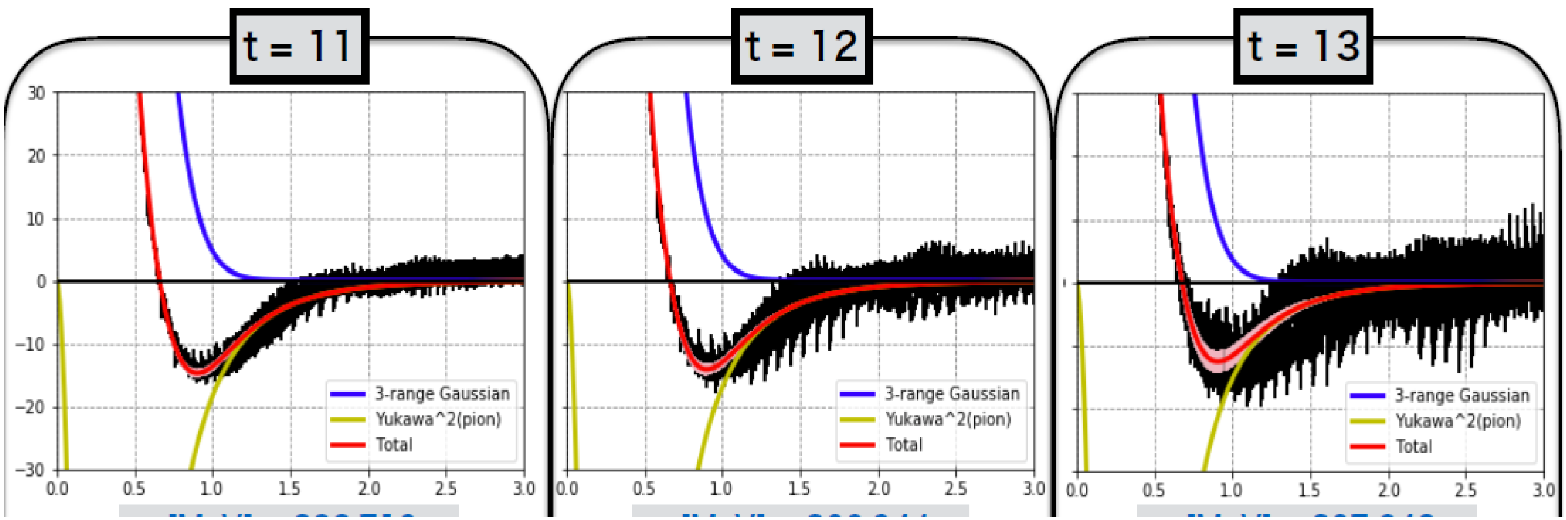
ΞN interaction

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),

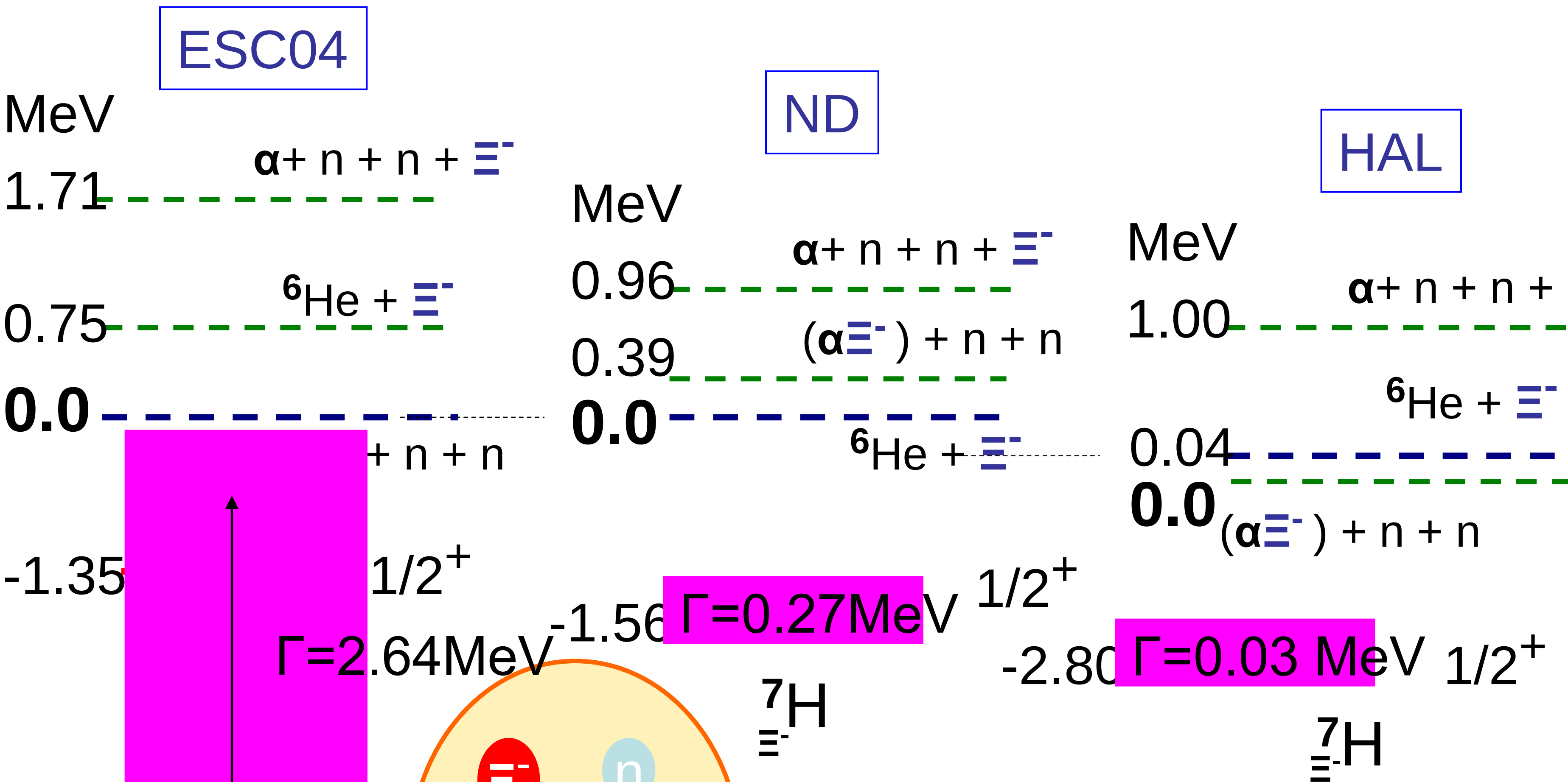
we find that the spin- and isospin-averaged property,

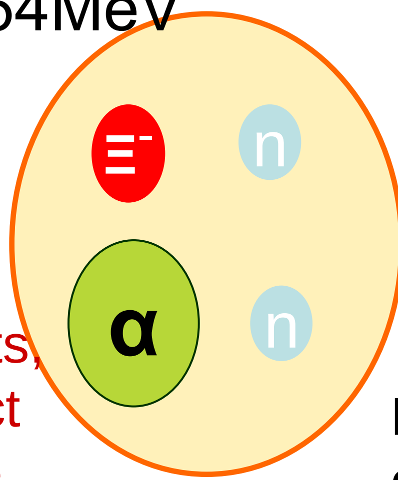
$$V_0 = [\, V(0,0) + 3V(0,1) + 3V(1,0) + 9V(1,1) \,] / 16,$$

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





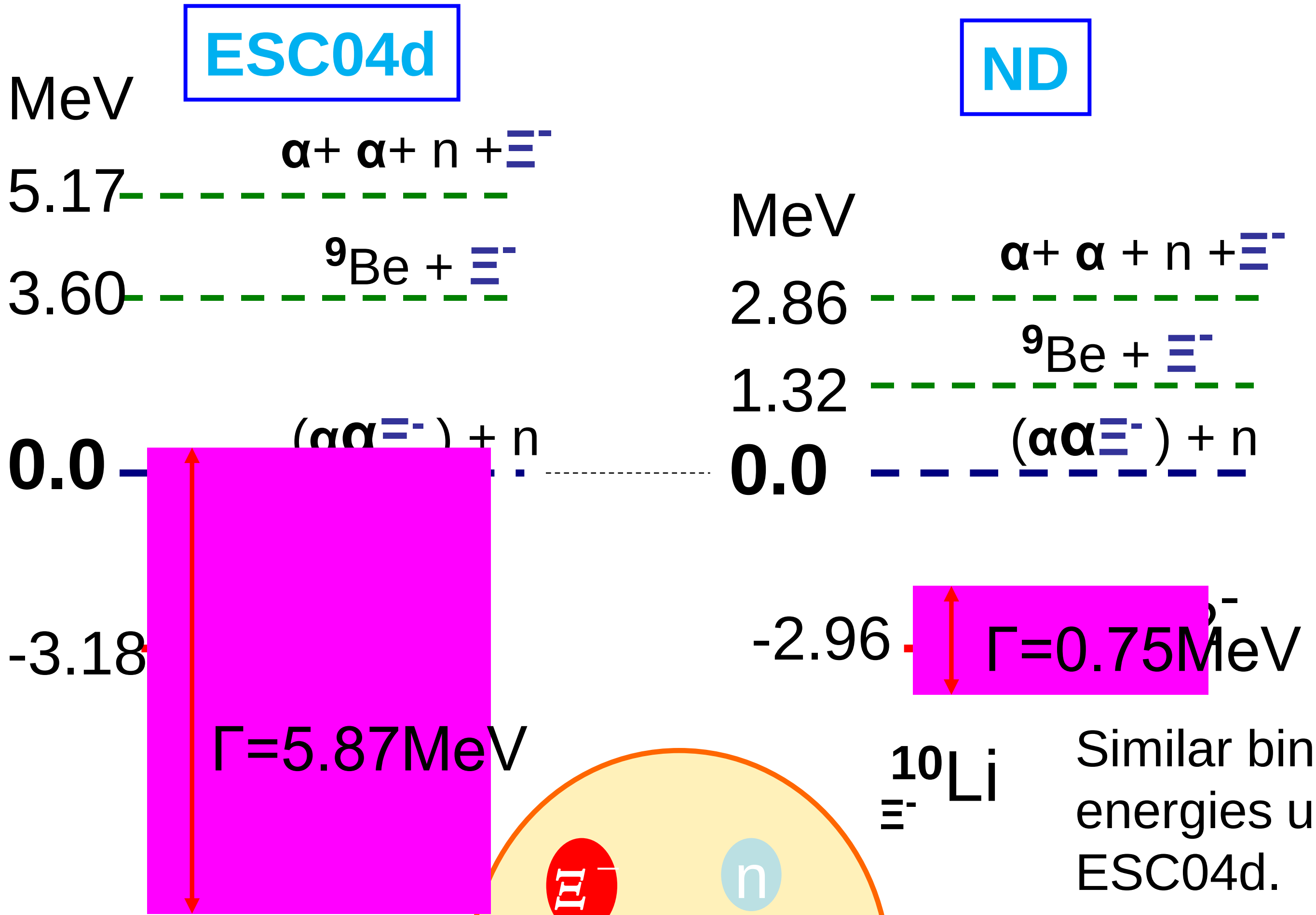
Similar binding energies using ND and ESC04.

In experiments, we can expect a bound state.

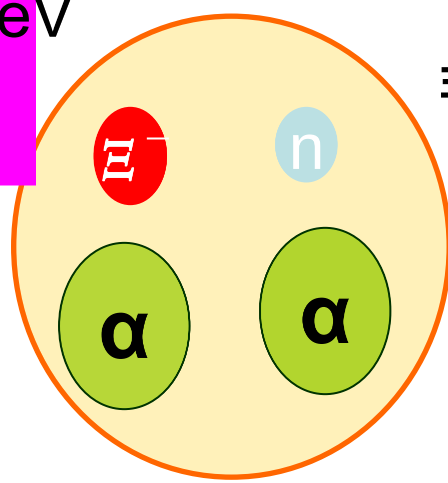
However, decay width is dependent on on employed ΞN potential

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

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



$^{10}_{\Xi^-}\mathrm{Li}$



Similar binding energies using ND and ESC04d.

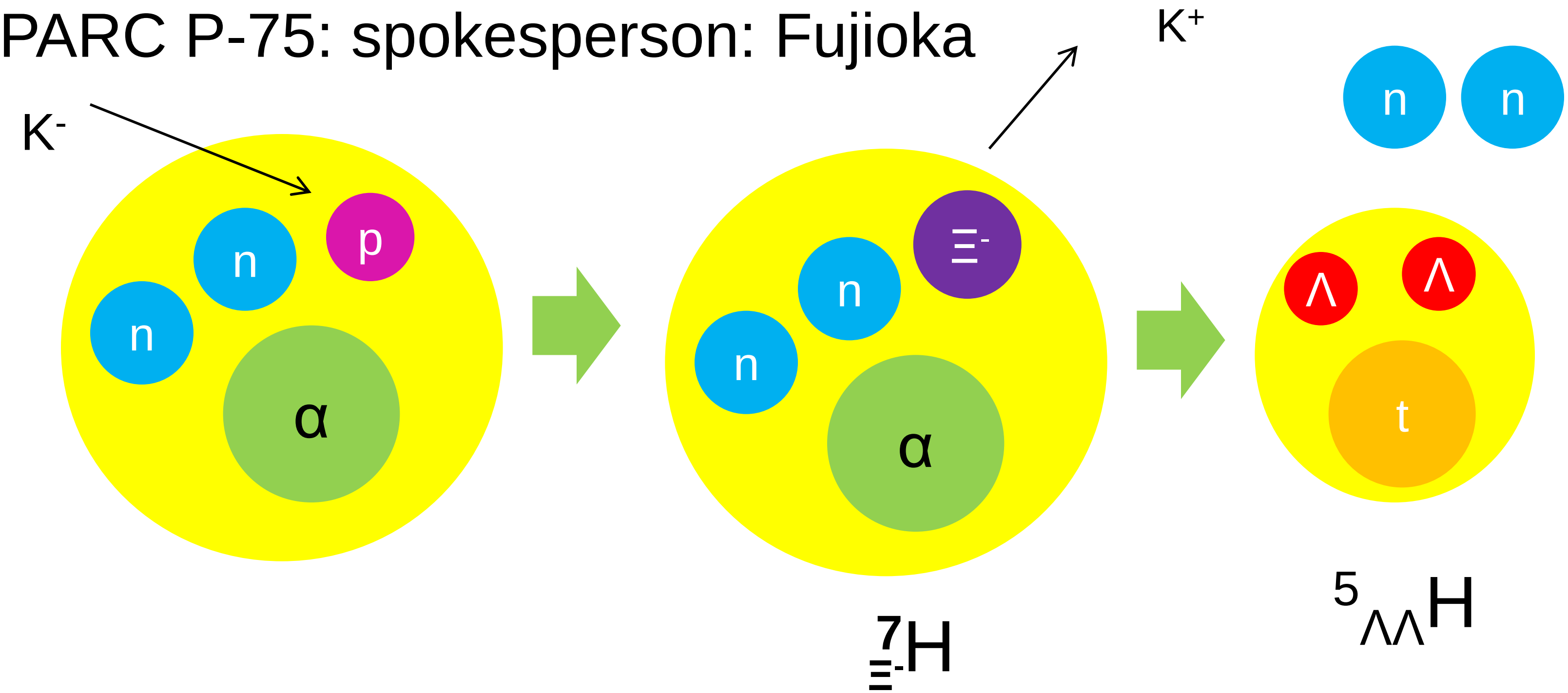
Independent on employed ΞN potential

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



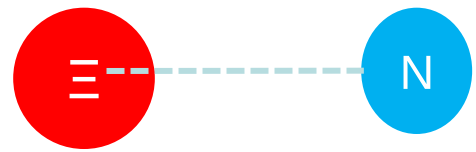
T S

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

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

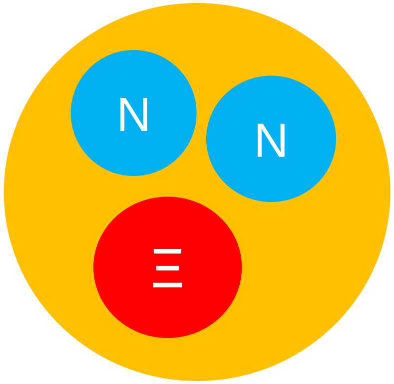
Cf. NN interaction

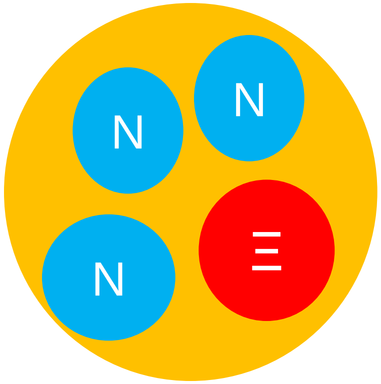
T=0, S=0
T=0, S=1
T=1, S=0
T=1,S=1

strong attraction to have a bound state as a deuteron

To obtain ΞN two-body interaction,
the suited systems to study are s-shell Ξ hypernuclei such as NNΞ and NNNΞ systems.

E. Hiyama et al., PRL124, 092501 (2020)





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)

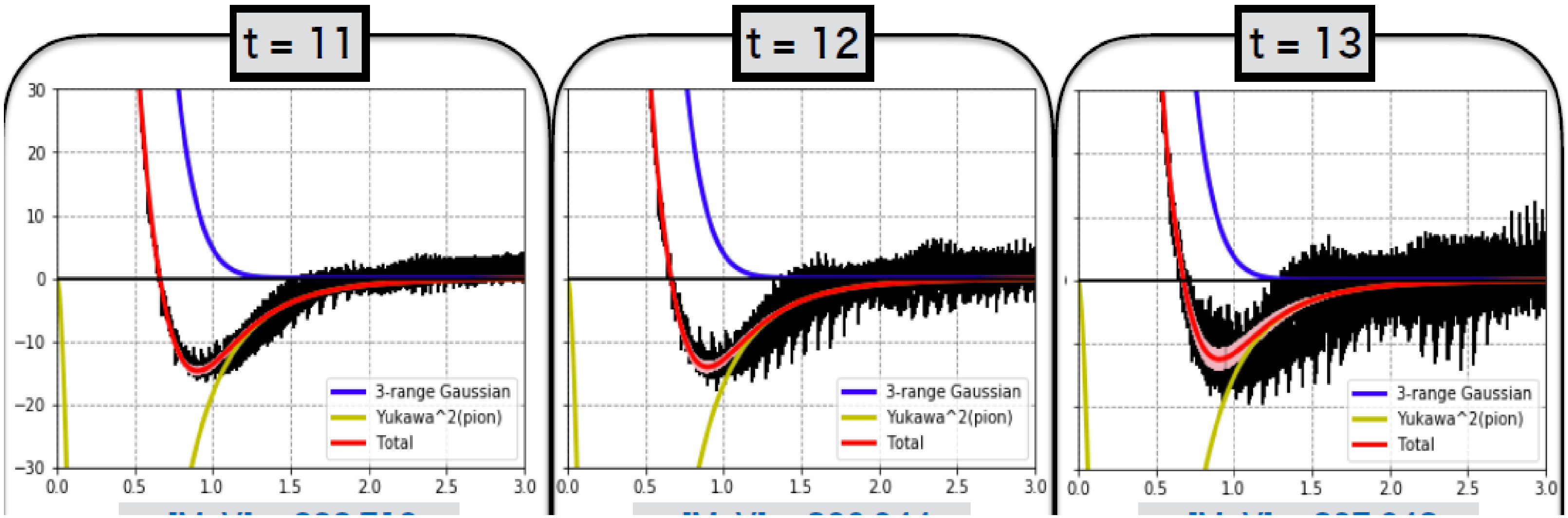
ΞN interaction by HAL collaboration (Lattice QCD calculation)

The potential was made by K. Sasaki, Miyamoto, Hatsuda and Aoki.

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.



$V_0(r)$

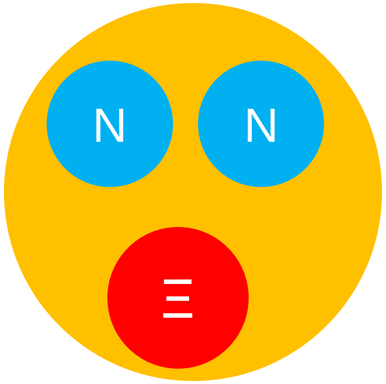
In HAL potential , the statistical errors are NOT included.

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

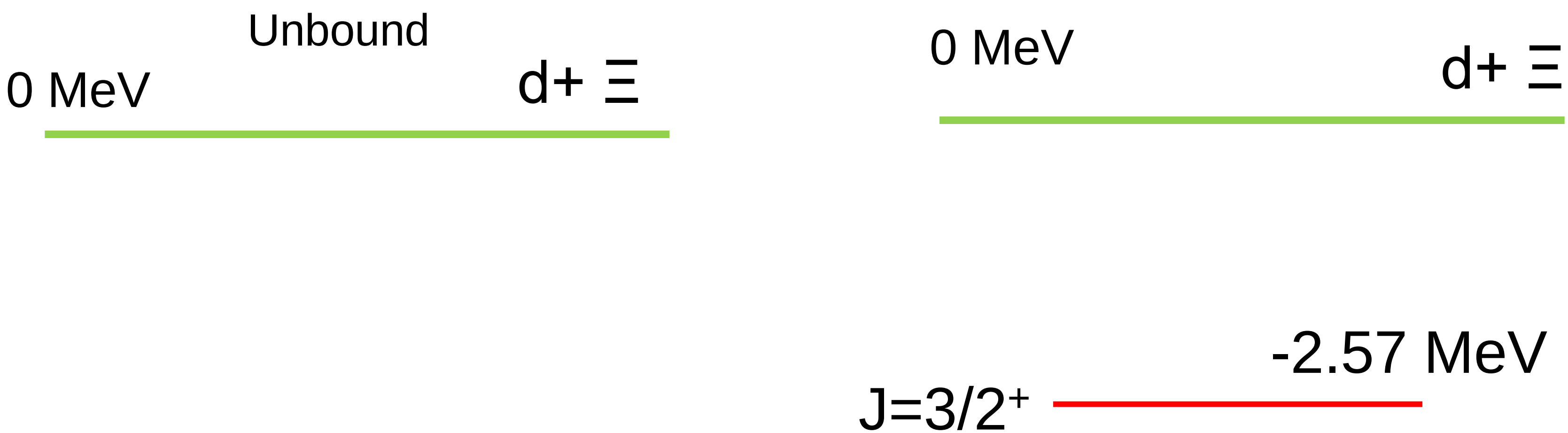
Although the spin- and isospin-components of these two models are very different between them.

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

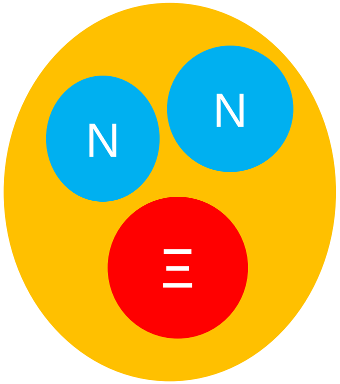


T=1/2, J=1/2$^+$ and J=3/2$^+$

ESC08c



However, I also have two bound states in three-body system.



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

HAL potential

0 MeV

d+ Ξ

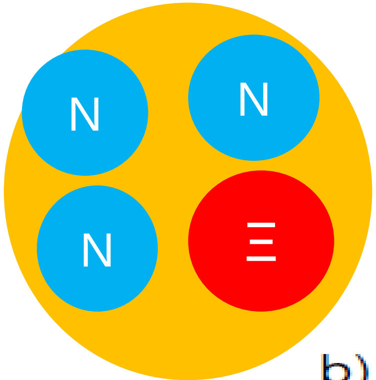
0 MeV

d+ Ξ

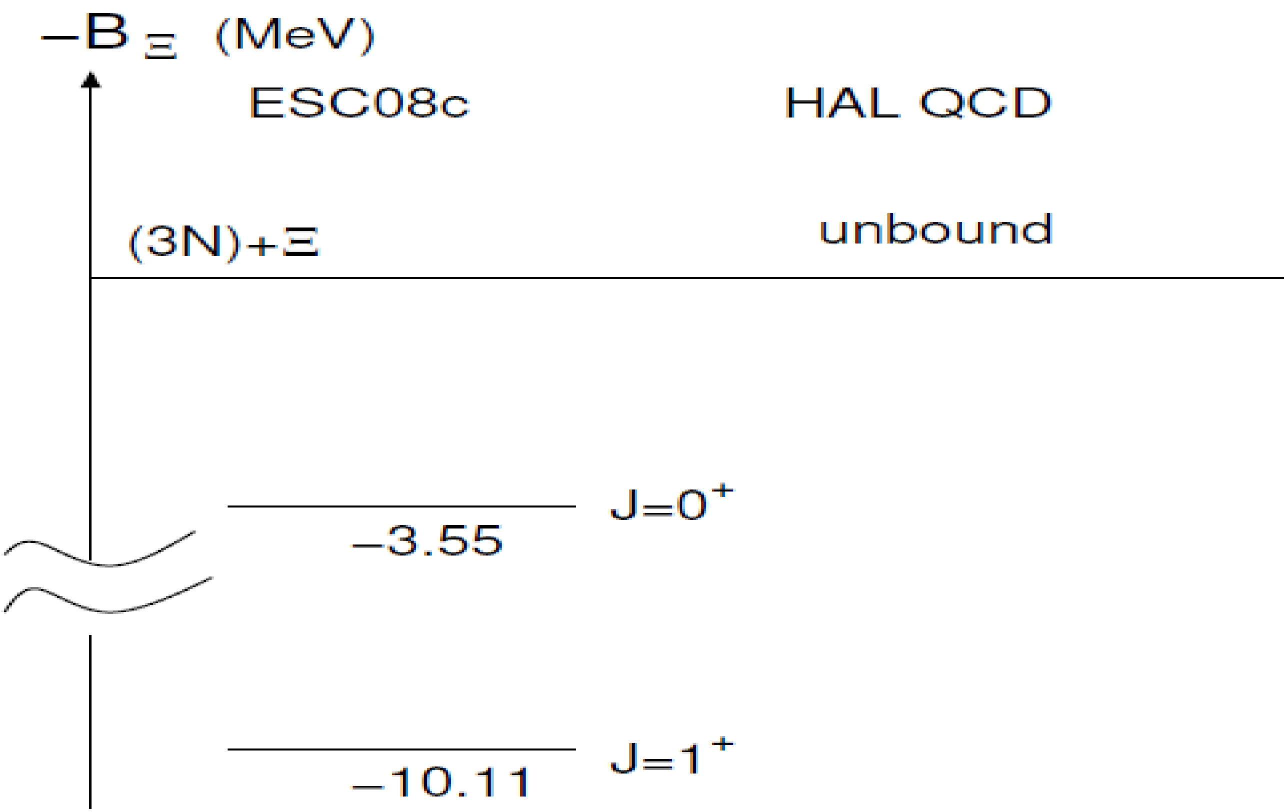
No bound state

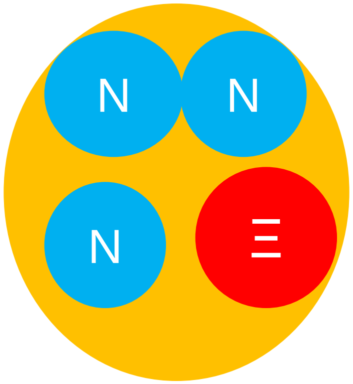
$J=3/2^+$

J=1/2+

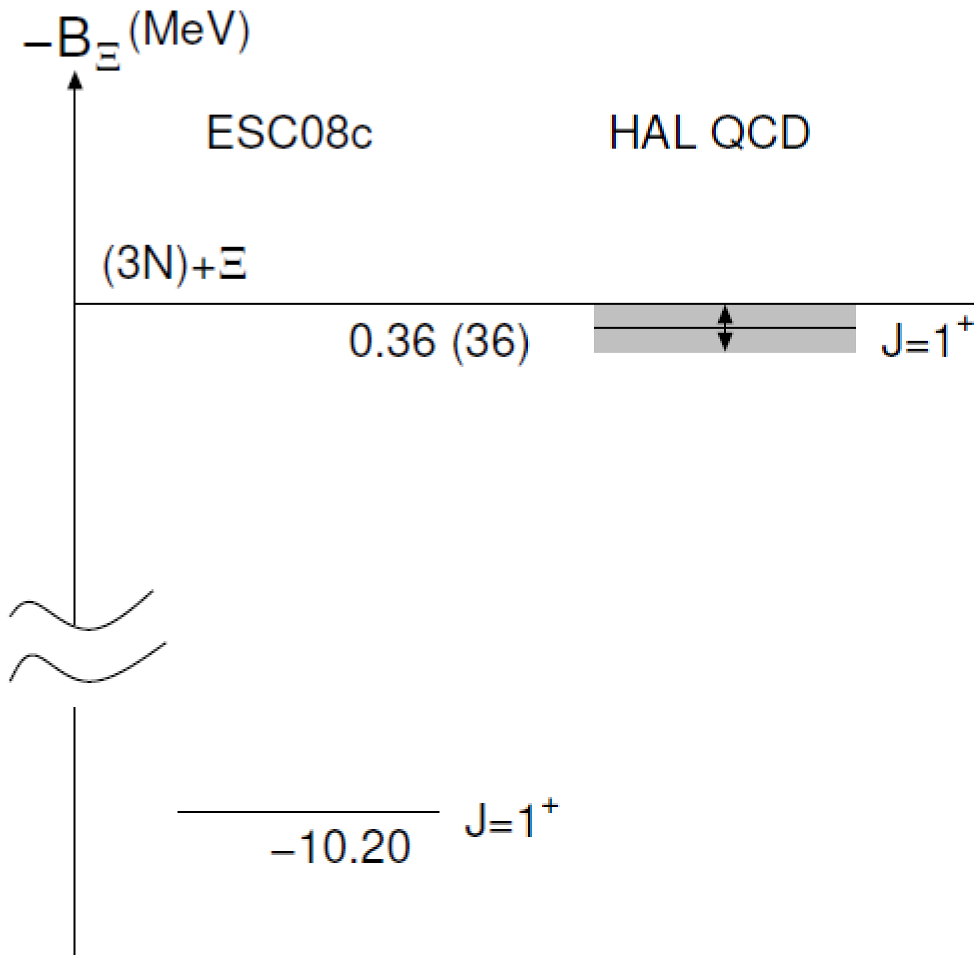


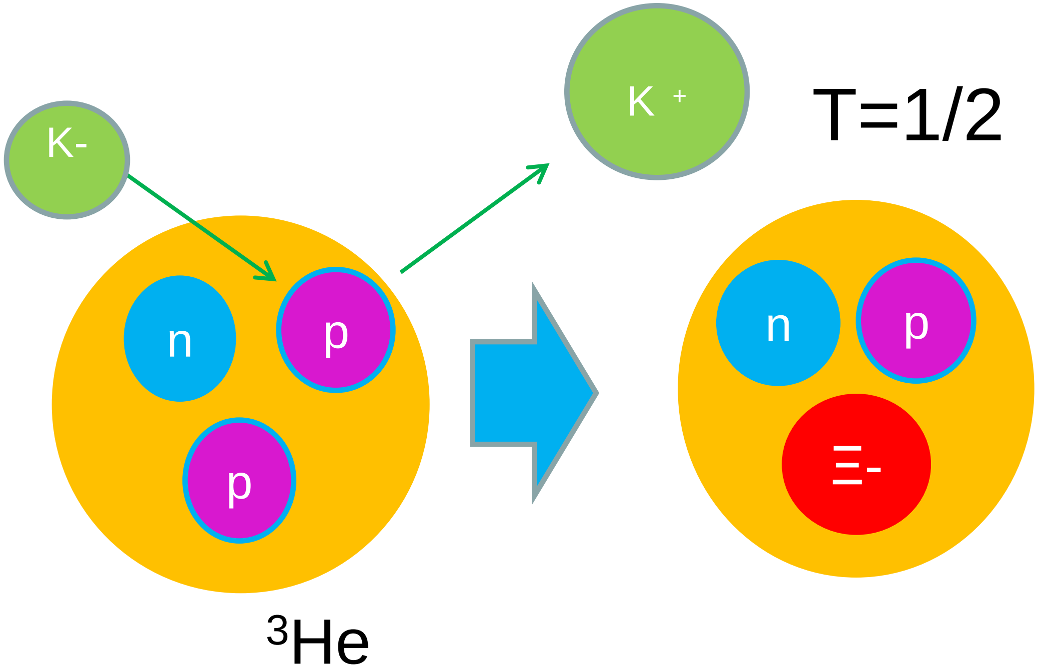
b) T=1





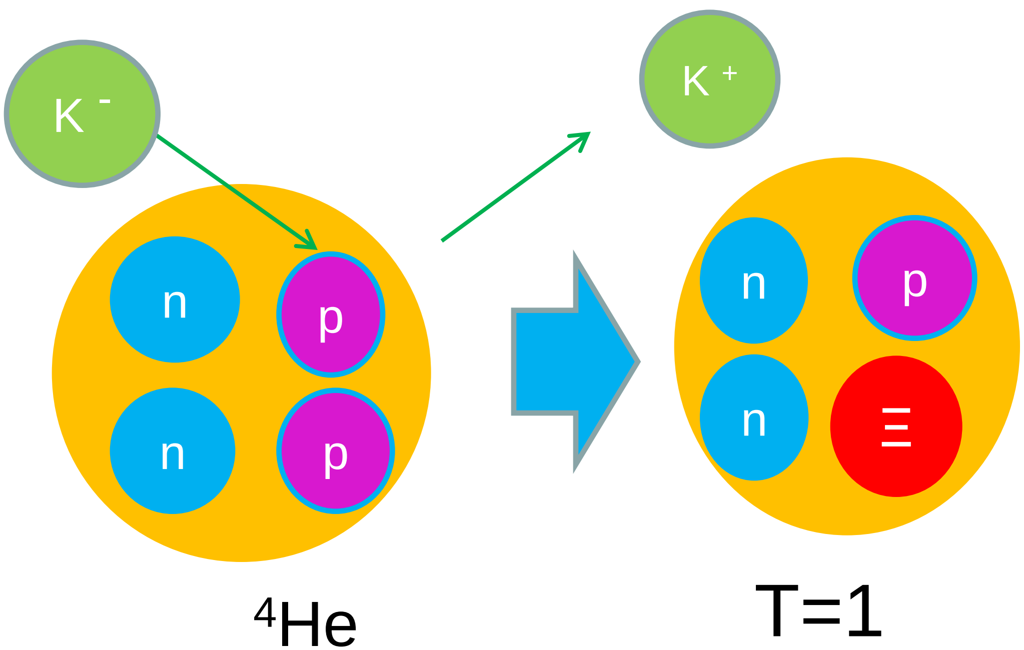
a) T=0





Using ^{3}He and ^{4}He target,
It might be possible
to produce NNΞ and NNNΞ
systems by (K^-,K^+) reaction.

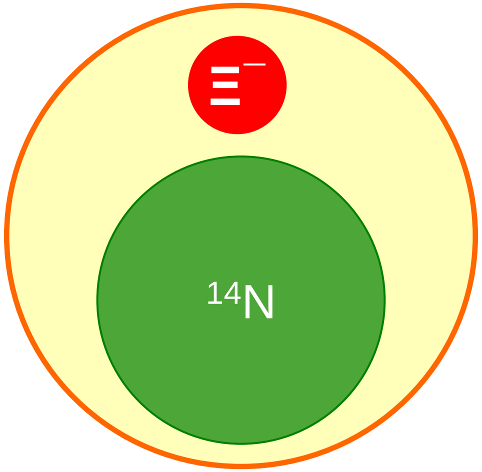
Another tool is to use
Heavy ion collision.



In the future,
we hope to observe
these light Ξ hypernuclei.

Conlcusion

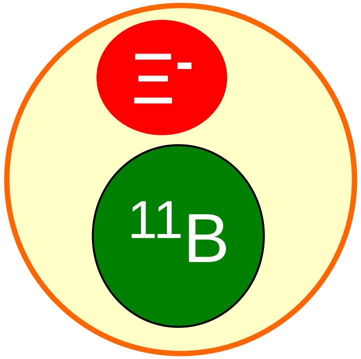
In hypernuclear physics, we have been obtaining YN and YY interactions.
In this talk, I focus on present status of study of Ξ hypernuclei.



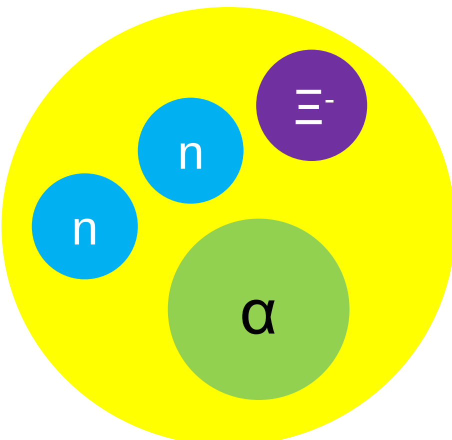
Observed!

ΞN interaction is attractive.

In near future,



J-PARC: E70: spokesperson
T. Nagae

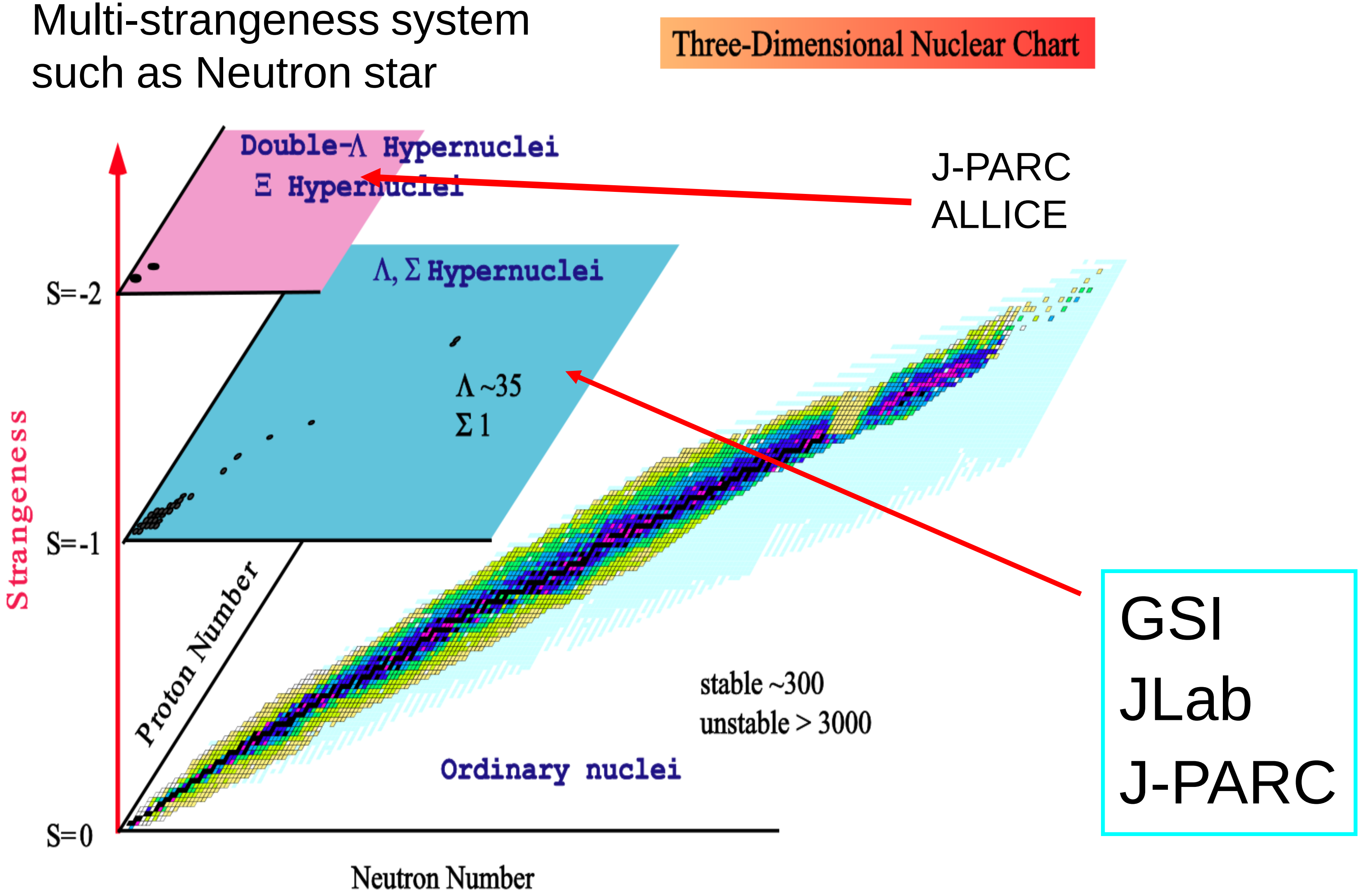


$^{7}_{\Xi^-}\mathrm{H}$

J-PARC P-75
Spokesperson:Fujioka

Concluding remark

Multi-strangeness system
such as Neutron star



Thank you!