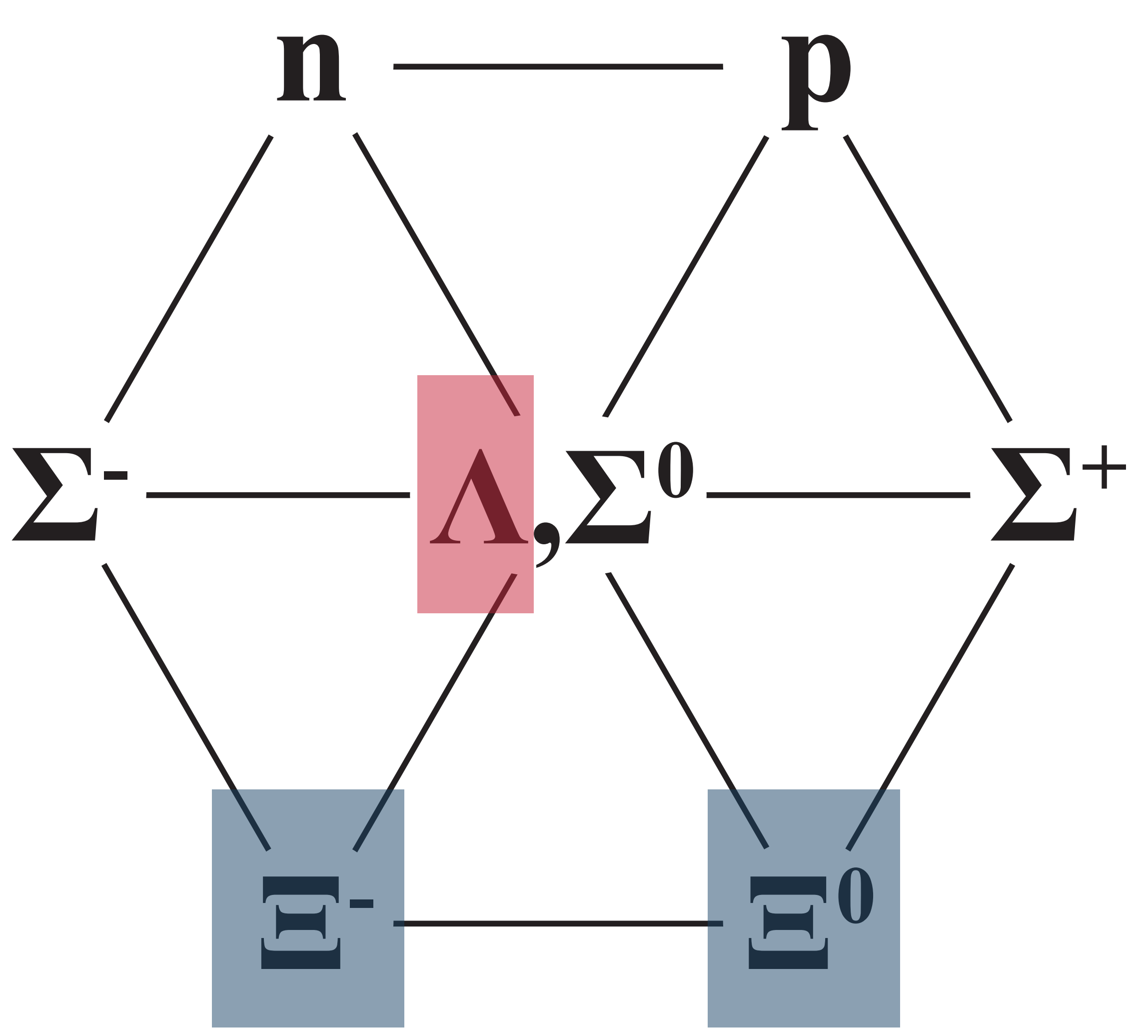
Production of light Ξ and double-Λ hypernuclei at J-PARC

Hiroyuki Fujioka (Tokyo Institute of Technology)
on behalf of the J-PARC E75 collaboration

東京工業大学
Tokyo Institute of Technology

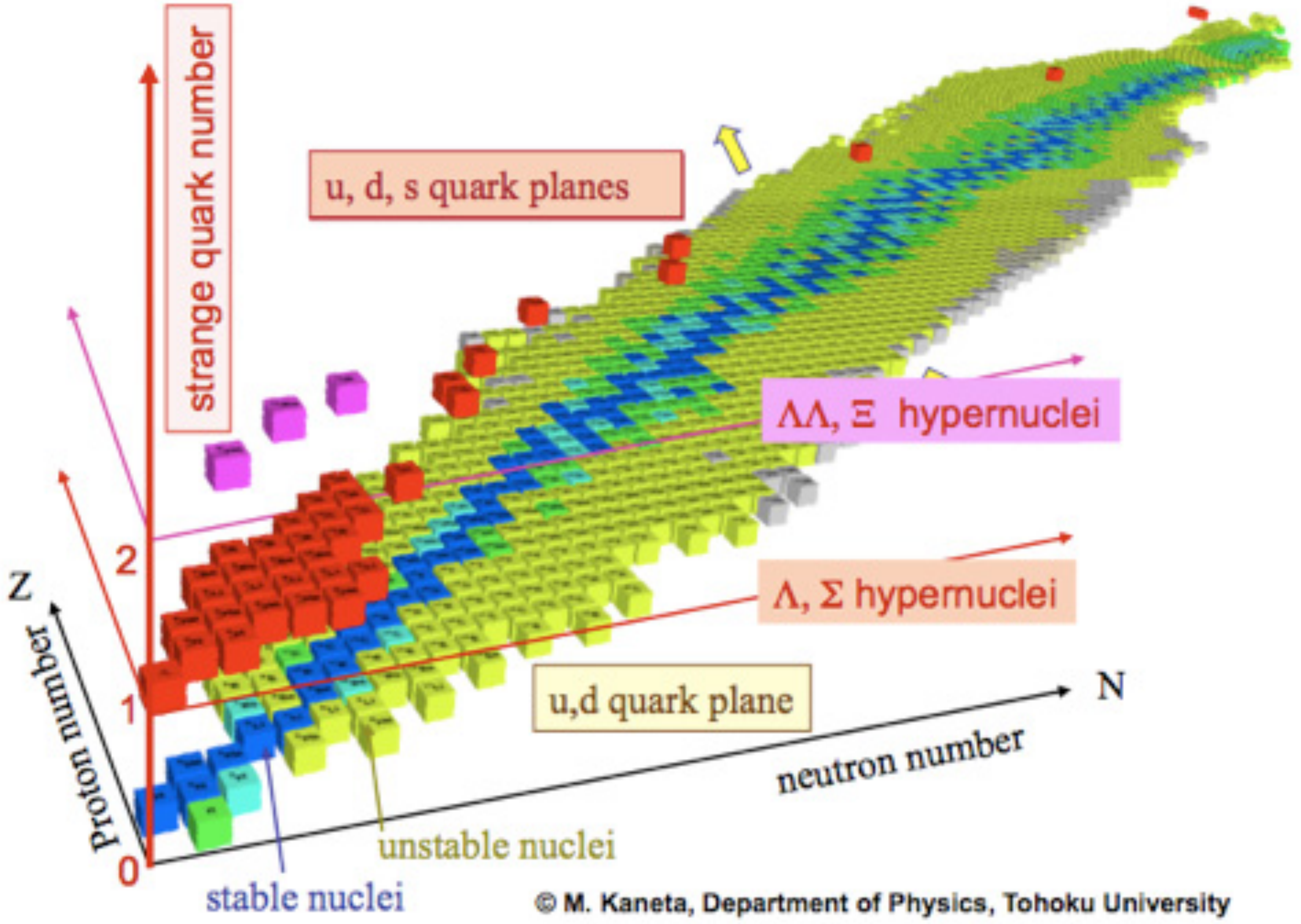
Hypernuclei with strangeness −2



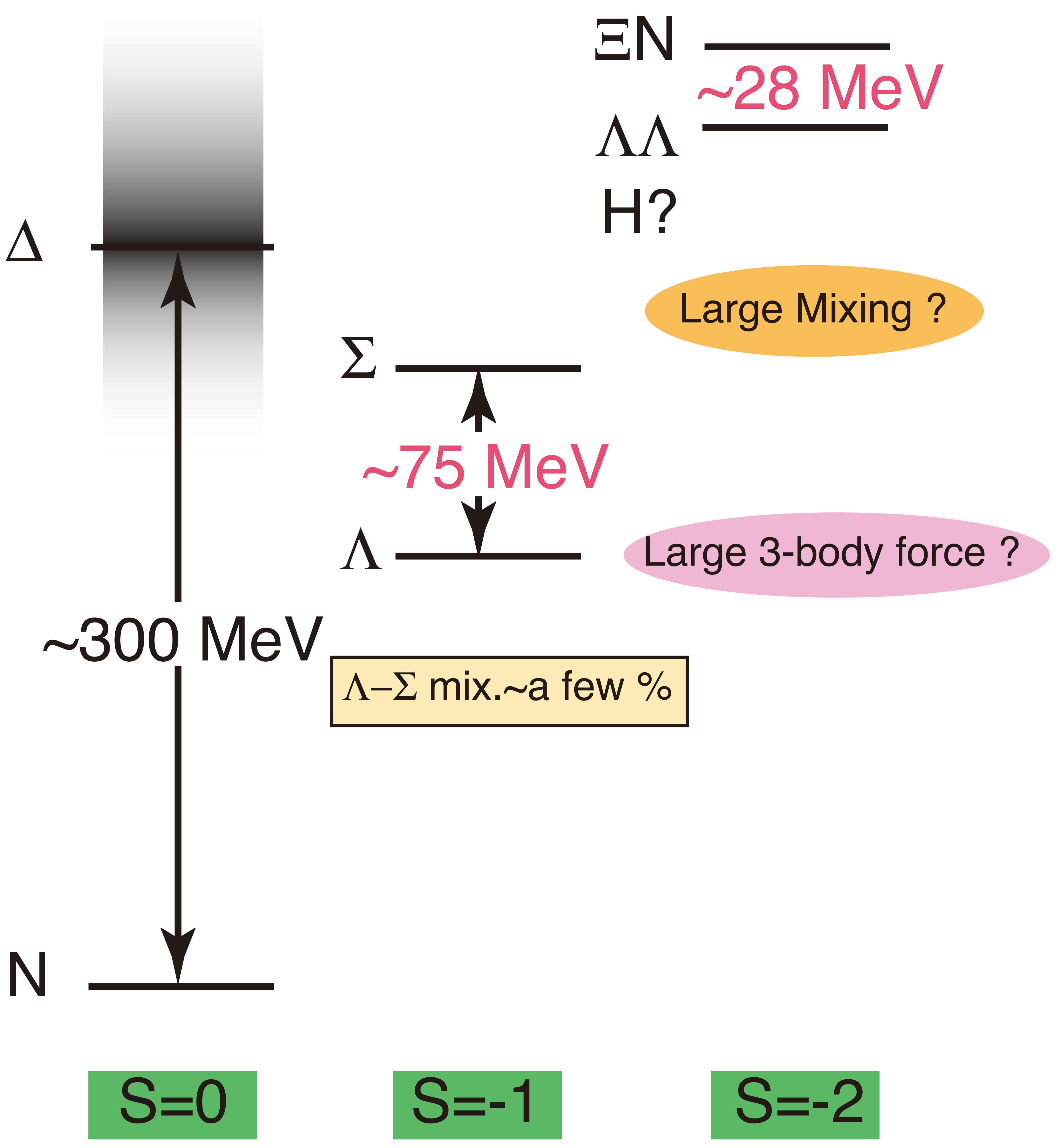
$S = 0$

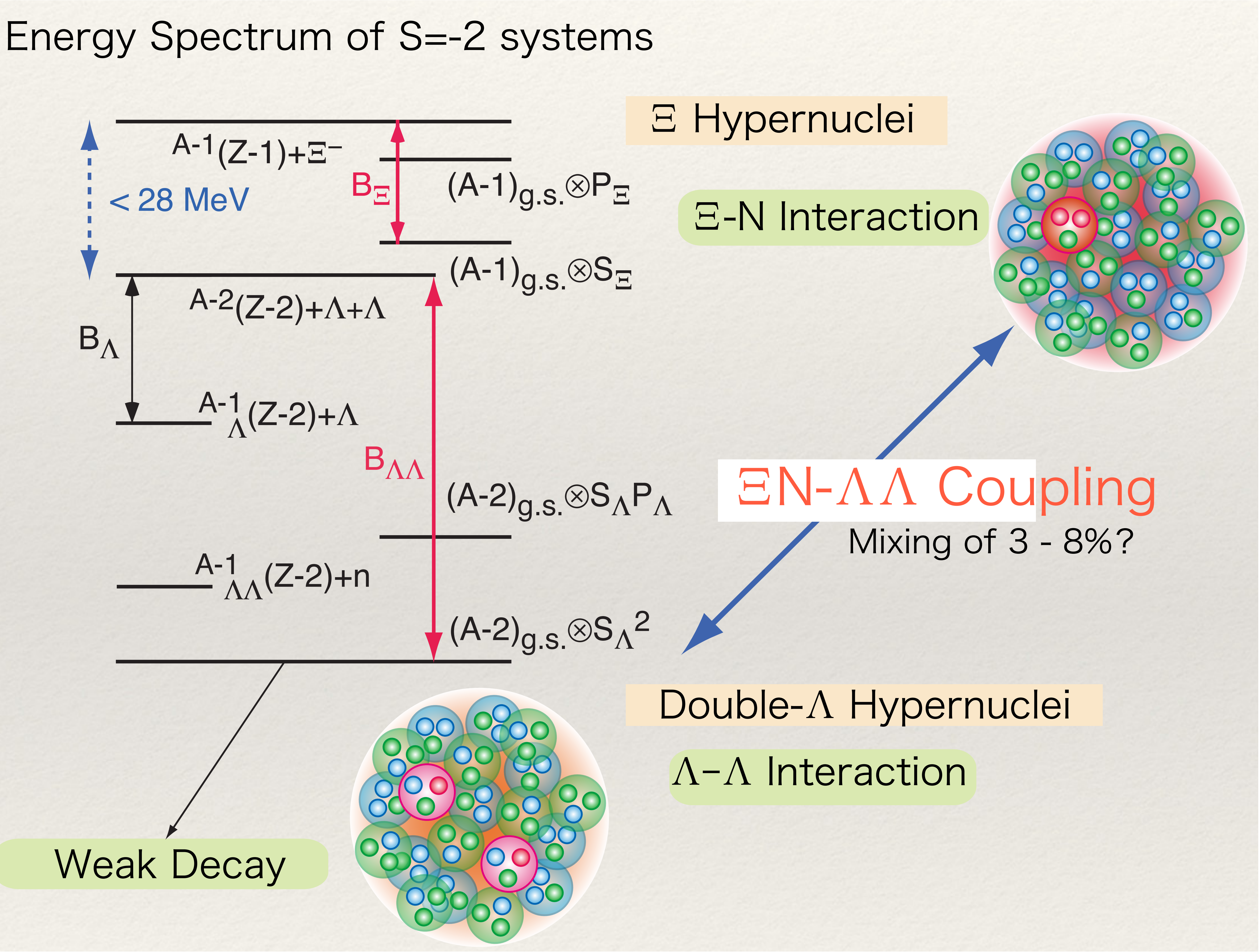
$S = -1$ ⟹ **Double Λ Hypernuclei**

$S = -2$ ⟶ **Ξ Hypernuclei**



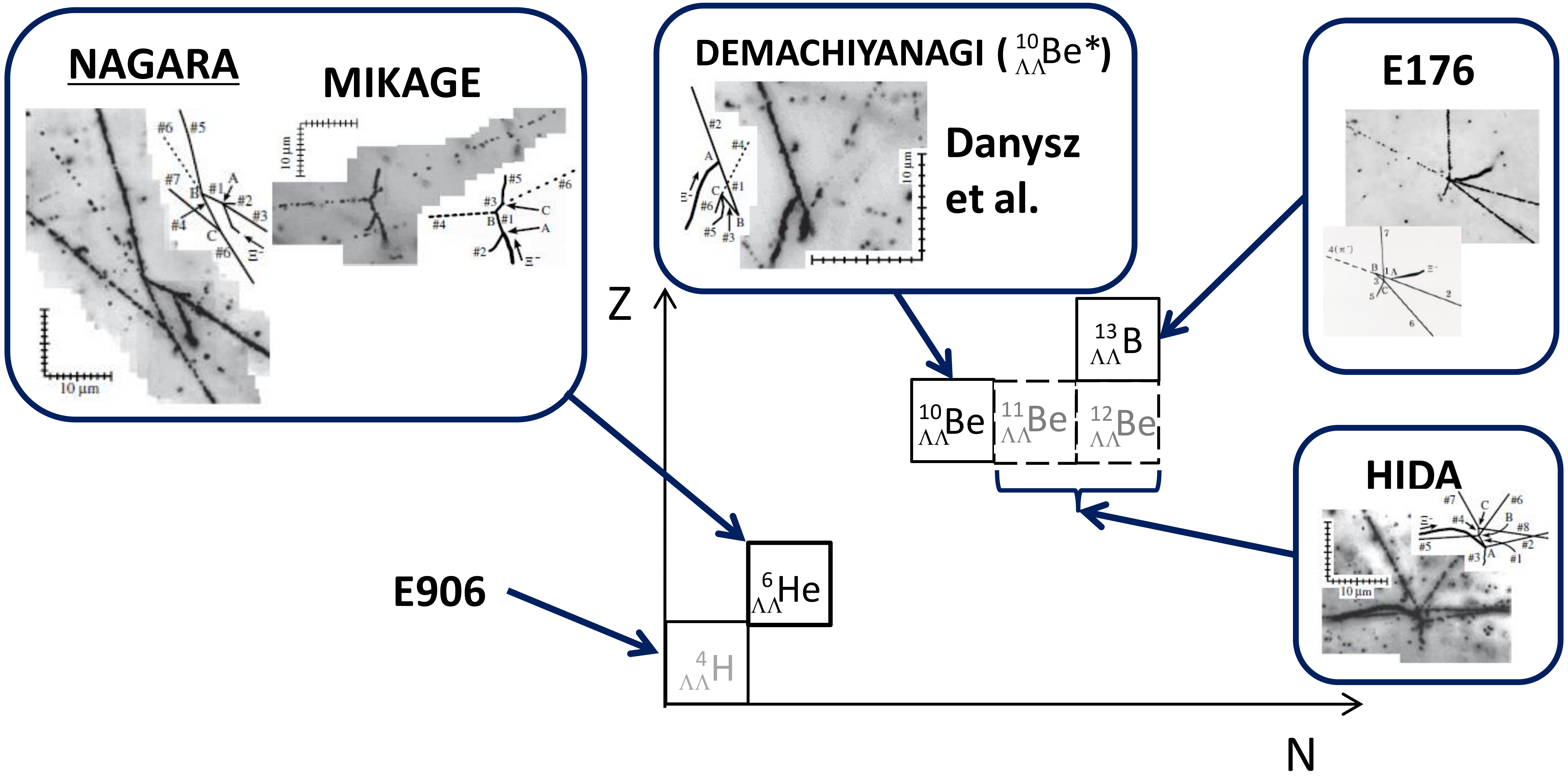
ΞN-ΛΛ coupling in S=−2 systems





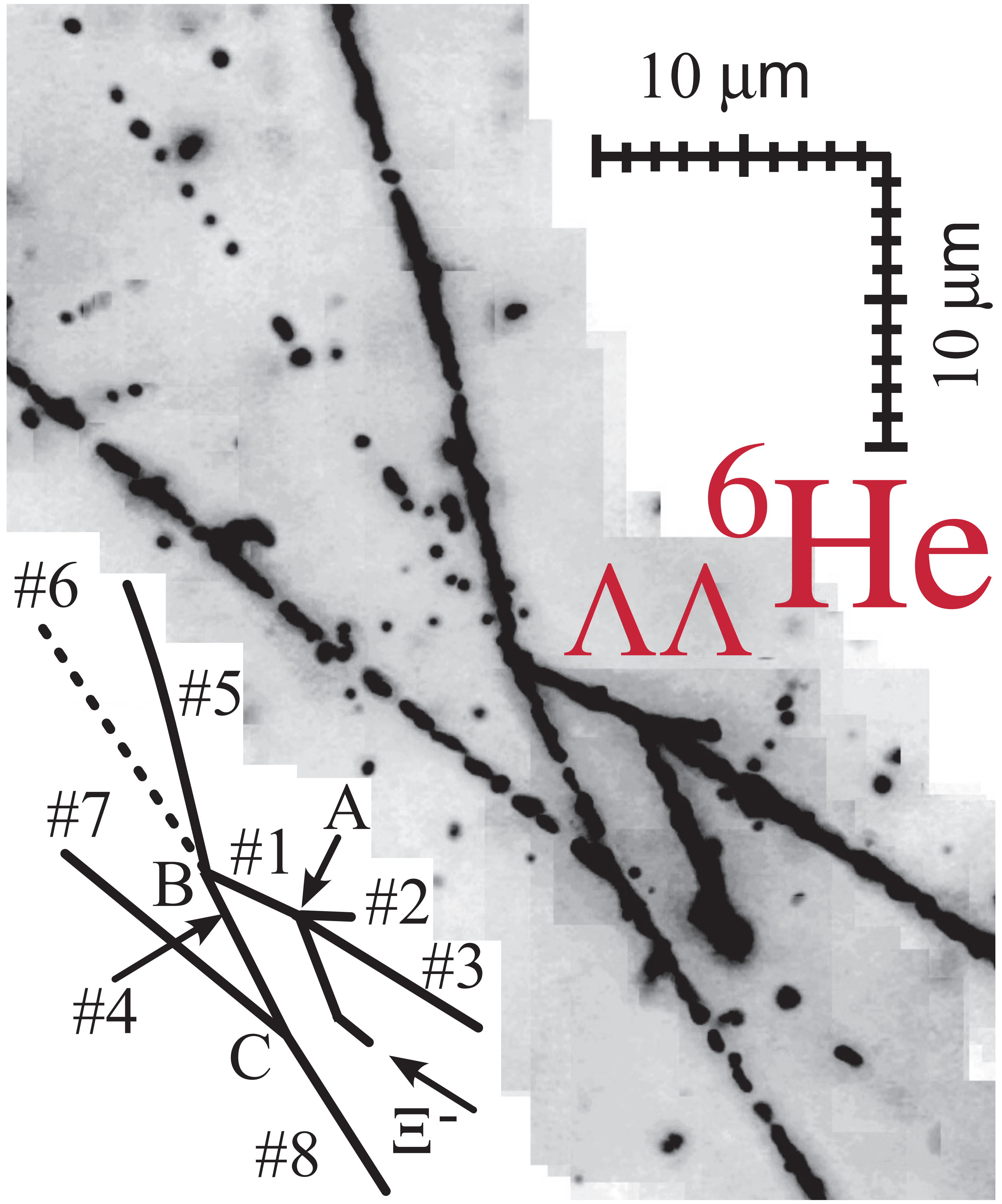
Double-Λ hypernuclear chart

ΛΛ-Hypernuclear Chart



「日本の核物理の将来レポート」(in Japanese) (2013)

NAGARA event (KEK-PS E373)



$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$$^{6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$

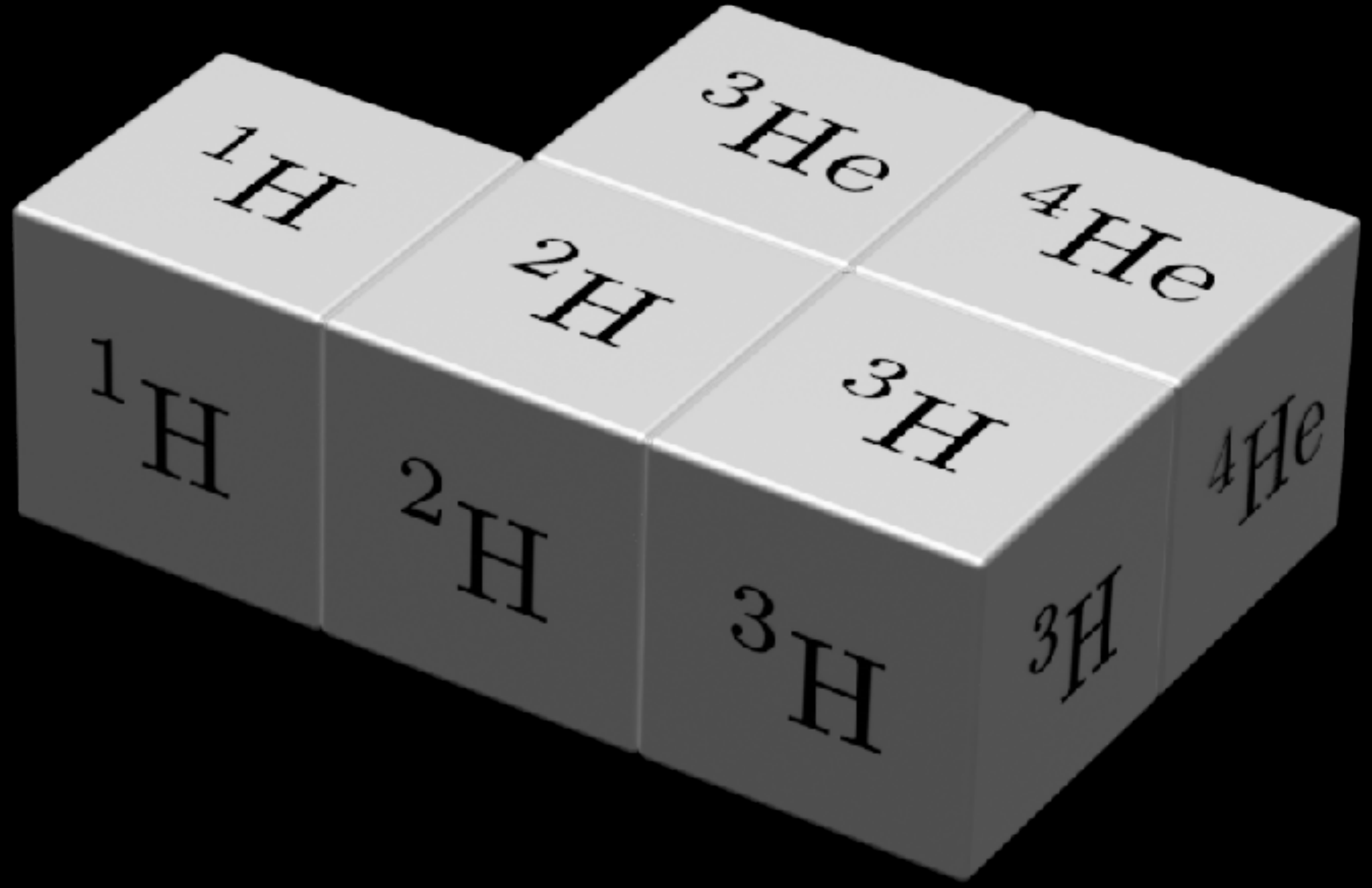
$$B_{\Lambda\Lambda} = 6.91 \pm 0.16\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17\,\mathrm{MeV}$$ Weakly attractive

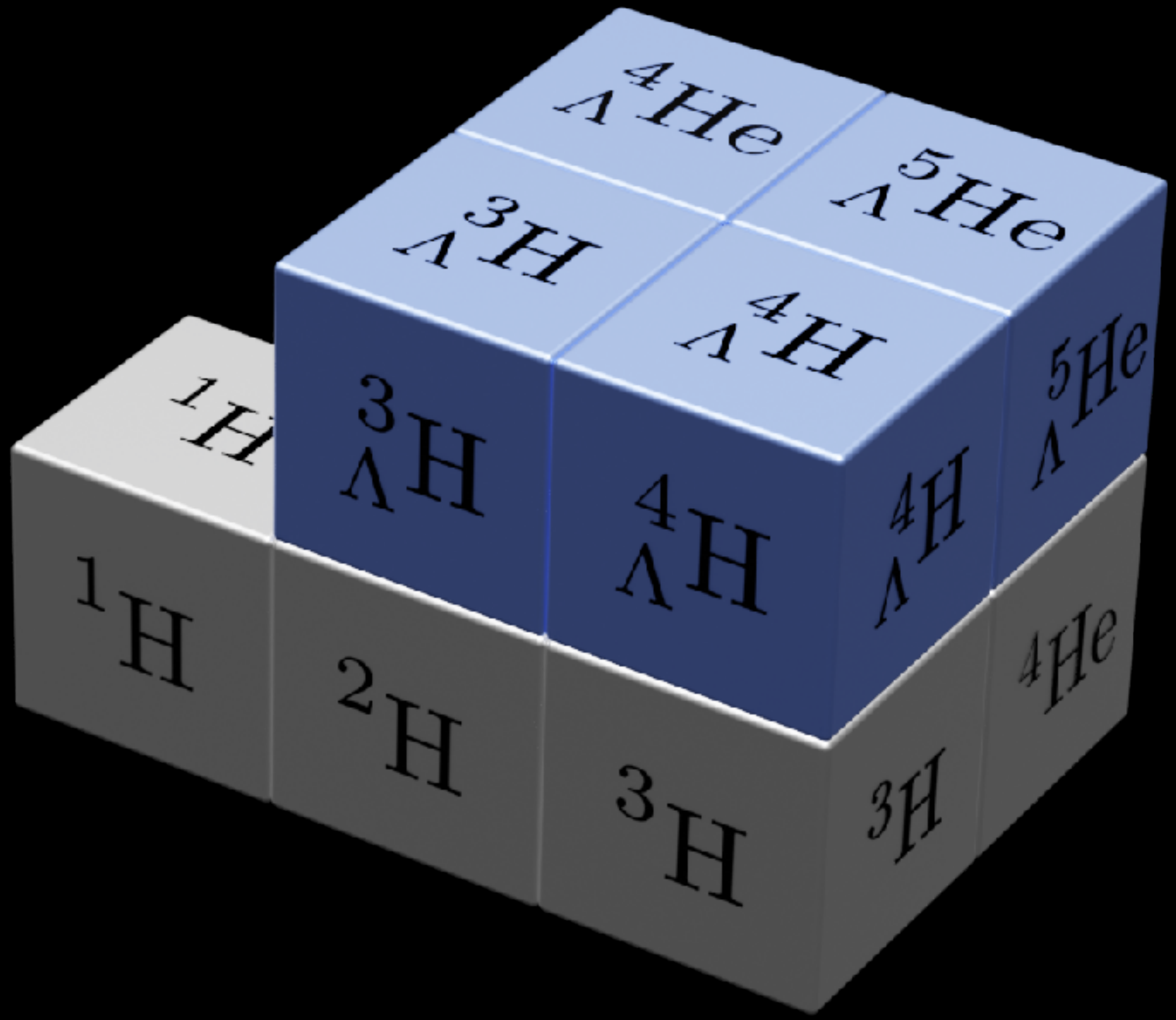
First double-Λ hypernuclear event without any ambiguity in identification

H. Takahashi et al., Phys. Rev. Lett. 87, 212502 (2001);
J.K. Ahn et al., Phys. Rev. C 88, 014003 (2013)

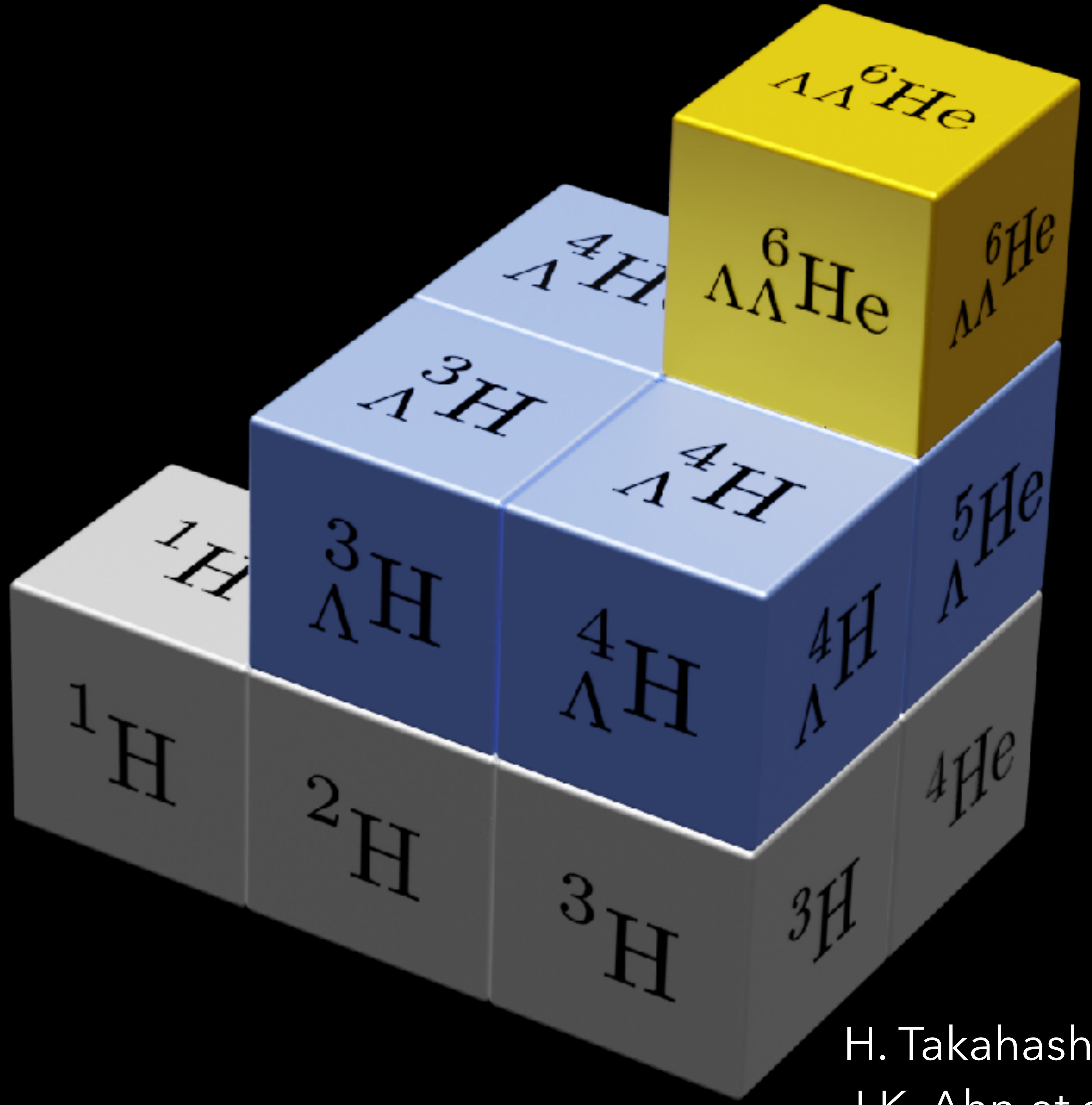
s-shell nuclei



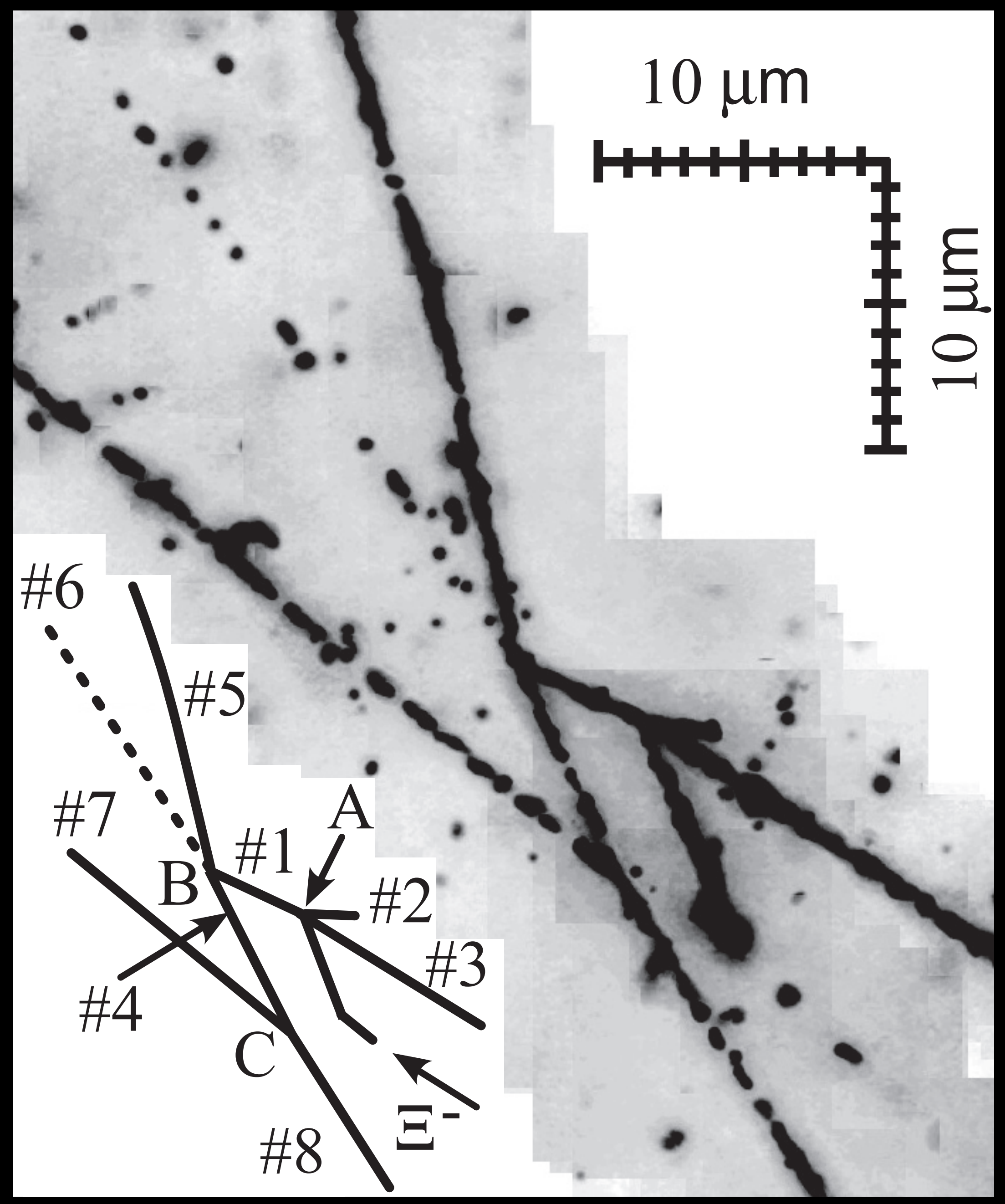
s-shell single-Λ hypernuclei



s-shell double-Λ hypernuclei



NAGARA Event



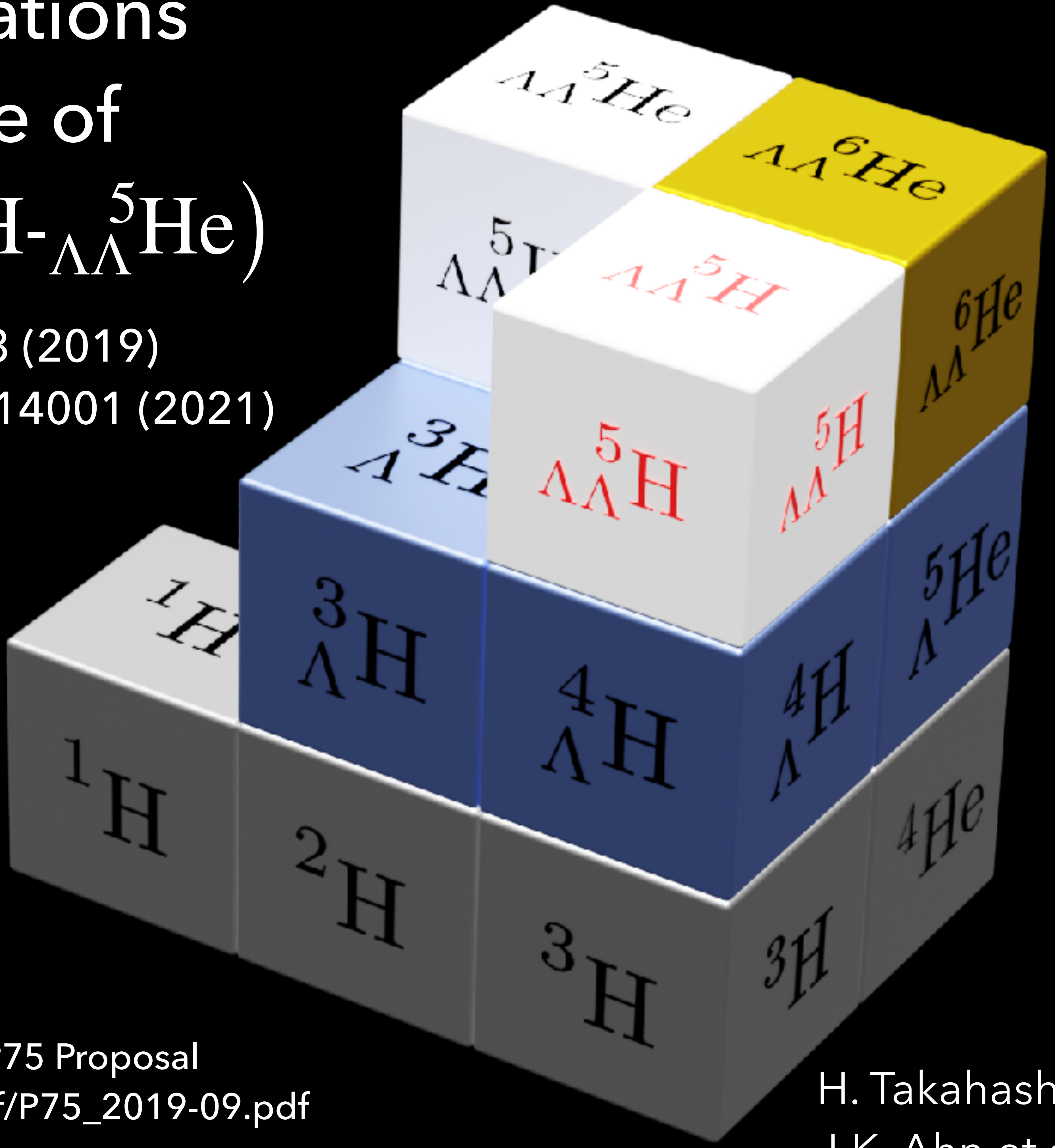
H. Takahashi et al., Phys. Rev. Lett. **87**, 212502 (2001);
J.K. Ahn et al., Phys. Rev. C **88**, 014003 (2013)

s-shell double-Λ hypernuclei

Many theoretical calculations supports the existence of the $A = 5$ isodoublet $\left({}^{5}_{\Lambda\Lambda}\mathrm{H}\text{-}{}^{5}_{\Lambda\Lambda}\mathrm{He}\right)$

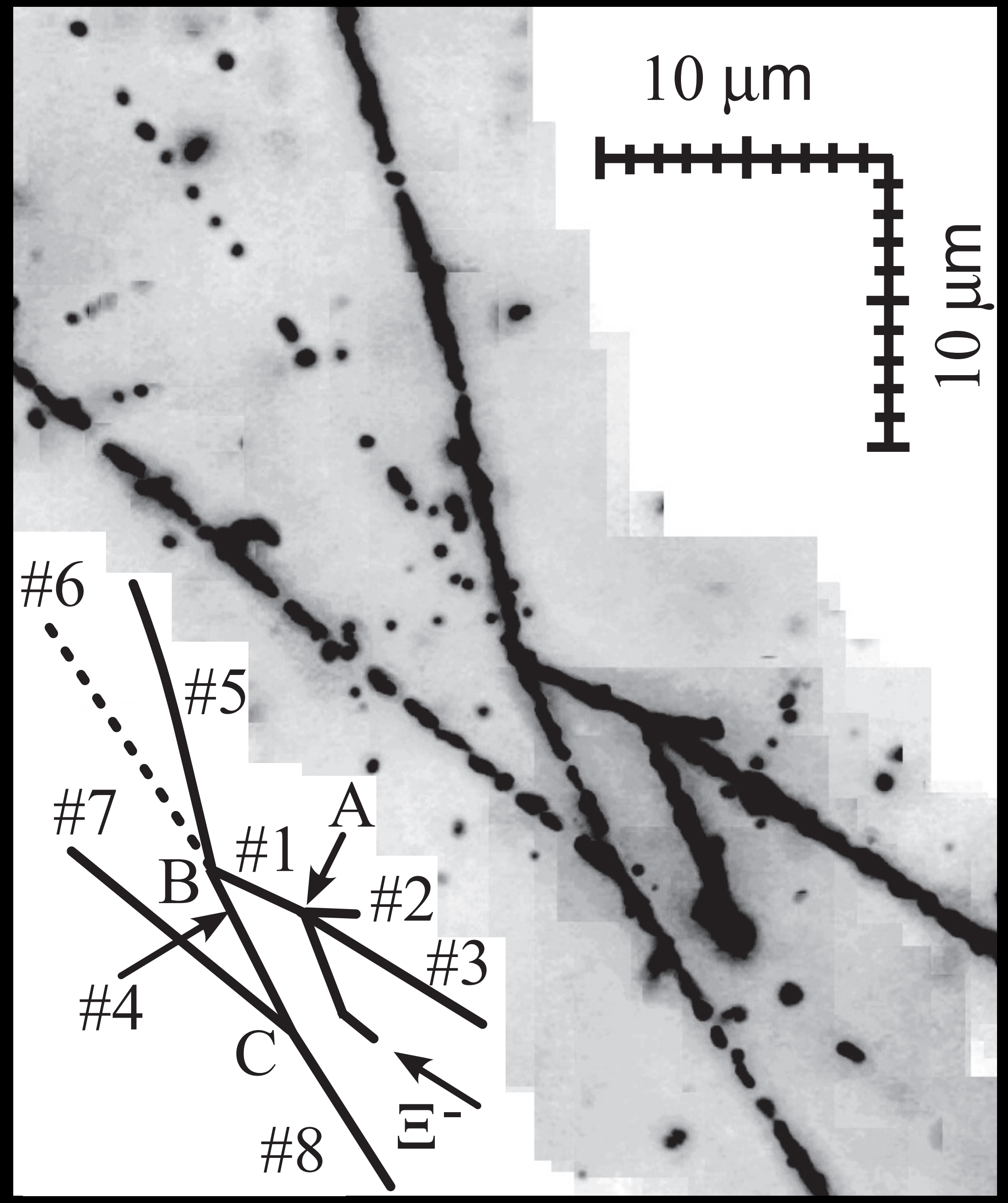
L. Contessi et al., Phys. Lett. B 797, 134893 (2019)
G. Meher and U. Raha, Phys. Rev. C 103, 014001 (2021)
H. Le et al., Eur. Phys. J. A 57, 217 (2021)
and references therein

J-PARC E75 Experiment will investigate ${}^{5}_{\Lambda\Lambda}\mathrm{H}$



H. Fujioka, T. Fukuda, E. Hiyama et al., J-PARC P75 Proposal
https://j-parc.jp/researcher/Hadron/en/pac_1901/pdf/P75_2019-09.pdf

NAGARA Event

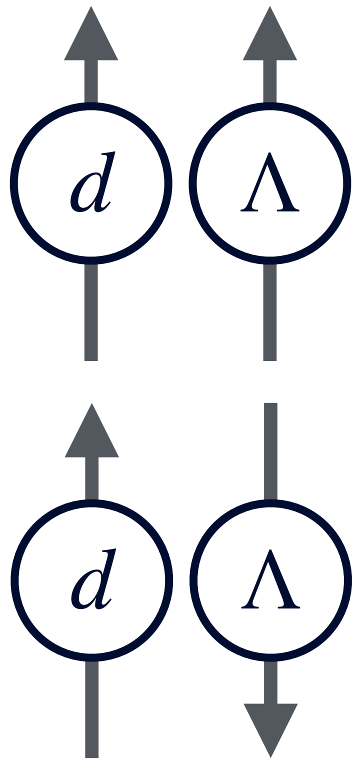


H. Takahashi et al., Phys. Rev. Lett. **87**, 212502 (2001);
J.K. Ahn et al., Phys. Rev. C **88**, 014003 (2013)

the lightest double-Λ hypernucleus

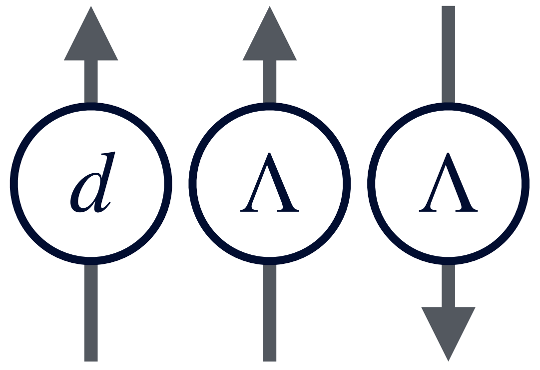
$\boxed{A = 4}$

$^{3}_{\Lambda}\mathrm{H} \Rightarrow {}^{4}_{\Lambda\Lambda}\mathrm{H}$



$3/2^{+}$: unbound

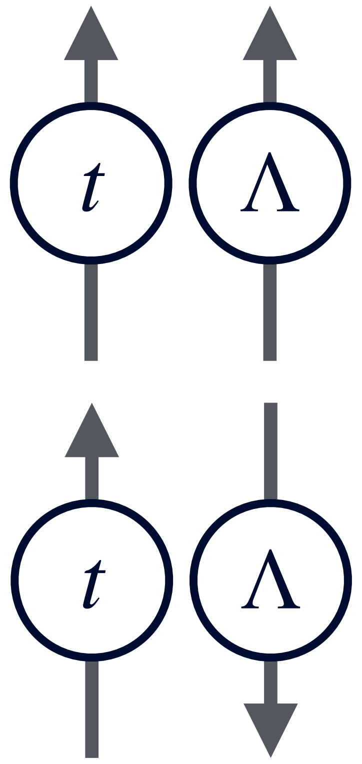
$1/2^{+}$: $B = 0.13\,\mathrm{MeV}$



most likely unbound

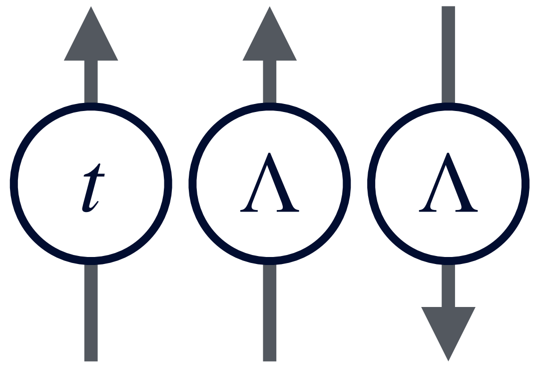
$\boxed{A = 5}$

$^{4}_{\Lambda}\mathrm{H} \Rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H}$



1^{+}: $B = 1.07\,\mathrm{MeV}$

0^{+}: $B = 2.16\,\mathrm{MeV}$



expected to be bound

The lightest Double Λ Hypernuclei will be $^{5}_{\Lambda\Lambda}\mathrm{H}/{}^{5}_{\Lambda\Lambda}\mathrm{He}$

$\Lambda\Lambda$-$\Xi^{-}p$ mixing in the A=5 system

cf. B.F. Gibson et al.,
Prog. Theor. Phys. Suppl. 117, 339 (1994)

$\boxed{A=5}$ ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ p n n Λ Λ

~11MeV mass difference

$\Lambda\Lambda \leftrightarrow \Xi^{-}p$ mixing

${}^{5}_{\Xi^{-}}\mathrm{H}$ p p n n Ξ^{-}

study of $\Lambda\Lambda$-ΞN interaction as well as $\Lambda\Lambda$ interaction

$\boxed{A=6}$ ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ p p n n Λ Λ

Triple-shell closure

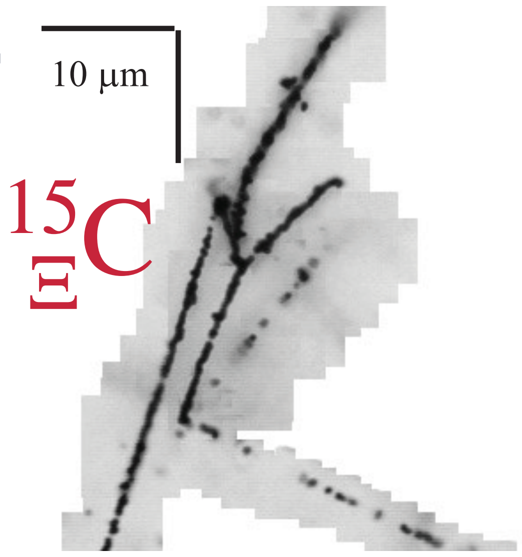
($A \geq 7$ as well)

study of $\Lambda\Lambda$ interaction

Suppression of $\Lambda\Lambda \leftrightarrow \Xi^{-}p$ mixing due to the Pauli principle

Ξ hypernuclei and double-Λ hypernuclei

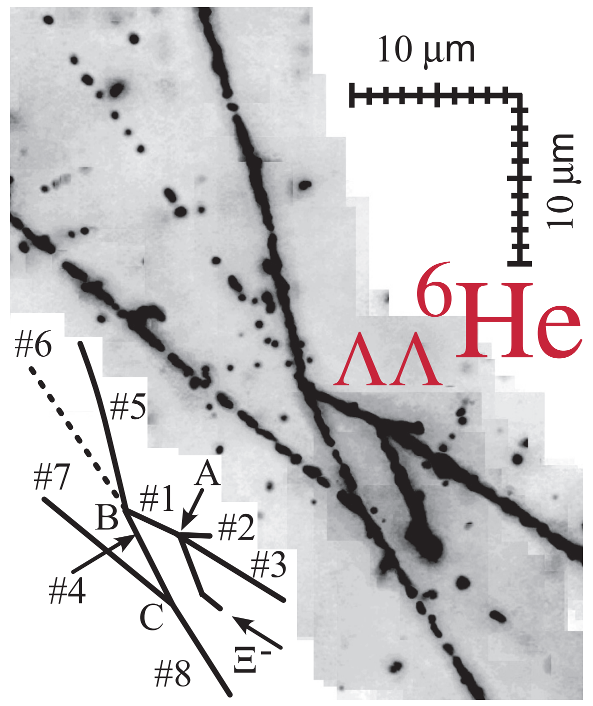
IRRAWADDY event



M. Yoshimoto et al.,
Prog. Theor. Exp. Phys. **2021**, 073D02

Ξ capture in C, N, O (emulsion)

NAGARA Event



$^{7}_{\Xi}\mathrm{H} \rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H} + n + n$

(K^-, K^+) reaction → Ξ hypernuclei → ΞN-ΛΛ conversion → double-Λ hypernuclei → weak decay

$^{12}\mathrm{C} \rightarrow {}^{12}_{\Xi}\mathrm{Be}$: E70 (2023)

$^{7}\mathrm{Li} \rightarrow {}^{7}_{\Xi}\mathrm{H}$: E75 Phase-1 (2023)

$^{5}_{\Lambda\Lambda}\mathrm{H}$: E75 Phase≧2

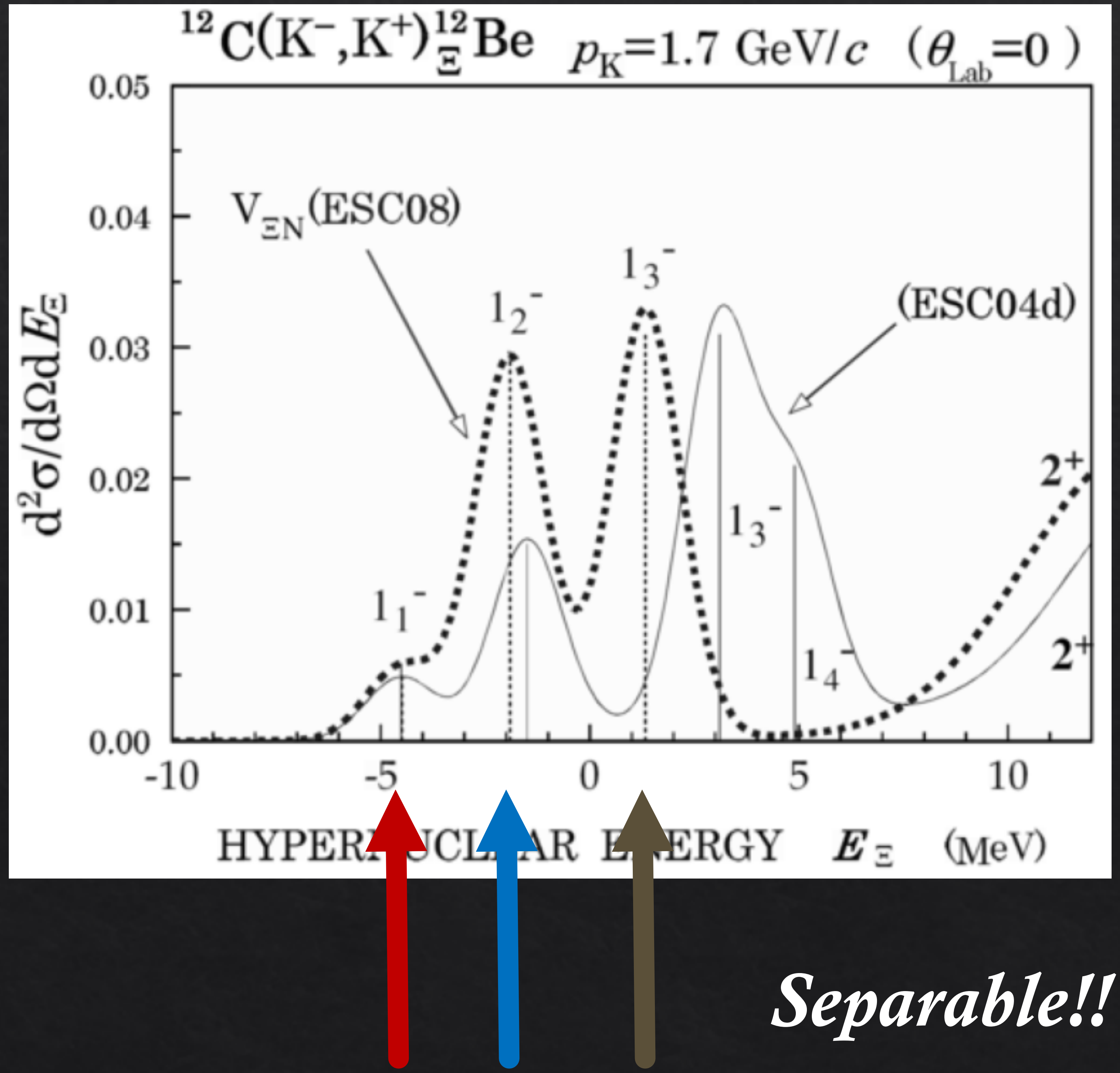
The E75 experiment will bridge
Ξ hypernuclei and double-Λ hypernuclei
with ΞN-ΛΛ conversion.

E70 with Strangeness −2 Spectrometer (S-2S)

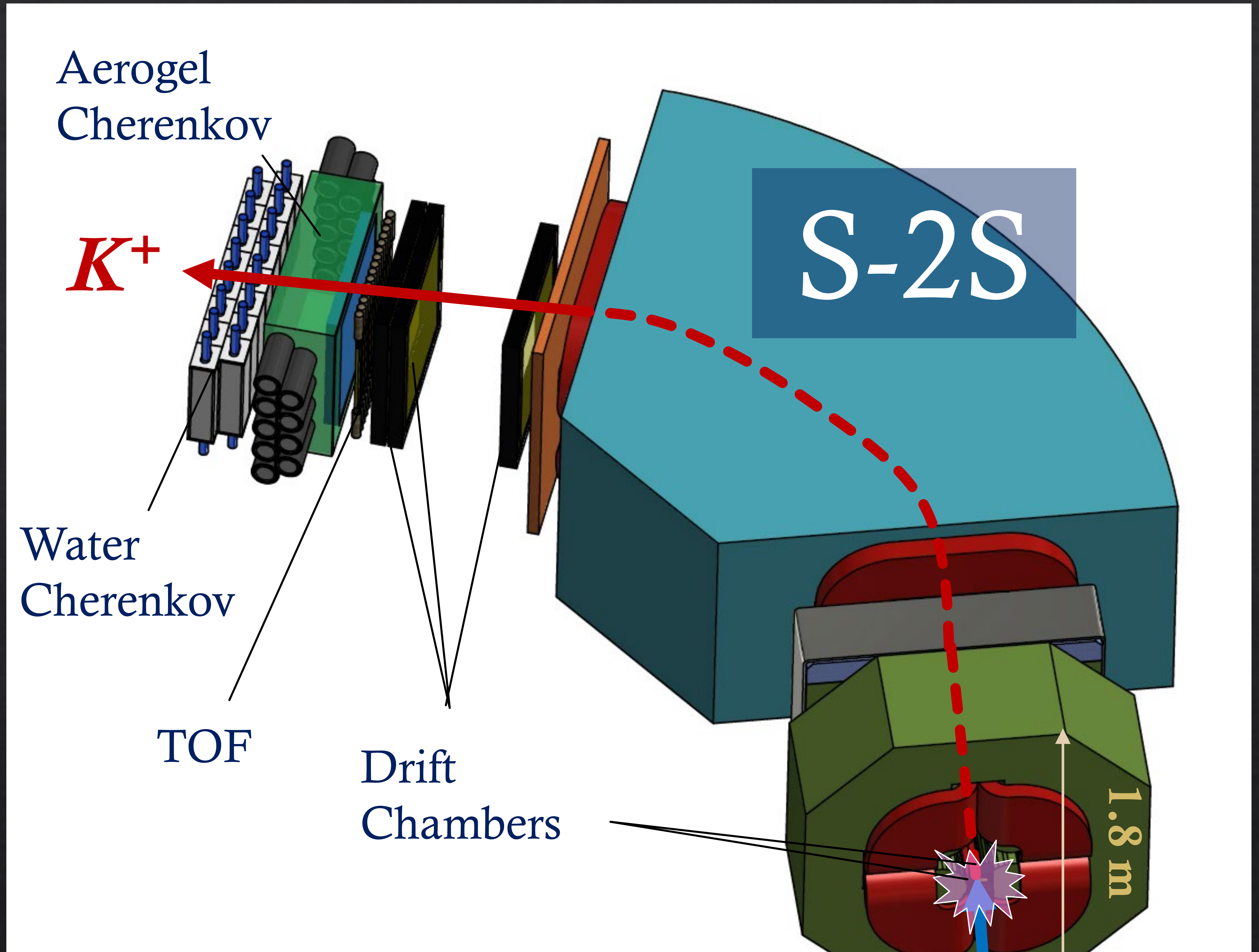
12/21

$$\Delta p/p = 6 \times 10^{-4}\ \text{(FWHM)}$$
$$\rightarrow \Delta E \sim 2\ \text{MeV (FWHM)}$$

T. Motoba and S. Sugimoto, *NPA* **835** (2010) 223-230



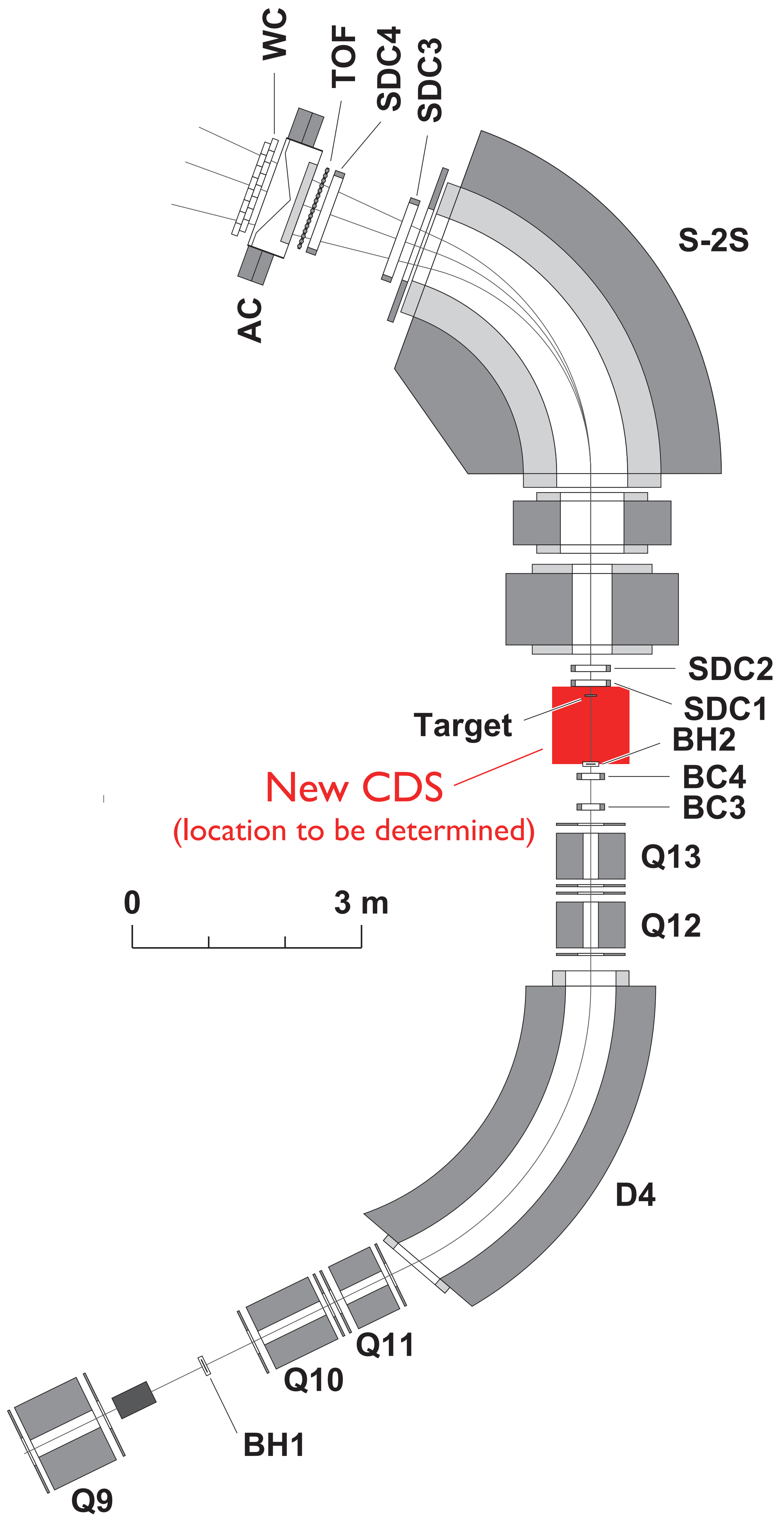
Separable!!



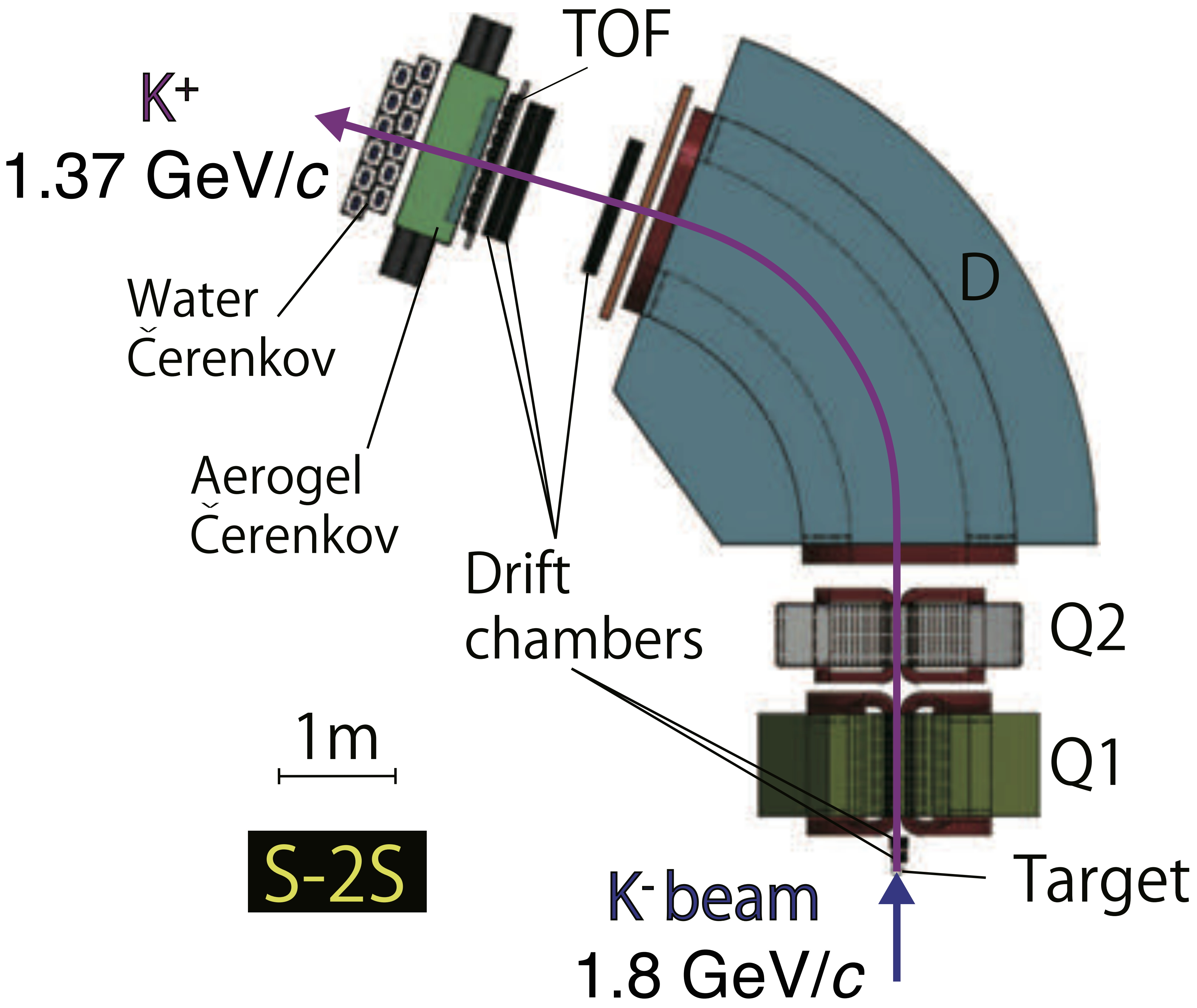
- Water-Cherenkov detector + PID: NIMA 817, 70-84 (2016).
- Recent preparation status: *J. Phys.: Conf. Ser.* **1643** 012133 (2020).

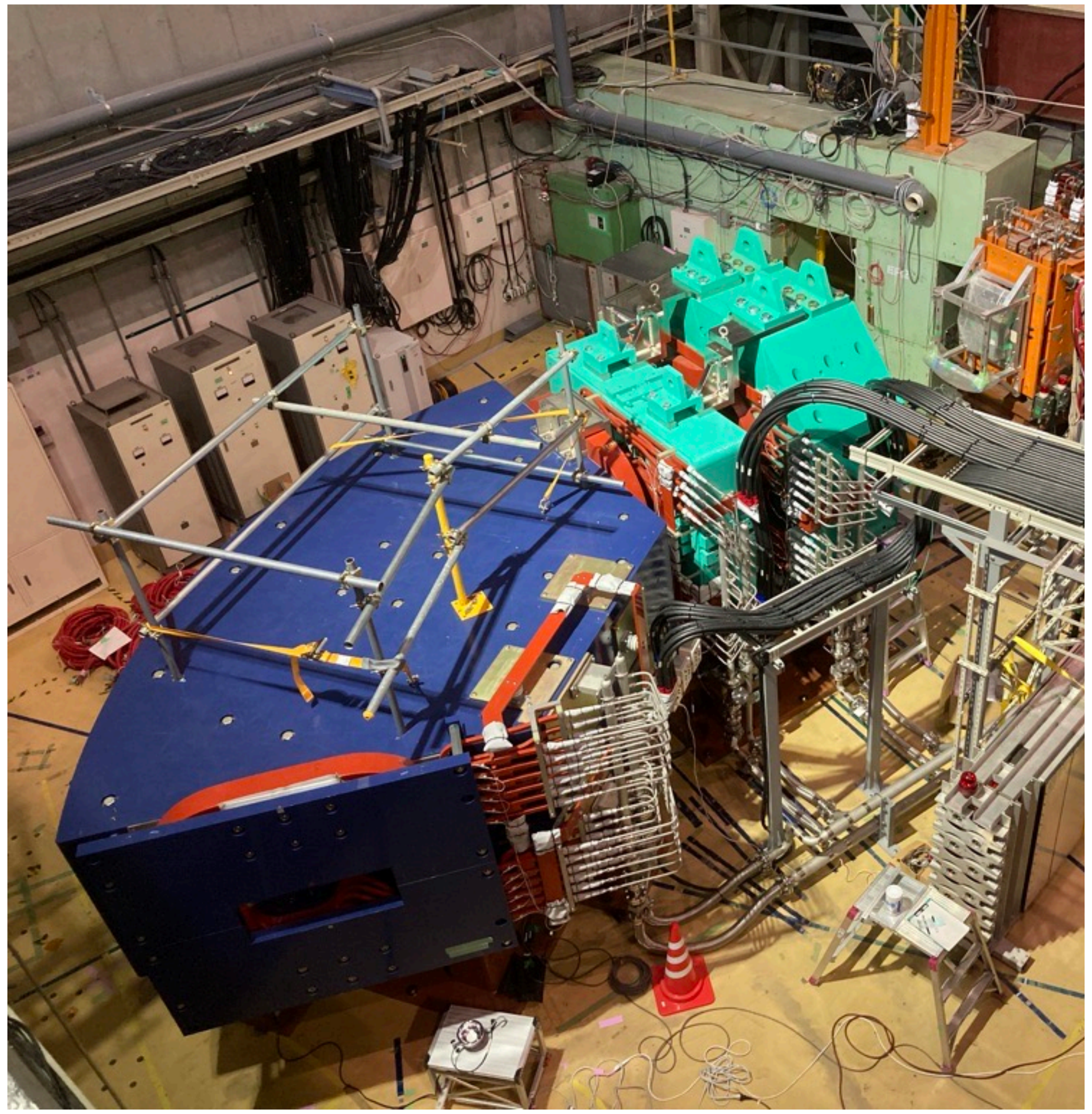
T. Gogami, HYP2022

Experimental setup

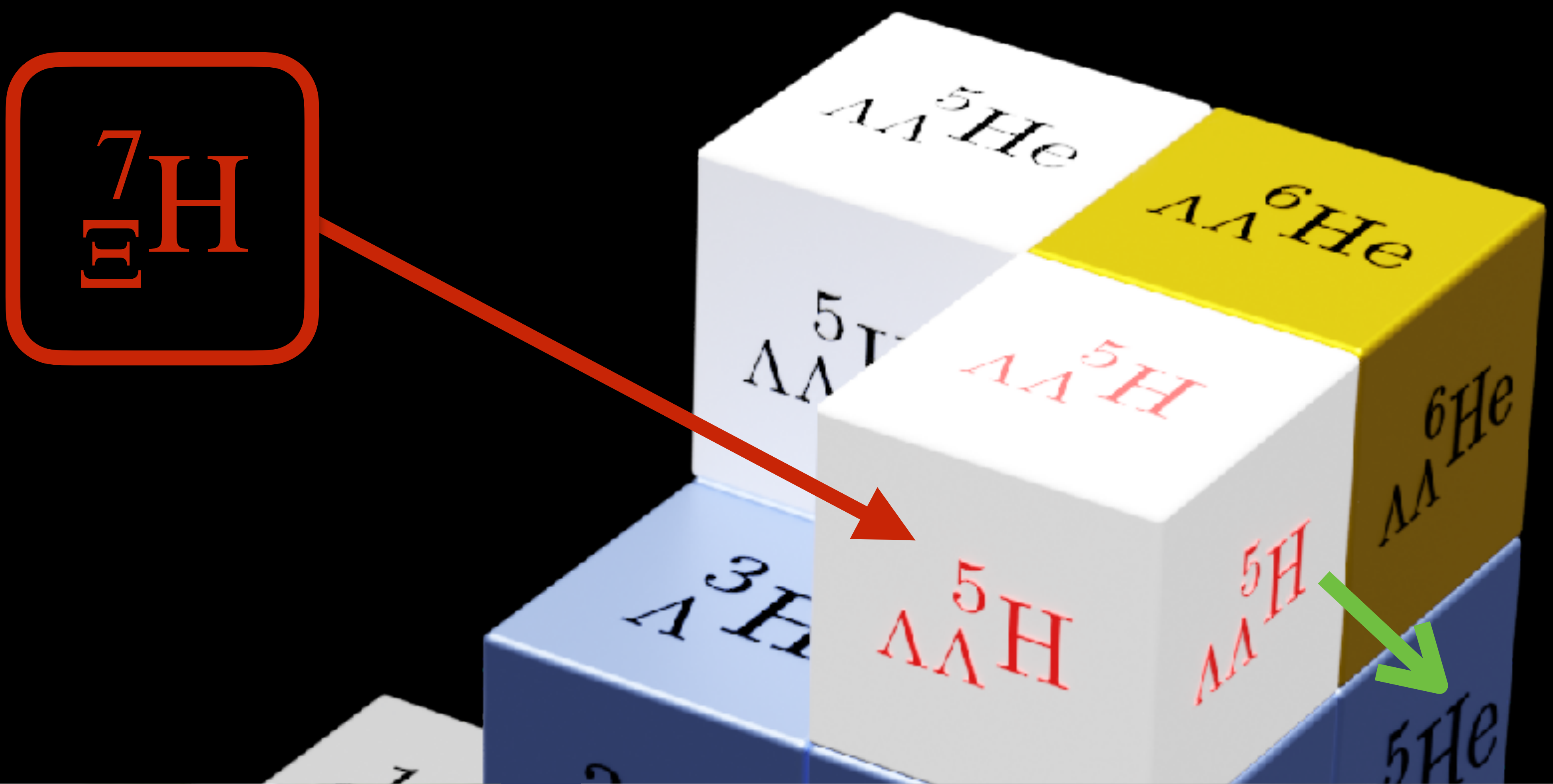


S-2S spectrometer





Production and Decay of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$



Mass of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will be determined
(decay pion spectroscopy)

$p_{\pi^-} \approx 132 - 135\ \mathrm{MeV}/c$

$$ {}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^- $$

Cylindrical Detector System
with a solenoid magnet
and a time projection chamber
(borrowed from LEPS/SPring-8 Gr.)

Characteristics of ${}^{7}_{\Xi}\mathrm{H}\ (= \alpha + n + n + \Xi^{-})$

1. **Close to the onset of Ξ binding**

   - Many calculations predict a bound state (next page)

   cf. A=4 NNNΞ: bound or unbound, depending on the ΞN interaction
   E. Hiyama et al., Phys. Rev. Lett. 124, 092501 (2020)
   H. Le et al., Eur. Phys. J. A 57, 339 (2021)

   - suited to investigate spin- and isospin-averaged $\alpha\Xi$ interaction

   - simple level structure: the ground state will be dominantly populated

2. Limited decay modes

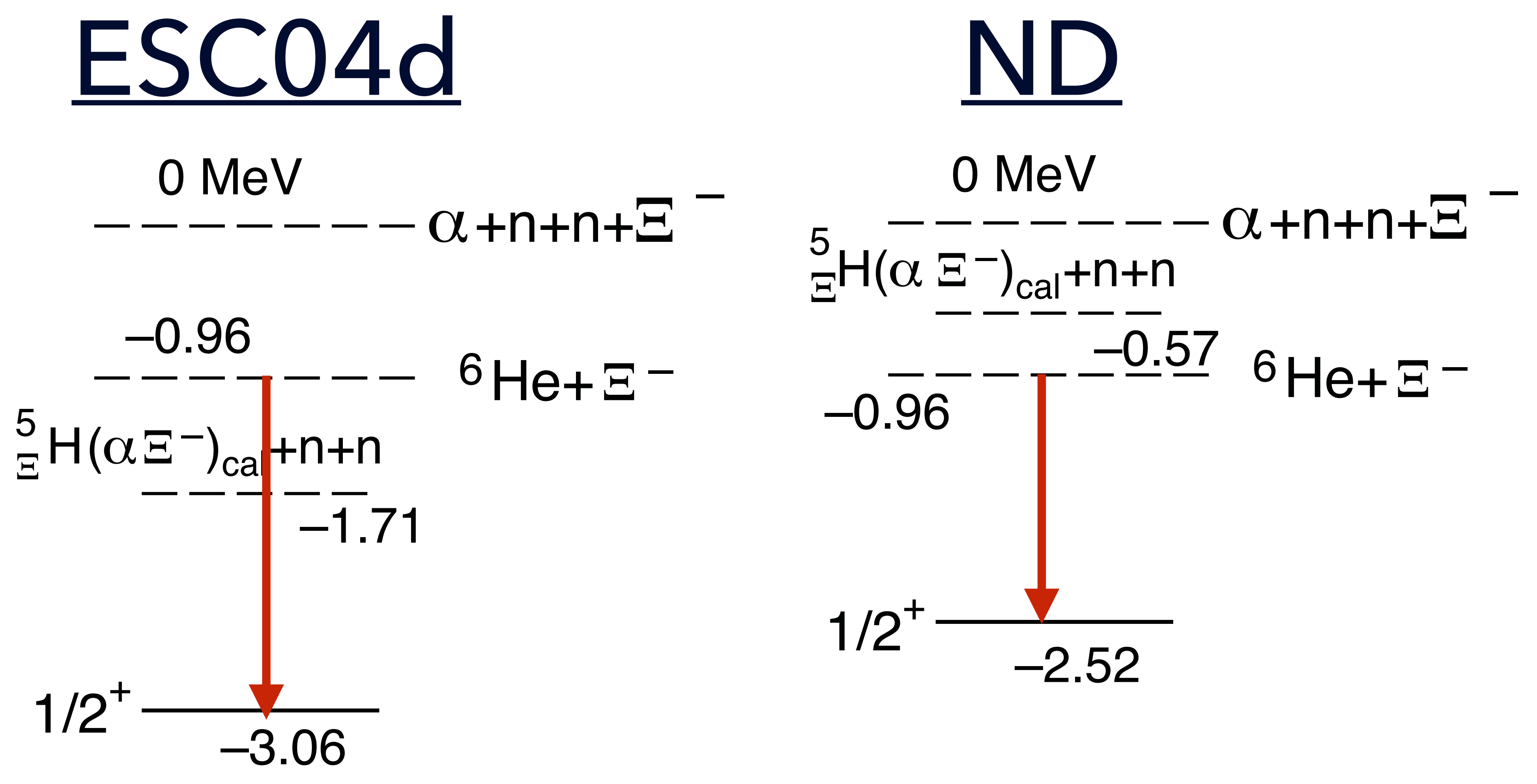
Ξ binding energy

narrow (<1MeV) bound state or not?

Table 1 Ξ separation energies B_Ξ and estimated decay widths Γ for $A = 4-7$ Ξ hypernuclei. All calculations are based on the YY-ΞN interaction NLO(500) and the NN interaction SMS N^{4}LO+(450). Both potentials are SRG-evolved to a flow parameter of $\lambda_{NN} = \lambda_{YY} = 1.6$ fm^{-1}. The values of B_Ξ in NNNΞ, ${}^5_\Xi$H and ${}^7_\Xi$H are measured with respect to the binding energies of the core nuclei ^{3}H, ^{4}He and ^{6}He, respectively

	B_Ξ [MeV]	Γ [MeV]
${}^4_\Xi$H$(1^+, 0)$	0.48 ± 0.01	0.74
${}^4_\Xi$n$(0^+, 1)$	0.71 ± 0.08	0.2
${}^4_\Xi$n$(1^+, 1)$	0.64 ± 0.11	0.01
${}^4_\Xi$H$(0^+, 0)$	–	–
${}^5_\Xi$H$(\frac{1}{2}^+, \frac{1}{2})$	2.16 ± 0.10	0.19
${}^7_\Xi$H$(\frac{1}{2}^+, \frac{3}{2})$	3.50 ± 0.39	0.2

H. Le et al., Eur. Phys. J. A 57, 339 (2021)



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

interaction model	B [MeV]	Γ [MeV]
ESC04d	1.80	2.64
ND	1.55	0.27
HAL $(t/a = 11)$	3.15	0.02

E. Hiyama, private communication

Characteristics of ${}^{7}_{\Xi}\mathrm{H}\ (=\alpha+n+n+\Xi^-)$

1. Close to the onset of Ξ binding

2. **Limited decay modes**

PHYSICAL REVIEW C VOLUME 54, NUMBER 1 JULY 1996

Double-Λ hypernuclear formation via a neutron-rich Ξ state

$$ {}^{7}_{\Xi}\mathrm{H}\rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H}+n+n \quad \sim 11\ \mathrm{MeV}, $$ BR~90%

$$ \rightarrow {}^{4}_{\Lambda}\mathrm{H}+\Lambda+n+n \quad \sim 7\ \mathrm{MeV}, $$

$$ \rightarrow {}^{4}_{\Lambda}\mathrm{H}^{*}+\Lambda+n+n \quad \sim 6\ \mathrm{MeV}, $$

$$ \rightarrow {}^{3}\mathrm{H}+\Lambda+\Lambda+n+n \quad \sim 5\ \mathrm{MeV}. $$

Only 4 decay modes kinematically allowed

I. Kumagai-Fuse, Y. Akaishi, Phys. Rev. C 54, R24 (1996)

PTEP Prog. Theor. Exp. Phys. 2020, 063D01 (17 pages)
DOI: 10.1093/ptep/ptaa047

pnnΛΛ

Statistical double Λ hypernuclear formation from Ξ^- absorption at rest in light nuclei

Akira Ohnishi[1,*], Chikako Ishizuka[2], Kohsuke Tsubakihara[2,3], and Yuichi Hirata[4]
[1]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Laboratory for Advanced Nuclear Energy, Institute of Innovative Research, Tokyo Institute of Technology, Tokyo 152-8550, Japan*
[3]*National Institute of Technology, Asahikawa College, Asahikawa 071-8142, Japan*
[4]*Central Institute of Isotope Science, Hokkaido University, Sapporo 060-0815, Japan*
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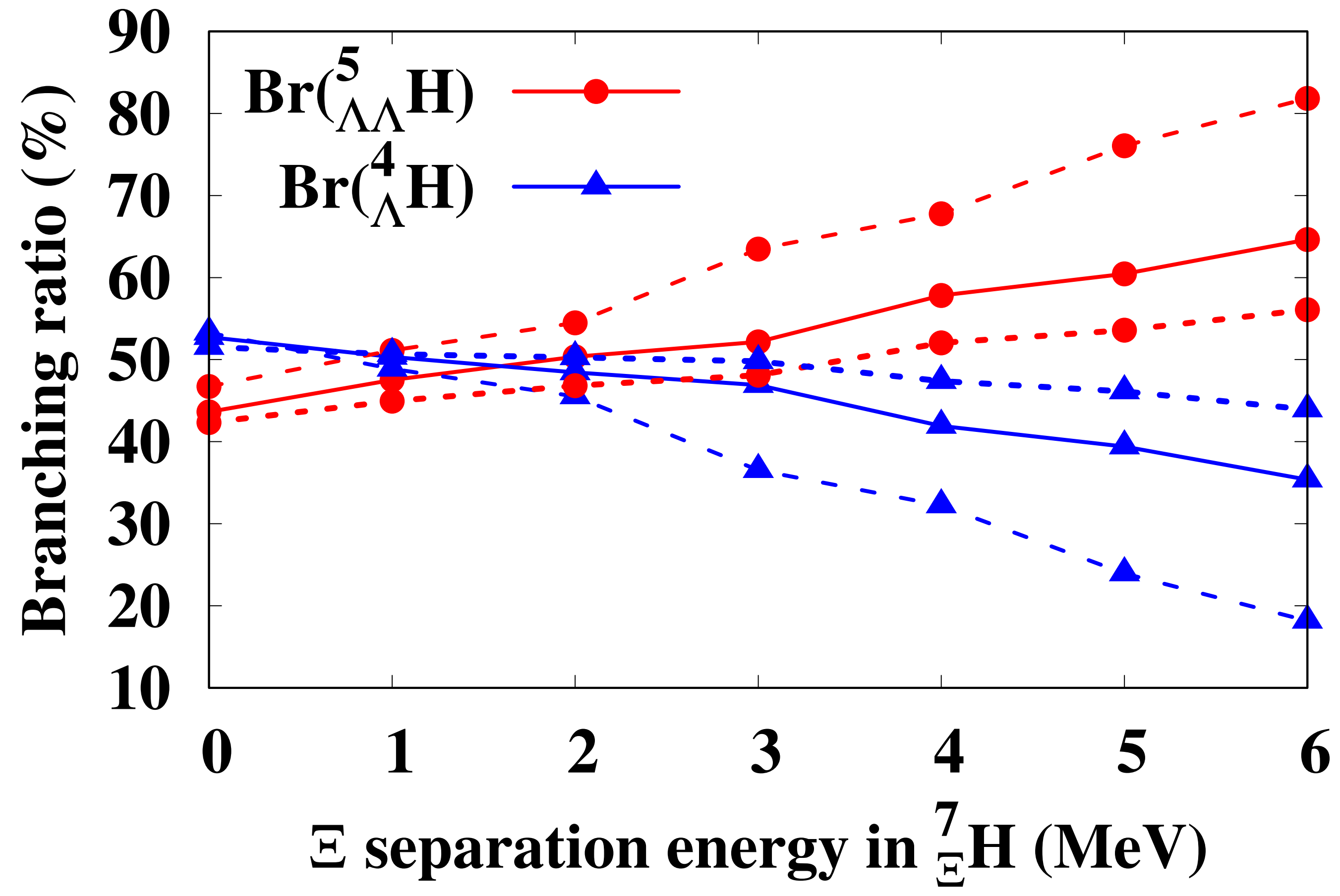
Received November 28, 2019; Revised March 16, 2020; Accepted March 17, 2020; Published June 18, 2020

${}^{5}_{\Lambda\Lambda}\mathrm{H}+2n$ BR~50% ${}^{4}_{\Lambda}\mathrm{H}(0^+,1^+)+\Lambda+2n$

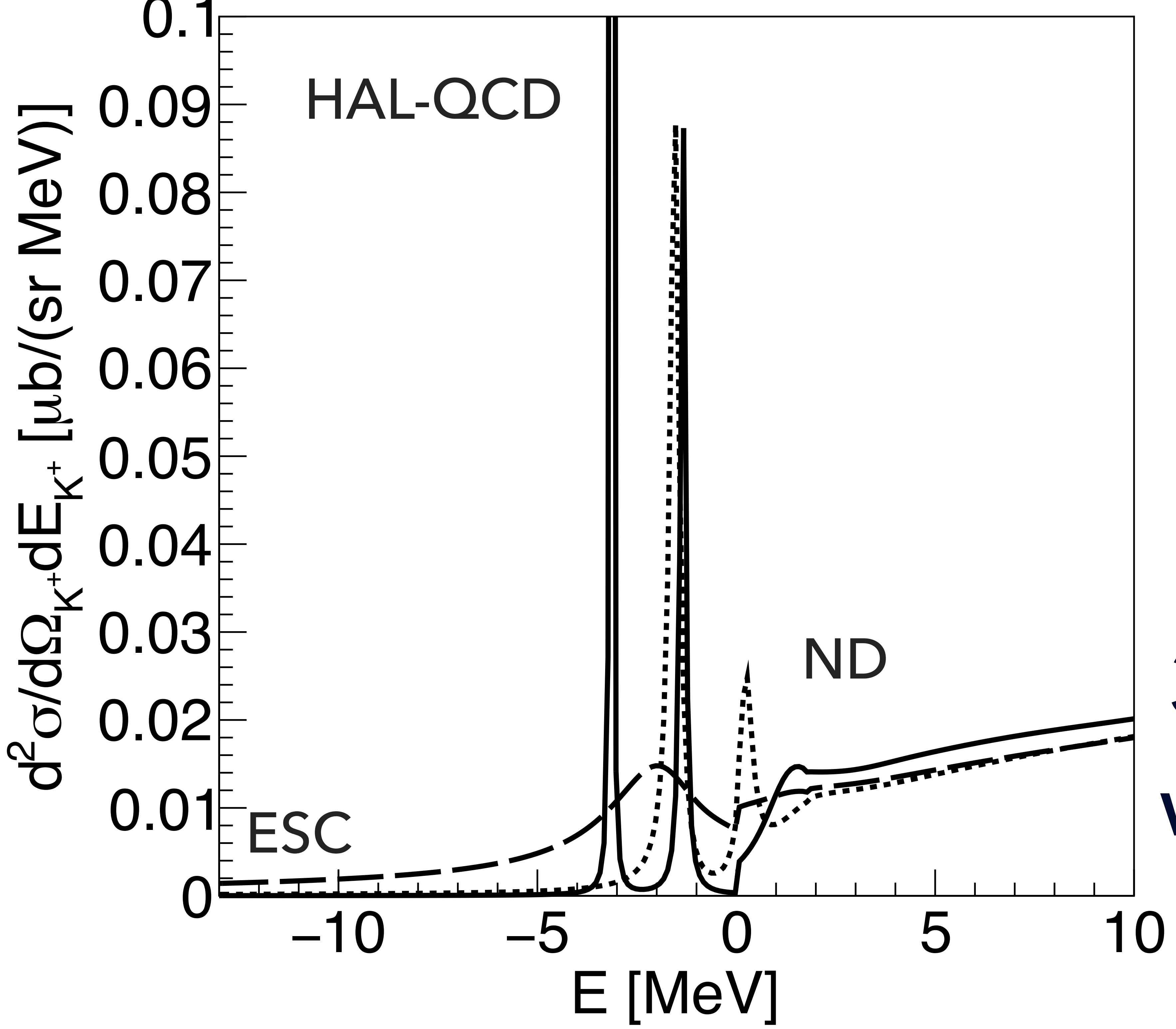


A. Ohnishi et al., Prog. Theor. Exp. Phys. 2020, 063D01 (2020)

${}^{7}_{\Xi}\mathrm{H}$ formation spectra

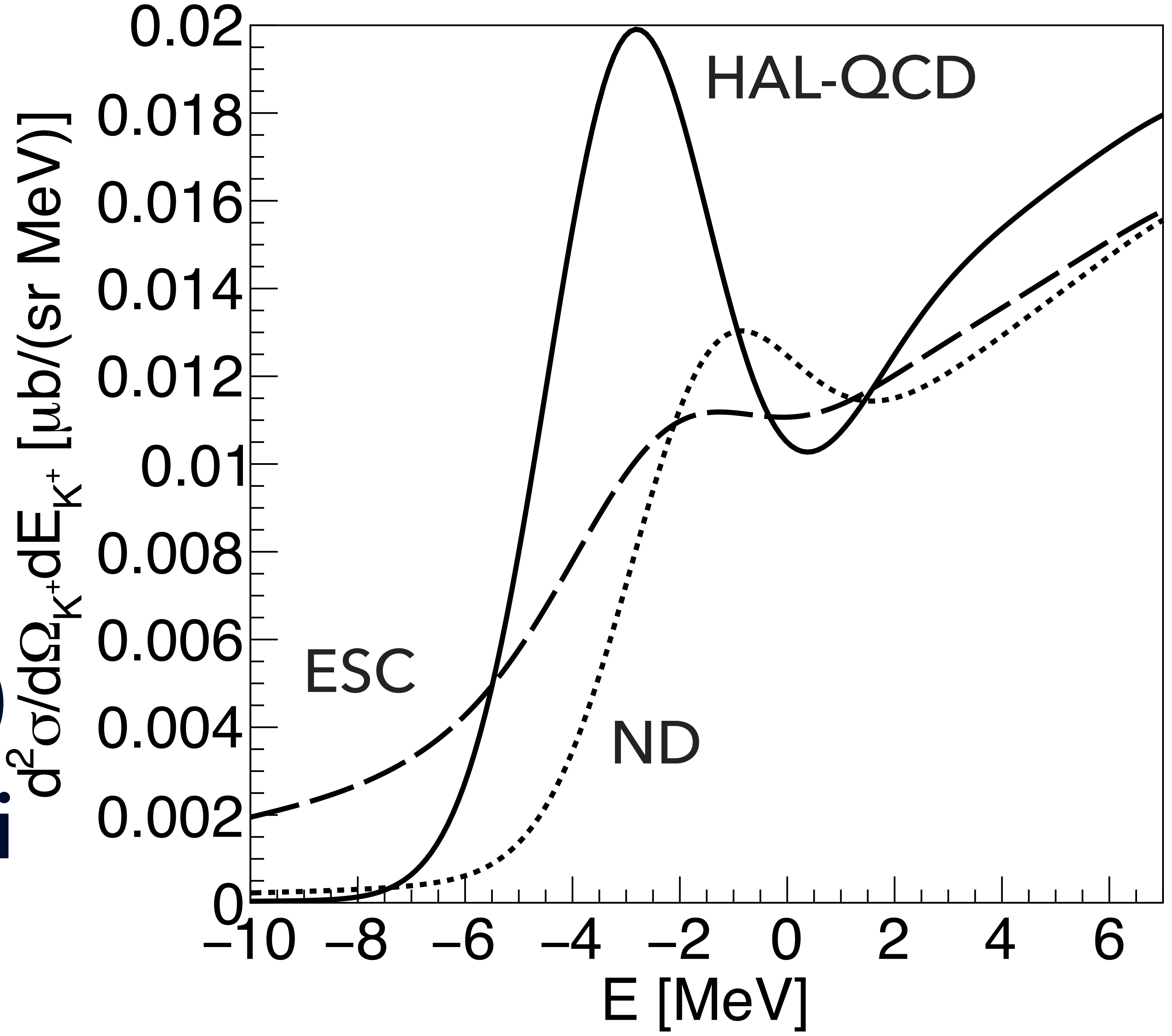
H. Fujioka. T. Fukuda, E. Hiyama et al., E75 Phase-1 Proposal
https://j-parc.jp/researcher/Hadron/en/pac_2001/pdf/P75_2020-02.pdf

56-104 “bound ${}^{7}_{\Xi}\mathrm{H}$” events for 1-week measurement



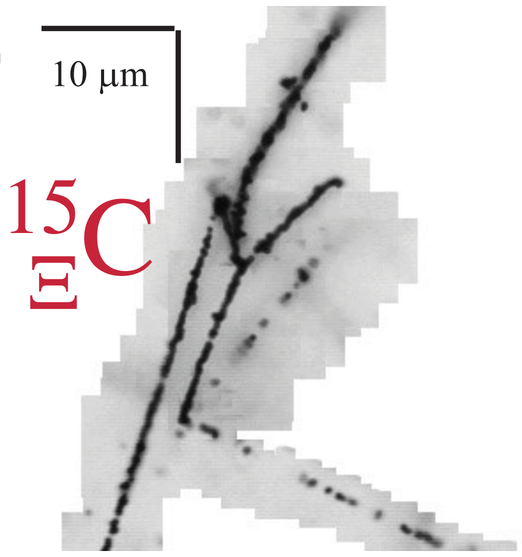
E. Hiyama and T. Koike, private communication

exp. resolution
3.5MeV(FWHM)
with 10g/cm² ⁷Li



Ξ hypernuclei and double-Λ hypernuclei

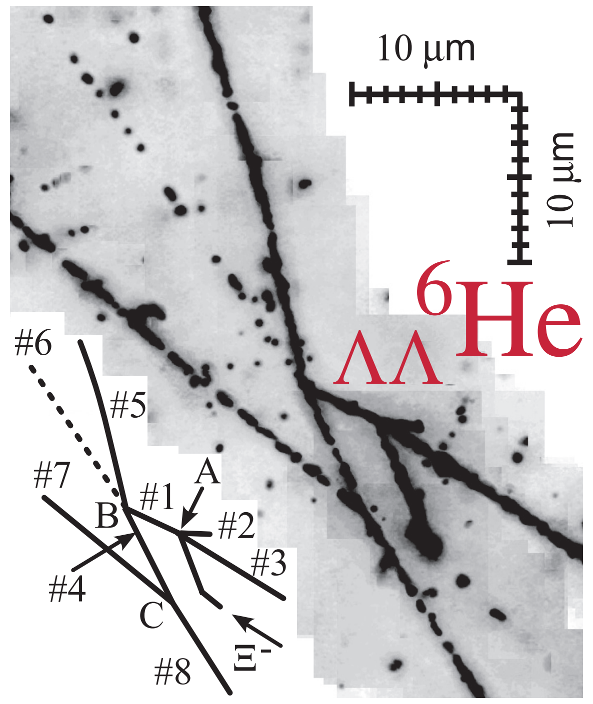
IRRAWADDY event



M. Yoshimoto et al.,
Prog. Theor. Exp. Phys. **2021**, 073D02

Ξ capture in C, N, O (emulsion)

NAGARA Event



$^{7}_{\Xi}\mathrm{H} \rightarrow {}^{5}_{\Lambda\Lambda}\mathrm{H} + n + n$

(K^-, K^+) reaction → Ξ hypernuclei → ΞN-$\Lambda\Lambda$ conversion → double-Λ hypernuclei → weak decay

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$^{5}_{\Lambda\Lambda}\mathrm{H}$: E75 Phase≧2

The E75 experiment will bridge
Ξ hypernuclei and double-Λ hypernuclei
with ΞN-$\Lambda\Lambda$ conversion.

Summary and Outlook

- The J-PARC E75 experiment will investigate almost the lightest double strange nuclei, ${}^{7}_{\Xi}\mathrm{H}$ and ${}^{5}_{\Lambda\Lambda}\mathrm{H}$.
- ${}^{7}_{\Xi}\mathrm{H}$ will be the lightest Ξ hypernuclei produced experimentally than ever. Probably it will be close to the onset of Ξ binding.
- Only four decay modes are allowed. Among them, a dominant decay mode into ${}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ will be utilized to produce ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ in future.
- We expect the missing-mass resolution of 3.5 MeV in FWHM with a thick target.