Neutron-rich Λ hypernuclei

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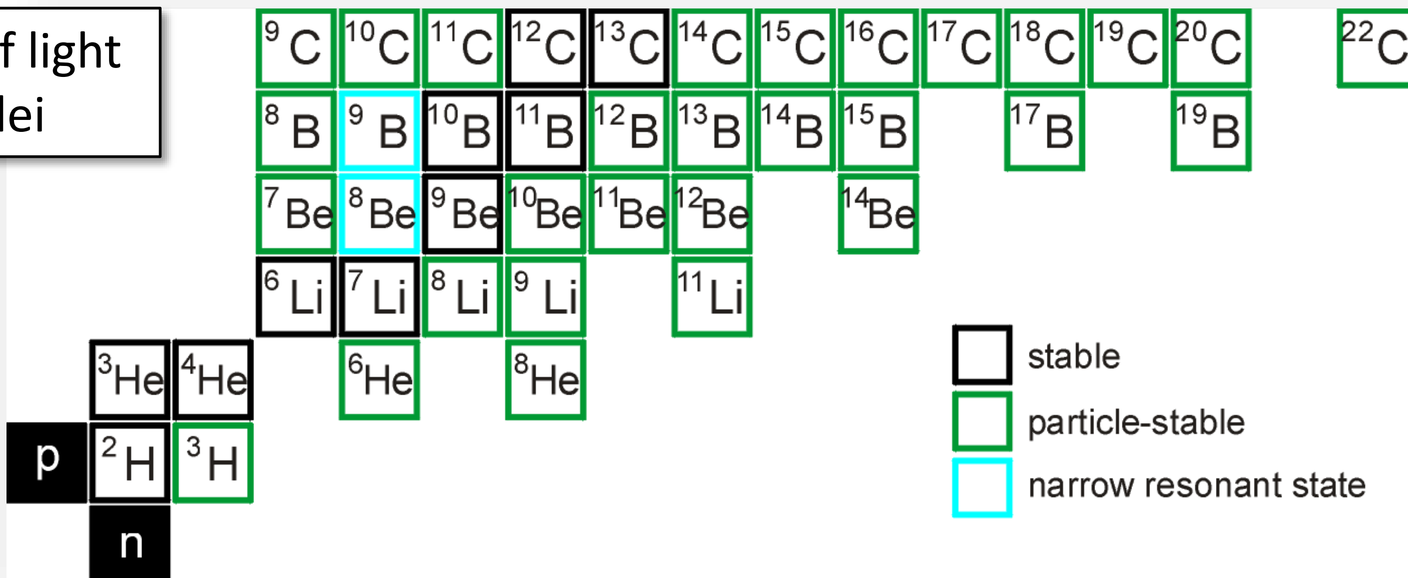
Why neutron-rich Λ hypernuclei?

- Extensive studies on neutron-rich nuclei
  - Nuclear chart has wide spreading in the neutron-rich side
    - Simple shell model is not enough to understand wide range of nuclear chart
  - Studies of these neutron-rich nuclei give us detailed information of nuclear interaction

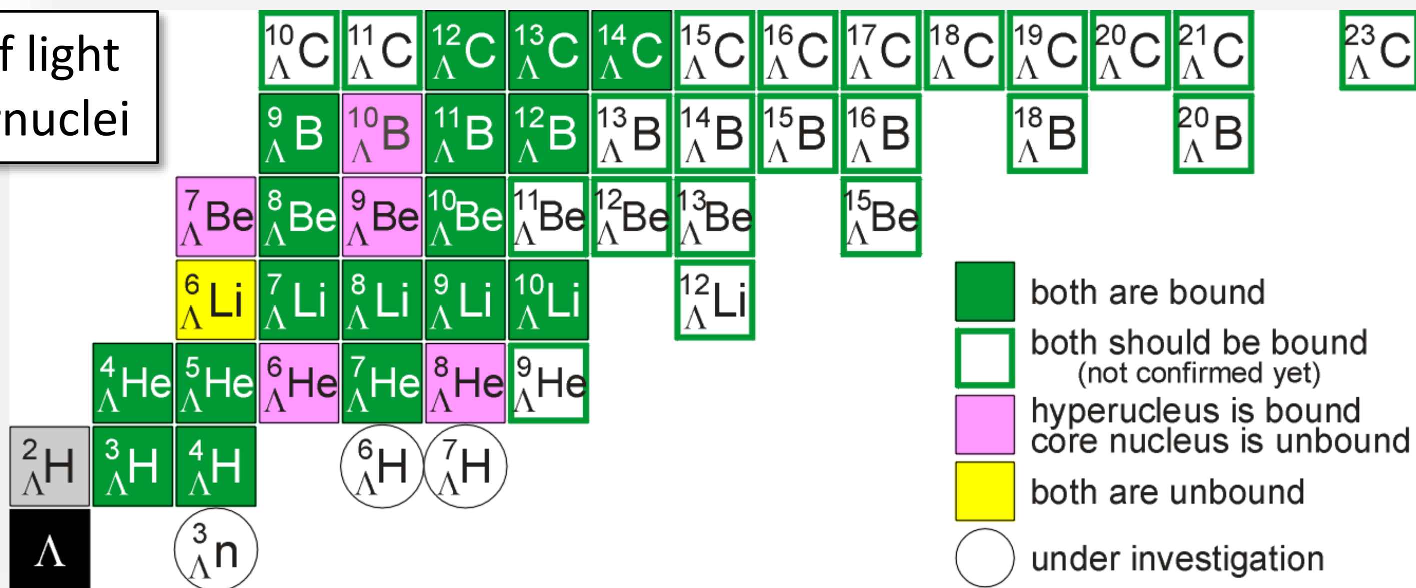
Chart of light nuclei



Why neutron-rich Λ hypernuclei?

- Chart of Λ hypernuclei
  - Particle-stable core nuclei guarantee stable Λ hypernuclei
    - Still there are many unobserved Λ hypernuclei
  - Λ-hyperon may reinforce the hypernuclear binding
    - Glue-like role of Λ-hyperon: also particle-unstable core nuclei may produce stable Λ hypernuclei

Chart of light Λ hypernuclei



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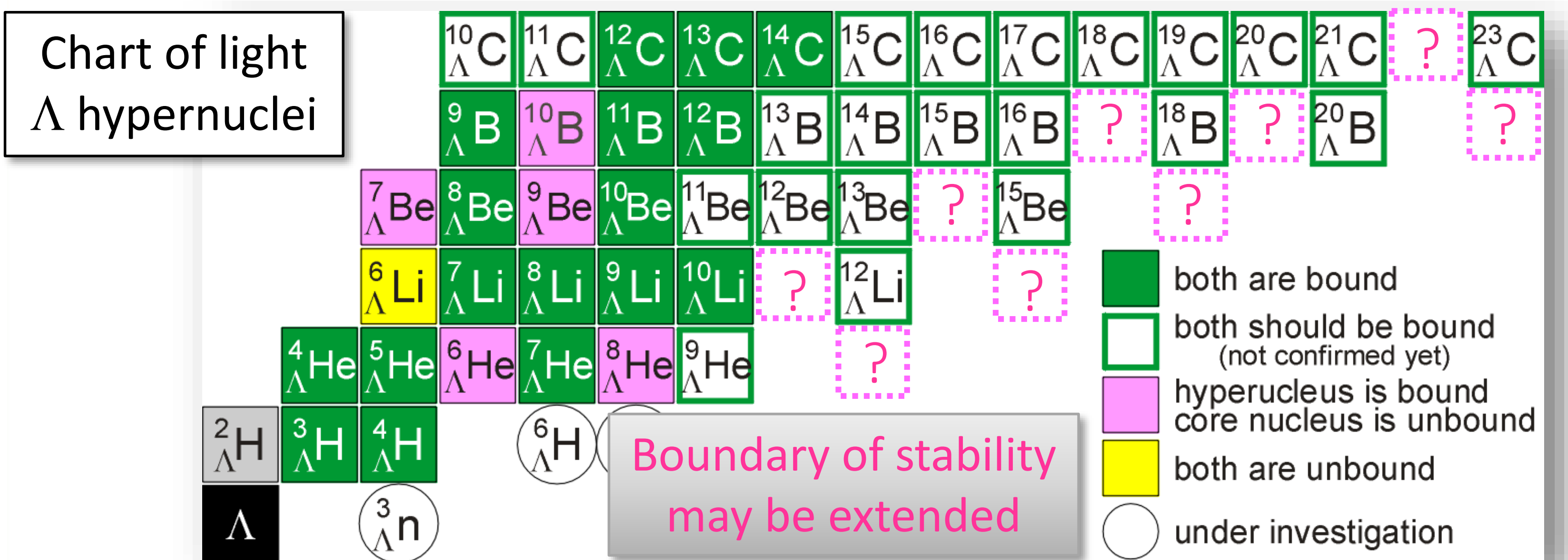
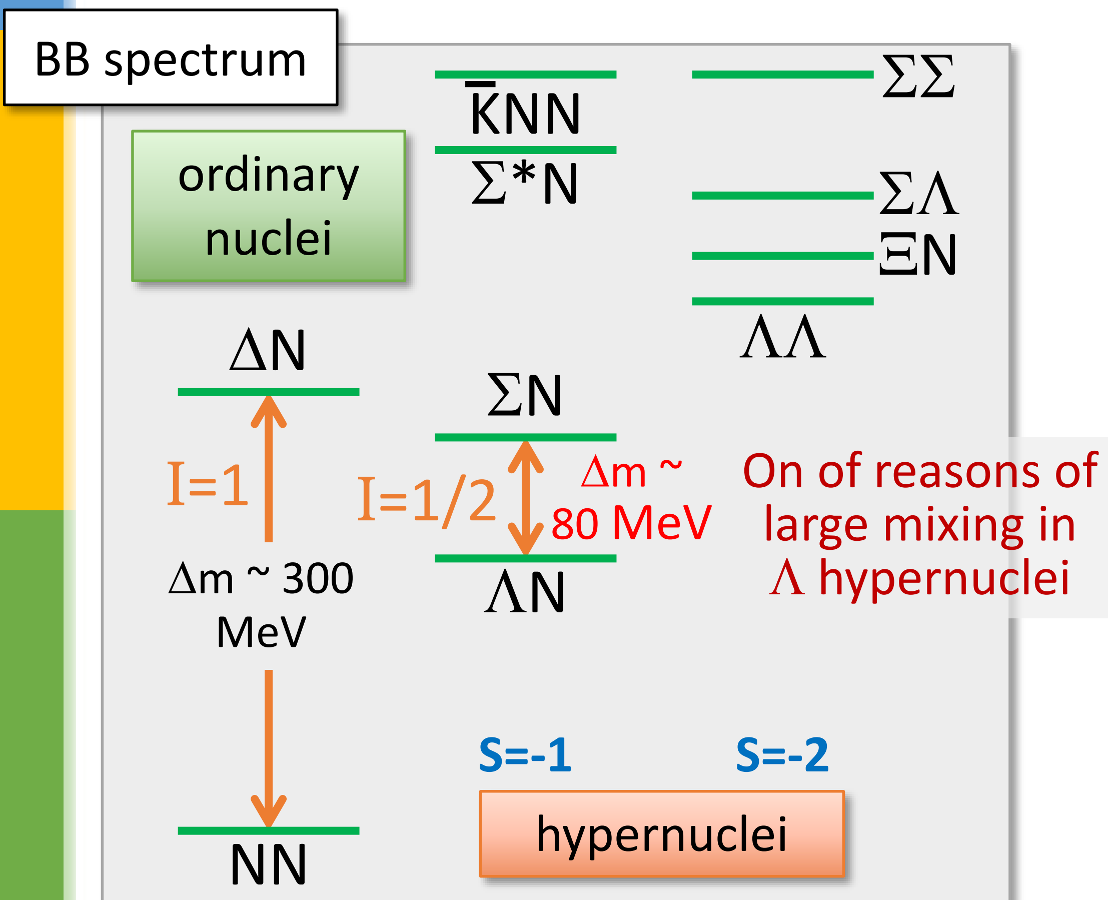
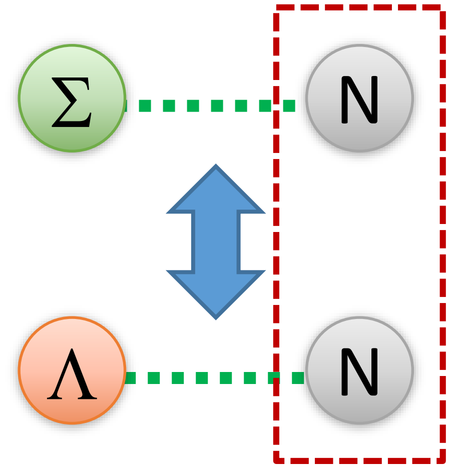


ΛN-ΣN mixing in n-rich Λ hypernuclei

- Large contribution of ΛN-ΣN mixing is expected
  - B.F. Gibson et al. PR C6 (1972) 741





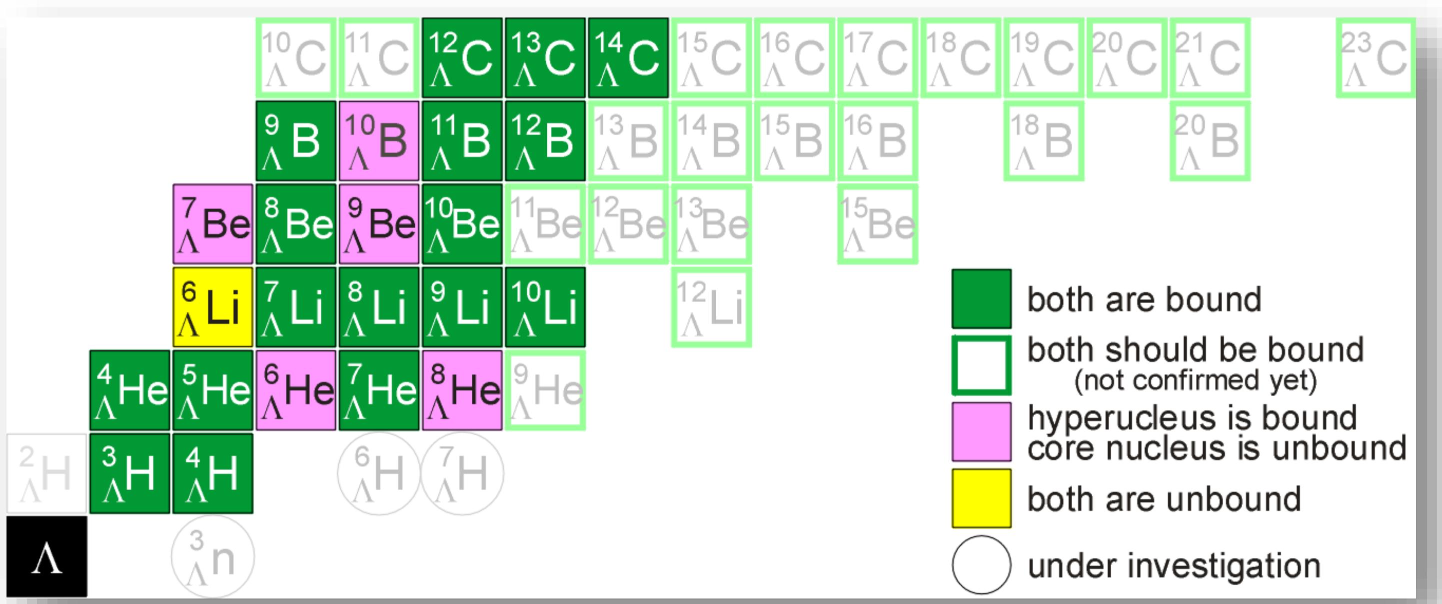
Large overlap in nucleon part only if N≠Z ($I_{core} \neq 0$)
Pauli blocking may be small

Core nucleus is a buffer of isospin

How large ΛN-ΣN mixing in neutron-rich Λ hypernuclei?

Tools to access n-rich Λ hypernuclei

- Old emulsion experiments with stopped-K$^-$ beams
  - Hypernuclear species were limited and yield was low



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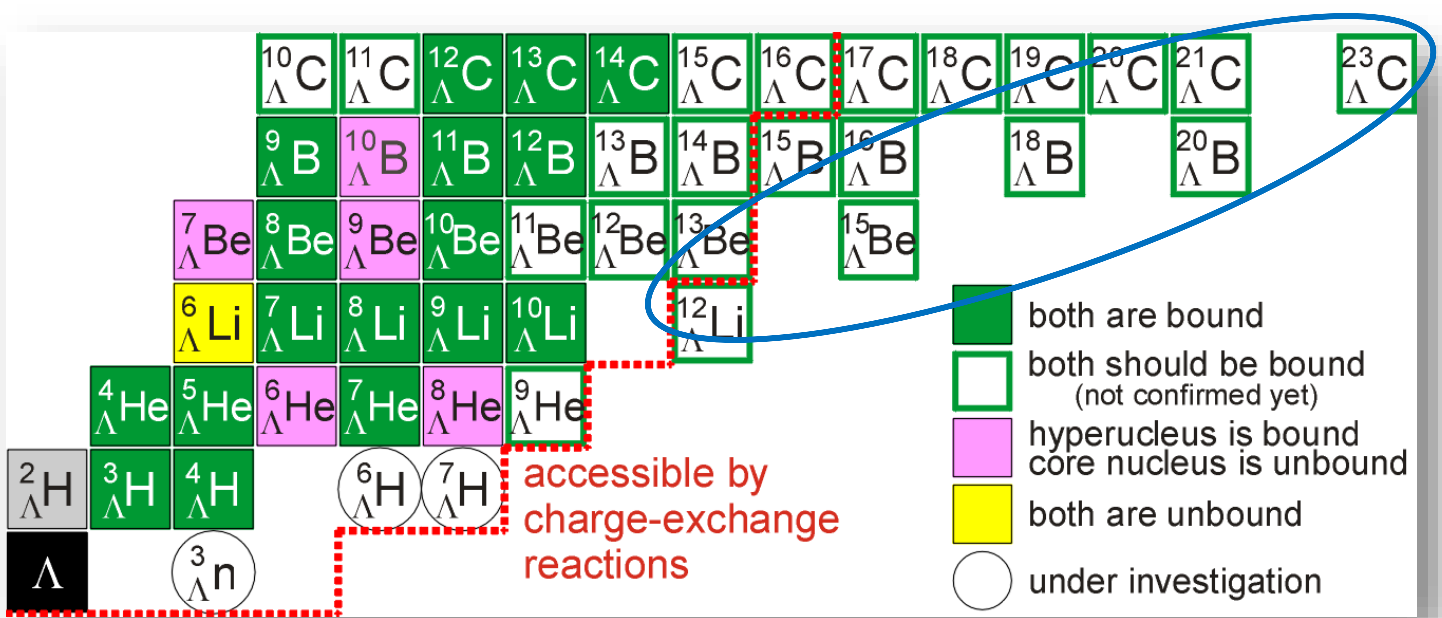
L. Majling, Nucl. Phys. A585 (1995) 211c

  - SCX: $(e,e'K^+)$, (K^-, π^0) DCX: (π^-,K^+), (K^-,π^+)

SCX: Single Charge-eXchange
DCX: Double Charge-eXchange

- Relativistic heavy-ion collisions



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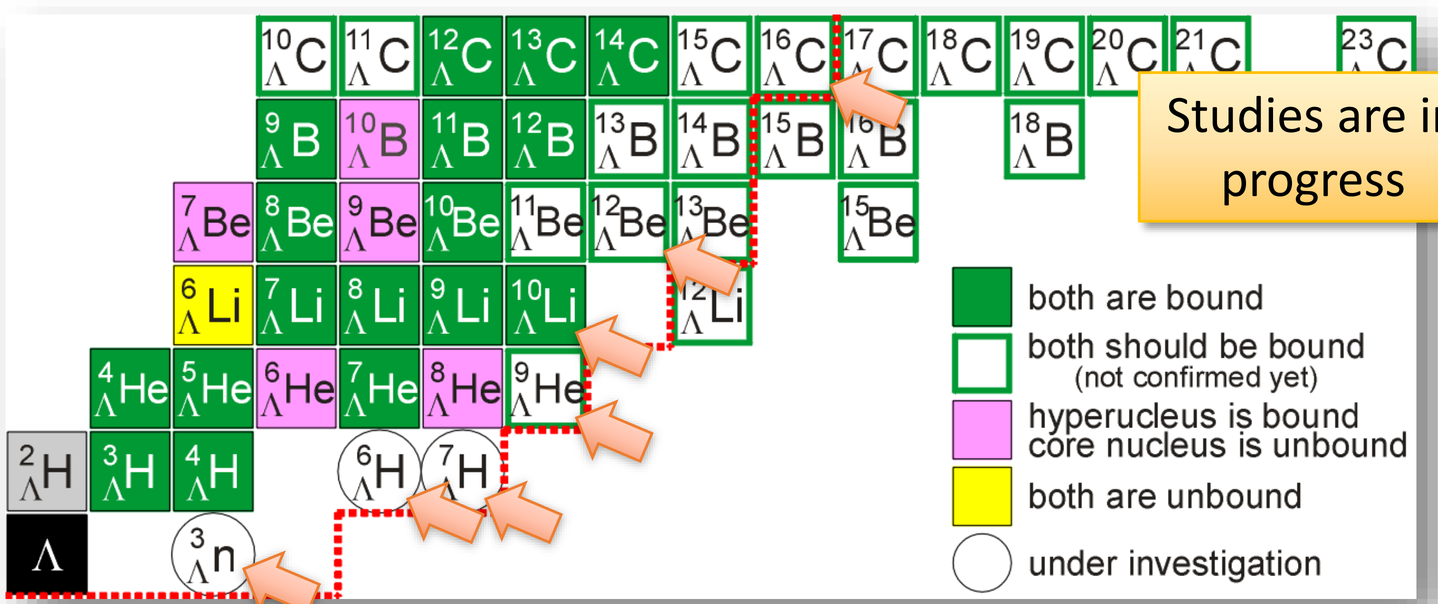


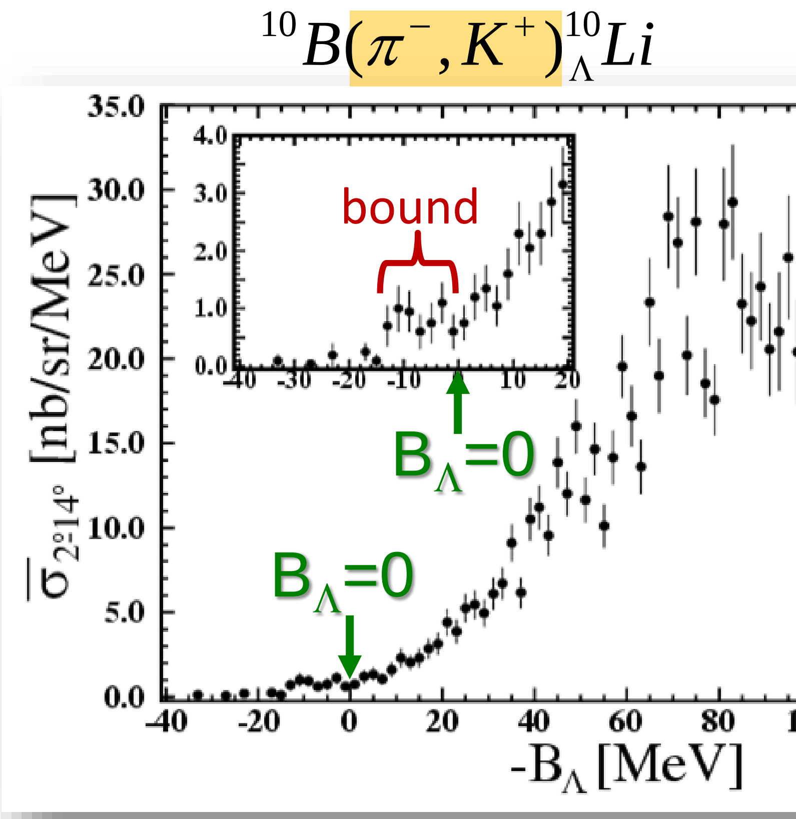
Study by using DCX reaction: $^{10}{}_{\Lambda}$Li

- **KEK E521**: P.K. Saha et al. PRL 94 (2005) 052501
  - Study of the ^{10}B(π^-,K$^+$) reaction
    - Successfully produced $^{10}{}_{\Lambda}$Li
    - Almost background free
  - Promising production method
  - Tiny production cross section

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX}, {}^{10}_{\Lambda}\mathrm{Li}) \approx 10\,\mathrm{nb/sr}$$

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX}) \Big/ \frac{d\sigma}{d\Omega}(\mathrm{NCX}) \approx 10^{-3}$$

DCX: (π^-,K$^+$) NCX: (π^+,K$^+$) for $^{12}{}_{\Lambda}$C



- High-intensity pion beams are necessary

Reaction mechanism of DCX reaction

- The (π^-,K^+) reaction basically has two-step nature
  - 2 nucleons participate in the elementary process

$$\pi^- p\ p \to K^+ \Lambda\ n$$

- Two possible reaction mechanisms
  - Simple two-step process
    - Sequential single charge-exchange reactions

$$\pi^- pp \to K^0 \Lambda p \to K^+ \Lambda n, \quad \pi^- pp \to \pi^0 np \to K^+ n \Lambda$$

  - "Single-step" process by ΛN-ΣN mixing

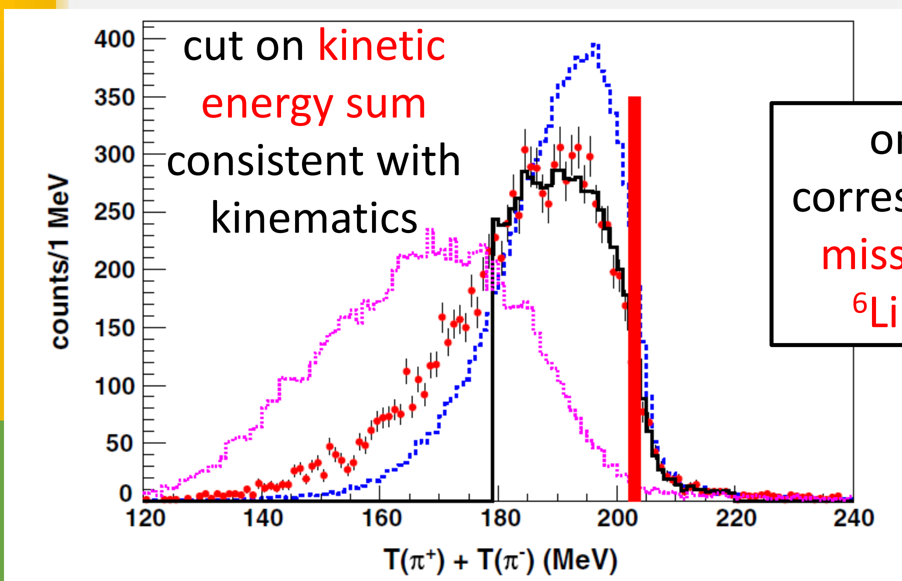
$$\pi^- pp \to K^+ \Sigma^- p \Leftrightarrow K^+ \Lambda n$$

- ΛN-ΣN mixing appears also in reaction mechanism
  - KEK-E521 data favors "single-step" at least for ${}^{10}_{\Lambda}$Li

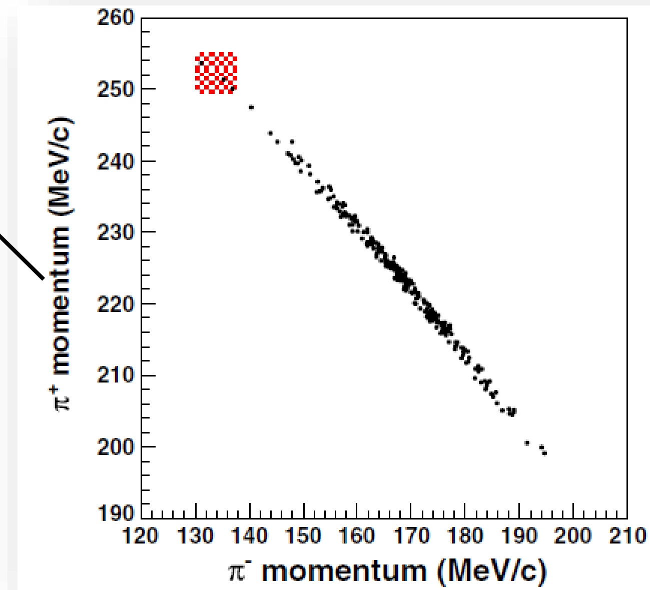
Study by using DCX reaction: $^{6}_{\Lambda}$H (1)

- **FINUDA**: M. Agnello et al. PRL 108 (2012) 042501
  - Study of the ^{6}Li(K^{-}_{stop},$\pi^{+}\pi^{-}$) reaction

$$^{6}\mathrm{Li}(K^{-}_{\mathrm{stop}},\pi^{+})^{6}_{\Lambda}\mathrm{H} \qquad ^{6}_{\Lambda}\mathrm{H}\rightarrow {}^{6}\mathrm{He}+\pi^{-}$$



one to one correspondence to missing-mass of ^{6}Li(K^{-}_{stop},π^{+})X



  - Reported 3 candidate events of $^{6}_{\Lambda}$H production

$$\mathrm{BR}(\mathrm{DCX},{}^{6}_{\Lambda}\mathrm{H})/\mathrm{BR}(\mathrm{NCX},{}^{12}_{\Lambda}\mathrm{C}) \approx 6\times10^{-3}$$

$$\mathrm{BR}(\mathrm{DCX},{}^{6}_{\Lambda}\mathrm{H})/\mathrm{BR}(\mathrm{NCX},{}^{4}_{\Lambda}\mathrm{He}) \approx 3\times10^{-4}$$

1-2 × 10^{-3} for A=6?

Possible level structure of $^{6}_{\Lambda}H$

- FINUDA reported 3 candidate events of $^{6}_{\Lambda}H$ production
- Sensitive to ΛN interaction and also properties of ^{5}H

Small ΛN-ΣN mixing

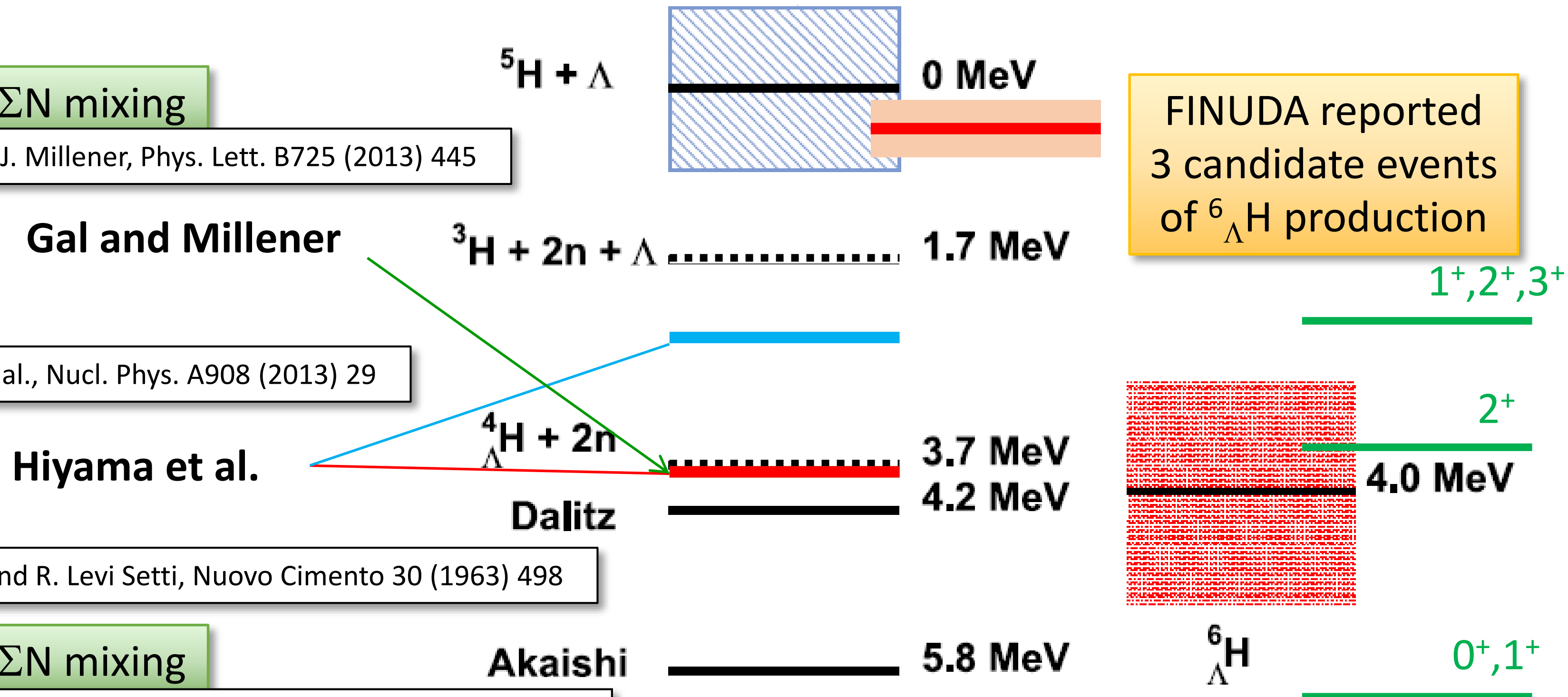
A. Gal and D.J. Millener, Phys. Lett. B725 (2013) 445

E. Hiyama et al., Nucl. Phys. A908 (2013) 29

R. H. Dalitz and R. Levi Setti, Nuovo Cimento 30 (1963) 498

Large ΛN-ΣN mixing

Y. Akaishi and T. Yamazaki, Frascati Phys. Ser. XVI (1999) 59



M. Agnello et al., FINUDA Collaboration, PRL 108 (2012) 042501
M. Agnello et al., FINUDA Collaboration, NPA 881 (2012) 269

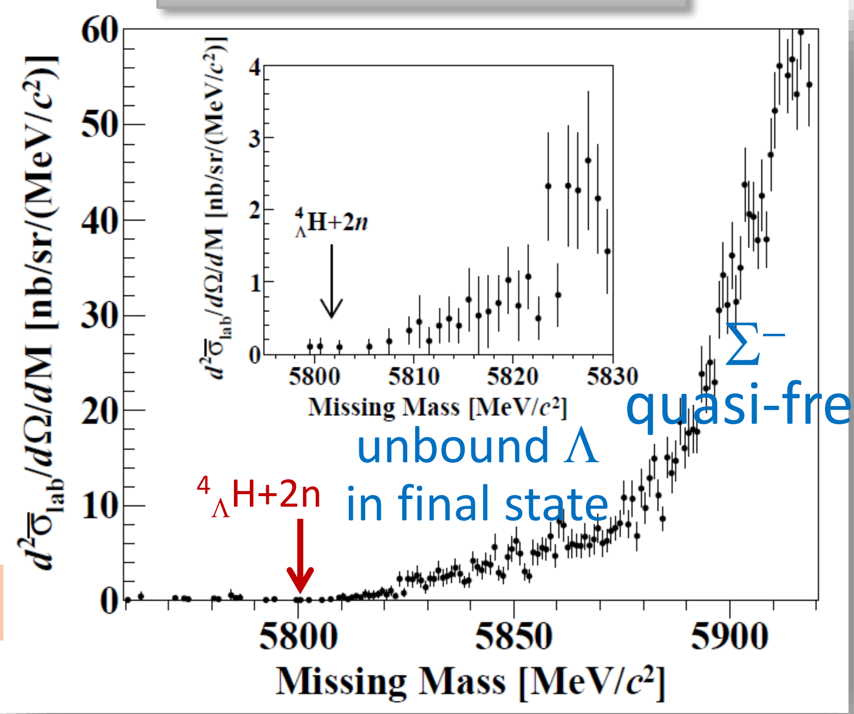
FINUDA data still have ambiguities. Complementary measurement is necessary.

Study by using DCX reaction: $^{6}_{\Lambda}H$ (2)

- **J-PARC-E10**: H. Sugimura et al., PLB 729 (2014) 39
  - Results of updated analysis will be presented by R. Honda
  - Missing-mass spectrum of the $^{6}Li(\pi^{-},K^{+})$ reaction

$^{6}Li(\pi^{-},K^{+})X$
θ_{LAB}=2-14 deg.

Results of last analysis



We saw no clear peak of $^{6}_{\Lambda}H$ production in threshold region

cross section is extremely smaller than we expected

$$\frac{d\sigma}{d\Omega}(\mathrm{DCX}) \bigg/ \frac{d\sigma}{d\Omega}(\mathrm{NCX}) < 1.5\times 10^{-4}$$

DCX: (π^{-},K^{+}) NCX: (π^{+},K^{+}) for $^{12}_{\Lambda}C$

Possible interpretations of ${}^{6}_{\Lambda}$H results

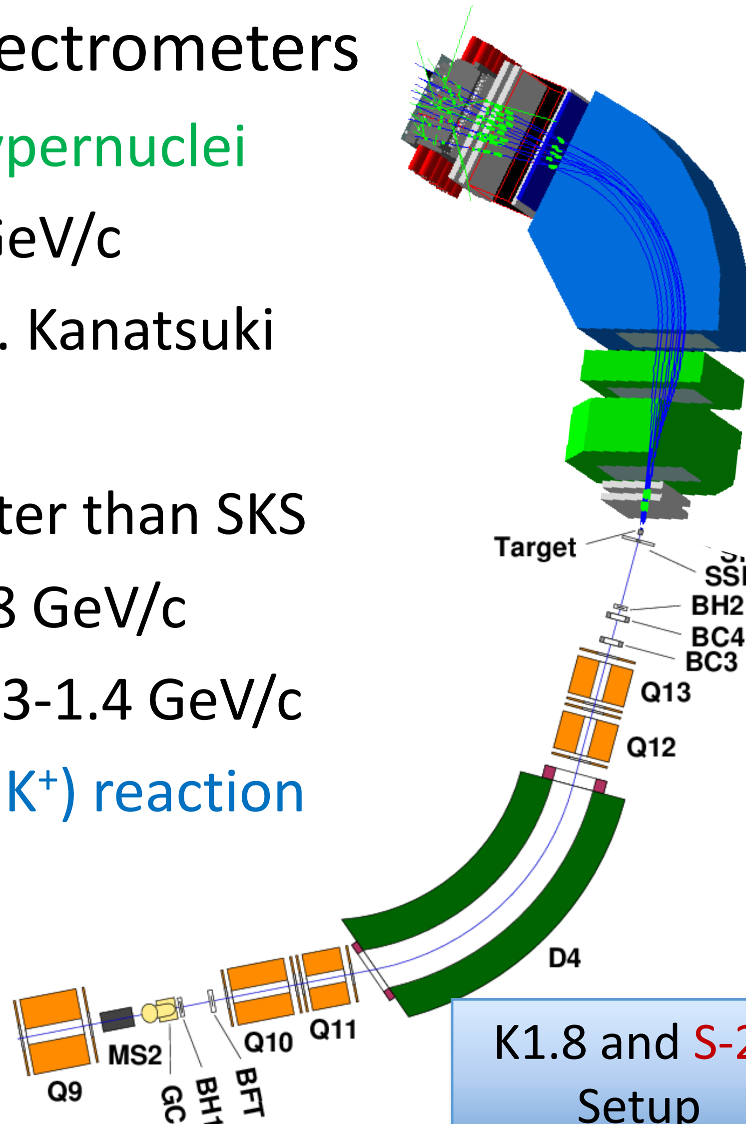
- Reaction mechanism?
  - Transition from ^{6}Li(1^+) to ${}^{6}_{\Lambda}$H(0^+) needs spin-flip amplitude
    - (K^-_{stop}, π^+) reaction also needs spin-flip to populate 0^+
    - FINUDA interpretation was population of ${}^{6}_{\Lambda}$H*(1^+) followed by γ-decay to ${}^{6}_{\Lambda}$H(0^+)
    - Why no population of ${}^{6}_{\Lambda}$H*(1^+) in J-PARC E10?
  - Very small ΛN-ΣN mixing for ${}^{6}_{\Lambda}$H?
    - Population of ${}^{6}_{\Lambda}$H(0^+) and ${}^{6}_{\Lambda}$H*(1^+) is sensitive to mixing
- Structure of ${}^{6}_{\Lambda}$H?
  - Core nucleus ^{5}H may affect largely to structure of ${}^{6}_{\Lambda}$H
- Smallness of cross section is not easy to understand
  - Information of other hypernuclei (${}^{9}_{\Lambda}$He etc.) is necessary

Near future plans at J-PARC

- Neutron-rich hypernuclei to be studied
  - $^{9}_{\Lambda}$He : I=2 (2nd phase of J-PARC E10)
    - Core nucleus is particle-stable halo-nucleus ^{8}He
    - Ground state $1/2^+$ is particle-stable and suitable to study ΛN-ΣN mixing effect. Non spin-flip amplitude is enough to populate $1/2^+$.
    - Also excited states $3/2^+$ and $5/2^+$, $^{8}\mathrm{He}^*(2^+)+\Lambda(1/2^+)$, may be particle-stable. Information of ^{8}He excited states may be extracted indirectly.
  - $^{12}_{\Lambda}$Be : I=3/2 (proposed by K. Tanida)
    - Parity inversion in ^{11}Be. Ground state is $1/2^+$ instead for $1/2^-$. What's happening in $^{12}_{\Lambda}$Be? Measurement of low-lying 0^-, 1^-, 0^+ and 1^+ states may be possible.

Near future plans at J-PARC

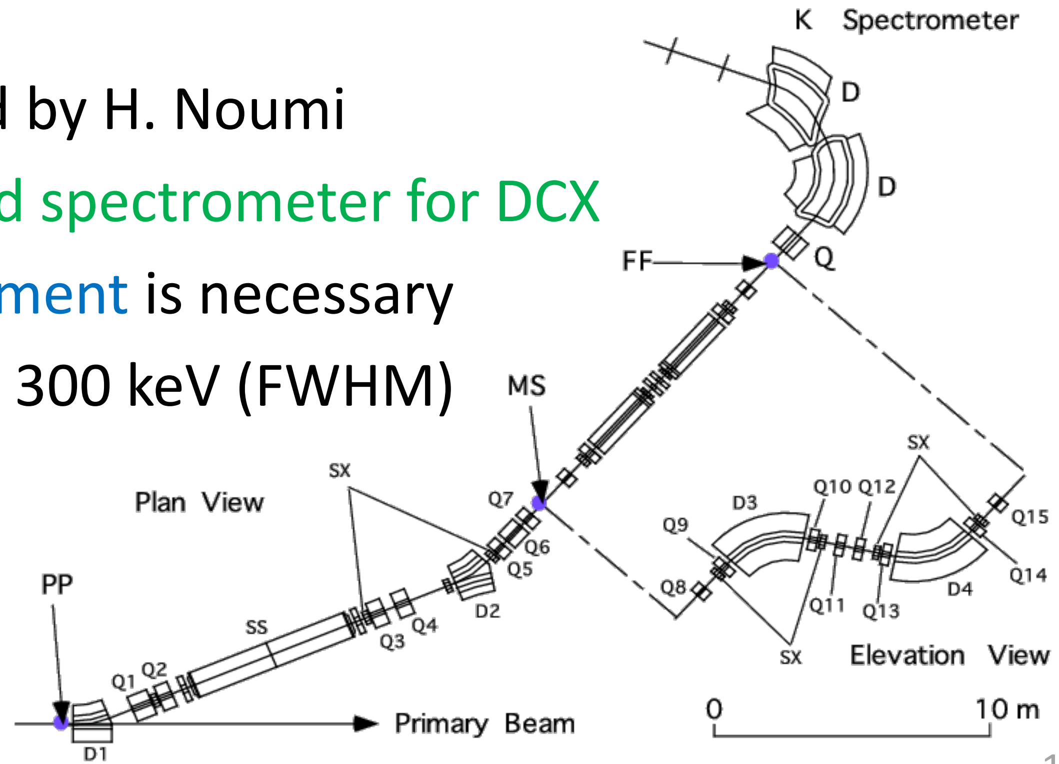
- K1.8 beam line and S-2S spectrometers
  - S-2S for spectroscopy of Ξ hypernuclei
    - (K^-,K^+) reaction up to 1.8 GeV/c
  - Developed by T. Nagae and S. Kanatsuki
    - Installation in 2017?
  - Momentum resolution is better than SKS
    - SKS: $dp/p \approx 1\text{-}2 \times 10^{-3}$@0.8 GeV/c
    - S-2S: $dp/p \approx 0.6 \times 10^{-3}$@1.3-1.4 GeV/c
  - S-2S is useful also for the (π^-,K^+) reaction



K1.8 and S-2S Setup

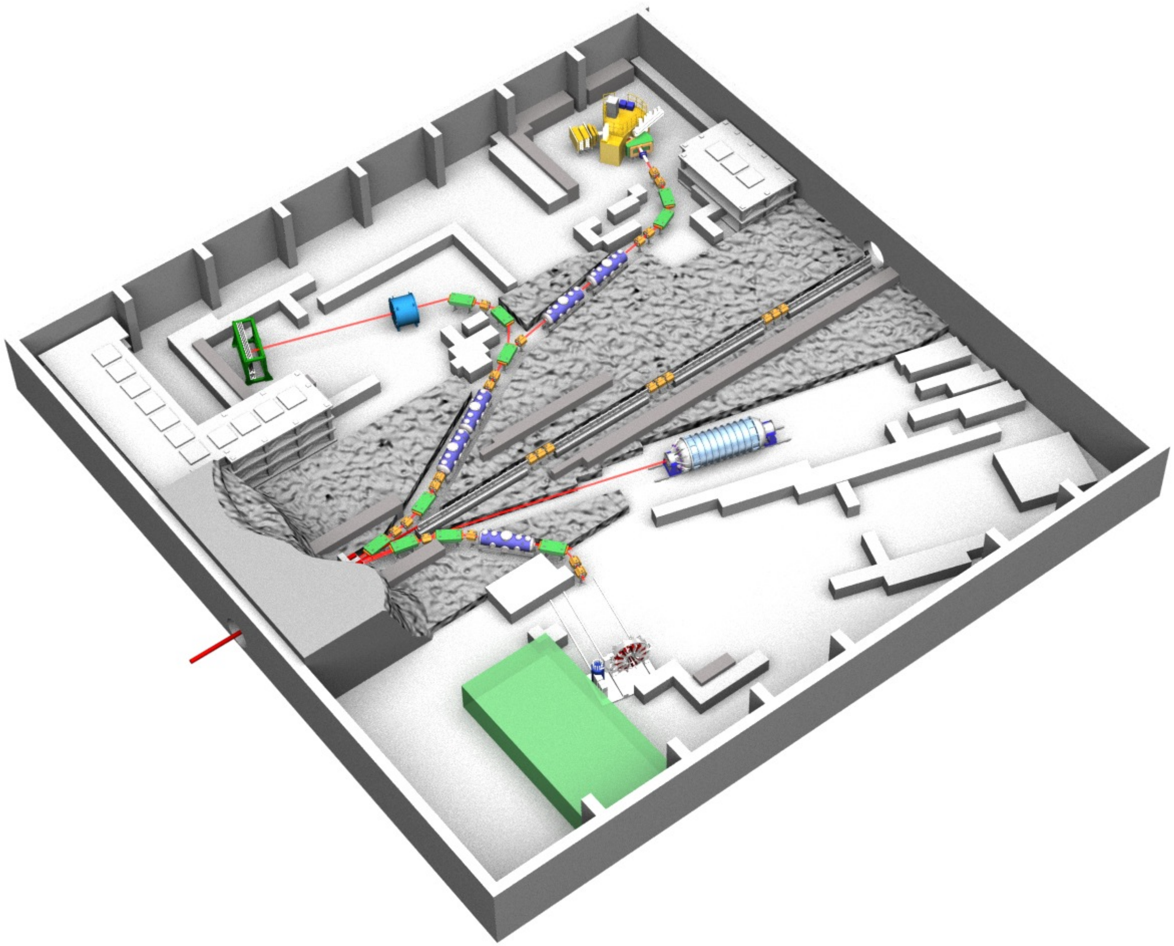
Future plan at J-PARC

- Systematic study of neutron-rich hypernuclei
  - Should override tiny production cross section
    - At least 10 times higher beam intensity (> 10^8/spill)
  - High-Intensity and High-Resolution (HIHR) beam line and spectrometer
    - Originally designed by H. Noumi
    - Ideal beam line and spectrometer for DCX
    - No beam measurement is necessary
    - Miss. mass resol. ~ 300 keV (FWHM)



Proposal of HD hall extension

- Hadron-hall layout plan and HIHR



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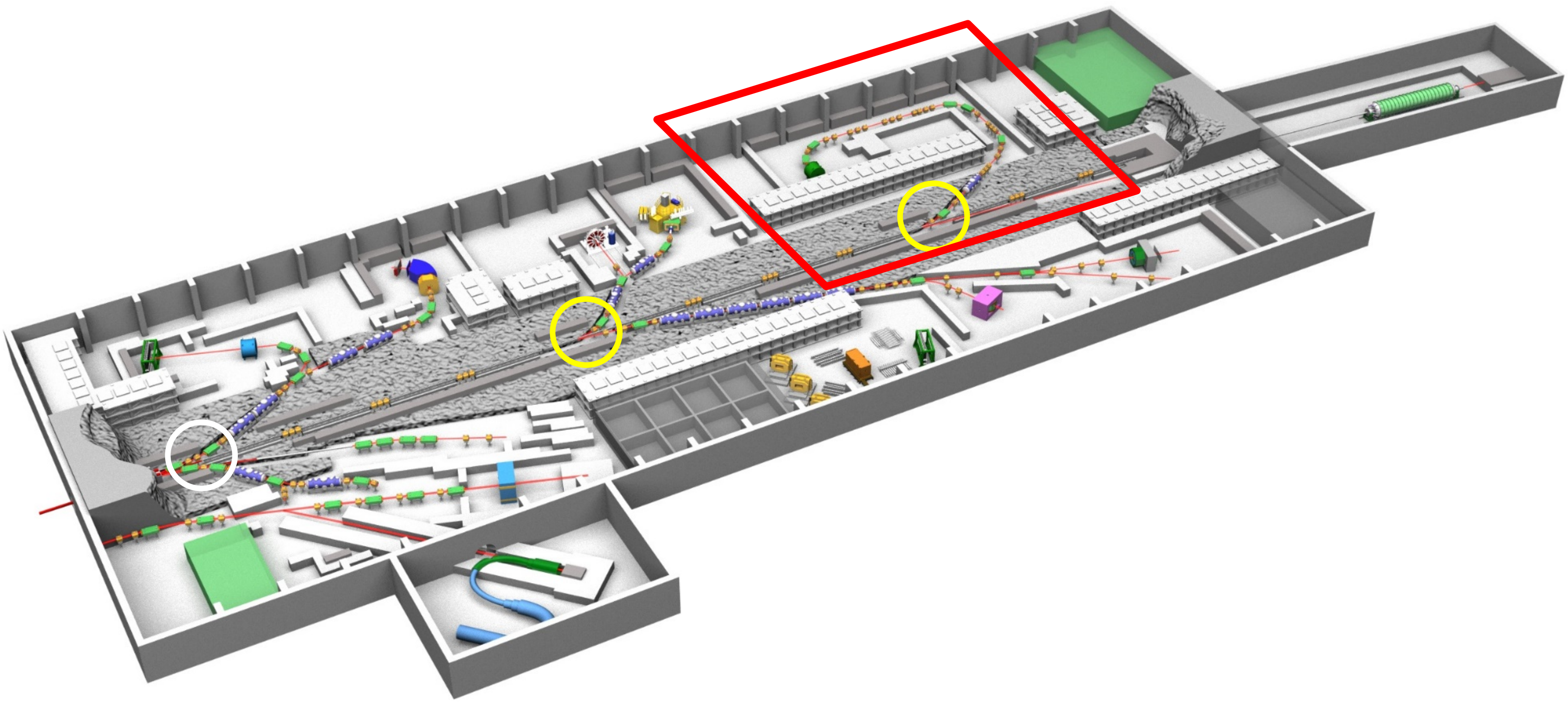

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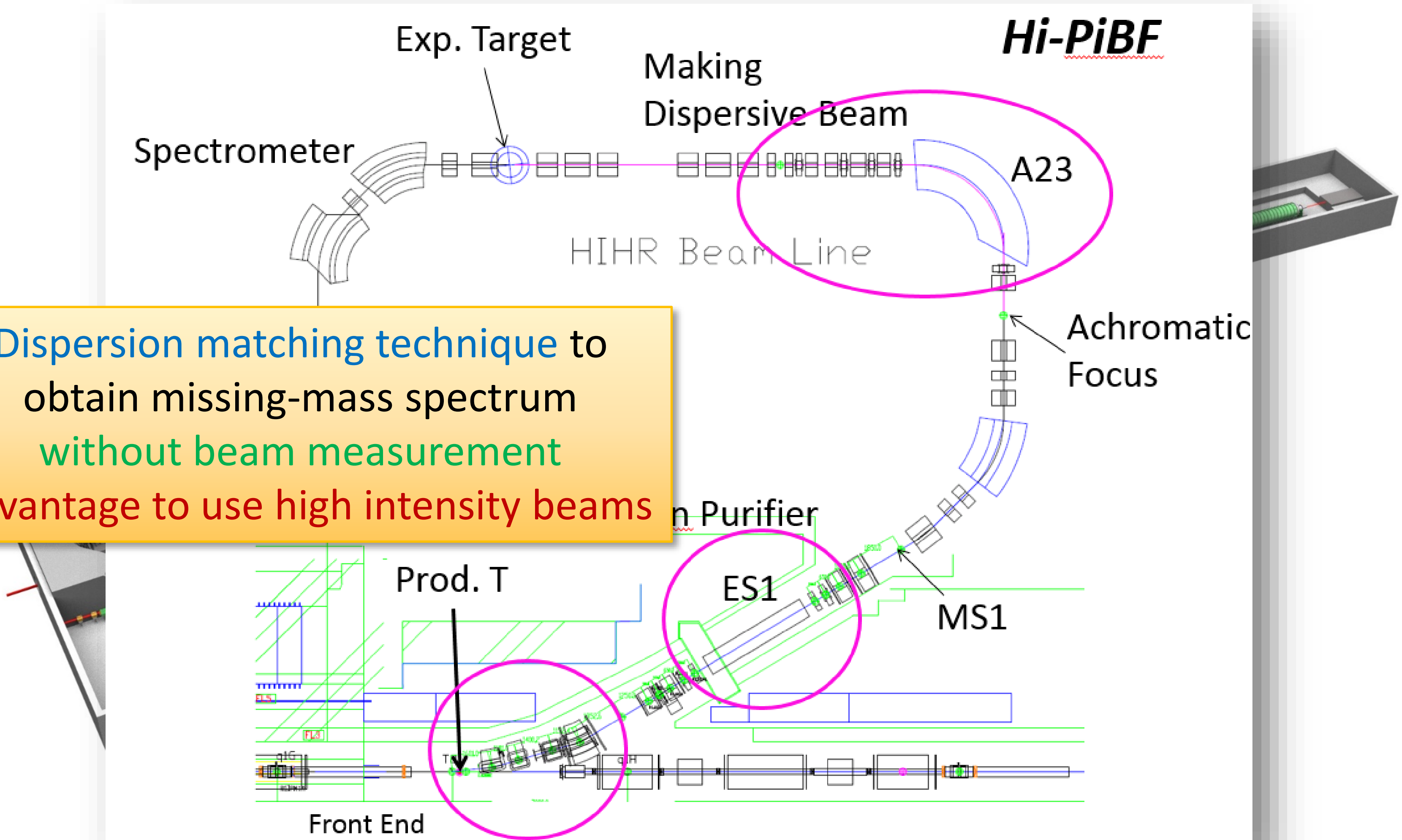

Dispersion matching technique to obtain missing-mass spectrum without beam measurement
Advantage to use high intensity beams

Summary

- Study of Λ hypernuclei close to neutron drip-line
  - Glue-like effect may extend boundary of stability
  - ΛN-ΣN mixing and neutron-rich hypernuclei
- Promising spectroscopic tools
  - Double charge-exchange (DCX) reaction is one of promising spectroscopic tools
- Several studies by DCX reactions are in progress
  - KEK E521 successfully produced ${}^{10}_{\Lambda}$Li
  - FINUDA and J-PARC E10 made measurement of ${}^{6}_{\Lambda}$H
  - Structure of ${}^{6}_{\Lambda}$H is not clear yet
- Future plans at J-PARC
  - ${}^{9}_{\Lambda}$He and ${}^{12}_{\Lambda}$Be as near future plans
  - HIHR beam line and spectrometer after HD hall extension