QUCS12   December 14, 2012

Strangeness Nuclear Physics

Present status and future prospect at J-PARC

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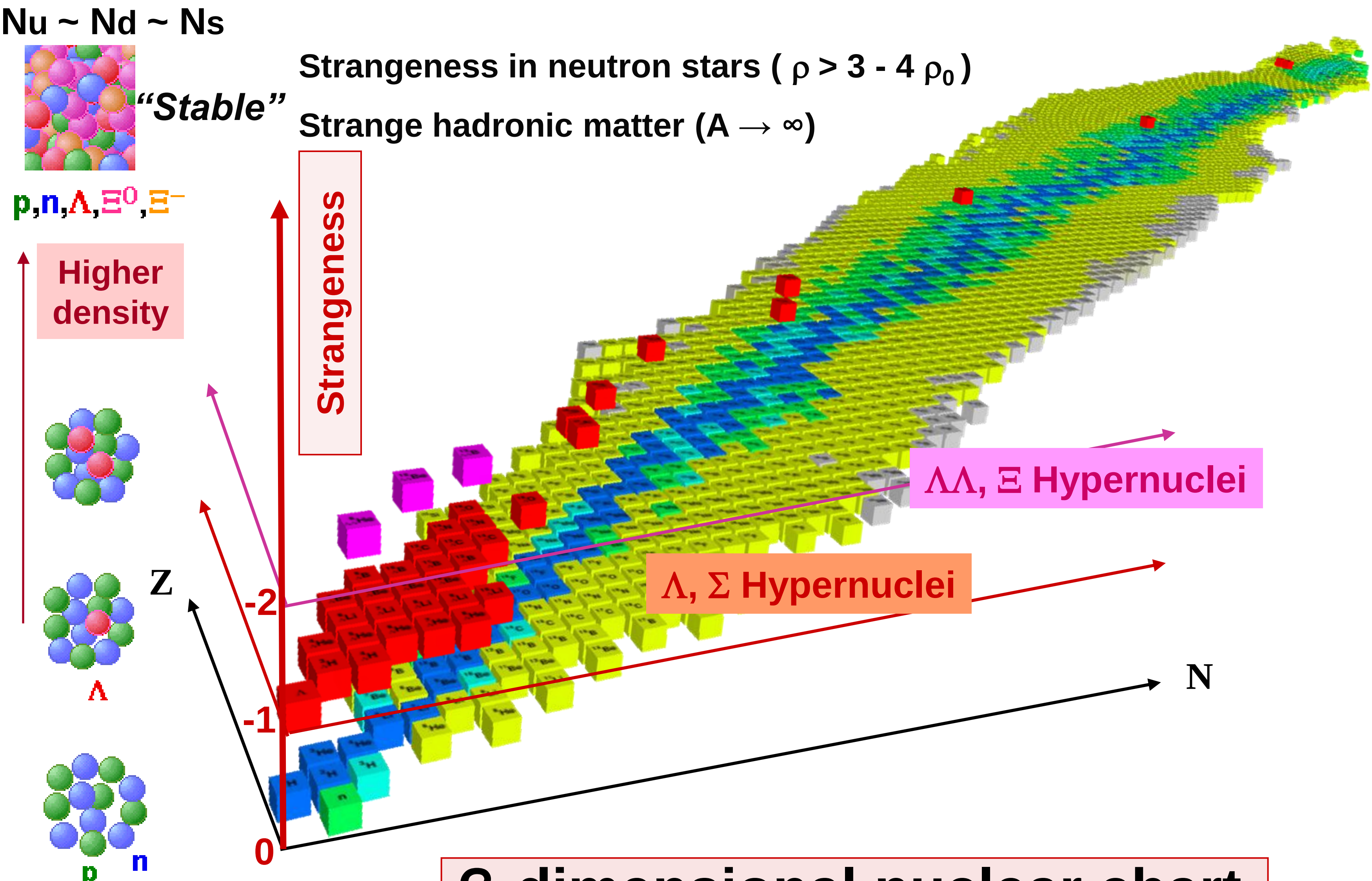
Contents

1. Introduction

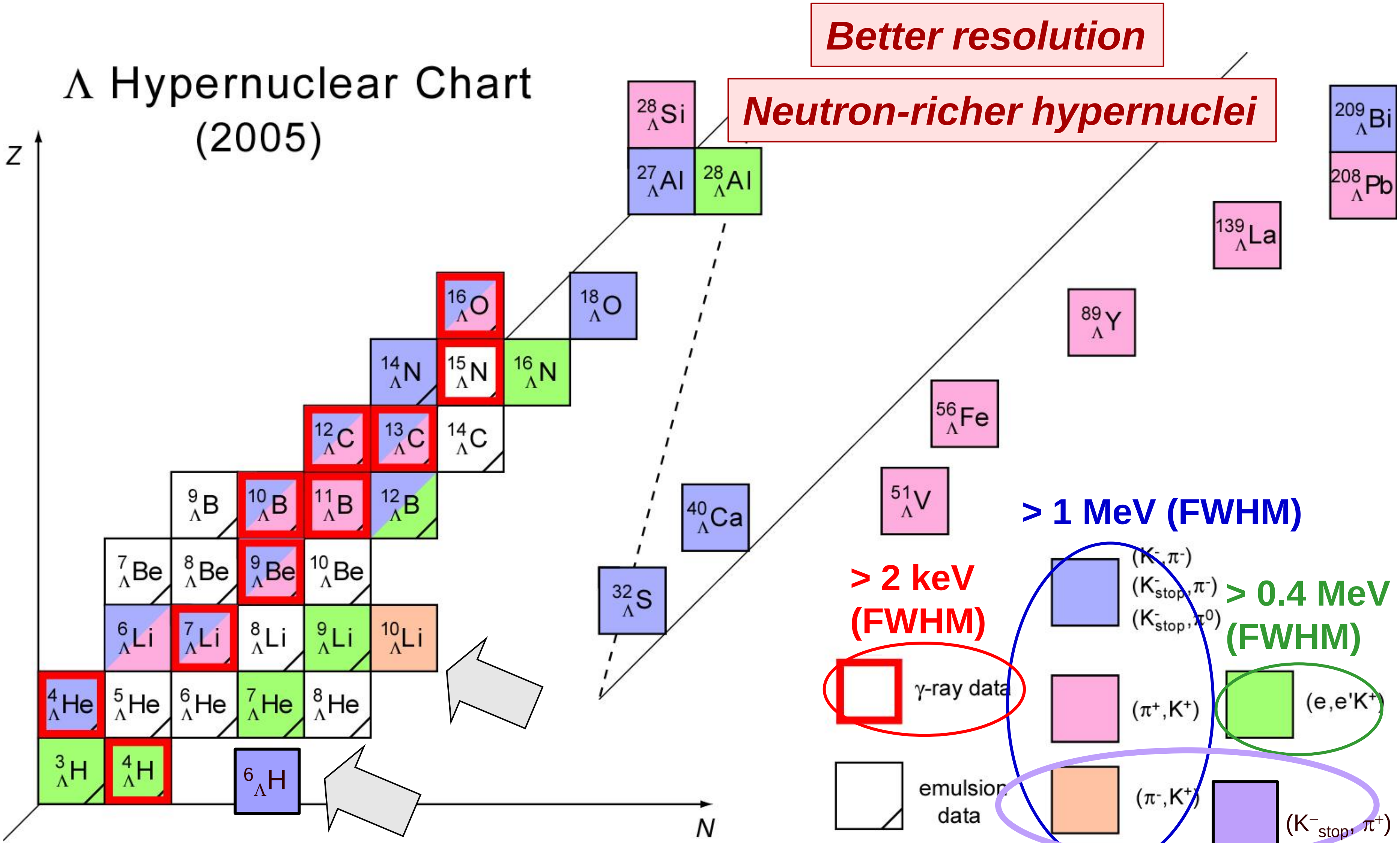
World of matter made of u, d, s quarks



3-dimensional nuclear chart

by M. Kaneta inspired by HYP06 conference poster

Λ hypernuclear chart

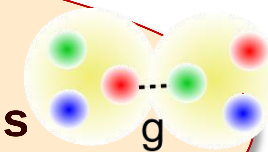


Updated from : O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Motivations of strangeness nuclear physics

Extension of 3D nuclear chart

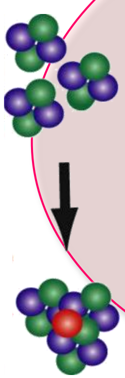
BB interactions



Unified understanding of BB forces by u,d ->u, d, s
particularly short-range forces by quark pictures

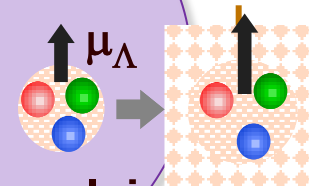
Test lattice QCD calculations

Impurity effect in nuclear structure



Changes of size,
deformation, clustering,
collective motions,
appearing new symmetry,
…

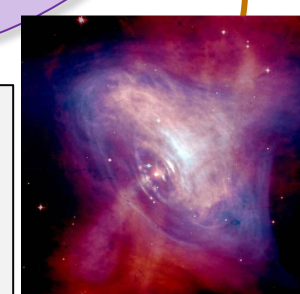
Modifications of baryon properties in nuclei



μ_Λ in a nucleus,
Levels of heavy Λ hypernuclei,
...

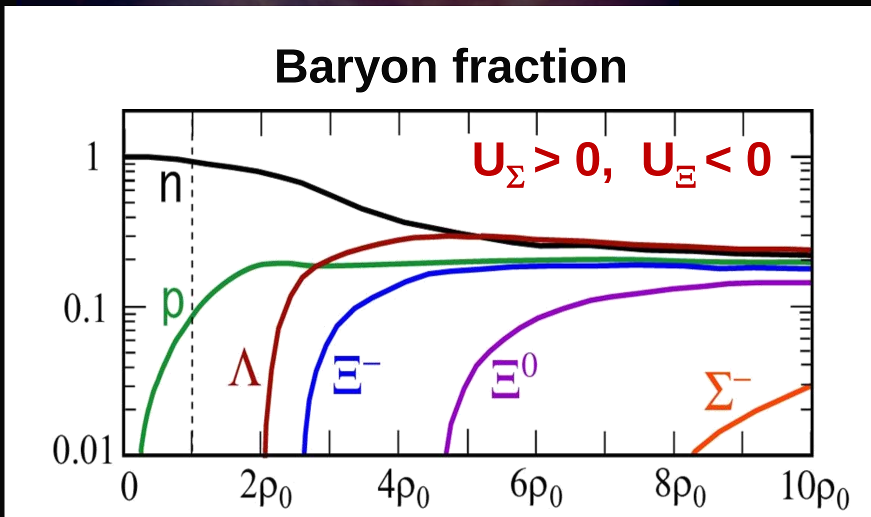
Clues to understand hadrons and nuclei from quarks

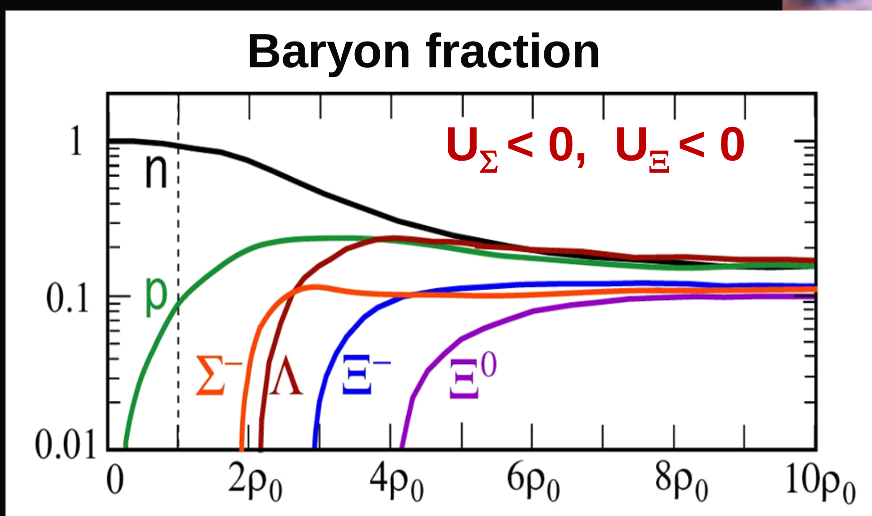
Cold and dense nuclear matter with strangeness

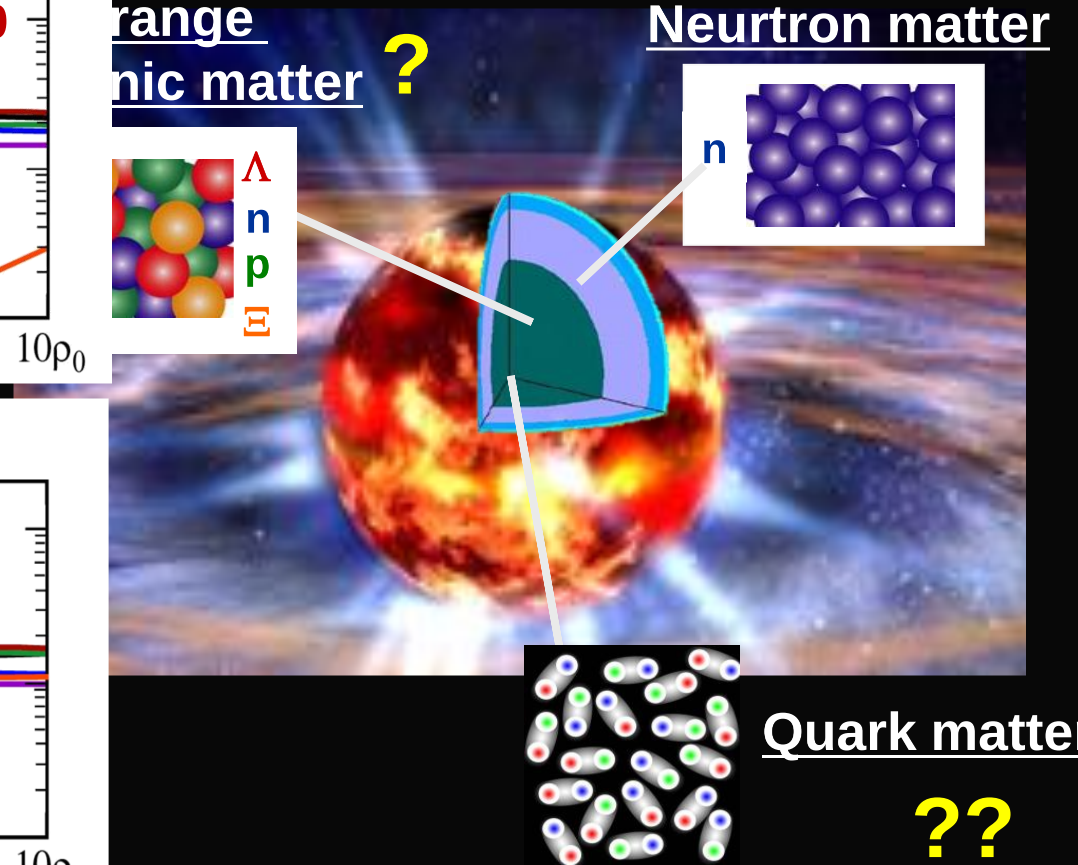


Nuclear matter in neutron stars

n be supported?







A new form of matter
actually existing in the universe

We still need
ΞN, ΣN, ΛΛ, K^{bar}N forces, ΛN odd-state force,
NNN and YNN force, …

Overview of Strangeness Nuclear Physics Experiments

- K^- or $\pi^{+/-}$ beams

  KEK-PS, BNL-AGS => J-PARC

  Intensity increasing.
  SNP programs just being started.

  Λ and Σ hypernuclear spectroscopy, γ-spectroscopy of Λ hypernuclei
  ΛΛ and Ξ hypernuclei,
  ΣN /ΛN scattering
  weak decays of Λ hypernuclei
  K^- nuclei, K^- atoms

- e^- beam

  Jefferson Lab (Hall A, Hall C), MAMI-C

  high-res. Λ hypernuclear spectroscopy, weak decays of Λ hypernuclei

- K^- from φ

  DAΦNE (FINUDA, SIDDHARTA, AMADEUS)

  spectroscopy of Λ hypernuclei, weak decays of Λ hypernuclei
  K^- nuclei, K^- atoms

- Heavy ion beams

  GSI (HypHI) **p-rich/n-rich hypernuclei, lifetimes, multi-strange nuclei**

2. Λ hypernuclei

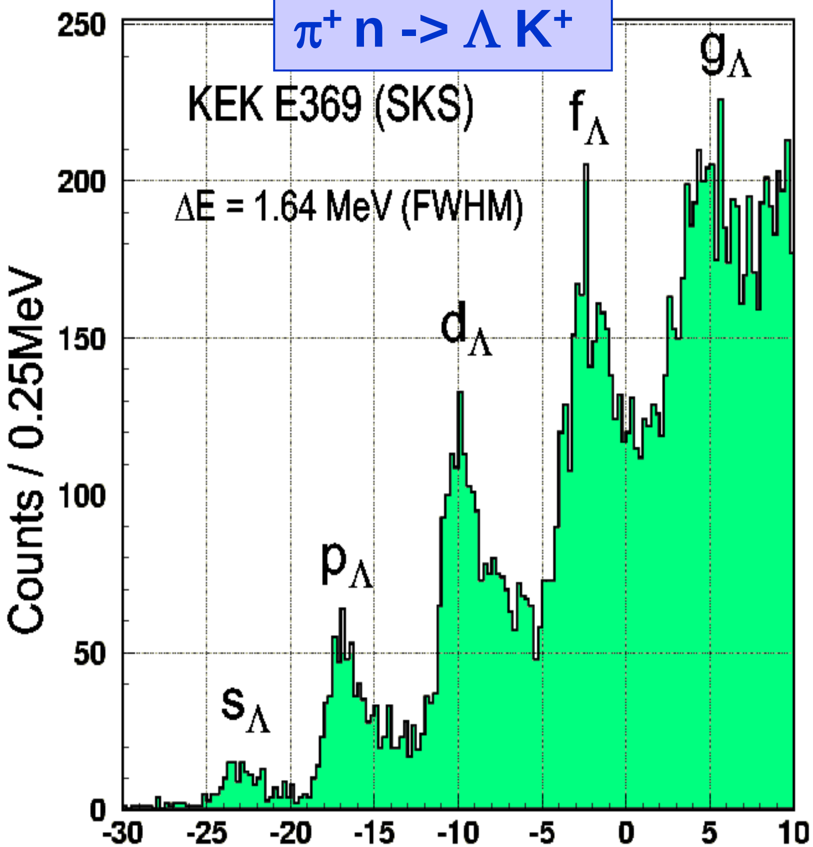
2.1 (π, K^+) spectroscopy and n-rich Λ hypernuclei

Previous (π^+,K^+) data and ΛN interaction

SKS at KEK-PS

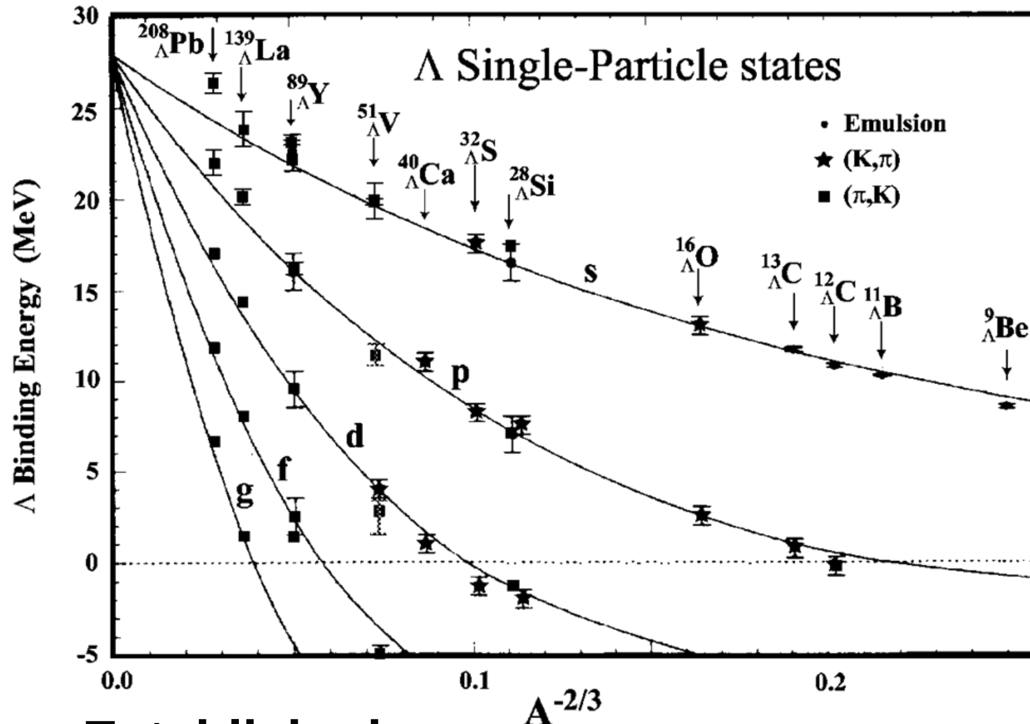
$^{89}Y\ (\pi^+,K^+)\ ^{89}_{\Lambda}Y$

$\pi^+ n \rightarrow \Lambda K^+$



Mass of hypernucleus $-B_\Lambda$ (MeV)

Hotchi et al., PRC 64 (2001) 044302



-> Established

U_Λ = - 30 MeV (c.f. U_N = -50 MeV)

Better resolution
p-rich/n-rich hypernuclei

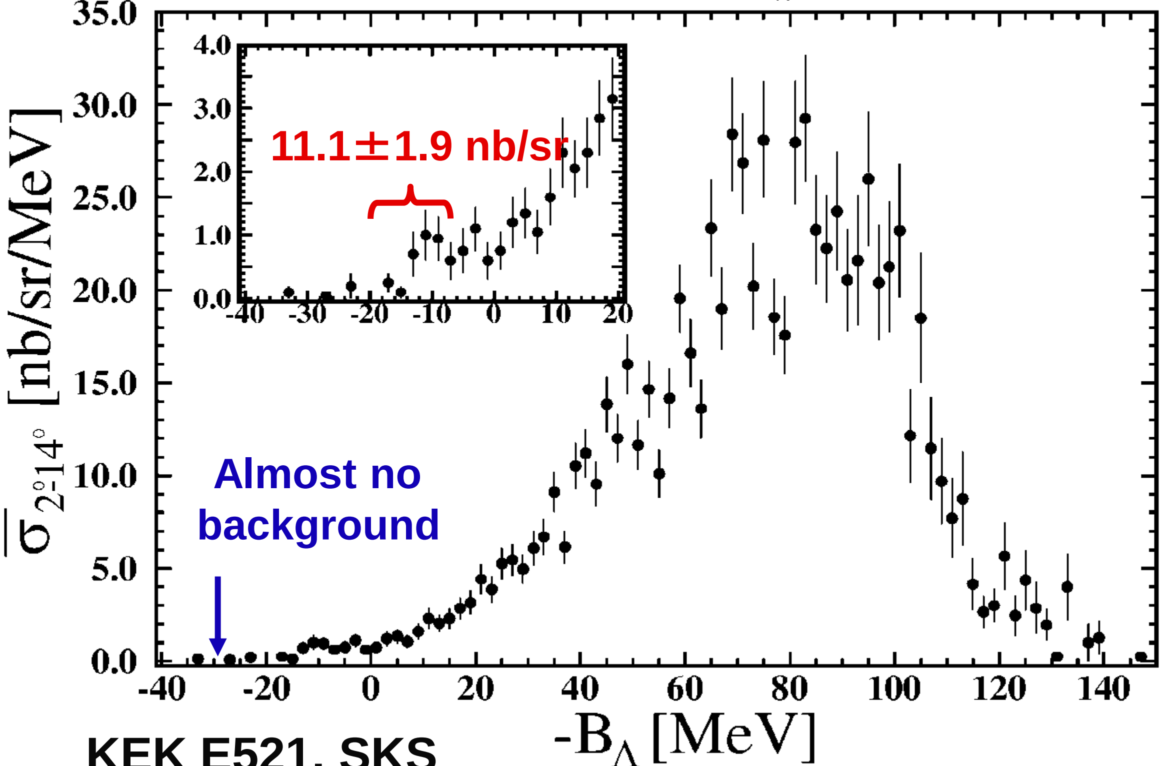
$(e,e'K^+)$ at Jlab, (π^-,K^+) reaction,
γ spectroscopy

Neutron-rich hypernuclei

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

2-step charge exchange
($\pi^- p \rightarrow \pi^0 n$, $\pi^0 p \rightarrow K^+ \Lambda$ etc.)
Via Σ^- admixture in Λ hyp.
($\pi^- p \rightarrow \Sigma^- K^+$, $\Sigma^- p \leftrightarrow \Lambda n$)

^{10}B (π^-, K^+) $^{10}{}_{\Lambda}Li$ $\quad p_\pi$~1.2 GeV/c

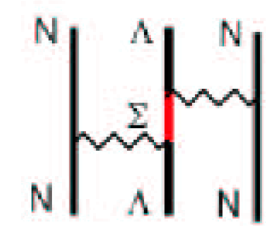


KEK E521, SKS

PRL 94 (2005) 052502

First data on n-rich hypernucleus

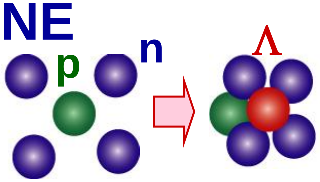
Λ–Σ coherent coupling
-> ΛNN attraction



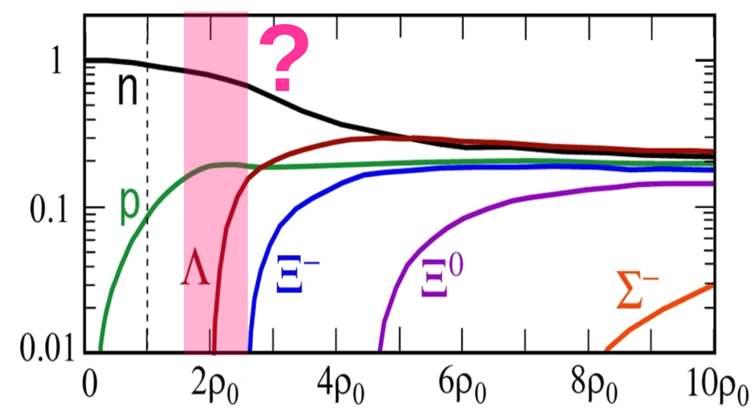
Akaishi et al., PRL 84 (2000) 3539

New data from FINUDA@DAΦNE
– $^{6}{}_{\Lambda}H$ events by $^{6}Li(K^-_{stop},\pi^+)$

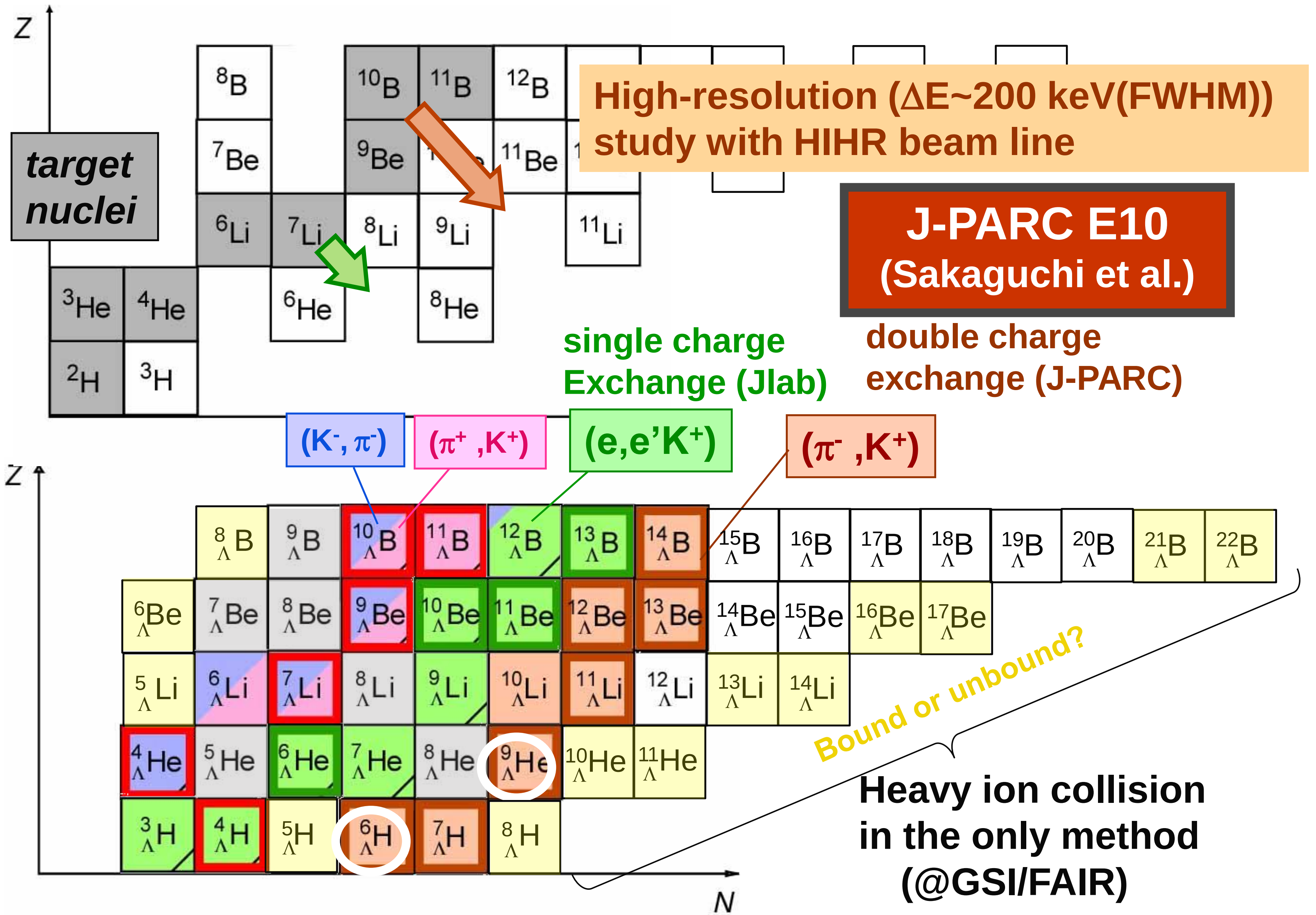
PRL 108 (2012) 042501



important in neutron stars

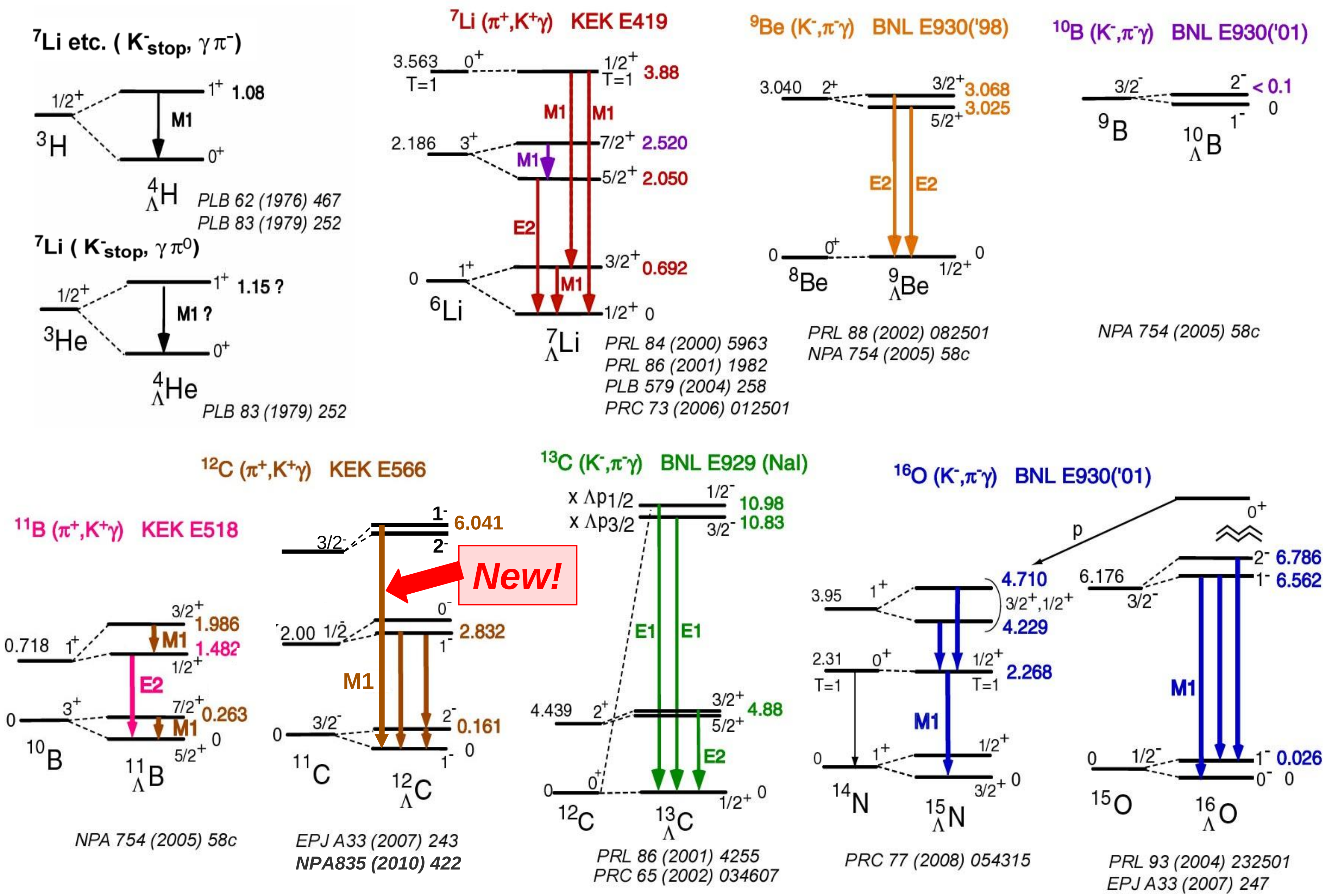


How to extend S=-1 nuclear chart?



2.2 γ spectroscopy

Hypernuclear γ-ray data (2012)



ΛN spin-dependent interactions

- **Two-body ΛN effective interaction**

Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

$$V_{\Lambda N}^{eff} = V_0(r) + V_\sigma(r)\,\vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\,\vec{l}_{\Lambda N}\vec{s}_\Lambda + V_N(r)\,\vec{l}_{\Lambda N}\vec{s}_N + V_T(r)\,S_{12}$$

$\bar{V}$ Δ S_Λ S_N T

well known from U_Λ = - 30 MeV

p-shell: 5 radial integrals for $s_\Lambda p_N$ w.f.

$$\Delta = \int V_\sigma(r)\,|u(r)|^2 r^2 dr, \quad \mathbf{r} = \mathbf{r}_{s_\Lambda} - \mathbf{r}_{p_N}$$

γ-ray data => Δ = 0.33 (0.43 for A=7), S_Λ = -0.01, S_N = -0.4, T = 0.03 [MeV]
Small spin-dependent forces have been established.

- **Feedback to BB interaction models thru G-matrix calc. (Millener)**

Nijmegen models

	Δ	S_Λ	S_N	T (MeV)
ND	-0.048	-0.131	-0.264	0.018
NF	0.072	-0.175	-0.266	0.033
NSC89	1.052	-0.173	-0.292	0.036
NSC97f	0.421	-0.149	-0.238	0.055
ESC04a	0.381	-0.108	-0.236	0.013
ESC08a	0.146	-0.074	-0.241	0.055
("Quark model"		0.0	-0.4)	
Exp.	0.4	-0.01	-0.4	0.03

LS force:

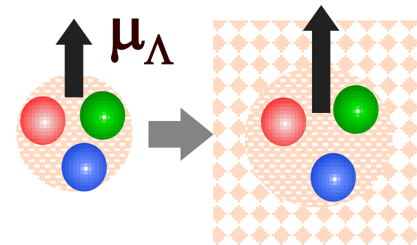
All Nijmegen models fail.

Quark model looks OK.

g-factor of Λ in a nucleus

Changes by partial restoration of chiral symmetry?

$$\mu_q = \frac{e\hbar}{2m_q c}$$ m_q : Const. quark mass



Reduction of m_q in nuclear matter -> enhancement of μ??

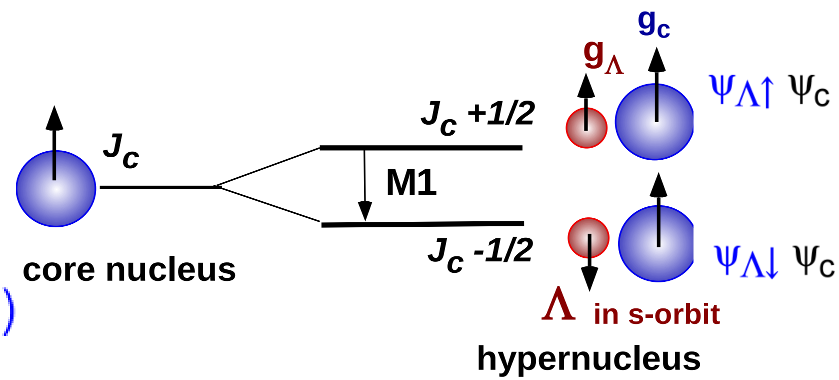
Λ-spin-flip M1 transition B(M1)

$$B(M1) = (2J_{up}+1)^{-1} |\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle|^2$$

$$= (2J_{up}+1)^{-1} |\langle \psi_{\Lambda\downarrow} \psi_c \| \mu \| \psi_{\Lambda\uparrow} \psi_c \rangle|^2$$

$$\mu = g_c J_c + g_\Lambda J_\Lambda = g_c J + (g_\Lambda - g_c)$$

$$= \frac{3}{8\pi} \frac{2J_{low}+1}{2J_c+1} (g_\Lambda - g_c)^2 \quad [\mu_N^2]$$



"Core polarization" (change of g_c by Λ) should be small.

~100%

Doppler Shift Attenuation Method

$$\Gamma = BR / \tau = \frac{16\pi}{9} E_\gamma^3 B(M1)$$

Prelim. data for $^7_\Lambda$Li(3/2⁺->1/2⁺) (BNL E930, M.Ukai)

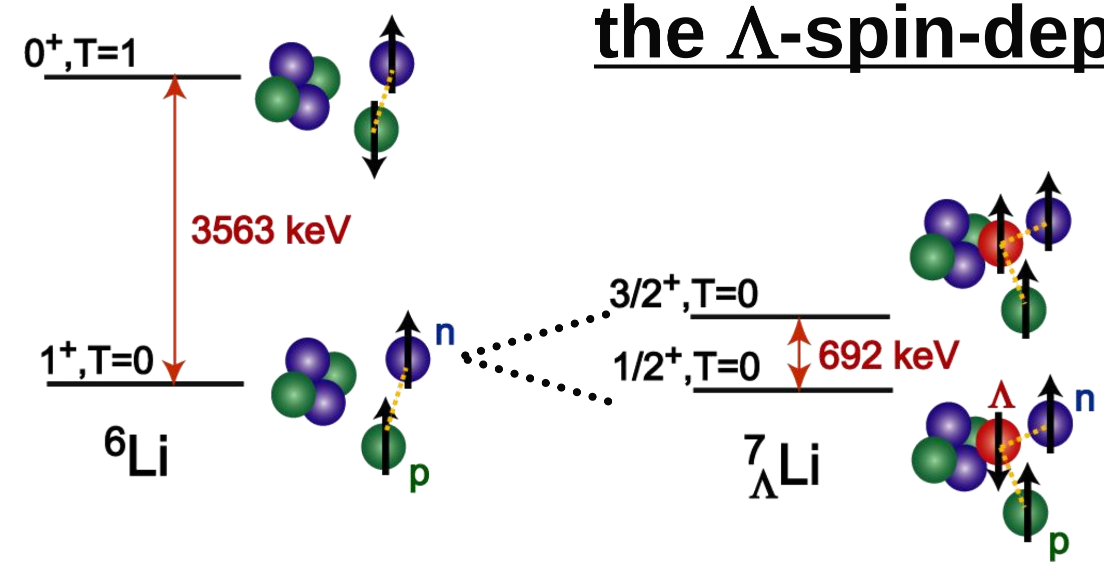
$g_\Lambda = -1.1^{+0.6}_{-0.4}\ \mu_N$

⬌ g_Λ(free) = -1.226 μ_N

J-PARC E13 (Tamura et al.)
γ spectroscopy of light Λ hypernuclei

$\Delta|g_\Lambda - g_c|$ ~ 3% for $^7_\Lambda$Li, ~10% for $^{19}_\Lambda$F

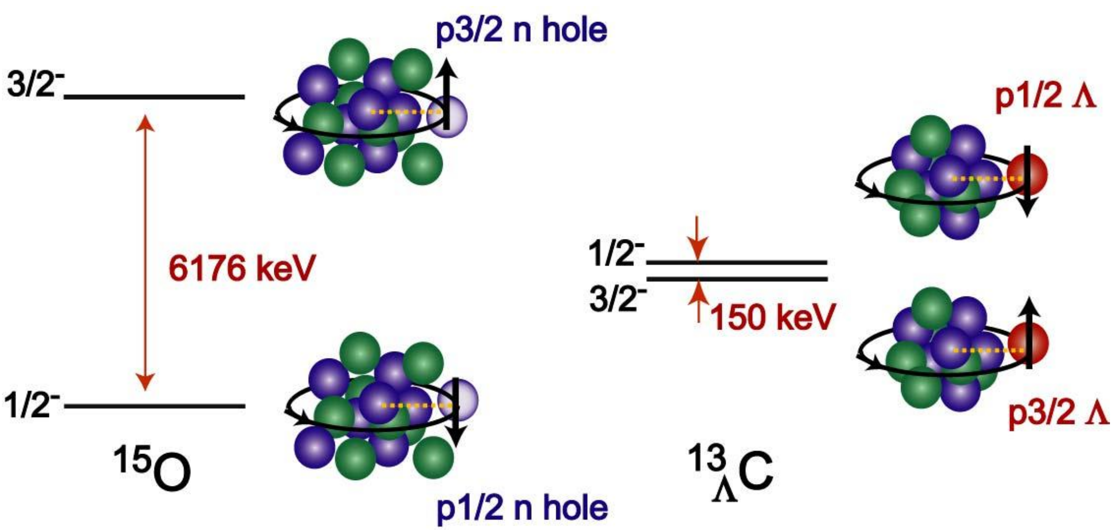
How weak are the Λ-spin-dependent forces?



Tamura et al., PRL 84 (2000) 5963

Δ = 0.42 MeV

=> ΛN spin-spin force
~ 1/10 of
NN spin-isospin force



Ajimura et al., PRL 86 (2001) 4255

(S_Λ = –0.01 MeV)

=> ΛN spin-orbit force
~ 1/40 of
NN spin-orbit force

But the core polarization effect should be theoretically estimated.
+ Meson exchange effect + Σ–Λ mixing effects should be estimated.

3. Σ-nuclear systems

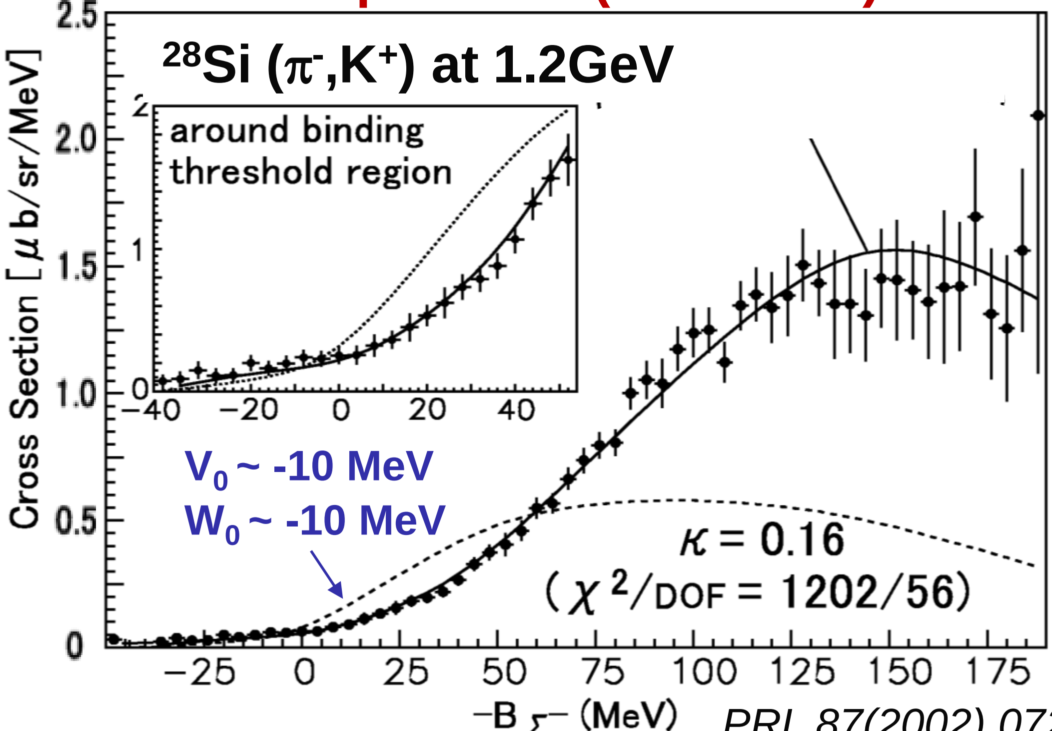
What we know about Σ–N force

Large spin-isospin dependence in ΣN force

$^4_\Sigma$He suggests (I,S) = (3/2,0), (1/2,1) attractive
(3/2,1), (1/2,0) repulsive

-- Consistent with meson exchange models

Σ^--^{28}Si Nuclear potential (KEK E438)

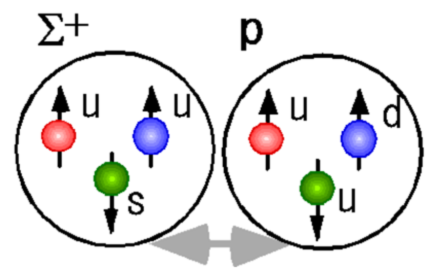


PRL 87(2002) 072301

-> <u>Strongly repulsive</u> potential (U~ +30 MeV)

How repulsive are (I,S) = (3/2,1), (1/2,0) channels?

- Strong repulsion comes from Pauli effect between quarks?
  - Quark Cluster Model
  - Lattice QCD



ΣN (I,S) = (3/2,1)

- Σ's never appear in n-stars?

High statistics

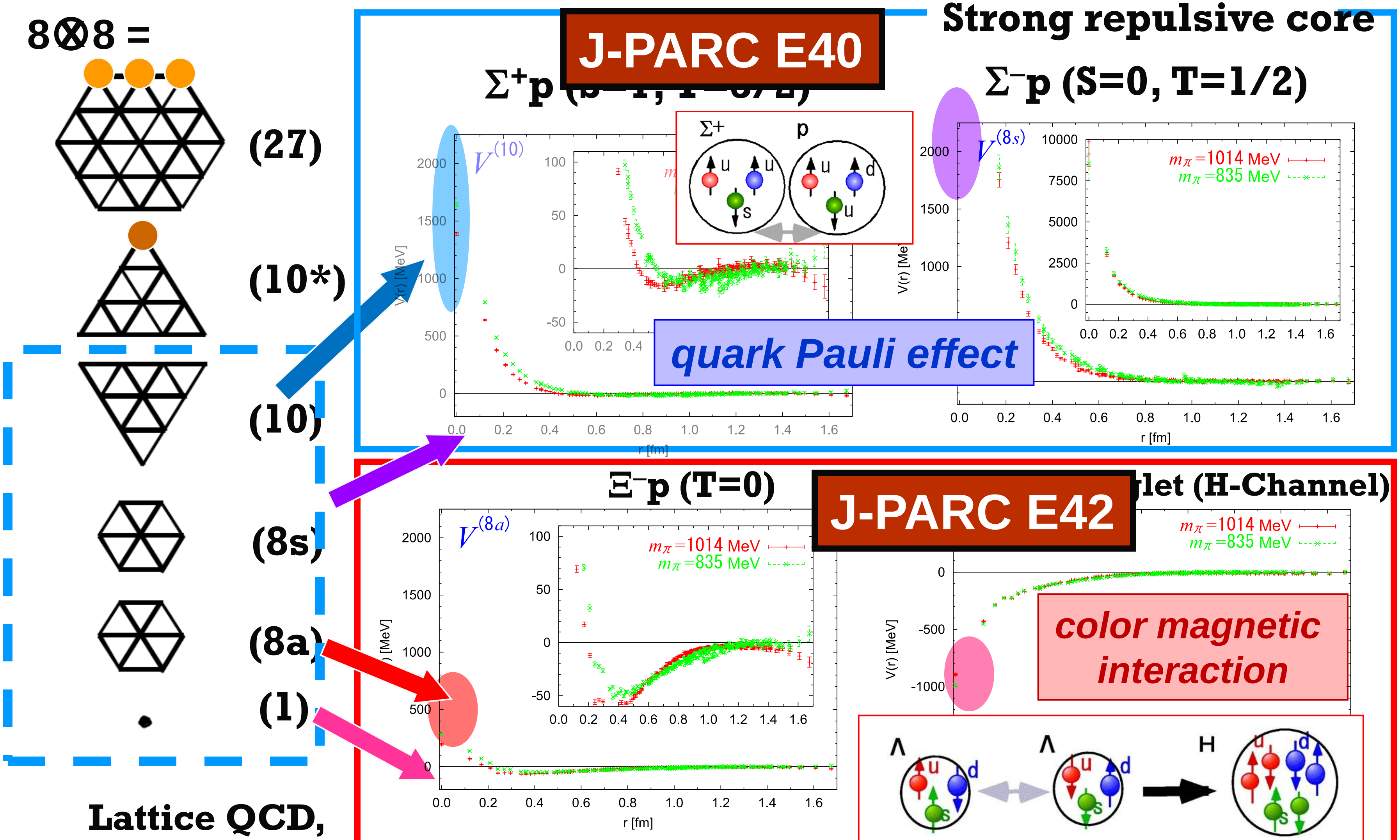
Σ^+p/ Σ^-p scattering experiment planned at J-PARC

Slide by Koji Miwa

Baryon I... D

The same behavior was predicted by Oka-Yazaki's Quark Cluster Model

6 independent



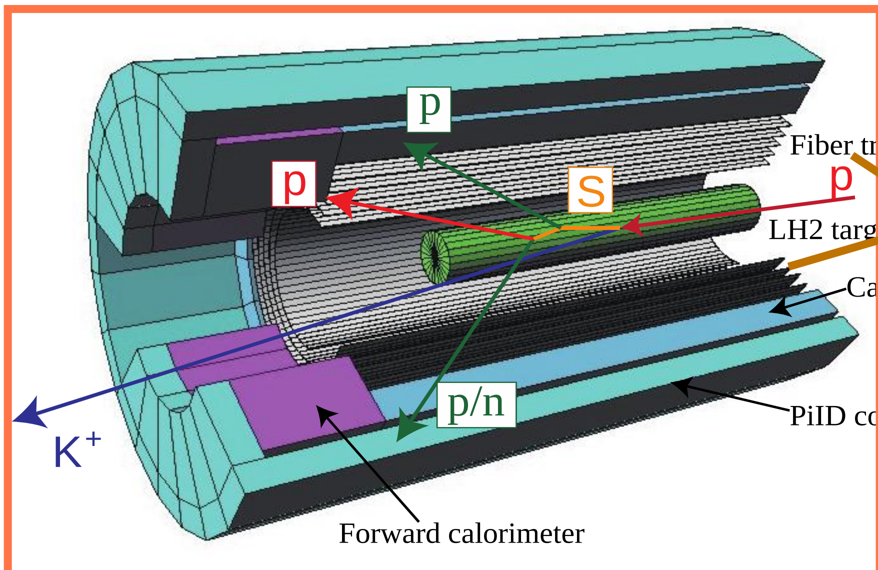
Weakly repulsive or attractive Core

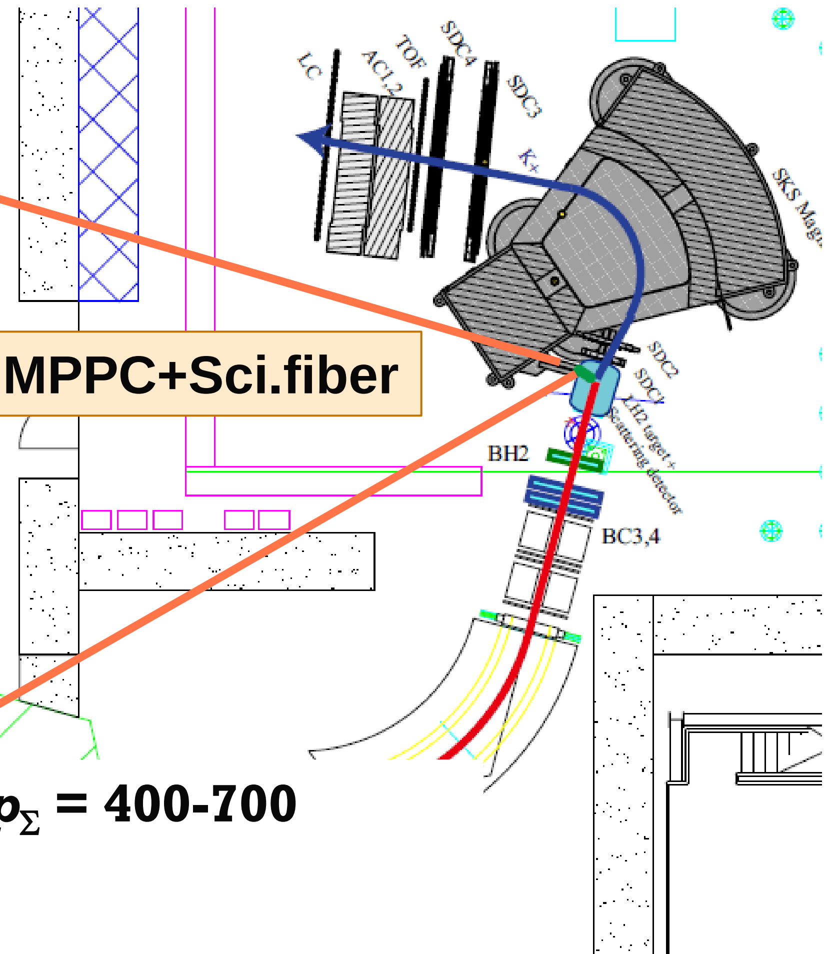
Lattice QCD, T. Inoue et al. Prog. Theor. Phys. 124 (2010) 4

J-PAR E40 (Miwa et al.)
Σp Scattering Experiment

- Hyperon production
  1.3 GeV/c π^{+-} p -> $K^{+}\Sigma^{+-}$ reaction
- Σ^{+-} track not directly measured
- Measure proton momentum vector
  -> kinematically complete

JPARC K1.8 beam line + SKS





=> $d\sigma/d\Omega$ for Σ^{+}p, Σ^{-}p, Σ^{-}p->Λn (p_{Σ} = 400-700 MeV/c)

Phase shift of $^{3}S_{1}$ channel

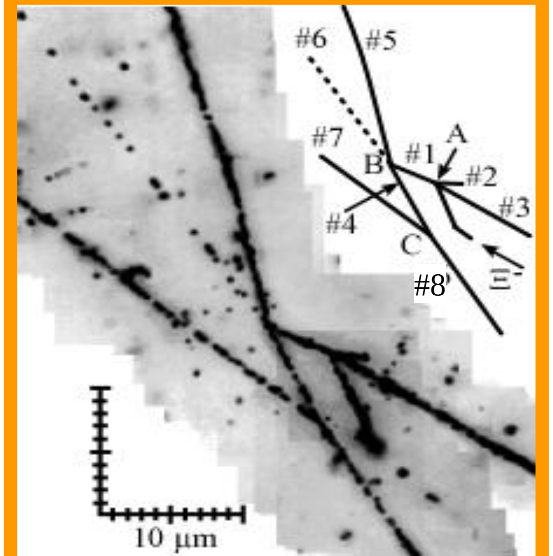
=> confirm quark Paul effect

4. Double strange nuclear systems

ΛΛ hypernuclei via emulsion+counter hybrid method (KEK E373)

Nakazawa (Hyp-X conf.)

Nagara event



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

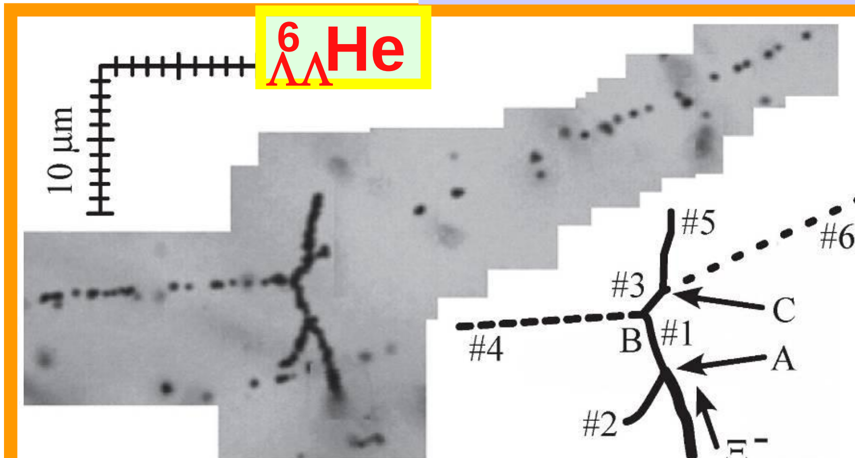
(unique and accurate)

$\Delta B_{\Lambda\Lambda}$= 0.67±0.17 MeV

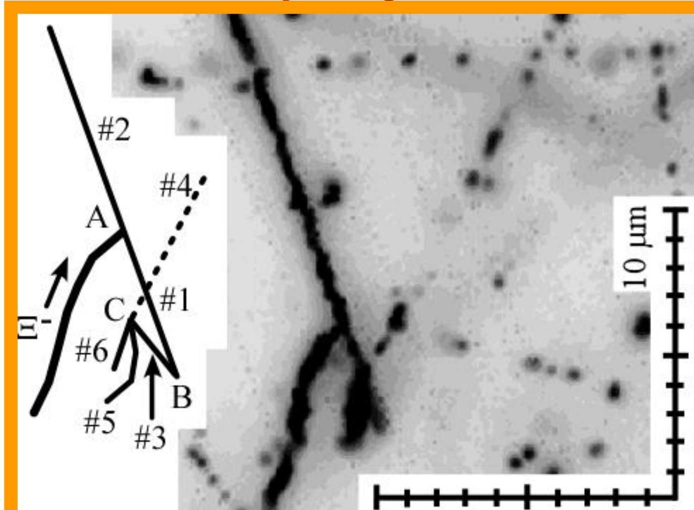
Mikage event

$\Delta B_{\Lambda\Lambda}$= 3.82 ±1.72 MeV

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



Demachi-yanagi event



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

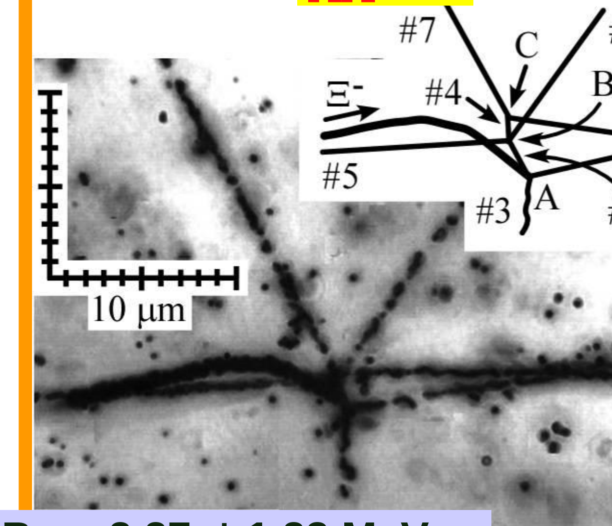
(w/ theoretical help)

$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0

cf. Ex = 3.0

Hida event

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

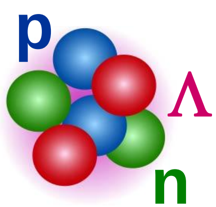


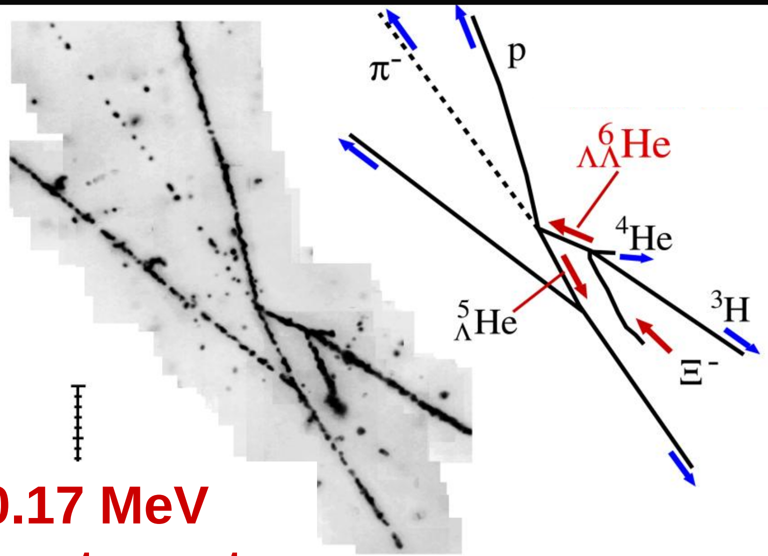
$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

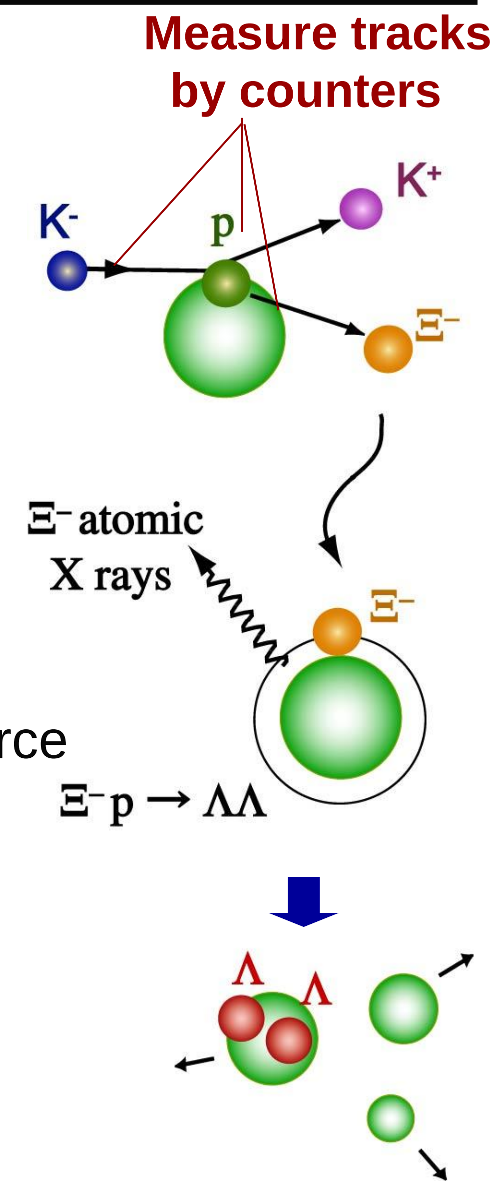
J-PARC E07 (Nakazawa, Imai, Tamura et al.)
S=-2 Systems with Emulsion-Counter Hybrid Method

Nagara event

PRL 87 (2001) 212502







$\Delta B_{\Lambda\Lambda}$ = 0.67+- 0.17 MeV

→ Big impact on neutron star

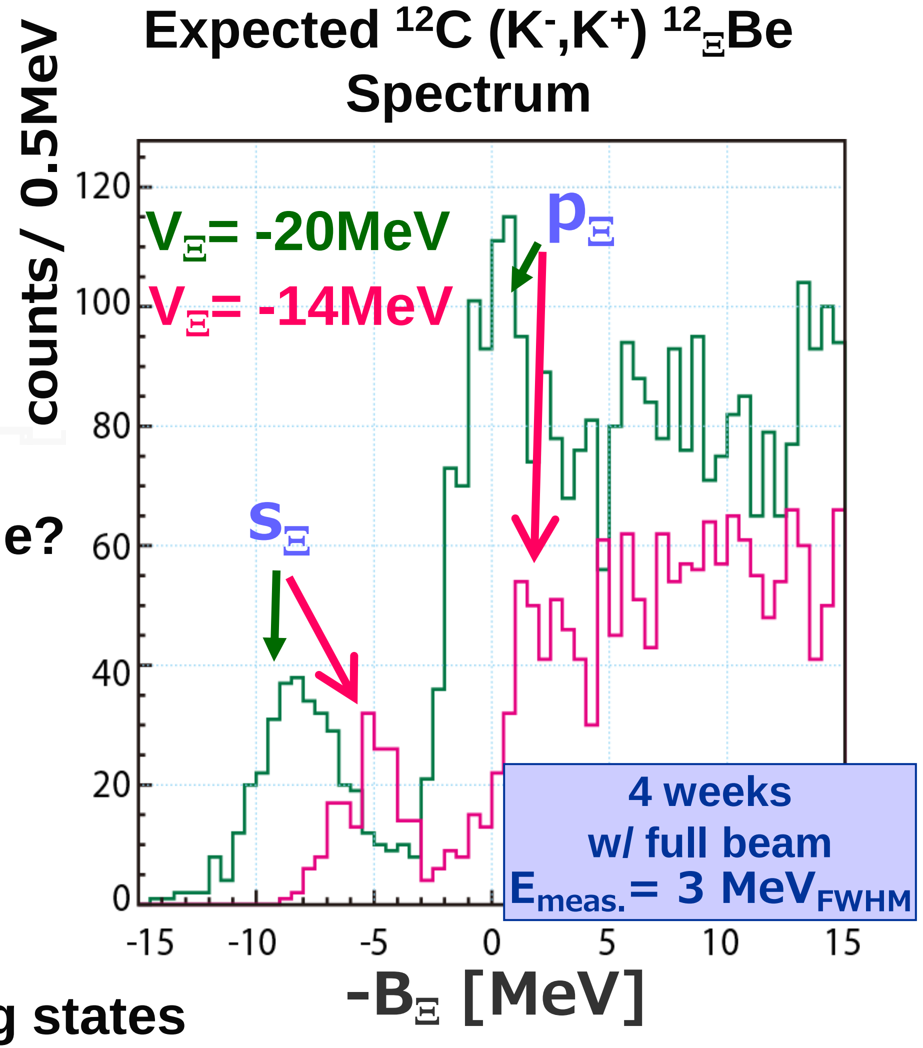
- **Ten times more events (~10²) of ΛΛ hypernuclei**
  - Remove nuclear dependence and details of ΛΛ force
  - Λ–Λ correlation (H dibaryon-like state) in nucleus from "ΛΛ" -> Σ⁻p decay
- **Measure Ξ⁻ -atomic X-rays with Hyperball-J**
  - Shift and width of X-rays -> Ξ-nuclear potential
  - Stopped Ξ⁻ events identified from emulsion

J-PARC E05 (Nagae et al.)

$K^- p \to \Xi^- K^+$

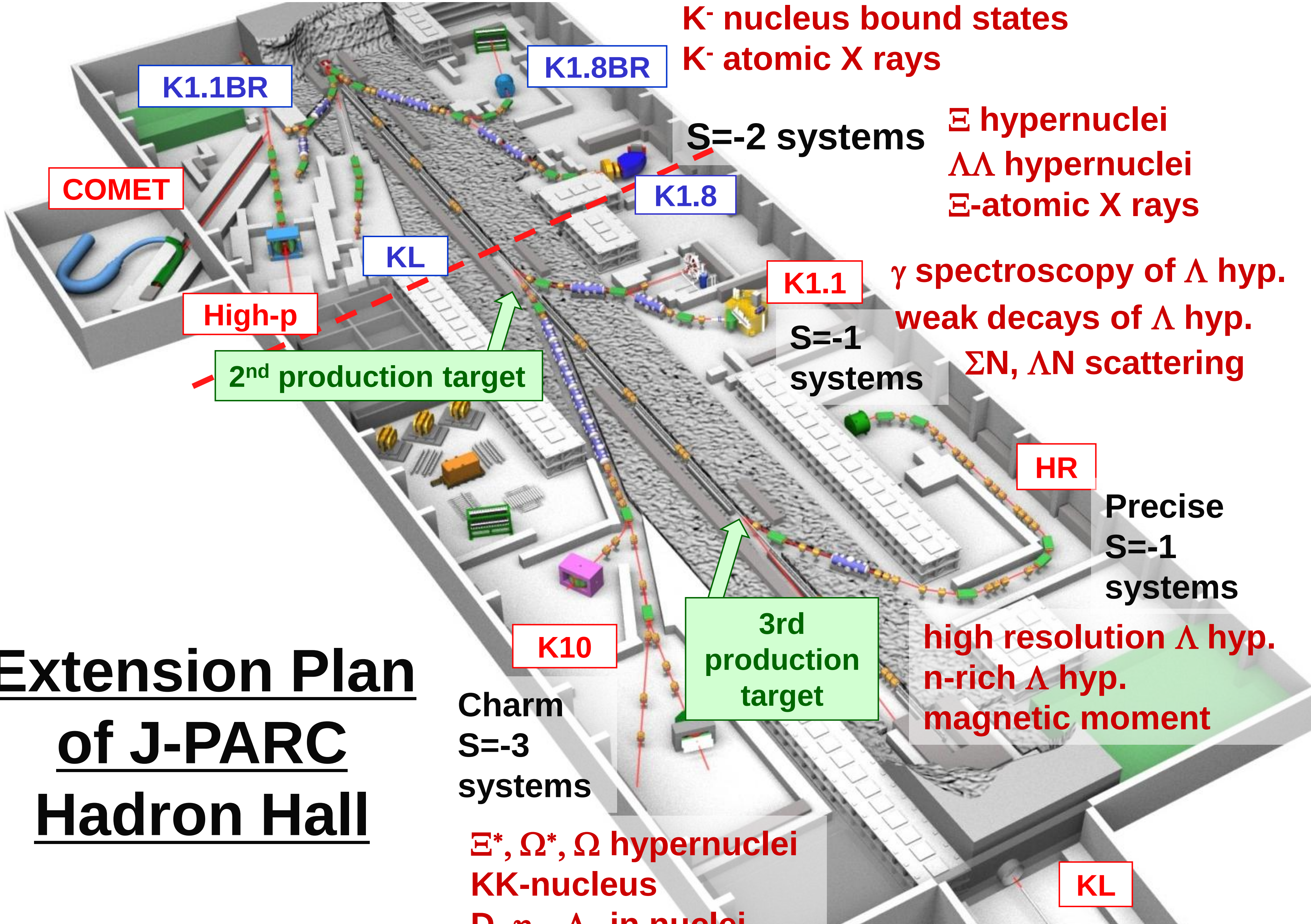
Ξ-hypernuclear spectroscopy by (K^-,K^+)

- First spectroscopic study of S=-2 systems in (K^-,K^+) reaction
- Properties of ΞN Interaction
  - Attractive or repulsive? How large? Ξ appears in neutron stars?
  - Isospin dependence ?
    - <- Different targets
  - ΞN-ΛΛ coupling force ?
    - <- $\Xi p \to \Lambda\Lambda$ conversion width
    - <- Ξ and ΛΛ hypernuclear mixing states



5. Future Plans at J-PARC

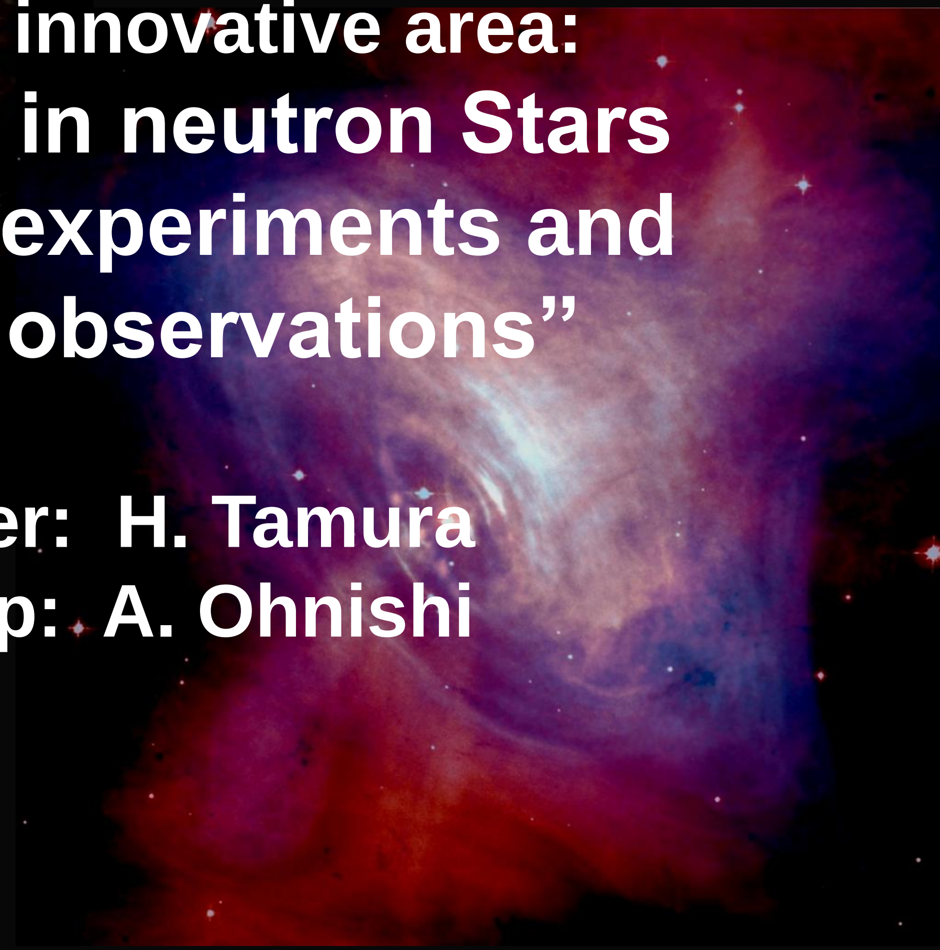
Extension Plan of J-PARC Hadron Hall



6. Summary

- **Strangeness nuclear physics studies BB forces, impurity effects, in-medium baryon properties and provides clues for neutron star matter.**
- **Λ hypernuclear spectroscopy: Neutron-rich $^{10}_{\Lambda}$Li and $^{6}_{\Lambda}$H observed. Will investigate ΛNN force in n-rich environment.**
- **γ-spectroscopy of Λ hypernuclei:**
  From p-shell data, spin-dependent ΛN int. strengths determined.
  In-medium g_{Λ} to be measured from B(M1).
- **Σ-nuclear systems: strongly repulsive potential observed.**
  Σ-p scattering experiment planned to confirm the quark Pauli effect.
- **Double strange systems: $^{6}_{\Lambda\Lambda}$He revealed $\Lambda\Lambda$ force weakly attractive.**
  Ξ hypernuclei to be first studied to measure the ΞN force.
- **Extension of J-PARC Hadron Hall will extend strangeness nuclear physics further.**

  Collaborations with theoretical studies of lattice BB forces, nuclear structure, etc. are more and more important.



2012-2016 新学術領域
「実験と観測で解き明かす中性子星の核物質」

Grant-in-aid for innovative area:

“Nuclear Matter in neutron Stars investigated by experiments and astronomical observations”

Project leader: H. Tamura

Theory group: A. Ohnishi