Status and Prospect of Hypernuclear Physics

Concettina Sfienti
Institut für Kernphysik
Johannes-Gutenberg Universität Mainz

Two motivations

Brief Overview

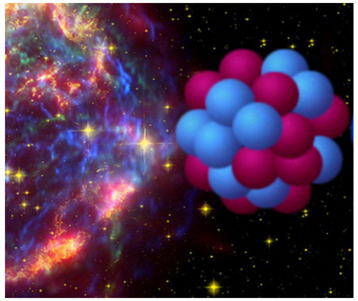
Rumsfeld Hypernuclei

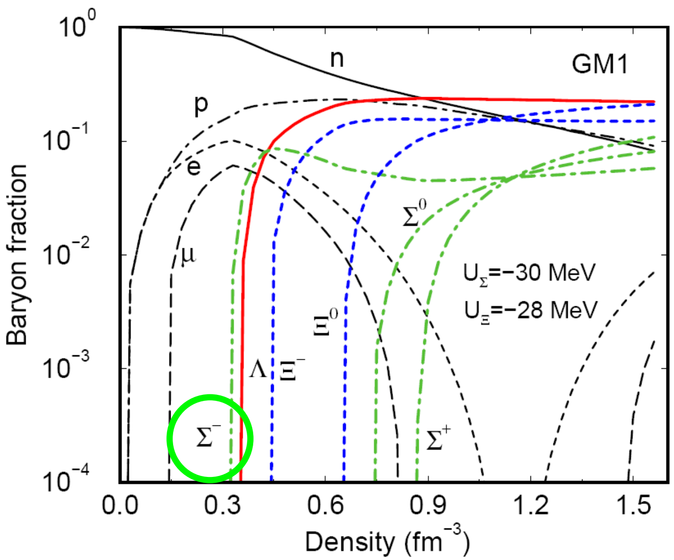
A keyhole to the future

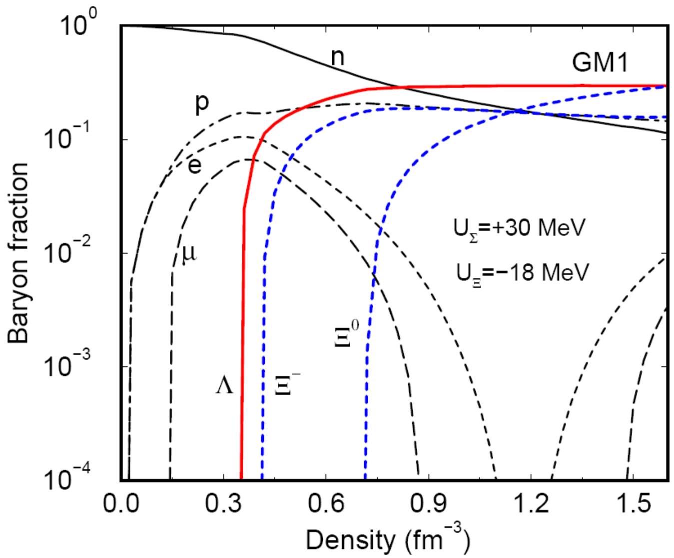
...for the visionary

What's (hyper)nuclear physics about?

Bridging the gap between nuclei and stars





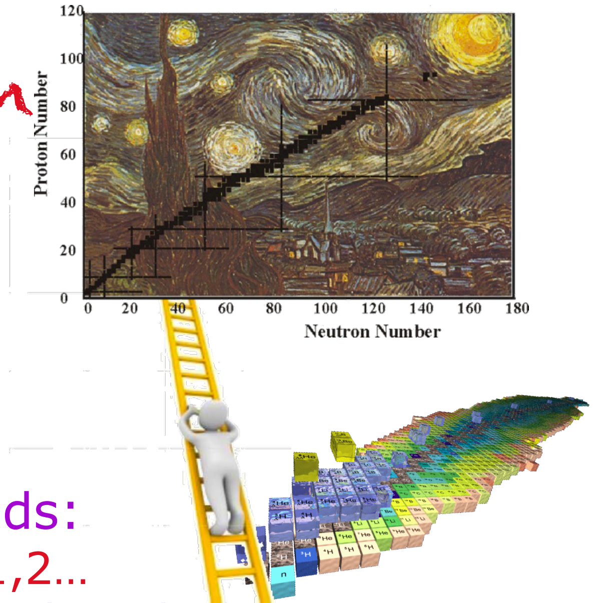


J. Schaffner-Bielich, NPA 804 (2008) 309

...for the realist

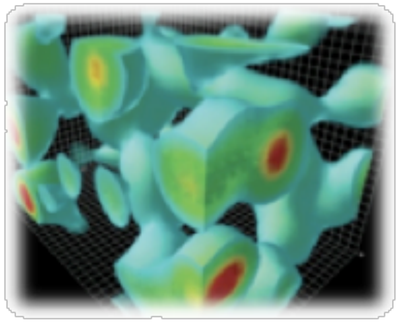
What's (hyper)nuclear physics about?

Describing complexity in term of fundamental interactions

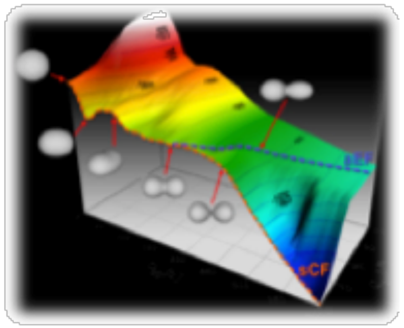


Theoretical Methods:

- ➢Lattice QCD A=0,1,2...
- ➢NCSM Faddeev-Yakubowsky, GFMC, ...: A=3÷16
- ➢Coupled cluster,...: A=16÷100
- ➢Density functional theory,...:A≥100



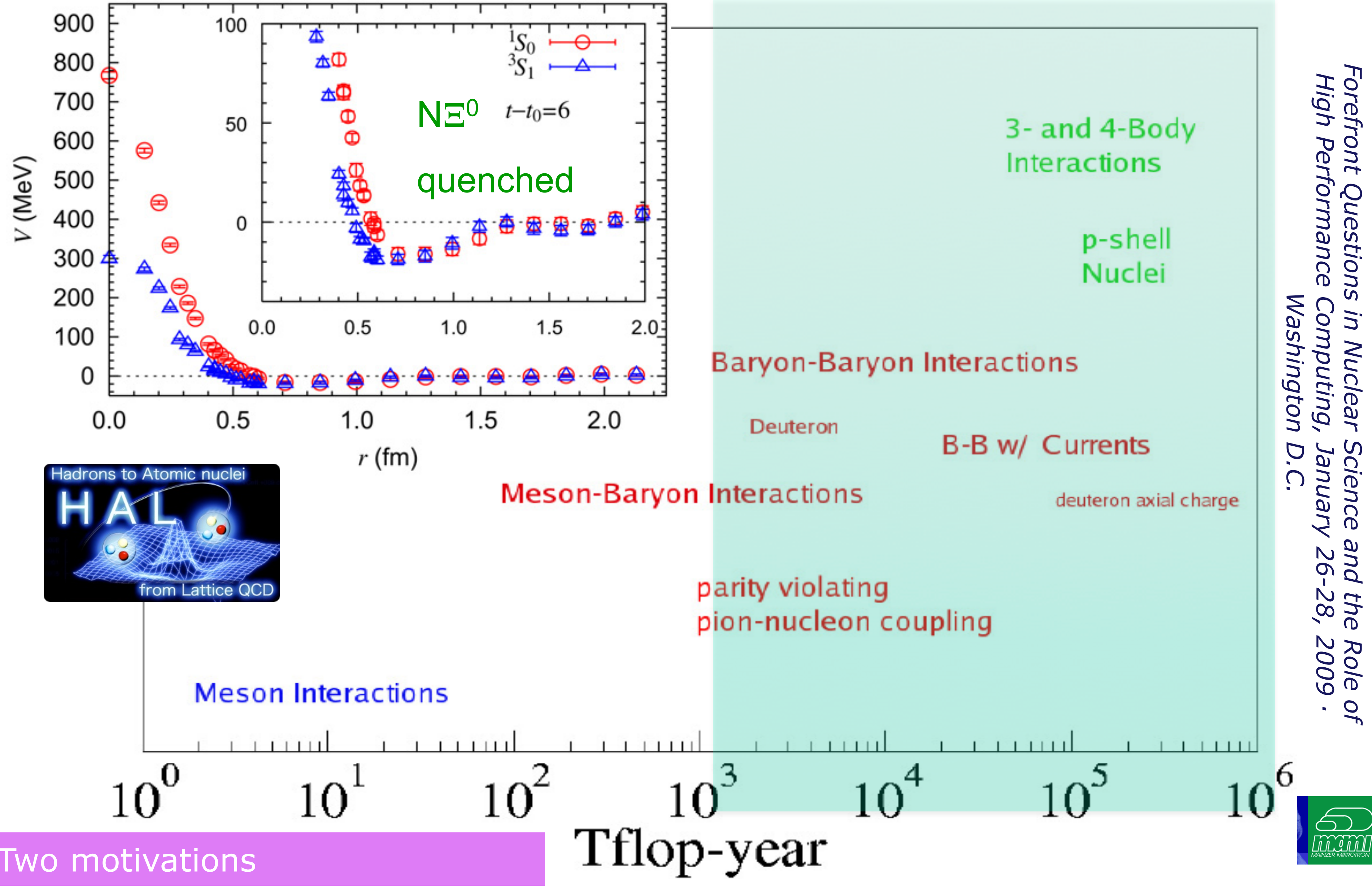
Cold QCD and Nuclear Forces



Nuclear Structure and Reactions

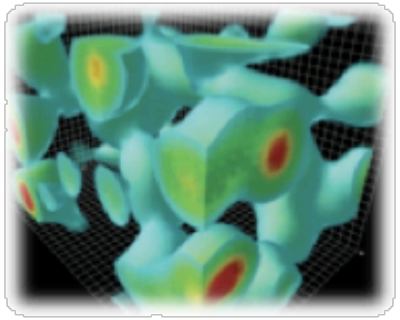
Nuclear forces from Lattice QCD

Nemura, Ishii, Aoki, Hatsuda, Phys.Lett.B673 (2009)136

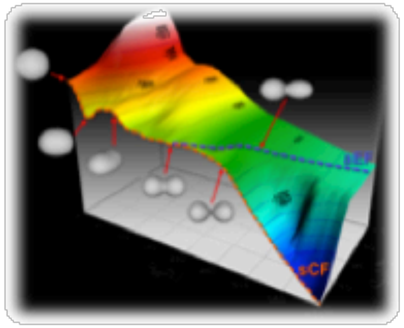


Two motivations

…for the realist



Cold QCD and Nuclear Forces



Nuclear Structure and Reactions

Theoretical Methods:

- ➢Lattice QCD A=0,1,2…
- ➢NCSM Faddeev-Yakubowsky, GFMC, …: A=3÷16
- ➢Coupled cluster,…: A=16÷100
- ➢Density functional theory,…:A≥100

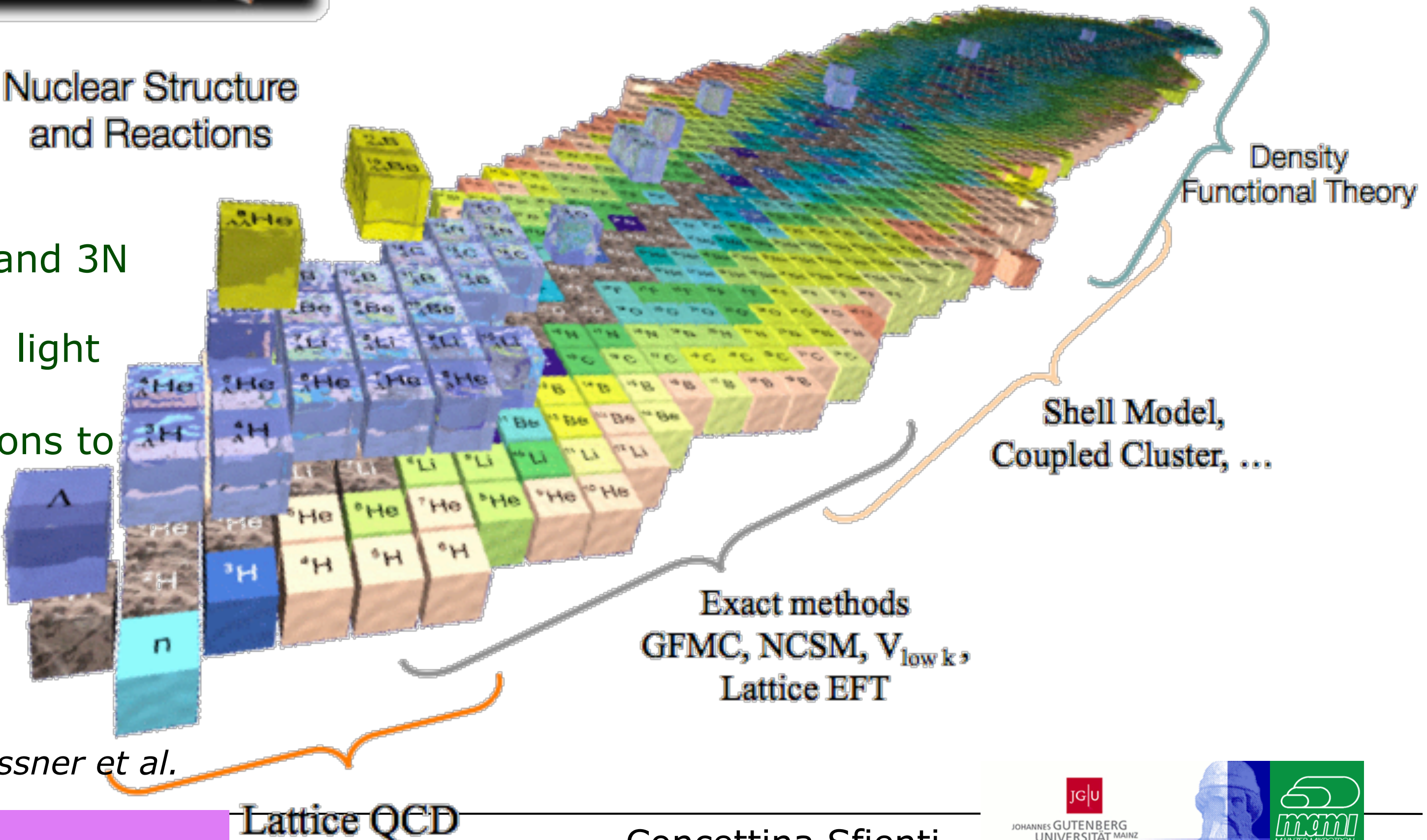
Chiral EFT:

☞Provides accurate NN and 3N forces

☞Successfully applied in light nuclei with A=2,3,4

☞Combine with simulations to get to larger A

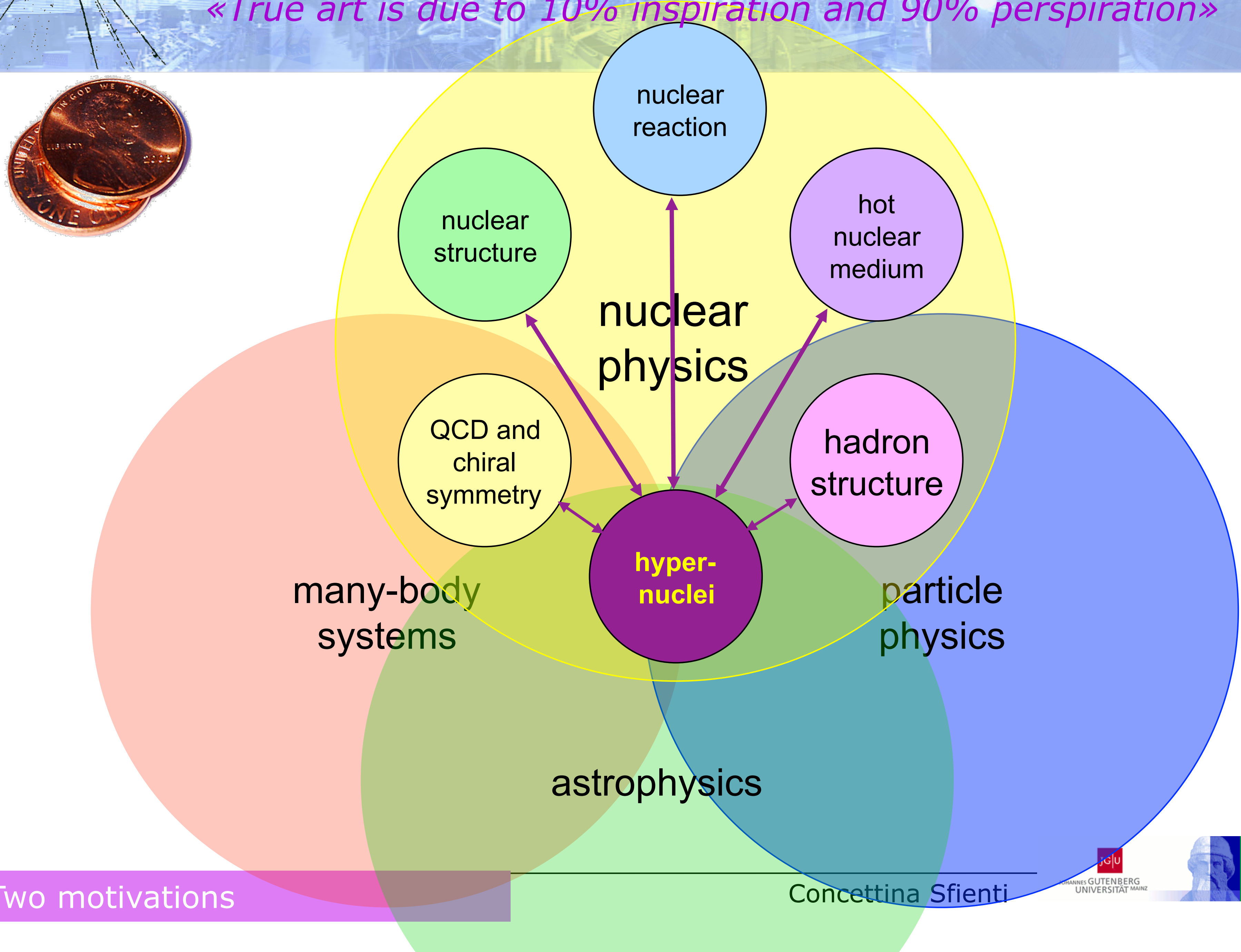
NN,YN,YY forces from chiral EFT



U-G Meissner et al.

Hypernuclear physics: a multicultural activity

«True art is due to 10% inspiration and 90% perspiration»



Getting introduced

$^{7}_{\Lambda}Li$

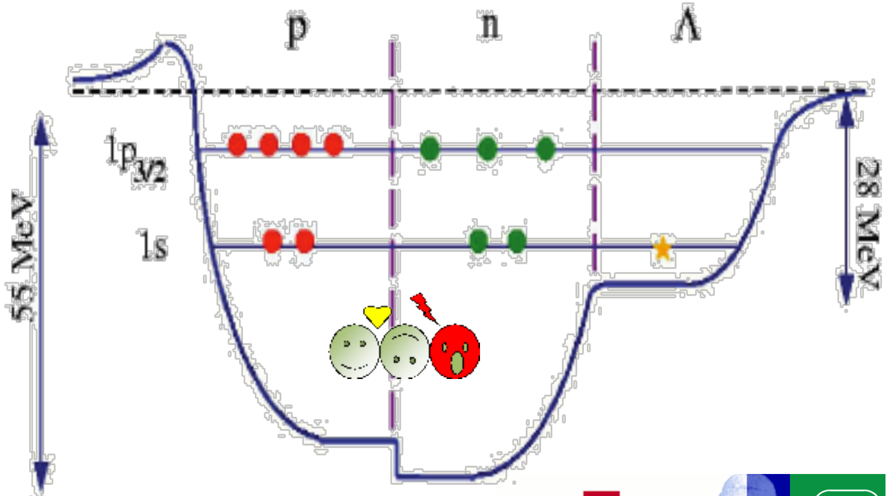
- Make the hyperon
- Get it into the nucleus
- Make sure it sticks there,
- Know all this has happened.

} Complementary methods and facilities

→ RESOLUTION!

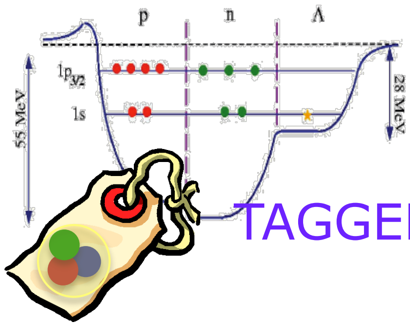
Known hypernuclei (beginning with 1953):
Λ-hypernuclei (~50 species)
Σ-hypernucleus ($^{4}_{\Sigma}He$ only??)
ΛΛ-hypernuclei (a few events)

Internal nuclear shell are **NOT Pauli-blocked** for hyperons

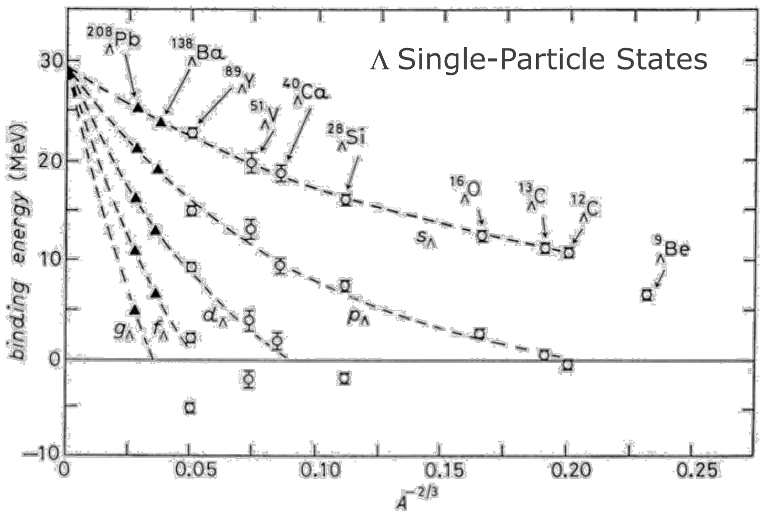


Getting introduced

Internal nuclear shell are ***NOT Pauli-blocked*** *for hyperons*

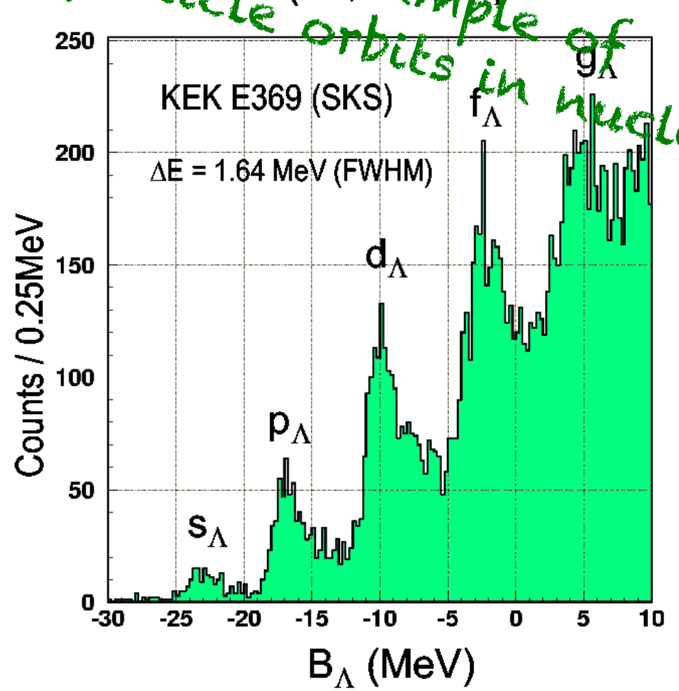


TAGGED NUCLEAR PHYSICS!



D. J. Millener et al., PRC38 (1988) 2700

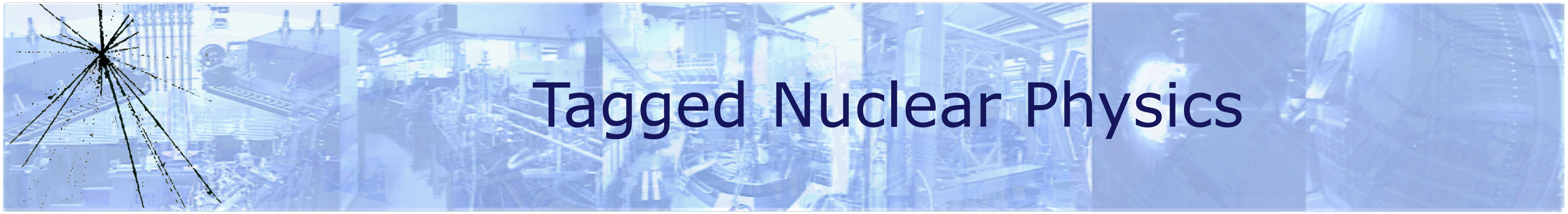
Textbook example of
Single-particle orbits in nucleus



Hotchi et al., PRC 64 (2001) 044302

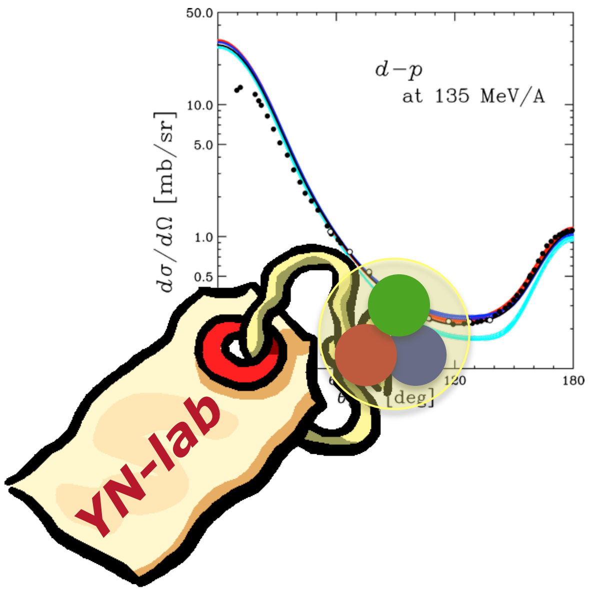
Λ's motion within the nucleus **not influenced** by the presence of the nucleons

The peak positions is well described by a **Wood-Saxon** potential

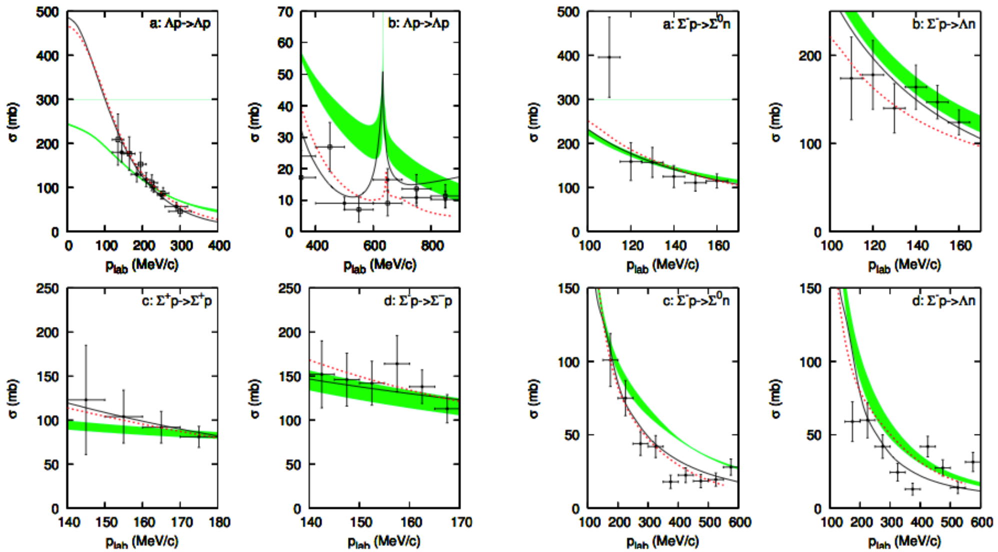


Tagged Nuclear Physics

NN scattering ➔NN interaction



Polinder, Haidenbauer, M., Nucl. Phys. A 779 (2006)



- Y-N interaction
  - •Low momentum YN scattering
  - •Exotic s=-1 Hypernuclei
- Y-Y interaction
  - •Exotic s=-2 Hypernuclei

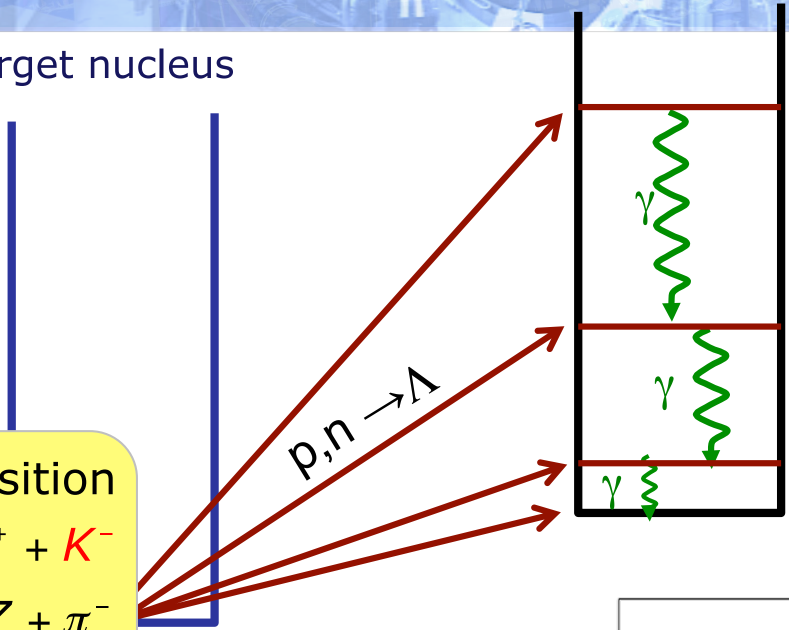
YN/YY interaction ➔ YN/YY scattering ?

Only ~600 data points exist

➔Hyperons live for only **fractions of a ns** *(ex.: τ_Λ = 0.26 ns)*

Birth, life and death of a hypernucleus

target nucleus



electromagnetic decays

strangeness deposition

$e^{+} + e^{-} \rightarrow \Phi \rightarrow K^{+} + K^{-}$

$K^{-}_{stopped} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^{-}$

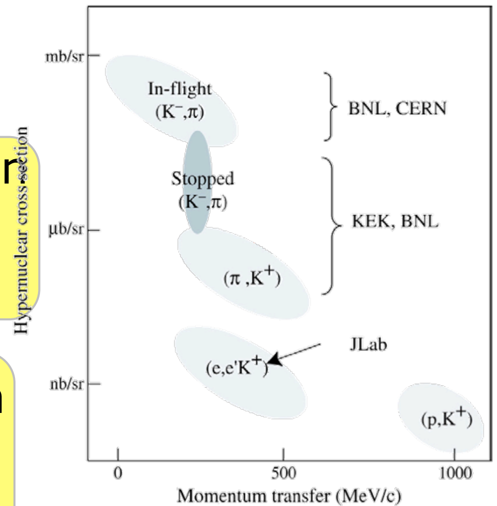
FINUDA

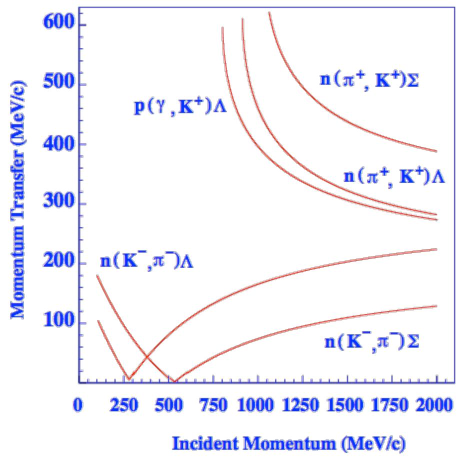
strangeness production
$(\pi^{+}, K^{+}), (\pi^{-}, K^{0})$
BNL,KEK

strangeness exchange
$(K^{-}, \pi^{-}), (K^{-}, \pi^{0})$

BNL,KEK,JPARC

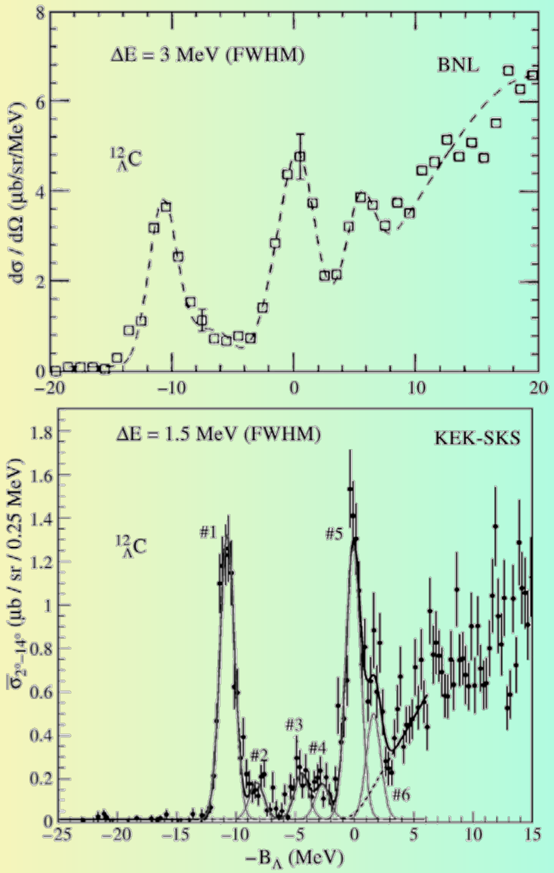
electroproduction
$(e,e'K^{+}), (\gamma,K^{+})$
Jlab, MAMI-C



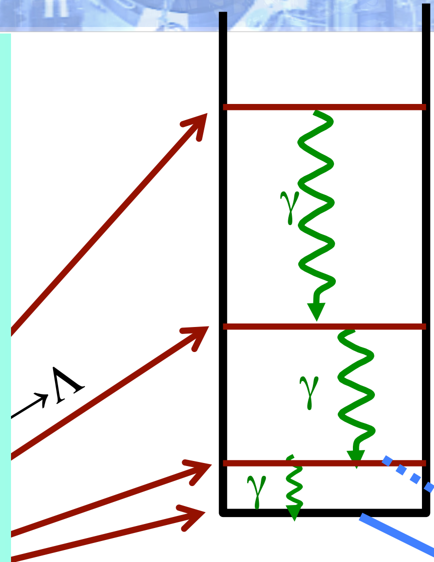


Birth, life and death of a hypernucleus

BNL-AGS Energy Resolution = 3MeV (FWHM)
(P.H.Pile et al., PRL 66 (1991) 2585)



KEK-SKS Energy Resolution = 1.5 MeV (FWHM)
(H.Hotch et al., PRC 64(2001) 044302)



electromagnetic decays

mesonic decays $\Lambda \to p\pi^-$ $\Lambda \to n\pi^0$

nonmesonic weak decay
$\Lambda p \to np$
$\Lambda n \to nn$
$\Lambda\Lambda \to YN$

hadronic decay in emulsion

Energy resolution
- K,p: 1-2 MeV
- $K_{stopped}$: 1 MeV
- e: 0.5 MeV
- γ-transitions: 5 keV

International Hypernuclear Network

STAR@RHIC
- HI Collider
- anti Λ-hypernuclei
- exotica?

PANDA @ FAIR
- anti-proton beam
- double Λ-hypernuclei
- γ-ray spectroscopy

ALICE@LHC
- URHIC Collider
- anti Λ-hypernuclei
- exotica?

Dubna
- heavy ion beam
- single Λ-hypernuclei
- weak decays

KAOS @ MAMI
- electro-production
- single Λ-hypernuclei
- Λ-wavefunction

HypHI@GSI
- heavy ion beams
- single Λ-hypernuclei at extreme isospins
- Magnetic moments

JLab
- electro-production
- single Λ-hypernuclei
- Λ-wavefunction

FINUDA @ DAFNE
- e^+e^- collider
- stopped-K^- reaction
- single Λ-hypernuclei
- γ-ray spectroscopy

J-PARC
- intense K^- beam
- single and double Λ-hypernuclei
- γ-ray spectroscopy for single Λ

2010 2020

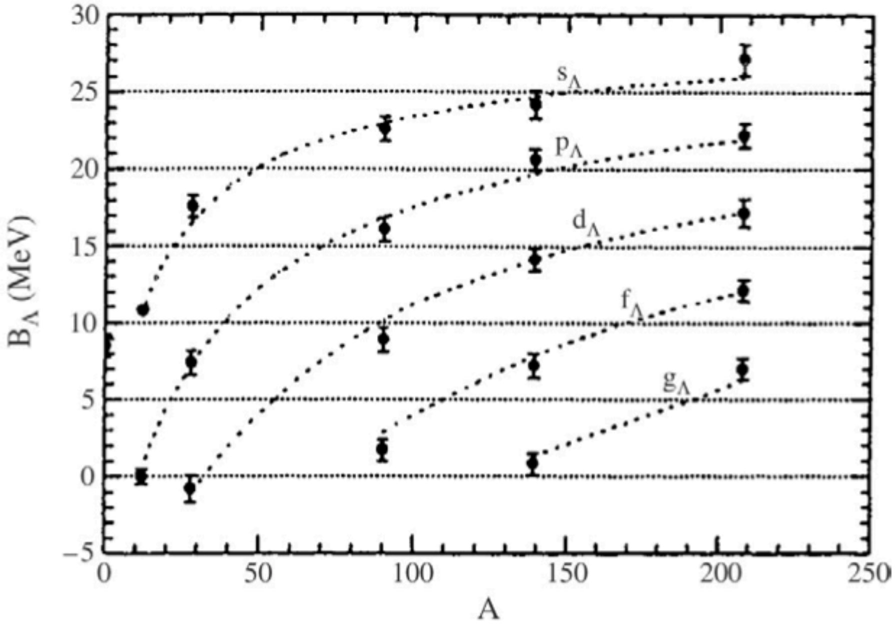
KEK JLAB HYPHI PANDA

FINUDA RHIC JPARC

LHC MAMI

"There are known knowns"

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



Nuclear potential of Λ
V_0^Λ =-30MeV (c.f.U_N =-50MeV)

ΛN force is **attractive** but weaker than NN

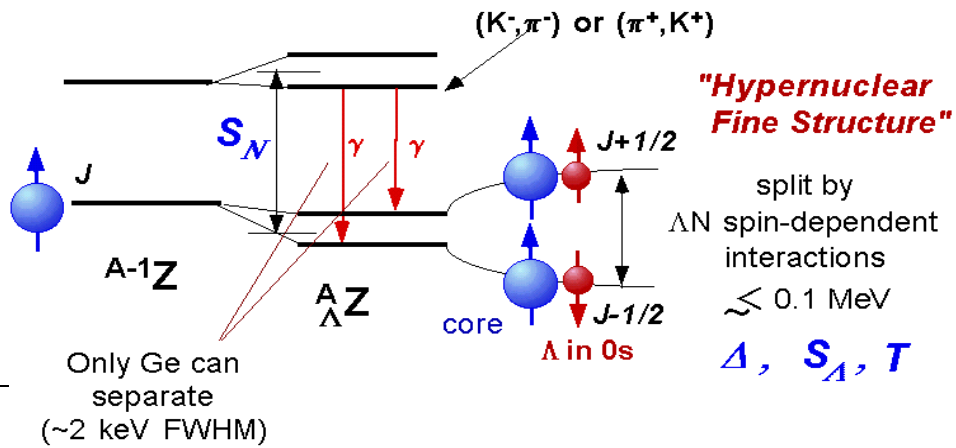
Better resolution is necessary for ΛN spin-dependent forces, ΛN-ΣN force, ..

Woods–Saxon for the Λ hypernuclear potential

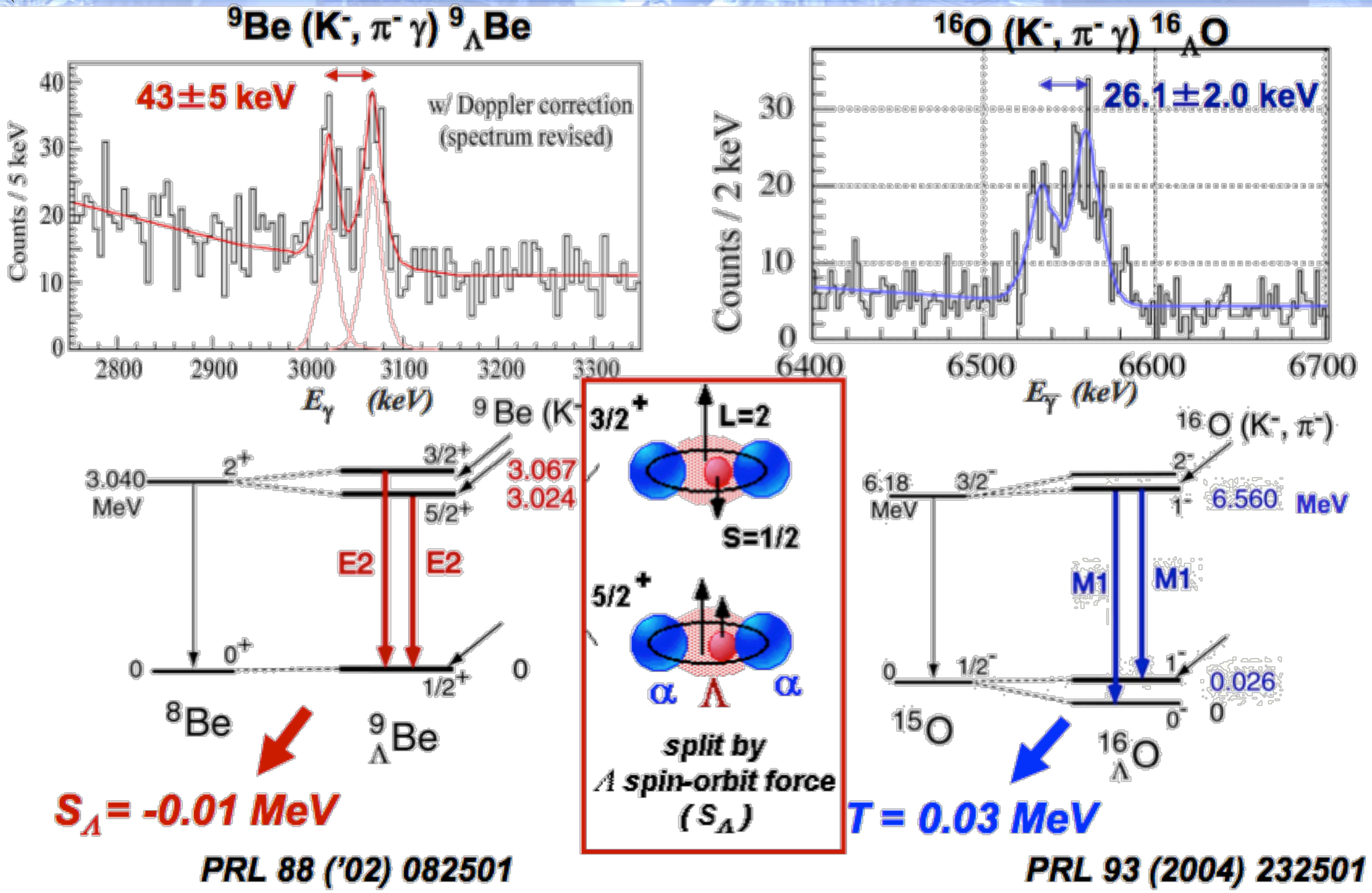
$$U_\Lambda = V_0^\Lambda f(r) + V_{LS}^\Lambda \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{\mathrm{d}f(r)}{\mathrm{d}r} \boldsymbol{ls}$$

$$f(r) = [1 + \exp((r - R)/a)]^{-1}.$$

Low-lying levels of Λ Hypernuclei



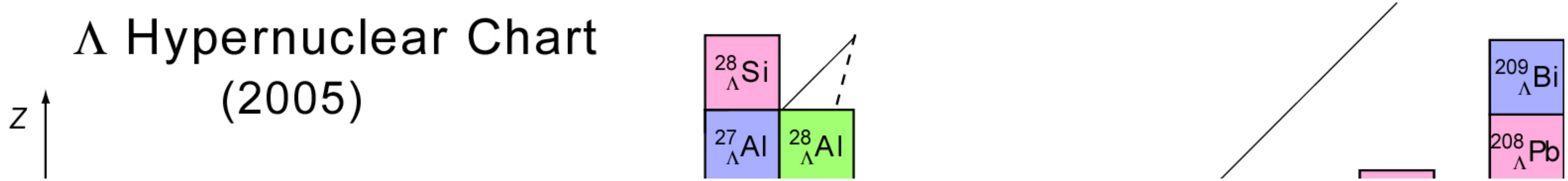
Spin-Orbit force in Hypernuclei



- surprisingly small spin-orbit force (~few percent of NN case)
- **Precision** is the key issue

Single Λ Hypernuclei

Λ Hypernuclear Chart (2005)



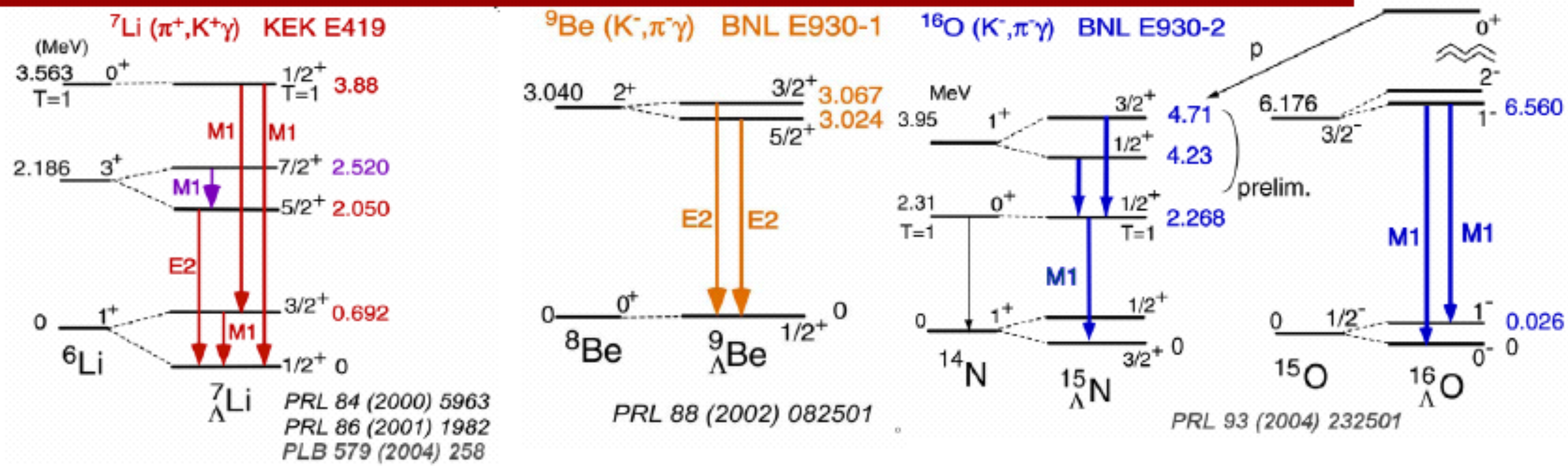
$$V_{\Lambda N}^{eff} = V_0 + \Delta(\vec{s}_\Lambda \cdot \vec{s}_N) + S_N(\vec{l}_{\Lambda N} \cdot \vec{s}_N) + S_\Lambda(\vec{l}_{\Lambda N} \cdot \vec{s}_\Lambda) + T(s_{12})$$

$^7_\Lambda$Li (3/2$^+$,1/2$^+$) → **Δ = 0.4 MeV**

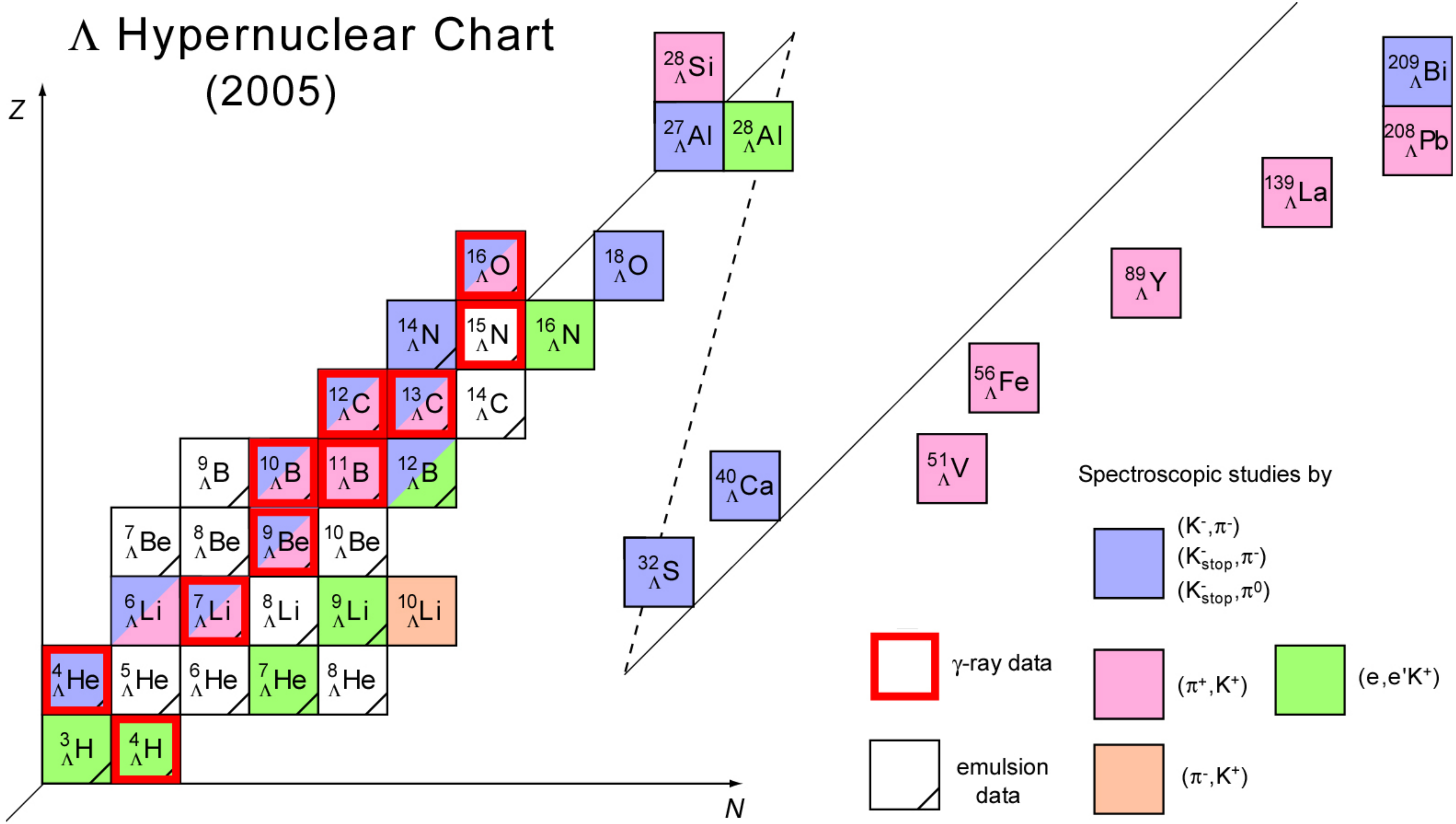
$^7_\Lambda$Li (5/2$^+$,1/2$^+$) → **S_N = - 0.4 MeV**

$^9_\Lambda$Be (3/2$^+$,5/2$^+$) → **S_Λ = - 0.01 MeV**

$^{16}_\Lambda$O (1$^-$,0$^-$) → **T = 0.03 MeV**



Single Λ Hypernuclei



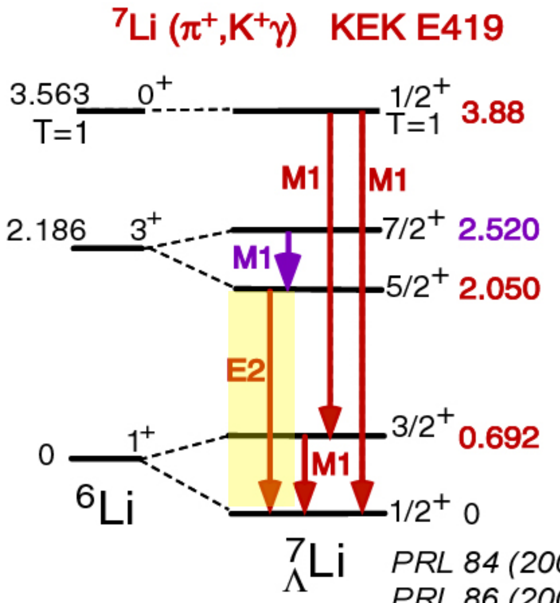
Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Impurity Effects

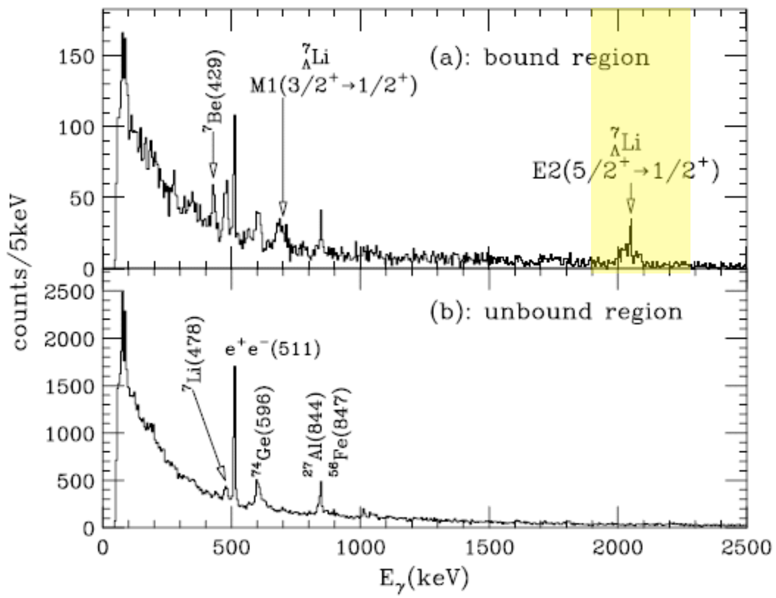
VOLUME 86, NUMBER 10 PHYSICAL REVIEW LETTERS 5 MARCH 2001

Measurement of the $B(E2)$ of ${}^{7}_{\Lambda}$Li and Shrinkage of the Hypernuclear Size

K. Tanida,[1] H. Tamura,[2] D. Abe,[2] H. Akikawa,[3] K. Araki,[2] H. Bhang,[4] T. Endo,[2] Y. Fujii,[2] T. Fukuda,[5] O. Hashimoto,[2] K. Imai,[3] H. Hotchi,[1] Y. Kakiguchi,[5] J.H. Kim,[4] Y.D. Kim,[6] T. Miyoshi,[2] T. Murakami,[3] T. Nagae,[5] H. Noumi,[5] H. Outa,[5] K. Ozawa,[2] T. Saito,[7] J. Sasao,[2] Y. Sato,[2] S. Satoh,[2] R.I. Sawafta,[8] M. Sekimoto,[5] T. Takahashi,[2] L. Tang,[9] H.H. Xia,[10] S.H. Zhou,[10] and L.H. Zhu[3,10]



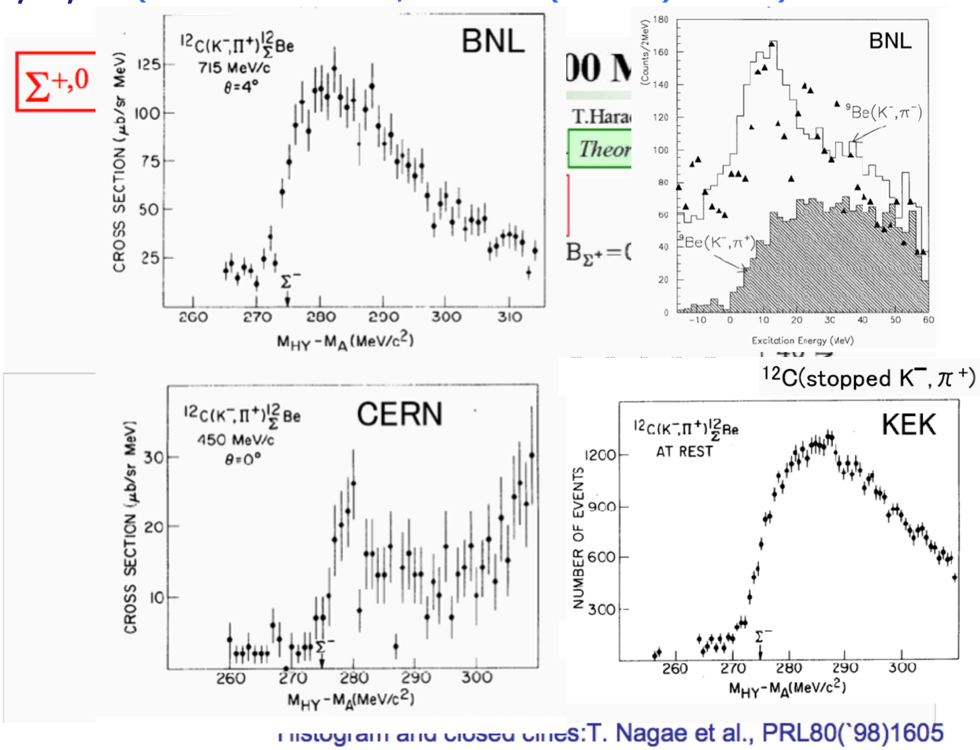
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501



“There are known unknowns”

Σ hyperons:

Isospin dependent U_{Σ} in light systems:
A bound state in A=4 at KEK (R.S.Hayano et al., PLB231(1989)355)
at BNL (T. Nagae et al, PRL80(1998)1605)
Systematics of $(K^-,\pi^{\pm})$ in A=4,6,9 (S. Bart at al., PRL83(1999)5238)
Poor YN Scattering date
$(K^-,\pi\pm)$ spectra on A≤16

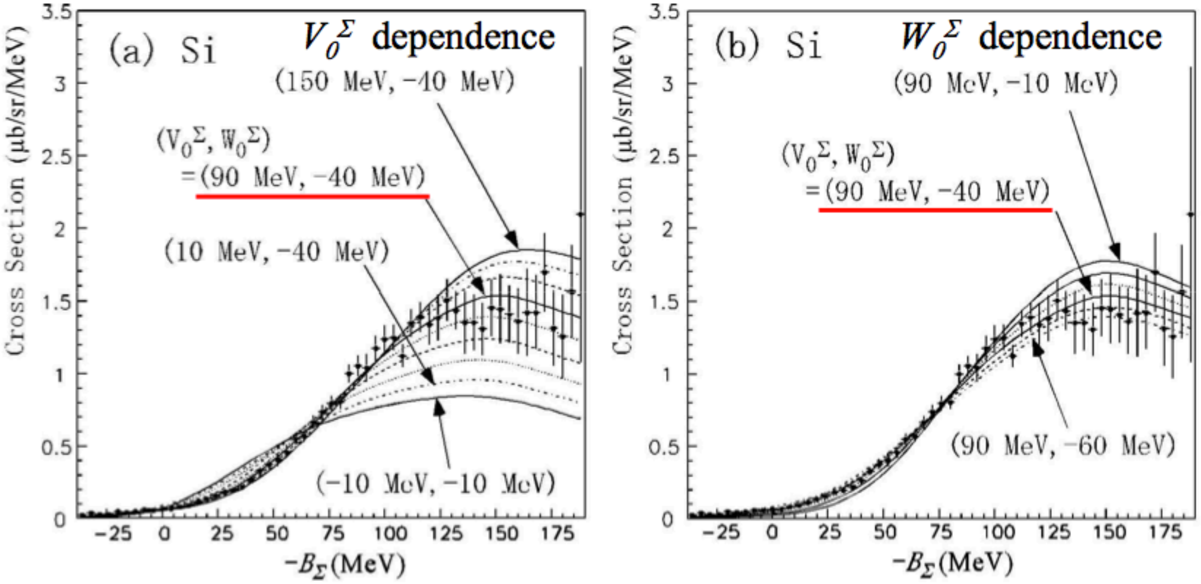


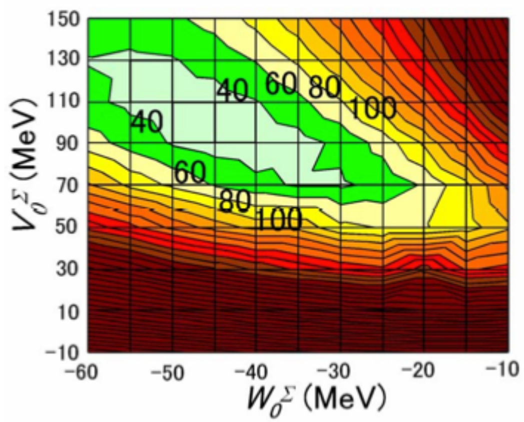
Σ Hyperon (E438@KEK)

VOLUME 89, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 2002

Sigma-Nucleus Potential in $A = 28$

H. Noumi,[1] P.K. Saha,[1,*] D. Abe,[2] S. Ajimura,[3] K. Aoki,[1] H.C. Bhang,[4] T. Endo,[2] Y. Fujii,[2] T. Fukuda,[1,*] H.C. Guo,[5] K. Imai,[7] O. Hashimoto,[2] H. Hotchi,[6,†] E.H. Kim,[4] J.H. Kim,[4] T. Kishimoto,[3] A. Krutenkova,[8] K. Maeda,[2] T. Nagae,[1] M. Nakamura,[6] H. Outa,[1] M. Sekimoto,[1] T. Saito,[2,‡] A. Sakaguchi,[3] Y. Sato,[1,2] R. Sawafta,[9] Y. Shimizu,[3,*] T. Takahashi,[2] L. Tang,[10] H. Tamura,[2] K. Tanida,[6] T. Watanabe,[2] H.H. Xia,[5] S.H. Zhou,[5] L.H. Zhu,[7] and X.F. Zhu[5]

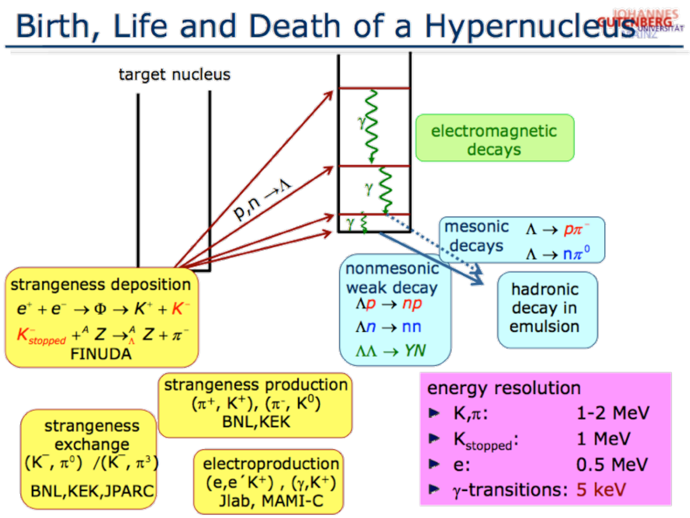




DIWA Analysis

Wood-Saxon Potential ≈ $(V_o^\Sigma + iW_o^\Sigma) \times f(r)$

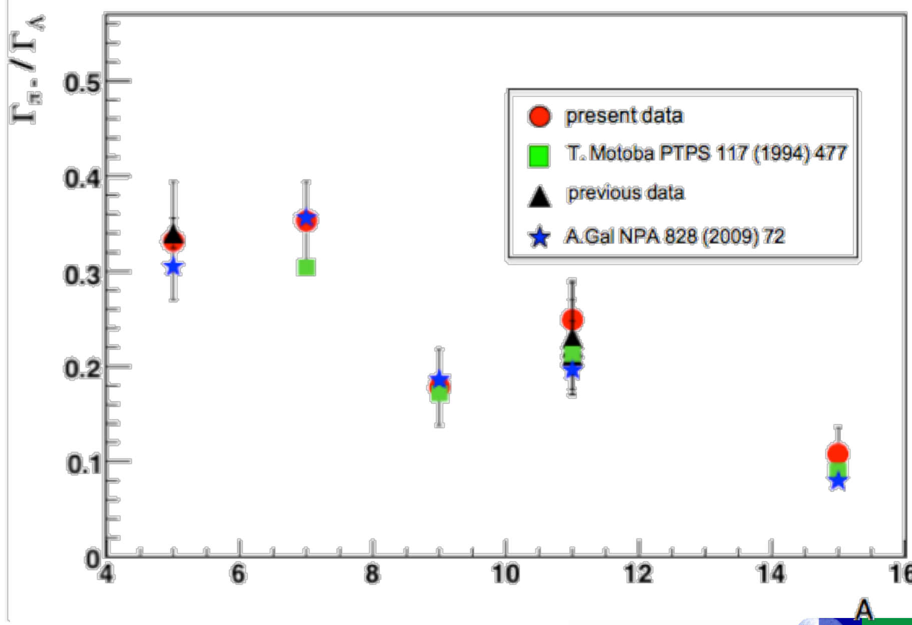
Weak Decay



HYP Weak Decay:

- Spin-parity of gs. hypernuclei
- NMWD: 4-baryons strangeness changing weak interaction
- Final State Interaction
- …

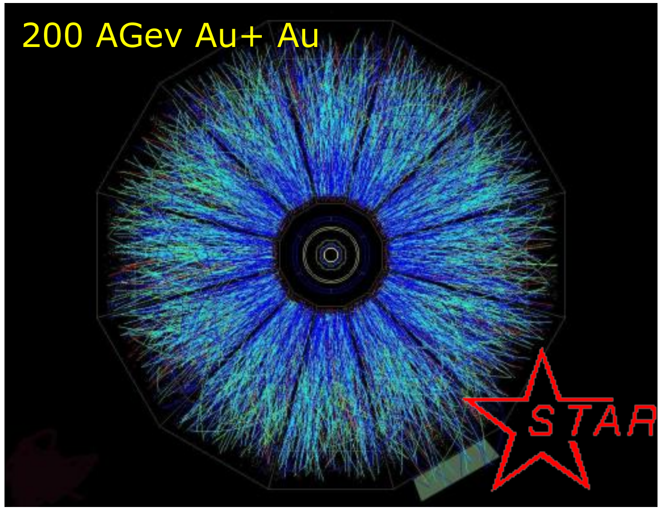
S. Bufalino SPHERE & JSPS Meeting, Prague, Czech (2010)

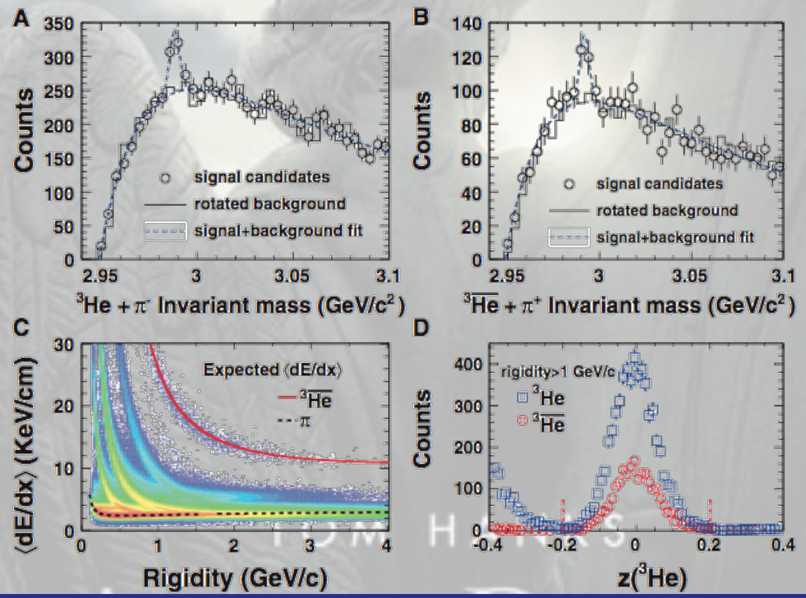


The FINUDA Era:

- Mesonic of p-shell HYP: Spin – parity assignement
- Nuclear Structure effects!
- First systematic study of p-induced NMWD (coincidence measurements)
- Final State Interactions!

Hypernuclei in Heavy Ion Reactions





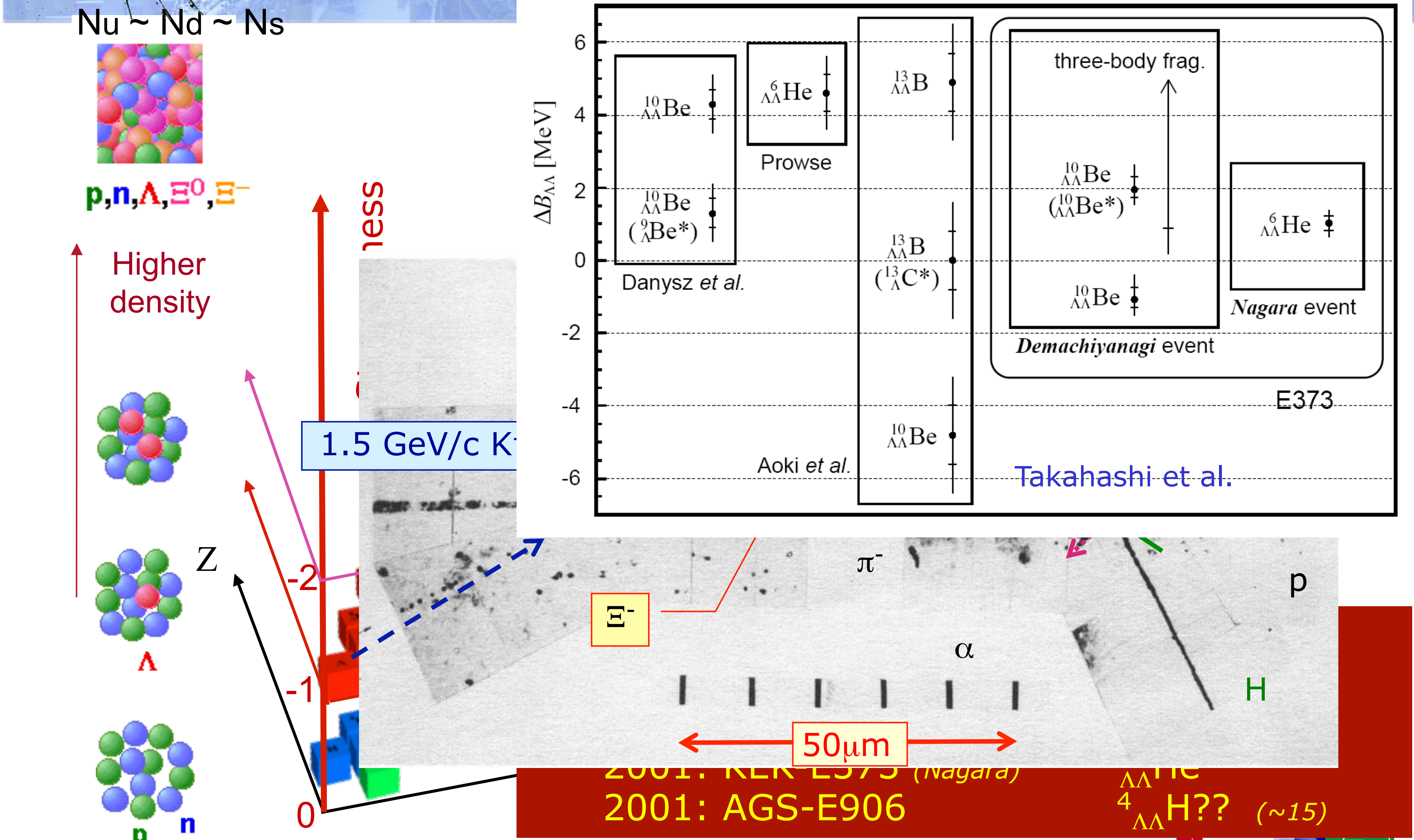
Other HI projects:

FOPI@GSI has also observed as signal compatible with hypertriton

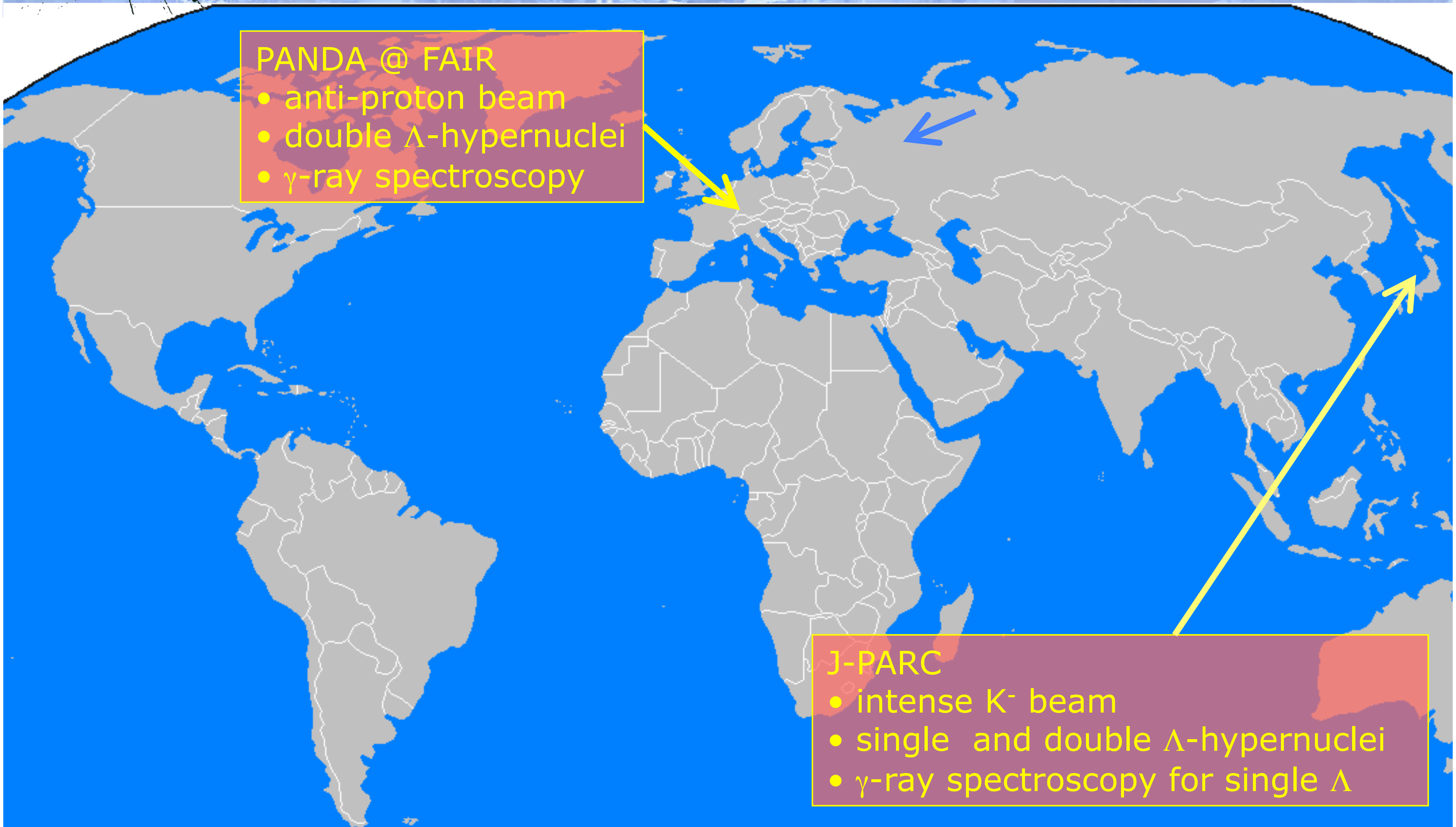
ALICE@LHC will also look for hypernucleus production

HYPHI@GSI: (*T. Saito – this afternoon, D. Nakajima – Friday afternoon -*)

"There are unknown unknowns"

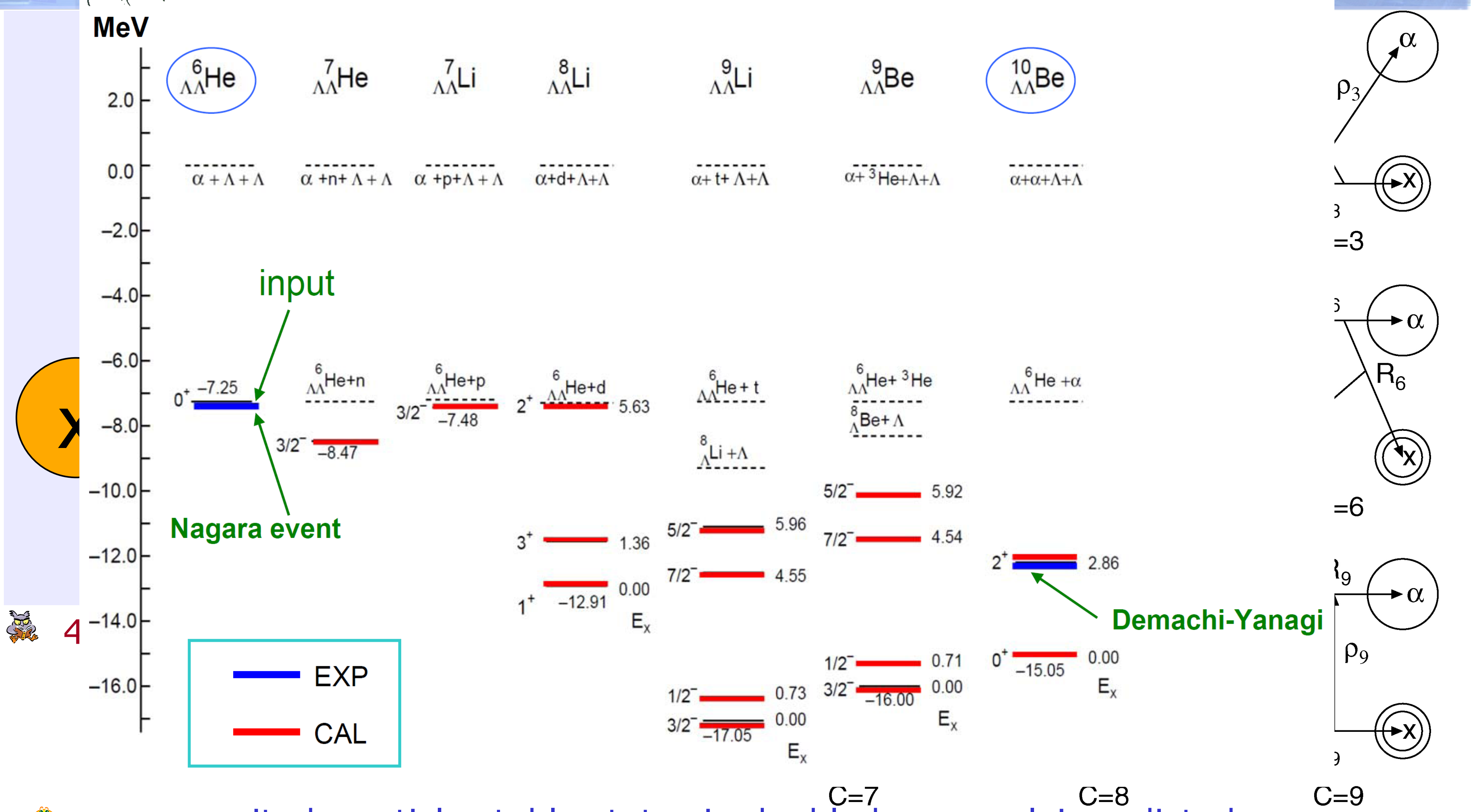


…where?

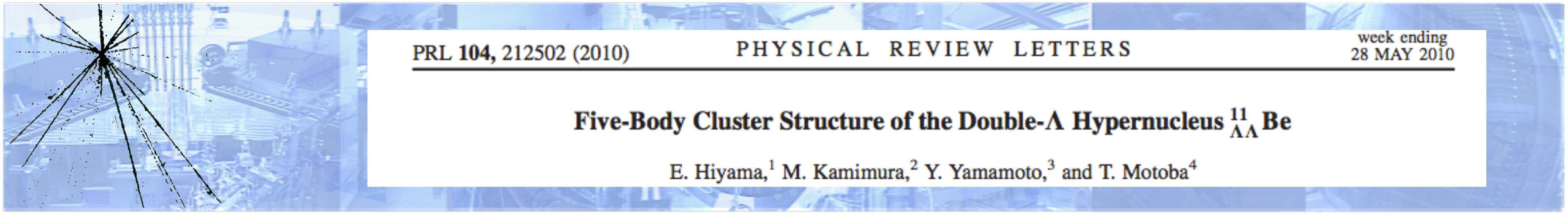

PANDA @ FAIR
• anti-proton beam
• double Λ-hypernuclei
• γ-ray spectroscopy
J-PARC
• intense K⁻ beam
• single and double Λ-hypernuclei
• γ-ray spectroscopy for single Λ

Spectroscopy of ΛΛ-hypernuclei

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



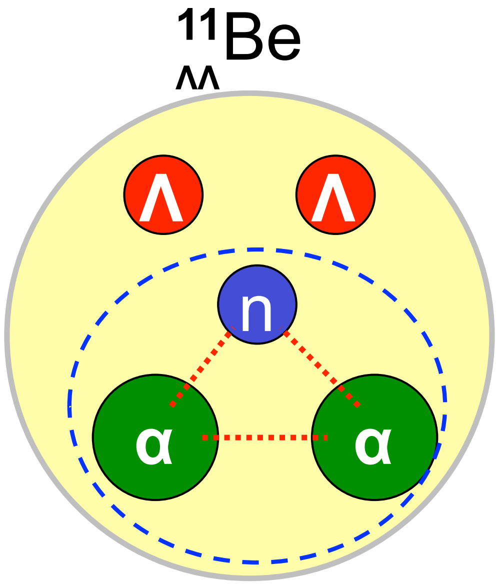
- many excited, particle stable states in double hypernuclei predicted
- γ-spectroscopy of these states is mandatory to study them

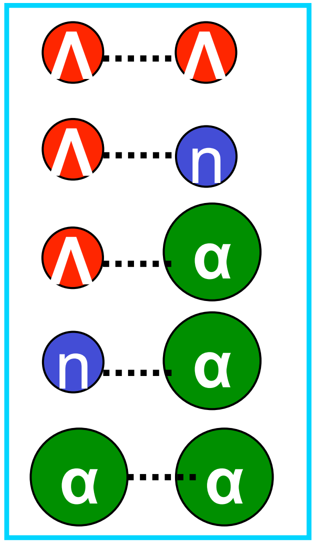


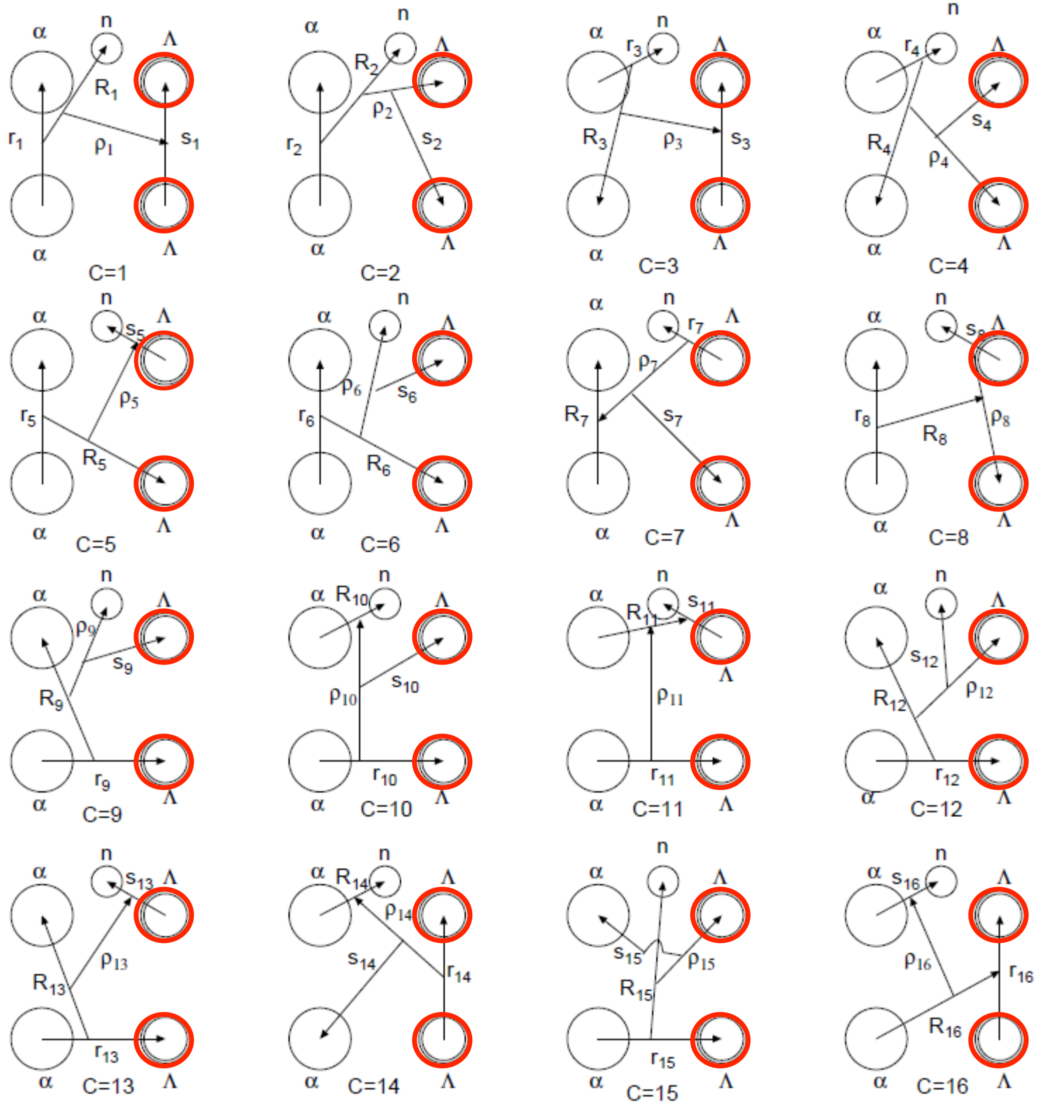
PRL 104, 212502 (2010) PHYSICAL REVIEW LETTERS week ending 28 MAY 2010

Five-Body Cluster Structure of the Double-Λ Hypernucleus $^{11}_{\Lambda\Lambda}$Be

E. Hiyama,[1] M. Kamimura,[2] Y. Yamamoto,[3] and T. Motoba[4]







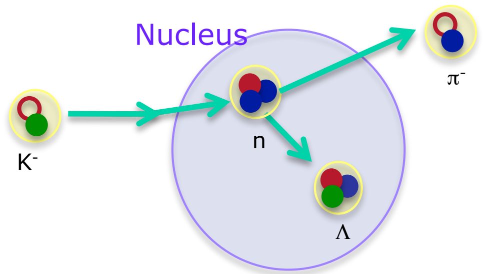
A keyhole to the future

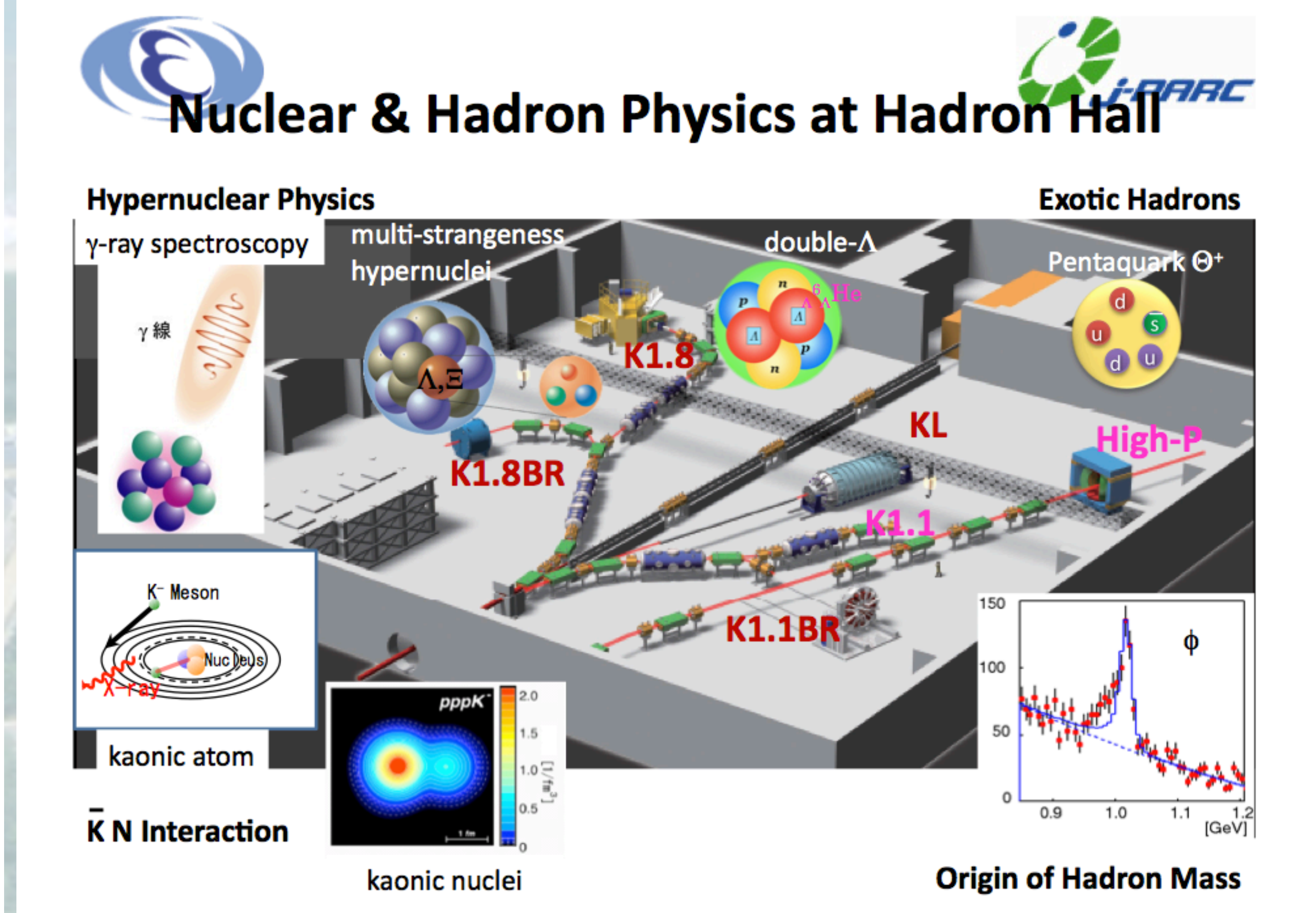
120 sets of Jacobi coordinates.

Strangeness@JPARC

T.Takahashi (KEK/J---PARC)

Strangeness exchange



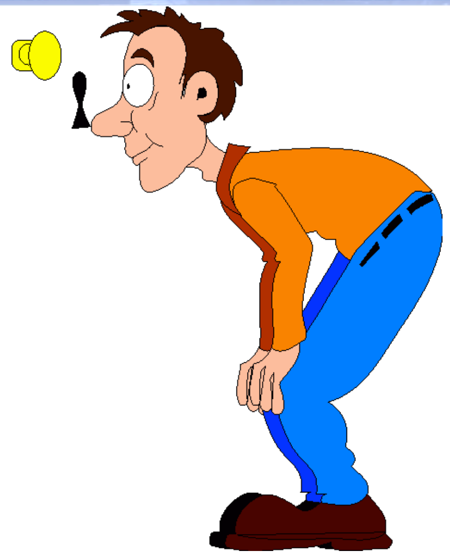


Intense K-π beams
Spectrometers Δp/p
γ-ray with HPGe

J-PARCs promises

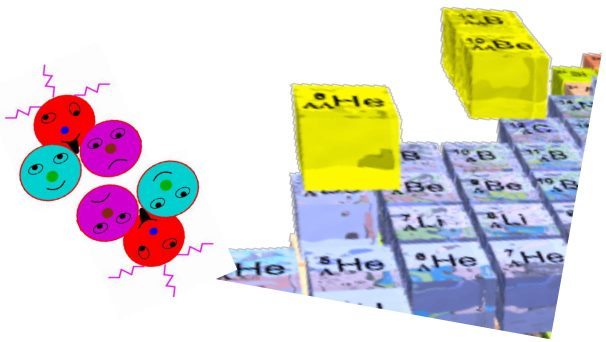
Approved Strangeness Experiments at J-PARC

Glossary: Stage-1 Stage-2 Stage-2 Day-1



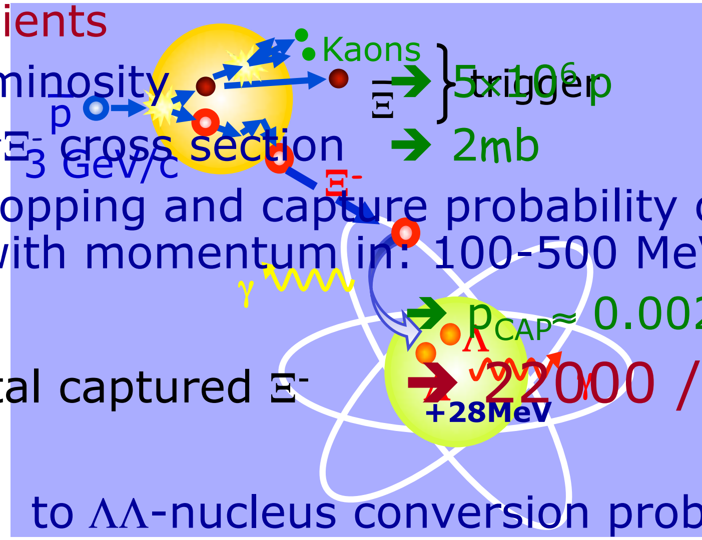
- E03: X rays from Ξ^- atoms (Tanida)
- E05: ^{12}C$(K^-, K^+)^{12}_{\Xi}$Be (Nagae)
- E07: S=-2 emulsion-counter studies (Imai, Nakazawa, Tamura)
- E10: DCX studies of neutron-rich $^{A}_{\Lambda}Z$ (Sakaguchi, Fukuda)
- E13: γ-ray spectroscopy of Λ hypernuclei (Tamura)
- E15: search for K^-pp in ^{3}He(K^-, n) (Iwasaki, Nagae)
- E17: kaonic ^{3}He $3d \rightarrow 2p$ X rays (Hayano, Outa)
- E18: $^{12}_{\Lambda}$C weak decays (Bhang, Outa, Park)
- E19: search for Θ^+ pentaquark in $\pi^- p \rightarrow K^- X$ (Naruki)
- E22: weak interactions in $^4_{\Lambda}$H – $^4_{\Lambda}$He (Ajimura, Sakaguchi)
- E27: search for K^-pp in $d(\pi^+, K^+)$ (Nagae)
- E31: study of $\Lambda(1405)$ by in-flight $d(K^-, n)$ (Noumi)

Strange Recipies @ PANDA



- High resolution γ-spectroscopy of double $\Lambda\Lambda$ hypernuclei
- weak decays

Ingredients



- luminosity → 5×10^6 p̄
- $\Xi^+\Xi^-$ cross section → 2mb
- stopping and capture probability of Ξ (with momentum in: 100-500 MeV/c) → $p_{CAP} \approx 0.002$
- total captured Ξ^- → 22000 / day
- Ξ^- to $\Lambda\Lambda$-nucleus conversion probability → $p_{\Lambda\Lambda} \approx 0.05$

$\Xi^- p \rightarrow \Lambda\Lambda$ + 28MeV

- total $\Lambda\Lambda$ hyper nucleus production → 4500 / month

→ large probability that two Λ's stick to same nucleus

- gamma emission/event, $p_\gamma \approx 0.5$
- γ-ray peak efficiency $p_{GE} \approx 0.1$

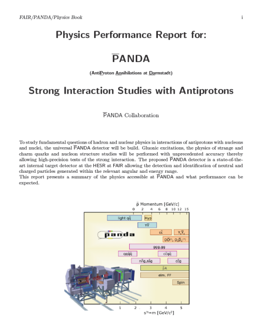
two-step process

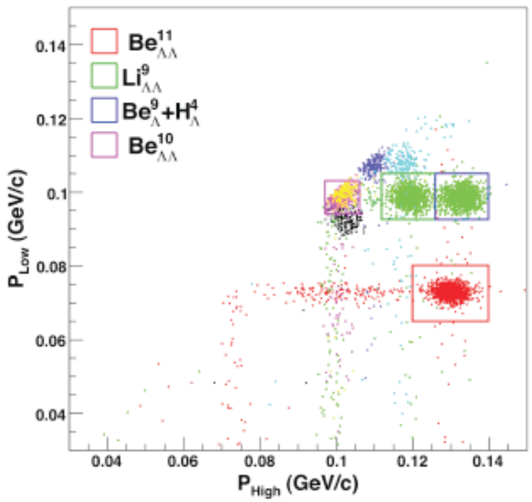
→ spectroscopic studies only via the decay products

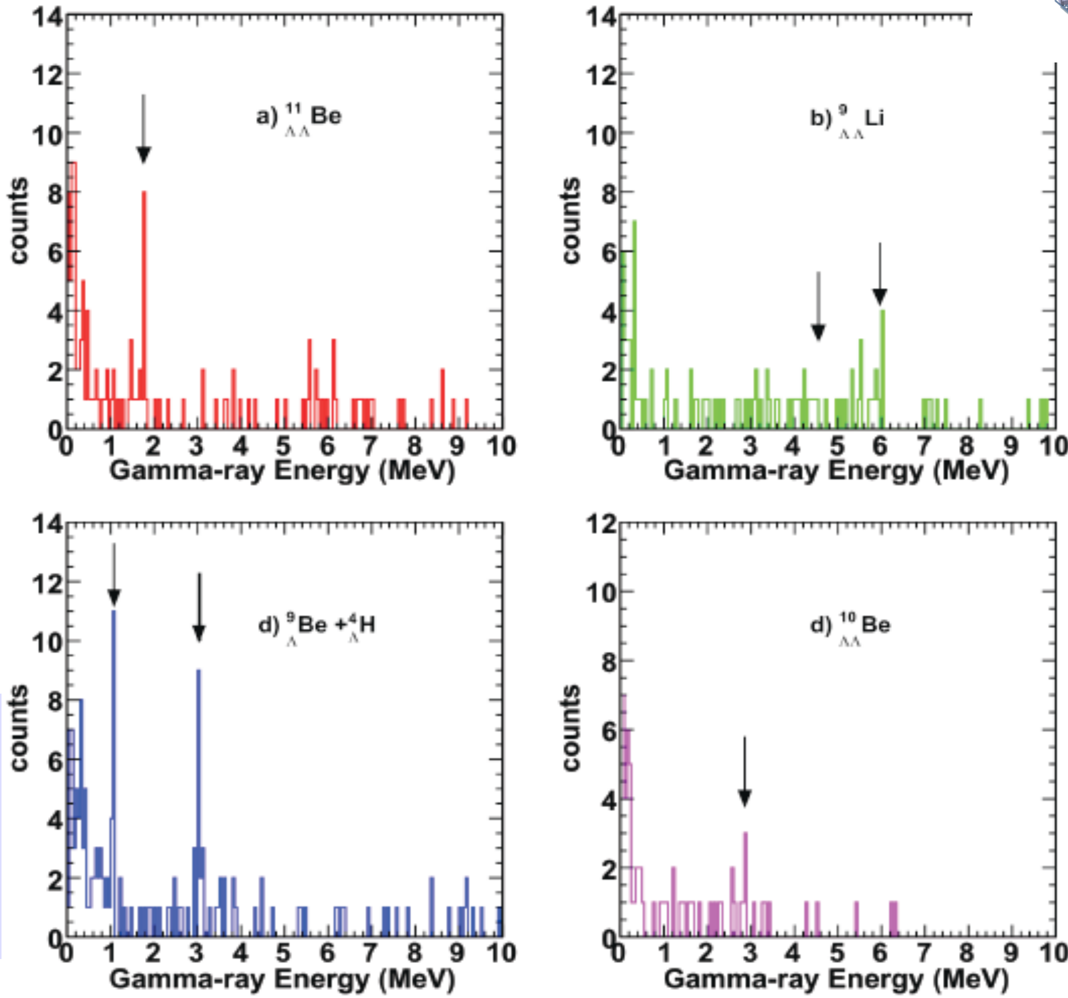
- **~7/day „golden" γ-ray events**

high resolution γ-spectroscopy of double hypernuclei will be feasible

... it works...





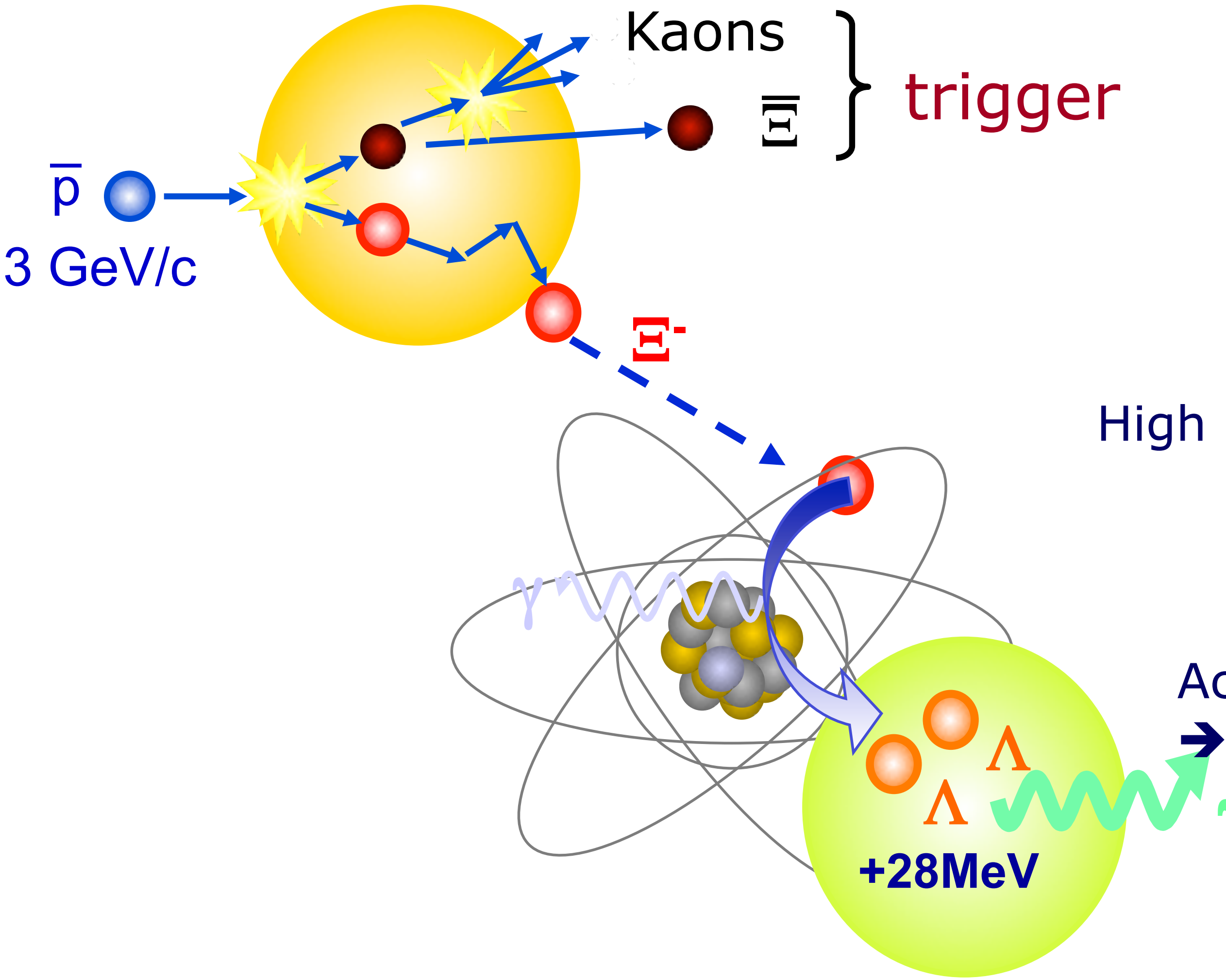


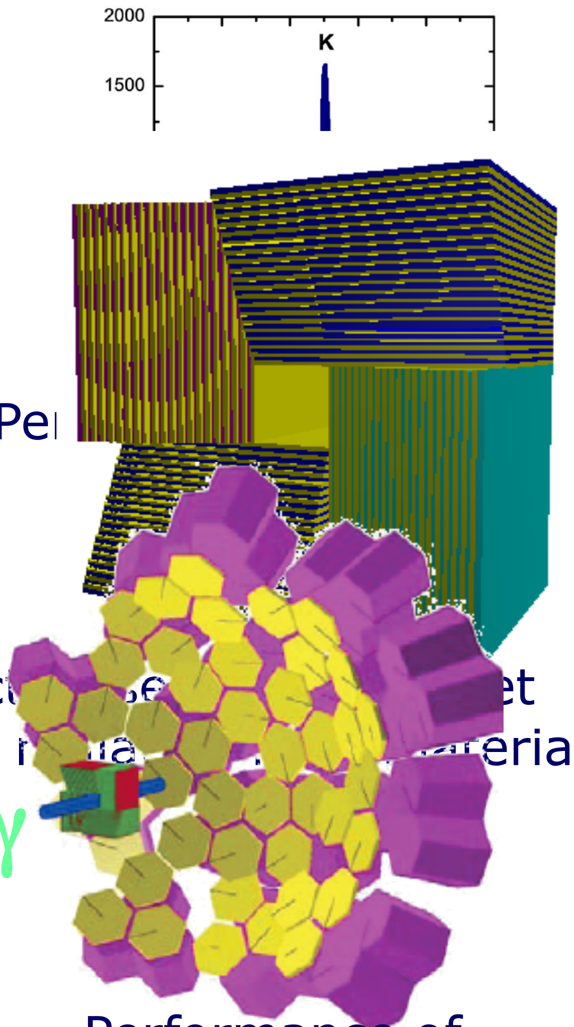
The background of Ξ free decay and Ξ⁺ annihilation

S/B ➔ 3:1

A. Sanchez-Lorente PhD JGU

...it does not come for free...





High Pe... n

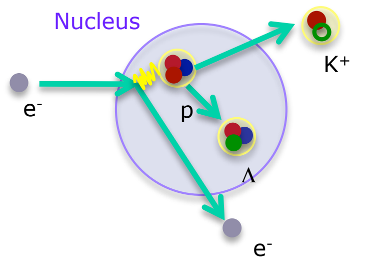
Act... et

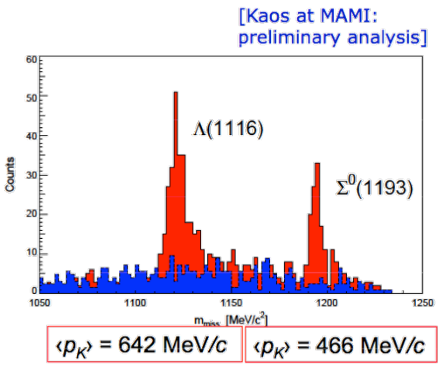
➔ r... erial

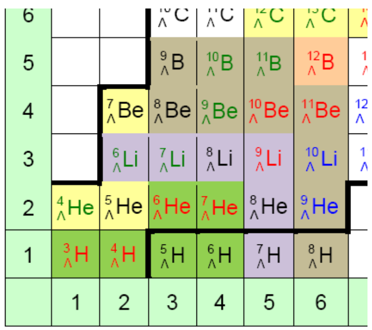
Performance of HPGe in strong B

…meanwhile…

Electroproduction







Main features

- Proton to Λ conversion

→*mirror and/or neutron-rich nuclei*

- Thin enriched target

→*access to new isotopes*

- Higher energy resolution than with meson beams

→ *detailed information on hyp. structure*

Pionic decay:

JSPS 日本学術振興会 Japan Society for the Promotion of Science

High resolution absolute mass (L. Tang, O. Hashimoto)

Light Hypernuclei:

n(2n)halos hpy – borromean

Mirror nuclei and CSB

Σ hyperons:

Light hypernuclei

Coulomb Assisted States?

Some keywords to conclude with…

- Modern theoretical approaches offer the chance to extract Y-N and Y-Y interaction from hypernuclei
- Hypernuclei offer a wide range of unique opportunities to study strong QCD in a multi-body environment

observable	n-rich	stable	p-rich
groundstate mass, energy levels			
Λ momentum distribution			
lifetime			
g-factors (M1, spinrotation)			
γ-decays			
weak decays			
ΛΛ-nuclei			
K-nuclei			
antibaryon-nuclei			

- Worldwide, several new activities will help to overcome present limitation
- γ-spectroscopy is among the key words