GSI March 22, 2007

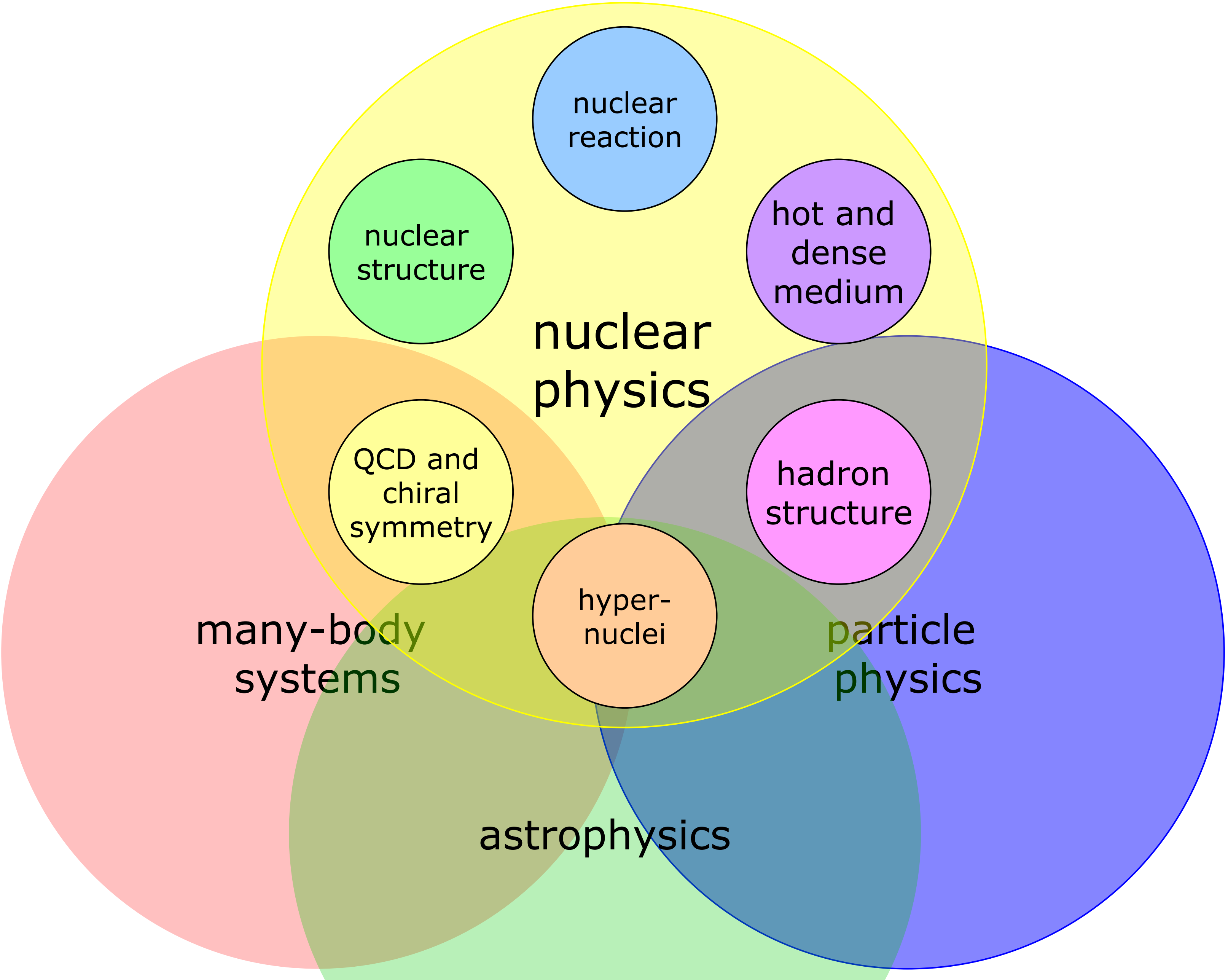
Sixth Framework Programme

Bundesministerium für Bildung und Forschung

STRANGE NUCLEI AT FAIR

- INTRODUCTION
- PHYSICS TOPICS OF HYPERNUCLEI
- HYPERNUCLEI AT FAIR
- CONCLUSION

Landscape of Modern Nuclear Physics



Physics of Hypernuclei

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- the Y-N and Y-Y strong interactions in the $J^P = 1/2^+$ baryon octet
- the role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena
- the nuclear structure, e.g. the origin of the spin-orbit interaction
- specific aspects baryon-baryon weak interactions
- possible existence of dibaryon particles
- hyperons (Λ, Σ, Ξ) and meson properties in the nuclear medium
- …

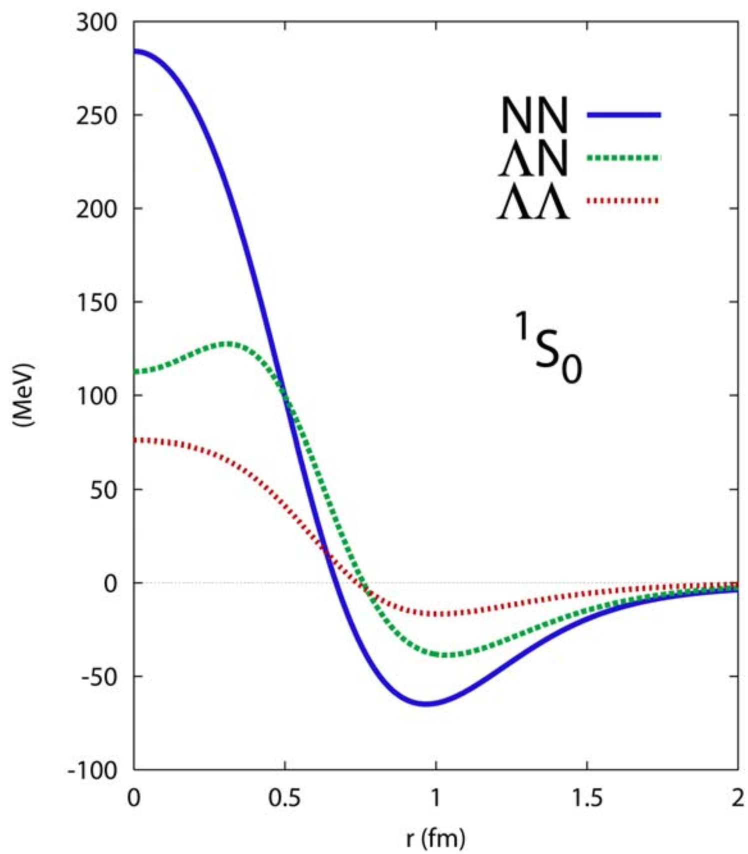
Exp. Approaches to Y-N interactions

- low energy baryon-baryon scattering
  - N-N: ~10^4 data points available
- for hyperon-nucleon only very few elastic data $\lesssim(\gtrsim)$300MeV/c
  - Λ-p→Λ-p: 12 (10) Σ^+-p→ Σ^+-p: 4 Σ^--p→ Σ^--p: 9 (3)
  - spin averaged → can not access LS or SS coupling
  - usually low statistics
    - Σ^-p: KEK-PS E289 (π^-,K$^+$) ⇒ 30 events
    - Σ^+p: KEK-PS 251 & KEK-PS E289 (π^+,K$^+$) ⇒ 31 events each
    - Ξ^- p: (K$^-$,K$^+$) ⇒ 1 candidate
  - JPARC: ~1000 events/day

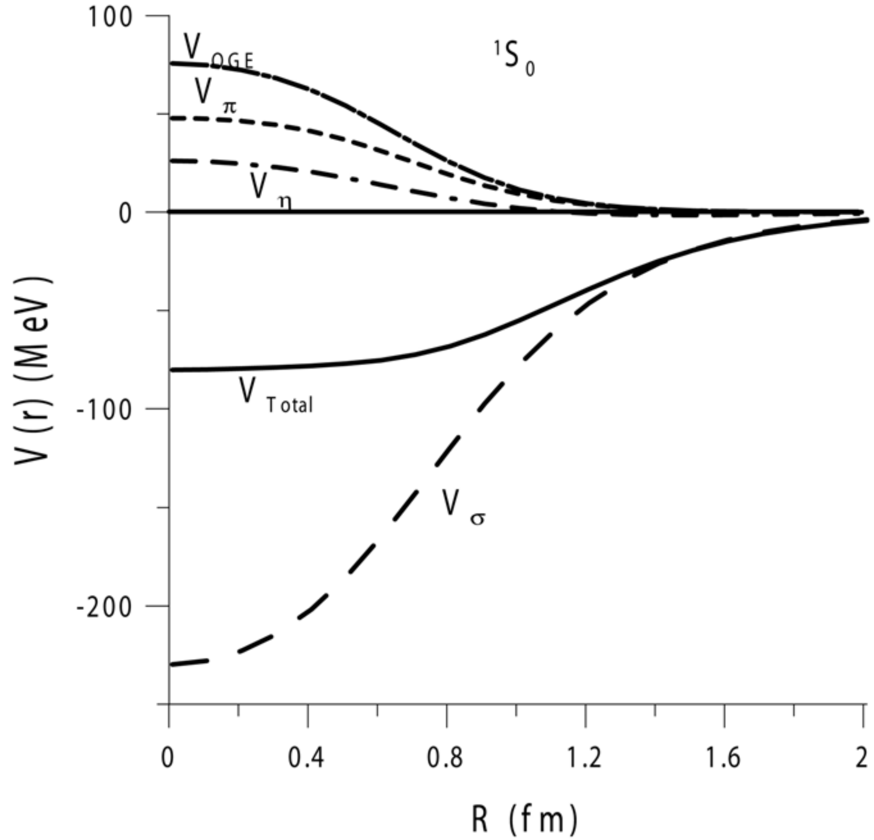
- for Y-Y interaction not practical
  - Y-Y final state interaction
    - KEK-PS E224, Physics Letters B 444, 267 (1998)
    - KEK-PS E522: K.Nakazawa, *HYP2006* (2006)
  - feasible but difficult to interpret (rescattering, size,…)
  - double hypernuclei

Λ-Λ Interaction

- Relative strength of attraction $|V_{\Lambda\Lambda}| < |V_{\Lambda N}| < |V_{NN}|$
- Interplay between gluon and meson exchange
- role of correlated two-meson exchange
- mixing



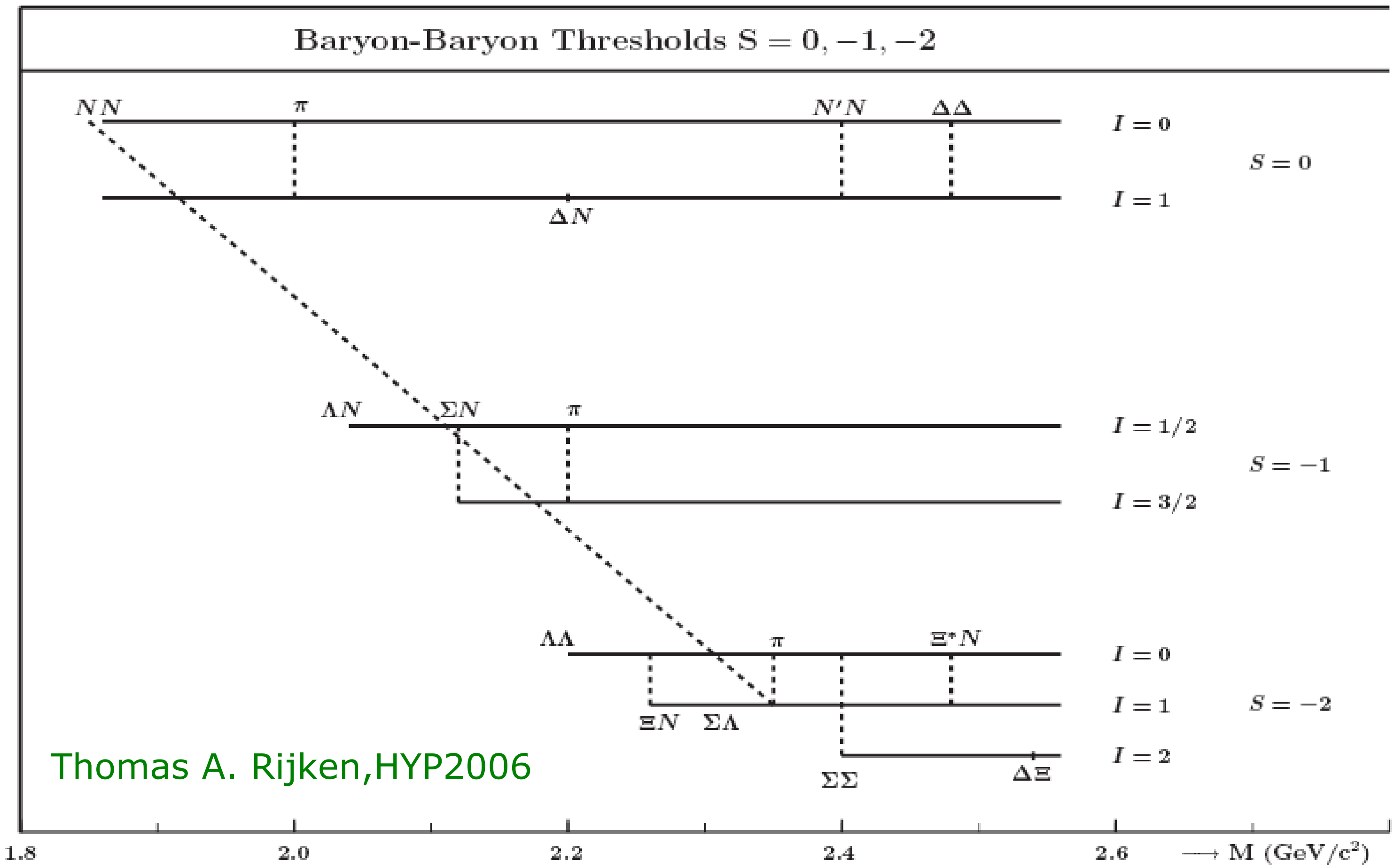
Fujiwara et al., nucl-th/0607013



Fernandez-Carames et al., PRD **72**, 054008 (2005)

Y-N or Y-Y Interaction in Hypernuclei

- Mass difference between Σ and Λ in single hypernuclei and $\Lambda\Lambda$, ΞN, $\Lambda\Sigma$ in double hypernuclei are small
  - m(Ξ^0n)-m($\Lambda\Lambda$)=23MeV   m($\Sigma^0\Lambda$)-m($\Lambda\Lambda$)=77MeV
- $\Rightarrow$ mixing important



Thomas A. Rijken,HYP2006

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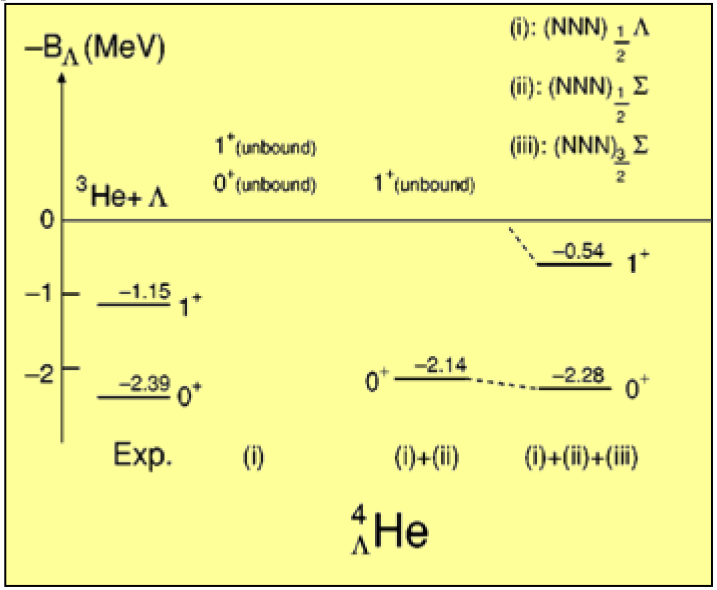
  E. Hiyama *et al.*, Phys. Rev. C65, 011301R (2001)



- impact on spin-orbit force

  N. Kaiser, W.Weise, PRC 71, 015203 (2005)

- magnitude of mixing depends strongly on nuclei and potential

  D. E. Lanskoy, Y. Yamamoto, PRC **69**, 014303 (2004)

  Nemura, HYP2006

	$^4_{\Lambda\Lambda}$H			$^5_{\Lambda\Lambda}$H			$^6_{\Lambda\Lambda}$He		
YY	$P_{N\Xi}$	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$	$P_{N\Xi}$	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$	$P_{N\Xi}$	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$
mND$_S$	0.06	0.25	0.00	4.56	2.49	0.06	0.28	1.17	0.05
NF$_S$	0.58	0.38	0.03	3.10	2.10	0.10	1.34	1.14	0.10

Understanding Nuclear Structure

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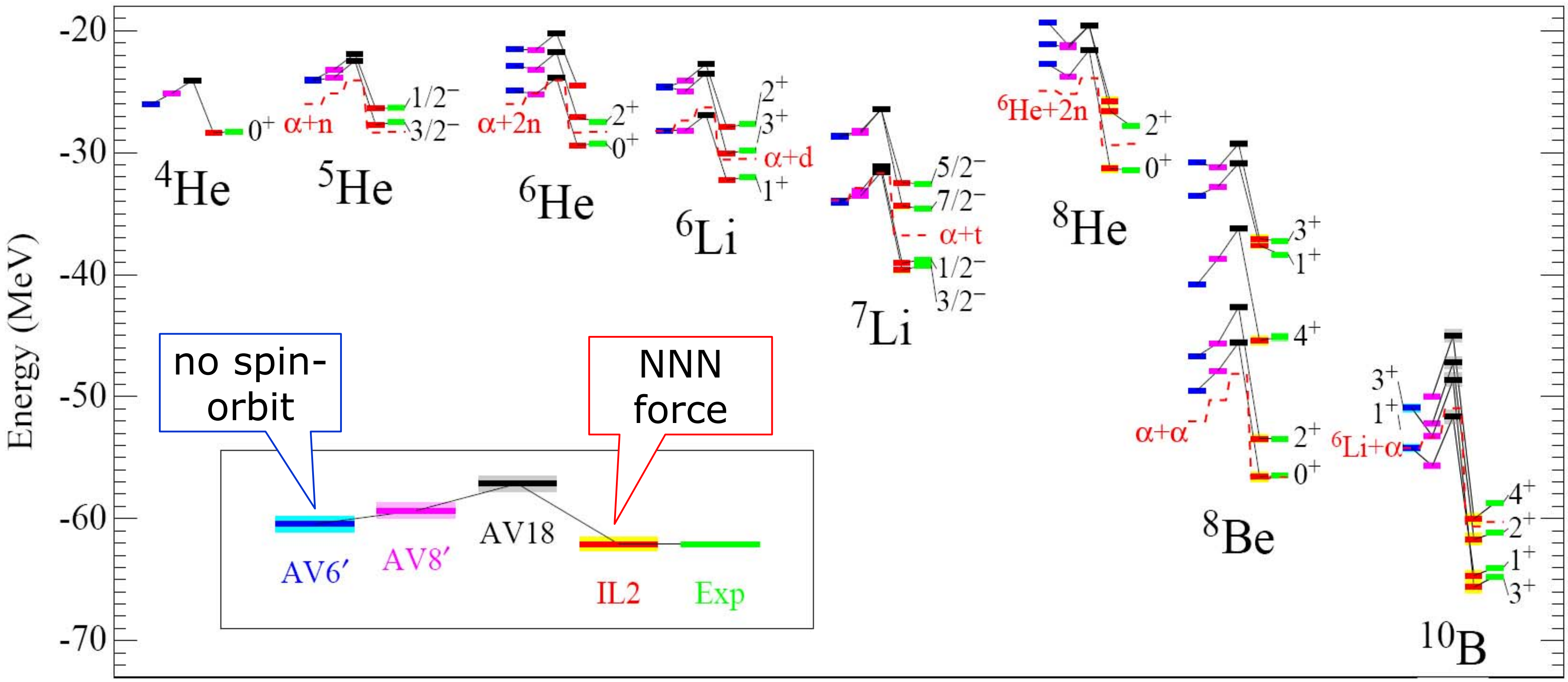
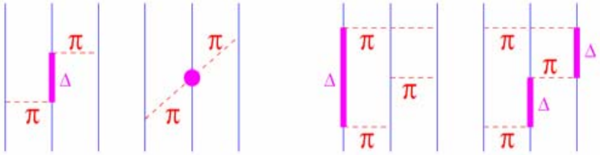
- Steven Stephen C. Pieper *et al.*, 2002
- potentials with increasing complexity

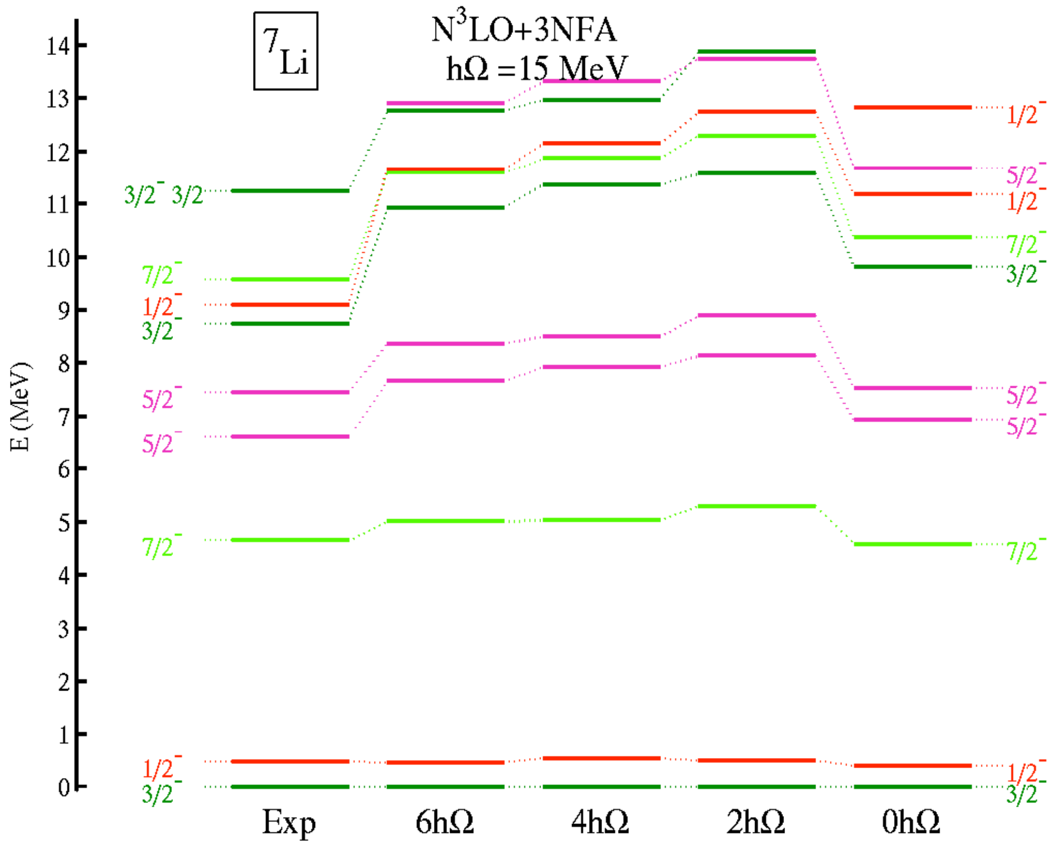


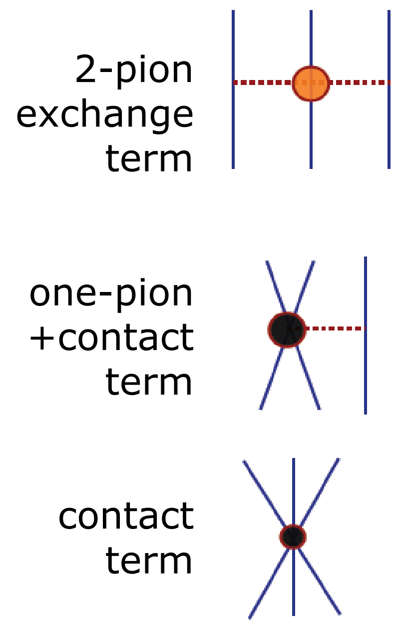
- spin-isospin and tensor forces present in long-range one-pion-exchange are essential
- multi-nucleon forces are vital
- sub-MeV precission (~3 parameters only)



Nuclear Spectra in χEFT

- great progress in recent years
  - e.g. Petr Navratil *et al.* (2005)
  - *consistent* (same cutoff parameter Λ) treatment of NN (N^3LO) and NNN force (N^2LO; from fit to ^3H and ^4He binding energies)

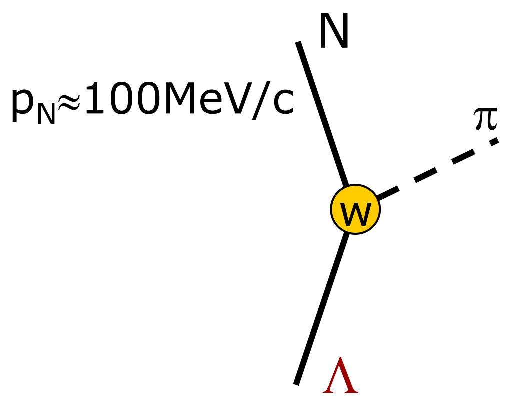




- no hypernuclei yet, but work in progress (N. Kaiser, Paolo Finelli…)
- lattice simulations + χEFT (Borasoy, Epelbaum, Meißner…)

Weak Decay of Λ Hypernuclei

free Λ decay



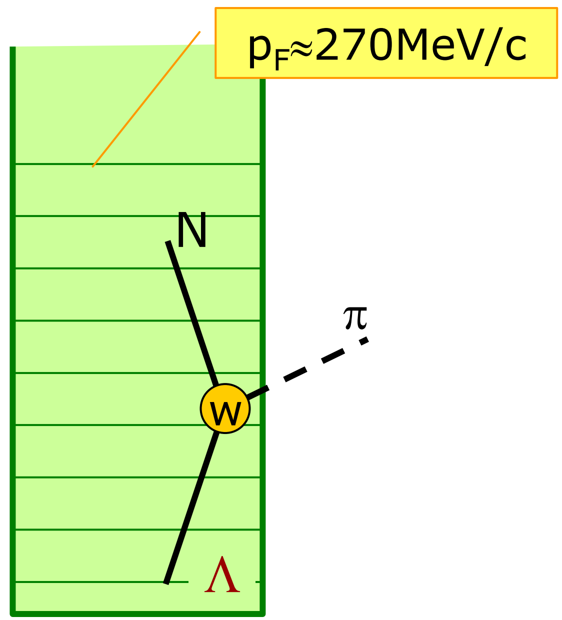
$\Lambda \to p\pi^- + 38\text{MeV}$ (64%)

$\Lambda \to n\pi^0 + 41\text{MeV}$ (36%)

$\tau_\Lambda = 263ps$

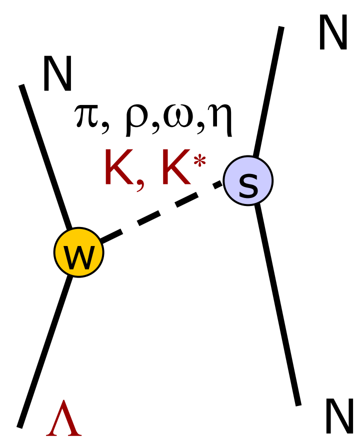
ΔI=1/2 rule

mesonic decay of hypernuclei



suppresed by Pauli blocking

non-mesonic decay of hypernuclei



$\Lambda p \to np + 176\text{MeV}$

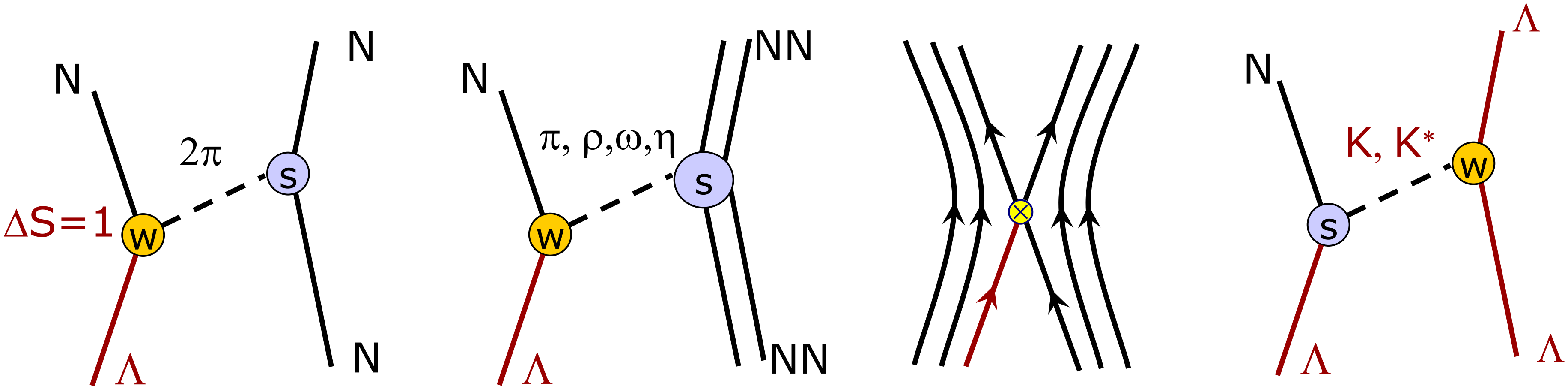
$\Lambda n \to nn + 176\text{MeV}$

dominant in all but the lightest hypernuclei

Weak Baryon-Baryon Interaction

ΛN→N N

ΛΛ→Y N

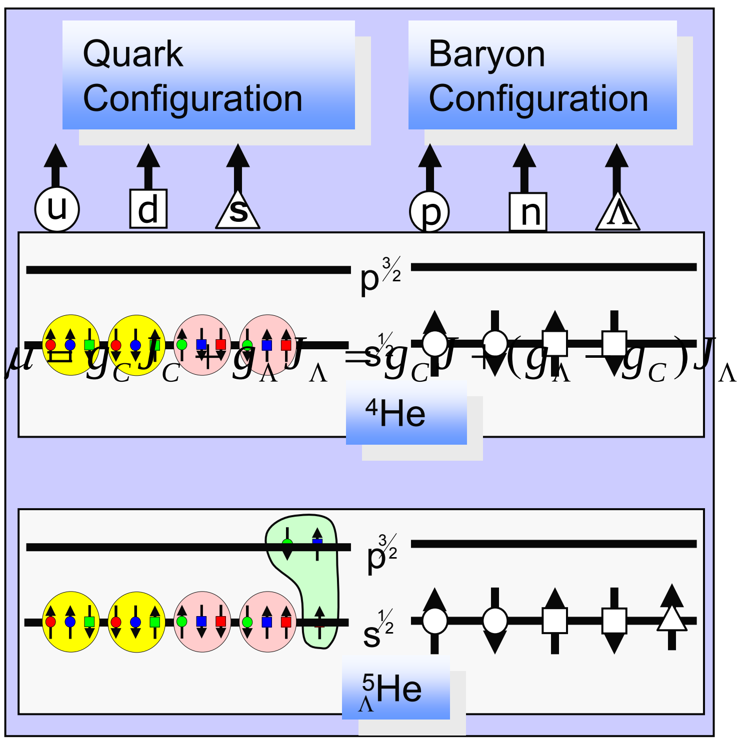


- two-pion exchange
- two-nucleon induced decays ΛNN→NNN
- meson vs. direct quark process
- ${}^{6}_{\Lambda\Lambda}He: \quad \Lambda\Lambda \rightarrow \Lambda n$ → access to weak ΛΛK vertex
  - A. Parreno, A. Ramos and C. Bennhold, Phys. Rev C **65**, 015205 : 3.6%
  - K. Sasaki, T. Inoue, and M. Oka, Nucl.Phys. A726 (2003) 349-355: 0.2%
  - K. Itonaga, T. Ueda, and T. Motoba, Nucl. Phys. A691 (2001) 197c: 2.5%

High statistics is a key issue

Magnetic moment of Λ in nuclei

- baryons do not „melt“ in nuclei: quark effects are small
- EMC-effect: whether there is any change in nucleon properties in nuclei remains controversial
  - if mass and size of a baryons changes inside nuclei, also it‘s magnetic moment might change
  - if so, why? meson current, ΛΣ mixing, partial deconfinement…?



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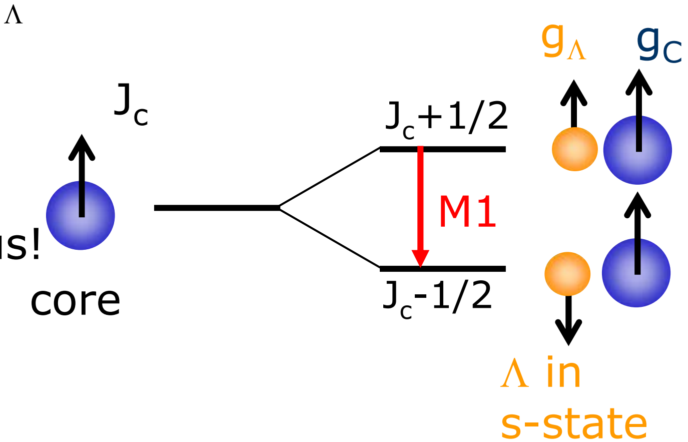
- experimental approach
  - the traditional approach: B(M1)   (KEK-PS E518)

$$B(M1) \propto \left|\left\langle \Psi_{low} \middle| \mu \middle| \Psi_{up} \right\rangle\right|^2 = \left|\left\langle \Psi_{\Lambda\downarrow}\Psi_C \middle| \mu \middle| \Psi_{\Lambda\uparrow}\Psi_C \right\rangle\right|^2 \propto (g_\Lambda - g_C)^2$$

$$\mu = g_C J_C + g_\Lambda J_\Lambda = g_C J + (g_\Lambda - g_C) J_\Lambda$$

    - M1 transition require $J_C \neq 0$
  - spin precession (HypHi)
    - Λ decay is self-analyzing
    - works also for doubly magic core nucleus!
    - g_Λ dominates



HYPERNUCLEI AT FAIR

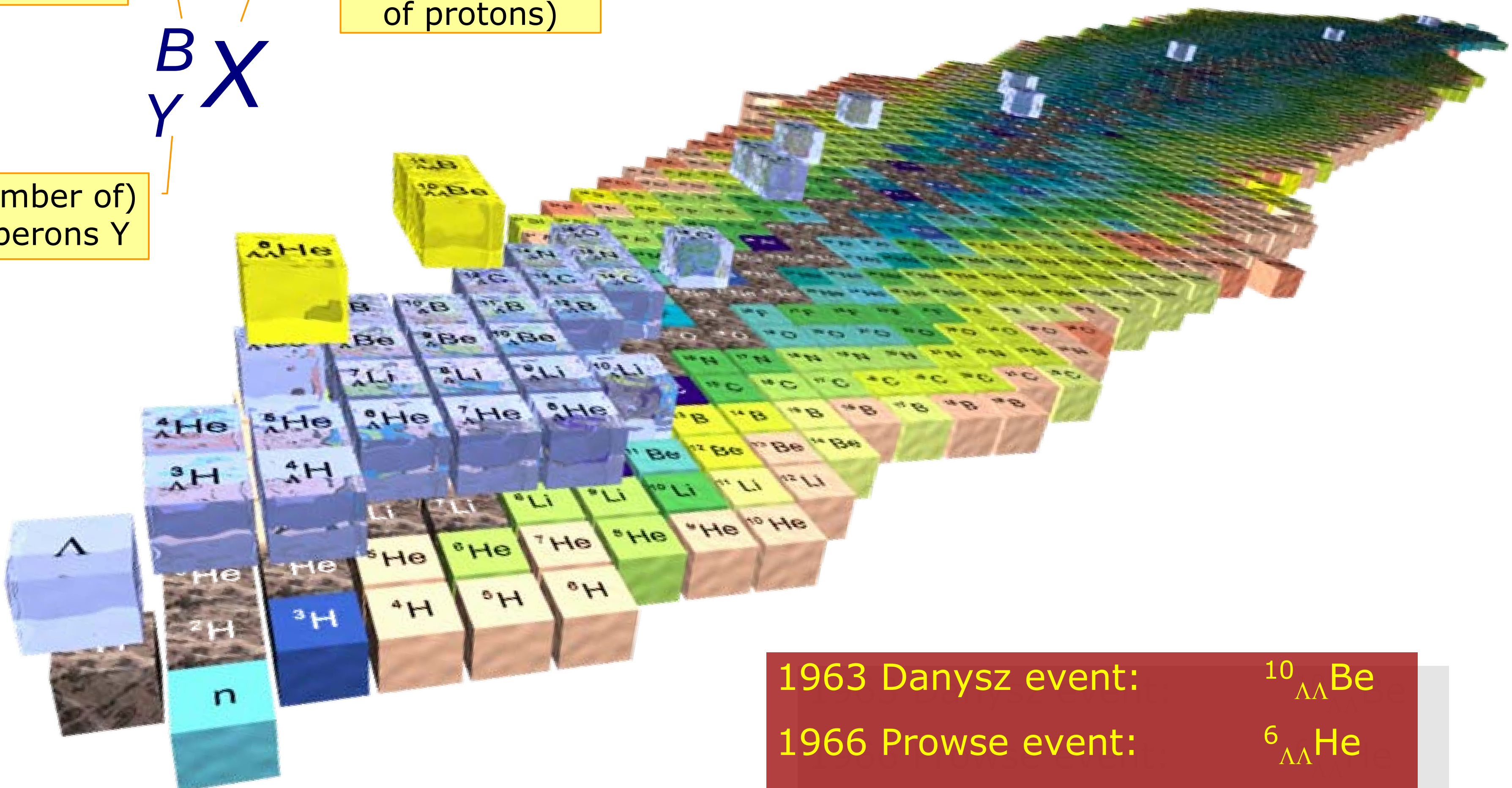
Hypernuclei – Present Situation

number of baryons N+Z+Y

element = total charge (not number of protons)

(number of) hyperons Y

$^{B}_{Y}X$



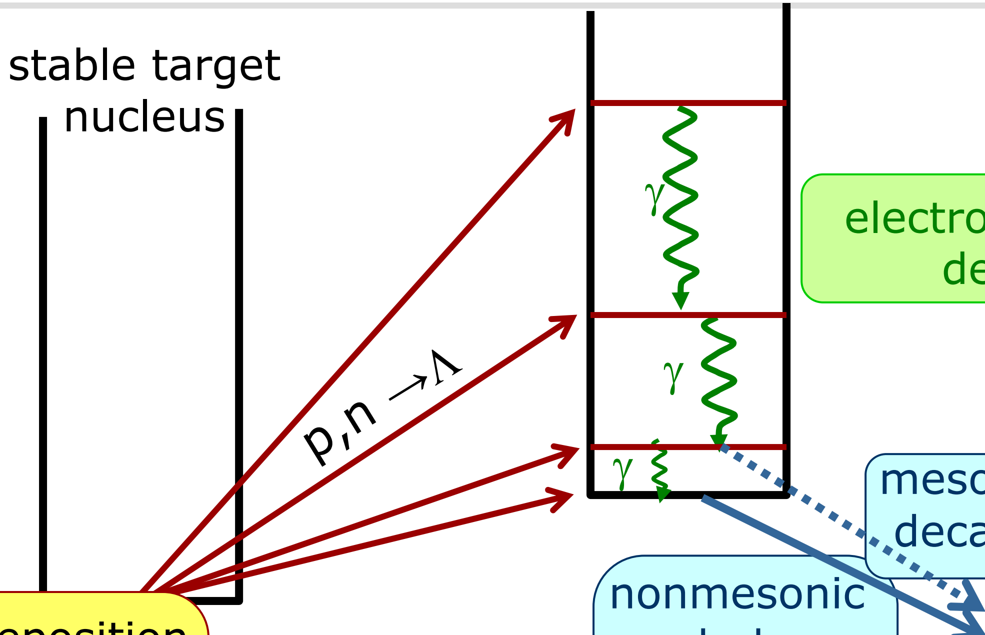
1963 Danysz event: $^{10}_{\Lambda\Lambda}Be$

1966 Prowse event: $^{6}_{\Lambda\Lambda}He$

1991 Aoki event: $^{13}_{\Lambda\Lambda}B$

2001 Nagara event: $^{6}_{\Lambda\Lambda}He$

Birth, Life and Death of a Hypernucleus



electromagnetic decays

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

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

hadronic decay in emulsion

strangeness deposition
$e^+ + e^- \rightarrow \Phi \rightarrow K^+ + K^-$
$K^-_{stopped} + {}^A Z \rightarrow {}^A_\Lambda Z + \pi^-$
FINUDA

strangeness production
(π^+, K^+), (π^-, K^0)
BNL,KEK

strangeness exchange
(K^-, π^-) ,(K^-, π^0)
BNL,KEK,JPARC

electroproduction
$(e,e'K^+)$, (γ,K^+)
Jlab, MAMI-C

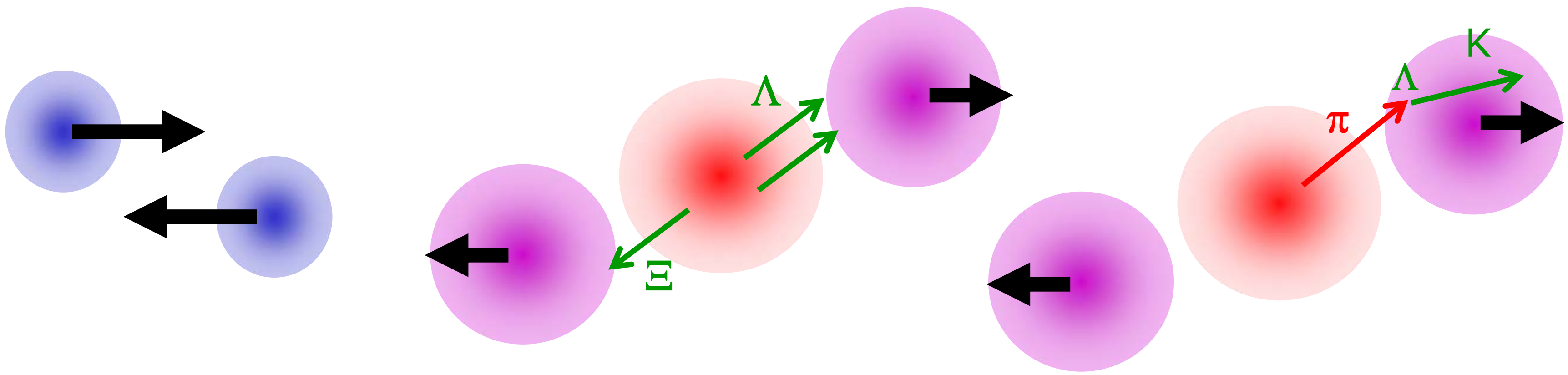
energy resolution

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

CHALLANGE 1: EXOTIC HYPERNCULEI

Relativistic Hypernuclei

- Production of hypernuclei in relativistic heavy ion collisions
  - production of many hyperons
  - multiple coalescence of hyperons with fragments
  - (π,K), (K,π) and (K^-,K^+) reactions on fragments



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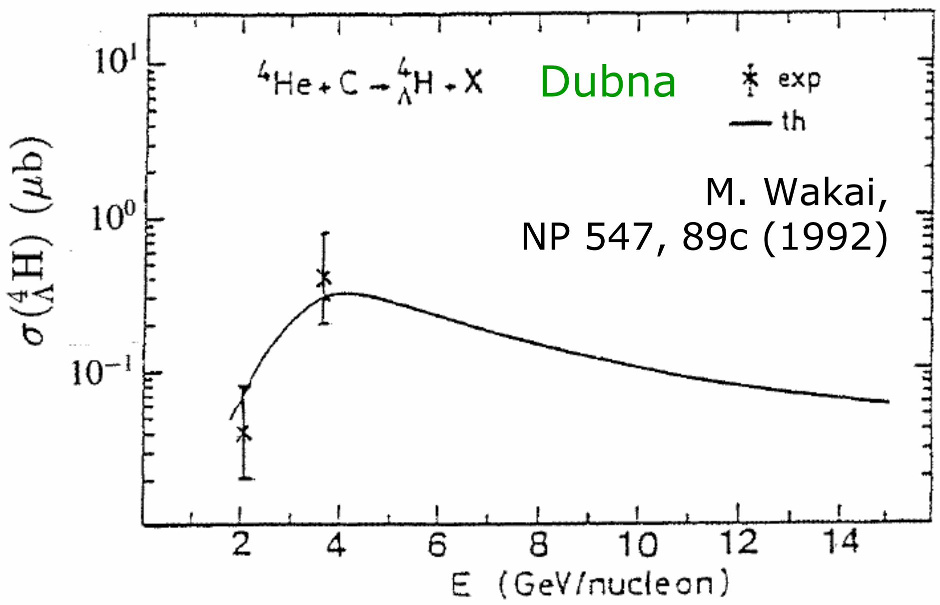
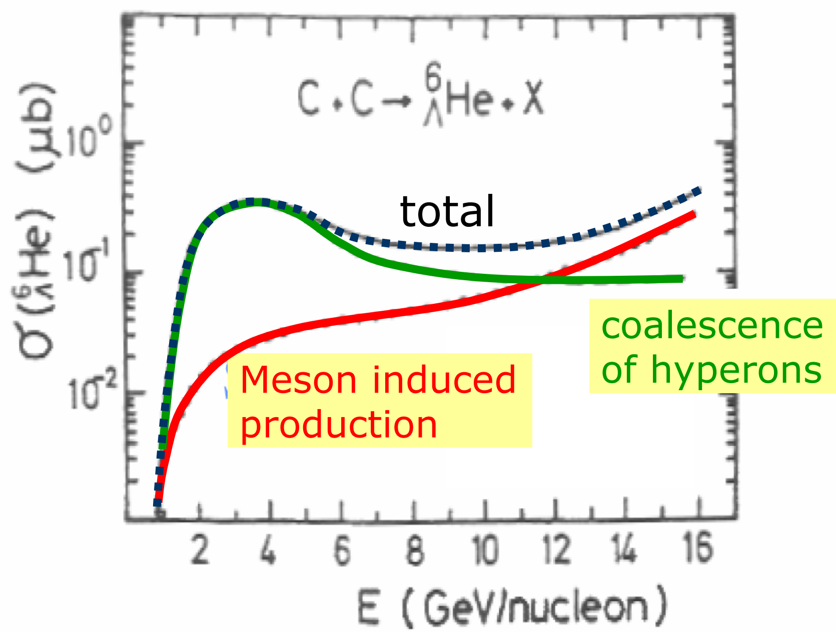
- Many predictions based on coalescence model

M. Sano, INS-PT-31 (1982)
M. Wakai, H. Bando and M. Sano, PRC 38, 748 (1988)
J. Aichelin and K. Werner, PLB 274, 260 (1992)
S. Hirenzaka, T. Suzuki and I. Tanihata, PRC 48, 2403 (1993)
M. Sano and M. Wakai, PTP Suppl. 117, 99 (1994)

- Cross sections





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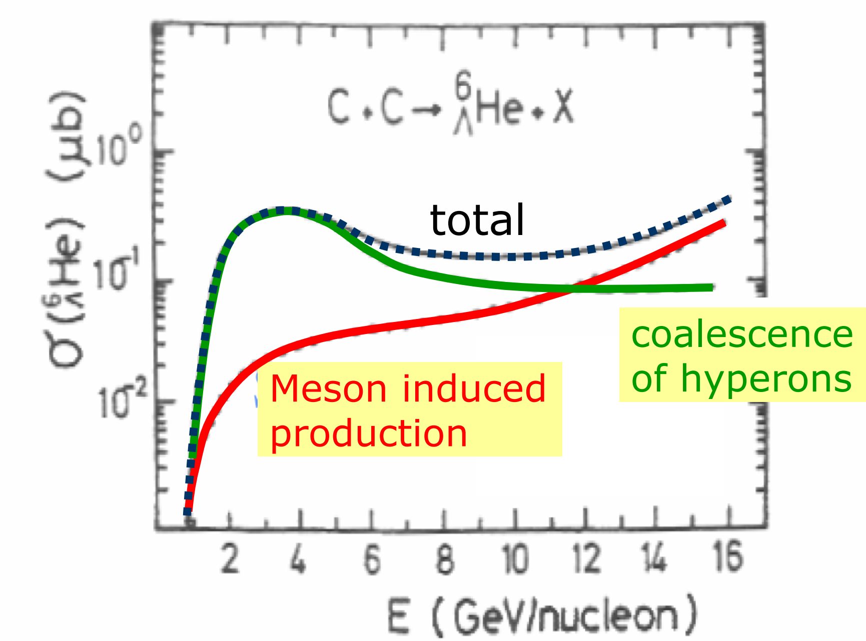
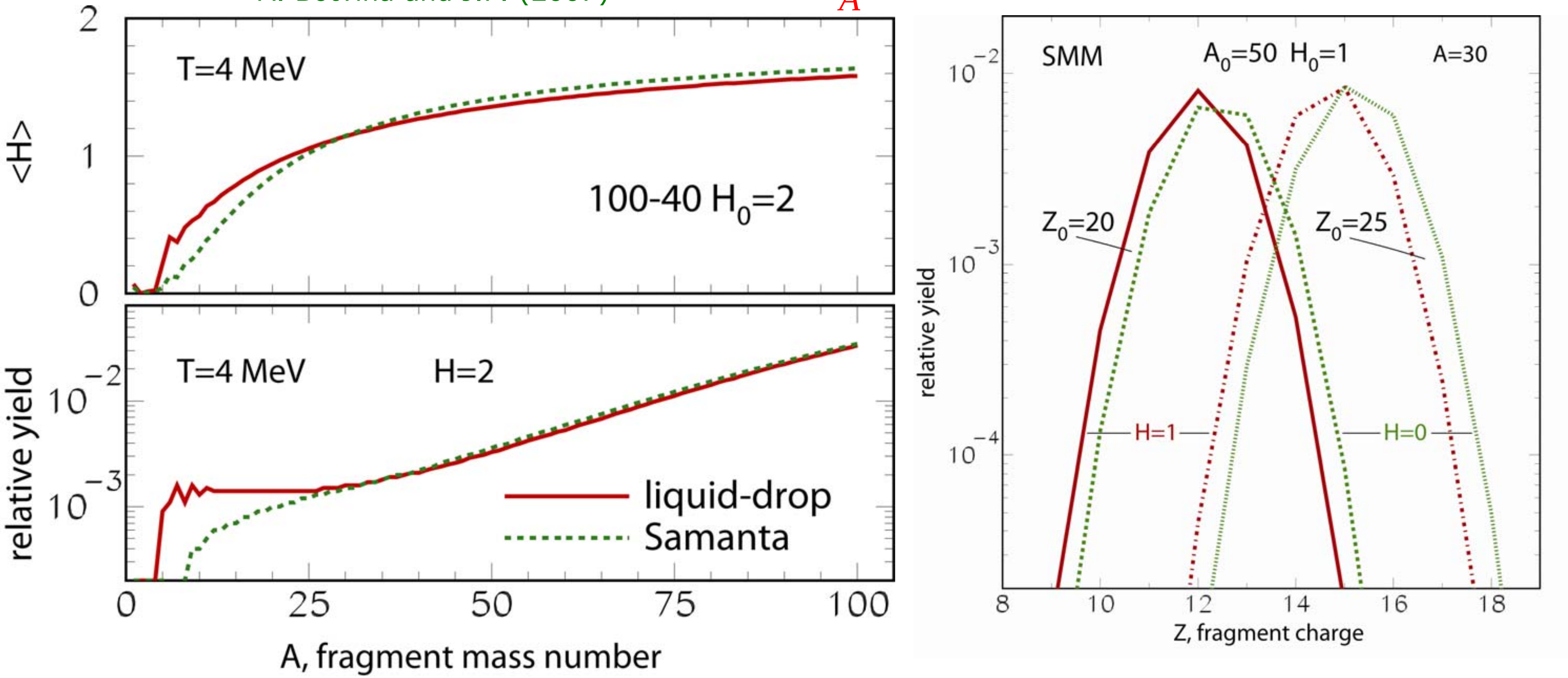
  M. Sano and M. Wakai, PTP Suppl. 117, 99 (1994)
- Cross sections
  - local maximum at ~4AGeV
  - single Λ-hypernuclei ~0.1μb
  - $\Lambda\Lambda$-hypernuclei ~0.01 nb
- Exotic beams at high energy offer unique chance at GSI-FAIR to produce hypernuclei with *extreme isospin*



Hypernuclei in Multifragmentation

- *hyperterm* in binding energy
  - Samanta *et al.*
    J. Phys. G 32, 363 (2006)
    $$E_{sam}^{hyp} = Y \cdot \left(-10.68 + \frac{48.7}{A^{2/3}} \right)$$
  - Liquid drop inspired
    A. Botvina and J.P. (2007)
    $$E_{LD}^{hyp} = \frac{Y}{A}\left(-10.68 + 21.27\, A^{2/3} \right)$$



- relative yields reflect properties of mass formulae of hypernuclei
- N/Z of projectile influences charge distribution of primary fragments

The HYPHI Project T. Saito

2004
- HypHI project started
- LOI and progress report to the GSI PAC, Design study

2005

2006
- Design study, preparation for the phase 0 experiment

2007
- Phase 0: experiment with ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{5}_{\Lambda}He$

2008
- Design study for the setup for hypernuclear non-mesonic weak decay measurements

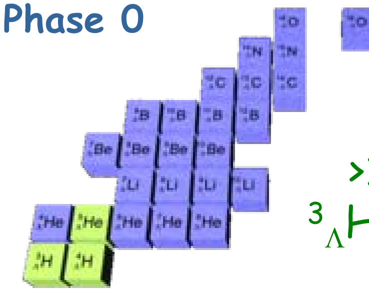
2009
- Phase 1: Experiments for proton rich hypernuclei

2010

~2011
- Phase2: Experiment for neutron rich hypernuclei at NuSTAR/FAIR

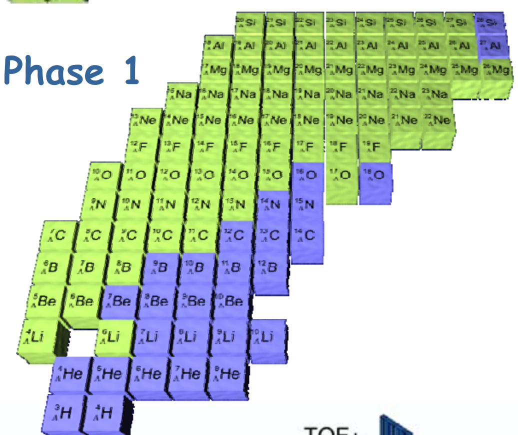
- Phase 3: Hypernuclear separator
  - Hypernuclear magnetic moments
  - Hypernuclear driplines

Phase 0

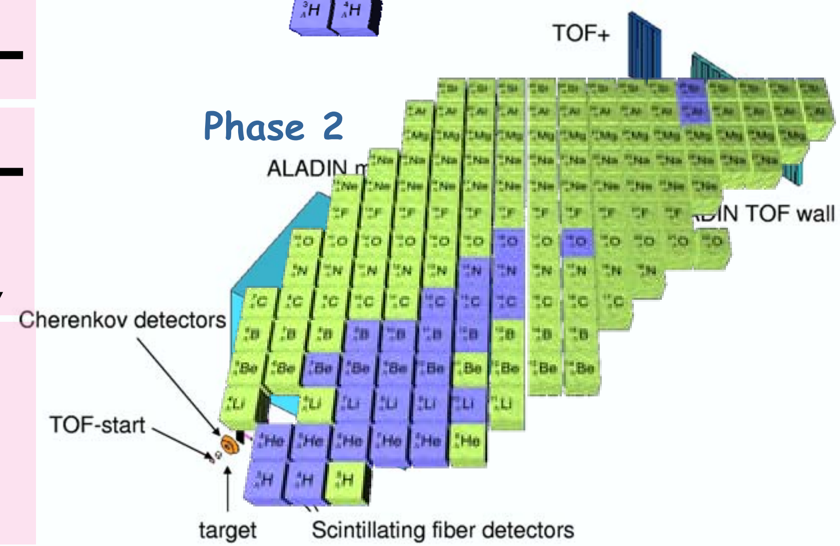


>10^4/week ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, ${}^{5}_{\Lambda}He$

Phase 1



Phase 2



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- Phase 0: experiment with ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{5}_{\Lambda}He$ — 2007
- Design study for the setup for hypernuclear non-mesonic weak decay measurements — 2008, 2009
- Phase 1: Experiments for proton rich hypernuclei — 2010
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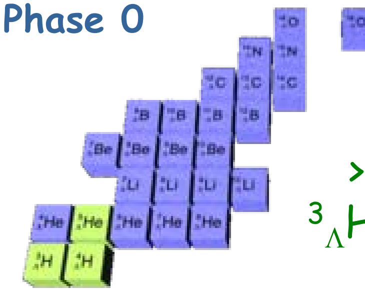
- Phase 3: Hypernuclear separator
  - Hypernuclear magnetic moments
  - Hypernuclear driplines

2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | ~2011

Phase 0



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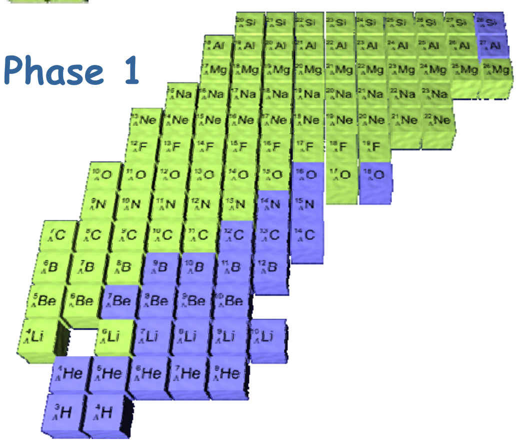
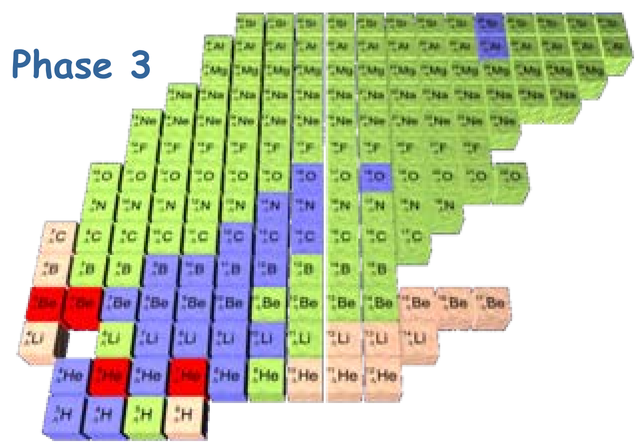


Phase 3



CHALLANGE 2: DOUBLE HYPERNUCLEI

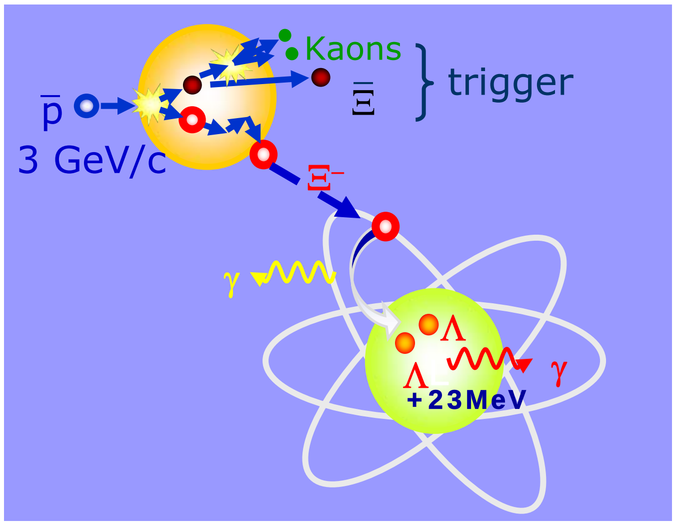
Production of ΛΛ–Hypernuclei

- simultaneous implantation of two Λ is not feasible
- reaction with lowest Q-value: $\Xi^- p \rightarrow \Lambda\Lambda$: 28MeV
  - large probability that two Λ's stick to same nucleus
- in most cases two-step process
  - production of Ξ^- in primary nucleus
  - slowing down and capture in a secondary target nucleus
- spectroscopic studies only possible via the decay products

- Production of slow Ξ^- by
  - strangeness exchange reaction $p(K^-,K^+)\Xi^-$
    - KEK (E176,E373), AGS (E906)
    - emulsion technique
  - antiproton capture and annihilation
    - FLAIR
  - direct implantation with energetic antiprotons
  - production with antiprotons and subsequent stopping and capture
    - PANDA

Production of Ξ^- at PANDA

- idea: make use of all $(1\text{-}10^{-4} \approx 1)$ *emitted* Ξ^-
- significant fraction of produced high momentum Ξ^- are degraded by elastic scattering in the primary nucleus to p ~ 200-500MeV/c

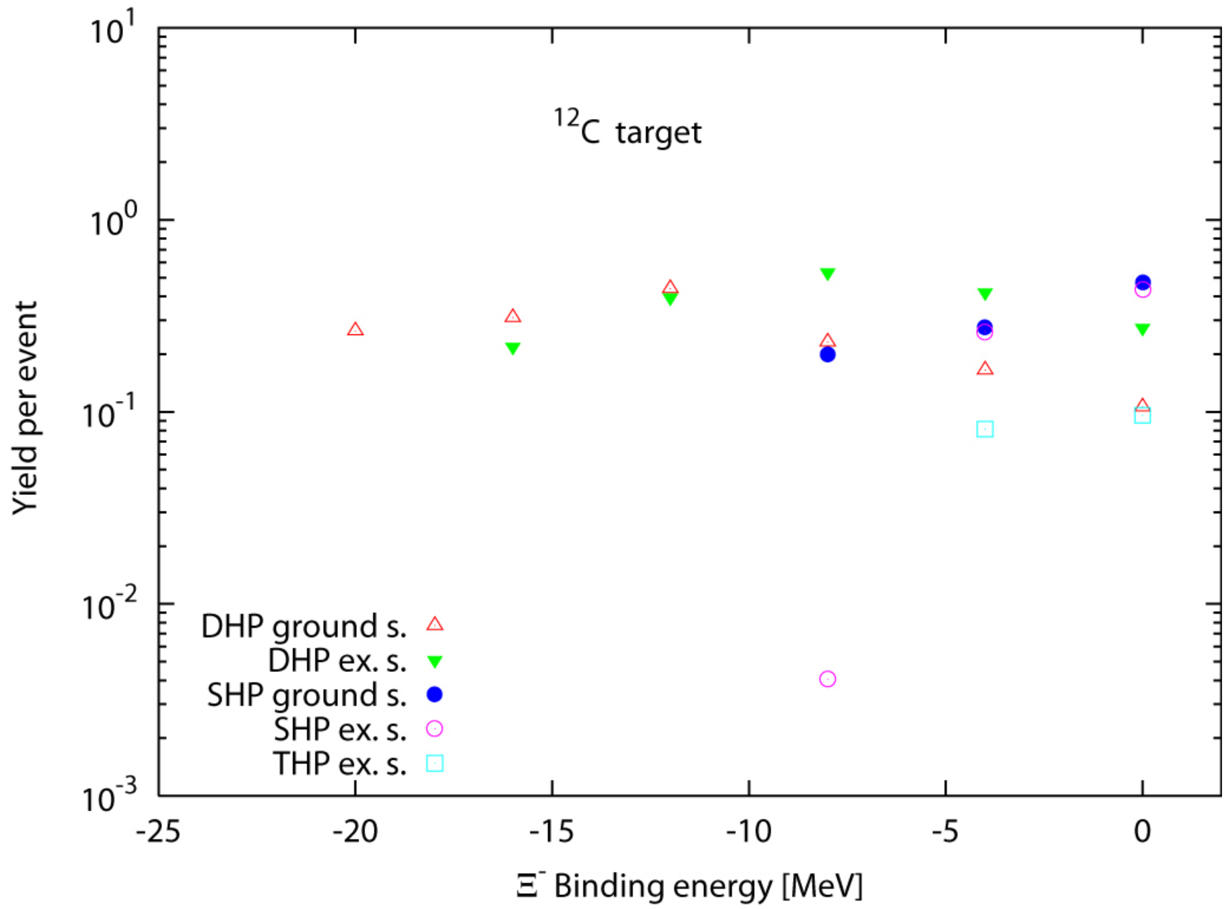


Facility	reaction	stopped Ξ^- /day
J-PARC	$(K^-,K^+)\Xi^-$	1000 (35000?)
FLAIR	$pp_{stopped} \rightarrow K^*K^*$	2000
PANDA	$pp \rightarrow \Xi^-\Xi^+$	50000

- capture of Ξ^- in secondary solid state target (short stopping time)
- secondary target only moderately excited (20-30MeV)
- antiproton momentum 3GeV/c
  - maximum Ξ production
  - low number of associated particles
  - particle background forward focused
- γ-ray detection at backward angles

Decay of excited ΛΛ hypernuclei

- conversion of Ξp→ΛΛ produces excited primary nucleus
  - Q-value, Ξ-binding energy
- SMM model calculations
  (A. Sanchez, A. Botvina, J.P.)
  - significant fraction of ΛΛ-hyper-nuclei in excited state



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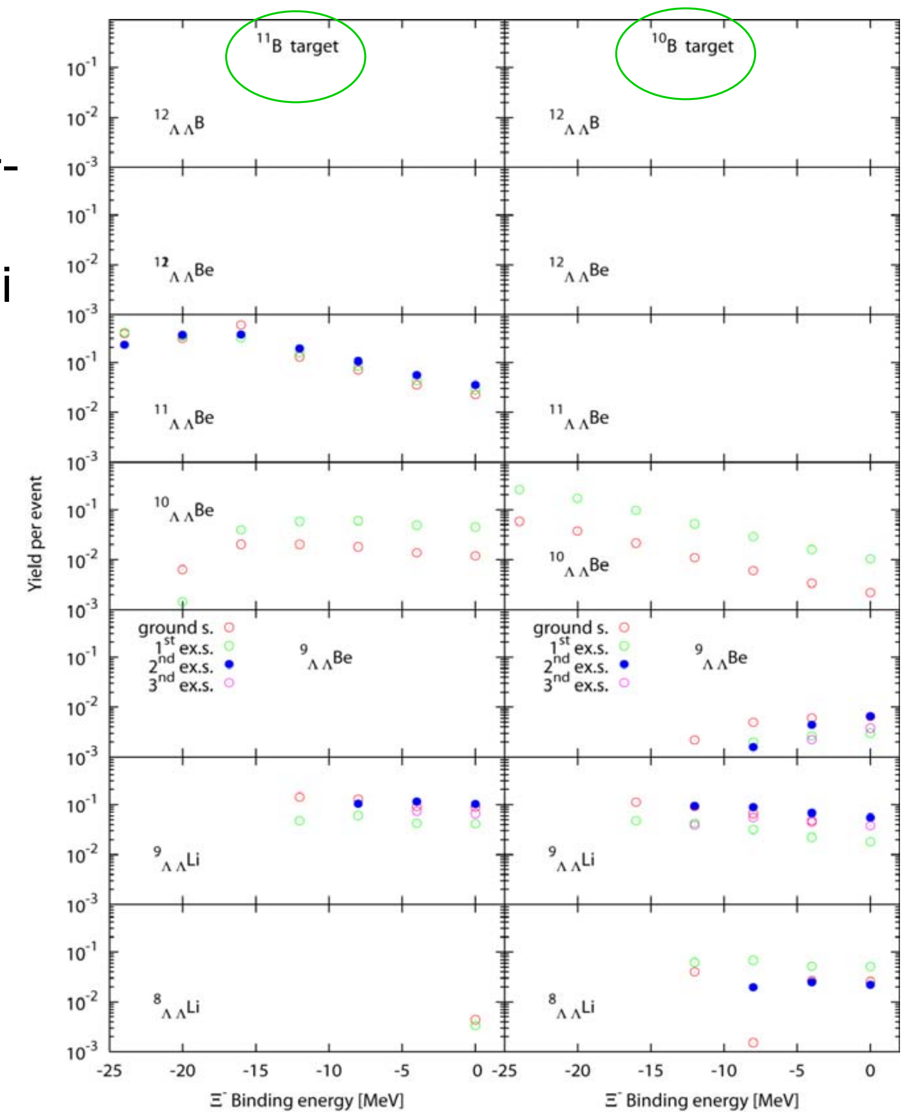
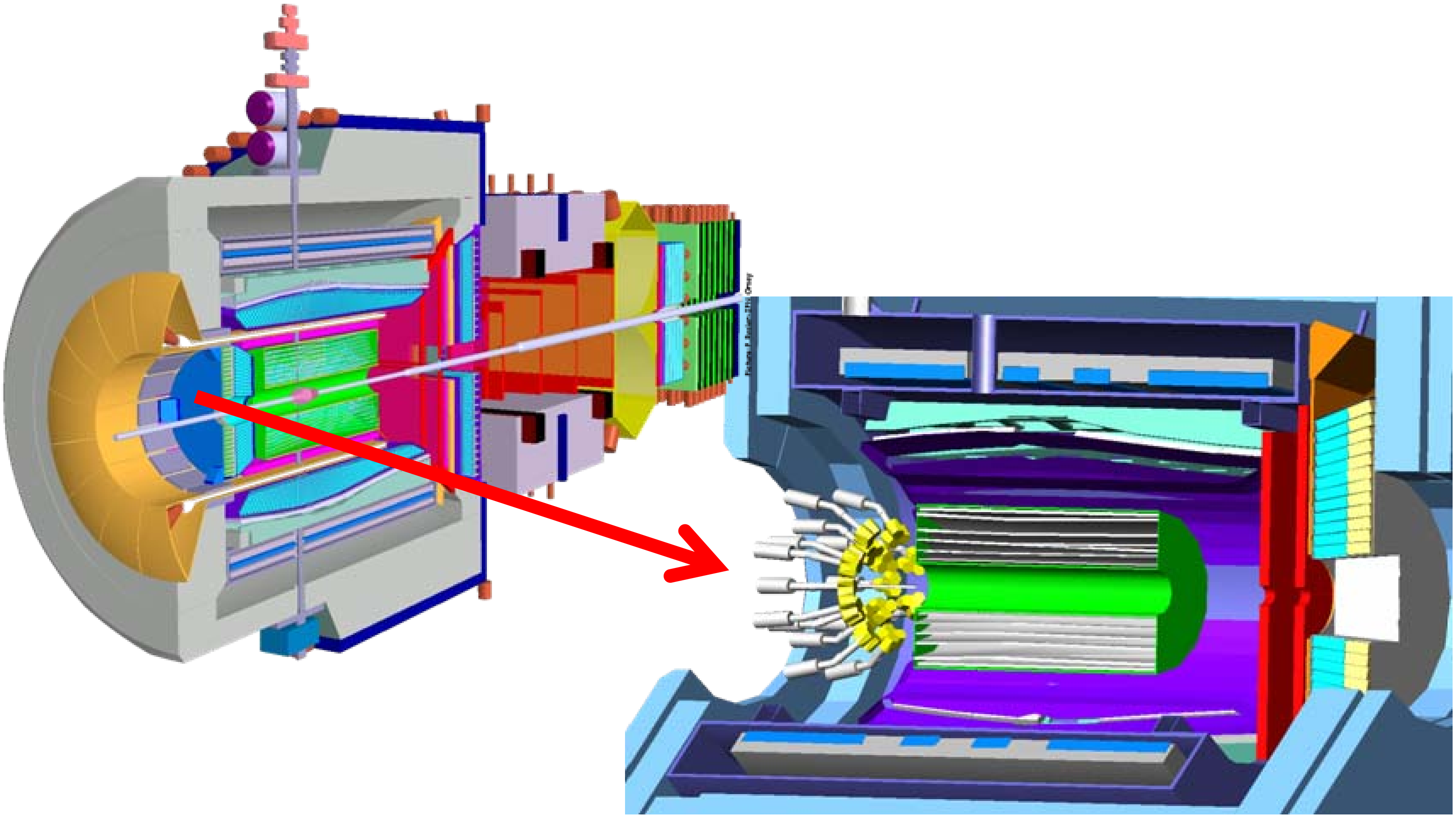
  - Q-value, Ξ-binding energy
- SMM model calculations
  (A. Sanchez, A. Botvina, J.P.)
  - significant fraction of ΛΛ-hypernuclei in excited state
- Various secondary target nuclei ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C, ^{13}C
  - individual transitions with 10% probability
  - comparison of targets allows assignment to specific nucleus



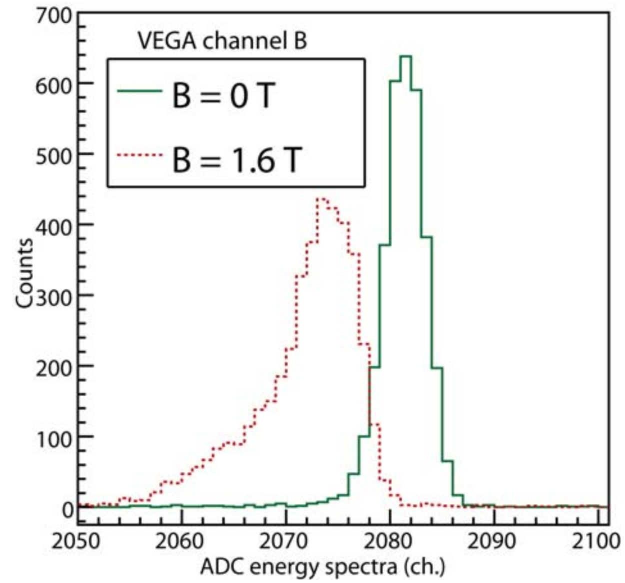
PANDA Setup

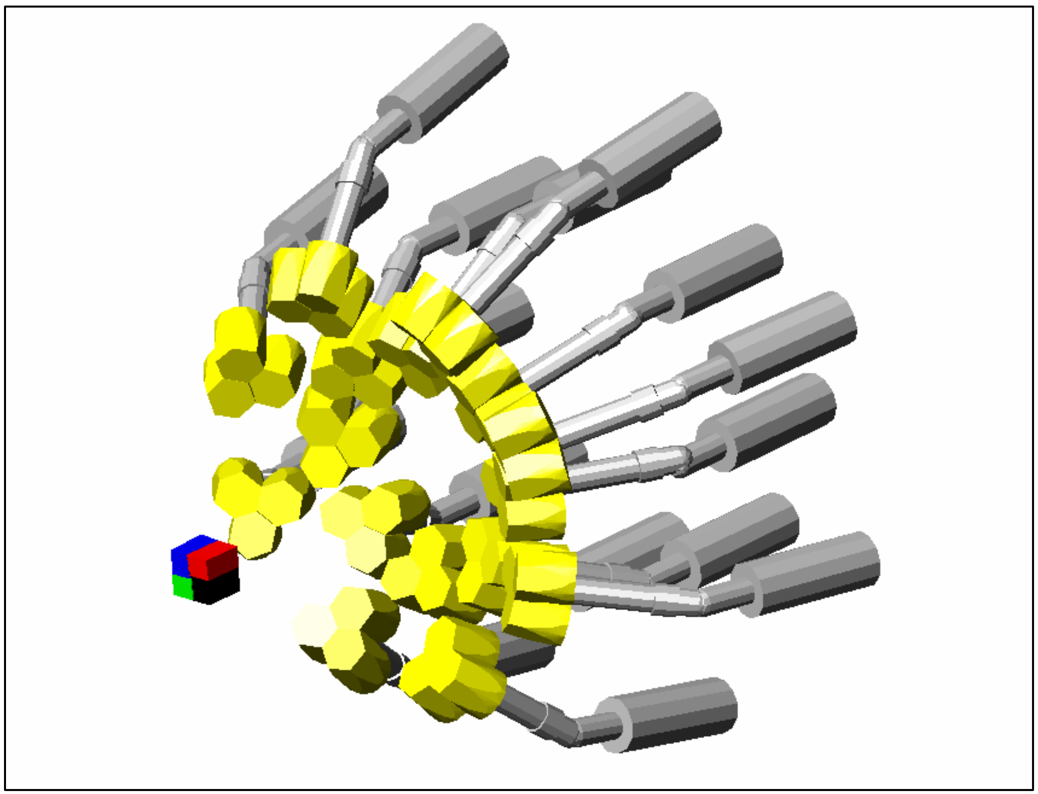
- θ_{lab}< 45°: Ξ-bar, K trigger (PANDA)
- θ_{lab}= 45°-90°: Ξ-capture, hypernucleus formation
- θ_{lab}>90°: γ-detection Euroball at backward angles
  - neutron background (4000n $cm^{-2}s^{-1}$)



Challenges for Ge Detectors

- Magnetic field ~ 1.2 T:
  - Change in the energy resolution and in the pulse shape
    A. Sanchez *et al.*, NIM A (in press)
- hadronic background and neutron damage
  - detector at backward angles
- Limited Space
  - need compact design of cooling system.





International Hypernuclear Network

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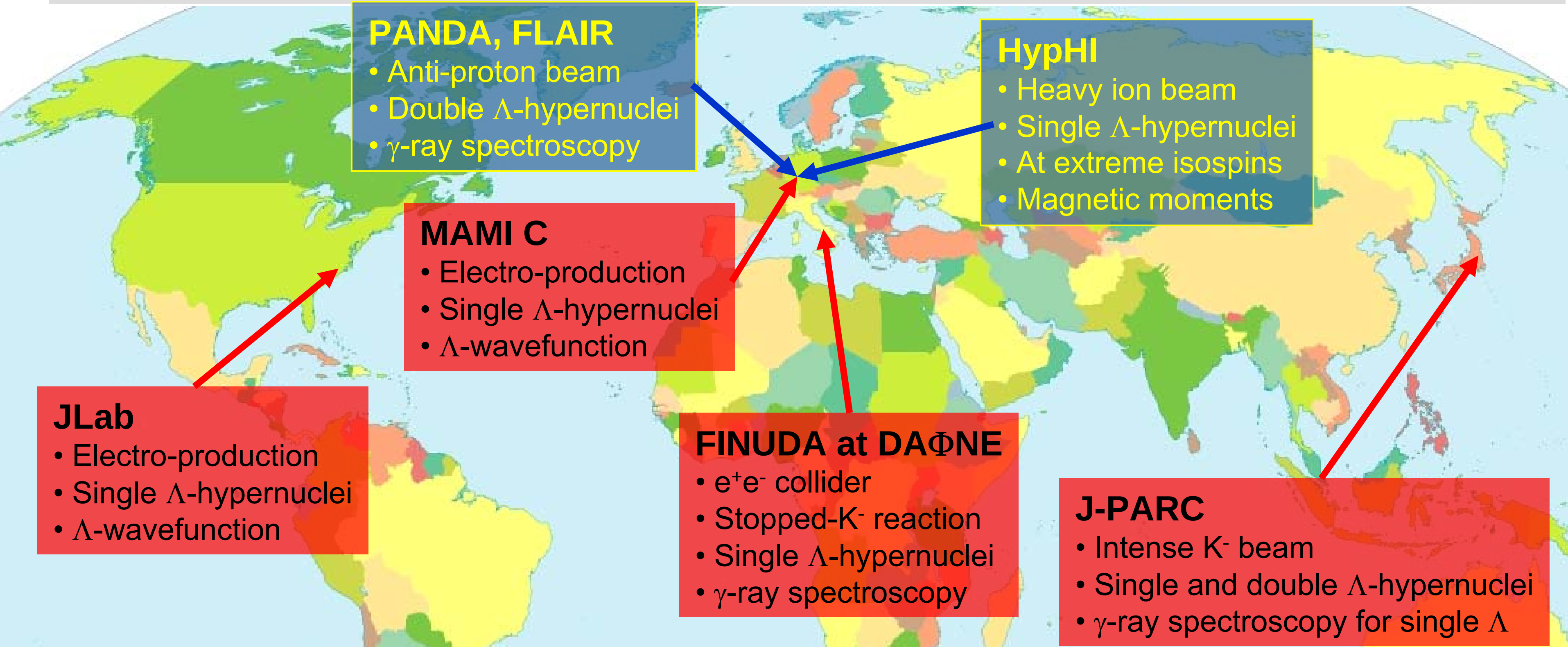

- Hypernuclei represent a bridge between traditional nuclear physics and hadron physics
- FAIR offers several unique opportunities to explore hypernuclei in hitherto unexplored regimes
  - HypHI: exotic hypernuclei
  - FLAIR, PANDA: double hypernuclei
- These studies will possible by a unique combination of experimental facilities at FAIR, e.g. *Ge detectors ⊕ PANDA ⊕ antiproton beams*