Sixth Framework Programme

Bundesministerium für Bildung und Forschung

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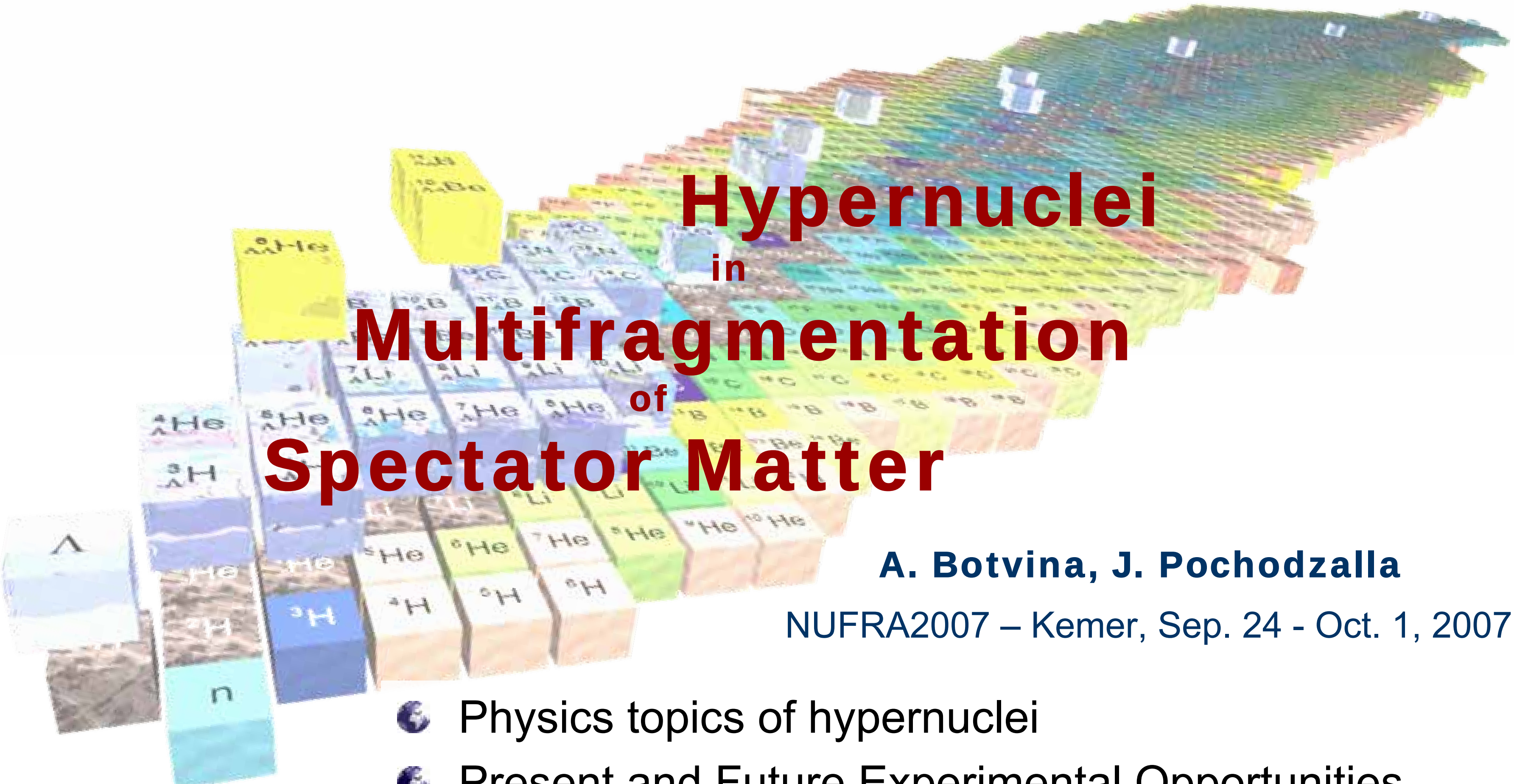
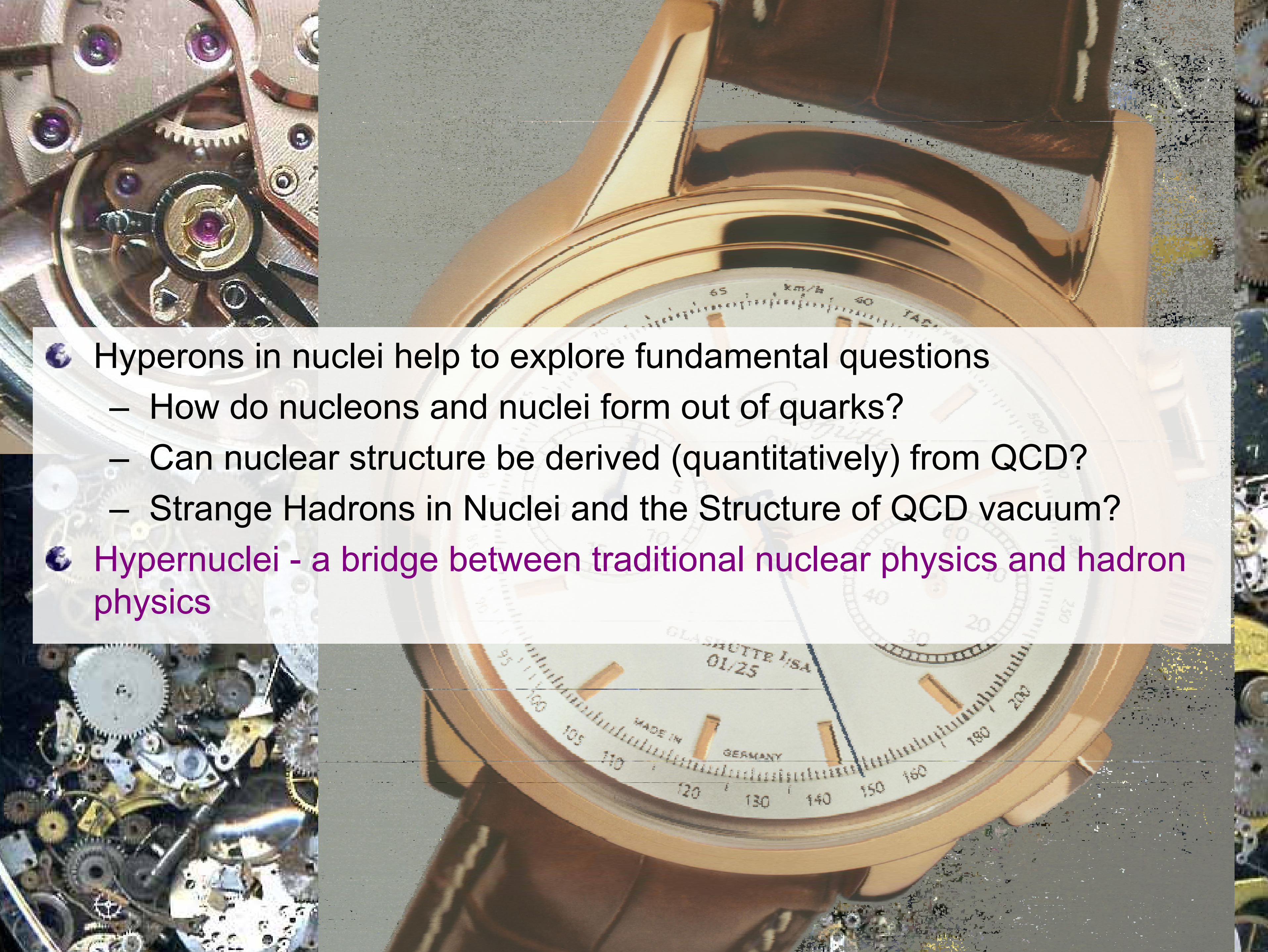


Hypernuclei
in
Multifragmentation
of
Spectator Matter

A. Botvina, J. Pochodzalla

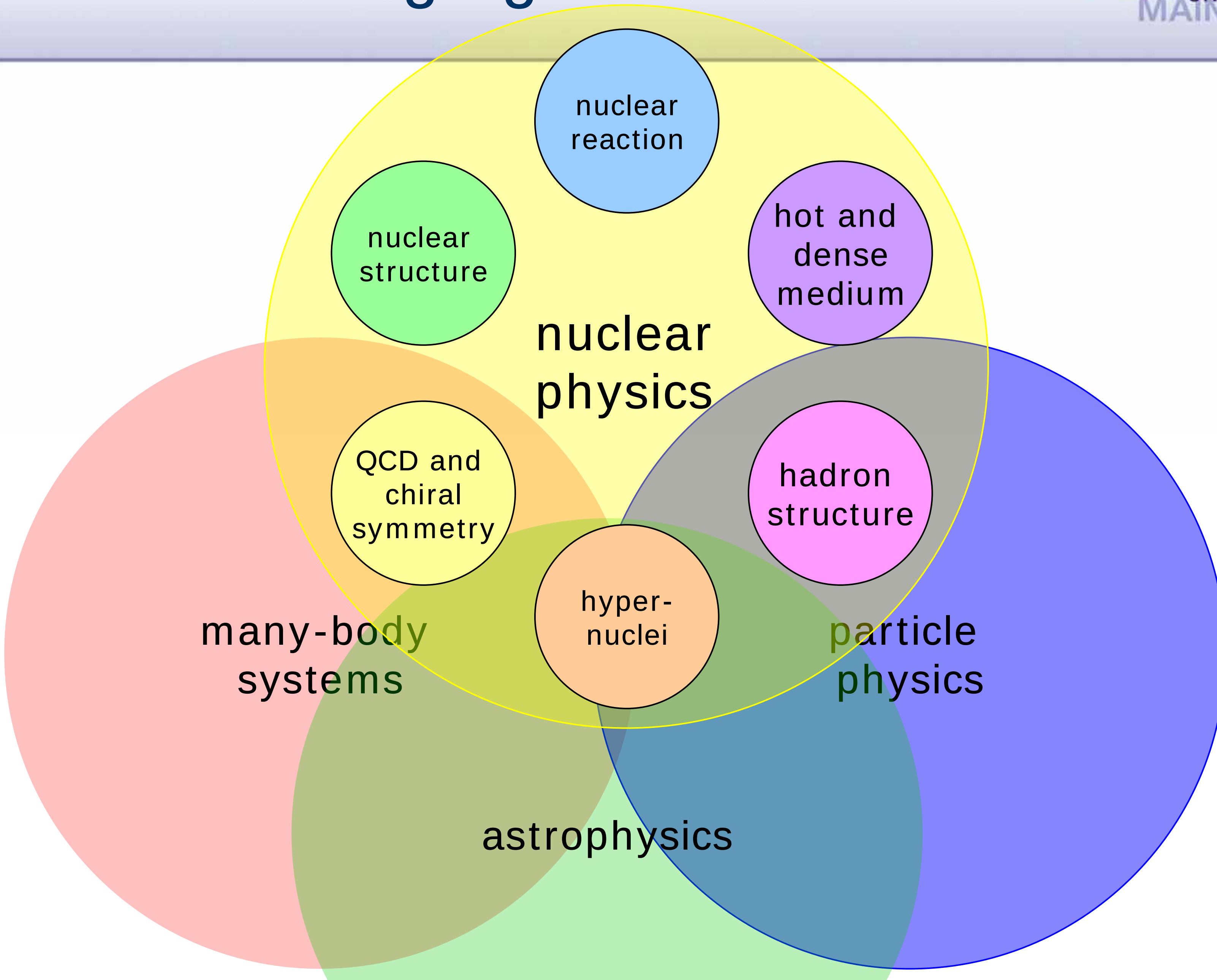
NUFRA2007 – Kemer, Sep. 24 - Oct. 1, 2007

- Physics topics of hypernuclei
- Present and Future Experimental Opportunities
- Hypernuclei in Fragmentation Reactions
- Conclusion



- Hyperons in nuclei help to explore fundamental questions
  - How do nucleons and nuclei form out of quarks?
  - Can nuclear structure be derived (quantitatively) from QCD?
  - Strange Hadrons in Nuclei and the Structure of QCD vacuum?
- Hypernuclei - a bridge between traditional nuclear physics and hadron physics

Nature of emerging structures



Physics of Hypernuclei

- the (low energy) Y-N interactions
  - 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
  - relevance for dense stellar systems
- Weak decays
  - baryon-baryon weak interactions
  - asymmetries of w.d. and the role of two-meson/σ exchange
  - role of FSI and nuclear structure
- $\Lambda\Lambda$-hypernuclei
  - Y-Y interaction
  - $\Lambda\Lambda$K vertex
- nuclear medium properties of hyperons (Λ, Σ, Ξ) and (anti)meson

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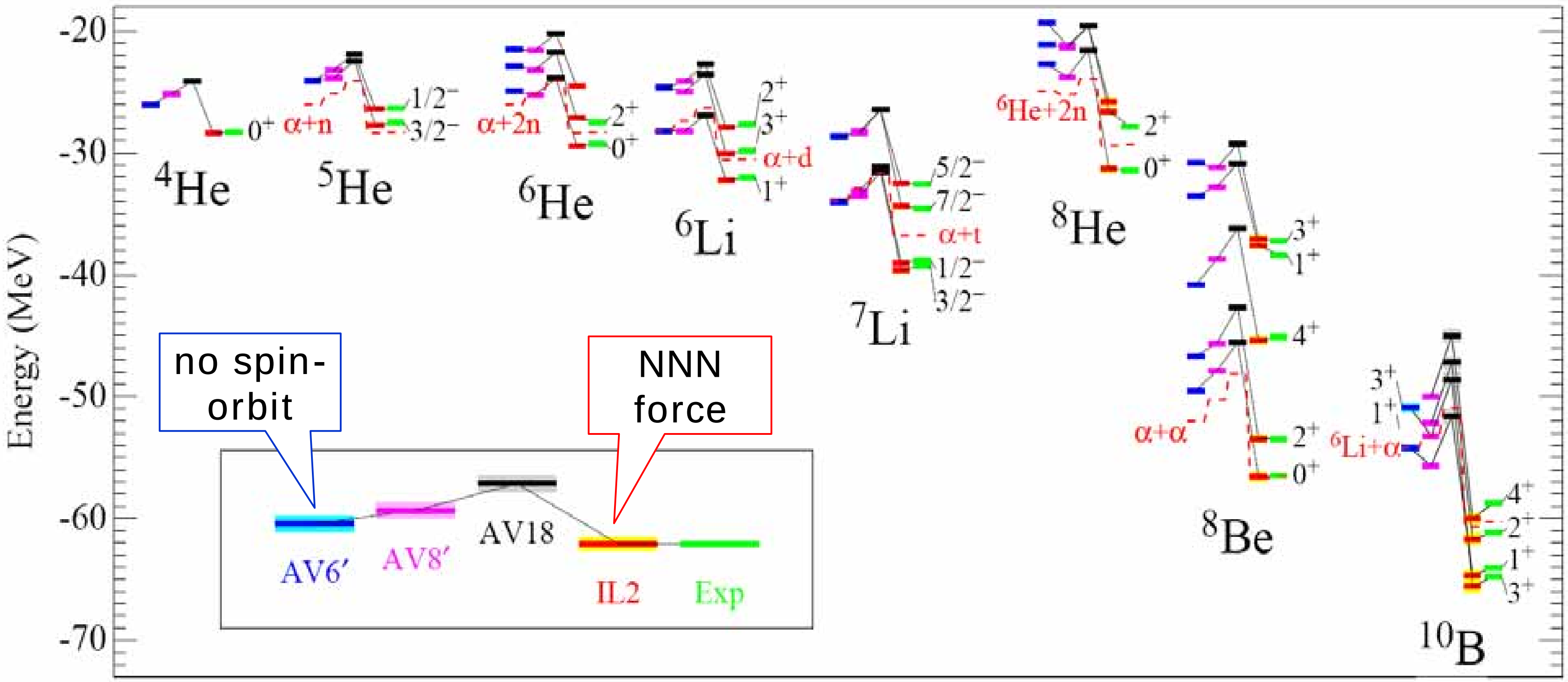
Strategy towards YN interaction

- Starting point: detailed knowledge of the
  - hypernuclear fine structure
  - angular distribution of γ–rays
  - transition probability B(E2)

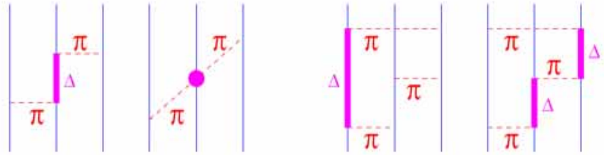
- Comparison to model calculations
  - *s*-shell hypernuclei: ${}_{\Lambda}^{3}H$, ${}_{\Lambda}^{4}H$, ${}_{\Lambda}^{4}He$, ${}_{\Lambda}^{5}He$,…
    - rigorous few-body calculations, using the bare interactions
  - *p*-shell hypernuclei: ${}_{\Lambda}^{6}Li$, ${}_{\Lambda}^{9}Be$, ${}_{\Lambda}^{12}C$, ${}_{\Lambda\Lambda}^{6}He$, ${}_{\Lambda\Lambda}^{10}Be$,…
    - cluster models (d,α) are efficient
  - medium and heavy hypernuclei: ${}_{\Lambda}^{89}Y$,…
    - mean field approach based on *G*-matrix +Thomas Fermi approximation

Understanding Nuclear Structure

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



- 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)



γ-spectroscopy – present status

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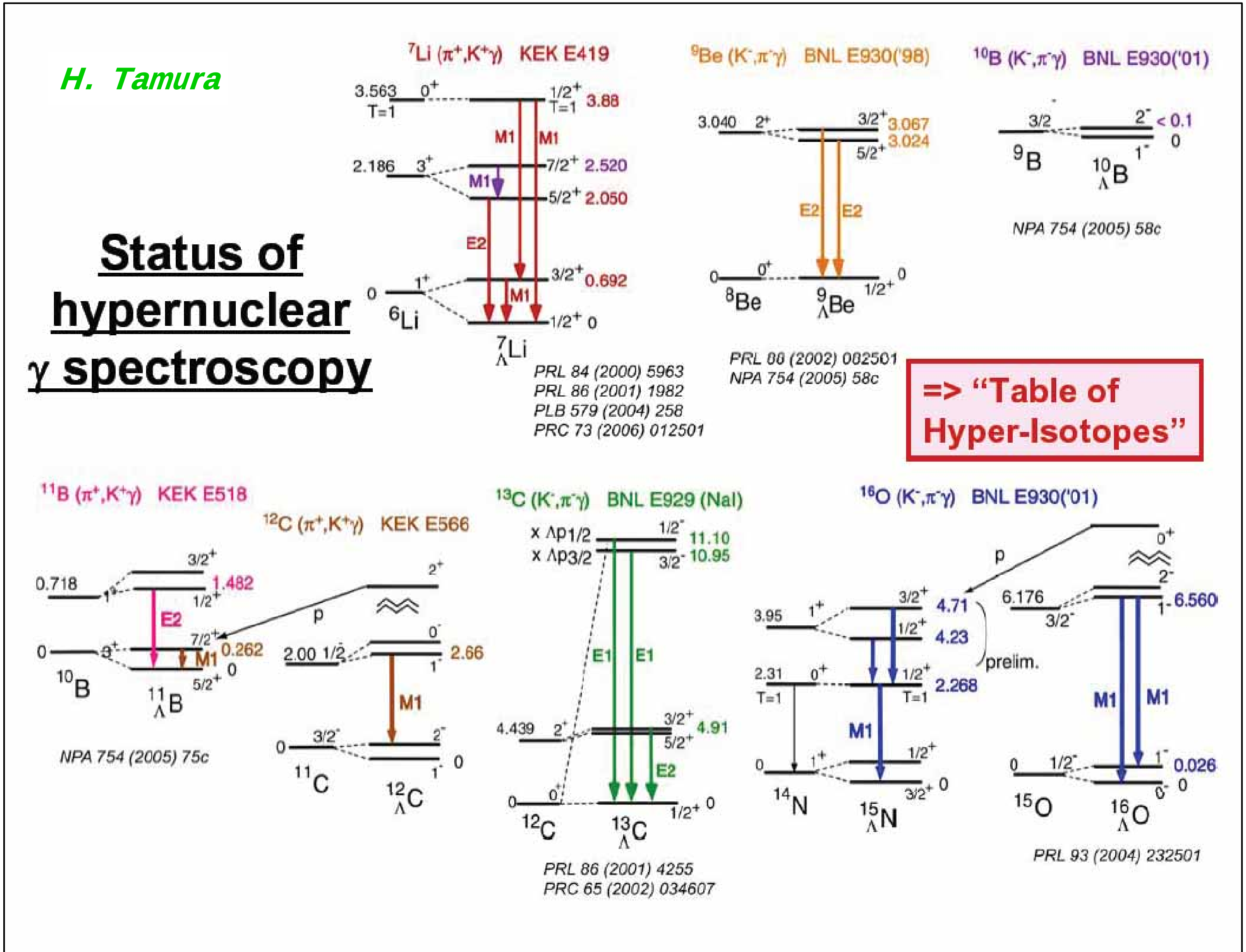

Status of hypernuclear γ spectroscopy

=> "Table of Hyper-Isotopes"

γ-spectroscopy of p-shell hypernuclei

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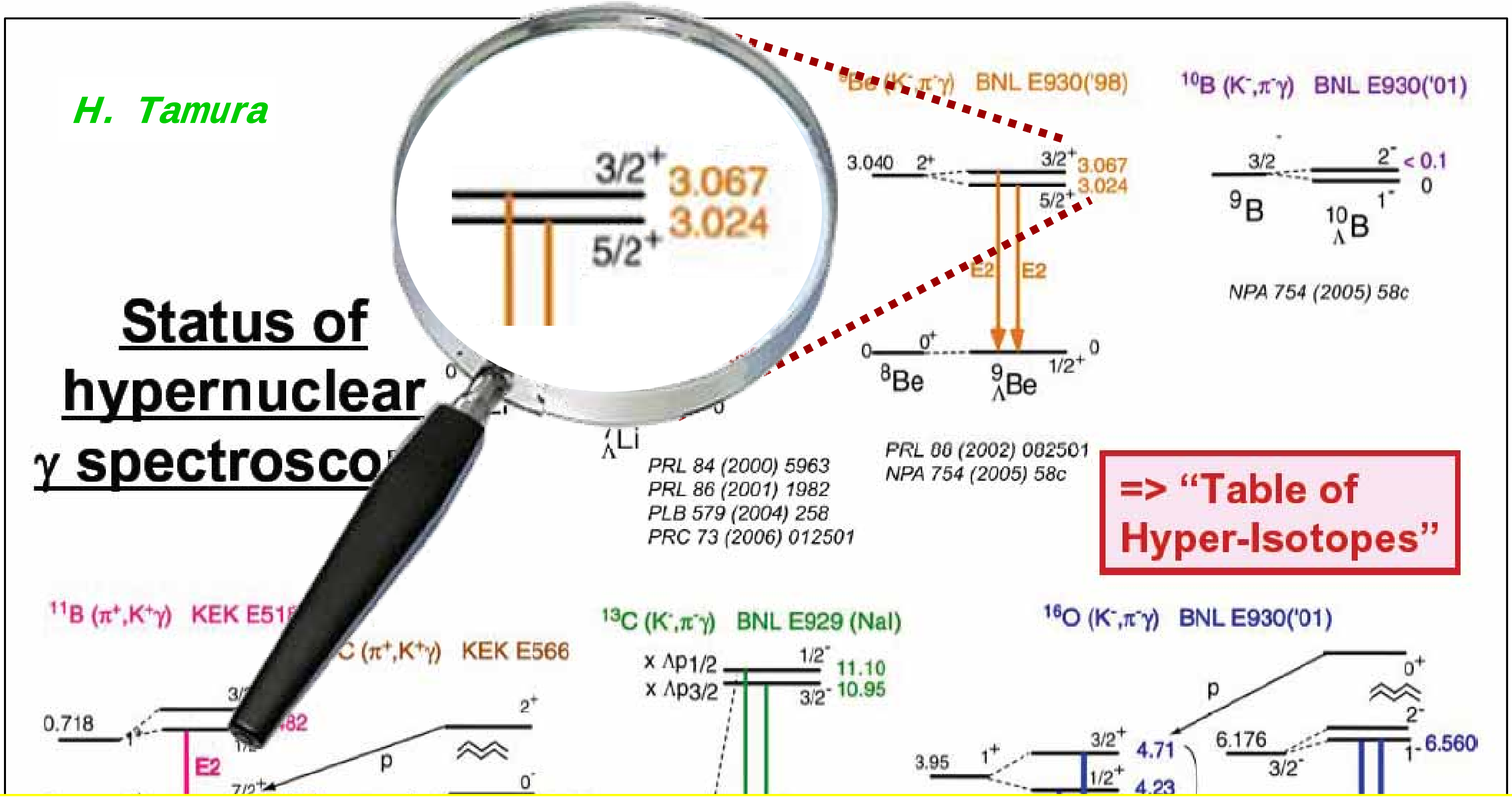

	Experiment	OME	QM
${}^{9}_{\Lambda}Be(5/2^{+} \rightarrow 3/2^{+})$	$31 \pm 2 keV$	$80 - 200 keV$	$35 - 40 keV$
${}^{13}_{\Lambda}C(3/2^{-} \rightarrow 1/2^{-})$	$152 \pm 36 keV$	$390 - 960 keV$	$150 - 200 keV$

ΛN-ΣN coupling important Kaiser+Weise (2005), Fujiwaraet al (2006)...

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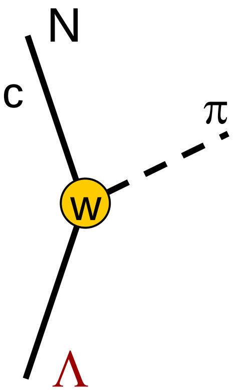
Weak Decay of Λ Hypernuclei

free Λ decay

$p_N \approx 100$MeV/c



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

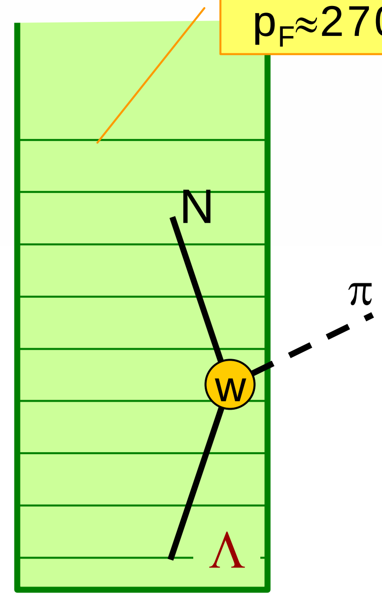
$\Lambda \rightarrow n\pi^0 + 41\text{MeV} \quad (36\%)$

$\tau_\Lambda = 263ps$

ΔI=1/2 rule

mesonic decay of hypernuclei

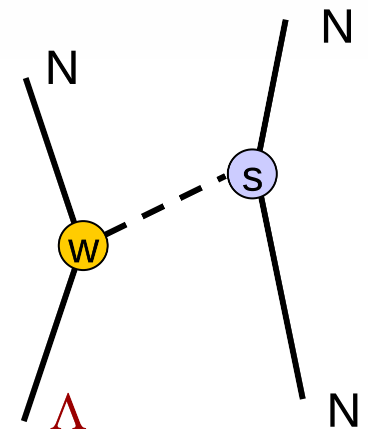
$p_F \approx 270$MeV/c



suppresed by Pauli blocking

non-mesonic decay of hypernuclei

dominant in all but the lightest hypernuclei

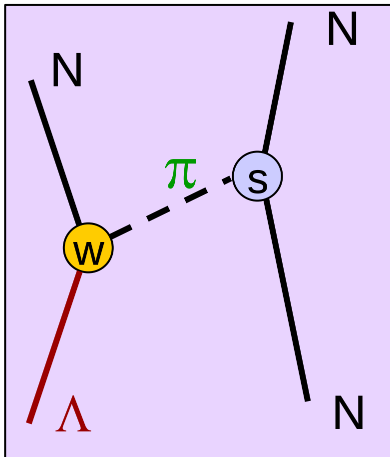


$\Lambda p \rightarrow np + 176\text{MeV}$

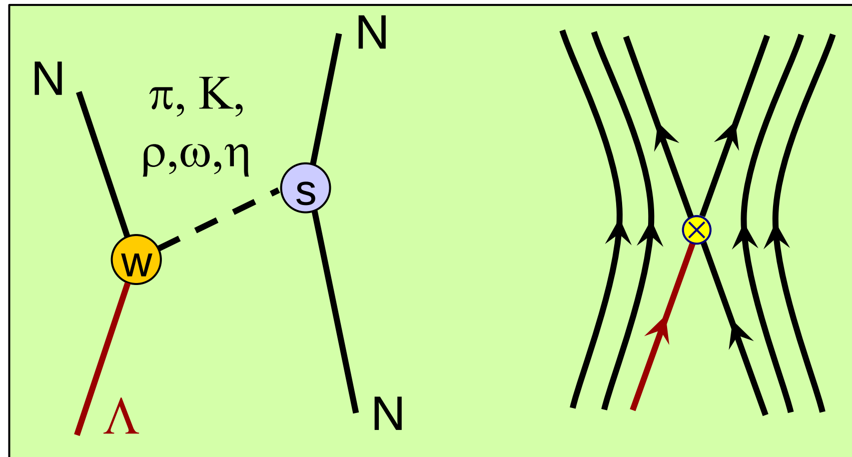
$\Lambda n \rightarrow nn + 176\text{MeV}$

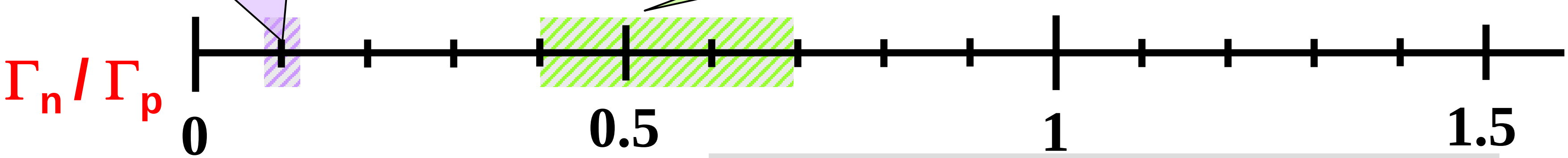
Γ_n/Γ_p and the isospin structure of NMWD

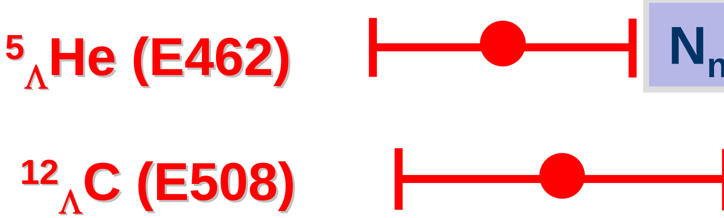
One Pion Exchange (OPE) | **Meson Exchange Mechanisms** | **Direct Quark Mechanism**



Tensor-dominant
→ requires the final NN pair to have isospin 0
→ Γ_p dominant







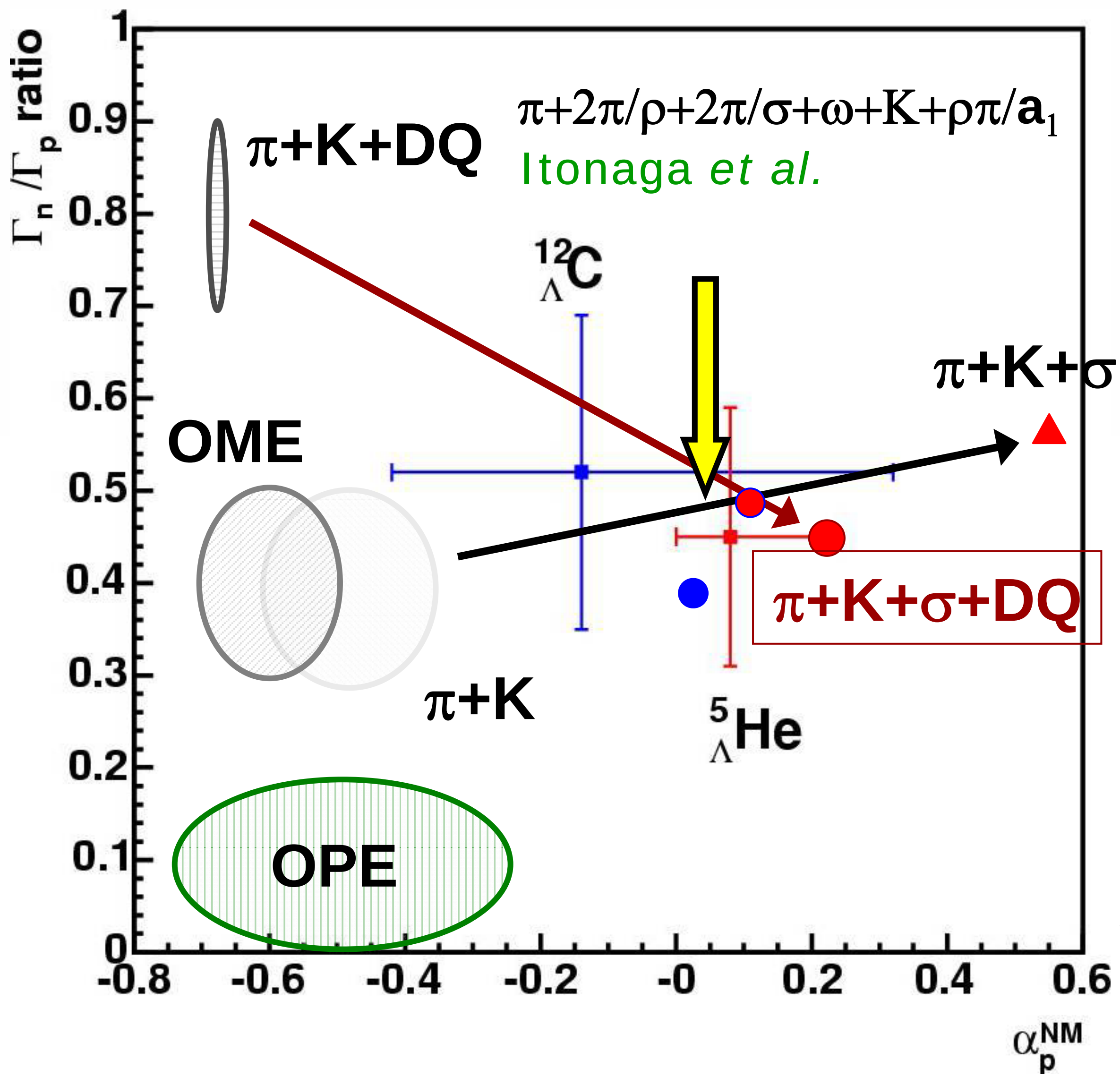
N_{nn} / N_{np} ($^5_\Lambda$He)= **0.45±0.11±0.03**

Kang *et al.* PRL 96 (2006) 062301

Γ_n / Γ_p ($^{12}_\Lambda$C)= **0.51±0.13±0.05**

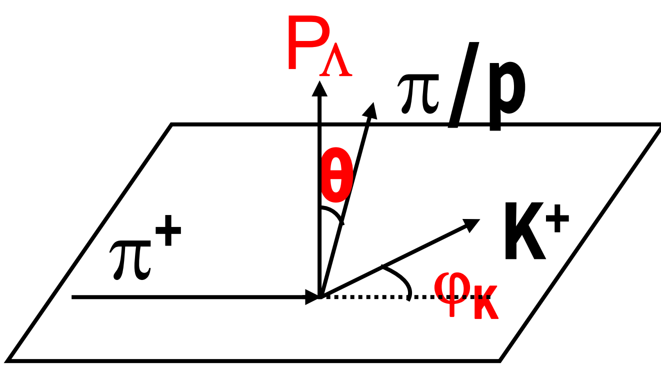
Kim *et al.* PLB 641 (2006) 28

Weak decay: Asymmtries and Γ_n/Γ_p



H. Outa, HYP2006

- π+K,OME can reproduce Γ_n/Γ_p ratio but predict large negative α^{NM}
- Γ_n/Γ_p and α^{NM} can be reproduced by π+K+σ+DQ model



$$N(\theta) = N_0(1 + \alpha^{NM} P_\Lambda \cos\theta)$$

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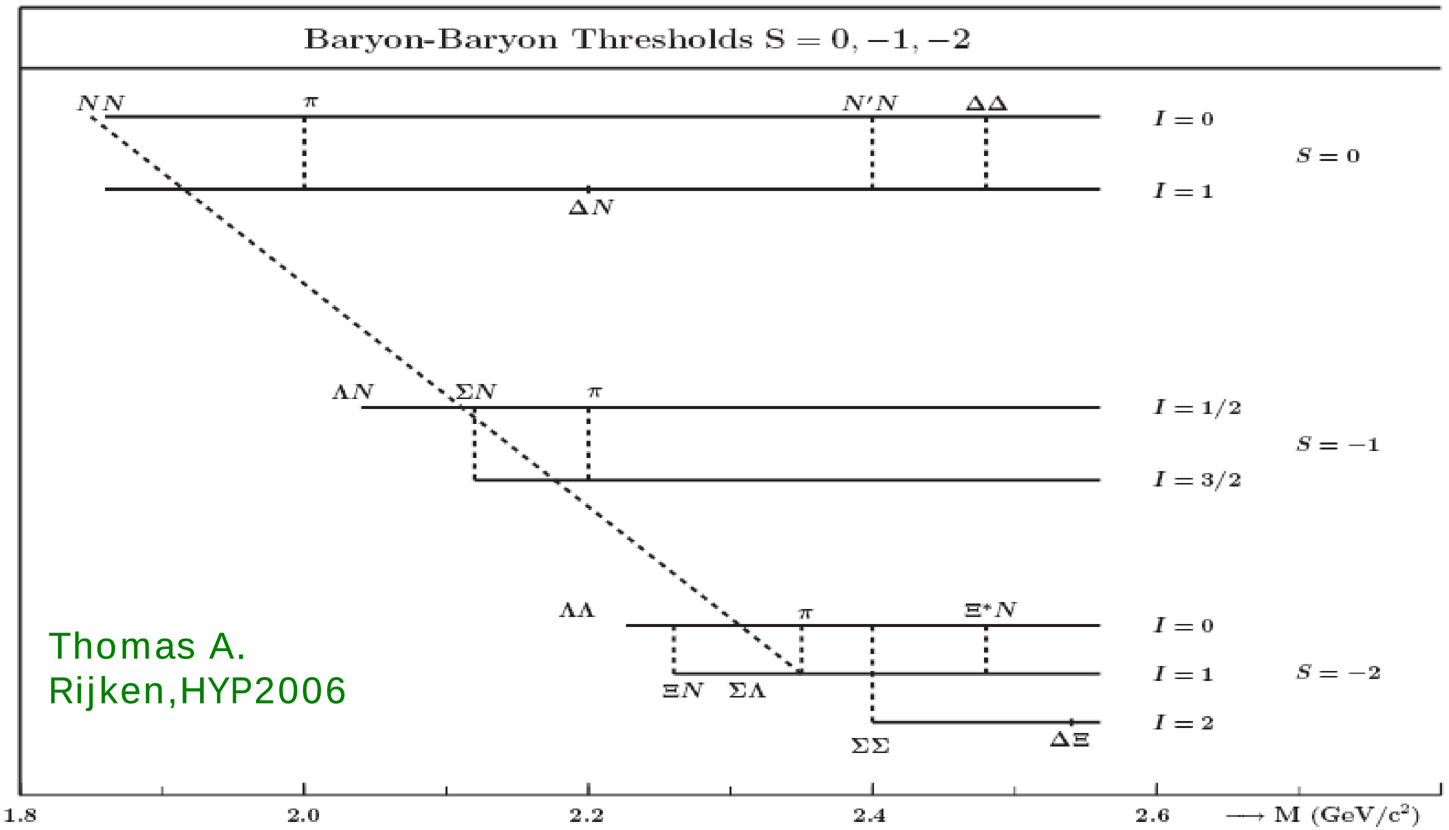
Y-N or Y-Y Interaction in Hypernuclei

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

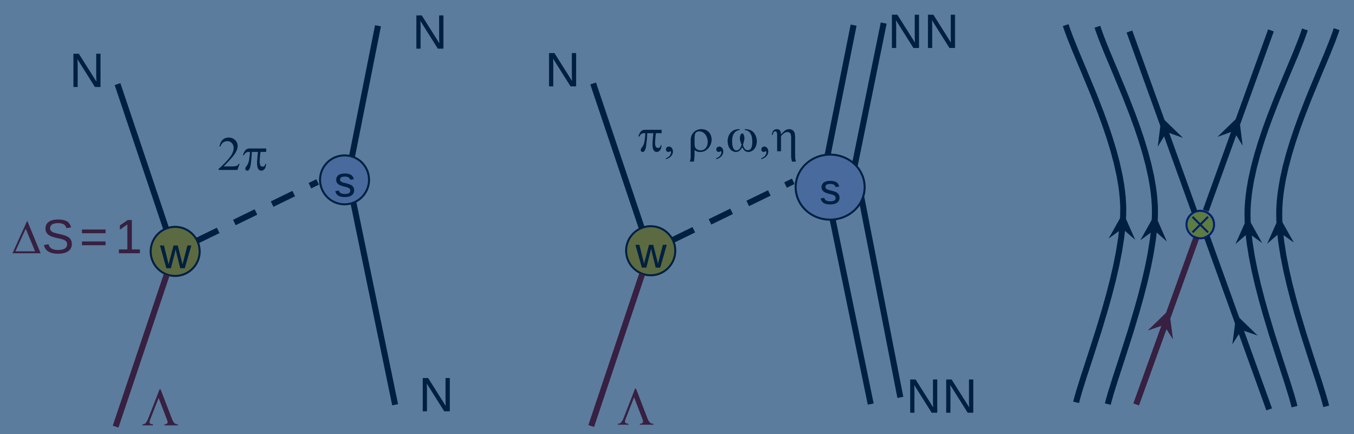


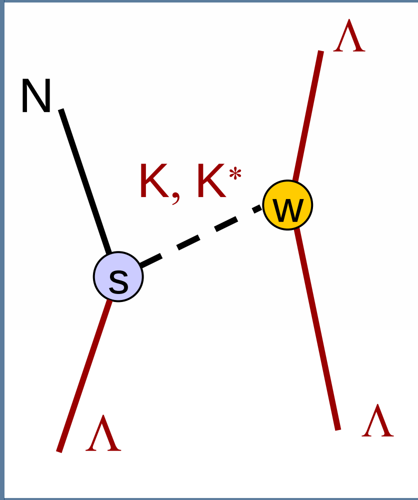
Thomas A. Rijken,HYP2006

Weak Hyperon-Hyperon Interaction

$\Lambda N \rightarrow N\ N$

$\Lambda\Lambda \rightarrow Y\ N$





- two-pion exchange
- two-nucleon induced decays $\Lambda NN \rightarrow NNN$
- meson vs. direct quark process
- ${}^{6}_{\Lambda\Lambda}He$: $\Lambda\Lambda \rightarrow \Lambda n$ → access to weak $\Lambda\Lambda K$ 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%

Physics of Hypernuclei

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Magnetic moment of Λ in nuclei

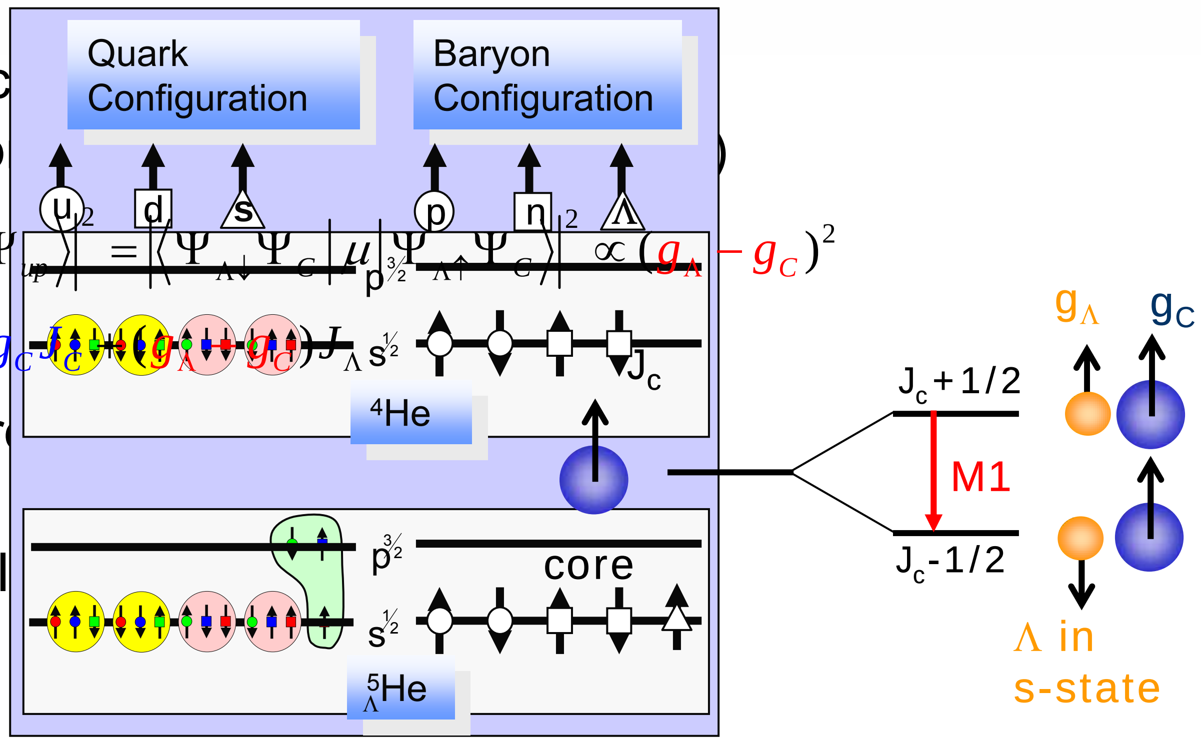
- baryons do not „melt“ in nuclei: quark effects are small
- EMC-effect: whether there is any change in nucleon properties in nuclei remains controversial
  - if mass and size of a baryons changes inside nuclei, also it‘s magnetic moment might change
  - if so, why? meson current, ΛΣ mixing, partial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

- experimental approac
  - the traditional app)

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

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

    - M1 transition r
  - spin precession
    - Λ decay is sel
    - works also for
    - g_Λ dominates



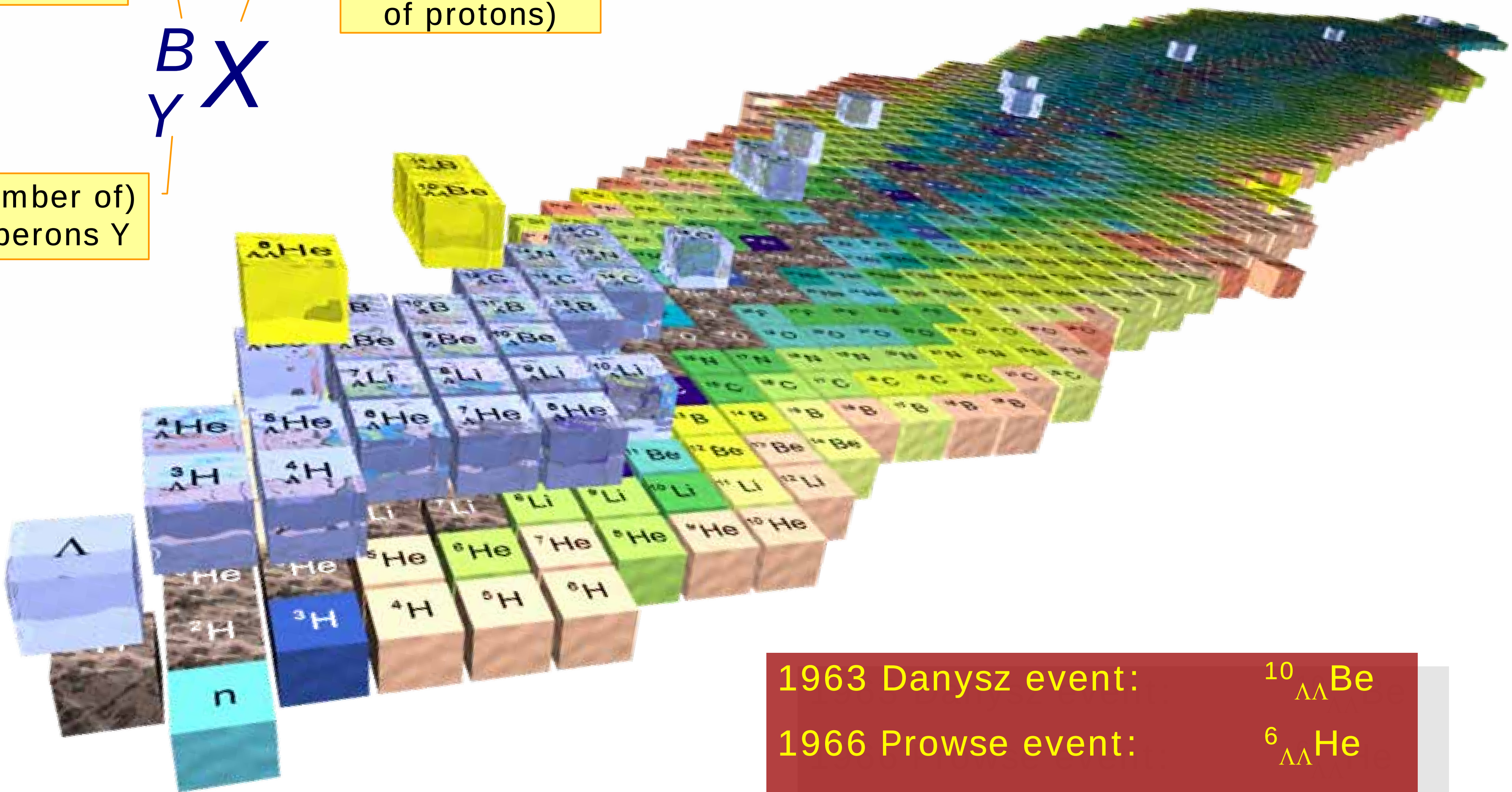
Hypernuclei – Present Situation

number of baryons N+Z+Y

element = total charge (not number of protons)

$${}^{B}_{Y}X$$

(number of) hyperons Y



1963 Danysz event:	${}^{10}_{\Lambda\Lambda}Be$
1966 Prowse event:	${}^{6}_{\Lambda\Lambda}He$
1991 Aoki event:	${}^{13}_{\Lambda\Lambda}B$
2001 Nagara event:	${}^{6}_{\Lambda\Lambda}He$

International Hypernuclear Network

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PANDA, FLAIR
• Anti-proton beam
clei
y

ction
rnuclei
n

Dubna
• heavy ion beam
• Single and double Λ-hypernuclei
• g-ray spectroscopy for single Λ

HypHI
• Heavy ion beam
• Single Λ-hypernuclei
• At extreme isospins
• Magnetic moments

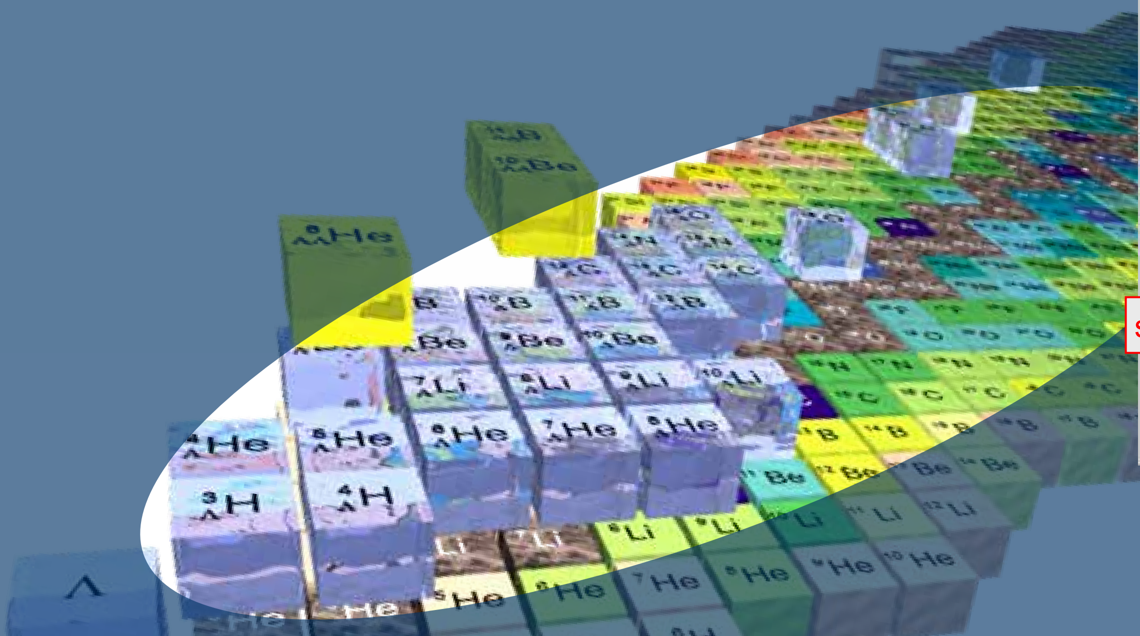
•FINUDA at DAFNE
• e+e- collider
• Stopped-K- reaction
• Single Λ-hypernuclei
• γ-ray spectroscopy

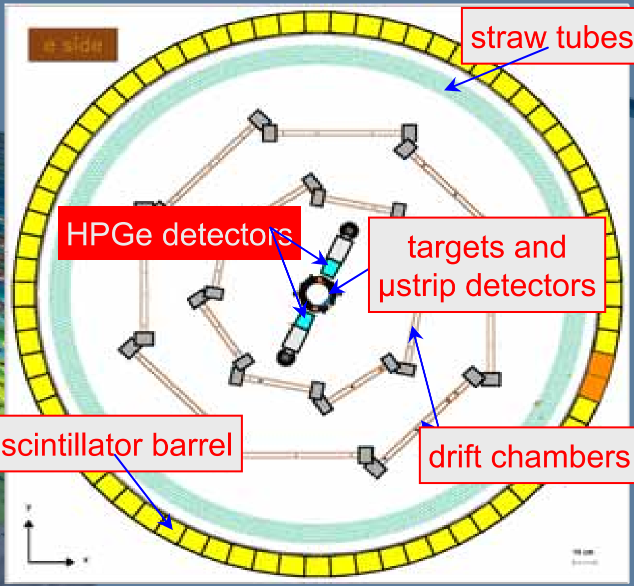
J-PARC
• Intense K- beam
• Single and double Λ-hypernuclei
• g-ray spectroscopy for single Λ

It is presently THE hypernuclear factory in Europe

Hypernuclei – Present Situation

FINUDA@DAΦNE





Future: high resolution γ-spectroscopy
- 2007: Letter of Intent
- 2008: completion of FINUDA physics program
- 2009: FINUDA upgrade; pilot run at DAΦNE (500 pb-1)
- 201X: ???

International Hypernuclear Network

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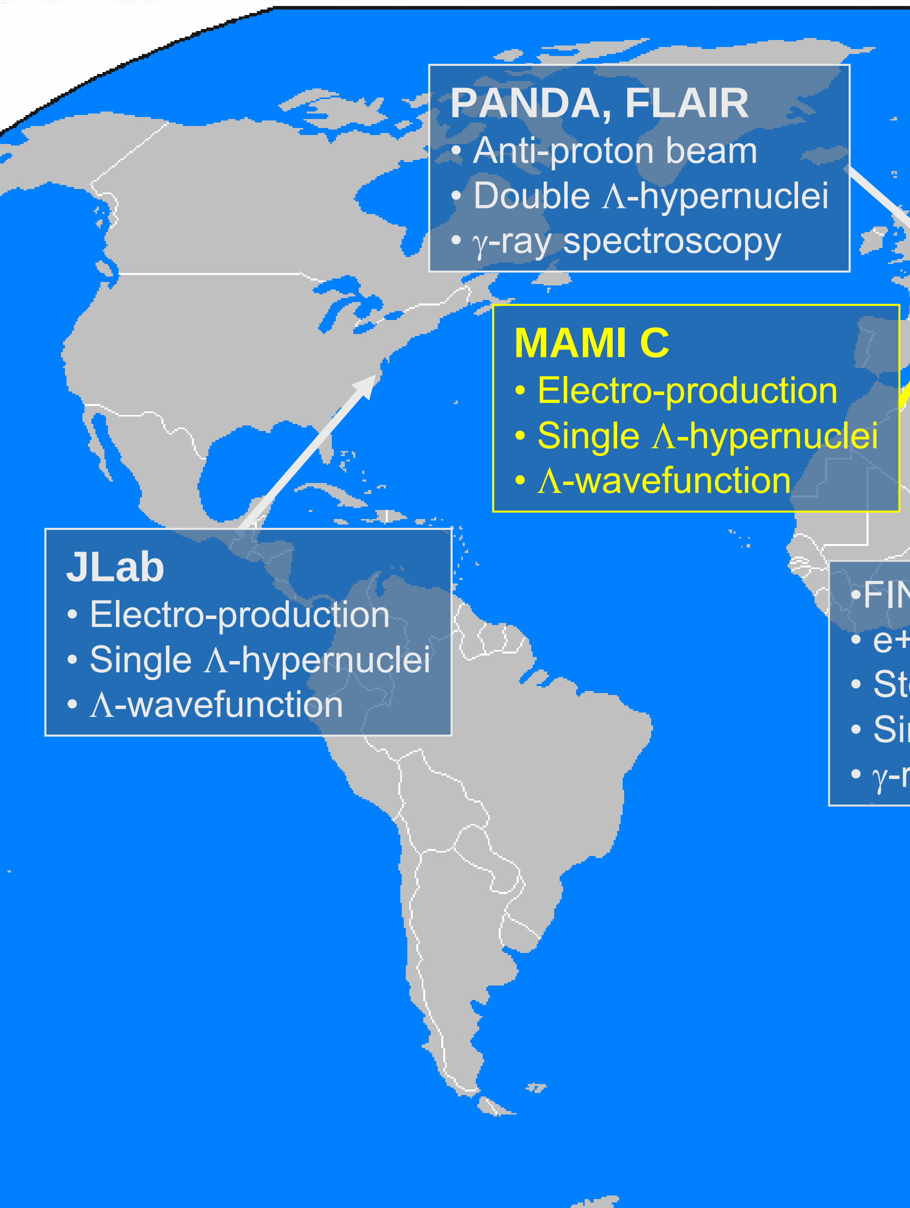
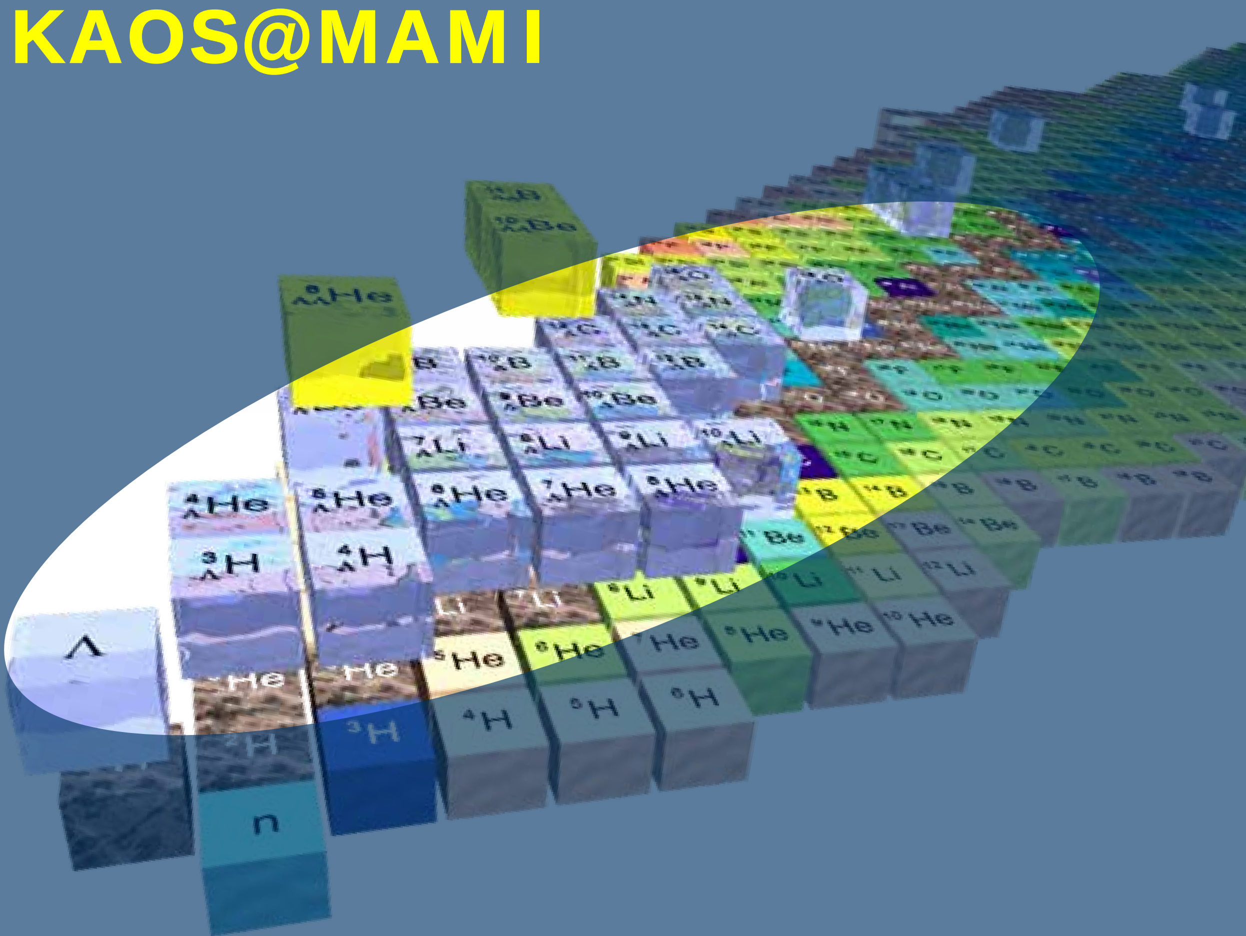
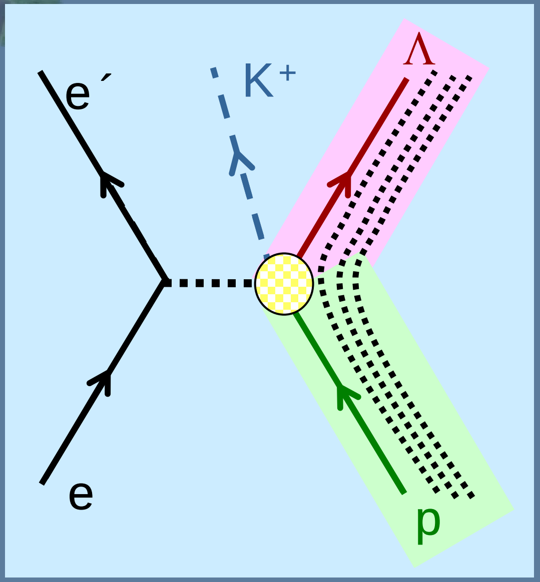


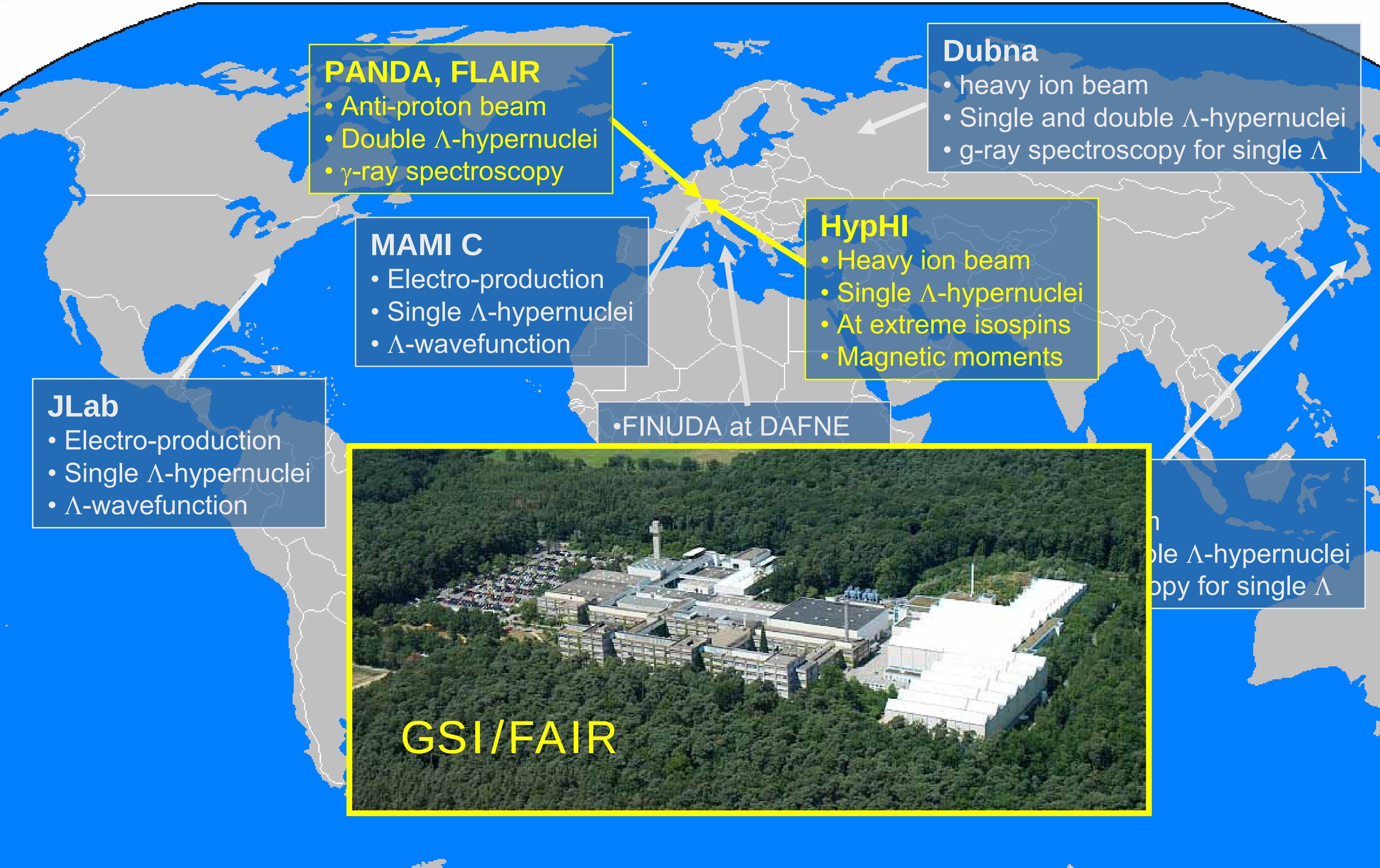
Hypernuclei – Present Situation

KAOS@MAMI





International Hypernuclear Network



Hypernuclei – Present Situation

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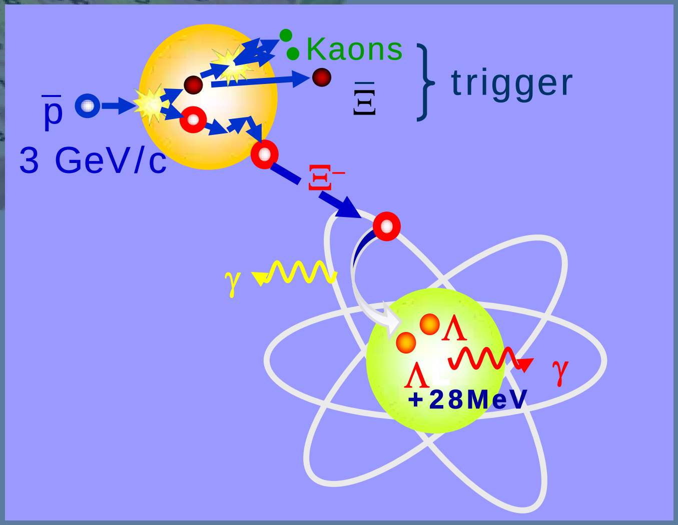
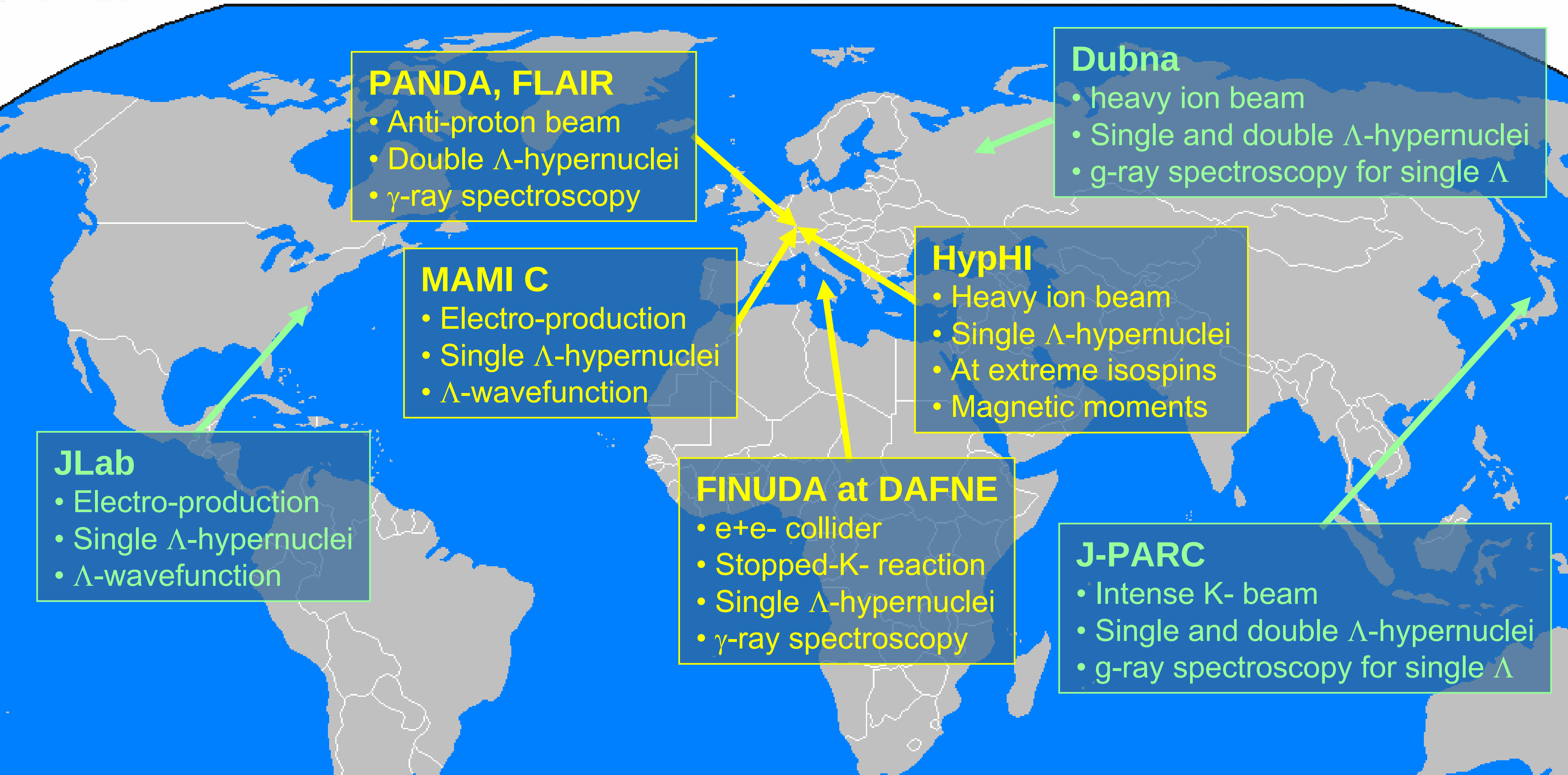
PANDA@FAIR >2014



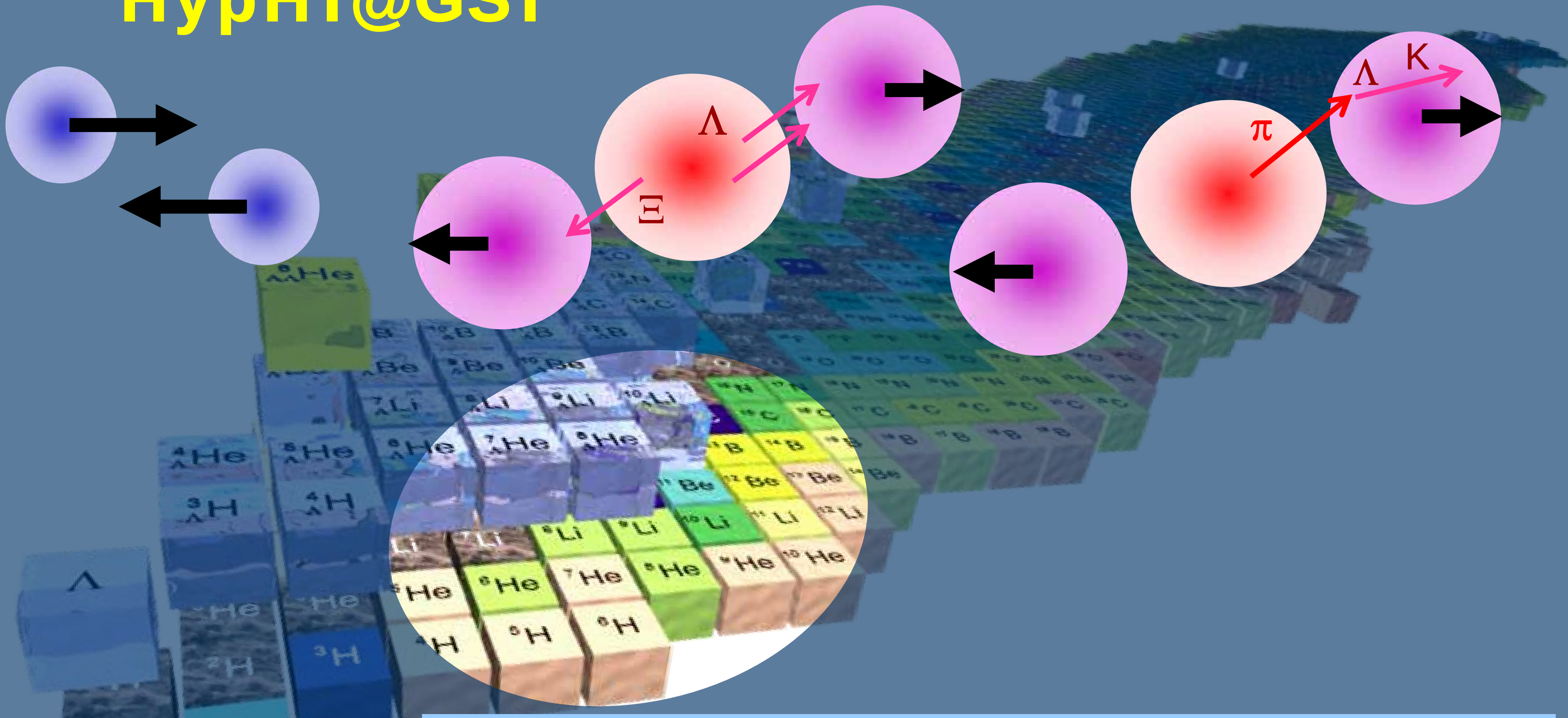
International Hypernuclear Network



- Worldwide, several new activities will help to overcome present limitations of this field

Hypernuclei – Present Situation

HypHI@GSI



Production of hypernuclei in relativistic heavy ion collisions

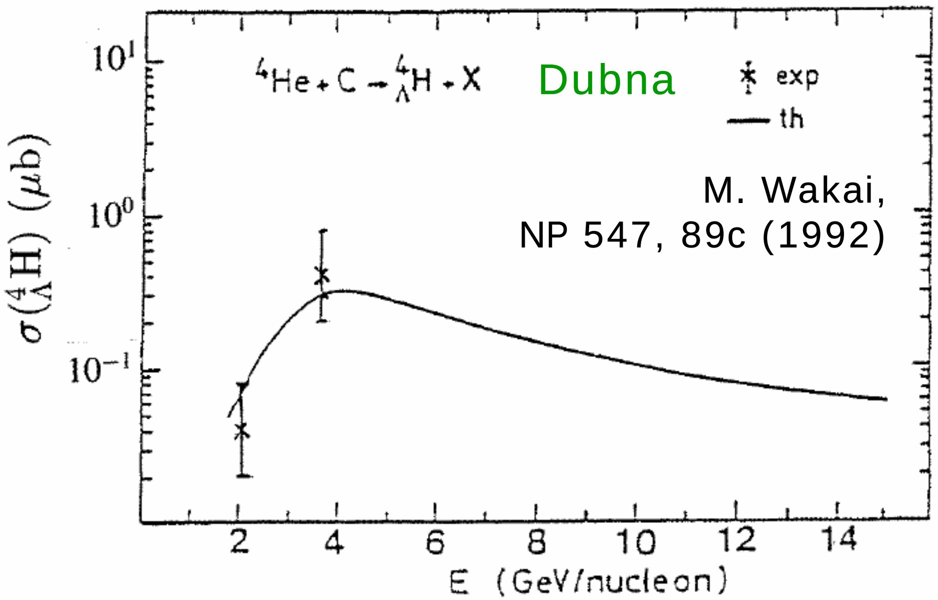
- production of many hyperons
- multiple coalescence of hyperons with fragments
- (π,K), (K,π) and (K^-,K^+) reactions on fragments

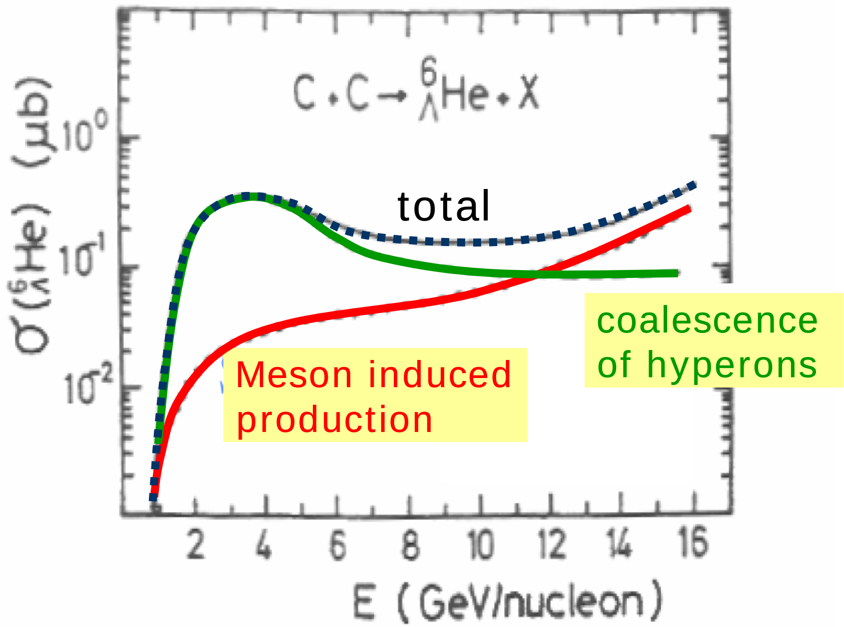
Physics of relativistic hypernuclei

- Hypernuclei with extreme isospin
  - lifetime
  - weak decays
  - hypermatter at finite temperature und low density
- Magnetic moment of Λ inside nuclei by spin rotation

Relativistic Hypernuclei

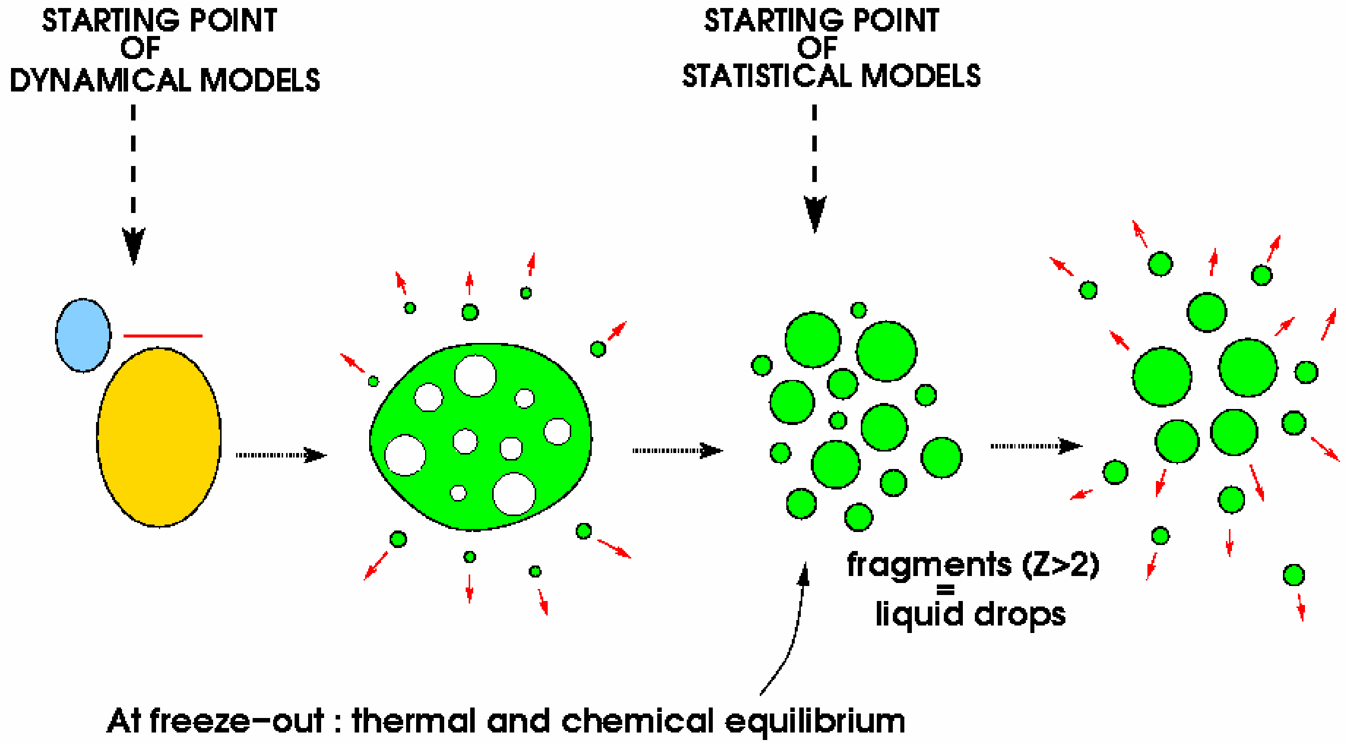
- Many predictions based on coalescence mode
  M. Sano, INS-PT-31 (1982)
  M. Wakai et al., PRC 38, 748 (1988)
  J. Aichelin et al., PLB 274, 260 (1992)
  S. Hirenzaka et al., PRC 48, 2403 (1993)
  M. Sano and M. Wakai, PTP Suppl. 117, 99 (1994)
- Cross sections
  - local maximum at ~4AGeV
  - single Λ-hypernuclei ~0.1μb
  - $\Lambda\Lambda$-hypernuclei ~0.01 nb





Projectile Fragmentation

- fragmentation of projectiles well understood
- short time ~100fm/c for primary fragment production
- freeze-out density is around $0.1\rho_0$
- high degree of equilibration at the freeze-out
- temperature 3-8MeV



Masses of hypernuclei

- liquid-drop description of fragments:
  - bulk, surface, symmetry, Coulomb (as in Wigner-Seitz approximation)

$$F_A^{Bulk}(T) = \left(-\omega_0 - \frac{T^2}{\varepsilon_0}\right) \cdot A$$

$$F_A^{Surf}(T) = \beta_0 \left(\frac{T_c^2 - T^2}{T_c^2 + T^2}\right)^{5/4} \cdot A^{2/3}$$

$$F_{AZH}^{sym} = \gamma \frac{(A-H-2Z)^2}{A-H}$$

$$\omega_0 = 16 MeV$$
$$\beta_0 = 18 MeV$$
$$T_c = 18 MeV$$
$$\gamma = 25 MeV$$
$$\varepsilon_0 \approx 16 MeV$$

- *hyperterm* in binding energy
  - Samanta *et al.*

    J. Phys. G 32, 363 (2006)
  - Liquid drop inspired

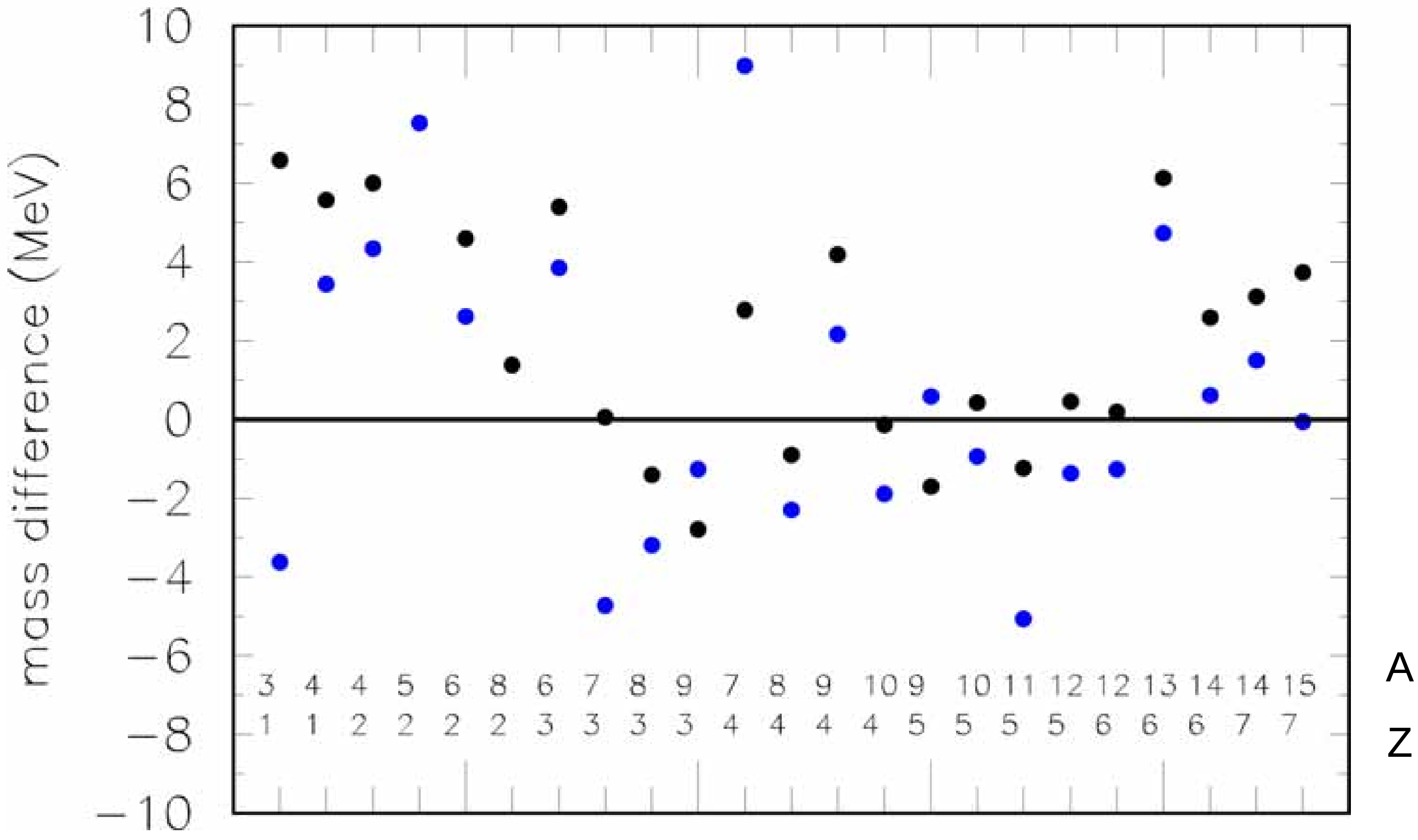
    A. Botvina and J.P. (2007)

$$F_{sam}^{hyp} = Y \cdot \left(-10.68 + \frac{48.7}{A^{2/3}}\right)$$

$$F_{LD}^{hyp} = \frac{Y}{A}\left(-10.68 + 21.27 A^{2/3}\right)$$

Mass predictions for hypernuclei

- Comparison to measured masses of single Λ-hypernuclei

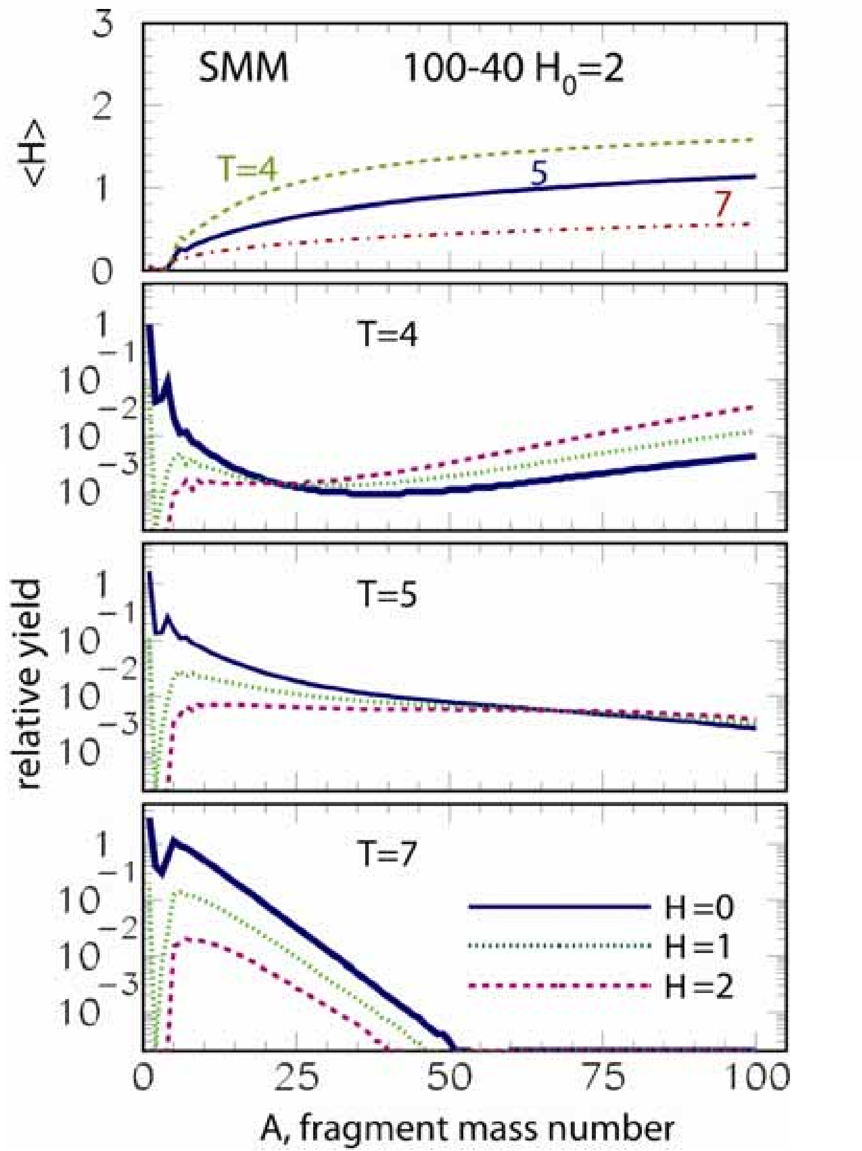


$$\langle \Delta m \rangle_{Samanta} = 2.48\,\text{MeV/c}^2 \qquad rms_{Samanta} = 4.61\,\text{MeV/c}^2$$

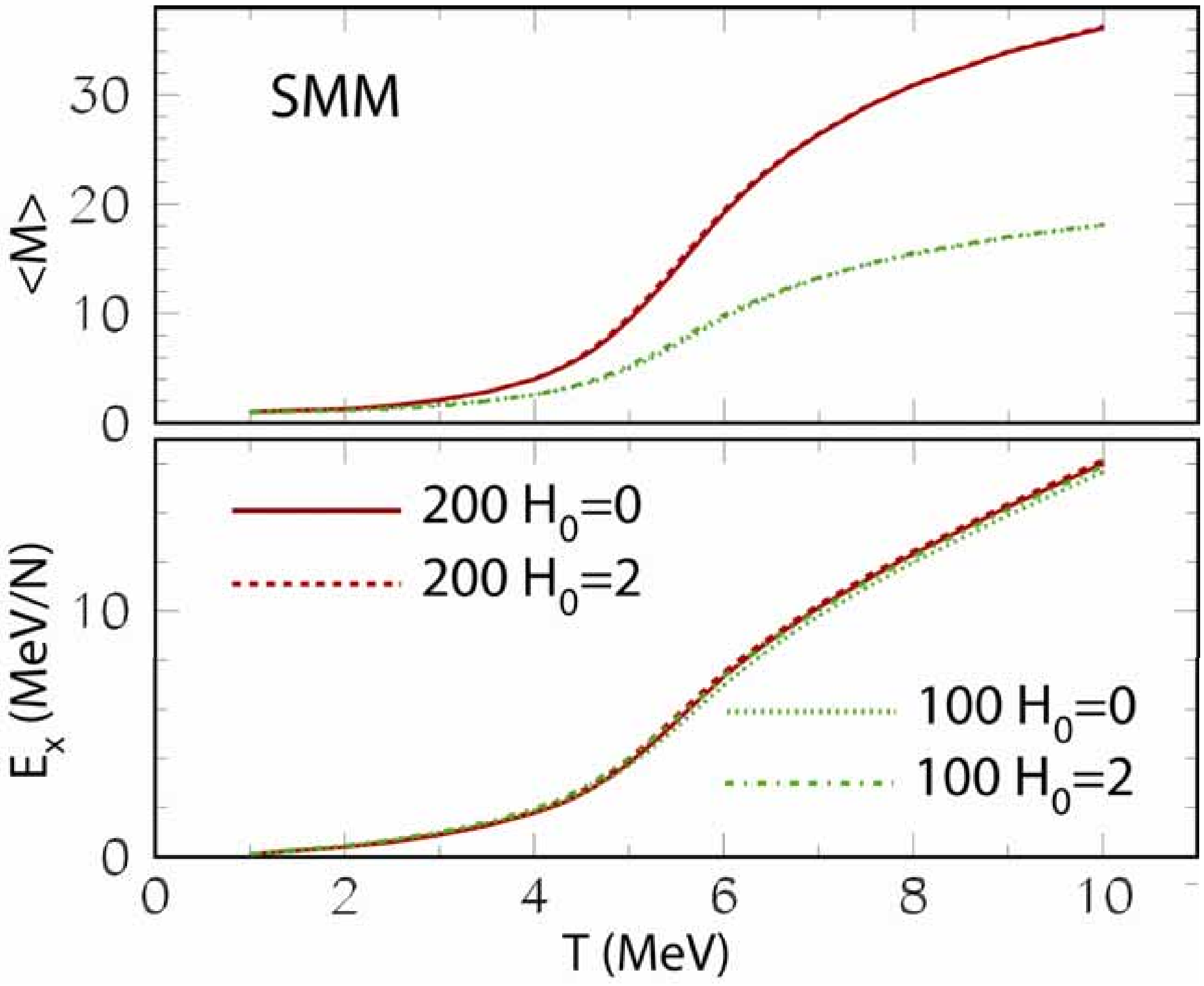
$$\langle \Delta m \rangle_{liquid\ drop} = 1.22\,\text{MeV/c}^2 \qquad rms_{liquid\ drop} = 4.44\,\text{MeV/c}^2$$

Fragment distribution

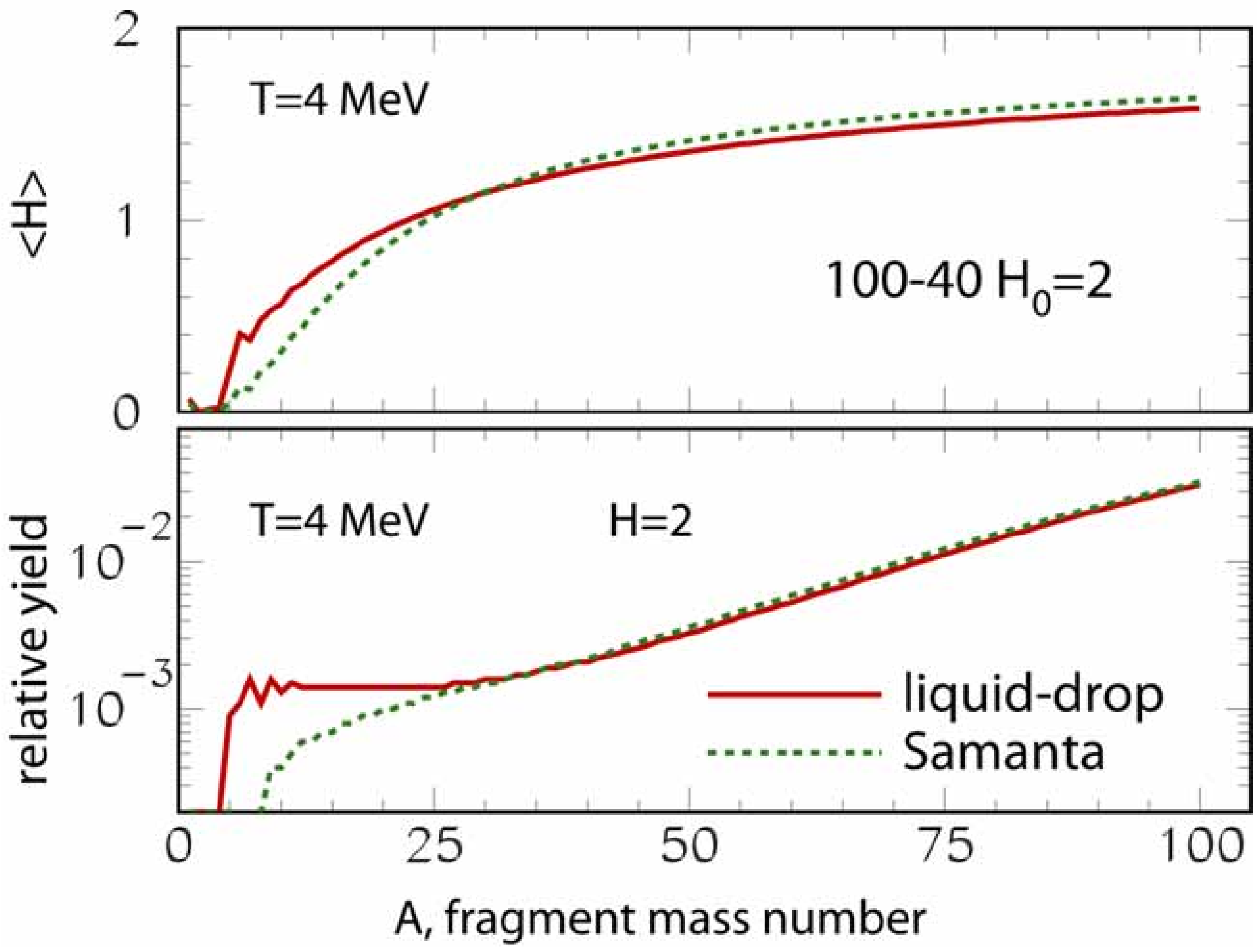
- Multifragmentation of source A_0=100, Z_0=40, H_0=2 and temperature T
- general thermodynamical characteristics of the hyper-systems (with small admixture of strangeness) are similar to the ones of conventional matter
  - production of large hypernuclei dominates at low excitation energies
  - smooth transition to small hypernuclei with increasing excitation energy;



Main Characteristics



Hypernuclei in Multifragmentation



$$E_{sam}^{hyp} = Y \cdot \left(-10.68 + \frac{48.7}{A^{2/3}} \right)$$

$$E_{LD}^{hyp} = \frac{Y}{A} \left(-10.68 + 21.27 A^{2/3} \right)$$

- relative yields reflect properties of mass formulae of hypernuclei

Hypernuclei with extreme isospin

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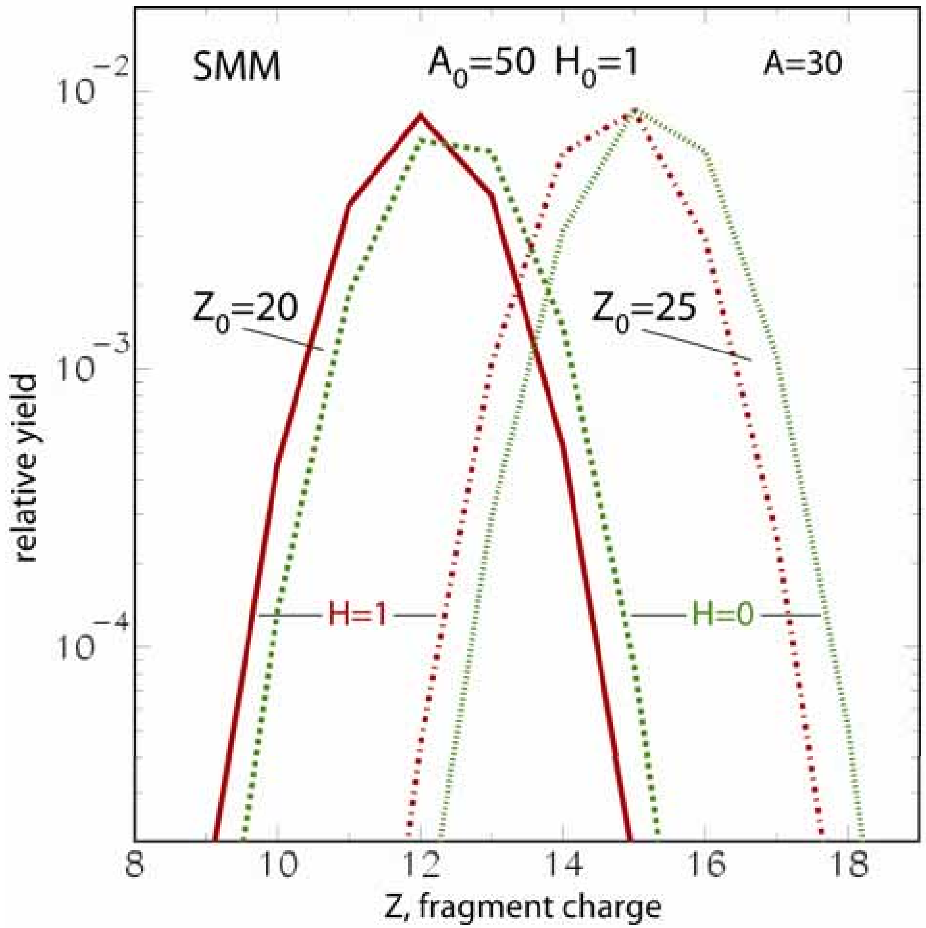


- N/Z of projectile influences charge distribution of primary fragments

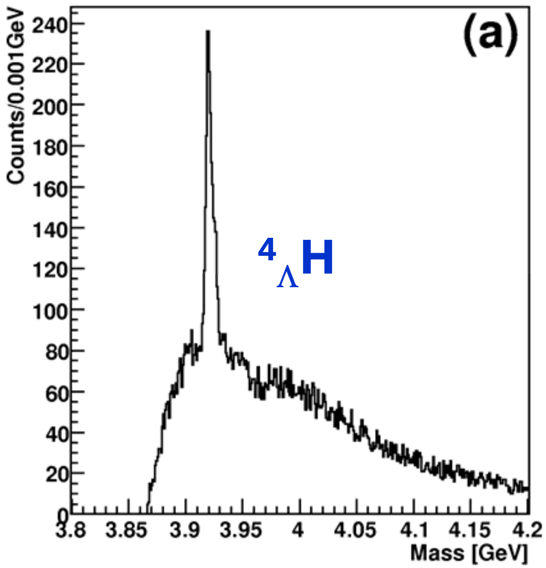
The HypHI Project at GSI

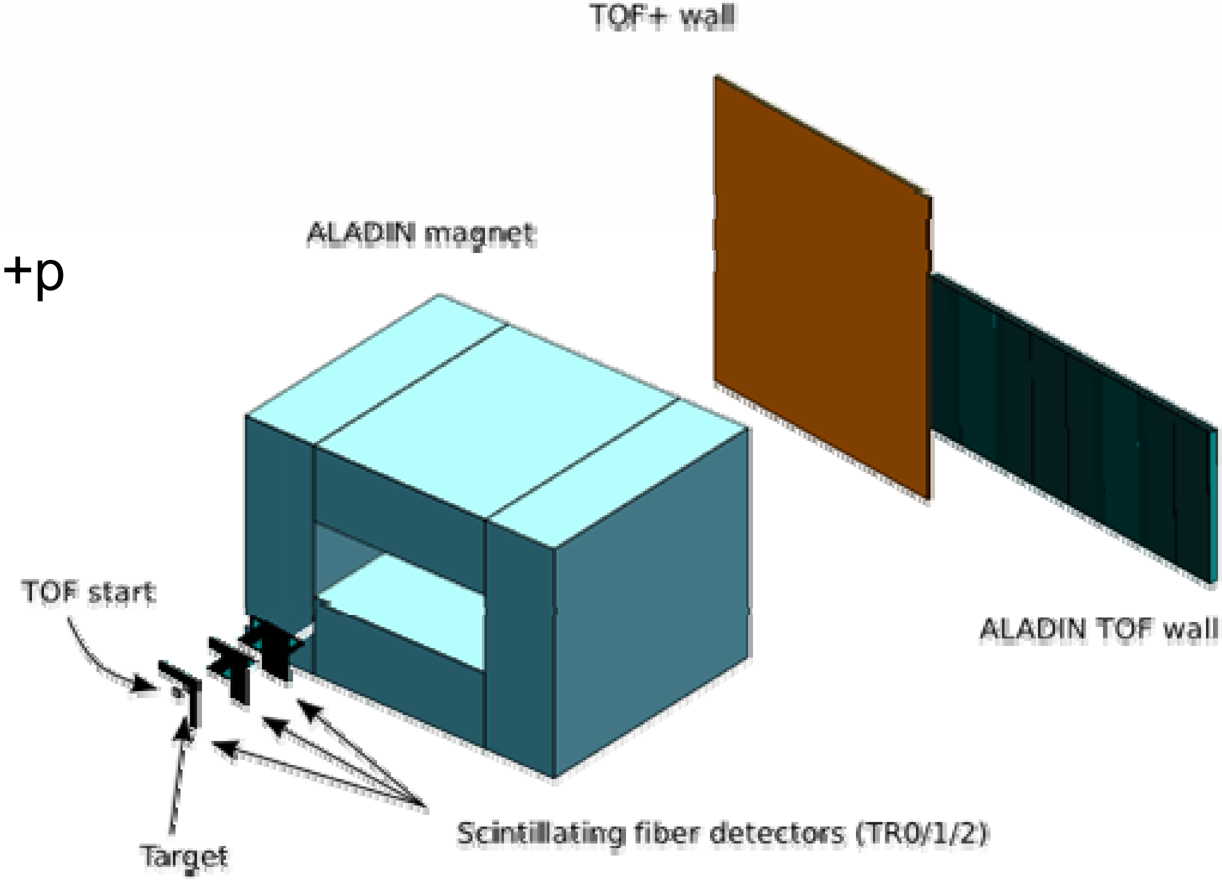
- Phase 0: The goal of the Phase 0 experiments
  - **To confirm Dubna's hypernuclear production at 2 A GeV with ^{6}Li primary beams : Mesonic decay $\Lambda \rightarrow \pi^- + p$**

$$^3_\Lambda H \rightarrow \pi^- + ^3He$$

$$^4_\Lambda H \rightarrow \pi^- + ^4He$$

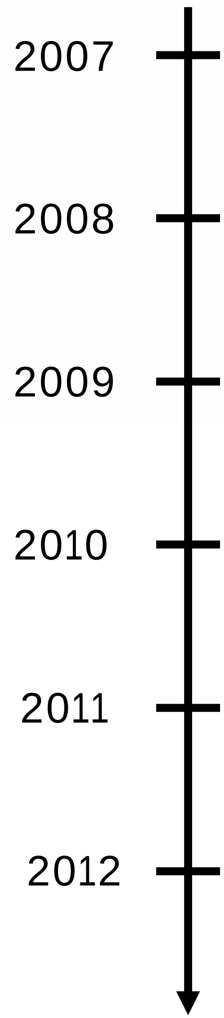
$$^5_\Lambda H \rightarrow \pi^- + ^4He + p$$

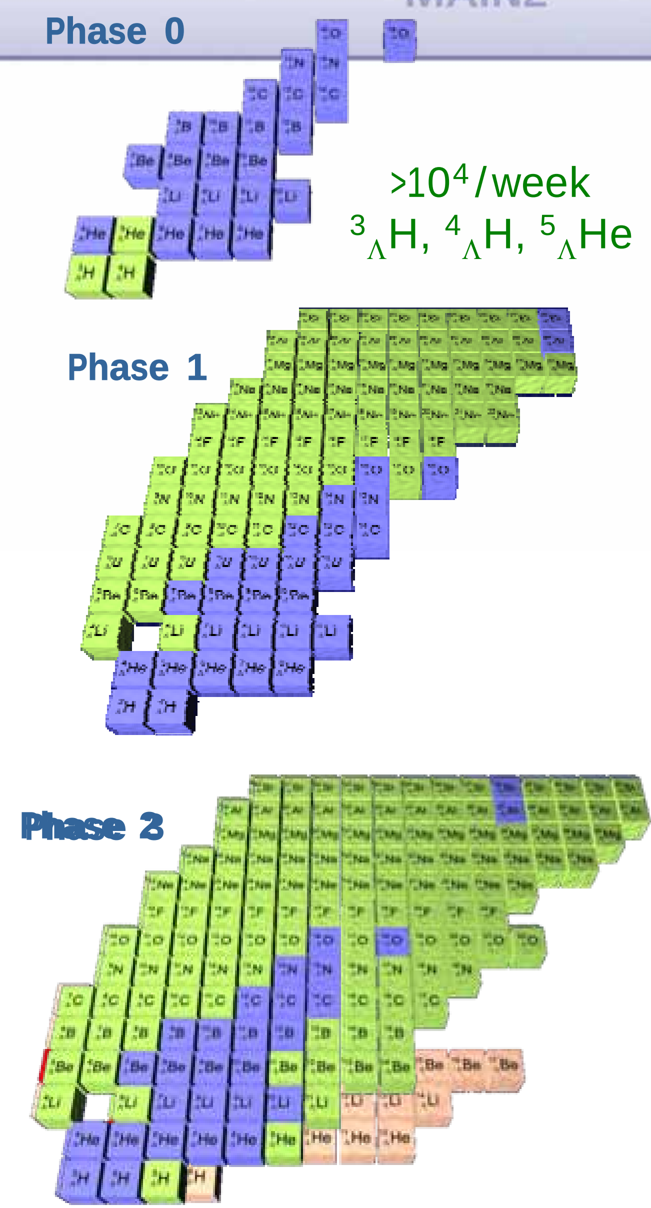




The HYPHI Project T. Saito

- Design study, preparation for the phase 0 experiment
- Phase 0: experiment with $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $^{5}_{\Lambda}He$
- Design study for the setup for hypernuclear non-mesonic weak decay measurements
- Phase 1: Experiments for proton rich hypernuclei
- Phase2: Experiment for neutron rich hypernuclei at NuSTAR/FAIR
- Phase 3: Hypernuclear separator
  - Hypernuclear magnetic moments
  - Hypernuclear driplines





Summary

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- Hypernuclei represent a unique bridge between traditional nuclear physics and hadron physics
- Worldwide, several new activities will help to overcome present limitations of this field
- Projectile fragmentation in energetic HI collisions allows to study nuclear systems containing hyperons at densities different from ρ_0
- Fragment distributions of hypernuclei show sensiivities to hyperon mass formulae

A. Botvina and J.P., Phys. Rev C **76**, 024909 (2007)

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Thank you!