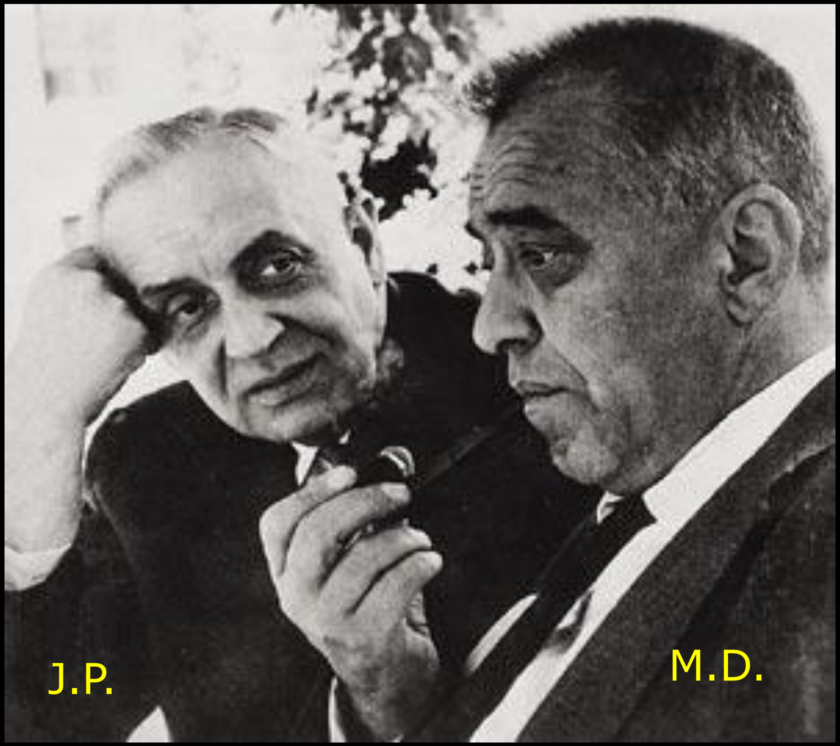
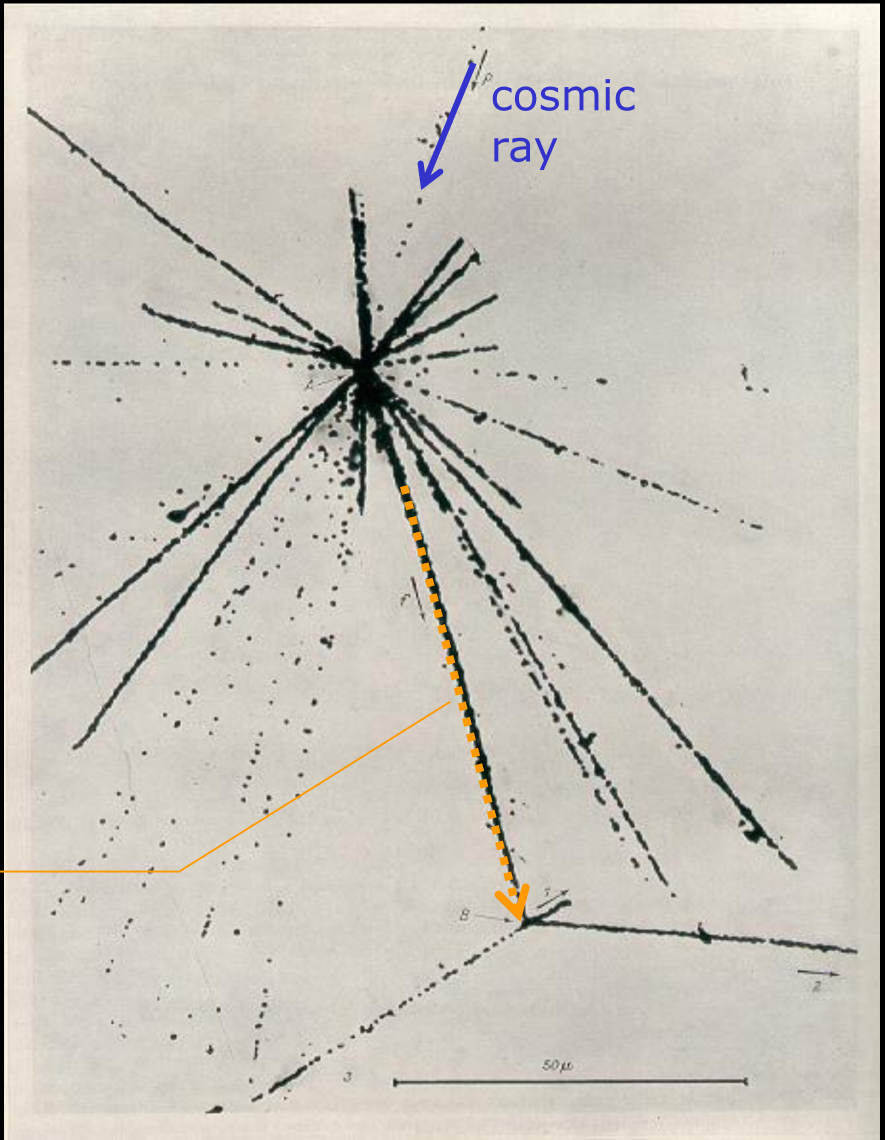
It gegan in Warsaw – September 19th 1952

- Marian Danysz, Jerzy Pniewski, et al. Bull. Acad. Pol. Sci. III **1**, 42 (1953)
- Marian Danysz, Jerzy Pniewski, Phil. Mag. **44**, 348 (1953)





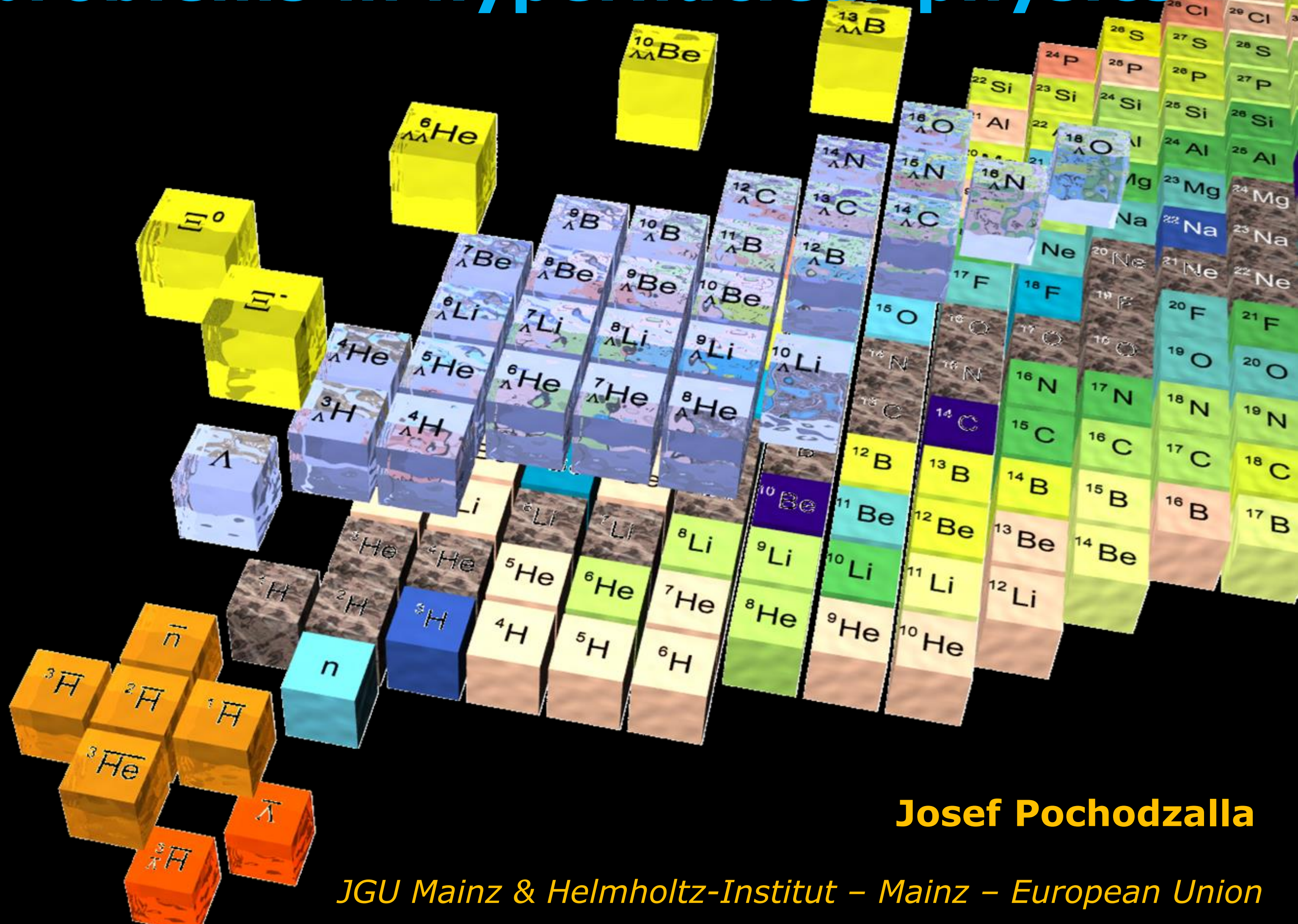
$$t > \frac{s}{c} \sim \frac{80\mu m}{300000 km/s} \approx 2.6 \cdot 10^{-13} s$$

$$\tau(\Lambda) = 2.6 \cdot 10^{-10} s$$

$\Rightarrow$ typical for weak decay

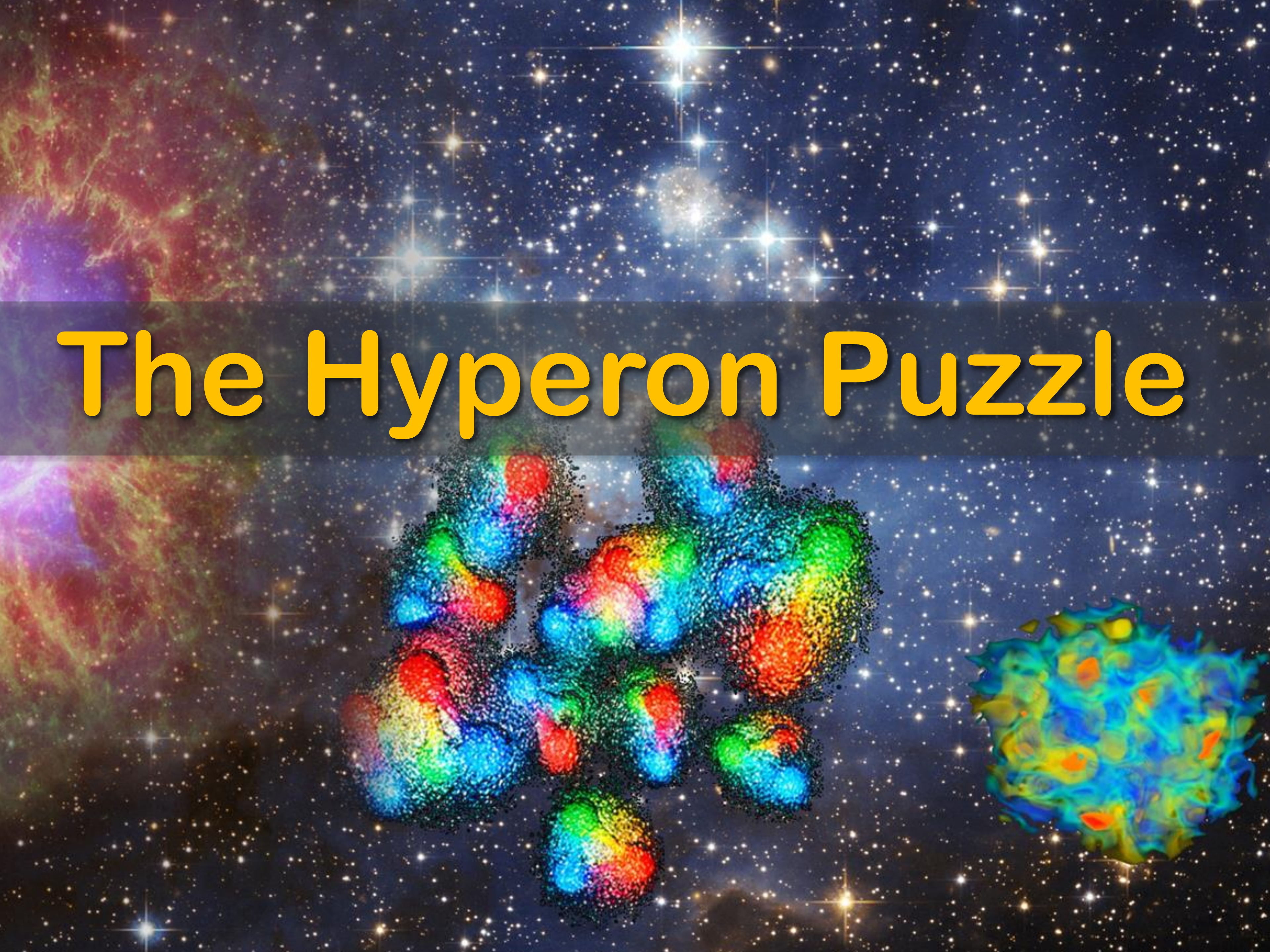
ENSAR2 - NUSPRASEN Workshop on
Nuclear Reactions (Theory and Experiment)
Warsawa - 22-24 January 2018

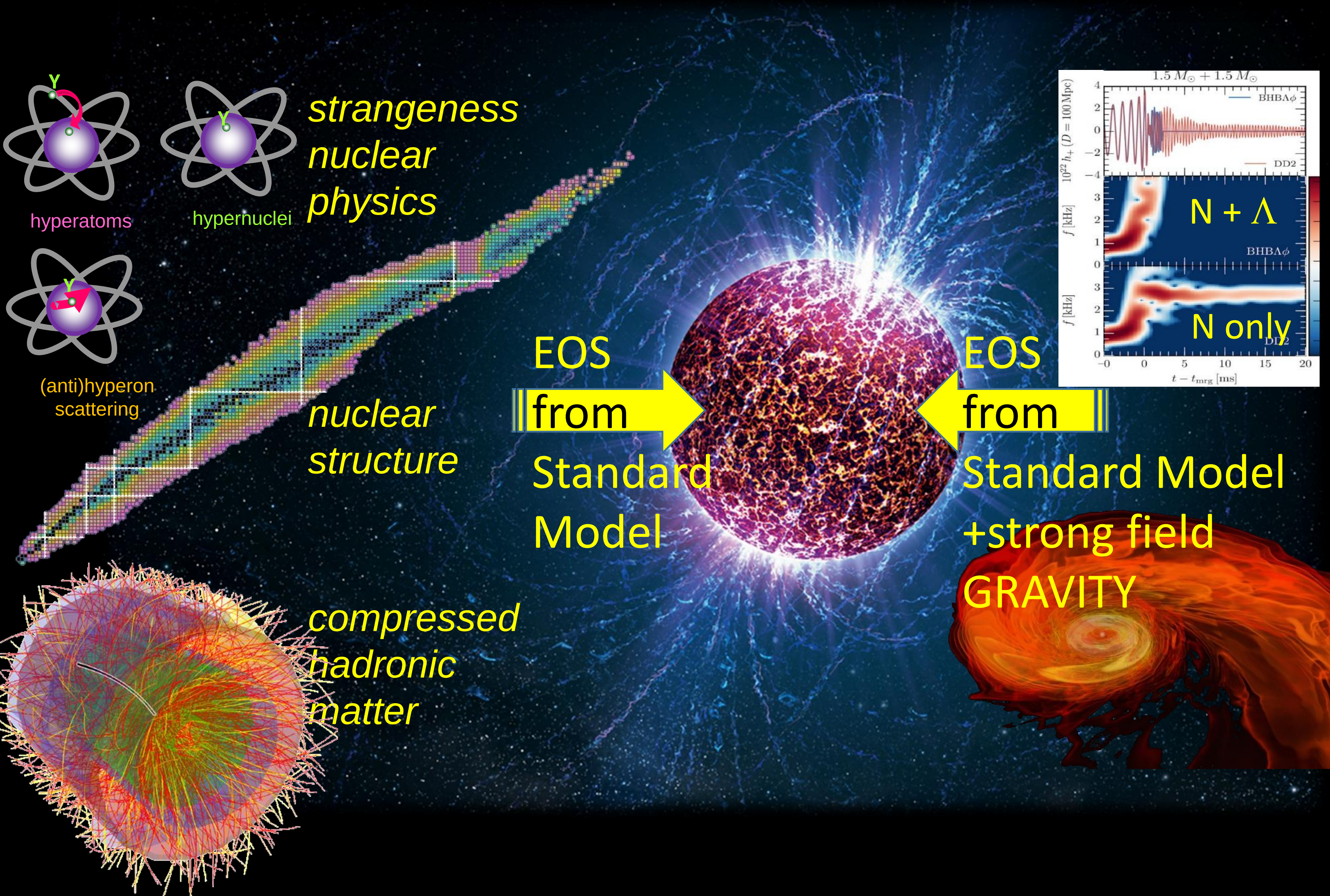
Open problems in hypernuclear physics



Josef Pochodzalla

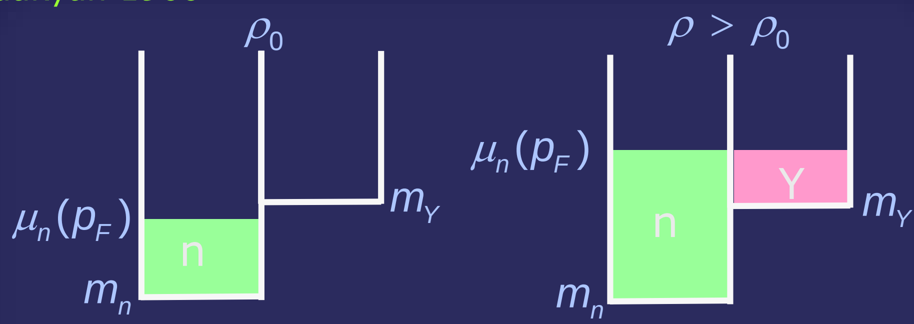
JGU Mainz & Helmholtz-Institut – Mainz – European Union


The Hyperon Puzzle


hyperatoms
hypernuclei
strangeness nuclear physics
(anti)hyperon scattering
nuclear structure
compressed hadronic matter
EOS from Standard Model
EOS from Standard Model +strong field GRAVITY
1.5 M⊙ + 1.5 M⊙
BHBΛφ
DD2
N + Λ
N only
$10^{22} h_+ (D = 100 \,\mathrm{Mpc})$
f [kHz]
$t - t_{\mathrm{mrg}}$ [ms]

Hyperon Puzzle

Cameron 1959,
Ambartsumyan &
Saakyan 1960



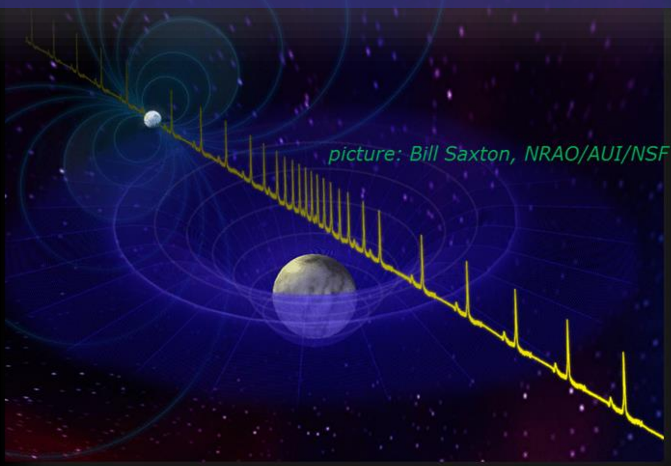
$e^- + p \to \nu_e + \Lambda$ $p_{F,n}^2 + m_n^2 \geq m_\Lambda^2$

m_Λ=1116 MeV, m_n= 939MeV $\Rightarrow p_{F,n} \approx 600 MeV \simeq 3 fm^{-1}$

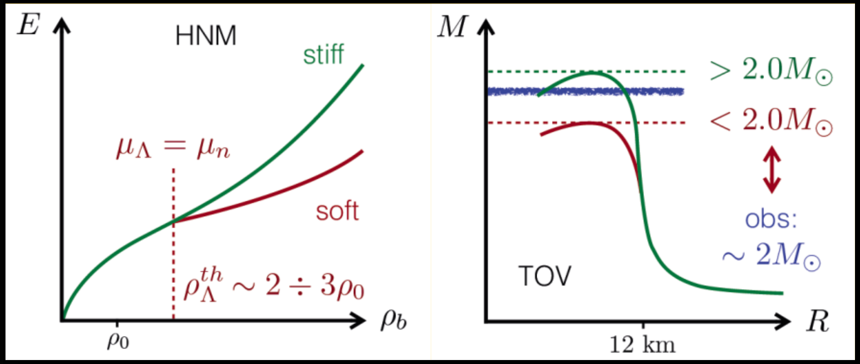
non-interacting Fermi-gas: $\rho = \frac{p_{F,n}^3}{3\pi^2} \Rightarrow p_{F,n}(\rho_0) = 1.7 fm^{-1}$

$\Rightarrow$ appearence of hyperons at $\rho_\Lambda \approx 5.5 \rho_0$

with interactions $\rho_\Lambda \approx 2 - 3 \rho_0$



But:
the appearance of hyperons
$\Rightarrow$ relieve of Fermi pressure
$\Rightarrow$ softer equation of state
$\Rightarrow$ reduction of maximal mass



M(PSR J1614-2230) =1.928 ± 0.017 $M_\odot$

M(PSR J0348+0432)=2.01 ± 0.04 $M_\odot$

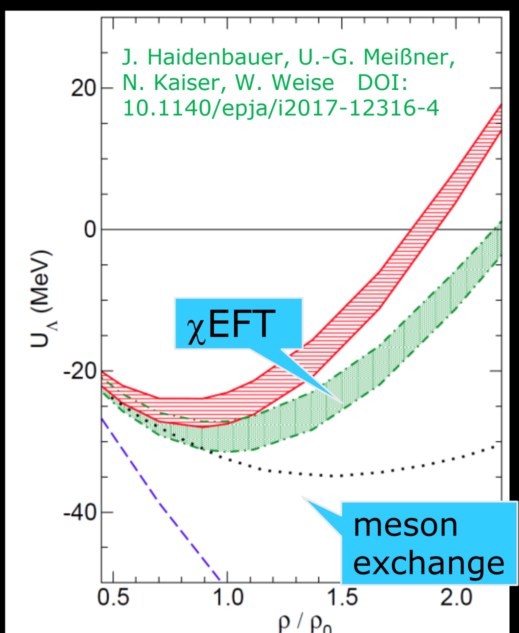
M(PSR J1946+3417)=1.828 ± 0.022 $M_\odot$

P. B. Demorest *et al.*, Nature 467 (2010)
update: E. Fonseca et al., ApJ 832, 167 (2016)
J. Antoniadis *et al.*, Science 340 (2013)
E.D. Barr *et al.*, MNRAS 465, 1711–1719 (2017)

Possible Solutions to the Puzzle

YN and YY Interaction

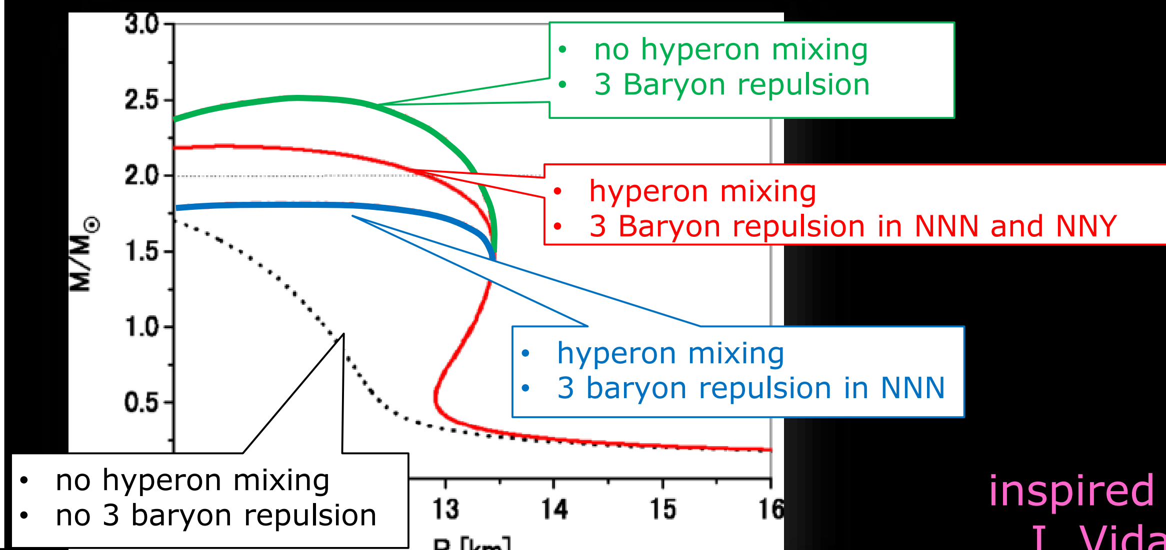
- YY vector meson repulsion: ϕ *meson coupled only to hyperons; yielding strong repulson at high* ρ
- Chiral forces: *YN from* χ*EFT predicts* Λ *s.p. potential more repulsive than from meson exchange*



Hyperonic Three-body force

- Natural solution based on the known importance of 3NN forces in nuclear physics

Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A Rijken, Phys. Rev. C 90, 045805 (2014)



Quark Matter

- Phase transition to deconfined QM at densities lower than hyperon appearence
- That requires QM which
- (i) is significantly repulsive
- (ii) attractive enough to avoid reconfinement

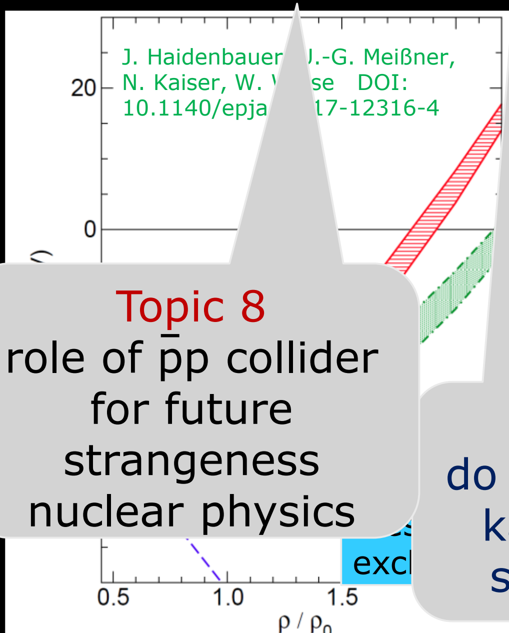
inspired by I. Vidana

Possible Solutions to the Puzzle

YN and YY Interaction

- YY vector meson repulsion: ϕ *meson coupled only to hyperons; yielding strong repulson at high* ρ
- Chiral forces: *YN from* χ*EFT predicts* Λ *s.p. potential more repulsive than from meson exchange*

J. Haidenbauer, U.-G. Meißner, N. Kaiser, W. W se DOI: 10.1140/epja 17-12316-4



Hyperonic Three-body force

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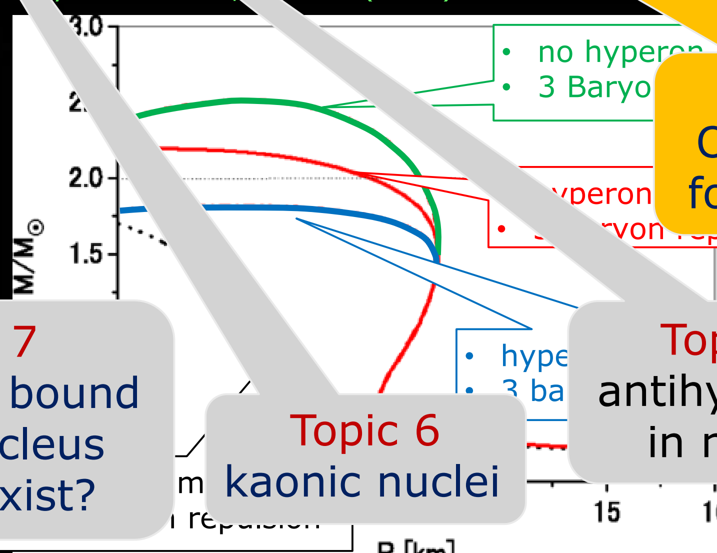


…er

- Ph… to de… at densities lower than hyperon… ce
- That … which
- (i) is significantly
- …h …ent

Topic 1
Hypertriton puzzle

Topic 2
nnΛ puzzle

Topic 3
Charge Symmetry breaking Λn - Λp

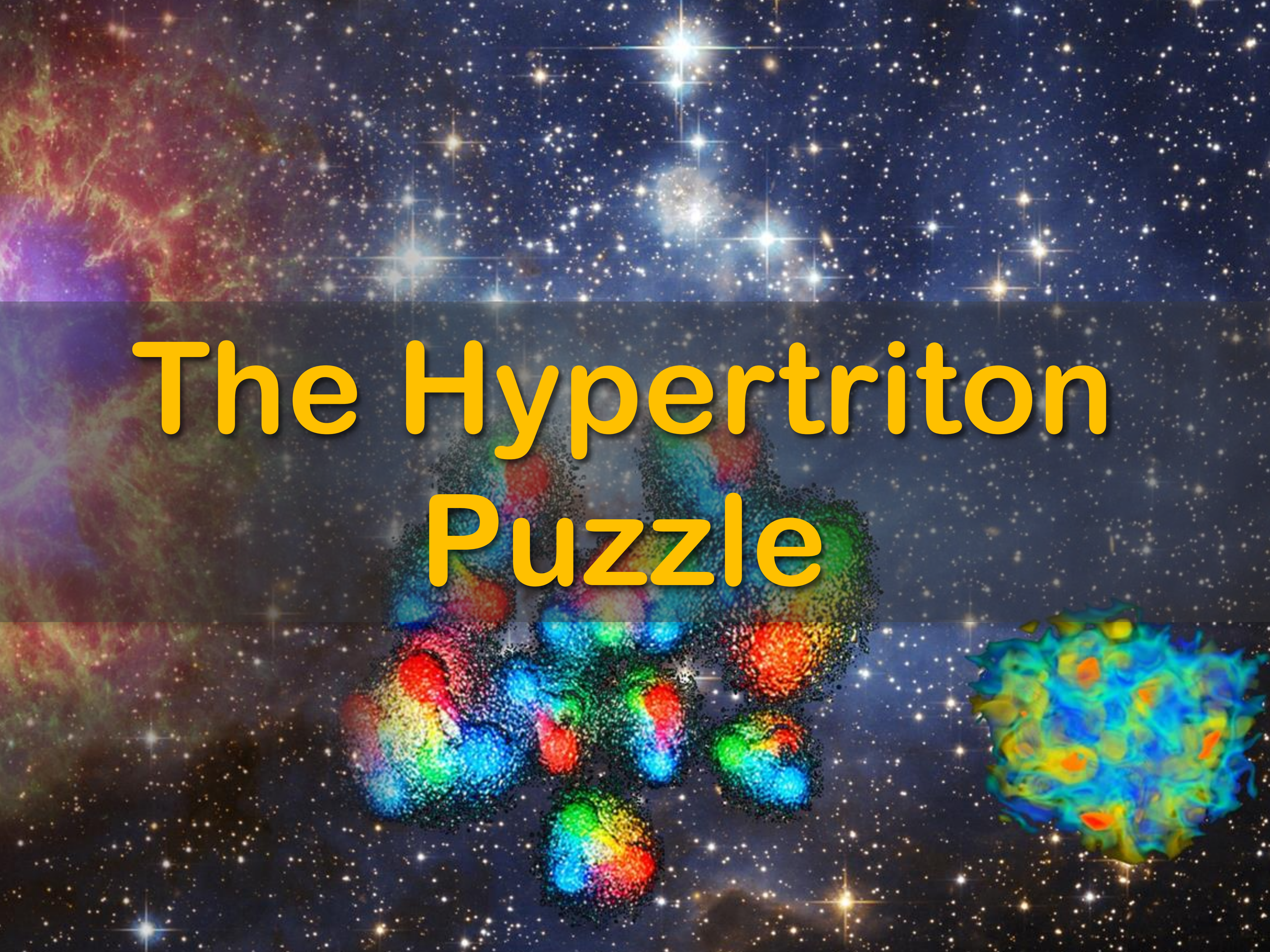
Topic 4
Optimal strategy for $\Lambda\Lambda$ hypernuclei

Topic 5
antihyperons in nuclei

Topic 6
kaonic nuclei

Topic 7
do deeply bound kaon-nucleus states exist?

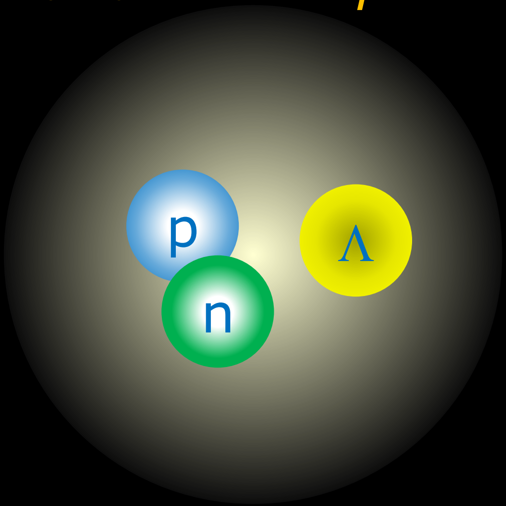
Topic 8
role of p̄p collider for future strangeness nuclear physics

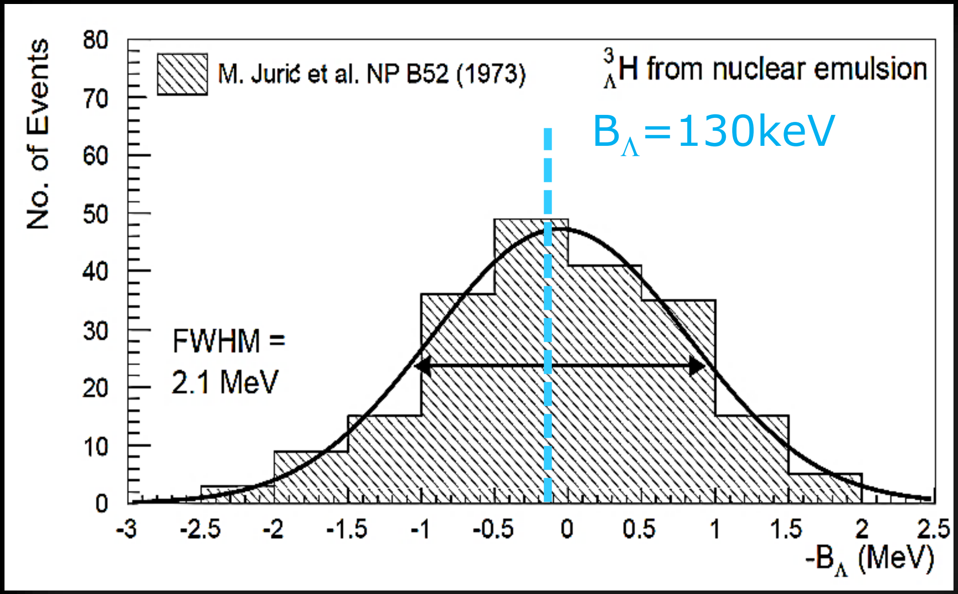

The Hypertriton
Puzzle

The Hypertriton Puzzle

Do we understand the simplest Hypernucleus?

$^{3}_{\Lambda}H$

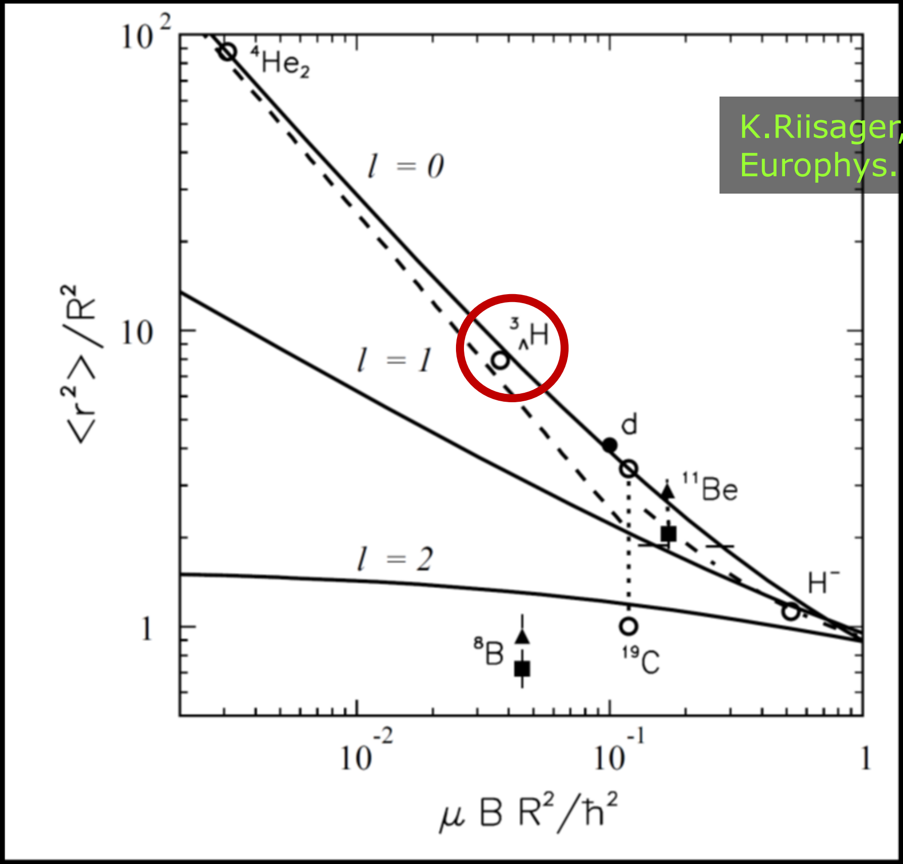




The $^3_\Lambda$H Puzzle: Part 1 - Λ Binding Energy

- $^3_\Lambda$H is most fascinating halo nucleus
  - Binding energy ≈130keV ⇒ Characteristic length of two-body s-wave halo system small

$$\langle \Delta r^2 \rangle = \hbar^2 / (4\mu B) \xrightarrow{^3_\Lambda \mathrm{H}} 10\,\mathrm{fm}$$

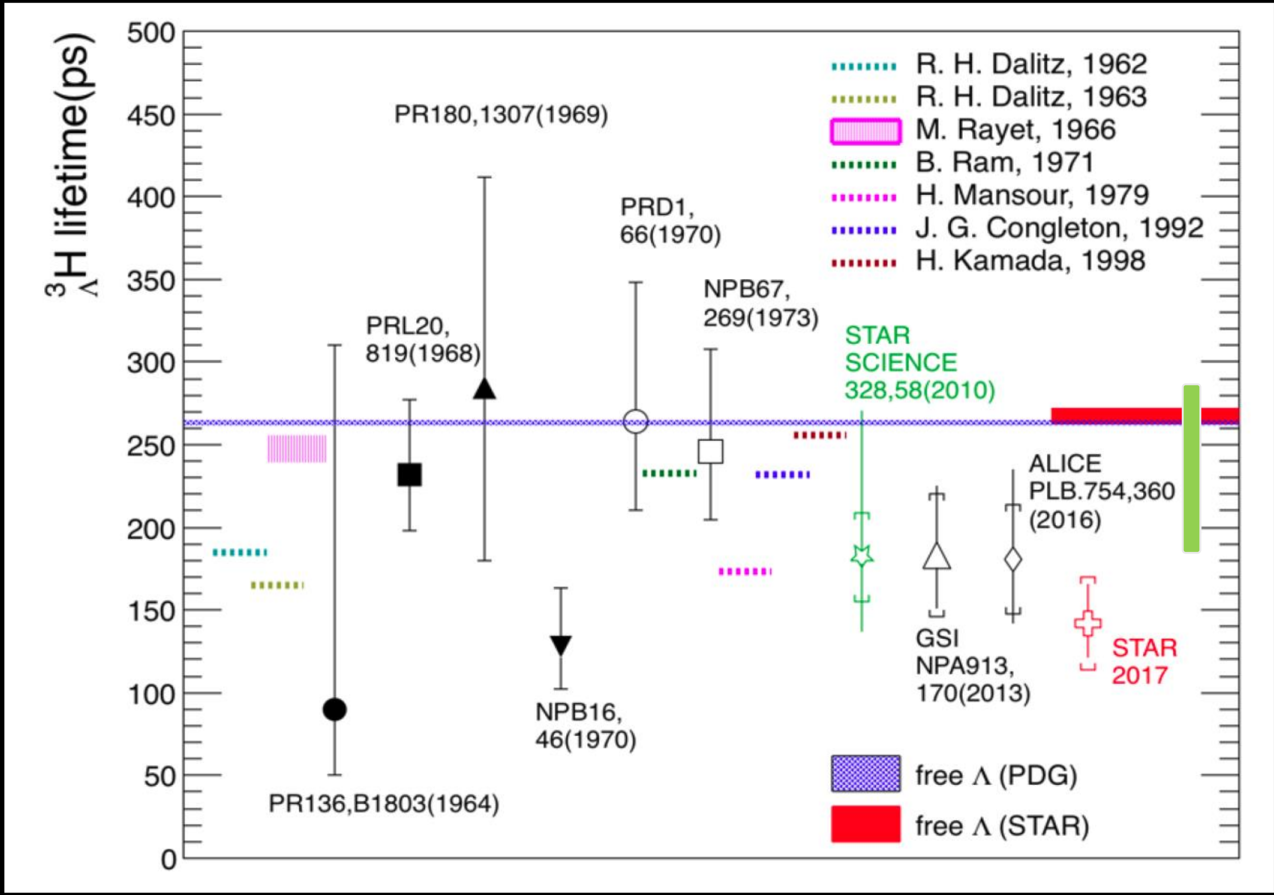


ratio of halo and core-potential square radii

scaled separation energy

K.Riisager,D.V.FedorovandA.S.Jensen, Europhys. Lett 49, 547 (2000)

The $^{3}_{\Lambda}H$ Puzzle: Part 2 - Lifetime



ALICE, preliminary
237^{+33}_{-36}(stat.)±17(syst.)ps

STAR arXiv:1710.00436v1 [nucl-ex] 1st Oct 2017

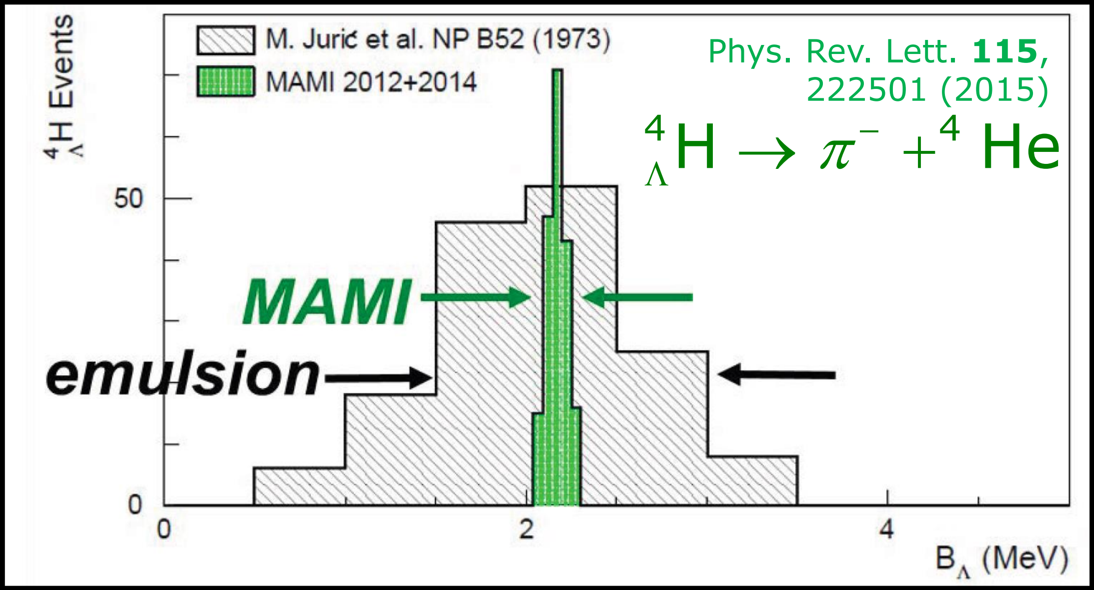
small binding energy ? small lifetime

Approaching the $^{3}_{\Lambda}$H Puzzle

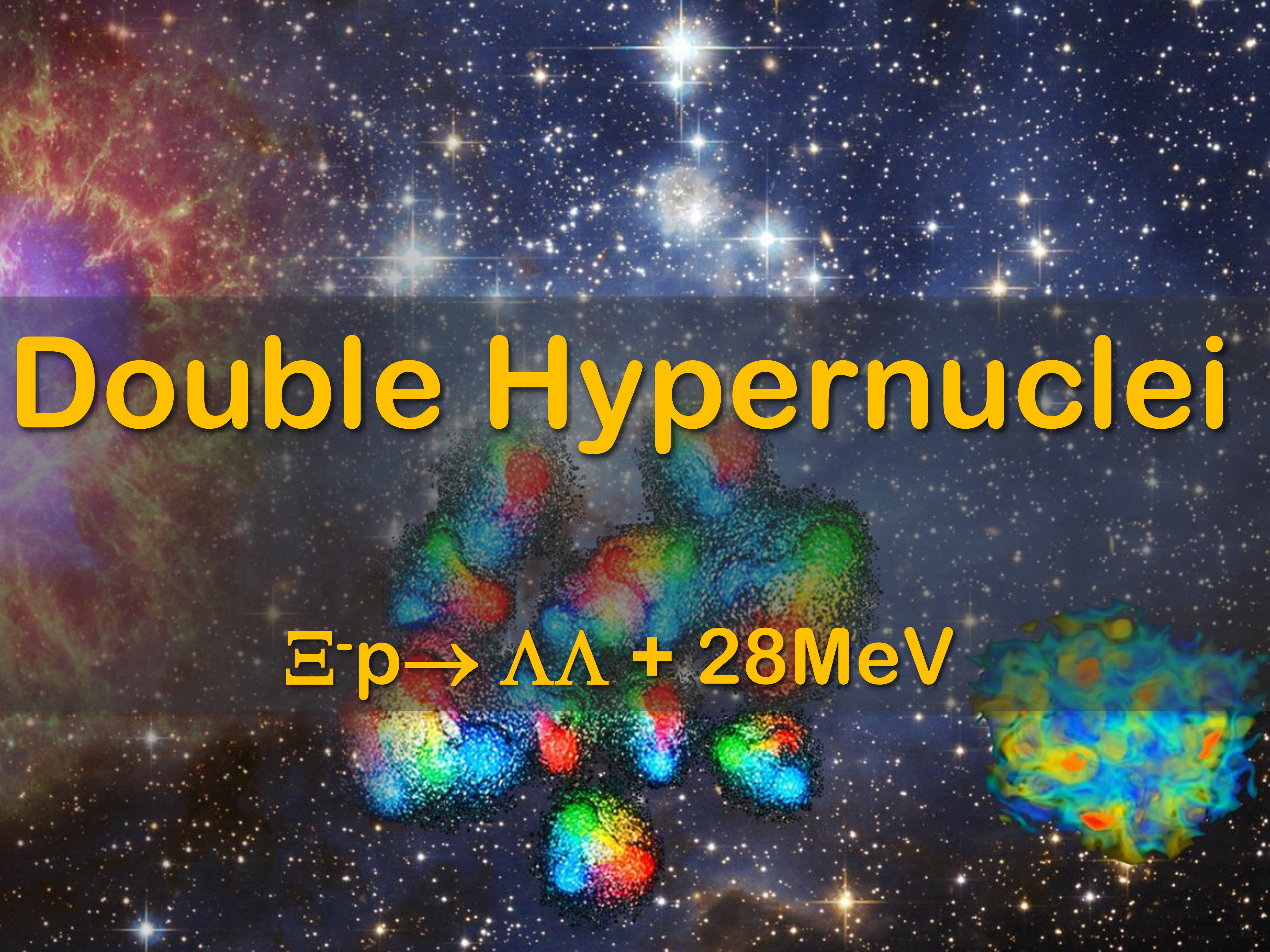
small binding energy ? small lifetime

- New precision mass measurement at MAMI in 2019
  - Make use of excellent beam quality at MAMI
  - Precision *absolute* energy calibration interference of undulator radiation

- new lifetime measurements
  - 2019: ELPH (γ,K^+)
  - 2019: WASA @ GSI/FAIR
  - 2018: ALICE - end Run2: 2x statistics
  - 2023: ALICE – end run 3: 200x stat.
  - 202x: J-PARC (π^-,K^0)

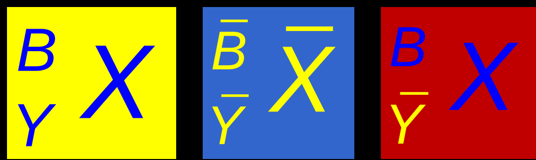


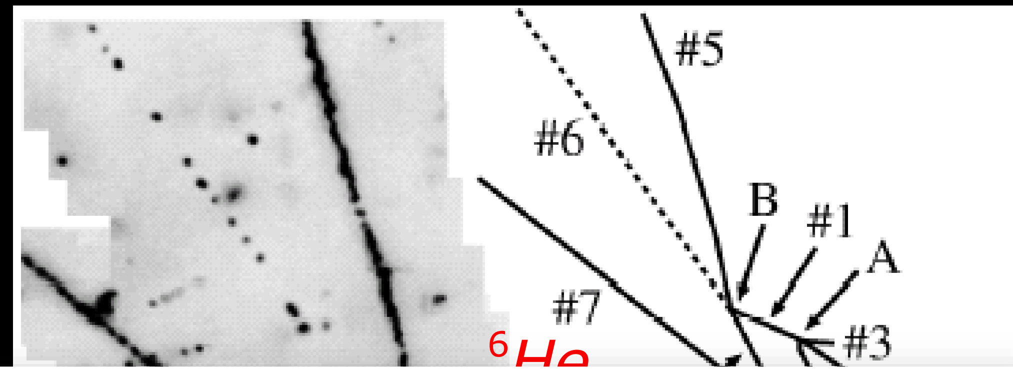
Double Hypernuclei



$$\Xi^{-}p \rightarrow \Lambda\Lambda + 28\text{MeV}$$

Double Hypernuclei are Shy



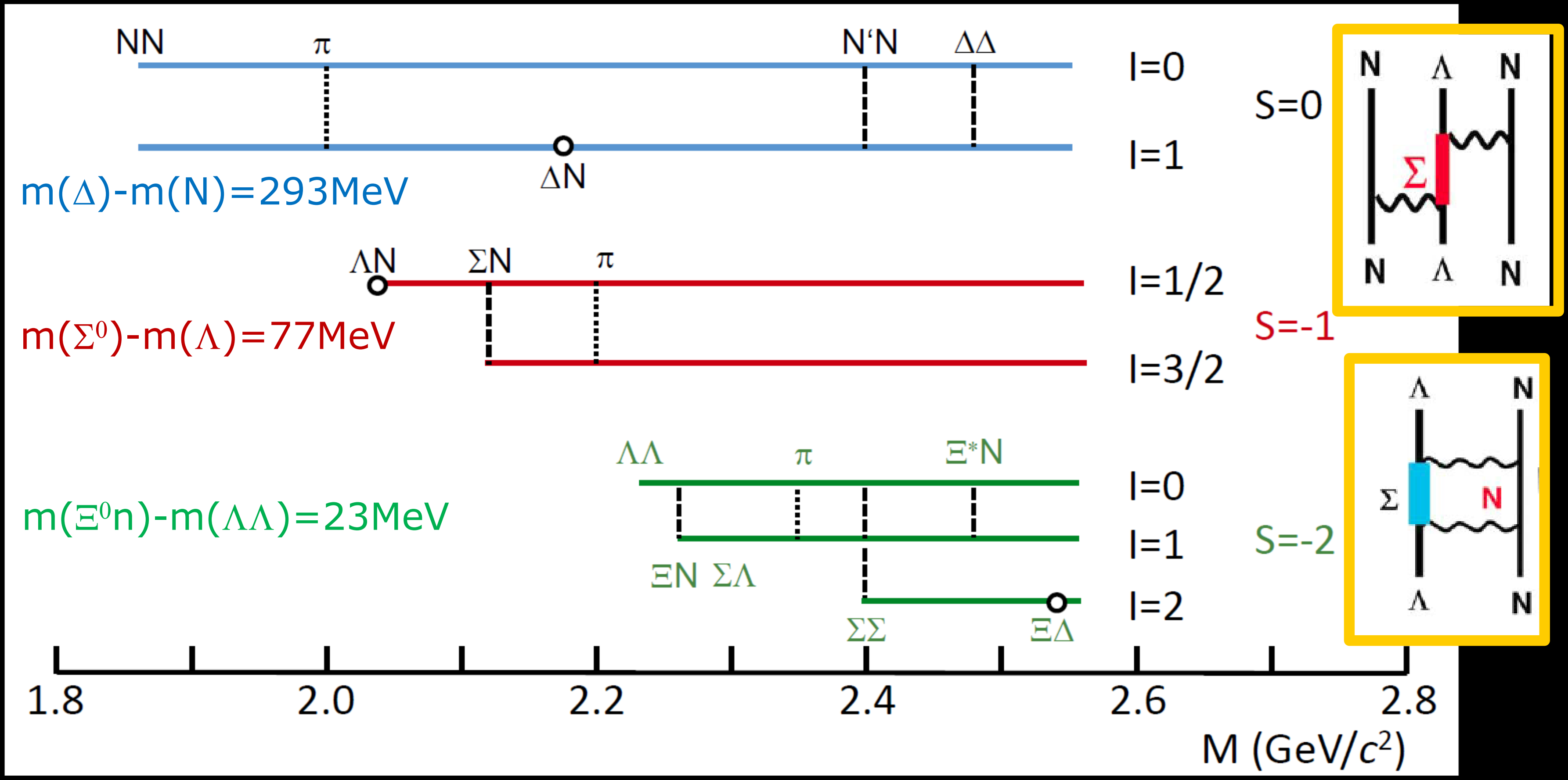


Nucleus	$\Delta B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z)$ (MeV)	Experiment	Reference	Remark
$^{10}_{\Lambda\Lambda}$Be	4.3 ± 0.4	Danysz (1963)	[77, 78] [74]	K^- + nuclear emulsion; $\Delta B_{\Lambda\Lambda}$ consistent with NAGARA if decay to $^{9}_{\Lambda}$Be* at $E_x \approx 3$ MeV [81, 11]
$^{6}_{\Lambda\Lambda}$He	4.7 ± 0.6	Prowse (1966)	[198]	K^- + nuclear emulsion only schematic drawing
$^{10}_{\Lambda\Lambda}$Be or $^{13}_{\Lambda\Lambda}$B	-4.9 ± 0.7 0.6 ± 0.8	KEK-E176 (1991) Aoki event	[20, 245] [88, 24, 172]	hybrid-emulsion $(K^-,K^+)\Xi^-_{stopped}$
$^{6}_{\Lambda\Lambda}$He	0.67 ± 0.17	KEK-E373 (2001) NAGARA event	[226, 172] [11]	hybrid emulsion
$^{10}_{\Lambda\Lambda}$Be or $^{10}_{\Lambda\Lambda}$Be*	-1.65 ± 0.15	KEK-E373 (2001) DEMACHIYANAGI event	[10, 172] [11]	$B_{\Lambda\Lambda}$ consistent with Danysz if $E_x \approx 2.8$ MeV
$^{6}_{\Lambda\Lambda}$He or $^{11}_{\Lambda\Lambda}$Be*	3.77 ± 1.71 3.95 ± 3.00 or 4.85 ± 2.63	KEK-E373 (2003) MIKAGE event	[227, 11]	
$^{12}_{\Lambda\Lambda}$Be or $^{11}_{\Lambda\Lambda}$Be*	2.00 ± 1.21 2.61 ± 1.34	KEK-E373 (2010) HIDA event	[172, 11]	

Mixing in Hypernuclei

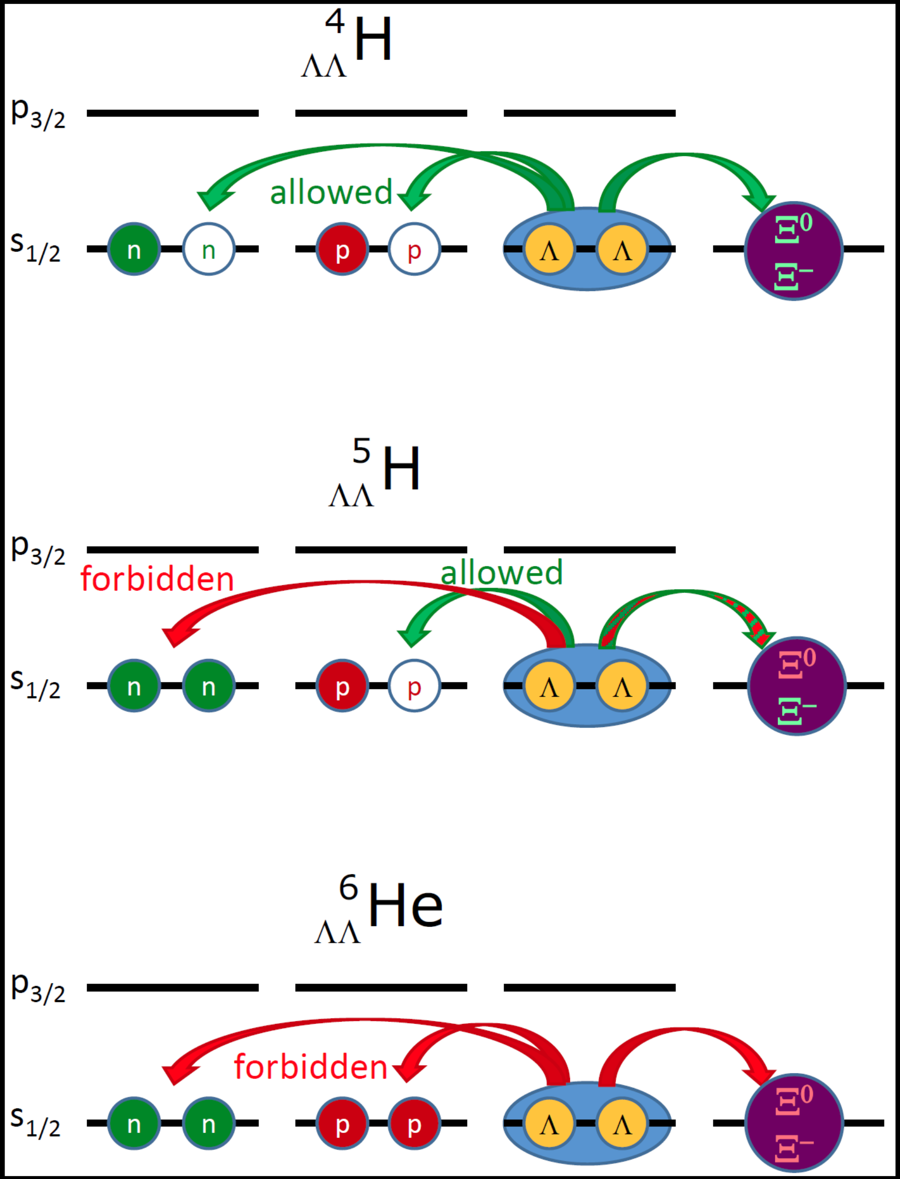
- Mass difference between Σ and Λ in single hypernuclei is small

Thomas Rijken



- hyperon coupling important phenomenon in hypernuclei

Mixing in Double Hypernuclei

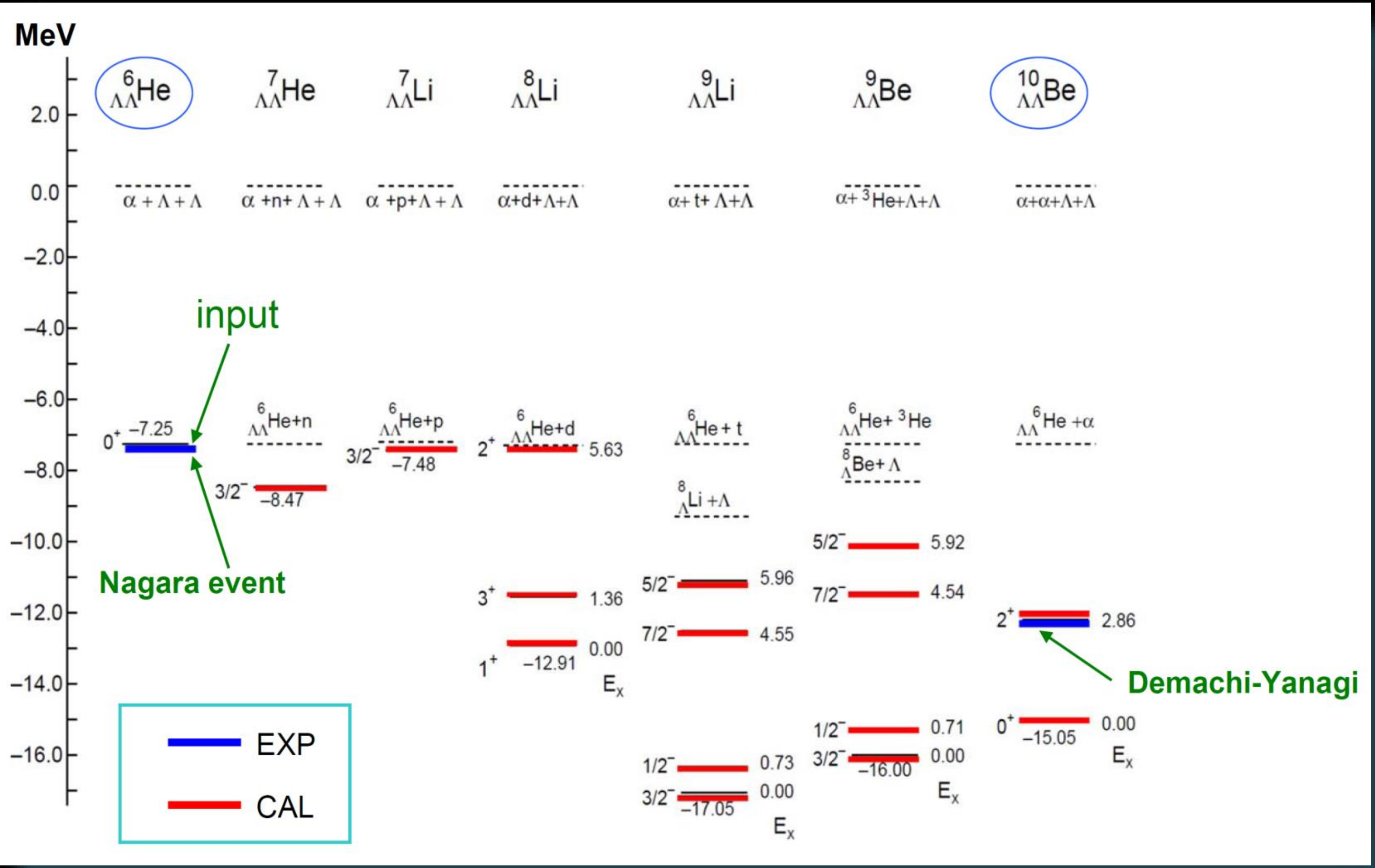


- mixing and Pauli repulsion may procduce an effectivde 3-body repulsion
- depends on spin/nuclear structure of hypernculei
- this mixing might be reflected in the level scheme of double hypernuclei
- precise study needed

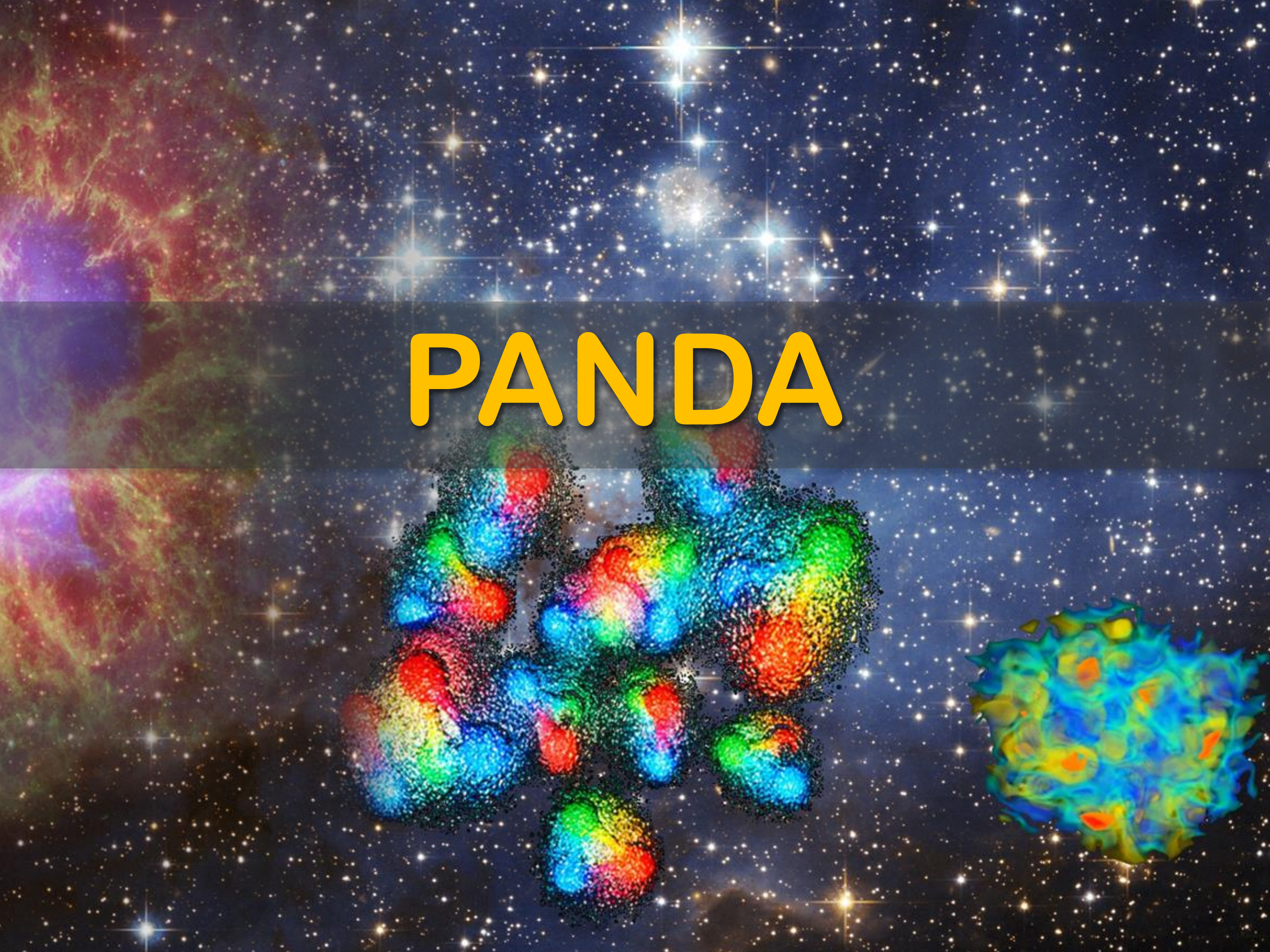
$\Rightarrow$ high resolution γ-spectroscopy

Spectroscopy of ΛΛ-hypernuclei

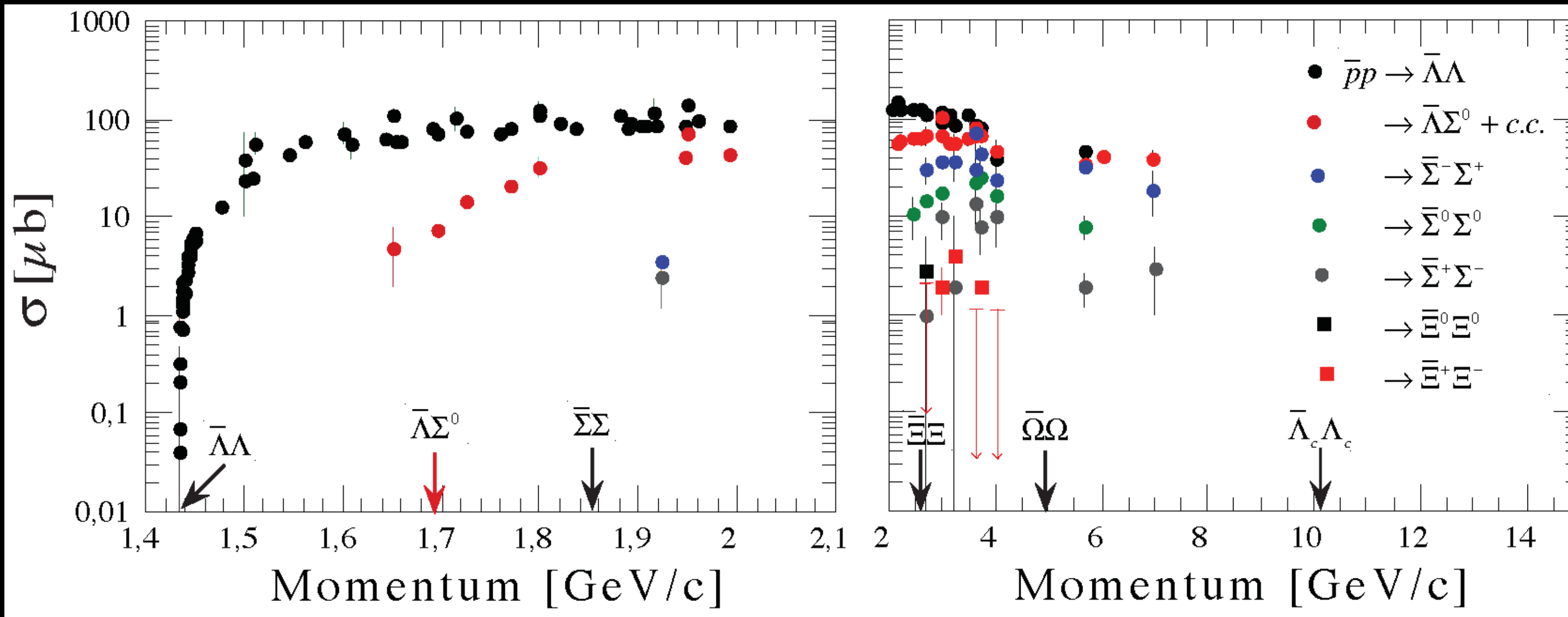
E. Hiyama, M. Kamimura, T.Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002) , 024007



- many excited, particle stable states in double hypernuclei predicted
- level structure reflects in 0th order levels of core nucleus


PANDA

P̄ANDA – a Factory for strange *and* charmed $Y\bar{Y}$-Pairs



Production Rates (1-2 (fb)$^{-1}$/y)

Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$ (→$_{\Lambda\Lambda}$ A)	2μb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ (→ e^+e^-, $\mu^+\mu^-$)	630nb	10^9
χ_2 (→ $J/\psi + \gamma$)	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

Strange Systems at PANDA

Ξ^- production
$\bar{p}N \rightarrow \Xi^- + X$

rescattering in
primary target nucleus

deceleration in
secondary target

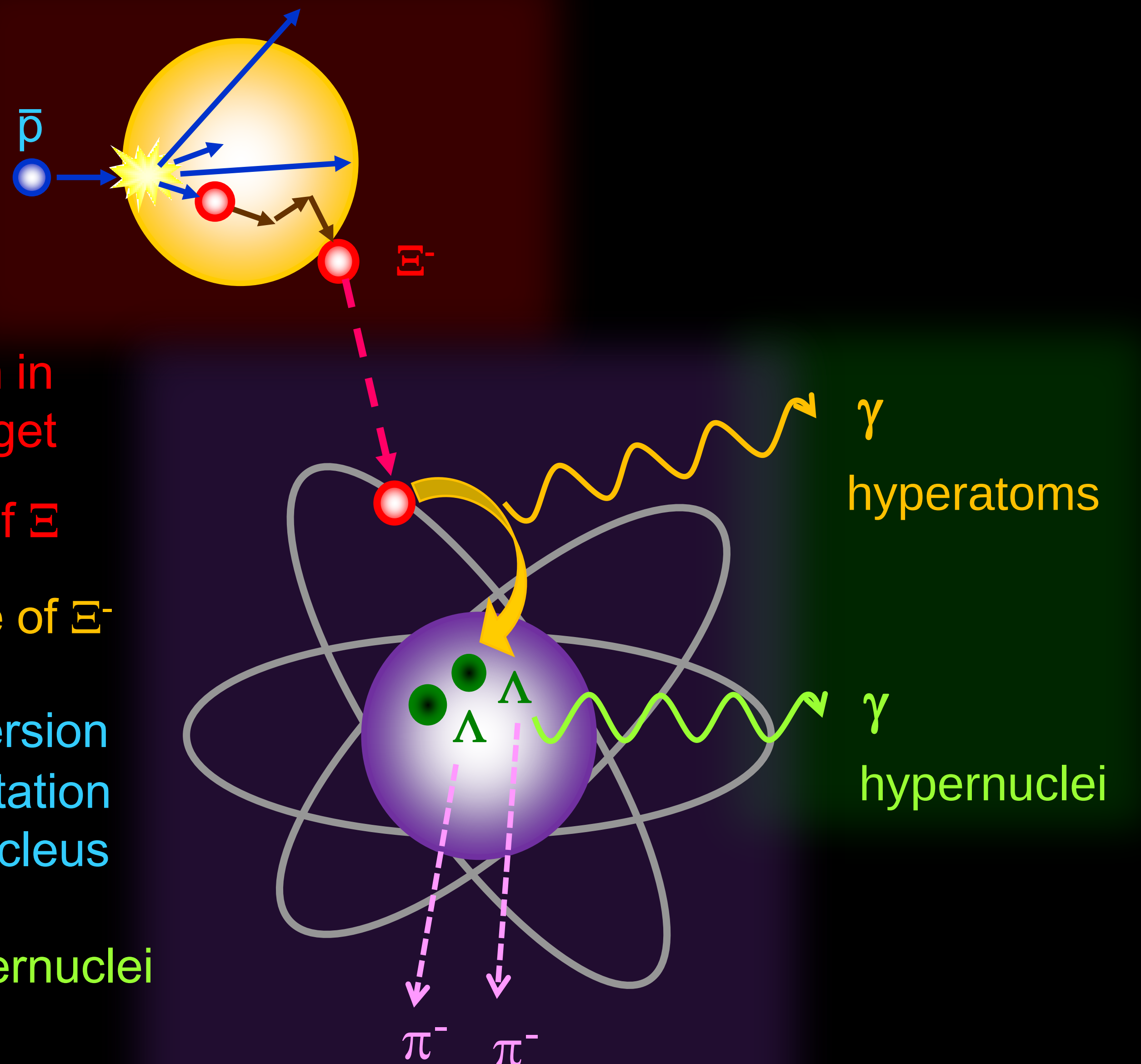
capture of Ξ

atomic cascade of Ξ^-

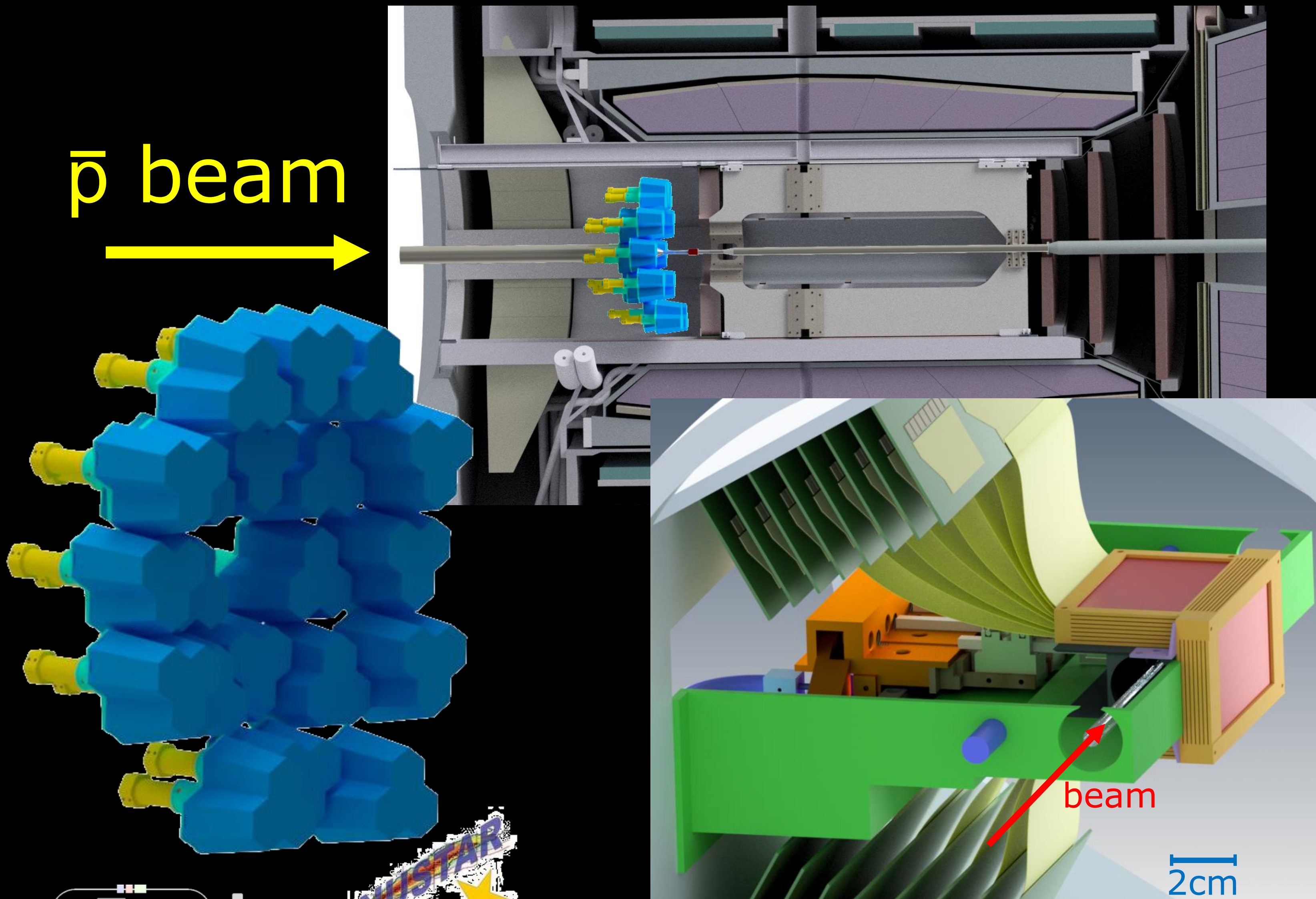
$\Xi^- p \rightarrow \Lambda\Lambda$ conversion
fragmentation
$\rightarrow$ excited $\Lambda\Lambda$-nucleus

γ-decay of $\Lambda\Lambda$ hypernuclei

weak pionic decay

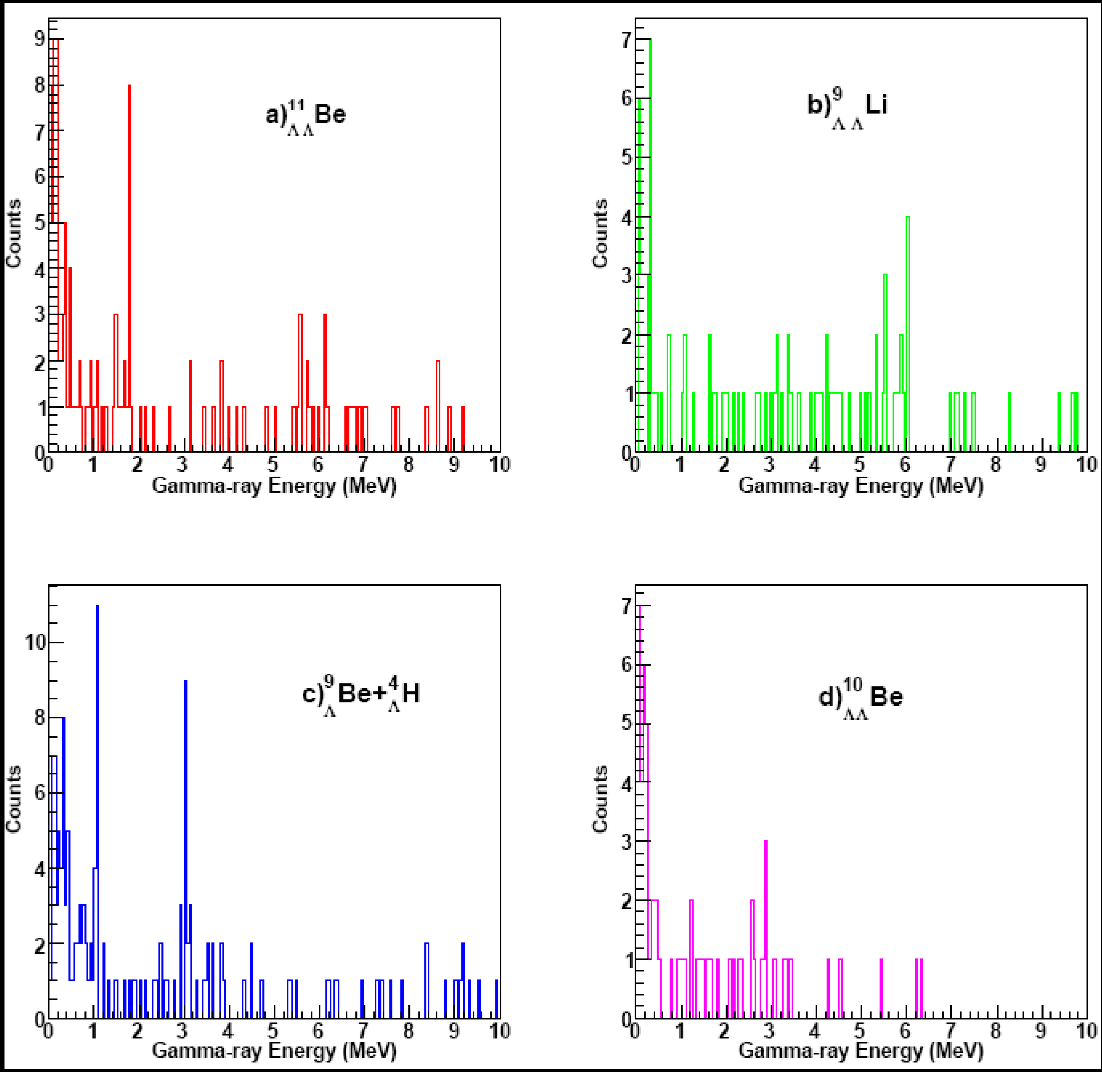


P̄ANDA-HYP setup



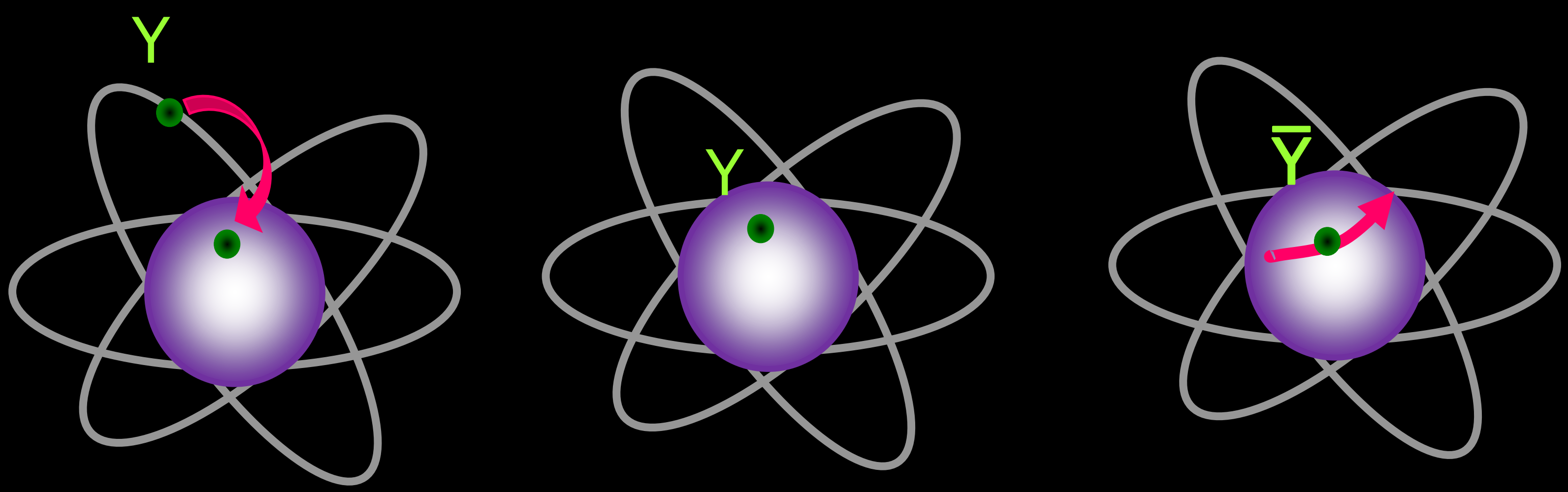
Simulation within PANDA_ROOT…

- Example: secondary ^{12}C target (~2 weeks)
- gated with 2 positive pion momenta



Strangeness Nuclear Physics

= Strangeness in cold nuclei



hyperatoms

hypernuclei

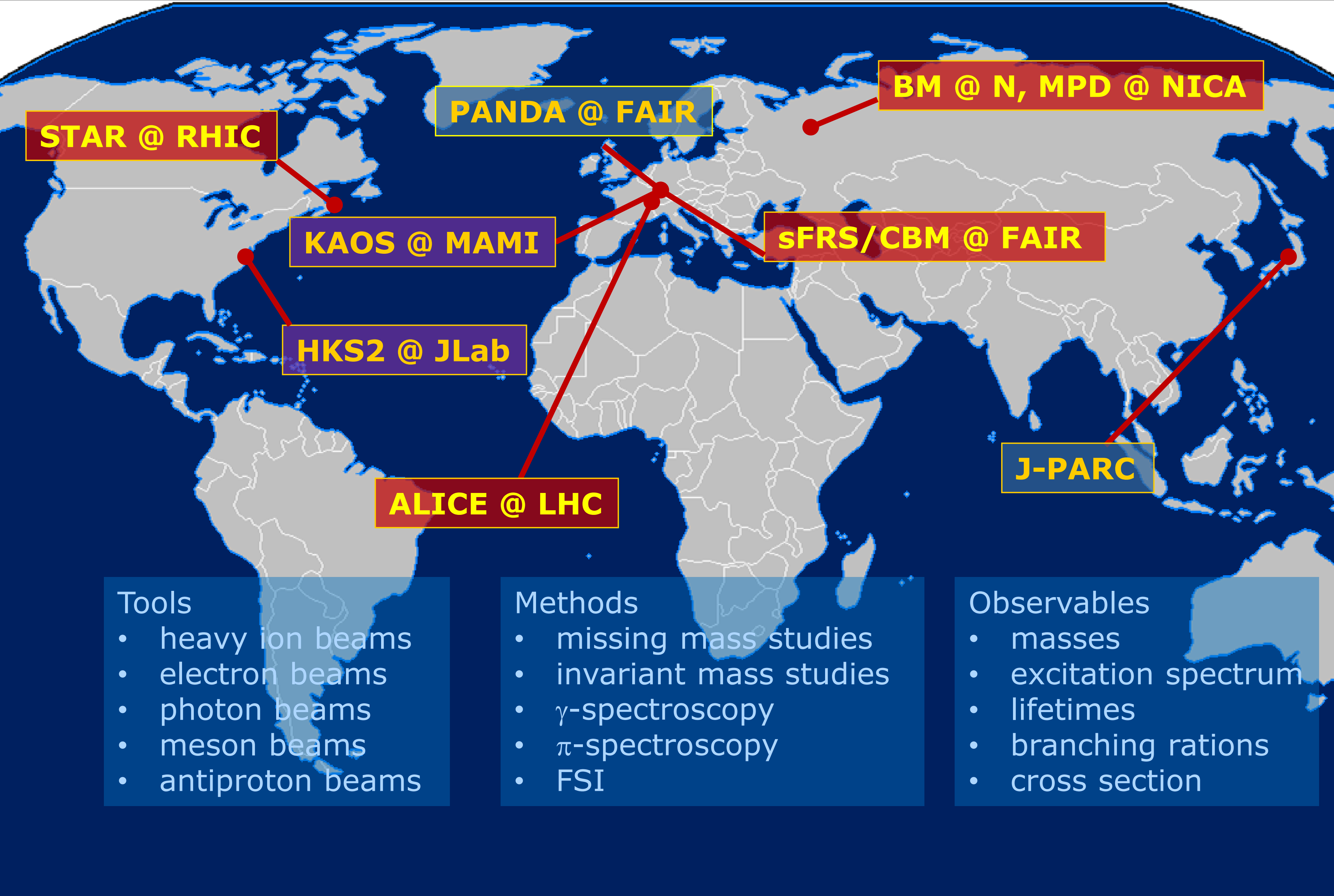
(anti)hyperon scattering

Recent Progress in Strangeness and Charm Hadronic and Nuclear Physics
Edts. A. Gal and JP
Nucl. Phys. A **954**, 1–2 (2016)

Theoretical considerations for HI:
PRC **86**, 011601(R) (2012)
PRC **88**, 054605 (2013)
PLB **742**, 7 (2015)
Eur. Phys. J. **52**, 242 (2016)
PRC **94**, 054615 (2016)
PRC **95**, 014902 (2017)

JP PLB **669**, 306 (2008)
Sanchez *et al.*, PLB 749, 421 (2015)

Hypernuclear Activities Today



Tools
- heavy ion beams
- electron beams
- photon beams
- meson beams
- antiproton beams

Methods
- missing mass studies
- invariant mass studies
- γ-spectroscopy
- π-spectroscopy
- FSI

Observables
- masses
- excitation spectrum
- lifetimes
- branching rations
- cross section


Thank you
for your attention