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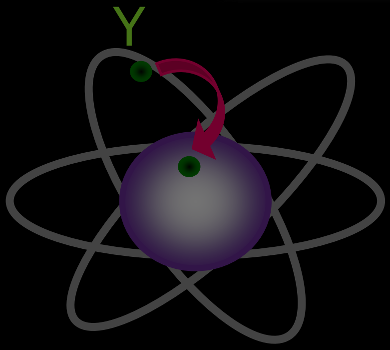
LEARN,
something new
EVERYDAY
If you
LISTEN

GSI - 14th December 2017

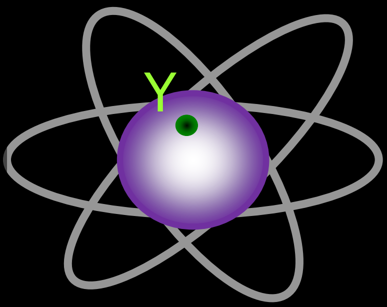
Overview of/ Motivation for Hypernuclear Physics

Bringing Heaven to Earth

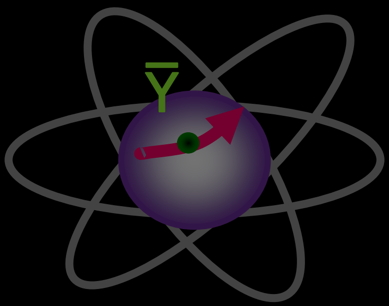
Josef Pochodzalla



hyperatoms



hypernuclei

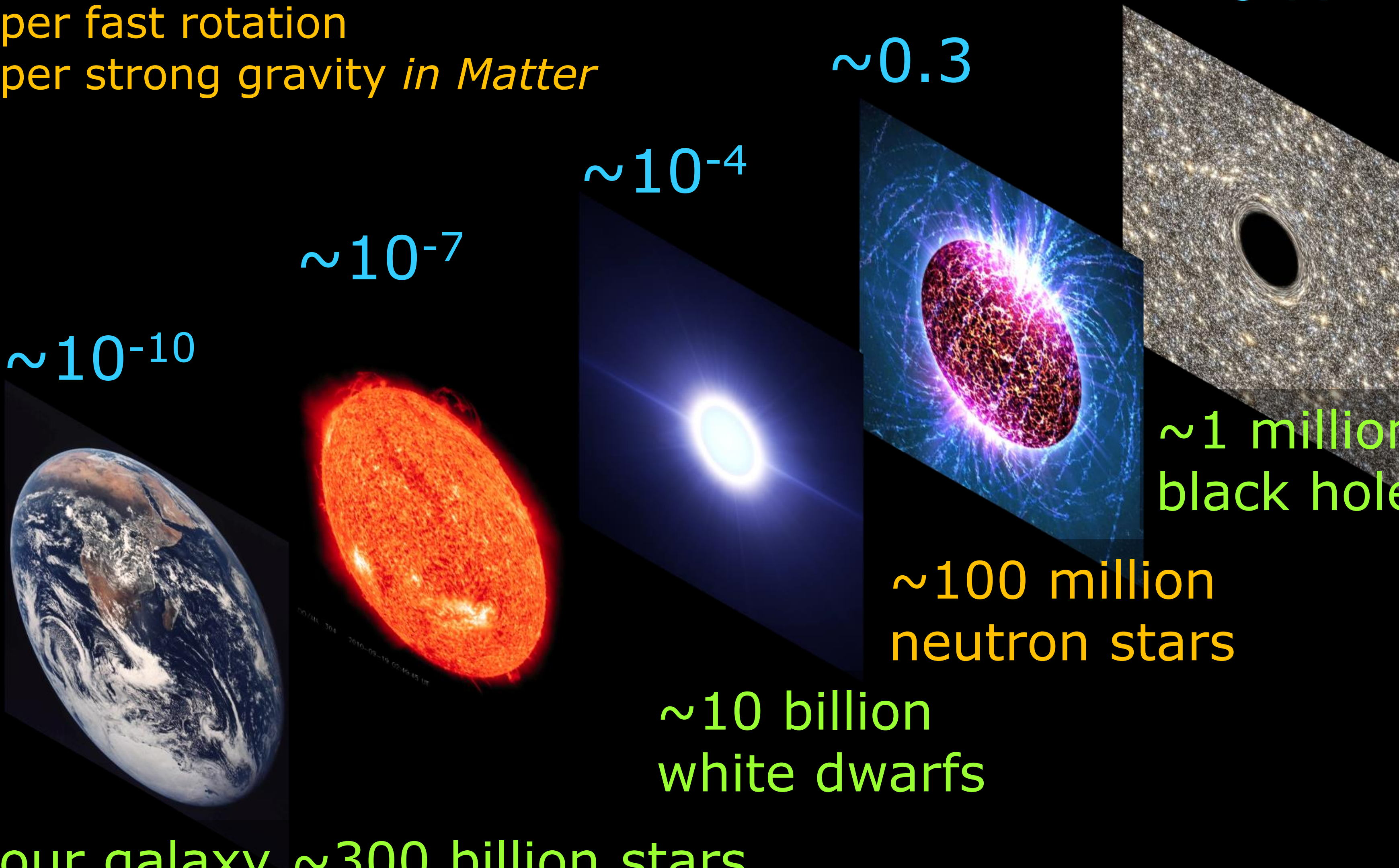


(anti)hyperon scattering

Motivation

Neutron stars are Superstars

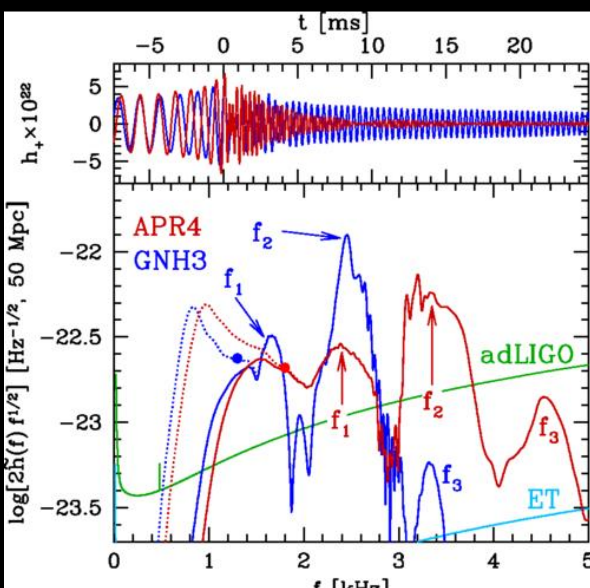
super high density
super strong magnetic fields
super fast rotation
super strong gravity *in Matter*

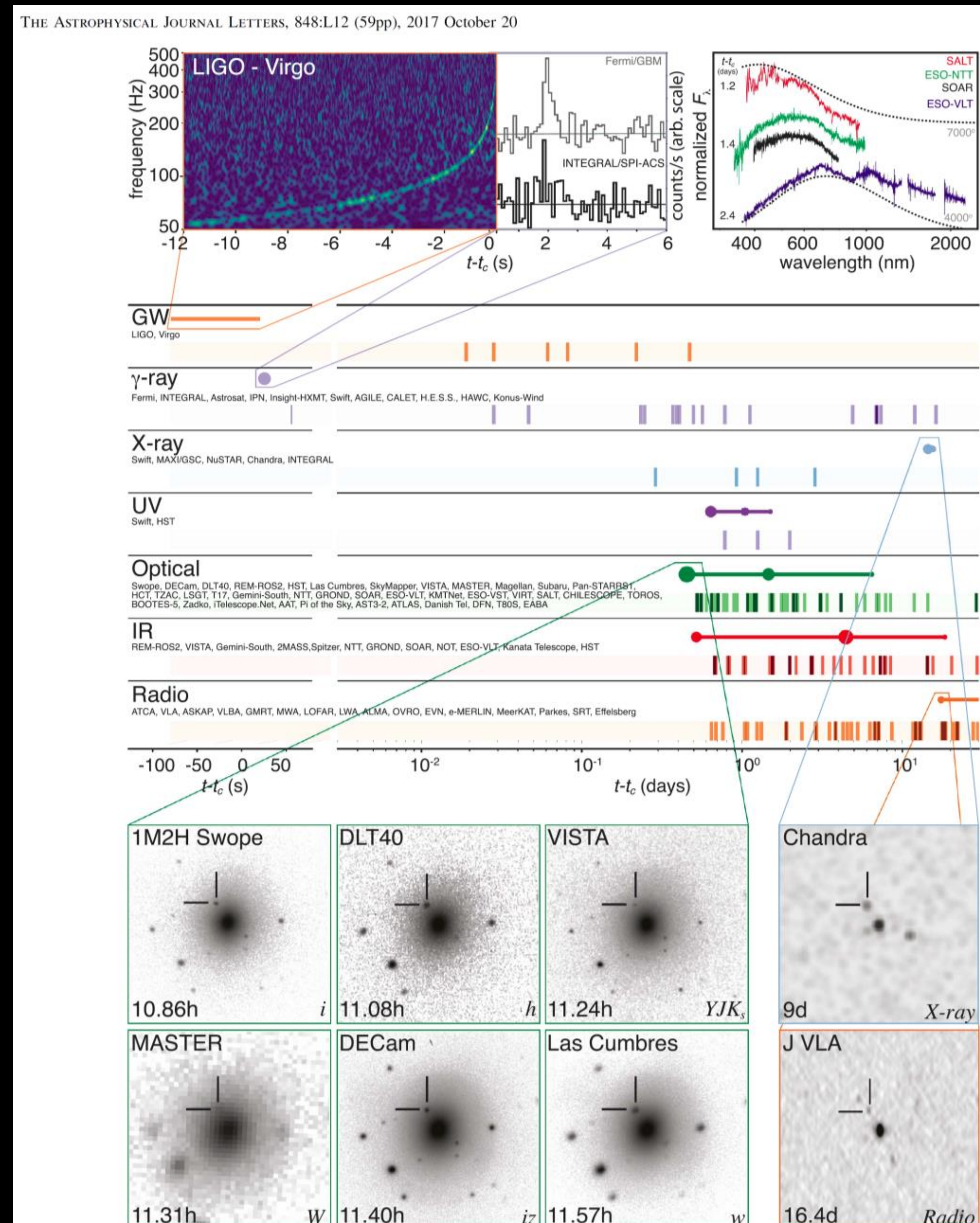


2017 August 17 12:41:04 UTC

- GW170817 detected by LIGO and Virgo
- First multi-messenger observations of a binary neutron star merger
- Constraints in radius, …
- With improved sensitivity to post-merger spectrum $\Rightarrow$ EOS

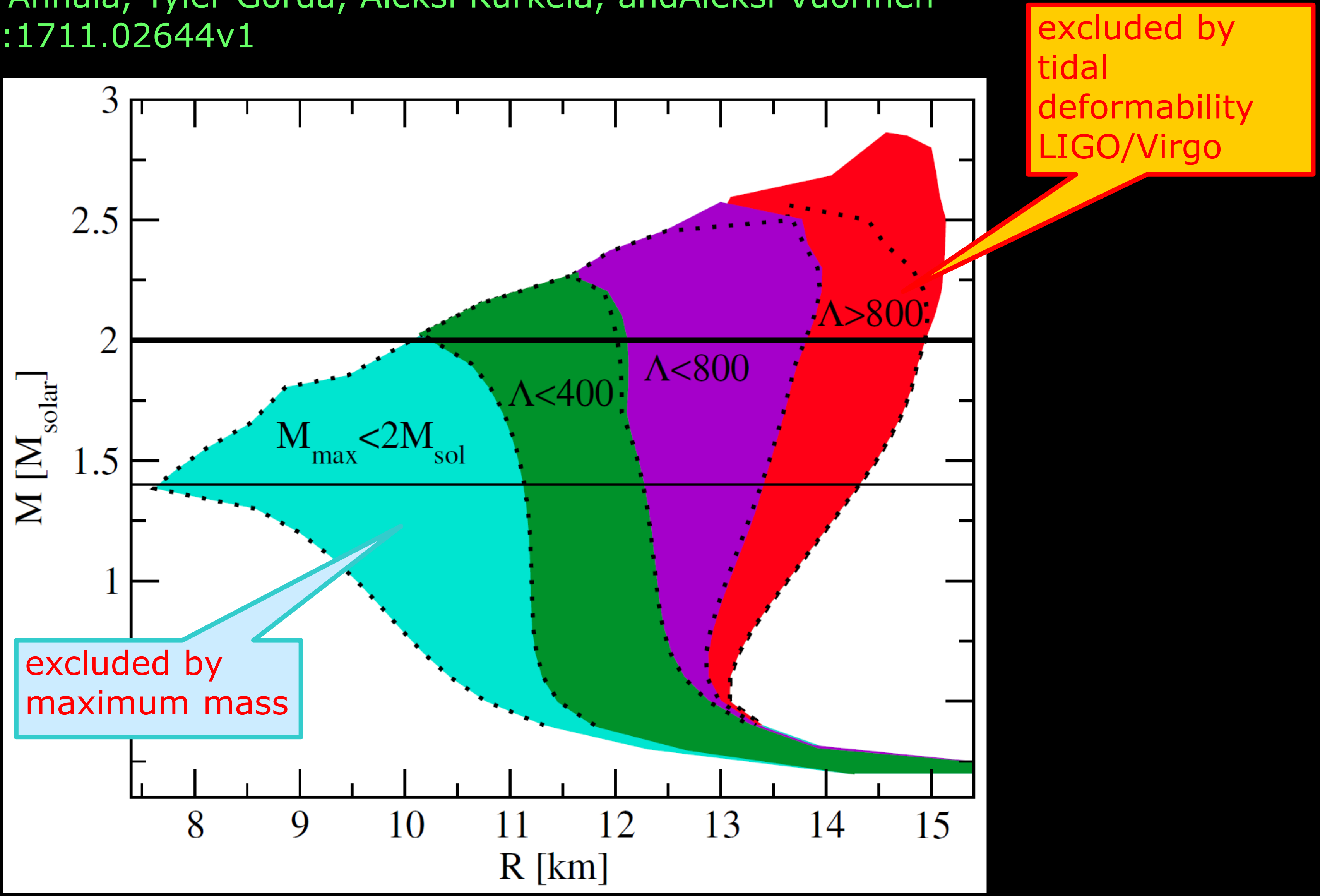
A. Kentaro Takami, Luciano Rezzolla, and Luca Baiotti Phys. Rev. Lett. **113**, 091104

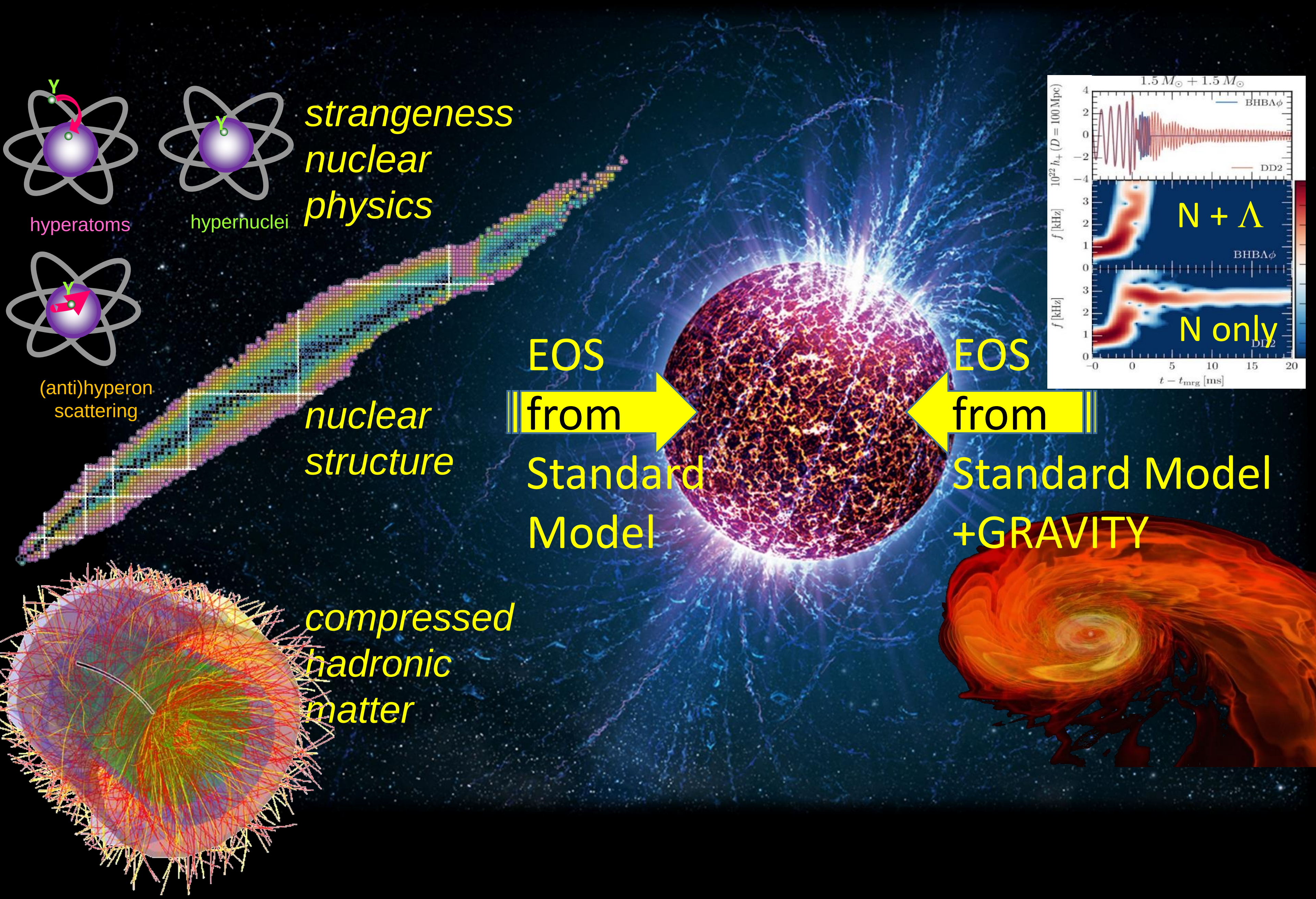




EOS from Astronomical Observations

Emel Annala, Tyler Gorda, Aleksi Kurkela, andAleksi Vuorinen
arXiv:1711.02644v1





hyperatoms
hypernuclei
(anti)hyperon scattering
strangeness nuclear physics
nuclear structure
compressed hadronic matter
EOS from Standard Model
EOS from Standard Model +GRAVITY
1.5 M⊙ + 1.5 M⊙
BHBΛφ
DD2
N + Λ
N only
f [kHz]
t − t_mrg [ms]

5 decades of hyperons in neutron sta

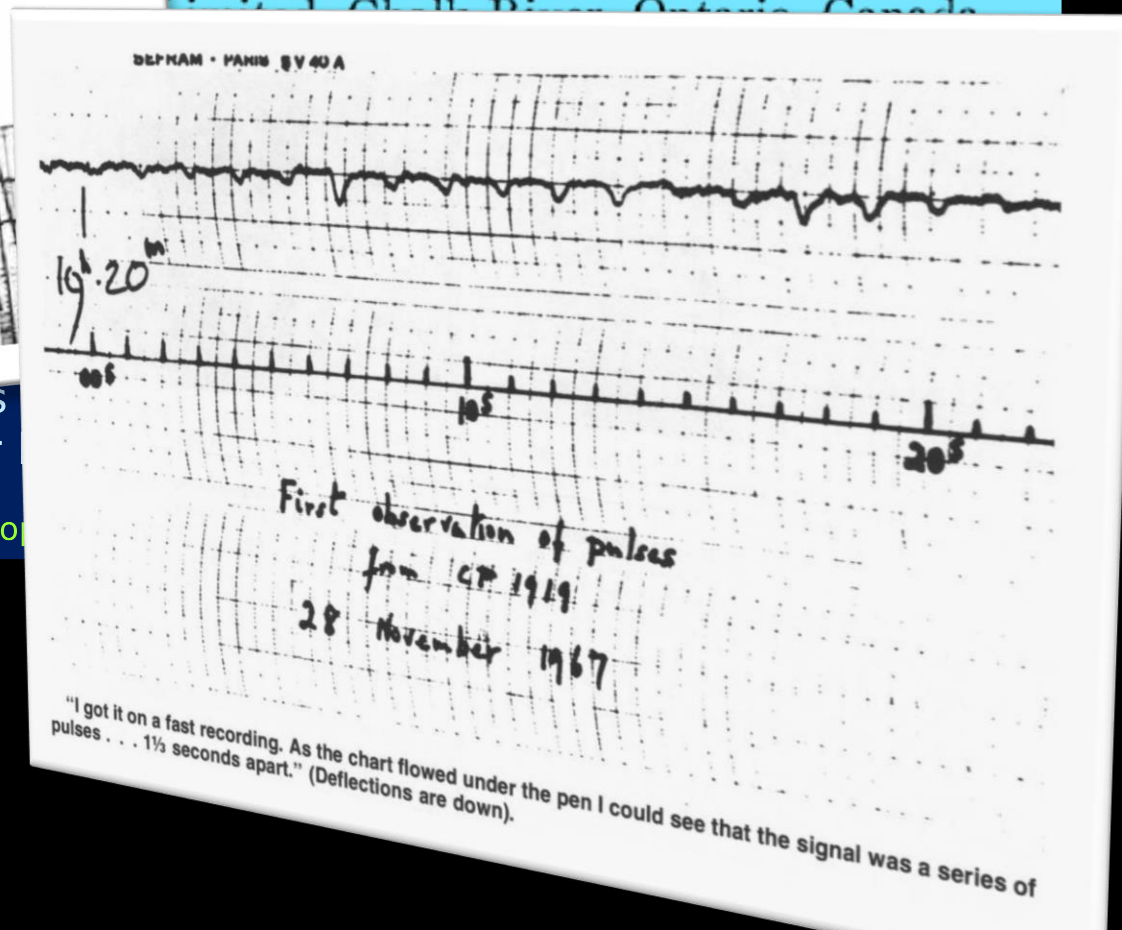
ON STAR MODELS

. W. CAMERON

must always

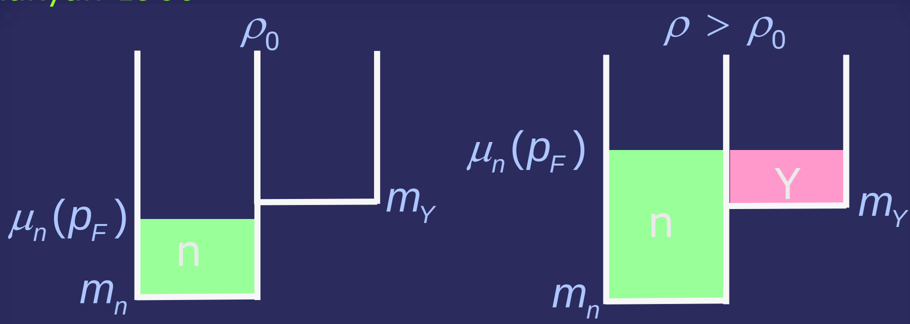
sometimes with other

Alastair G.W. Cameron, Astro



Hyperon Puzzle

Cameron 1959,
Ambartsumyan &
Saakyan 1960



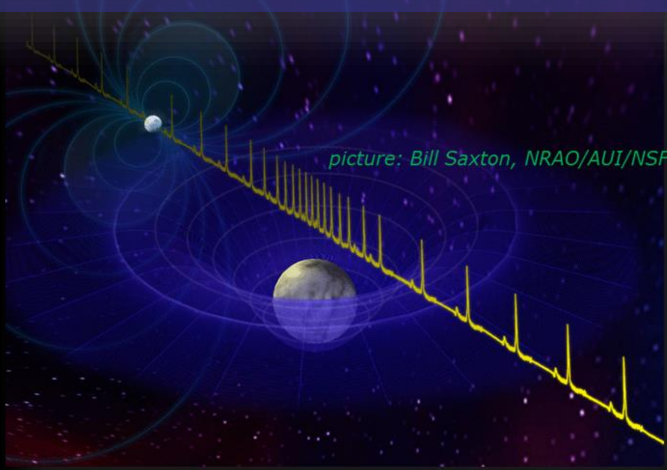
$e^- + p \to \nu_e + \Lambda$ $\qquad p_{F,n}^2 + m_n^2 \geq m_\Lambda^2$

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

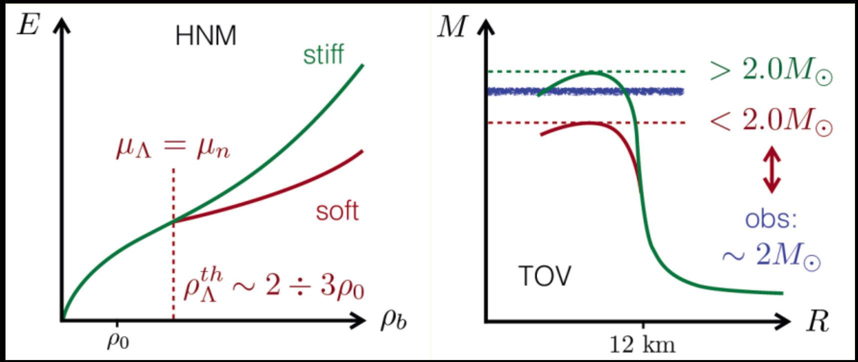
non-interacting Fermi-gas: $\rho = \dfrac{p_{F,n}^3}{3\pi^2} \Rightarrow p_{F,n}(\rho_0) = 1.7 fm^{-1}$

$\Rightarrow$ 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 $M_\odot$

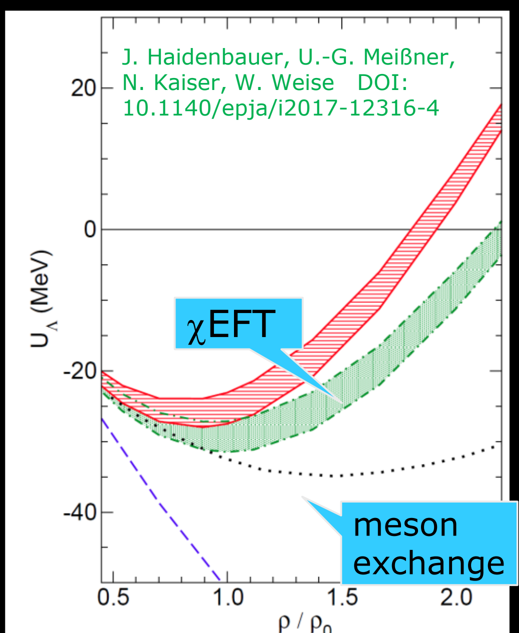
M(PSR J1946+3417)=1.828 ± 0.022 $M_\odot$

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

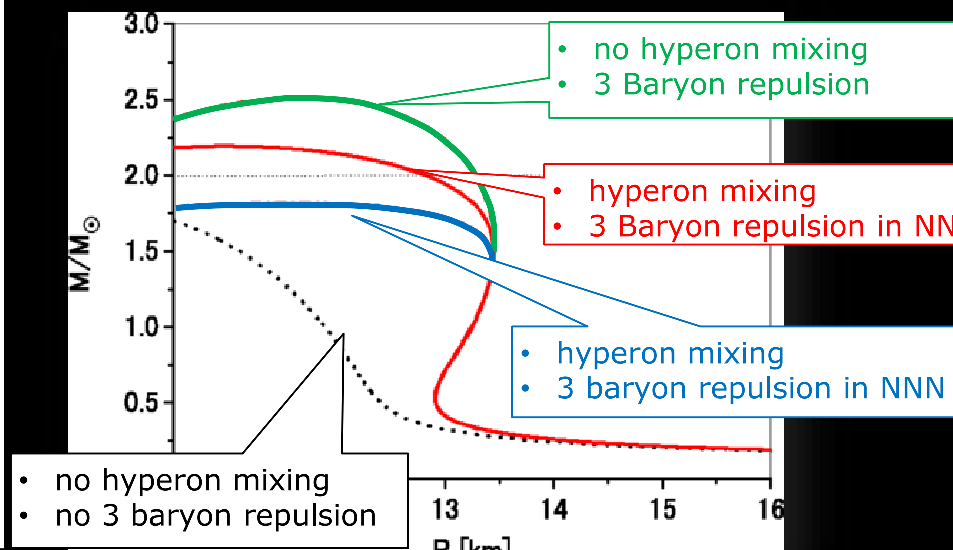
- YY vector meson repulsion: ϕ *meson coupled only to hyperons; yielding strong repulson at high* ρ
- Chiral forces: *YN from* χ*EFT predicts* Λ *s.p. potential more repulsive than from meson exchange*



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

A Few Basics

Nomenclature

- a hypernucleus is specified by
  - the number of neutrons N
  - the number of protons Z
  - the number of hyperons Y

number of baryons N+Z+Y

(number of) hyperons Y

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

element = total charge (*not number of protons*)

  - since we have more than one hyperon (Λ, Ξ^-, Σ^{-+0}) one usually writes explicitely the symbols of one (or more) hyperon
  - examples:

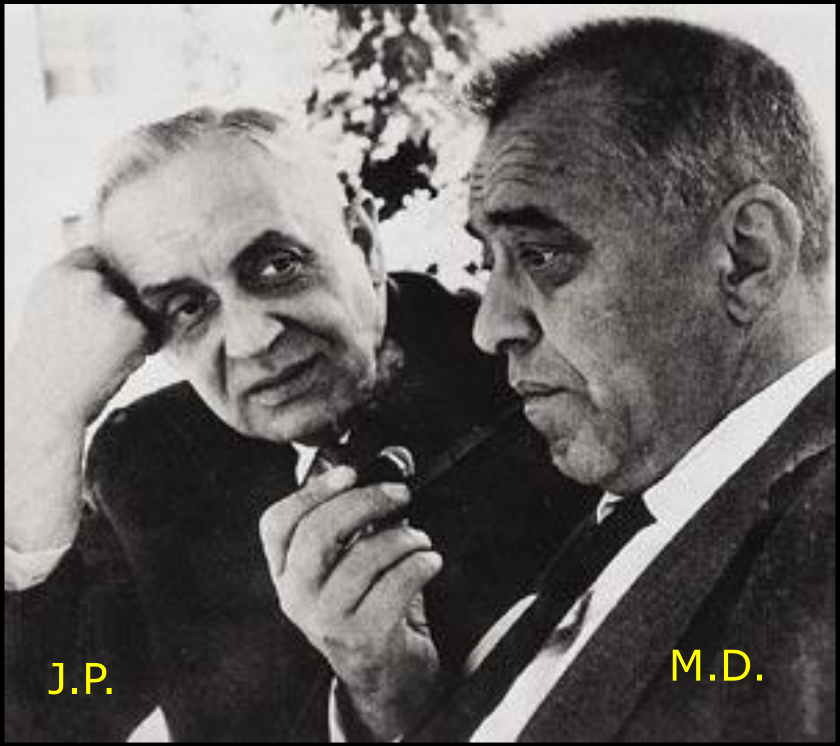
$${}^{4}_{\Lambda}H \rightarrow \begin{cases} \Lambda \rightarrow 1 \text{ lambdas} \\ H \rightarrow 1 \text{ proton} \\ 4 \rightarrow 4\text{-}1\text{-}1 = 2 \text{ neutrons} \end{cases}$$

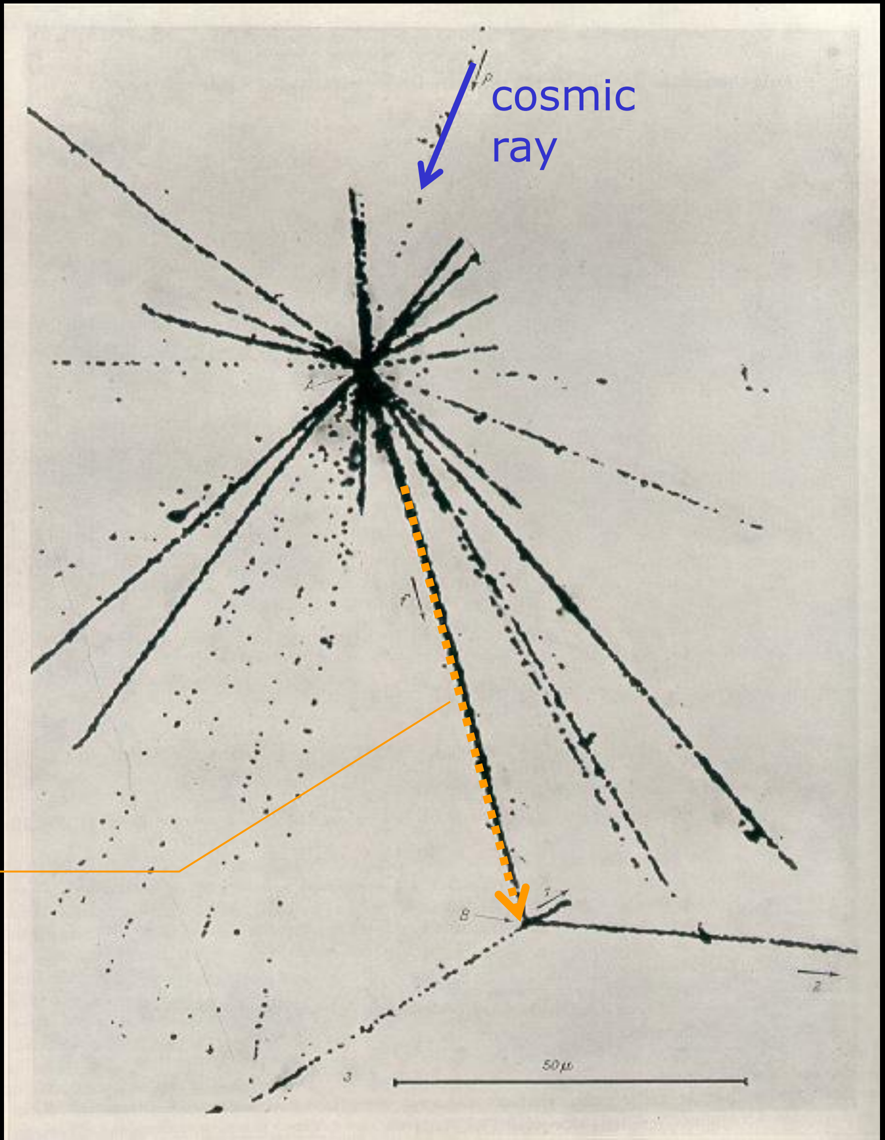
$${}^{10}_{\Lambda\Lambda}Be \rightarrow \begin{cases} Be \rightarrow 4 \text{ protons} \\ \Lambda\Lambda \rightarrow 2 \text{ lambdas} \\ 10 \rightarrow 10\text{-}4\text{-}2 = 4 \text{ neutrons} \end{cases}$$

$${}^{4}_{\Sigma}He \rightarrow \begin{cases} 1p + 2n + 1\Sigma^{+} \\ 2p + 1n + 1\Sigma^{0} \\ 3p + 0n + 1\Sigma^{-} \end{cases} \quad \text{indistinguishable}$$

How it began

- 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

The second event

COMPTES RENDUS

HEBDOMADAIRES

DES SÉANCES

DE L'ACADÉMIE DES SCIENCES,

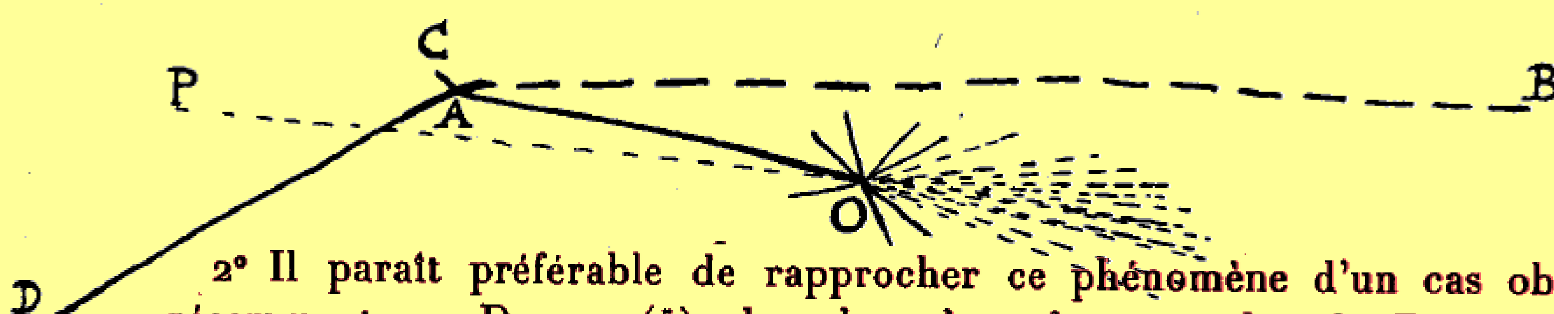
PUBLIÉS,

CONFORMÉMENT A UNE DÉCISION DE L'ACADÉMIE

EN DATE DU 13 JUILLET 1835,

PHYSIQUE NUCLÉAIRE. — *Émission probable d'un fragment nucléaire contenant une particule* V°. Note de MM. **Jean Crussard** et **Daniel Morellet**, présentée par M. Louis Leprince-Ringuet.

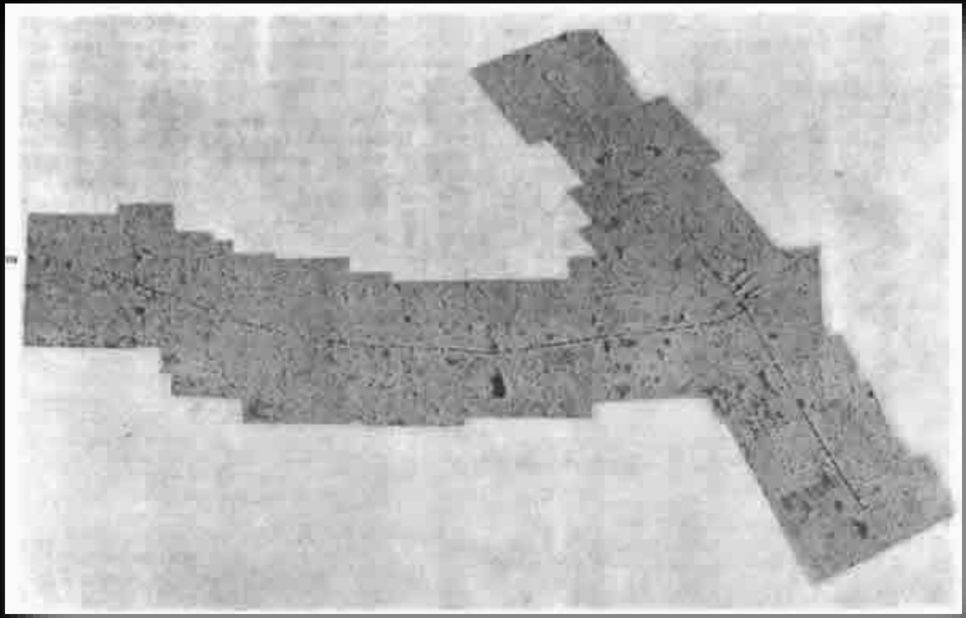
probable. Un méson π est exclu (scattering trop faible). Un noyau lourd plus rapide est impossible (absence de rayons δ). On ne peut affirmer que la particule s'arrête en A, mais sa vitesse résiduelle y est en tous cas très faible.



2° Il paraît préférable de rapprocher ce phénomène d'un cas observé récemment par Danysz ([7]), dans lequel un fragment lourd ($Z \geq 8$), émis

Nuclear Emulsion

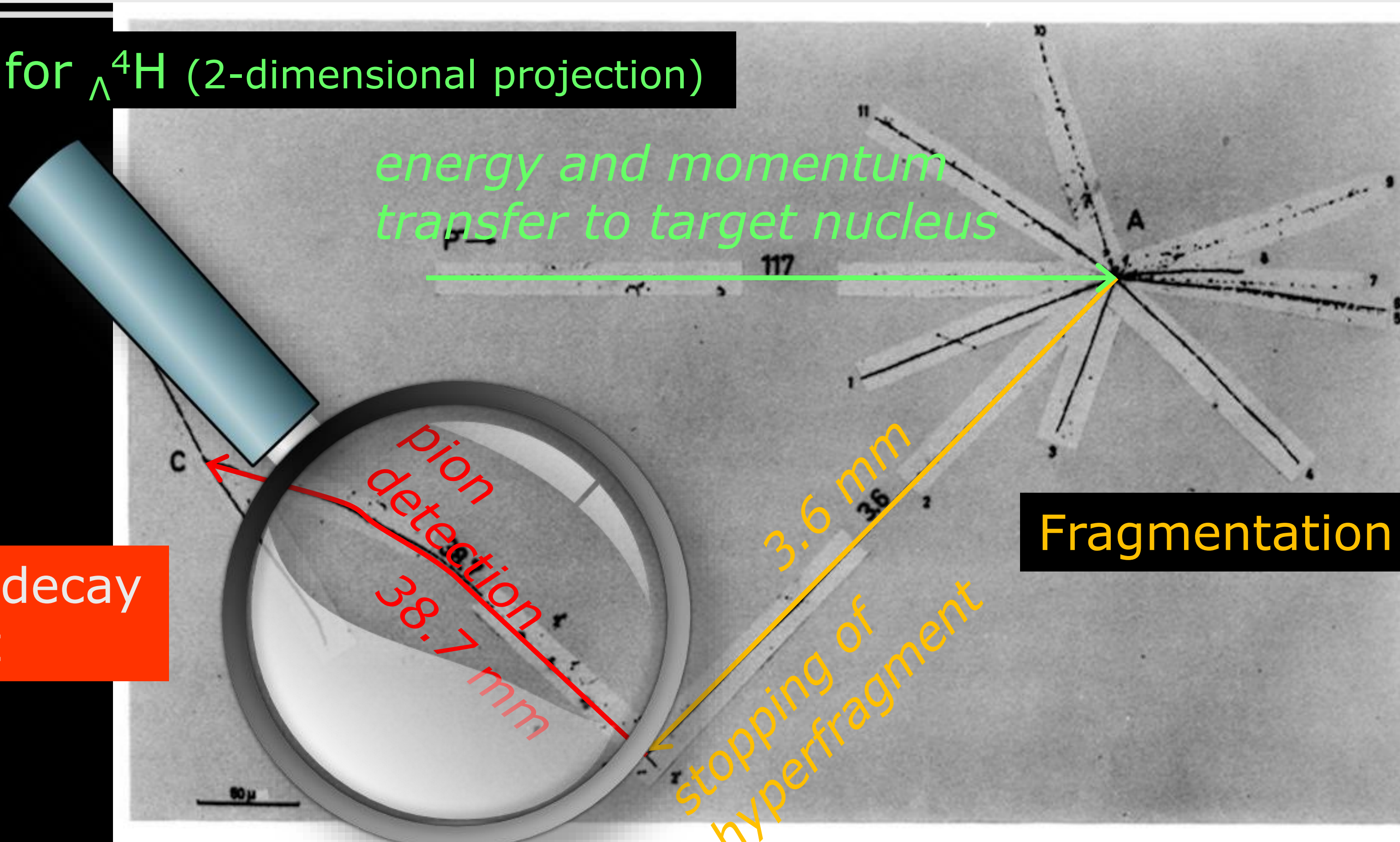
- Cecil Frank Powell (1903-1969)
  - Nobel Prize in Physics 1950
- Multiple layers of emulsion were historically the first means of visualizing charged particle tracks
  - very high positional precision
  - ionisation density (dE/dx)
  - range
  - 3-dimensional view of the interaction



- An emulsion is made, as for photographic film, of a silver salt, (AgBr), embedded in gelatine and spread thinly on a substrate.
  - grain size 0.2-0.5μm (today: 40nm)
  - during developement excited grains are reduced to elemental silver
  - density 3g/cm^3
- Data acquisition by automated means (e.g. by scanning the film with a CCD camera) is now possible.

Decay-pion spectroscopy in emulsion

Example for $_{\Lambda}^{4}$H (2-dimensional projection)



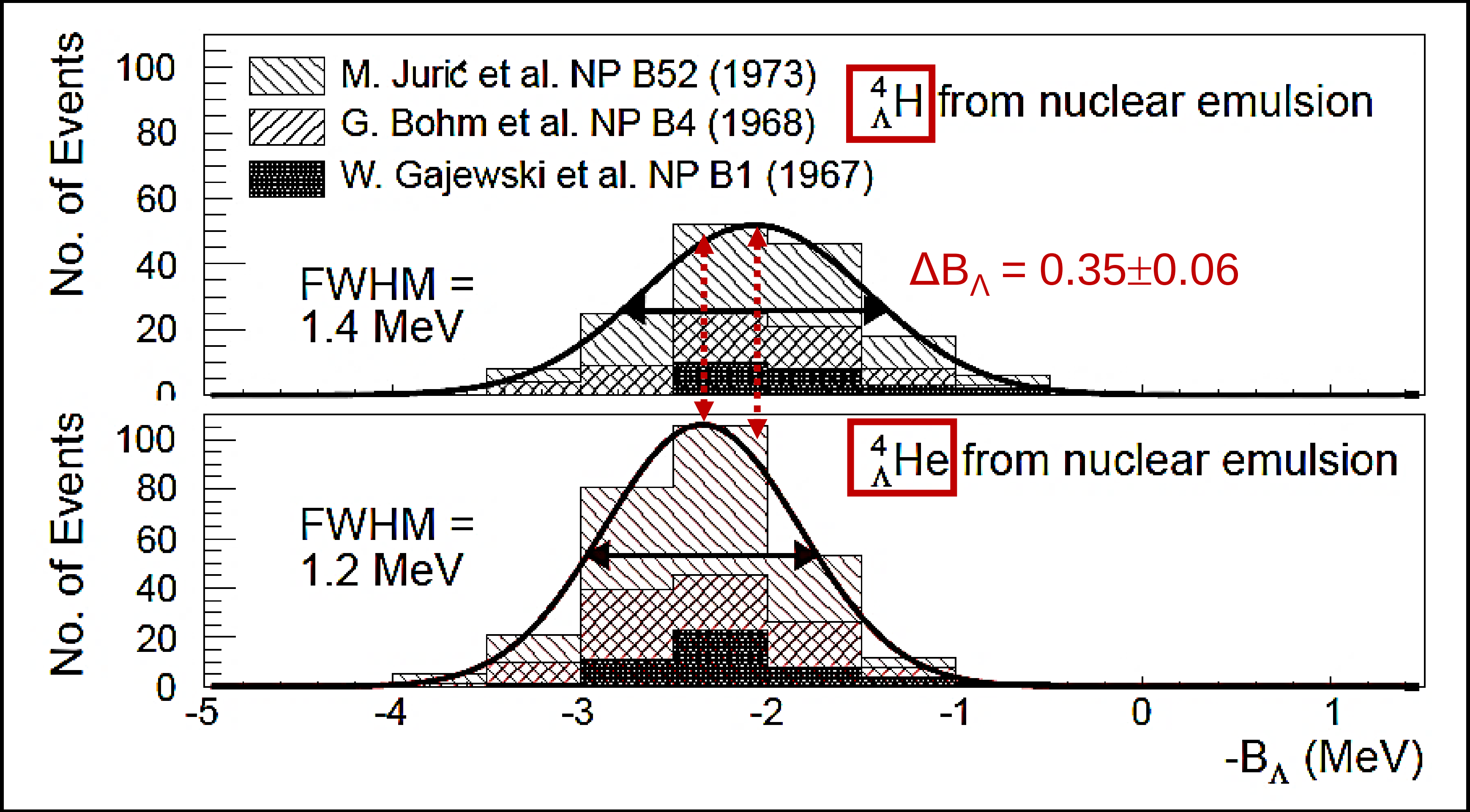
The result is that the event is consistent only with a $_{\Lambda}H^4$ fragment undergoing mesonic two-body decay. The binding energy of the Λ in $_{\Lambda}H^4$ is then $B_{\Lambda} = 2.6 \pm 1.0$ Mev, which is consistent also with other measurements of this quantity.[9]

$$_{\Lambda}H^4 \to He^4 + \pi^- + Q,$$

where $Q = 54.6 \pm 1.0$ Mev.

A.G. Ekspong *et al.*, Phys. Rev. Lett. **3,** 103 (1959)

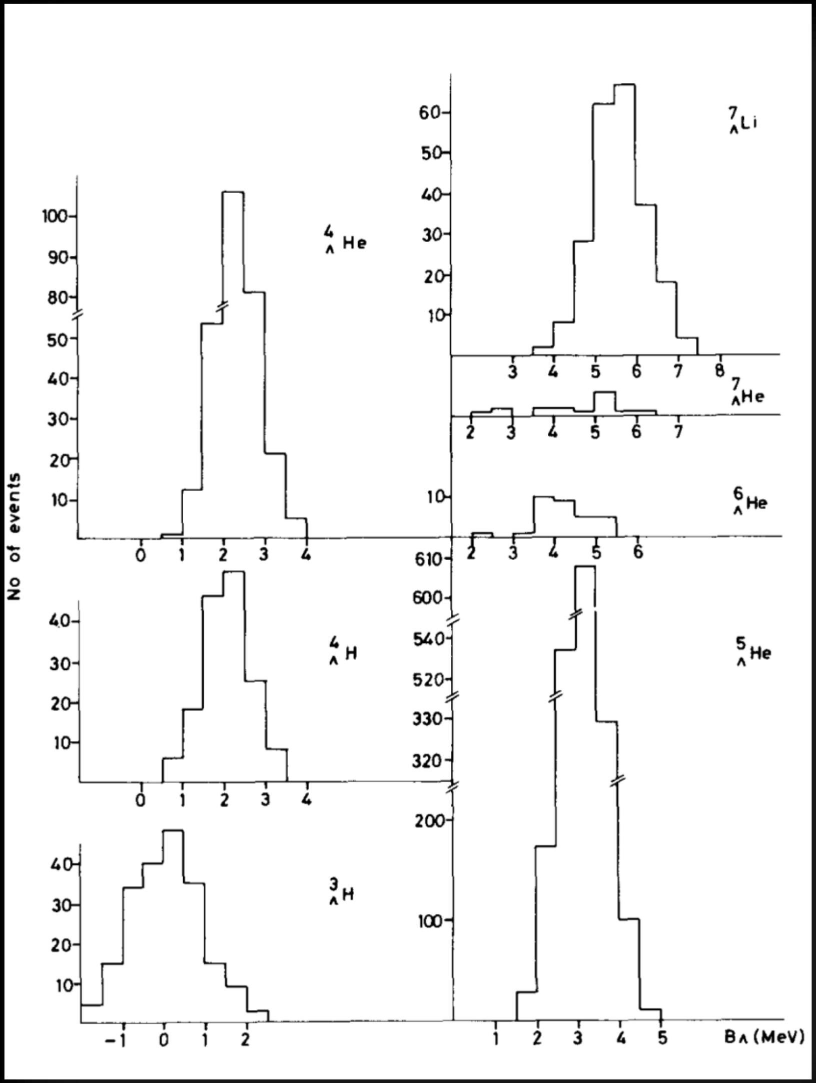
Emulsion results on ${}_{\Lambda}^{4}H$ and ${}_{\Lambda}^{4}He$

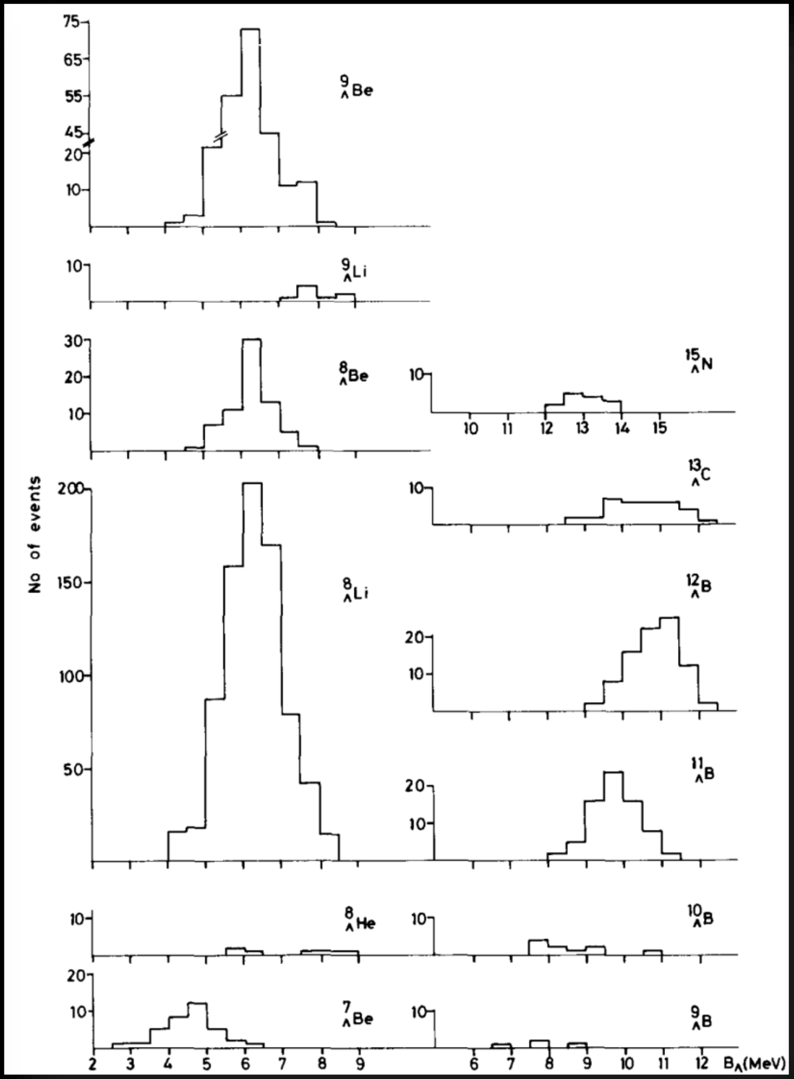


- only three-body decay modes used for hyperhydrogen
- 155 events for hyperhydrogen, 279 events for hyperhelium

World data from emulsion (1973)

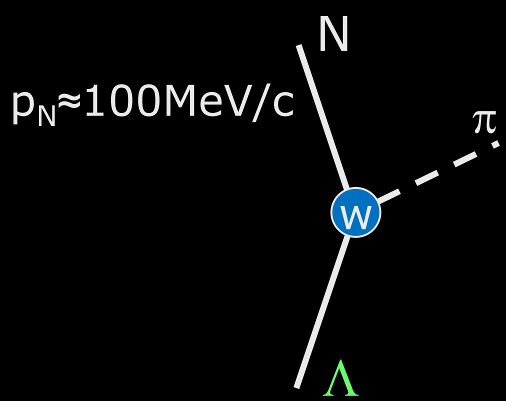
- M. Juric at al, Nucl. Phys. B52, 1 (1973)
  - 4042 uniquely identified events in 1973





Weak decay of Λ hypernuclei

free Λ decay



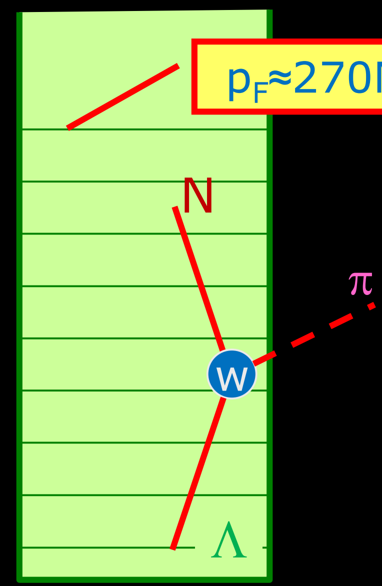
$\Lambda \to p\pi^- + 38\text{MeV}\ \ (64\%)$

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

$\tau_\Lambda = 263ps$

$\Delta I = 1/2$ rule

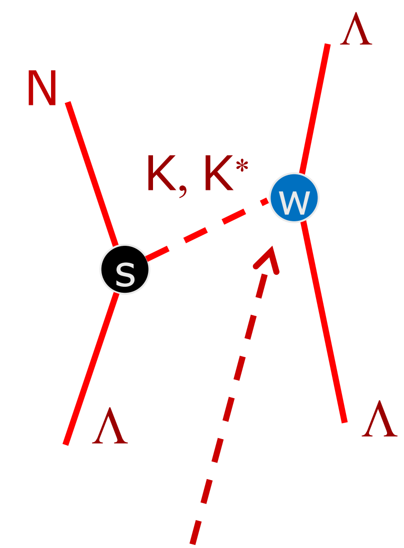
mesonic decay of hypernuclei



suppressed by Pauli blocking

non-mesonic decay of hypernuclei

$\Lambda\Lambda \to Y\ N$



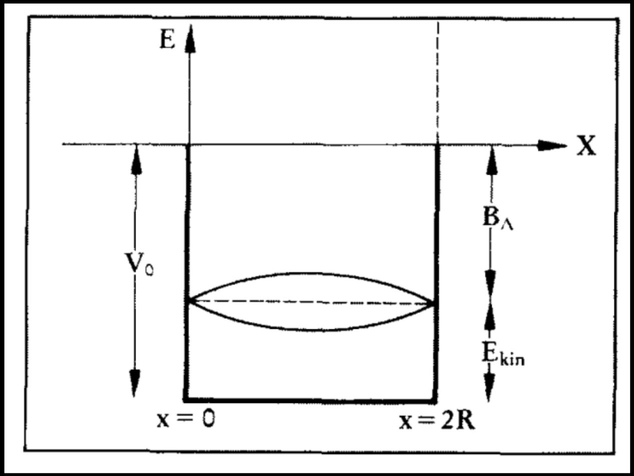
weak $\Lambda\Lambda$K vertex!

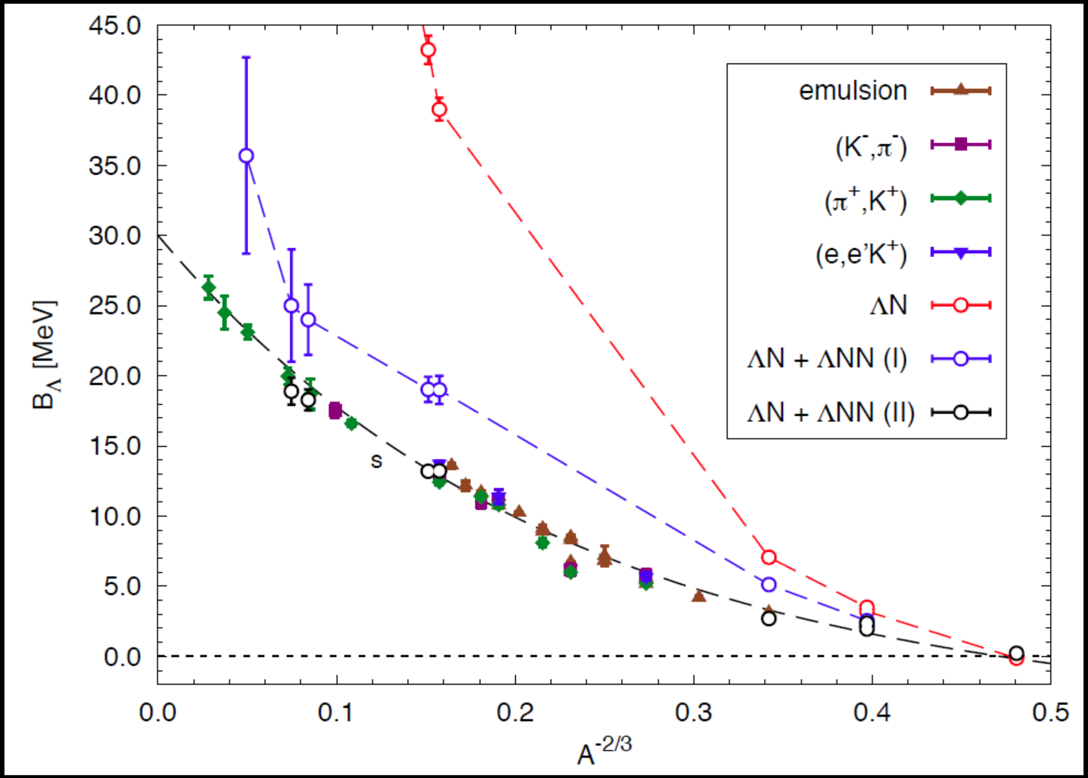
but the lightest hypernuclei

- q~400 MeV/c $\Rightarrow$ probes short distances of baryon-baryon weak interaction

Three-body forces in Hypernuclei

Bogdan Povh, Michael Uhrmacher
Physik in unserer Zeit 5, 138 (1981)





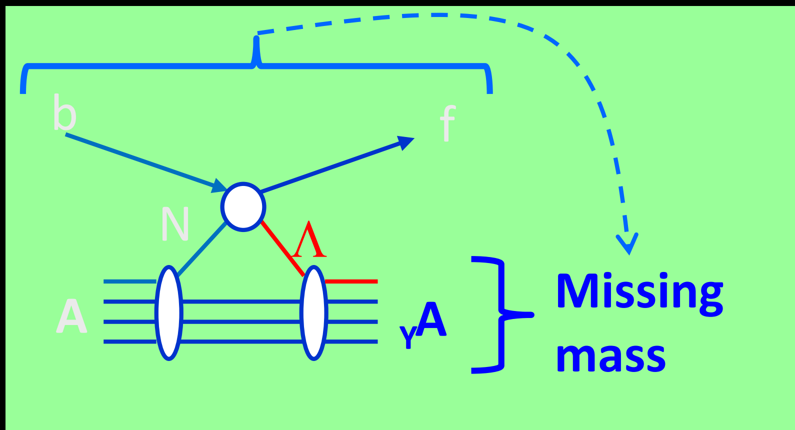
Stefano Gandolfi Diego Lonardoni,
arXiv: 1512.06832

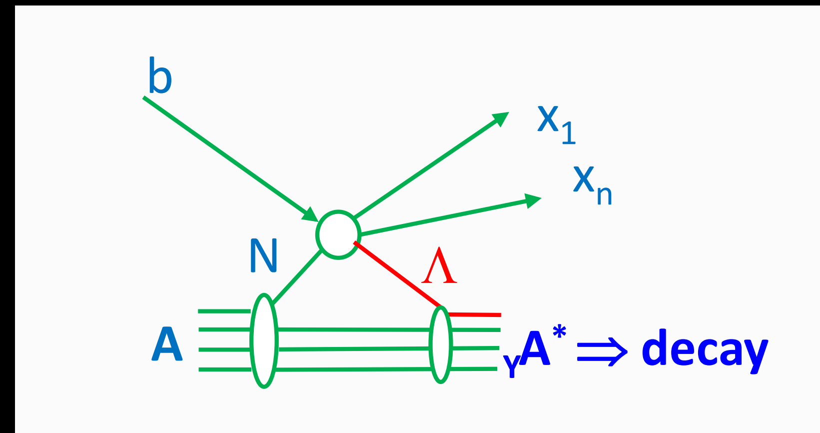
Boxsize $L = 2r_0 \cdot A^{1/3}$

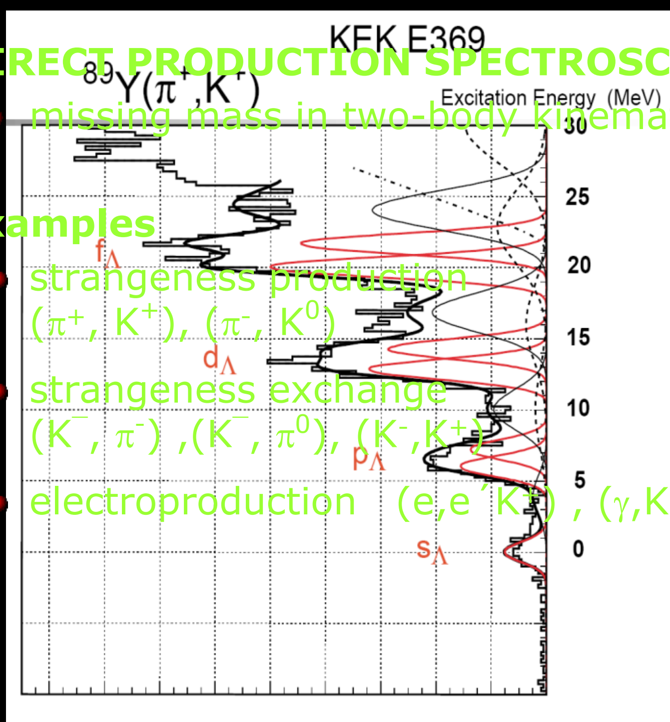
$$\Rightarrow E_{g.s.} = V_0 - B_\Lambda = \frac{3\hbar^2\pi^2}{8m_\Lambda r_0^2} A^{-2/3}$$

Three baryon interactions involving hyperons are essential
$\Rightarrow$ precission studies of light hypernuclei

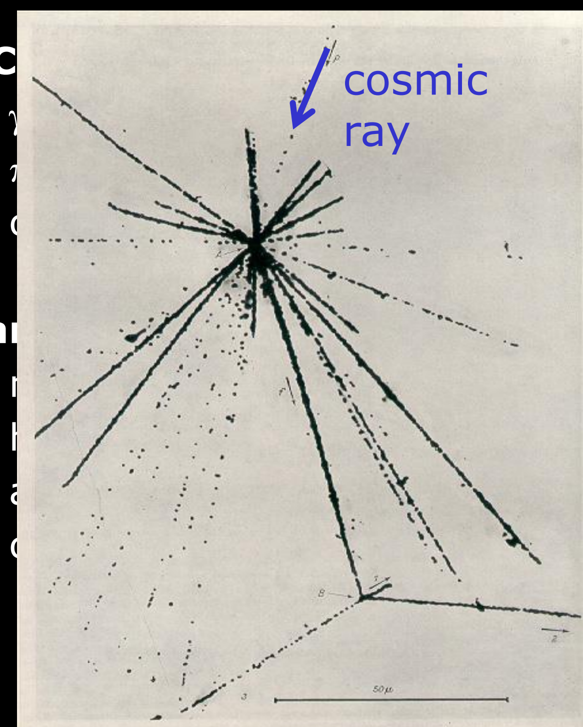
The twofold way to hypernuclei







- **DIRECT PRODUCTION SPECTROSCOPY**
  - missing mass in two-body kinematics
- **Examples**
  - strangeness production (π^+, K^+), (π^-, K^0)
  - strangeness exchange (K^-, π^-), (K^-, π^0), (K^-,K^+)
  - electroproduction $(e,e'K^+)$, (γ,K^+)



- **DEC**
  - γ
  - π
  - c
- **Exa**
  - r
  - h
  - a
  - c +)

Missing Mass & Decay Spectroscopy

Cosmic ray interactions (Emulsion)
Heavy Ion (HypHI, STAR, ALICE, CBM…)
Precission Pion Spectroscopy (MZ)
Antiprotons

Proton Number																				
10						${}^{17}_{\Lambda}\mathrm{Ne}$	[illegible]	${}^{19}_{\Lambda}\mathrm{Ne}$	${}^{20}_{\Lambda}\mathrm{Ne}$	${}^{21}_{\Lambda}\mathrm{Ne}$	${}^{22}_{\Lambda}\mathrm{Ne}$	${}^{23}_{\Lambda}\mathrm{Ne}$	${}^{24}_{\Lambda}\mathrm{Ne}$	${}^{25}_{\Lambda}\mathrm{Ne}$	${}^{26}_{\Lambda}\mathrm{Ne}$	${}^{27}_{\Lambda}\mathrm{Ne}$	${}^{28}_{\Lambda}\mathrm{Ne}$	${}^{29}_{\Lambda}\mathrm{Ne}$	${}^{30}_{\Lambda}\mathrm{Ne}$	${}^{31}_{\Lambda}\mathrm{Ne}$
9						${}^{16}_{\Lambda}\mathrm{F}$	${}^{17}_{\Lambda}\mathrm{F}$	${}^{18}_{\Lambda}\mathrm{F}$	${}^{19}_{\Lambda}\mathrm{F}$	${}^{20}_{\Lambda}\mathrm{F}$	${}^{21}_{\Lambda}\mathrm{F}$	${}^{22}_{\Lambda}\mathrm{F}$	${}^{23}_{\Lambda}\mathrm{F}$	${}^{24}_{\Lambda}\mathrm{F}$	${}^{25}_{\Lambda}\mathrm{F}$	${}^{26}_{\Lambda}\mathrm{F}$	${}^{27}_{\Lambda}\mathrm{F}$	${}^{28}_{\Lambda}\mathrm{F}$	${}^{29}_{\Lambda}\mathrm{F}$	${}^{30}_{\Lambda}\mathrm{F}$
8				${}^{13}_{\Lambda}\mathrm{O}$	${}^{14}_{\Lambda}\mathrm{O}$	${}^{15}_{\Lambda}\mathrm{O}$	${}^{16}_{\Lambda}\mathrm{O}$	${}^{17}_{\Lambda}\mathrm{O}$	${}^{18}_{\Lambda}\mathrm{O}$	${}^{19}_{\Lambda}\mathrm{O}$	${}^{20}_{\Lambda}\mathrm{O}$	${}^{21}_{\Lambda}\mathrm{O}$	${}^{22}_{\Lambda}\mathrm{O}$	${}^{23}_{\Lambda}\mathrm{O}$	${}^{24}_{\Lambda}\mathrm{O}$	${}^{25}_{\Lambda}\mathrm{O}$	${}^{26}_{\Lambda}\mathrm{O}$	${}^{27}_{\Lambda}\mathrm{O}$		
7				${}^{12}_{\Lambda}\mathrm{N}$	${}^{13}_{\Lambda}\mathrm{N}$	${}^{14}_{\Lambda}\mathrm{N}$	${}^{15}_{\Lambda}\mathrm{N}$	${}^{16}_{\Lambda}\mathrm{N}$	${}^{17}_{\Lambda}\mathrm{N}$	${}^{18}_{\Lambda}\mathrm{N}$	${}^{19}_{\Lambda}\mathrm{N}$	${}^{20}_{\Lambda}\mathrm{N}$	${}^{21}_{\Lambda}\mathrm{N}$	${}^{22}_{\Lambda}\mathrm{N}$	${}^{23}_{\Lambda}\mathrm{N}$	${}^{24}_{\Lambda}\mathrm{N}$				
6			${}^{10}_{\Lambda}\mathrm{C}$	${}^{11}_{\Lambda}\mathrm{C}$	${}^{12}_{\Lambda}\mathrm{C}$	${}^{13}_{\Lambda}\mathrm{C}$	${}^{14}_{\Lambda}\mathrm{C}$	${}^{15}_{\Lambda}\mathrm{C}$	${}^{16}_{\Lambda}\mathrm{C}$	${}^{17}_{\Lambda}\mathrm{C}$	${}^{18}_{\Lambda}\mathrm{C}$	${}^{19}_{\Lambda}\mathrm{C}$	${}^{20}_{\Lambda}\mathrm{C}$	${}^{21}_{\Lambda}\mathrm{C}$						
5			${}^{9}_{\Lambda}\mathrm{B}$	${}^{10}_{\Lambda}\mathrm{B}$	${}^{11}_{\Lambda}\mathrm{B}$	${}^{12}_{\Lambda}\mathrm{B}$	${}^{13}_{\Lambda}\mathrm{B}$	${}^{14}_{\Lambda}\mathrm{B}$	${}^{15}_{\Lambda}\mathrm{B}$	${}^{16}_{\Lambda}\mathrm{B}$	${}^{17}_{\Lambda}\mathrm{B}$	${}^{18}_{\Lambda}\mathrm{B}$								
4		${}^{7}_{\Lambda}\mathrm{Be}$	${}^{8}_{\Lambda}\mathrm{Be}$	${}^{9}_{\Lambda}\mathrm{Be}$	${}^{10}_{\Lambda}\mathrm{Be}$	${}^{11}_{\Lambda}\mathrm{Be}$	${}^{12}_{\Lambda}\mathrm{Be}$	${}^{13}_{\Lambda}\mathrm{Be}$	${}^{14}_{\Lambda}\mathrm{Be}$	${}^{15}_{\Lambda}\mathrm{Be}$										
3		${}^{6}_{\Lambda}\mathrm{Li}$	${}^{7}_{\Lambda}\mathrm{Li}$	${}^{8}_{\Lambda}\mathrm{Li}$	${}^{9}_{\Lambda}\mathrm{Li}$	${}^{10}_{\Lambda}\mathrm{Li}$	${}^{11}_{\Lambda}\mathrm{Li}$	${}^{12}_{\Lambda}\mathrm{Li}$												
2	${}^{4}_{\Lambda}\mathrm{He}$	${}^{5}_{\Lambda}\mathrm{He}$	${}^{6}_{\Lambda}\mathrm{He}$	${}^{7}_{\Lambda}\mathrm{He}$	${}^{8}_{\Lambda}\mathrm{He}$	${}^{9}_{\Lambda}\mathrm{He}$														
1	${}^{3}_{\Lambda}\mathrm{H}$	${}^{4}_{\Lambda}\mathrm{H}$																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Neutron Number

$n \to \Lambda$: (K^-, π^-)

(K^-_{stop}, π^-)

(π^+, K^+)

$p \to \Lambda$: $(e, e'K^+)$

(K^-_{stop}, π^0)

$pp \to n\Lambda$: (π^-, K^+)

Past Hypernuclei Activities

1 MeV

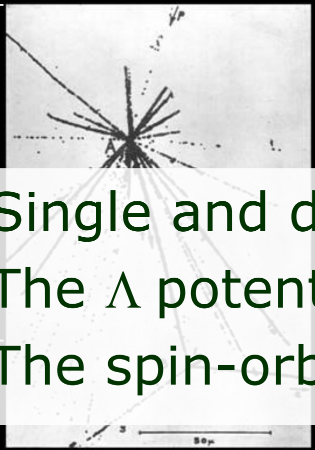
100 keV

10 keV

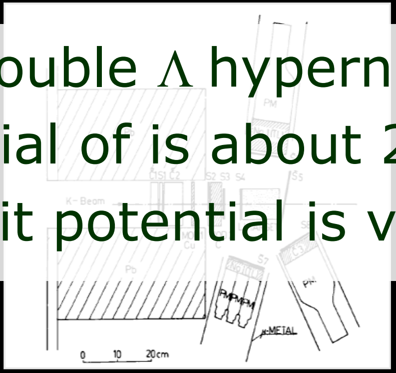
1950

2000

Emulsion

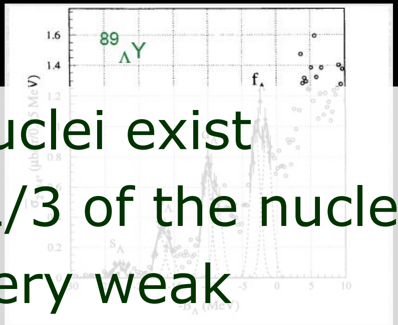


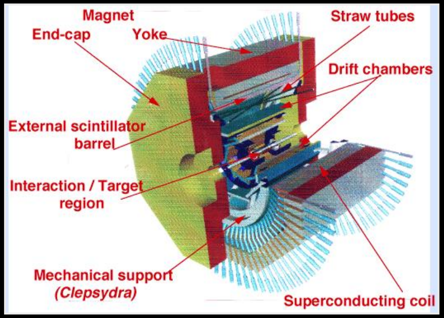
CERN PS



AGS

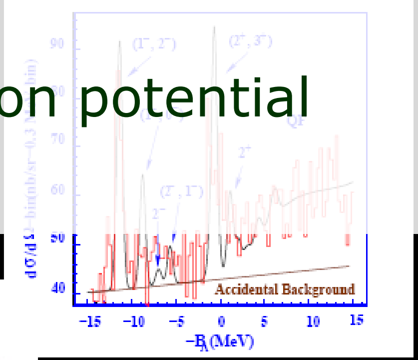
KEK

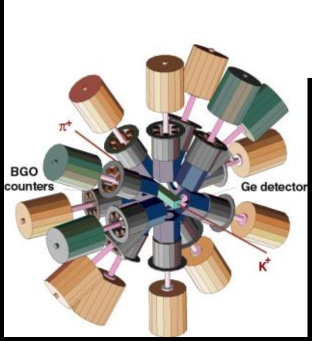




FINUDA

JLAB

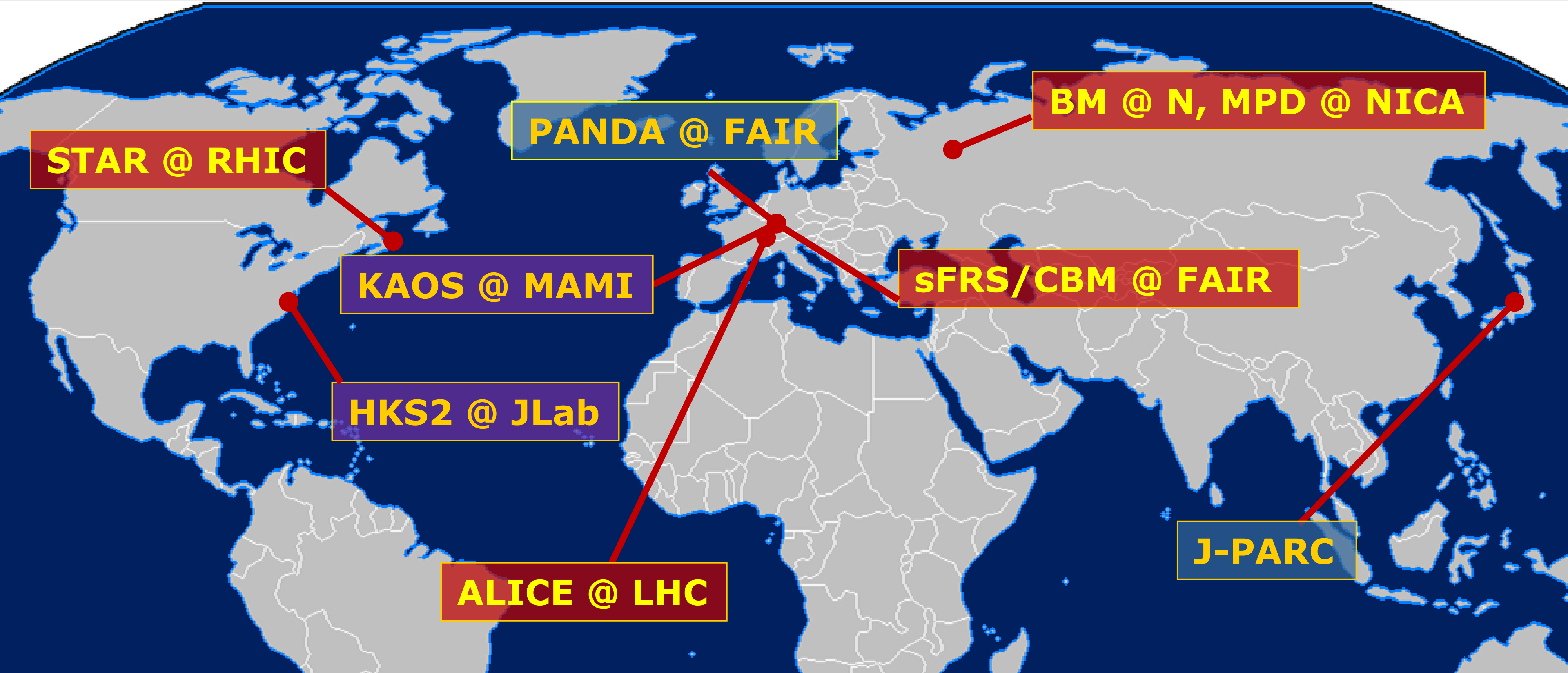




HYPERBALL

- Single and double Λ hypernuclei exist
- The Λ potential of is about 2/3 of the nucleon potential
- The spin-orbit potential is very weak

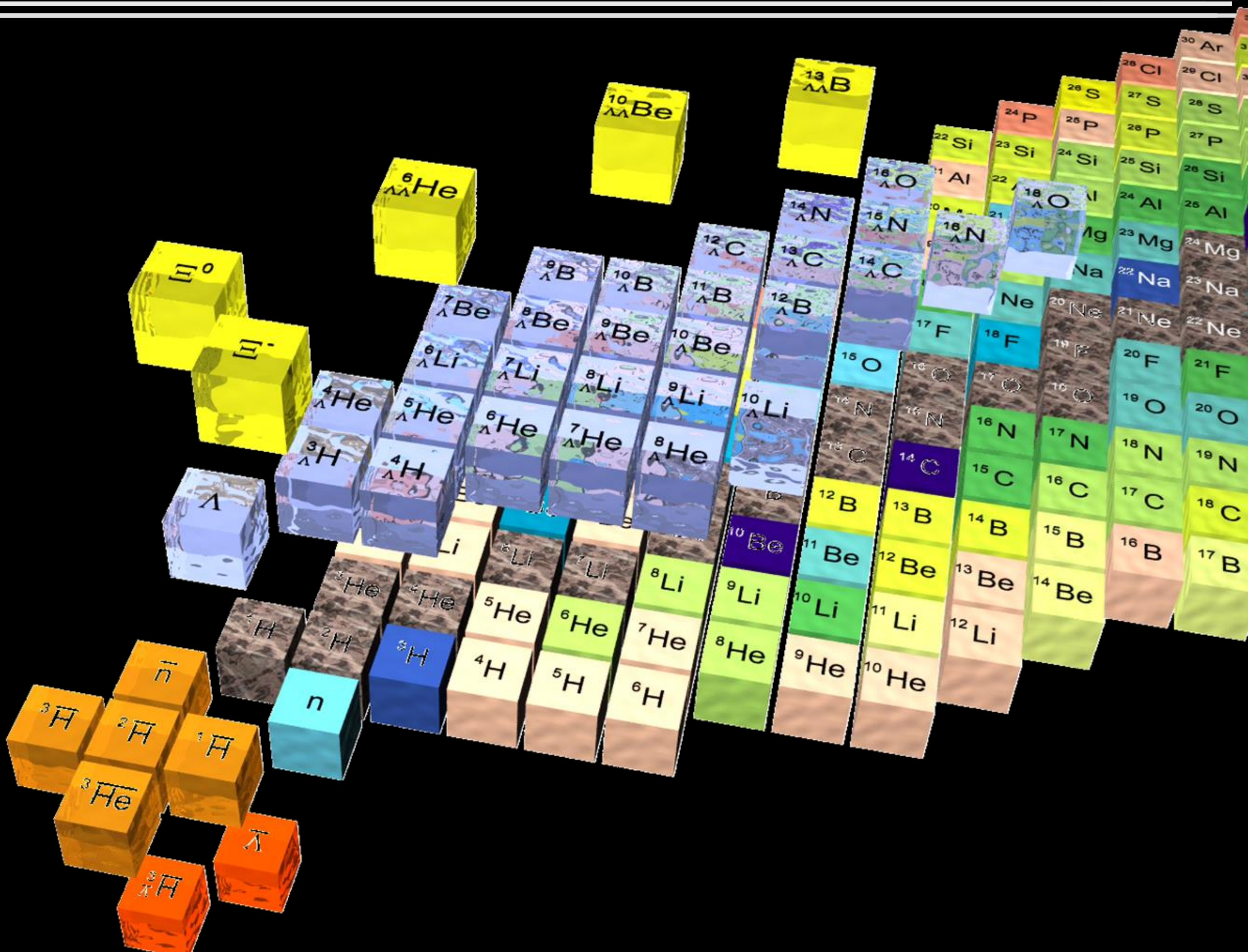
Hypernuclear Activities Today



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

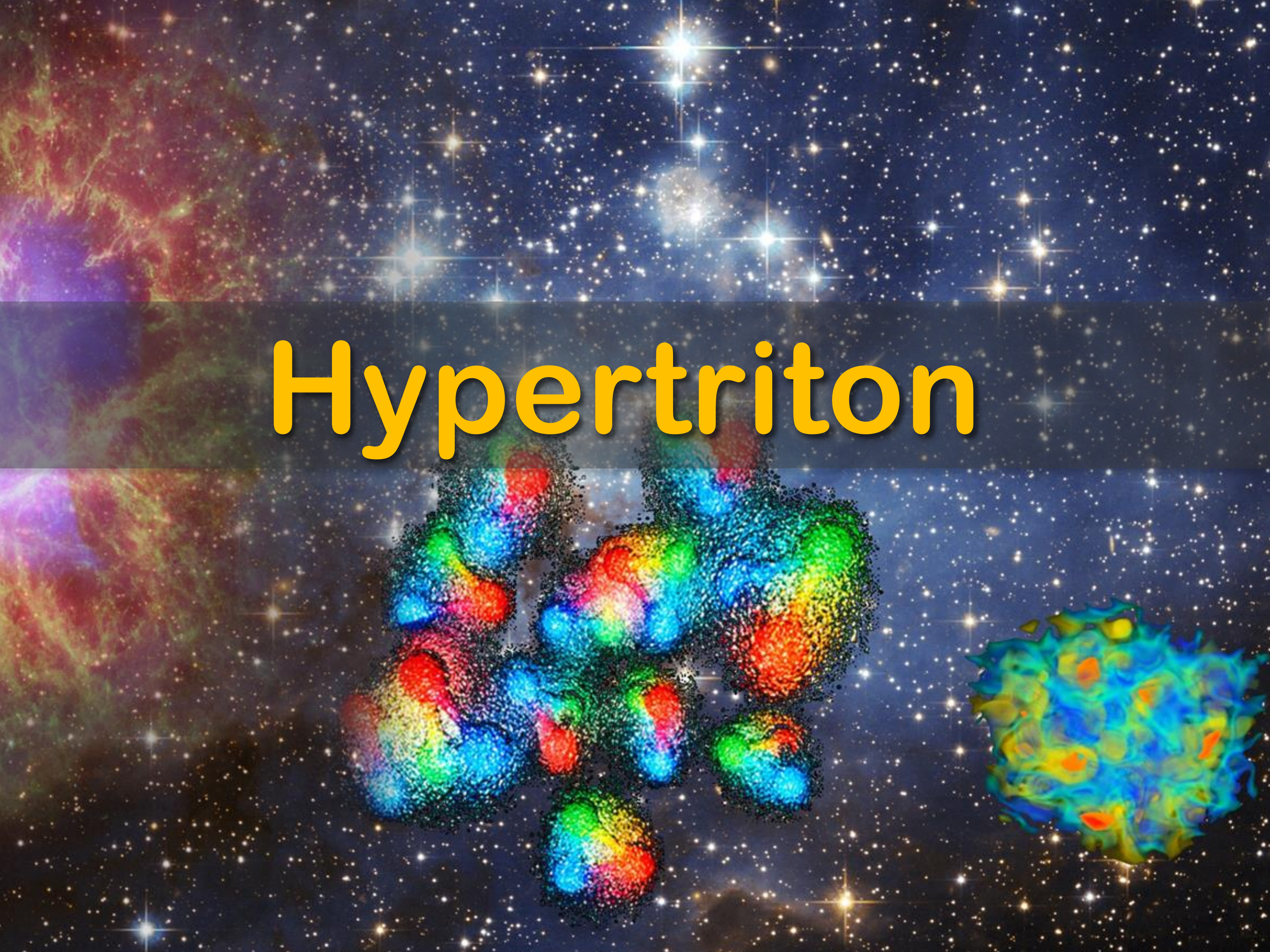
Methods
- missing mass studies
- invariant mass studies
- γ-spectroscopy
- π-spectroscopy
- FSI

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



Ξ⁰
Ξ⁻
Λ
⁶ΛΛHe
¹⁰ΛΛBe
¹³ΛΛB
³ΛH
⁴ΛH
⁴ΛHe
⁵ΛHe
⁶ΛHe
⁷ΛHe
⁸ΛHe
⁶ΛLi
⁷ΛLi
⁸ΛLi
⁹ΛLi
¹⁰ΛLi
⁷ΛBe
⁸ΛBe
⁹ΛBe
¹⁰ΛBe
⁹ΛB
¹⁰ΛB
¹¹ΛB
¹²ΛB
¹²ΛC
¹³ΛC
¹⁴ΛC
¹⁴ΛN
¹⁵ΛN
¹⁶ΛN
¹⁶ΛO
¹⁸ΛO
n
³H
⁴H
⁵H
⁶H
⁵He
⁶He
⁷He
⁸He
⁹He
¹⁰He
⁸Li
⁹Li
¹⁰Li
¹¹Li
¹²Li
¹⁰Be
¹¹Be
¹²Be
¹³Be
¹⁴Be
¹²B
¹³B
¹⁴B
¹⁵B
¹⁶B
¹⁷B
¹⁴C
¹⁵C
¹⁶C
¹⁷C
¹⁸C
¹⁶N
¹⁷N
¹⁸N
¹⁹N
¹⁵O
¹⁹O
²⁰O
¹⁷F
¹⁸F
²⁰F
²¹F
²²Na
²³Na
²³Mg
²⁴Mg
²⁴Al
²⁵Al
²²Si
²³Si
²⁴Si
²⁵Si
²⁶Si
²⁴P
²⁵P
²⁶P
²⁷P
²⁶S
²⁷S
²⁸S
²⁸Cl
²⁹Cl
³⁰Ar
n̄
¹H̄
²H̄
³H̄
³He̅
Λ̄

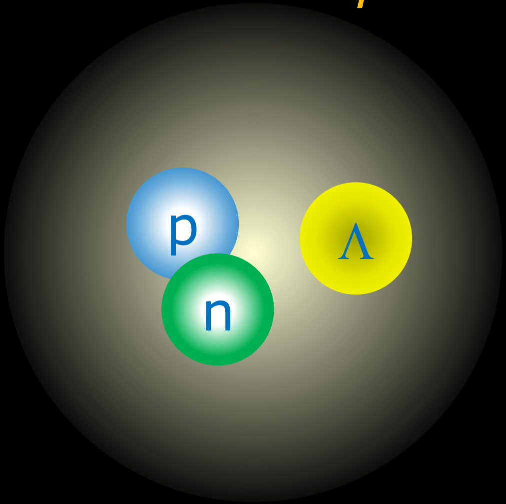
Hypertriton

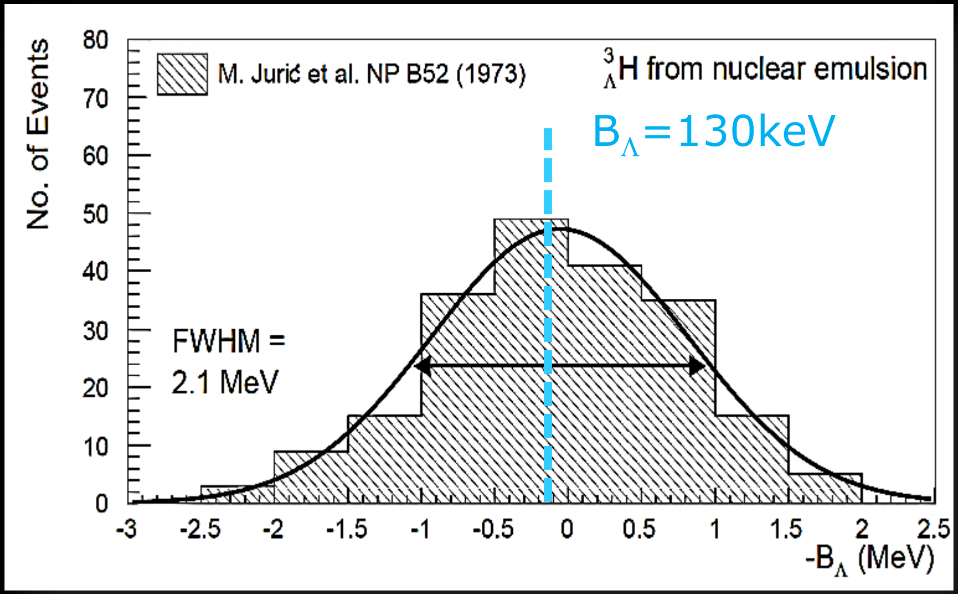


The Hypertriton Puzzle

Do we understand the simplest Hypernucleus?

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



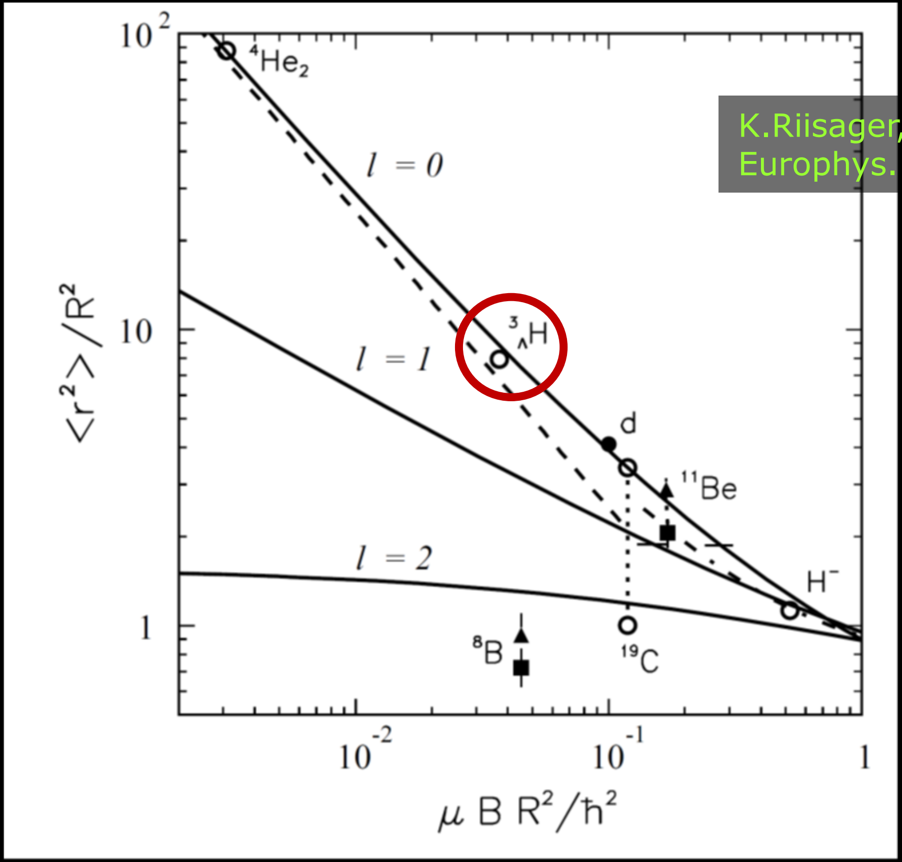


The $^3_\Lambda H$ Puzzle: Part 1 - Λ Binding Energy

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

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

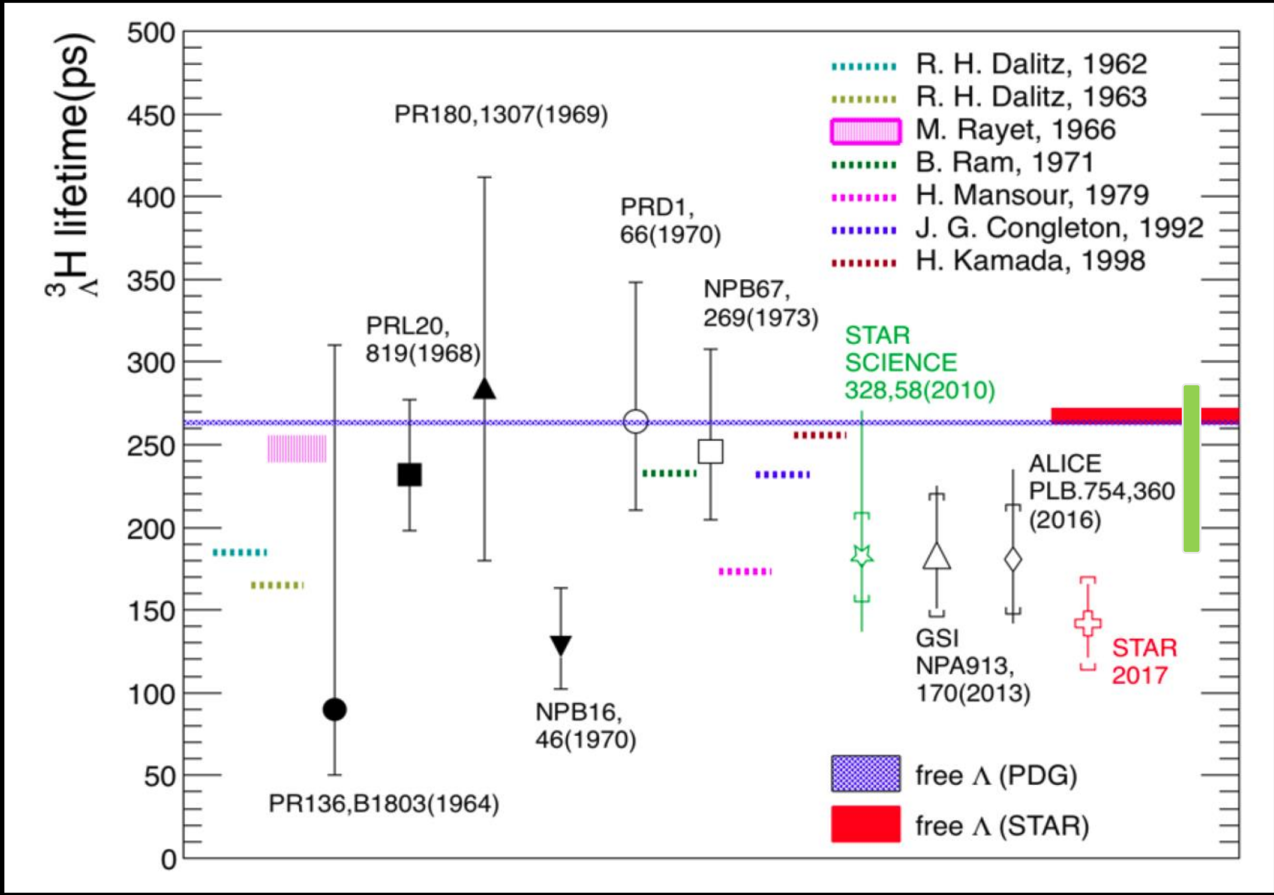
ratio of halo and core-potential square radii



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

scaled separation energy

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



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

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

small binding energy ? small lifetime

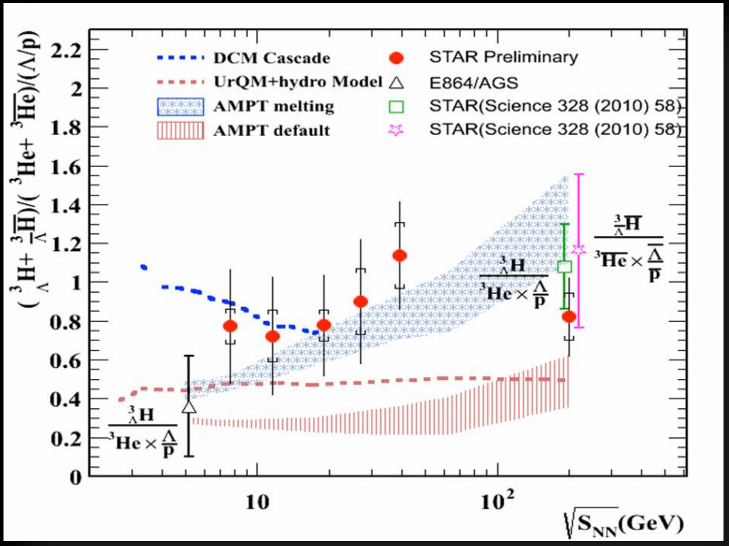
Approaching the $^{3}_{\Lambda}H$ Puzzle

small binding energy ? small lifetime

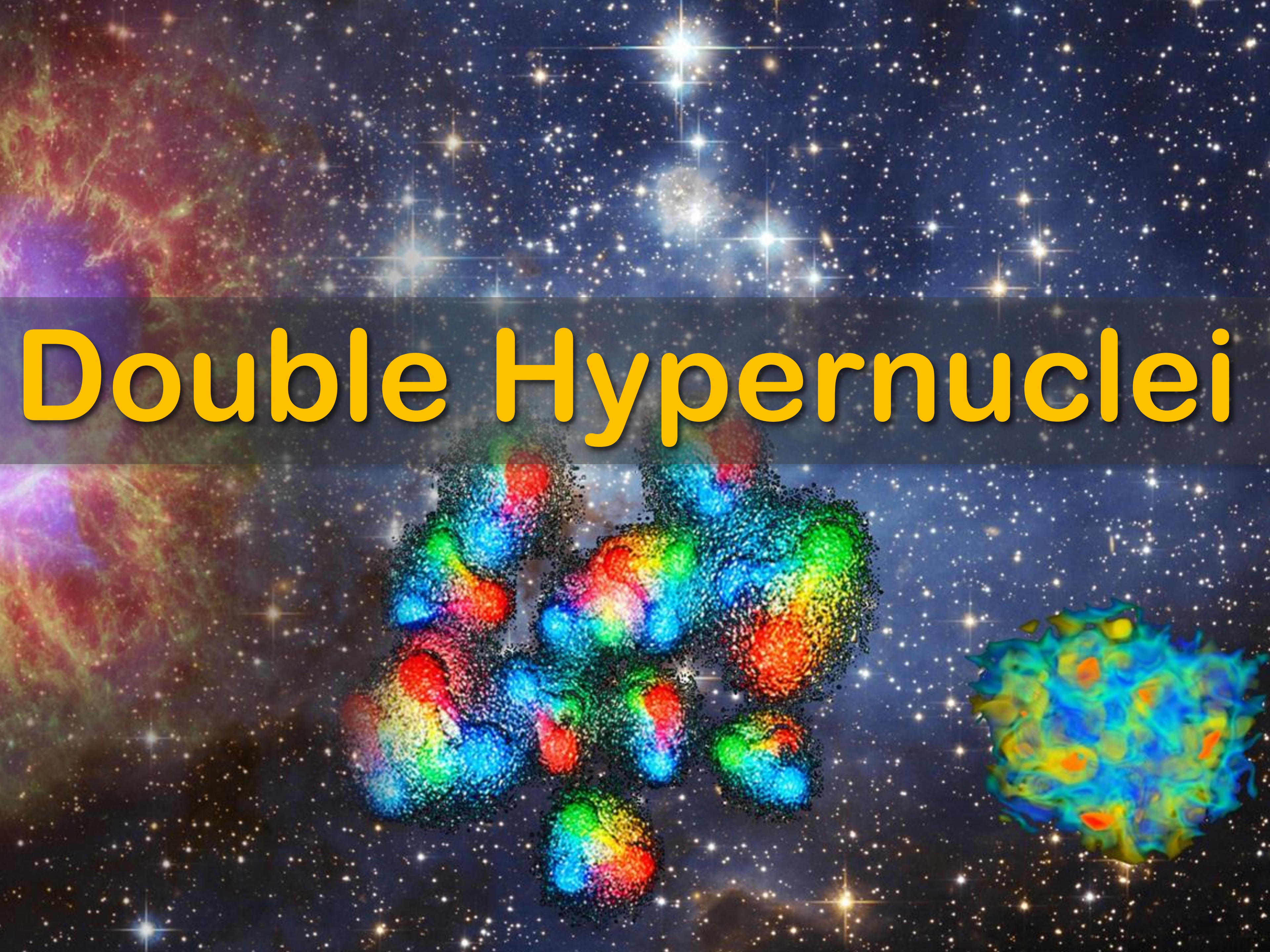
- New precision mass measurement at MAMI in 2019
  - Make use of excellent beam quality at MAMI
  - Precision *absolute* energy calibration interference of undulator radiation

- 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})

$$\frac{\overbrace{(np\Lambda)}^{^{3}_{\Lambda}H} / \Lambda}{\underbrace{(npp)}_{^{3}He} / p}$$



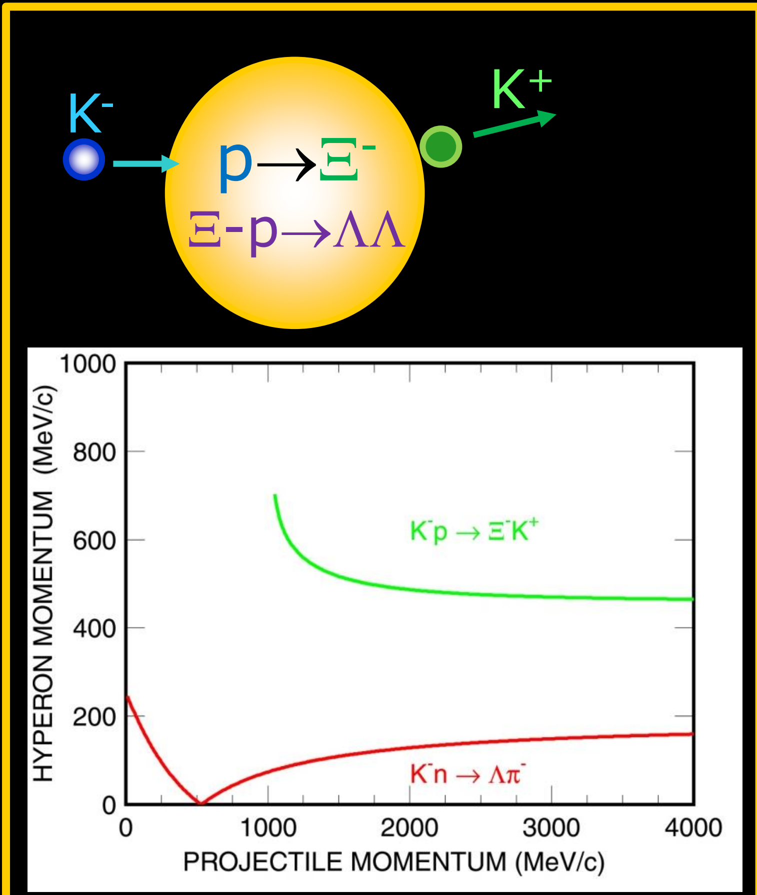
ALICE

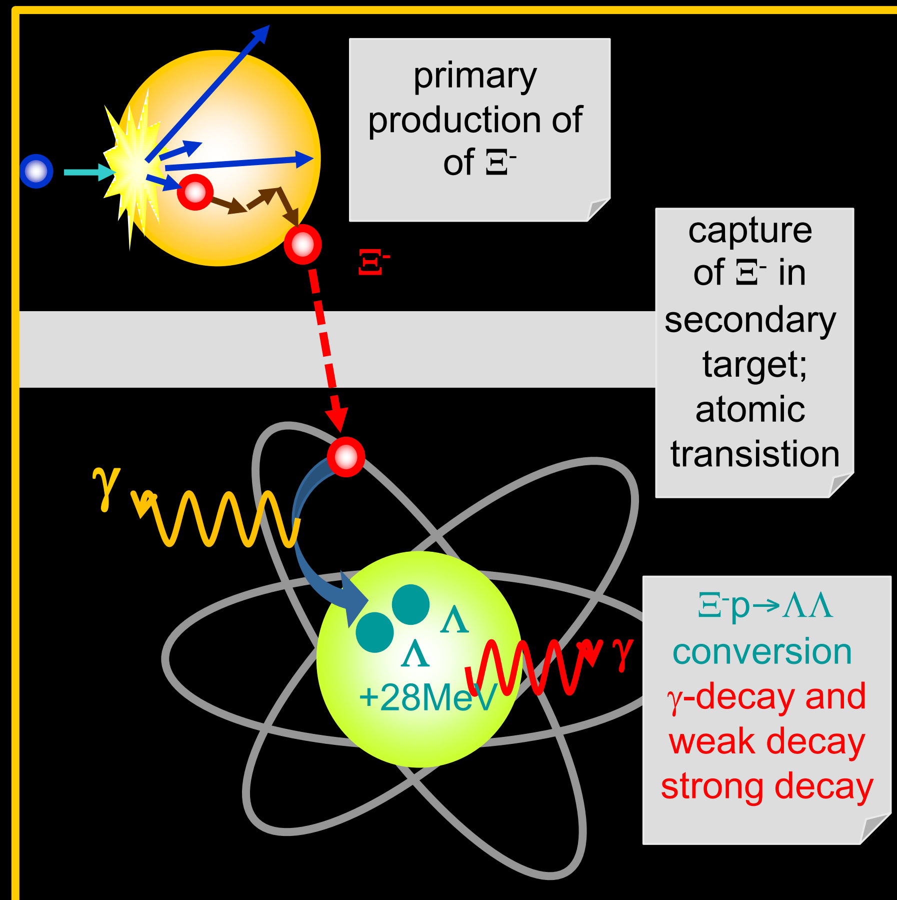

Double Hypernuclei

Production of ΛΛ Hypernuclei

- simultaneous implantation of two Λ's impossible
- Ξ⁻ conversion in 2Λ: $\Xi^- + p \rightarrow \Lambda + \Lambda$ + 28MeV

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



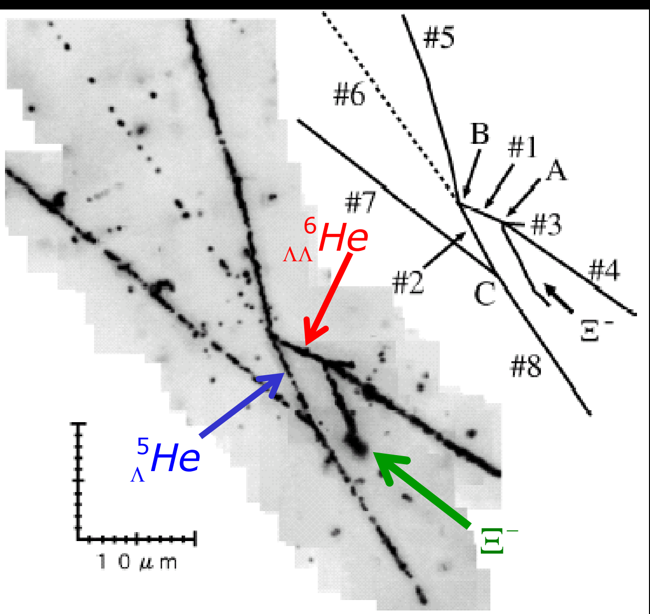


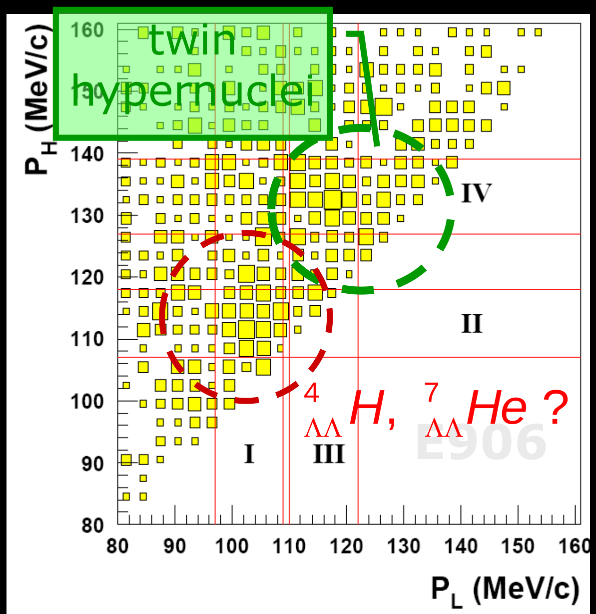
- two-step process

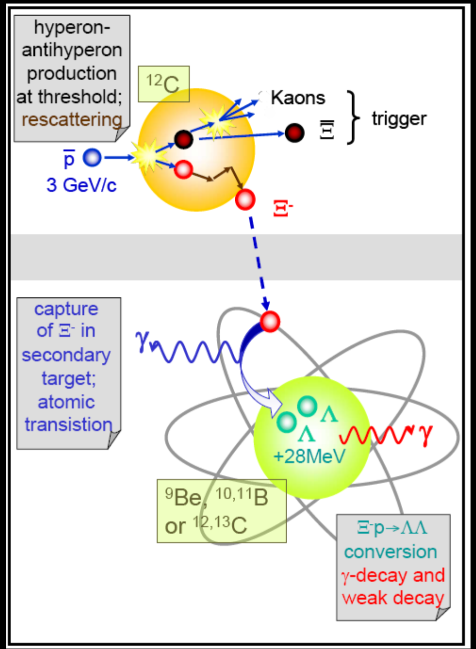
⇒ spectroscopic studies only via the decay products

Hypernuclei

- nuclear fragments ⇒ emulsion hadron+nucleus
  - detection of charged products only
  - limited to light nuclei
- weak decay products ⇒ BNL-AGS E906 $^{9}Be(K^{-},K^{+})X$
  - resolution limited
  - no information on excited states
  - interpretation not unique because π momenta are similar
- γ- spectroscopy ⇒ PANDA $\bar{p}$+A
  - no excited states observed yet, but theoretically predicted
  - How to identify the nucleus ?







The first event (1)

- 1.3-1.5 GeV/c K^-+Emulsion; 31000 K^-

Volume 11, Number 1 PHYSICAL REVIEW LETTERS 1 July 1963

OBSERVATION OF A DOUBLE HYPERFRAGMENT

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and

E. R. Fletcher
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and

J. Lemonne, P. Renard,* and J. Sacton
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and

W. T. Toner†
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and

D. O'Sullivan, T. P. Shah, and A. Thompson
Institute for Advanced Studies, Dublin, Ireland

and

P. Allen, Sr.,‡ M. Heeran, and A. Montwill
University College, Dublin, Ireland

and

J. E. Allen, M. J. Beniston, D. H. Davis, and D. A. Garbutt
University College, London, England

and

V. A. Bull, R. C. Kumar, and P. V. March
Westfield College, London, England

(Received 3 April 1963)

- carefully reanalyzed
  - 1963 by P.H. Fowler, V.M. Mayes and E.R. Fletcher
  - Dalitz *et al.*, Proc. R. Soc. Lond. A426, 1 (1989)

During a systematic scan for interactions of 1.3- and 1.5-GeV/c K^- mesons[1] in emulsions irradiated in the separated K^- meson beam at CERN,[2] an event has been found which is interpreted as the production and subsequent mesonic

of all the charged particles involved in these processes are summarized in Table I. All reasonable interpretations of this event, other than that of a Ξ^- hyperon capture at B leading to the emission of a double hyperfragment, have been

The observed first event

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\mathrm{MeV}$$

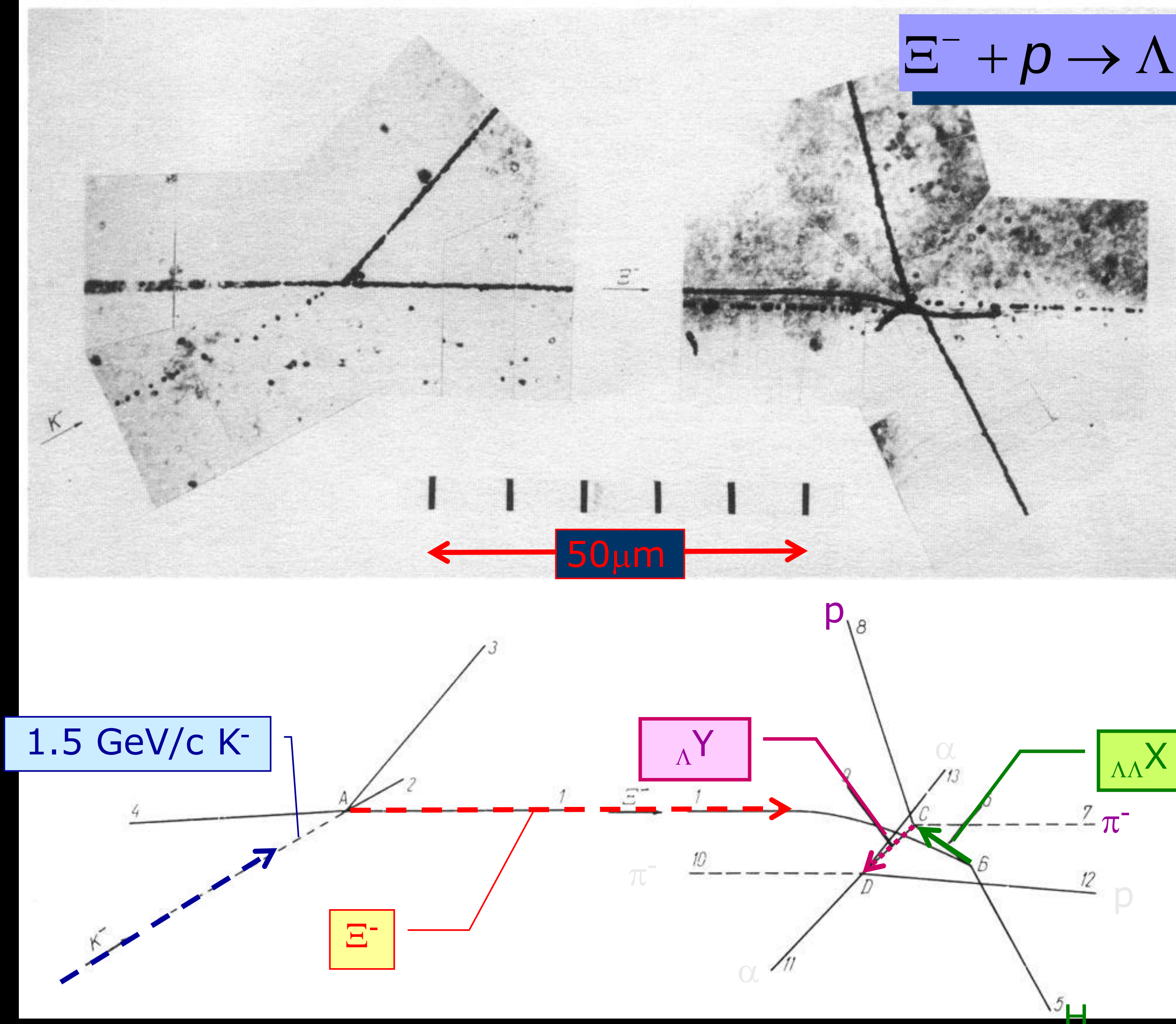


FIG. 1. A photomicrograph and a schematic drawing of the production of a Ξ^- hyperon in a 1.5-GeV/c K^--meson interaction at A followed by capture at rest of the Ξ^- hyperon at B with the emission of a double hyperfragment decaying in cascade at C and D.

Analysis of the Danysz-Event

- Ionisation density $\Rightarrow$ dE/dx $\Rightarrow$ charge, momentum
- Range $\Rightarrow$ mass, charge, momentum

Star C: Decay mode of the double *HF*	Binding energy of a Λ^0 hyperon in the double *HF* $B_{\Lambda}(_{\Lambda\Lambda}Z)$ (MeV)	Star D: Decay mode of the resulting ordinary *HF*	Binding energy of the Λ^0 hyperon in the ordinary *HF* $B_{\Lambda}(_{\Lambda}Z)$ (MeV)	Momentum unbalance Δp(MeV/c)
$_{\Lambda\Lambda}Be^{10} \rightarrow {}_{\Lambda}Be^{9} + H^{1} + \pi^{-}$	11.0 ± 0.4	$_{\Lambda}Be^{9} \rightarrow 2He^{4} + H^{1} + \pi^{-}$	7.2 ± 0.6	20 ± 12
$_{\Lambda\Lambda}Be^{11} \rightarrow {}_{\Lambda}Be^{9} + H^{1} + n + \pi^{-}$	$< 7.6 \pm 0.7$	$_{\Lambda}Be^{9} \rightarrow 2He^{4} + H^{1} + \pi^{-}$	7.2 ± 0.6	20 ± 12
$_{\Lambda\Lambda}Be^{11} \rightarrow {}_{\Lambda}Be^{10} + H^{1} + \pi^{-}$	11.1 ± 0.4	$_{\Lambda}Be^{10} \rightarrow 2He^{4} + H^{2} + \pi^{-}$	7.5 ± 0.6	17 ± 20
$_{\Lambda\Lambda}Li^{8} \rightarrow {}_{\Lambda}Li^{7} + H^{1} + \pi^{-}$	10.8 ± 0.4	$_{\Lambda}Li^{7} \rightarrow He^{4} + H^{2} + H^{1} + \pi^{-}$	6.5 ± 0.6	40 ± 14
$_{\Lambda\Lambda}Li^{9} \rightarrow {}_{\Lambda}Li^{8} + H^{1} + \pi^{-}$	10.9 ± 0.4	$Li^{8} \rightarrow He^{4} + H^{3} + H^{1} + \pi^{-}$	5.4 ± 0.6	27 ± 15
$_{\Lambda\Lambda}Li^{10} \rightarrow {}_{\Lambda}Li^{8} + H^{1} + n + \pi^{-}$				27 ± 15

$$\Xi^{-} + {}^{12}C \rightarrow {}^{10}_{\Lambda\Lambda}Be + p + 2n$$

$$\hookrightarrow {}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}Be + p + \pi^{-}$$

$$\hookrightarrow {}^{9}_{\Lambda}Be \rightarrow \alpha + \alpha + p + \pi^{-}$$

12 ... 75 ± 5
13 ... 26 ± 10

[a] The errors given for the angles include those resulting from measurements. The errors in ranges take into account, apart from measurement errors, also those resulting from straggling.
[b] The interpretation in terms of a $_{\Lambda\Lambda}Li^{8,9,10}$ hyperfragment requires the emission of an additional charged particle from star *B* which does not give rise to an observable track.
[c] Large errors in the determination of the range and direction of this track results from the observational difficulties and are to be treated as maximum errors.
[d] A capture star is observed at the end of this track.

interaction?

- The binding energy B_Λ of a Λ particle in a hypernucleus can be determined from energy balance of the decay products at point C
  - for example

$$\boxed{{}^{9}_{\Lambda}Be \rightarrow \alpha + \alpha + p + \pi^-}$$

$$m\left({}^{9}_{\Lambda}Be\right) = m(\alpha) + m(\alpha) + m(p) + m(\pi^-) + \sum T''_{kin}$$

$$B_\Lambda\left({}^{9}_{\Lambda}Be\right) = m({}^{8}Be) + m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right)$$

$$= m({}^{8}Be) + m(\Lambda) - m(\alpha) - m(\alpha) - m(p) - m(\pi^-) - \sum T''_{kin}$$

$$\boxed{{}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}Be + p + \pi^-}$$

$$m\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{9}_{\Lambda}Be\right) + m(p) + m(\pi^-) + \sum T'_{kin}$$

$$B_\Lambda\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{9}_{\Lambda}Be\right) + m(\Lambda) - m\left({}^{10}_{\Lambda\Lambda}Be\right)$$

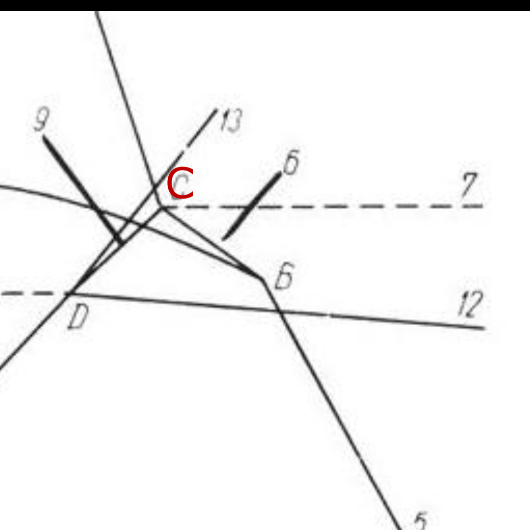
$$= m\left({}^{9}_{\Lambda}Be\right) + m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right) - m(p) - m(\pi^-) - \sum T_{kin}$$

$$= m(\Lambda) - m(p) - m(\pi^-) - \sum T_{kin}$$

$$B_{\Lambda\Lambda}\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{8}Be\right) + 2m(\Lambda) - m\left({}^{10}_{\Lambda\Lambda}Be\right)$$

$$= m\left({}^{8}Be\right) + 2m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right) - m(p) - m(\pi^-) - \sum T'_{kin}$$

$$\boxed{= m\left({}^{8}Be\right) + 2m(\Lambda) - 2m(\alpha) - 2m(p) - 2m(\pi^-) - \sum T_{kin}}$$

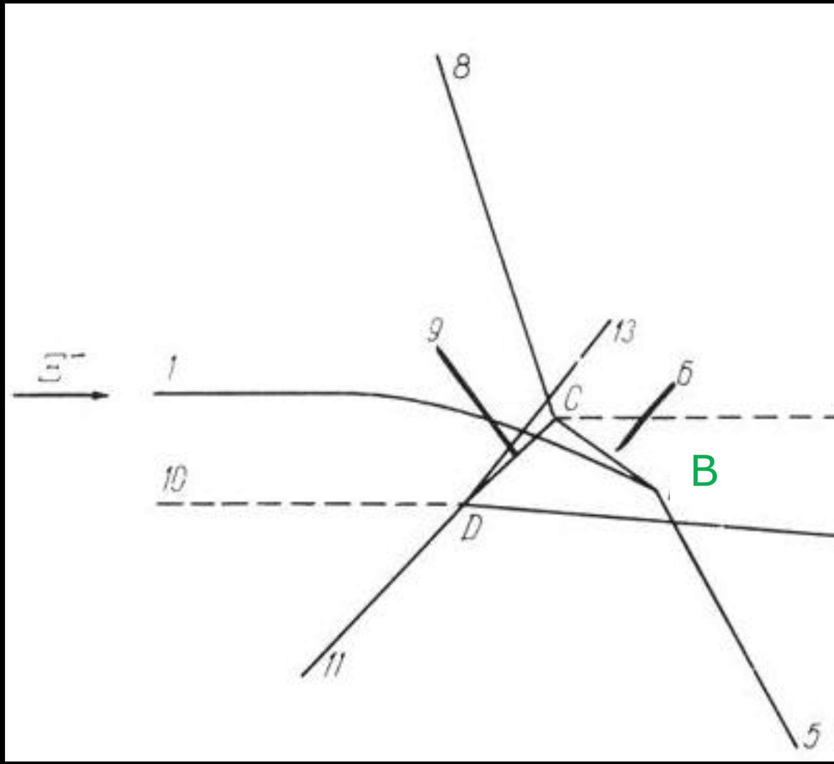


- Problem: if excited states in ${}^{9}_{\Lambda}Be$ involved $\rightarrow$ $B_{\Lambda\Lambda}$ overestimated
- Result: $B_{\Lambda\Lambda}$=17.5±0.4MeV

Production analysis

- Capture of the negative Ξ by an atom
- Ξ^- Binding energy B_Ξ
- $B_{\Lambda\Lambda}$ from point B

$$\Xi^- + {}^{12}C \rightarrow {}^{10}_{\Lambda\Lambda}Be + {}^{3}H$$



$$m(\Xi) - B_\Xi + m({}^{12}C) = m\left({}^{10}_{\Lambda\Lambda}Be\right) + m({}^{3}H) + \sum T^{p}_{kin}$$

$$m\left({}^{10}_{\Lambda\Lambda}Be\right) = m(\Xi) - B_\Xi + m({}^{12}C) - m({}^{3}H) - \sum T^{p}_{kin}$$

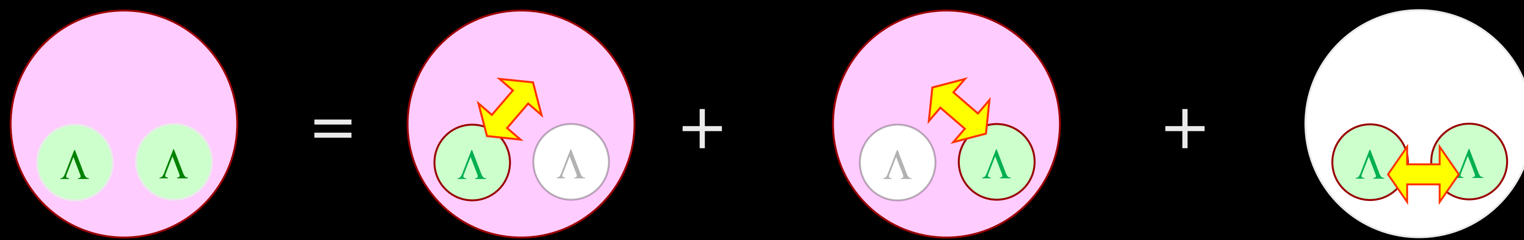
$$B_{\Lambda\Lambda}\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{8}Be\right) + 2m(\Lambda) - m\left({}^{10}_{\Lambda\Lambda}Be\right)$$

$$= m\left({}^{8}Be\right) + 2m(\Lambda) - m(\Xi) + B_\Xi - m({}^{12}C) + m({}^{3}H) + \sum T^{p}_{kin}$$

- $B_{\Lambda\Lambda}$=10.9±0.6MeV
- Lower limit

First approach to the ΛΛ interaction

- We are mainly interested in the additinal binding energy *between* the two Λ's



$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) \qquad -B_{\Lambda}({}^{A-1}_{\Lambda}Z) \qquad -B_{\Lambda}({}^{A-1}_{\Lambda}Z) \quad = \quad \Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$$

- in the case of the Danysz-event one obtains

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (17.7 \pm 0.4)\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (4.3 \pm 0.4)\,\mathrm{MeV}$$

- positive ⇒ attractive interaction
- this is the net ΛΛ binding provided that
  - the core is not distorted by adding one Λ after the other
  - the core spin is zero
  - no γ-unstable excited states are produced

note:

$\Delta B_{\Lambda\Lambda}$ is proportional to the kinetic energy of the produced pions

The Prowse Event (1)

VOLUME 17, NUMBER 14 PHYSICAL REVIEW LETTERS 3 OCTOBER 1966

$_{\Lambda\Lambda}He^6$ DOUBLE HYPERFRAGMENT*

D. J. Prowse
University of Wyoming, Laramie, Wyoming, and University of California, Los Angeles, California
(Received 14 July 1966)

An event has been found in an emulsion stack exposed to about 10^6 K^- mesons at 4 to 5 BeV which appears to be consistent with the production and decay of a $_{\Lambda\Lambda}He^6$ double hyperfragment. It confirms that double hyperfragments exist and confirms the value of the low-energy Λ-Λ interaction, first measured by Danysz et al.,[1] at some 4.6 ± 0.5 MeV.

Description of the event.—(1) Production: The event shown in Fig. 1 is initiated by a Ξ^- hyperon which is apparently captured at rest by a light emulsion nucleus producing only two products, which are collinear. Their ranges are 13.4 and 30.0 μ; the shorter track appears by inspection to be caused by a fragment of a higher charge than the other track. Assuming that the fragment initiating the two-star chain is a double hyperfragment, there are three interpretations involving double hyperfragments and a relatively stable recoil fragment which balance momentum, and which are consistent with the capture of a Ξ^- hyperon by a light emulsion nucleus.

These interpretations, shown in Table I, are $_{\Lambda\Lambda}He^6$ together with Li^7, $_{\Lambda\Lambda}He^8$ with Be^7, or $_{\Lambda\Lambda}Li^7$ with Be^{10}. The visible energies for each of these possibilities are 14.5, 18.3, and 23.9 MeV, respectively. The Q values for the nuclear capture of a Ξ^- hyperon giving two free Λ hyperons are negative except for the $_{\Lambda\Lambda}He^6$ possibility. The total binding energies of the Λ hyperons necessary to explain the measured visible energies are 10.9, 27.8, and 32.0 MeV, respectively.

The Prowse event (2)

- interpreted as ${}^{6}_{\Lambda\Lambda}He$
- very likely no excited state
- core spin is zero

$$B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) = (10.9 \pm 0.5)\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) = (4.7 \pm 0.6)\,\mathrm{MeV}$$

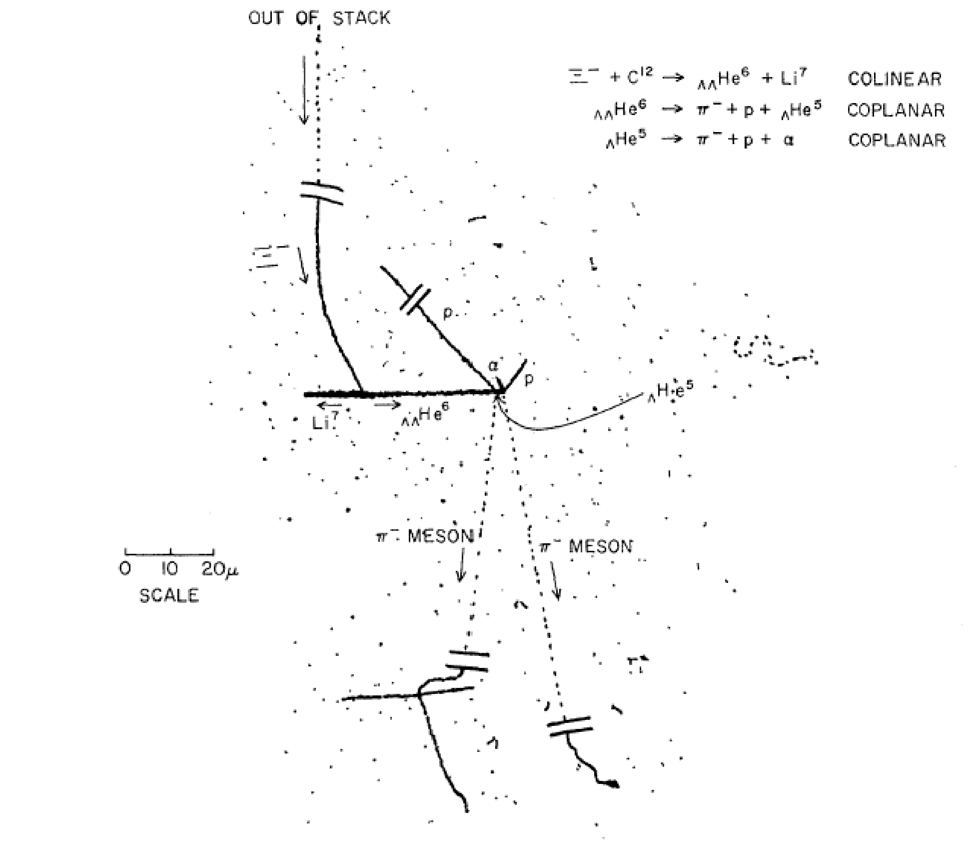


FIG. 1. Drawing of the event.

- no independent study of the event
- reconsidered by Dalitz *et al.*, Proc. R. Soc. Lond. A426, 1 (1989)
- event is now regarded as questionable

Pros and Cons of Emulsion Technique

+ excellent track resolution
- time consuming analysis: it just takes a long time to find the very few interesting events
  - higher K-rates needed
  - combine emulsion technique with electronic counters
    - use (K^-,K^+) to produce Ξ^-
    - track K^- and K^+ to determine interaction point in the emulsion/target
    - e.g. suggested 1989 by Dalitz *et al*.

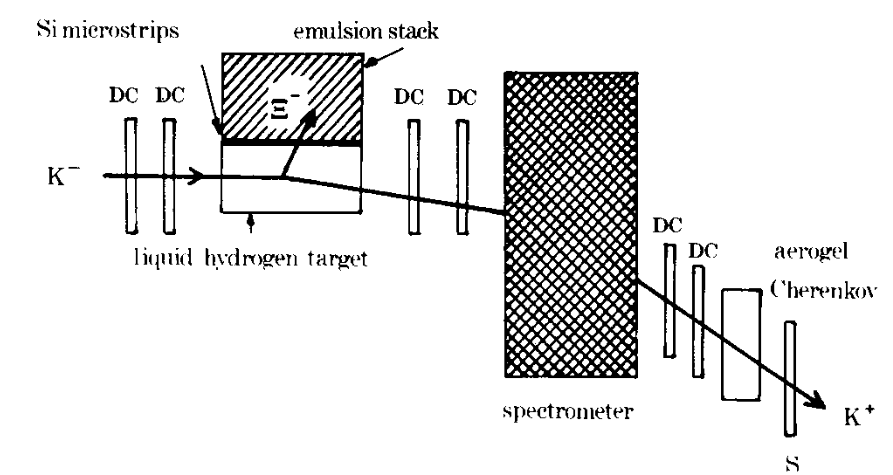
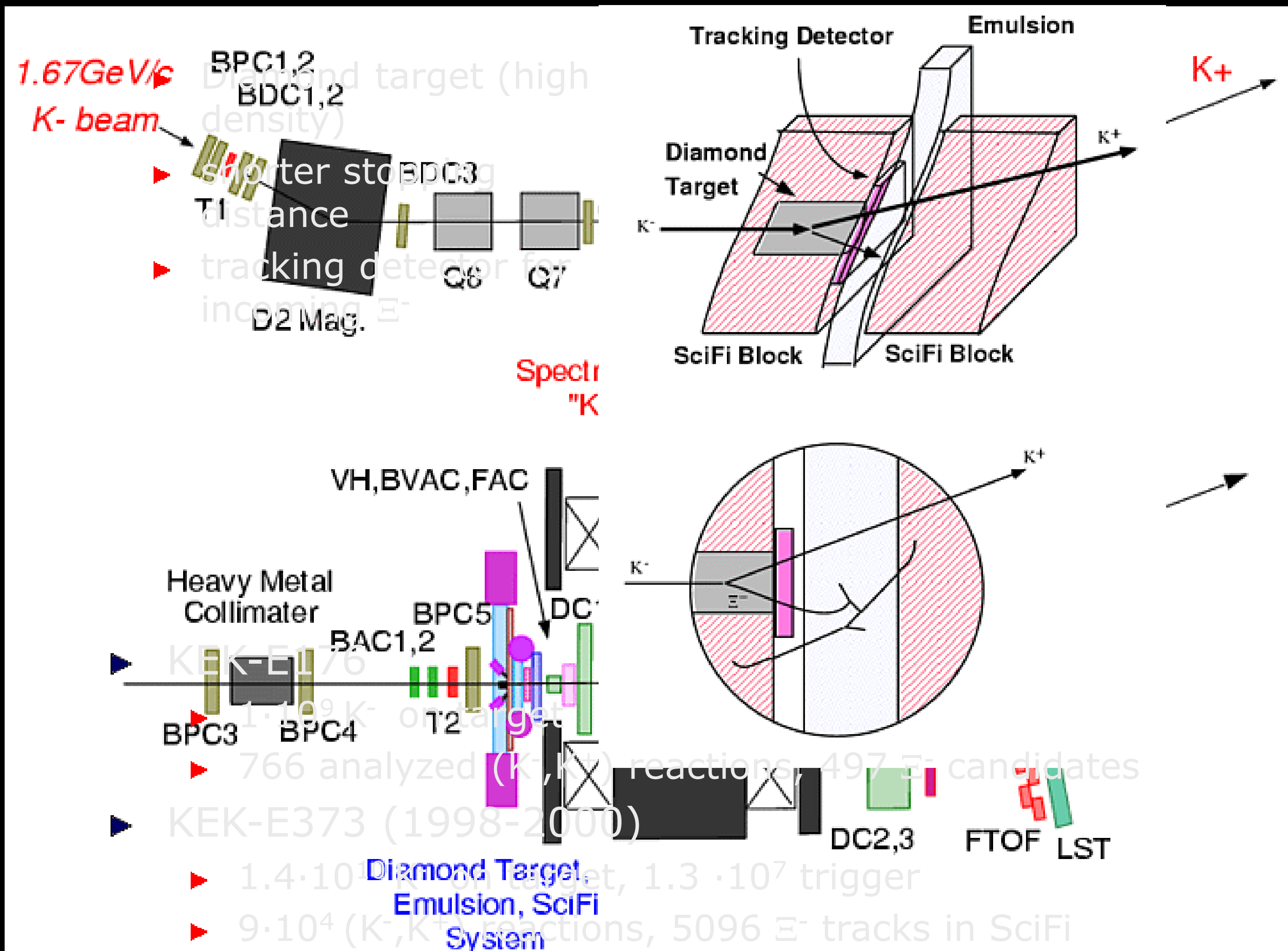


FIGURE 3. Schematic diagram of proposed hybrid emulsion experiment to study double hypernuclei. (DC is drift chamber and S is scintillator.)

- applied by KEK-E176 and KEK-E373 collaboration and today E07@J-PARC

The KEK-E373 Experiment

- KEK proton synchrotron
- 1.66 GeV/c K^- beam



- Diamond target (high density)
  - shorter stopping distance
  - tracking detector for incoming Ξ^-
- KEK-E176
  - $1\cdot10^9$ K^- on target
  - 766 analyzed (K^-,K^+) reactions, 497 Ξ^- candidates
- KEK-E373 (1998-2000)
  - $1.4\cdot10^{[illegible]}$ K^- on target, $1.3\cdot10^7$ trigger
  - $9\cdot10^4$ (K^-,K^+) reactions, 5096 Ξ^- tracks in SciFi

KEK-E373: the NAGARA event

- H. Takahashi *et al.*, PRL 87, 212502-1 (2001)
  - hybrid emulsion technique
  - cleanest event so far (also theoretically)

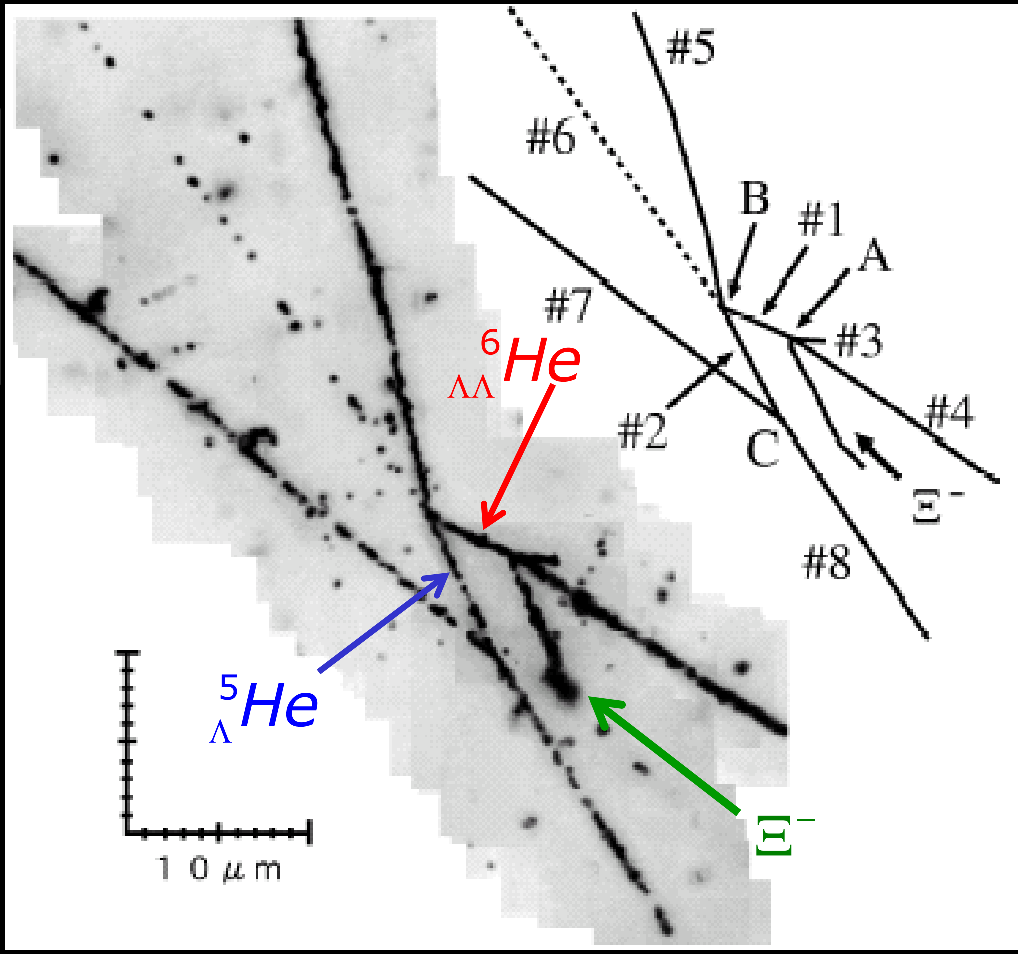
$$\Xi^- + {}^{12}C \rightarrow {}^{4}He + t + {}_{\Lambda\Lambda}^{6}He$$

$${}_{\Lambda\Lambda}^{6}He \rightarrow {}_{\Lambda}^{5}He + p + \pi^-$$

$$\Rightarrow \Delta B_{\Lambda\Lambda} = +1.01 \pm 0.2^{+0.18}_{-0.11}\mathrm{MeV}$$

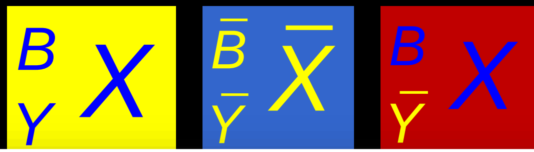
  - inconsistent with Prowse event
- one additional event
  - Demachiyanagi-event:

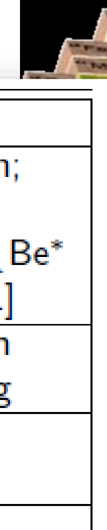
$${}_{\Lambda\Lambda}^{10}Be$$



Double Hypernuclei Today

H. Takahashi et al., PRL 87, 212502-1 (2001)

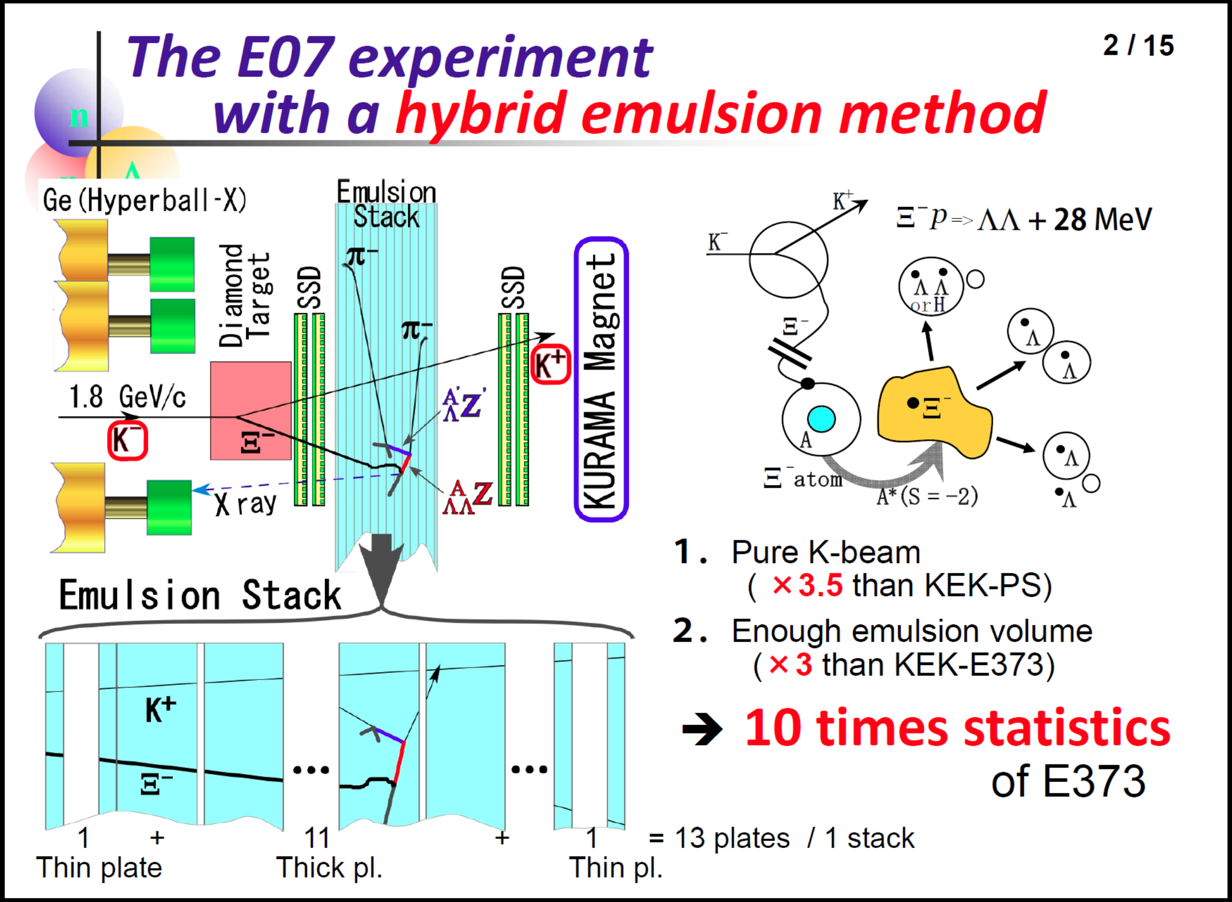




Nucleus	$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ (MeV)	Experiment	Reference	Remark
${}^{10}_{\Lambda\Lambda}$Be	4.3 ± 0.4	Danysz (1963)	[77, 78] [74]	K^- + nuclear emulsion; $\Delta B_{\Lambda\Lambda}$ consistent with NAGARA if decay to ${}^{9}_{\Lambda}$Be* at $E_x \approx 3$ MeV [81, 11]
${}^{6}_{\Lambda\Lambda}$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]	

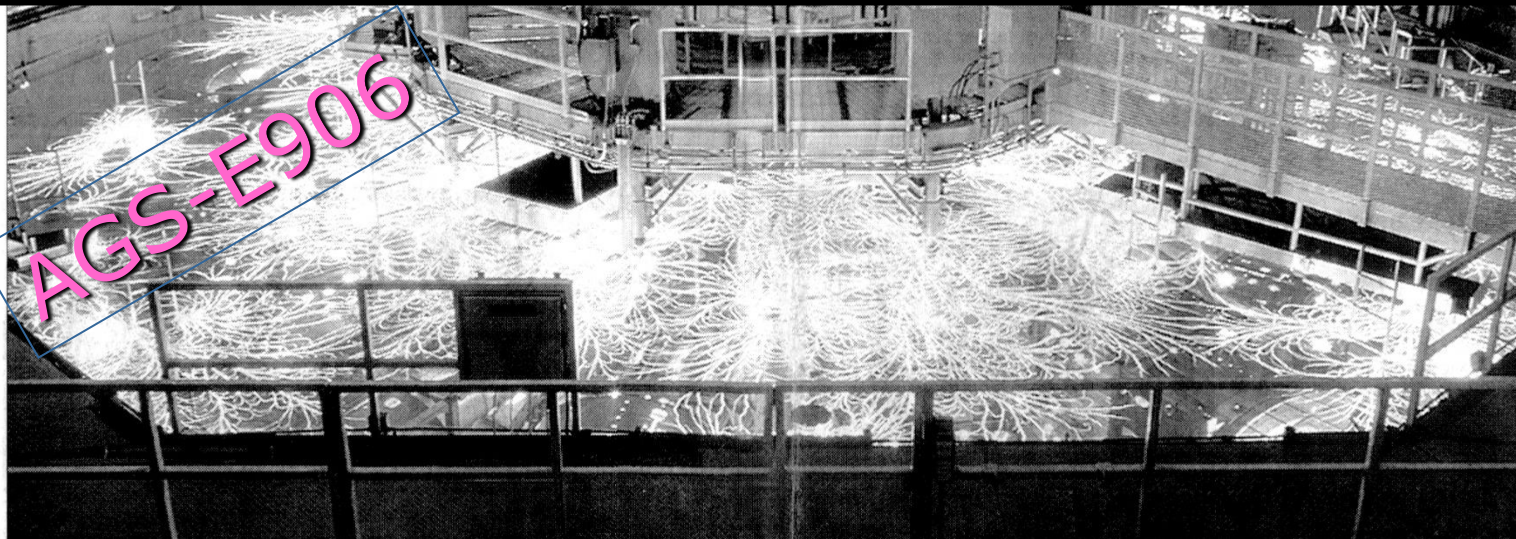
$\Xi^- p \rightarrow \Lambda\Lambda + 28\,\mathrm{MeV}$

E07 @ J-PARC



- Beam exposure has successfully been performed for all emulsion stacks in 2016/2017
- auto-scanning has started
- limitation: only ground state masses for ΛΛ-hypernuclei can be determined

DIE WELT 4. September 2001



Mit riesigen Maschinen wandeln die modernen Alchimisten Materie ineinander um oder erzeugen gar Materieformen, die es auf der Erde überhaupt nicht gibt. Das Foto zeigt eine Kernfusionsanlage in Neu-Mexiko

Doppelt seltsame Atomkerne synthetisiert

Nach 40 Jahren gelingt Physikern in den USA die Herstellung von exotischer Neutronenstern-Materie

VON BRIGITTE RÖTHLEIN

Brookhaven – Drei Jahre nach Abschluss einer Serie von Experimenten konnten Forscher im Brookhaven National Lab auf Long Island bei der Auswertung der Ergebnisse eine bisher nicht bekannte Art von Materie nachweisen. Sie entstand 1998 bei Zusammenstößen von Wolframatomen mit superschnellen Protonen.

Die Physiker sprechen von „doppelt seltsamen Kernen" und bringen damit zum Ausdruck, dass sich bei den Kollisionen im Beschleuniger ein Komplex aus mehreren Teilchen gebildet hat, der normalen Atomkernen nicht unähnlich ist. Das Besondere daran ist jedoch, dass diese Gebilde je zwei „seltsame" Teilchen enthalten.

Die Experimente von Teilchenforschern laufen in Sekundenbruchteilen ab. Man lässt dabei beschleunigte Elementarteilchen auf Ziele prallen und untersucht mit Hilfe großer Detektoren, welche Bruchstücke dabei entstehen. Die Vielzahl der in den letzten Jahrzehnten auf diese Weise entdeckten Teilchen hat gezeigt, dass sich unsere „normale" Materie auf zwei so genannte Quarks (mit den Namen „up" und „down") und Elektronen zurückführen lässt.

Daneben gib es aber auch noch exotische Arten von Materie, die aus schwereren Teilchen bestehen und auf der Erde üblicherweise nicht vorkommen. Zur Unterscheidung erhielten die Quarks dieser Materie die willkürlich gewählten Namen „strange" (seltsam) und „charme".

Aus den Millionen von Daten, die während einer Messkampagne entstehen, müssen die Physiker am Ende die wirklich relevanten „Ereignisse" herausfinden, die sprichwörtliche Nadel im Heuhaufen. In Brookhaven hat sich die Mühe offenbar gelohnt; aus 100 Millionen infrage kommenden Ereignissen filterten Computer zunächst 100 000 heraus, unter denen man dann 30 bis 40 mit den gesuchten Eigenschaften fand. „Hier wurde zum ersten Mal eine größere Anzahl von seltsamen Atomkernen erzeugt", erklärt Adam Rusek, der stellvertretende Sprecher der 50 beteiligten Physiker aus sechs Ländern.

40 Jahre lang hatte man in den USA, Europa und Japan nach den Gebilden gesucht, aber nur je eines davon gefunden, zum Teil mit zweifelhafter Sicherheit. Nun gelang es nachzuweisen, dass über einen mehrstufigen Zerfallsprozess Strukturen entstanden waren, die aus einem Neutron, einem Proton und zwei Lambda-Teilchen bestanden. Diese enthalten je ein up- und ein down-Quark und ein seltsames (strange) Quark. Die Lambda-Paare sind nun die bejubelten „doppelt seltsamen Kerne". Es ist allerdings sehr schwierig, sie näher zu untersuchen, da sie bereits nach weniger als einer Milliardstel Sekunde wieder zerfallen.

Die Forscher erhoffen sich vom Studium der seltsamen Kerne Erkenntnisse über jene Kräfte, die zwischen den Teilchen wirken. Daraus wollen sie Rückschlüsse auf die Prozesse in so genannten Neutronensternen ziehen. Diese Himmelskörper entstehen, wenn heiße Sterne am Ende ihres Lebens ausgebrannt sind und in sich zusammenstürzen. Man vermutet, dass sie große Mengen seltsamer Teilchen enthalten und dass sie der einzige Ort im All sind, wo seltsame Materie stabil existiert.

Weitere Informationen im Web:
www.bnl.gov

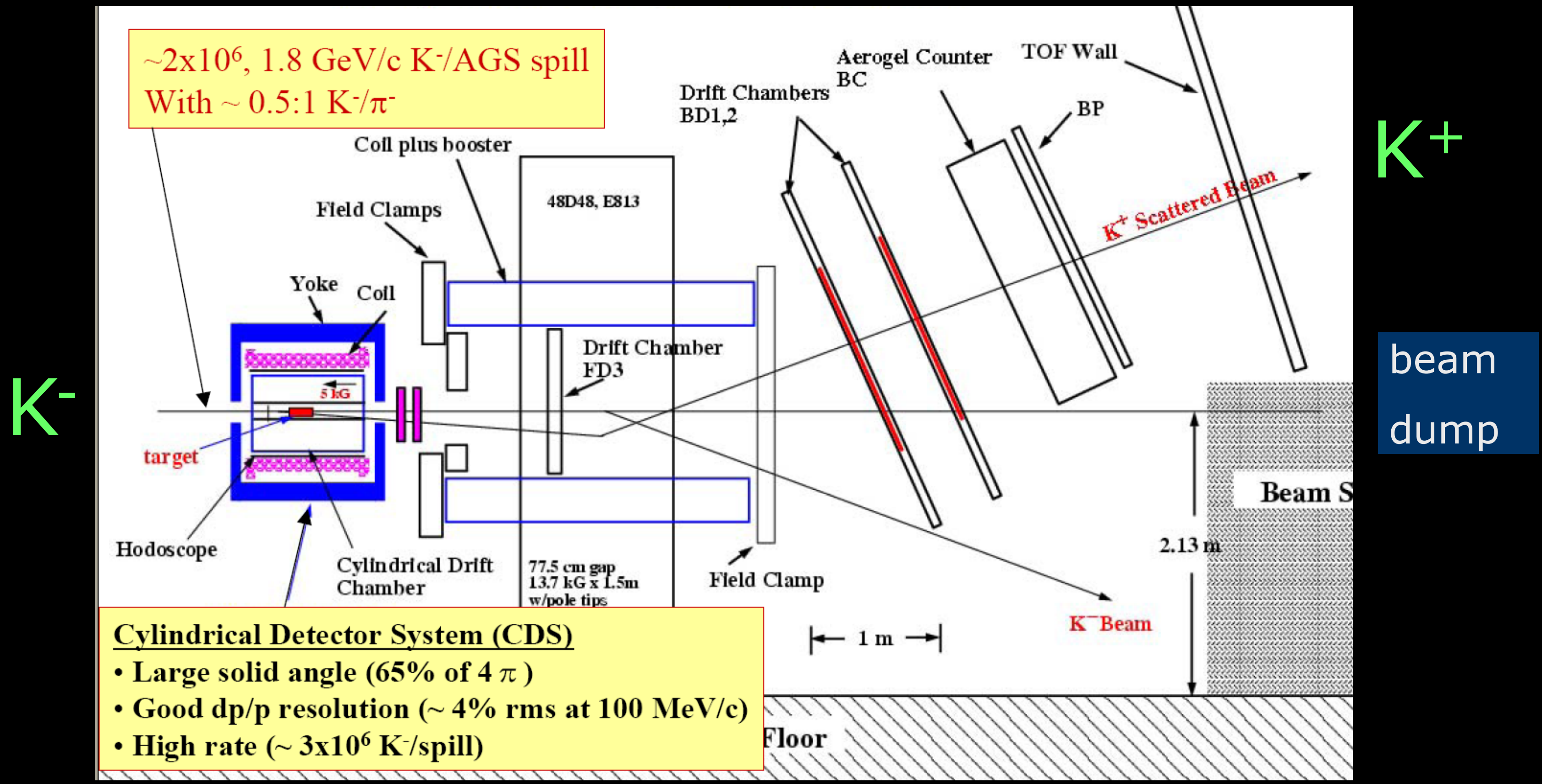
The E906: ^{9}Be(K$^-$,K$^+\pi^-\pi^-$)

Doube Hypernulei $\quad {}^{A0}_{\Lambda\Lambda}Z^* \to {}^{A}_{\Lambda\Lambda}Z + X$

$$\to \pi^- + {}^{A}_{\Lambda}(Z+1)$$

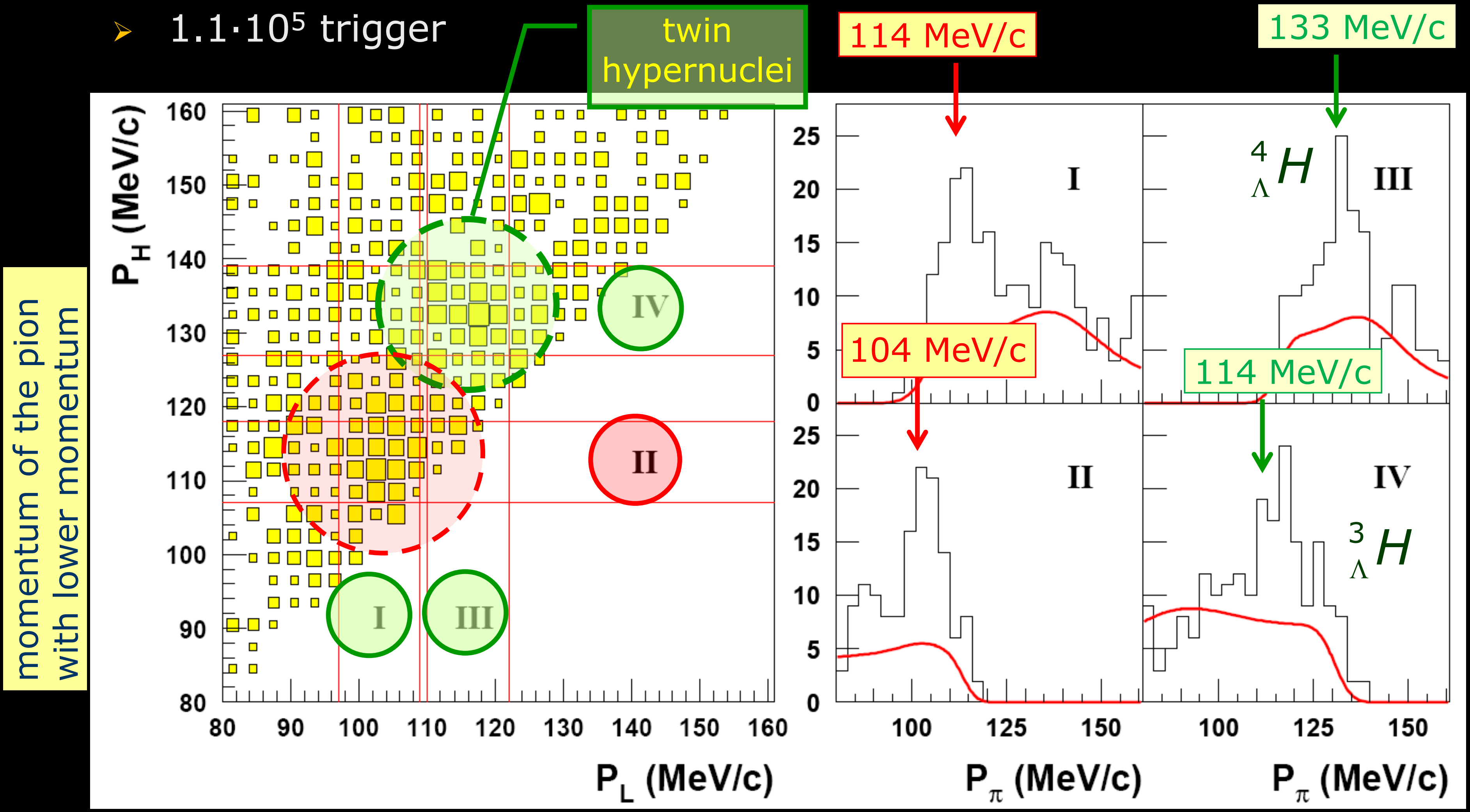
$$\to \pi^- + {}^{A}(Z+2)$$

Twin Hypernuclei $\quad {}^{A0}_{\Lambda\Lambda}Z^* \to {}^{A1}_{\Lambda}Z_1 + {}^{A2}_{\Lambda}Z_2 + X$



E906

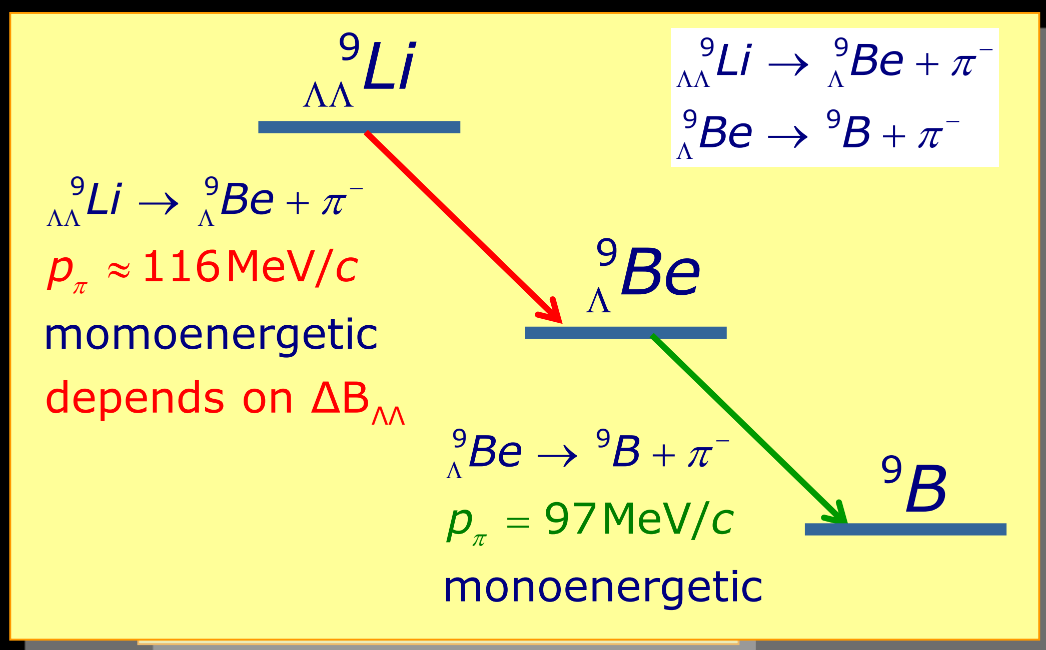
- $9 \cdot 10^{11}$ K^- on Be target
- $1.1 \cdot 10^5$ trigger



momentum of the pion with lower momentum

The E906 strategy

- fully electronic detector
- use $p(K^-,K^+)\Xi^-$ to produce Ξ^- on a nuclear target
- $\Xi^- p \rightarrow \Lambda\Lambda$ conversion after capture by another target (^{9}Be)
- Identification of $\Lambda\Lambda$ hypernucleus through sequential weak decay via π^- emission
  - in light nuclei the pionic weak decay significant
  - the pion kinetic energy is proportional to $\Delta B_{\Lambda\Lambda}$
  - coincidences between two pions help to trace the decay of the $\Lambda\Lambda$-nucleus
- example



E906 – What is it?

VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 2001

Production of ${}^{4}_{\Lambda\Lambda}$H Hypernuclei

J. K. Ahn,[13] S. Ajimura,[10] H. Akikawa,[7] B. Bassalleck,[9] A. Berdoz,[2] D. Carman,[2] R. E. Chrien,[1] C. A. Davis,[8,14]
P. Euge… K. Imai,[7]
S. H. … Landry,[8]
M. May, … Paschke,[2]

$${}^{4}_{\Lambda\Lambda}H \rightarrow \pi^{-}_{114MeV/c} + {}^{4}_{\Lambda}He \rightarrow \pi^{-}_{114MeV/c} + \pi^{-}_{97MeV/c} + {}^{4}H$$

PHYSICAL REVIEW C **66**, 014003 (2002)

Pionic weak decay of the lightest double-Λ hypernucleus ${}^{4}_{\Lambda\Lambda}$H

Izumi Kumagai-Fuse and Shigeto Okabe
Center for Information and Multimedia Studies, Hokkaido University, Sapporo 060-0811, Japan
(Received 31 December 2001; published 22 July 2002)

$${}^{3}_{\Lambda}H + {}^{6}_{\Lambda}He$$

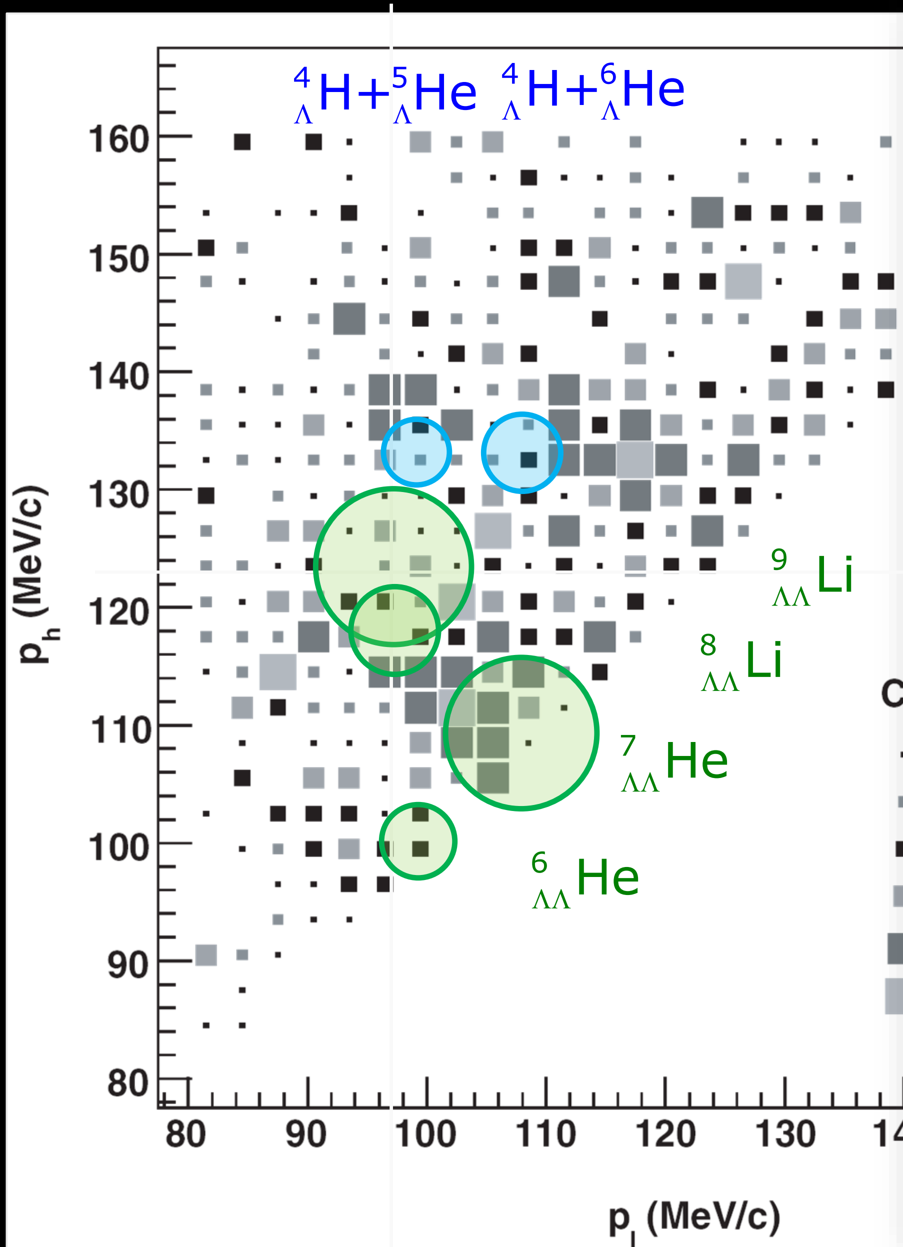
PHYSICAL REVIEW C **76**, 064308 (2007)

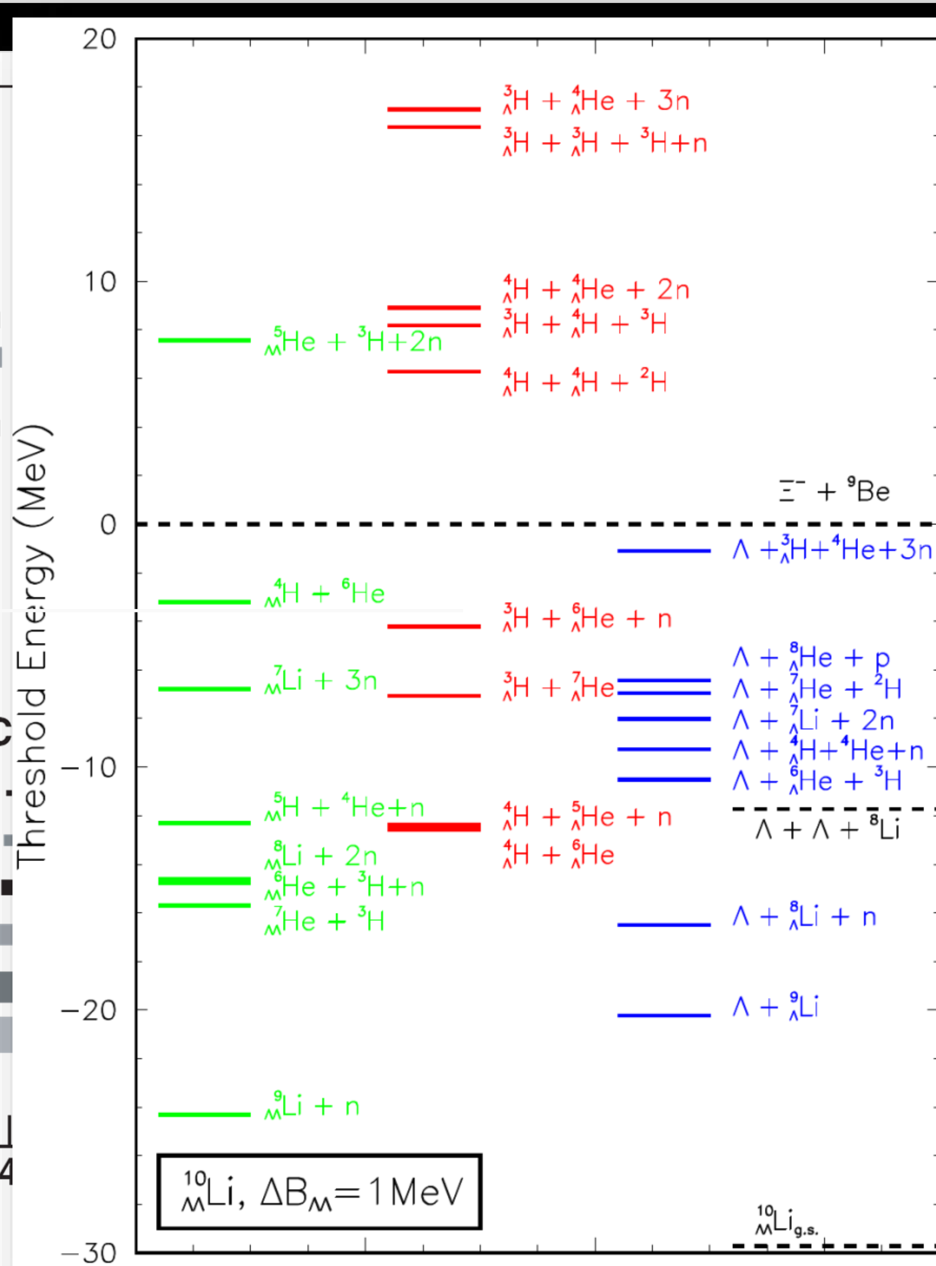
Reevaluation of the reported observation of the ${}^{4}_{\Lambda\Lambda}$H hypernucleus

S. D. Randeniya and E. V. Hungerford
Department of Physics, University of Houston, Houston, Texas 77204, USA
(Received 11 June 2007; published 10 December 2007)

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

Ξ^- Stopping & Fusion: $\Xi^- + {}^9Be \rightarrow {}^{10}_{\Lambda\Lambda}Li^*$





Suggested decay mode (104/114)

- PRL 87, 132504-1 (2001)
  - $\Delta B_{\Lambda\Lambda}$ depends then on excitation energy

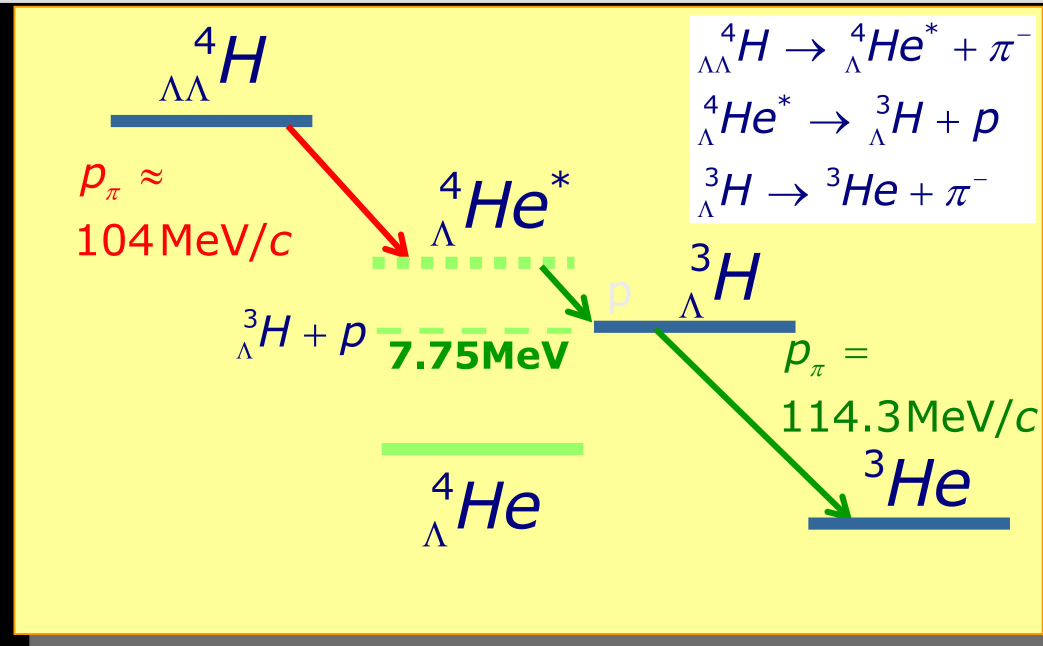
E_x (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)
7.75	1.8
8.75	0.8
9.84	-0.26

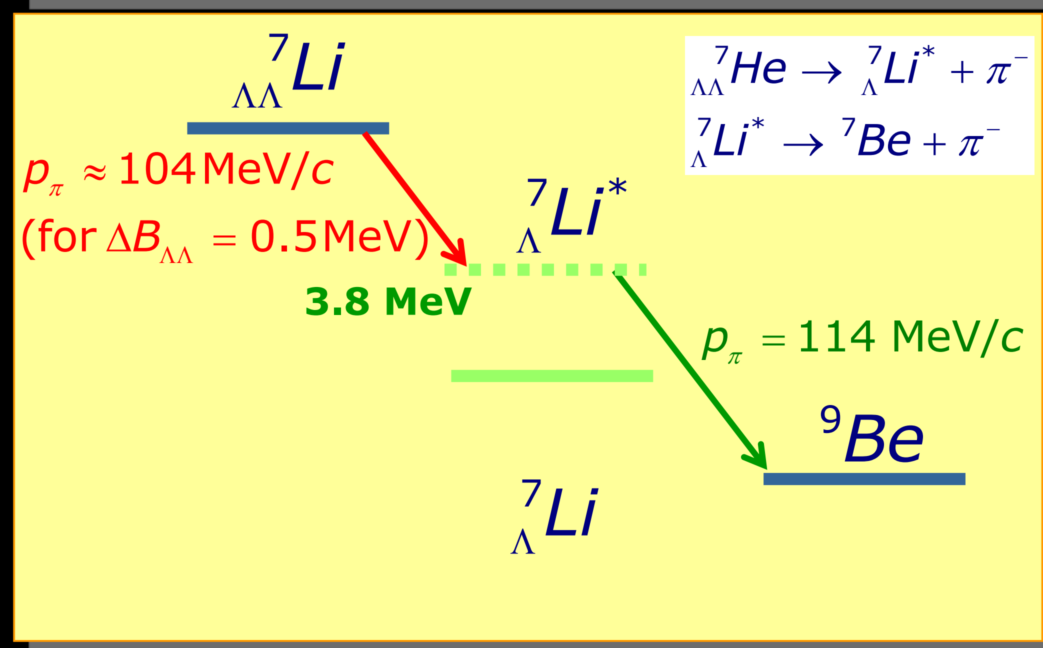
- Hungerford (HYP03)
  - requires isomeric state at 3.8MeV
- Gal (HYP03)

$${}^{3}_{\Lambda\Lambda}n \rightarrow {}^{3}_{\Lambda}H + \pi^{-} \text{(104MeV/c)}$$

$$\text{for } \Delta B_{\Lambda\Lambda} = 4\text{MeV}$$

$${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} \text{(114.3MeV/c)}$$

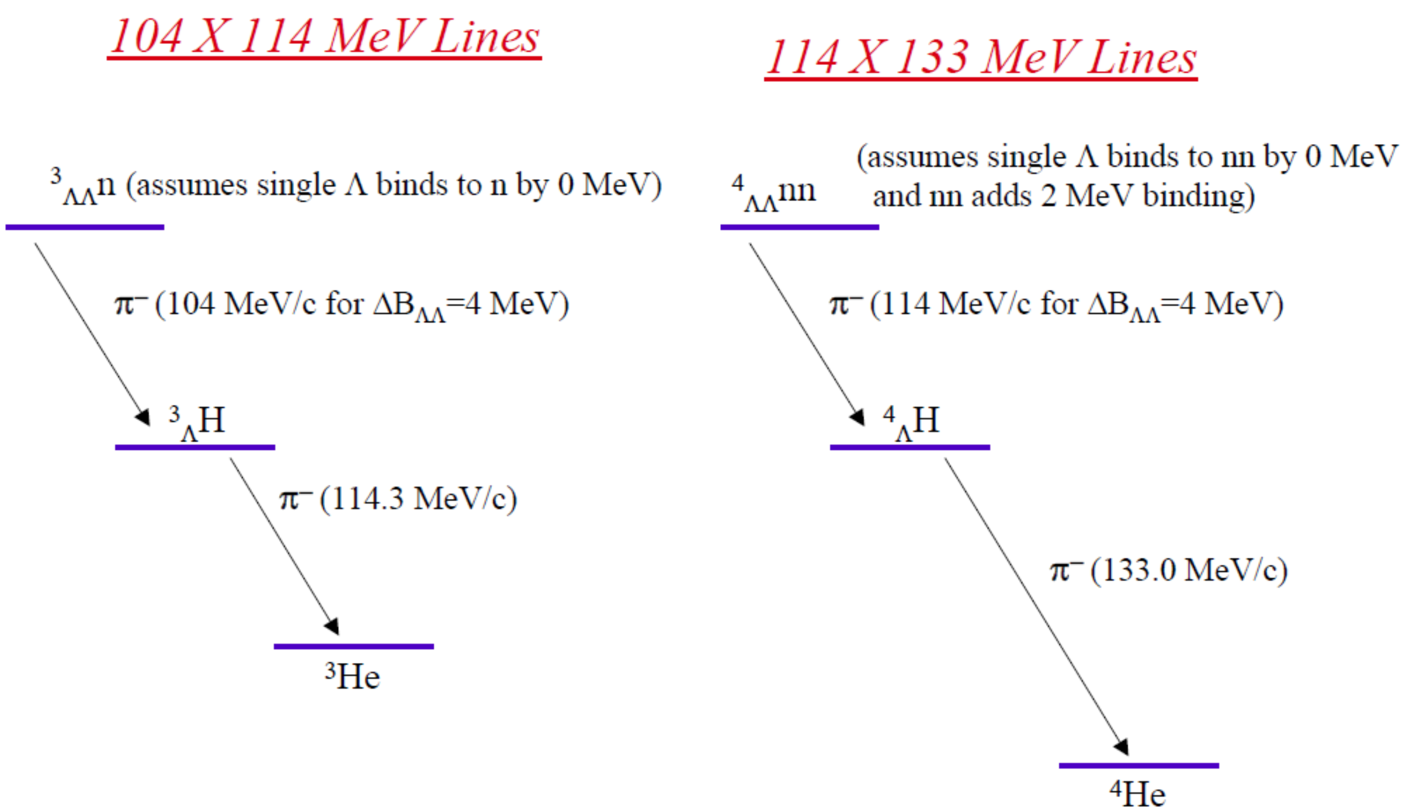




Can nnΛΛ solve the puzzle?

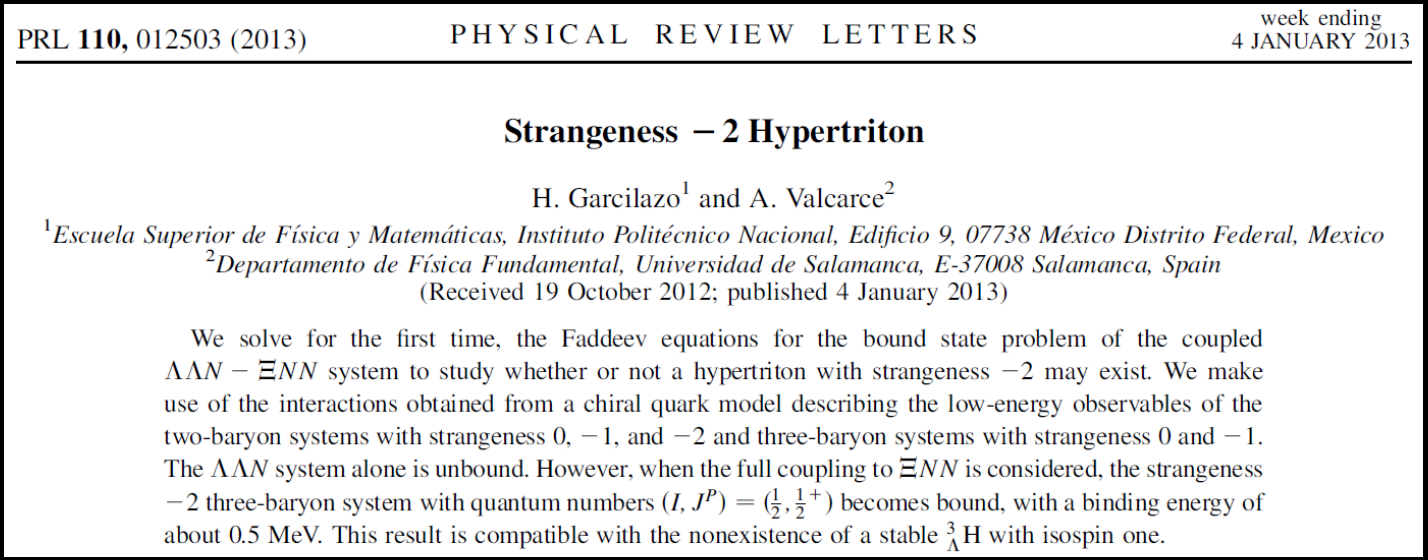
A. Gal, HYP2003

Another Possibility $^{4}_{\Lambda\Lambda}n$ (Gal)



Are $n\Lambda\Lambda$ and $nn\Lambda\Lambda$ bound ?

- $\Lambda\Lambda$n possibly bound



PRL **110,** 012503 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Strangeness −2 Hypertriton

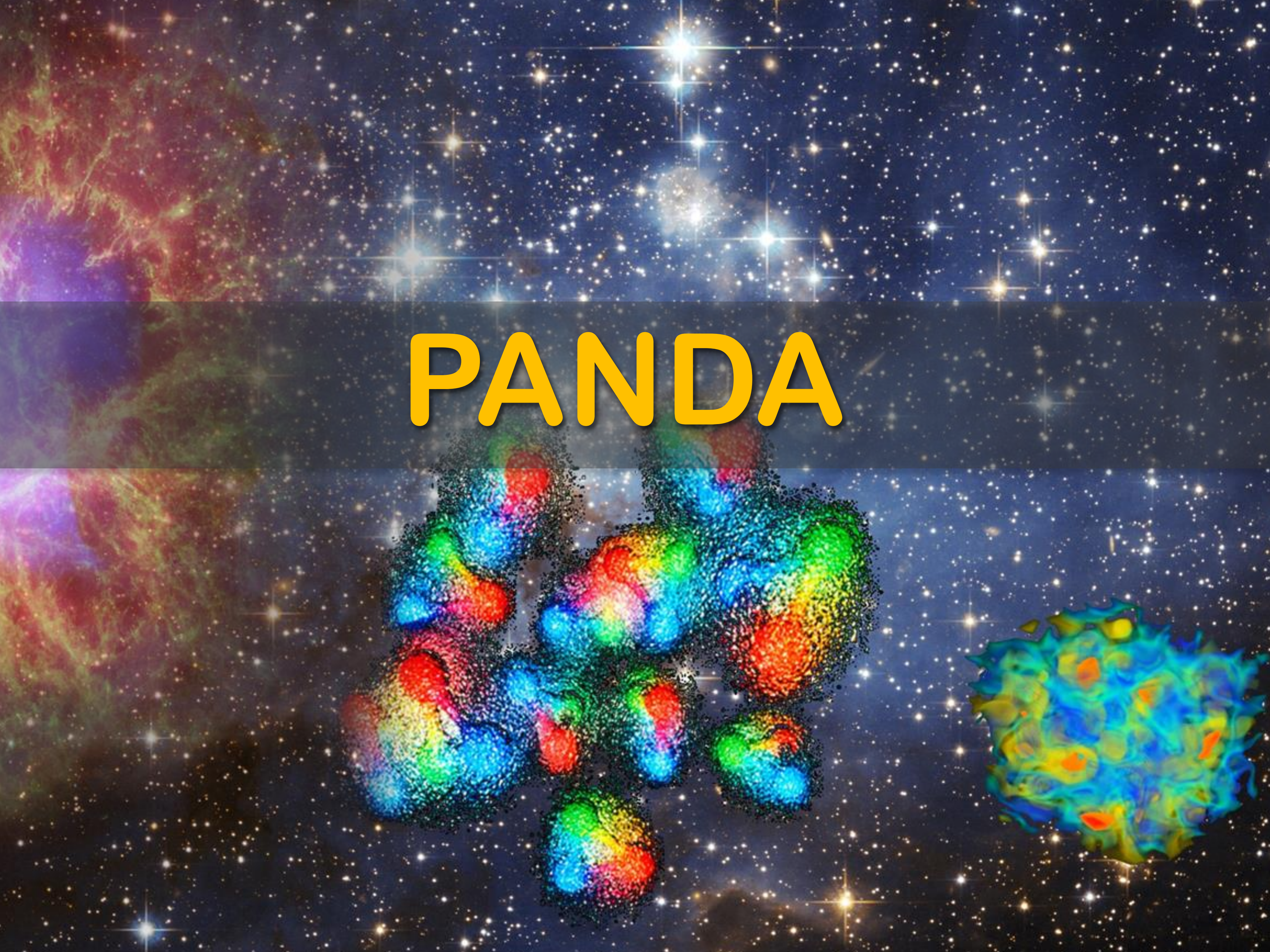
H. Garcilazo[1] and A. Valcarce[2]
[1]*Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, Edificio 9, 07738 México Distrito Federal, Mexico*
[2]*Departamento de Física Fundamental, Universidad de Salamanca, E-37008 Salamanca, Spain*
(Received 19 October 2012; published 4 January 2013)

We solve for the first time, the Faddeev equations for the bound state problem of the coupled $\Lambda\Lambda N - \Xi NN$ system to study whether or not a hypertriton with strangeness −2 may exist. We make use of the interactions obtained from a chiral quark model describing the low-energy observables of the two-baryon systems with strangeness 0, −1, and −2 and three-baryon systems with strangeness 0 and −1. The $\Lambda\Lambda N$ system alone is unbound. However, when the full coupling to ΞNN is considered, the strangeness −2 three-baryon system with quantum numbers $(I, J^P) = (\frac{1}{2}, \frac{1}{2}^+)$ becomes bound, with a binding energy of about 0.5 MeV. This result is compatible with the nonexistence of a stable ${}^3_\Lambda$H with isospin one.

- $nn\Lambda\Lambda$ may be bound (particularly if $nn\Lambda$ is bound)
  - S=0, I=1, L=0
  - No Pauli blocking
  - Groundstate: $J^P=0^+$
  - calculation still rather schematic

  J.-M. Richard, Q. Wang, and Q. Zhao, Phys. Rev. C 91, 014003 (2015)

- If $n\Lambda\Lambda$ and $nn\Lambda\Lambda$ are bound, they might help to understand the E906 puzzle


PANDA

The Discovery of the anti-Xi

- discovered simulataniously at CERN and SLAC

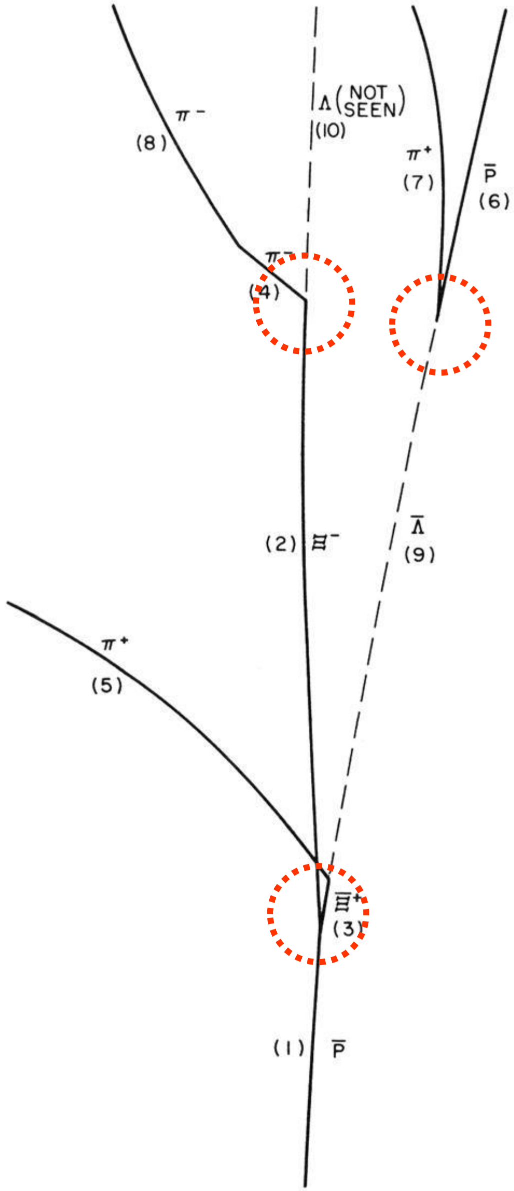
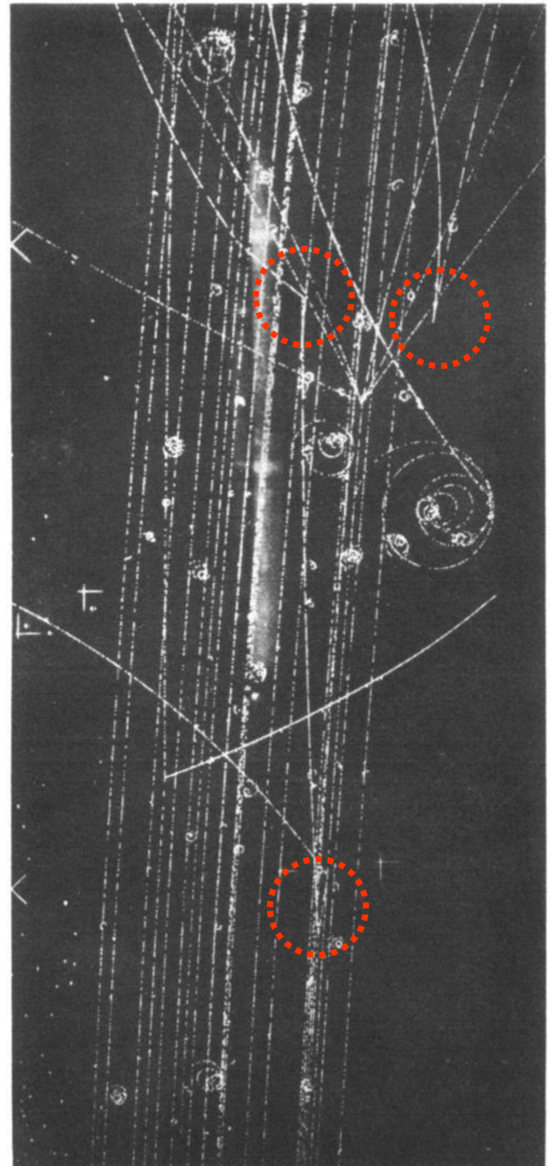
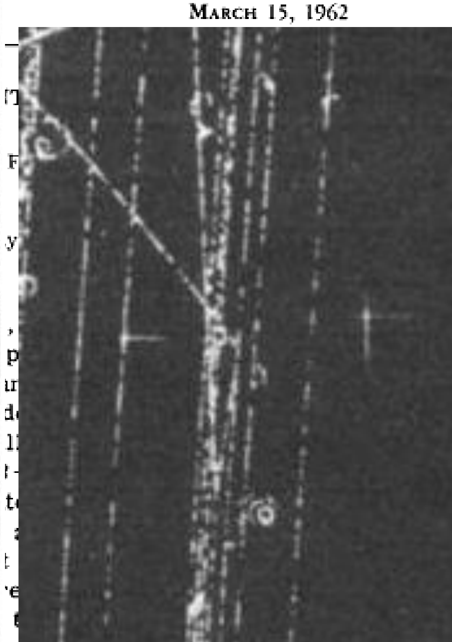


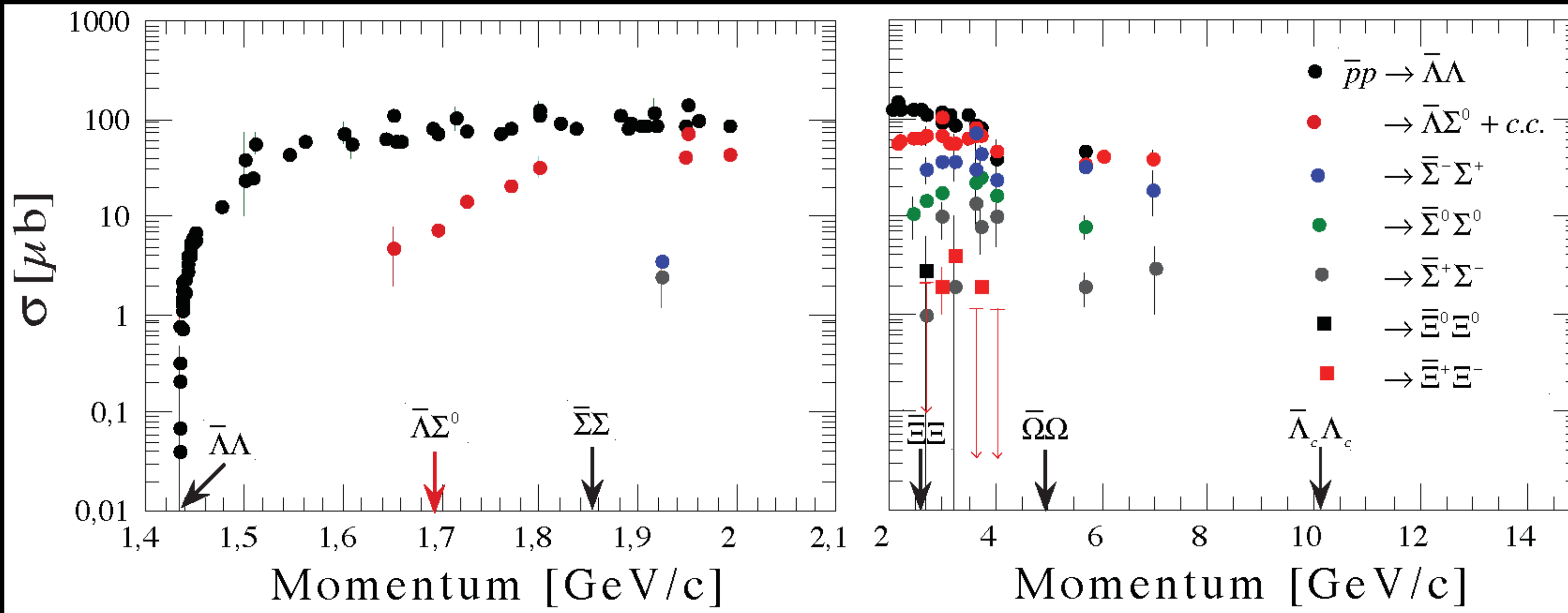
FIG. 1. A print of the event $\bar{p}+p \rightarrow \Xi^- + \bar{\Xi}^+$ as photographed in the BNL 20-in. liquid hydrogen bubble chamber is shown. The sketch of the event as shown is labelled according to the most likely mass interpretation for each observed track. The numbers on each track are those used in Table I.



March 15, 1962



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}
$\Xi\bar{\Xi}$ ($\rightarrow_{\Lambda\Lambda}$ A)	2µb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ ($\rightarrow e^+e^-, \mu^+\mu^-$)	630nb	10^9
χ_2 ($\rightarrow J/\psi + \gamma$)	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

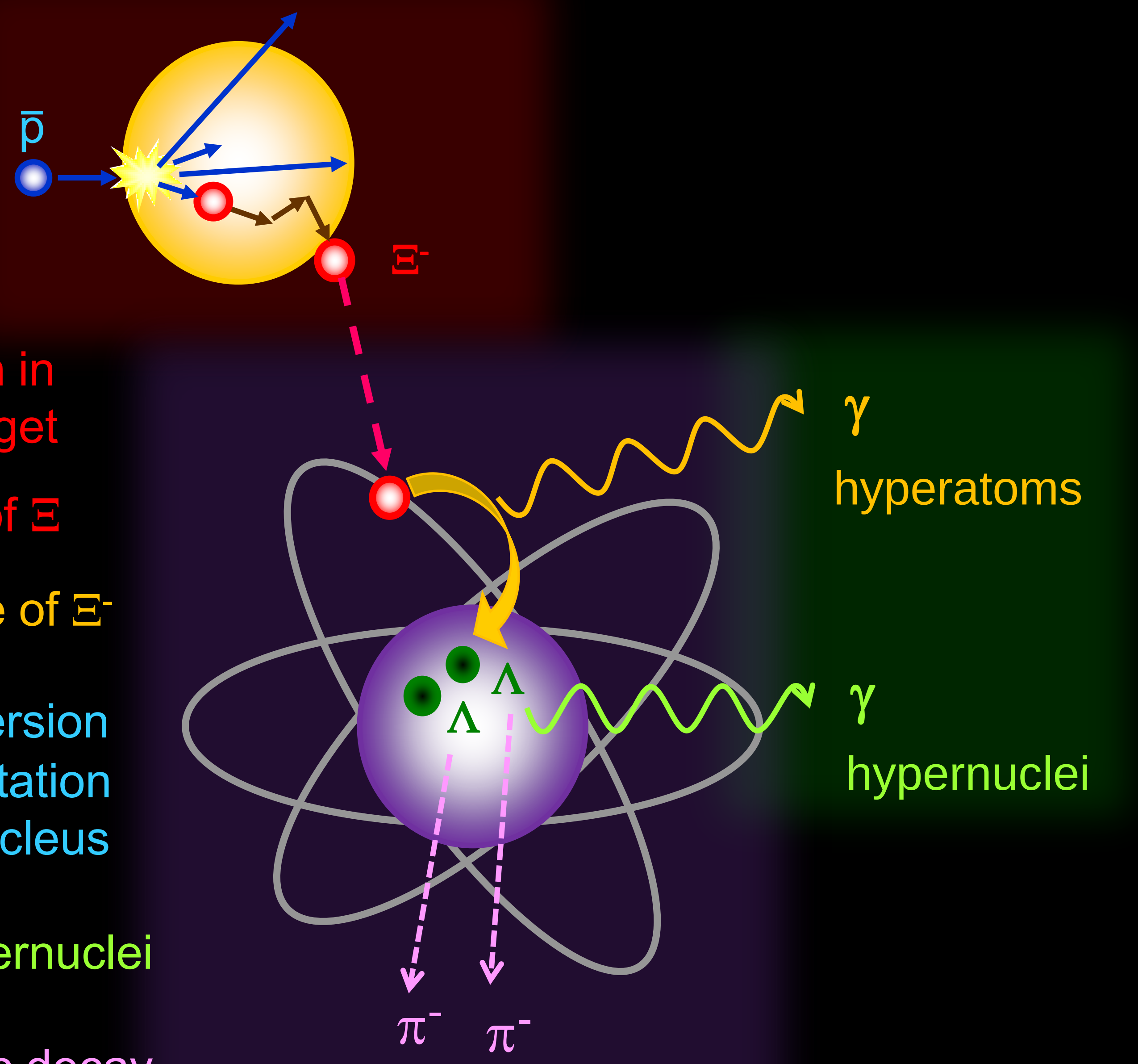
capture of Ξ

atomic cascade of Ξ^-

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

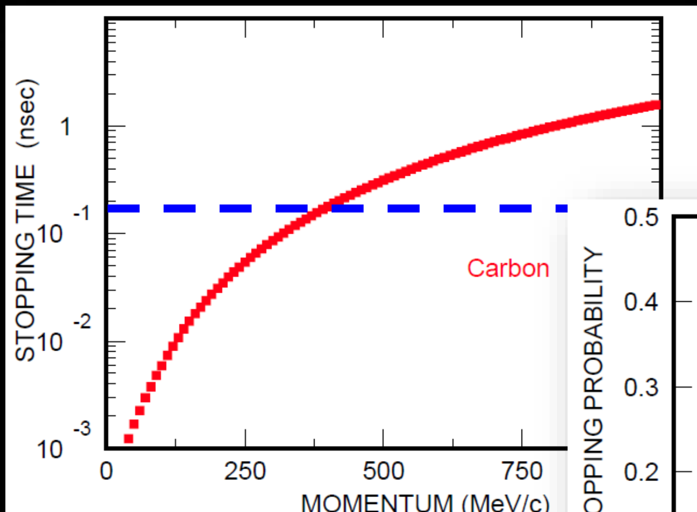
γ-decay of $\Lambda\Lambda$ hypernuclei

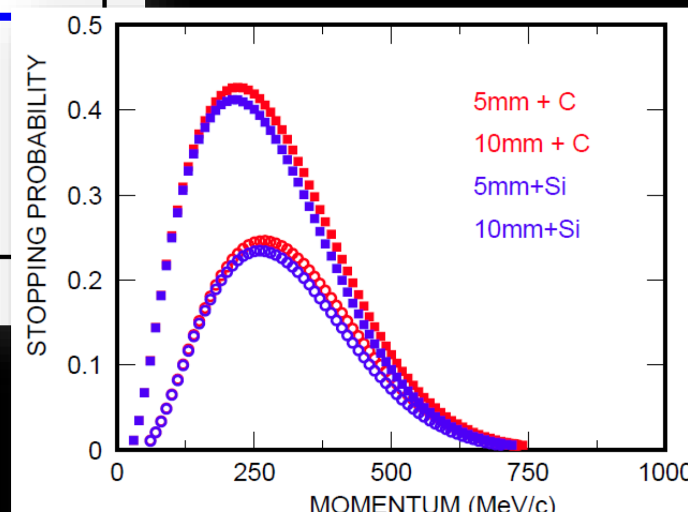
weak pionic decay

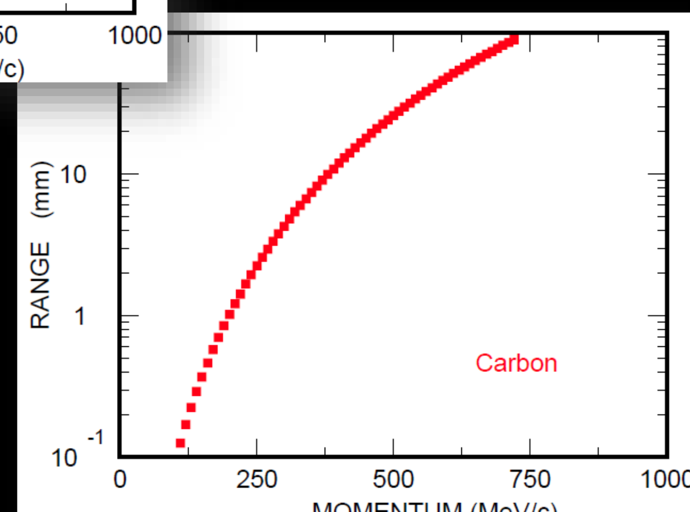


Ξ^- properties determine setup

- Ξ^- mean life 0.164 nsec

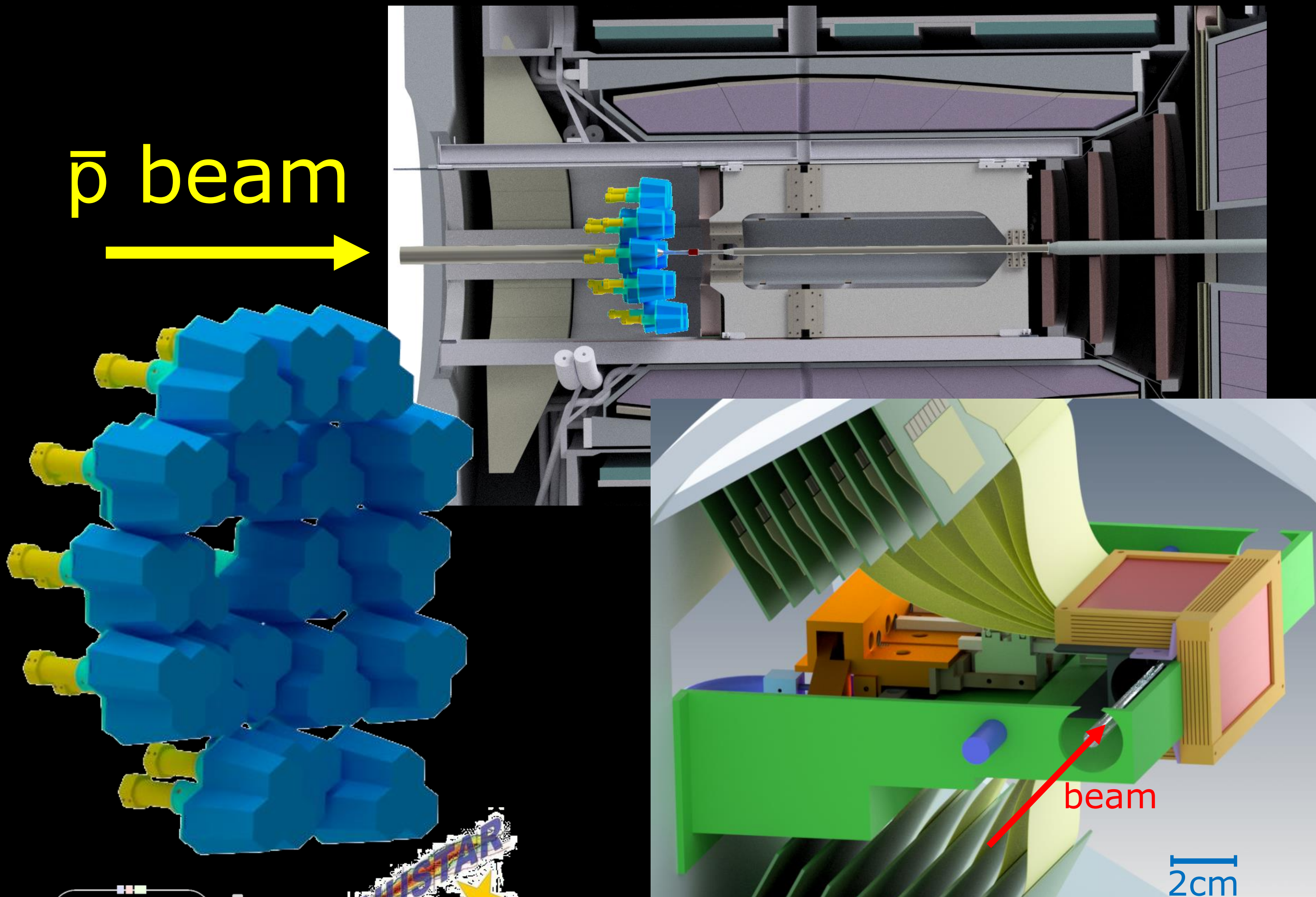


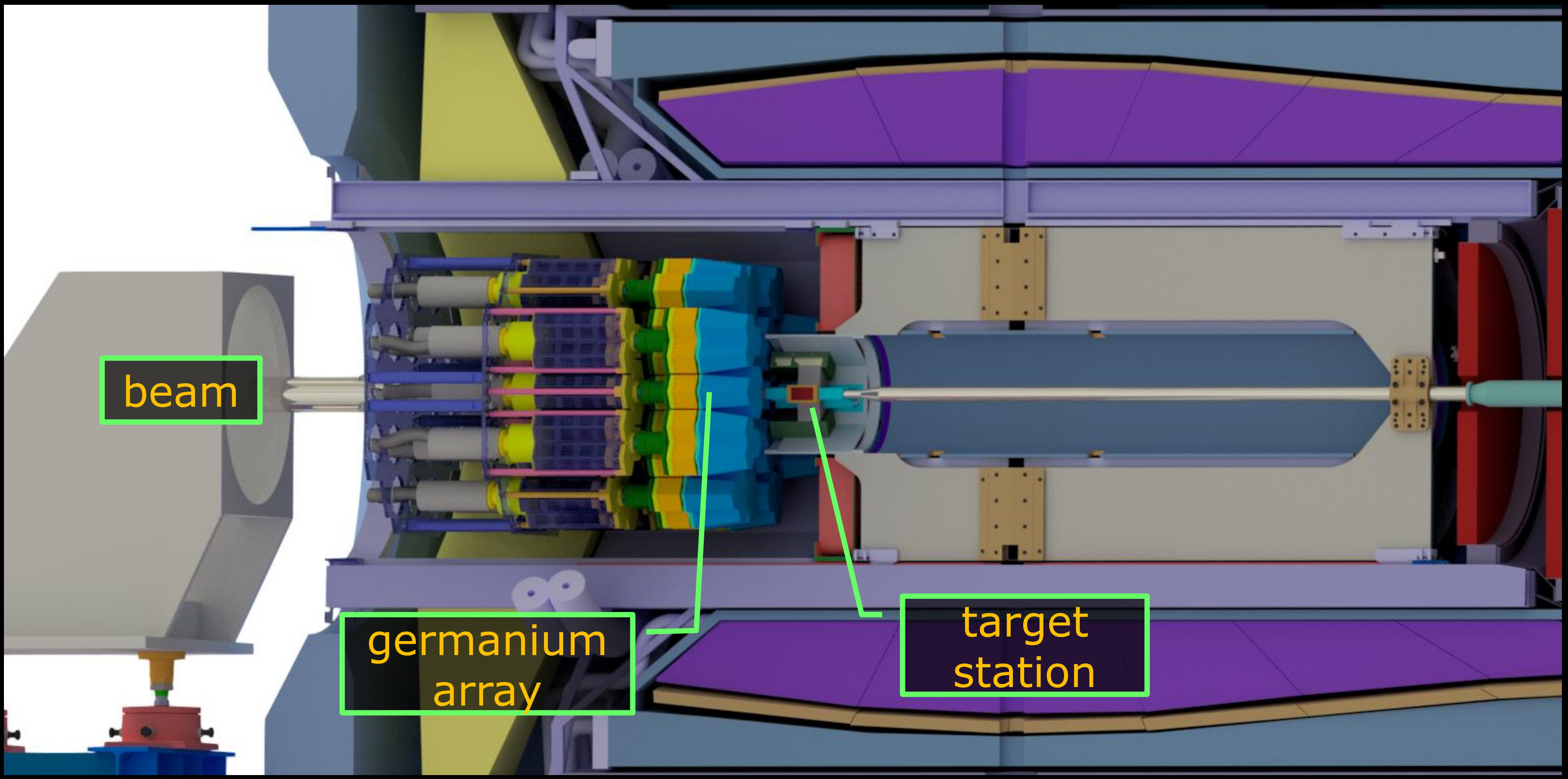




- minimizeminimize distance production & capture
- initial momentum 100-500 MeV/c
- thickness od secondary target few mm

$\bar{\text{P}}$ANDA-HYP setup




beam
germanium array
target station


Thank you
for your attention