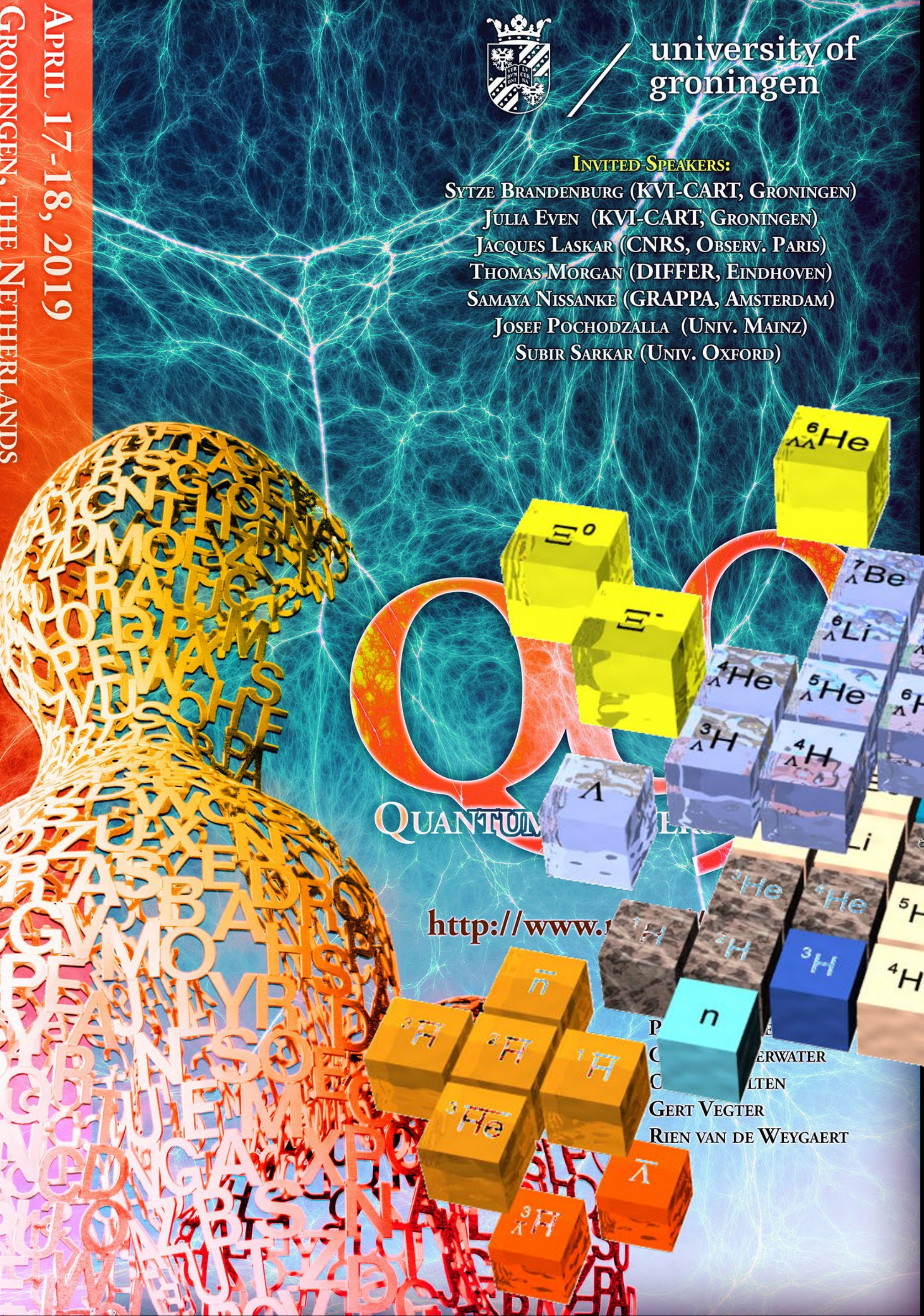
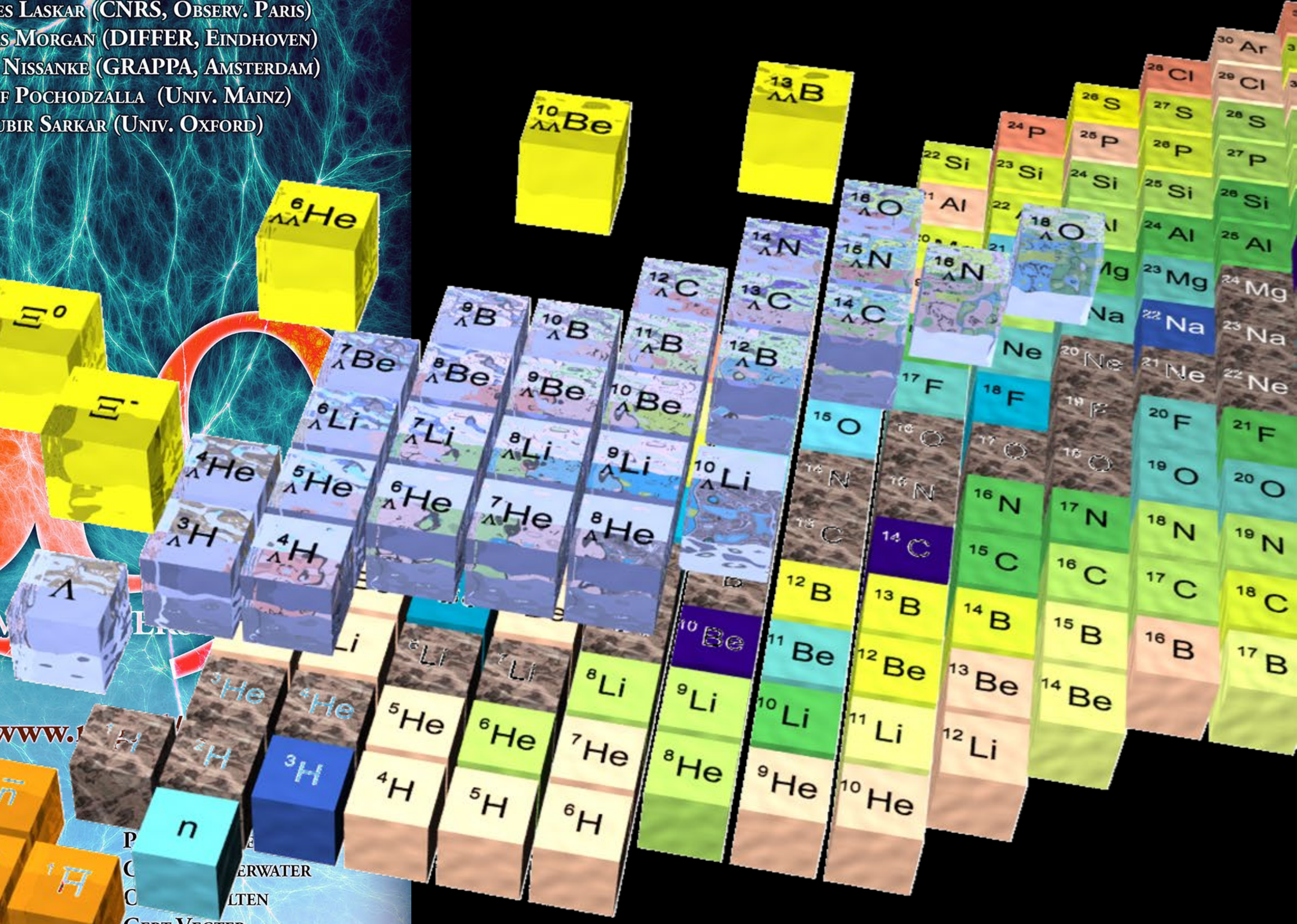
QU9 – Quantum Universe
Groningen - 18April 2019

Hypernuclei & Hyperatoms

Bringing heaven to earth





Josef Pochodzalla

JGU Mainz

& Helmholtz-Institut – Mainz

European Union

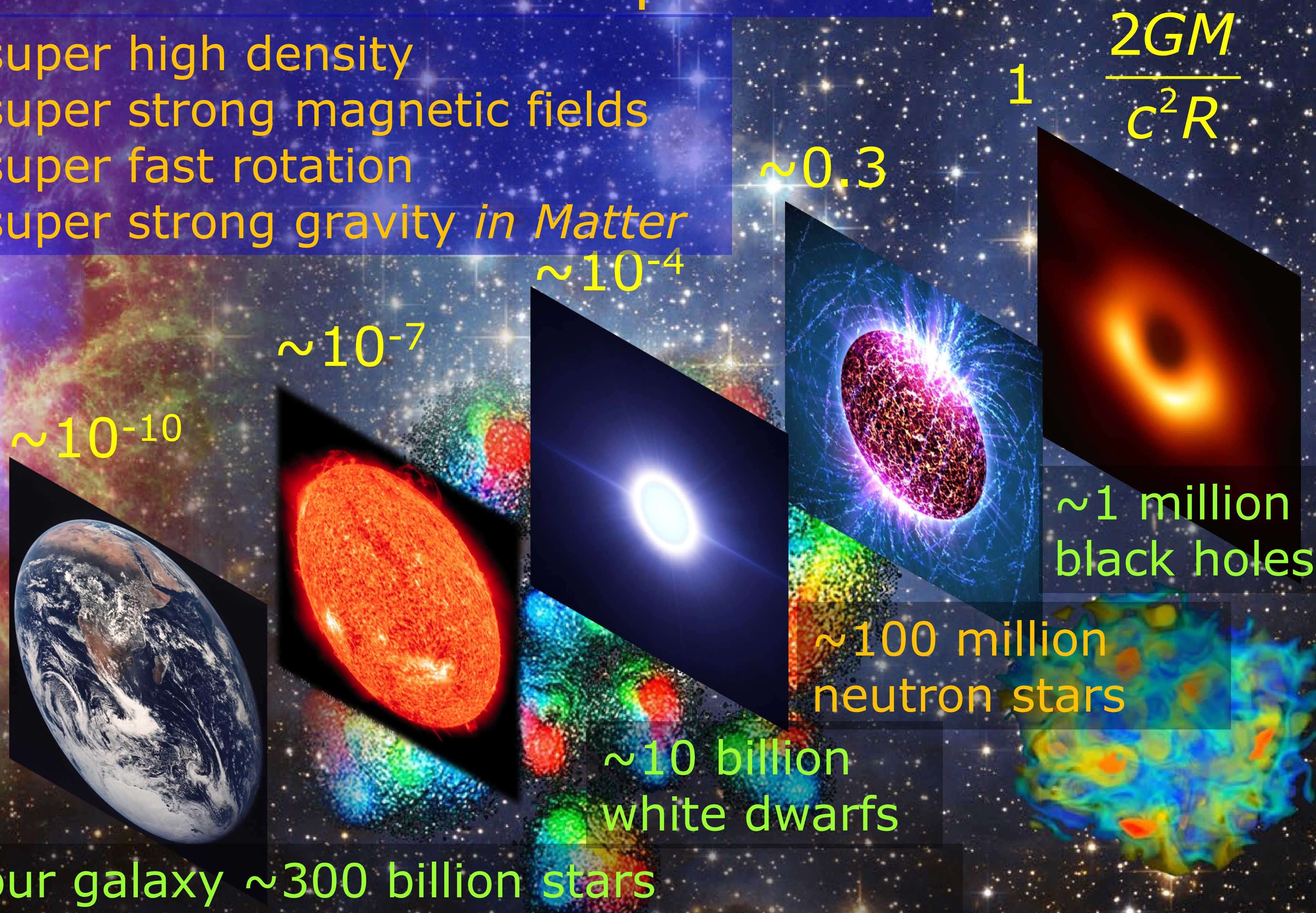
2017 August 17 12:41:04 UTC

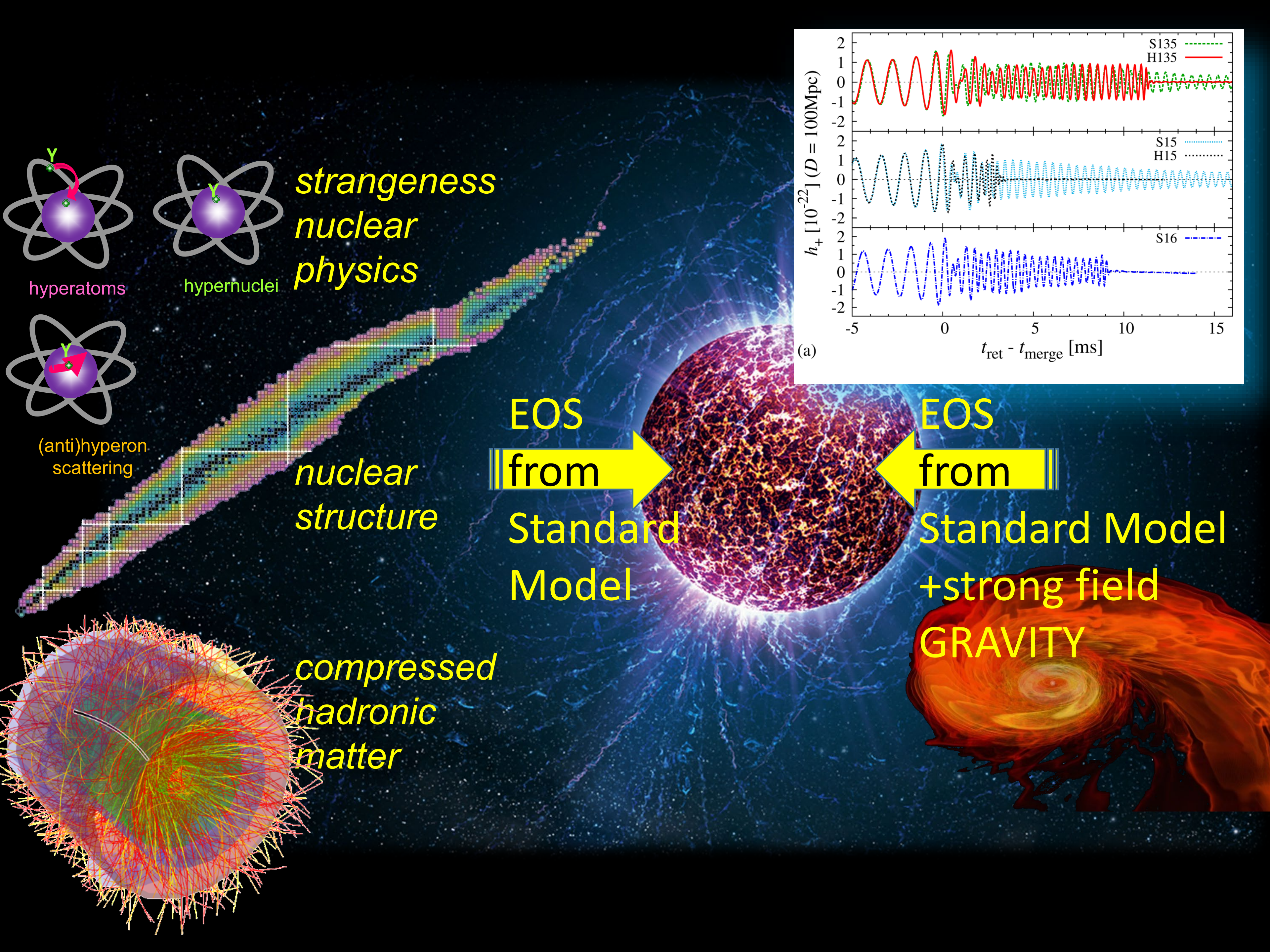
- First multi-messenger observations of a binary neutron star merger

video: National Radio Astronomy Observatory: https://public.nrao.edu/gallery/animation-of-neutron-star-merger-and-aftermath/

Neutron stars are Superstars

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





hyperatoms
hypernuclei
strangeness nuclear physics
(anti)hyperon scattering
nuclear structure
compressed hadronic matter
EOS from Standard Model
EOS from Standard Model +strong field GRAVITY
S135
H135
S15
H15
S16
$h_+ [10^{-22}]$ $(D = 100\text{Mpc})$
$t_{ret} - t_{merge}$ [ms]
(a)

5 decades of hyperons in neutron sta

NEUTRON STAR MODELS

A. G. W. CAMERON
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
Received June 17, 1959

„Another reason why the writer has not taken into account complications inherent in using a realistic equation of state is that no such things such pure neutron stars can be expected to exist. The neutrons must always be contaminated with some protons and sometimes with other kinds of nucleons (hyperons or heavy mesons).„

Alastair G.W. Cameron, Astrophysical Journal, vol. 130, p.884 (1959)

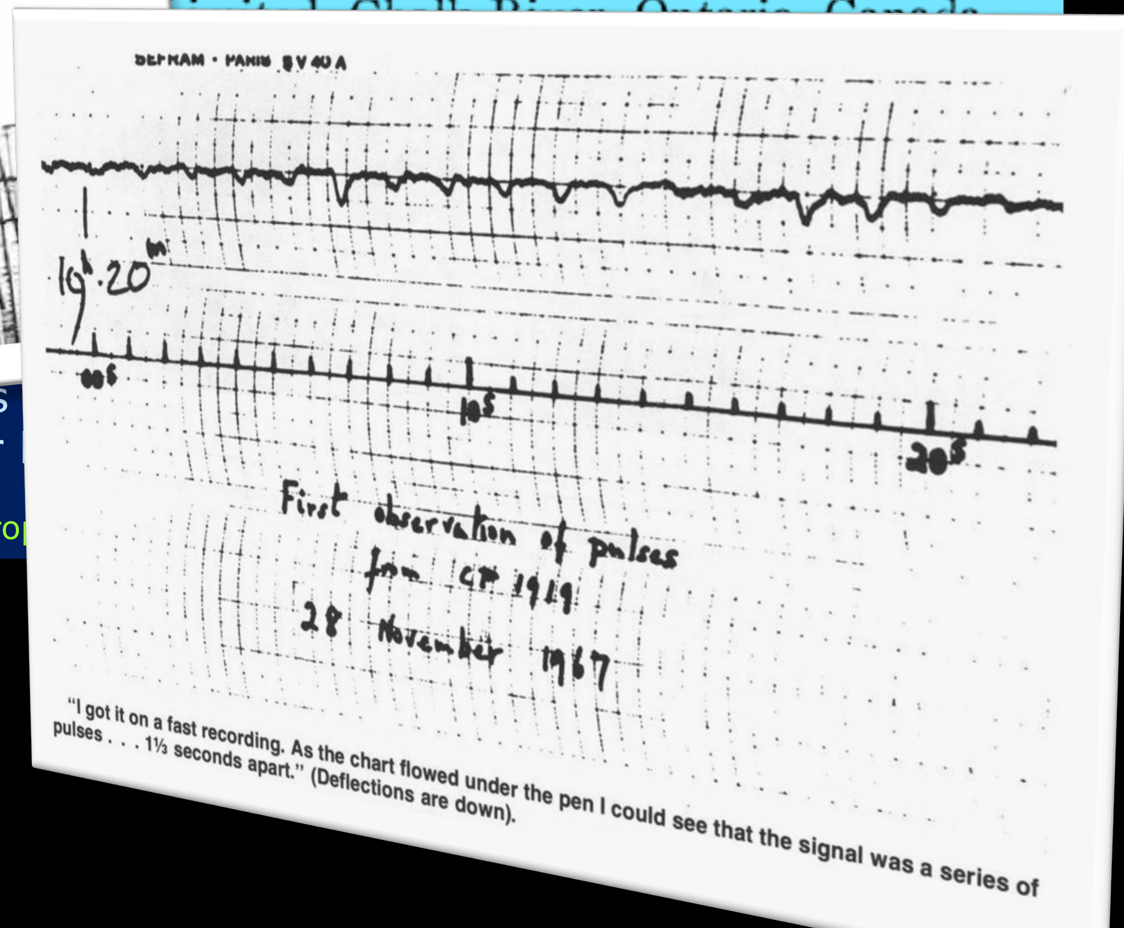
5 decades of hyperons in neutron sta

ON STAR MODELS

. W. CAMERON

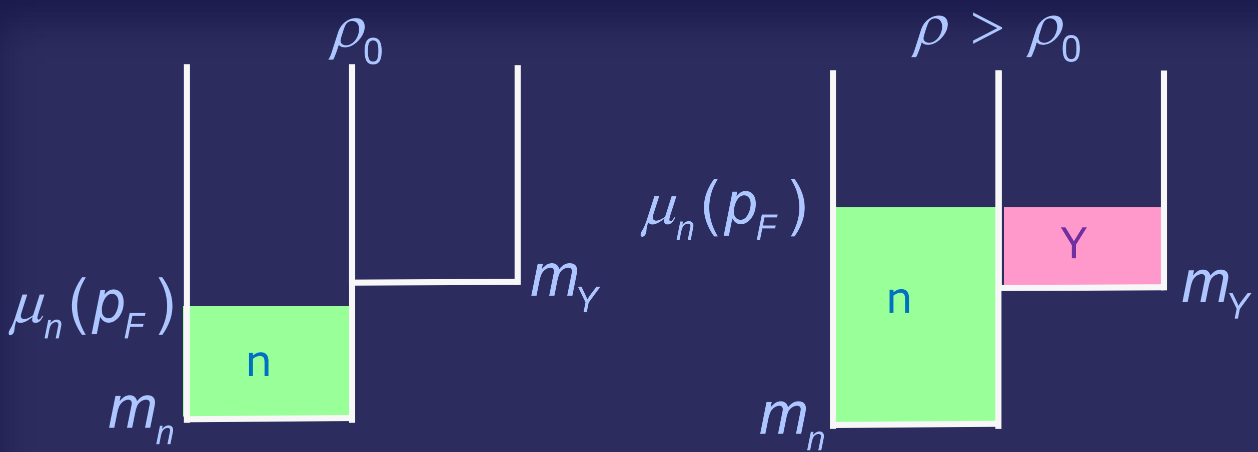
must always
sometimes with other

Alastair G.W. Cameron, Astro



"I got it on a fast recording. As the chart flowed under the pen I could see that the signal was a series of pulses . . . 1⅓ seconds apart." (Deflections are down).

Hyperons in Neutron stars



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

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

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

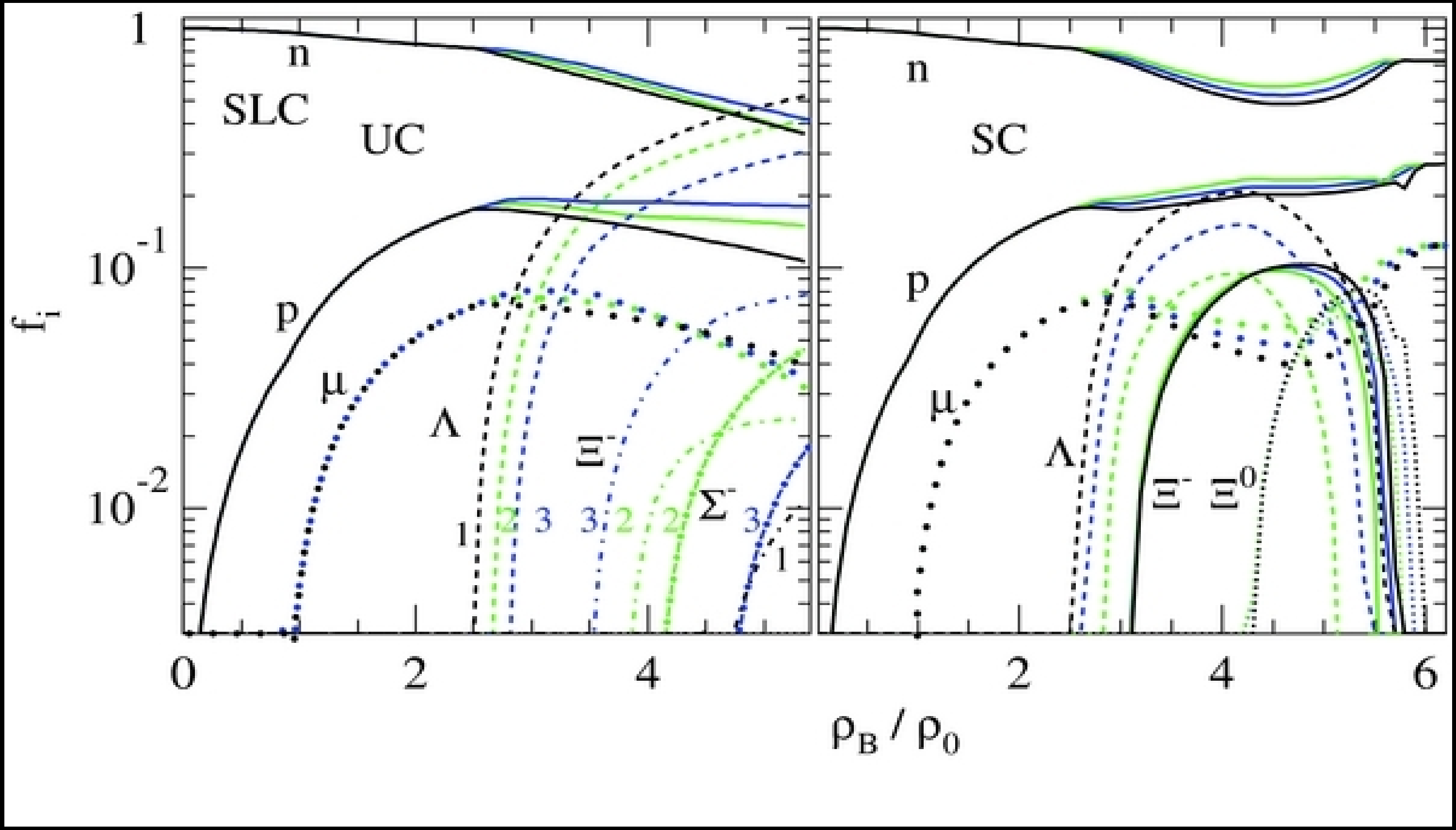
$\Rightarrow$ appearence of hyperons at $\rho_\Lambda \approx 5.5\rho_0$

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

Cameron 1959, Ambartsumyan & Saakyan 1960

Appearance of Hyperons

- Sequence of hyperon appearance depends on B-B interaction
- Σ –N interaction repulsive $\Rightarrow$ Σ will probably appear latest

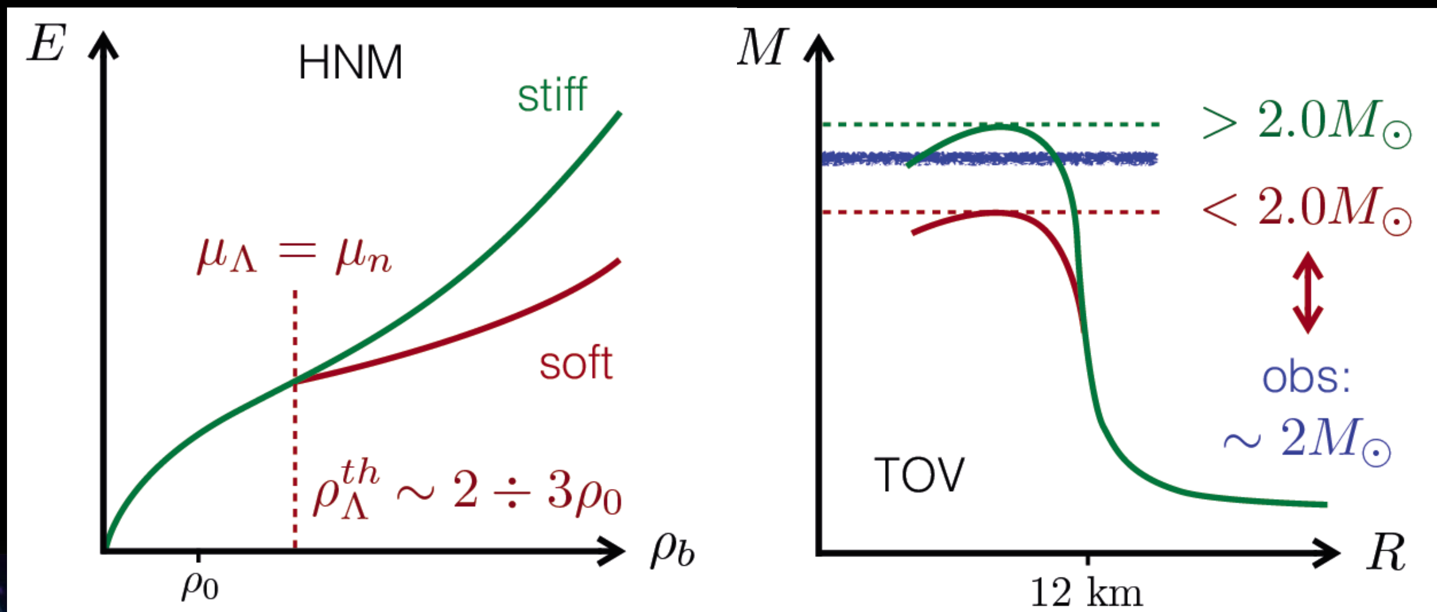


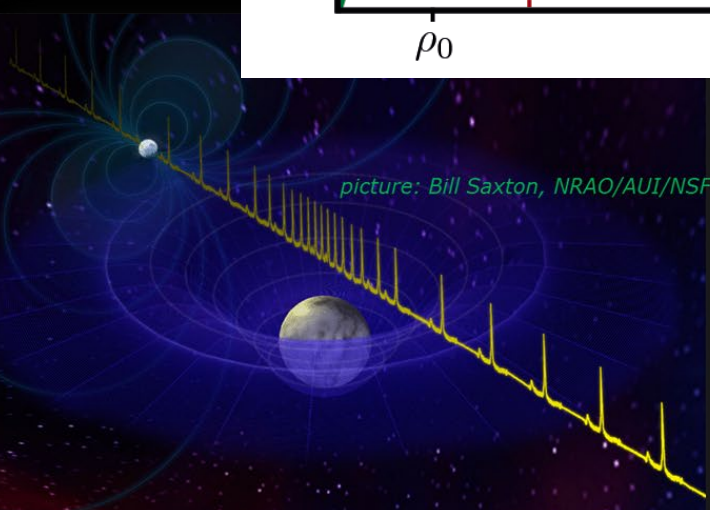
Wei-Zhou Jiang, Bao-An Li, and Lie-Wen Chen, The Astrophysical Journal, Volume 756, Number 1

Hyperon Puzzle

appearance of hyperons $\Rightarrow$ relieve of Fermi pressure $\Rightarrow$ softer EOS

$\Rightarrow$ reduction of maximal mass





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

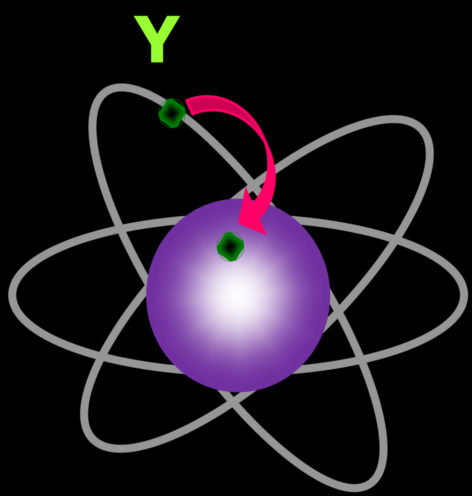
M(PSR J0348+0432)=2.01 ± 0.04 $M_\odot$

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

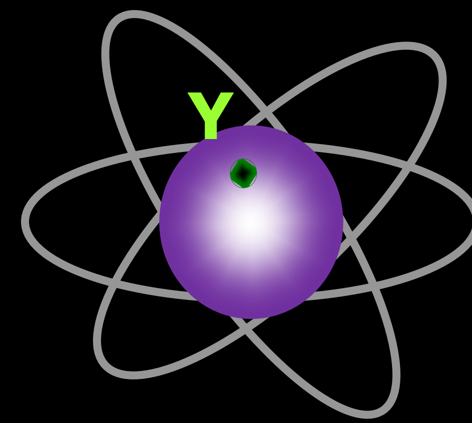
P. B. Demorest *et al.*, Nature 467 (2010)
update: E. Fonseca et al., ApJ 832, 167 (2016)
J. Antoniadis *et al.*, Science 340 (2013)
E.D. Barr *et al*., MNRAS 465, 1711–1719 (2017)

Hyperons in Nuclei

hyperatoms



hypernuclei



Objects

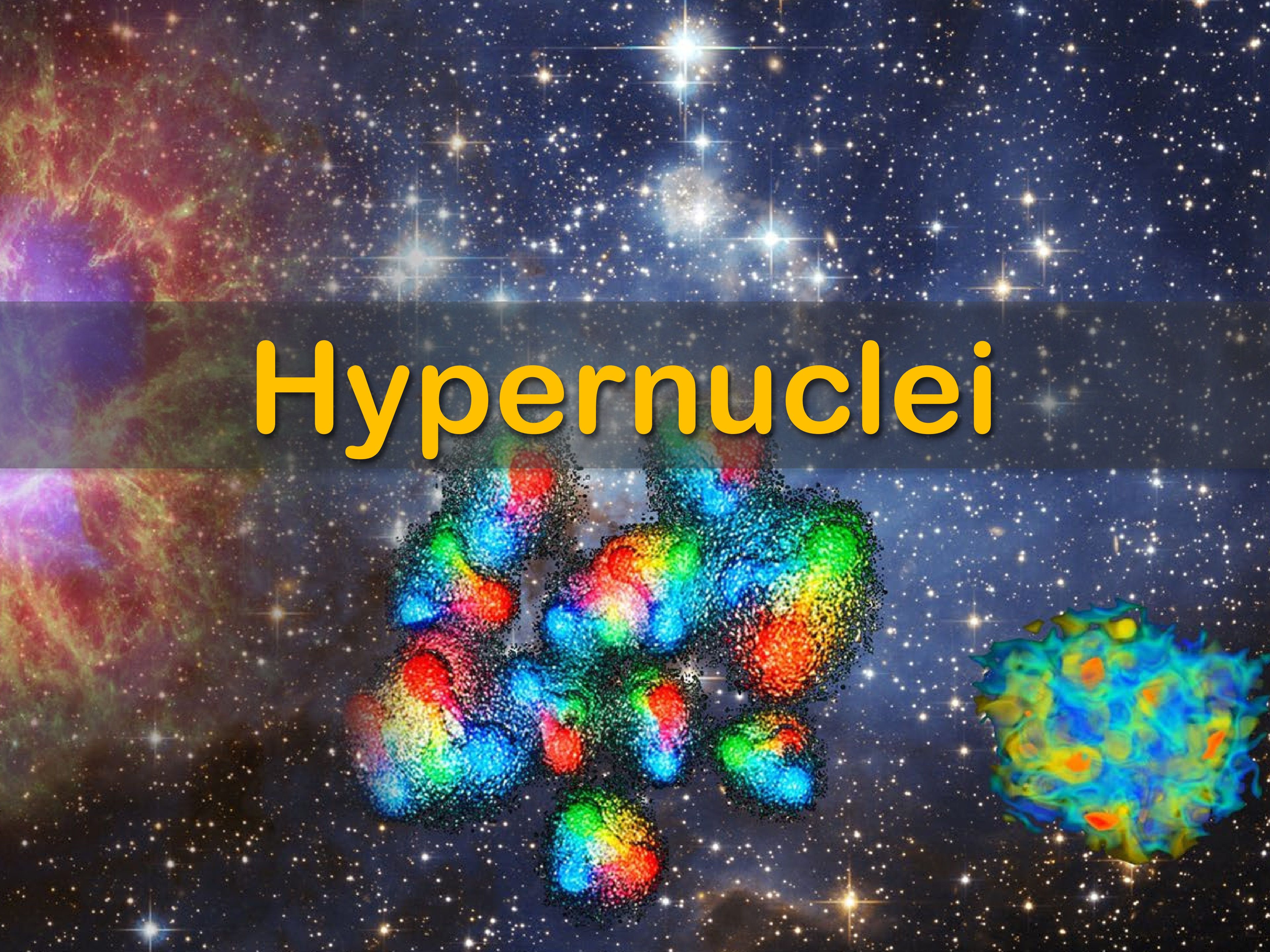
Hyperons in atomic levels within the nuclear periphery

Hyperons bound by strong interaction within nuclei

Methodology

Width and shift of Σ^-, Ξ^- and Ω^- atomic levels

Masses, excited state spectrum of Λ and $\Lambda\Lambda$ hypernuclei,


Hypernuclei

What is a hypernucleus?

- 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:

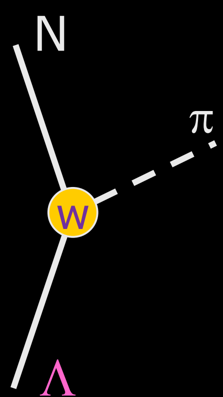
$${}^{4}_{\Lambda}H \rightarrow \begin{cases} \Lambda \rightarrow \text{1 lambda} \\ H \rightarrow \text{1 proton} \\ 4 \rightarrow 4\text{-}1\text{-}1=2 \text{ neutrons} \end{cases}$$

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

Weak decay of hypernuclei

free Λ decay

$p_N \approx 101 MeV/c$



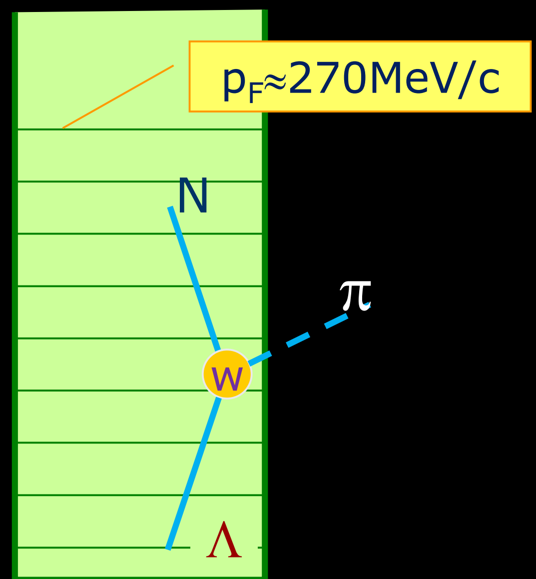
$\Lambda \rightarrow p\pi^- + 38MeV$ (64%)

$\Lambda \rightarrow n\pi^0 + 41MeV$ (36%)

$\tau_\Lambda = 263 ps$

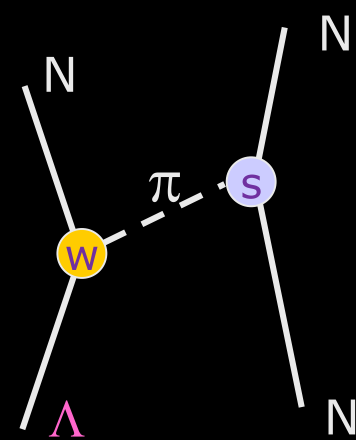
ΔI=1/2 rule

mesonic decay of hypernuclei



suppressed by Pauli blocking

non-mesonic decay of hypernuclei



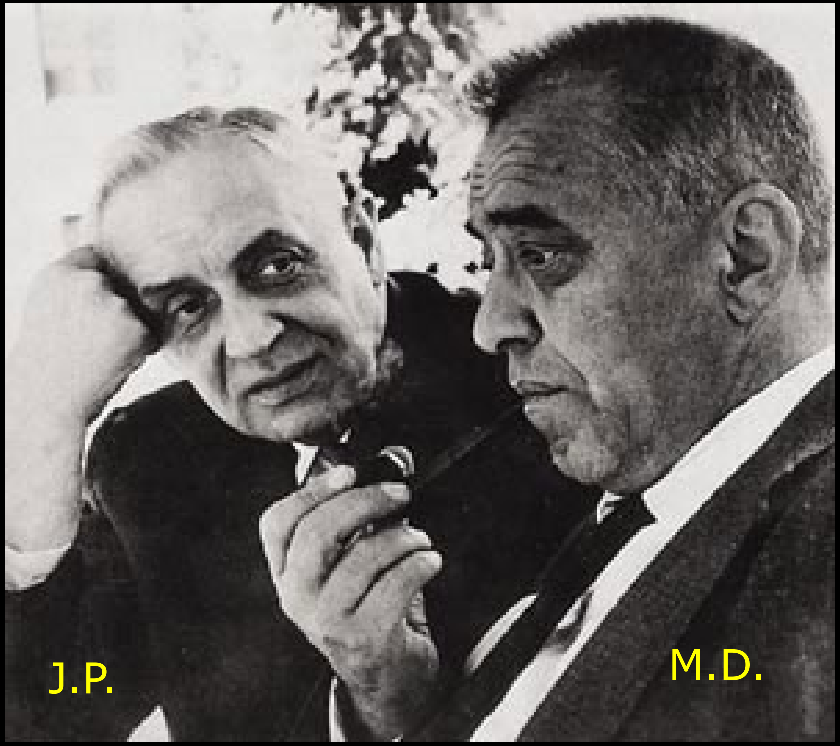
$\Lambda p \rightarrow np + 176MeV$

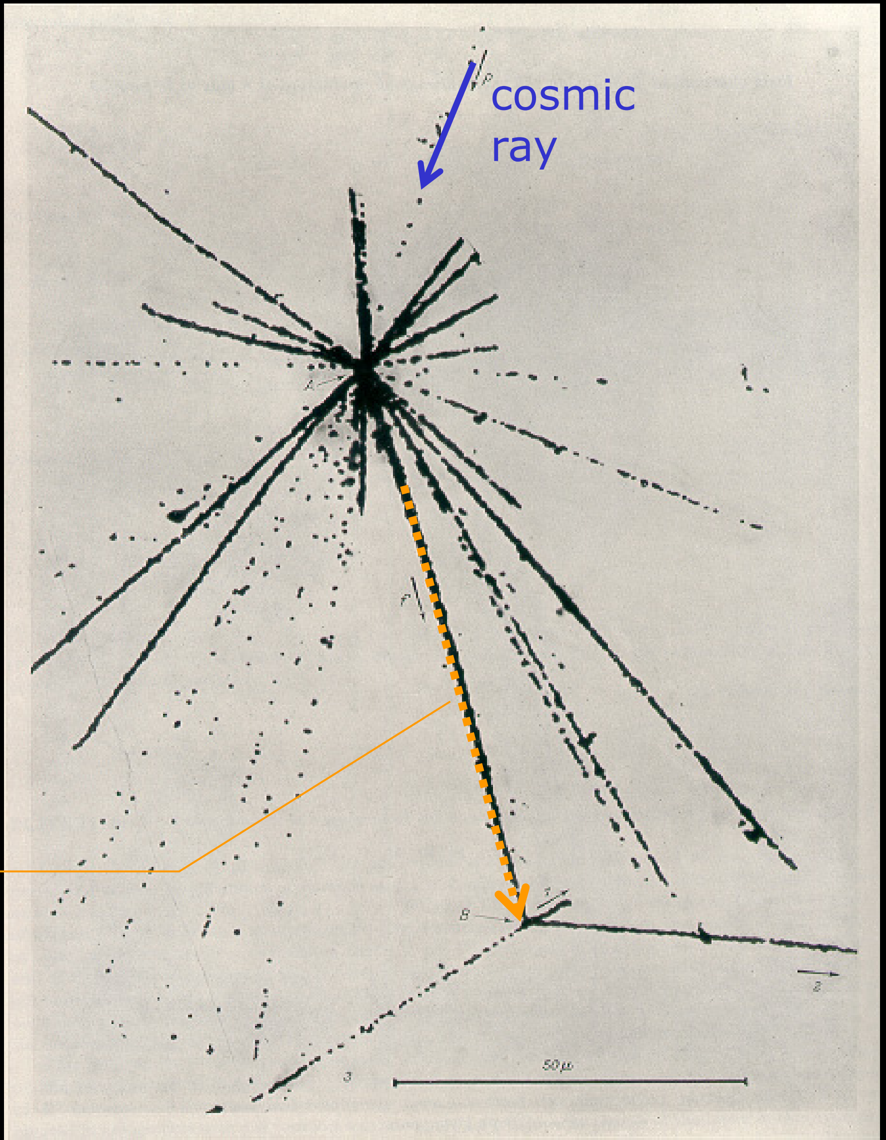
$\Lambda n \rightarrow nn + 176MeV$

dominant in all but the lightest hypernuclei

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)



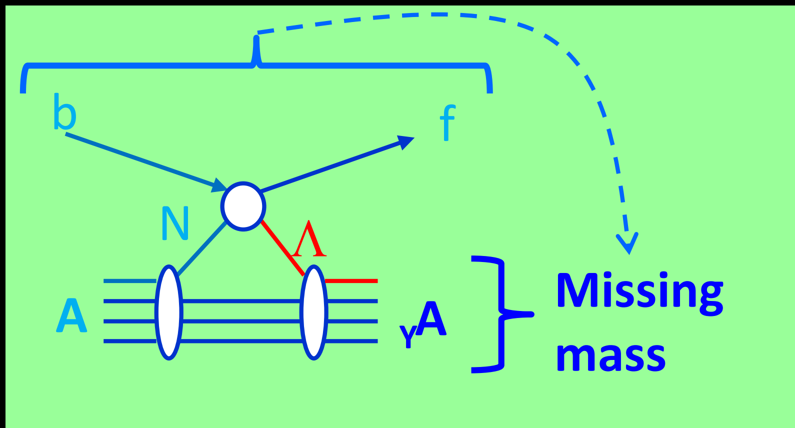


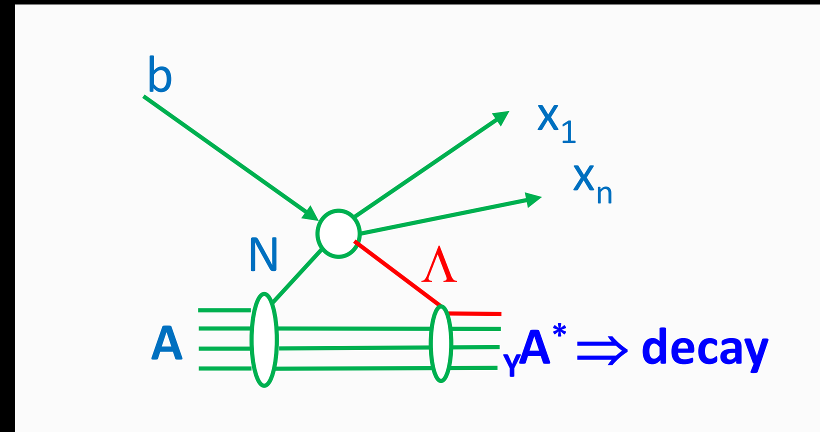
$$t > \frac{s}{c} \sim \frac{80\mu m}{300000 km/s} \approx 2.6 \cdot 10^{-13} s$$

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

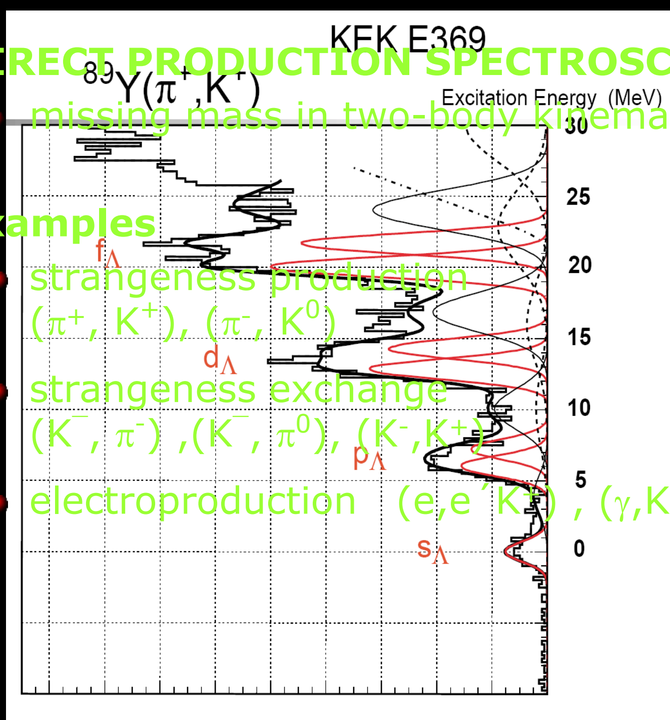
$\Rightarrow$ typical for weak decay

The twofold way to hypernuclei



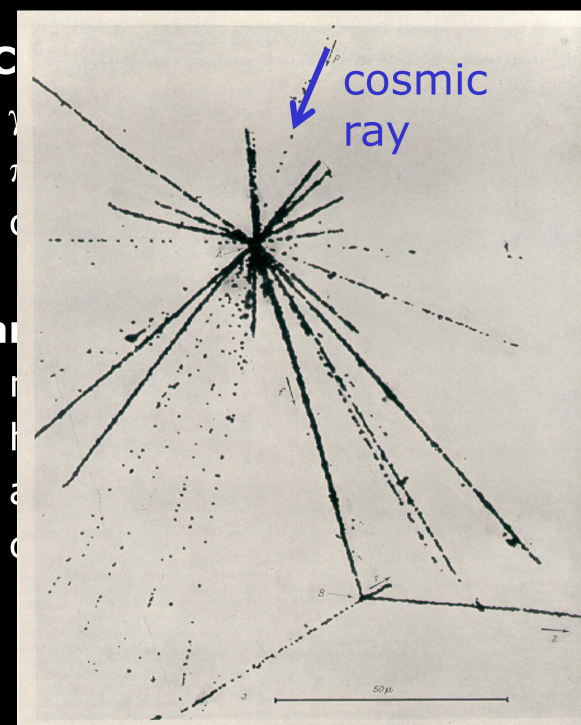


- **DIRECT PRODUCTION SPECTROSCOPY**
  - missing mass in two-body kinematics
- **Examples**
  - strangeness production (π^+, K^+), (π^-, K^0)
  - strangeness exchange (K^-, π^-) ,(K^-, π^0), (K^-,K^+)
  - electroproduction $(e,e'K^+)$, (γ,K^+)

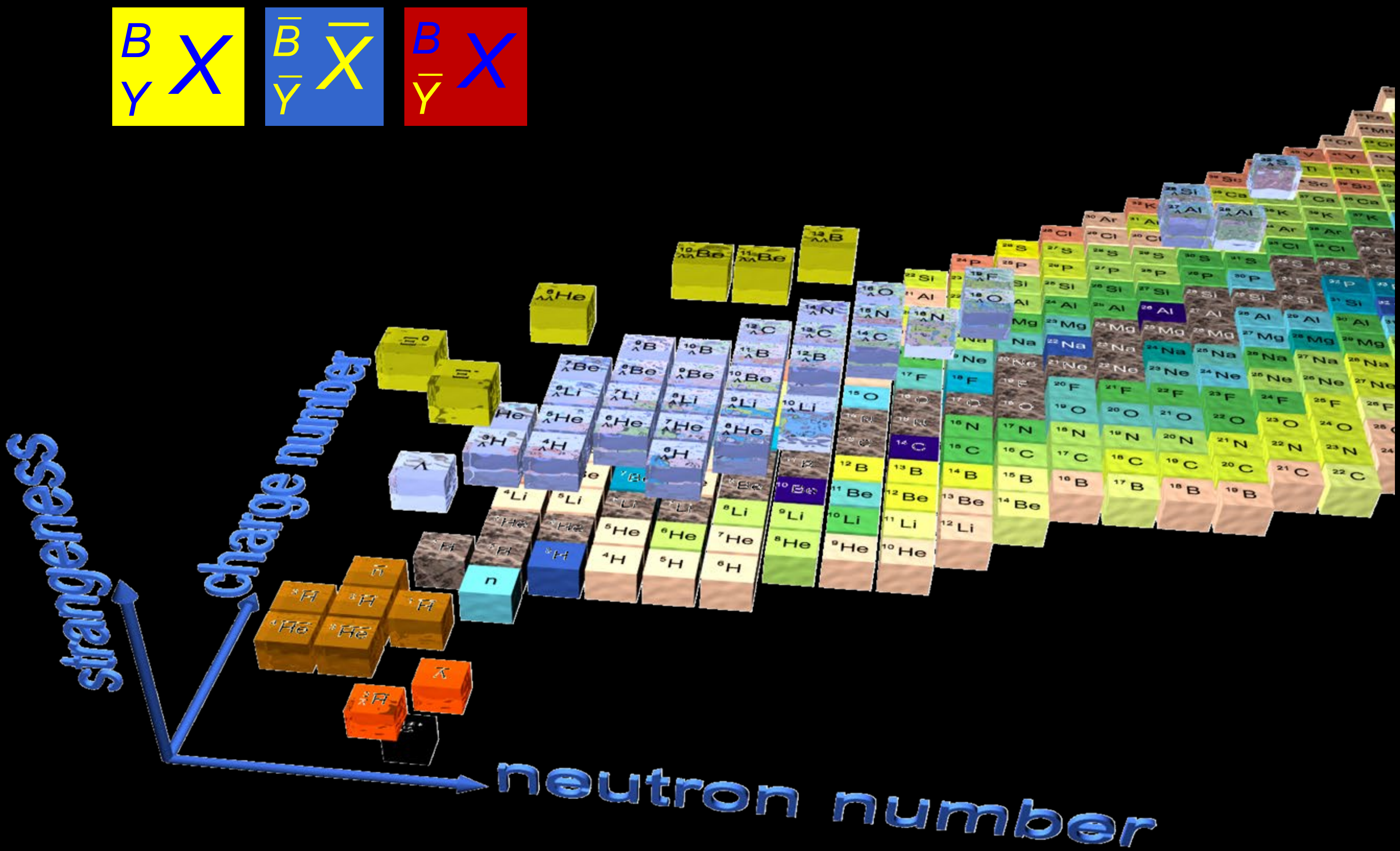


- **DEC**
- **Exa**

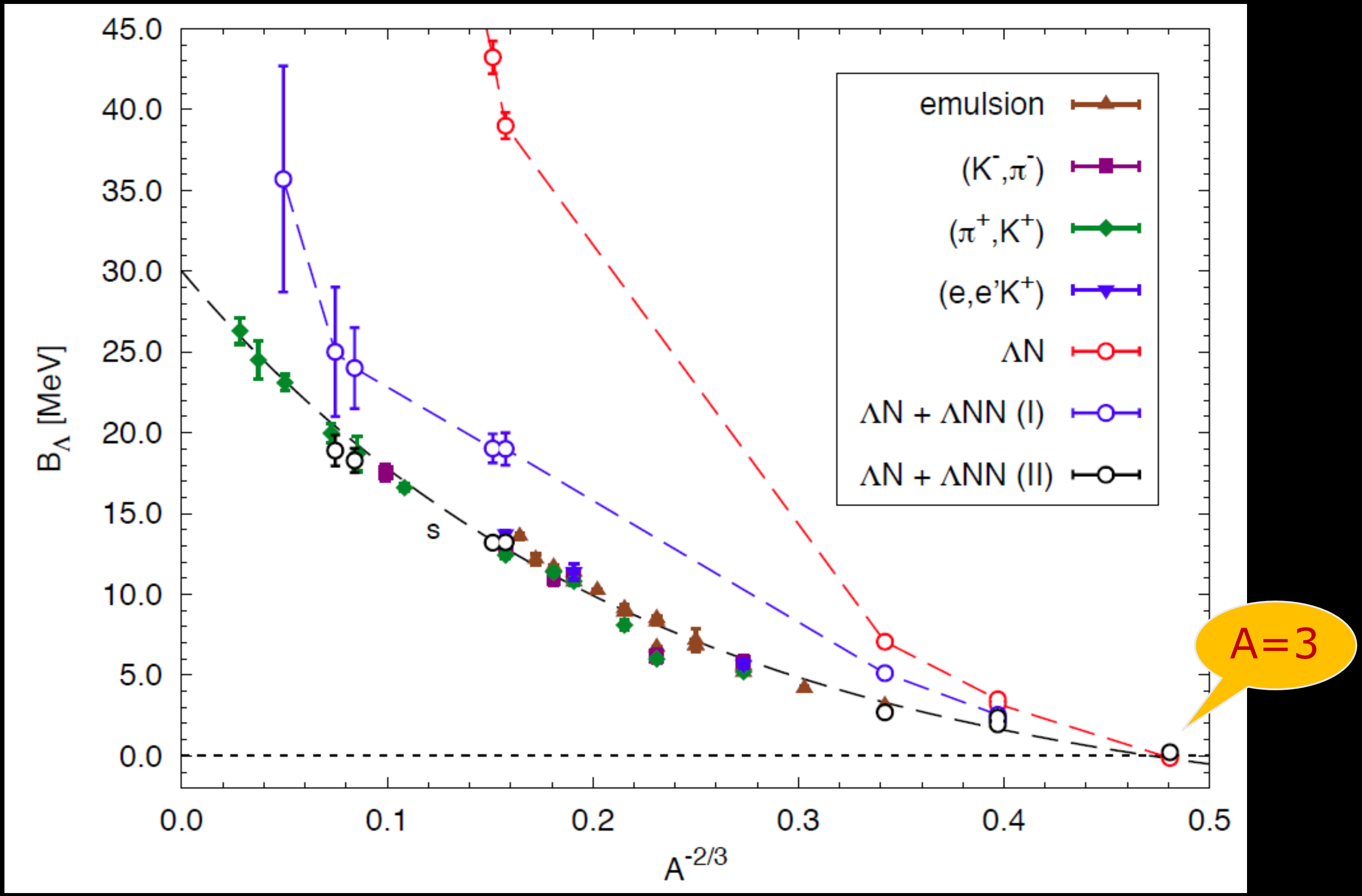
+)



Hypernuclei are very exotic nuclei



Three-body forces in Hypernuclei



Three baryon interactions involving hyperons are essential

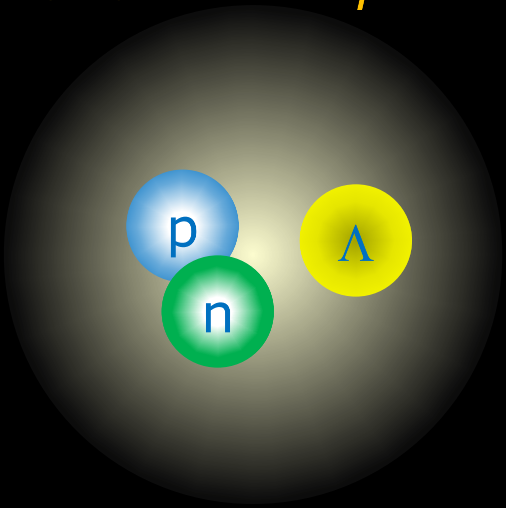
Stefano Gandolfi Diego Lonardoni,
arXiv: 1512.06832

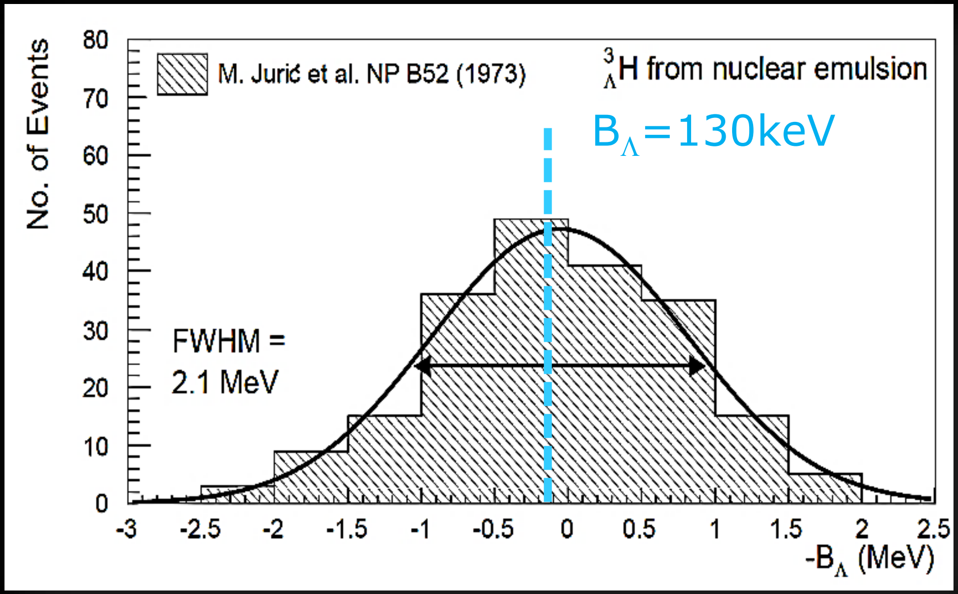

The Hypertriton
Puzzle

The Hypertriton Puzzle

Do we understand the simplest Hypernucleus?

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

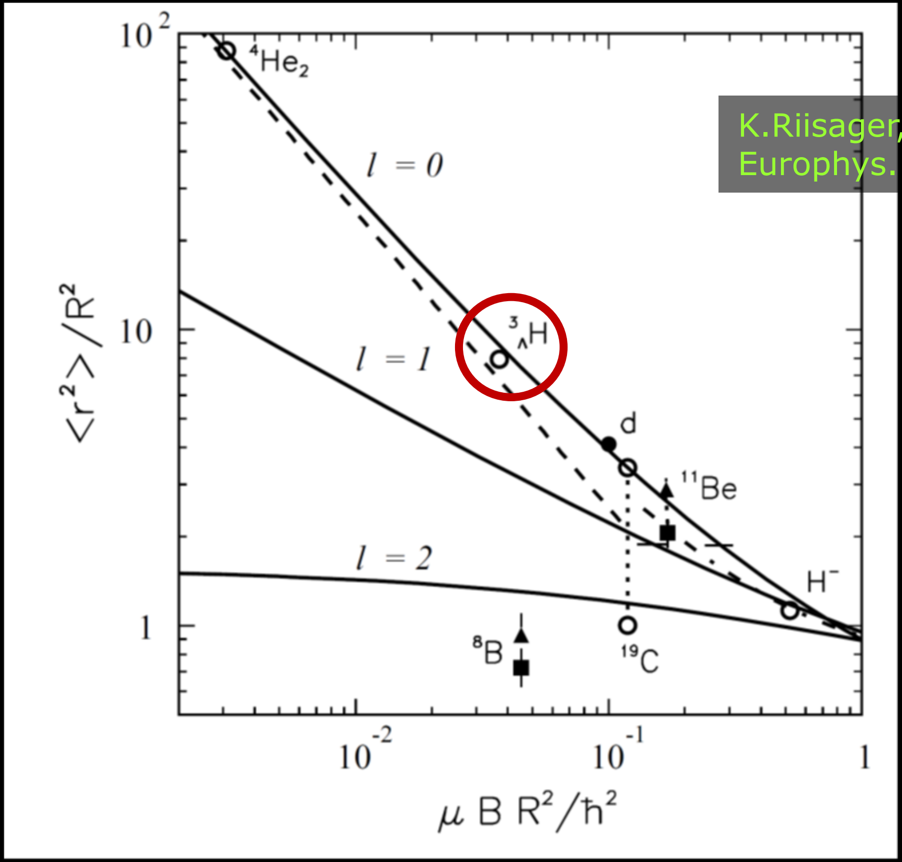




The ${}^{3}_{\Lambda}H$ Puzzle: Part 1 - Λ Binding Energy

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

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



ratio of halo and core-potential square radii

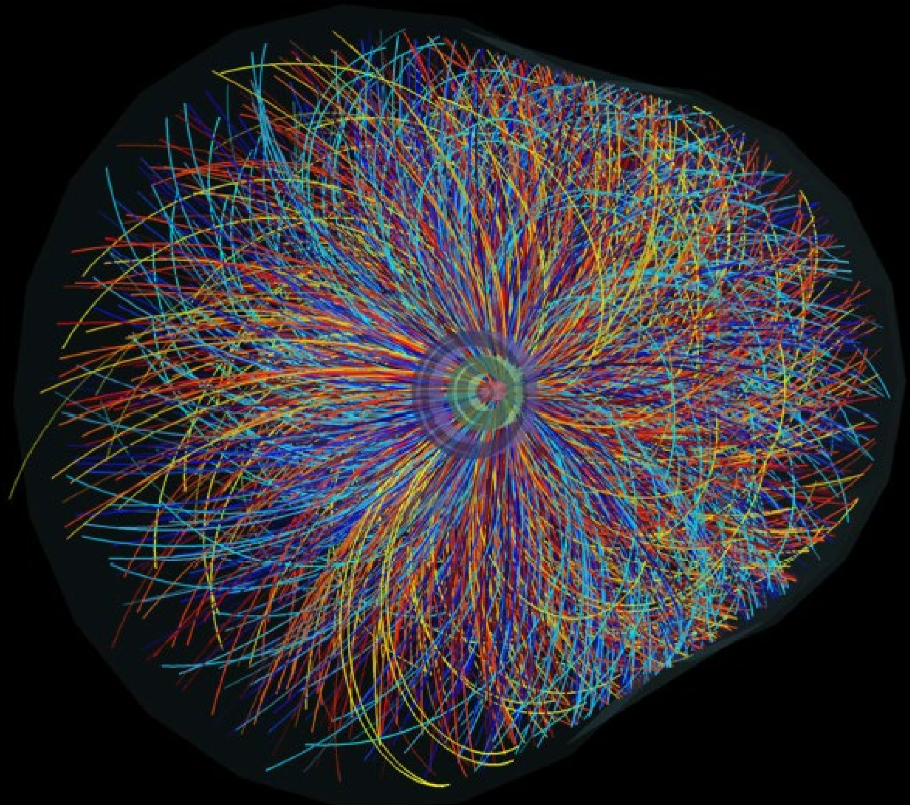
scaled separation energy

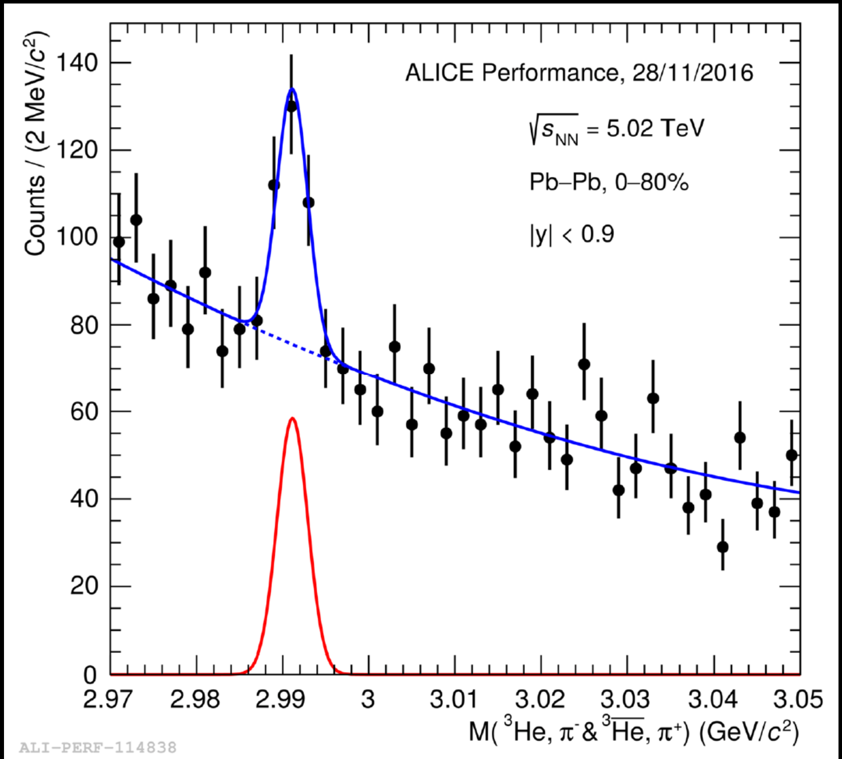
K.Riisager,D.V.FedorovandA.S.Jensen, Europhys. Lett 49, 547 (2000)

Hypernuclei in RHIC

- Searching the needle in the haystack

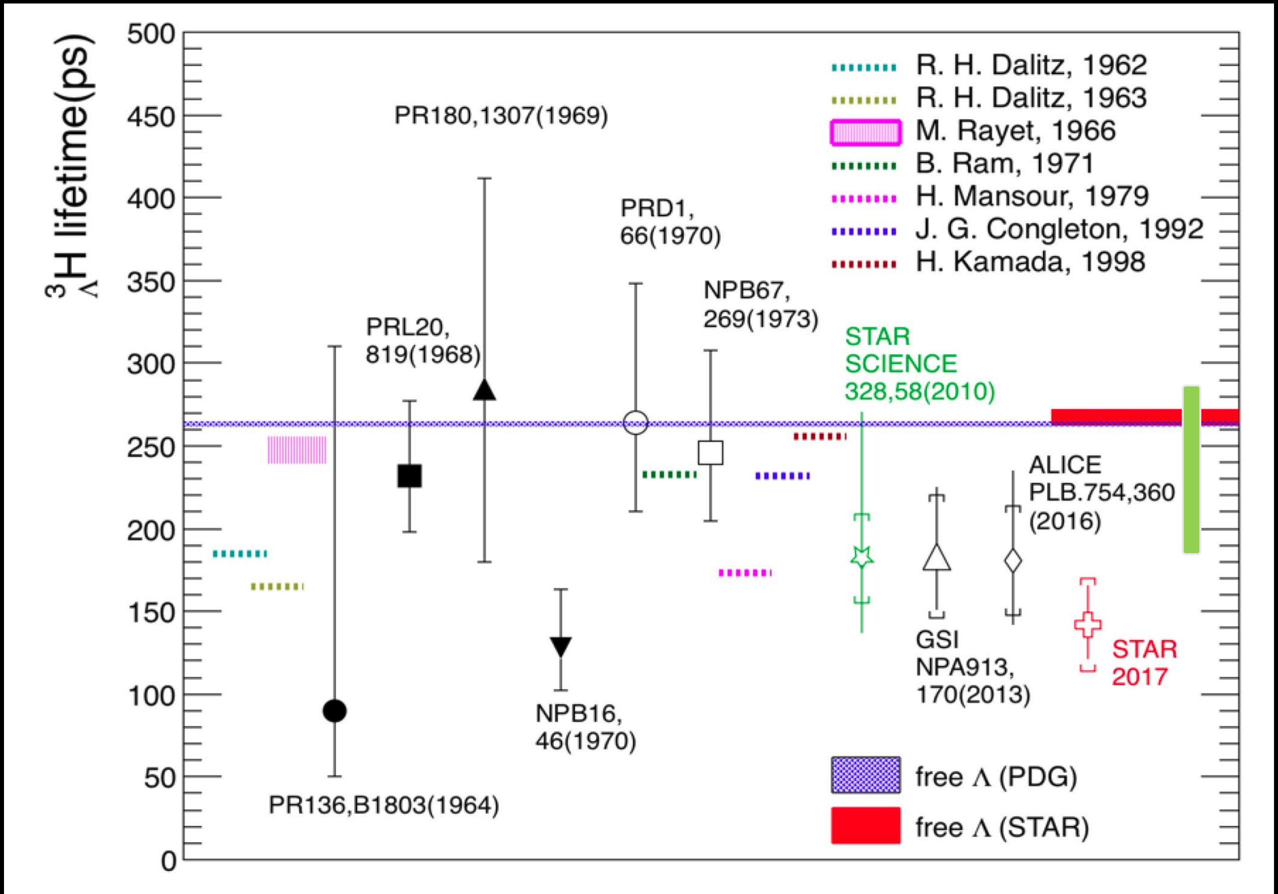
$$^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$$





Experiment	Reaction	$\langle y/y_{cm}\rangle$	$\sqrt{s_{NN}}$ [GeV]	$^3_\Lambda$H	$^3_{\overline{\Lambda}}\overline{H}$	$^4_\Lambda$H
E864	Au+Pt	0.3	5.0	1220±854	-	-
HADES	Ar+KCl	-0.45	2.6	$\frac{^3_\Lambda H}{N_\Lambda}$ <$2.5\cdot10^{-2}$	-	-
STAR	Au+Au	0	7.7-200	≈400	≈200	-
ALICE	Pb+Pb	0	2760	≈124	≈90	-

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



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

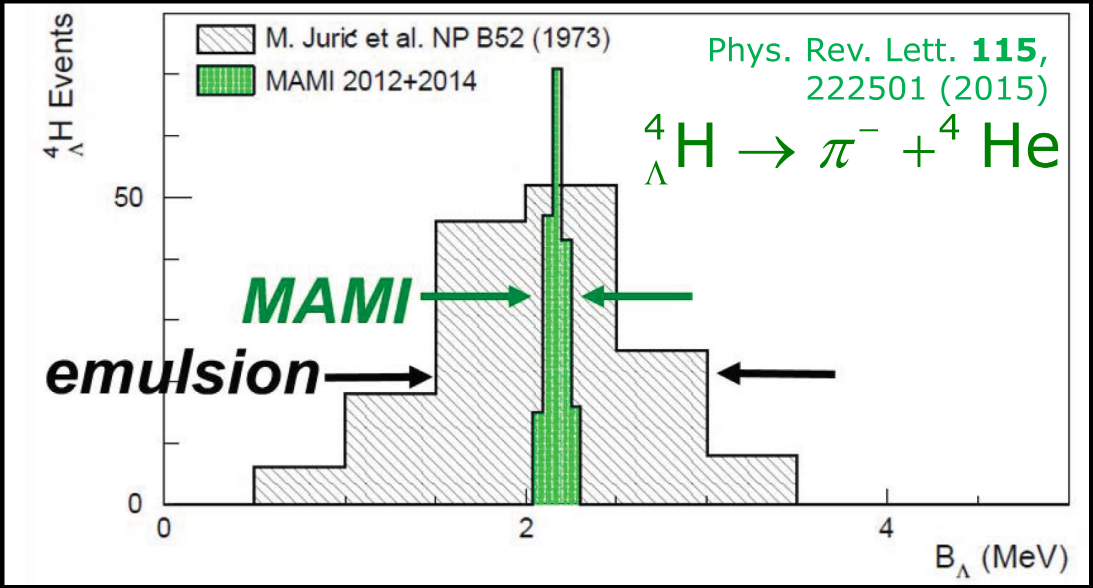
STAR arXiv:1710.00436v1 [nucl-ex] 1st Oct 2017

small binding energy ? small lifetime

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

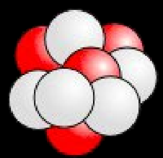
small binding energy ? small lifetime

- New precision mass measurement at MAMI in 2020
  - Make use of excellent beam quality at MAMI
  - Precision *absolute* energy calibration interference of undulator radiation

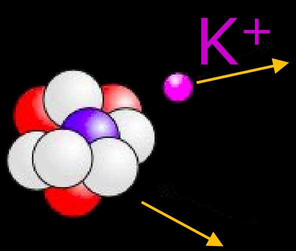


- new lifetime measurements
  - 2020: ELPH (γ,K^{+})
  - 2020: WASA @ GSI/FAIR
  - 2018: ALICE - end Run2: 2x statistics
  - 2023: ALICE – end run 3: 200x stat.
  - 202x: J-PARC (π^{-},K^{0})

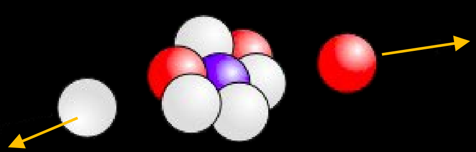
High resolution pion spectroscopy



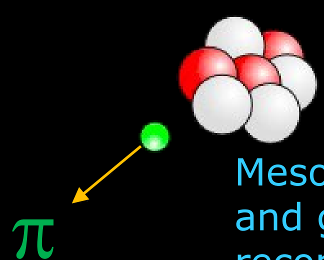
Electroproduction of excited hypernuclei on ^{9}Be Target



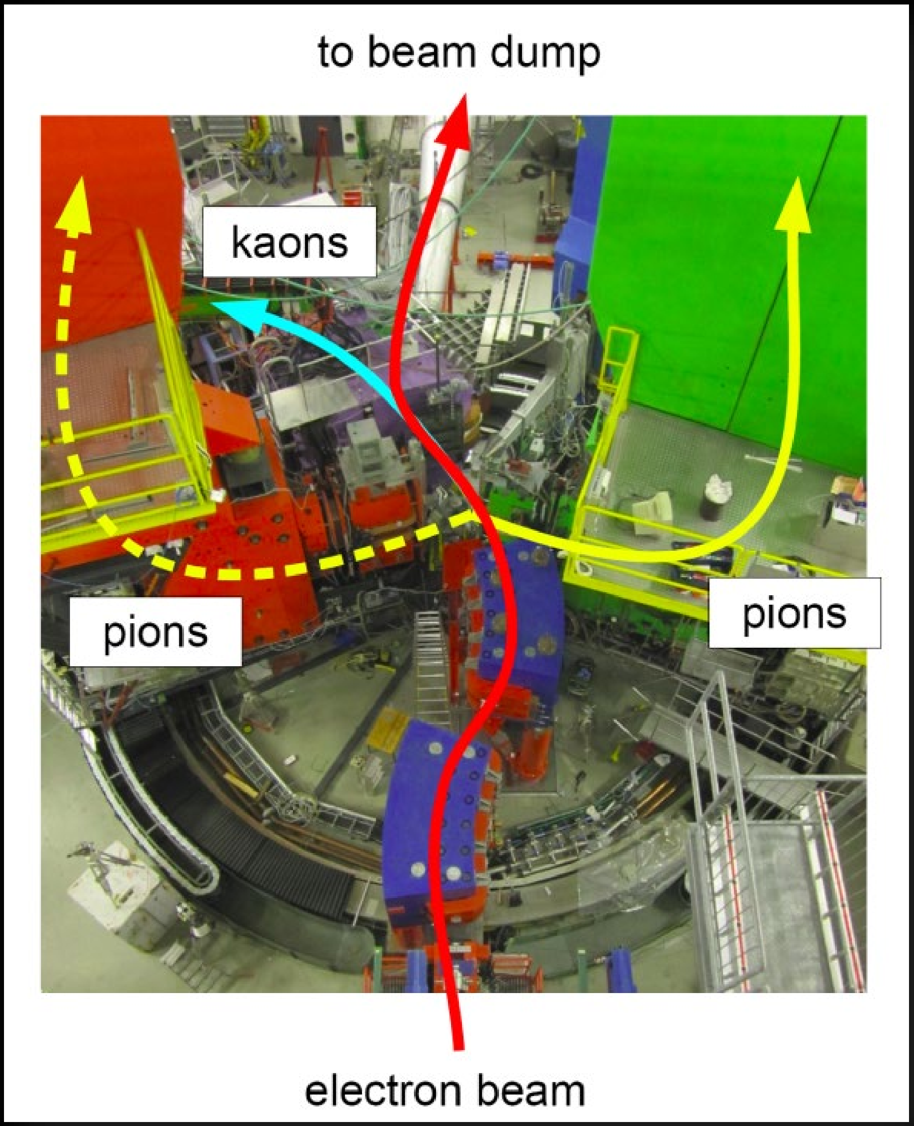
Event tagging by kaon detection



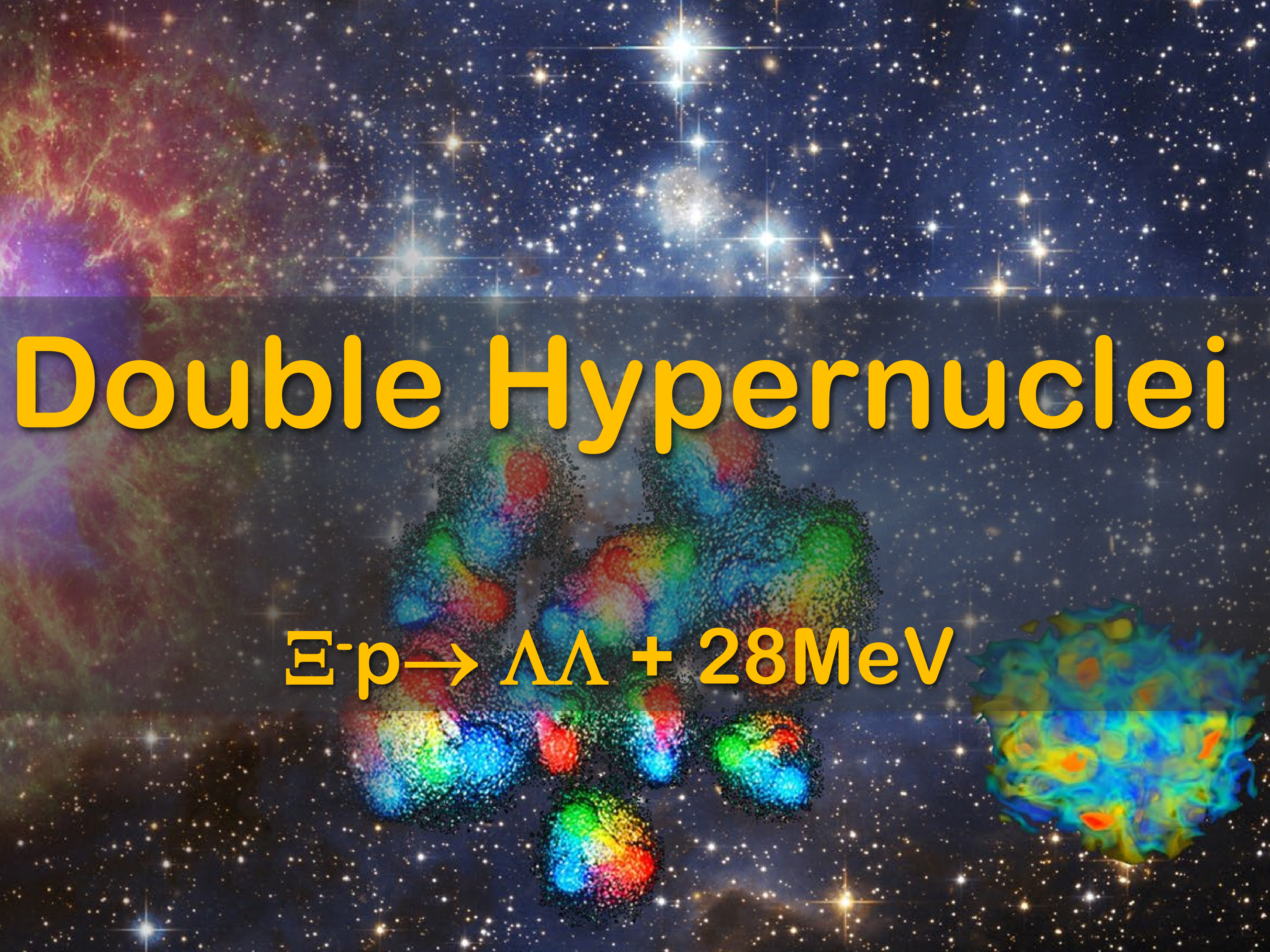
Fragmentation produces several light hypernuclei



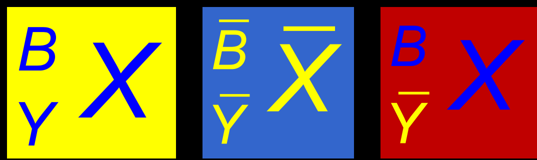
Mesonic weak decay and groundstate mass reconstruction by spectroscopy of pions from two-body decay

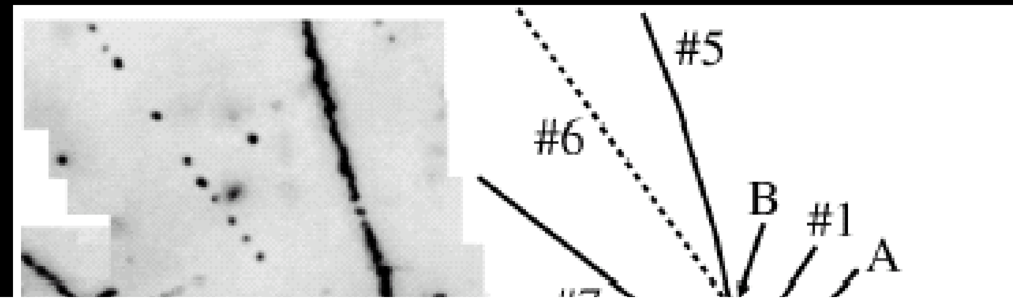


Phys. Rev. Lett. **115**, 222501 (2015)


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

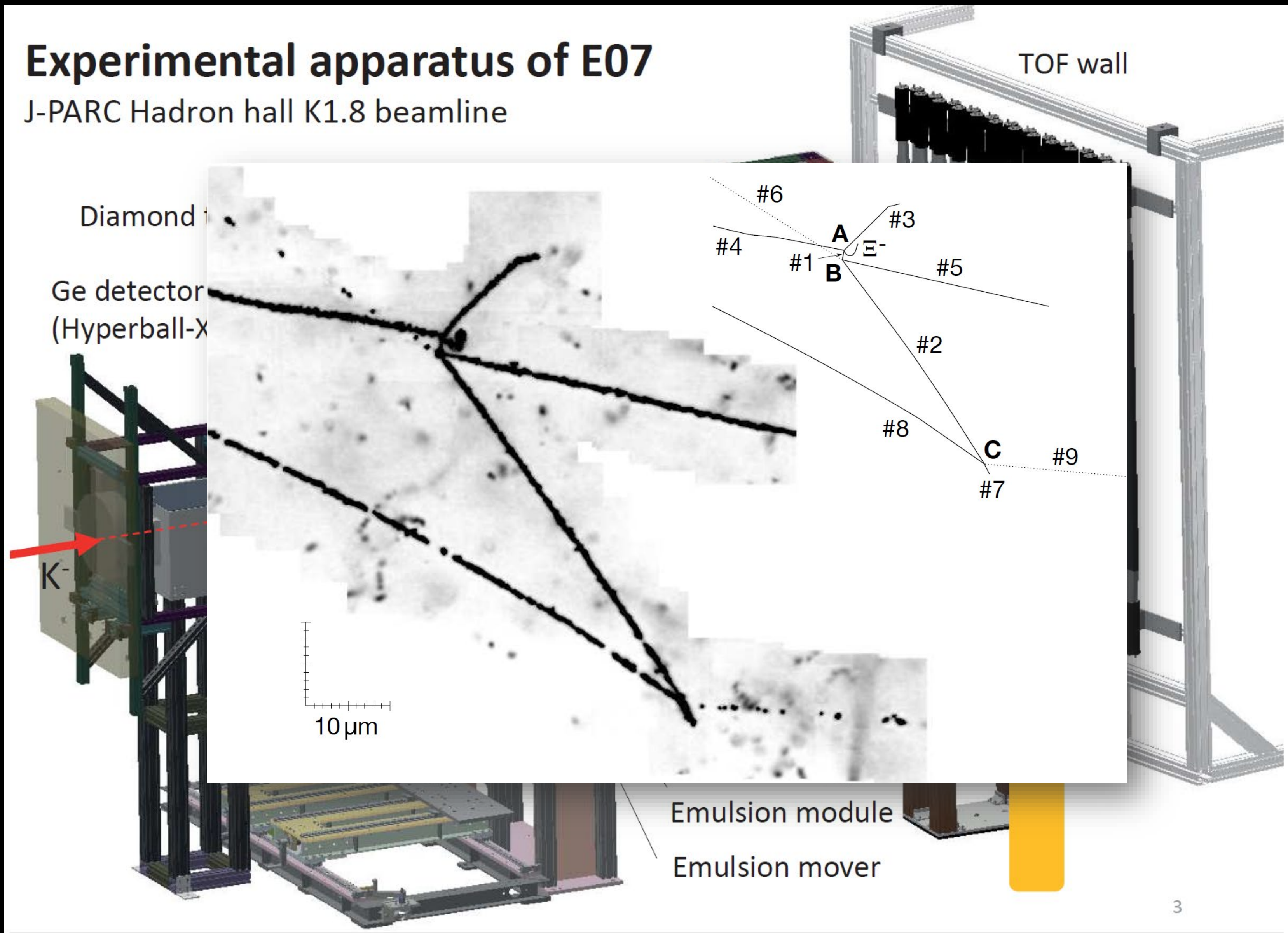
Double Hypernuclei are Shy





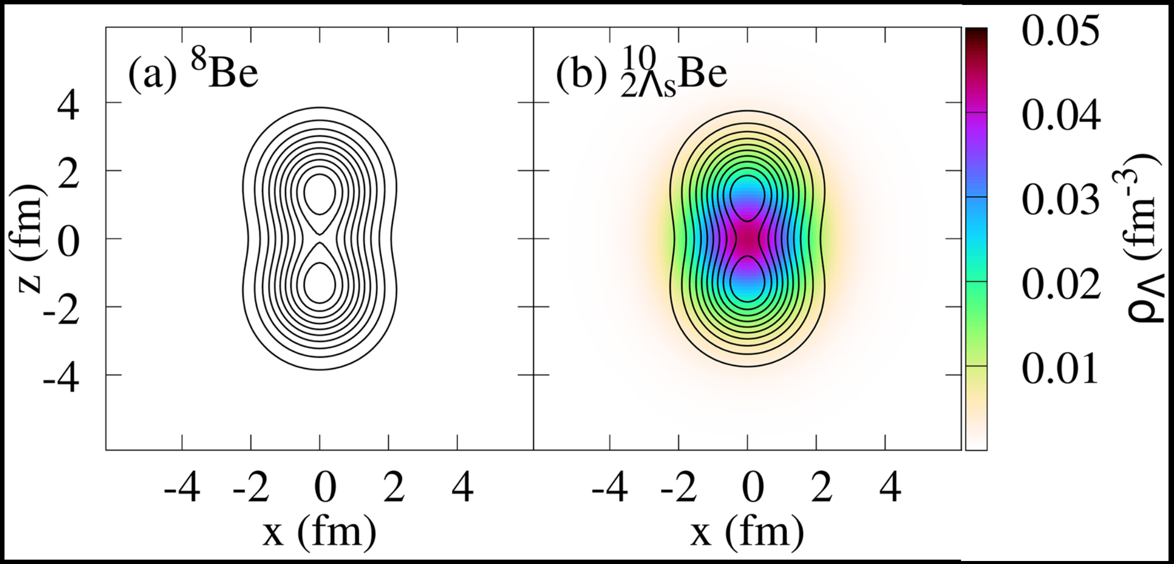
Nucleus	$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ [MeV]	Experiment	Reference	Remark
${}^{10}_{\Lambda\Lambda}$Be	4.3 ± 0.4	Danysz (1963)	[179, 180] [174]	$K^- +$ nuclear emulsion; $\Delta B_{\Lambda\Lambda}$ consistent with NAGARA if decay to ${}^{9}_{\Lambda}$Be* at $E_x \approx 3$ MeV [20, 181]
${}^{6}_{\Lambda\Lambda}$He	4.7 ± 0.6	Prowse (1966)	[475]	$K^- +$ 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	[47, 618] [49, 195, 424]	hybrid-emulsion $(K^-,K^+)\Xi^-_{stopped}$
${}^{6}_{\Lambda\Lambda}$He	0.67 ± 0.17	KEK-E373 (2001) NAGARA event	[424, 557] [20]	hybrid emulsion
${}^{10}_{\Lambda\Lambda}$Be or ${}^{10}_{\Lambda\Lambda}$Be*	-1.65 ± 0.15	KEK-E373 (2001) DEMACHIYANAGI event	[21, 424] [20]	$B_{\Lambda\Lambda}$ 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	[20, 558]	
${}^{12}_{\Lambda\Lambda}$Be or ${}^{11}_{\Lambda\Lambda}$Be*	2.00 ± 1.21 2.61 ± 1.34	KEK-E373 (2010) HIDA event	[20, 424]	
${}^{10}_{\Lambda\Lambda}$Be or ${}^{11}_{\Lambda\Lambda}$Be or ${}^{12}_{\Lambda\Lambda}$Be	1.63 ± 0.14 1.87 ± 0.37 -2.7 ± 1.0	J-PARC E07 MINO event	[349]	most probable ${}^{11}_{\Lambda\Lambda}$Be

E07 @ J-PARC

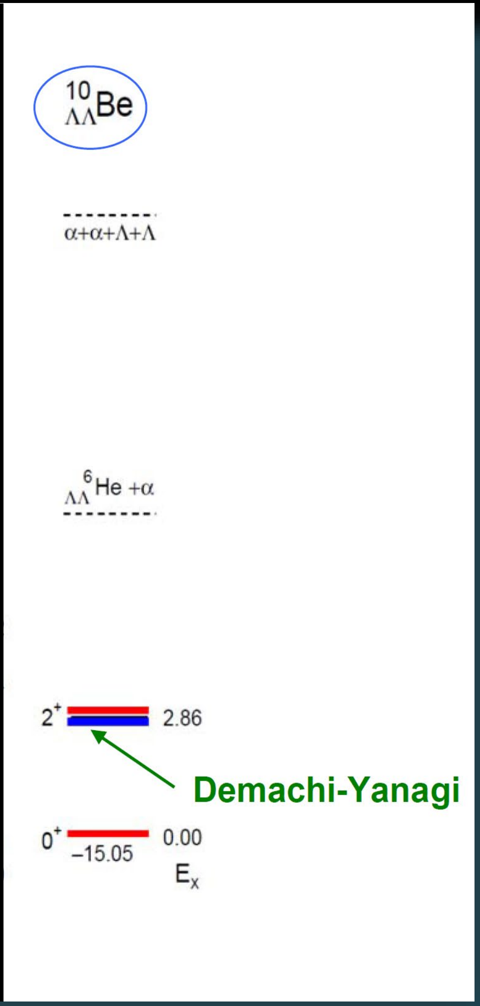

Experimental apparatus of E07
J-PARC Hadron hall K1.8 beamline
TOF wall
Diamond t
Ge detector
(Hyperball-X
K-
#6
#3
A
#4
Ξ-
#1
#5
B
#2
#8
C
#9
#7
10 μm
Emulsion module
Emulsion mover
3

Spectroscopy of ΛΛ-hypernuclei

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

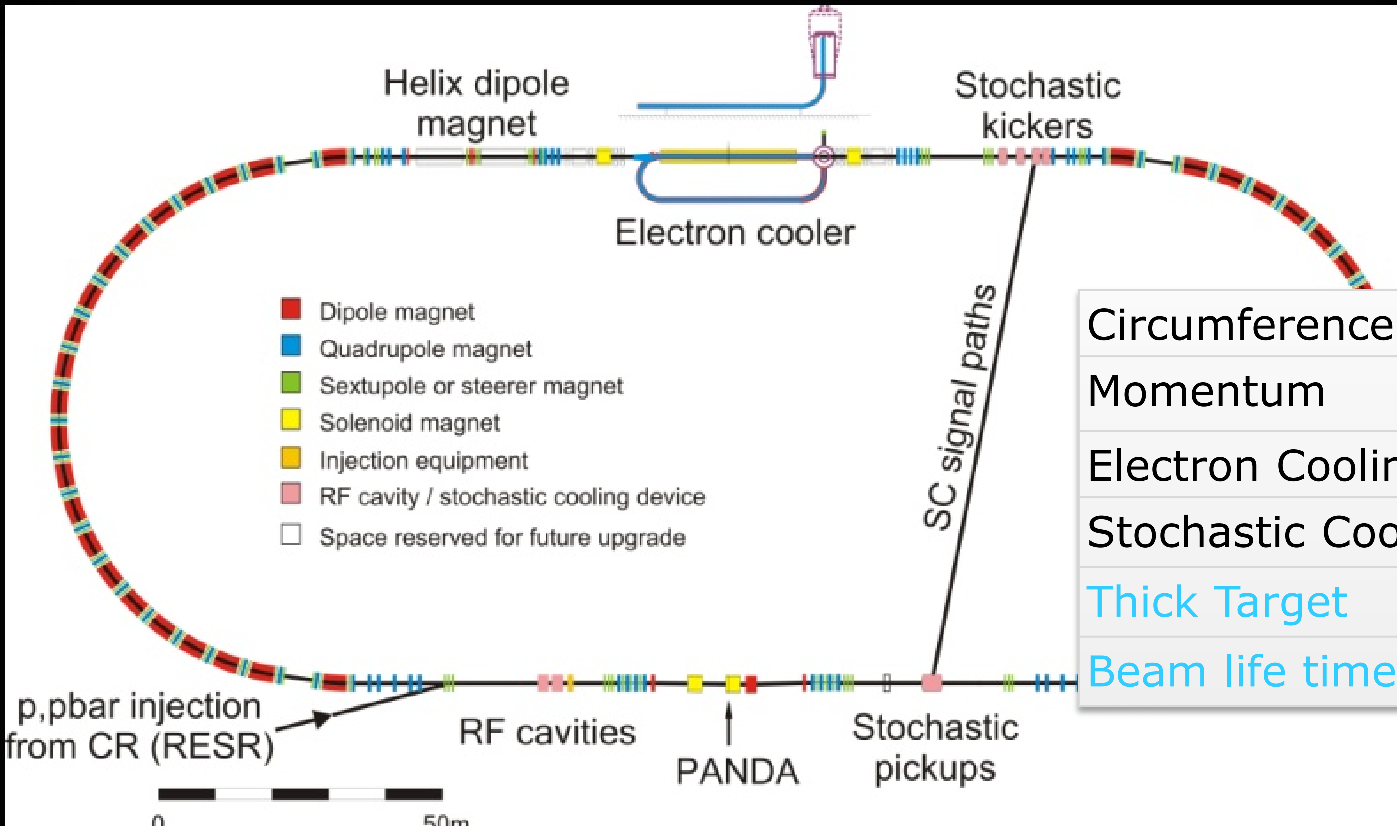


Yusuke Tanimura
Phys. Rev. C 99, 034324 (2019)



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

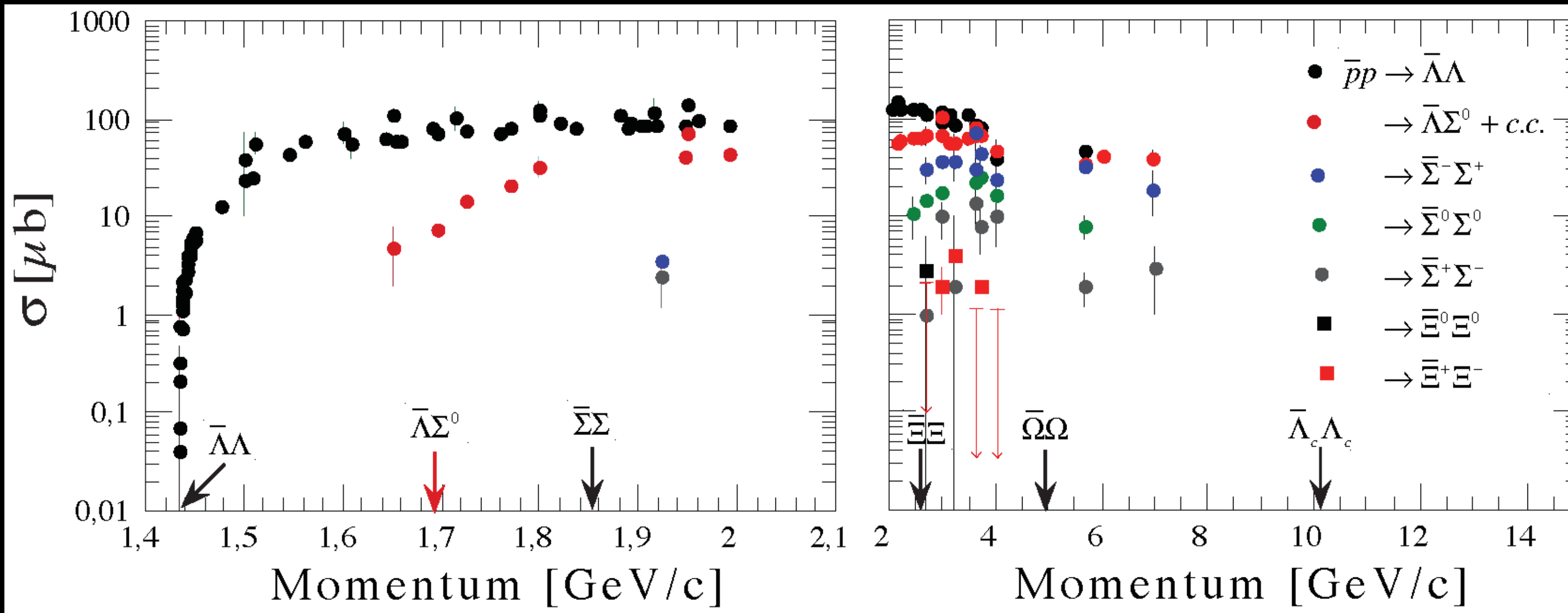
HESR with PANDA and Electron Cooler



Circumference	575 m
Momentum	1.5 – 15 GeV/c
Electron Cooling	up to 9 GeV/c
Stochastic Cool.	Full range
Thick Target	$4\cdot10^{15}$ cm^{-2}
Beam life time	>30 min

- High resolution mode
  - e^- cooling $1.5 \leq p \leq 8.9$ GeV/c
  - 10^{10} antiprotons stored
  - Luminosity up to $2\cdot10^{31}$ cm^{-2}s^{-1}
  - $\Delta p/p \leq 4\cdot10^{-5}$
- High luminosity mode
  - Stochastic cooling $p \geq 3.8$ GeV/c
  - 10^{11} antiprotons stored
  - Luminosity up to $2\cdot10^{32}$ cm^{-2}s^{-1}
  - $\Delta p/p \leq 2\cdot10^{-4}$

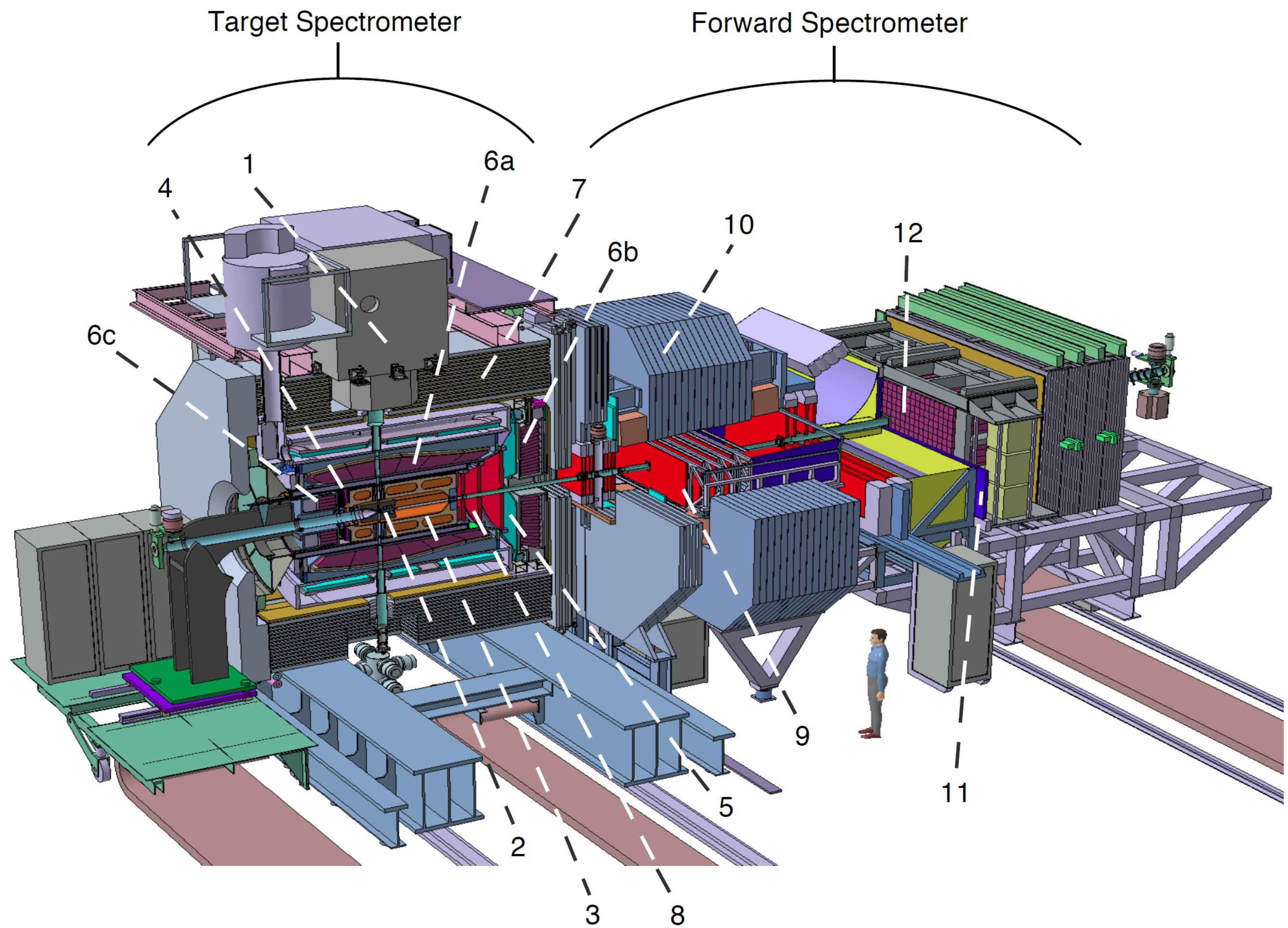
$\bar{\text{P}}$ANDA – a Factory for strange *and* charmed $Y\bar{Y}$-Pairs



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
$J/\psi\,(\rightarrow e^+e^-, \mu^+\mu^-)$	630nb	10^9
$\chi_2\,(\rightarrow J/\psi+\gamma)$	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

The PANDA Detector



1: Cluster-Target
2: Mikrovertex-Detektor
3: STT-Tracker
4: DIRC
5: Disc-DIRC
6a: Barrel-EMC
6b: Forward-EMC
6c: Backward-EMC
7: Solenoid Yoke with Muon Chambers
8: GEM-Tracker
9: Forward Tracker
10: Dipole
11: Forward TOF wall
12: Shashlyk-EMC

not visible (downstream): Luminosity Detector
not visible: Hypernuclear Setup

Strange Systems at PANDA

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

rescattering in
primary target nucleus

deceleration in
secondary target

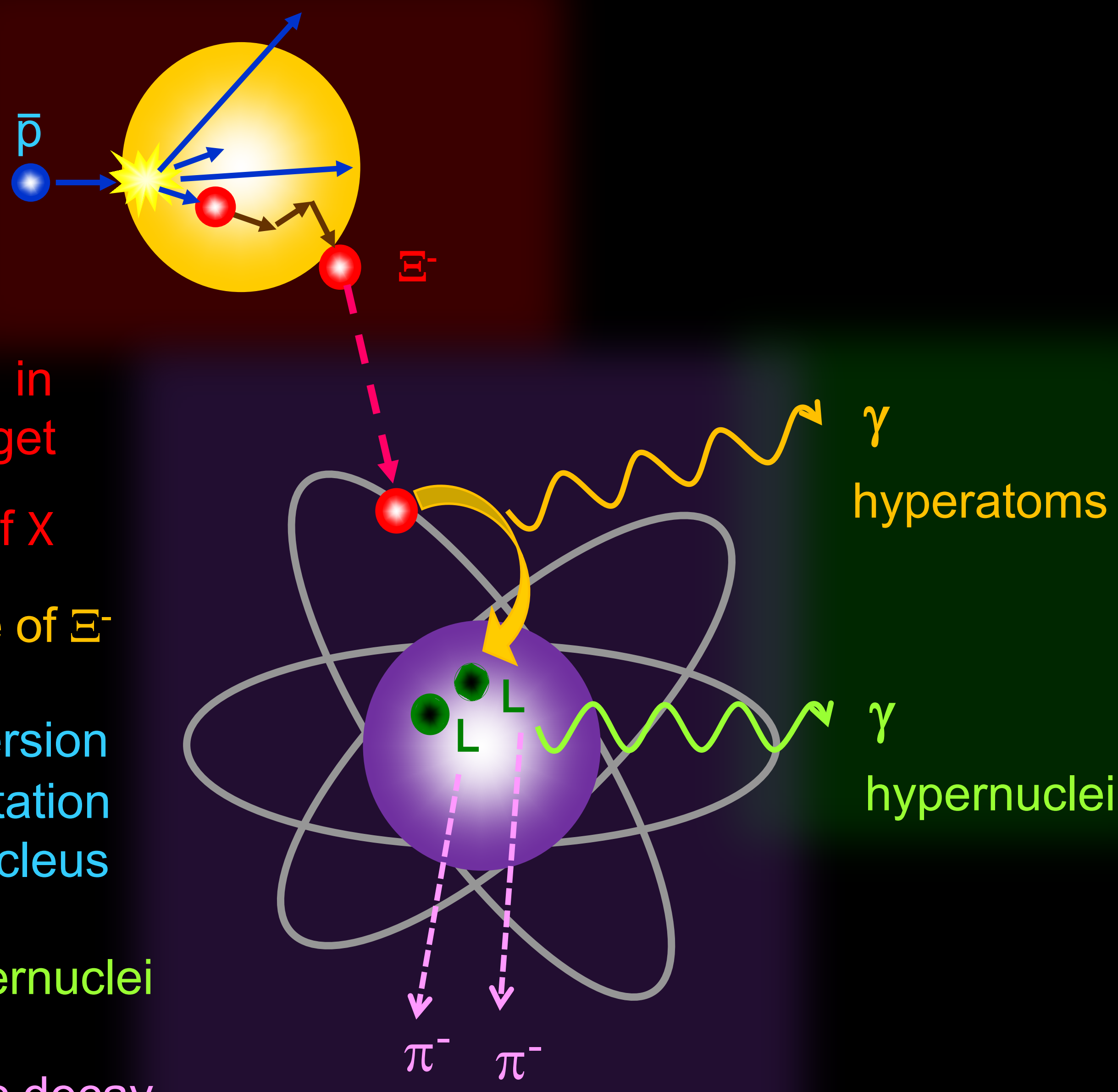
capture of X

atomic cascade of Ξ^-

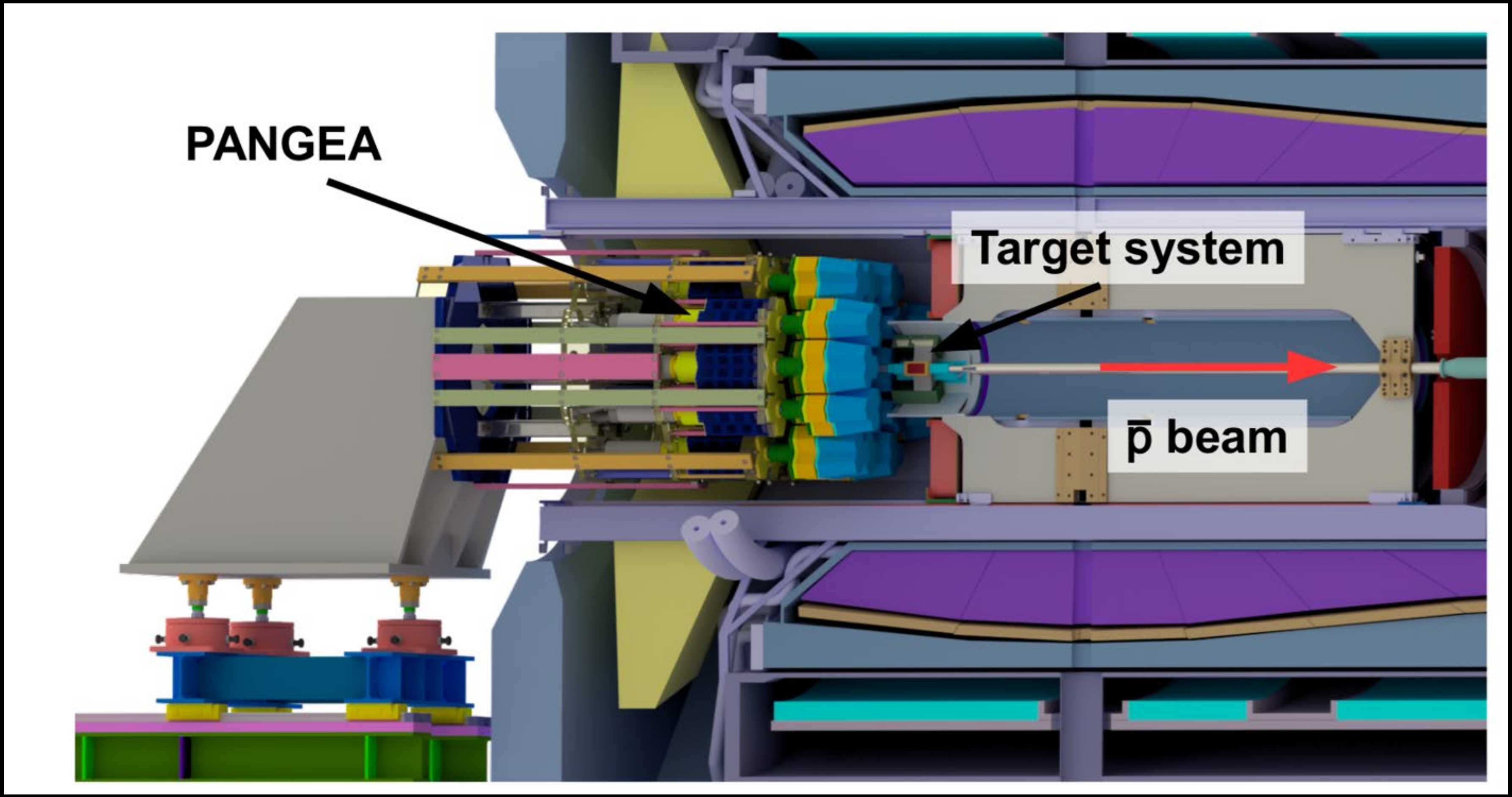
Ξ^-p $\Lambda\Lambda$ conversion
fragmentation
$\rightarrow$ excited $\Lambda\Lambda$-nucleus

γ-decay of $\Lambda\Lambda$ hypernuclei

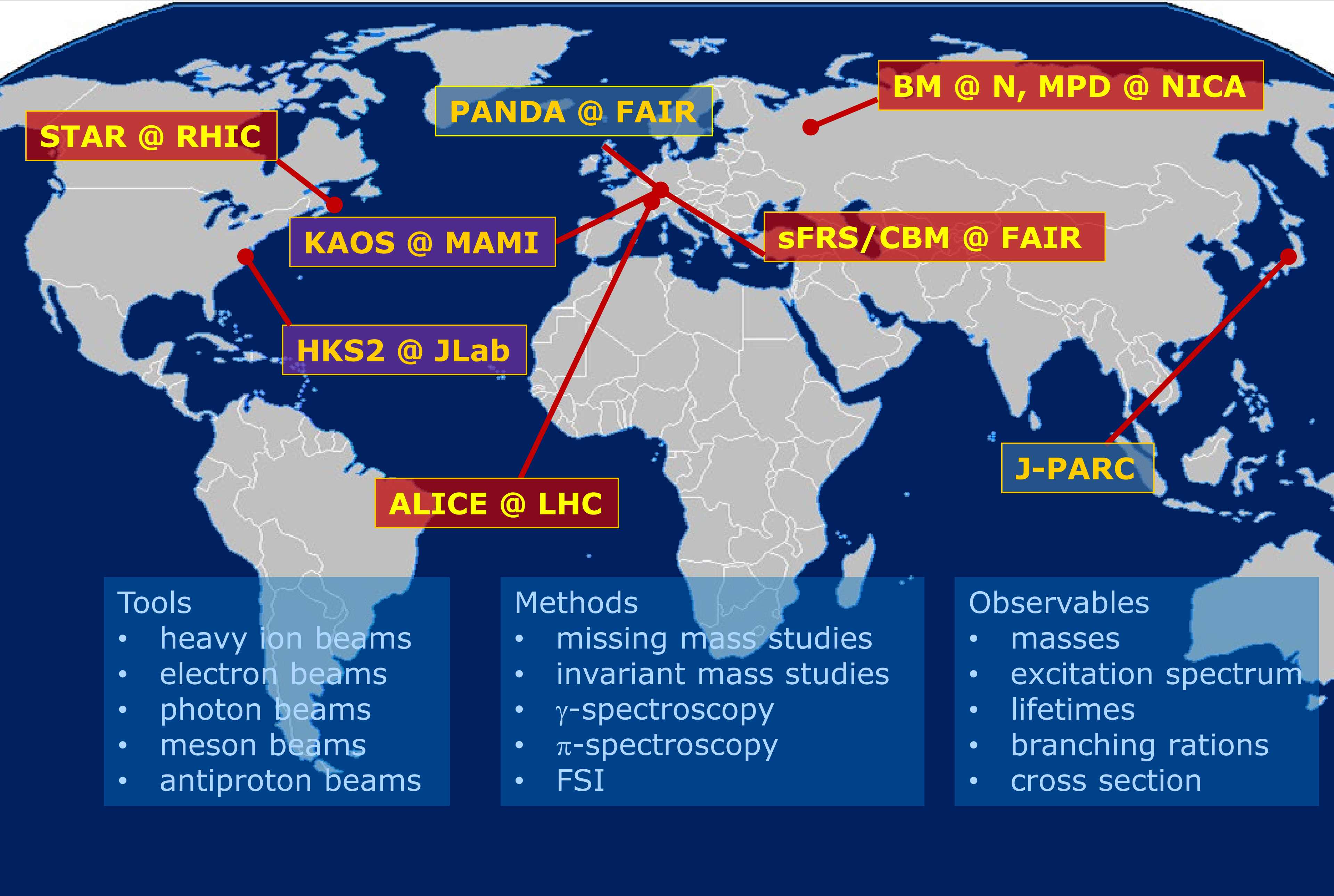
weak pionic decay



PANDA + PANGEA



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

Take-home message

- Strangeness nuclear physics is embedded in the quest to determine the EOS of dense stellar systems
- Hyperon puzzle of neutron stars is still not solved
- Hypernuclei and hyperatoms are femto-laboratories for Y^nN^m interaction
- After 60 years still many puzzles: hypertriton, existence of neutral hypernuclei $nn\Lambda$, $nn\Lambda\Lambda$, …
- Coming generation of experiments focus on precision studies


Thank you
for your attention