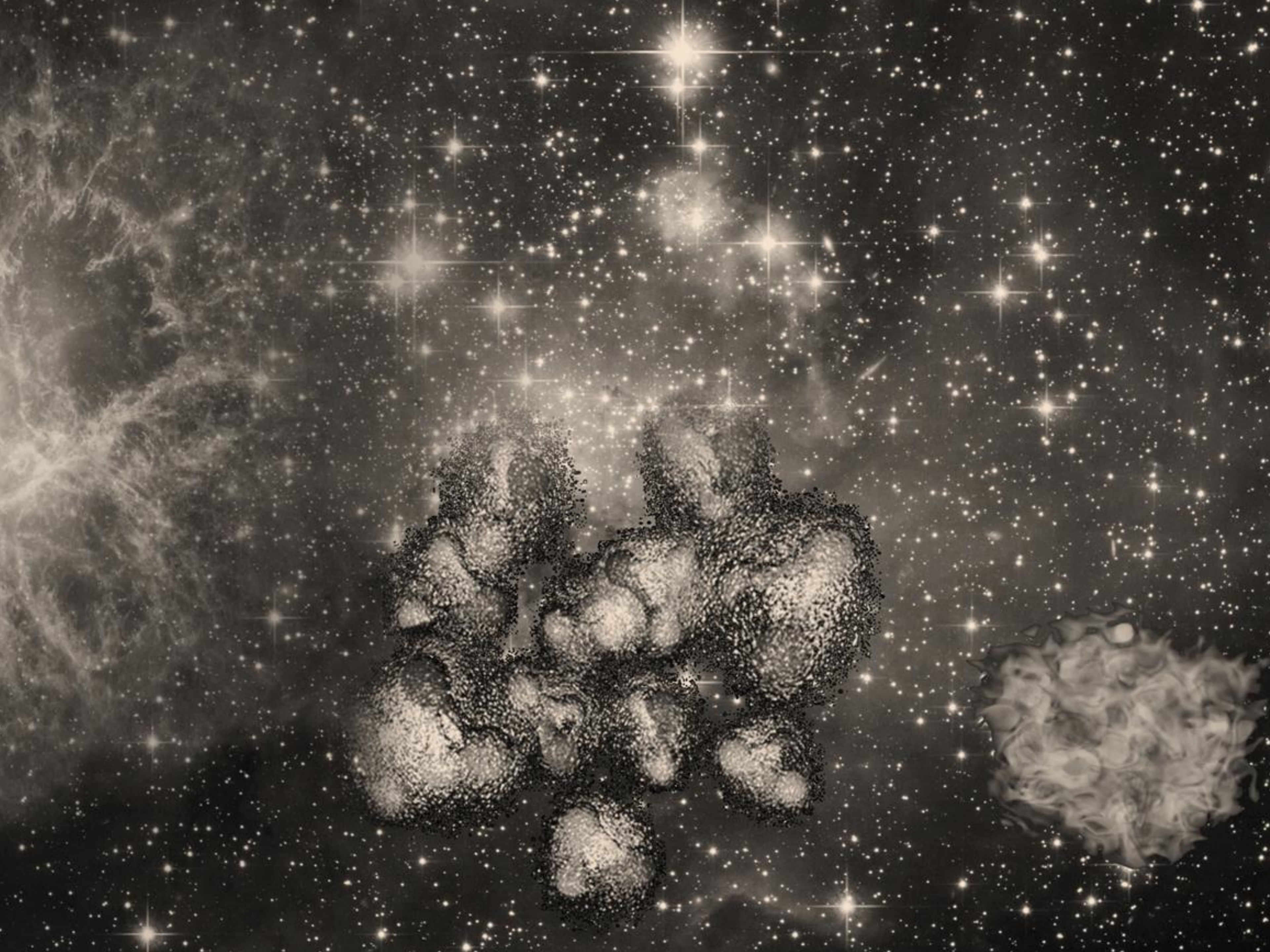
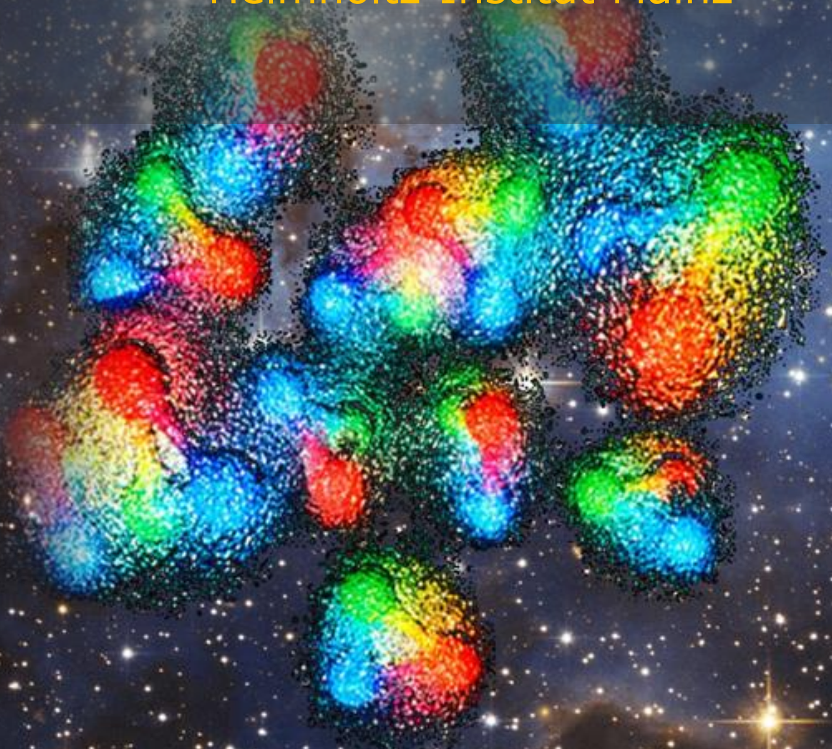
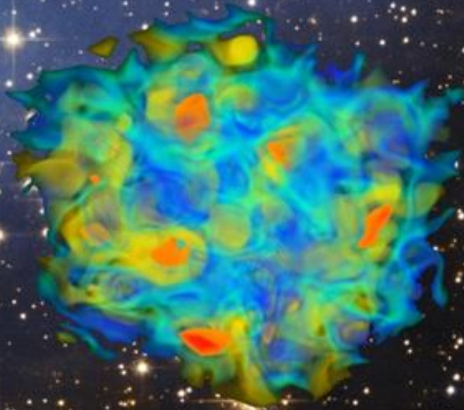


It’s a strange world
where
QCD meets Gravity

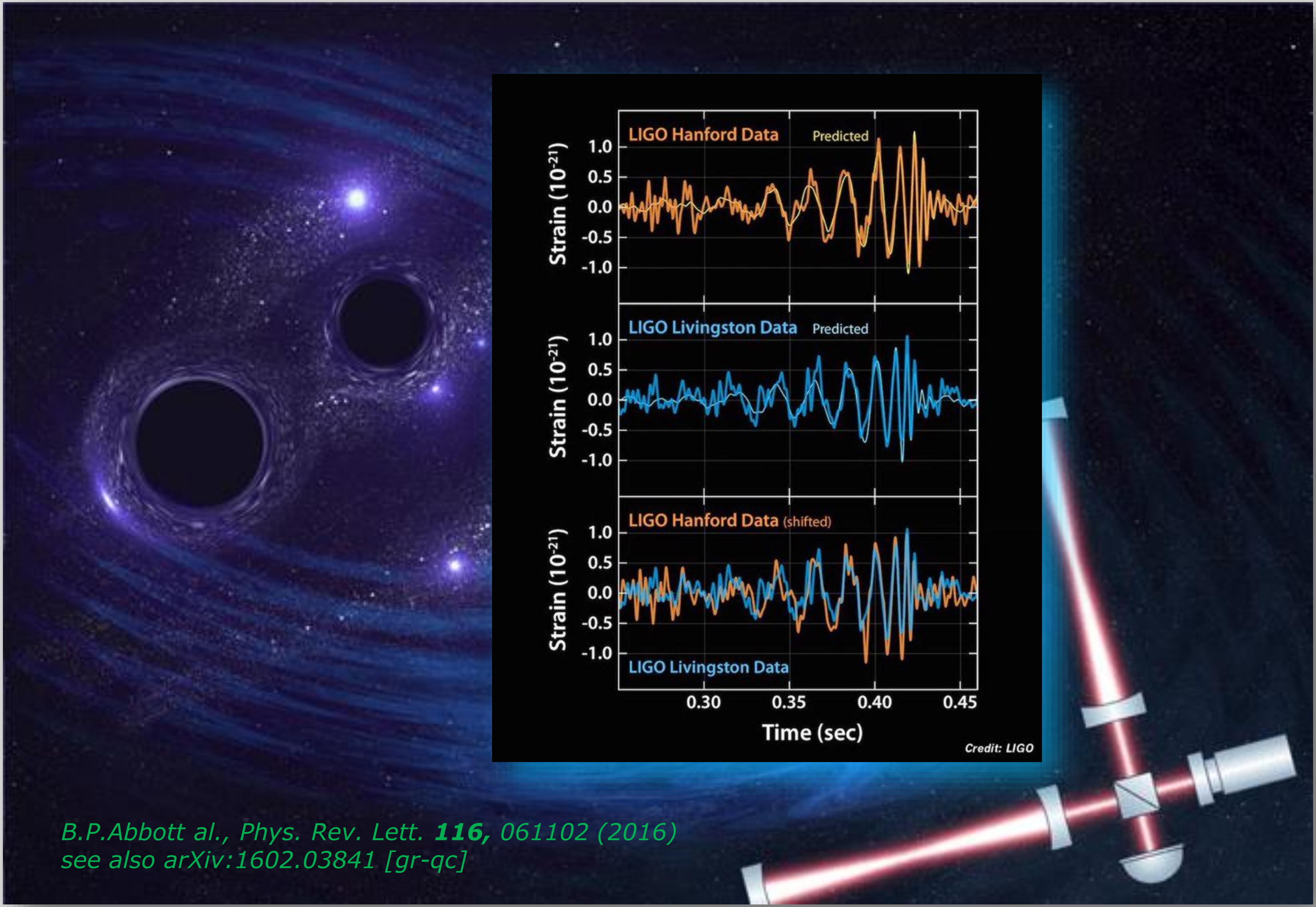
Josef Pochodzalla

Helmholtz-Institut Mainz



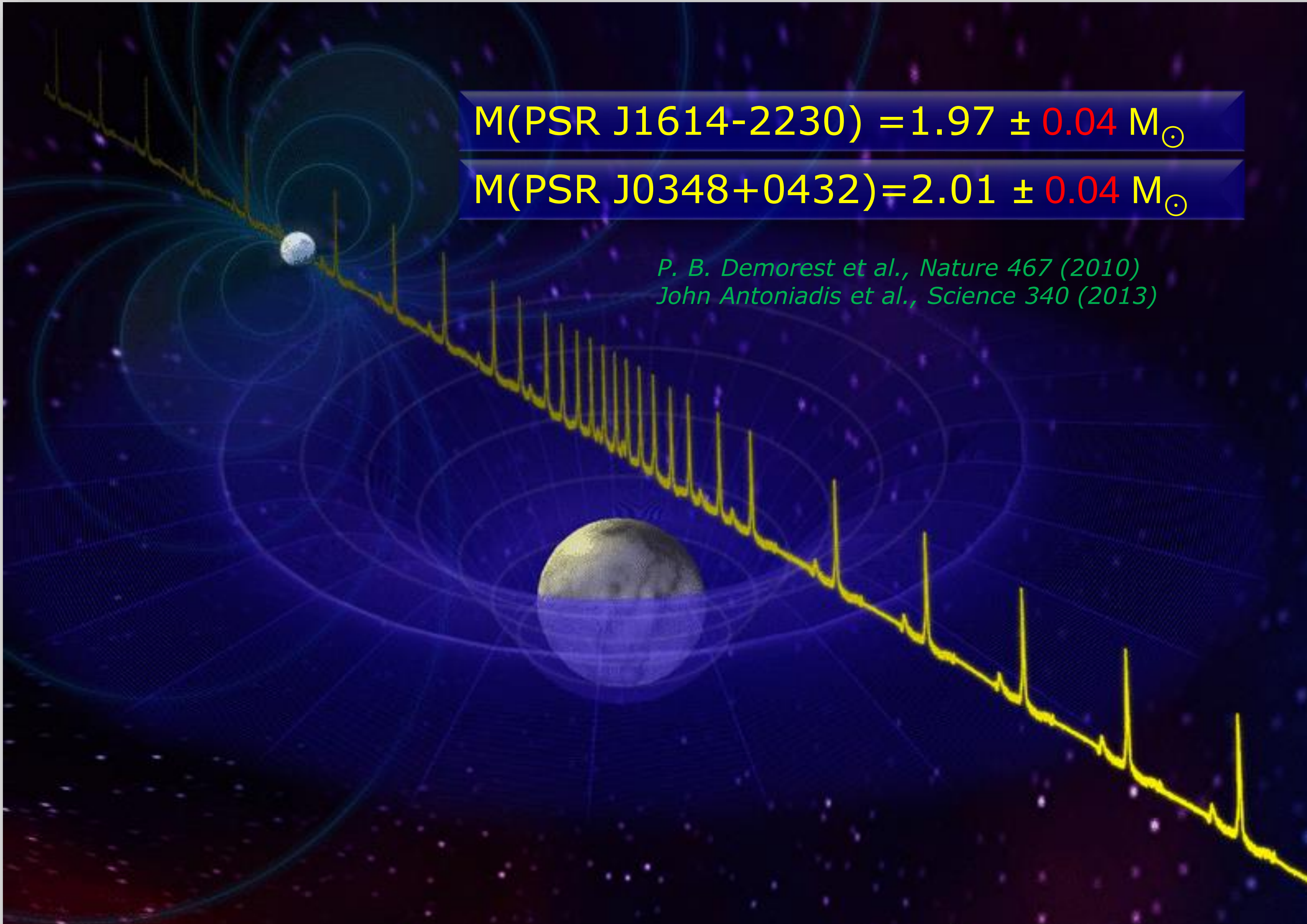


Gravitational Waves

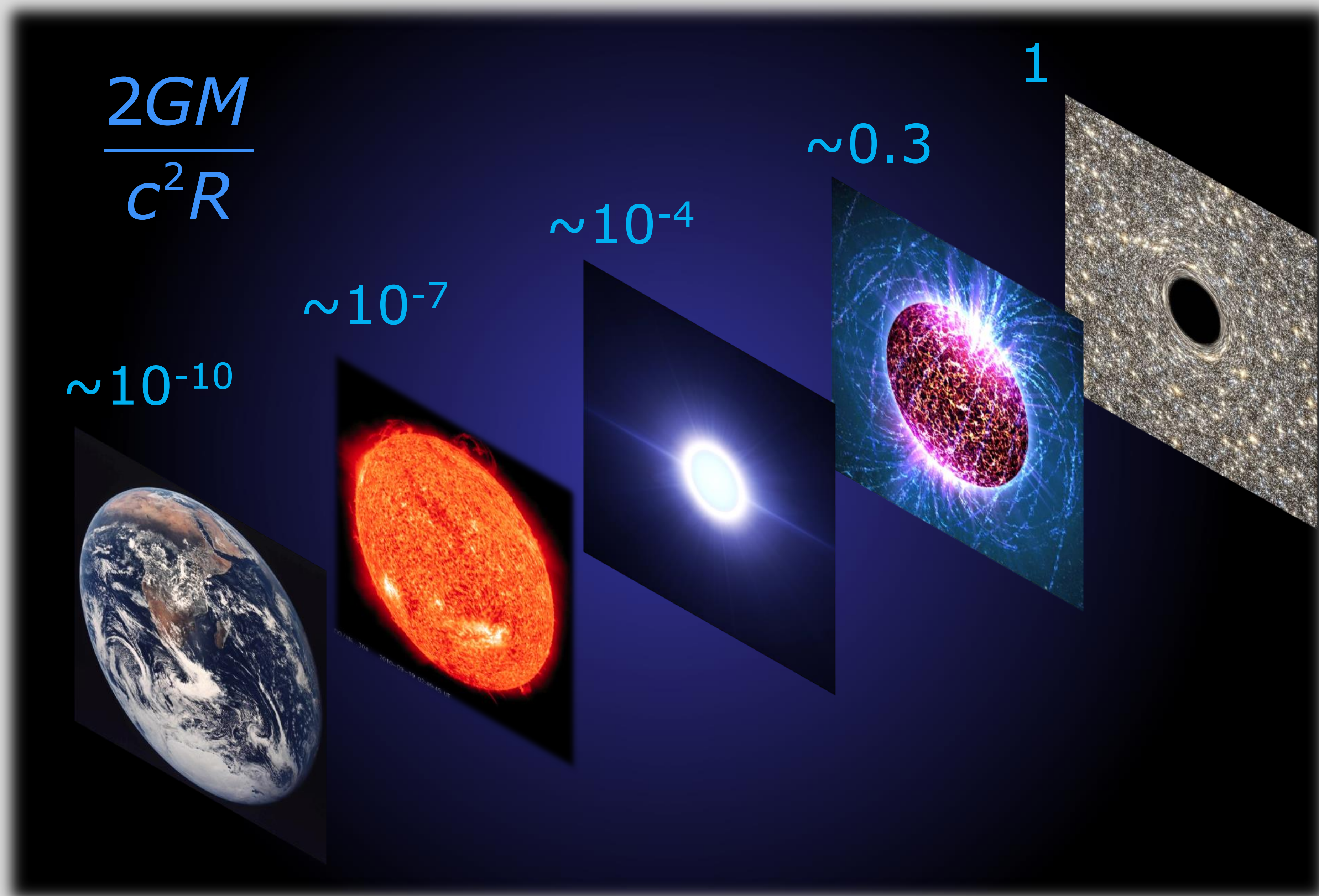


B.P.Abbott al., Phys. Rev. Lett. ***116,*** *061102 (2016)*
see also arXiv:1602.03841 [gr-qc]

Neutron Stars

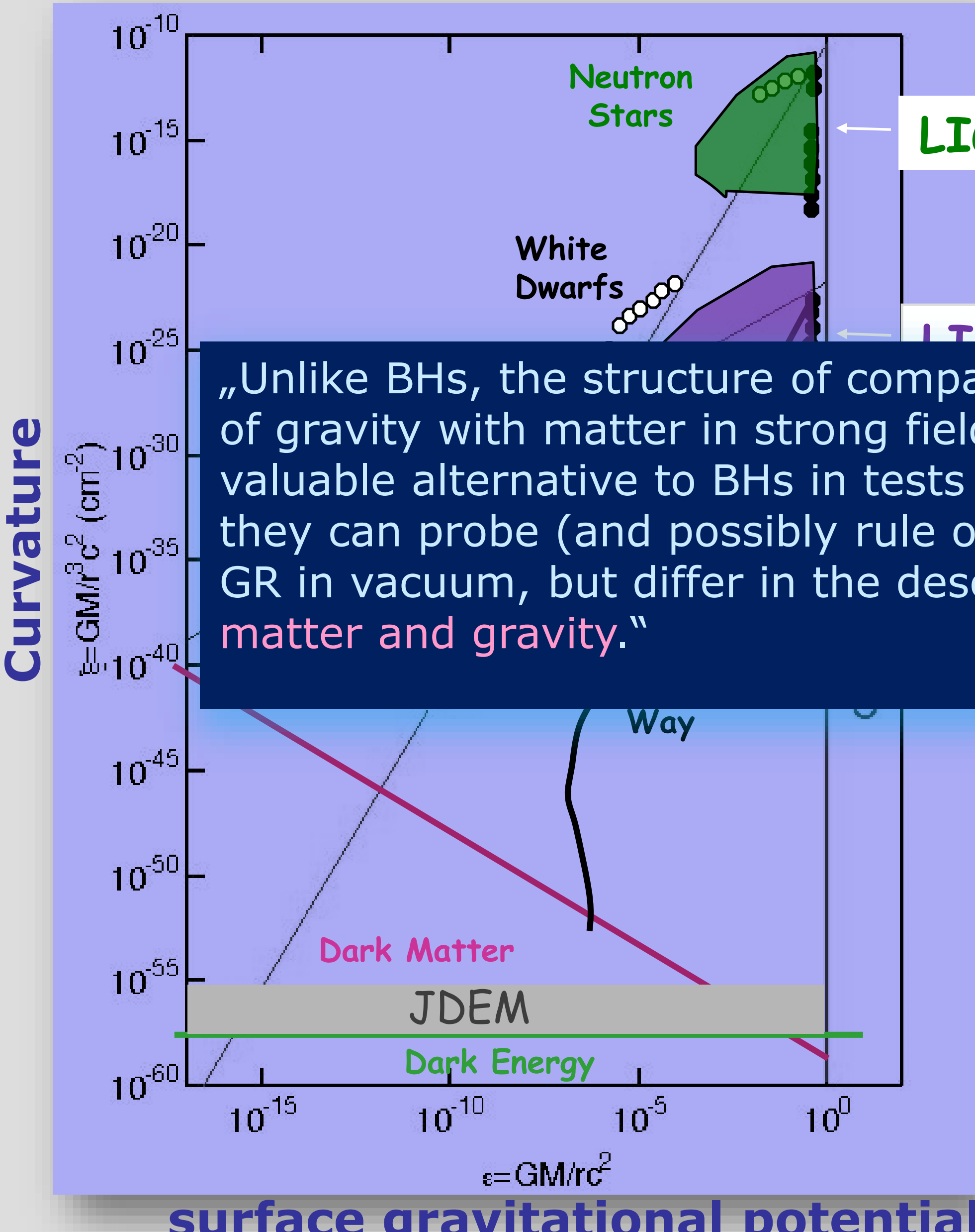


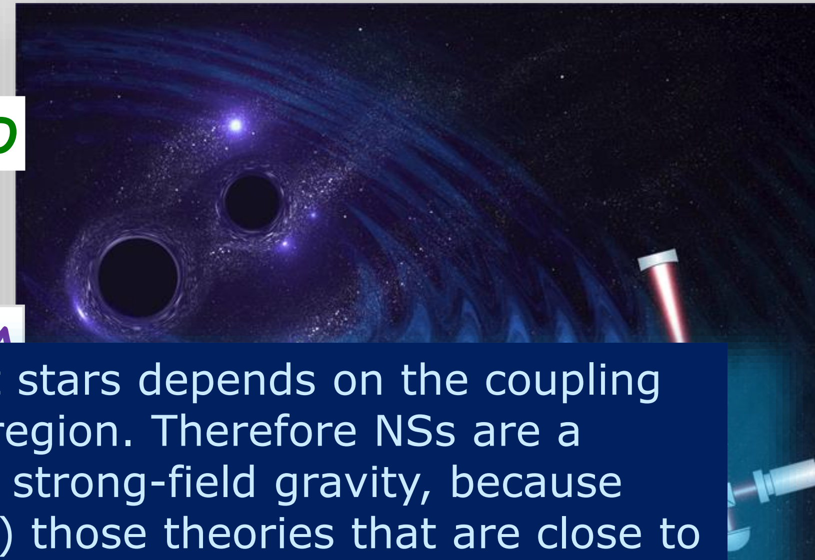
Surface Gravitational Potential

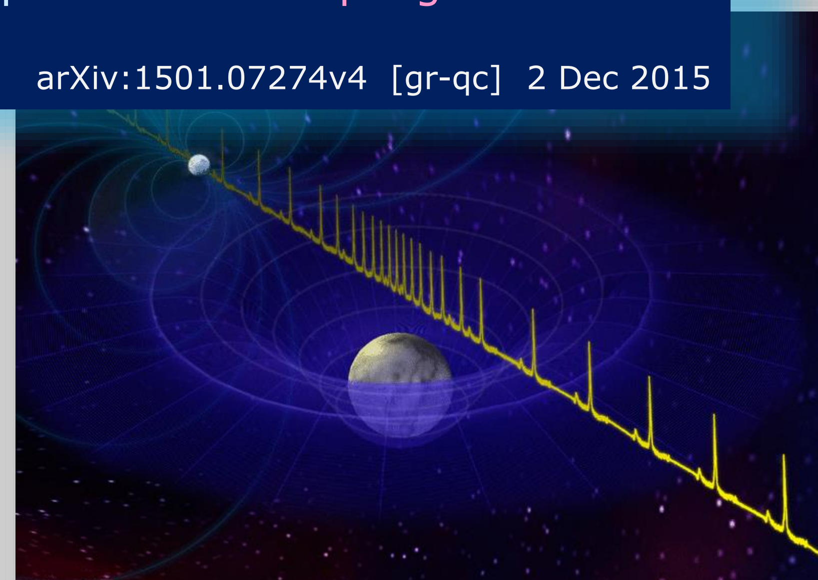


Regime of Strong-field Gravity

*D. Psaltis, Living Rev. Relativity **11**, 9 (2008)*







„Unlike BHs, the structure of compact stars depends on the coupling of gravity with matter in strong field region. Therefore NSs are a valuable alternative to BHs in tests of strong-field gravity, because they can probe (and possibly rule out) those theories that are close to GR in vacuum, but differ in the description of the coupling between matter and gravity."

arXiv:1501.07274v4 [gr-qc] 2 Dec 2015

2M … n Stars: Hyperon Puzzle

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 00 (2013) 1–4

Three-body couplings in RM…
and its effects on hyperonic star equatio…

… Tsubakihara[a], A. Ohnishi[b]

… Laboratory, Hokkaido University,
… oretical Physics, Kyoto University,

…eutron star mass and the resolution of hyperon puzzle in modified gravity

Artyom V. Astashenok[1], Salvatore Capozziello[2,3,4], Sergei D. Odintsov[5,6,7]

[1]I. Kant Baltic Federal University, Institute of Physics and Technology, Nevskogo st. 14, 236041 Kalinin…
[2]Dipartimento di Fisica, Universita' di Napoli "Federico II" and
[3]Istituto Nazionale di Fisica Nucleare (INFN) Sez. di Napoli,
Compl. Univ. di Monte S. Angelo, Ed. G., Via Cinthia, 9, I-80126, Na…
[4]Gran Sasso Science Institute (INFN), Viale F. Crispi, 7, I-67100, L…
[5]Institució Catalana de Recerca i Estudis Avançats (ICREA), B…
[6]Institut de Ciencies de l'Espai (IEEC-CSIC), C…
Torre C5-Par-2a pl, E-08193 Bellaterra, B…
[7]Tomsk State Pedagogical University, …
National Research Tomsk State Univ…

The influence of Strong Magnetic Field in Hyperonic Neutron Stars

…ebora Peres Menezes
…anta Catarina

Hyperon mixing and universal many-body repulsion in neutron stars

Y. Yamamoto[1], T. Furumoto[2], N. Yasutake[3], and Th.A. Rijken[4,1]
[1]Nishina Center for Accelerator-Based Science, Institute for Physi…
and Chemical Research (RIKEN), Wako, Saitama …
[2]National Institute of Technology, Ichinoseki College, Ichin…
[3]Department of Physics, Chiba Institute o…
2-1-1 Shibazono Narashino, Chiba 275-0…
[4]IMAPP, University of Nijmegen, Nij…

A multi-pomeron exchange potential (MP…
body repulsion in baryonic systems …
interaction. The strength of MP…
G-matrix folding model …
Λ binding energi…
includin…
th…

PHYSICAL REVIEW D 89, 043014 (2014)

Can very compact and very massive neutron stars both exist?

Alessandro Drago,[1] Andrea Lavagno,[2] and Giuseppe Pagliara[1]
…ica e Scienze della Terra dell'Università di Ferrara and INFN Sezione di Fer…
Via Saragat 1, I-44100 Ferrara, Italy
…d Science and Technology, Politecnico di Torino, I-10129 Torino, Ital…
INFN Sezione di Torino, I-10126 Torino, Italy
…3 October 2013; published 25 February 2014)

PHYSICAL REVIEW C 89, 025803 (2014)

Effects of fermionic dark matter on properties of neutron stars

…iang,[1,2] Wei-Zhou Jiang,[1,3,4,*] Dong-Rui Zhang,[1] and Rong-Yao Yang[1]
…ent of Physics, Southeast University, Nanjing 211189, China
…Physics, Chinese Academy of Sciences, Beijing 100049, China
…Heavy Ion Accelerator, Lanzhou 730000, China
…e Physics, University of California, Santa Cruz, California 95064, USA
…16 November 2013; published 13 February 2014)

…w hyperon equations of state for supernovae and
in density dependent hadron field th…

Sarmistha Banik
…BITS Pilani, Hyderabad Campus, Hyde…
Matthias He…
…tement Physik, Universit…
…el, …
Astropart…

PHYSICAL REVIEW D 89, 063003 (2014)

What does a measurement of mass and/or radius of a neutron star constr…
Equation of state or gravity?

Kazım Yavuz Ekşi,* Can Güngör, and Murat Metehan Türkoğ…
Istanbul Technical University, Faculty of Science and Letters, Department o…
34469 Maslak, Istanbul, Turkey
(Received 29 November 2013; published 6 March 2014)

PHYSICAL REVIEW D 85, 084020 (2012)

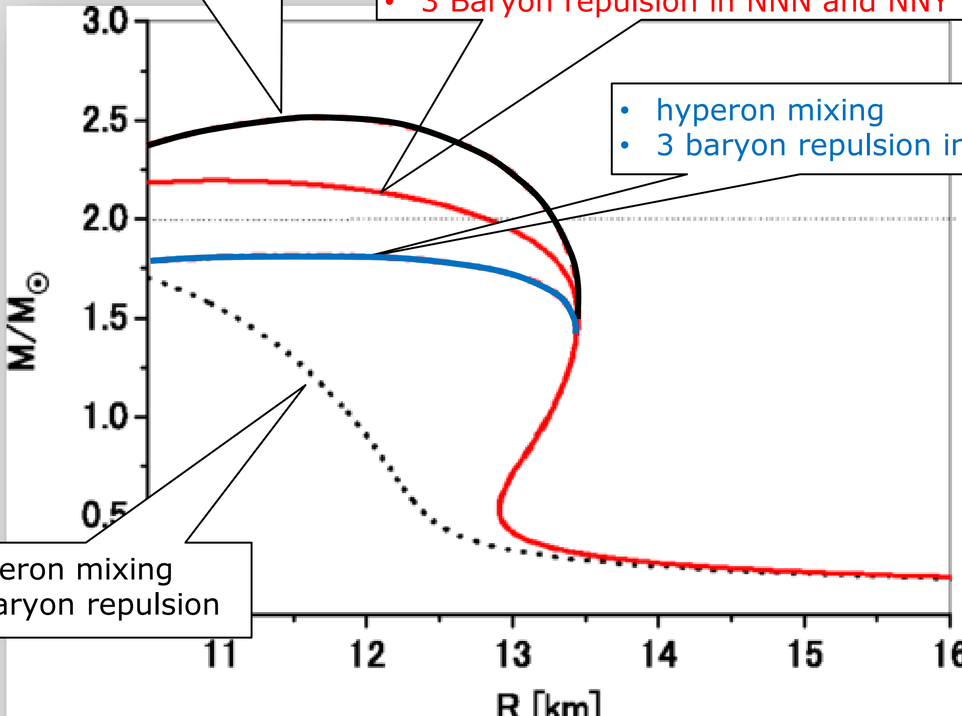
Eddington-inspired Born-Infeld gravity: Phenomenology of nonlinear gravity-matter coup…

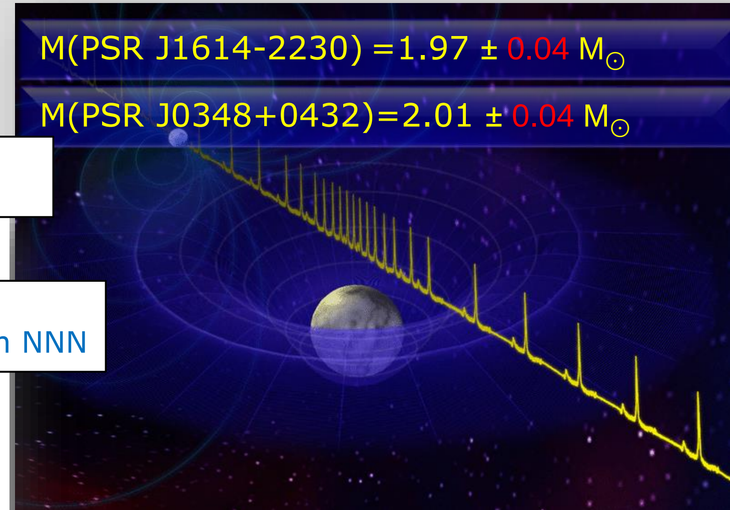
Paolo Pani,[1] Térence Delsate,[1,2] and Vitor Cardoso[1,3]
[1]CENTRA, Departamento de Física, Instituto Superior Técnico, Universidade Técnica de Lisboa—UTL,
Av. Rovisco Pais 1, 1049 Lisboa, Portugal
[2]Theoretical and Mathematical Physics Dept., Université de Mons, UMons, 20, Place du Parc 7000 Mons, Belgiu…
[3]Department of Physics and Astronomy, The University of Mississippi, University, Mississippi 38677, USA
(Received 17 January 2012; published 19 April 2012)

…el, Switzerland
…ndia … of Nuclear Physi…

The Hyperon Puzzle…

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





- model constrained by terrestrial experiments
- universal many-body repulsion
- no ad hoc parameter to stiffen EOS

Yamamota (HYP2015):

"Including 3- and 4-body repulsions leads to massive neutron stars with $2M_\odot$ in spite of significant softening of EOS by hyperon mixing"….

"Hyperon puzzle is a quantitative problem"

Hypernuclear Activities

Tools
- Heavy Ion beams
- Electron beams
- Photon beams
- Meson beams
- Antiproton beams

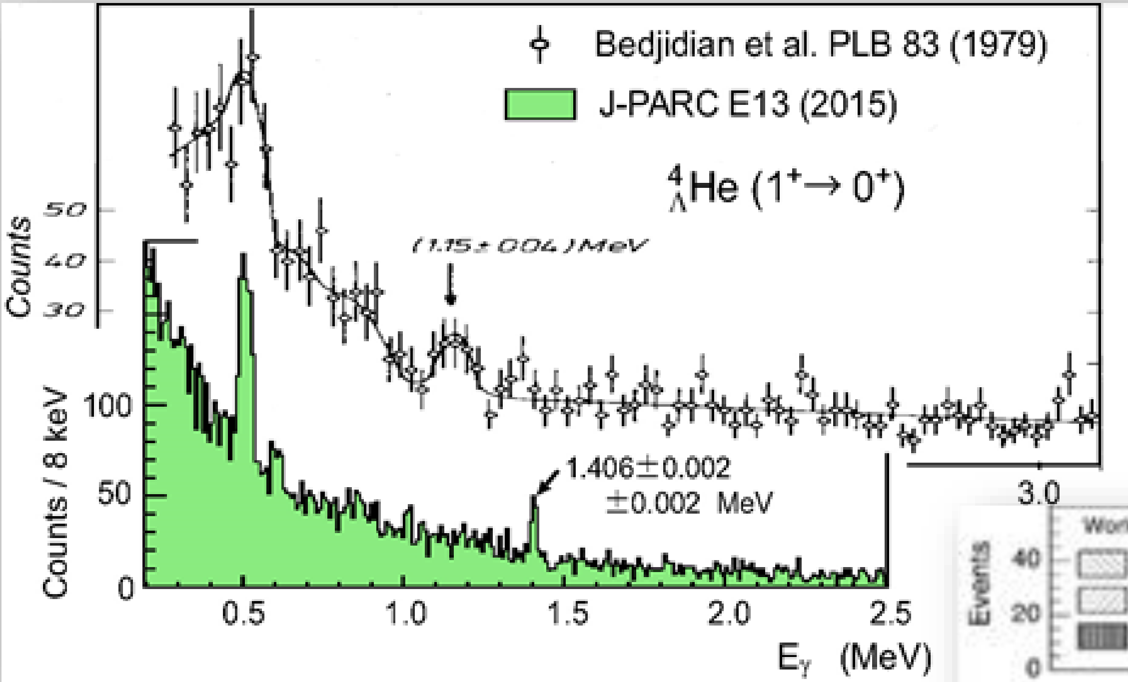
Methods
- Invariant mass studies
- Missing mass studies
- γ-spectroscopy
- π-spectroscopy

Observables
- Masses
- Excitation spectrum
- Lifetimes

PART 1

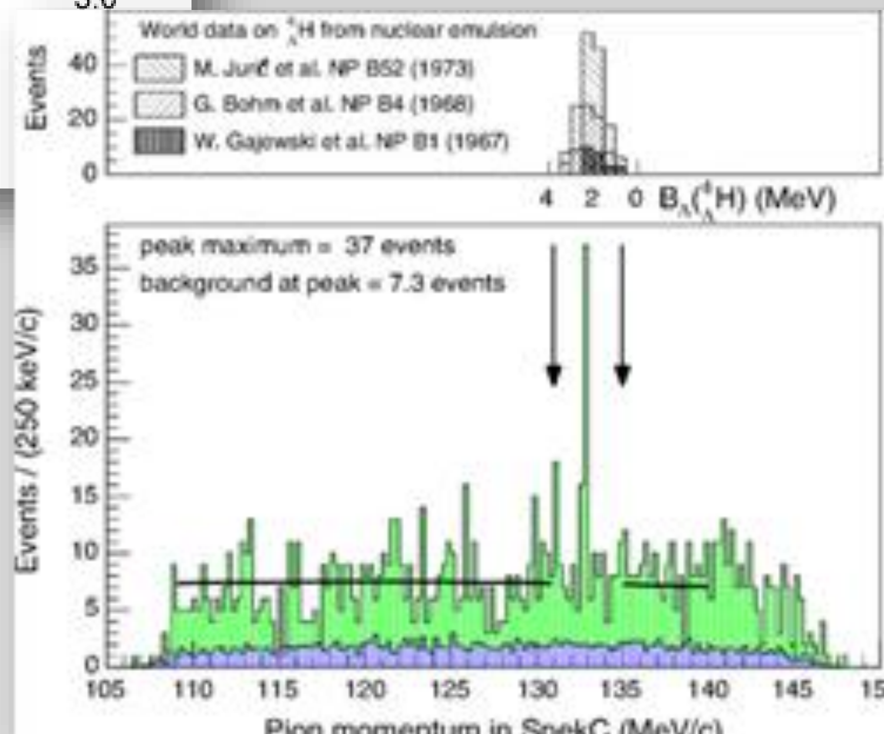
PRECISSION STUDIES OF Λ HYPERNUCLEI

Success of novel Techniques



Phys. Rev. Lett. **114**, 232501 (2015)

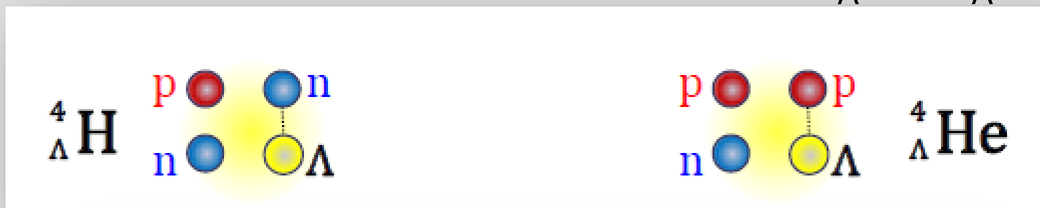
Phys. Rev. Lett. **115**, 222501 (2015)

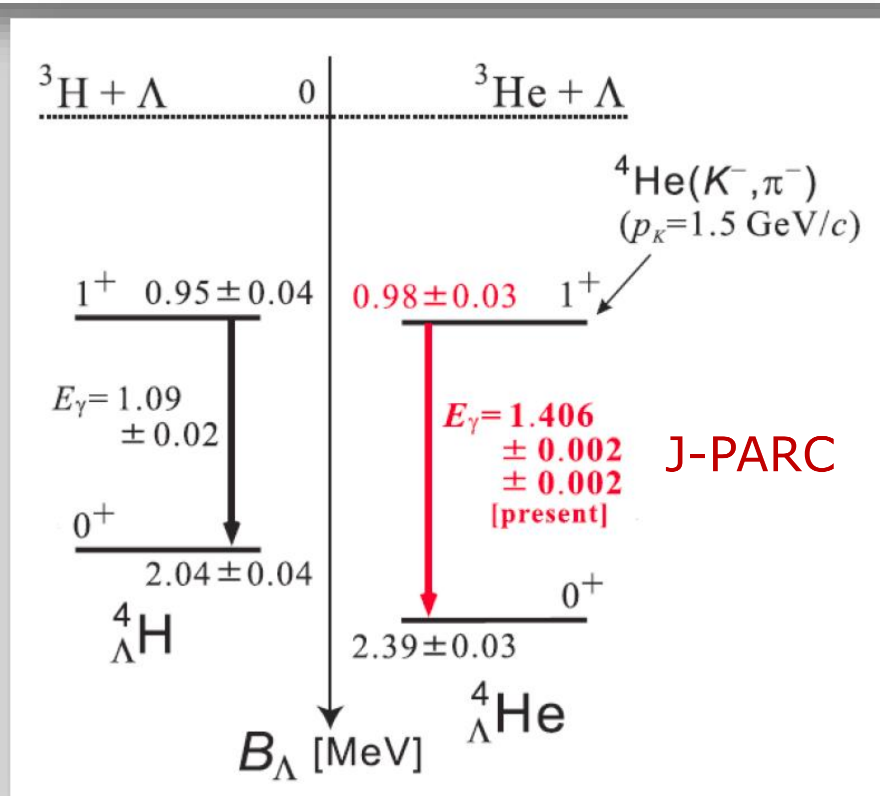


- Demonstrates the need for complementary experiments

Charge Symmetry Breaking

- CSB for NN interactions is 70 keV in the mirror nuclei ^{3}H and ^{3}He
- Coulomb corrections are < 50 keV for the $^4_\Lambda$H - $^4_\Lambda$He pair

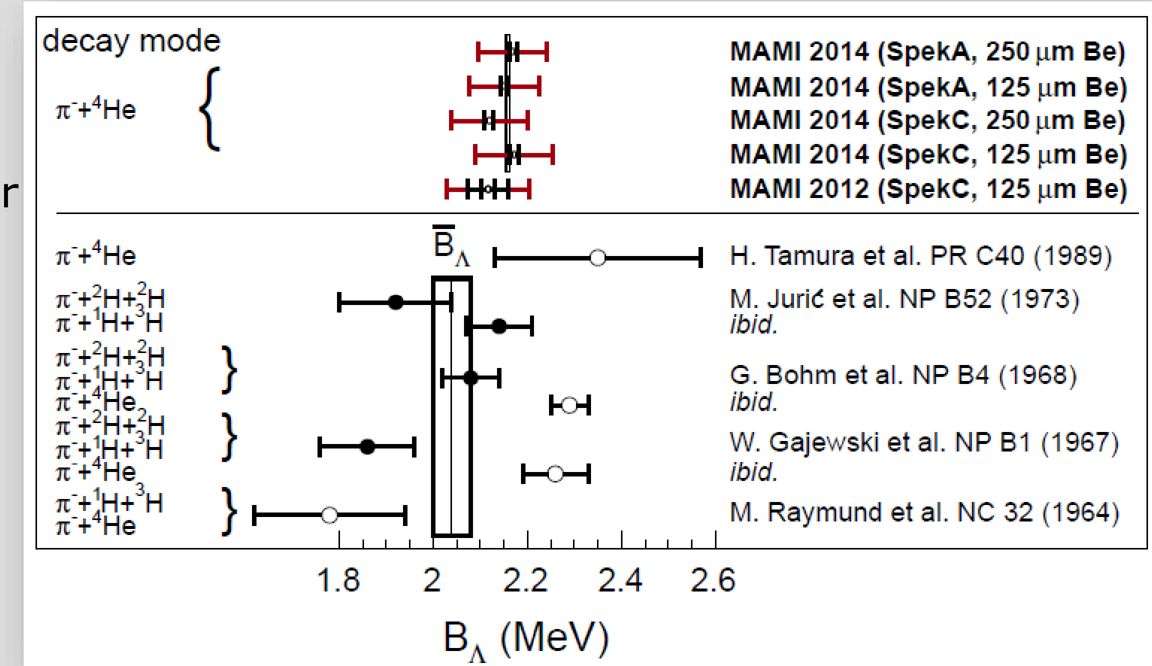




- strong, spin-dependent charge symmetry breaking (CSB) in A = 4 mirror hypernuclei !

Continuation of Experiment in 2014

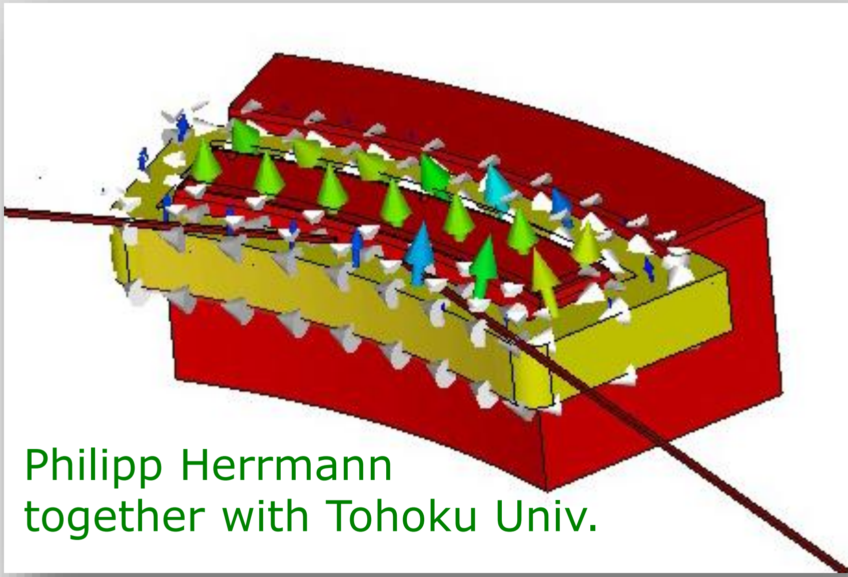
- Many inmprovements
  - better pion rejection by improved aerogel
  - suppression of background by improved shielding
  - suppression of background by trigger upgrade in SpekA & C
  - suppression of background by beam-line upgrade
  - dedicated collimator for decay region
  - better control of magnet field variations
  - full overlap of SpekA and SpekC momentum acceptance



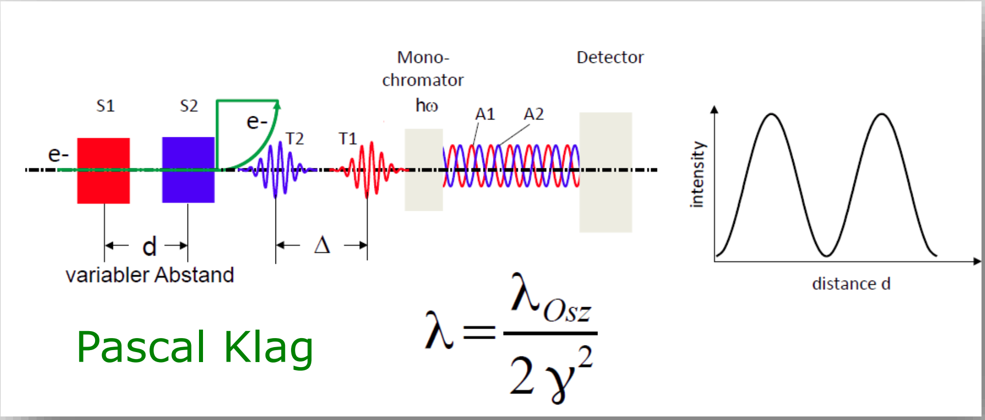
- independent measurement in two spectr., two targets, two beam-times
- consistent result for $B_\Lambda({}^4_\Lambda H)$ from MAMI 2012 and MAMI 2014

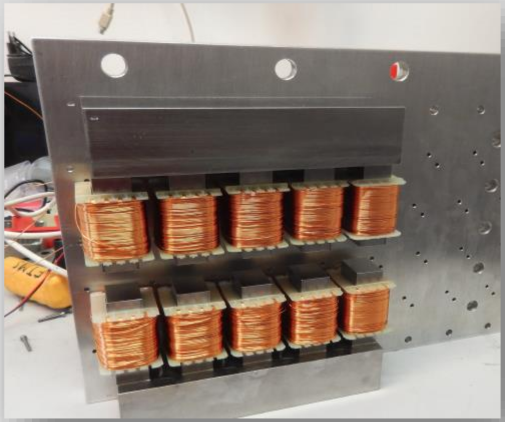
Reducing the systematic error

- two options to measure MAMI energy $O(10^{-4})$
  - measuring the absolute MAMI enery in a precisely calibrated magnet



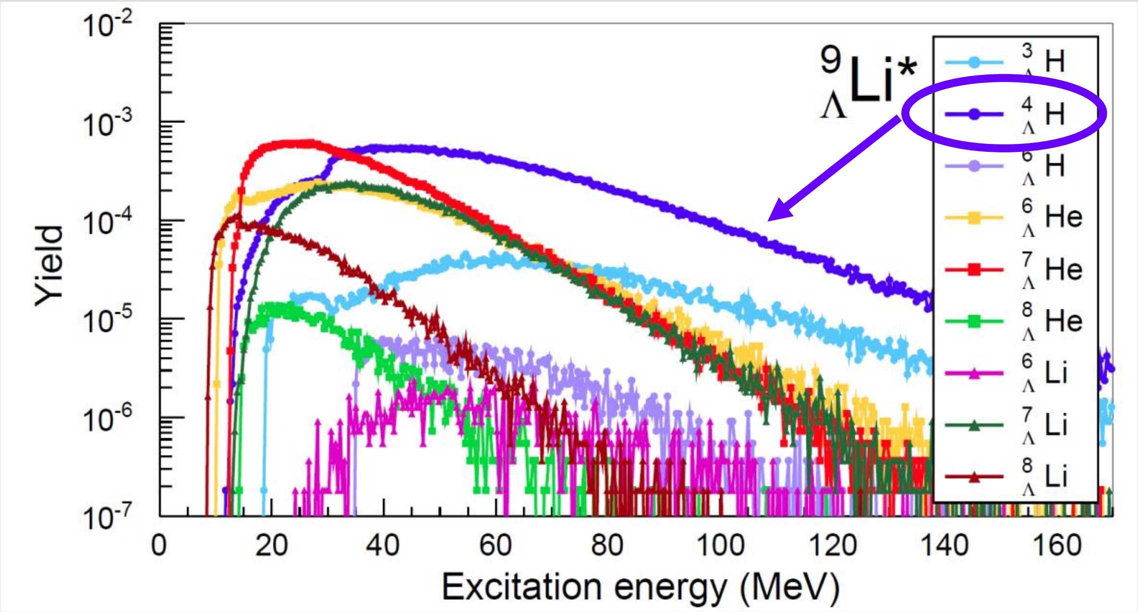
  - Interference of undulator radiation





Why no other Hypernuclei?

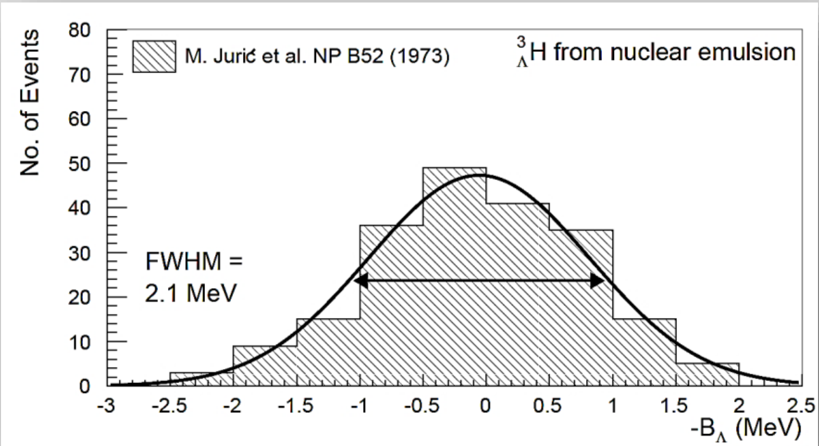
- Statistical decay calculations were performed
- Scenario 1: direct production of ${}^{9}_{\Lambda}\mathrm{Li}^*$

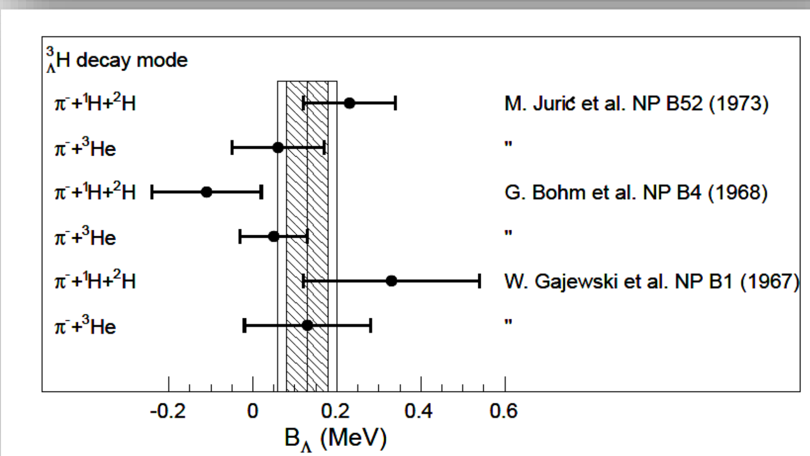


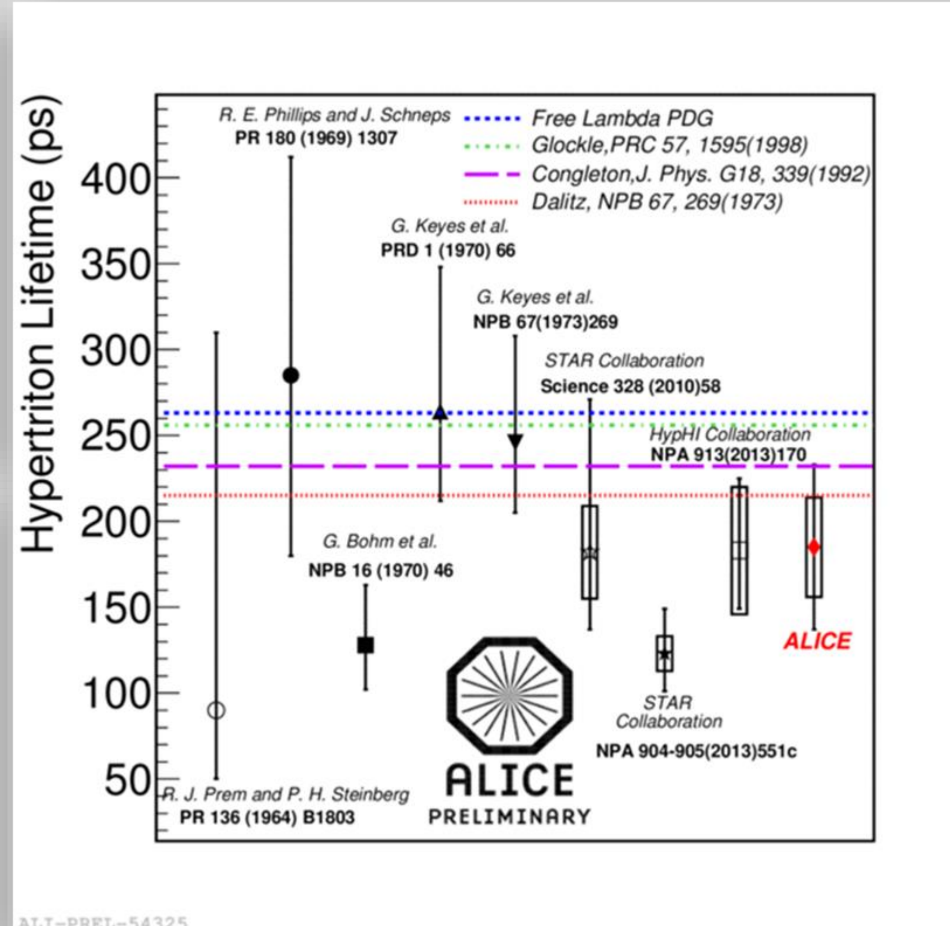
- Expected excitation energy
  - convert proton into $\Lambda \Rightarrow$ proton hole state ~ 20 MeV
  - kinetic energy of captured Λ $p_{FERMI}^2/2M_\Lambda$ ~ 20 MeV
  - Binding energy of Λ ~ 10 MeV
- at E_x~50 MeV ${}^{4}_{\Lambda}\mathrm{H}$ most probable and other nuclei more than factor 3 less likely produced
- similar for nucleon knock-out scenario

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

- Small B_Λ (from about 200 analyzed events from emulsion)





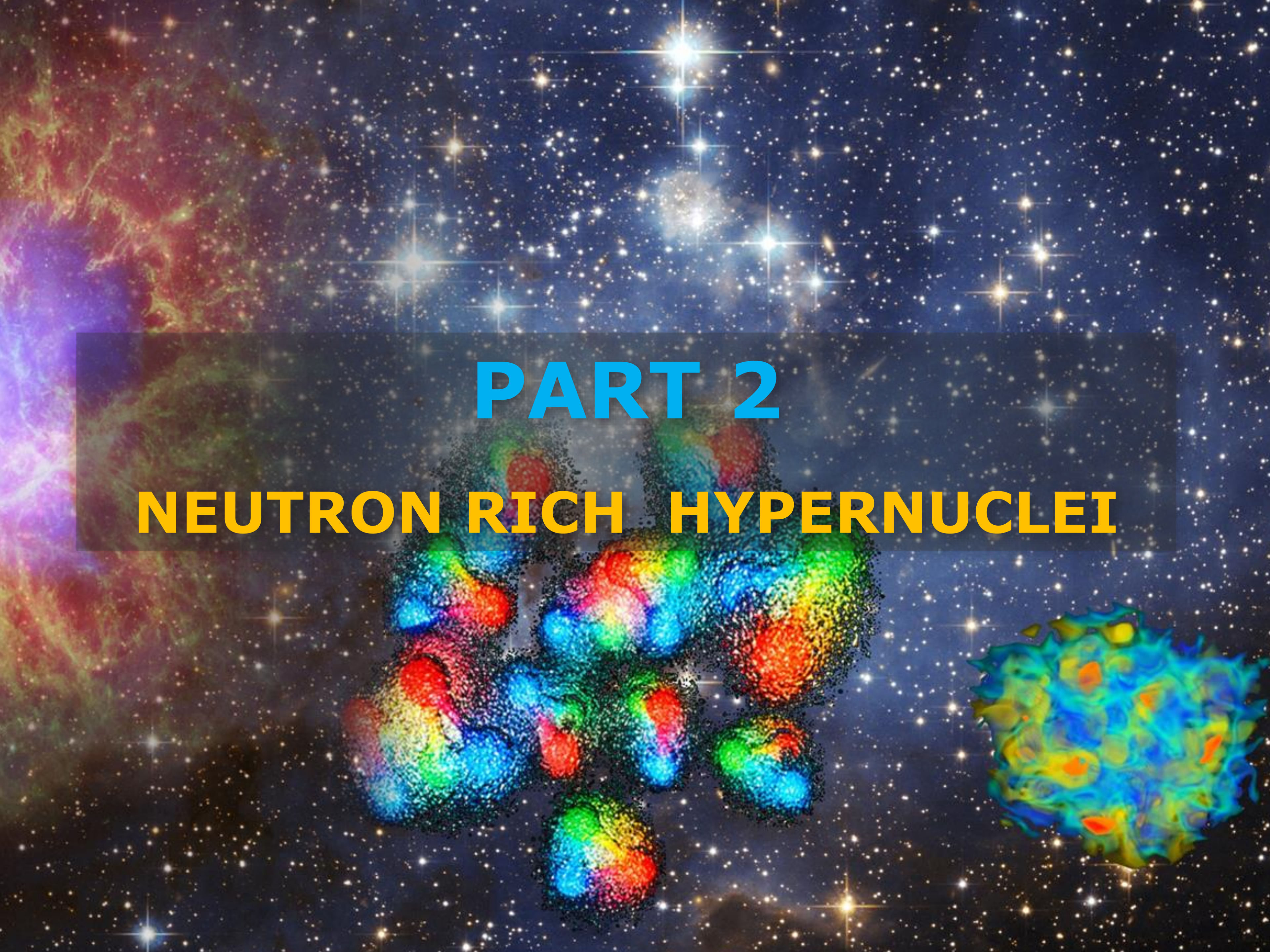


Achenbach, Pochodzalla, Schulz (PANIC 2014)

…and Lifetime surprisingly small

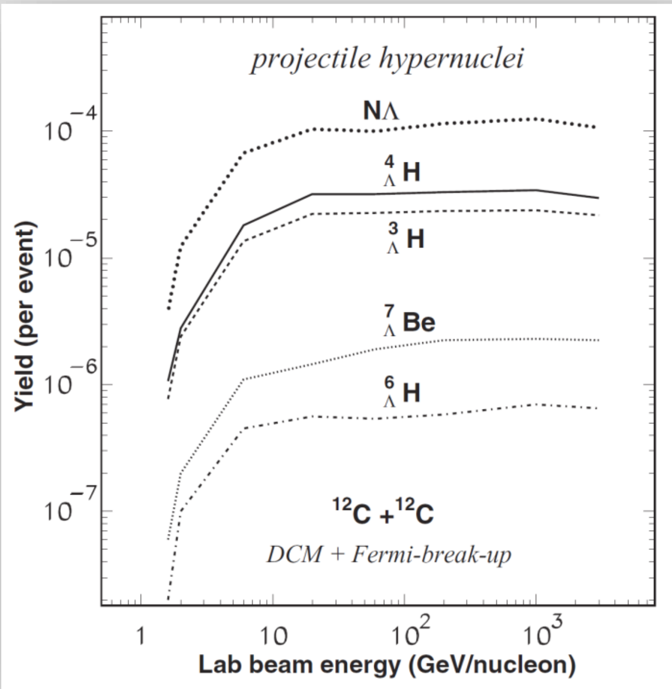
PART 2

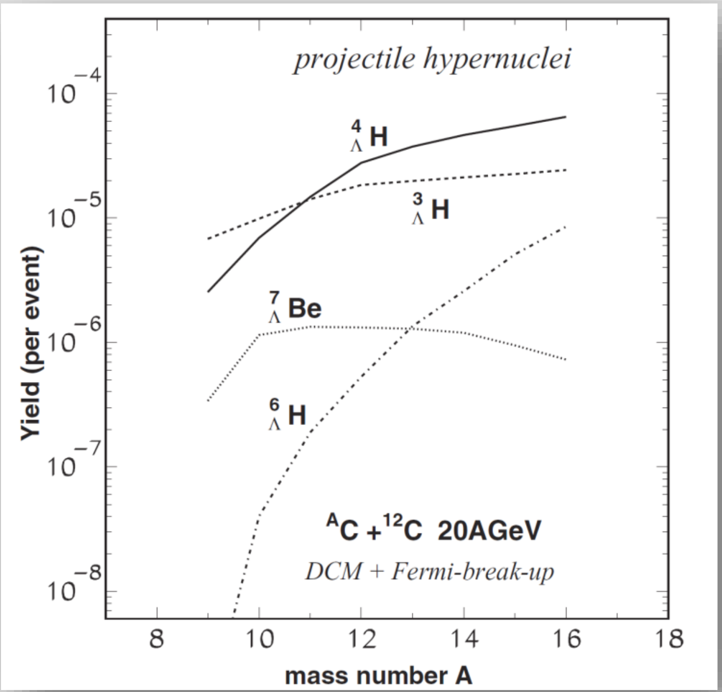
NEUTRON RICH HYPERNUCLEI



Neutron rich nuclei

- Light nuclei
  - meson induced reactions → spectroscopy
  - projectile fragmentation like HYPHI, SuperFRS with exotic beams → lifetime





Botvina, Gudima, Pochodzalla PRC 88 (2013)

- Heavy neutron rich nuclei using exotic targets
  - electron beams and ^{40}Ca, ^{48}Ca → spectroscopy
  - fragmentation- fission → lifetime

Photoinduced Hyperfission

- First experiment done at J-Lab (L. Tang); analysis not finalized
- Observed: two fragment with $Z \geq 6$
- decay time relative to beam nano time structure

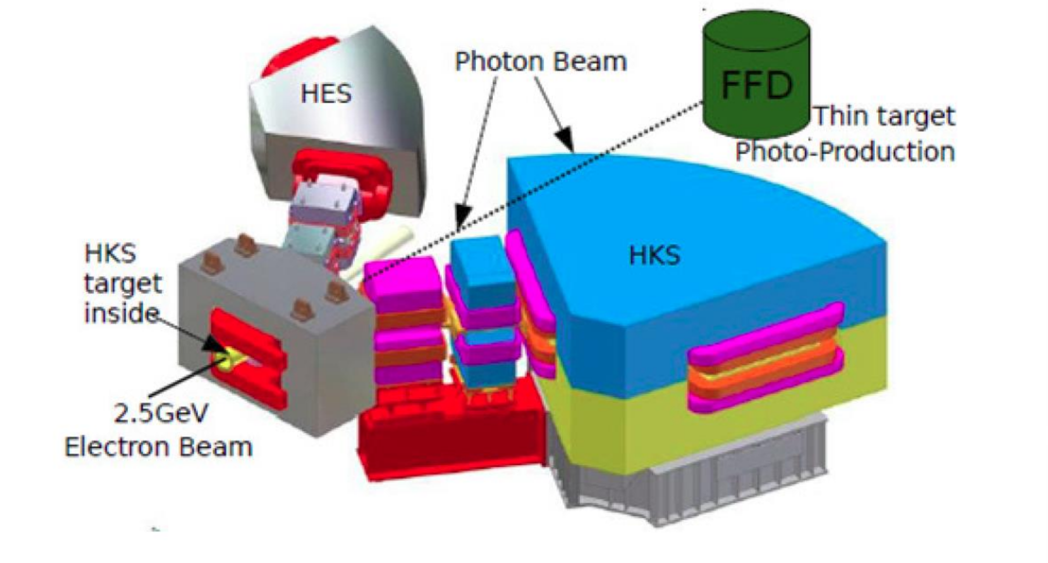


FIG. 2. The experimental setup of E05-115 and E02-017 in Hall C at JLab.

- Targets Fe, Cu, Ag, Bi, (Au, U) simultaneously

  $\Rightarrow$ some systematic errors cancel

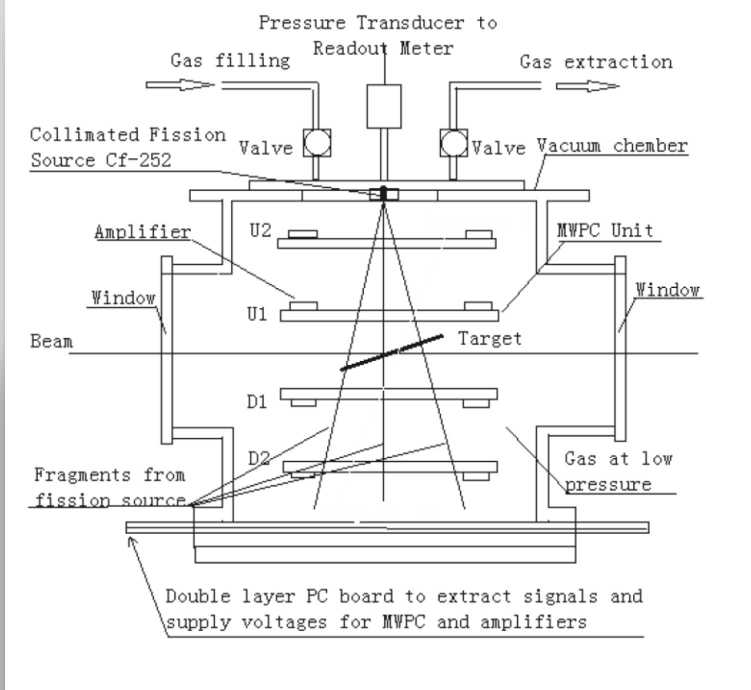
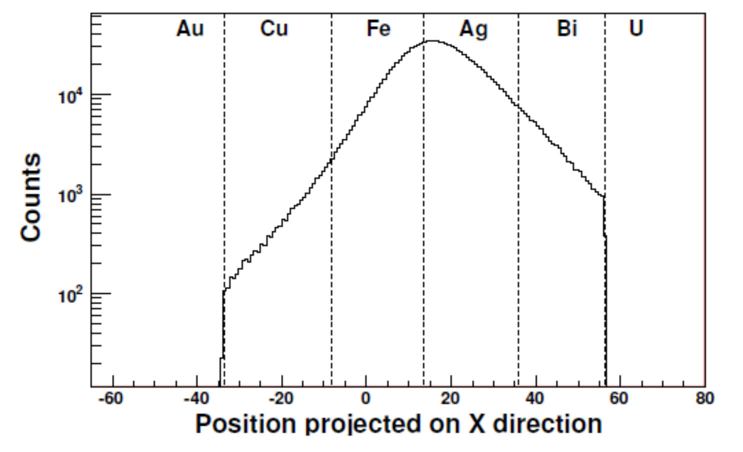
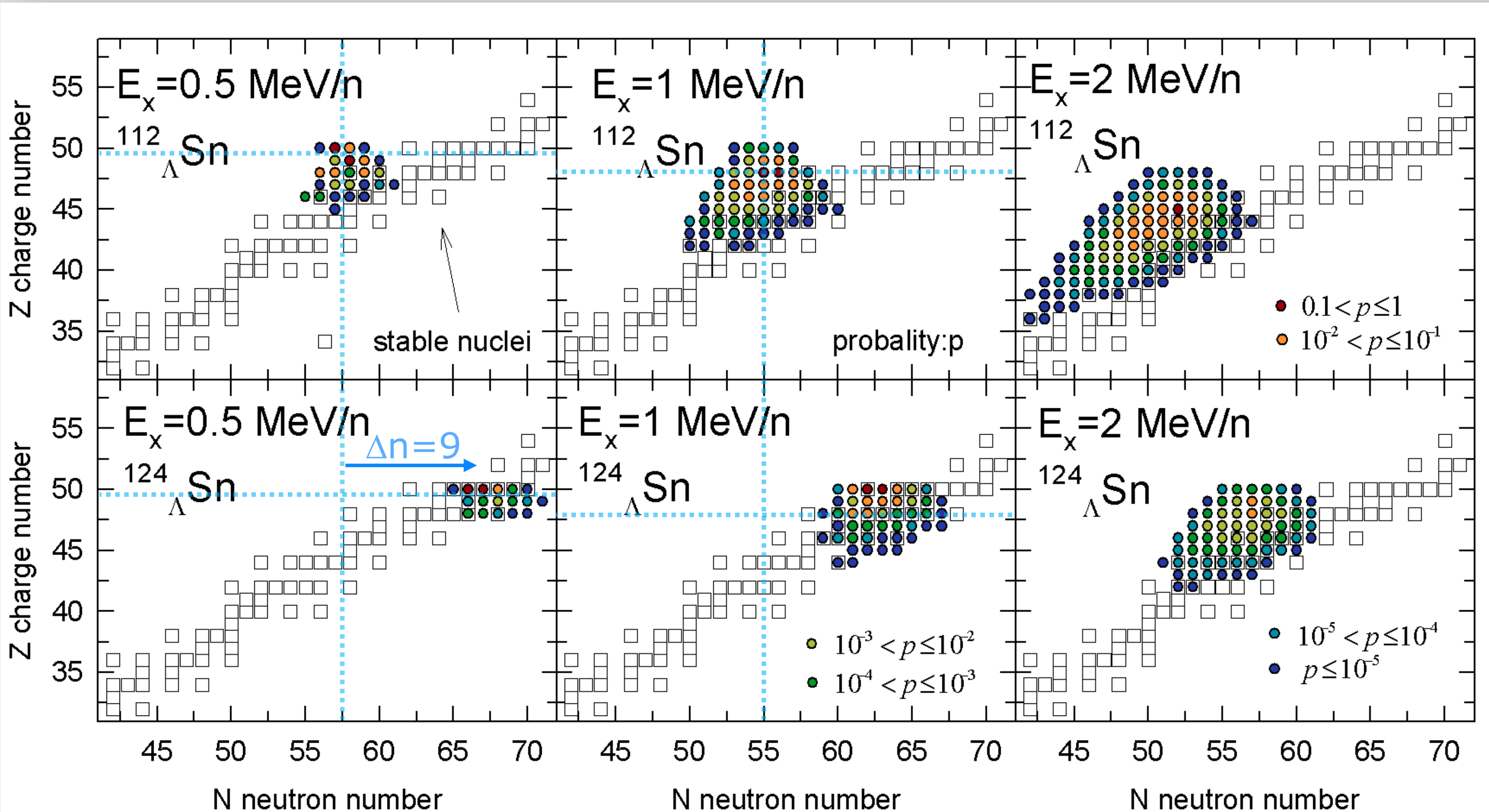


FIG. 1. Schematic sketch of the fission fragment detector (FFD) [20].



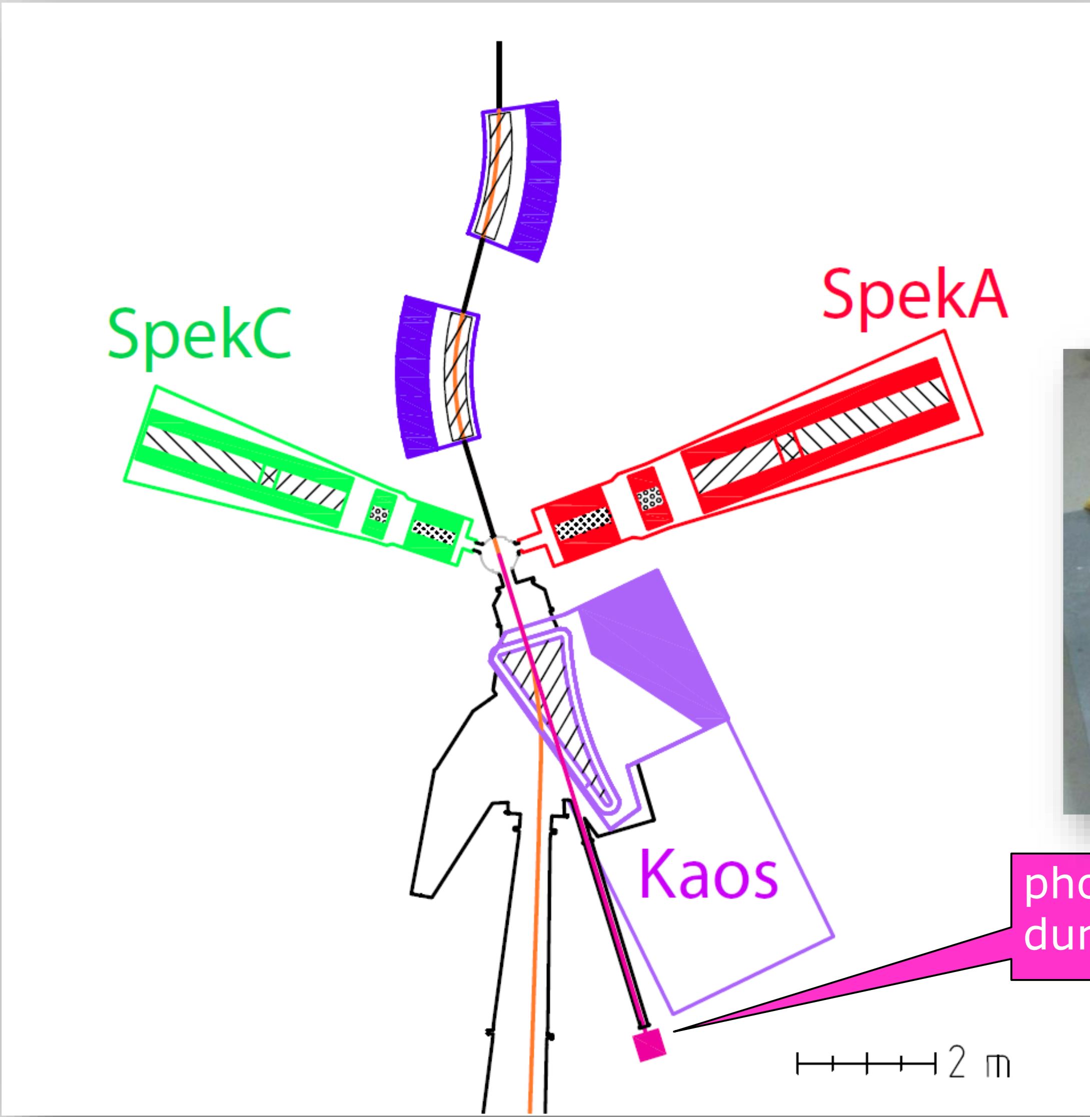
WD induced fragmentation

- expected excitation energy as before ~1MeV/nucleon
- produced hyperresidues reflect N/Z of target



Nihal Byukcizmeci *et al.*

Possible setup at A1

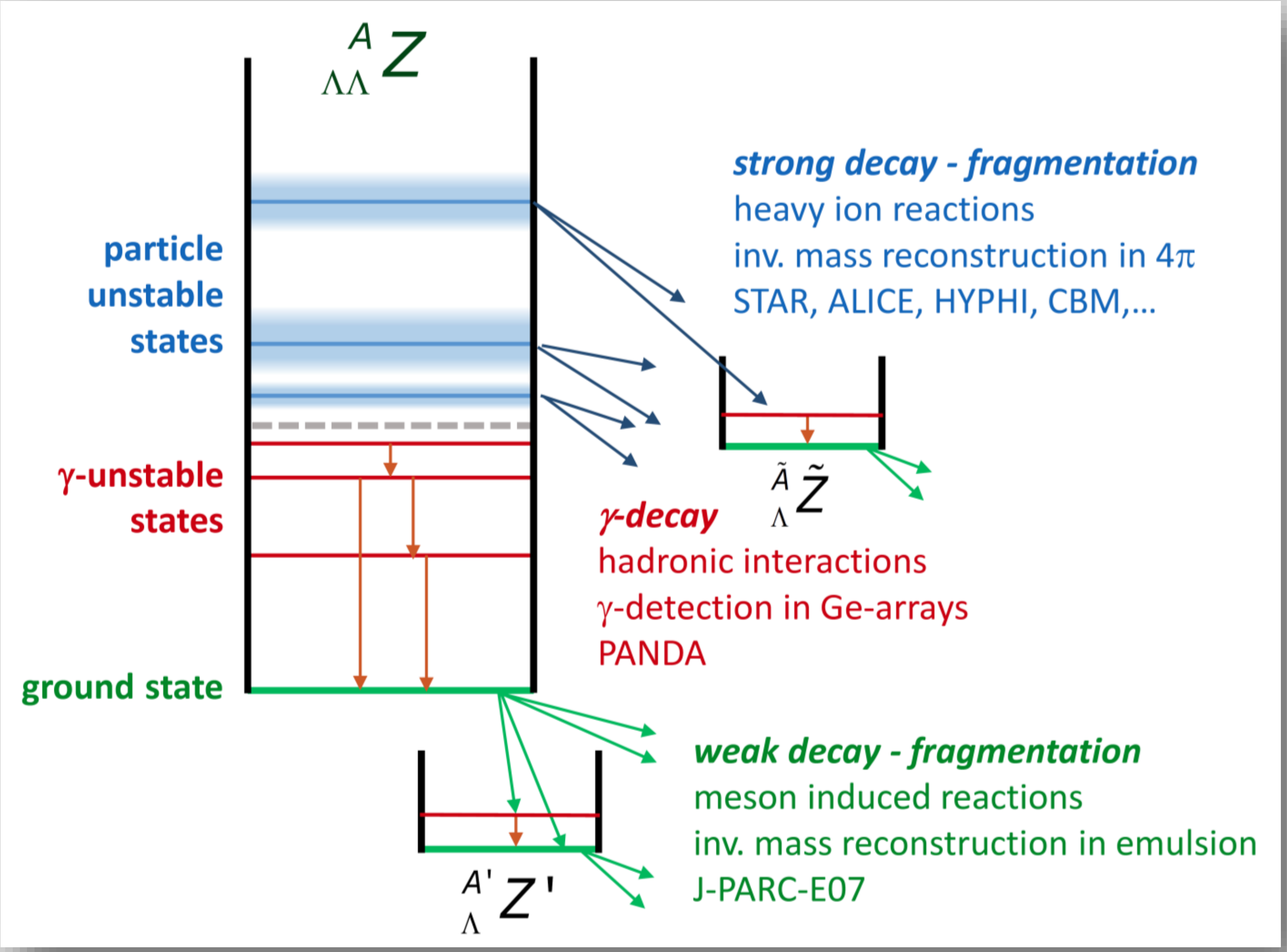


PART 3

S=-2 SYSTEMS

S=-2 systems

- missing mass (K^-,K^+) reactions ⇒ Ξ bound state J-PARC
- Ξ capture ⇒ Ξ atoms J-PARC, FAIR
- Ξ capture and $\Xi^- p \rightarrow \Lambda\Lambda$ ⇒ ΛΛ hypernuclei J-PARC, FAIR,HI



Strange Systems at PANDA

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

rescattering in
primary target nucleus

deceleration in
secondary target

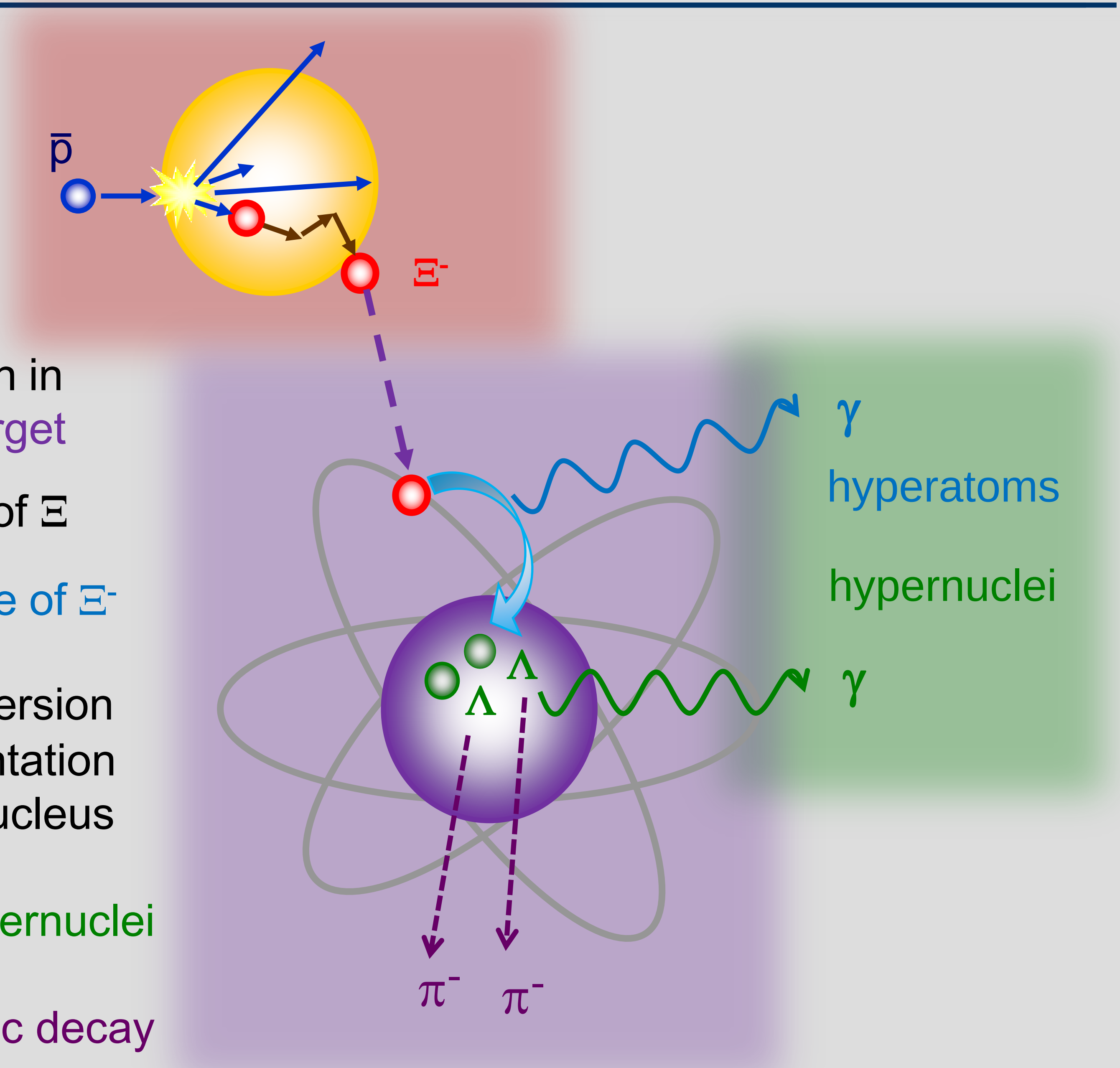
capture of Ξ

atomic cascade of Ξ^-

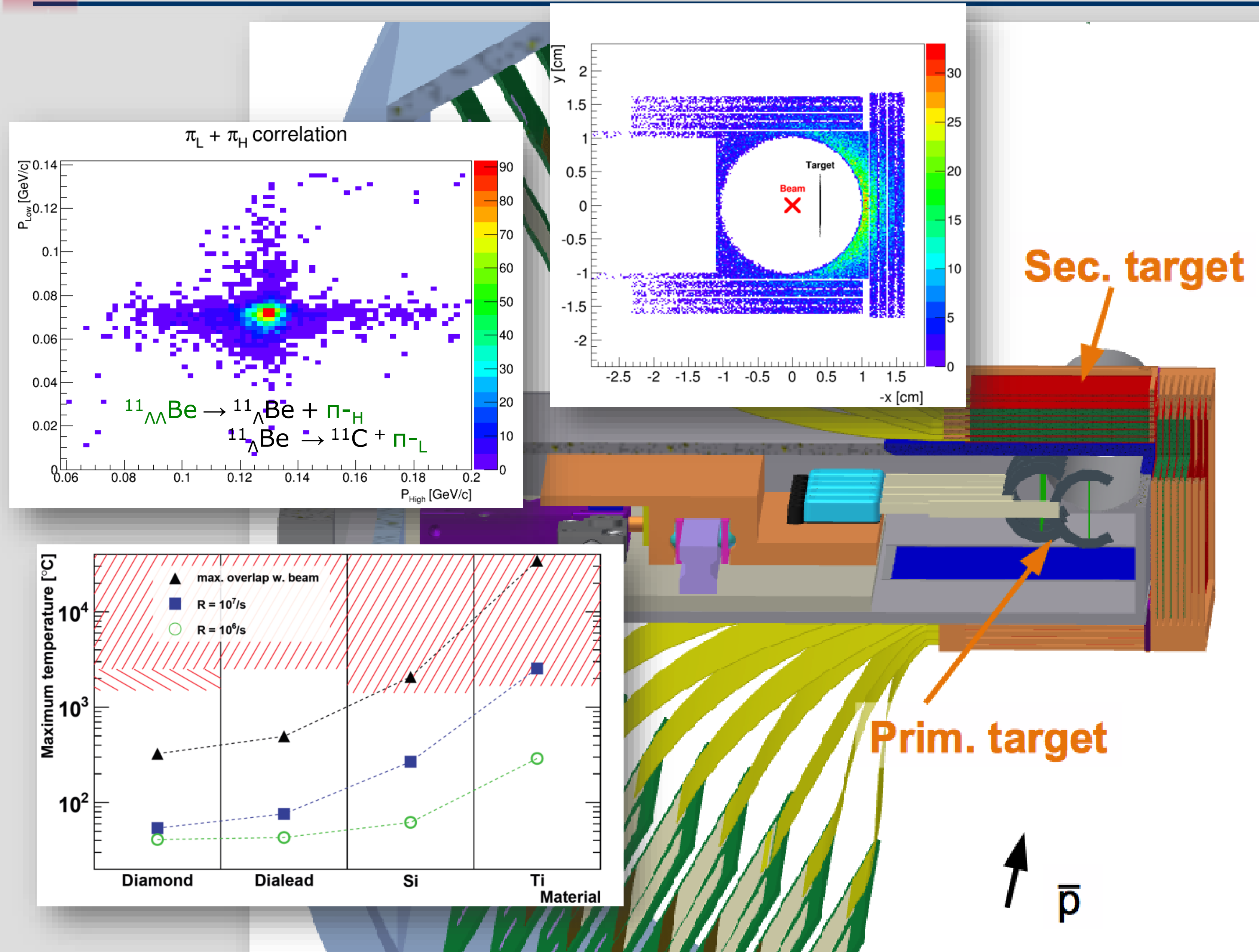
$\Xi^- p \rightarrow \Lambda\Lambda$ conversion
fragmentation
$\rightarrow$ excited $\Lambda\Lambda$-nucleus

γ-decay of $\Lambda\Lambda$ hypernuclei

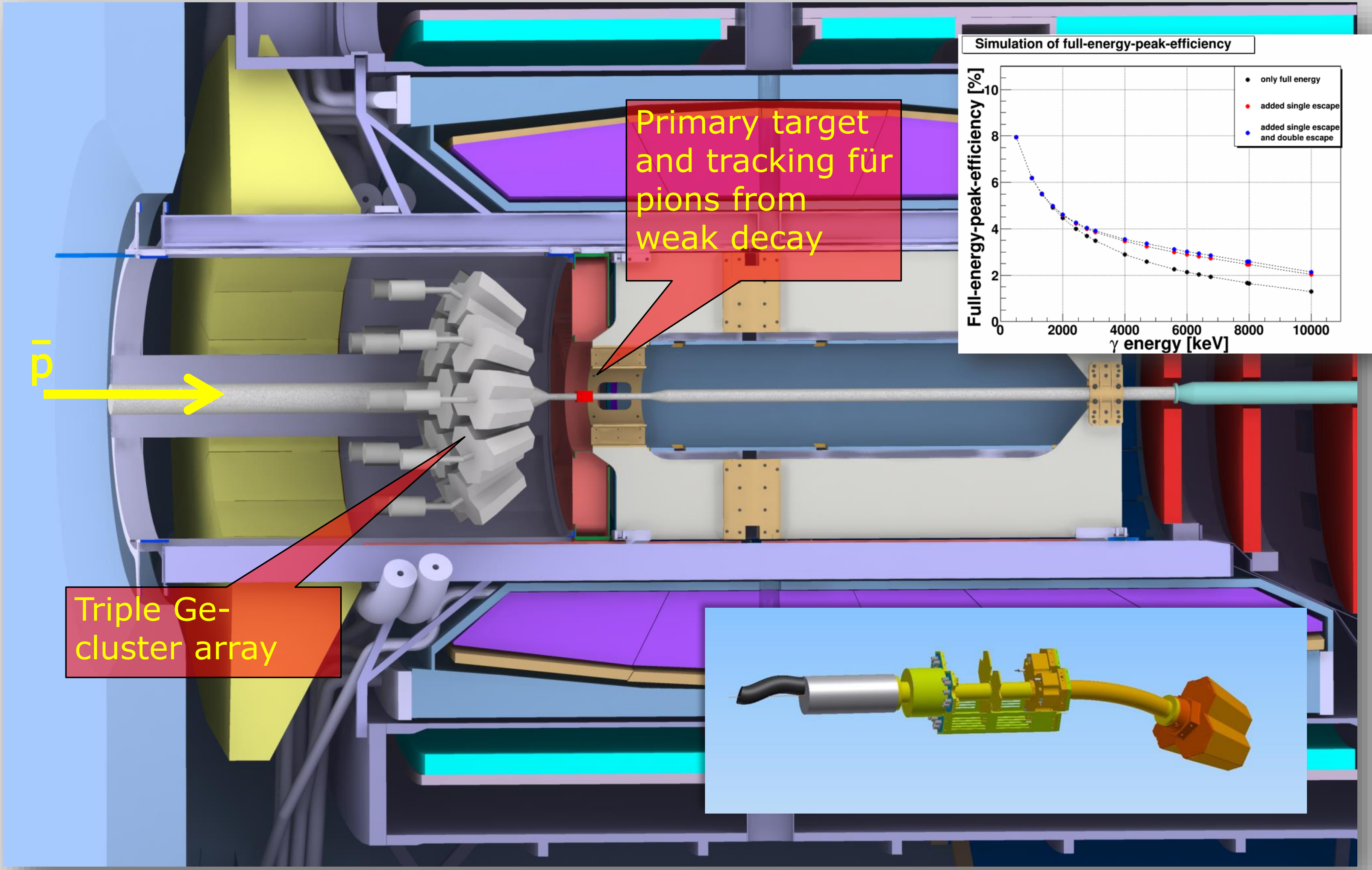
weak pionic decay

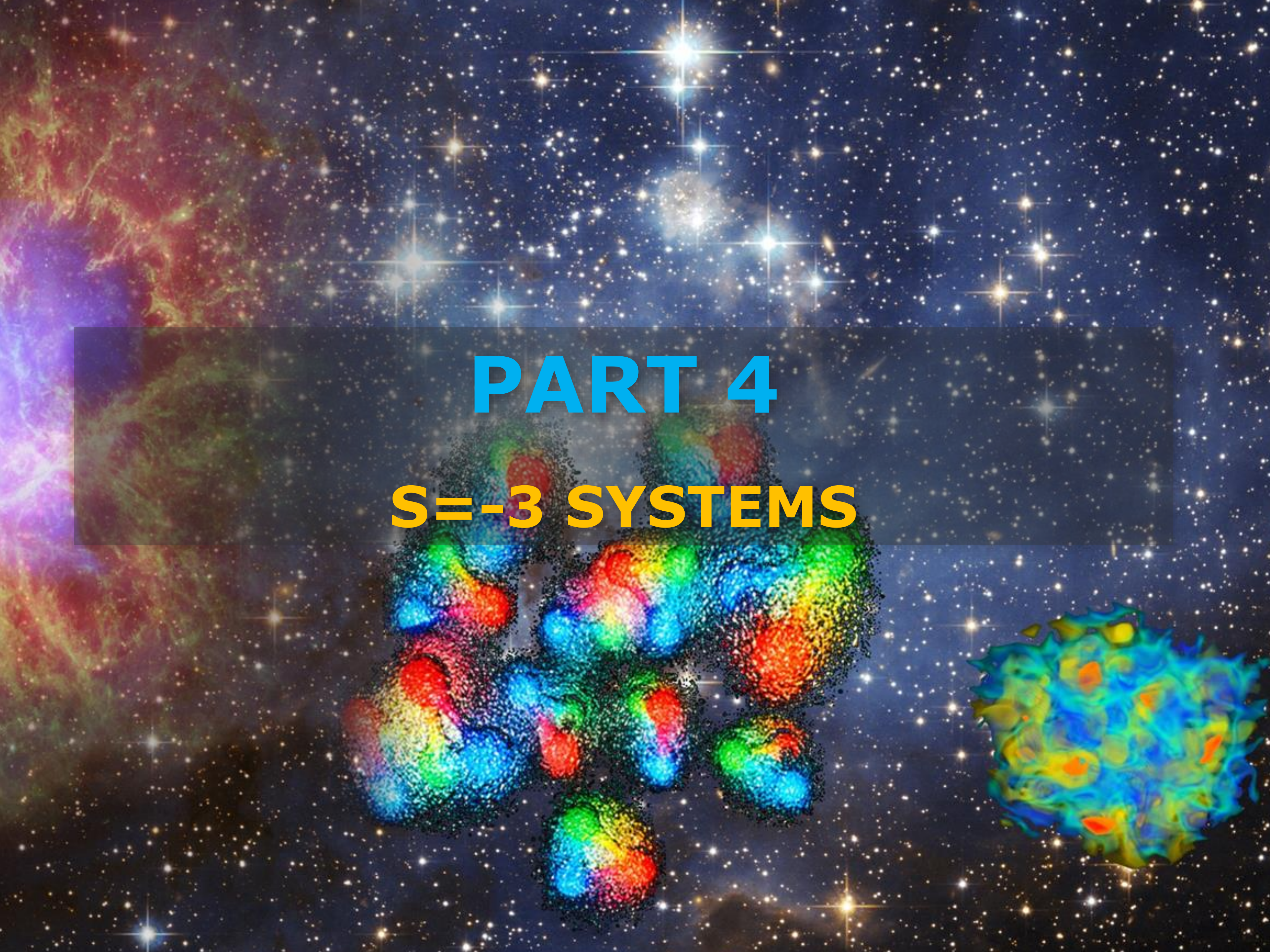


Primary and secondary targets



The HYP setup at PANDA





PART 4

S=-3 SYSTEMS

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

PHYSICAL REVIEW D VOLUME 8, NUMBER 3 1 AUGUST 1973

Certification of Three Old Cosmic-Ray Emulsion Events as Ω^- Decays and Interactions

Luis W. Alvarez
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 10 April 1972; revised manuscript received 3 May 1973)

In the "pre-accelerator years," when large stacks of emulsion were exposed to cosmic rays at high altitude, three events were found in which K^- mesons were emitted from slowly moving particles. The Ω^- is the only presently known particle that can give rise to a K^- when moving at nonrelativistic speed, but none of the three events has until now been clearly identified as an Ω^-. One of the cosmic-ray events (Eisenberg, 1954) has been incorrectly interpreted as an Ω^- decaying in flight; it is now shown to be an interaction in flight of an Ω^- with a silver nucleus. The second event is a clear-cut example of an Ω^- decaying in orbit, bound to an emulsion nucleus. The third event is quite complicated, but can be unambiguously attributed to the decay of an Ω^- atomically bound to an N^{14} nucleus, followed by a collision of the daughter Λ with the N^{14}, in which the compound system then fragments into ${}_{\Lambda}C^{13} + p + n$. The mass of the Ω^- as determined by each of the last two events (Fry *et al.*, 1955) agrees closely with the mean of all bubble-chamber events.

- Note: in nuclei secondary processes possible

$$\bar{p} + n \to \bar{\Xi}^- + \Xi^0 \qquad \Xi^0 + X \to \Omega^- + K^+ + X$$

$$\bar{p} + p \to \bar{\Xi}^- + \Xi^- \qquad \Xi^- + X \to \Omega^- + K^0 + X$$

…seen in emulsions ~10 years prior to the „discovery" at Brookhaven

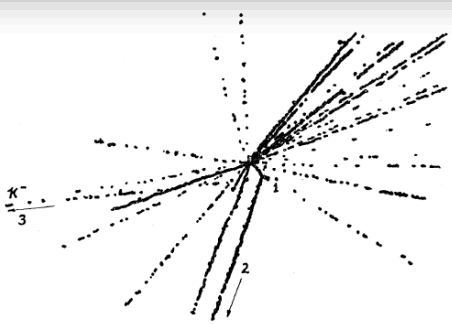
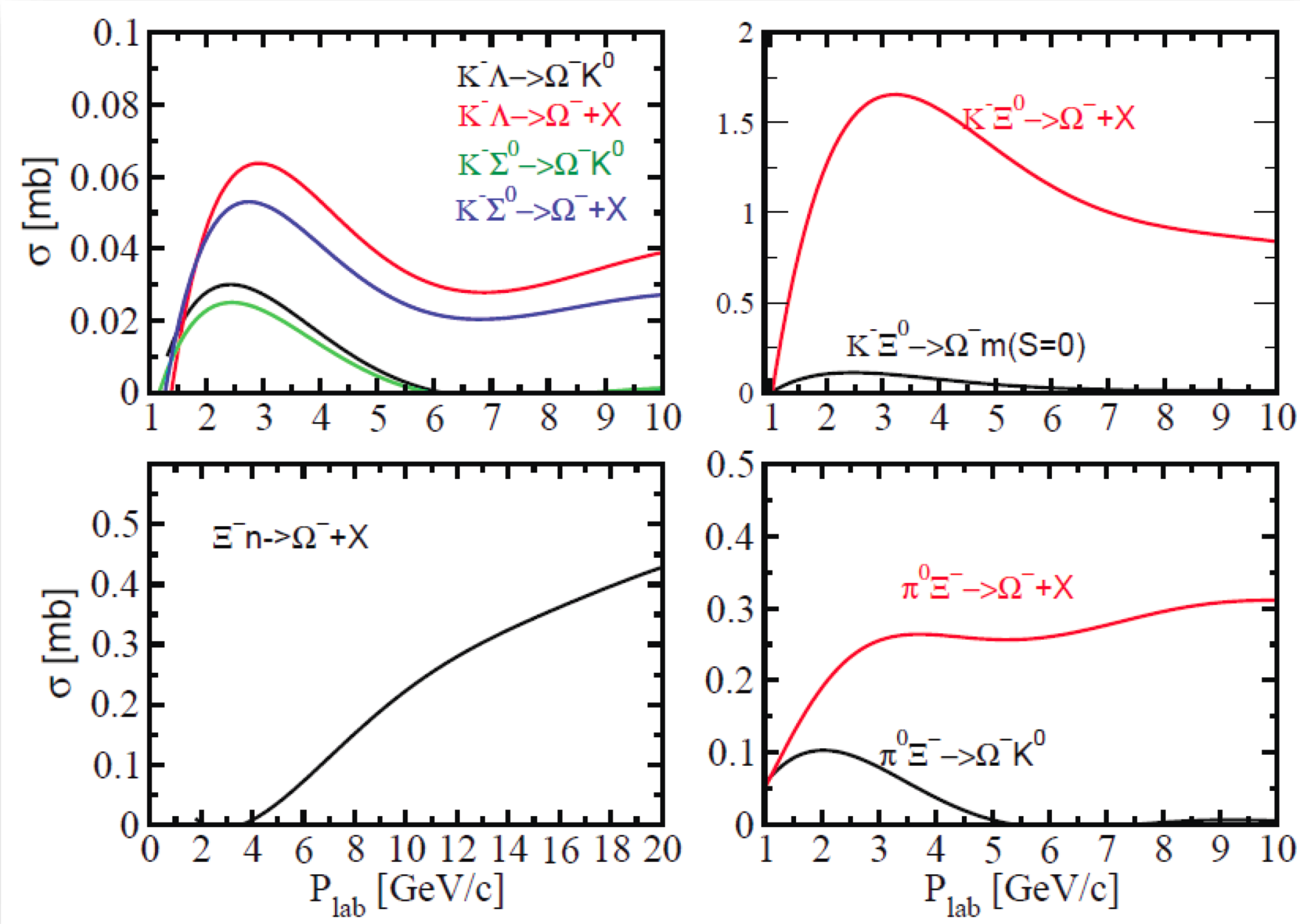


FIG. 1. A projection drawing of the K-mesonic decay of a slow particle is shown above. Track 1 is a short recoil. Track 2 was produced by a particle of $Z=1$. Track 3 was produced by a negative K-meson. A few tracks of particles from the primary star which are in the same direction as the connecting track, but at a different depth, were omitted from the drawing for the sake of clarity.

…in-medium Ω⁻ production at J-PARC ?



H. Lenske *et al., proceedings HYP 2015*

The Ω - the known unknown

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

$\Omega(2250)^-$ $I(J^P) = 0(?^?)$ Status: ***

$\Omega(2250)^-$ MASS

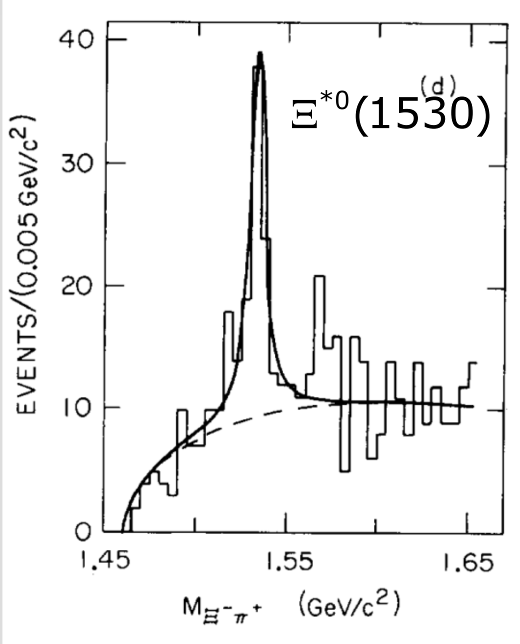
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2252± 9 OUR AVERAGE					
2253±13	44	ASTON	87B	LASS	$K^- p$ 11 GeV/c
2251± 9±8	78	BIAGI	86B	SPEC	SPS Ξ^- beam

$\Omega(2380)^-$ Status: **

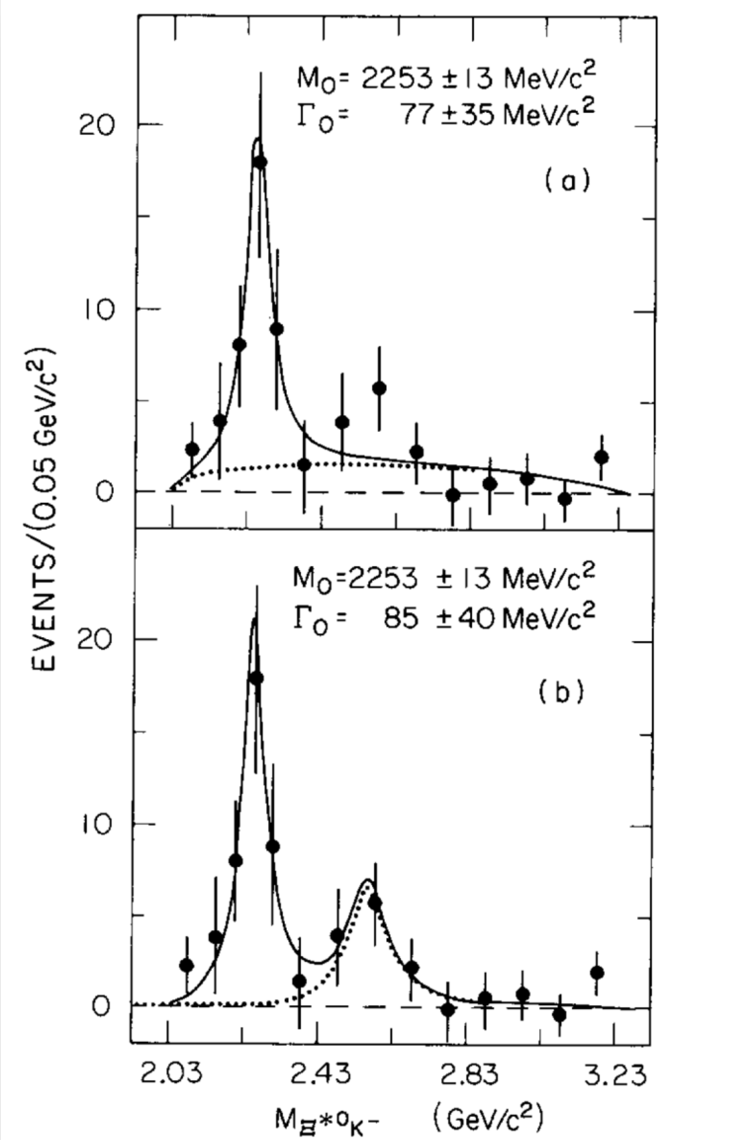
OMITTED FROM SUMMARY TABLE

$\Omega(2380)^-$ MASS

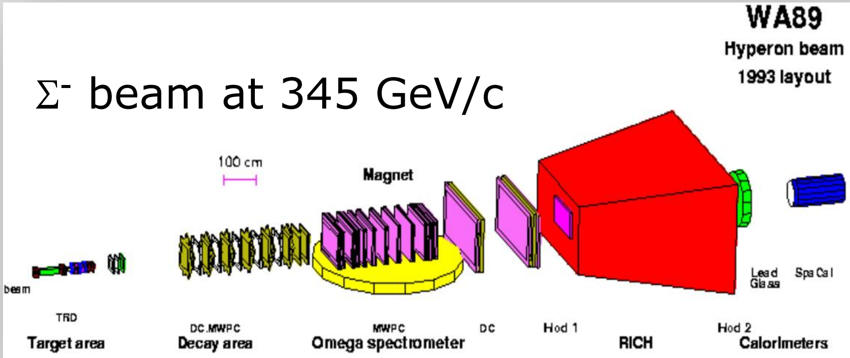
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
≈ 2380 OUR ESTIMATE					
2384±9±8	45	BIAGI	86B	SPEC	SPS Ξ^- beam

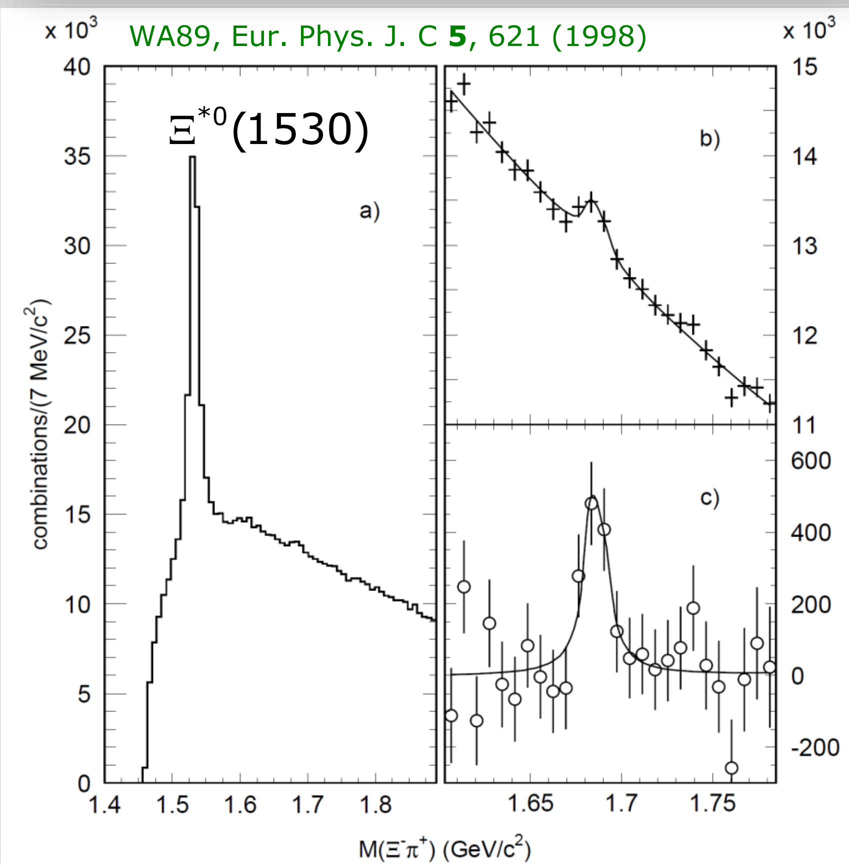


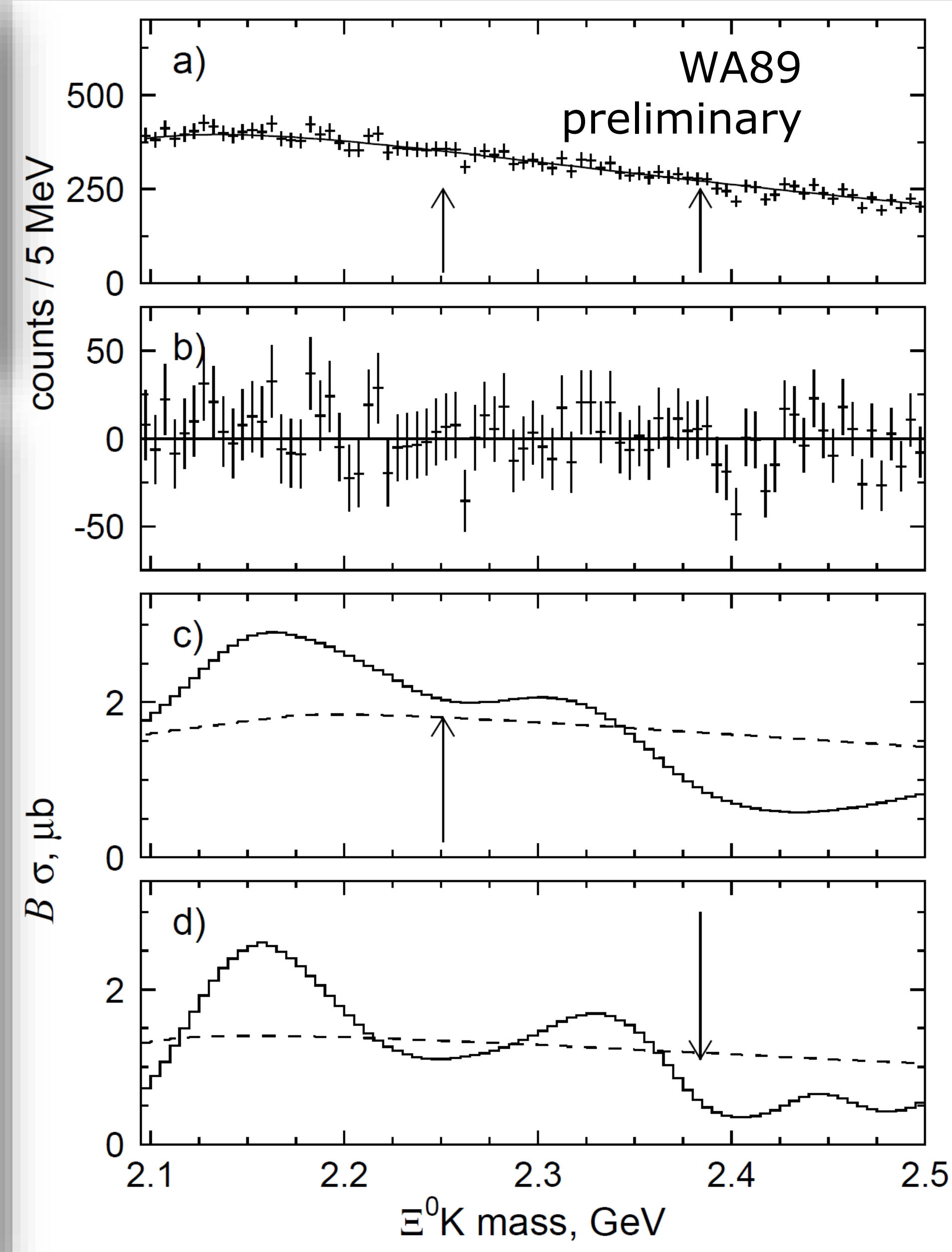
D. Aston *et al.*, Phys. Lett. B **194**, 579 (1987)



Hyperon beam experiment WA89







Spin Effect

WA89

J. Pochodzalla
universität mainz

$\Sigma^- = |d\uparrow d\uparrow s\downarrow\rangle$

octet

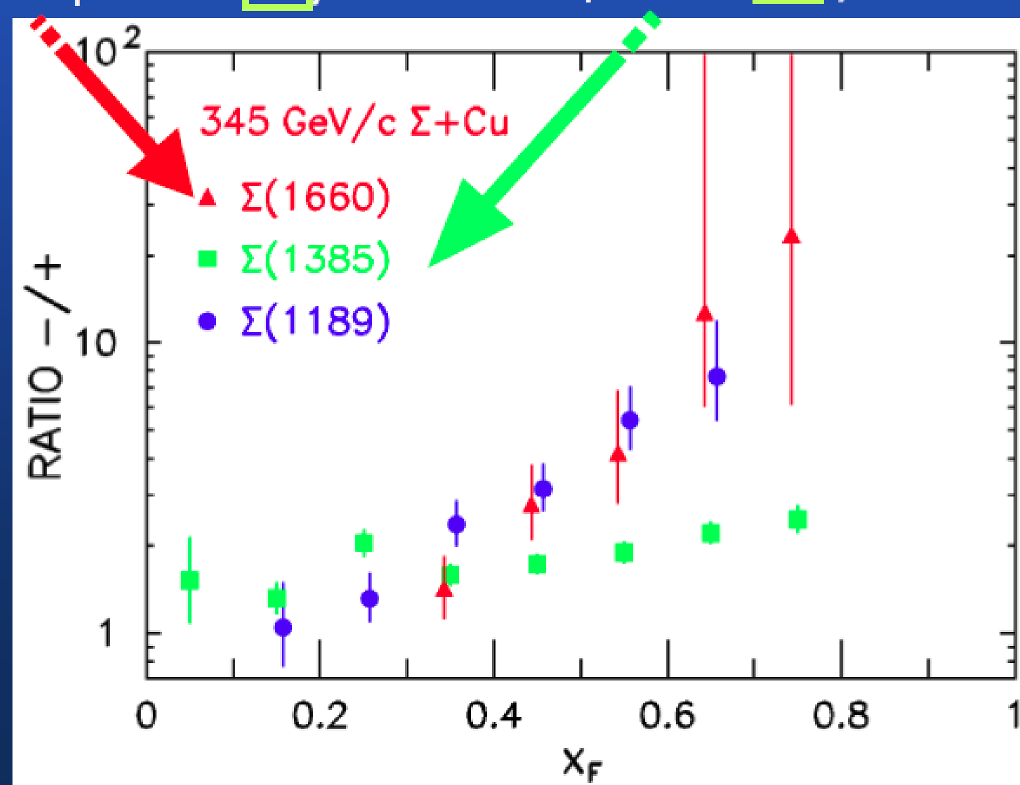
$\Sigma^- = |d\uparrow d\uparrow s\downarrow\rangle$

$\Sigma^+ = |u\uparrow u\uparrow s\downarrow\rangle$

decuplet

$\Sigma^- = |d\uparrow d\uparrow s\uparrow\rangle$

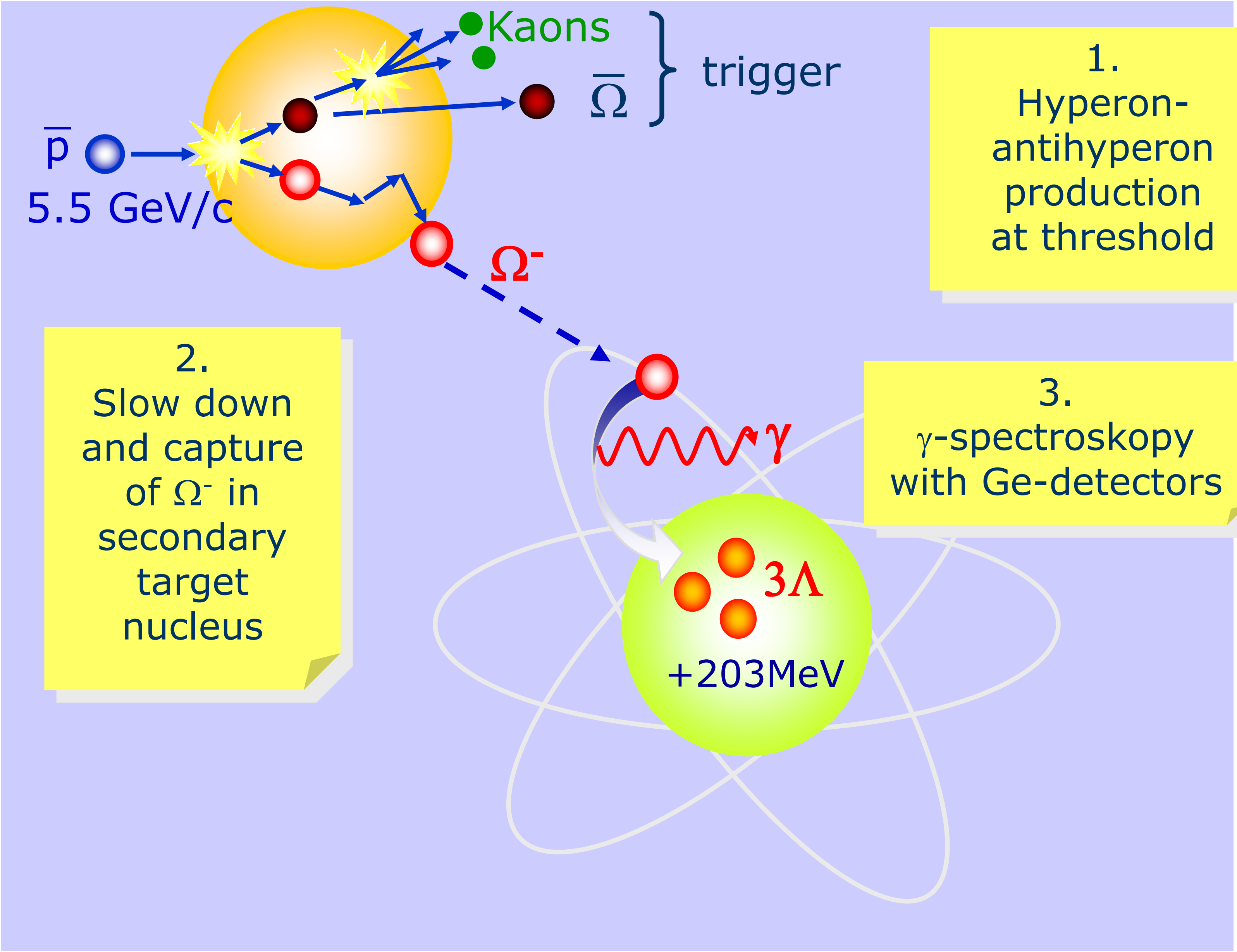
$\Sigma^+ = |u\uparrow u\uparrow s\uparrow\rangle$



Leading effect…

- **depends on diquark (spin) structure of projectile**

Production of Ω-Atoms



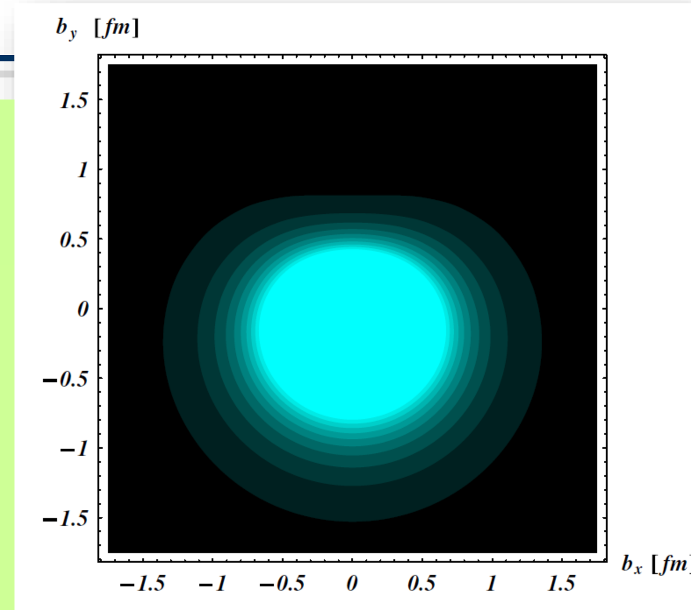
Proton vs. Omega

PHYSICAL REVIEW D **83,** 054011 (2011)

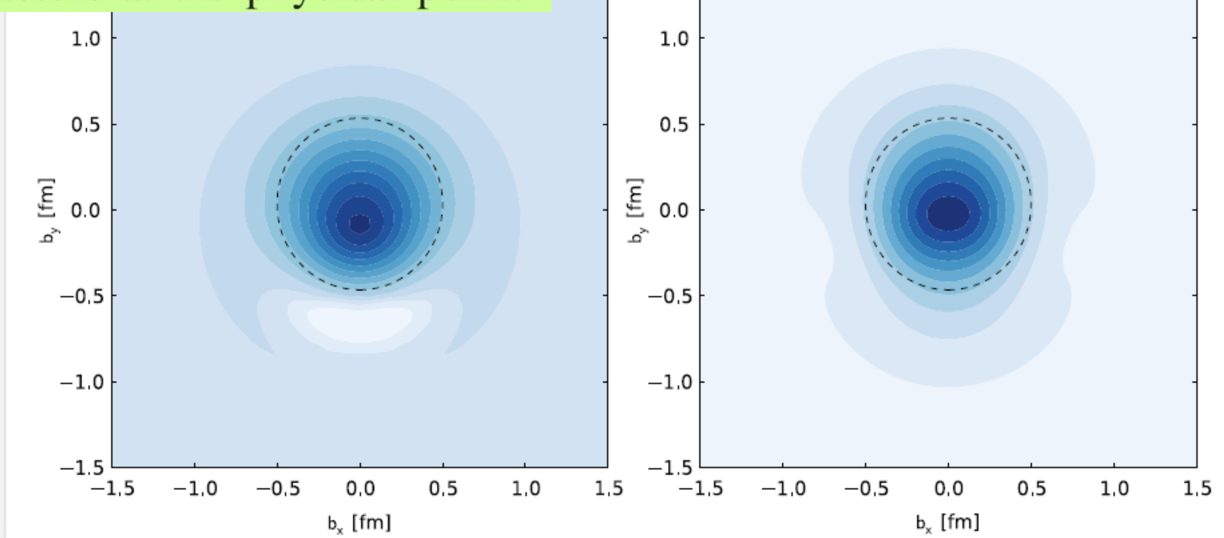
Extracting the Ω^- electric quadrupole moment from lattice QCD data

G. Ramalho[1] and M. T. Peña[1,2]

Another important issue is that in sea quark effects for the Ω^- only at most one single light quark participates, and therefore the pion has no role in this case. As in chiral perturbation theory loops involving mesons heavier than the pion are suppressed, the Ω^- becomes then a special case where meson cloud corrections to the valence quark core are expected to be small. A consequence of the smallness of the meson cloud effects is that lattice QCD simulations, quenched or unquenched, should be a good approximation to Ω^- form factors at the physical point.



he x axis. Left: $\rho^{\Omega}_{T3/2}(\vec{b})$. Right: $\rho^{\Omega}_{T1/2}(\vec{b})$. A
valuation of the densities we used the dipole



Deformation of a Baryon

- J=1/2 baryons have no *spectroscopic* quadrupole moment

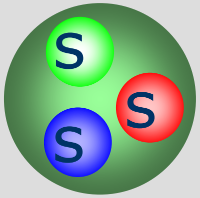
$$Q_i = \int d^3r\, \rho(r)(3z^2 - r^2)$$

$$Q_s \propto (3J_z^2 - J(J+1)) \xrightarrow[J_z=1/2]{J=1/2} 0$$

- The Ω^- Baryon is the only „elementary“ particle whose quadrupole moment can be measured
  - J=3/2
  - long mean lifetime $0.82 \cdot 10^{-10}$ s

- Contributions to *intrinsic* quadrupole moment of baryons
  - General: One-gluon exchange and meson exchange
  - Ω: only one-gluon contributions to quadrupole moment

  A.J. Buchmann Z. Naturforsch. **52** (1997) 877-940



    - sensitive to SU(3) symmetry e.g. within SU(3) limit $m_u/m_s=1$

$$Q_\Omega = Q_\Delta(gluon)$$

A very strange Atom

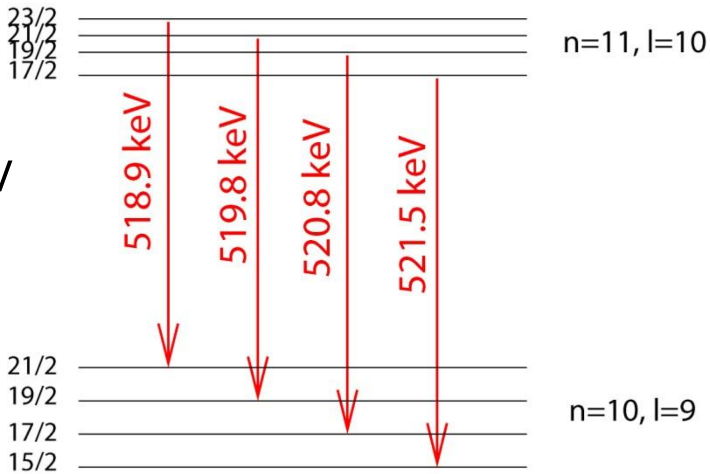
- hyperfine splitting in Ω-atom
  $\Rightarrow$ electric quadrupole moment of Ω

spin-orbit	$\Delta E_{ls} \sim (aZ)^4\, l \cdot m_\Omega$
quadrupole	$\Delta E_\Theta \sim (aZ)^4 Q m^3_\Omega$

R.M. Sternheimer, M. Goldhaber, Phys. Rev. A 8, 2207 (1973)

M.M. Giannini, M.I. Krivoruchenko, Phys. Lett. B 291, 329 (1992)

- prediction $Q_\Omega = (0 - 3.1)\ 10^{-2}\ \text{fm}^2$
  - $E(n=11, l=10 \rightarrow n=10, l=9) \sim 520$ keV
    - calibration with 511keV line!
  - $\Delta E_\Theta \sim$ few tenth of keV for Pb

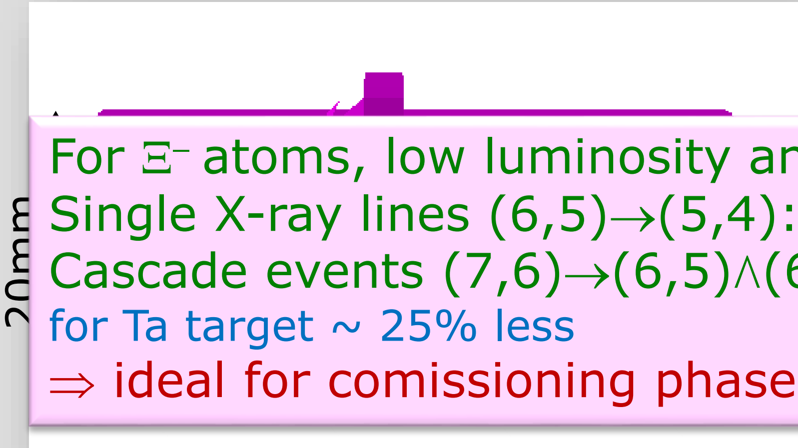


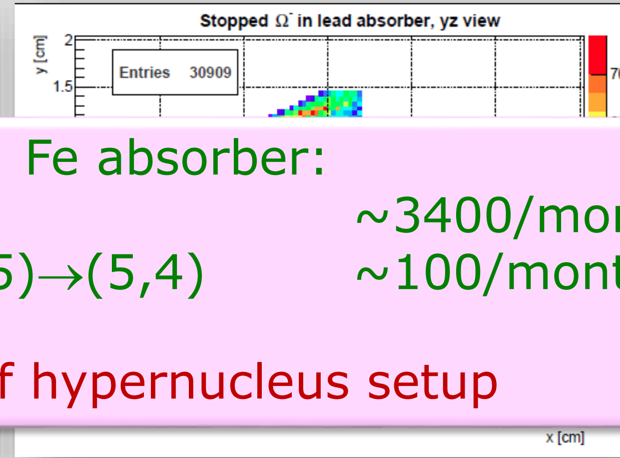
$Q_\Omega = 0.02\text{fm}^2$

Ω^- Quadrupole Moment

Model	Q [fm²]	Reference
NRQM	0.018	S.S. Gershtein,Yu.M., ZinovievSov. J. Nucl. Phys. 33, 772 (1981)
NRQM	0.004	J.-M. Richard, Z. Phys. C 12, 369 (1982)
NRQM	0.031	N. Isgur, G. Karl, R. Koniuk, Phys. Rev. D 25, 2395 (1982)
SU(3) Bag model	0.052	M.I. Krivoruchenko, Sov. J. Nucl. Phys. 45, 109 (1987)
QCD-SR	0.1	K. Azizi, Eur. Phys. J C 61, 311 (2009); T.M. Aliev, etal., arxiv: 0904.2485
NRQM with mesons	0.0057	W.J. Leonard, W.J. Gerace, Phys. Rev. D 41, 924 (1990)
NQM	0.028	M.I. Krivoruchenko, M.M. Giannini, Phys. Rev. D 43, 3763 (1991)
Lattice QCD	0.005	D.B. Leinweber, T. Draper, R.M. Woloshyn, Phys. Rev. D 46, 3067 (1992)
HBχPT	0.009	M.N. Butler, M.J. Savage, R.P. Springer, Phys. Rev. D 49, 3459 (1994)
Skyrme	0.024	J. Kroll, B. Schwesinger, Phys. Lett. B 334, 287 (1994)
Skyrme	0.0	Yoongseok Oh, ep-ph/9506308
QM	0.022	A.J. Buchmann, Z. Naturforschung 52a, 877 (1997)
χQM	0.026	G. Wagner, A.J. Buchmann, A. Faessler, J. Phys. G 26, 267 (2000)
GP QCD	0.024	A.J. Buchmann, E.M. Henley, Phys. Rev. D 65,073017 (2002)
χPT+qlQCD	0.0086	L.S. Geng, J. Martin Camalich, M.J. Vicente Vacas, Phys. Rev. D80, 034027 (2009)
Lattice QCD	0.0096±0.0002	G. Ramalho, M.T. Pena, Phys.Rev.D83:054011 (2011), arxiv:1012.2168

PANDA Setup for Ω^--Hyperatoms





For Ξ^- atoms, low luminosity and Fe absorber:

Single X-ray lines $(6,5)\rightarrow(5,4)$: ~3400/month

Cascade events $(7,6)\rightarrow(6,5)\wedge(6,5)\rightarrow(5,4)$ ~100/month

for Ta target ~ 25% less

$\Rightarrow$ ideal for comissioning phase of hypernucleus setup

Estimate of $\Omega\bar{\Omega}$ compared to $\Xi\bar{\Xi}$ (full luminosity)

Production yield:	$\times$ 1/100	(A.B. Kaidalov, Volkovitsky, Z. Phys. C63, 517 (1994)
Stopping probability	$\times$ 1/100	
Ω^- atoms	~5/day	
Single X-rays	~4/month	

$\Rightarrow$ For the first time this textbook experiment is within reach

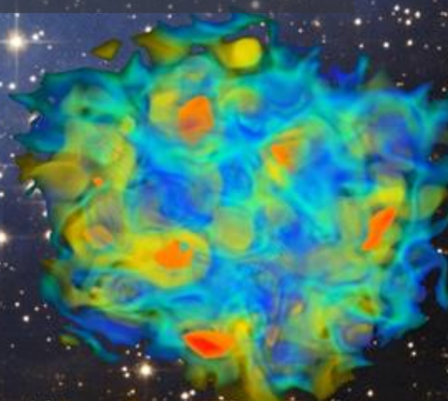
but: stil many open questions: trigger, background,…

Many more things…

…kaonic atoms…

…antihyperons in nuclei…

…hyperon scattering …




Thank you

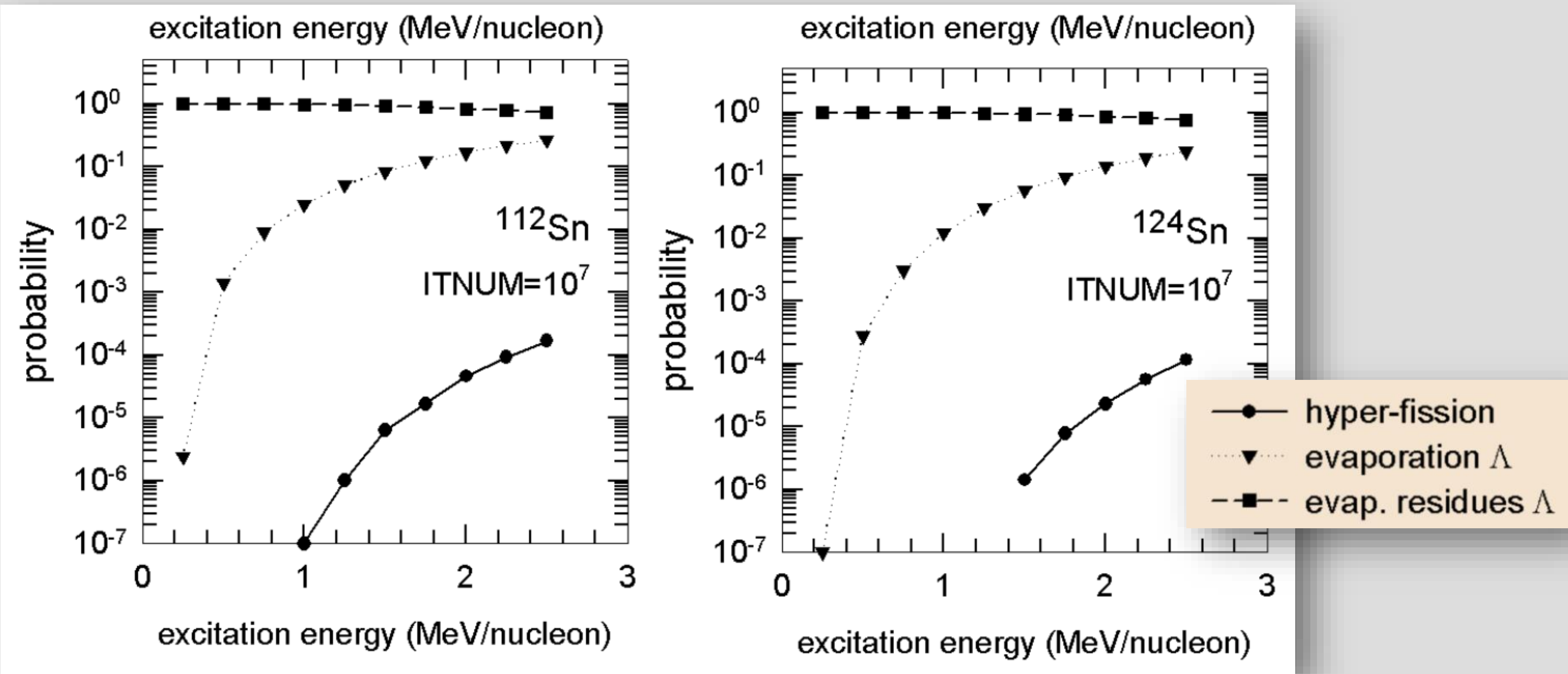
What about neutron-rich targets?

- expected excitation energy of initial excited hyperfragment ~50-100MeV i.e. ~1MeV/nucleon

$$
{}_{\Lambda}A^* \rightarrow \begin{cases} \text{n.m. weak decay} \rightarrow F_1 + l.p. \\ {}_{\Lambda}F_0 \quad + F_2 + \text{l.p.} & \text{hyperfission } \bullet \\ F_1 + F_2 + \Lambda + \text{l.p.} & \Lambda \text{ evaporation } \blacktriangledown \\ {}_{\Lambda}F_0 \quad + \text{l.p.} & \text{evaporation } \Lambda\text{– residues } \blacksquare \\ \text{n.m. weak decay} \rightarrow F_0 \rightarrow F_1 + F_2 + l.p. \end{cases}
$$

Tang: „delayed"
⇒ 1 prompt + 1 delayed fragment

⇒ two promt fragments
⇒ two delayed fragments
Tang: „prompt"



- use different isotopes as target