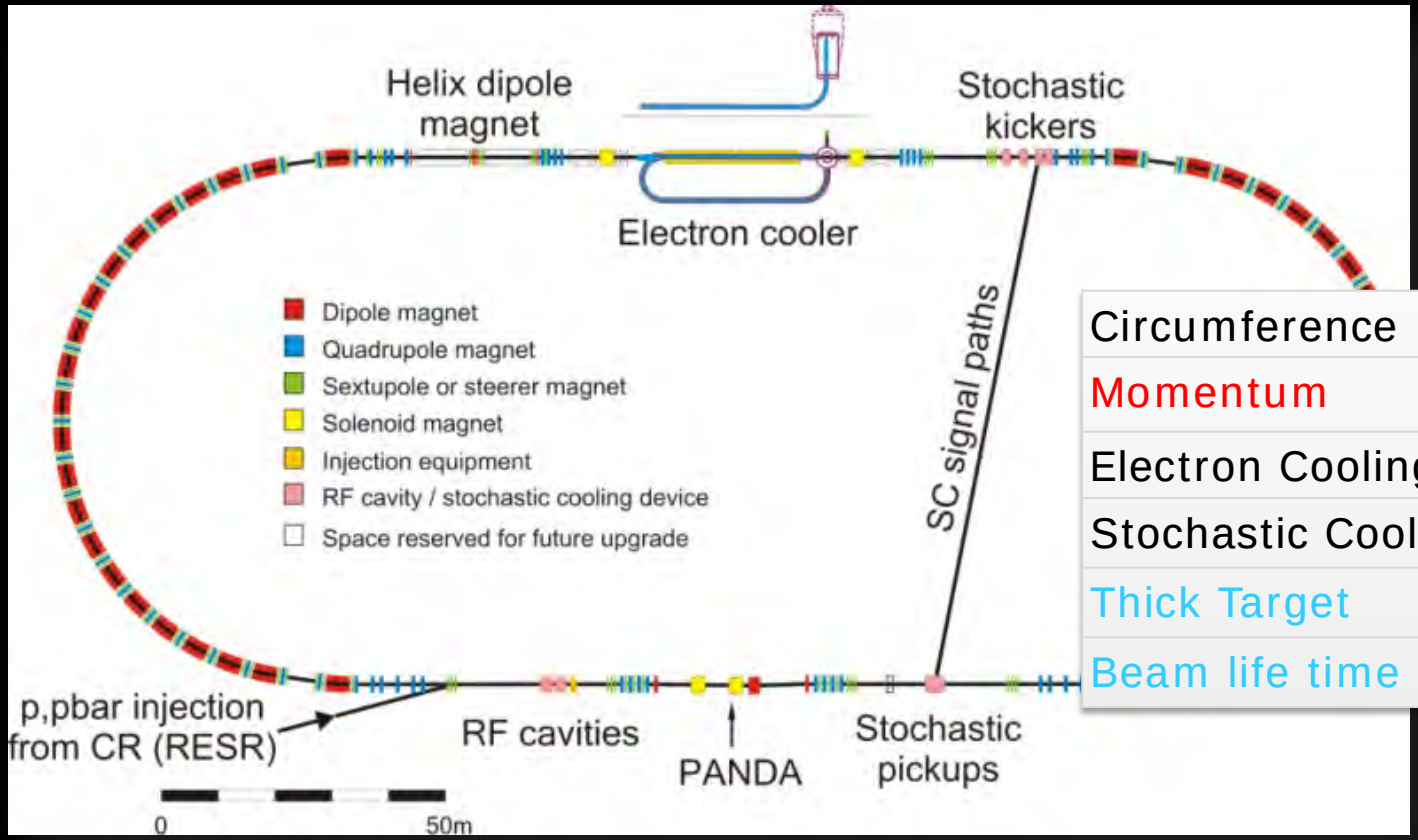
Antiproton-nucleus interactions and related phenomena
ECT* 17-21 June 2019

Hyperatoms at PANDA

- The PANDA Experiment
- Strangness Nuclear Physics at PANDA
- Hyperatom and Hypernucleus Setup
- Ξ^- hyperatoms at PANDA

Josef Pochodzalla
JGU Mainz
& Helmholtz-Institut – Mainz
European Union

HESR with PANDA and e⁻ Cooler



Circumference	575 m
Momentum	1.5 – 15 GeV/c
Electron Cooling	up to 9 GeV/c
Stochastic Cool.	Full range
Thick Target	$4 \cdot 10^{15}$ 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 $2 \cdot 10^{31}$ cm^{-2}s^{-1}
  - $\Delta p/p \leq 4 \cdot 10^{-5}$
- High luminosity mode
  - Stochastic cooling $p \geq 3.8$ GeV/c
  - 10^{11} antiprotons stored
  - Luminosity up to $2 \cdot 10^{32}$ cm^{-2}s^{-1}
  - $\Delta p/p \leq 2 \cdot 10^{-4}$

Versatility of antiprotons

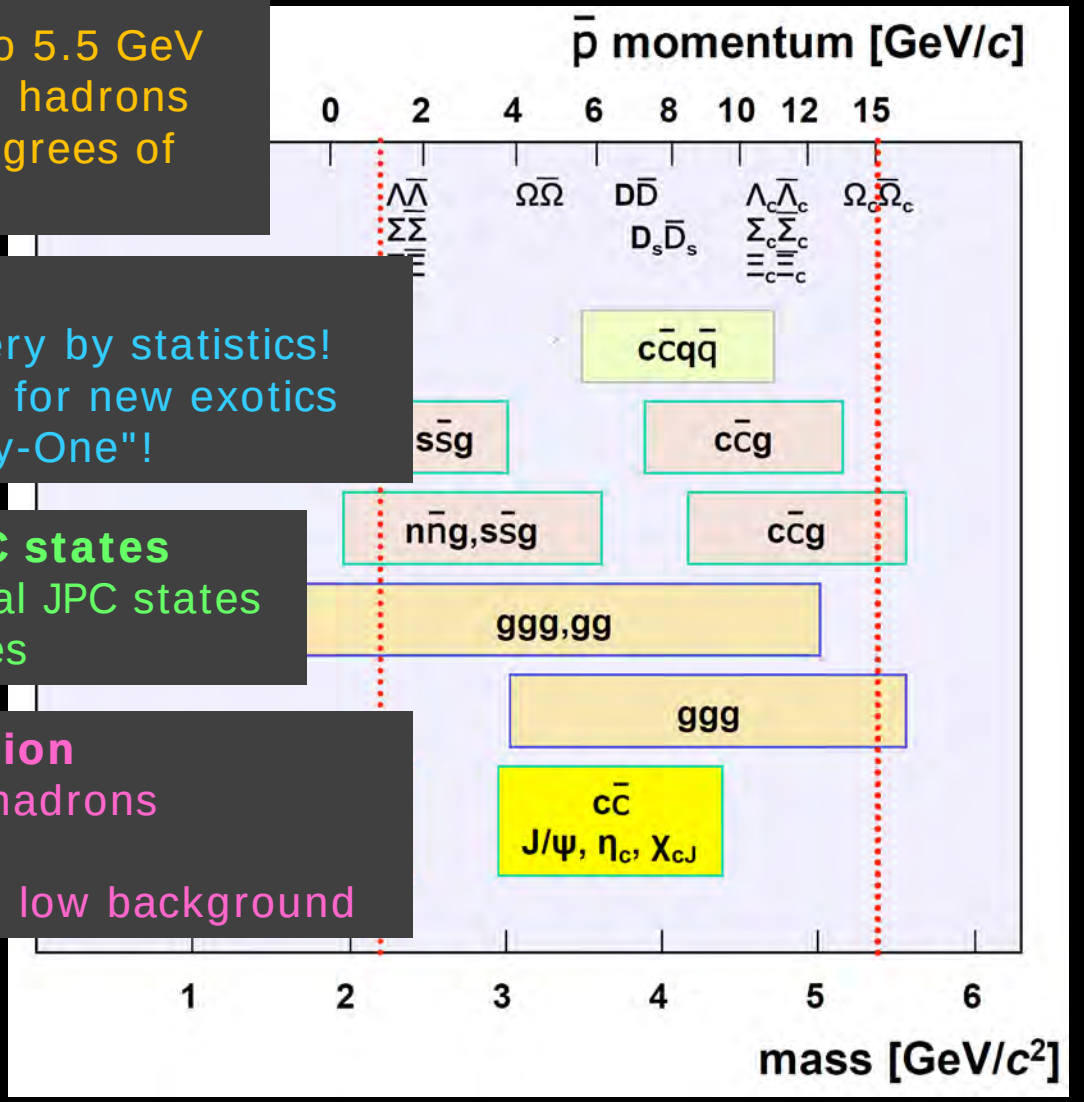
Johan Messchendorp

Large mass-scale coverage
- center-of-mass energies from 2 to 5.5 GeV
- from light, strange, to charm-rich hadrons
- from quark/gluons to hadronic degrees of freedom

High hadronic production rates
- charm+strange factory ⇒ discovery by statistics!
- gluon-rich production ⇒ potential for new exotics
- good perspectives already at “Day-One"!

Access to large spectrum of JPC states
- direct formation of *all* conventional JPC states
- large sensitivity to high spin states

Associated hadron-pair production
- access to hidden-strange/charm hadrons
- tagging possibilities
- near thresh.: good resolution and low background



Systematic and precise tool to rigorously study the dynamics of QCD

Physics Pillars of PANDA

COMPLEX STATES OF STRONG INTERACTION ON ALL SCALES

SPECTROSCOPY

- **New narrow XYZ:**
  Search for partner states
- **Production of exotic QCD states:**
  Glueballs and hybrids

NUCLEON STRUCTURE

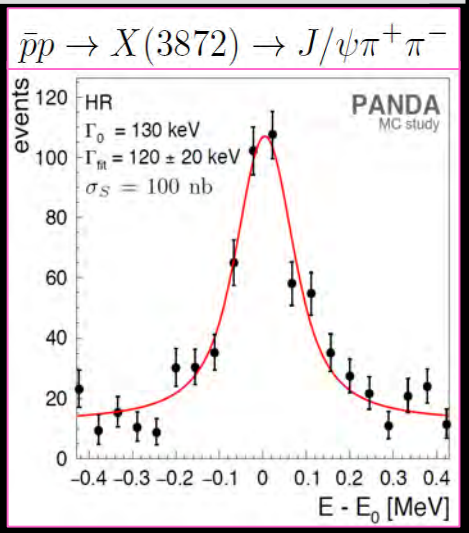
- **Generalized parton distributions:** Orbital angular momentum
- **Drell Yan process:** Transverse structure, valence anti-quarks
- **Time-like form factors:** *low and high E, e and μ pairs*

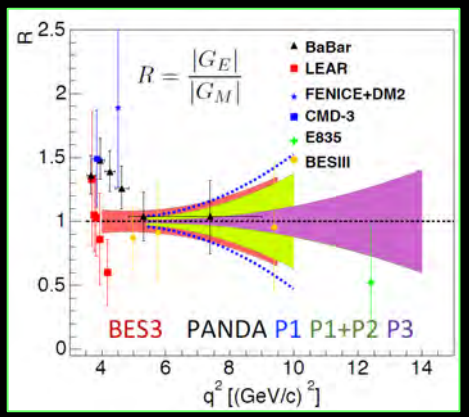
STRANGENESS

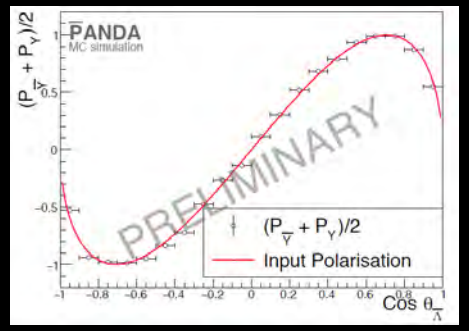
- **Strange baryons:**
  spectroscopy, polarization

NUCLEAR PHYSICS

- **S=-2 Hypernuclei and -atoms:**
  double hypernuclei, heavy Ξ atoms
- **Antihyperons in nuclei**

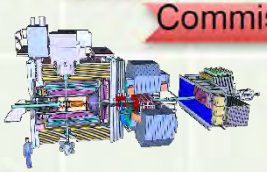




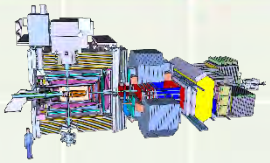


PANDA planing

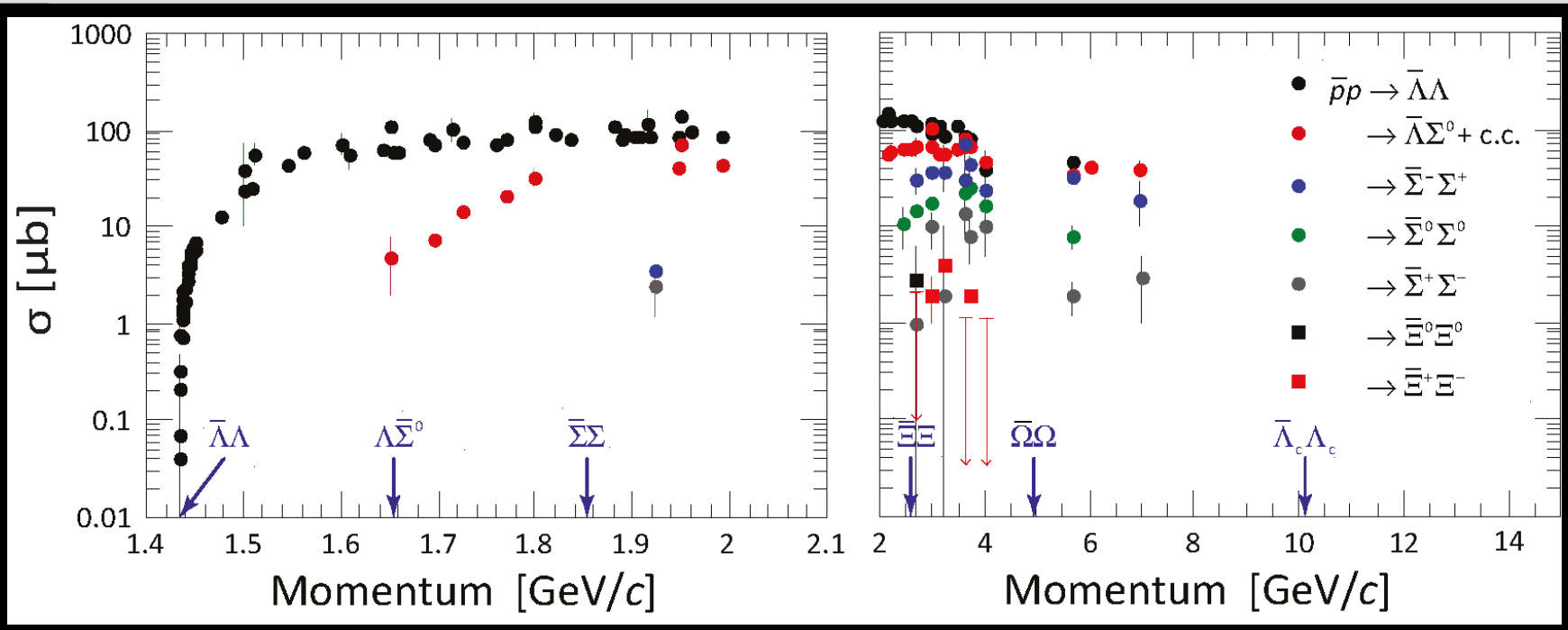
Planning	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026 +
PANDA Phase 0				Pre-Commissioning							
PANDA Start Setup		Design		Construction			Installation	Commissioning			
PANDA Phase 1					PANDA Hall assumed available Q4/2021				Physics	0.5 fb^{-1}	
PANDA Full Setup		Design			Construction					Installation	
PANDA Phase 2										Physics	
PANDA Phase 3: RESR											



Day-One ~5 pb^{-1}



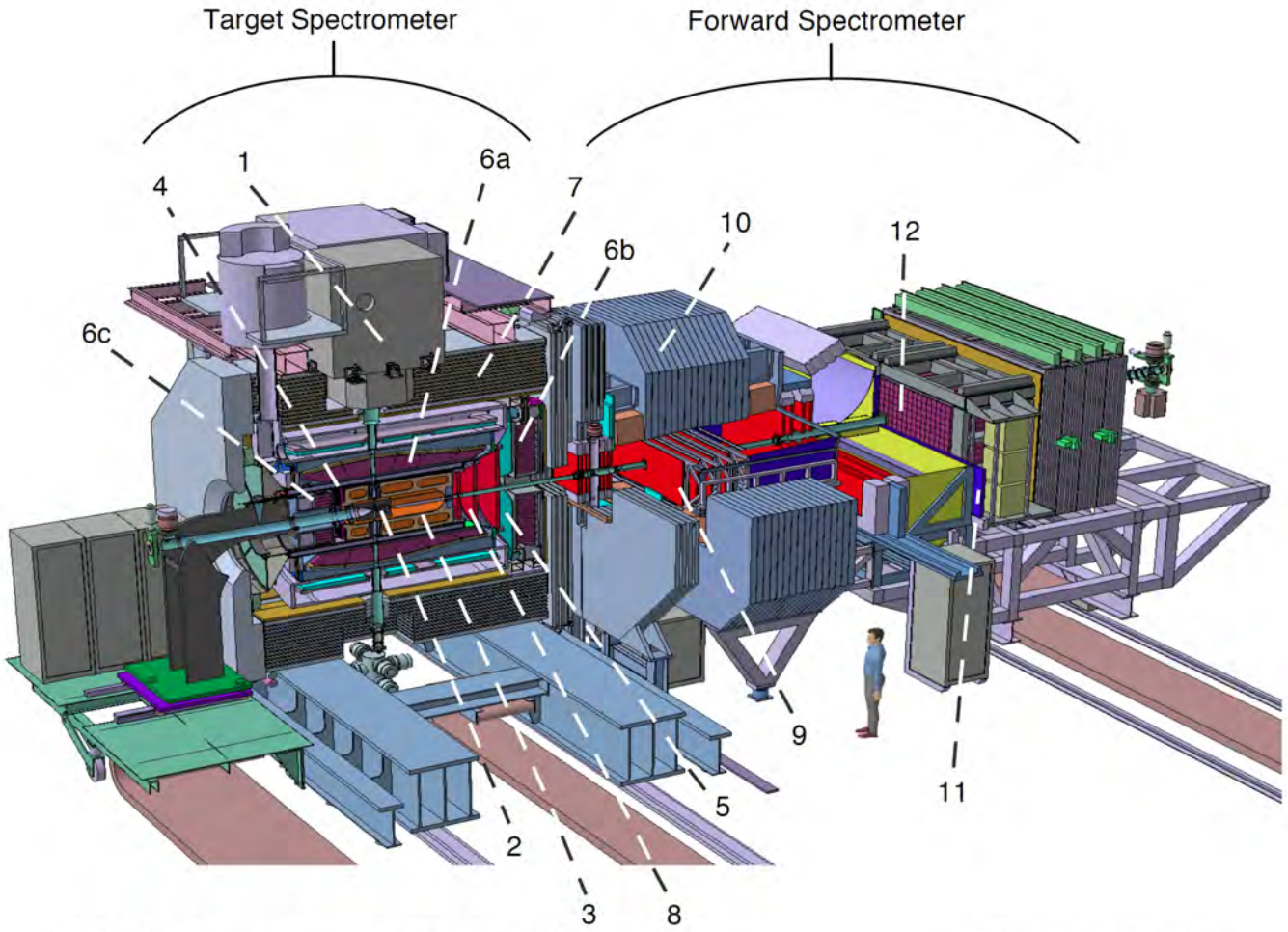
Factory for strange *and* charmed $\bar{Y}Y$-Pairs



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}
$\Xi\bar{\Xi}$ ($\to_{\Lambda\Lambda}$ A)	2μb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ ($\to e^+e^-, \mu^+\mu^-$)	630nb	10^9
χ_2 ($\to$ J/ψ + γ)	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

The PANDA Detector

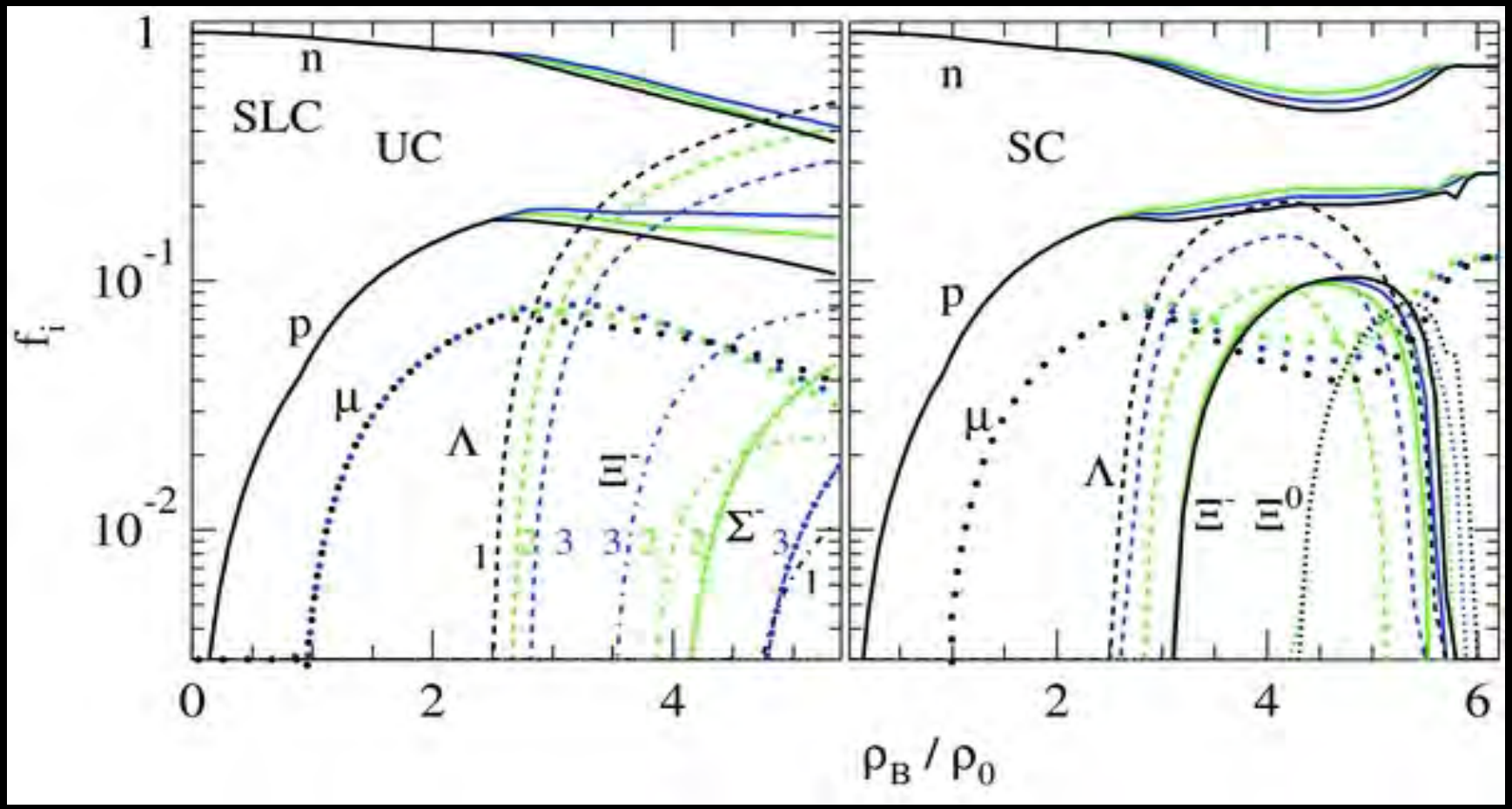


1: Cluster-Target
2: Mikrovertex-Detektor
3: STT-Tracker
4: DIRC
5: Disc-DIRC
6a: Barrel-EMC
6b: Forward-EMC
6c: Backward-EMC
7: Solenoid Yoke with Muon Chambers
8: GEM-Tracker
9: Forward Tracker
10: Dipole
11: Forward TOF wall
12: Shashlyk-EMC

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

Hyperons in Neutron Stars

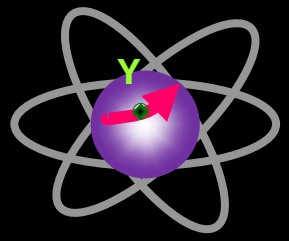
- Sequence of hyperon appearance depends on B-B interaction
- Σ –N interaction repulsive $\Rightarrow$ Σ will probably appear latest



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

Strangeness Nuclear Physics

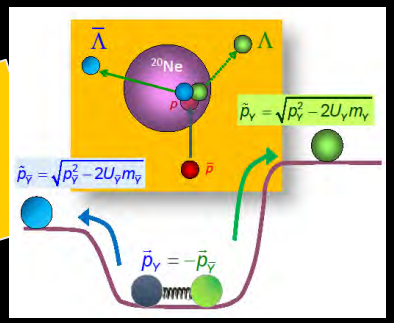
(anti)hyperon propagation



antihyperon potential in cold baryonic matter

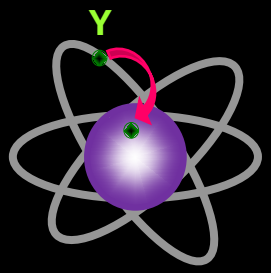
$Y\bar{Y}$ momentum correlations at threshold

Day-One
~weeks
standard PANDA



breakthrough measurement in first years of operation

hyperatoms



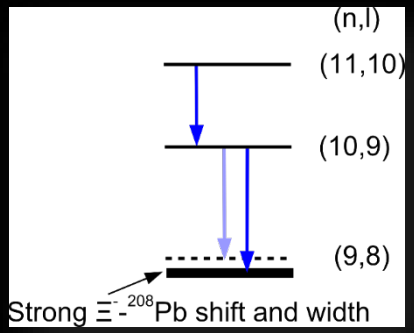
Physics Topic at $\bar{P}$ANDA

Ξ^- potential in neutron-rich baryonic matter

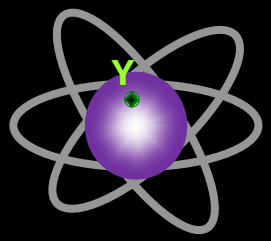
Methodology

Width and shift of atomic levels in Ξ^- ^{208}Pb atoms

PHASE 1
stable running 180d
DEGAS+pr. target



hypernuclei

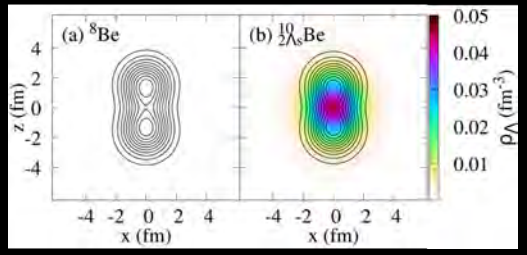


Structure of double $\Lambda\Lambda$ hypernuclei, hyperon mixing

Excited state spectrum of light $\Lambda\Lambda$ hypernuclei

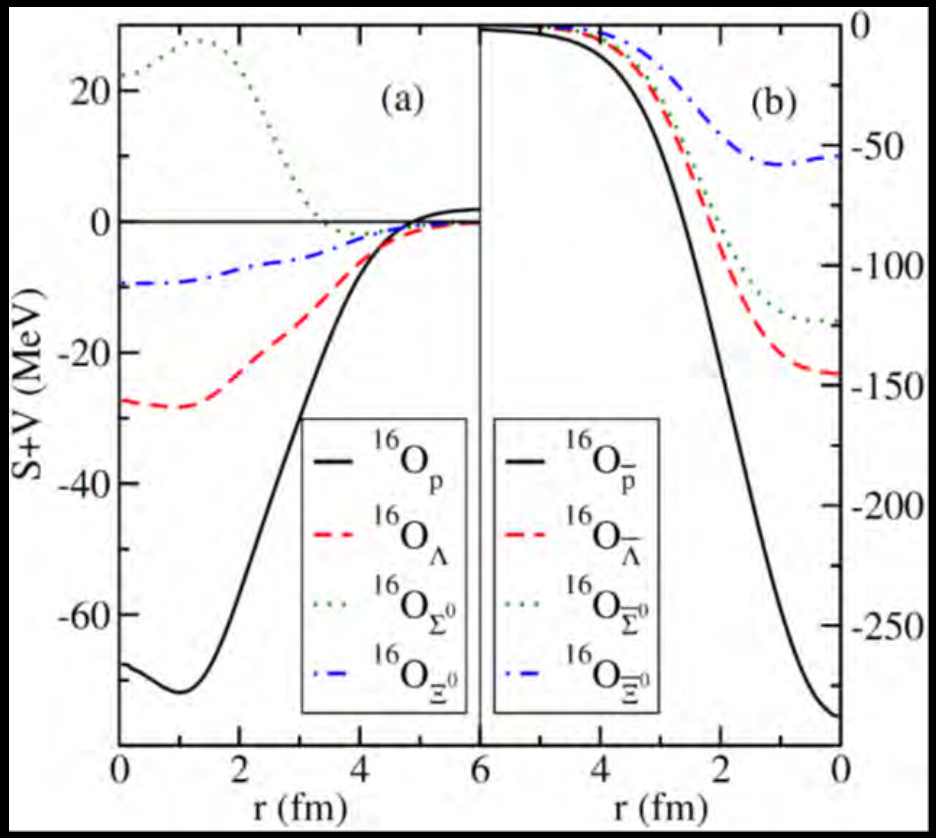
PHASE 2

DEGAS+active sec. target

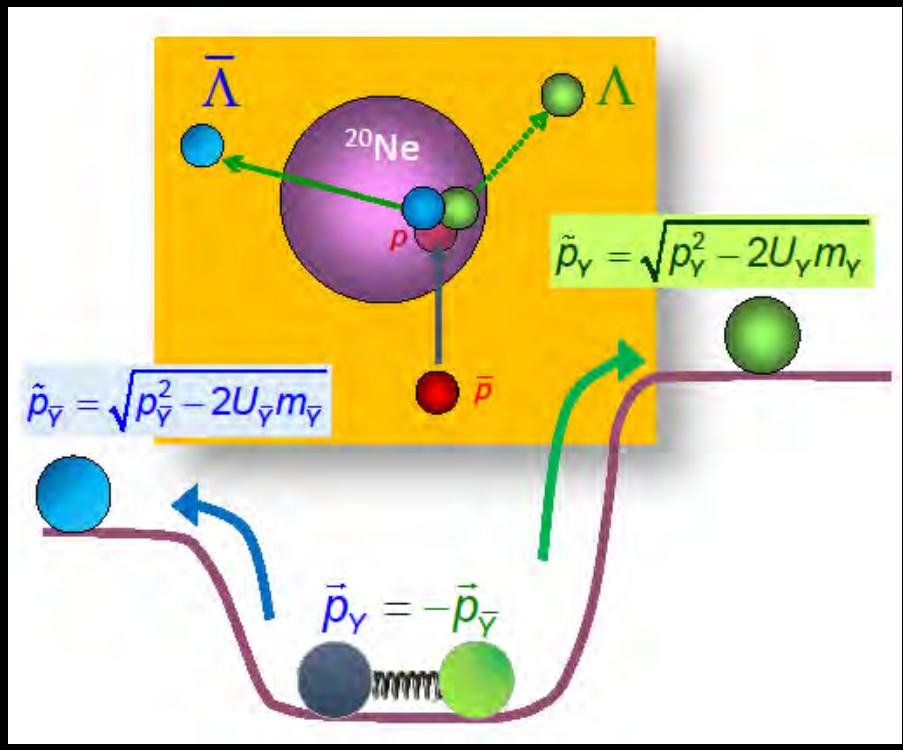


Yusuke Tanimura
Phys. Rev. C 99, 034324 (2019)

$\bar{\Lambda}$ Potential in Nuclei

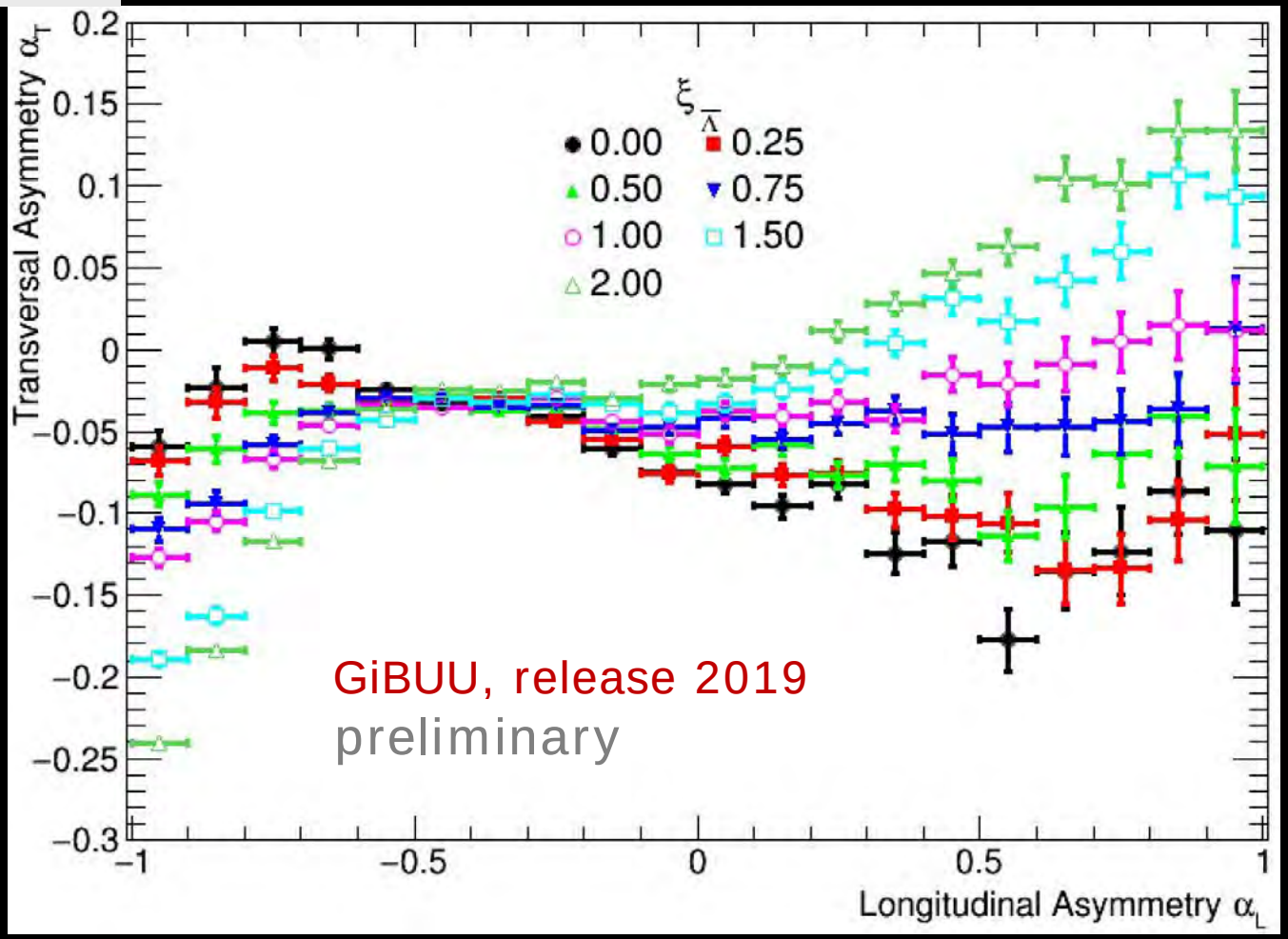


Jaroslava Hrtankova



$\bar{\Lambda}$ in Nuclei

$$\alpha_{\perp} = \left\langle \frac{p_{\perp}(\Lambda) - p_{\perp}(\bar{\Lambda})}{p_{\perp}(\Lambda) + p_{\perp}(\bar{\Lambda})} \right\rangle$$



Large production yield at PANDA ⇒ DAY-ONE experiment

Ξ⁻-Nucleus Interaction

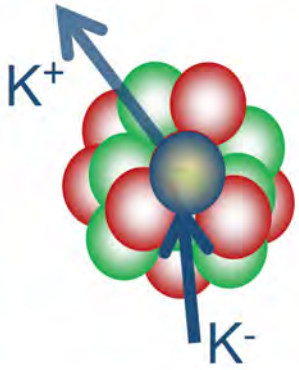
Ξ⁻ hypernuclei decays in emulsion

$^{A}_{\Xi}Z \rightarrow ^{A_1}_{\Lambda}Z_1 + ^{A_2}_{\Lambda}Z_2$

K. Nakazawa et al., PTEP (2015) 033D02

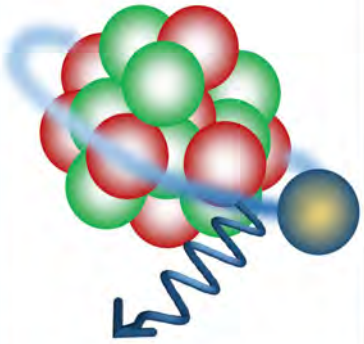
J-PARC E07

missing mass spectroscopy of Ξ⁻ hypernuclei (K⁻,K⁺) reactions



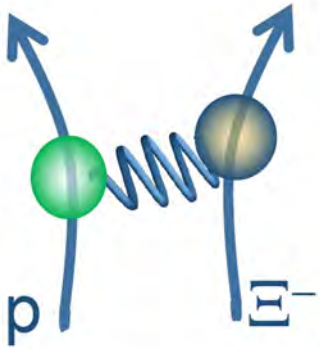
KEK E224
BNL E885
J-PARC E05
J-PARC E70

γ-spectroscopy of heavy Ξ⁻ hyperatoms

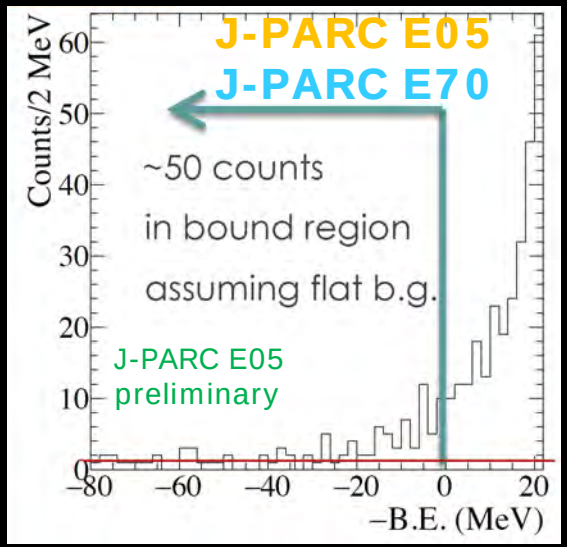


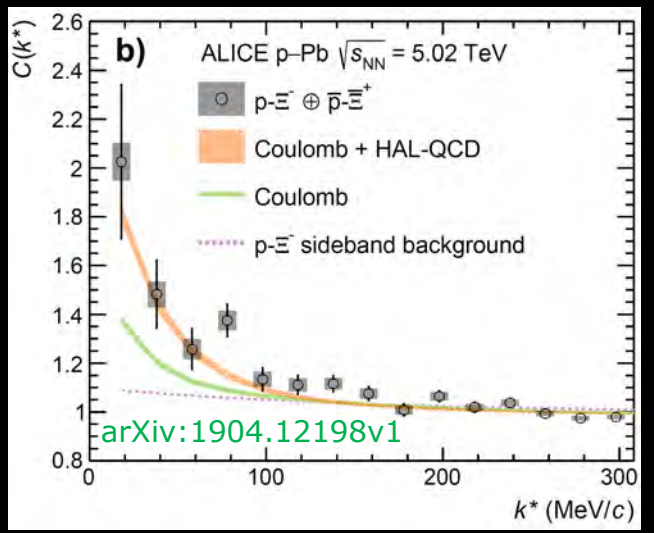
J-PARC E07
J-PARC E03
PANDA

scattering or final state interaction



STAR
ALICE





S=-2 Systems at PANDA

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

rescattering in primary target nucleus

deceleration in secondary target

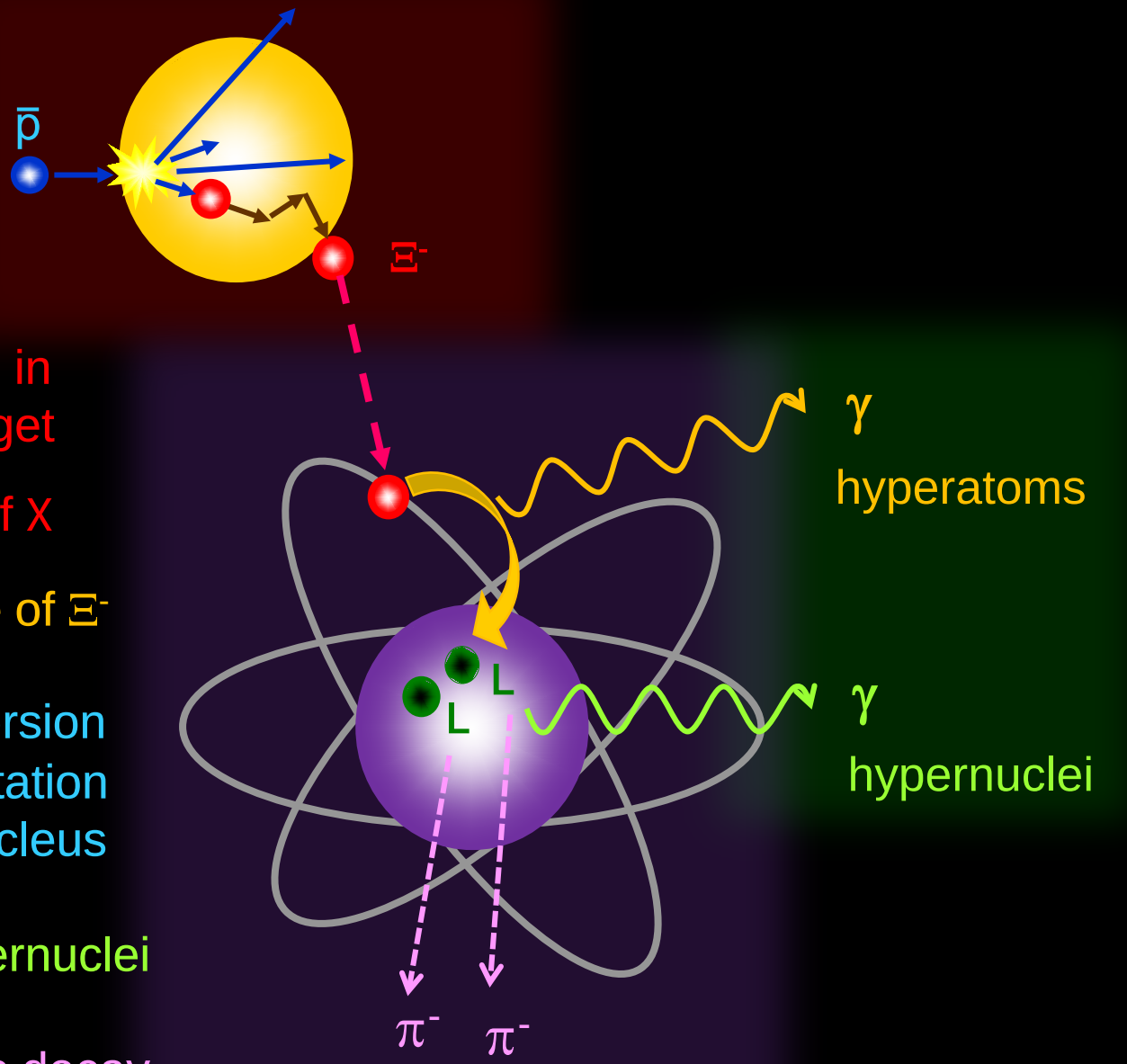
capture of X

atomic cascade of Ξ^-

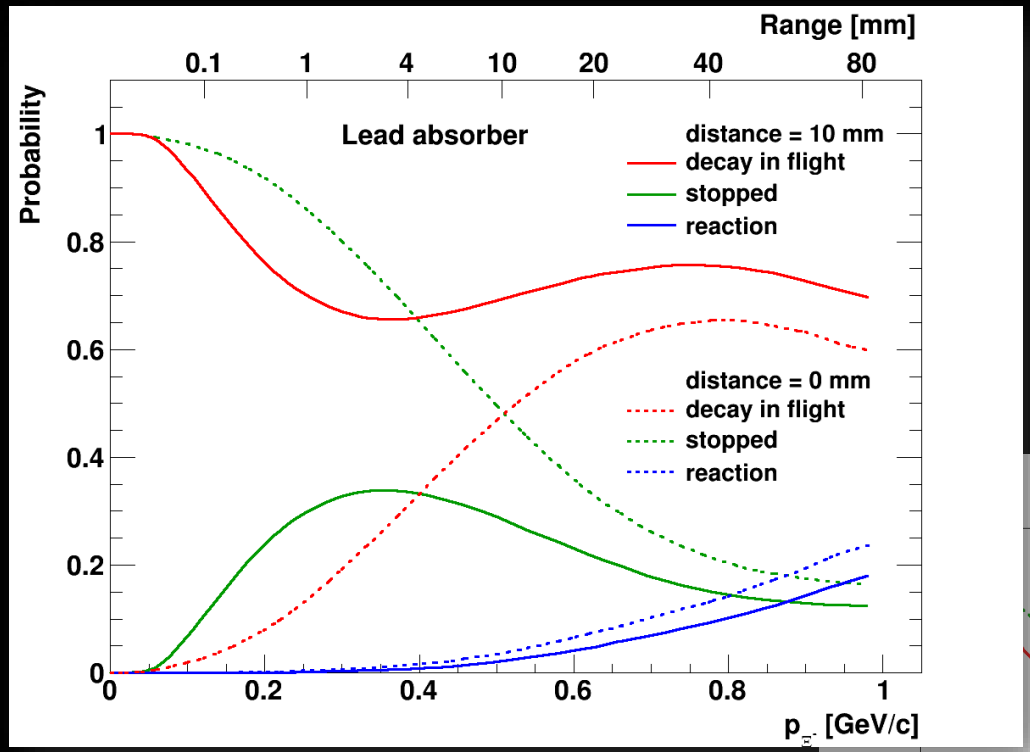
$\Xi^-p \rightarrow \Lambda\Lambda$ conversion fragmentation
$\rightarrow$ excited $\Lambda\Lambda$-nucleus

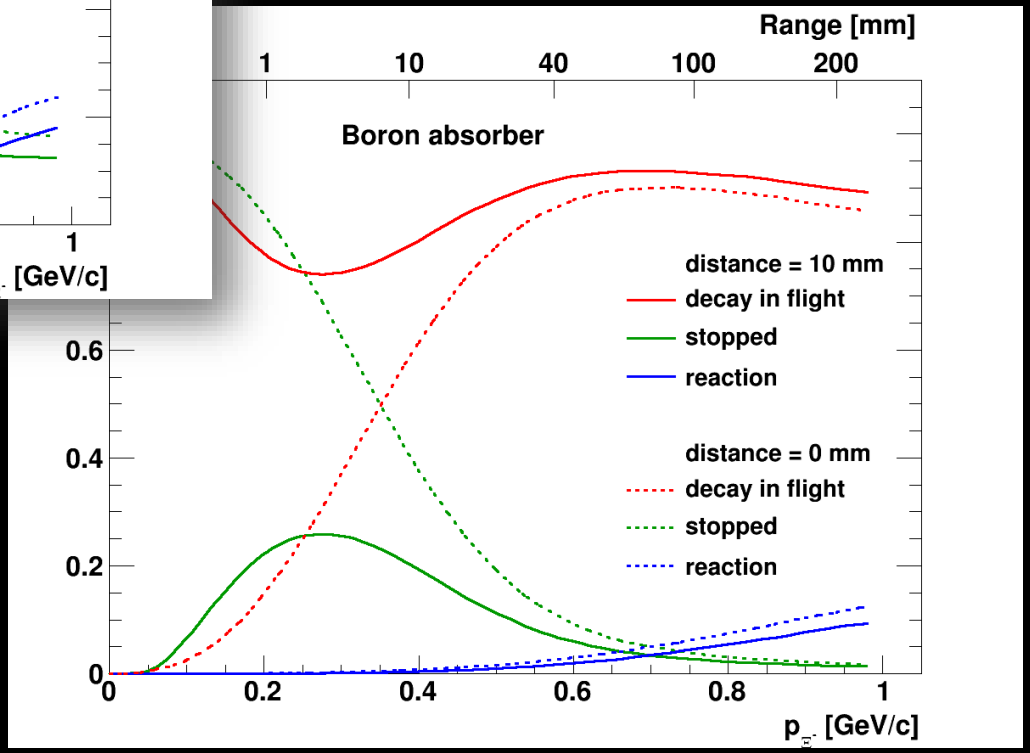
γ-decay of $\Lambda\Lambda$ hypernuclei

weak pionic decay

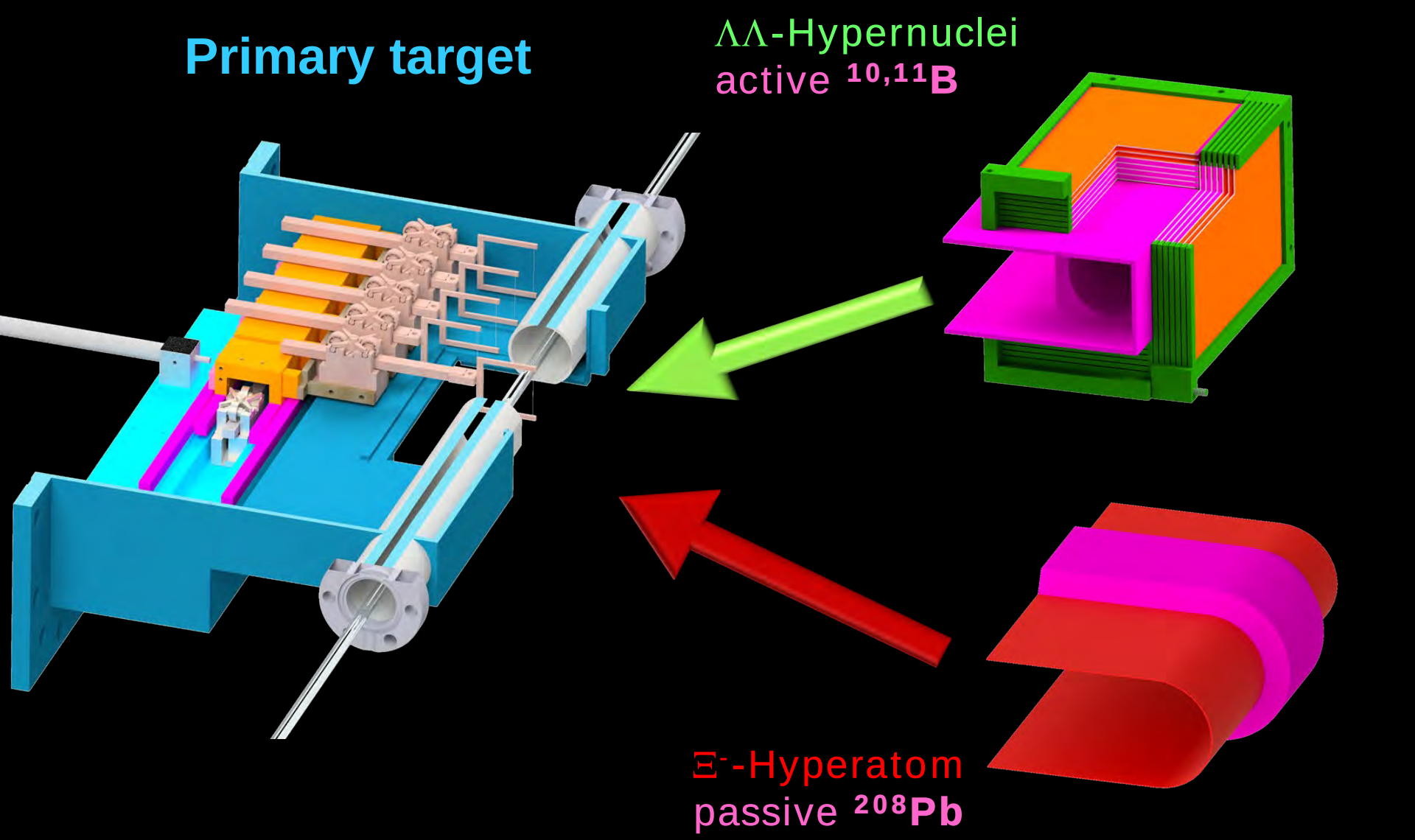


Stopping of Secondary Hyperons



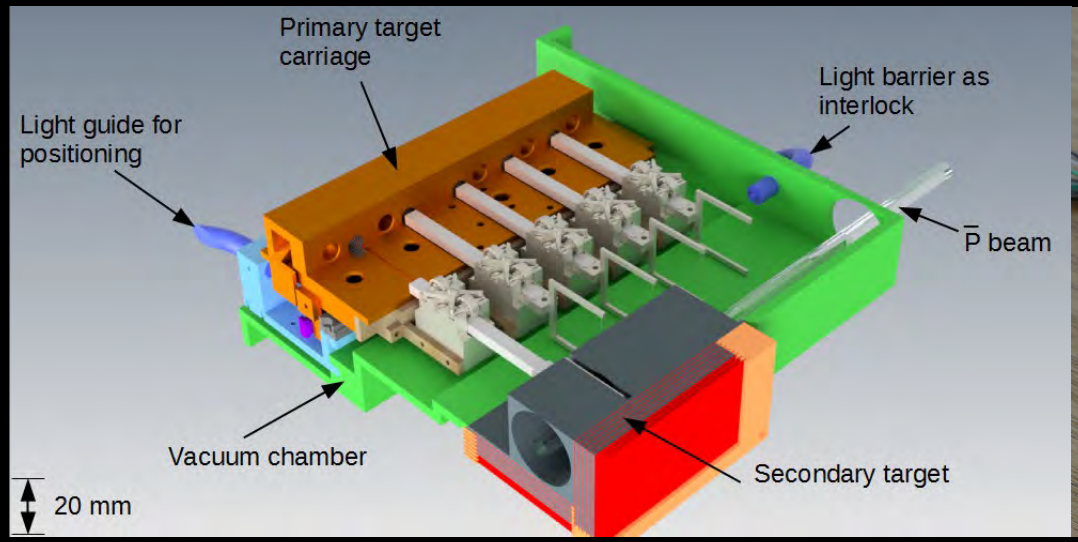


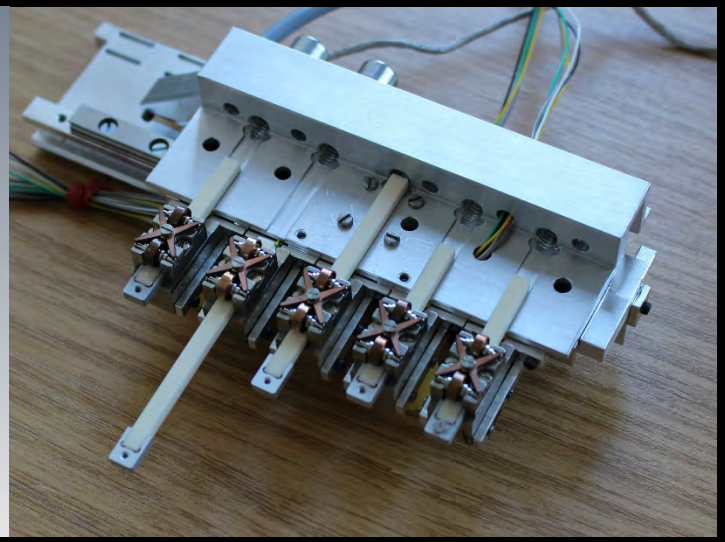
Target Stations

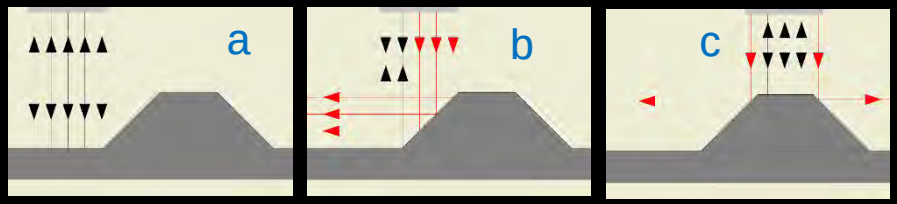


Primary Target

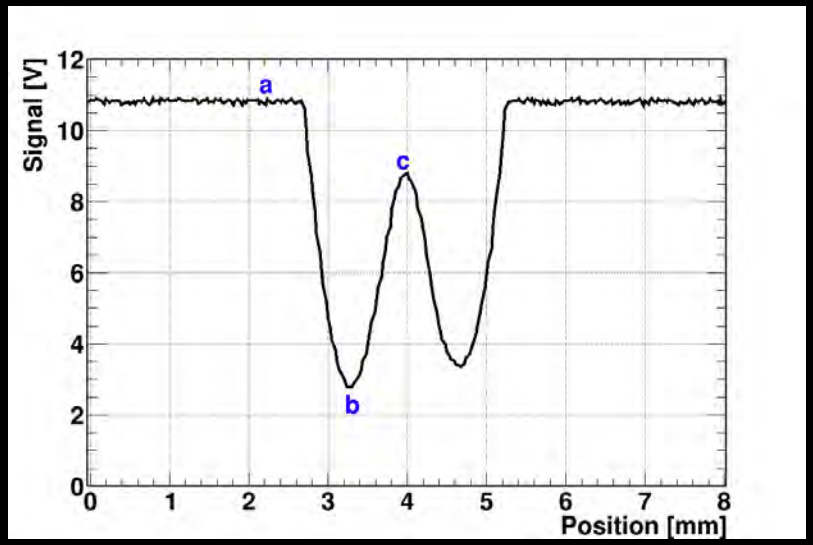
- Task: Ξ^- production by a ~5μm thin carbon filament



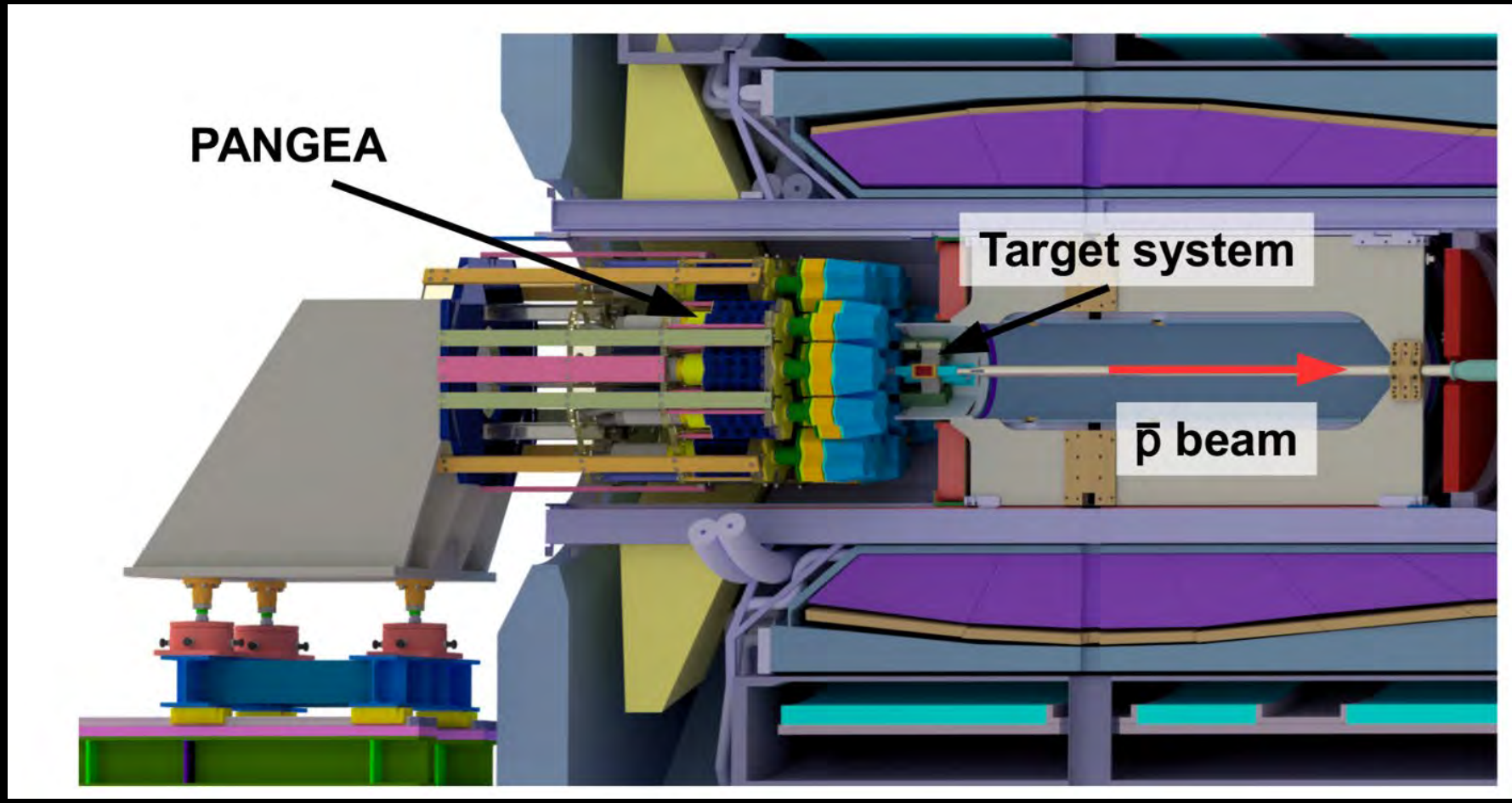




passive, radiation hard position control of the target carriage with piezo motors by measuring light reflected off a plane with grooves



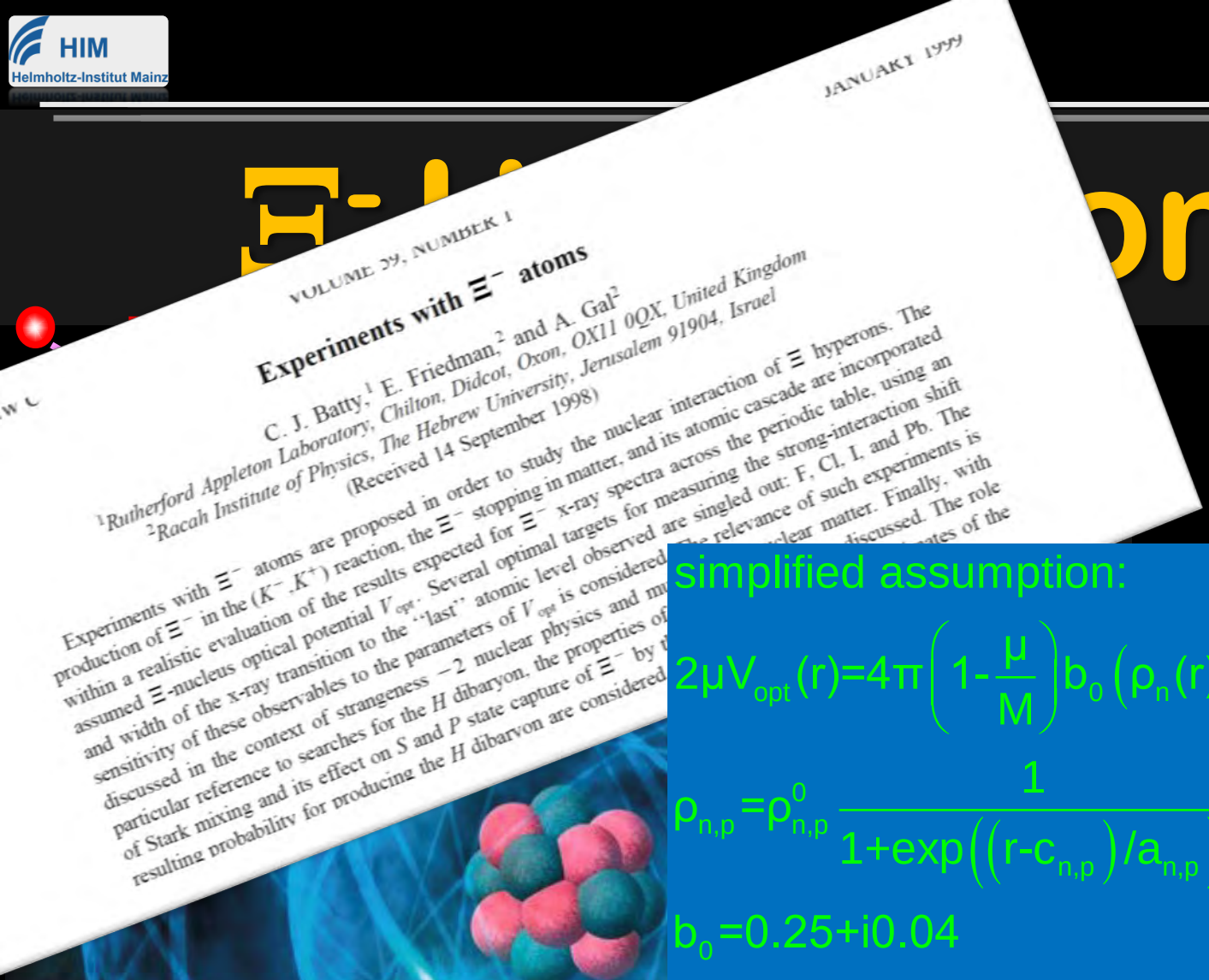
PANDA + PANGEA



HIM
Helmholtz-Institut Mainz

panda

Ξ- atoms



VOLUME 29, NUMBER 1 JANUARY 1999

Experiments with Ξ^- atoms

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[2]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

(Received 14 September 1998)

Experiments with Ξ^- atoms are proposed in order to study the nuclear interaction of Ξ hyperons. The production of Ξ^- in the (K^-,K^+) reaction, the Ξ^- stopping in matter, and its atomic cascade are incorporated within a realistic evaluation of the results expected for Ξ^- x-ray spectra across the periodic table, using an assumed Ξ-nucleus optical potential V_{opt}. Several optimal targets for measuring the strong-interaction shift and width of the x-ray transition to the "last" atomic level observed are singled out: F, Cl, I, and Pb. The sensitivity of these observables to the parameters of V_{opt} is considered. The relevance of such experiments is discussed in the context of strangeness -2 nuclear physics and nuclear matter. Finally, with particular reference to searches for the H dibaryon, the properties of the Ξ^- atomic states of the of Stark mixing and its effect on S and P state capture of Ξ^- by u resulting probability for producing the H dibaryon are considered

simplified assumption:

$$2\mu V_{opt}(r)=4\pi\left(1-\frac{\mu}{M}\right)b_0\left(\rho_n(r)+\rho_p(r)\right)$$

$$\rho_{n,p}=\rho^0_{n,p}\,\frac{1}{1+\exp\left(\left(r-c_{n,p}\right)/a_{n,p}\right)}$$

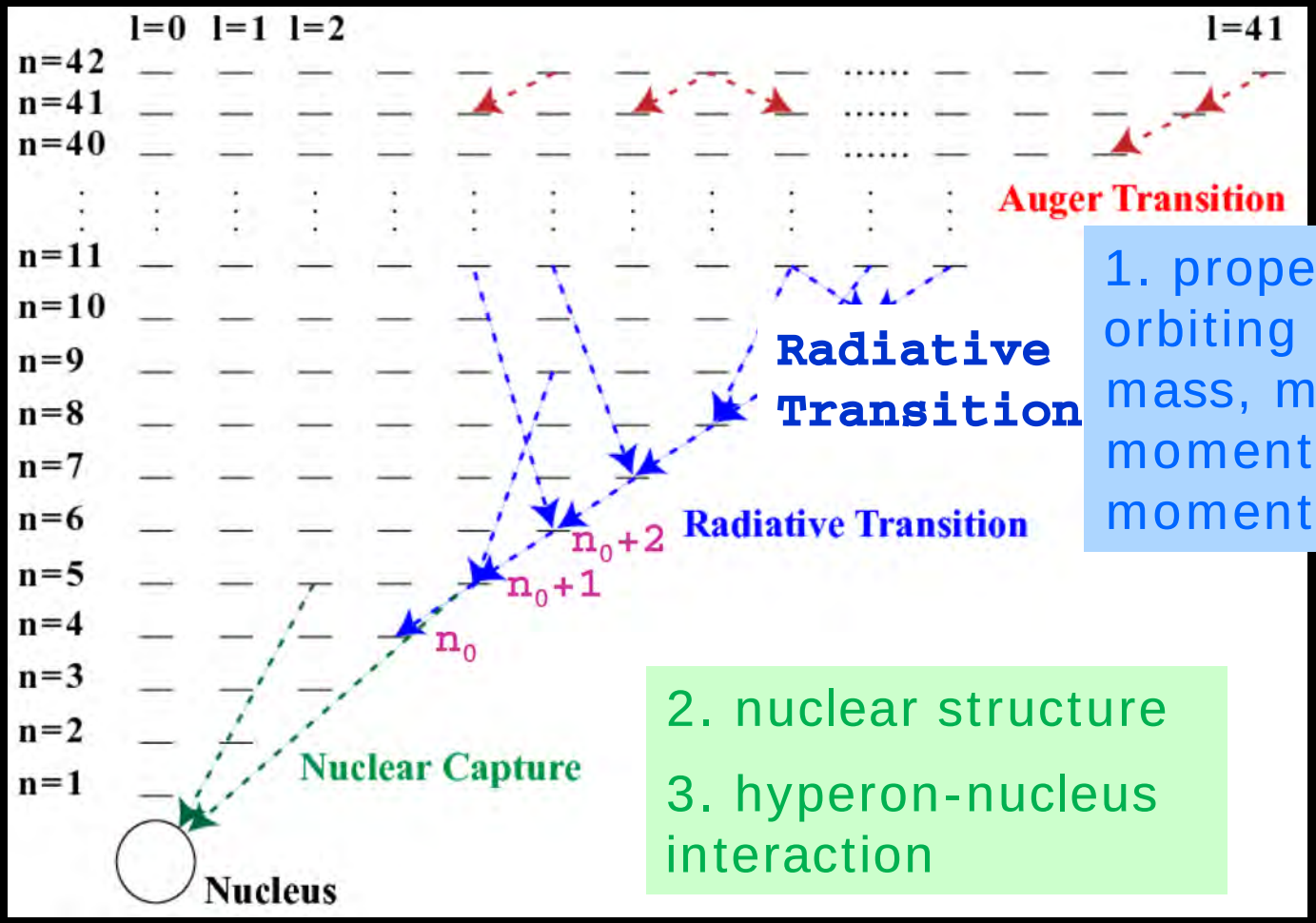
$b_0=0.25+i0.04$

$a_n=a_p=0.475\text{fm}$

$c_{n,p}$ fixed by $R_{p,rms}$ and neutron skin thickness

$\rho^0_{n,p}$ from N and Z

Three Sides of a Coin

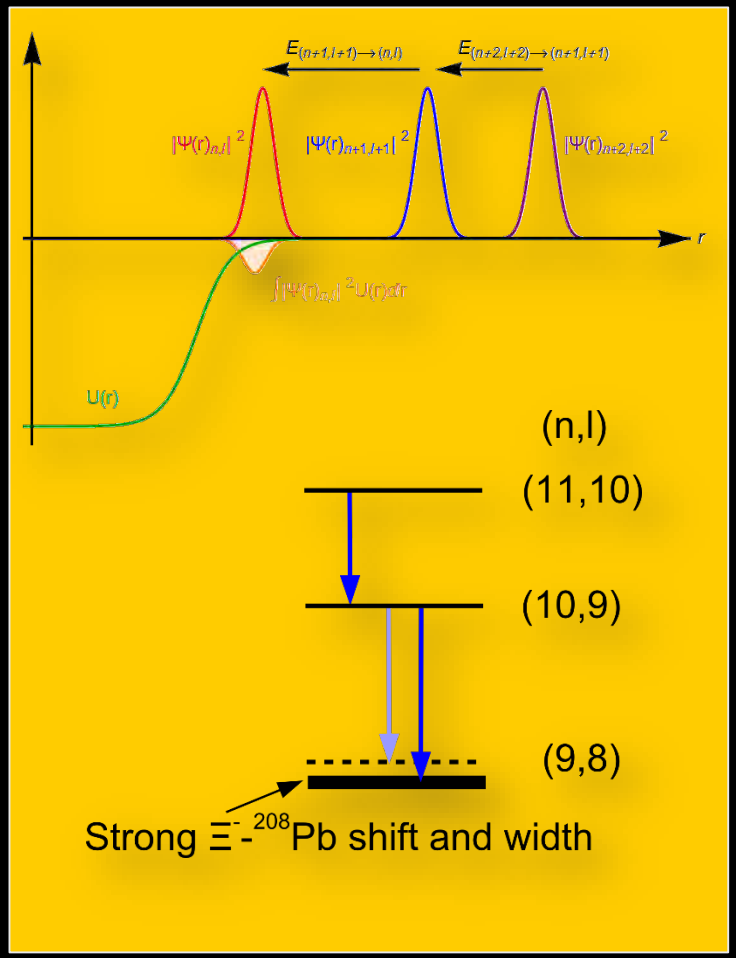


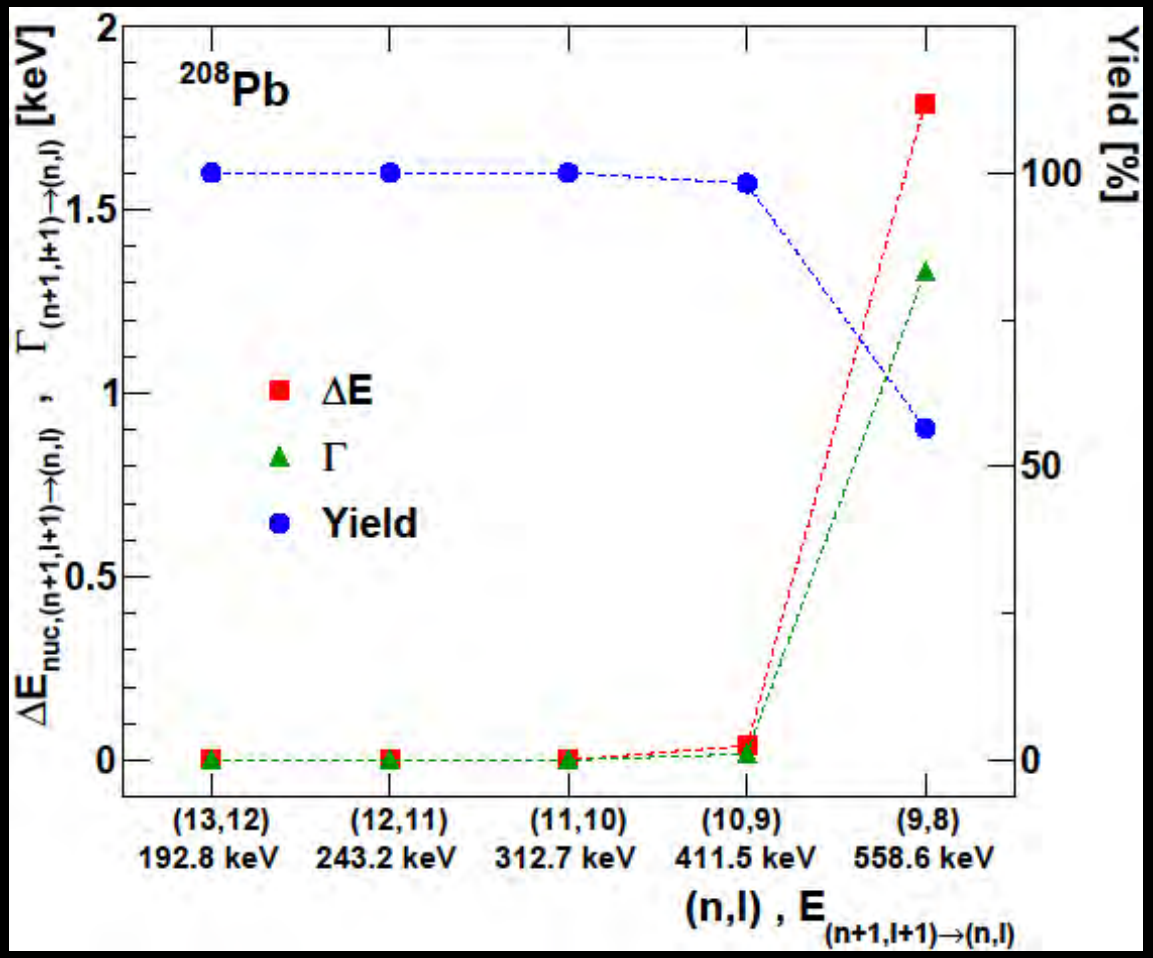
1. properties of orbiting particle e.g. mass, magnetic moment, quadrupole moment

2. nuclear structure

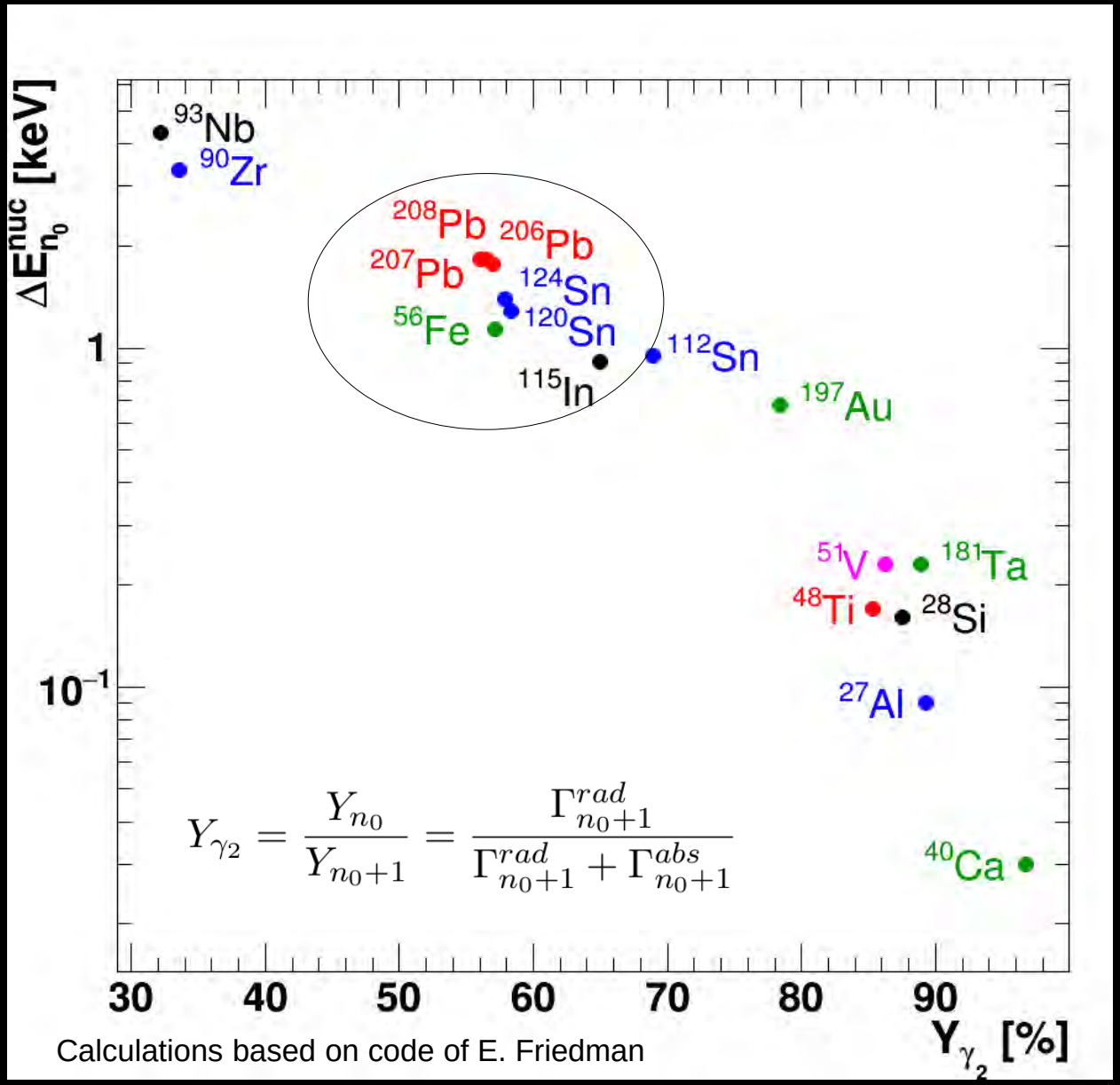
3. hyperon-nucleus interaction

Observable Quantities





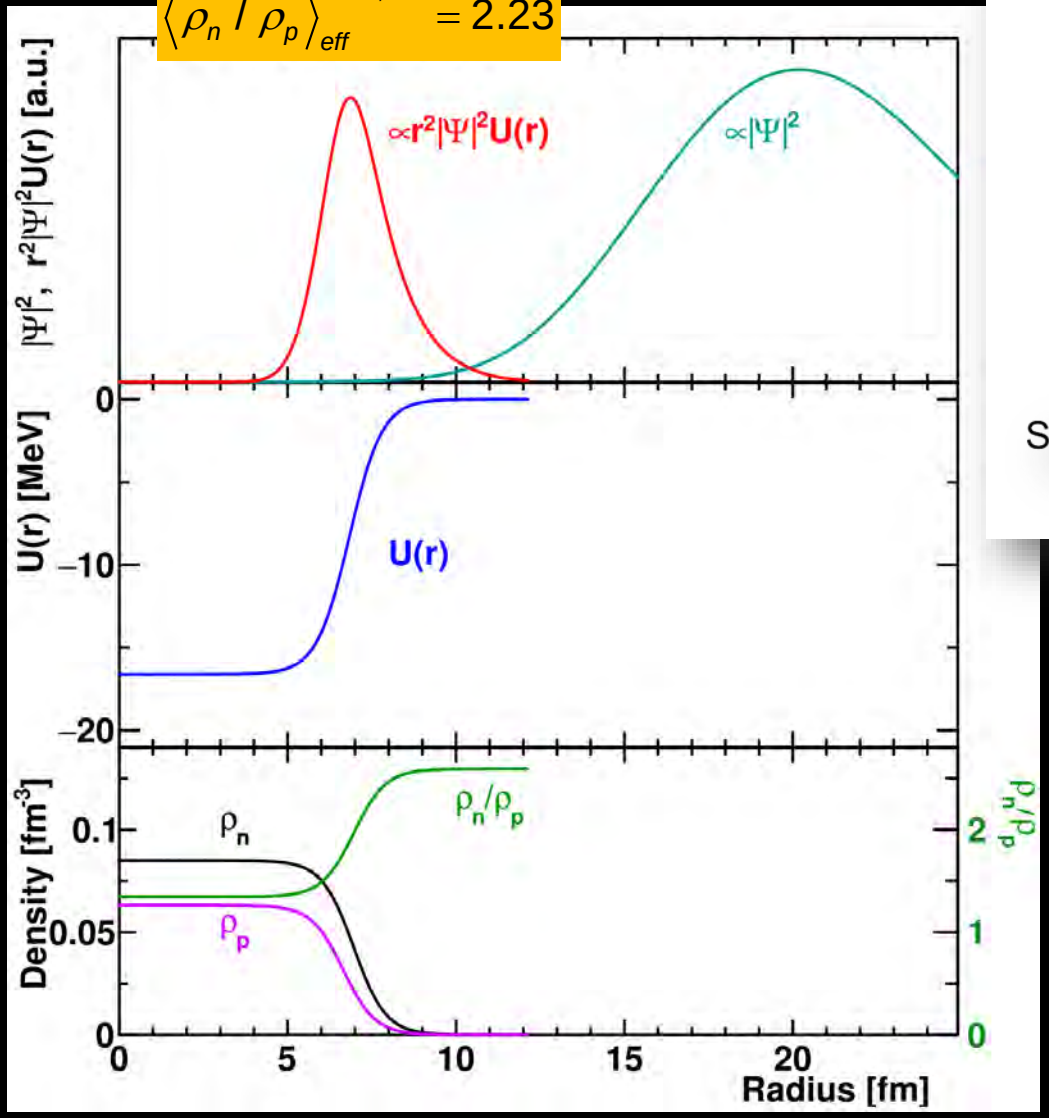
Choice of target nucleus

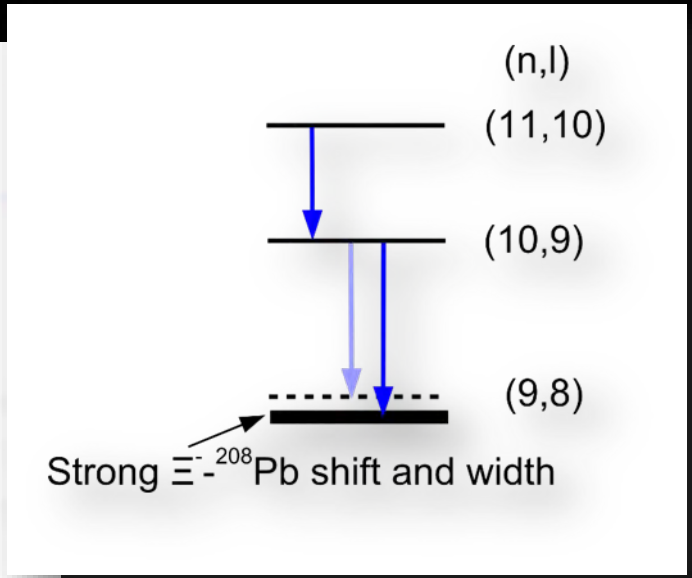


Calculations based on code of E. Friedman

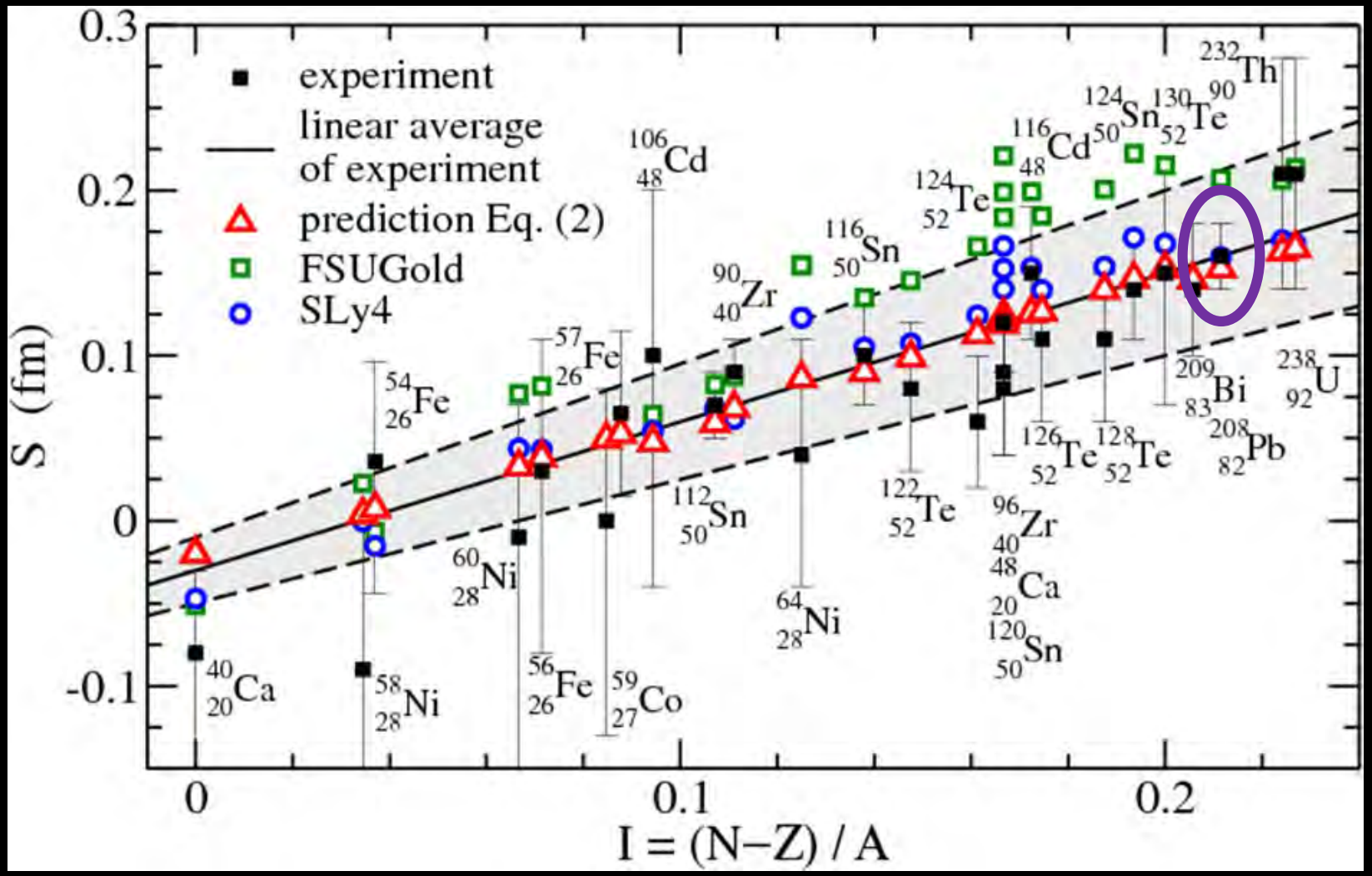
Why Pb is interesting?

$\left\langle \rho_n / \rho_p \right\rangle_{eff}^{n=10,l=9} = 2.23$



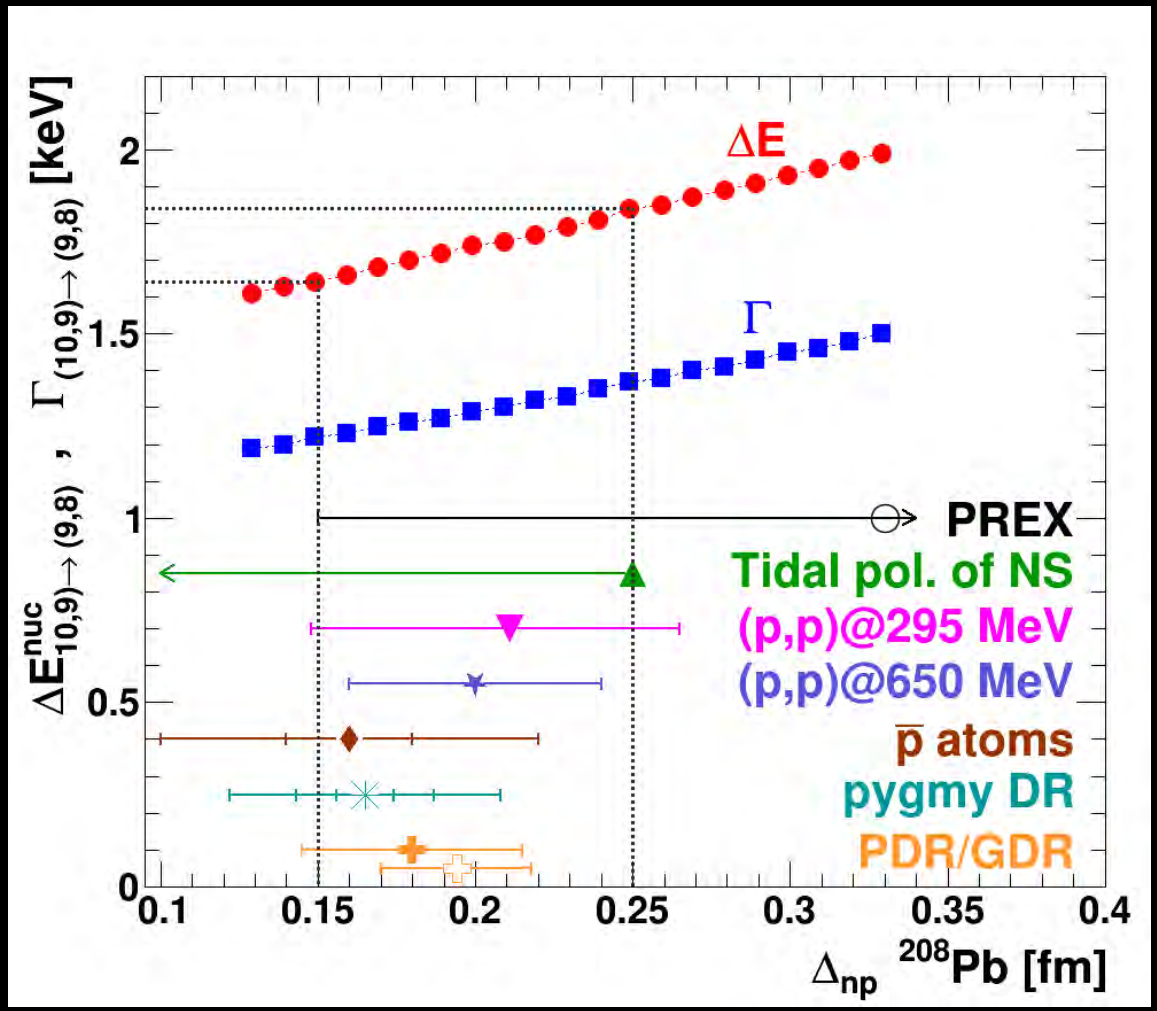


$\bar{p}$-Nuclei and Neutron Skins

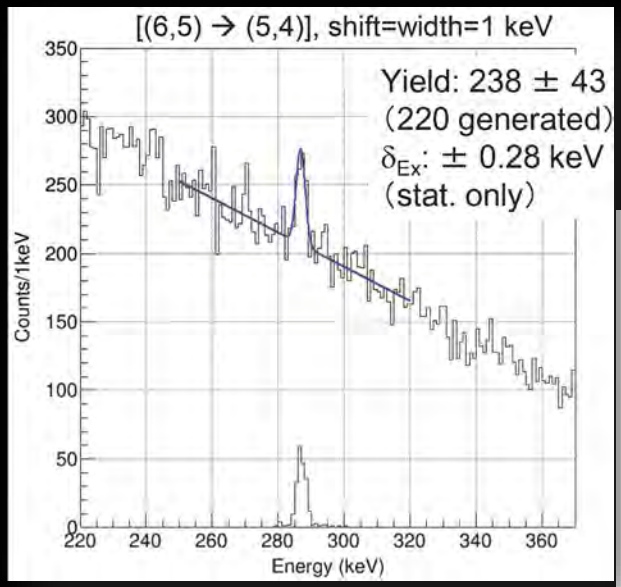


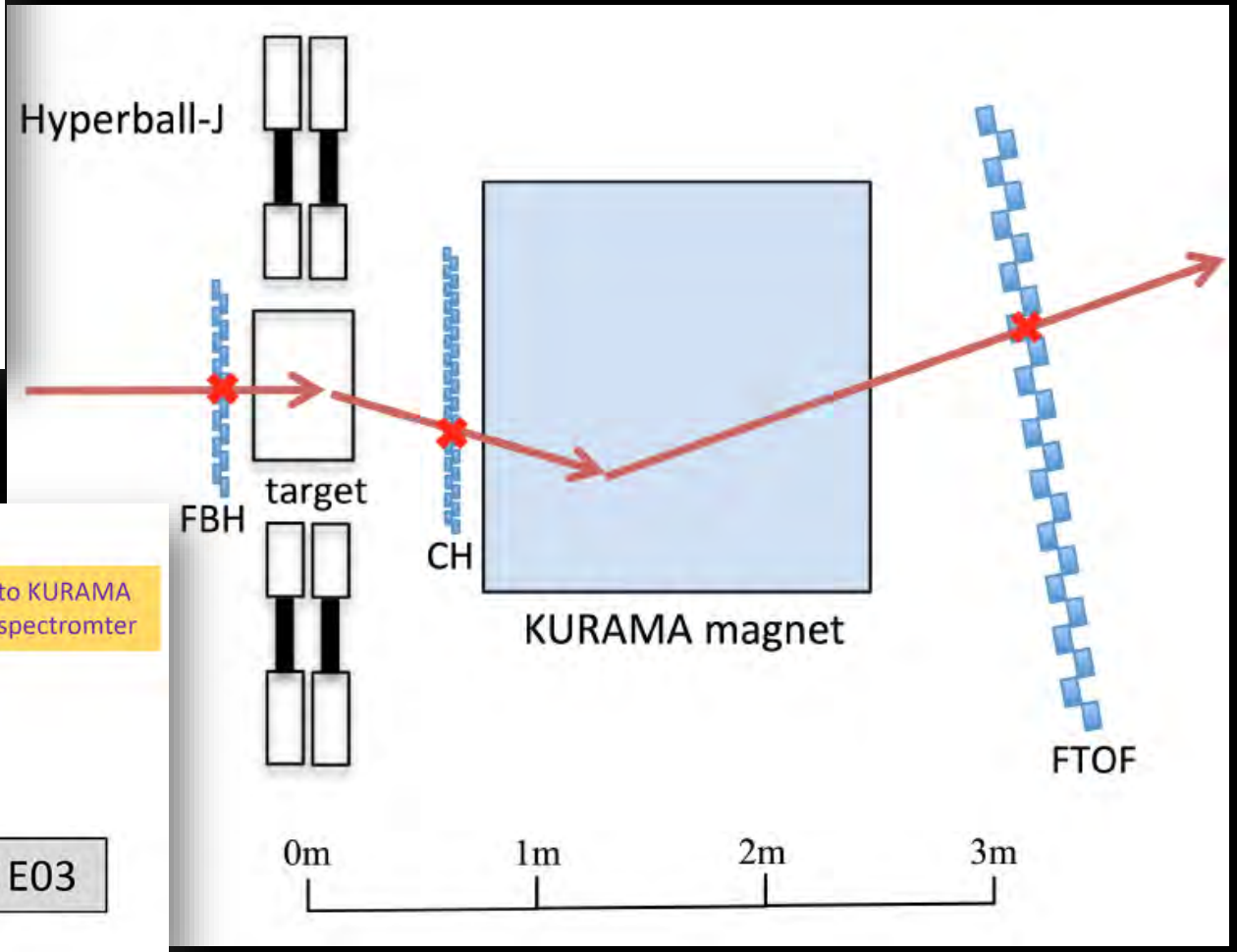
A. Trzcinska *et al.*

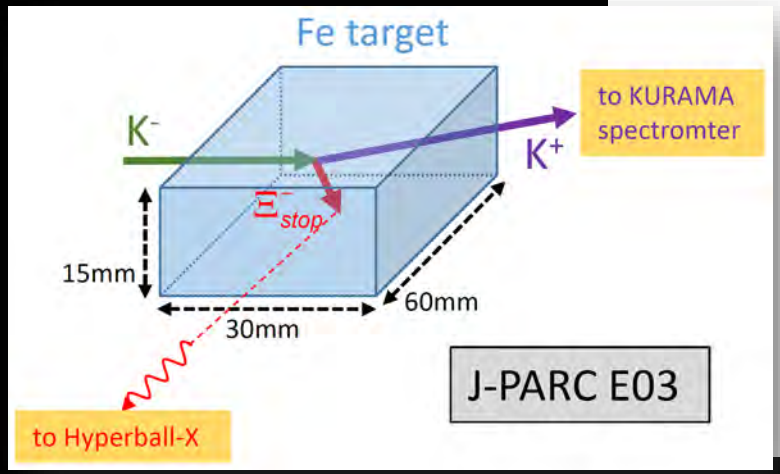
Let‘s Talk About Uncertainties



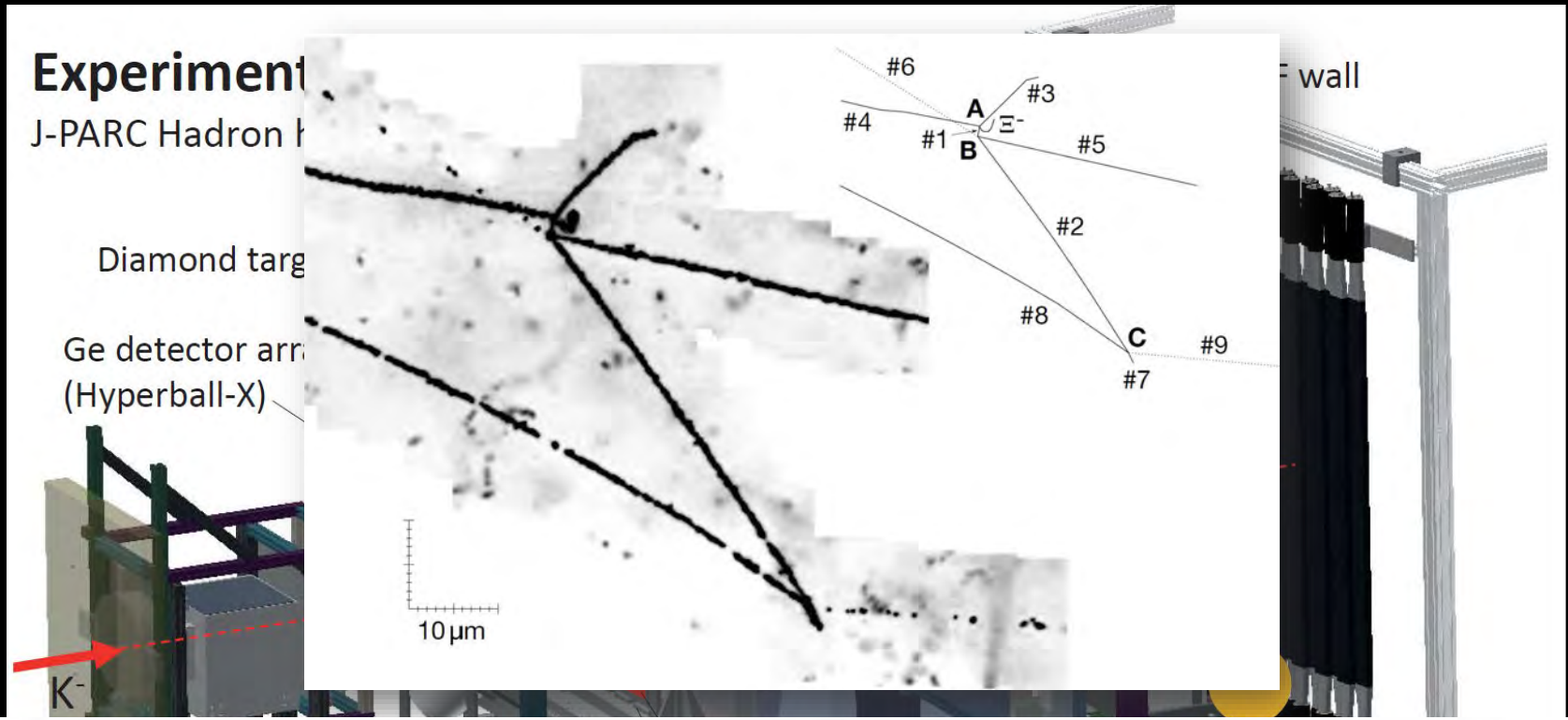
J-PARC E03

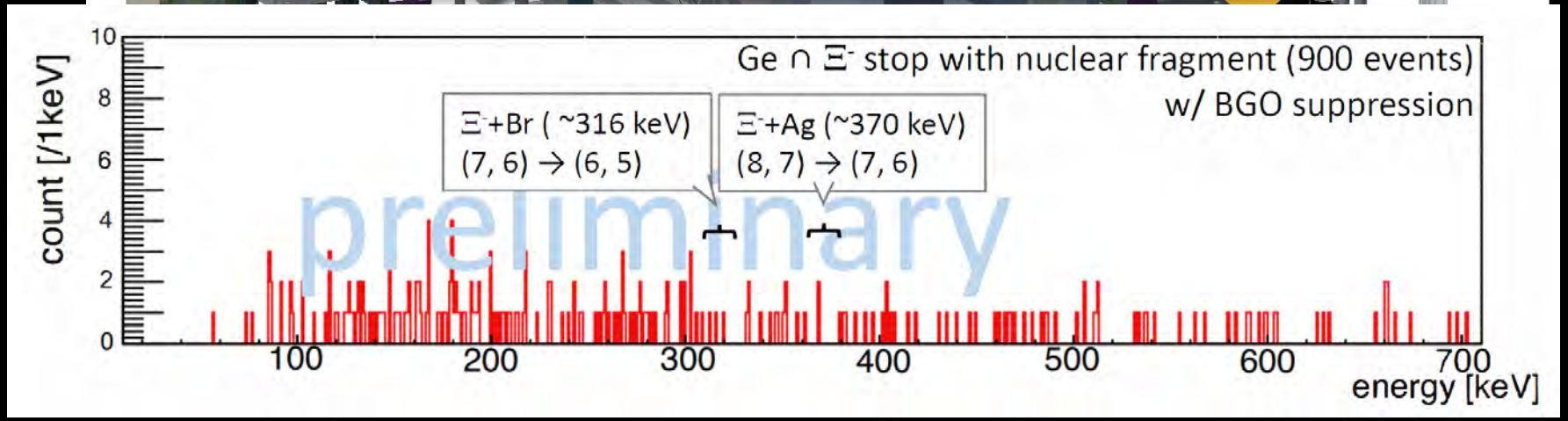

[(6,5) → (5,4)], shift=width=1 keV
Yield: 238 ± 43
(220 generated)
δ_{Ex}: ± 0.28 keV
(stat. only)
Counts/1keV
Energy (keV)


Hyperball-J
FBH
target
CH
KURAMA magnet
FTOF
0m
1m
2m
3m


Fe target
K⁻
K⁺
to KURAMA spectromter
Ξ⁻ stop
15mm
30mm
60mm
J-PARC E03
to Hyperball-X

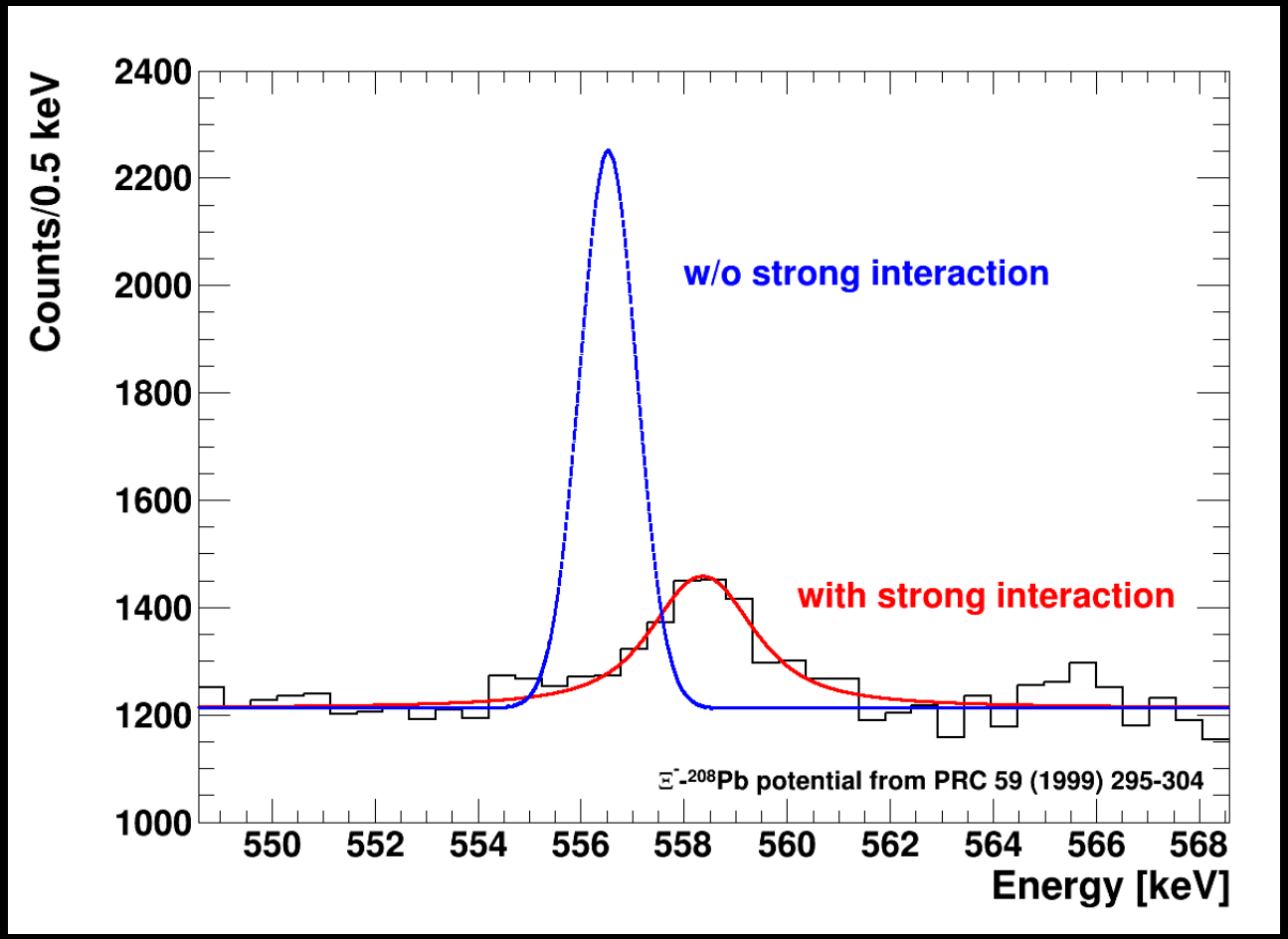
E07 @ J-PARC


Experiment
J-PARC Hadron
Diamond targ
Ge detector arr
(Hyperball-X)
K⁻
wall
#6
#3
#4
A
Ξ⁻
#1
B
#5
#2
#8
C
#9
#7
10 μm

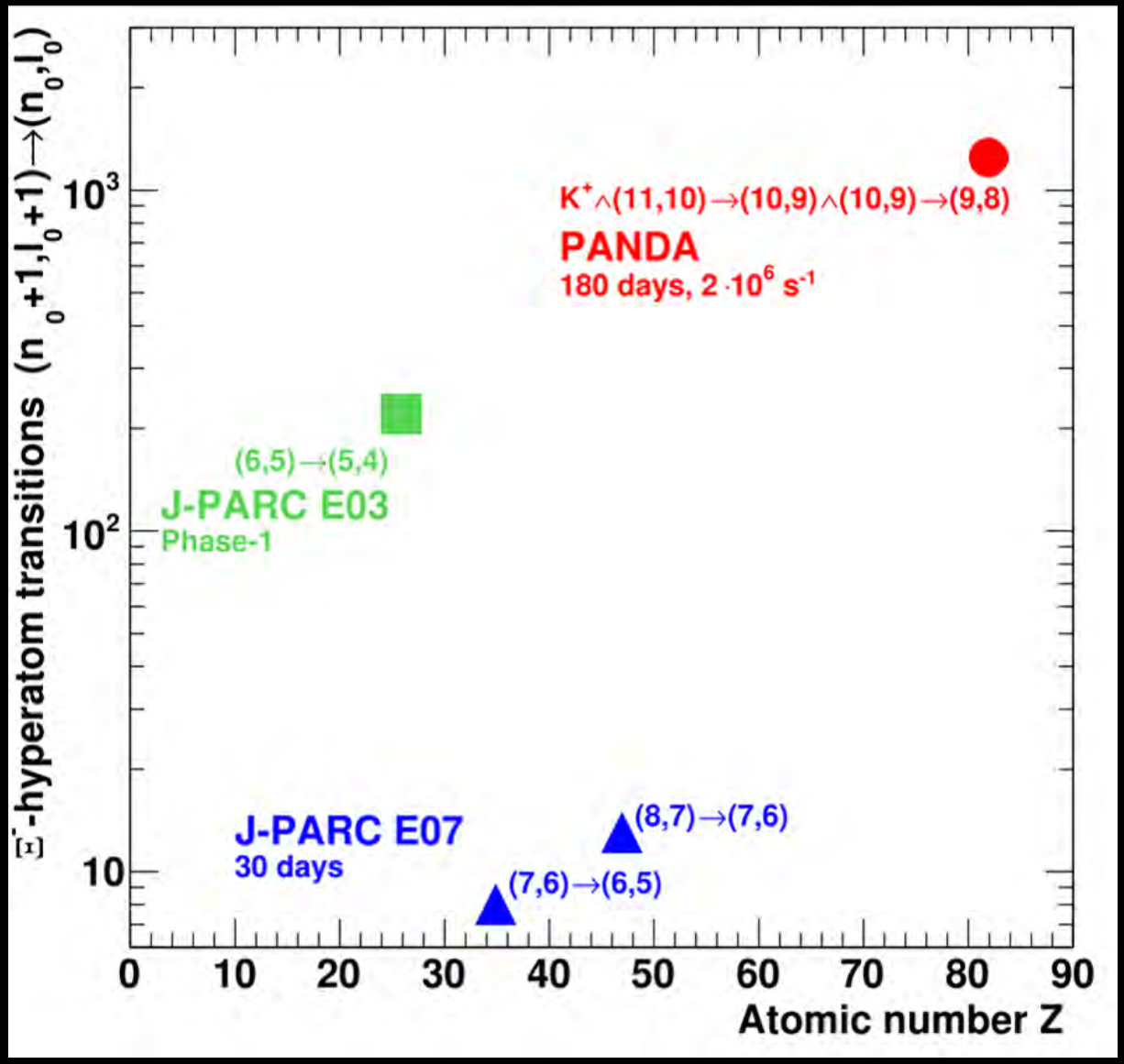

Ge ∩ Ξ⁻ stop with nuclear fragment (900 events)
w/ BGO suppression
Ξ⁻+Br (~316 keV)
(7, 6) → (6, 5)
Ξ⁻+Ag (~370 keV)
(8, 7) → (7, 6)
preliminary
count [/1keV]
energy [keV]
0
2
4
6
8
10
100
200
300
400
500
600
700

PANDA Expectation

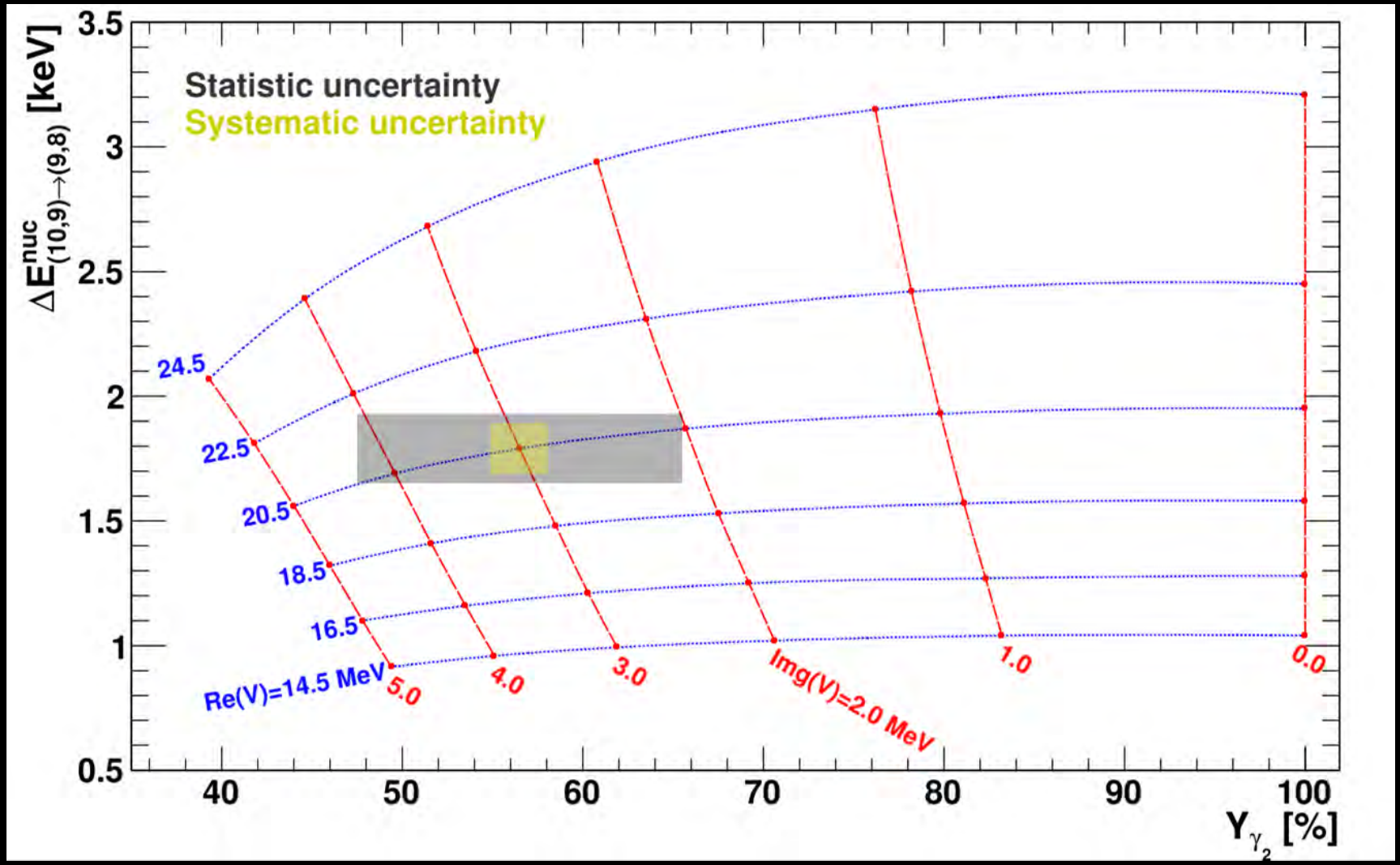
- 180 days data taking
- $2 \cdot 10^6$ interactions/s
- full simulation



Expected Ξ^- Atom Rates

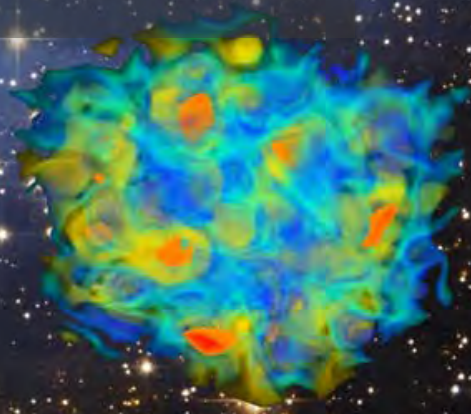


Ξ^- optical potential



Take-home message

- PANDA@HESR is a versatile experiment with a broad unique physics program
- Strangeness nuclear physics is embedded in the quest to determine the EOS of dense stellar systems
- Hypernuclei and hyperatoms are unique femto-laboratories for Y^nN^m interaction



Thank you for your attention