Heavy Ξ^- hyperatoms at $\bar{\mathrm{P}}$ANDA

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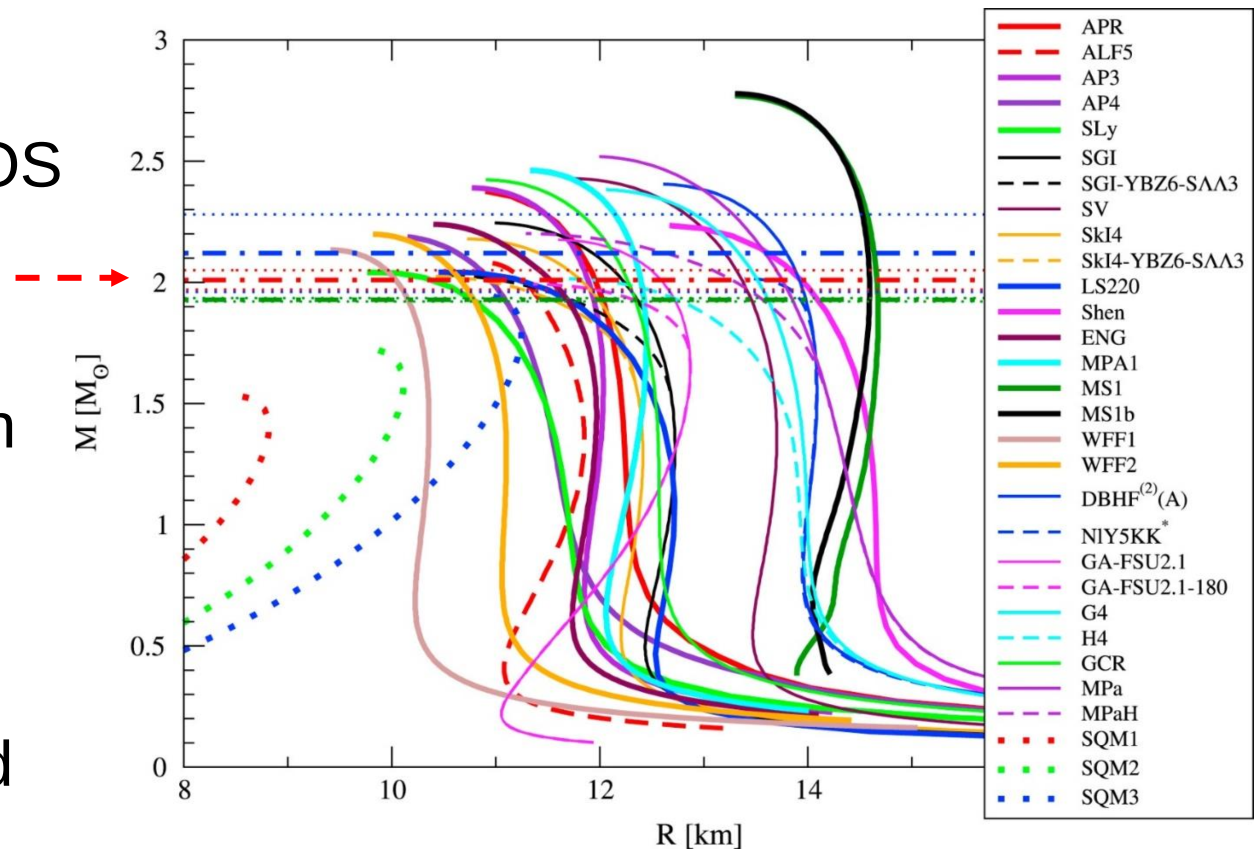
for the $\bar{\mathrm{P}}$ANDA collaboration

Helmholtz-Institut Mainz

PANIC 2021, Lisbon, 05/09/2021

Description of neutron stars

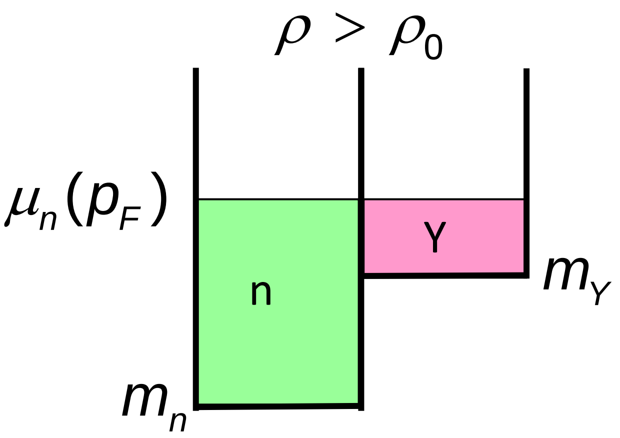
- Neutron stars described by EOS
- EOS must reach 2 m_{sun} threshold
- Models vary in composition and interaction

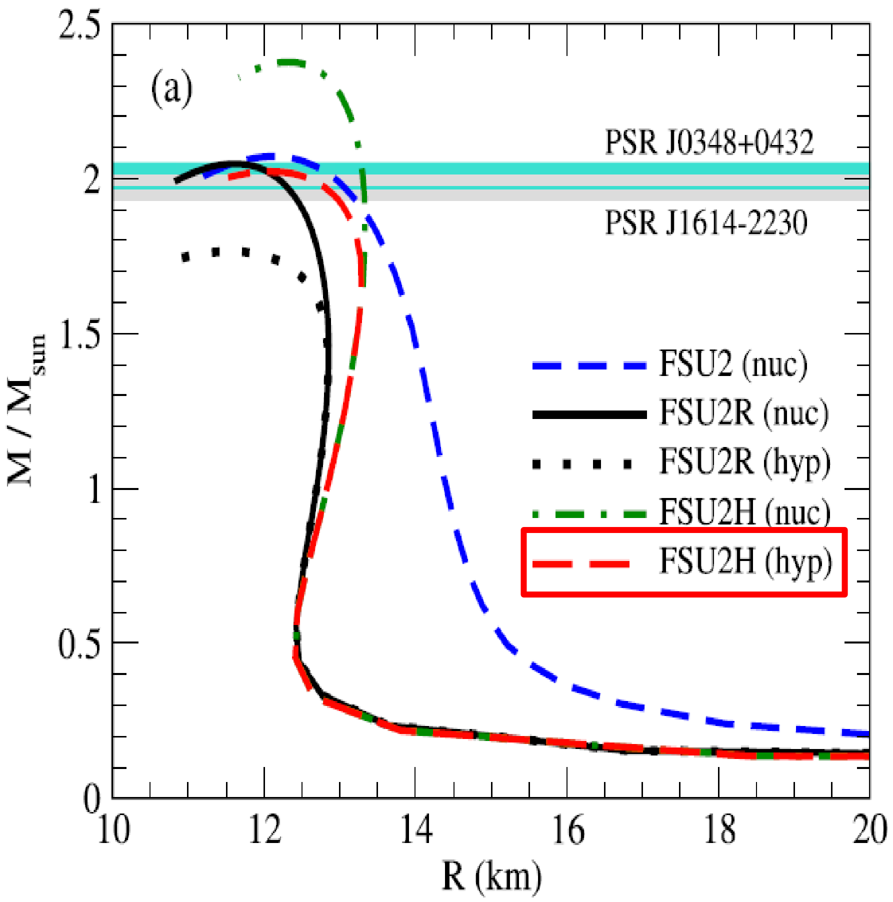


Demorest, R. et al. Nature 467 (2010)
Antoniadis, J. et al. Science 340.6131 (2013)

Yagi, K. et al. Phys Rep. 681 (2017)

Hyperon puzzle

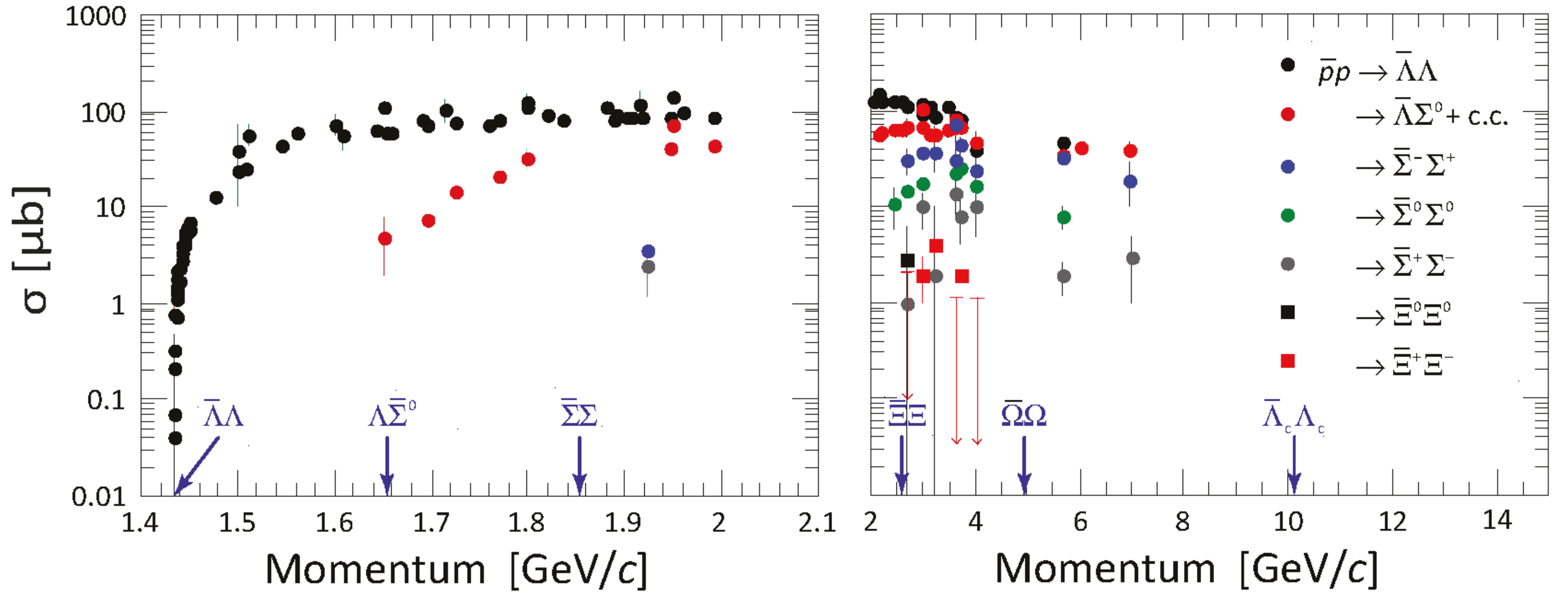




- Hyperons offer a new degree of freedom at 2*ρ_{nuc}
- Softening of EOS
- EOS with hyperons tuneable to be compatible with 2 m_{sun}

Bombaci, I JPS Conf. Proc. 17 (2017)
Antoniadis, J. et al. Science 340.6131 (2013)
Negreiros, R. et al. Astrophys. J. 863 (2018) 104

$\bar{\text{P}}$ANDA as hyperon factory



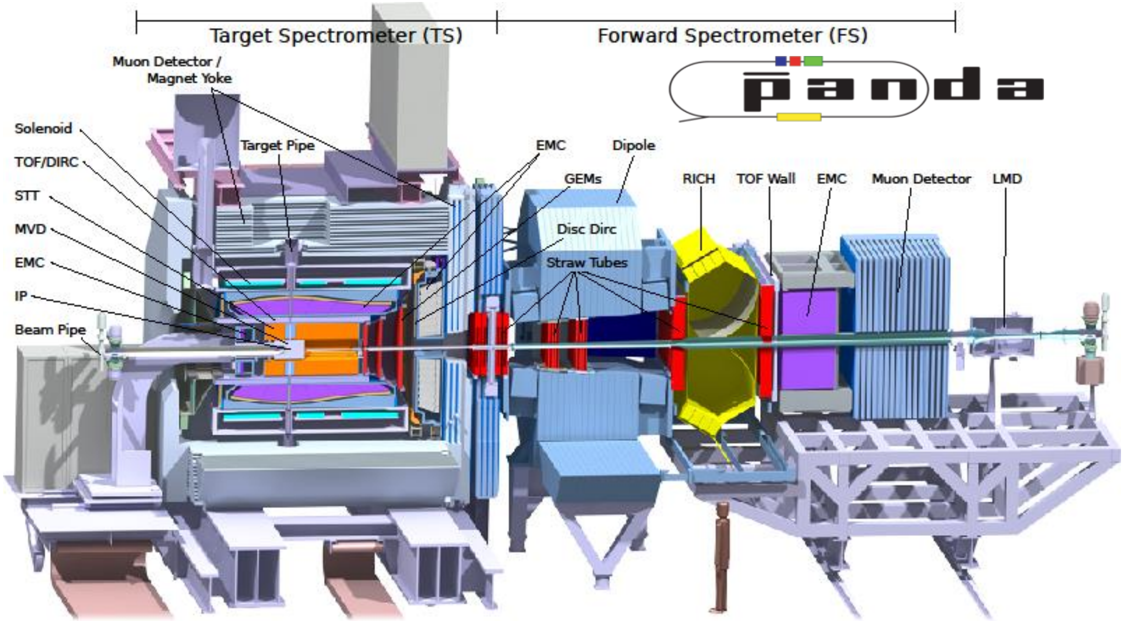
Production rates:	$\Lambda\bar{\Lambda}$	~1000 /s
@ 2 MHz p̄p	$\Xi^-\bar{\Xi}^+$	~100 /s

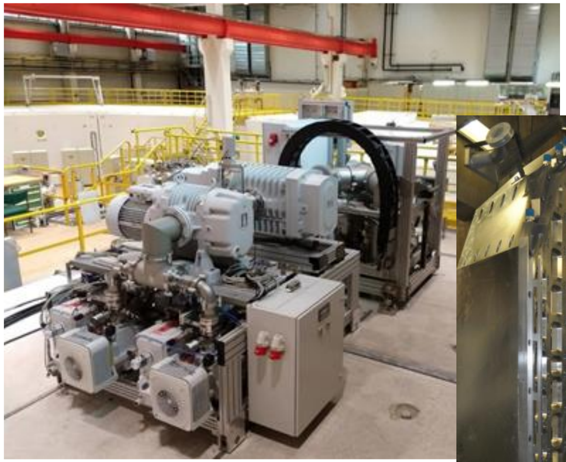
Panda Collaboration, Physics Performance Report for PANDA

P̄ANDA at FAIR

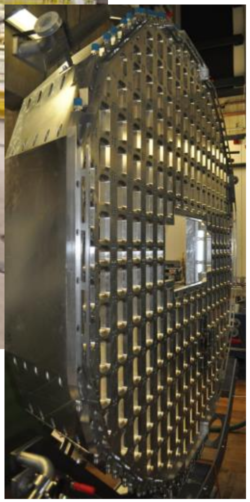
https://www.gsi.de/forschungbeschleuniger/fair/bau_von_fair/bilder_und_videos.htm

P̄ANDA detector





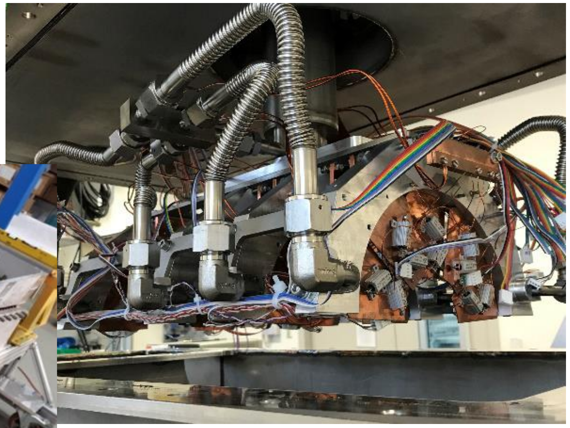
Cluster Jet-target



Calorimeter forward endcap

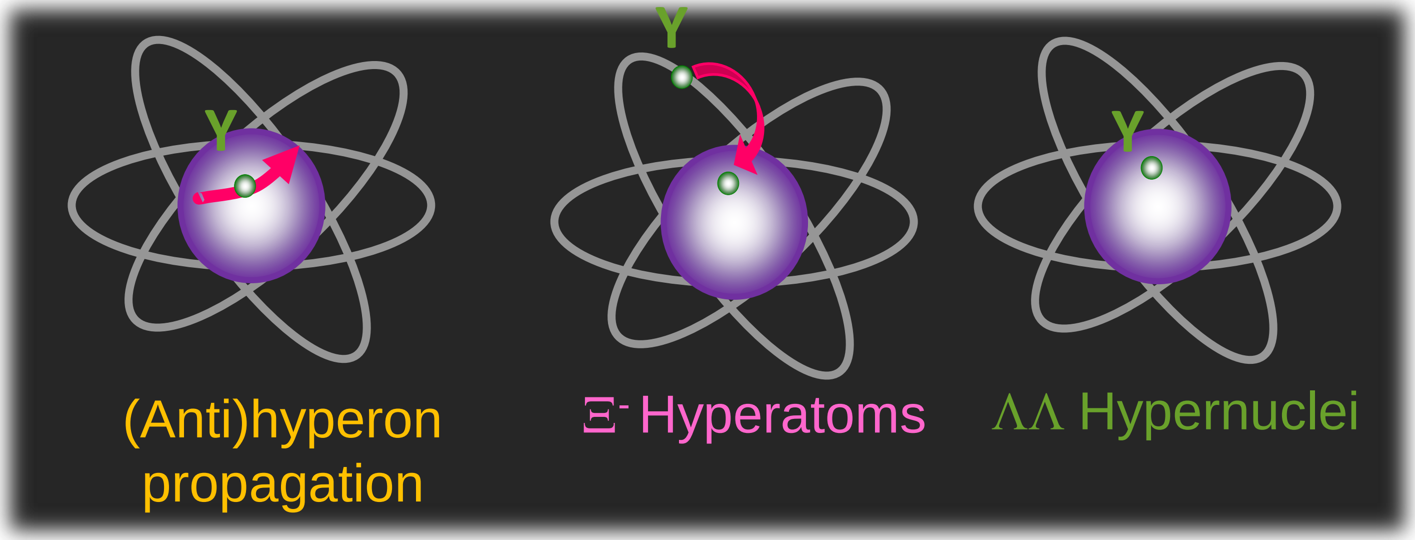
- Fixed target setup
- Target + forward spectrometer
- Solid angle ~4π

Slice of barrel calorimeter



Luminosity detector

Strangeness nuclear physics at $\bar{\text{P}}$ANDA



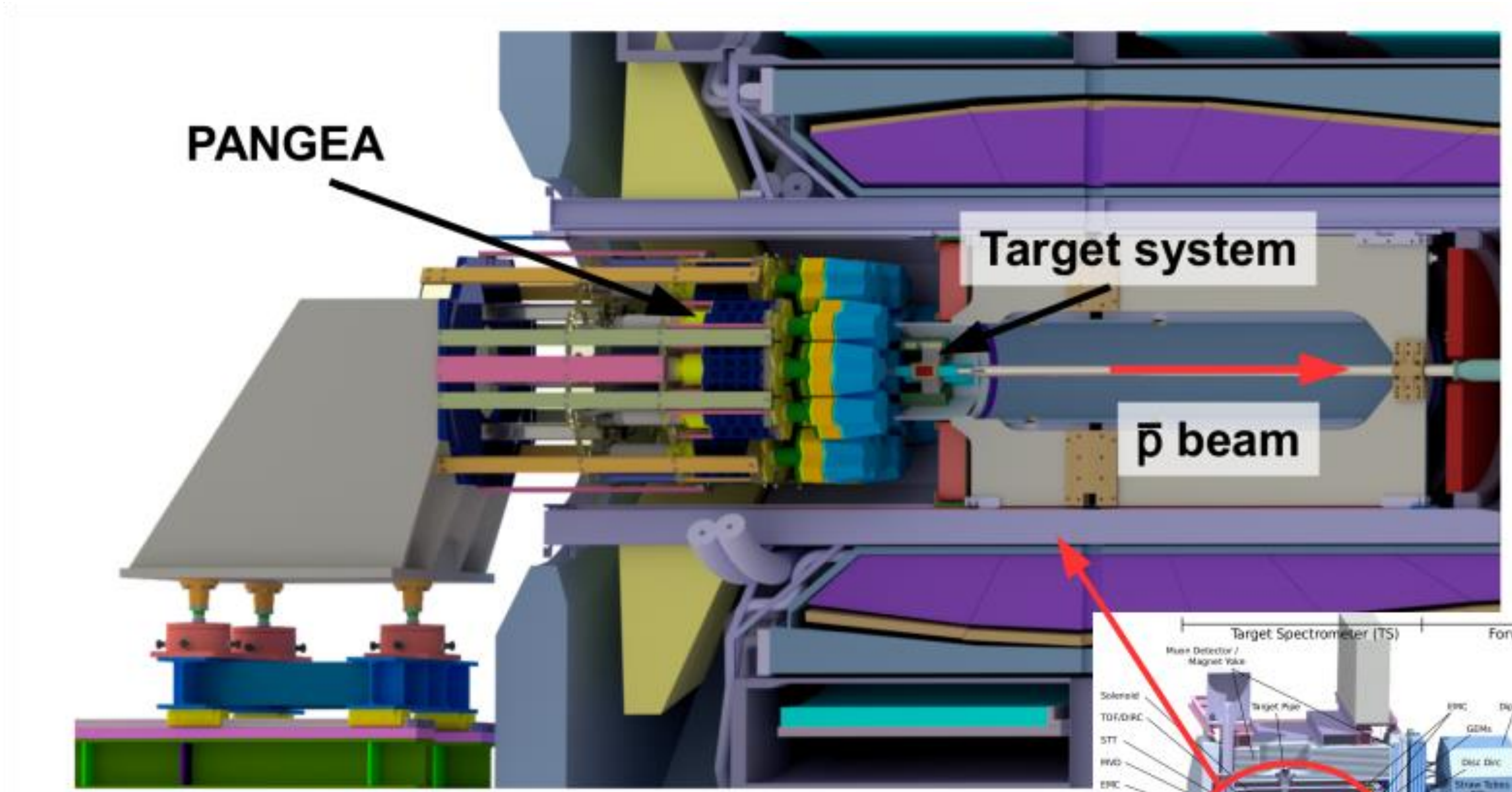
Phase 1 (~2026)

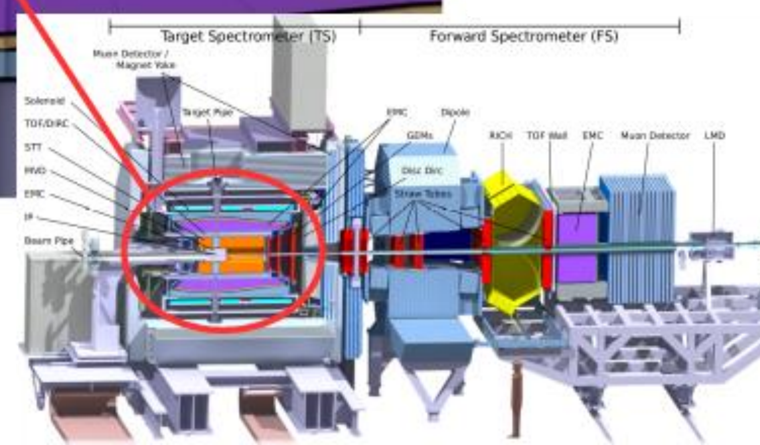
Phase 2 (2027+)

Pochodzalla et al. Nuclear Physics A 954 (2016)

Sanchez Lorente et al. Physics Letters B 749 (2015)

Hyperatom/nuclear setup

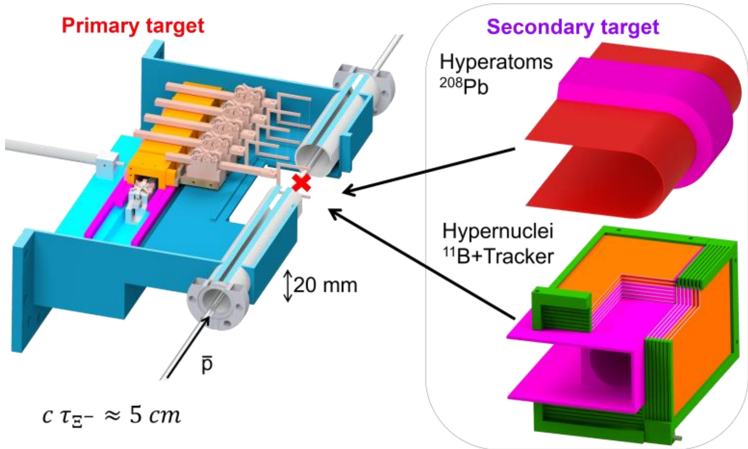


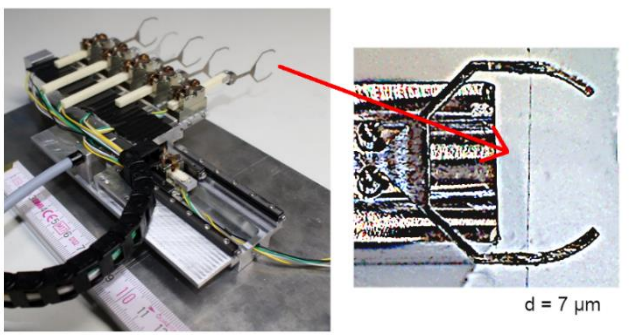


- Dedicated two-step target system
- PANda GErmanium Array

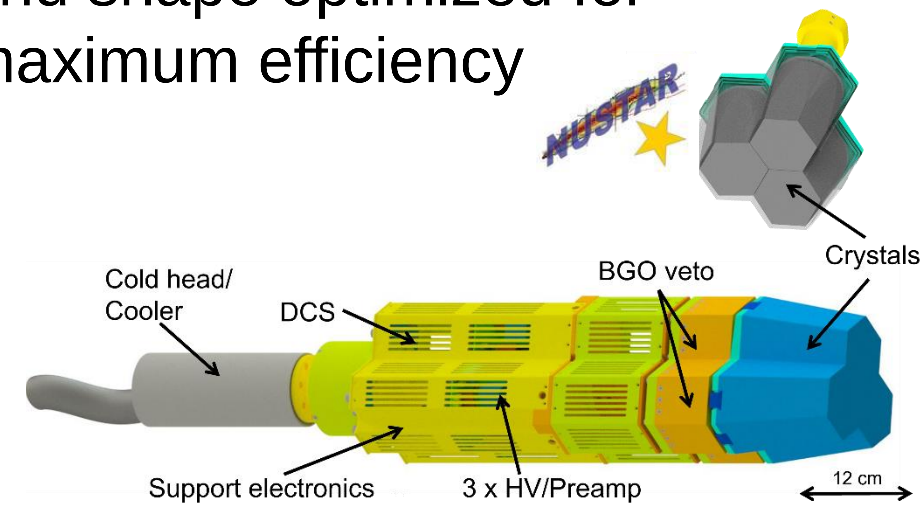
HIM HELMHOLTZ Helmholtz-Institut Mainz

Hyperatom/nuclear setup

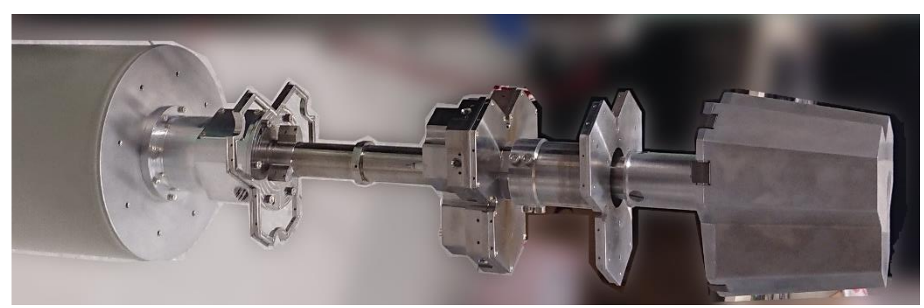




- Primary target constructed and tested
- Secondary target designed and shape optimized for maximum efficiency

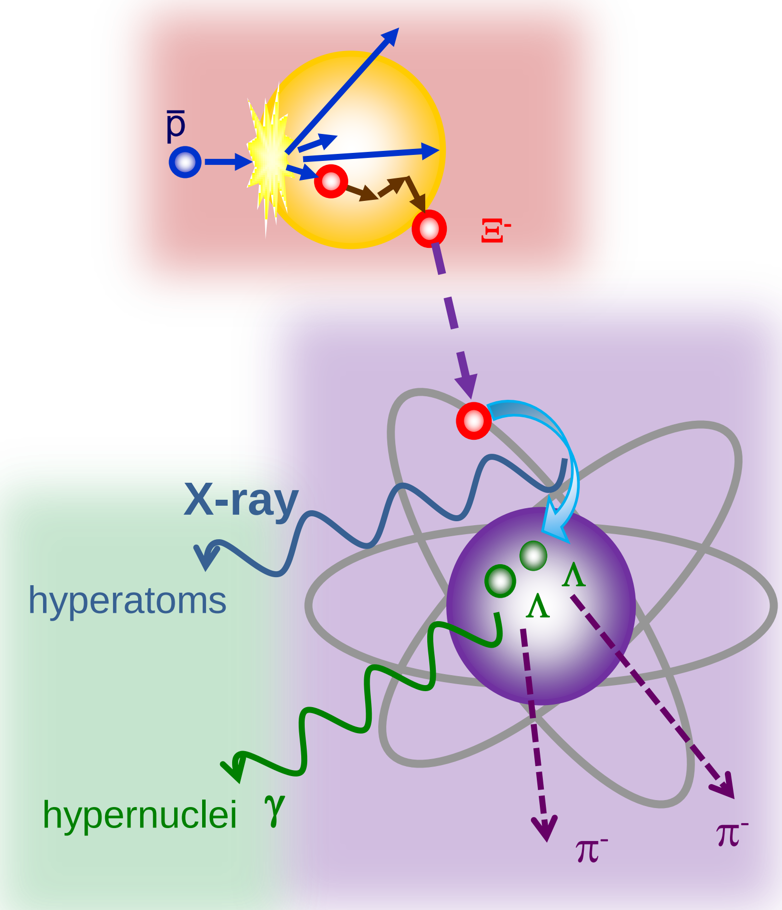


- Radiation hardness of PANGEA tested
- First detectors constructed in collaboration with NUSTAR

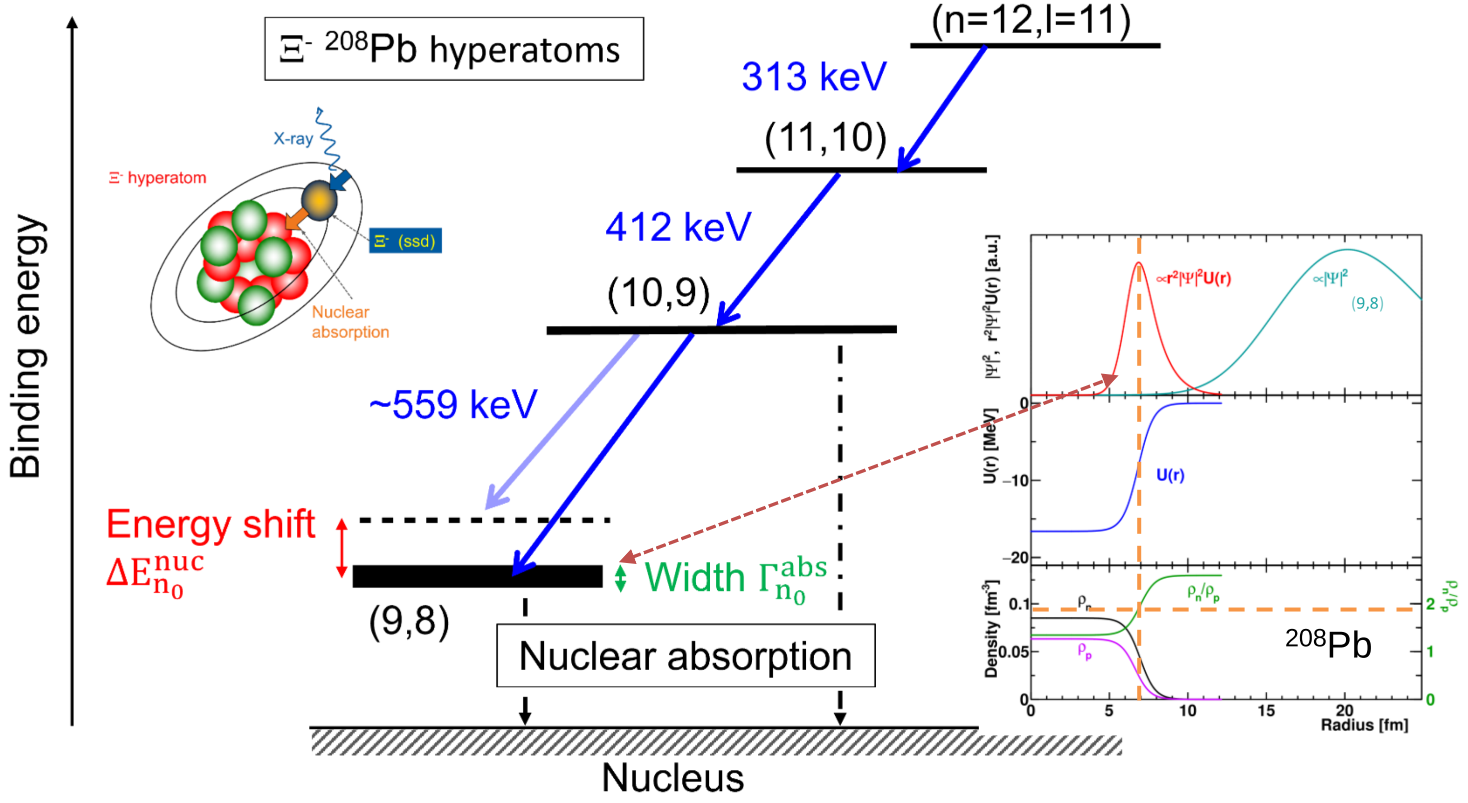


Production of hyperatoms

- **Primary target**
  - Production of Ξ^-
    $\bar{p}\,A \rightarrow \Xi^- \bar{\Xi}^{+/0} + A'$
  - K^+ from $\bar{\Xi}^{+/0}$ decay as tag
- **Secondary target**
  - Stopping of Ξ^- before decay
  - **Atomic** cascade of Ξ^-
  - Nuclear conversion
    $\Xi^- + p \rightarrow \Lambda\Lambda + 28$ MeV
- **PANGEA**
  - X-ray spectroscopy of heavy Ξ^- **hyperatoms** (0.1 - 1 MeV)
  - γ spectroscopy of light $\Lambda\Lambda$ hypernuclei (0.1 - 10 MeV)



X-ray spectroscopy of Ξ⁻ hyperatoms

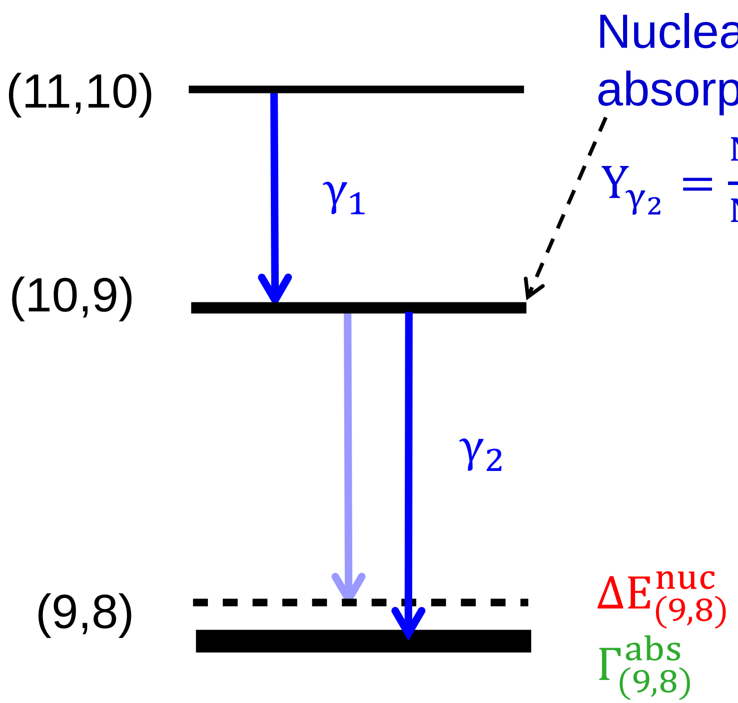


Measurement of energy shift and width

-> complex V_Ξ in neutron-rich nuclear periphery

Succesful method for π^-, K^-, $\bar{p}$, Σ^- atoms

Observables

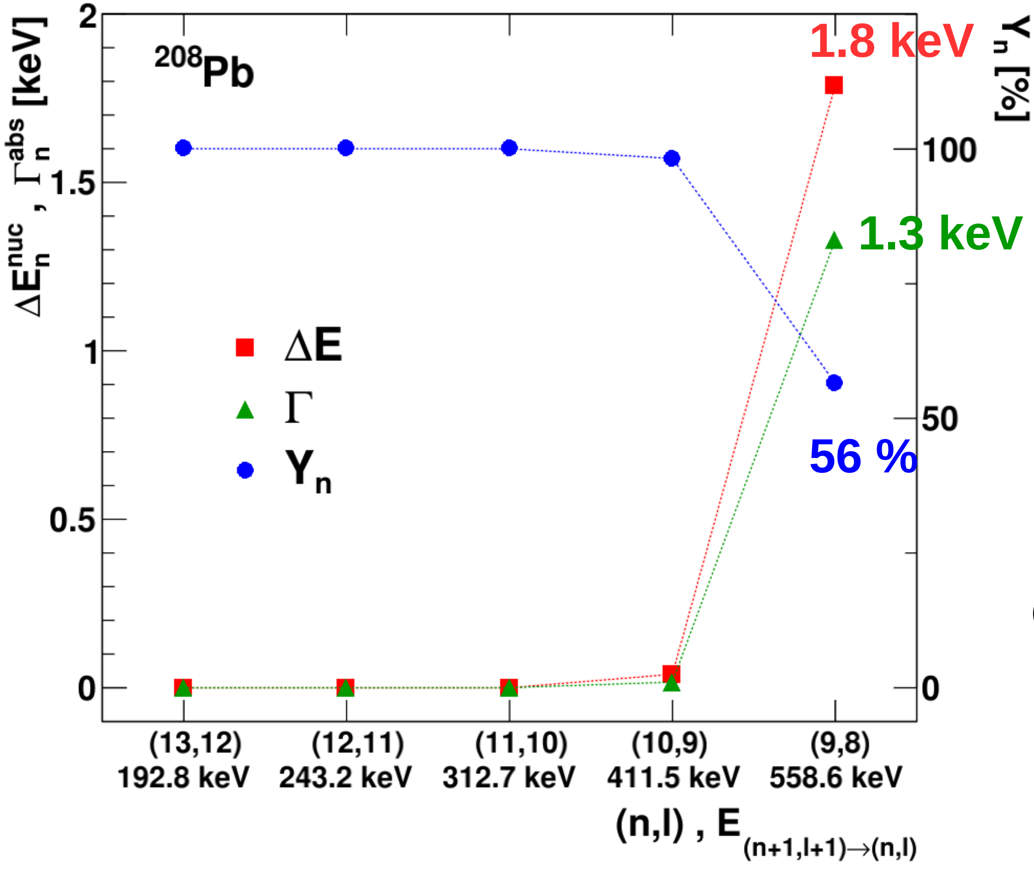


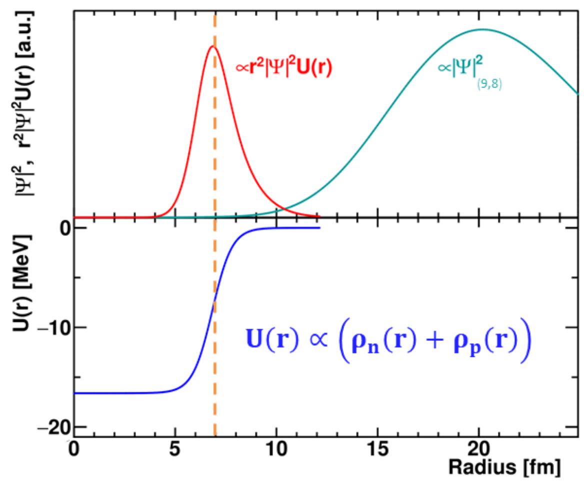
$$Y_{\gamma_2} = \frac{N_{\gamma_2}}{N_{\gamma_1}} = \frac{\Gamma^{em}_{(10,9)}}{\Gamma^{em}_{(10,9)} + \Gamma^{abs}_{(10,9)}}$$

Observables calculated for various possible hyperatoms

Calculations performed with code by Eli Friedman based on Batty, C. J. et al. Phys. Rev. C 59 (1999)

Observables of Ξ⁻ - ^{208}Pb



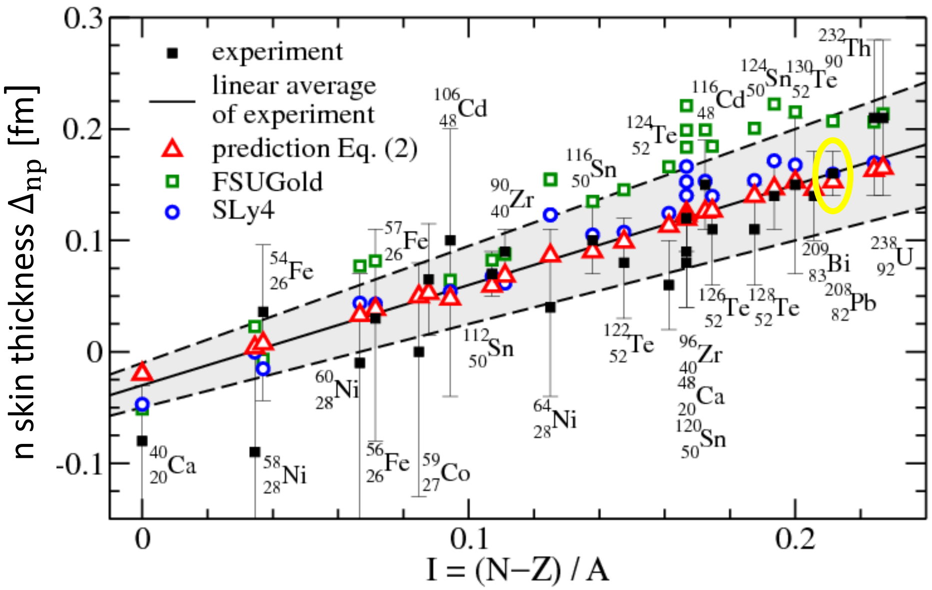


Observables influenced by

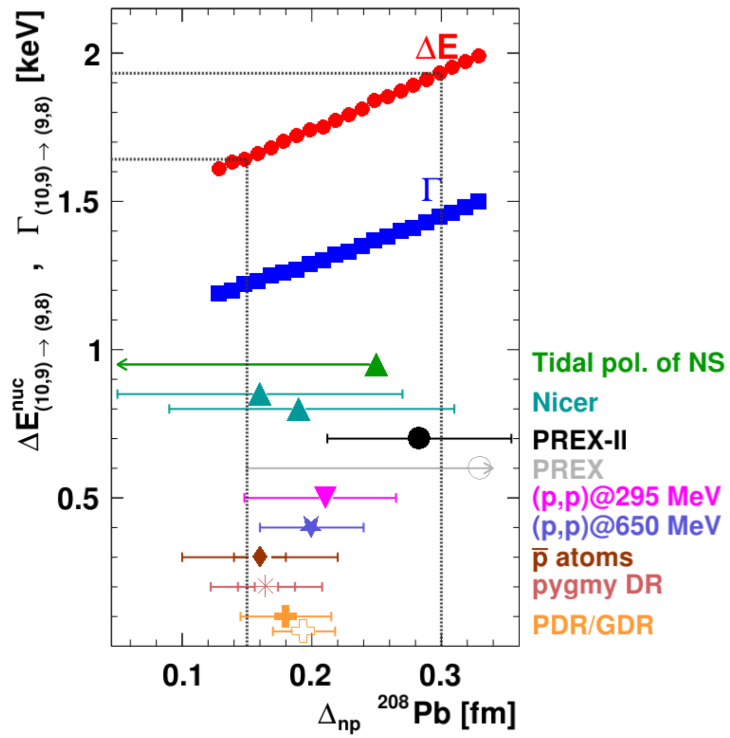
- Ξ⁻ - nucleus interaction
- Ξ⁻ wave form (QED)
- Nucleon distribution

Calculations performed with code by Eli Friedman based on Batty, C. J. et al. Phys. Rev. C 59 (1999)

Systematic uncertainties

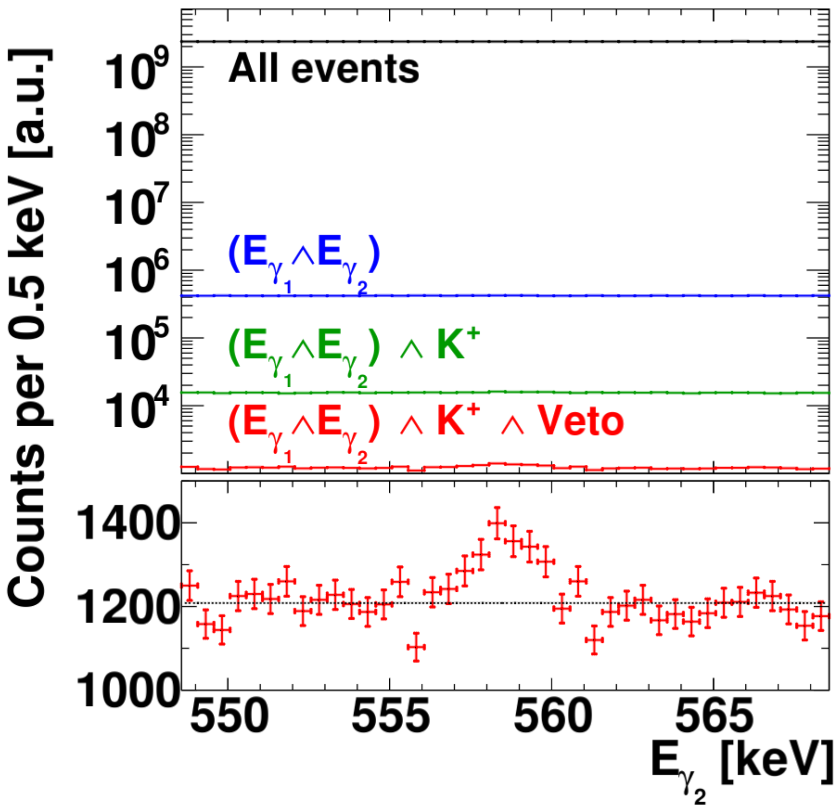


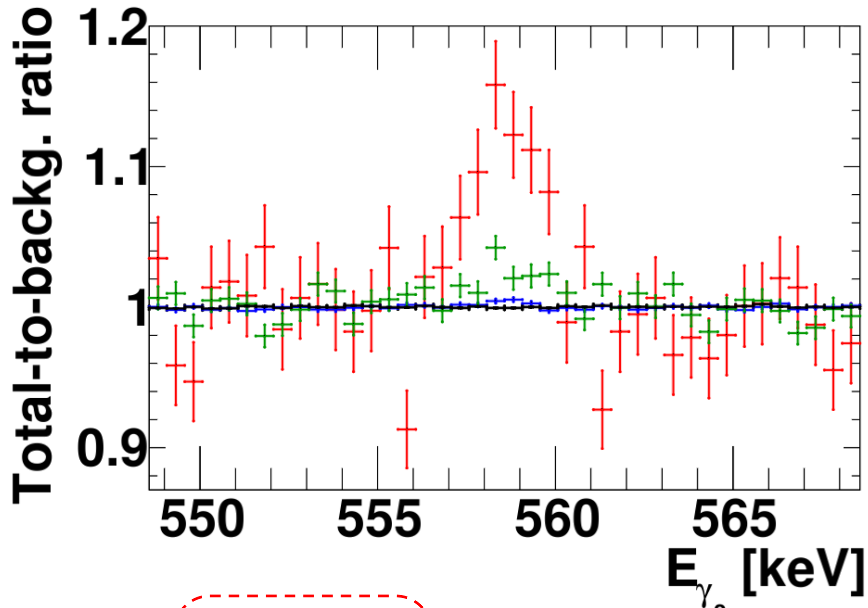
Centelles et al. Phys.Rev.Lett. 102 (2009) 122502

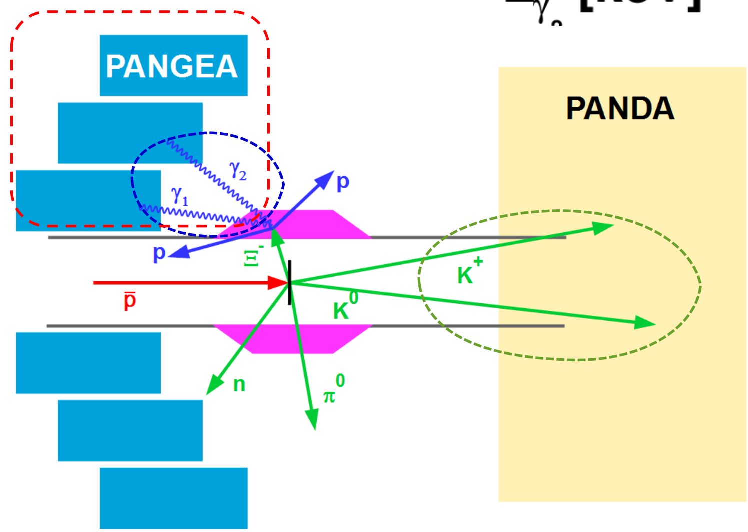


- Neutron skin Δ_{np} in ^{208}Pb well-known
- Present uncertainty of Δ_{np} → Systematic uncertainty in observables
- $\boldsymbol{\delta\left(\Delta E^{nuc}_{(10,9)\rightarrow(9,8)}\right)_{sys}}$ **~ ± 150 eV**

Full simulation in PandaRoot

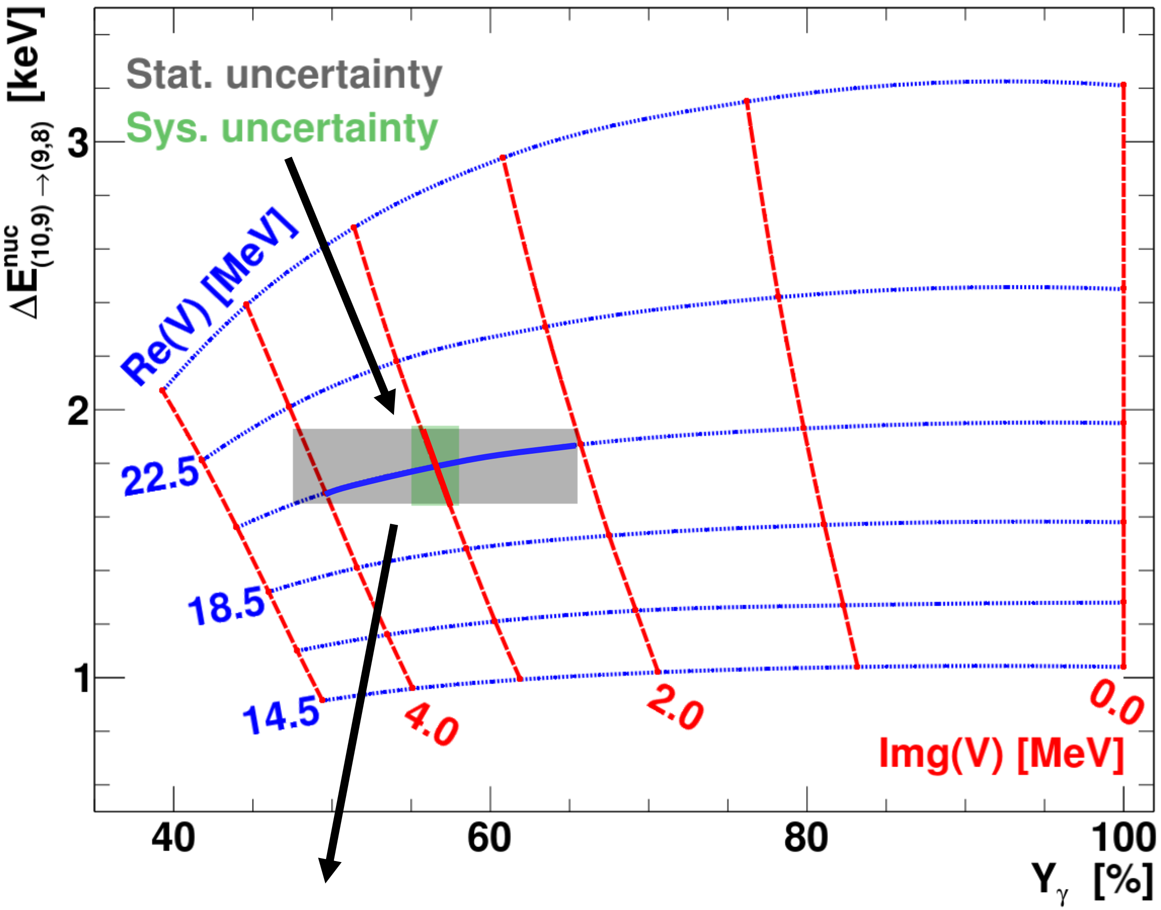






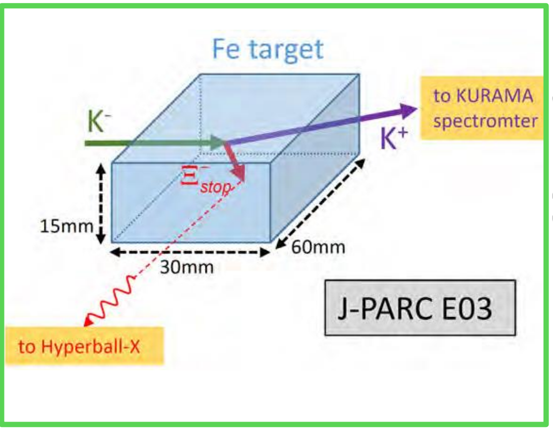
- Remaining Signal: 1237 (6.2 %)
  - 180 days at 2 MHz $\bar{p}$C
- $\boldsymbol{\delta\left(\Delta E^{nuc}_{(10,9)\rightarrow(9,8)}\right)_{stat}}$ **= ± 140 eV**

Estimation of V_{Ξ}

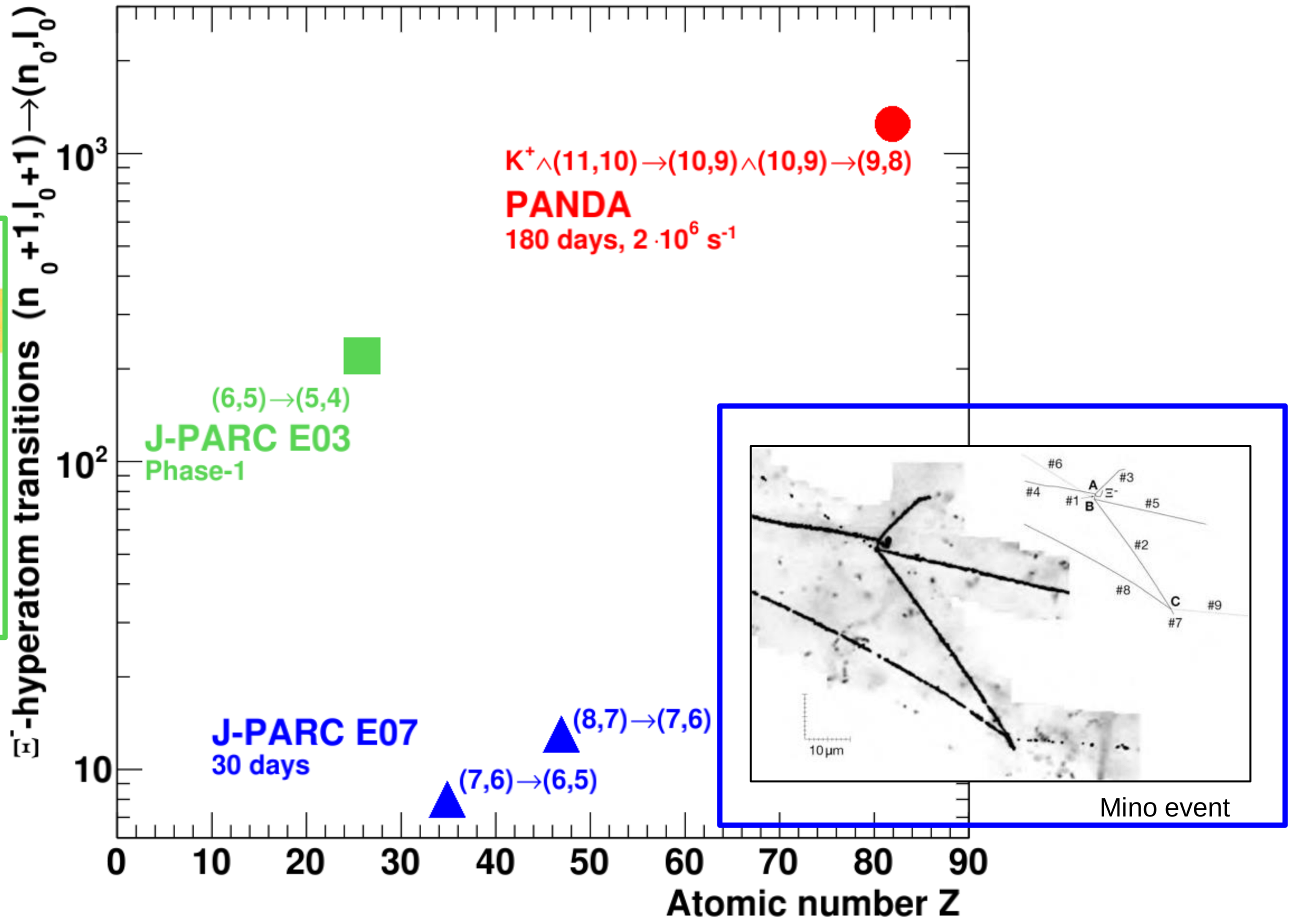


$$\delta(\mathrm{Re}(V_{\Xi}))_{stat} \approx \delta(\mathrm{Im}(V_{\Xi}))_{stat} \approx 1\ \mathrm{MeV}$$

Complementary experiments



K.Tanida et al. Proposal J-PARC E03



H. Ekawa et al. Prog. Theor. Exp. Phys. 2019, 2 (2019)

Details on J-PARC hyperatom activities:
Talk of T. O. Yamamoto (wednesday)

Take-home message

- Strangeness nuclear physics at $\bar{\text{P}}$ANDA can help to understand the inner structure of neutron stars.
- X-ray spectroscopy of heavy Ξ^- hyperatoms at $\bar{\text{P}}$ANDA is unique and complementary to J-PARC E03/07.
- Work on the simulations is progressing (background suppression, K^+ efficiency, more channels?)
- Development of hardware is ongoing