JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

HELMHOLTZ Helmholtz-Institut Mainz

# High precision X-ray spectroscopy of $\Xi^-$ hyperatoms at $\bar{\text{P}}$ANDA

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Helmholtz-Institut Mainz

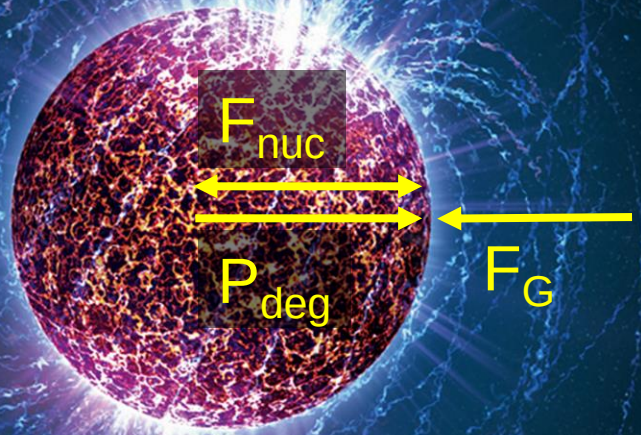
Mündliche Doktorprüfung, 20.5.2020

# Outline

- Neutron stars and hyperons
- Strangeness nuclear physics at $\bar{P}$ANDA
- $\Xi^-$ $^{208}$Pb hyperatom experiment at $\bar{P}$ANDA

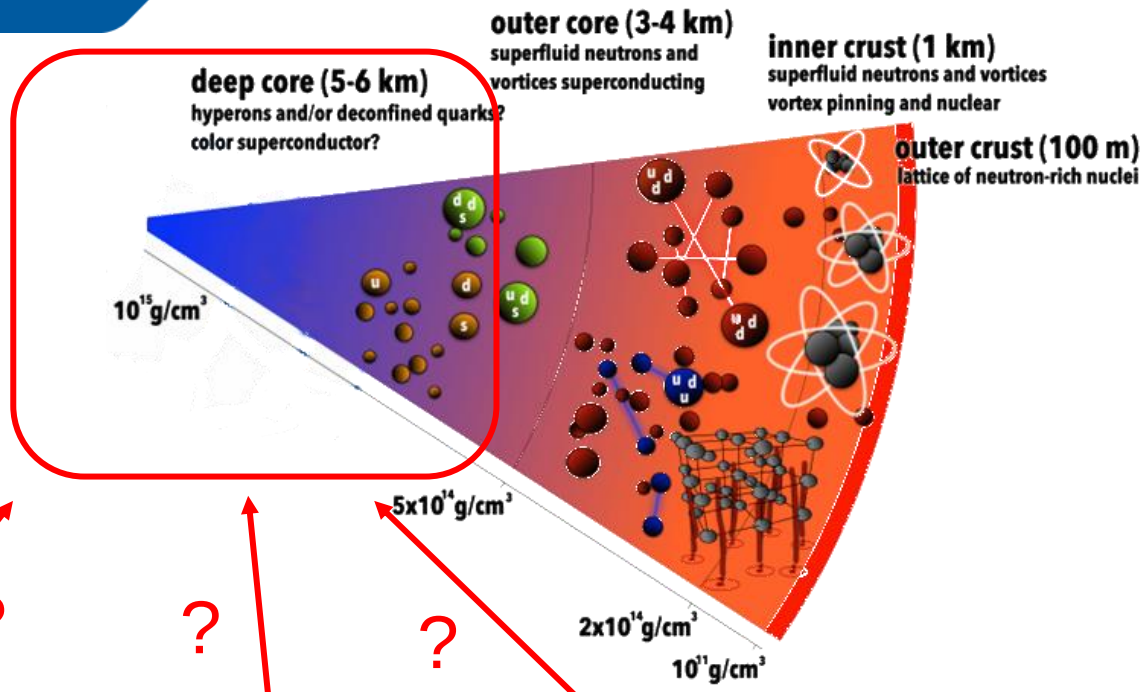
# Neutron stars

- Extremely dense stellar objects
  - $M_{NS} \sim 1\text{-}2\ M_{\odot}$
  - $R \sim 12$ km
    - → $\rho_{Core} > \rho_{nuc}$
- Giant nucleus



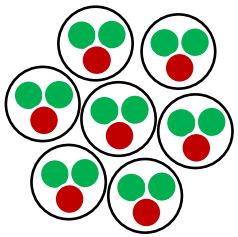

- Evolution of neutron stars described by Equation of state (EOS) $P = P(\rho,T)$

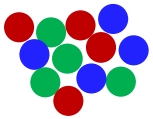
# Composition of neutron stars

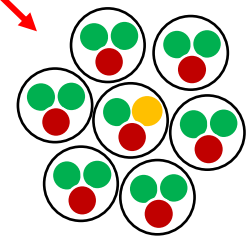



- up quark
- down quark
- strange quark

? ? ?







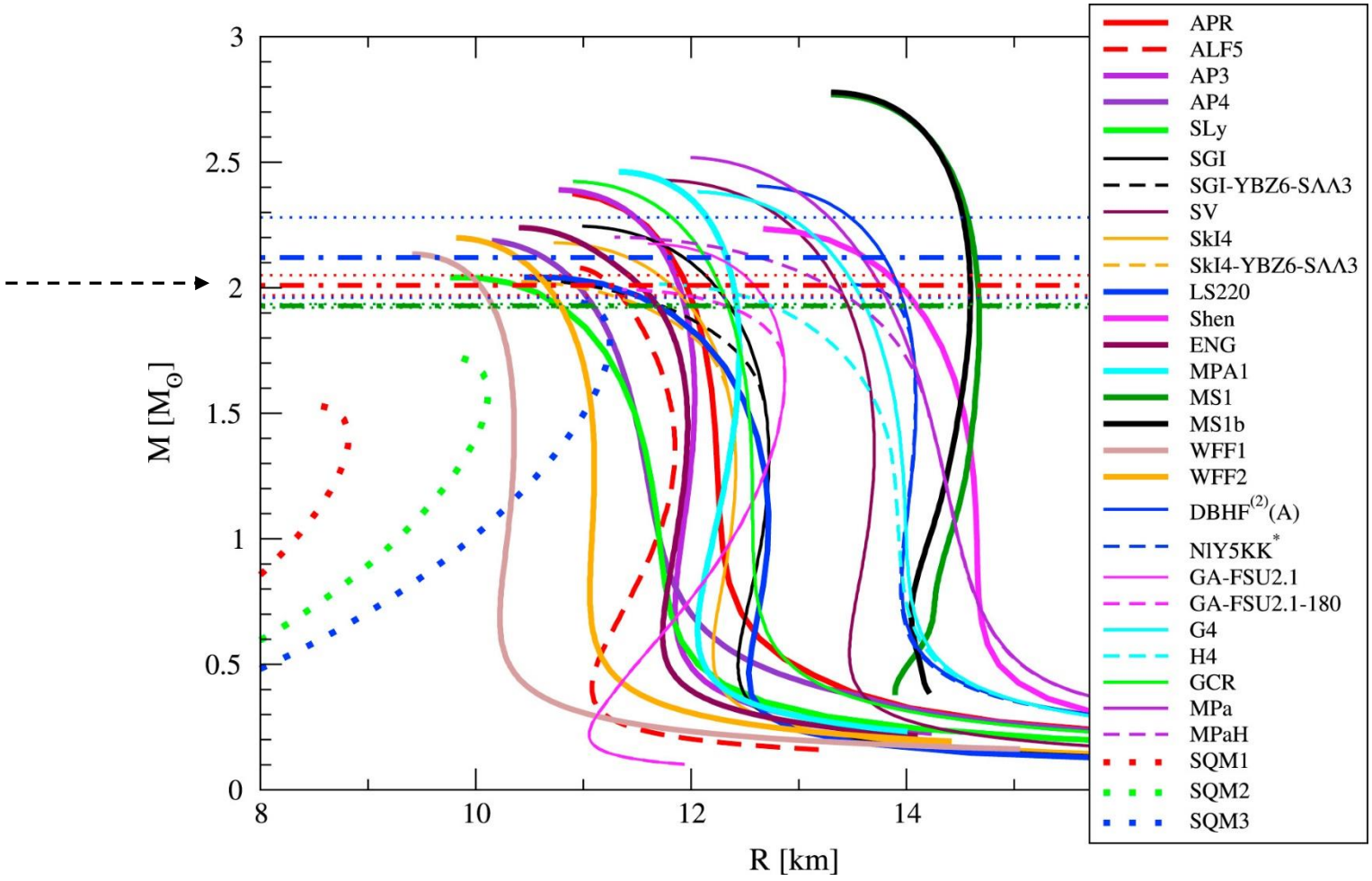
Neutron-only star

Quark star

Neutron+Hyperon star

*Watts, A. et al. PoS AASKA14 (2015) 053*

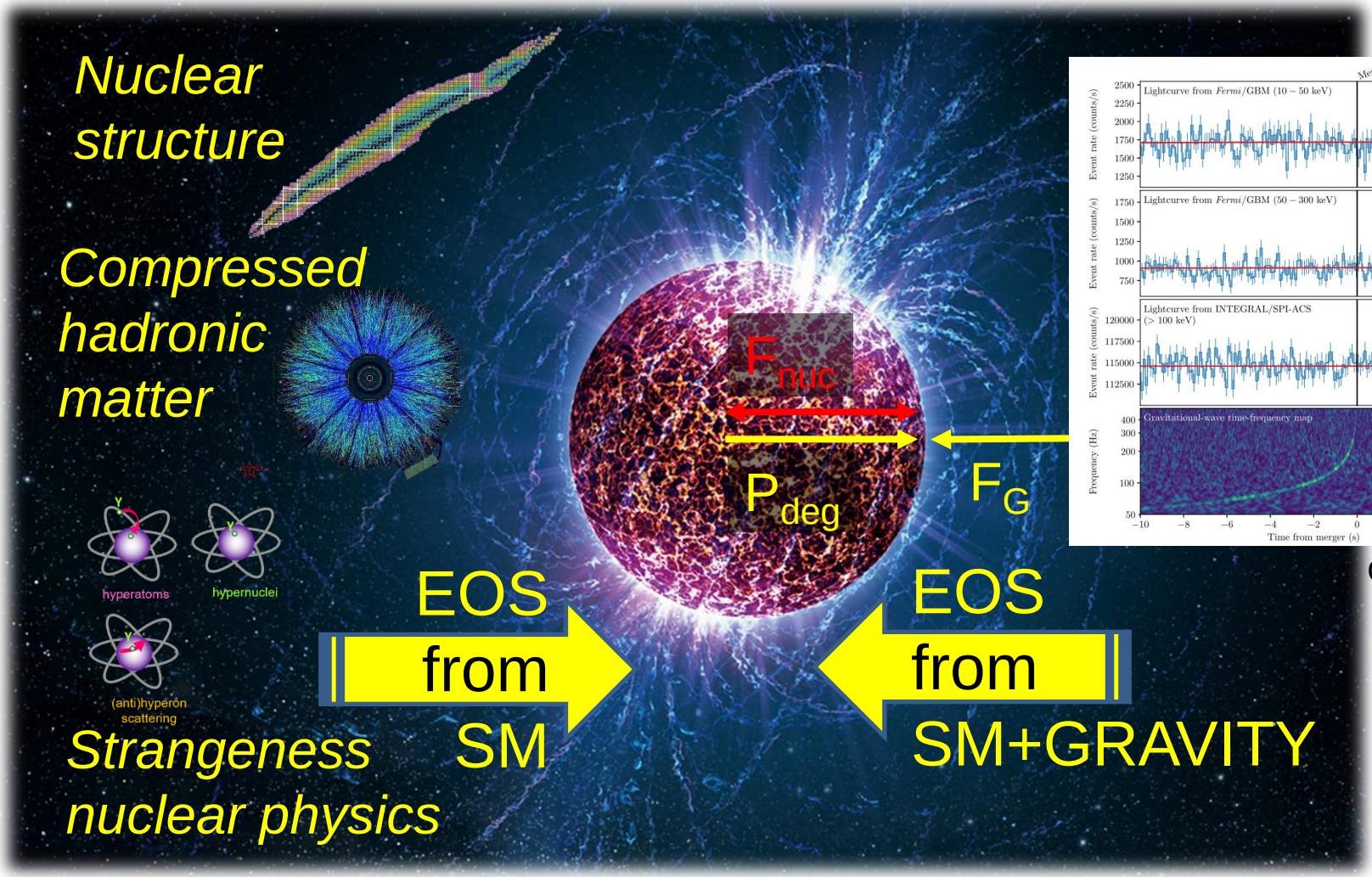
# Comparison of various compositions




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

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

# Neutron stars



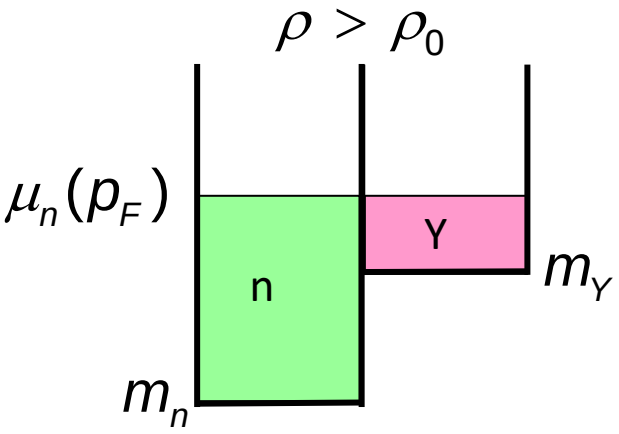




GW170817

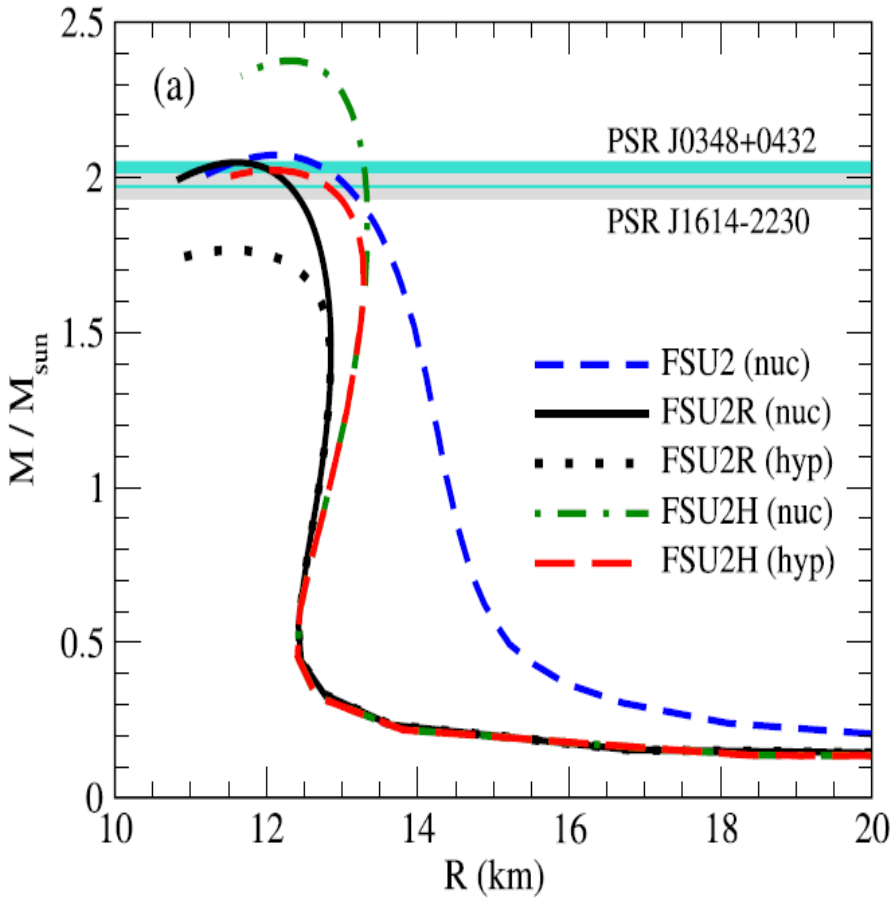
*Abbott, B. P. et al. Astr. Phys. J Lett. 848 (2017)*

# Hyperon puzzle



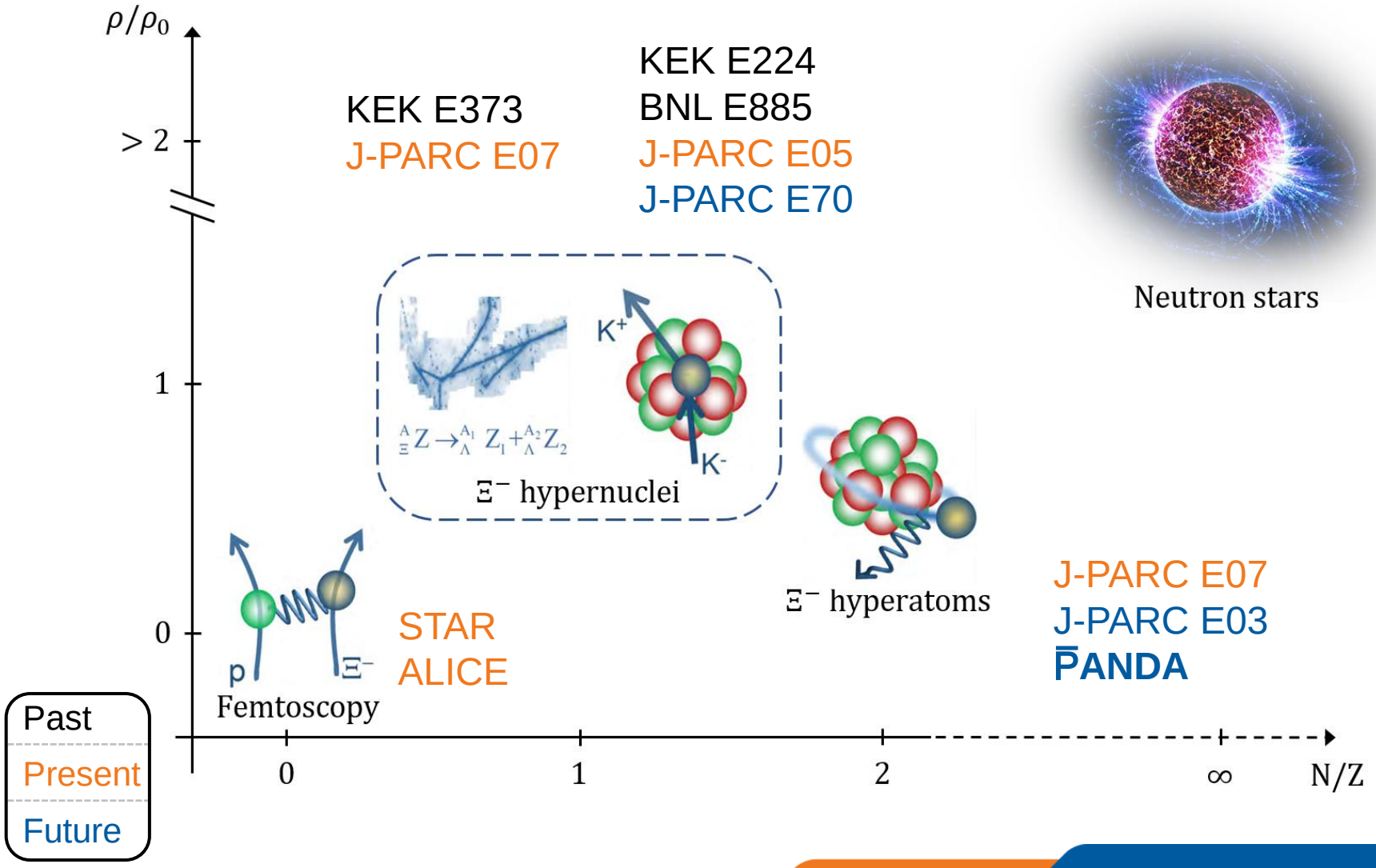

Interacting Fermi-gas

$\rho_\Lambda \approx 2 - 3\rho_{nuc}$



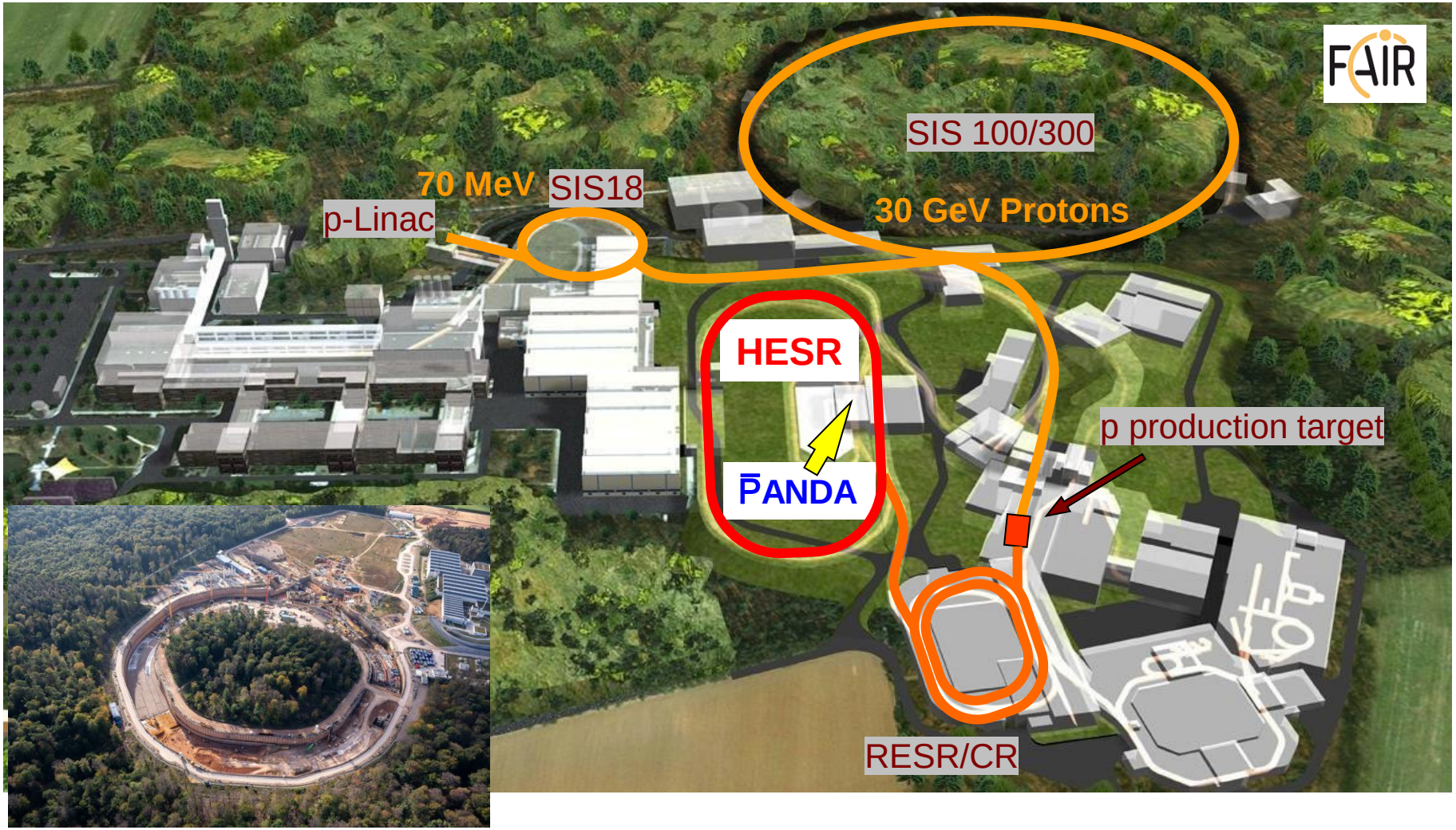

*Bombaci, I JPS Conf. Proc. 17 (2017)*
*Antoniadis, J. et al. Science 340.6131 (2013)*
*Negreiros, R. et al. Astrophys. J. 863 (2018) 104*

# $\Xi^-$-nucleus interaction



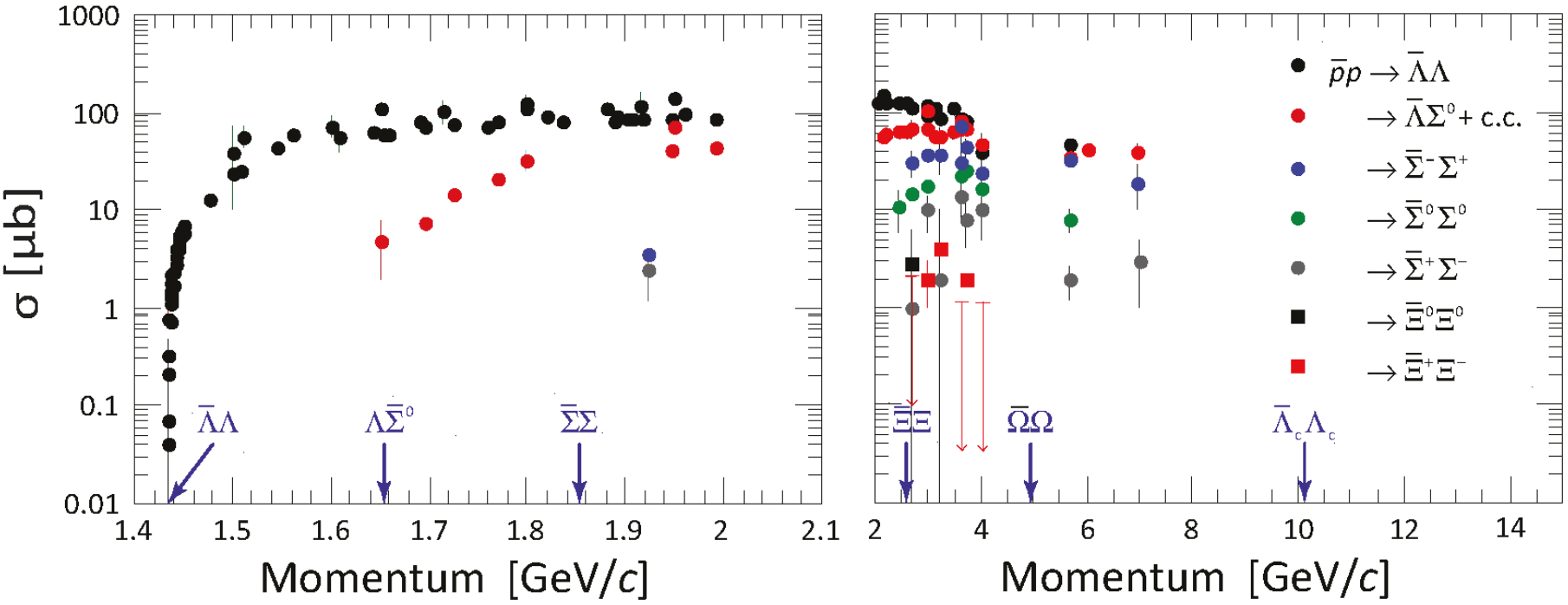
# Strangeness nuclear physics at P̄ANDA

# P̄ANDA at FAIR




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

# P̄ANDA as hyperon factory

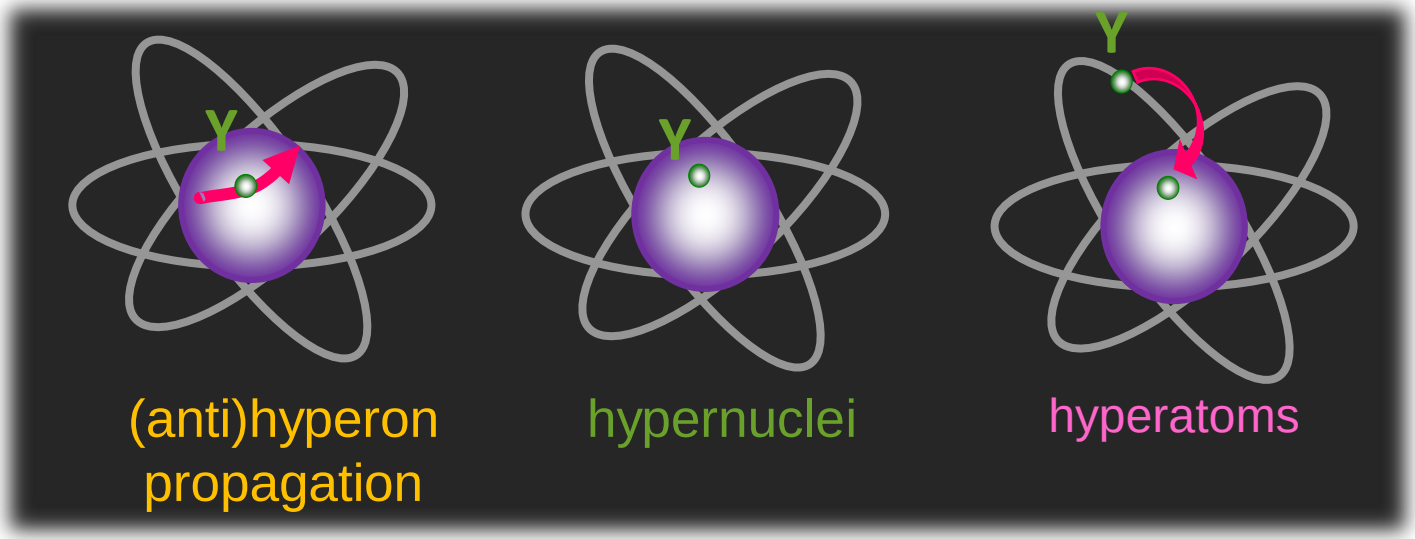



Production rates:
@ 2 MHz p̄p

| | |
|---|---|
| $\Lambda\bar{\Lambda}$ | ~1000 /s |
| $\Xi^-\bar{\Xi}^+$ | ~100 /s |

*Panda Collaboration, Physics Performance Report for PANDA*

# Strangeness nuclear physics




***Physics Topic***

antihyperon potential in cold baryonic matter

***Observable***

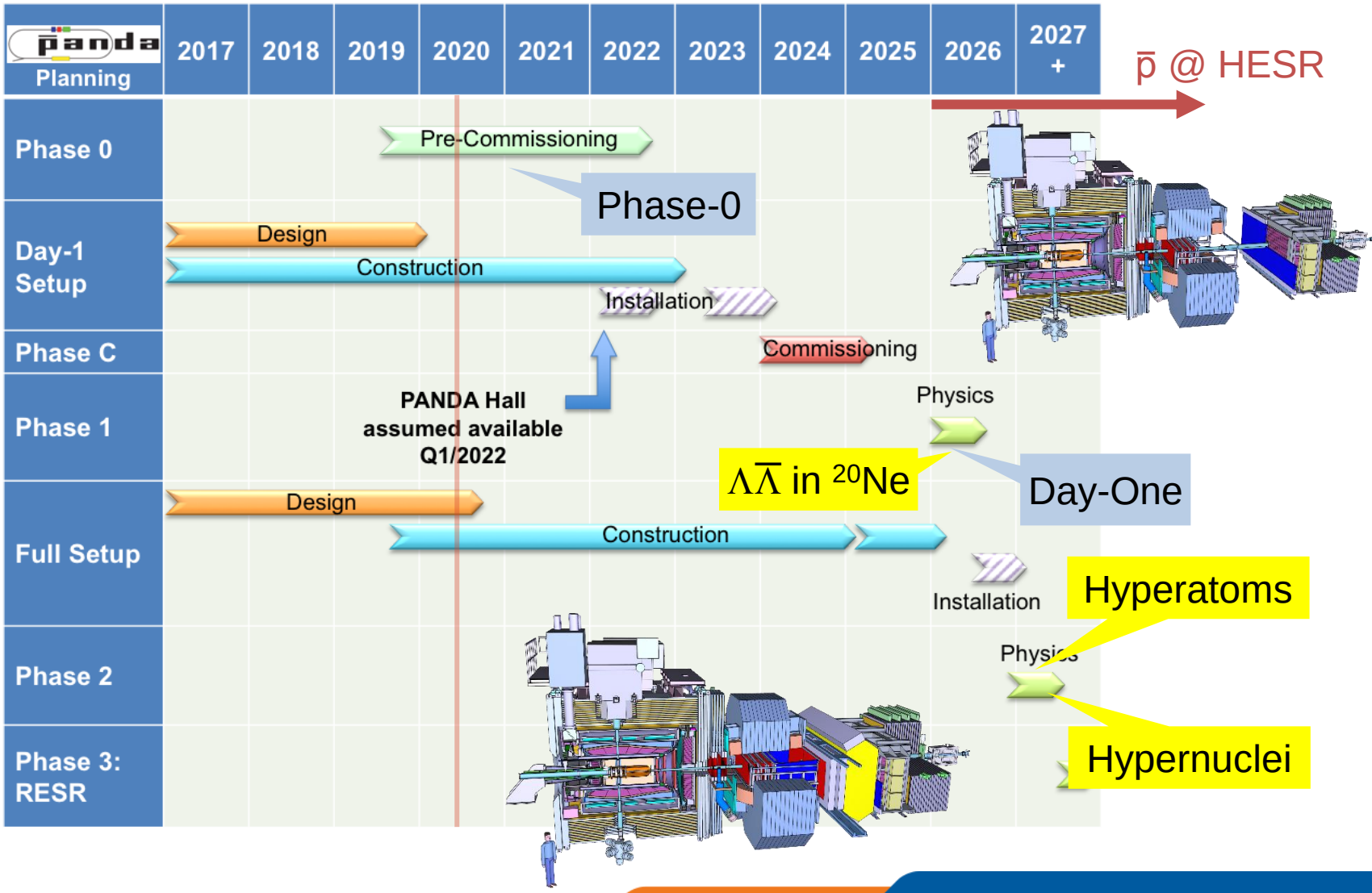
$Y\bar{Y}$ momentum correlations at threshold

HIM

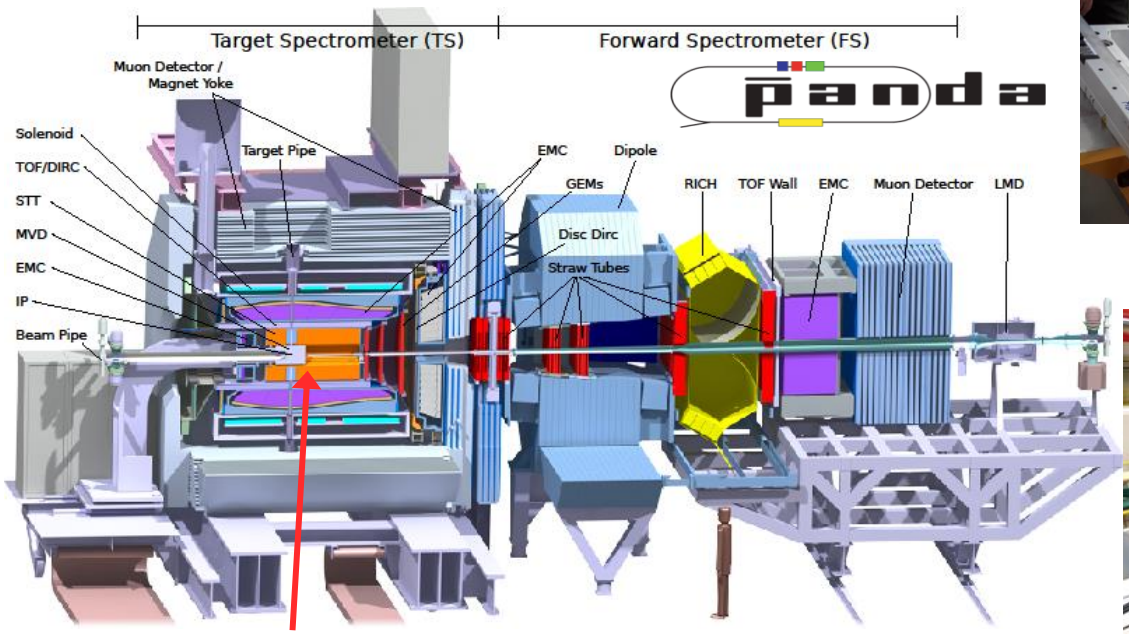
*Sanchez Lorente et al. Physics Letters B 749 (2015)*

*Pochodzalla et al. Nuclear Physics A 954 (2016)*

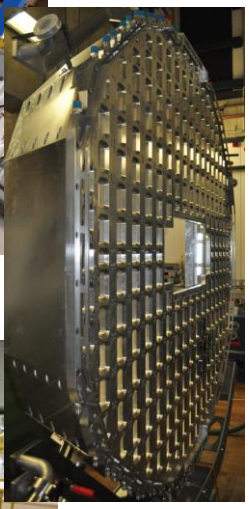
# $\bar{P}$ANDA schedule

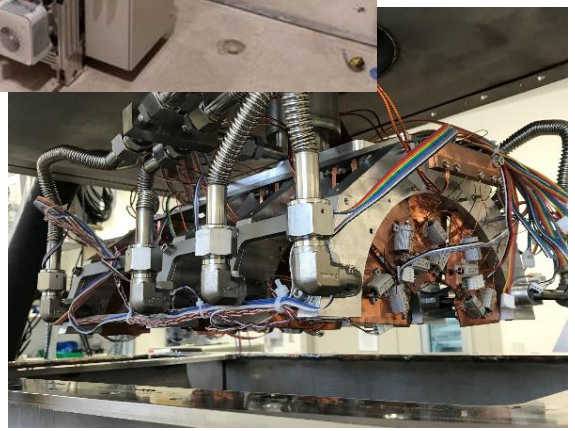


# $\bar{P}$ANDA detector



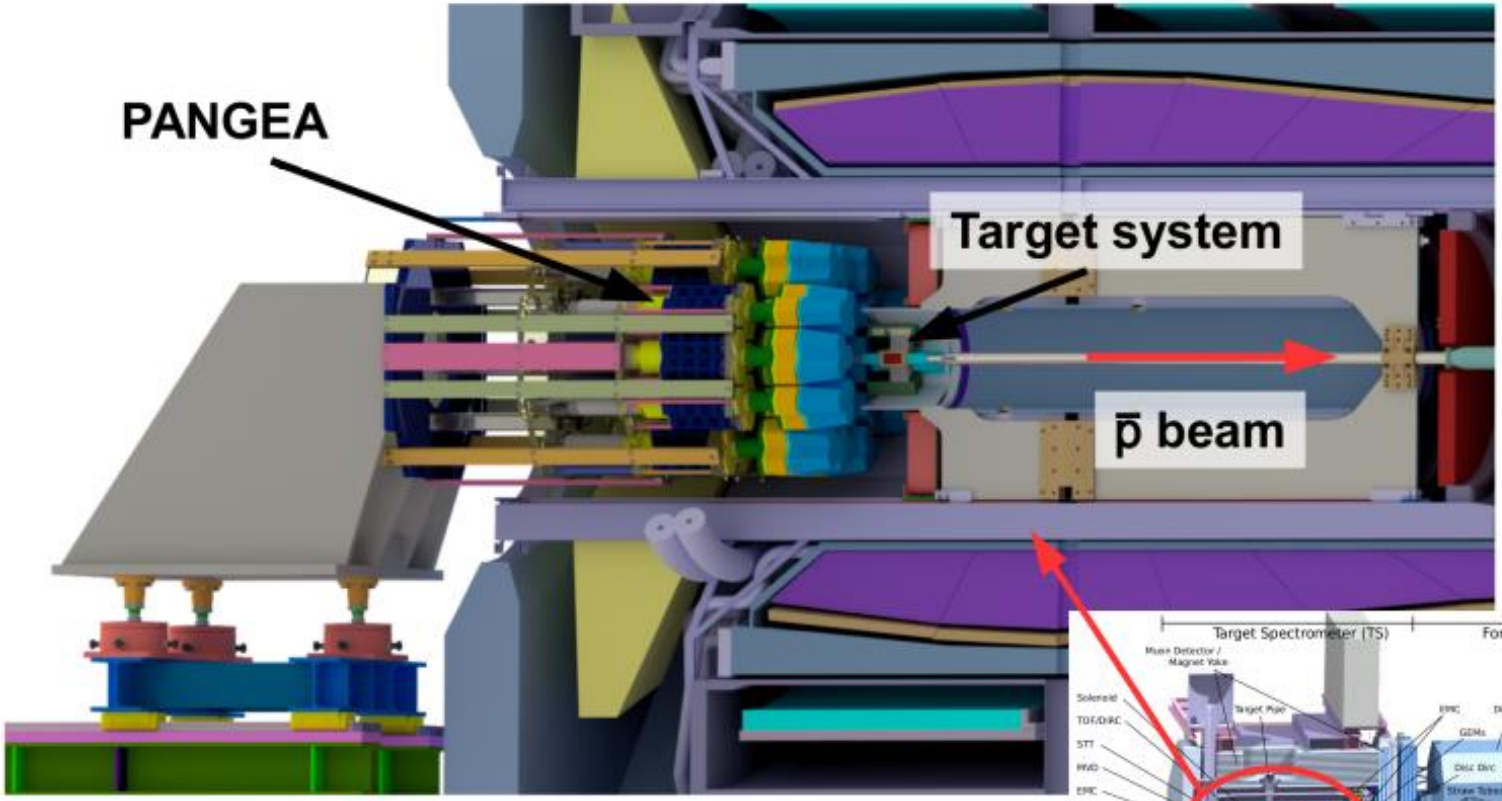

*Hyperatom/nuclear setup will be installed here*

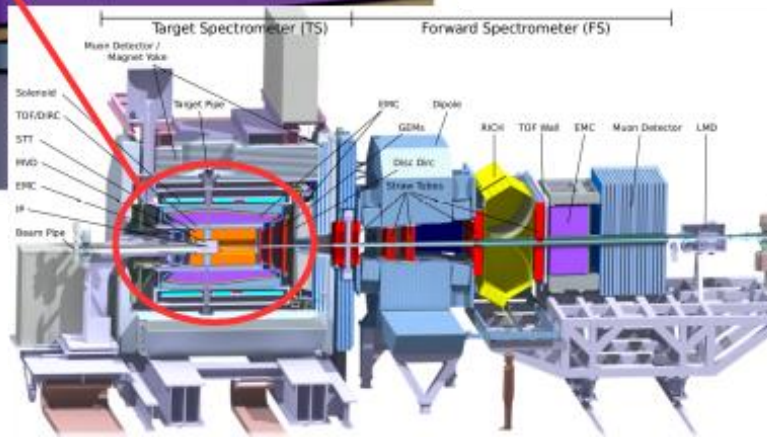




- Fixed target setup
- Target + forward spectrometer
- B ≤ 2 T
- Solid angle ~4π

# Hyperatom/nuclear setup

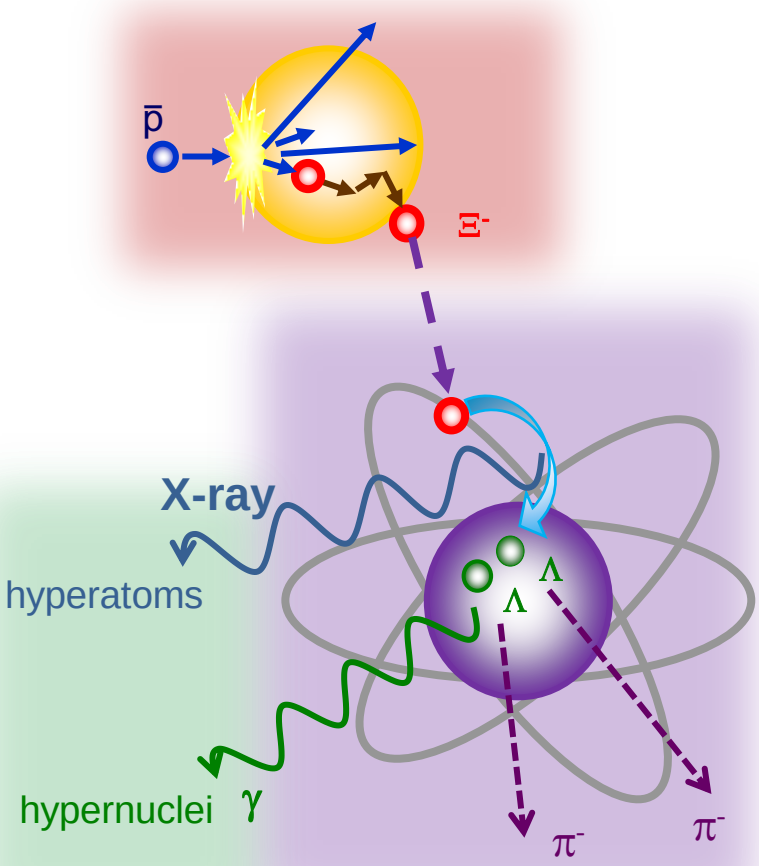



- Dedicated two-step target system
- PANGEA

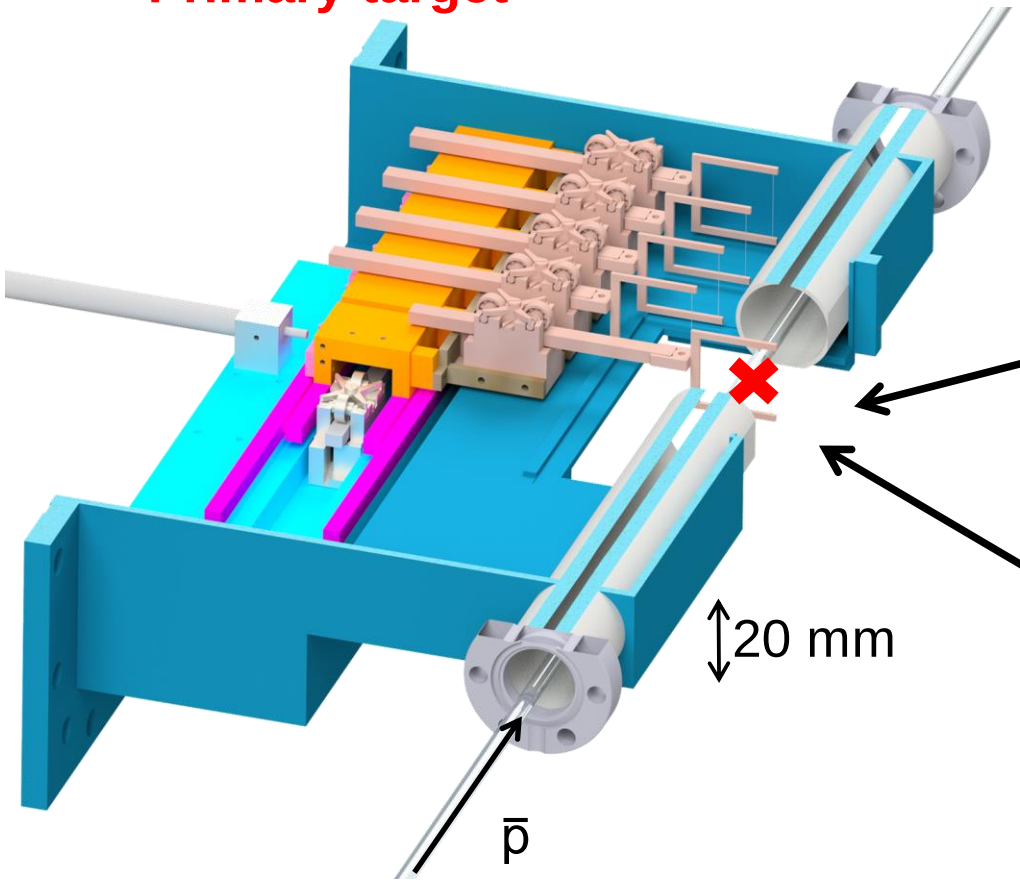
# Production of hyperatoms/nuclei

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



# Target system

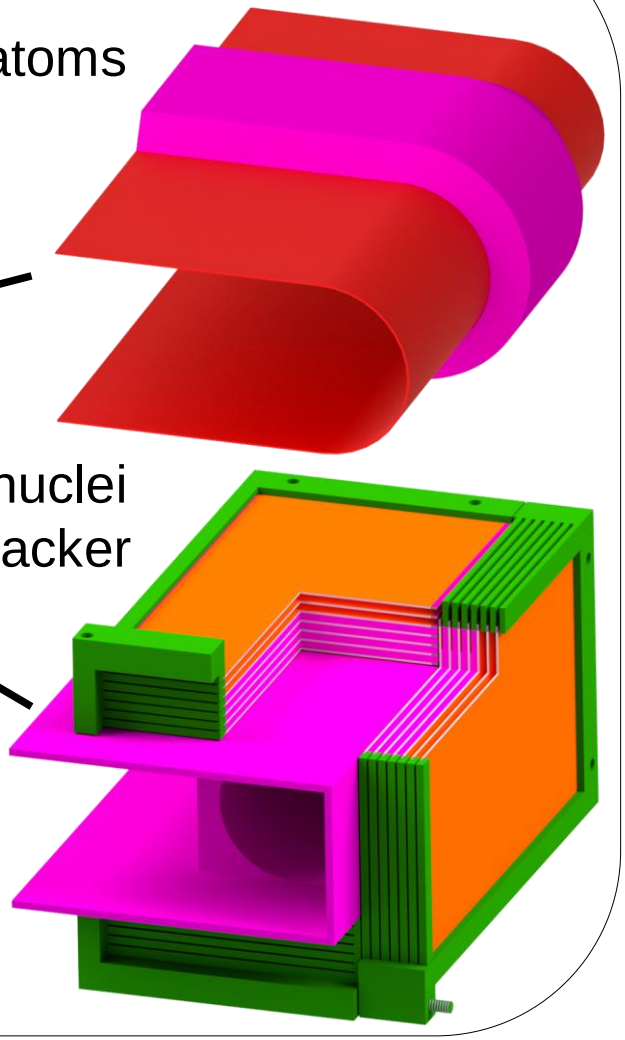
**Primary target**




**Secondary target**

Hyperatoms
$^{208}$Pb

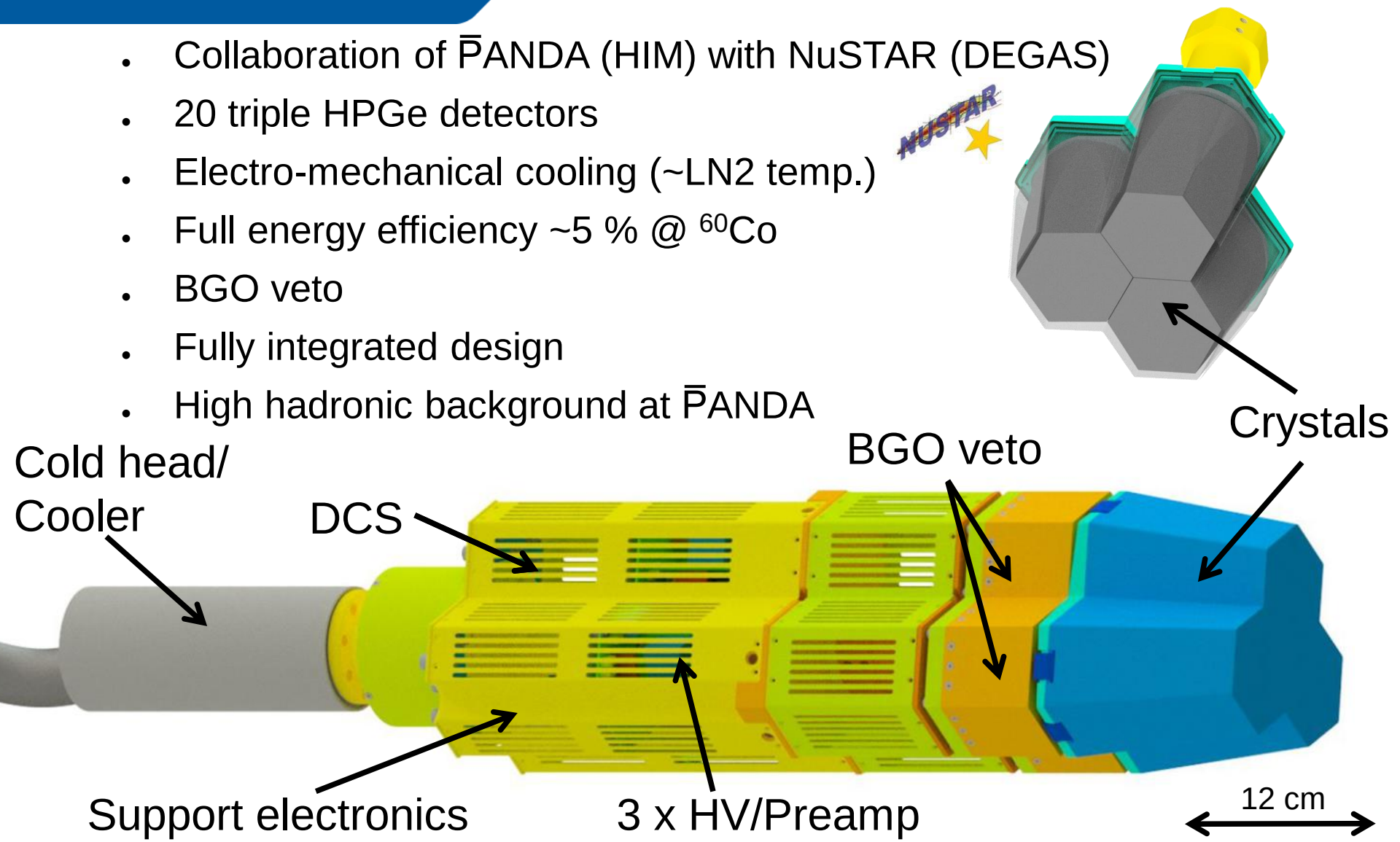
Hypernuclei
$^{11}$B+Tracker



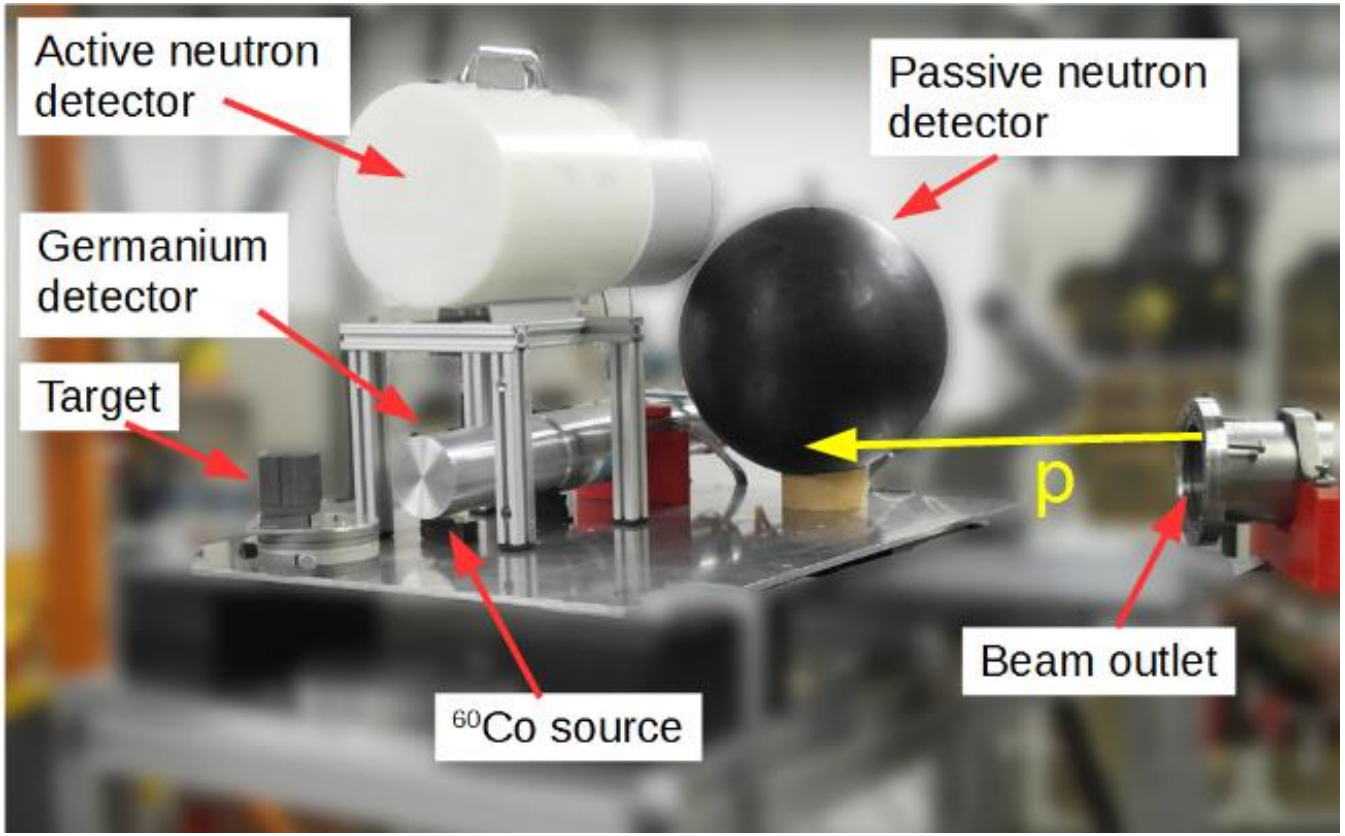
$$c\,\tau_{\Xi^-} \approx 5\ cm$$

# PANda GErmanium Array

- Collaboration of P̄ANDA (HIM) with NuSTAR (DEGAS)
- 20 triple HPGe detectors
- Electro-mechanical cooling (~LN2 temp.)
- Full energy efficiency ~5 % @ $^{60}$Co
- BGO veto
- Fully integrated design
- High hadronic background at P̄ANDA



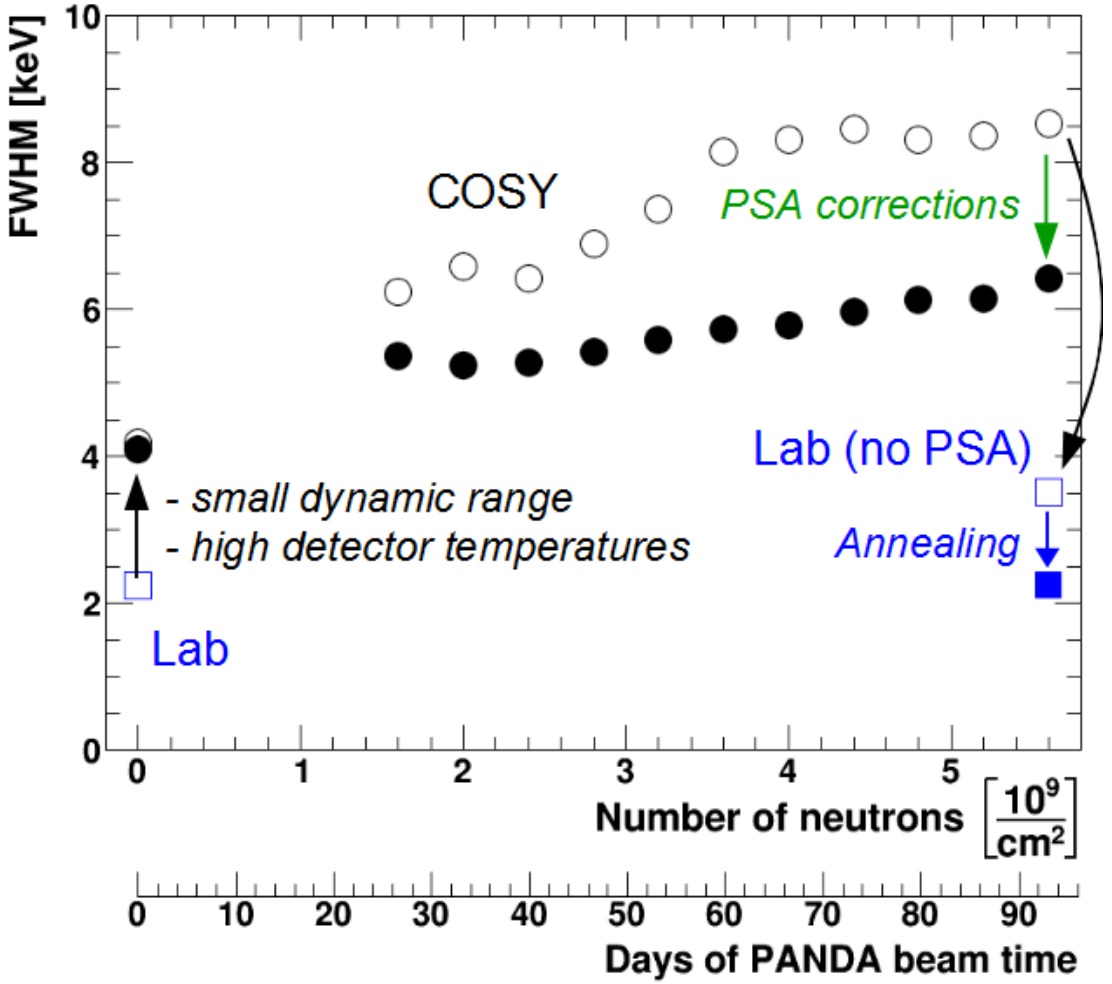
# HPGe irradiation test



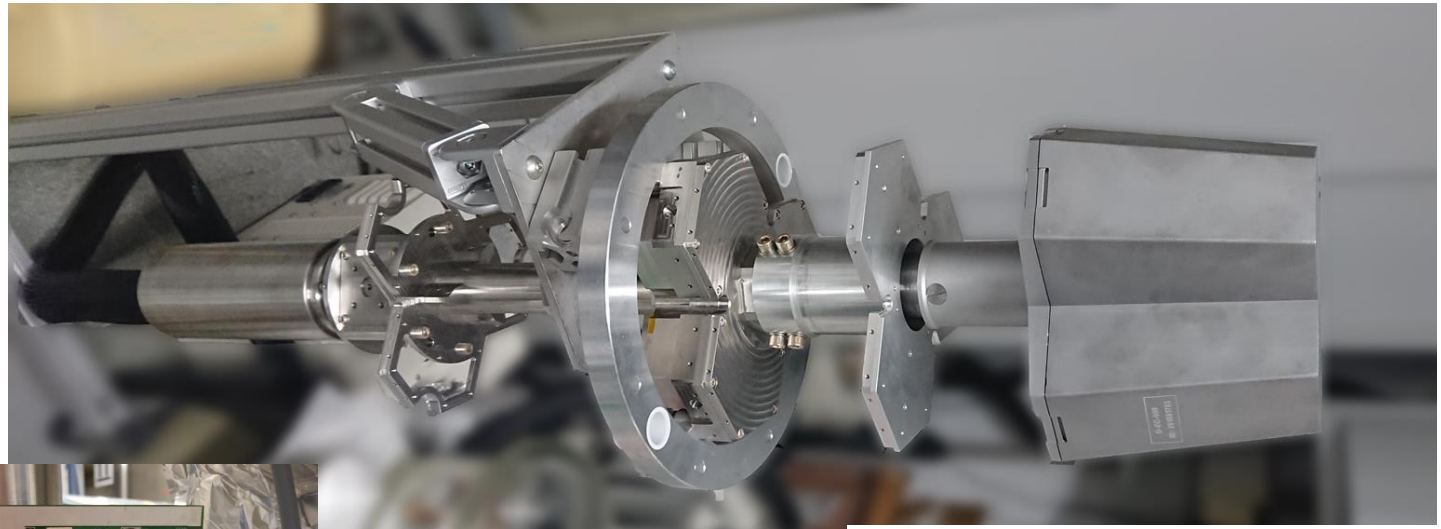

- Irradiation test at COSY using single crystal prototype
- 5.5 days at COSY
  → 94 days at $\bar{P}$ANDA

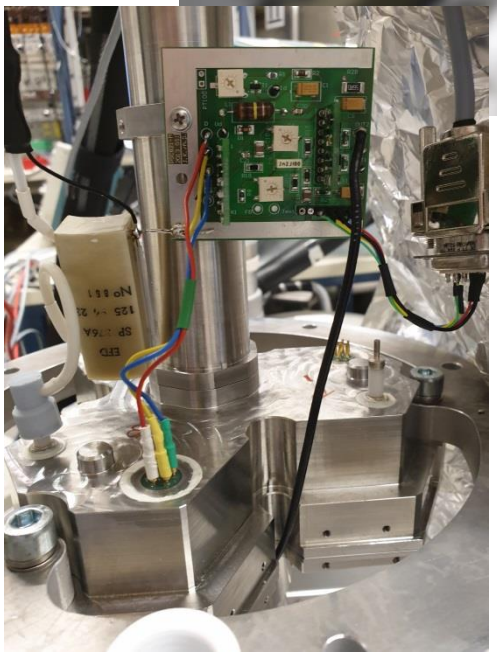
# Results

- Performance influenced by experimental conditions
- Irradiation worsens resolution
  - Pulse shape analysis allows partial recovery
- Annealing recovers initial crystal performance
  → Detector withstands irradiation
- Additional test at TRIGA planned



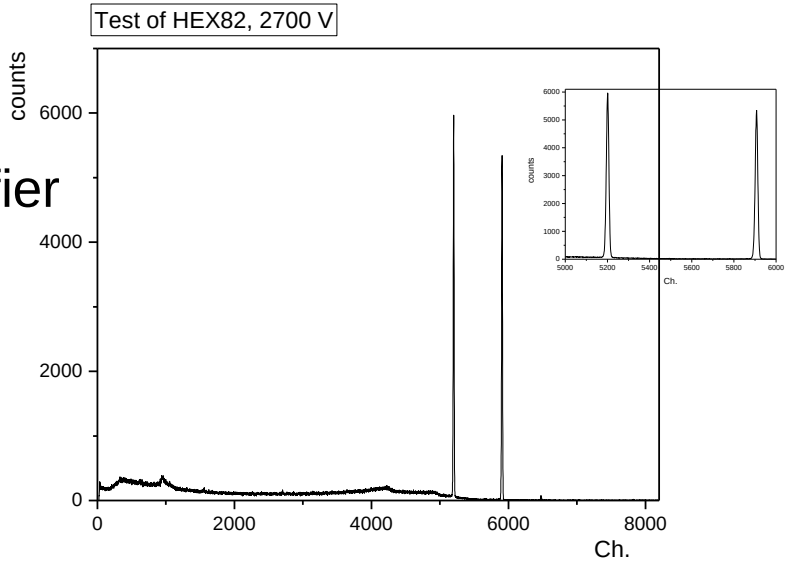
# PANGEA – Prototype





Test setup with prototype of preamplifier

Resolution: 2.8 keV while not fully biased

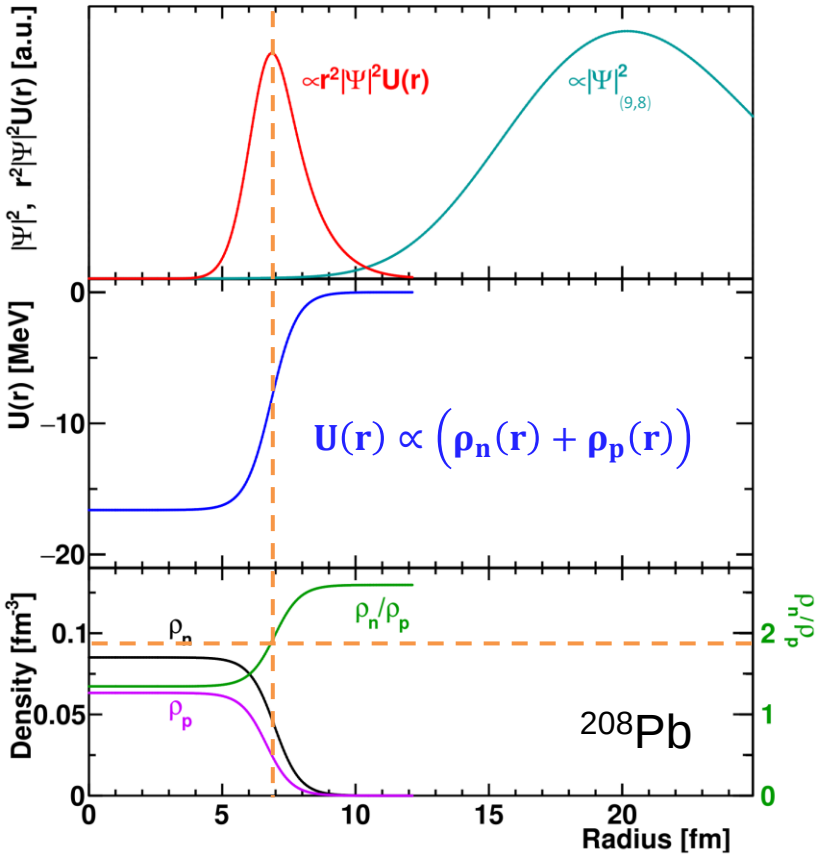



*Courtesy of I. Kojouharov*

# $\Xi^-$ hyperatoms at $\bar{P}$ANDA

# $\Xi^-$ hyperatoms

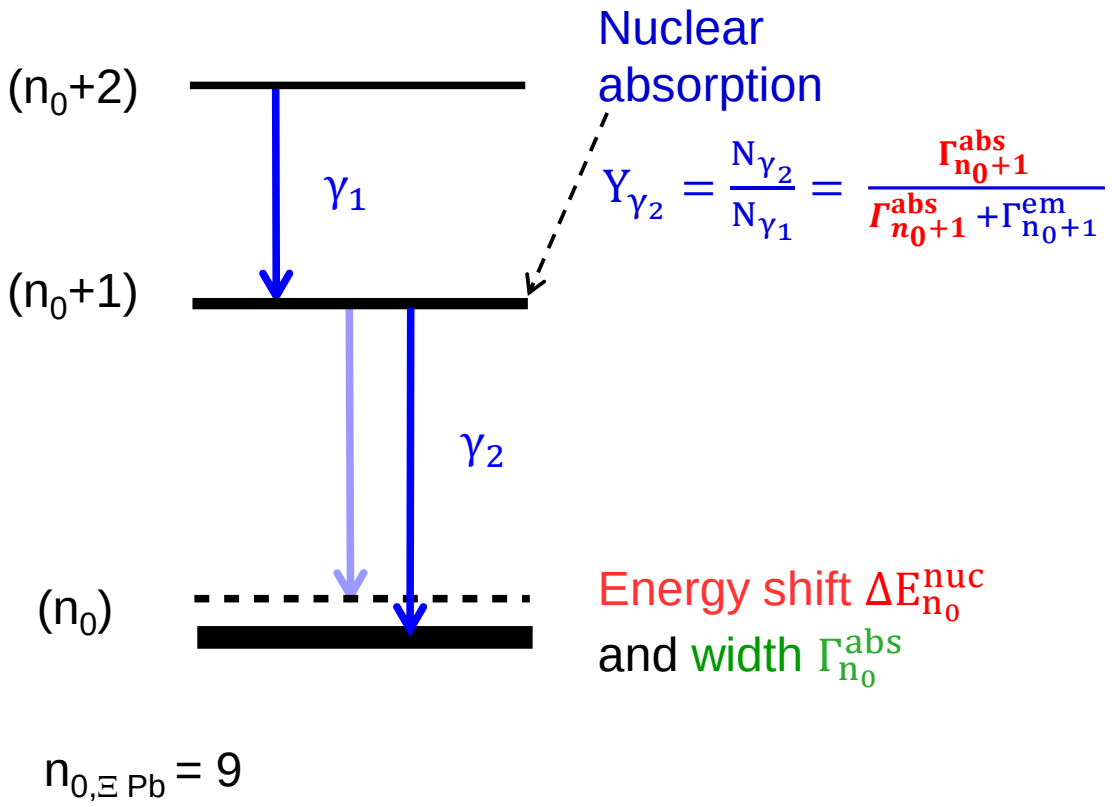
- Exotic atoms with heavy negatively charged particle
- $m_{red,\Xi} \approx 2570\ m_{red,e}$
- Shrinking of states: $< r > \propto \frac{1}{m_{red}}$
  - $E_{n+1\to n} \propto Z^2\ m_{red}$
    → Germanium detectors
  - Probing of nuclear potential in periphery
    → Measurement of complex $V_\Xi$ in neutron-rich matter



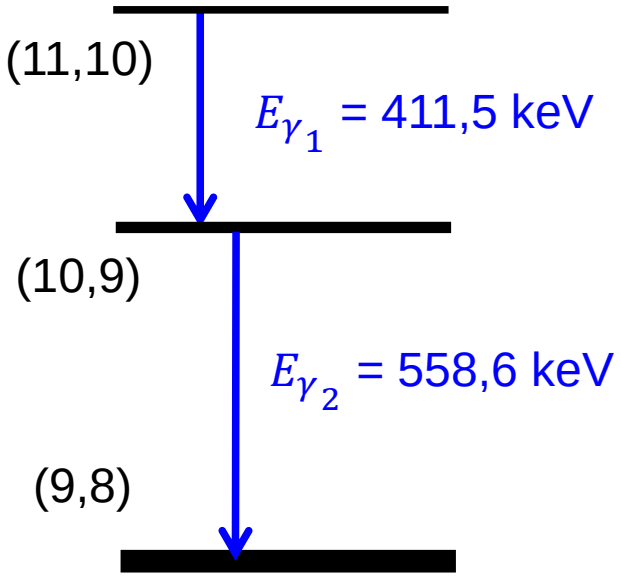

$$\rho_{n,p}(r) = \rho^0_{n,p} \frac{1}{1 + \exp\left(\frac{r - c_{n,p}}{a_{n,p}}\right)}$$

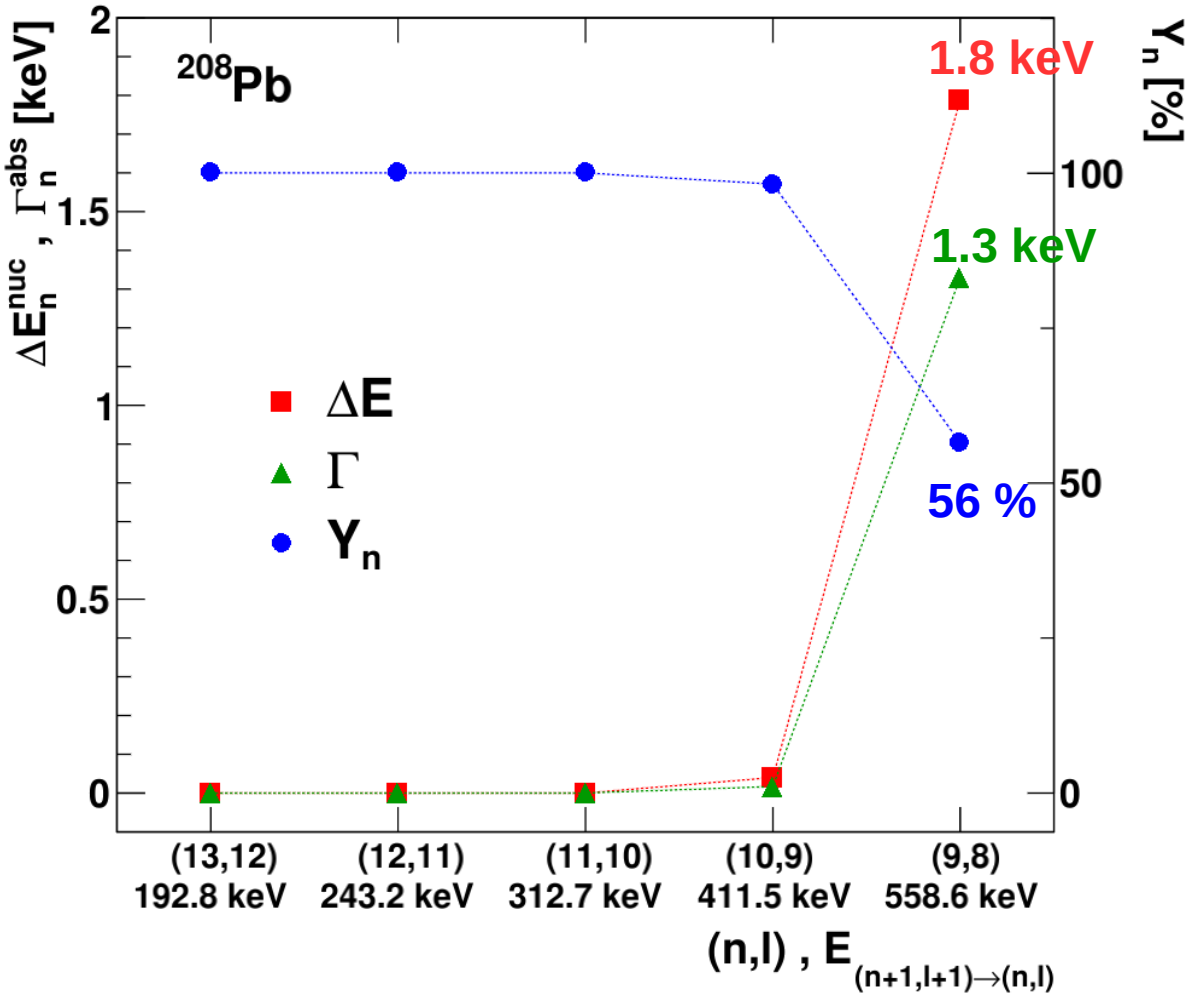
*Calculations performed with code based on Batty, C. J. et al. Phys. Rev. C 59 (1999)*

# Observables



# $\Xi^-$ - $^{208}$Pb

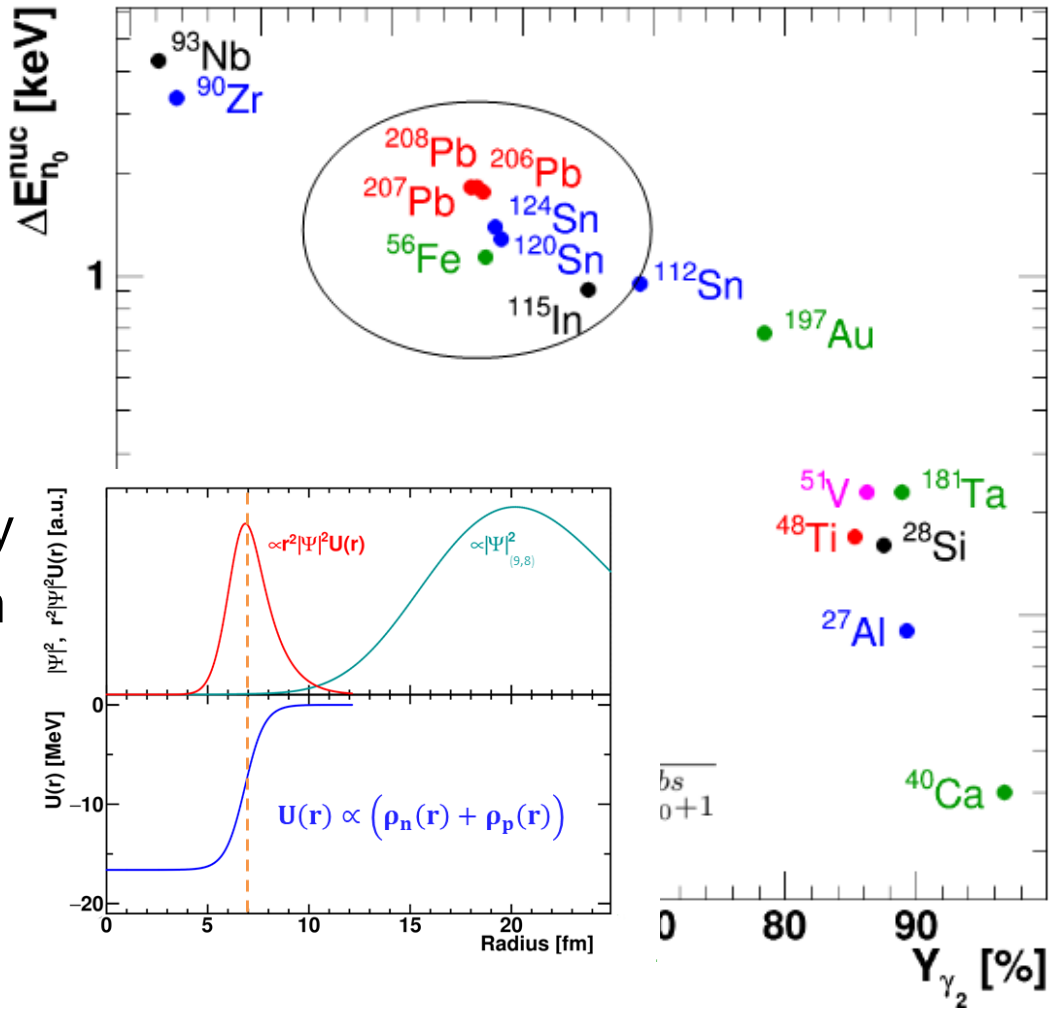



*Calculations performed with code based on Batty, C. J. et al. Phys. Rev. C 59 (1999)*

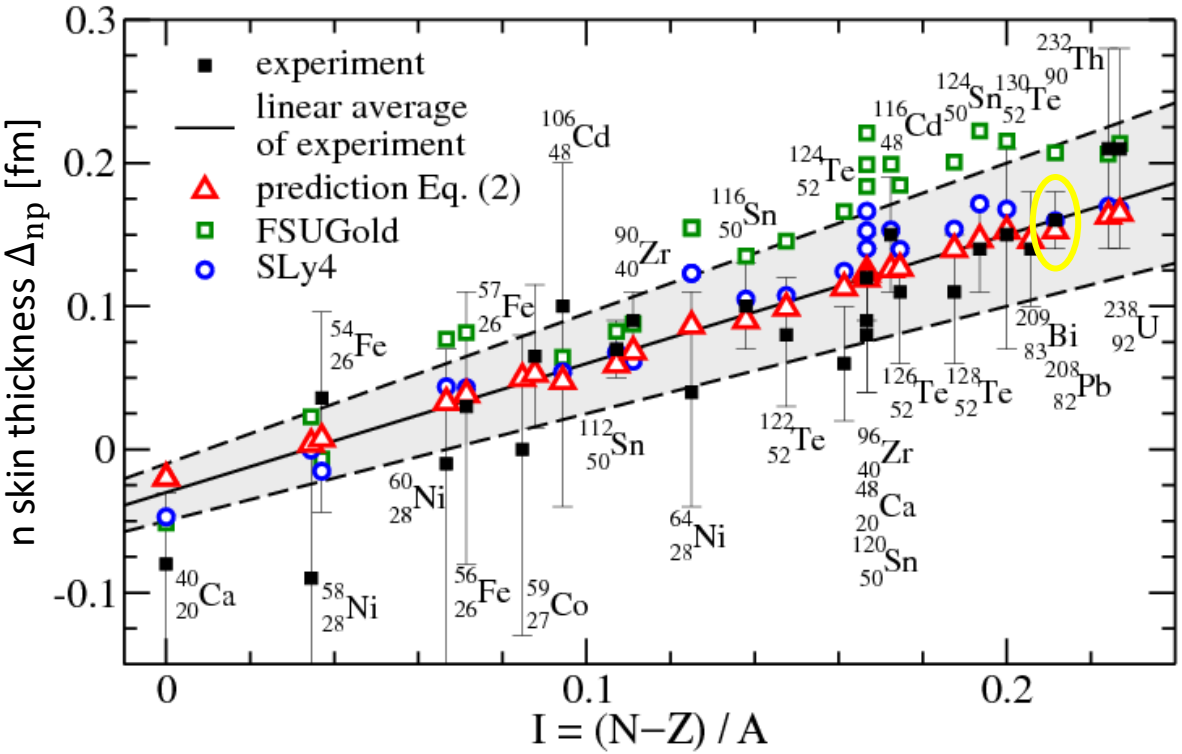
# Possible secondary targets

- Criteria:
  - High $\Delta E_{n_0}^{nuc}$
  - Moderate $Y_{\gamma_2}$
- Observables influenced by
  - $\Xi^-$ - nucleus interaction
  - $\Xi^-$ wave form (QED)
  - Nucleon distribution




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

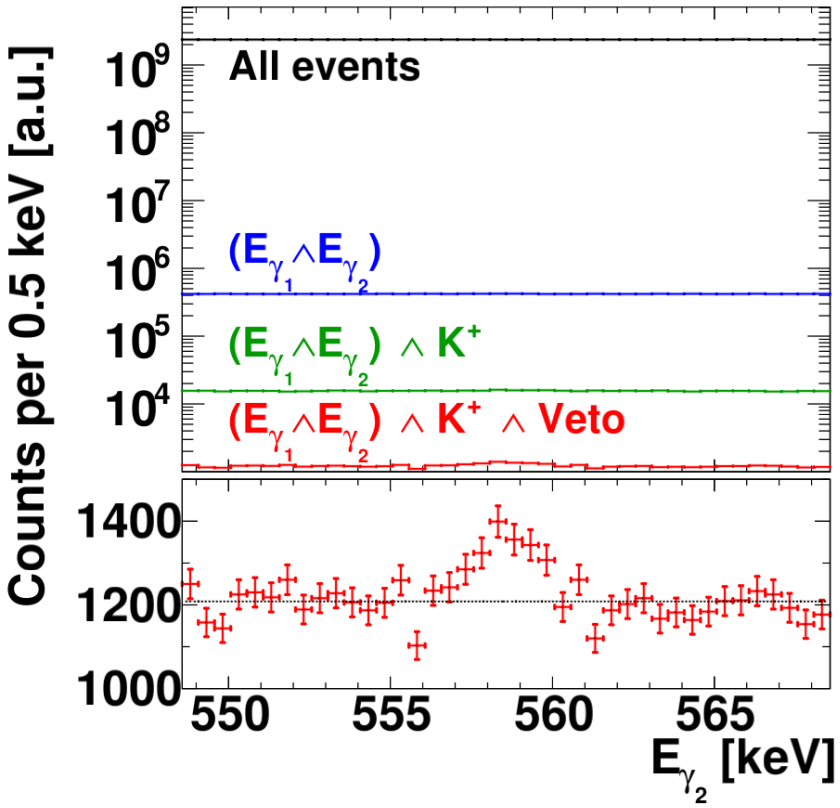
# Systematic uncertainties

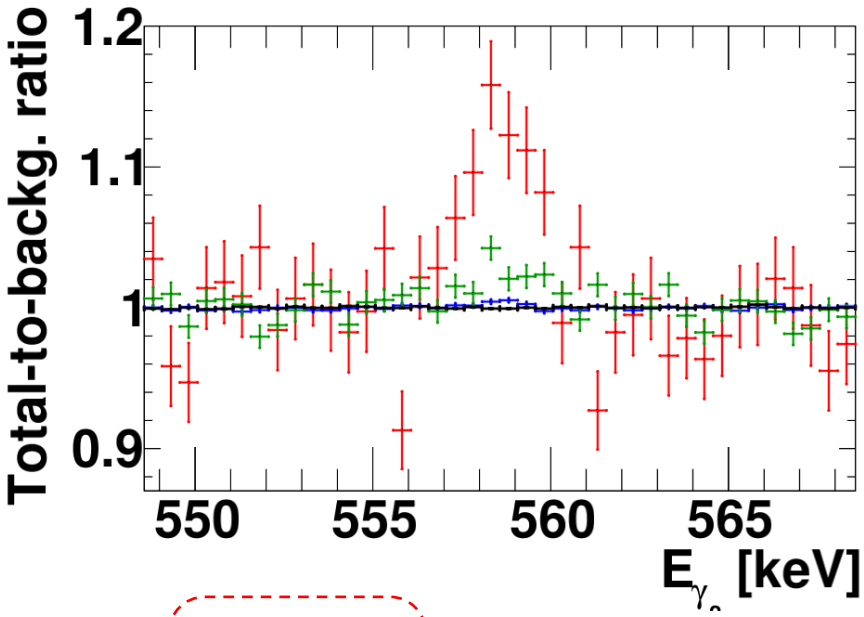


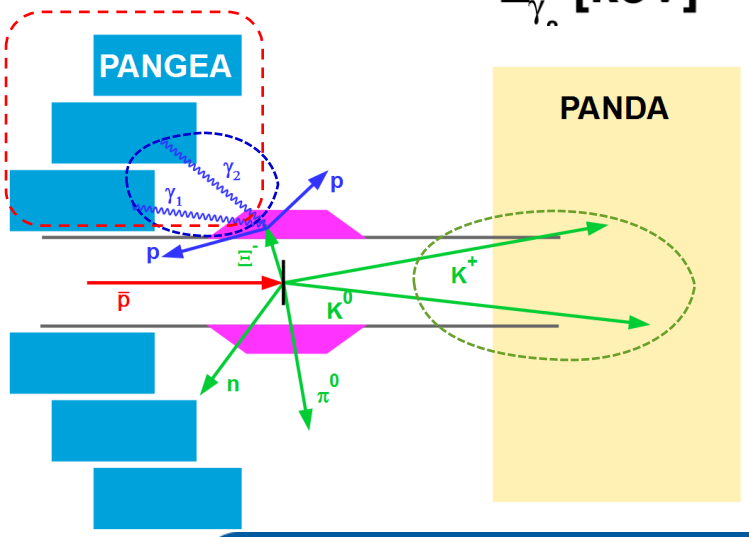

*Centelles et al. Phys.Rev.Lett. 102 (2009) 122502*

- Neutron skin $\Delta_{np}$ in $^{208}$Pb well-known
- Present uncertainty of $\Delta_{np}$ → Systematic uncertainty in observables
- $\boldsymbol{\delta\left(\Delta E^{nuc}_{(10,9)\rightarrow(9,8)}\right)_{sys}}$ **~ ± 100 eV**

# Full simulation in PandaRoot

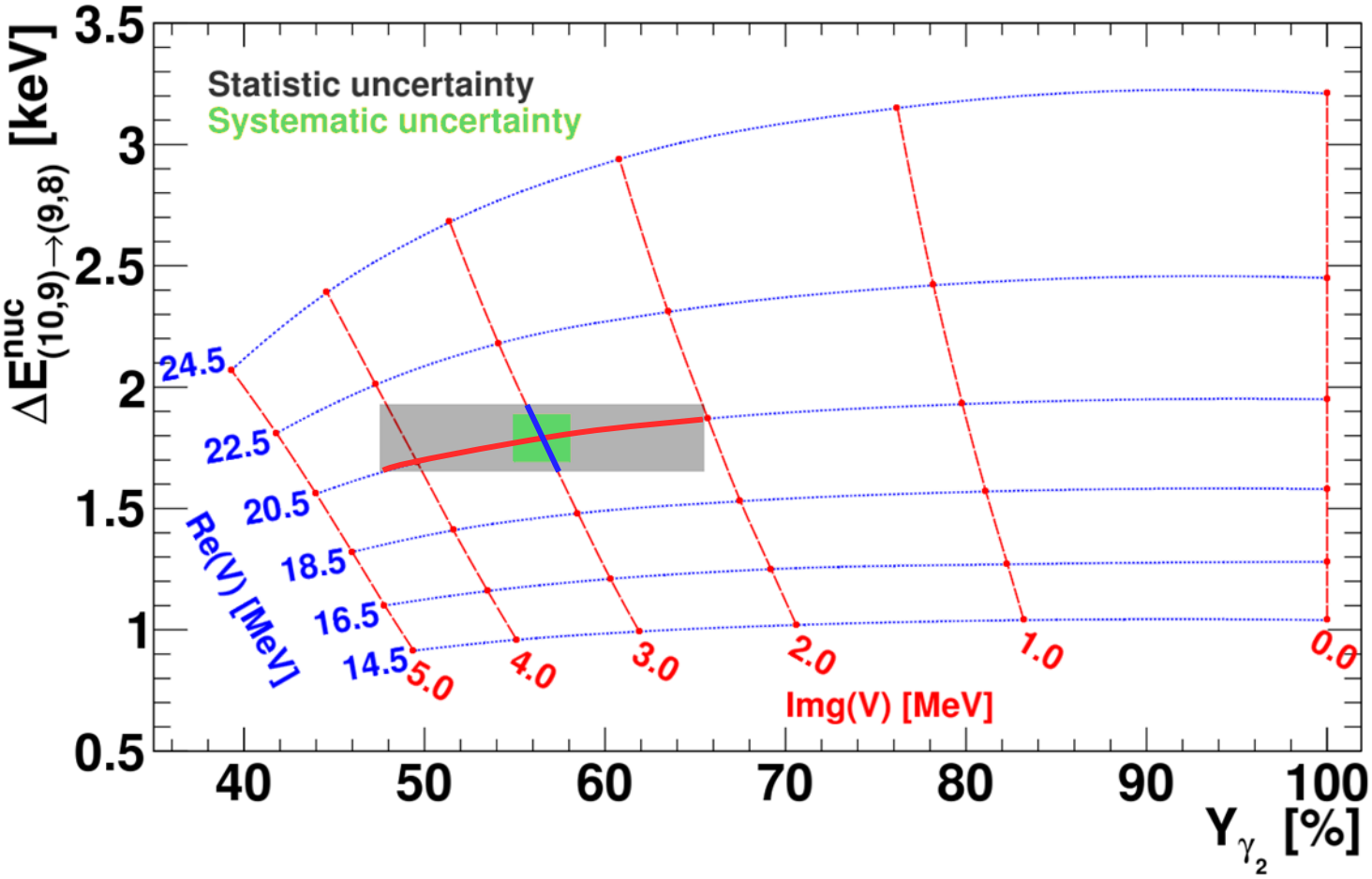


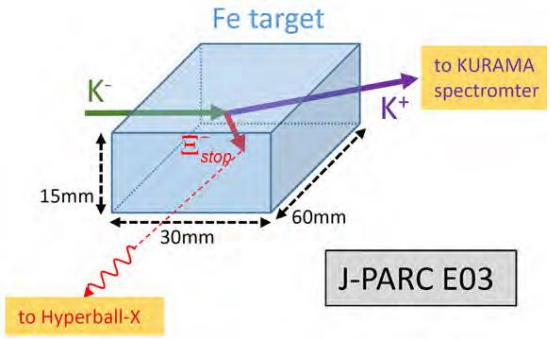

- Signals after cuts and efficiencies: 1237
  - 180 days at 2 MHz p̄C
- $\delta\left(\Delta E^{nuc}_{(10,9)\rightarrow(9,8)}\right)_{stat}$ = ± 140 eV

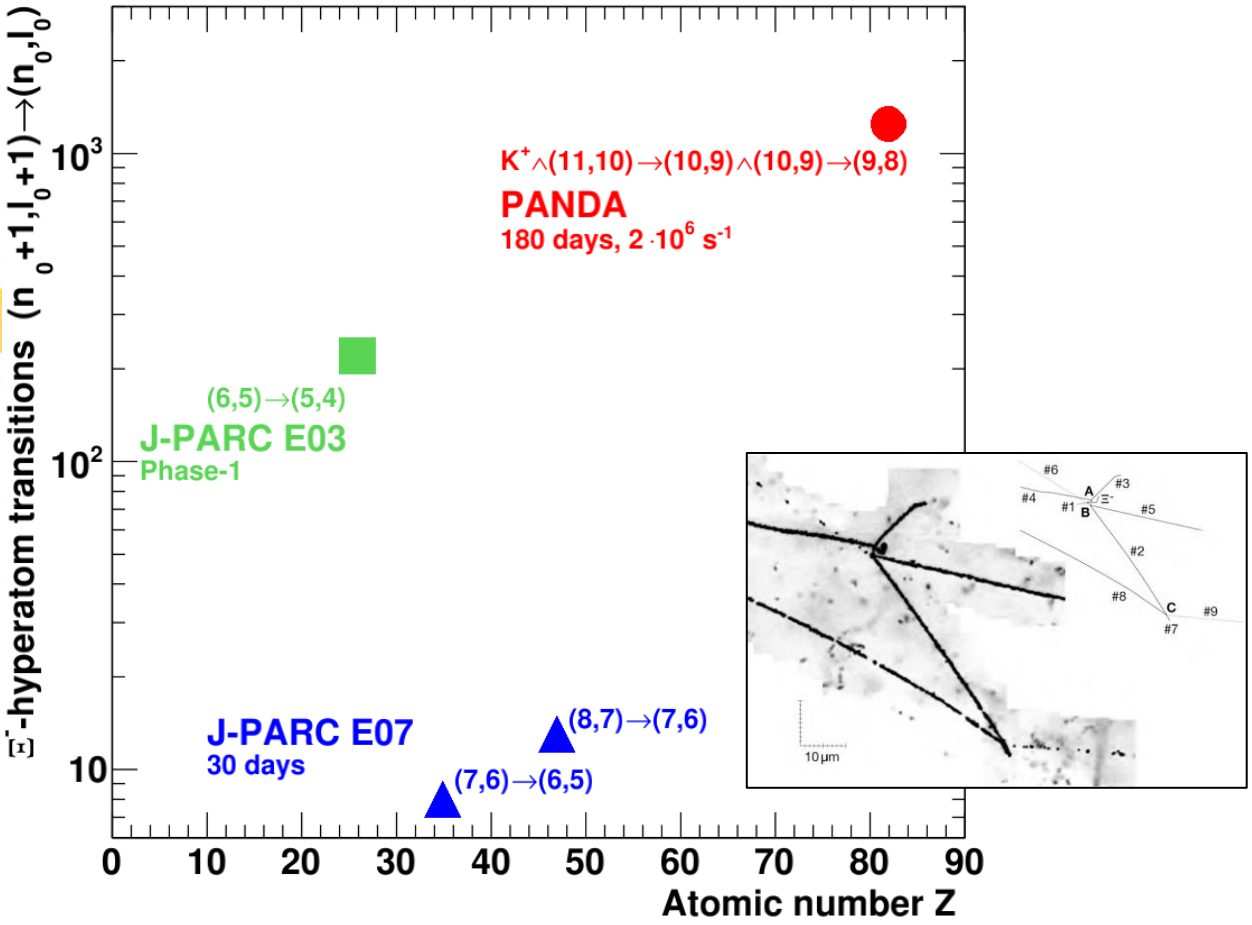
# Estimation of $V_\Xi$




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

# Complementary experiments



# Take-home message

- Strangeness nuclear physics at $\bar{P}$ANDA can help to understand the inner structure of neutron stars.
- Development of PANGEA and the target system is on schedule - promising results from prototypes.
- X-ray spectroscopy of heavy $\Xi^-$ hyperatoms at $\bar{P}$ANDA is unique and complementary to J-PARC E03/07.

Thank you for your attention

JG|U DAAD STRONG 2020 HIM