Radioactive Ion projects at CERN and FAIR based on Cryogenics

TECHNISCHE UNIVERSITÄT DARMSTADT

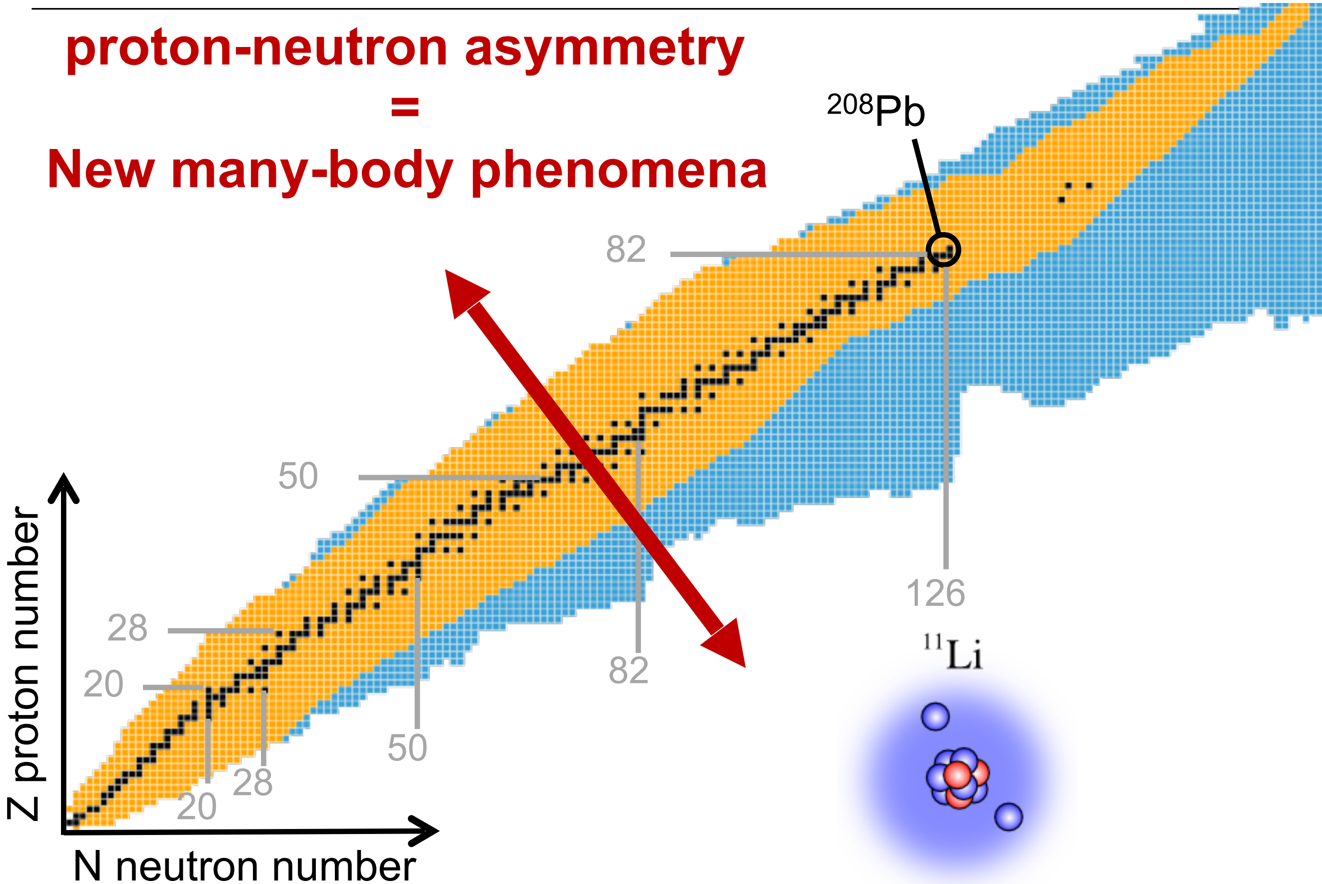
Alexandre Obertelli
TU Darmstadt

May 3rd, 2018

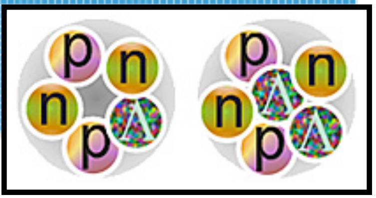
Neutron-rich nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

proton-neutron asymmetry
=
New many-body phenomena

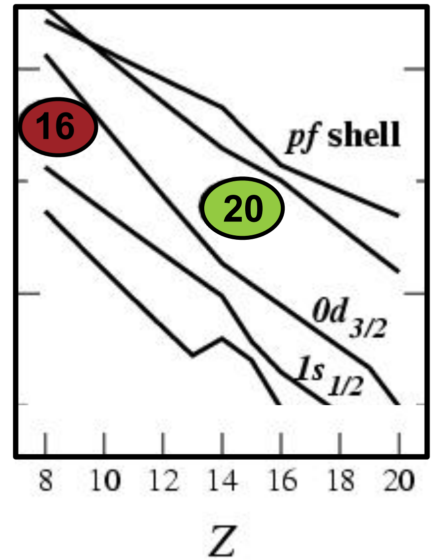


hypernuclei



neutron skins & halos

shell evolution



Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

New group at TU Darmstadt, with projects related to **FAIR** and **cryogenics**

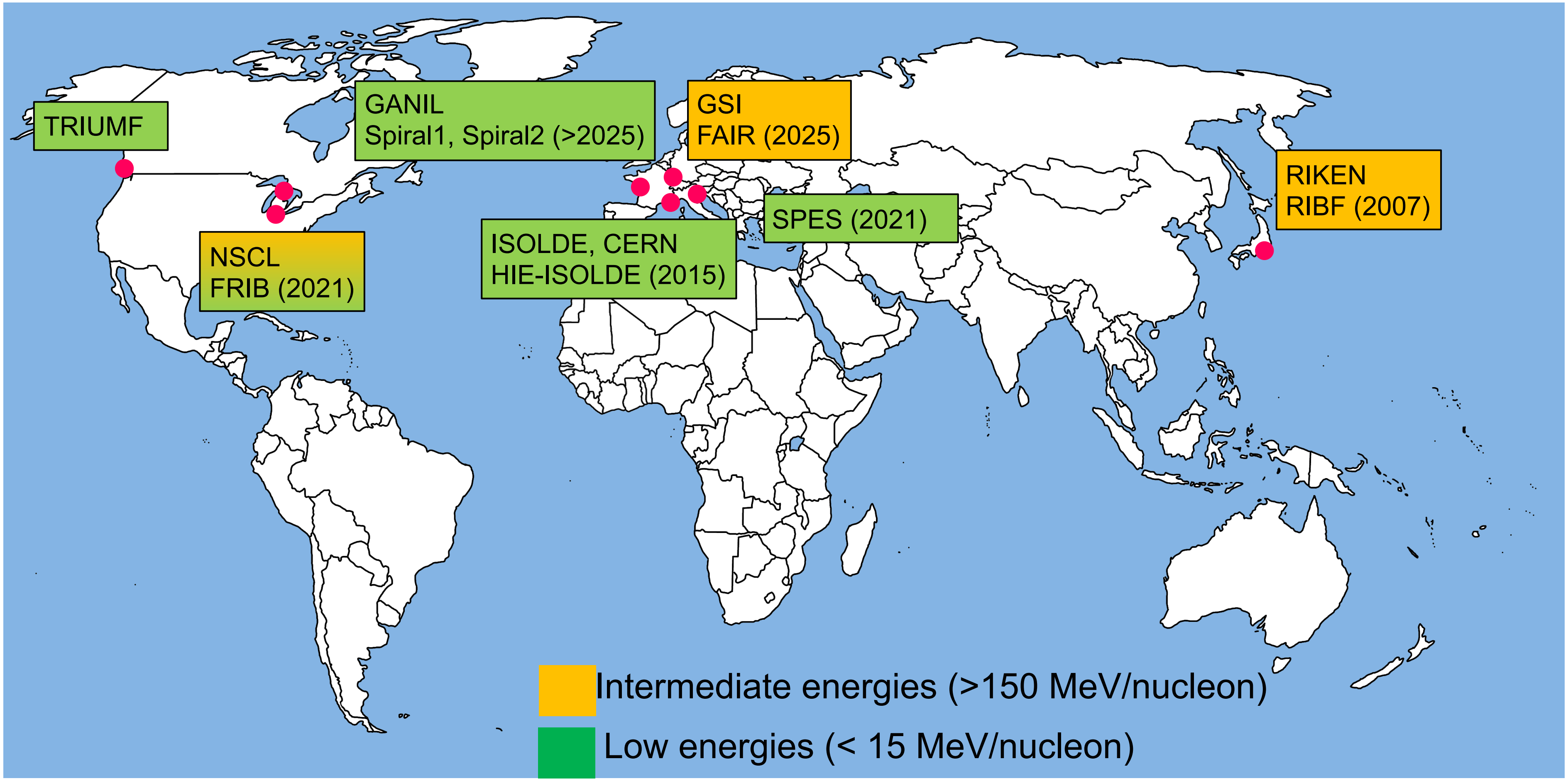
- **Shell evolution**
  A ***cryogenic H_2 target*** and vertex tracker for AGATA - ***HISPEC***

- **Hypernuclei**
  Cryogenic H_2 target and charged particle tracker inside GLAD at ***R3B***

- **Halo nuclei**
  A transportable ***cryogenic trap*** at CERN for antiprotons. A step towards ***FLAIR***

RIB facilities worldwide

TECHNISCHE UNIVERSITÄT DARMSTADT



Hydrogen targets for nuclear studies

TECHNISCHE UNIVERSITÄT DARMSTADT

- ➢ Higher **luminosity** (150 mm H_2 = 1 g.cm^{-2} = 4. 10^{23} cm^{-2})
- ➢ Hydrogen: "structureless" target
- ➢ **Quasifree** *(p,2p)* or *(p,pn):* "clean" probe

- ➢ Minimized **background** (pure H_2 target, less bremsstrahlung/neutrons)
- ➢ Improved **energy resolution :** cancelation of the target contribution

Past and present times, many uses at GSI/FAIR :

- ➢ quasifree scattering
- ➢ spallation
- ➢ proton-induced fission
- ➢ interaction cross section measurements
- ➢ high-momentum nucleon transfer
- ➢ pionic atoms

… with the (manageable) difficulty of cryogenic infrastructure and safety.

Brief history of LH2 target developments

TECHNISCHE UNIVERSITÄT DARMSTADT

Historical engineering expertise at CEA Saclay

1990 to 1997: Several LH_2 targets for the Saturne National Laboratory

1995 to 1997* : *POLDER project at J.LAB. LH_2 target Ø 150 mm L = 150 mm

1996 to 2000: FRS1 project at GSI. LH_2 target Ø 20 mm L = 10 mm

1999 to 2004: *FRS2 project at GSI*. LH_2 target Ø 20 mm L = 60 mm and Ø 60 mm L = 200 mm

2006 to 2007: *Spaladin project at GSI*. Two simultaneous LH_2 targets Ø 25 mm, L1 = 1 mm and L2 = 4 mm

2010 to 2011: *Prespec project at GSI*. LH_2 target Ø 75 mm L = 70 mm

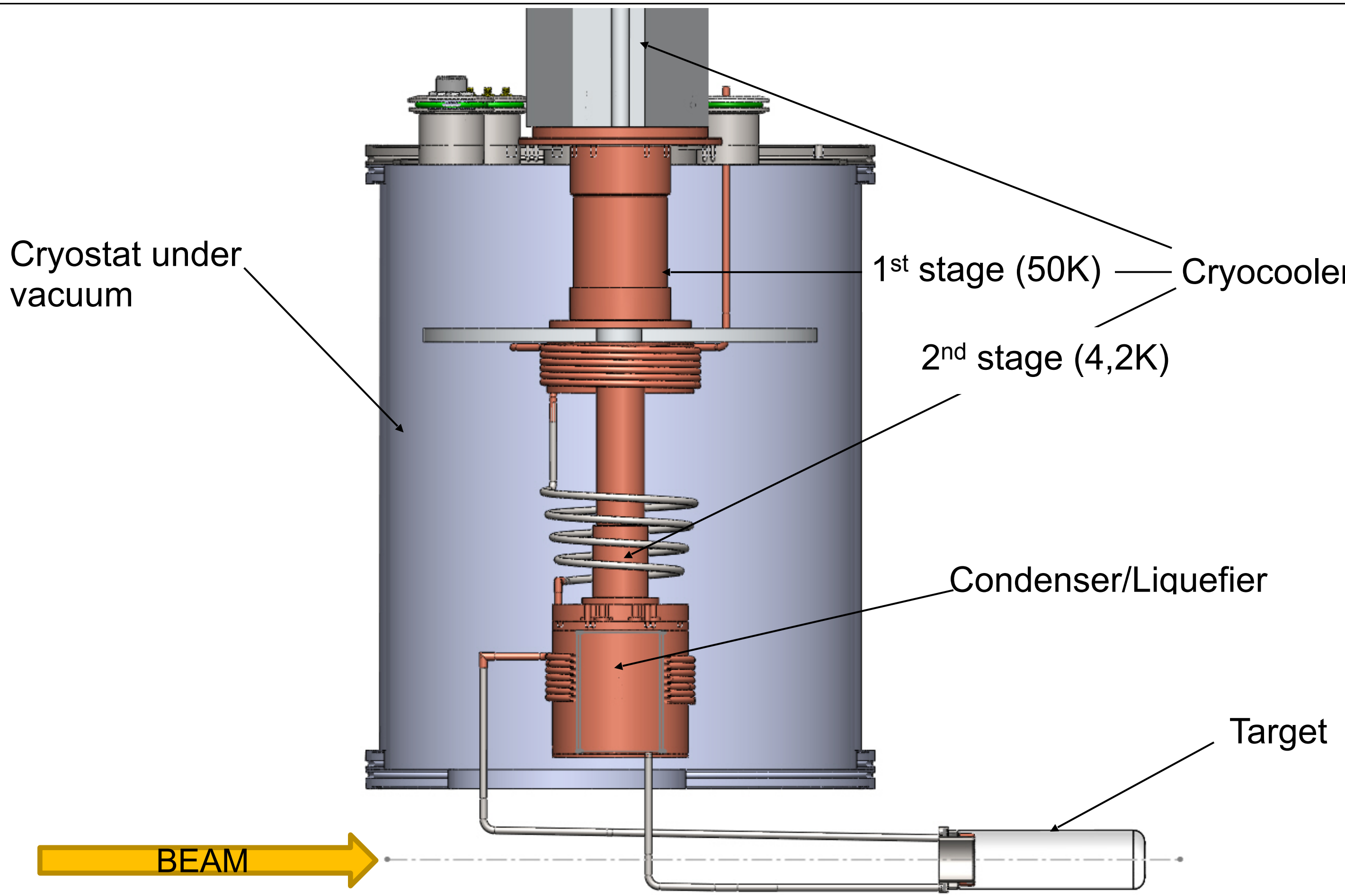
2011: *Sofia project at GSI*. Upgrade of Spaladin with a Ø 25 mm L = 10 mm target

Since 2011: *Minos project at Riken*. LH_2 targets Ø 40 mm, L1 = 50 mm, L2 = 100 mm, L3 = 150 mm

Since 2017: Cocotier *project at R3B/GSI*. LH_2 targets Ø 30 mm, L1 = 15 mm, L2 = 150 mm

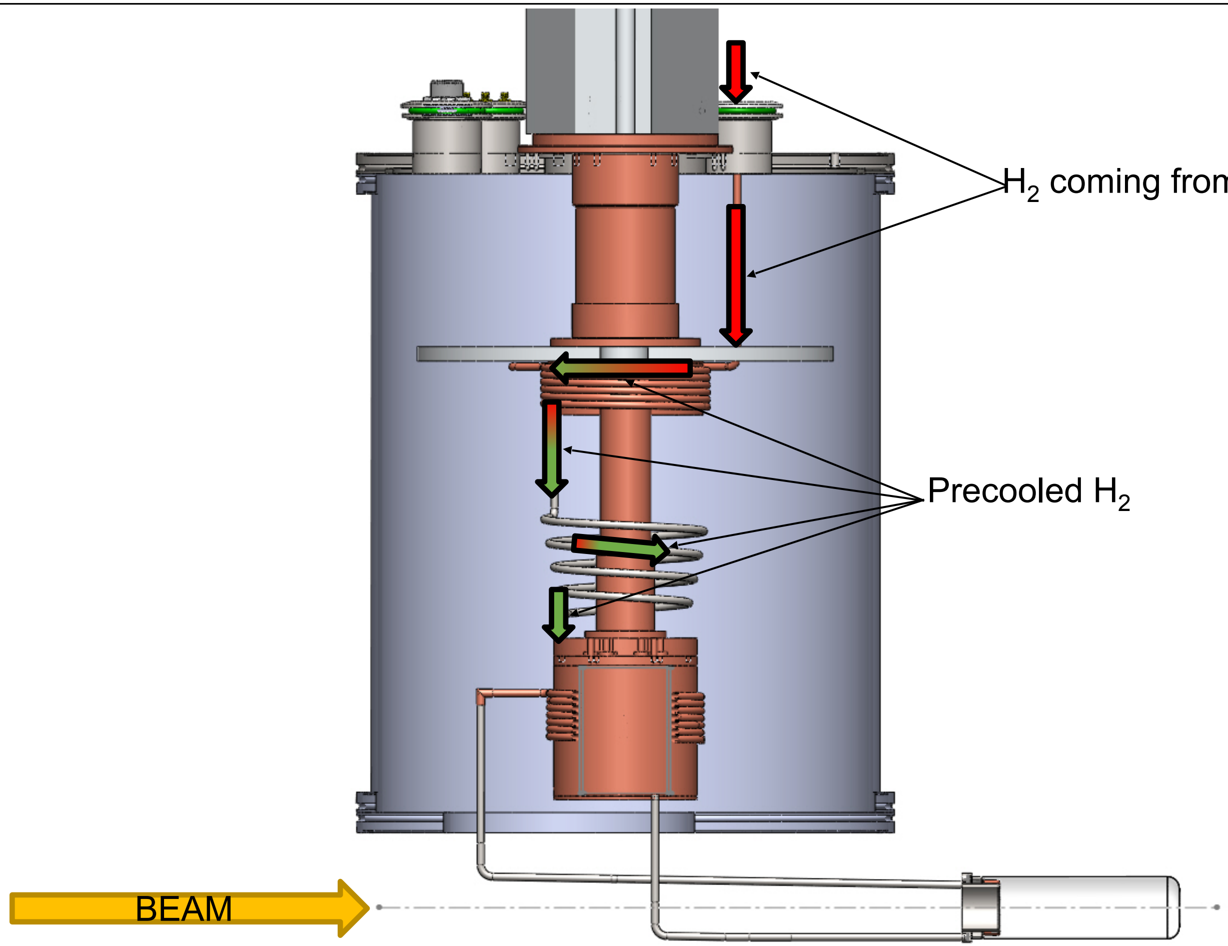
Slide J.-M. Gheller (CEA)

Operation



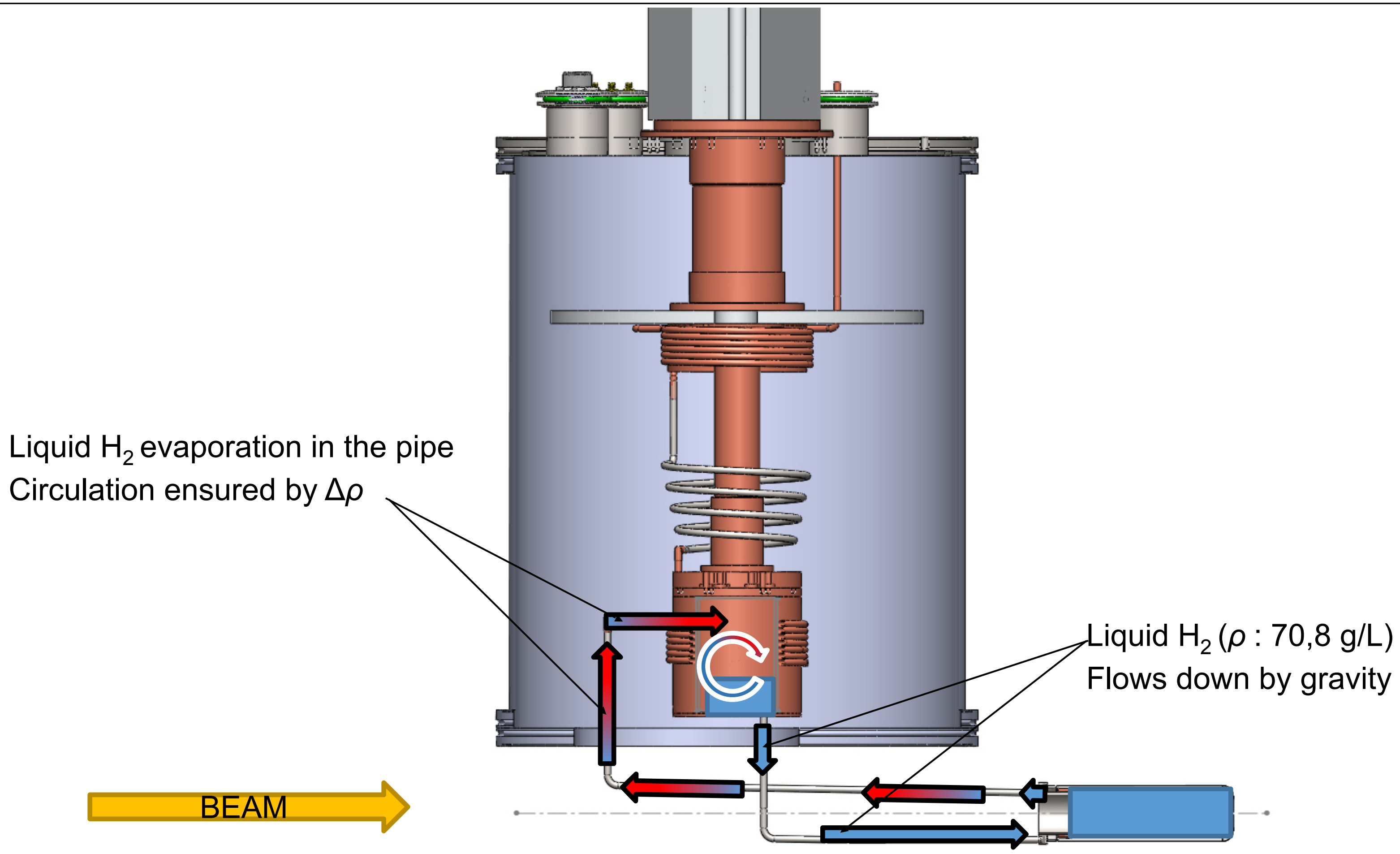
Slide A. Corsi, G. Authelet (CEA)

Operation



Slide A. Corsi, G. Authelet (CEA)

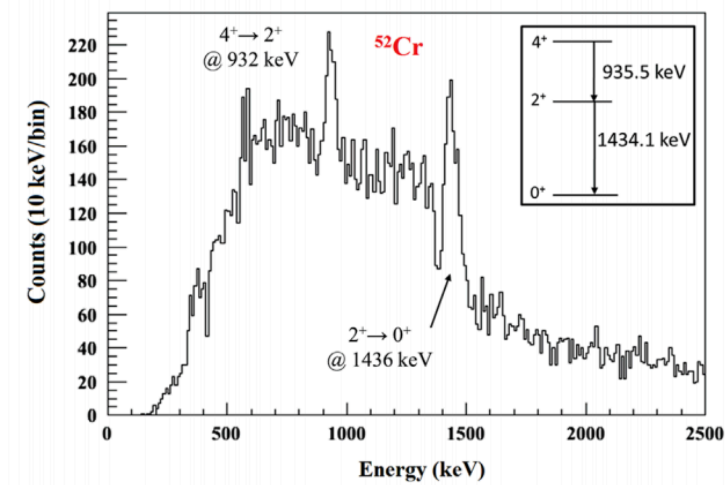
Operation



Slide A. Corsi, G. Authelet (CEA)

PRESPEC hydrogen target (in-beam validation)

TECHNISCHE
UNIVERSITÄT
DARMSTADT



2012: in-beam validation at GSI
with RISING gamma detectors (PRESPEC)

70-mm thick, 60-mm diameter
200 micron thick Mylar cell

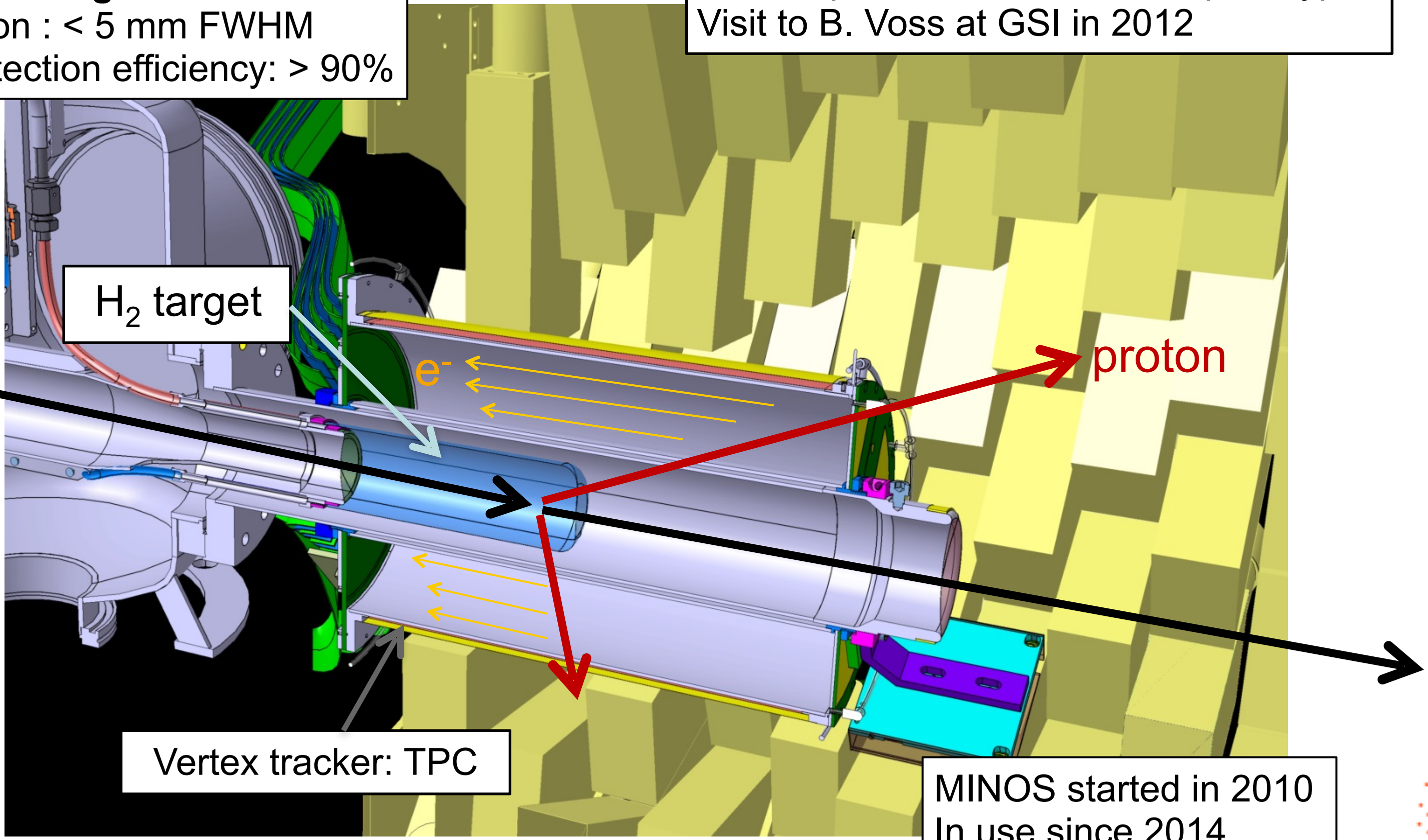
Very positive results
Spectra show low background

C. Louchart *et al.*, NIM A 736, 81 (2014)

DALI2 and MINOS at the RIBF (Japan)

liquid hydrogen target + tracker
Vertex resolution : < 5 mm FWHM
Total *(p,2p)* detection efficiency: > 90%

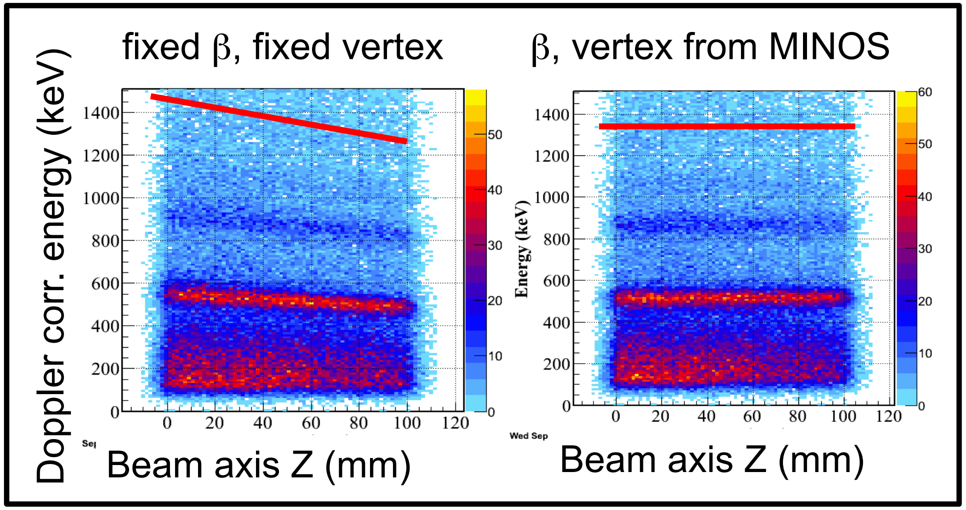
TPC inspired from the PANDA prototype
Visit to B. Voss at GSI in 2012

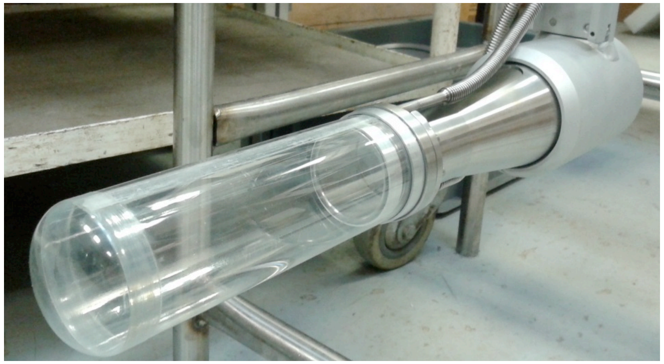


MINOS started in 2010
In use since 2014

A. Obertelli *et al.,* Eur. Phys. Jour. A **50**, 8 (2014)

MINOS working principle



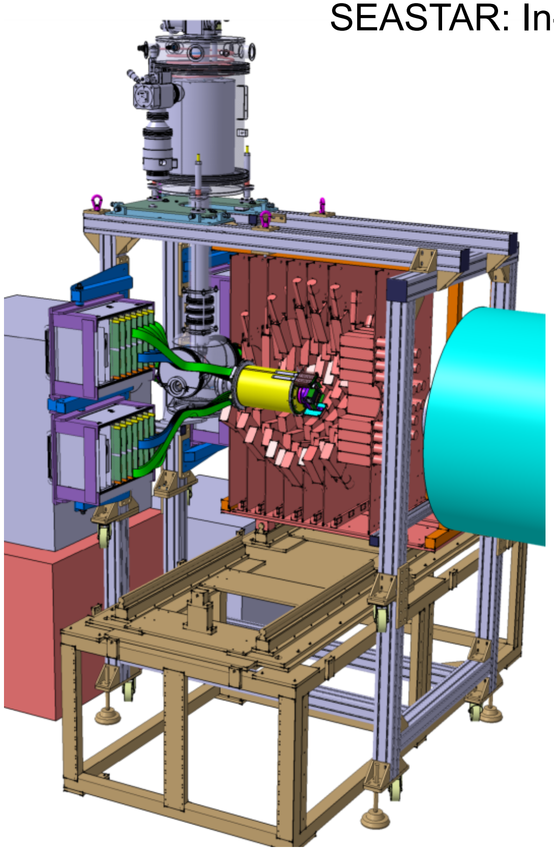


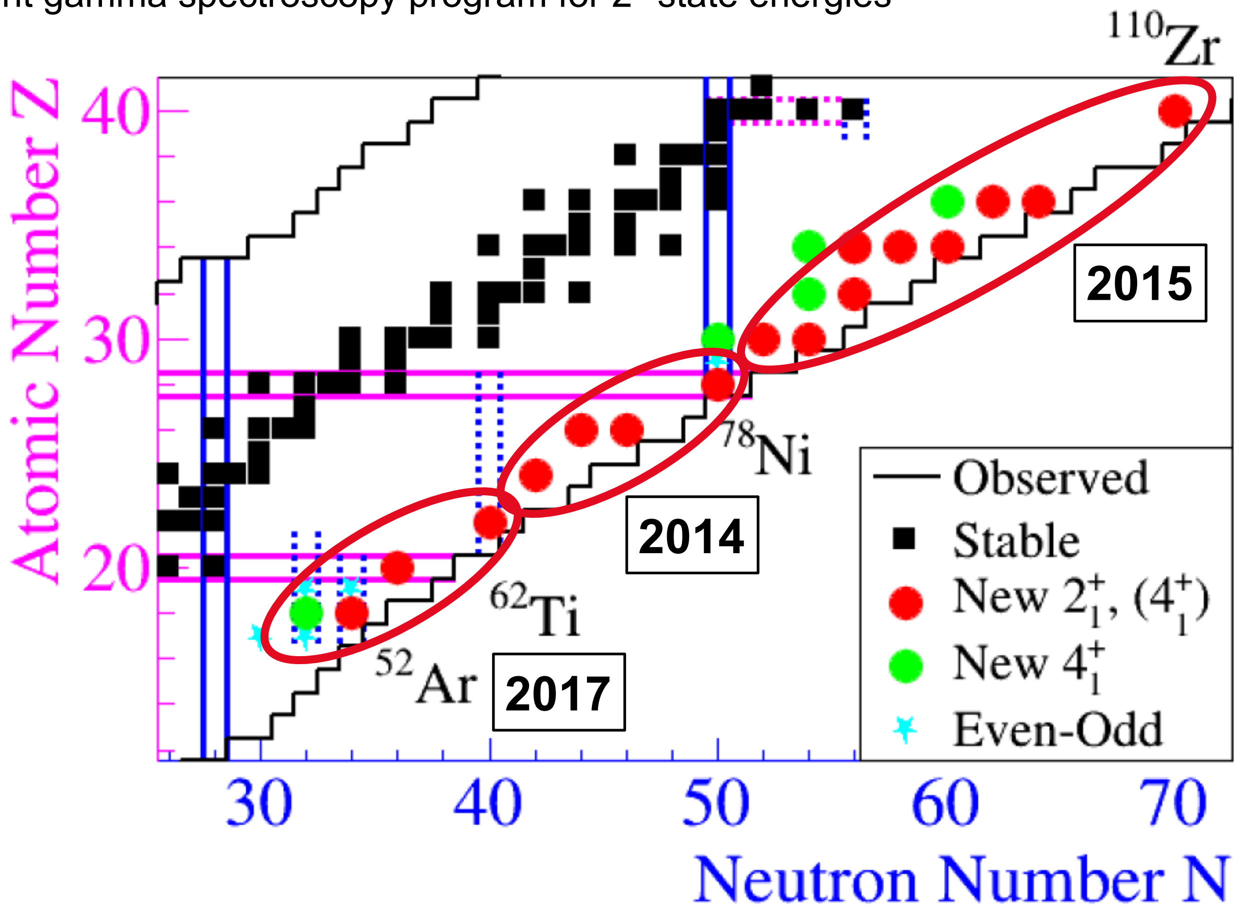
Liquid H2 target
- 20 K
- 100-150 mm thick
- 0.073 g / cm^3
- 150 µm Mylar cell

SEASTAR physics program: 2014 - 2017

TECHNISCHE UNIVERSITÄT DARMSTADT

SEASTAR: In-flight gamma spectroscopy program for 2^+ state energies

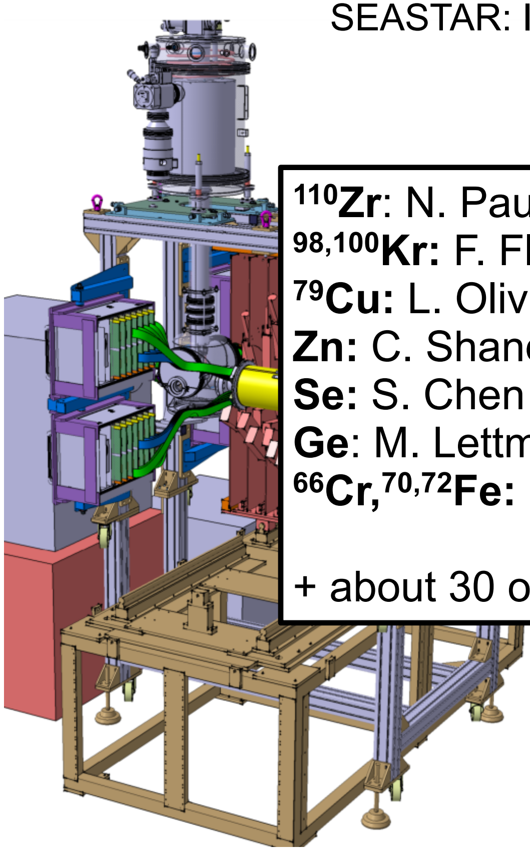


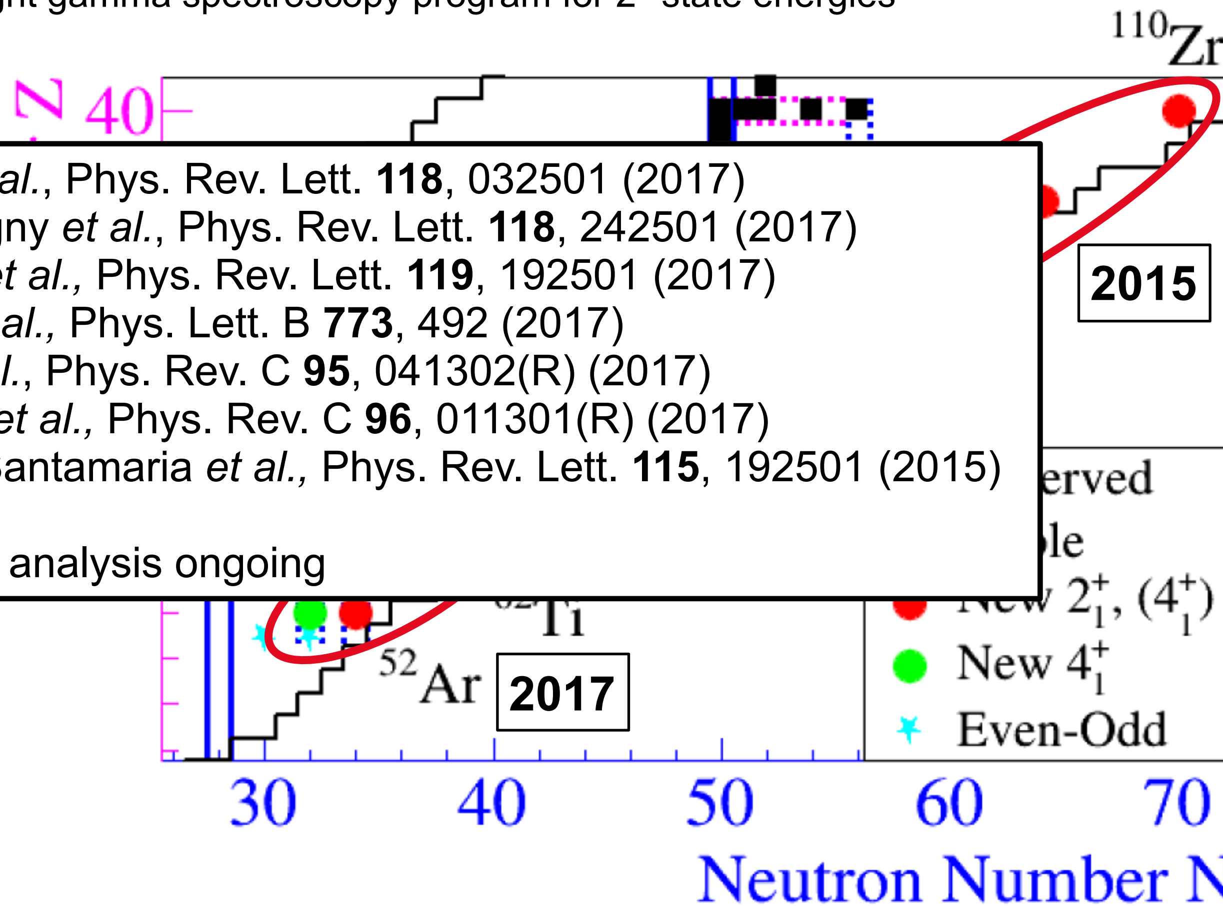


SEASTAR spokespersons: P. Doornenbal (RIKEN), A. Obertelli

SEASTAR physics program: 2014 - 2017

SEASTAR: In-flight gamma spectroscopy program for 2^+ state energies





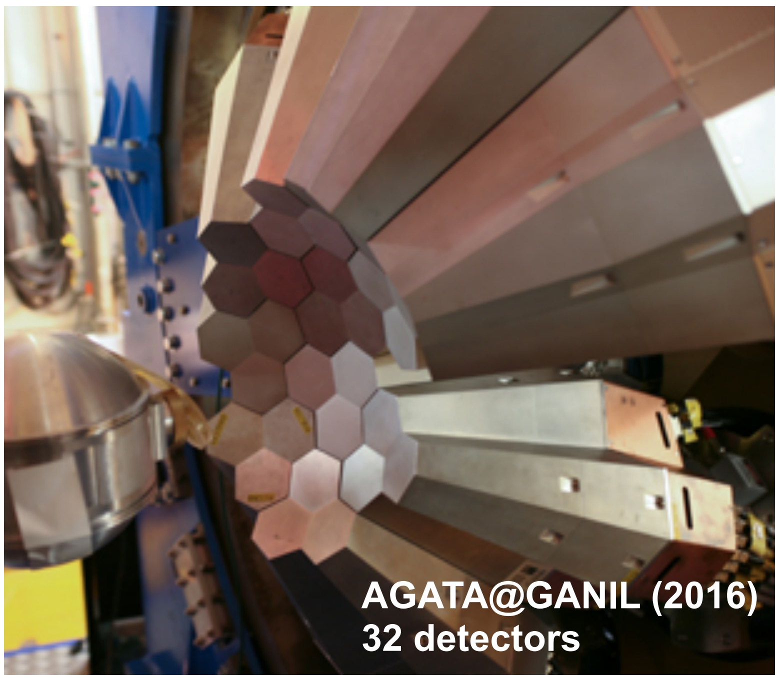
^{110}Zr: N. Paul *et al.*, Phys. Rev. Lett. **118**, 032501 (2017)
^{98,100}Kr: F. Flavigny *et al.*, Phys. Rev. Lett. **118**, 242501 (2017)
^{79}Cu: L. Olivier *et al.*, Phys. Rev. Lett. **119**, 192501 (2017)
Zn: C. Shand et *al.*, Phys. Lett. B **773**, 492 (2017)
Se: S. Chen *et al.*, Phys. Rev. C **95**, 041302(R) (2017)
Ge: M. Lettman *et al.*, Phys. Rev. C **96**, 011301(R) (2017)
^{66}Cr,^{70,72}Fe: C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015)

+ about 30 other analysis ongoing

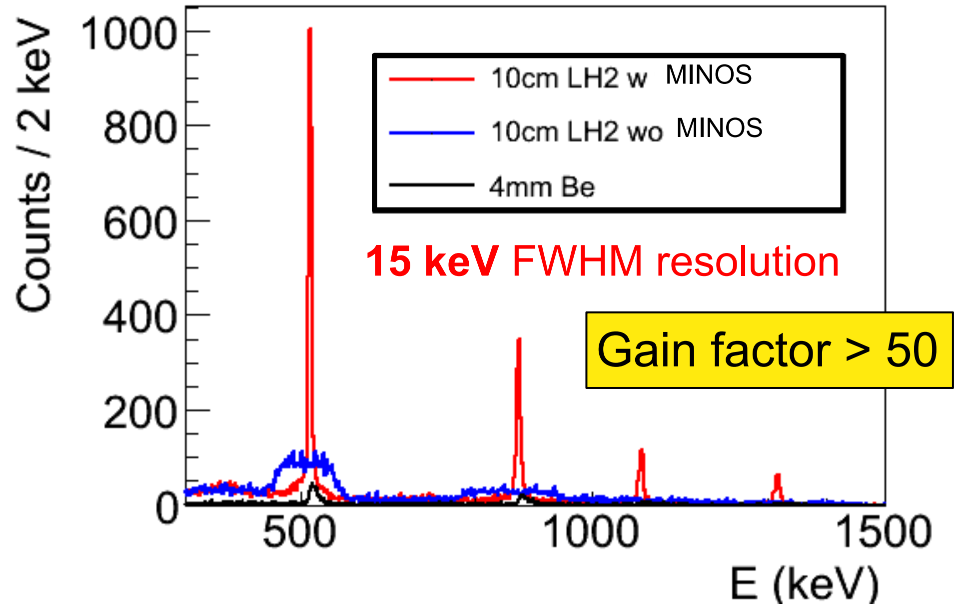
SEASTAR spokespersons: P. Doornenbal (RIKEN), A. Obertelli

Future: high-resolution with AGATA

- High-resolution Ge tracking arrays open new opportunities
- Excellent energy resolution (0.2%), spatial resolution of first interaction point <5-mm
- Upcoming plan: build a MINOS-like device for AGATA @ FAIR
- Requires a compact geometry (23-cm diameter of AGATA): **Silicon tracker around H_2 target**



^{69}Co(p,2p)^{68}Fe at 200 MeV/nucleon



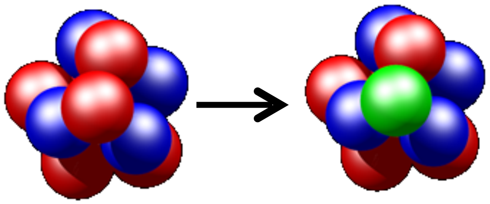
AGATA@FAIR simulation, 30 detectors

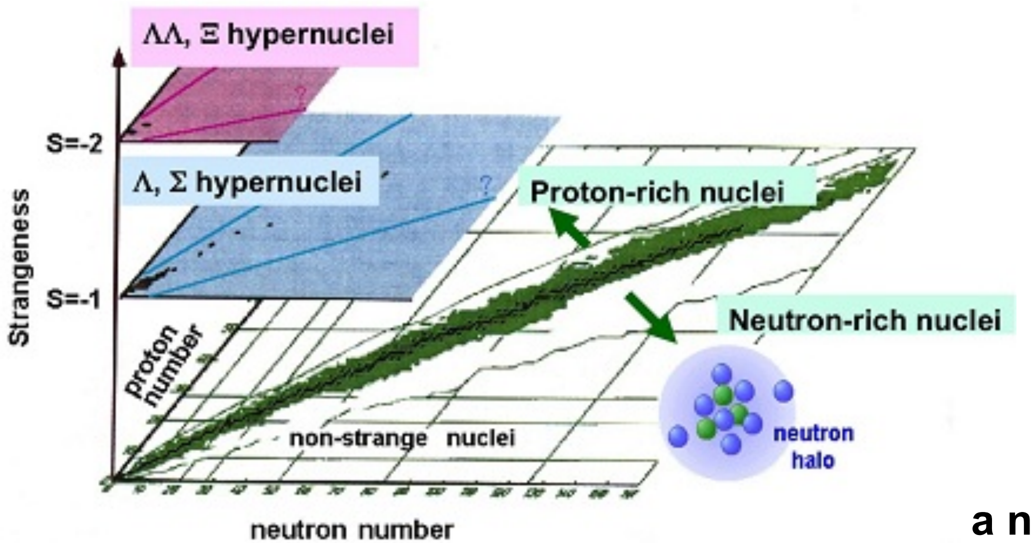
Hypernuclei

Hypernucleus consists of nucleons (n,p) + hyperon (**Y**)

Notation $_{Y}^{A}Z$, Y: hyperon, $A=N_n + N_p + N_Y$

- Λ (usd), lowest mass hyperon (1150 MeV)
- free Λ lifetime: τ=261 ps
- Hypernuclei: **weak decay** (mesonic / non mesonic)

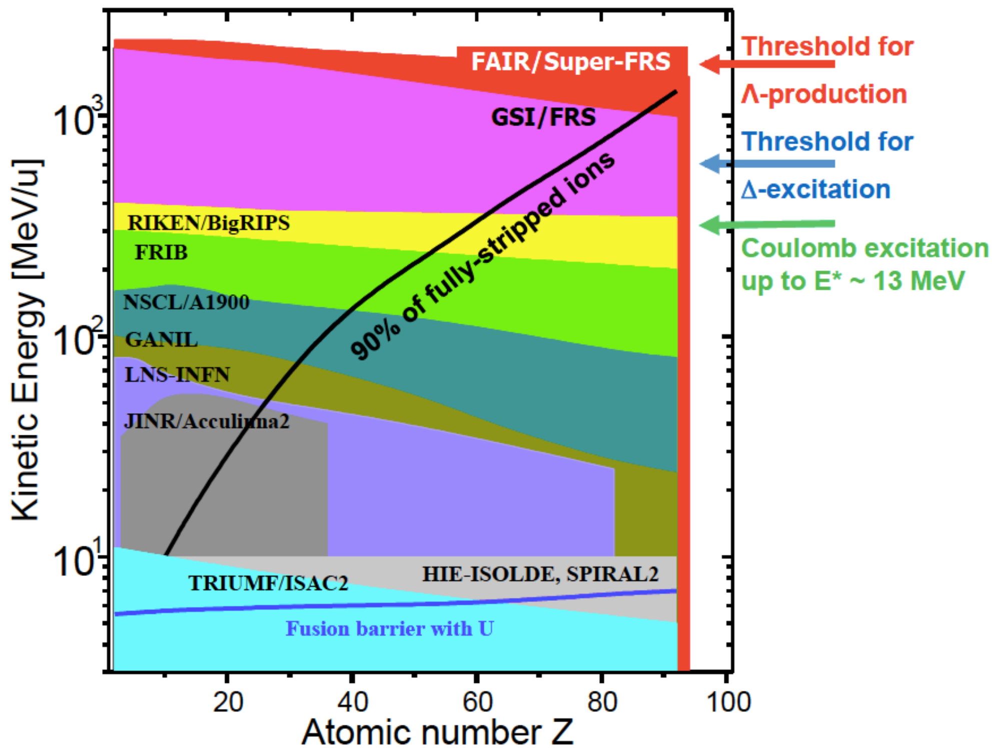


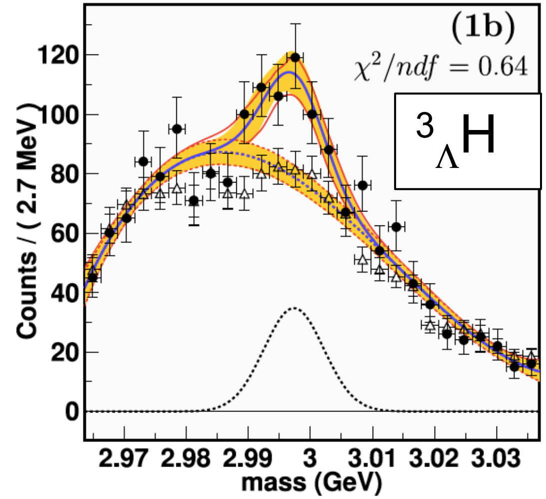


Strangeness
=
a new dimension to explore

Hypernuclei @ GSI / FAIR

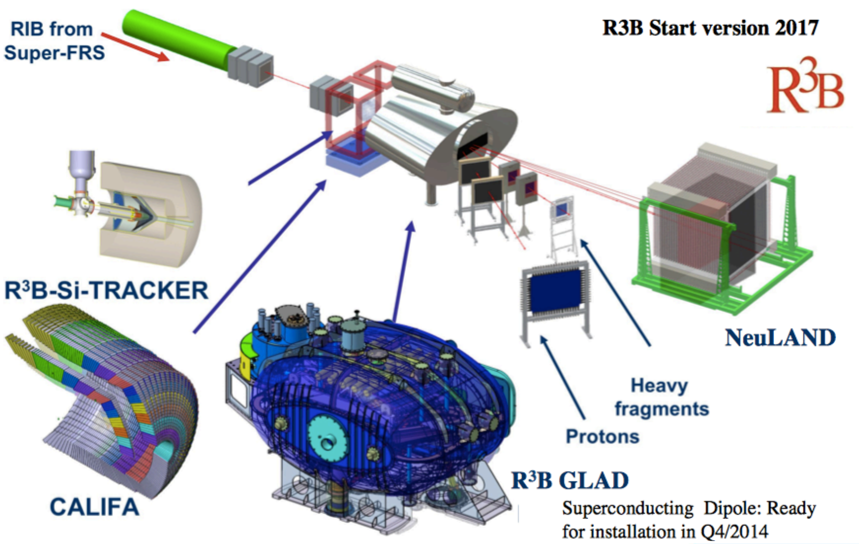
- **GSI / FAIR a unique facility to produce hyper nuclei**
- Heavy ion collisions at E > 2 GeV/nucleon, **NN -> Λ K N (thr.: 1.6 GeV)**
- Pioneering work by **T. Saito** (GSI) / proof of principle performed with HYPHI0, GSI





HyPHI collaboration,
Nucl. Phys. A **913**, 170 (2013)

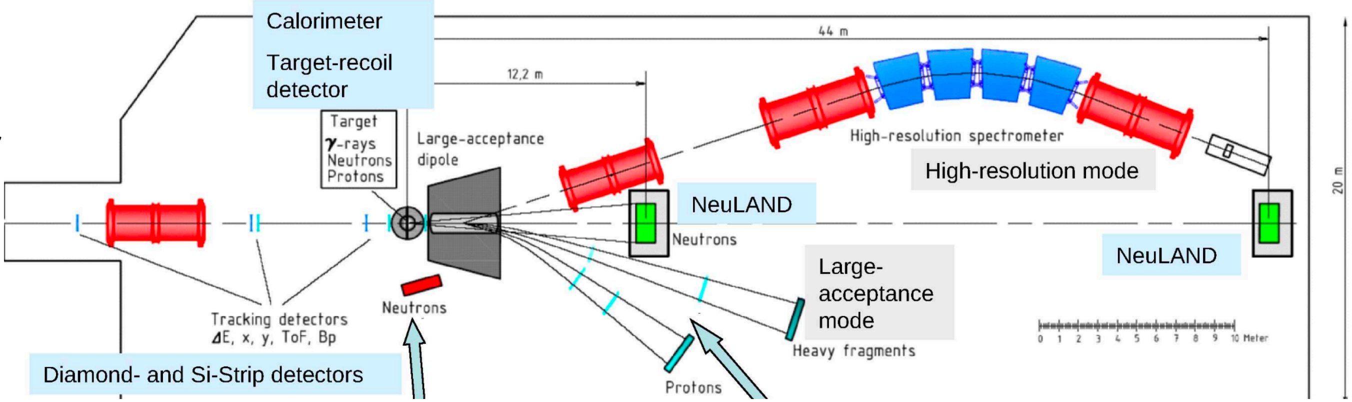
Hypernuclei @ R3B



kinematically complete measurements in inverse kinematics

High-resolution spectrometer not funded yet

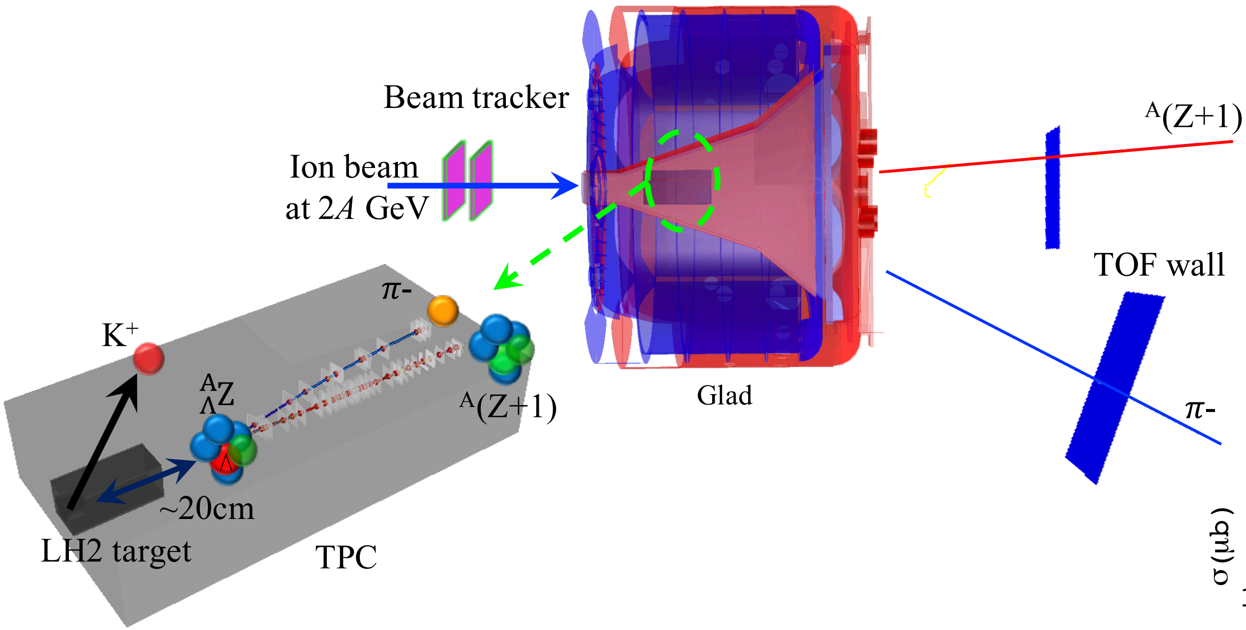
Design ongoing (T. Aumann)

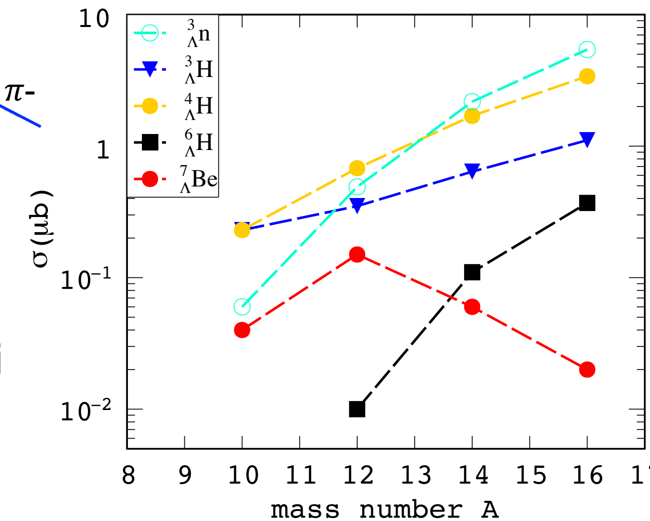


Plan: hypernuclei studies at R3B

TECHNISCHE UNIVERSITÄT DARMSTADT

Courtesy: Yelei Sun





- **hydrogen target** competitive to produce hypernuclei
- Better signal over noise ratio
- Goal: tag BOTH strangeness production and decay
- Cross sections / lifetimes / binding energy

Y. Sun *et al.*, submitted to PRC (2017)
Production of light hypernuclei with light-ion beams and targets

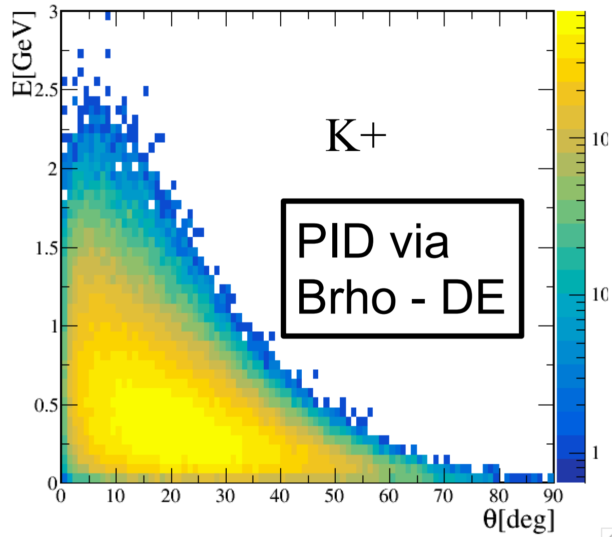
Plan: hypernuclei studies at R3B

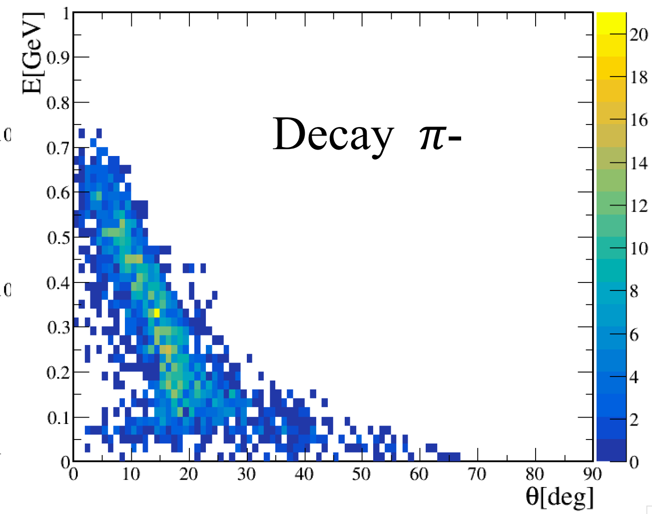
^{12}C + proton at 2AGeV

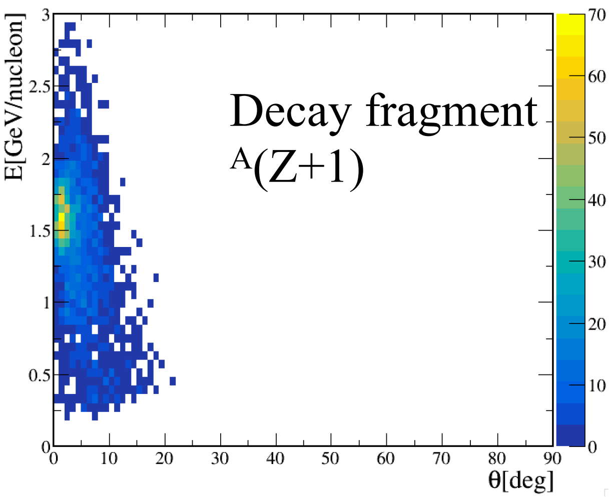
Mesonic decay of hypernuclei

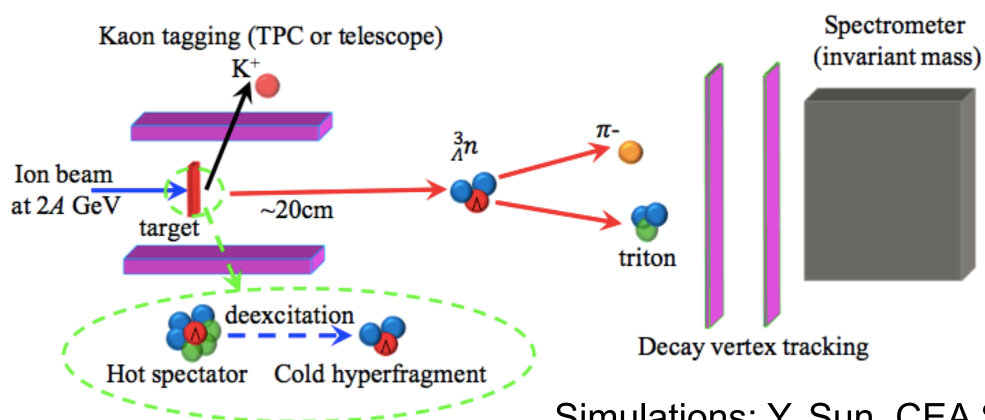
$^{A}Z_{\Lambda} \rightarrow$ $^{A}(Z+1) + \pi$-

Considered hypernuclei in the decay:
LN, LNN, 3LH, 4LH, 6LH, 4LHe



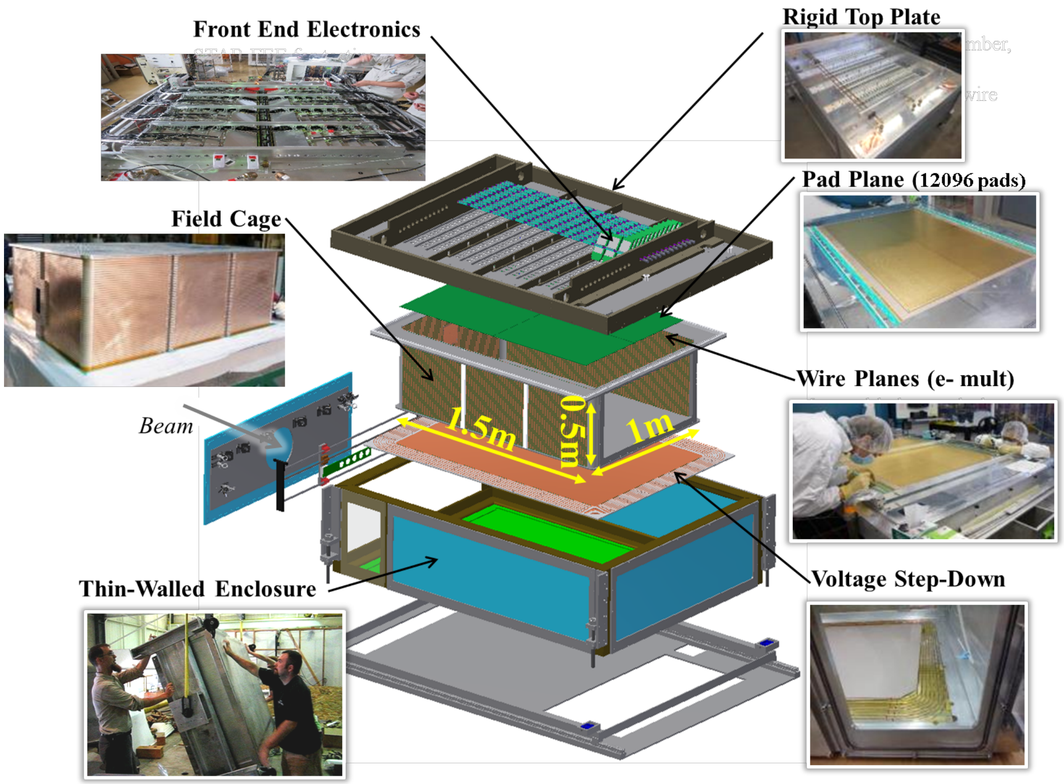


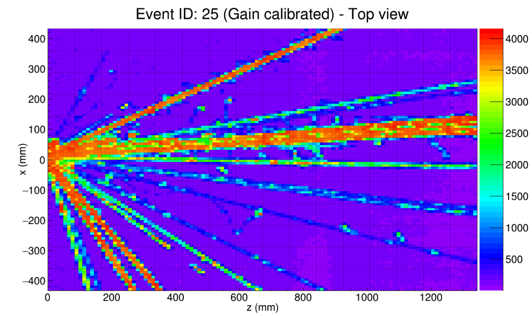


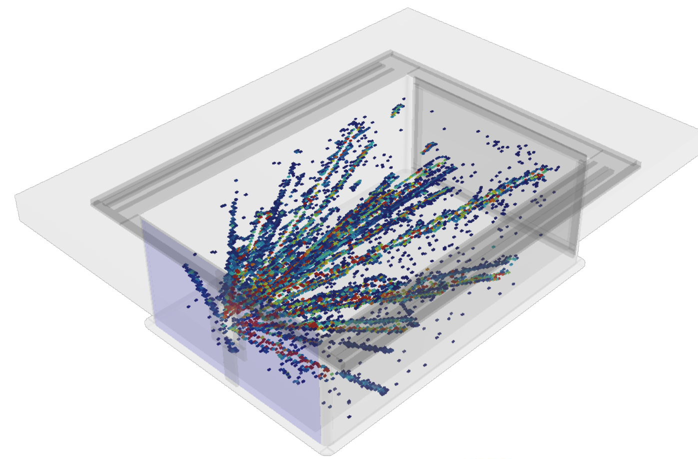


Simulations: Y. Sun, CEA Saclay

Example: TPC inside SAMURAI (RIBF)







Bean intensity limited to 10^4 pps so far
Expected limitation rate of 10^5 pps

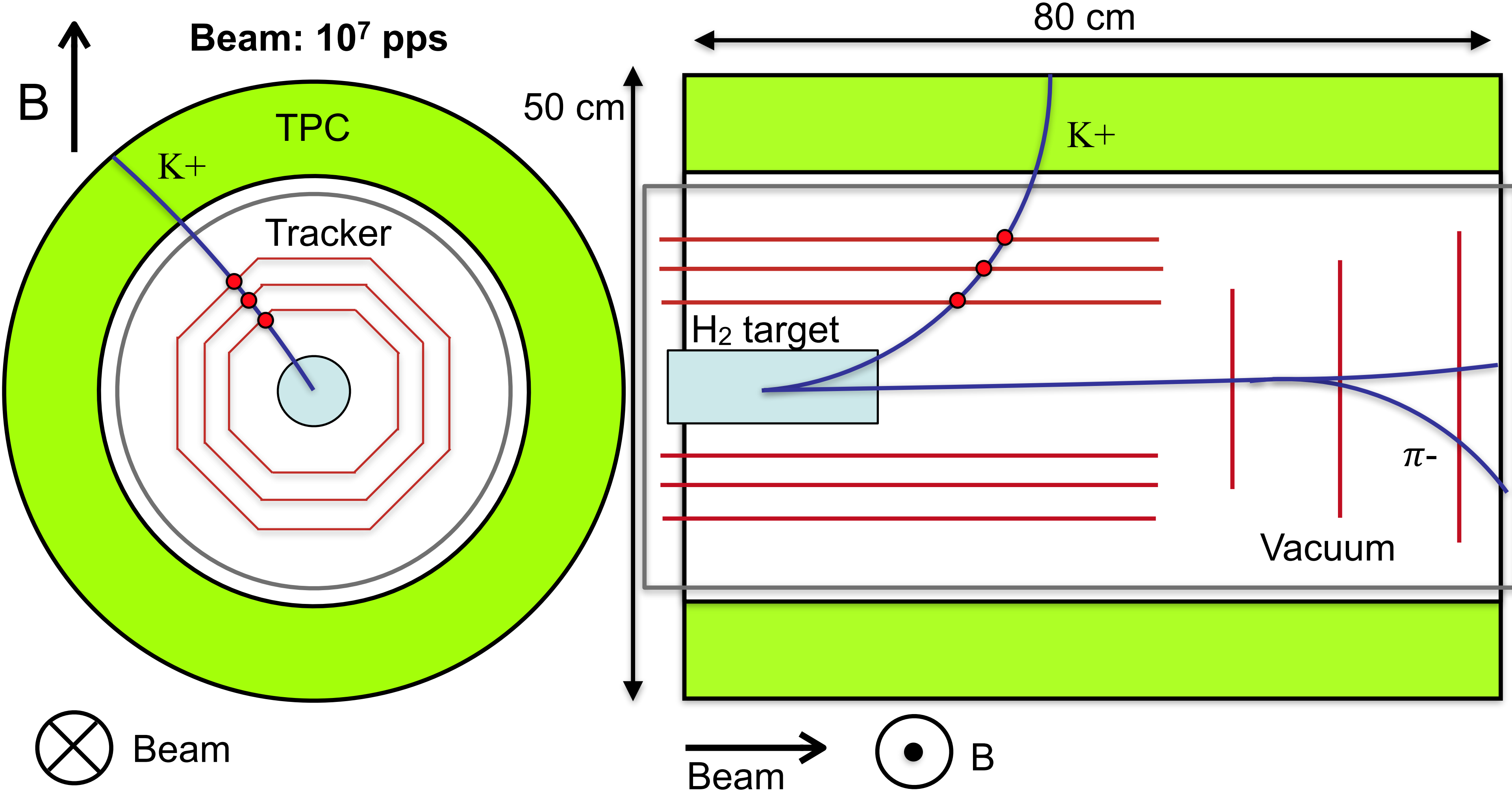
U.S. DEPARTMENT OF ENERGY Office of Science

SπRIT

文部科学省 MEXT

High-granularity hybrid system inside GLAD

TECHNISCHE UNIVERSITÄT DARMSTADT



A future cryogenic target laboratory

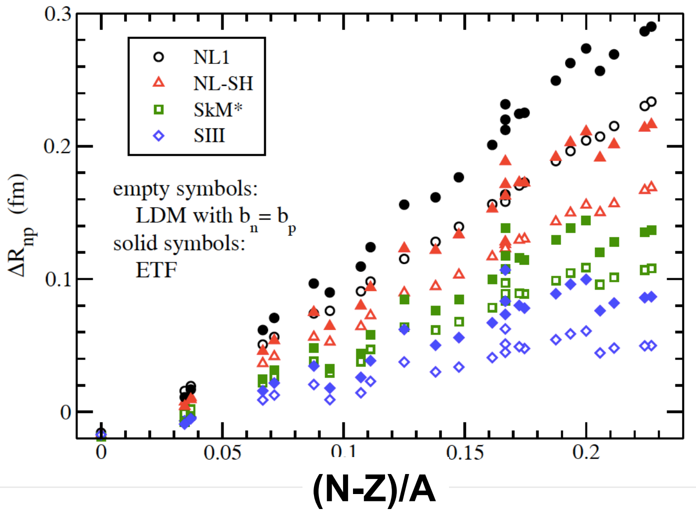
TECHNISCHE UNIVERSITÄT DARMSTADT

- A project at TU Darmstadt
- **Objectives**
  - cryogenic hydrogen targets combined with trackers
  - liquid TPCs for nuclear physics
  - R&D
- **Possible first projects**
  - H2 target + Si tracker for high resolution in-beam gamma spectroscopy
  - H2 target + tracker for R3B GLAD
  - H2 targets for S-FRS to be considered
- **infrastructure**
- **Collaboration**
  - Technical and physics collaborations with GSI, CEA to be discussed
  - Contact person at GSI would highly beneficial

Halos and neutron skins

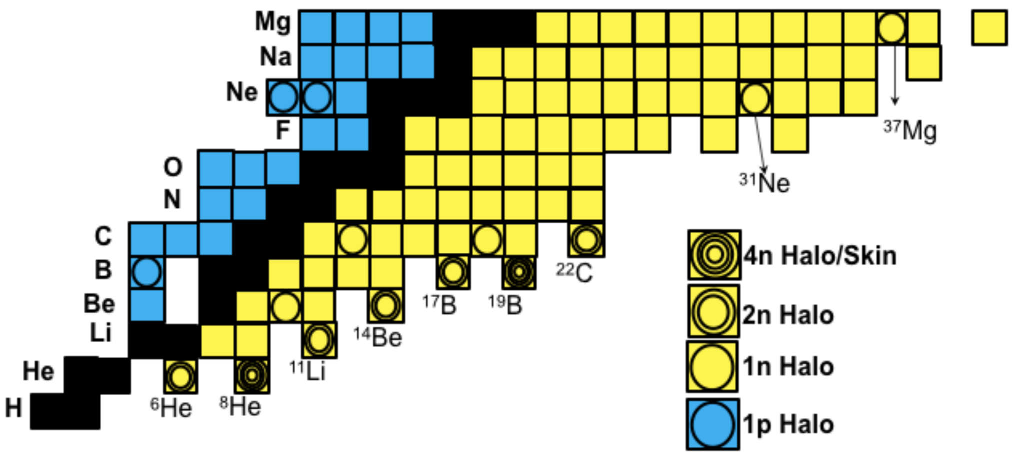
neutron skin thickness

$$\Delta r_{np} = \langle r_n \rangle - \langle r_p \rangle \approx \langle r_m \rangle - \langle r_c \rangle$$



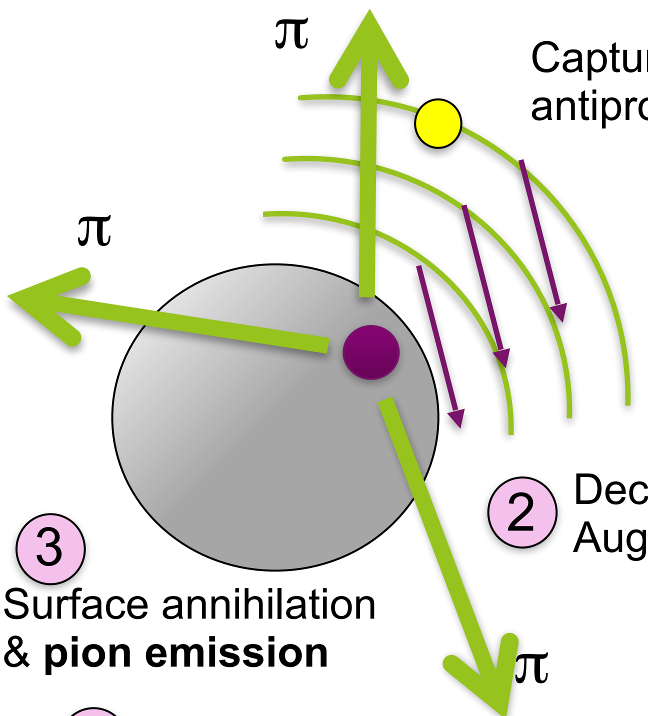
X. Vinas *et al.*, Eur. Phys. J A 50, 27 (2014)

neutron and proton halos



- ❑ **neutron skins and halos** have been extensively studied
- ❑ structure phenomenon difficult to characterise and to measure accurately
- ❑ skins also motivated by the Nuclear Equation of State (EOS)
- ❑ **Halos** not known well (at all) beyond mass 15, while predicted

Antiproton annihilation: a probe for the nuclear density tail



1 Captured antiproton

2 Decay **X-rays** Auger electrons

3 Surface annihilation & **pion emission**

4 Cascade & **residue production**, decay

Brookhaven NL: W. M. Buggs et al., Phys. Rev. Lett. 31, 475 (1973)

Antiproton-proton, $\bar{p}p$ [43]

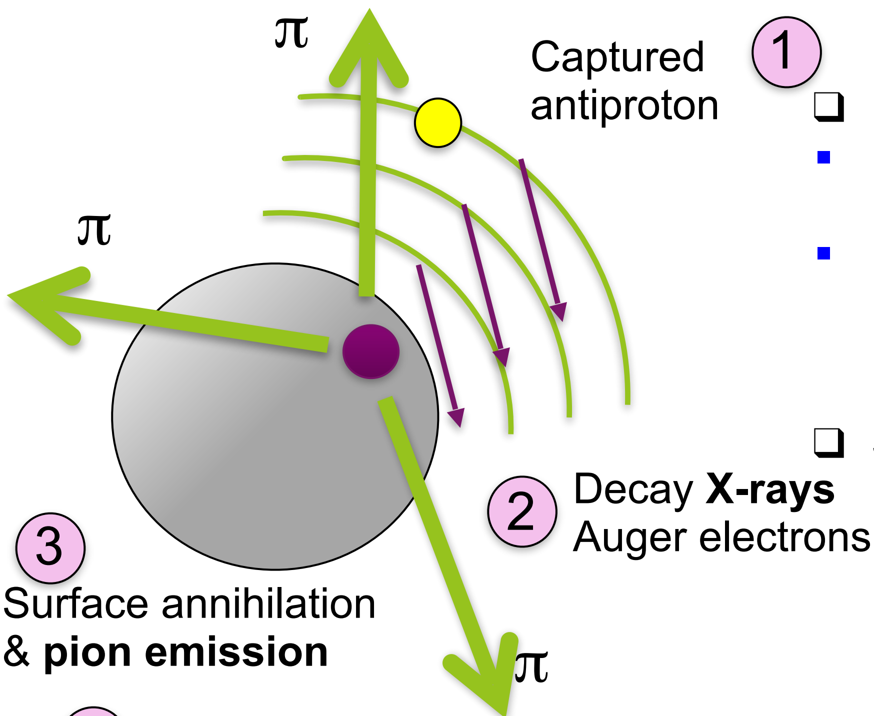
Pion final state	Branching ratio
$\pi^0\pi^0$	0.00028
$\pi^0\pi^0\pi^0$	0.0076
$\pi^0\pi^0\pi^0\pi^0$	0.03
$\pi^+\pi^-$	0.0032
$\pi^+\pi^-\pi^0$	0.069
$\pi^+\pi^-\pi^0\pi^0$	0.093
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028
$\pi^+\pi^-\pi^+\pi^-$	0.069
$\pi^+\pi^-\pi^+\pi^-\pi^0$	0.196
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	0.166
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$	0.042
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	0.021
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$	0.019

Antiproton-neutron, $\bar{p}n$ [46]

Pion final state	Branching ratio
$\pi^-\pi^0$	0.0075
$\pi^- k\pi^0$ $(k > 1)$	0.169
$\pi^-\pi^-\pi^+$	0.023
$\pi^-\pi^-\pi^+\pi^0$	0.17
$\pi^-\pi^-\pi^+ k\pi^0$ $(k > 1)$	0.397
$\pi^-\pi^-\pi^-\pi^+\pi^+$	0.042
$\pi^-\pi^-\pi^-\pi^+\pi^+\pi^0$	0.12
$\pi^-\pi^-\pi^-\pi^+\pi^+ k\pi^0$ $(k > 1)$	0.066
$\pi^-\pi^-\pi^-\pi^-\pi^+\pi^+\pi^+ k\pi^0$ $(k \geq 0)$	0.0035

Antiproton annihilation:
a probe for the nuclear density tail

TECHNISCHE UNIVERSITÄT DARMSTADT



4
Cascade & **residue production**, decay

- Features:
  - **High cross section** (Mbarns) **at low energy** (100 eV)
  - **Net electric charge conservation**
    - **-1**: neutron annihilation
    - **0**: proton annihilation
- Sensitive to **neutron-proton density ratio at surface**

Emitted pions Multiplicity M Total charge Σ	←FSI→	$\frac{N_n}{N_p}$	←theory→	$\left.\frac{\rho_n}{\rho_p}\right\vert_{surface}$
Measured		**Extracted**		**Calculated**

M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

FLAIR

TECHNISCHE UNIVERSITÄT DARMSTADT

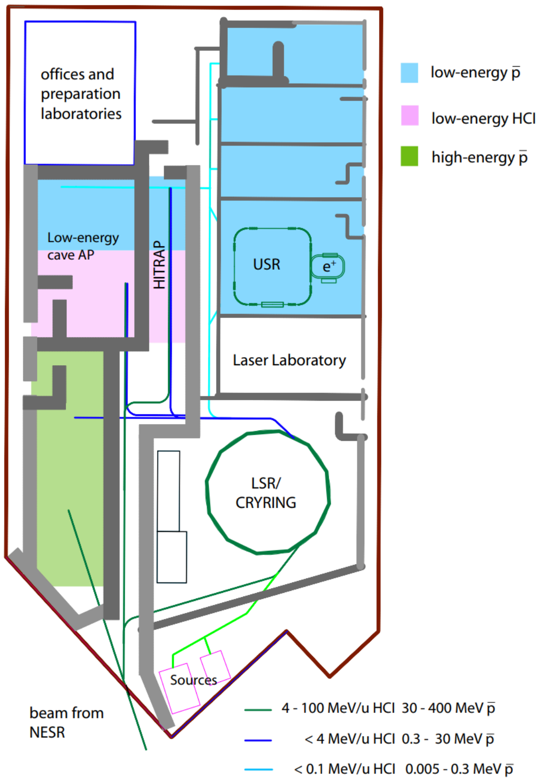
- **FLAIR = Facility for Low-energy Antiproton and Ion Research**

- Proposed in 2004
- Not included in the Modularized Start Version of FAIR

LoI have been submitted:
- X-ray of light antiprotons atoms
- X-ray of heavy antiprotons atoms
- production of strangeness

- antiprotons and exotic nuclei proposed by Wada, Yamasaki
  M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

- Still possibilities at FAIR after CRYRING
  E. Widmann, Physica Scripta T166 (2015)

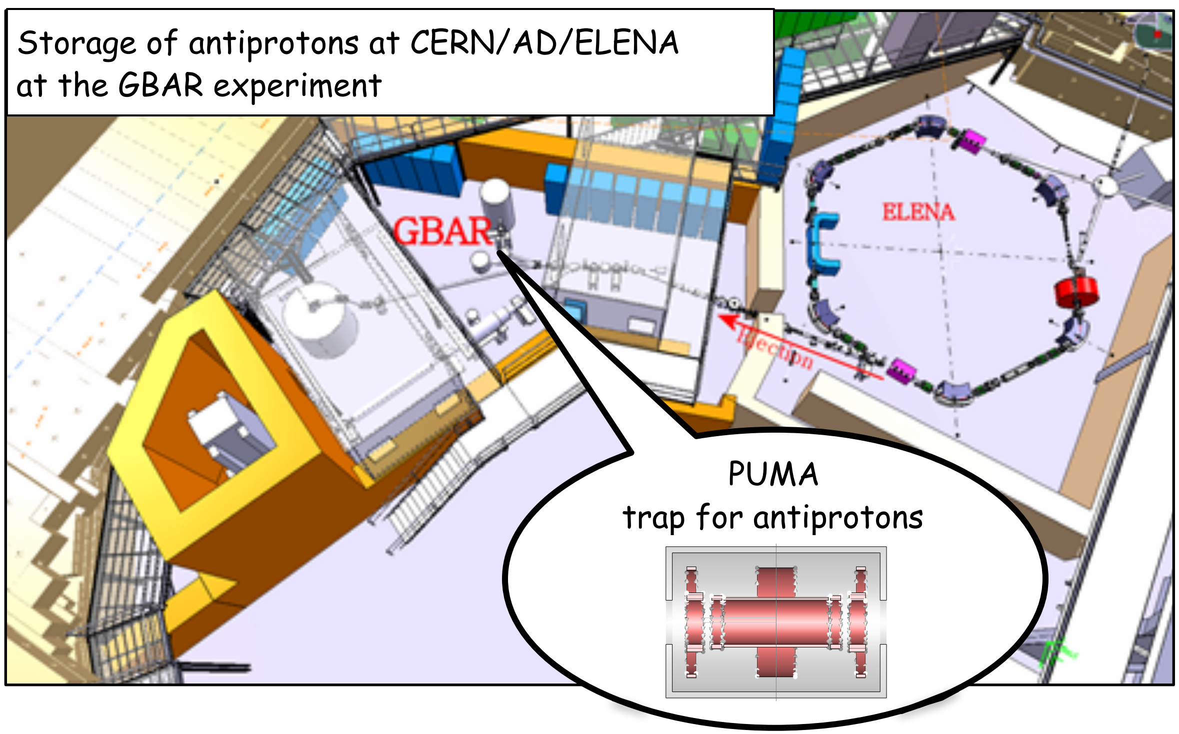


PUMA: Pbar Unstable Matter Annihilation

TECHNISCHE UNIVERSITÄT DARMSTADT

erc

- Transport antiprotons from ELENA (CERN) to ISOLDE
- Device to be build (funded from 01/2018, for 5 years)
- First experiment at ISOLDE foreseen in 2022
- Pioneer experiment with antiprotons as a probe for short-lived nuclei



Storage of antiprotons at CERN/AD/ELENA at the GBAR experiment

Transport the antiprotons…

… to ISOLDE at CERN for unstable ion annihilation.

PUMA : schematic description

NEWS · 20 FEBRUARY 2018 · CORRECTION 20 FEBRUARY 2018

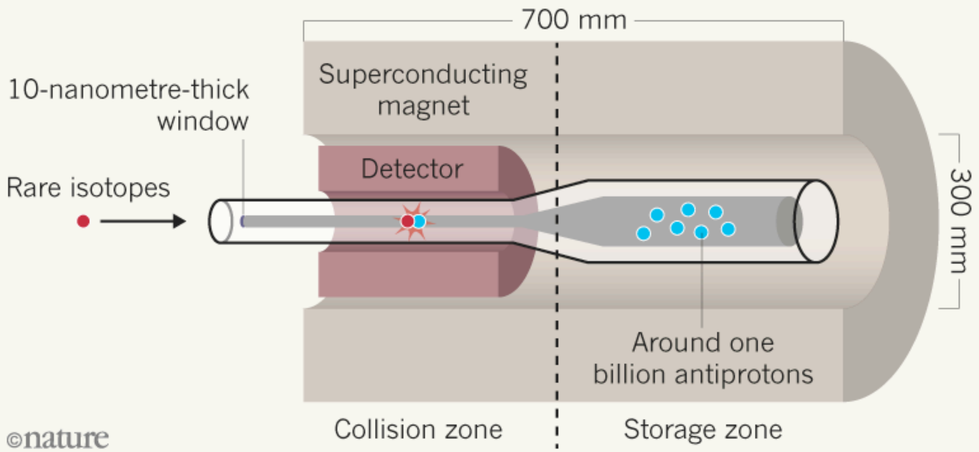
Physicists plan antimatter's first outing — in a van

Researchers intend to transport the elusive material between labs and use it to study the strange behaviour of rare radioactive nuclei.

Elizabeth Gibney

ANTIMATTER TO GO

To reveal the surface structure of atomic nuclei, physicists send ions of rare isotopes into a bottle 700 millimetres long — where they annihilate with antiprotons stored in the trap.



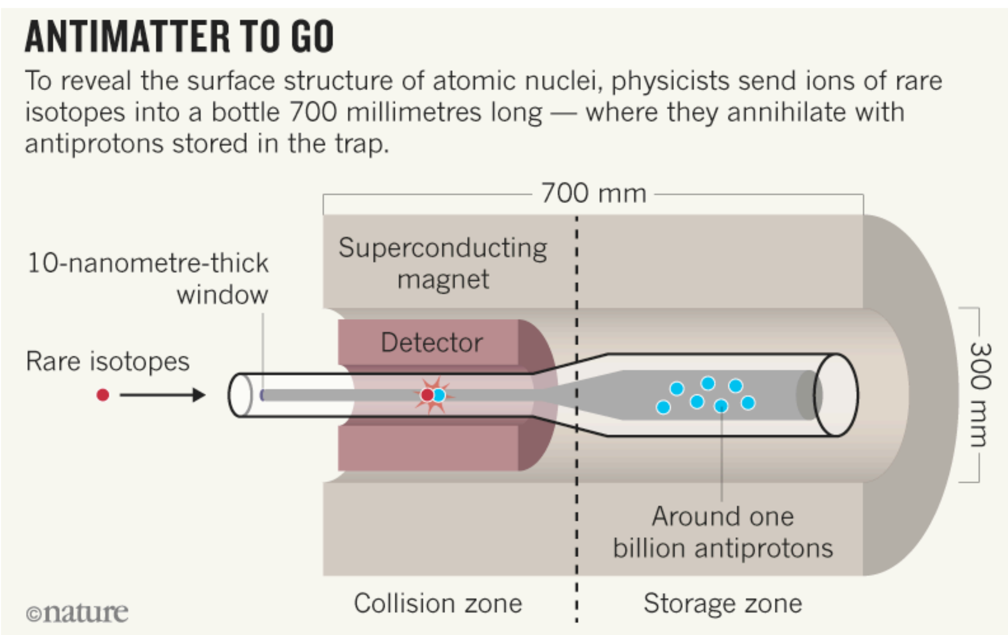
PUMA : schematic description

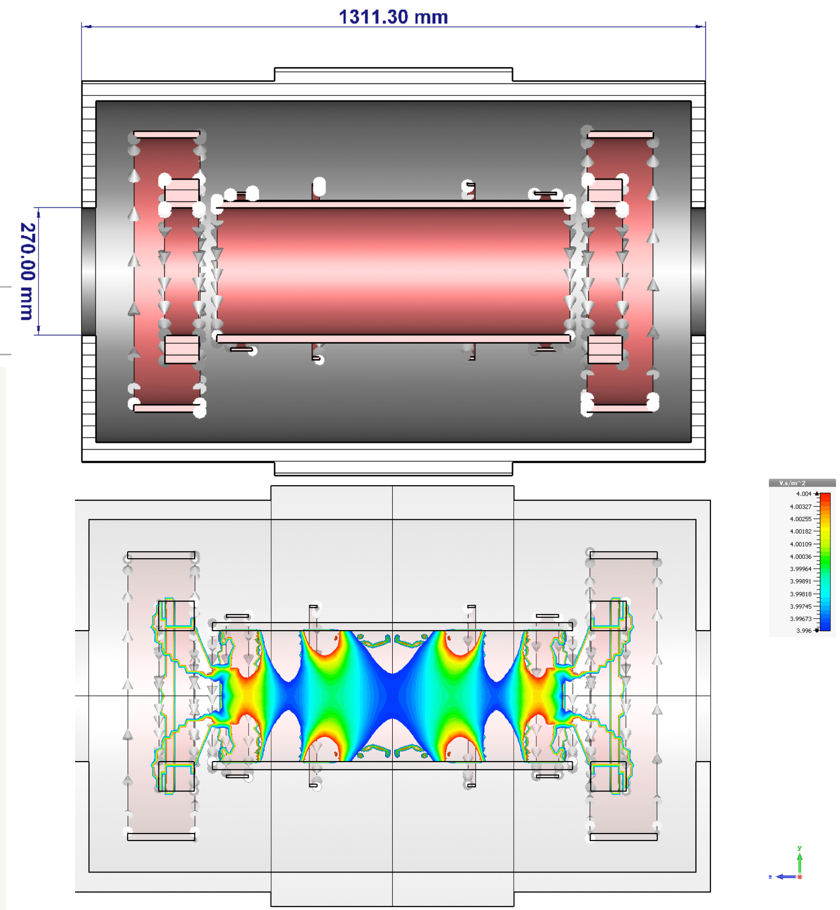
NEWS · 20 FEBRUARY 2018 · CORRECTION 20 FEBRUARY 2018

Physicists plan antimatter's first outing — in a van

Researchers intend to transport the elusive material between labs and use it to study the strange behaviour of rare radioactive nuclei.

Elizabeth Gibney





Design, N. Marsic, H. De Gersem, W. Müller
TEMF institute, TU Darmstadt

Challenges

- ❑ Cryostat suited for **ultra-high vacuum (<10^{-17} mbar)** and insertion of low-energy ions
  - sealed by thin entrance window (20 nm, proposed solution Si3N4)
  - 4K
  - ions & antiprotons cooling

  C. Smorra et al., Int. Jour. Mass. Spec. 189, 19 (2015)

- ❑ Trapping of **one billion antiprotons**

- ❑ **Transportable trap** that meets contrains from environment (GBAR / ISOLDE, costs)

  C.H. Tseng and G. Gabrielse, Hyperfine Interactions 76, 381 (1993)

- ❑ **Final state** interaction correction uncertainties

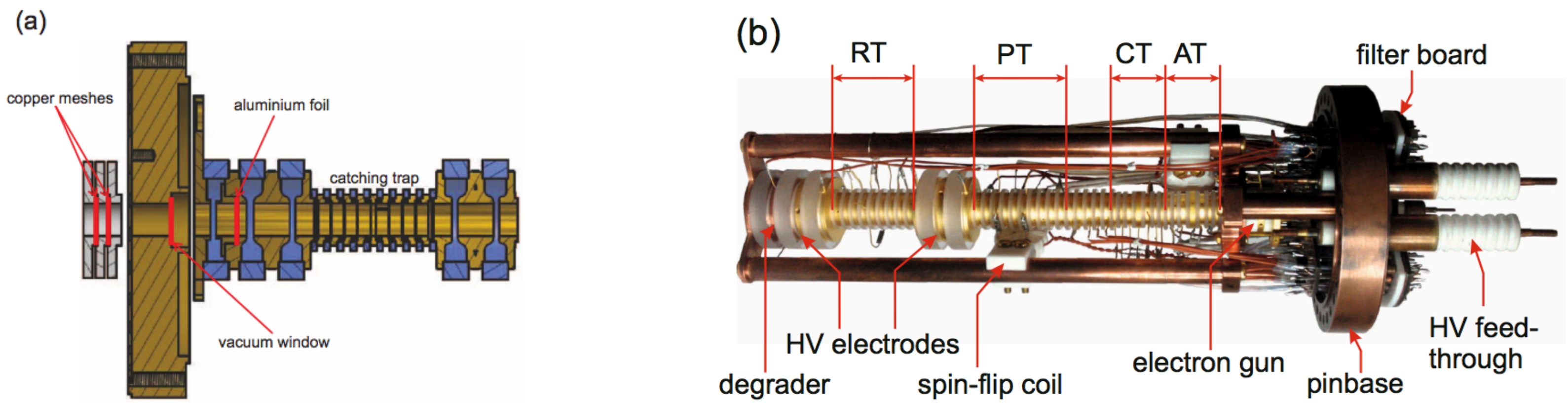
  M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

Sealed trap for antiprotons

- Lifetime of antiprotons determined by the vacuum

$$P_H(mbar) = 6\times10^{-16}\, T(K)/\tau(jours)$$

- **ONE solution: cryogenic (4 K) sealed vacuum**
- Done on regular basis at CERN for antiproton physics: $P<10^{-17}$ mbar
- Ex. S. Ulmer, BASE experiment at CERN / AD
  Lifetime of stored antiprotons (about 15) estimated > 25 years



C. Smorra *et al.*, EPJ Spec. Topics 224, 3055 (2015)

Thin sealing window for Radioactive Ions

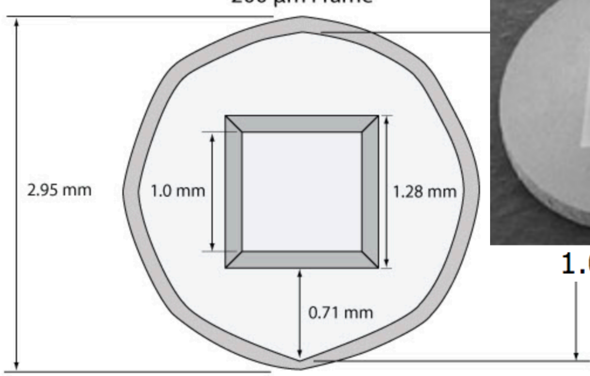
- Si_3N_4: Silicon nitrite spread in industry
- Preferred material for TEM windows
- Stands pressure difference of 1 bar
- 4 mm^2 for 10 nm remains a challenge

Ex. OCTALAB, Singapore, created in 2008

Film Thicknesses Available
on 200 micron thick frames

Single Window	Pure Silicon	Silicon Oxide	Silicon Nitride
(1) 0.1 mm window			20 • 50
(1) 0.5 mm window			20 • 50
(1) 1.0 mm window			50

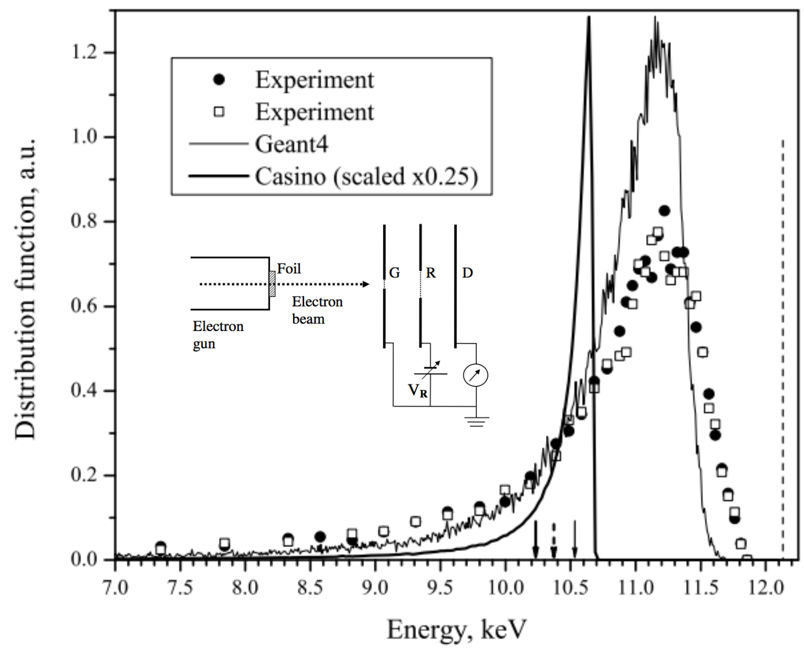
Single Square - 1mm² Window
200 µm Frame



1.0 x 1.0mm

- high vacuum implies special soldering technique of the substrat to a surface
- expertise at TU Munchen: J. Wieser, A. Ulrich
- window from e$^-$ gun to gas volume

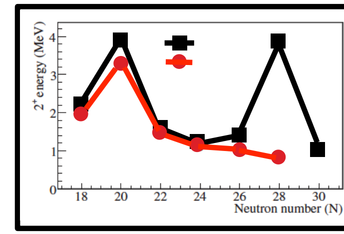
J. Wieser *et al.*, EPJD 48, 383 (2008)
12 keV e$^-$ beam through a 250 nm membrane



Summary

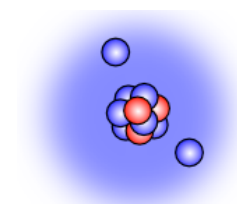
- ❑ **New projects related to GSI/FAIR involving cryogenics**

- ❑ A compact MINOS-like system for in-beam spectroscopy with AGATA
- ❑ **H2 target / Silicon tracker** inside a 23-cm diameter chamber
- ❑ Prototype in 2020



- ❑ Production and study of **hypernuclei at R3B**
- ❑ **H2 target / TPC / low-material budget tracking system**
- ❑ Prototype in 2021

- ❑ Excess of neutrons may develop into **thick skins** or **halos**
- ❑ First use of **antiprotons** as a probe for rare isotopes
- ❑ Transportable **cryogenic trap** for 1 billion antiprotons (PUMA)
- ❑ First experiments in 2022
- ❑ A program at CERN towards FLAIR



- ❑ A **laboratory for cryogenics developments** at TU Darmstadt is foreseen
- ❑ Collaboration with GSI/FAIR is welcome / desired