PUMA: probing the nuclear matter density tail in radioactive nuclei with antiprotons

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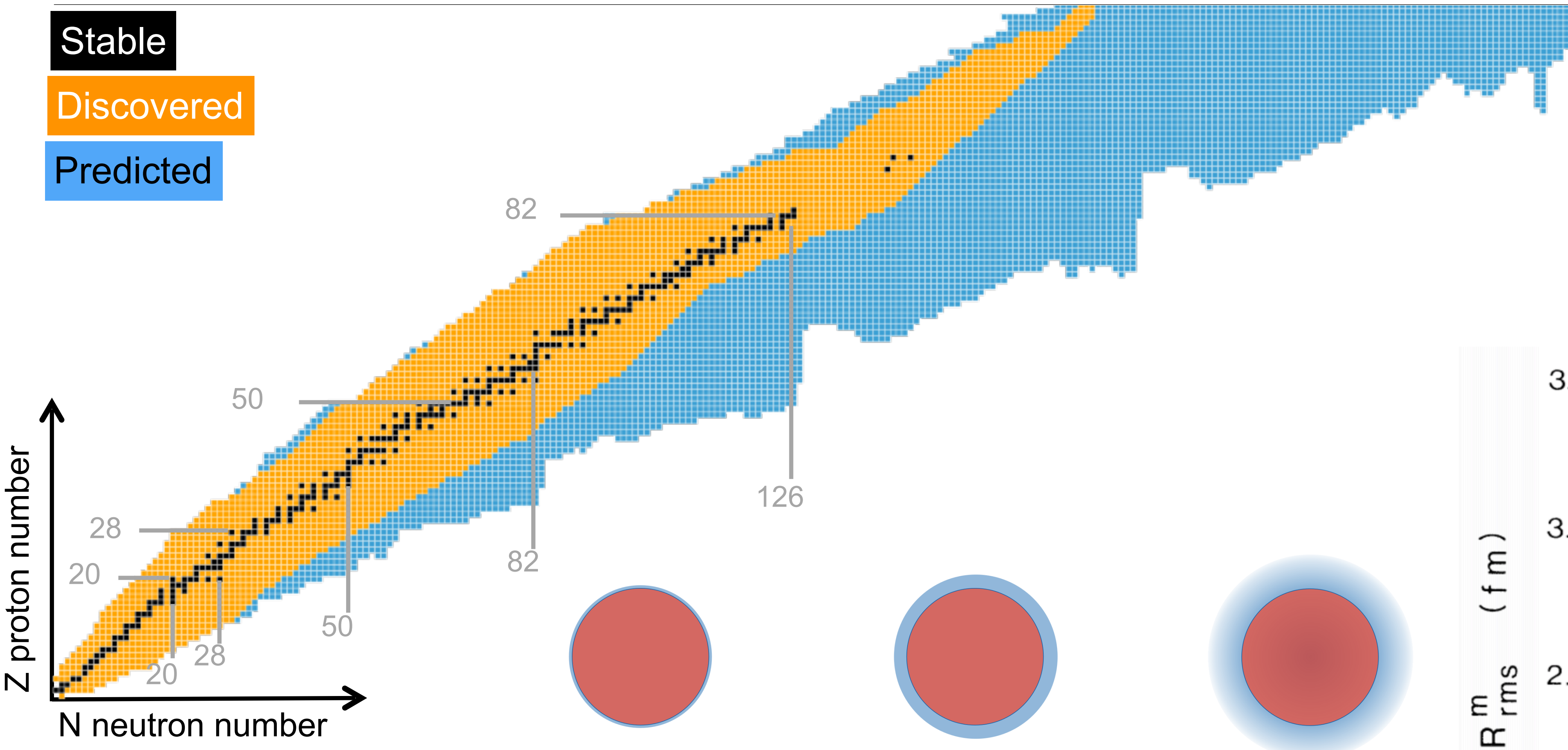
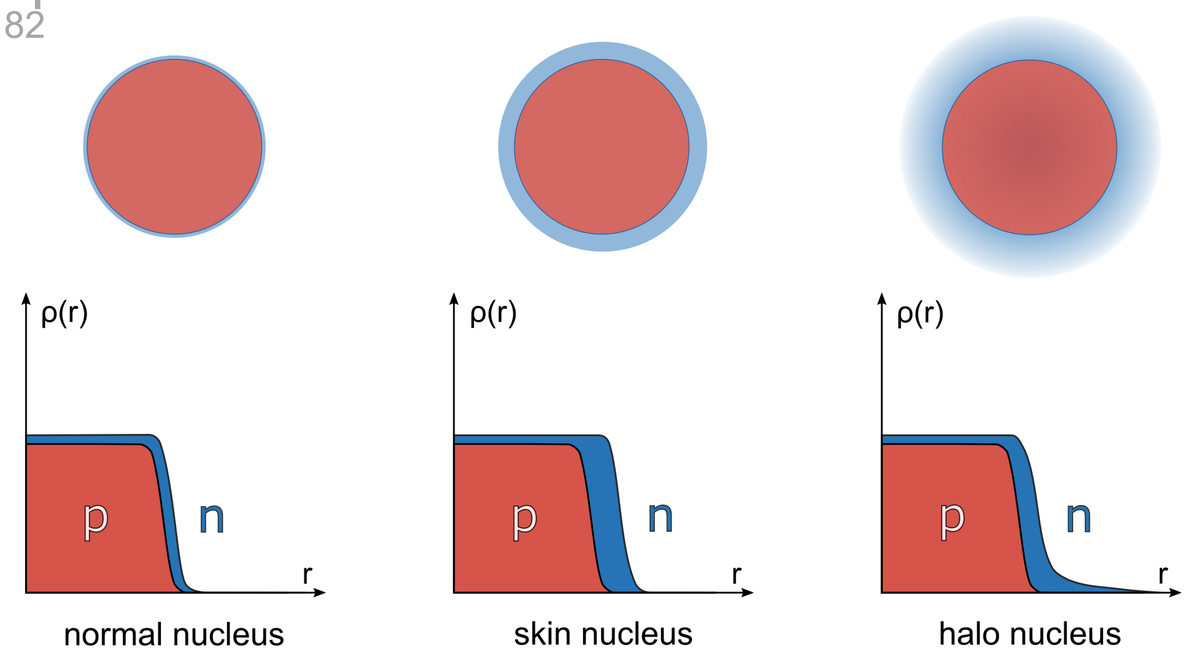
for the PUMA collaboration

58th Winter Meeting on Nuclear Physics
Bormio, Italy

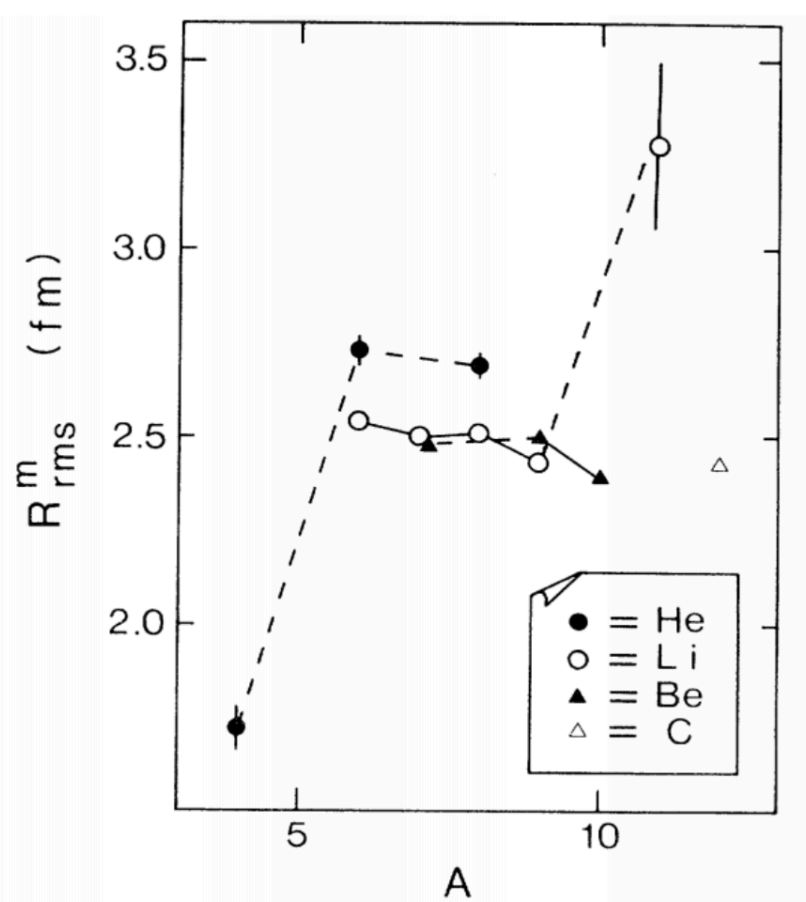
Neutron excess in nuclei: Halo and neutron skin





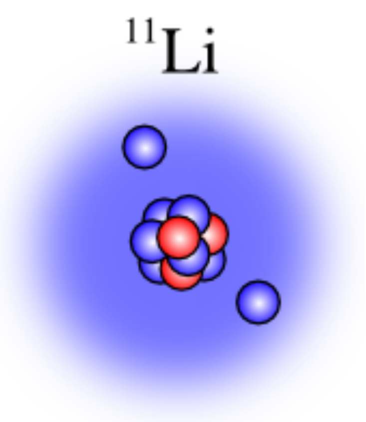
courtesy of A. Schmidt

^{11}Li mass radius

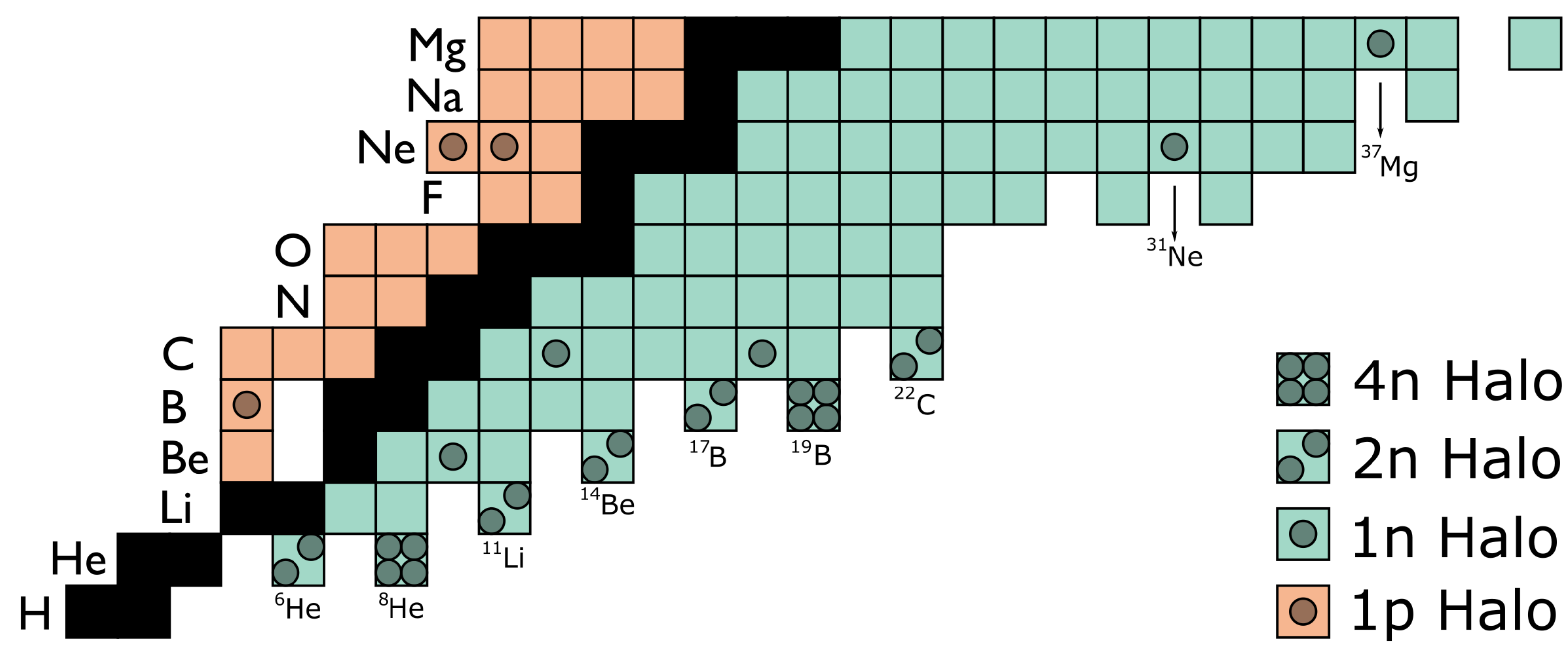


I. Tanihata et al, PRL 55 (1985)

Halos



Neutrons are loosely bound to the nucleus

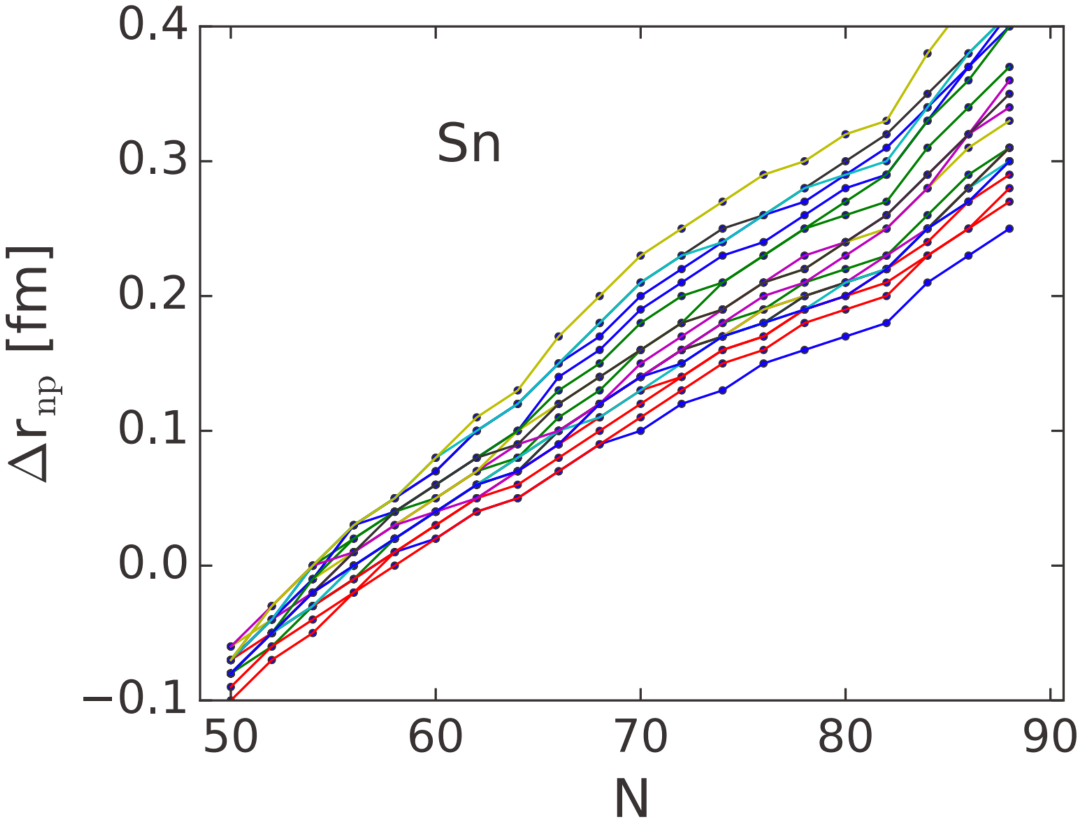


courtesy of A. Schmidt

- Neutron halos were observed only in light nuclei.
  [Tanihata et al., PRL 55 (1985), Hansen and Jonson, Europhys. Lett. 4 (1987)]
- Indirect observations of neutron halos in medium-mass nuclei (Ne, Mg).
  [Nakamura et al., PRL 112 (2014)]
- Prediction of proton halos in light mass nuclei & neutron halos in heavy nuclei.
  [Rotival et al., PRC 79 (2009)]

Neutron skin

- Depends on nuclear interaction: saturation, symmetry energy, correlations
- Actively studied by experiment and theory.
- Neutron skin of heavy nuclei correlated to equation of state of neutron stars.
  [C. J. Horowitz and J. Piekarewicz, PRL 86 (2001)]



Bertulani and Valencia, PRC 100 (2019)

Neutron skin thickness: $\Delta r_{np} = \langle r_n \rangle - \langle r_p \rangle$

Antiproton annihilation: a probe for the nuclear density tail

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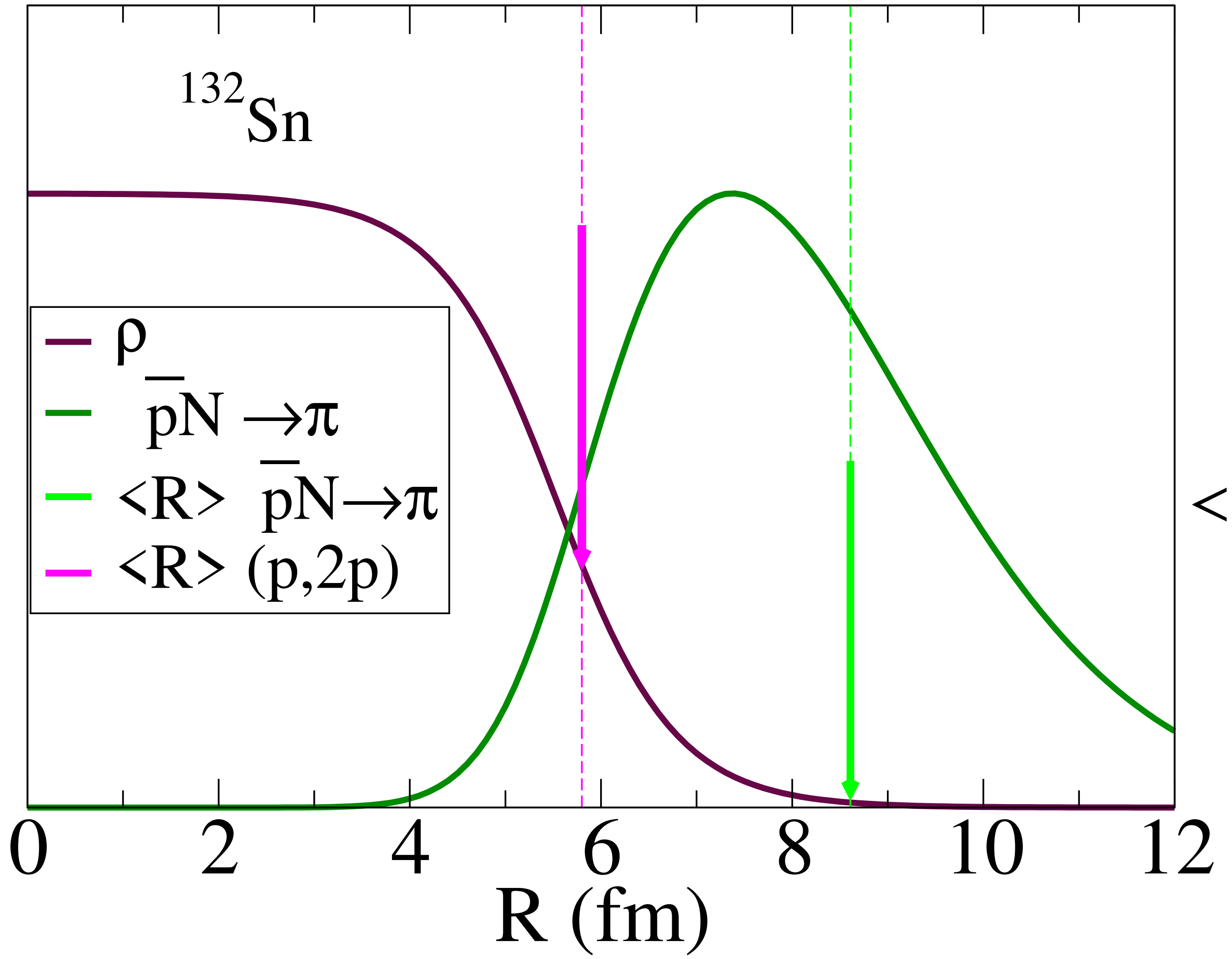
Antiprotons annihilate in the density tail of the nuclei



$$< R_{\bar{p}N} > = \int r^2 \left| \Psi_{n,l}(r) \right|^2 \mathrm{Im} V_{\bar{p}N}(r) dr$$

PUMA Proposal, CERN-SPSC-2019-033. SPSC-P-361 (2019)

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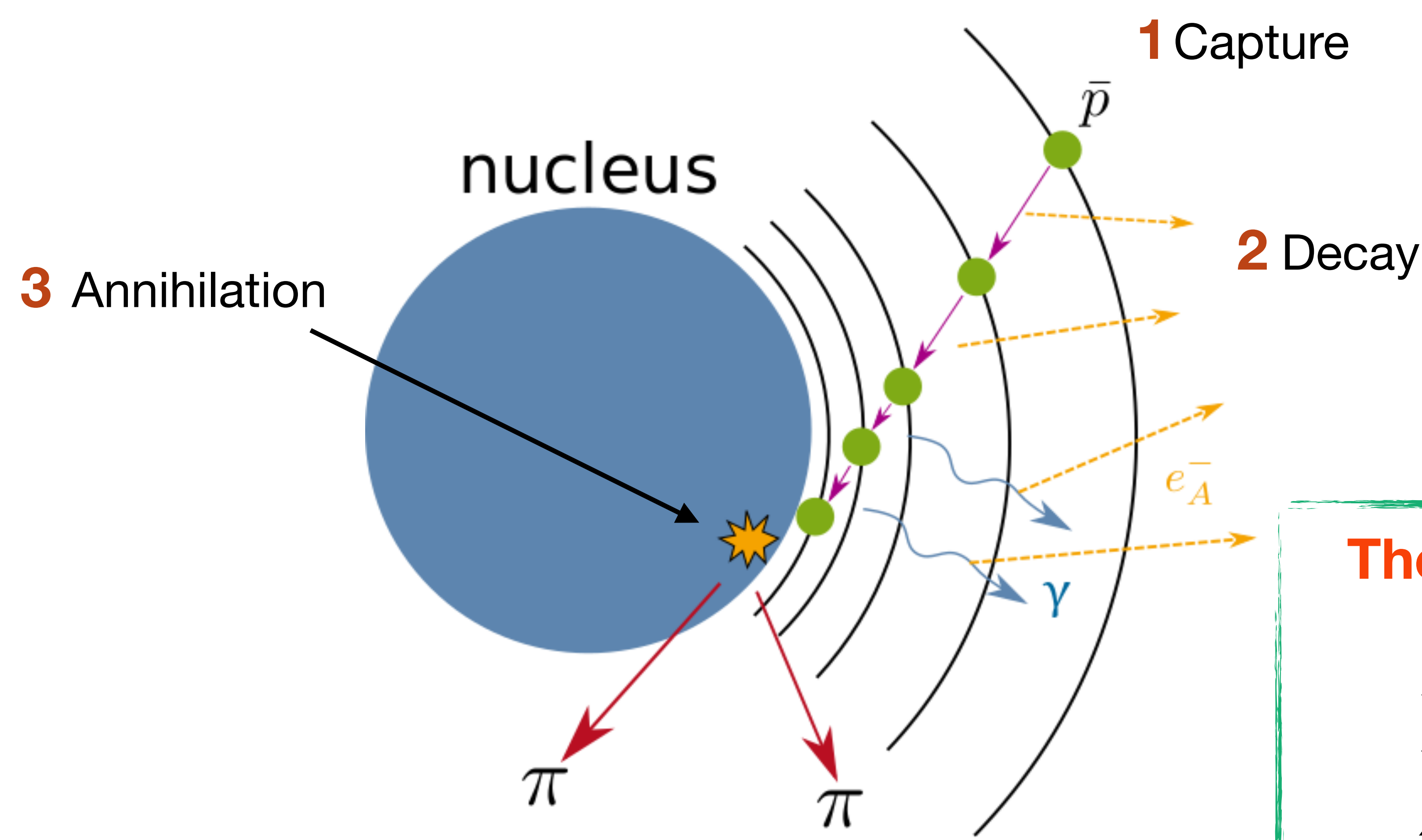


The electric charge is conserved

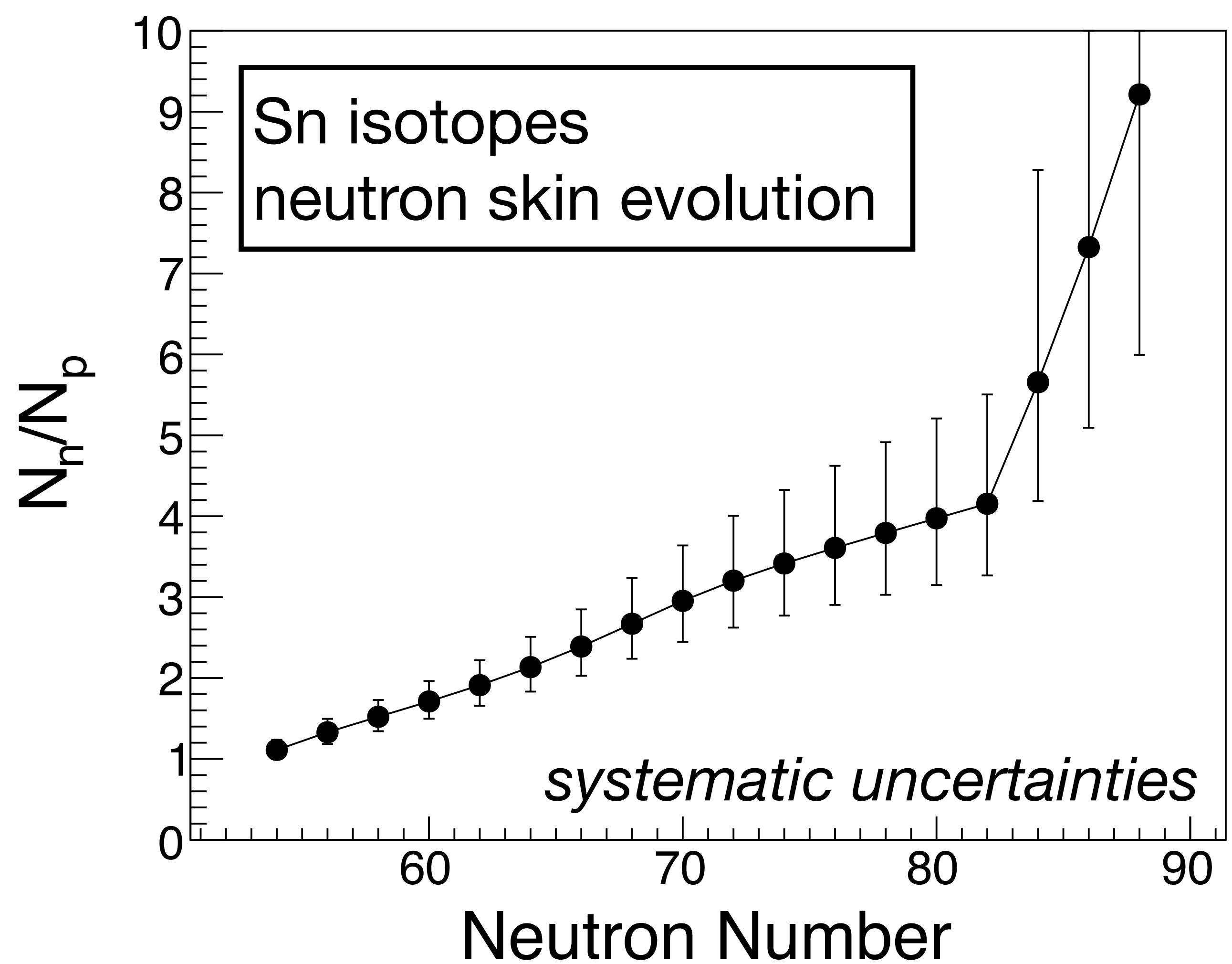
$$\sum \pi^+ + \sum \pi^- = 0 \quad \text{for} \quad p\bar{p}$$

$$\sum \pi^+ + \sum \pi^- = -1 \quad \text{for} \quad n\bar{p}$$

[Proposed by M. Wada, Y. Yamazaki, NIMB 214 (2004)]

PUMA Objectives

- To provide the neutron-to-proton annihilation ratio for radioactive nuclei.
- Evidence new proton and neutron halos.
- To understand neutron skin development along isotopic chains.



PUMA: antiProton Unstable Matter Annihilation

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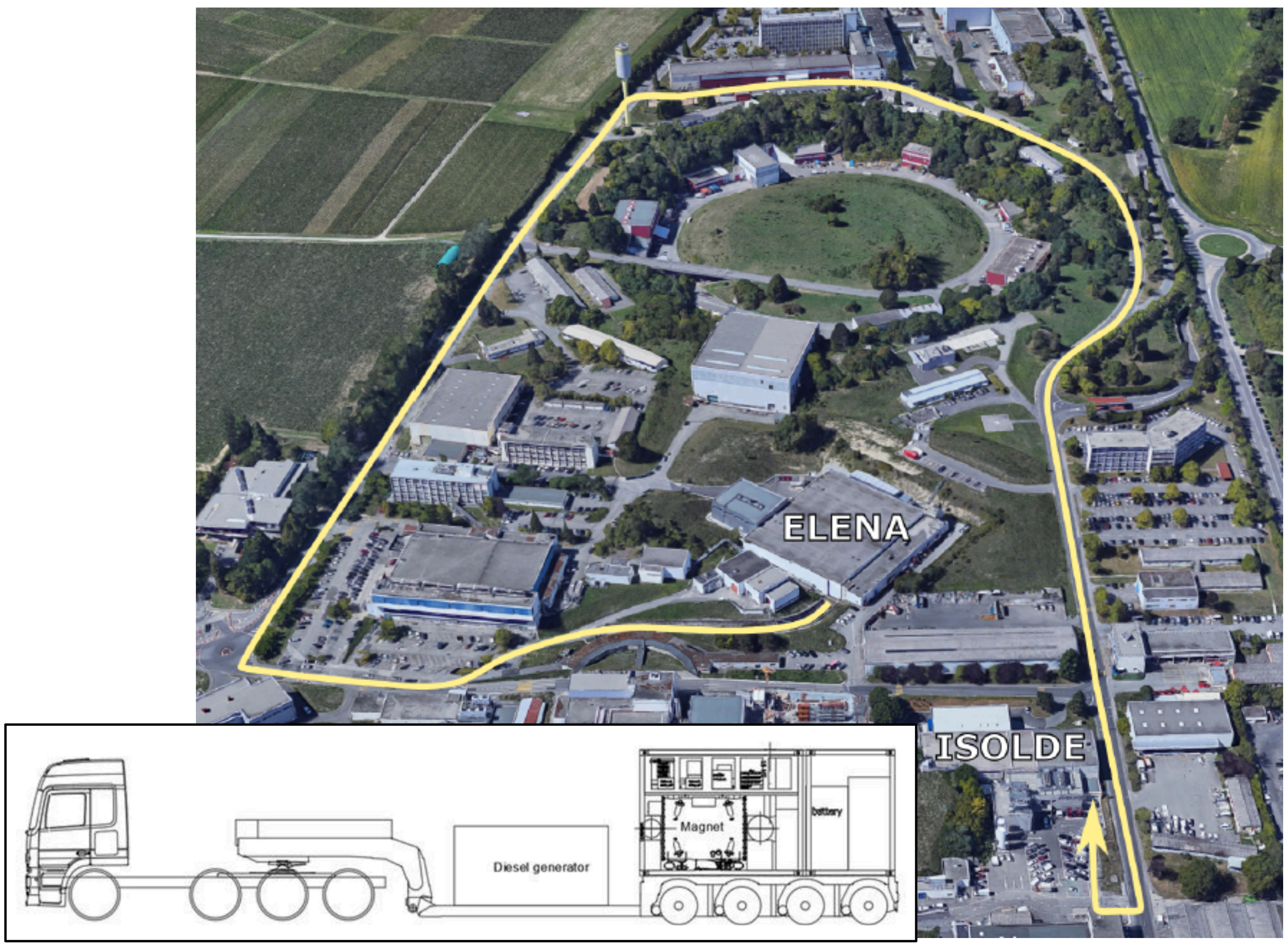
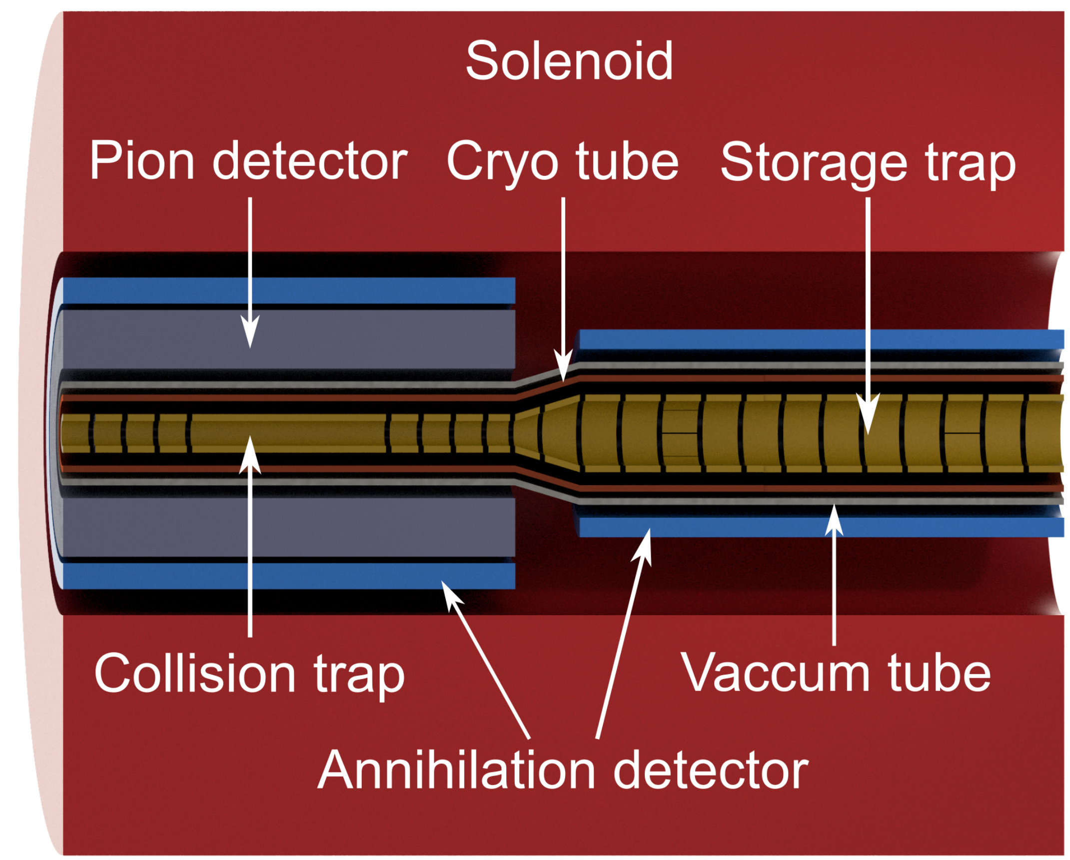
- 10^9 antiprotons to be stored.
- Transported from ELENA to ISOLDE at CERN.
- Extreme high vacuum is needed (10^{-17} mbar) for antiproton storage.





How will the ultra high vacuum be achieved?

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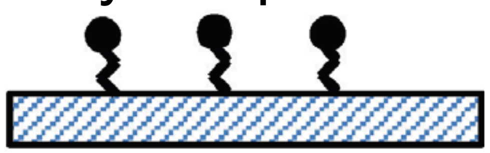
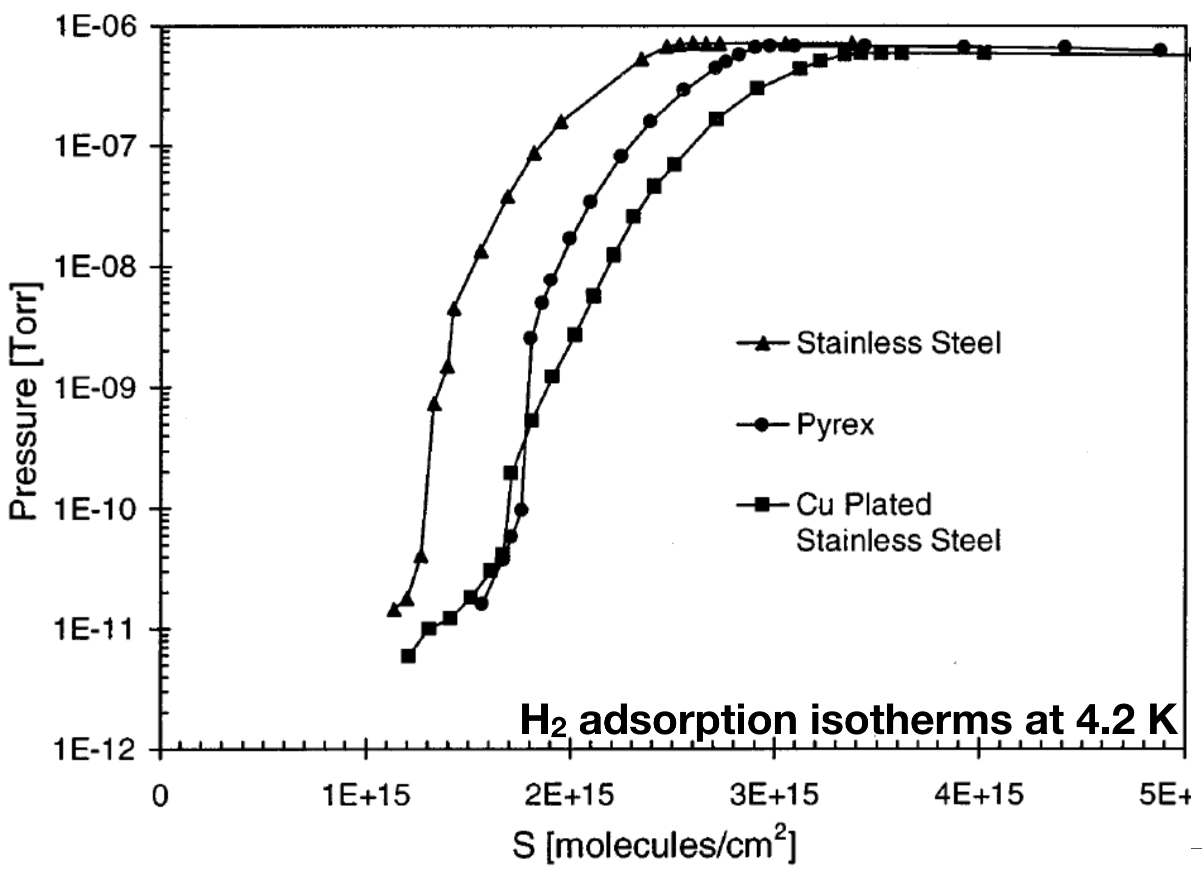
Cryopumping

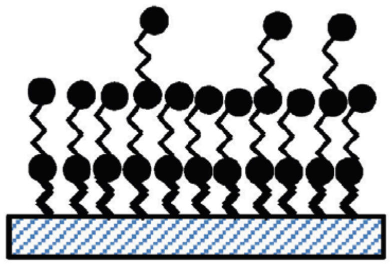
Cryosorption



- Strong gas-substrate interaction.
- Works until monolayer is filled.
- Driven by H_2 adsorption isotherms.



Cryocondensation



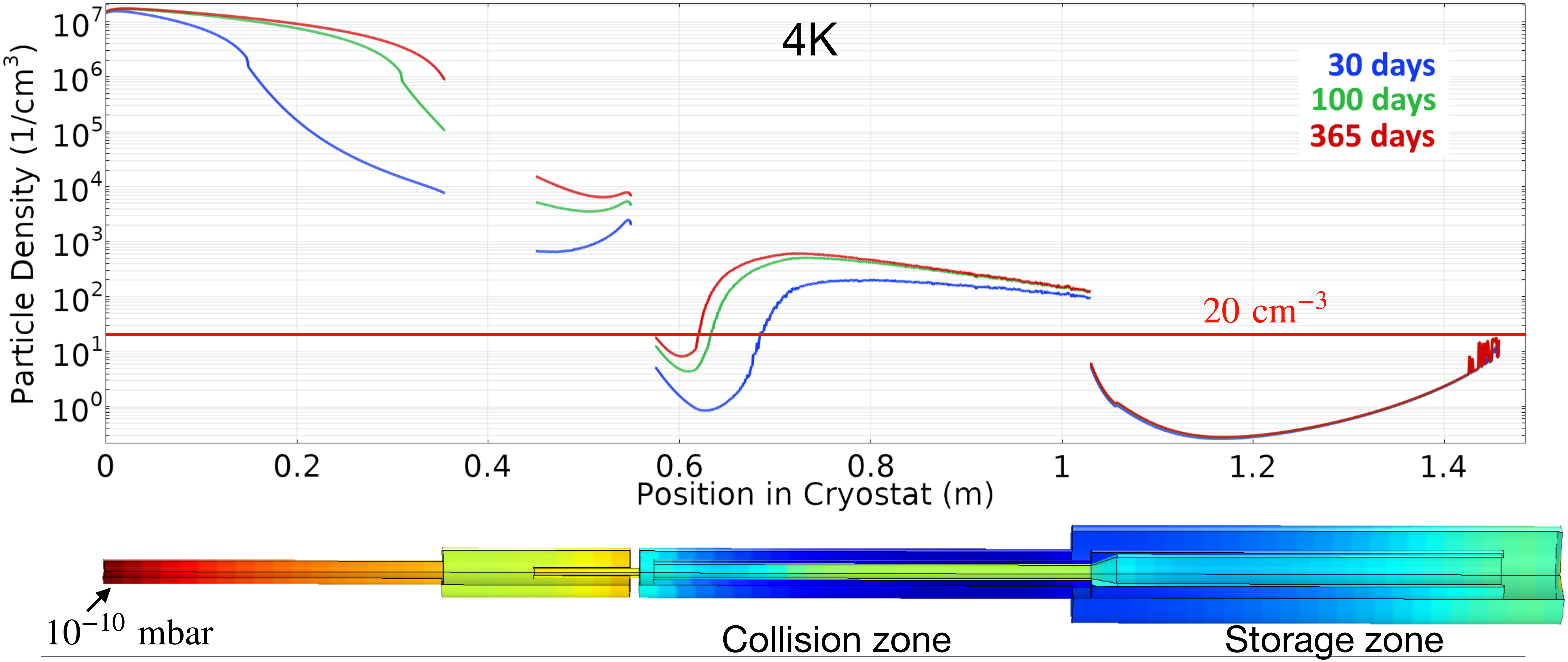
- Driven by intermolecular Van der Waals forces.
- Depends on the saturated vapour pressure (Pv).

Objective of PUMA: minimise residual gas entering the traps.

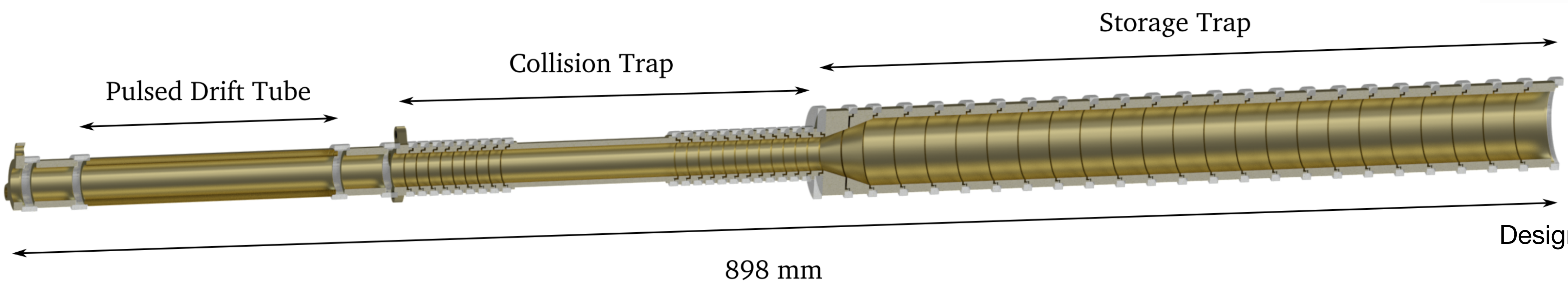
[Wallen, Jour. Vac. Sci. Tec. 15 (1997)]

Vacuum simulations

PUMA Requirement: residual gas density < $20\ \mathrm{cm}^{-3}$ (10^{-17}mbar).



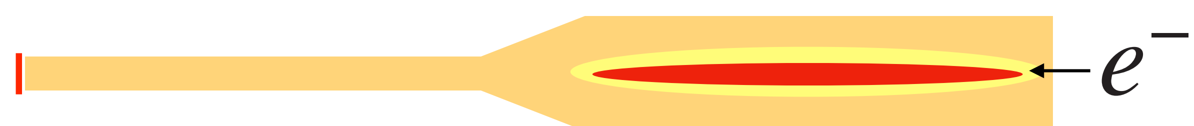
PUMA Trap



Design by N. Nakatsuka (TUD)

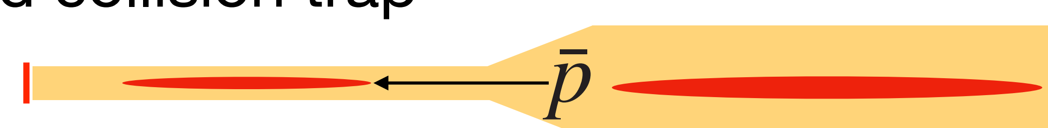
1. Loading antiprotons into reservoir trap

2. Sympathetic electron cooling

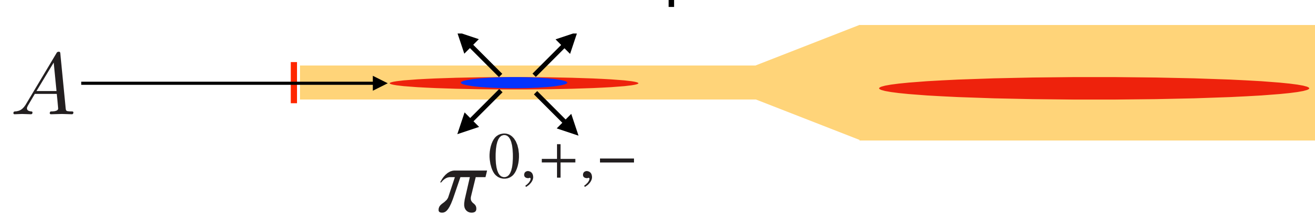


3. Rotating Wall technique for ion cloud shaping

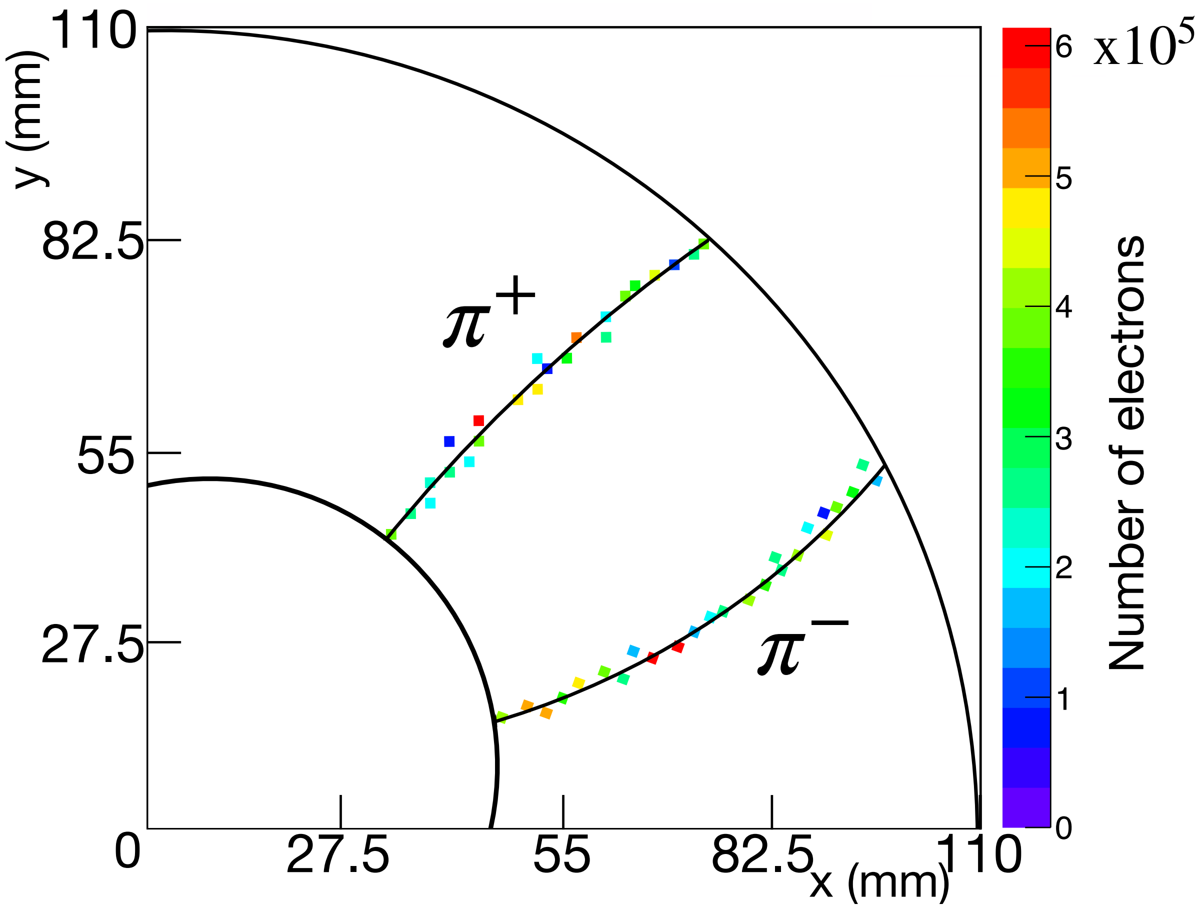
4. Transport fraction of $\bar{p}$ into nested collision trap

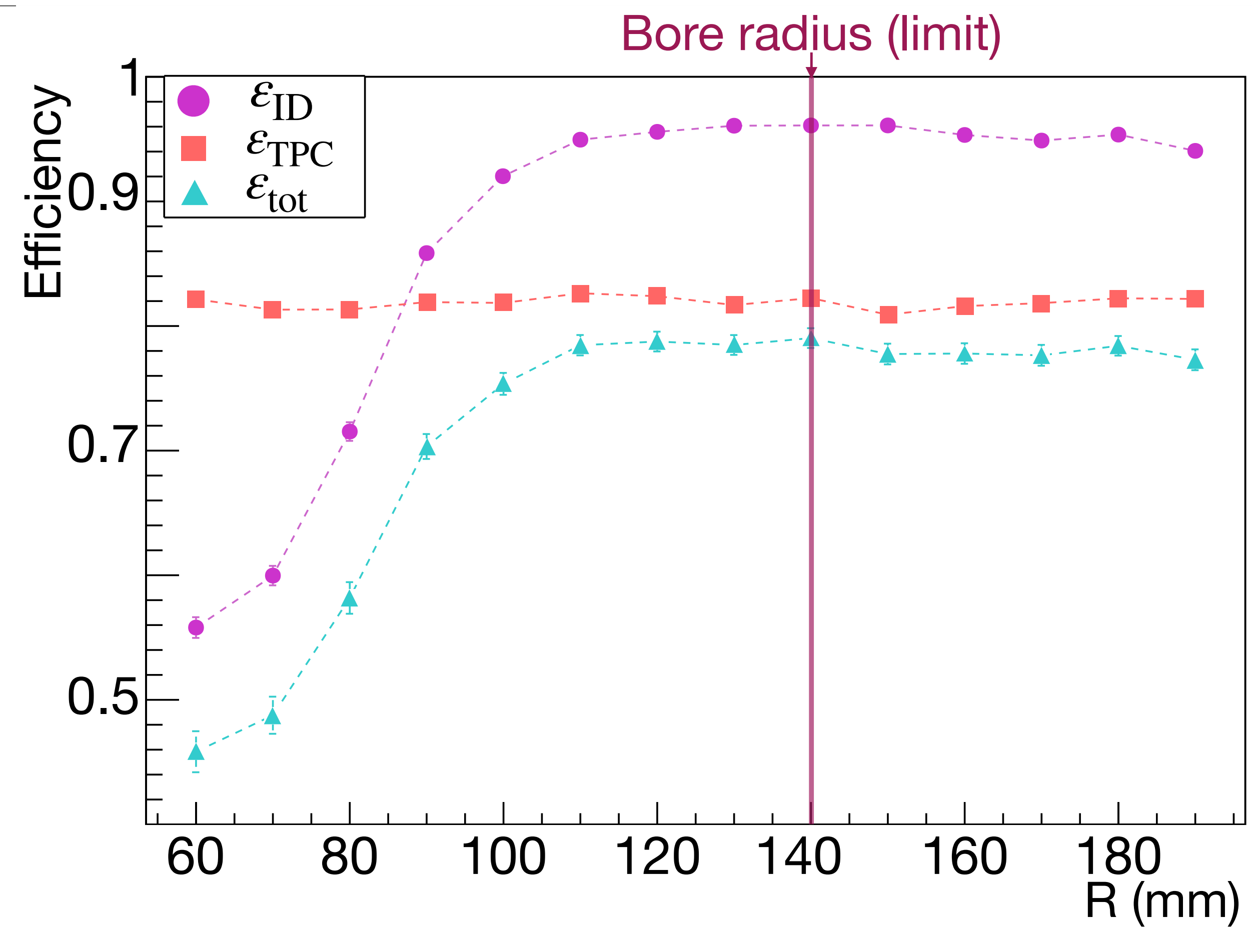


5. Loading unstable nuclei into nested collision trap

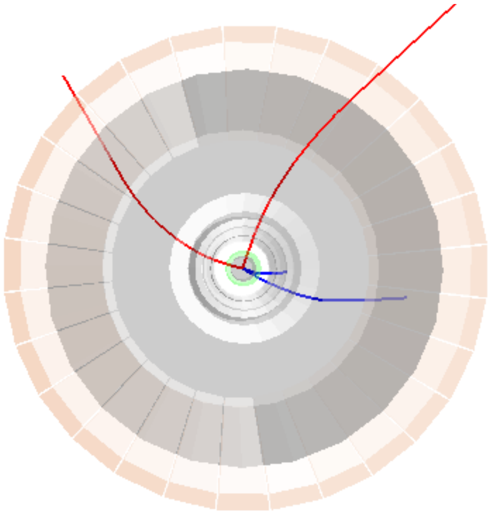


Detection system





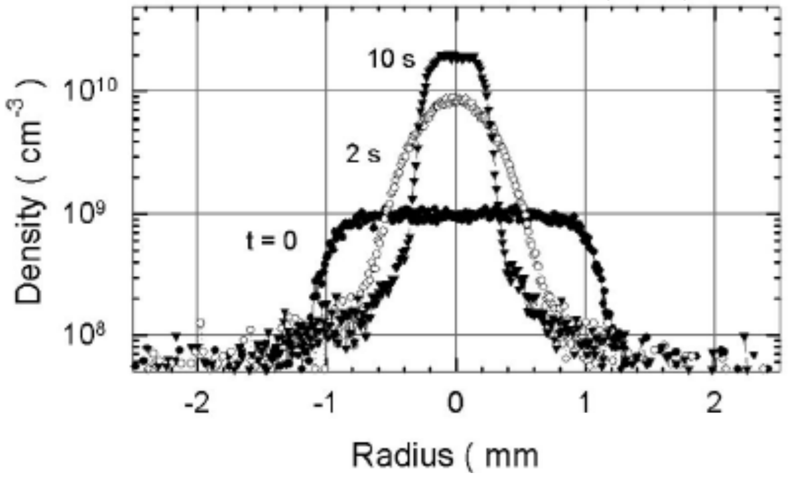
- Time-Projection Chamber tracker (under design).
- Plastic scintillator barrels for trigger and antiproton plasma monitoring.
- Simulations carried out show 78% efficiency (pion detection+ID).
- Targeted systematic uncertainties Nn/(Nn+Np) < 5%.

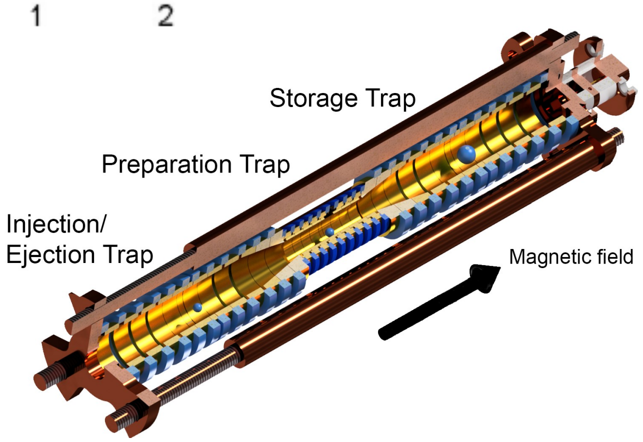


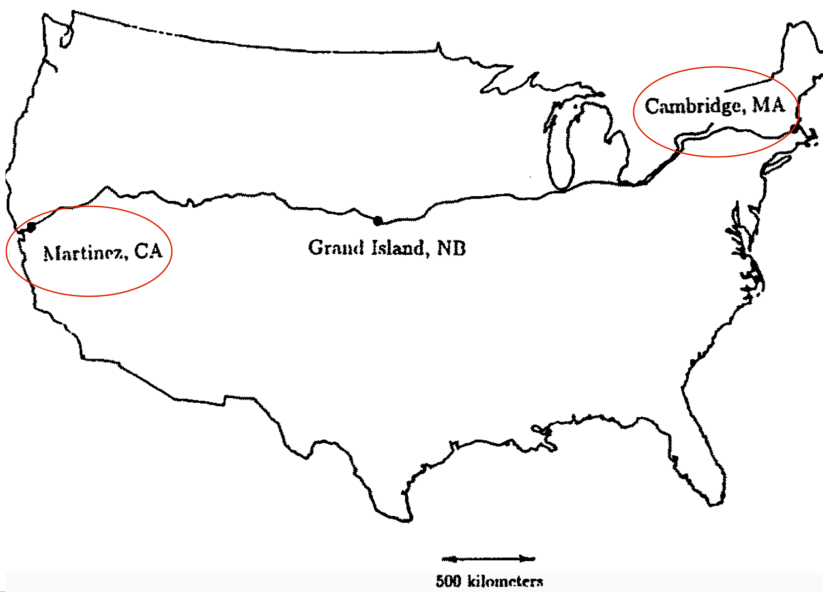
Previous trapping achievements

- Storing 10^9 electrons at 2.10^8 cm^{-3}
  [Hollman, Anderegg, Driscoll, Phys. Plasmas 7 (2000)]
- Rotating wall and sympathetic cooling
  [Hall and Gabrielse, PRL 77 (1996), Anderegg, Hollman, Driscoll, PRL 81 (1998)]
- Storing antiprotons at BASE (CERN) Sealed trap, lifetime > 30 years
- Other project to transport antiprotons within the BASE experiment
  [C. Smorra, ERC Starting Grant 2019]
- Transporting electrons in a Penning trap by truck over 5000 km
  [Tseng and Gabrielse, Hyperfine Int. 76 (1993)]

Danielson, Surko, PRL 94 (2005)

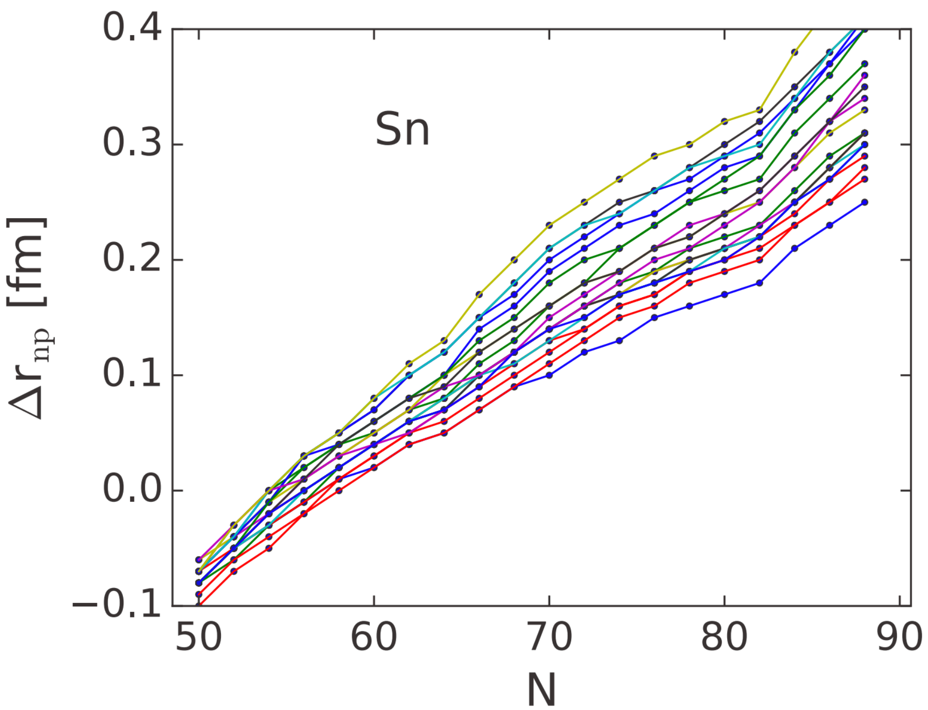


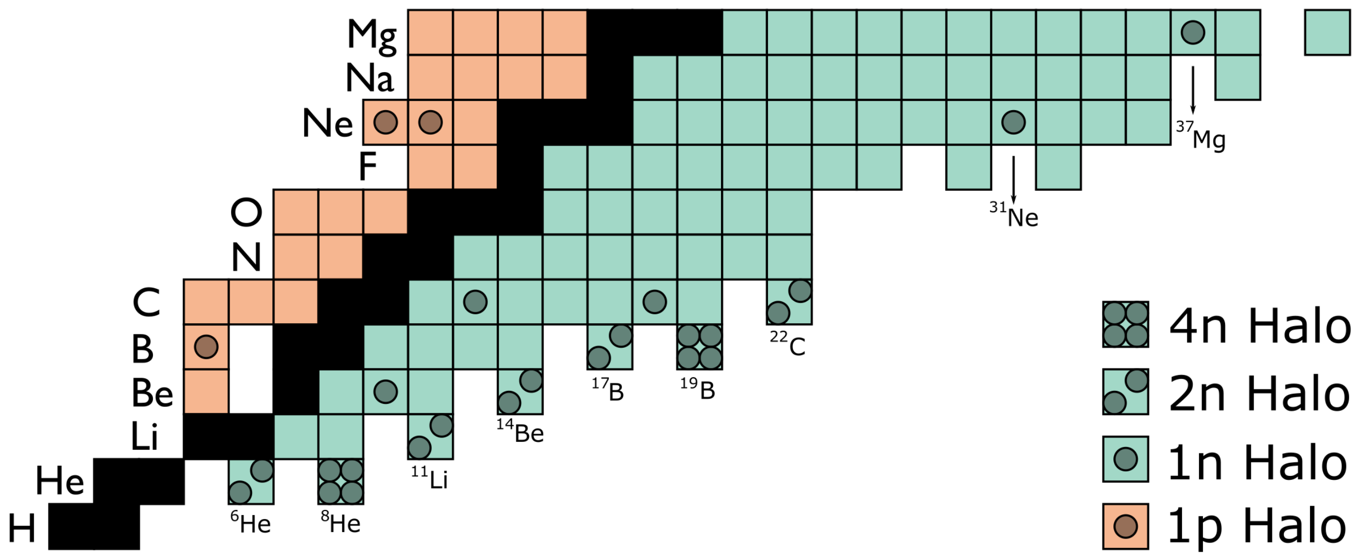




Summary

- Halos, thick neutron skins in medium mass nuclei predicted but not observed.





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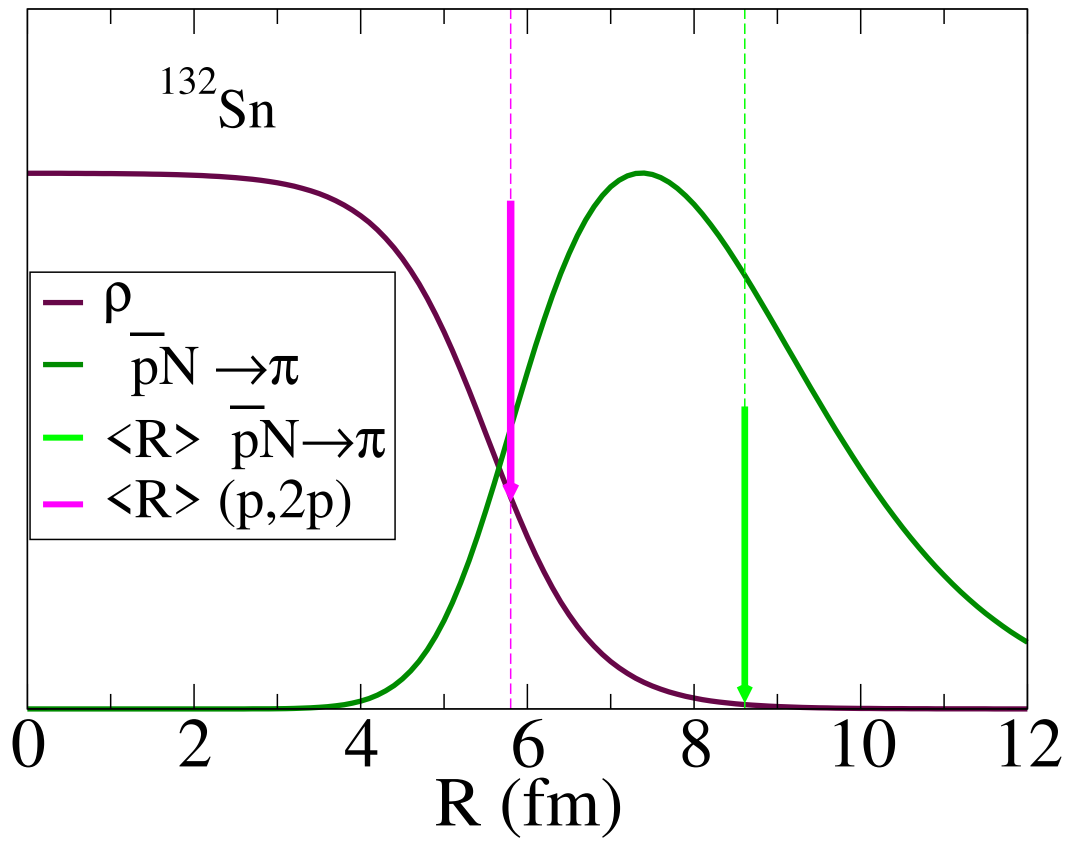

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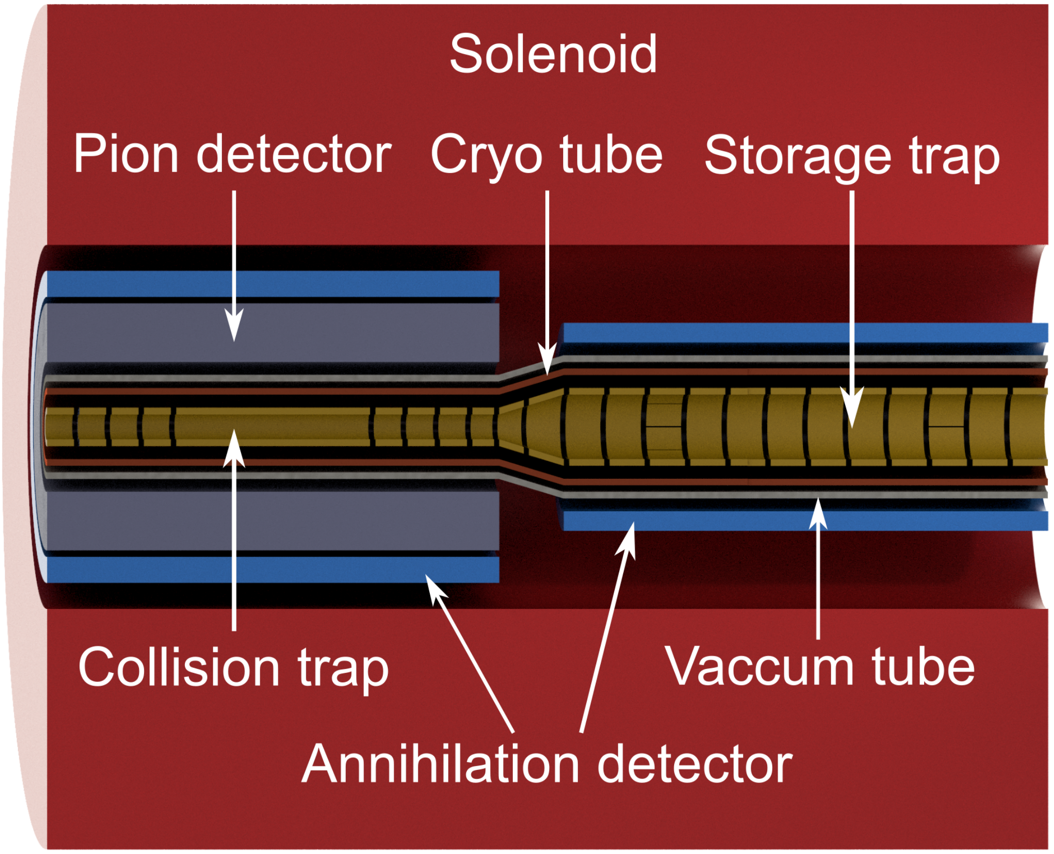
- Ongoing construction of the setup.



Summary

- Halos, thick neutron skins in medium mass nuclei predicted but not observed.
- PUMA will use antiprotons to probe the density tail of radioactive nuclei.
- Ongoing construction of the setup.
- First physics experiments at ISOLDE targeted in 2022.

Collaboration

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T. Aumann, W. Bartmann, A. Bouvard, O. Boine-Frankenheim, A. Broche, F. Butin, D. Calvet, J. Carbonell, P. Chiggiato, H. De Gersem, R. De Oliveira, T. Dobers, F. Ehm, J. Ferreira Somoza, J. Fischer, M. Fraser, E. Friedrich, J.-L. Grenard, G. Hupin, K. Johnston, Y. Kubota, M. Gomez-Ramos, P. Indelicato, R. Lazauskas, S. Malbrunot-Ettenauer, N. Marsic, W. Müller, S. Naimi, N. Nakatsuka, R. Necca, G. Neyens, A. Obertelli, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, D. Rossi, H. Scheit, R. Seki, A. Schmidt, L. Schweikhard, S. Sels, E. Siesling, T. Uesaka, M. Wada, F. Wienholtz, S. Wycech, S. Zacarias

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LKB

RCNP
Research Center for Nuclear Physics
OSAKA UNIVERSITY

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Back-up Slides

PUMA physics program

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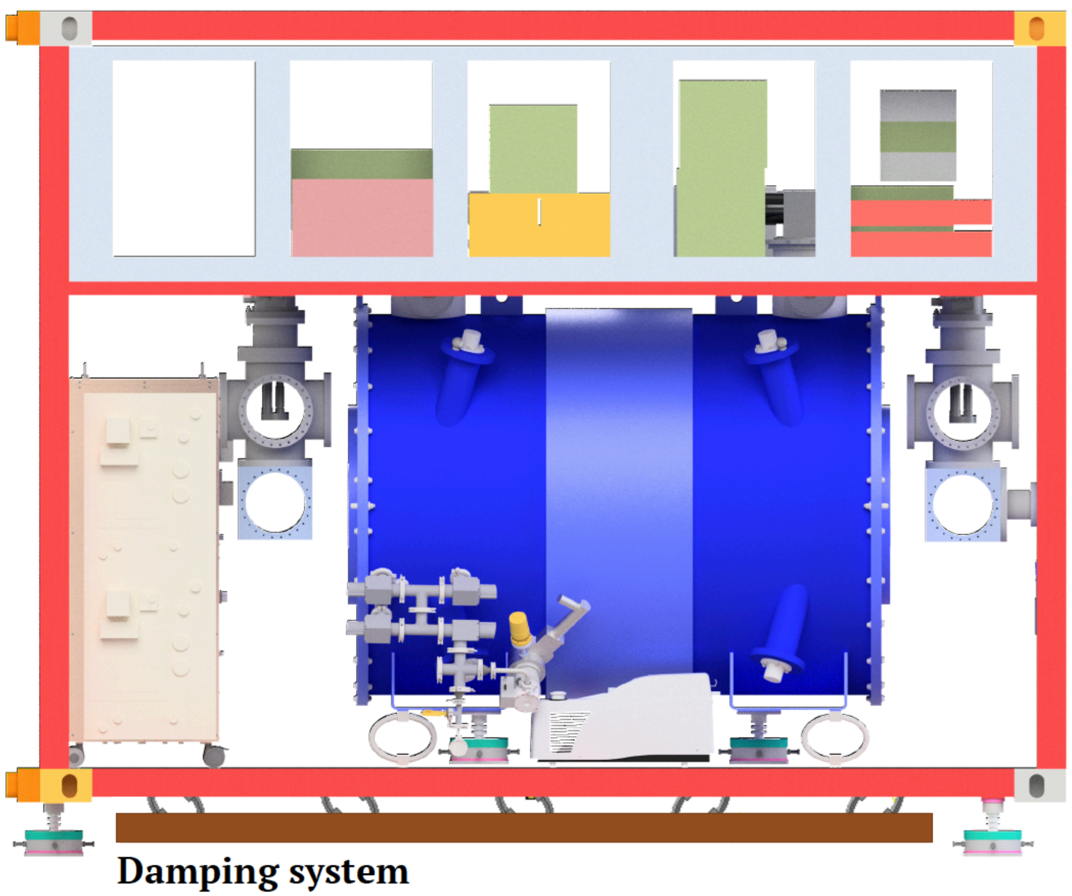
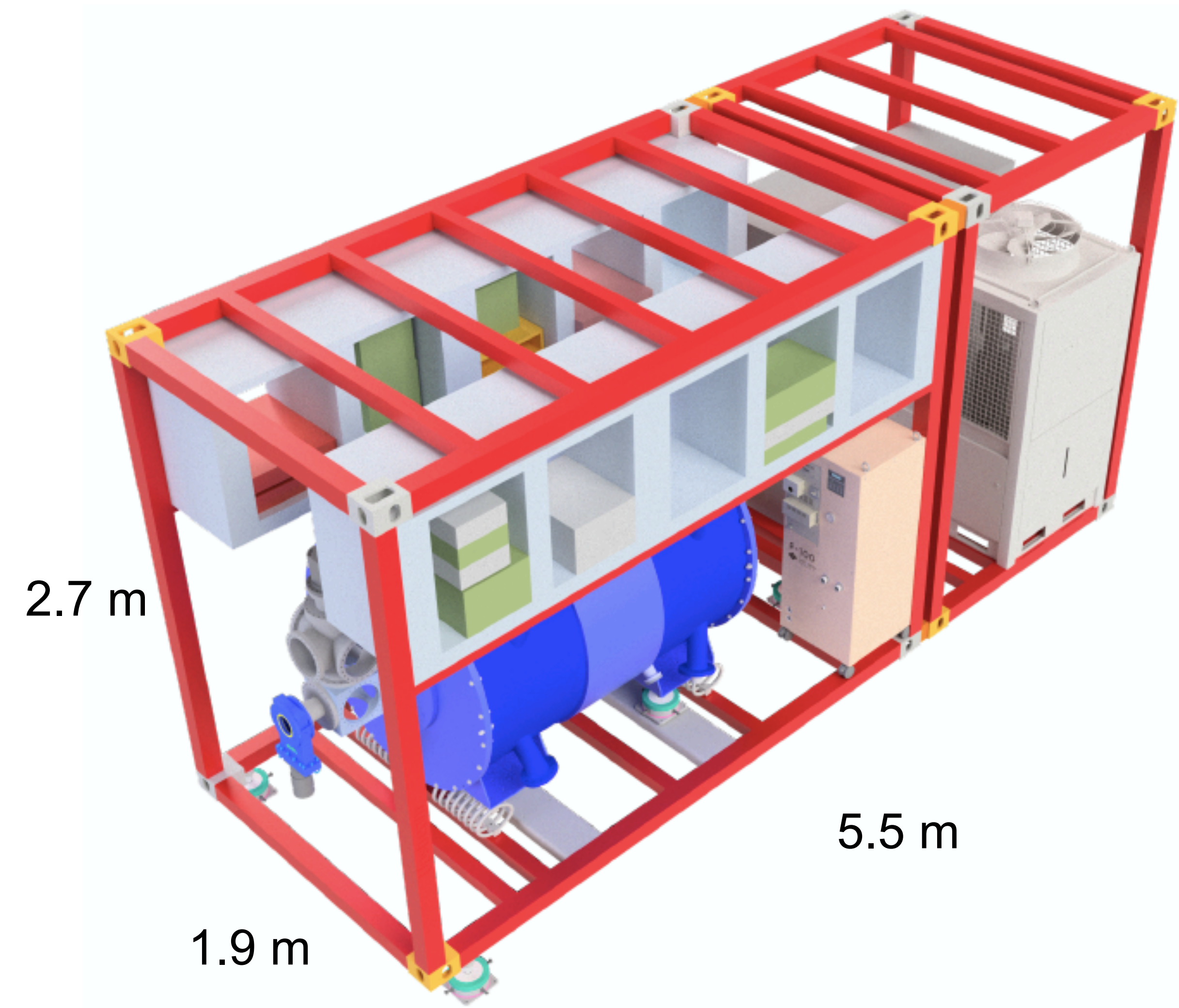
ELENA	p,d	detector response
	^{3}He,^{4}He	ab initio benchmark
	^{16}O,^{40}Ar,^{132}Xe	mass dependence
	$^{112-124}$Sn	isotopic chain
ISOLDE	^{6,8}He,^{7,9,11}Li	neutron halos
	^{8}B,^{17,18}Ne	proton halos
	$^{26-31}$Ne,$^{28-33}$Mg	medium-mass halos
	$^{14-22}$O,$^{104-138}$Sn	neutron skin evolution

PUMA device





PUMA vacuum

Capture cross section of antiprotons on molecular hydrogen $\sigma = 3\pi a_0^2 \sqrt{\frac{27.2\text{eV}}{E}}$

a0 = 5.3×10^{-11} m, Bohr radius

annihilation probability $\Gamma = \frac{1}{\tau} = n_{\text{gas}} v \sigma$ where $v = \sqrt{2E/m_{\text{p}}}$

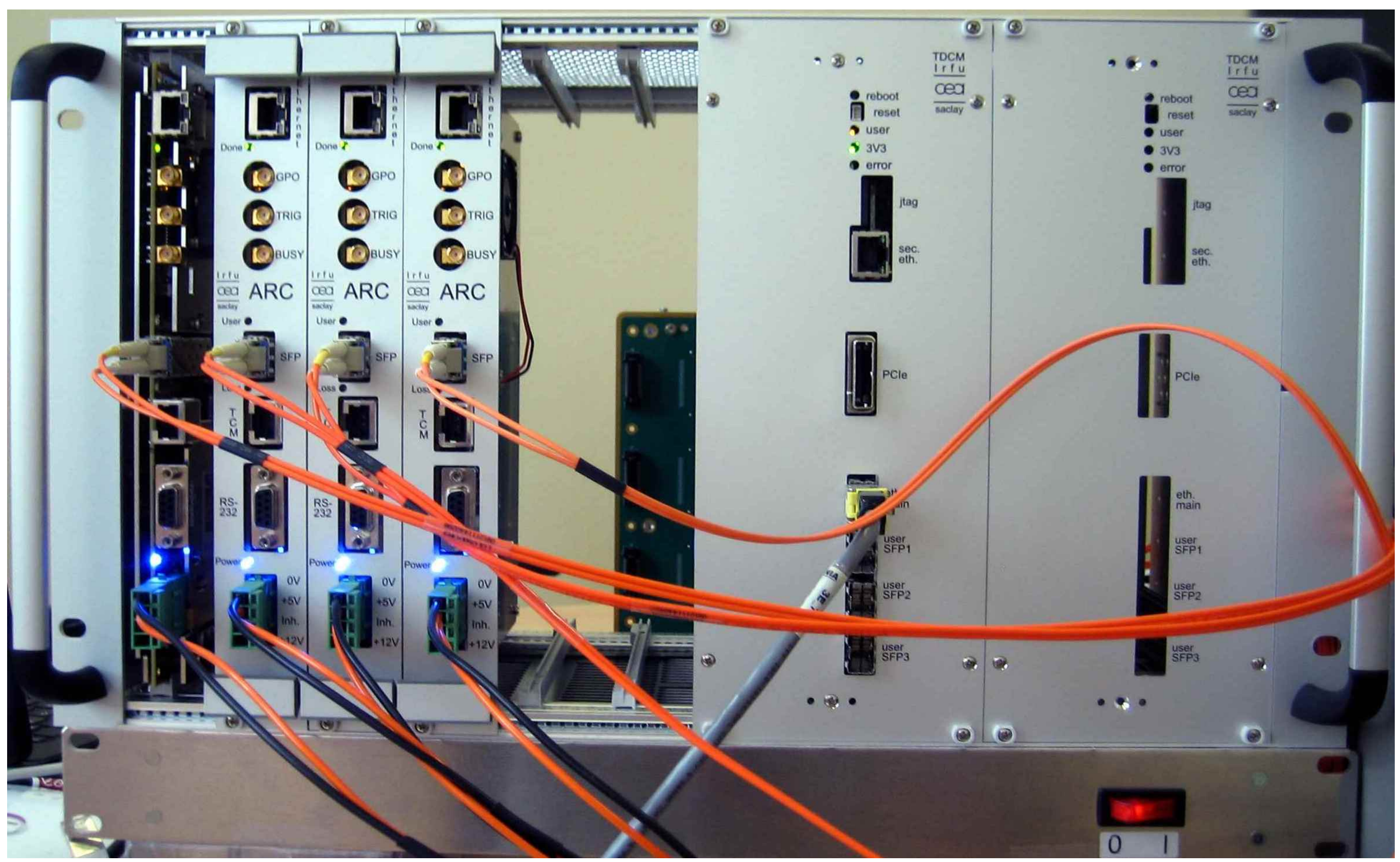
$$n_{\text{gas}} = \frac{1}{\tau} \left(3\sqrt{2}\pi a_0^2 \times \sqrt{\frac{27.2\text{eV}}{m_{\text{p}}}} \right)^{-1} \approx \frac{1}{\tau} \left(5.2 \times 10^8\right) \text{s} \cdot \text{cm}^{-3}$$

Rate of events

Example : ^{132}Sn at 10^5 pps $\sigma = 10^{-16}$ cm^2 at 100 eV

"antiproton thickness" $= 10^8$ cm^2 100eV$\rightarrow 10^4$ m.s^{-1} $\rightarrow 10^5$

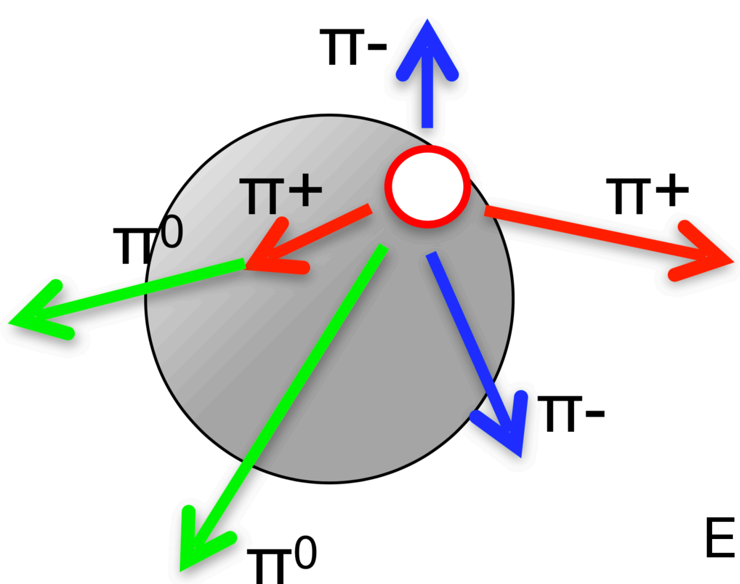
cycles in 1 s 100 annihilations / second, 8. 10^6 /day



Final State interactions (FSI)

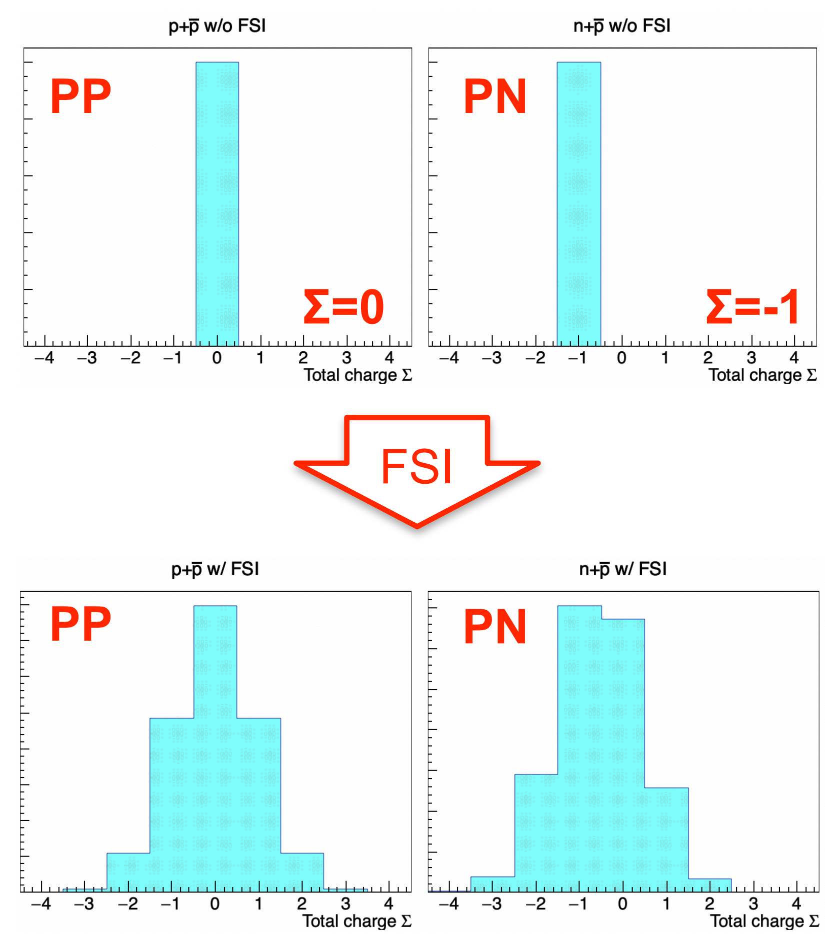
- Produced pions can interact with residual nucleus
- FSIs change total charge of pions/event (∑) and charged pion multiplicity/event (M)

$P\bar{P}$ annihilation



Initial state:
(π+,π-,π0) = (2,2,1)
Σ = 0, M= 4

Final state:
(π+,π-,π0) = (1,2,2)
Σ = -1, M = 3



Emitted pions
Multiplicity M
Total charge ∑

$$\longleftrightarrow \frac{N_n}{N_p} \longleftrightarrow \left.\frac{\rho_n}{\rho_p}\right|_{\text{surface}}$$

Extracted from data

Final State interactions (FSI)

- Neural network trained with simulations considering FSI.
- Expected **accuracy: 5 %** (ongoing).

- Find **N/P** using machine learning