# Nuclear surface probed with antiprotons

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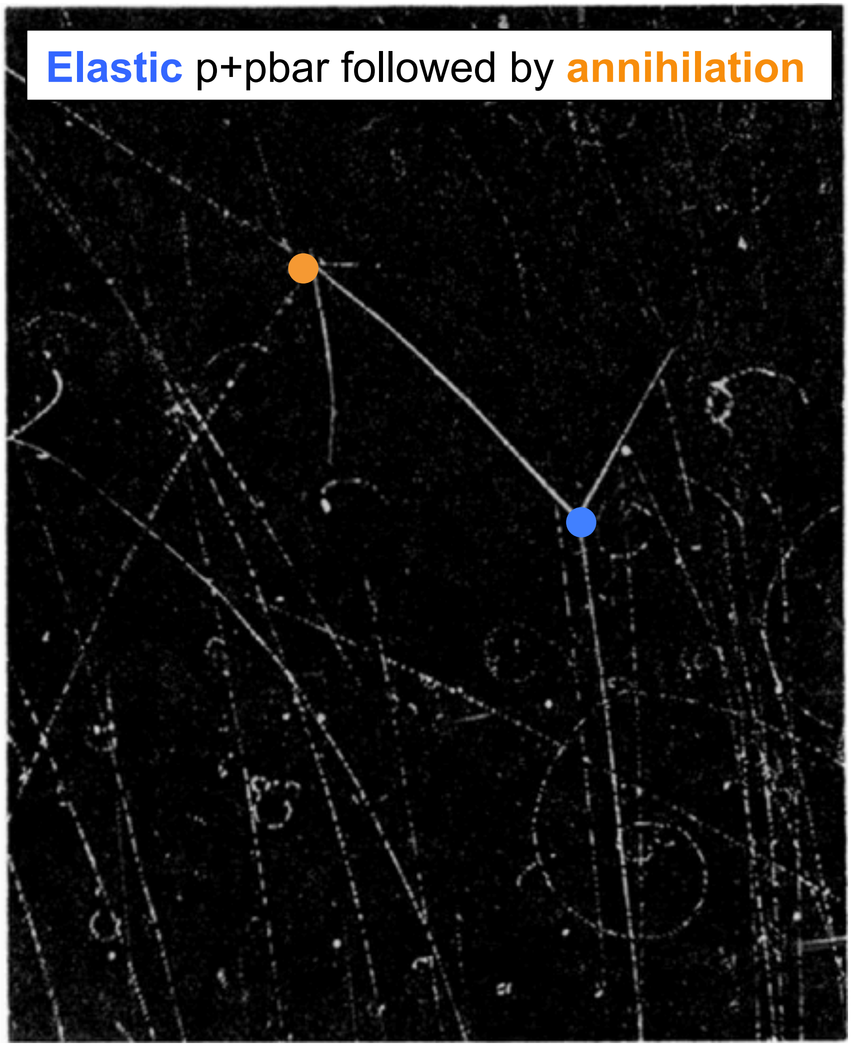
*Neutron Skin of Nuclei workshop*
*MITP, May 17th-27th, 2016*

# Outline

- Antiprotonic atoms
- Methods, past studies from Brookhaven & CERN
- Sensitivity to neutron skin thickness and uncertainties
- Perspectives with unstable nuclei

# Antiproton-nucleon annihilation




L. Agnew *et al.*, Phys. Rev. 110 (1958)

- ✓ **Annihilation with protons AND neutrons**
- ✓ **Mostly pions emitted**
- ✓ **Electrical charge conserved**

  **-1**: neutron annihilation

  **0**: proton annihilation

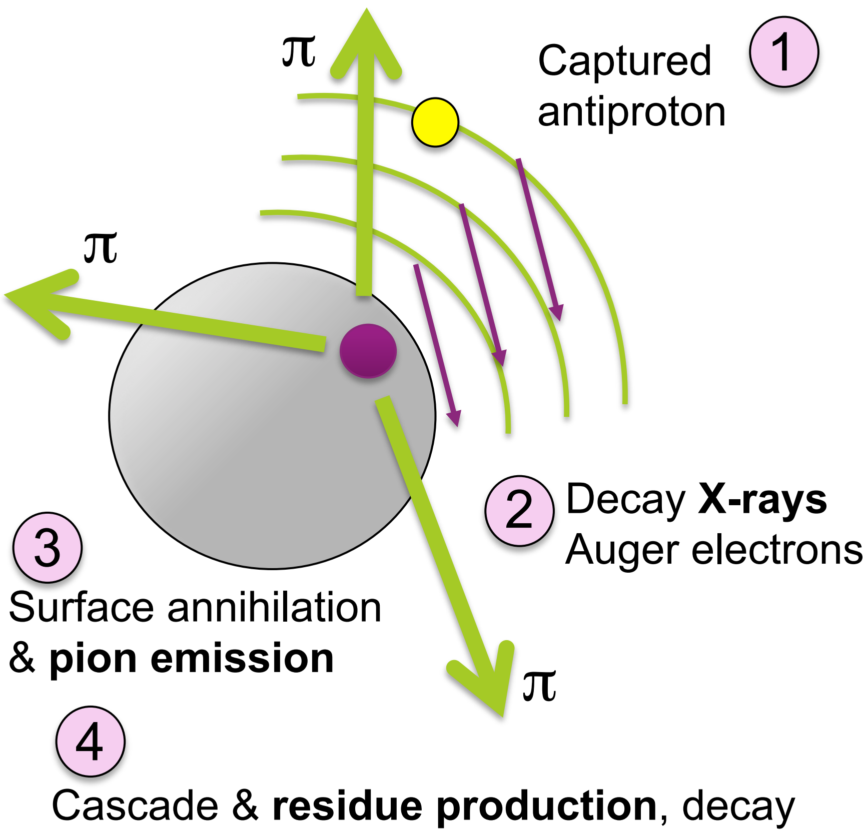
**Proton-antiproton** annihilation at rest:

- charged pion M= 3.0(2), neutral M=2.0(2)
- Fraction of neutral annihilation: 4% (*ex*. multiple $\pi^0$)

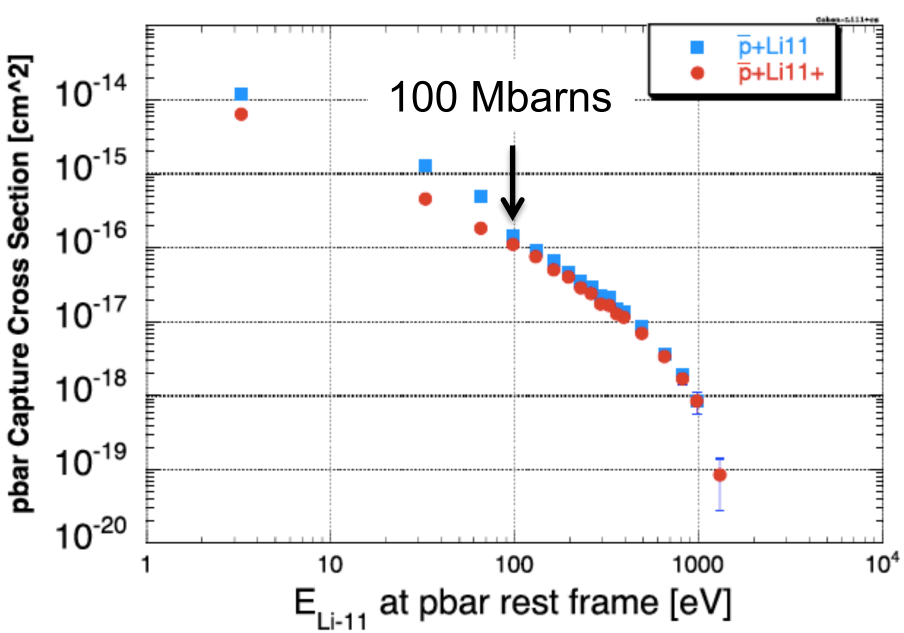
**Neutron-antiproton** annihilation at rest:

- $2\pi^-\pi^+n\pi^0$ : 60%
- $3\pi^-2\pi^+n\pi^0$: 23%
- $3\pi^-2\pi^+n\pi^0$: 15%
- …

# Antiprotonic atoms

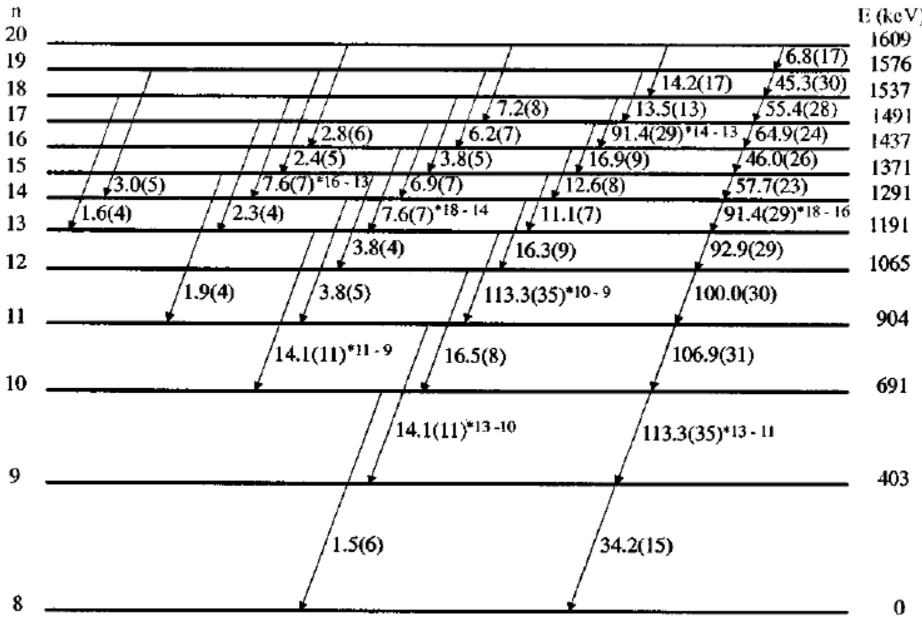


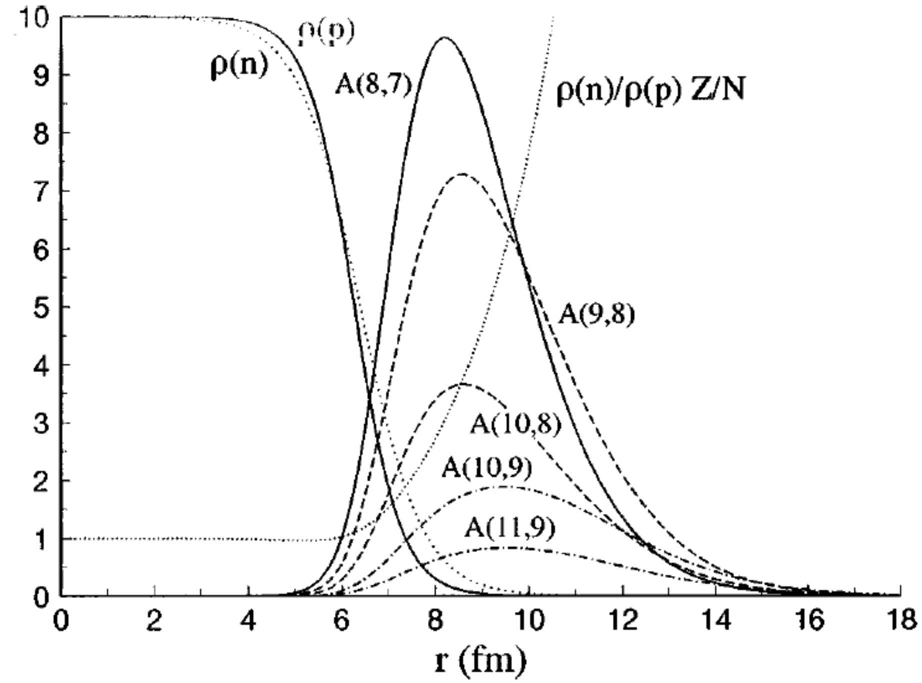

**High cross section** (≈100 Mbarns)
**at low relative energy** (≈100 eV)
J.S. Cohen, PRA 69 (2004)



# Antiprotonic atoms

***Ex.* $^{172}$Y,** R. Schmidt *et al.*, PRC 58, 3195 (1998)




**Γ** reaction probability

**$\Phi_{nl}$** antiproton radial wave function

***V(r)*** antiproton-nucleus potential

***a*** effective N-antiproton scattering length
*ex.* a=-1.53 – 2.5 ***i*** fm (Batty, NPA 1997)

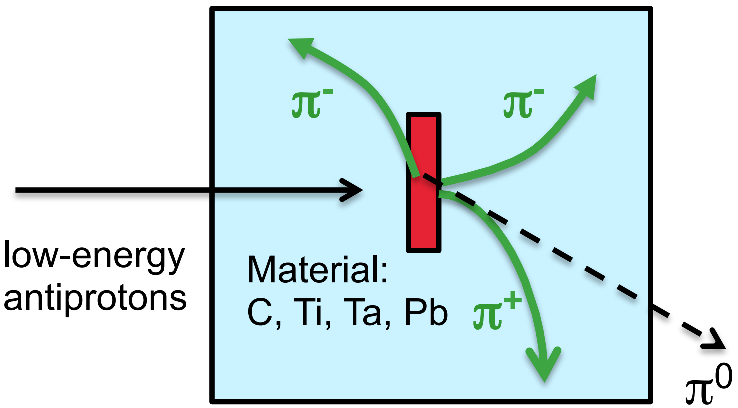
ρ(r) nuclear density convoluted with pbar-N range (0.75-1 fm if finite range)

$$\Gamma_{n\ell} = \int \mathrm{Im}\, V(r) \left|\Psi_{n\ell}(r)\right|^2 r^2 dr$$

$$\text{with } V(r) = \frac{2\pi}{\mu} a \rho(r)$$

# Antiprotonic atoms (1): *p,n* annihilation ratio

Brookhaven national laboratory, W. M. Buggs *et al.*, Phys. Rev. Lett. 31, 475 (1973)




Bubble chamber

$$\left.\frac{\rho_n}{\rho_p}\right|_{surface} = \frac{N_{\bar{p}n}}{N_{\bar{p}p}} \times \frac{\operatorname{Im} a_{\bar{p}p}}{\operatorname{Im} a_{\bar{p}n}} \times \varepsilon$$

**Example of $^{208}$Pb:**

- 1982 annihilation events, with 1805 $\pi^+$ and 2626 $\pi^-$
- hydrogen events: 232
- after absorption, charge –exchange, geometry corrections: **1654 $\pi^+$, 2606 $\pi^-$**

=> **1750 annihilations** from Pb, 4260 pions: multiplicity **2.44** (to be compared to **3.13** with deuton)

- Excess of $\pi^-$: **2606-1654=947**
- N(pbar-n)= **947** * **3.13/2.44** = **1216**
- N(pbar-p)= 1750-1216= **534**
- Ratio: N(pbar-n)/N(pbar-p)=**2.27** (R= 0.632 for carbon due to difference of p/n cross sections)
- Normalized to carbon, ratio=2.27/R=**3.59** to be compared to N/Z=1.54, **« halo factor: f=2.3(5) »**

# Antiprotonic atoms (1): *p,n* annihilation ratio

$$f_{halo} = \frac{N_{(\bar{p}n)}}{N_{(\bar{p}p)}} \times \frac{Z}{N} \times \frac{N_{\bar{p}p}}{N_{\bar{p}n}}\Bigg|_{Carbon}$$

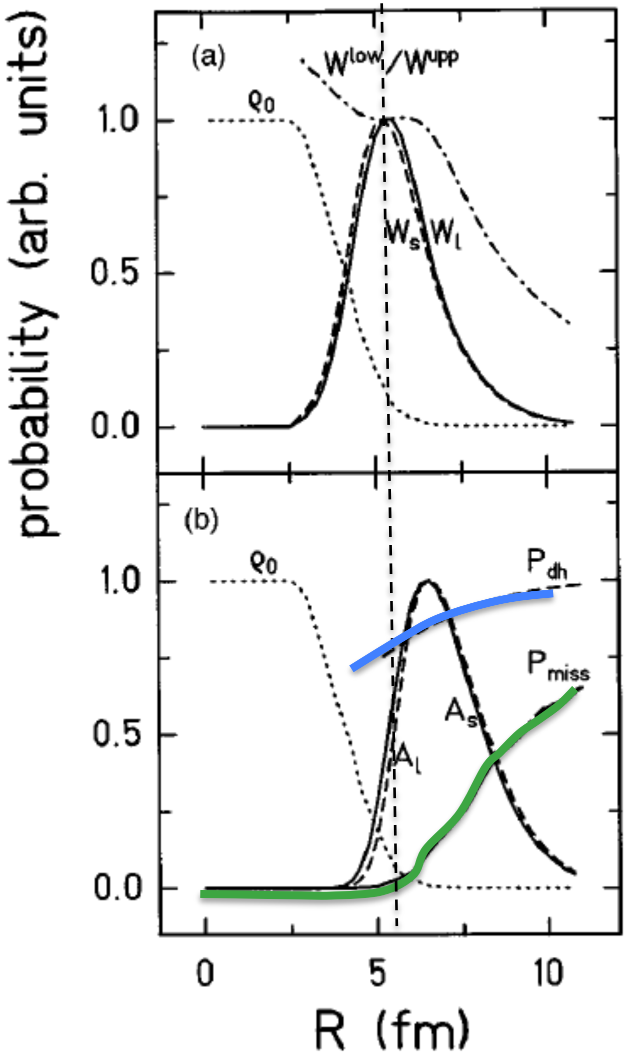
TABLE IV. "Halo factor" analysis.

| Element | $N(\pi^-) - N(\pi^+)$ | $N(\bar{p}n)$ | $N(\bar{p}p)$ | $\frac{N(\bar{p}n)}{N(\bar{p}p)}$ | $\frac{N(\bar{p}n)}{N(\bar{p}p)}\Big/\frac{N(\bar{p}n)}{N(\bar{p}p)}\Big\|_c$ | $\frac{N}{Z}$ | Halo factor |
|---|---|---|---|---|---|---|---|
| C | 2302 | 2586 | 4089 | 0.632 | 1.00 | 1.00 | 1.00 |
| Ti | 881 | 1067 | 1111 | 0.960 | 1.52 | 1.18 | 1.29 ± 0.21 |
| Ta | 1006 | 1276 | 931 | 1.371 | 2.17 | 1.48 | 1.46 ± 0.24 |
| Pb | 947 | 1216 | 534 | 2.270 | 3.59 | 1.54 | 2.34 ± 0.50 |

- Evidence for « **neutron halo** » at the nuclear surface for heavy systems
- Halo factor extraction assumes that the relative pbar-n and pbar-p amplitudes are constant for all elements (**$R_{np}$=0.632** obtained from carbon data).
- Theoretical estimates difficult due to **final state interactions** (pion interaction with residue)

# Antiprotonic atoms (2): radio-chemical analysis

**Concept:** selection of « cold » residues after annihilation, *i.e.* (Z-1,A-1) and (Z,A-1)




**No selection**

$$\operatorname{Im} V(r)\left|\Psi_{n\ell}(r)\right|^2$$

**Selection** on cold residues by counting radioactive decays

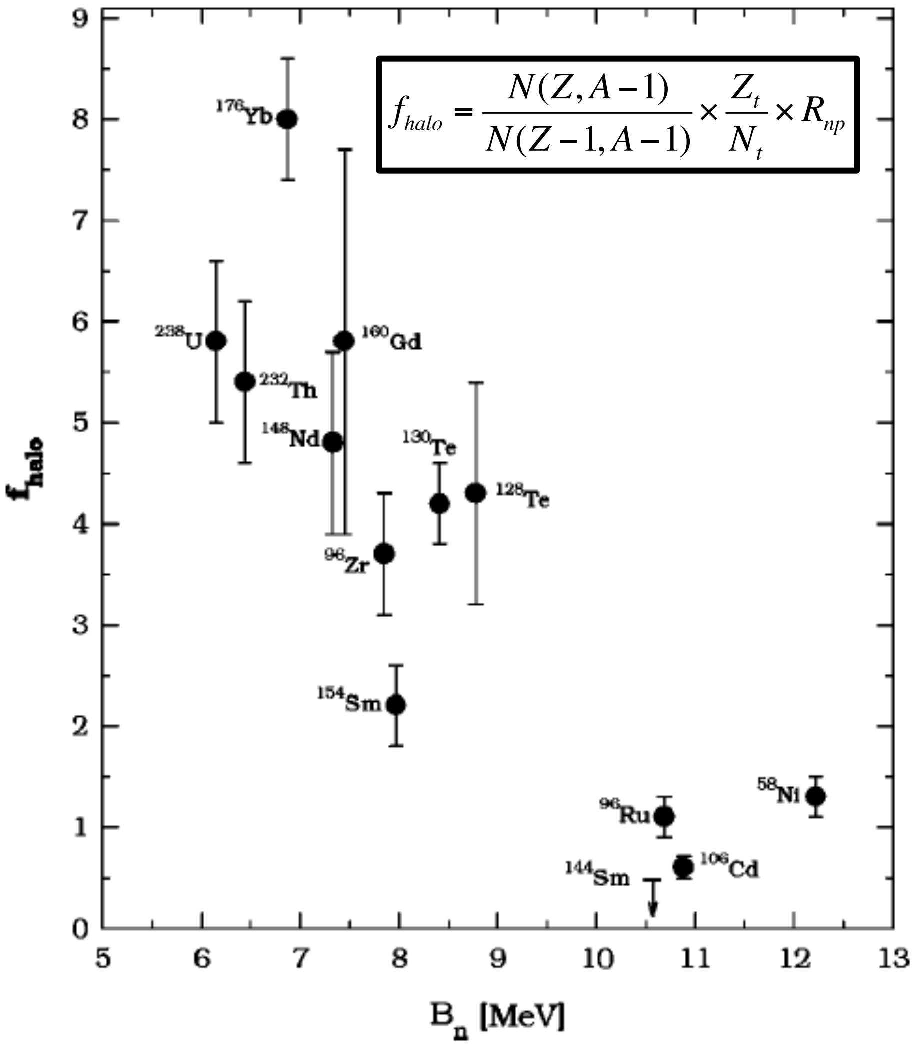
$$\operatorname{Im} V(r)\left|\Psi_{n\ell}(r)\right|^2 P_{miss}(r) P_{dh}(r)$$

Probability that the populated final state is bound (SF)

Probability that pions do not interact with the residue

S. Wycech *et al.*, PRC **54**, 1832 (1996).

# Antiprotonic atoms (2): radio-chemical analysis




P. Lubinski *et al.*, Phys. Rev. Lett. 73, 3199 (1994)
P. Lubinski *et al.*, Phys. Rev. C 57, 2962 (1998)

# Antiprotonic atoms (2): comparison to theory

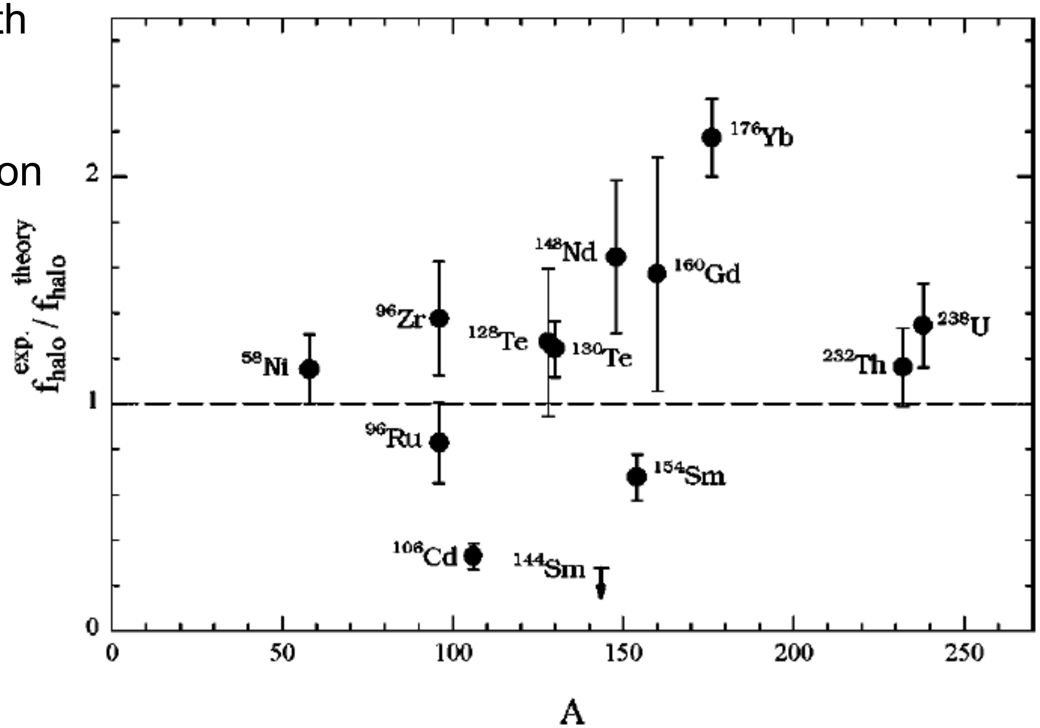
**Theoretical assumptions:**

- a=-1.5 –*i* 2.5 fm, pbar-N scattering length
- Range pf pbar-N: 0.75 fm
- Capture from orbitals (n=l+1,l)
- Sudden approximation for pion absorption (Pmiss) / A-1 residues selected
- HFB shell structure (Pdh) with SKP
- $R_{np}$=0.63

**Not quantified theoretical uncertainties**

**Ignored in the calculation:**

- fission of residue
- deformation
- density or isovector dependance of $R_{np}$



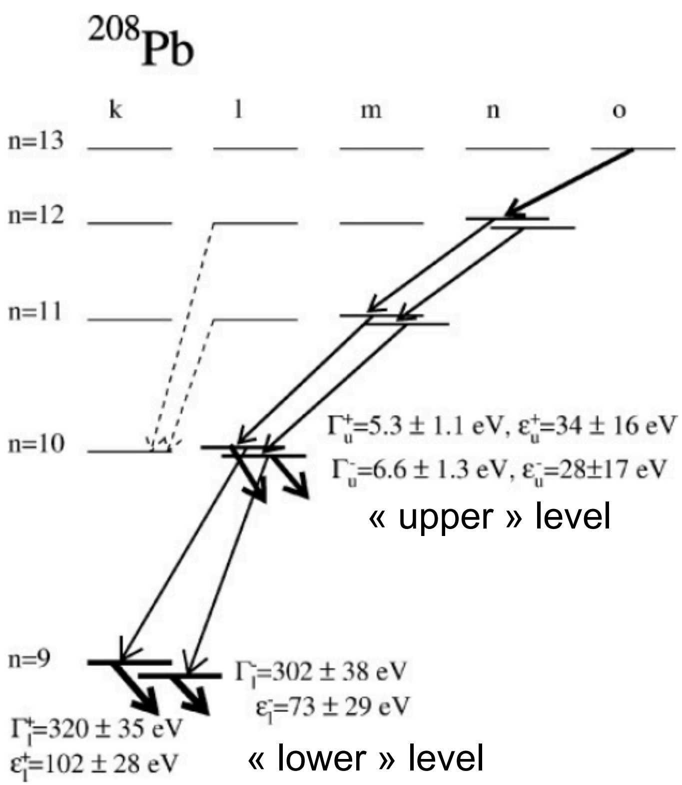

P. Lubinski *et al.*, Phys. Rev. C 57, 2962 (1998)

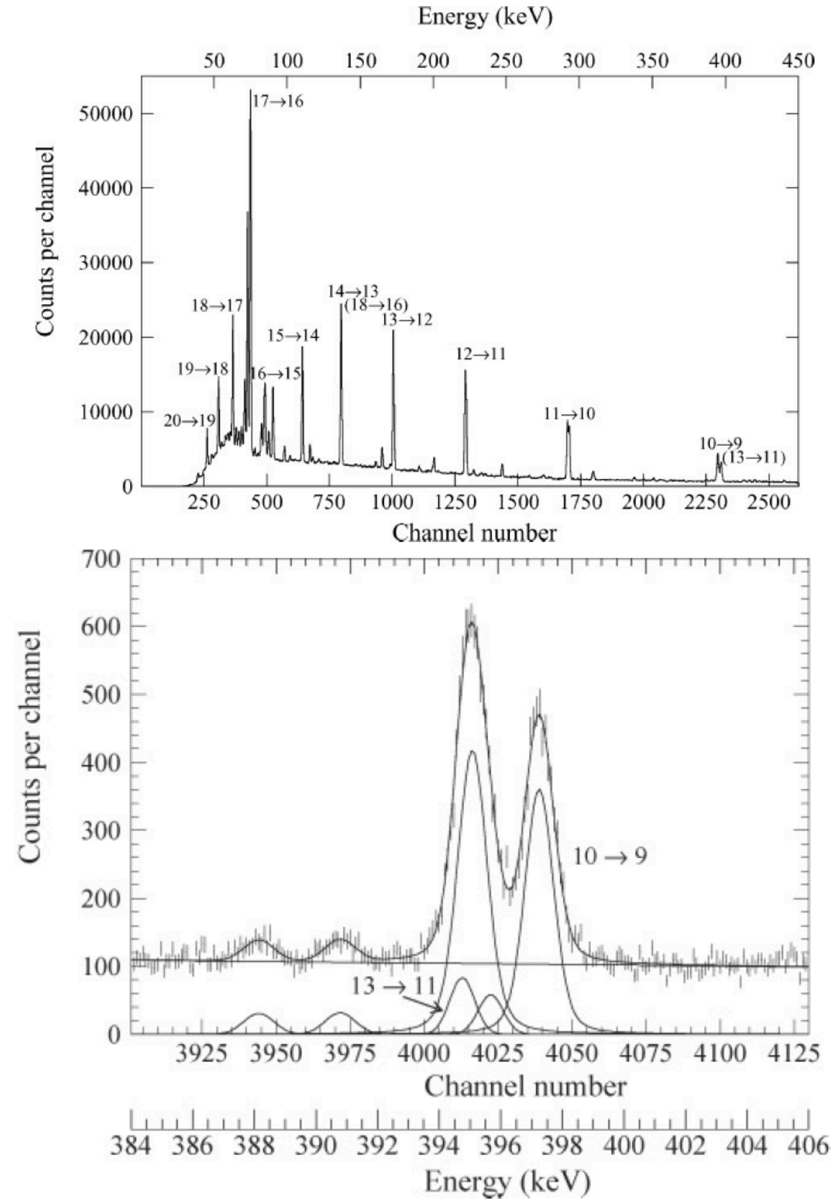
**Main conclusions:**

- **clear and unique dependence over $\rho_n/\rho_p$**
- **complementary observable to radii (sensitive to 2-4 fm from the half-max density radius)**
- **more systematic microscopic theoretical estimates needed**

# Antiprotonic atoms (3): X rays

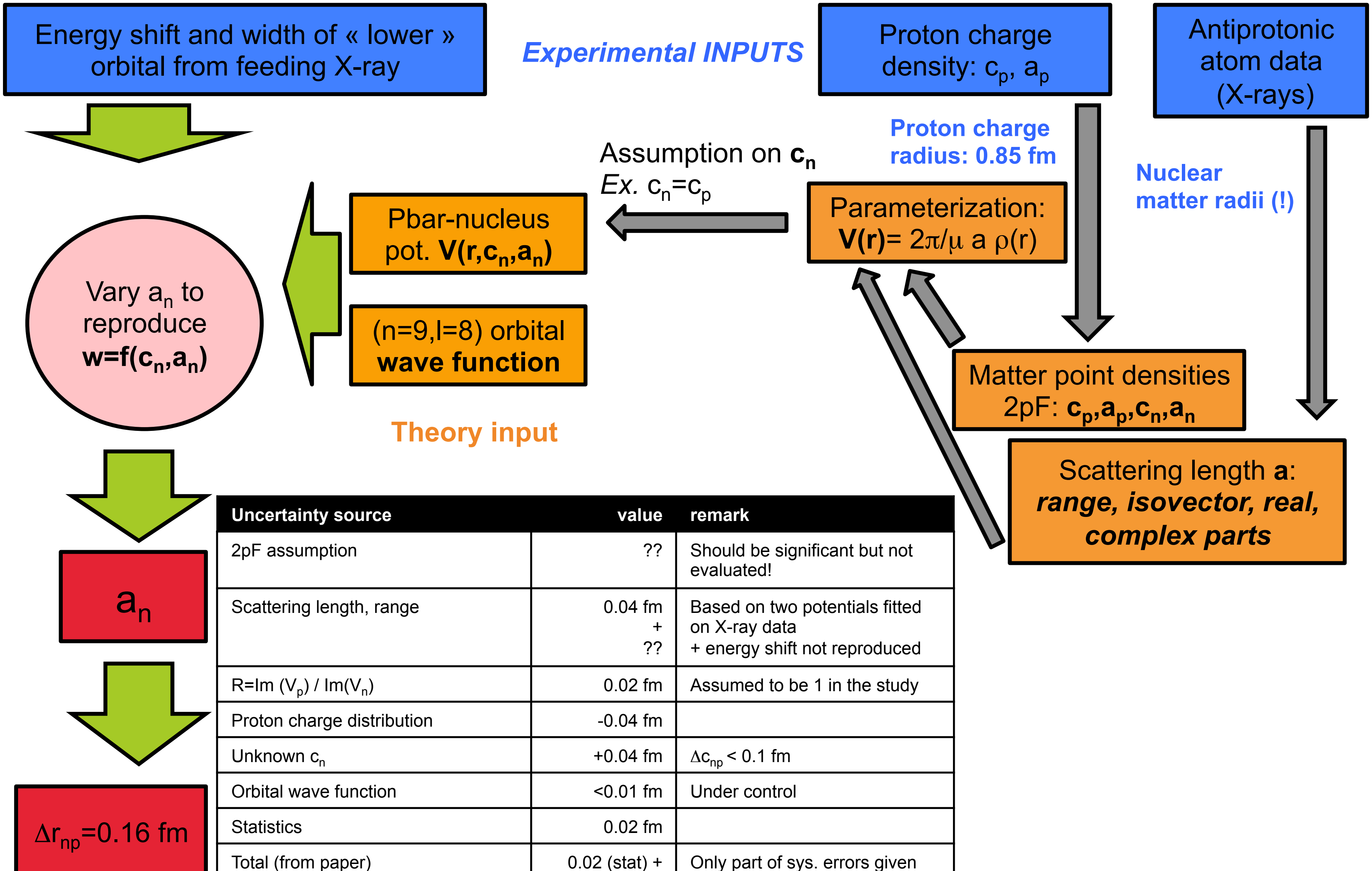
Energy width and shift modified by the strong interaction at the nuclear surface compared to pure EM orbital & decay




B. Klos *et al.*, Phys. Rev. C 76, 014311 (2007).

# Antiprotonic atoms (3): X rays and NS thickness



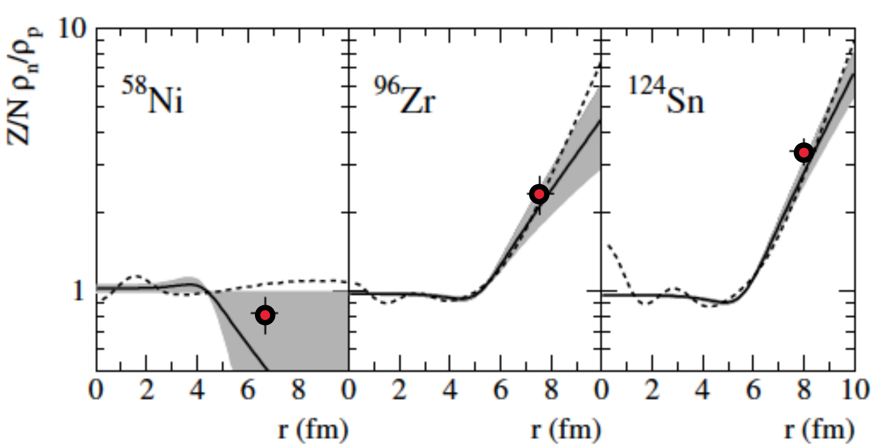

| Uncertainty source | value | remark |
|---|---|---|
| 2pF assumption | ?? | Should be significant but not evaluated! |
| Scattering length, range | 0.04 fm + ?? | Based on two potentials fitted on X-ray data + energy shift not reproduced |
| R=Im ($V_p$) / Im($V_n$) | 0.02 fm | Assumed to be 1 in the study |
| Proton charge distribution | -0.04 fm | |
| Unknown $c_n$ | +0.04 fm | $\Delta c_{np} < 0.1$ fm |
| Orbital wave function | <0.01 fm | Under control |
| Statistics | 0.02 fm | |
| Total (from paper) | 0.02 (stat) + 0.04 (sys) | Only part of sys. errors given |

# Antiprotonic atoms (2 & 3): radiochemical & X rays

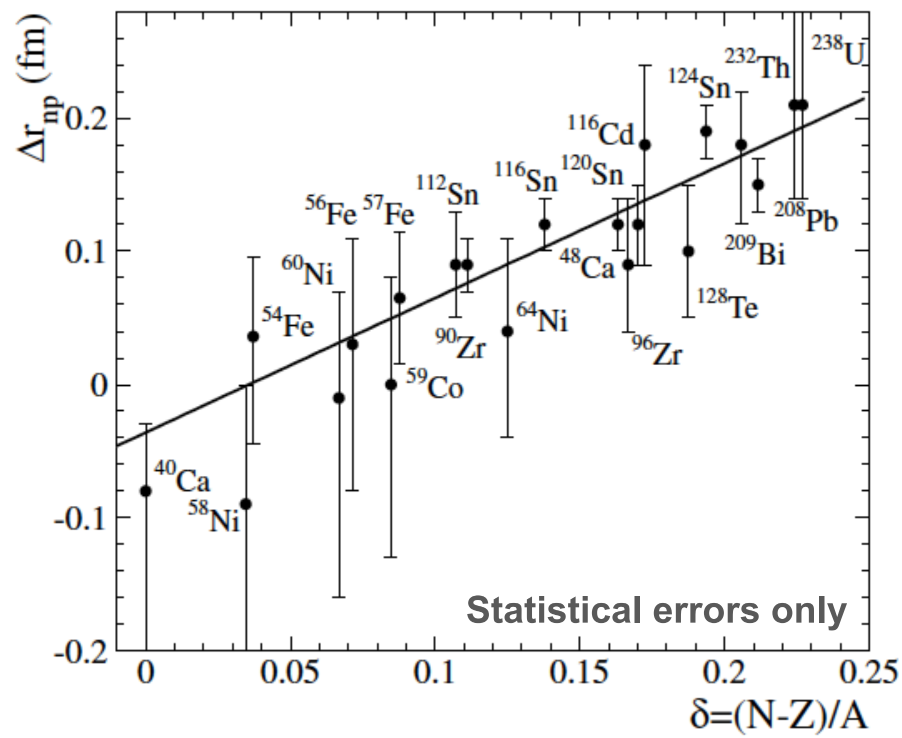
- Stable nuclei from $^{40}$Ca to $^{238}$U
- X-ray method « consistent » with radiochemical with **R=1** (R=0.63 in previous works)

$$f_{halo} = \frac{N(Z,A-1)}{N(Z-1,A-1)} \times \frac{Z_t}{N_t} \times R$$

- Neutron distributions (2pF) « deduced » from X-ray data
- **a = 2.5(3) + *i* 3.4(3) fm, zero range**
- charge distributions from published tables
- assume pure halo: $\mathbf{c_n = c_p}$
- $\Delta a_{np}$ ajusted to best reproduce E shift, width




- ● radioachemical
- —— from X-ray measurement
- - - - HFB




A. Trzcinska *et al.*, Phys. Rev. Lett. **87**, 082501 (2001)

# Neutron skins and halos in neutron-rich nuclei

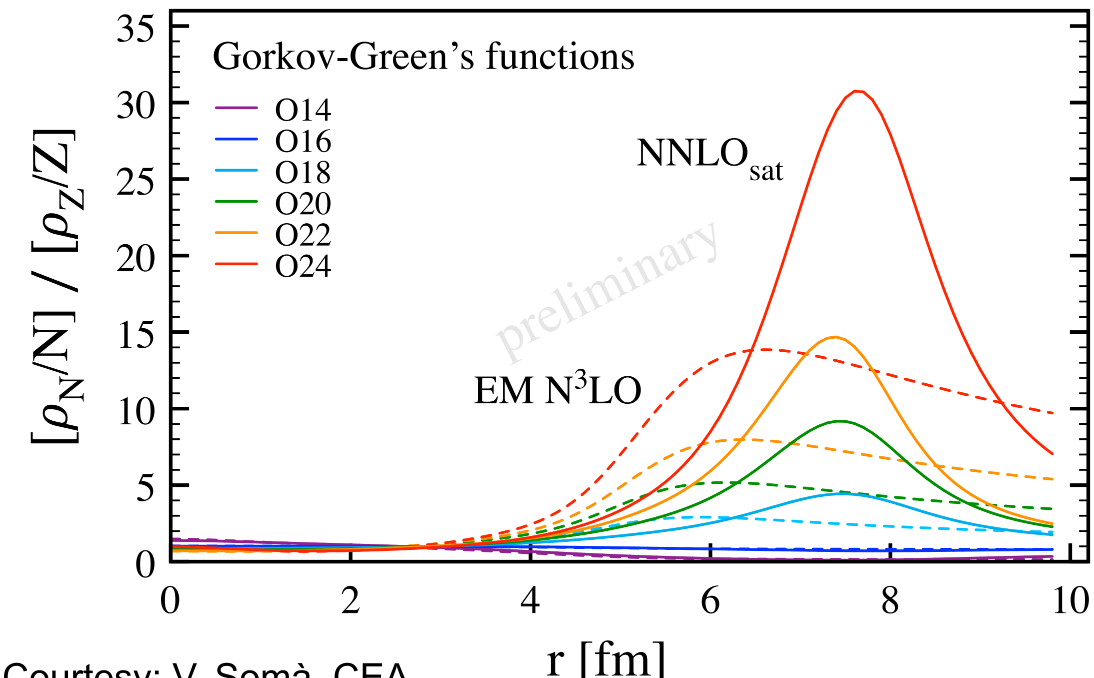
Nupecc Long Range Plan (2016-2026) / under preparation

## 5. How do neutron halos and skins evolve across the nuclear chart?

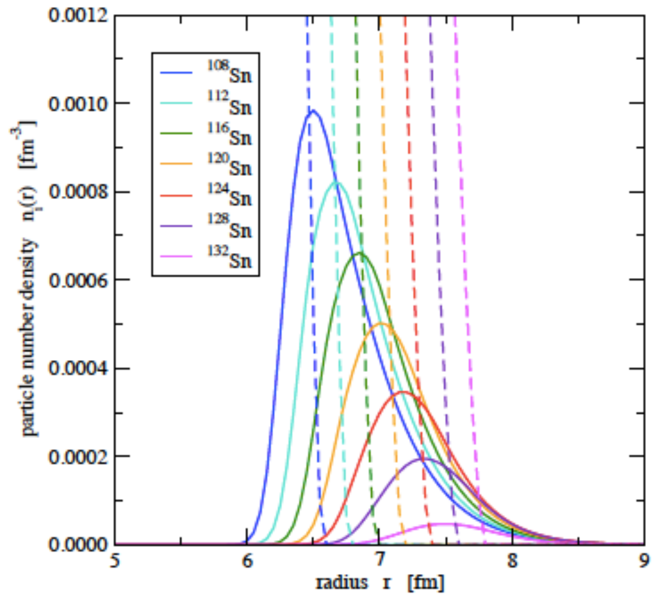
« A systematic study of neutron skins would open the way to map out its evolution and the occurrence of low-density neutron matter as a function of proton number. […] »

## 6. How do nucleon correlations appear in dilute neutron matter?

“Cluster correlations are also an important feature in heavier nuclei. Recent generalized relativistic functional calculations predict a significant alpha cluster at the surface of heavy nuclei with a more pronounced effect in neutron-rich nuclei. A systematic search from alpha quasi-free scattering or transfer along isotopic chains should be pursued in the coming years. The surface α clustering affects the correlation of the neutron skin thickness of heavy nuclei with the density dependence of the symmetry energy.”




Courtesy: V. Somà, CEA




S. Typel, GSI

# Antiprotonic atoms with radioactive ions: concept

- **Concept:**

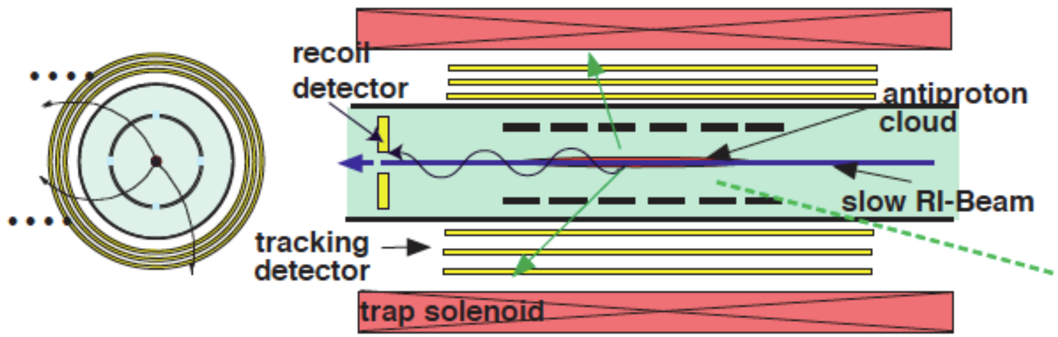
Collision of low-energy antiprotons and unstable nuclei
Low luminosity counter-balanced by high capture cross section + Radioactive ion cycles

- **Method:** RI ring or trapped ions

Ex. future FLAIR program at FAIR

- **Physics case:**

$\rho_n/\rho_p$ at the nuclear surface
in very neutron-rich & short-lived nuclei
(halos, thick neutron skins)




M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214**, 196 (2004).

- **Uncertainties:**

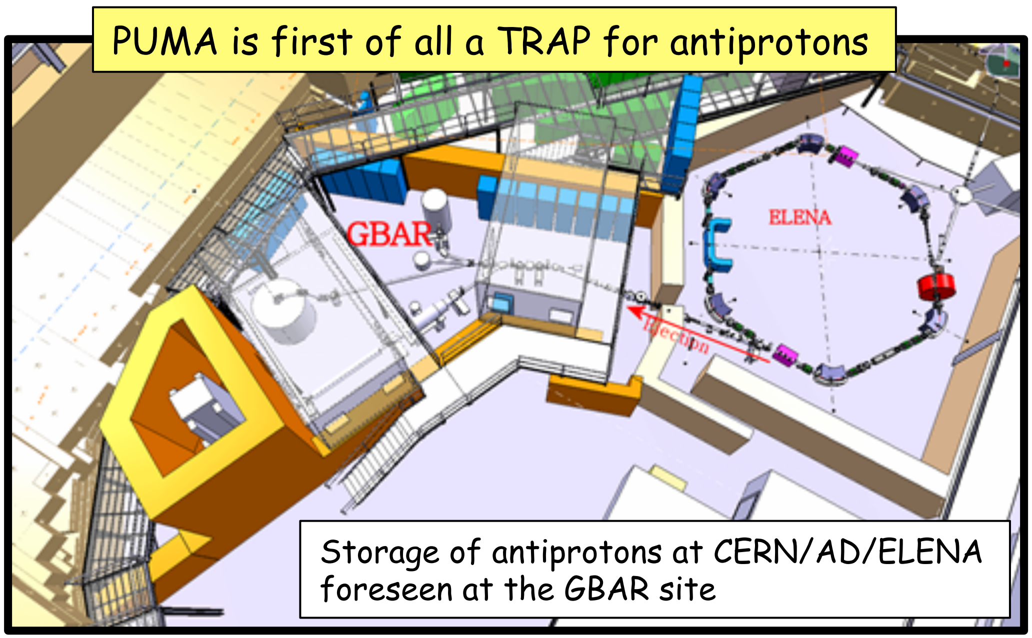
$f_{halo}$ impacted by (1) statistics, (2) final state interactions (FSI)

If enough statistics, $f_{halo}$ and FSI can be constrained from the data.
**<10% uncertainties** can be reached.

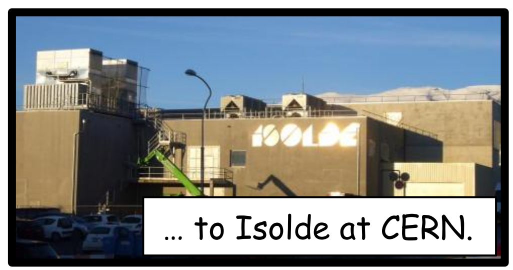
# PUMA: original experimental method

- PUMA: antiProton Unstable Matter Annihilation

- The antiproton filling at CERN/ELENA
- Transportation of antiprotons to CERN/ISOLDE
- In-trap annihilations and measurement **from 2020**







# Summary

- **Antiprotonic atoms** have been used to study neutron skins / halos at the nucleus surface
- A unique **sensitivity** to proton/neutron densities **« beyond » the nuclear surface (tail)**

- Three methods have been used:
  - pion emission ($\rho_n/\rho_p$) after annihilation
  - radiochemical (cold residue selection)
  - X-ray measurement

- **Model dependences** are the main limitation to precision

- Neutron skin thicknesses extracted have significant **systematic errors**
  1) choice of 2pF for radial density profiles
  2) antiproton-N optical potential (parameterization, range,…)
  - given systematic errors estimated to **0.04 fm** for $\Delta R_{np}$ are **underestimated**

- More theoretical/microscopic efforts necessary are needed for comprehensive uncertainties

- Method could be applied to **unstable nuclei**
  - evidence of halos in medium-mass neutron-rich nuclei
  - neutron-skin thickness evolution along long isotopic chains
- New opportunities at **ELENA** low-energy ring at CERN/AD from 2020 (after the CERN LS2)
  Later possibilities at FLAIR, when/if available
- New project (PUMA) for unstable nuclei studies under development