PUMA : Exotic Nuclei & Antiprotons

TECHNISCHE UNIVERSITÄT DARMSTADT

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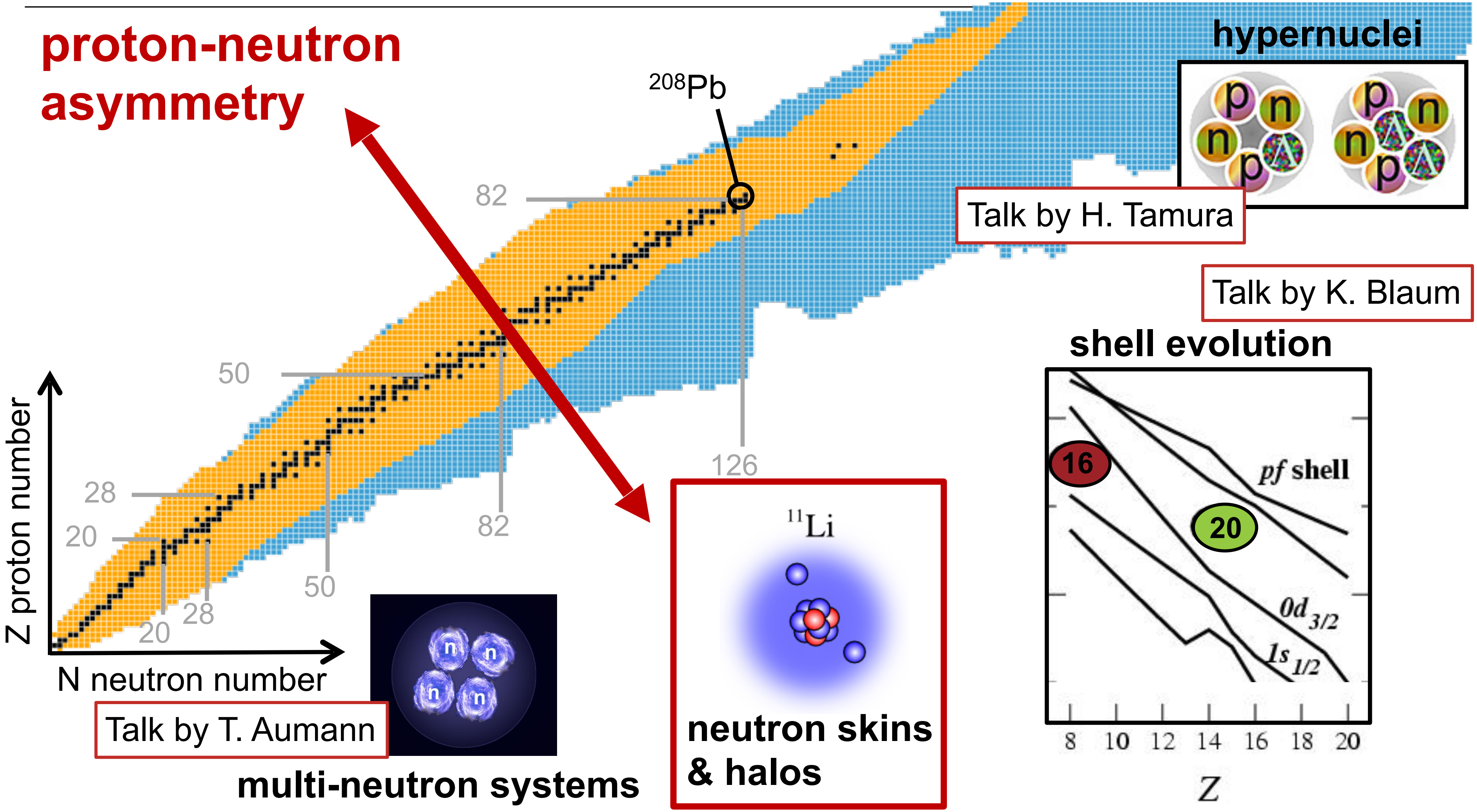
TU Darmstadt

Bormio Winter Meeting on Nuclear Physics
January 23rd, 2018

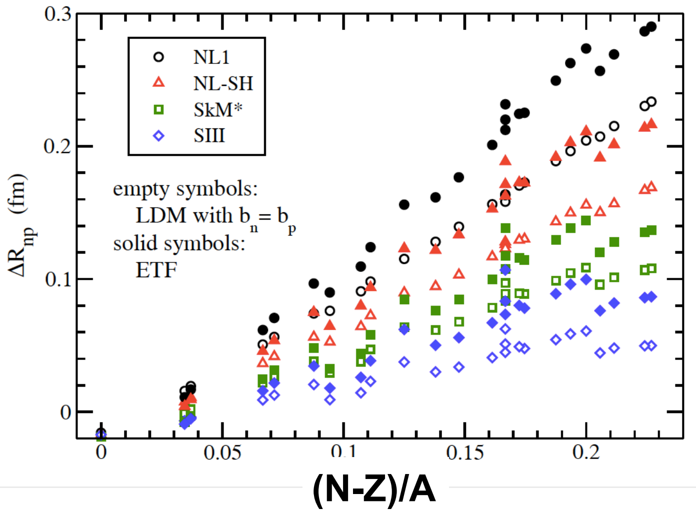
Context: neutron- rich / deficient nuclei



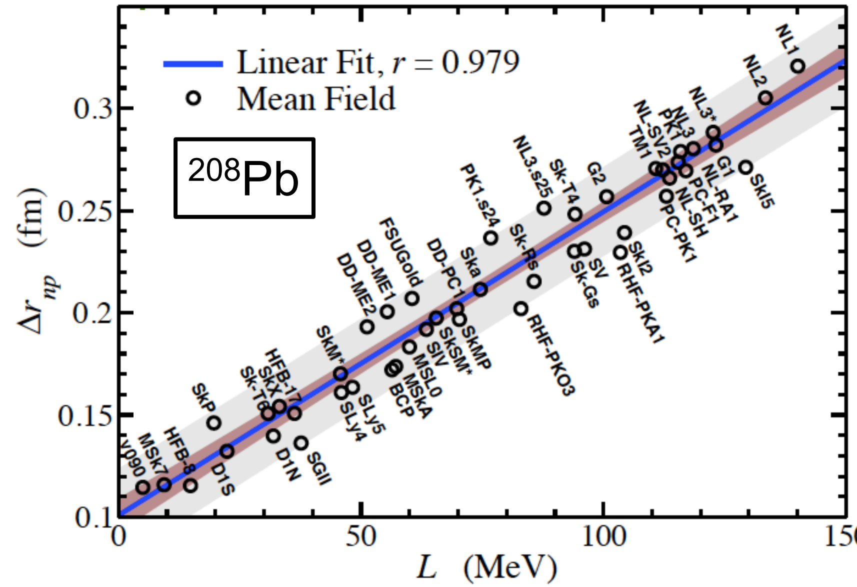
Neutron skins

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)

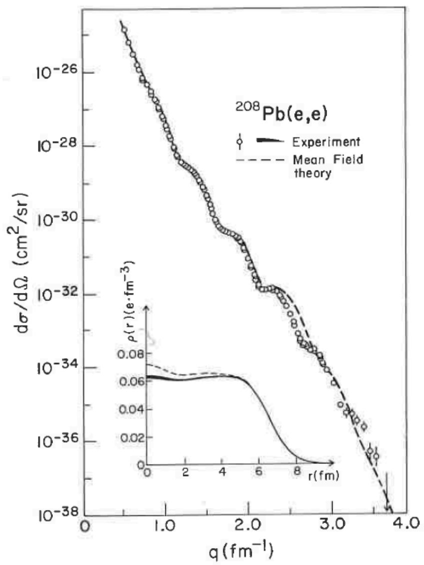


$$\frac{E}{A}(\rho_n,\rho_p) = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 \qquad L \propto \left.\frac{\partial S(\rho)}{\partial \rho}\right|_{\rho_0}$$

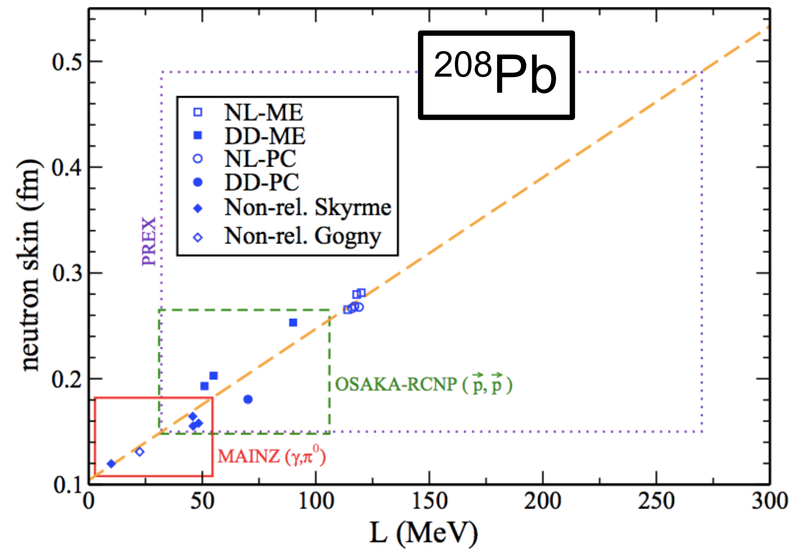
X. Roca-Maza *et al.*, Phys. Rev. Lett. **106**, 252501 (2011)

- **neutron skins** have been extensively studied
- motivated by the Nuclear Equation of State (EOS) as well
- structure phenomenon difficult to characterise and to measure accurately

Charge and matter/neutron radii, ex. of ^{208}Pb



A. Meucci *et al.*, PRC **90**, 027301 (2014)



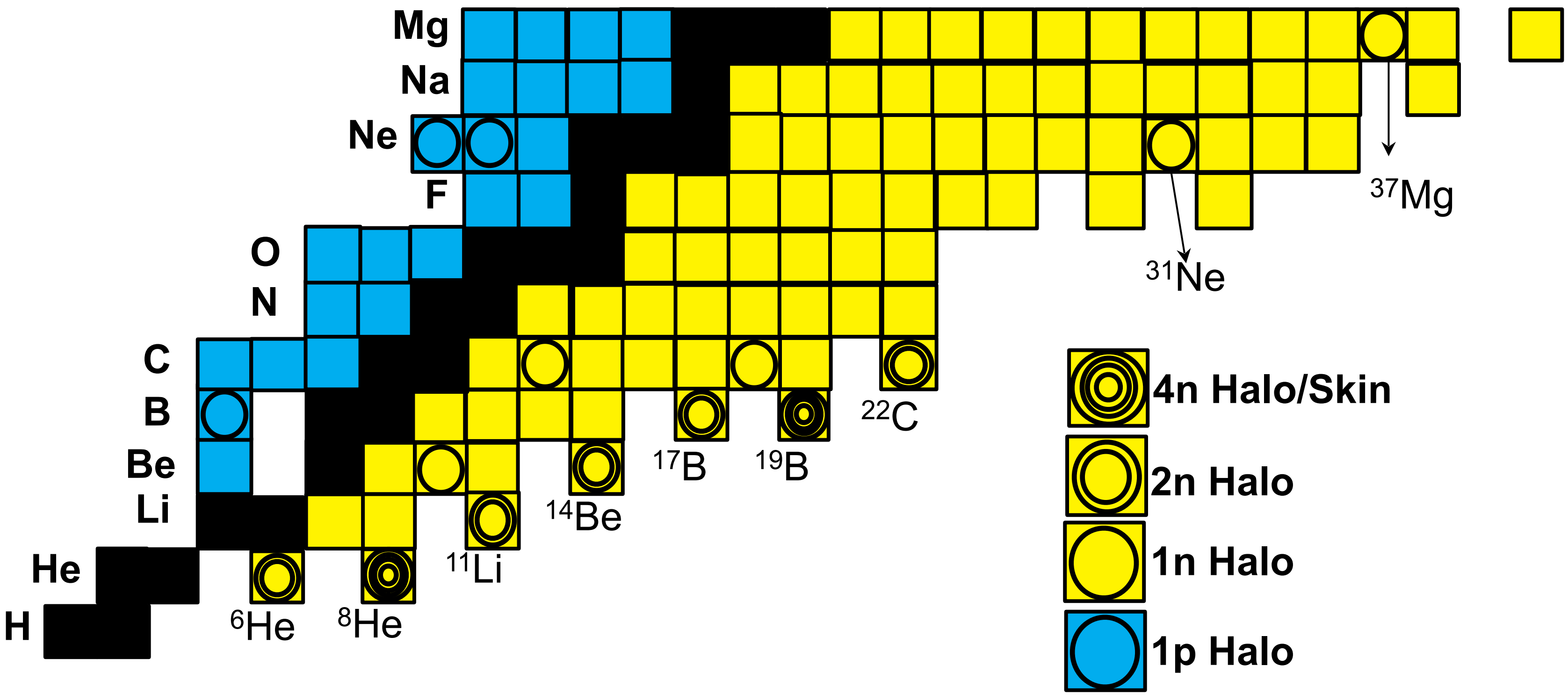
Charge radii:

- ❑ Charge density distributions extracted from *(e,e')* for stable nuclei
- ❑ Not accessible for short-lived nuclei, except at SCRIT at RIKEN since 2017
- ❑ Charge radii of unstable nuclei from fine structure (relative) studies (*ex.* ISOLDE)

Matter radii:

- ❑ proton scattering, coherent π^0 photoproduction, parity-violation expts, reaction cross sections
  - ex. dedicated SFB workshop, MITP Mainz 2016
  - T. Aumann *et al.,* Phys. Rev. Lett. **119**, 262501 (2017)

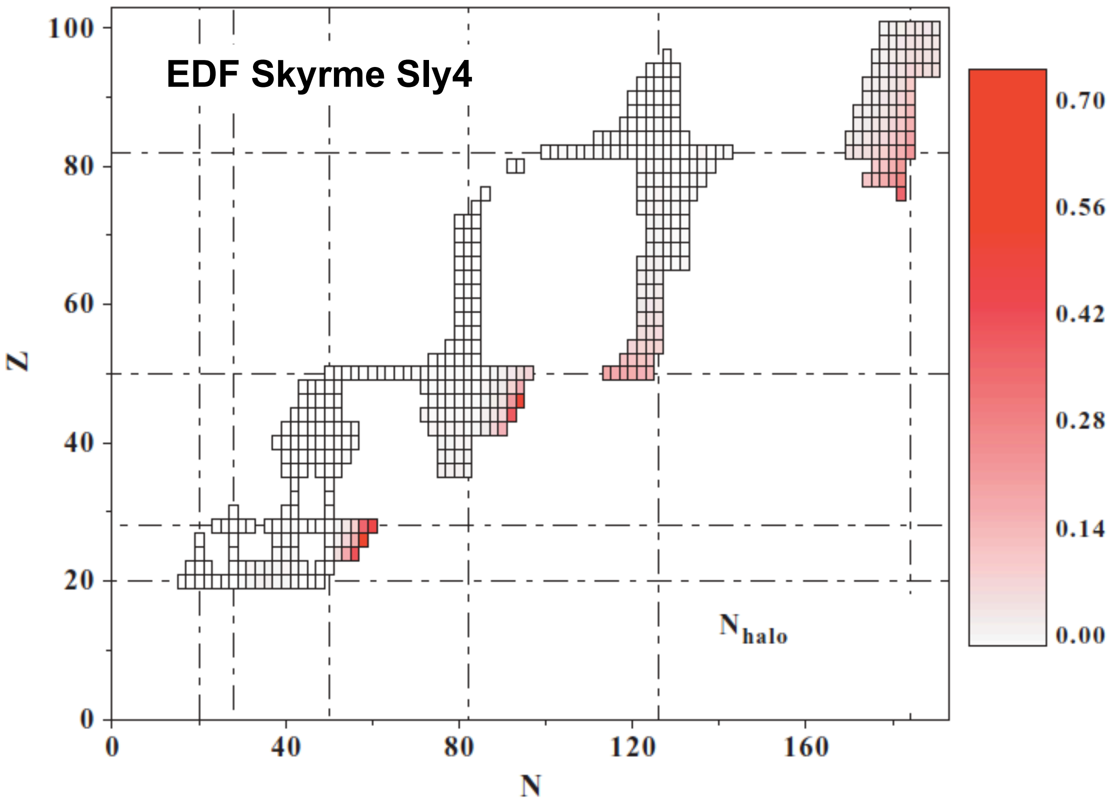
Neutron halos



S-wave dominate: ^{11}Be, ^{15}C , ^{19}C,
P-wave dominate: ^{6}He, ^{8}He, ^{31}Ne, ^{37}Mg

Necessary conditions for halos:
- ❑ Small separation energy (<1MeV)
- ❑ Low orbital angular momenta (*l*=0 or 1)

Neutron skins, halos in medium-mass nuclei

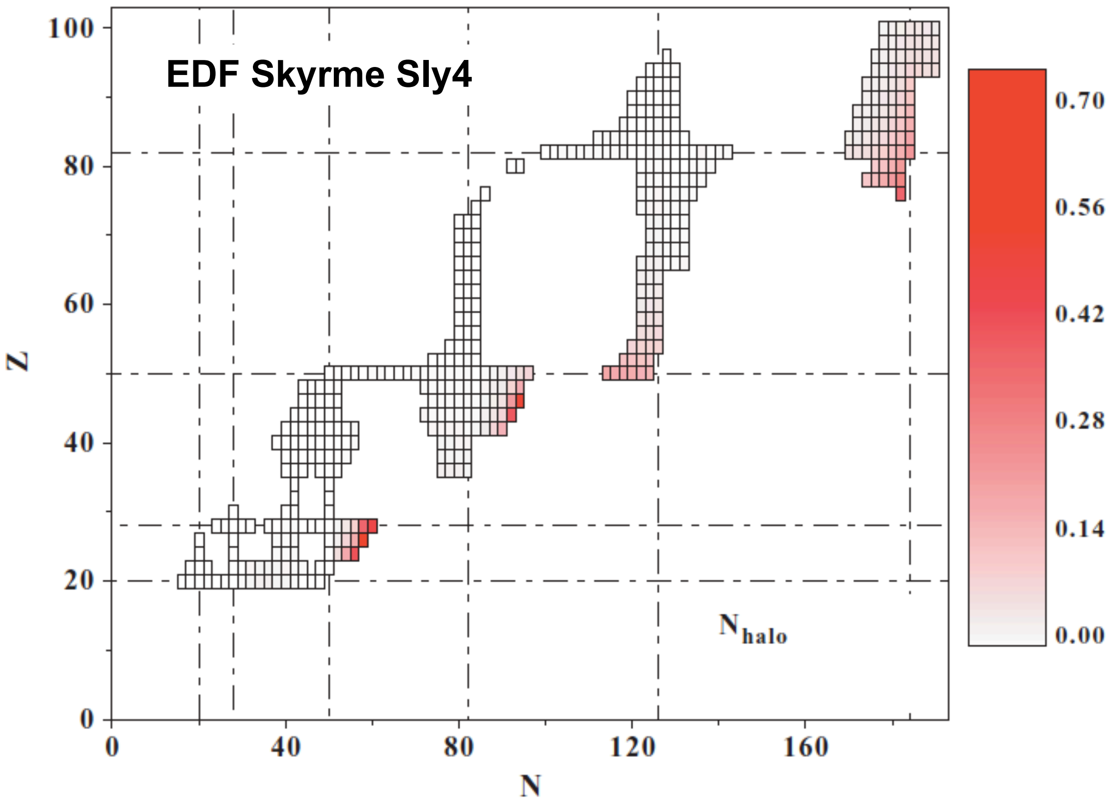


V. Rotival, K. Bennaceur and T. Duguet, Phys. Rev. C **79**, 054309 (2009)

$$N_{halo} = \int_{r_0}^{+\infty} \rho(r) r^2 \, dr$$

Beyond the radius r0 : core density is one order of magnitude smaller than the halo one.

Neutron skins, halos in medium-mass nuclei



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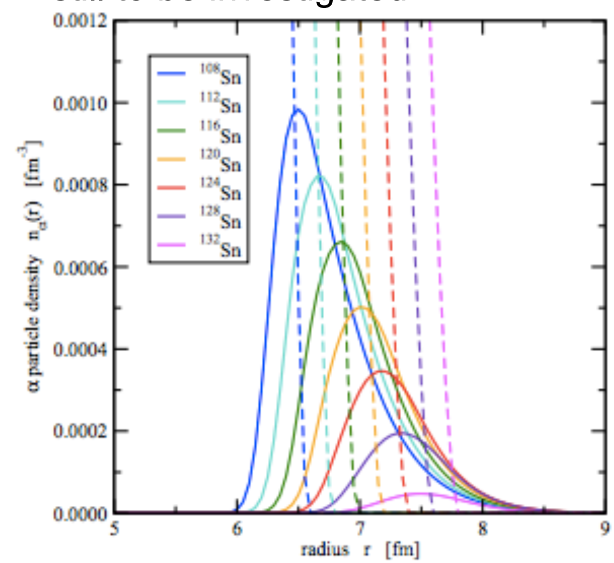
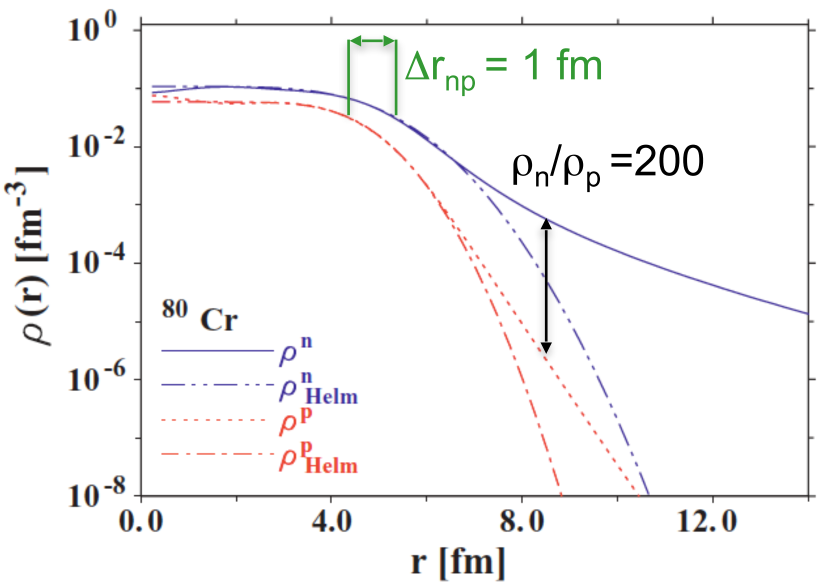
Beyond the radius r0 : core density is one order of magnitude smaller than the halo one.

Correlations within the neutron-skin still to be investigated

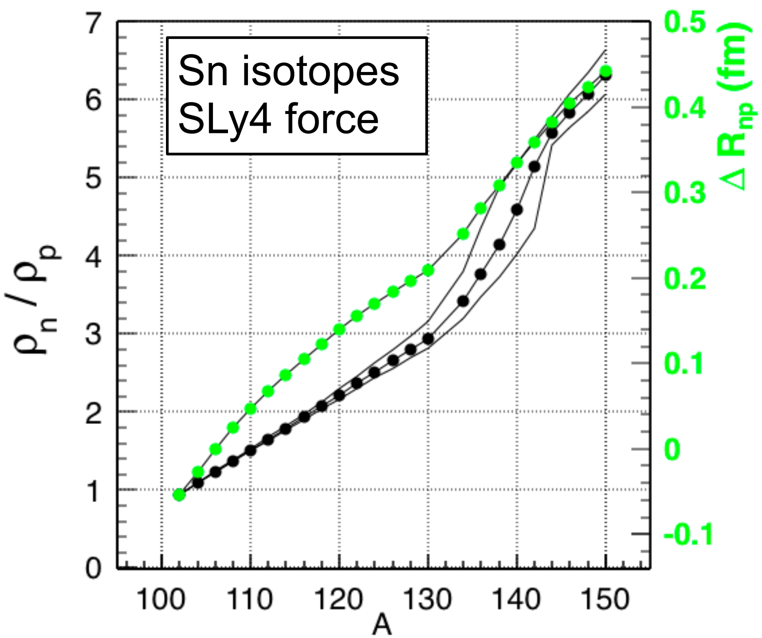


S. Typel *et al.,* Phys. Rev. C **89**, 064321 (2014)

Antiproton annihilation: a probe for the nuclear density tail



From V. Rotival *et al.*, PRC 79 (2009)



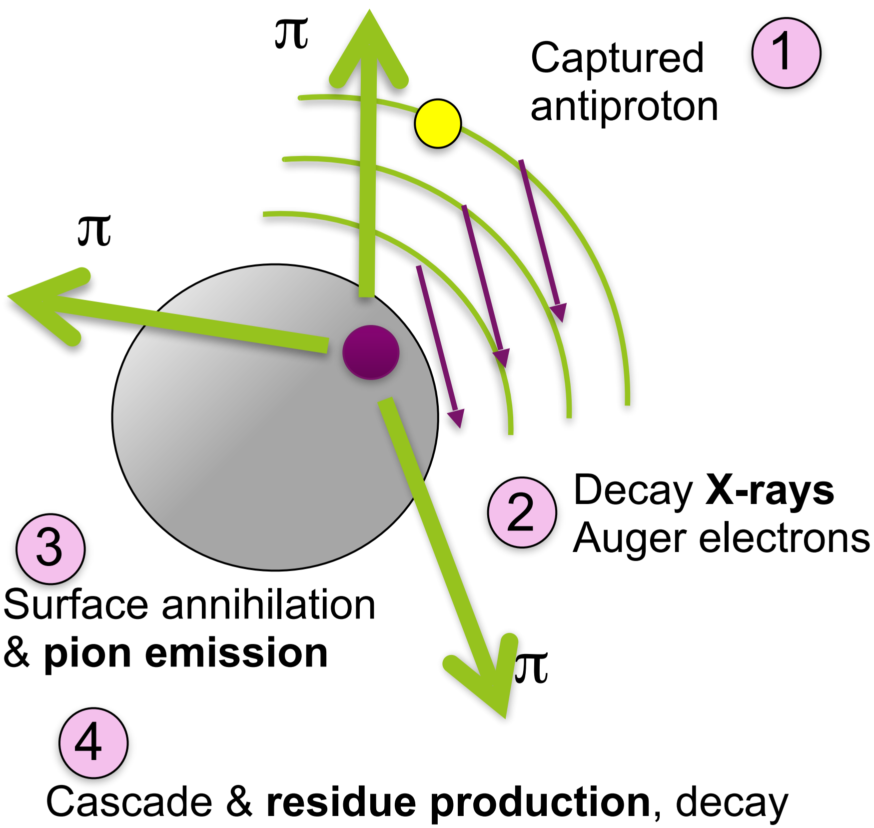
What would be an ideal probe?

- ❑ **isospin** sensitivity: differentiating between protons and neutrons
- ❑ sensitivity to the **tail** of the nuclear density
- ❑ usable for **short-lived nuclei**

… **low-energy antiprotons** fulfill these requirements

[was proposed in the past at CERN and GSI/FAIR (FLAIR project)]

Antiproton annihilation:
a probe for the nuclear density tail



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

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

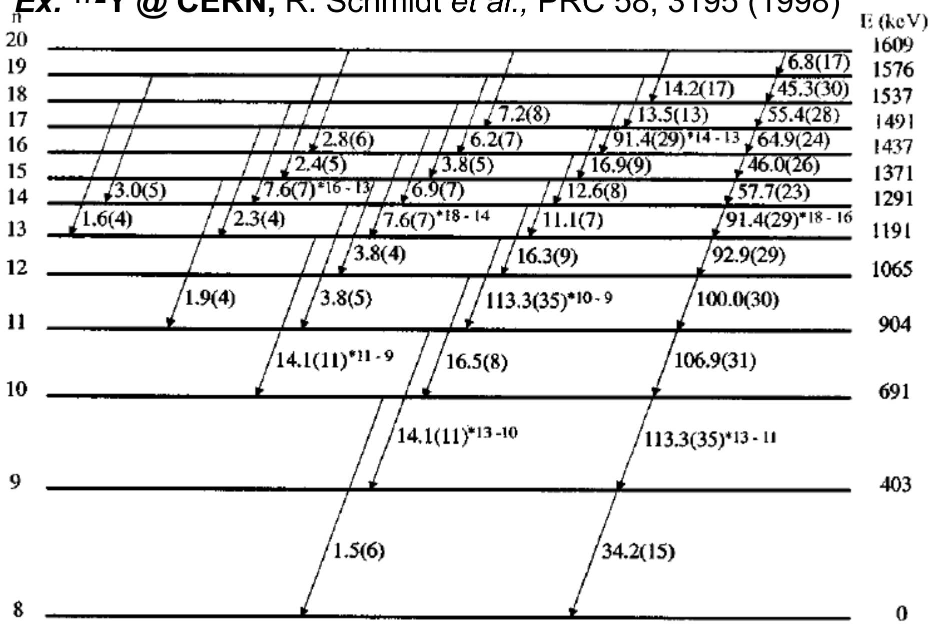
Pion final state	Branching ratio
$\pi^0\pi^0$	0.00028
$\pi^0\pi^0\pi^0$	0.0076
$\pi^0\pi^0\pi^0\pi^0$	0.03
$\pi^+\pi^-$	0.0032
$\pi^+\pi^-\pi^0$	0.069
$\pi^+\pi^-\pi^0\pi^0$	0.093
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028
$\pi^+\pi^-\pi^+\pi^-$	0.069
$\pi^+\pi^-\pi^+\pi^-\pi^0$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

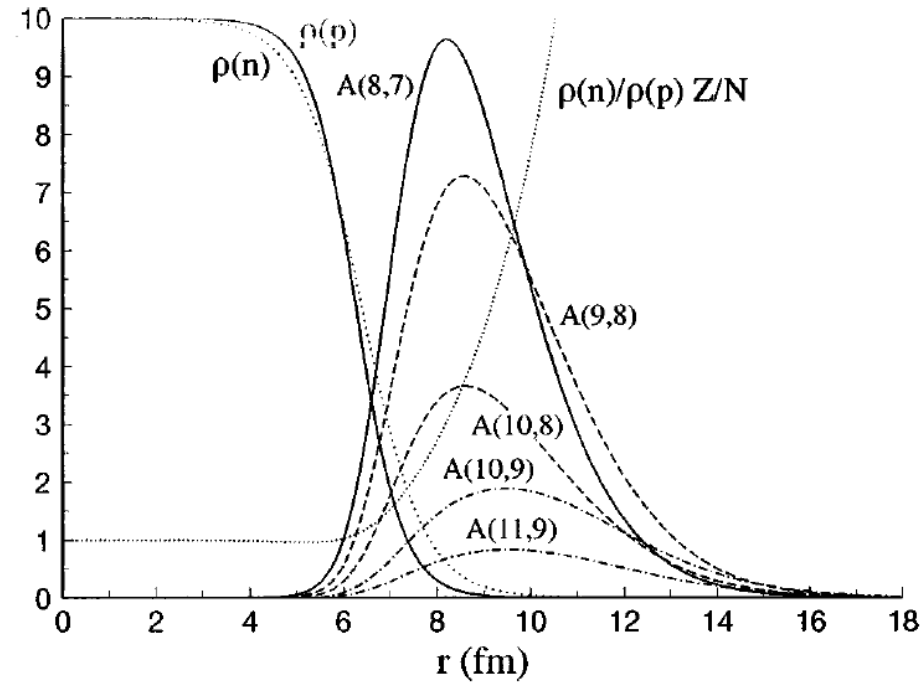
Antiproton-neutron, $\bar{p}n$ [46]

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

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





Γ reaction probability

Φ_{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)

$$\boxed{\begin{aligned}\Gamma_{n\ell} &= \int \mathrm{Im}\, V(r) \left|\Psi_{n\ell}(r)\right|^2 r^2 dr \\ \text{with } V(r) &= \frac{2\pi}{\mu} a\rho(r)\end{aligned}}$$

Antiproton annihilation:
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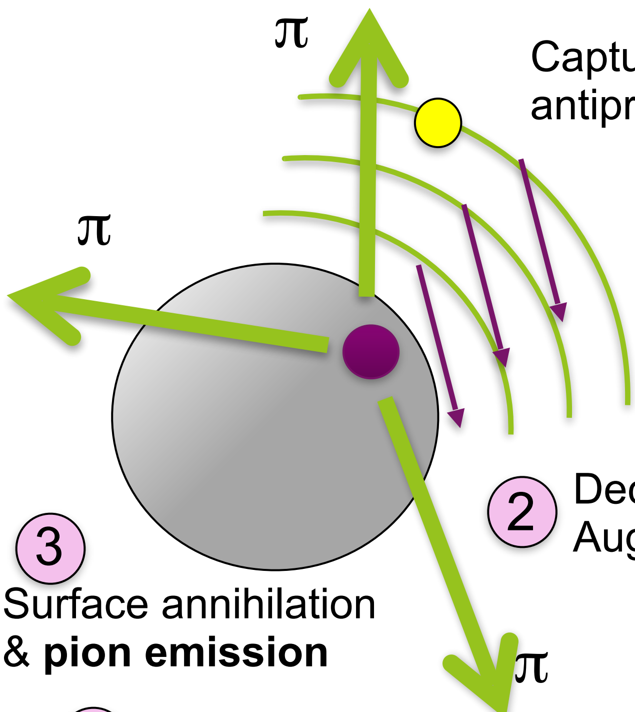

1 Captured antiproton

2 Decay **X-rays**
Auger electrons

3 Surface annihilation
& **pion emission**

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

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

Extracted from data

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

PUMA: Pbar Unstable Matter Annihilation

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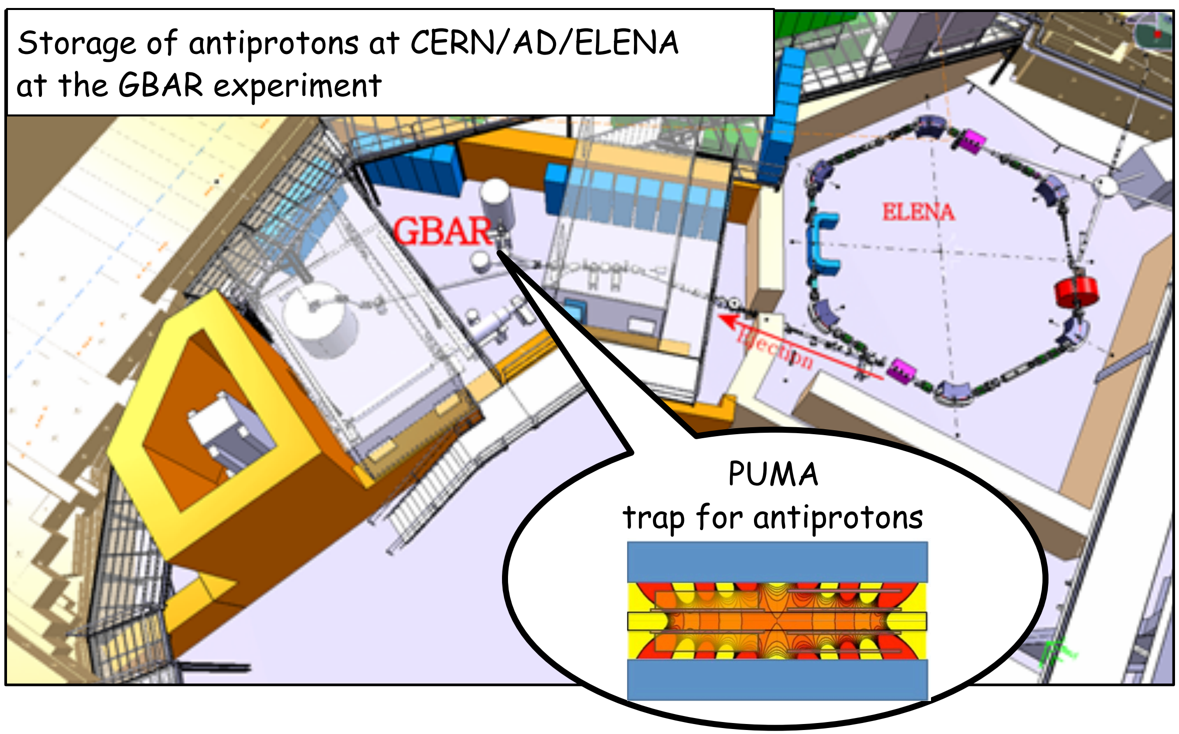
- Transport antiprotons from ELENA (CERN) to ISOLDE
- Device to be build (funded from 01/2018, for 5 years)
- First experiment at ISOLDE foreseen in 2022
- Pioneer experiment with antiprotons as a probe for short-lived nuclei



The GBAR experiment

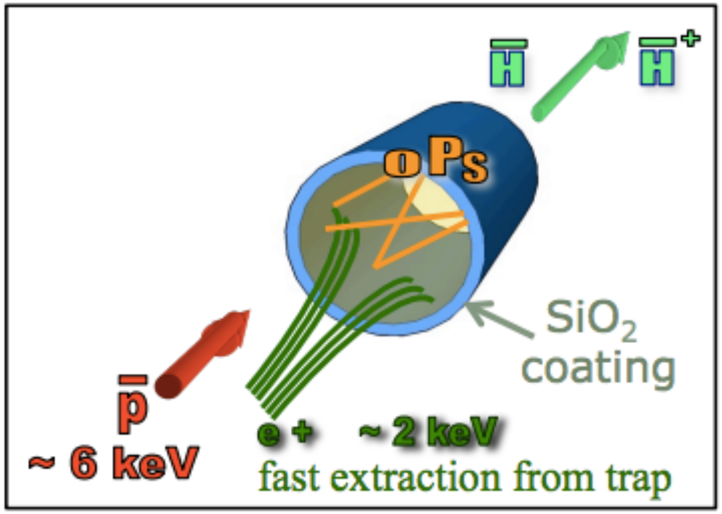
How does antimatter falls in the gravitational field?

Classical free fall: $z = z^0 + v_z^0 \, t + \frac{1}{2} \, g t^2$

Main perturbation

- Produce ion $\bar{H}^+$
- Sympathetic cooling 20 μK
- Photodetachment of e^+
- Time of flight

Error dominated by temperature of $\bar{H}^+$



Spokesperson: P. Pérez (CEA/IRFU)

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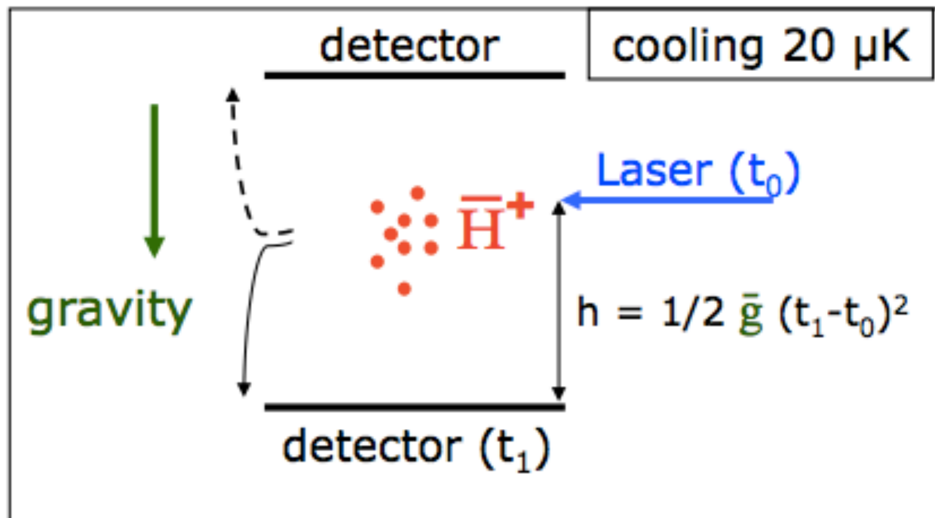
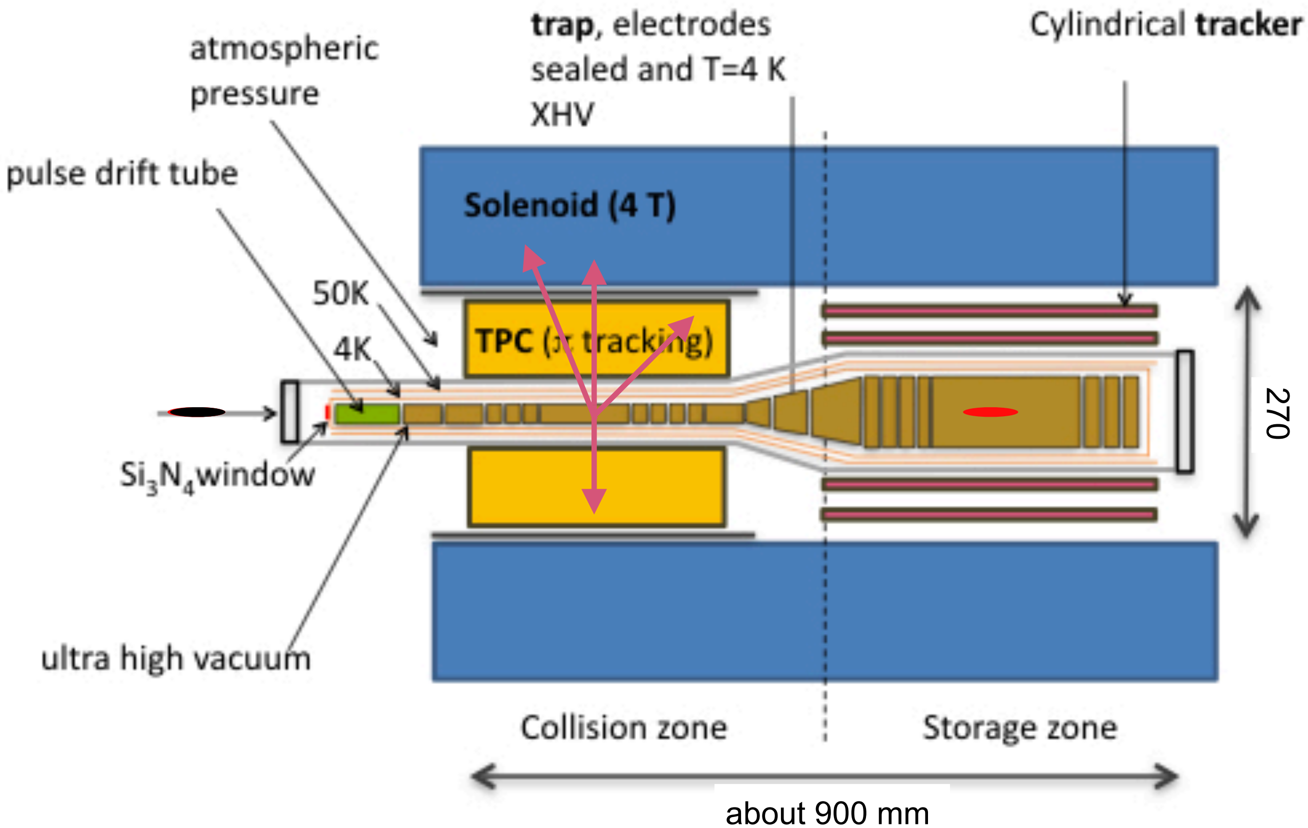
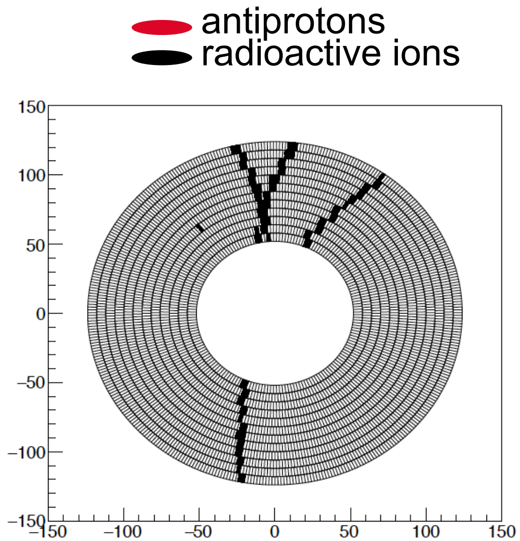


J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

Spokesperson: P. Pérez (CEA/IRFU)

PUMA: a magnetic bottle for antiprotons

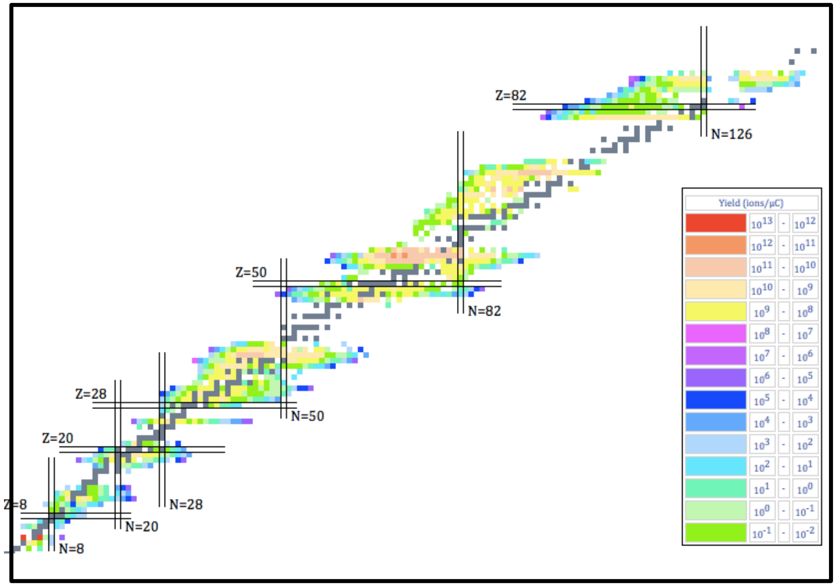




Technical challenges:

- ❑ Store a large number of antiproton ($<10^8$) for a long time
- ❑ Transport low-energy ions inside the ultra high vacuum

Day-1 experiments at ISOLDE



Production rates at ISOLDE

Nucleus	$T_{1/2}$	Statistics 1 day beam	Expected ρ_n/ρ_p
^{6}He	807 ms	10^7	Neutron halo > 100
^{8}He	119 ms	$4.\ 10^6$	Thick skin 70(10)
^{11}Li	8 ms	$2\ 10^3$	Neutron halo > 100
^{17}Ne	109 ms	10^4	Proton halo < 0.010
^{31}Ne	3 ms	$5.\ 10^2$	Neutron halo > 100
$^{104-138}$Sn		$>10^3$	Progression of skin: From 1.0(2) to 4.0(6)

- ❑ Example of yield estimate:
- At relative energy of about 100 eV, the capture cross section is 10^{-16} cm^2 (**100 Mbarns**)
- **10^7 cm^{-2} antiproton** « target », 6-cm long
- **trapping time of 10 ms**: ions go through antiprotons 10^4 times each
- **1000 pps production rate** of radioactive Ion (10 ions / bunch of 10 ms)
- this least to an **annihilation rate of 1 / minute (10^2 / day)**

Trapping challenges

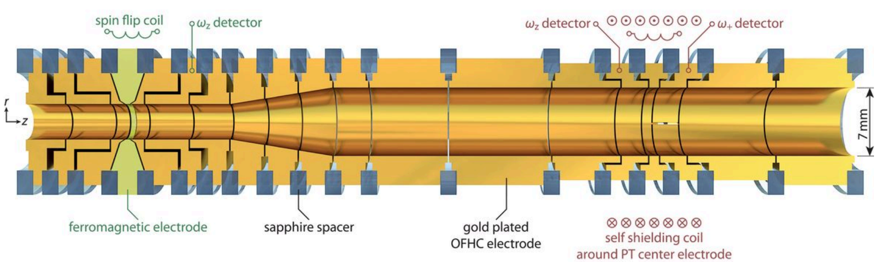
- **Transporting** charges in a Penning trap
  C.H. Tseng and G. Gabrielse, Hyperfine Interactions **76**, 381 (1993)

- Trapping a **large amount** of antiprotons
  In 2006, few 10^6 antiprotons trapped by the ASACUSA collaboration

- Trapping antiprotons for a **long time**
  BASE experiment (antiprotons stored without loss for >1.5 year)
  C. Smorra *et al.,* Nature **550**, 371 (2017)

- Efficient extraction of a **subpart of stored antiprotons**
  C. Smorra *et al.,* Int. Jour. Mass Spectroscopy (2015)

- High efficiency **transfer of charges** from a trap to another with smaller diameter
  G. Schneider *et al.,* Science **358**, 1081 (2017)



Main challenge of PUMA: all the above in one

< 10^{-17} mbar ultra high vacuum

- Lifetime of antiprotons determined by the vacuum

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

- **ONE solution: cryogenic (4 K) sealed vacuum**

- PUMA: **thin sealing window** needed for ion insertion
  - Material candidate: Si3N4. Well known properties, highly used membranes.
  - Membranes commercially available from 8 nm, few mm size

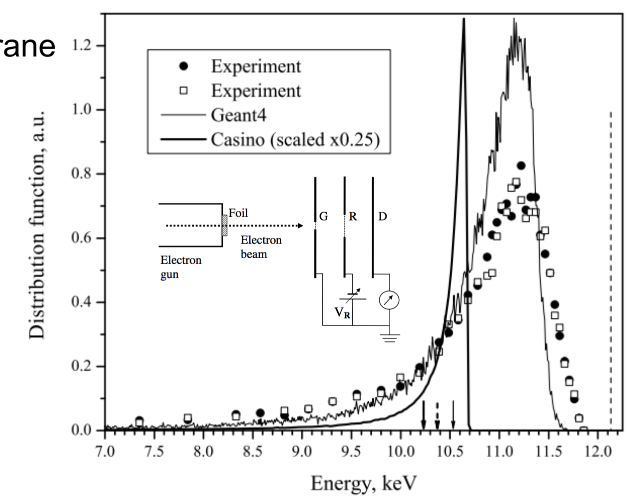
J. Wieser *et al.*, EPJD 48, 383 (2008)
12 keV e^- beam through a 250 nm membrane

Ex. OCTALAB, Singapore, created in 2008

1.0 x 1.0mm

Film Thicknesses Available
on 200 micron thick frames

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



Summary

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- **PUMA**: new program at **CERN / ELENA and ISOLDE** (started in January 2018)

- antiprotons as a probe for the nuclear density tail of short-lived nuclei

- Proton-to-neutron annihilation rate after capture, related to the proton-to-neutron density ratio
- search for halos and characterise thick neutron skins in short-lived nuclei

- (1) store, (2) transport antiprotons, (3) insert short-lived nuclei, (4) annihilate nucleons

- first physics experiments expected in 2022

- Foreseen challenges:
  - trap and transport 10^9 antiprotons
  - ultra-high vacuum with thin entrance window
  - corrections from final state interactions
  - estimate of uncertainties from theory

Sensitivity to final state interactions

- ❑ Pions may re-interact with residual nucleus
  Stable nuclei: probability 20-50%

- ❑ Solution: analyse charged pion multiplicity (M) AND sum charge (Sigma_c)

- ❑ treatment of final state interactions:

λ^+: π^0 + p -> π^+ + n
λ^-: π^0 + n -> π^- + p
ω^+: π^- + p -> π^0 + n
ω^-: π^+ + n -> π^0 + p

- ❑ analysis of M-Sigma matrices should lead to N(pbar-n)/N(pbar-p) with good accuracy and precision (**<5%** for 10^5 annihilations)

- ❑ new and systematic analysis based on simulated Monte-Carlo annihilations in progress (A. Corsi *et al.*)

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

$M\backslash\Sigma_c$	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	
0	0	0	0	0	0	0	0	0	0	0	(11386)*
1	0	0	0	0	17223	0	11233	0	0	0	28456
2	0	0	0	7530	0	21437	0	2844	0	0	31811
3	0	0	1029	0	11901	0	6591	0	179	0	19700
4	0	44	0	1904	0	4394	0	519	0	5	6866
5	1	0	99	0	979	0	451	0	13	0	1543
6	0	2	0	75	0	133	0	14	0	0	224
7	0	0	1	0	7	0	3	0	0	0	11
8	0	0	0	1	0	1	0	0	0	0	2
9	0	0	0	0	1	0	0	0	0	0	1
	1	46	1129	9510	30111	25965	18278	3377	192	5	88612