PUMA

Exotic Nuclei & Antiprotons @ CERN ISOLDE & ELENA

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Seminar @ ISOLDE, CERN
January 11th, 2018

Neutron-rich nuclear systems

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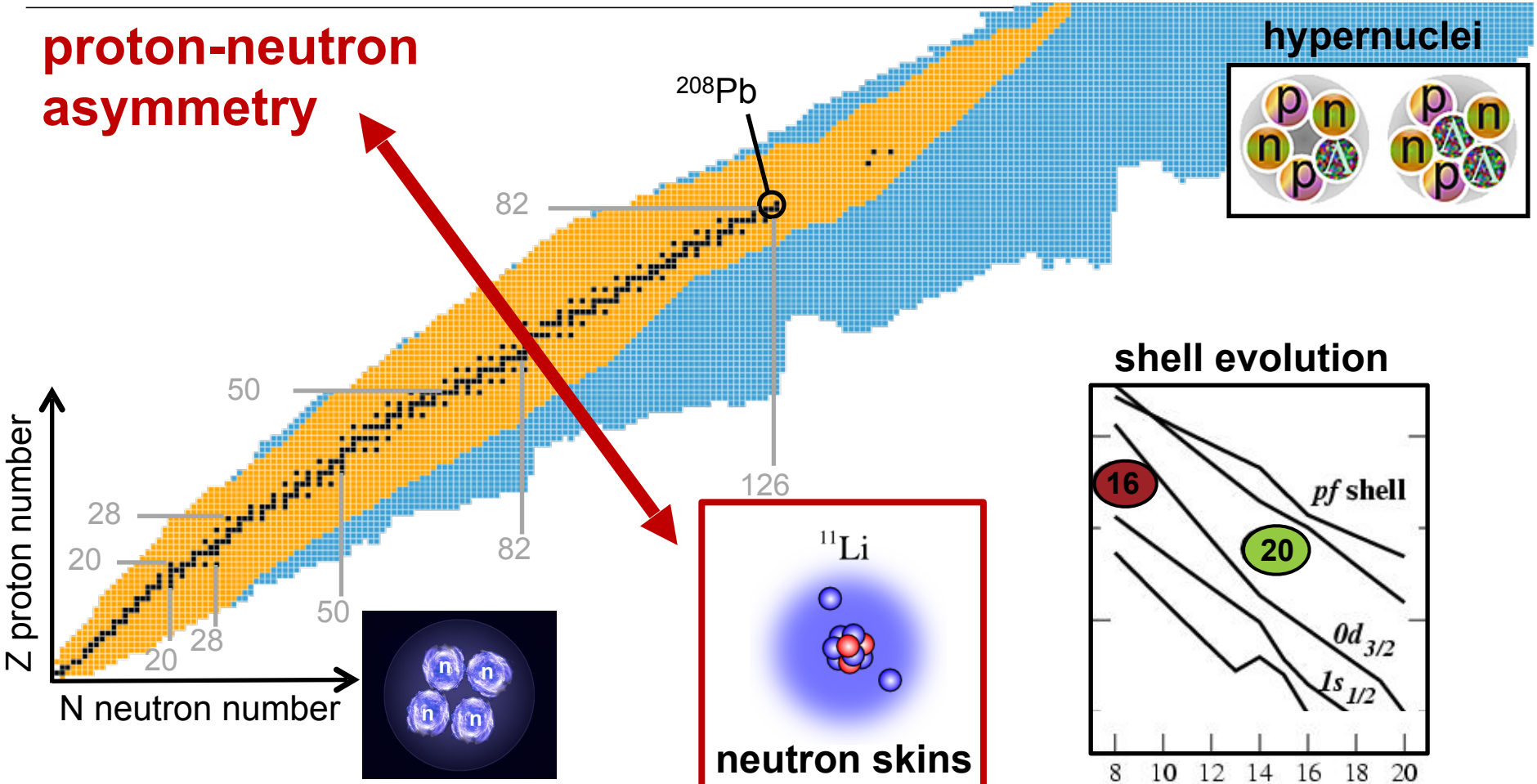
proton-neutron asymmetry

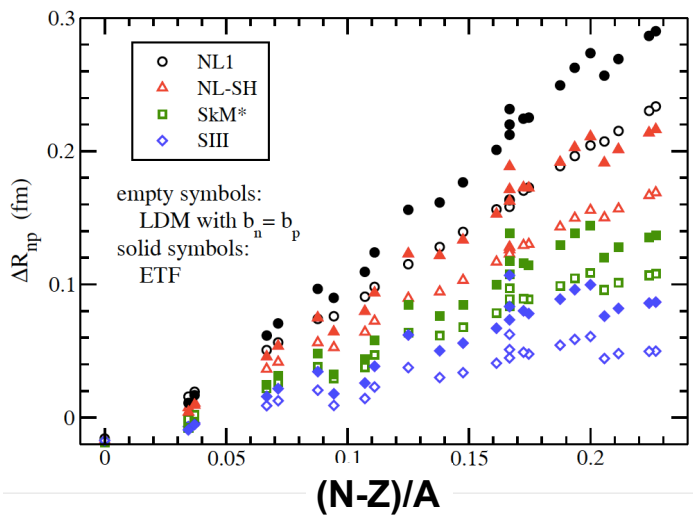


multi-neutron systems

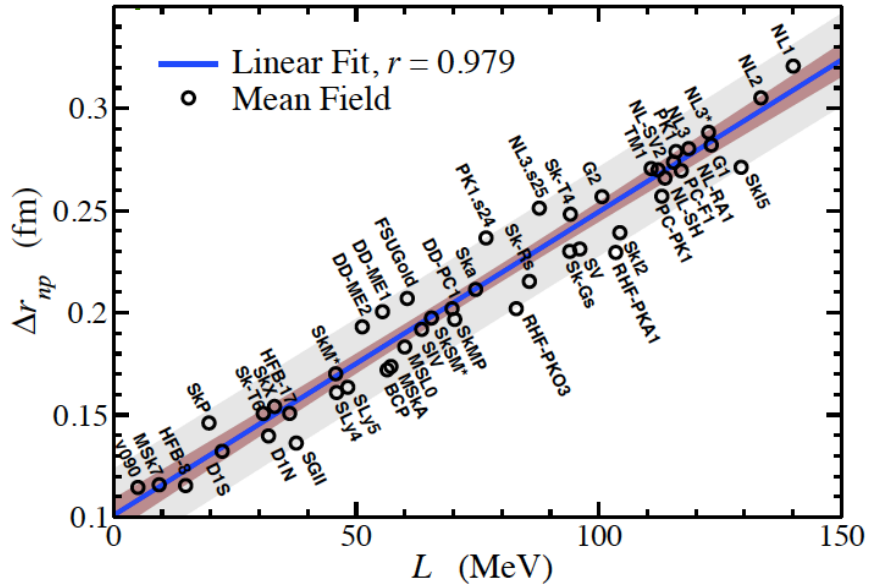
Neutron skins

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)

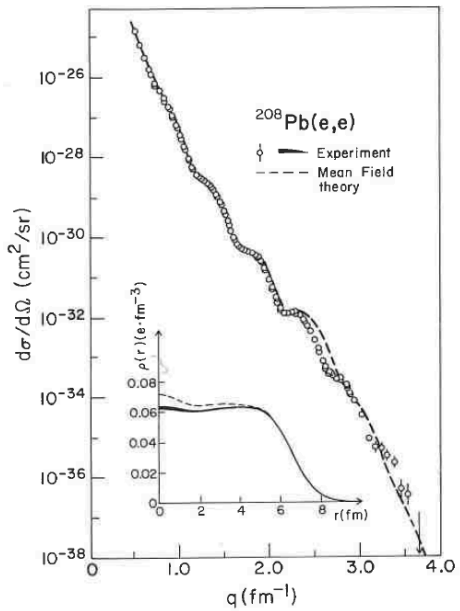


$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + \mathcal{S}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 \qquad L \propto \left.\frac{\partial \mathcal{S}(\rho)}{\partial \rho}\right|_{\rho_0}$$

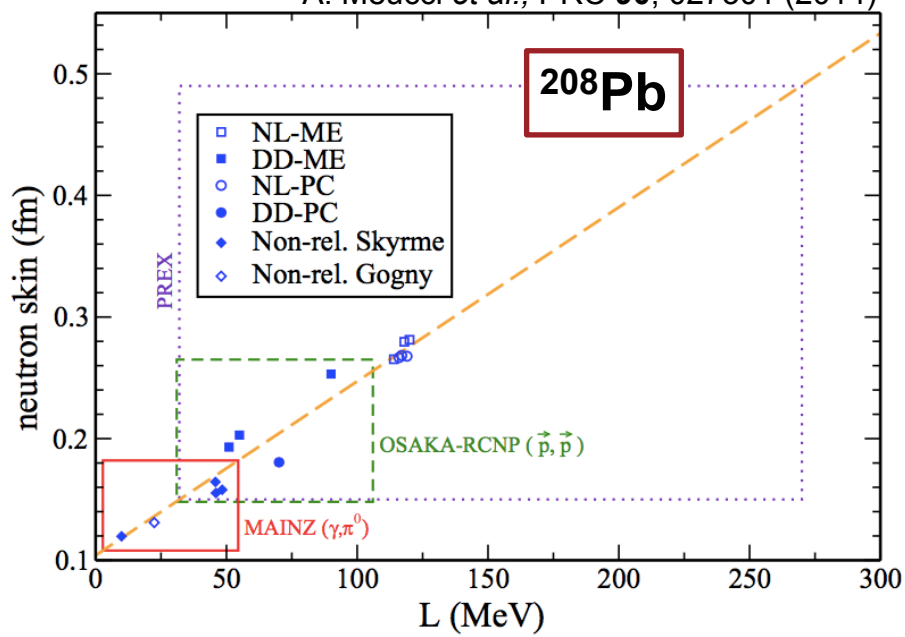
X. Roca-Maza *et al.*, Phys. Rev. Lett. **106**, 252501 (2011)

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

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') measurements for stable nuclei
- ❑ Not accessible for short-lived nuclei, except at SCRIT at RIKEN (starting)
- ❑ Relative charge radii from fine structure studies (*ex.* ISOLDE)

Matter radii:

- ❑ Most precise: proton scattering, coherent π^0 photoproduction, parity-violating expts (JLab)

Discovery of halos

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Experiment @ Berkeley, USA
[I. Tanihata *et al.,* Phys. Rev. Lett. 55, 2676 (**1985**)]

- I. Tanihata, experiment at LBL (1984)
- ^{12}C, ^{16}O primary beams at 800 A MeV
- interaction cross section for Be, Li isotopes

Interpretation @ ISOLDE
[G. Hansen and B. Jonson, Eur. Phys. Letters 4, 409 (**1987**)]

- Halo nuclei have a diffuse neutron wave function extending « out » of the nucleus through tunnelling

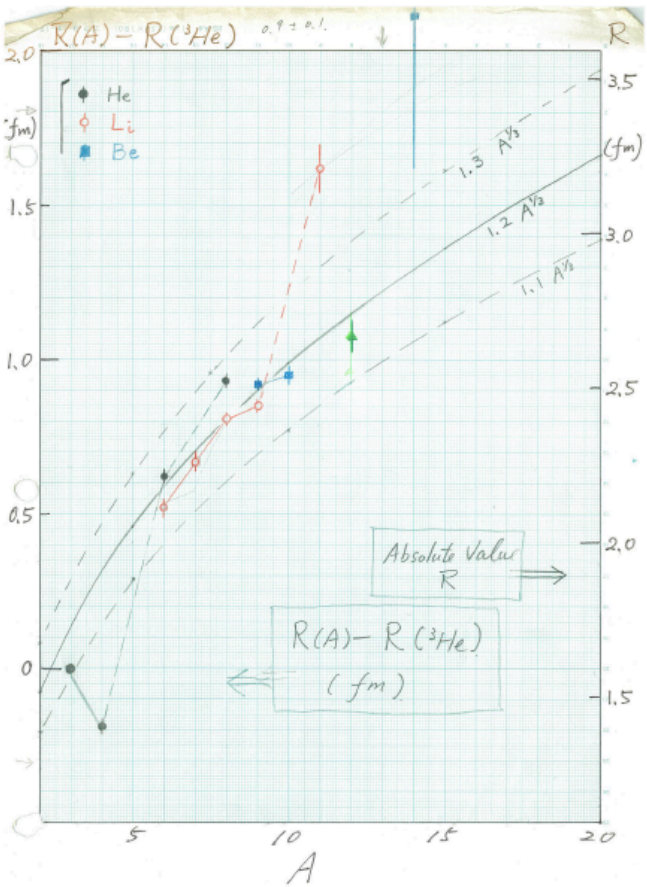
- ^{9}Li-2n two body system, zero-binding energy for 2n system

$$\psi(r) \propto \frac{e^{-r/\rho}}{r}$$

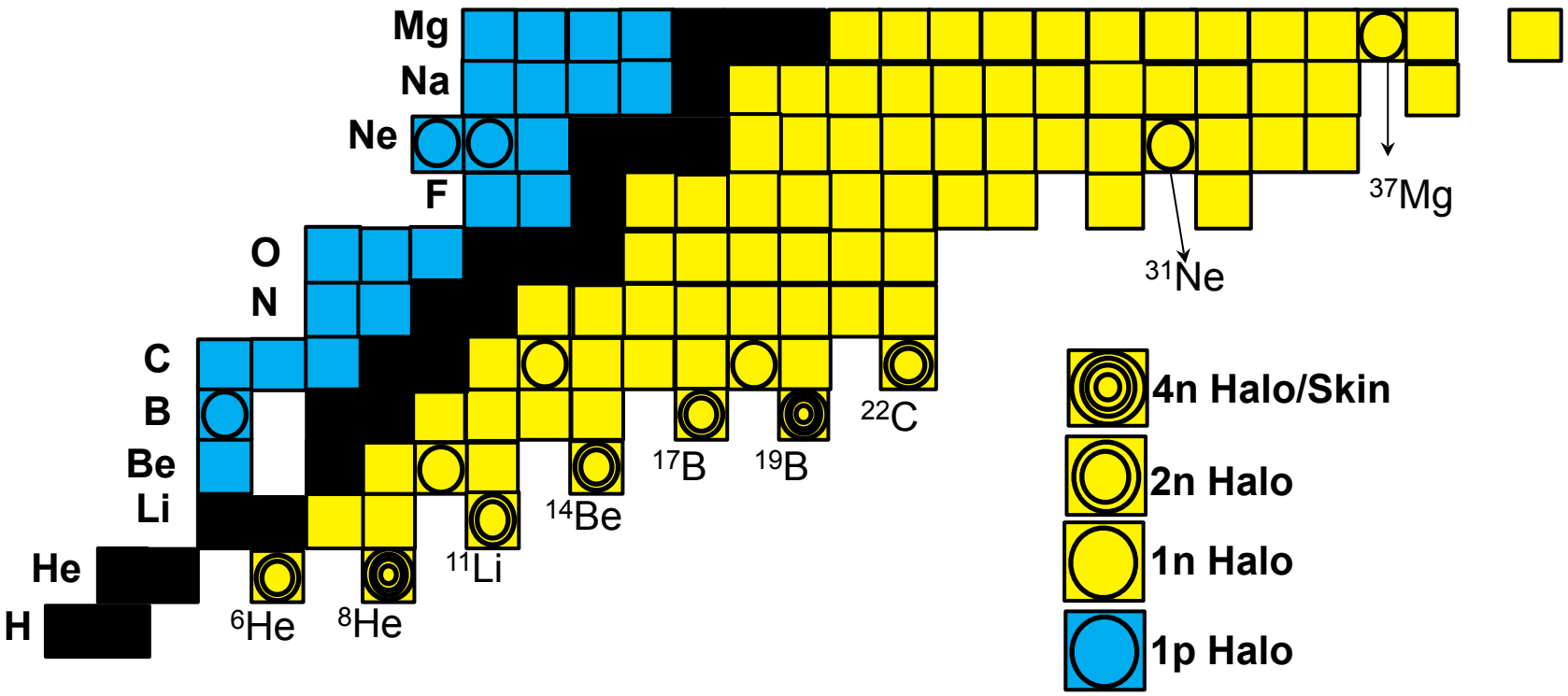
with $\rho = \hbar / \sqrt{2\mu B}$

μ reduced mass,
B two-neutron binding energy

Archives (1984) from I. Tanihata



Neutron halos



S-wave dominate: ^{11}Be, ^{15}C , ^{19}C,
P-wave dominate: ^{6}He, ^{8}He, ^{31}Ne, ^{37}Mg
^{11}Li: mix of *s* wave and *p* wave
^{14}Be: mix of *s* wave and *d* wave

Necessary conditions for halos:

- ❑ Small separation energy (<1MeV)
- ❑ Low orbital angular momenta (*l*=0 or 1)

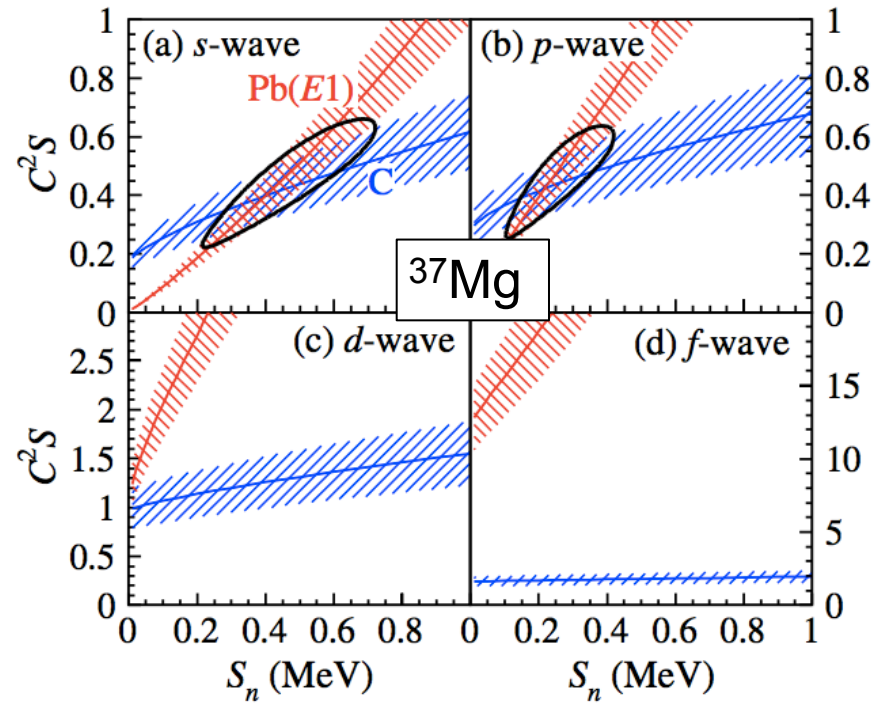
P-wave halos in Ne and Mg isotopes

- **^{31}Ne, ^{37}Mg** are claimed to be *p-wave deformed* neutron halos

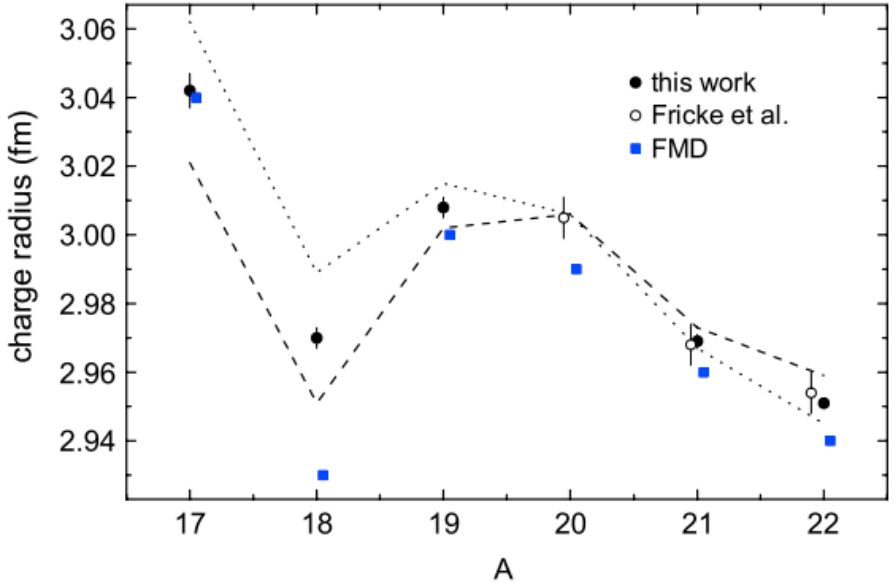
Case of ^{37}Mg: RIBF, 6 pps

- Pb and C targets @ 240 MeV/nucleon
  Combined Coulomb & nuclear breakup reactions
  1-neutron removal channel
- **Large σ(E1)=0.5 barn found: hint of a halo**
- S_n and C^2S(gs-gs) are (model-dependently) extracted from cross sections
- data consistent with *s* or *p* waves
- Shell model excludes the *s* wave option
- ^{37}Mg is considered to be a *p*-wave halo with S_n = 0.22(10) MeV

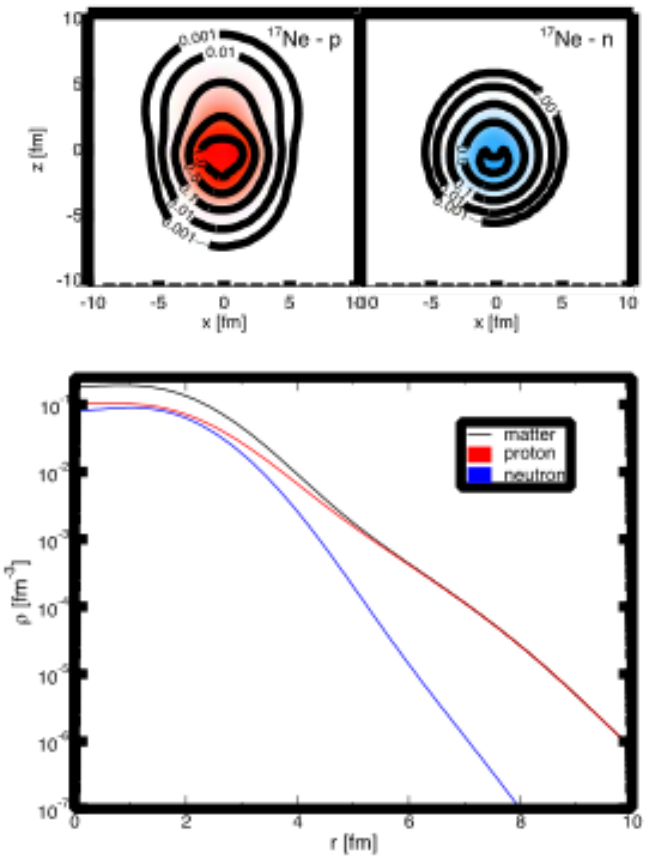
N. Kobayashi *et al.*, Phys. Rev. Lett. **112**, 242501 (2014)



Do proton halos exist?

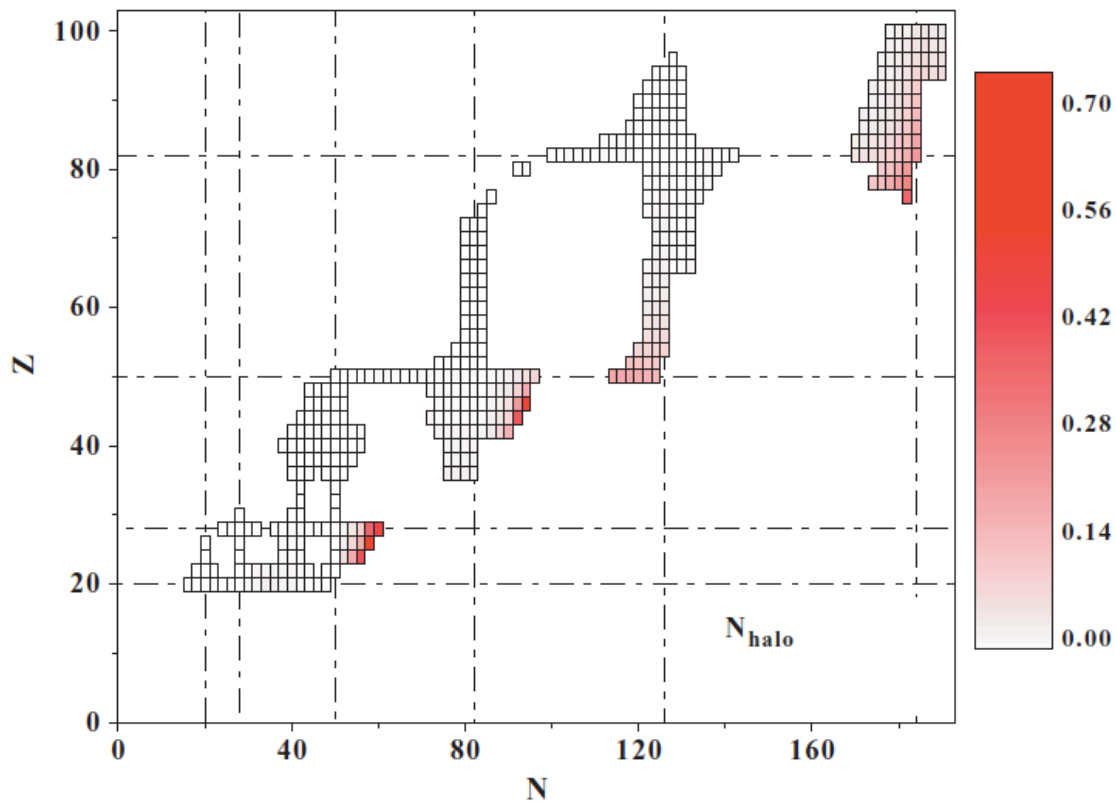


W. Geithner et al., Phys. Rev. Lett. 101 (2008)



- ^{17,18}Ne proposed as proton halos from charge radii
  W. Geithner et al., PRL 101 (2008)
- In agreement with Molecular Dynamic model (FMD) which predict a proton halo in ^{17}Ne
- No “direct” evidence yet

Neutron skins 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.

EDF with **Sly4 Skyrme** force

Correlations in the low-density surface region

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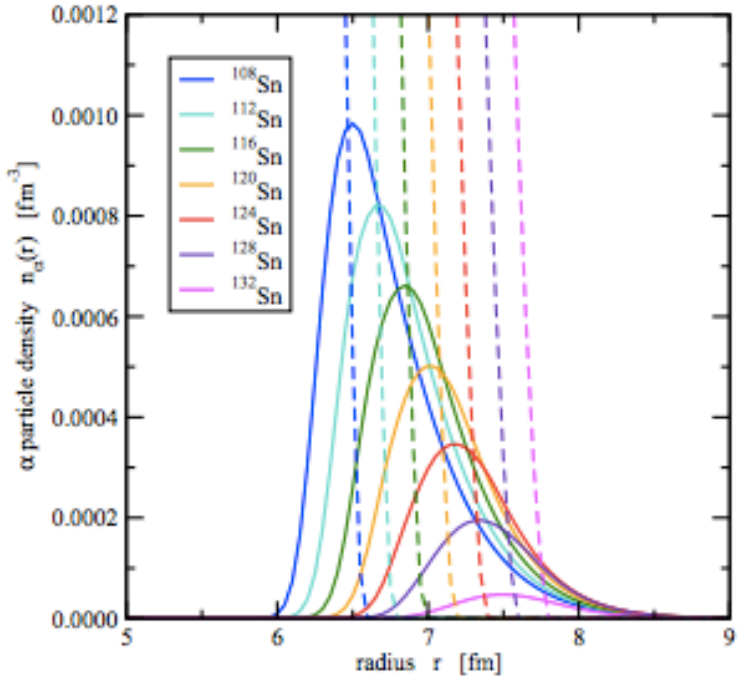
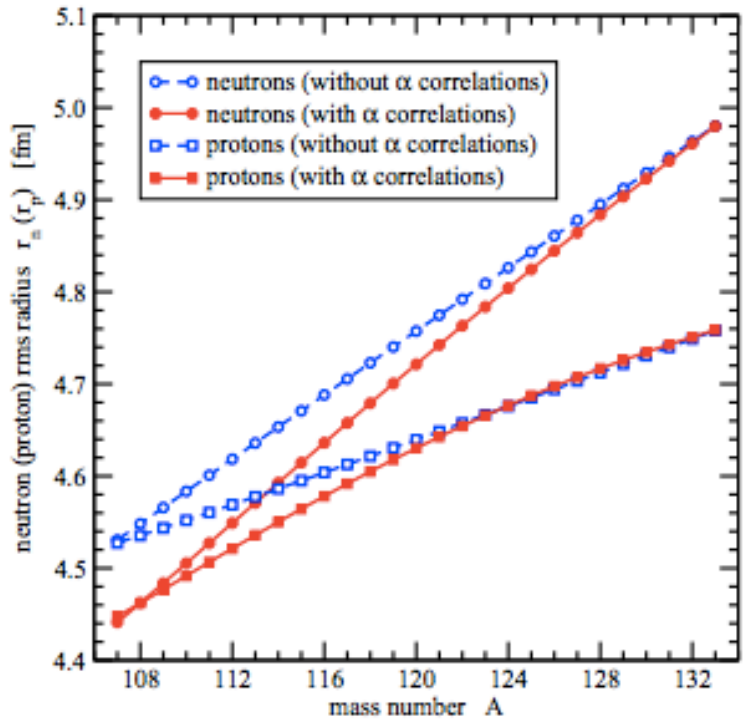
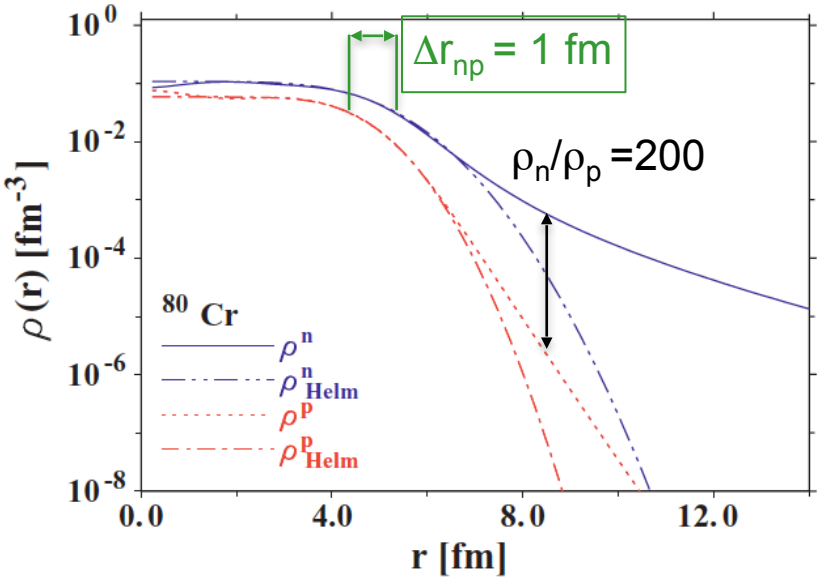
- Correlations at low density / deformation may modify the picture of neutron skins / halos
- Example:
  - Generalized relativistic density functional
  - Alpha clustering at low density, increasing with N,Z asymmetry (neutron skin)



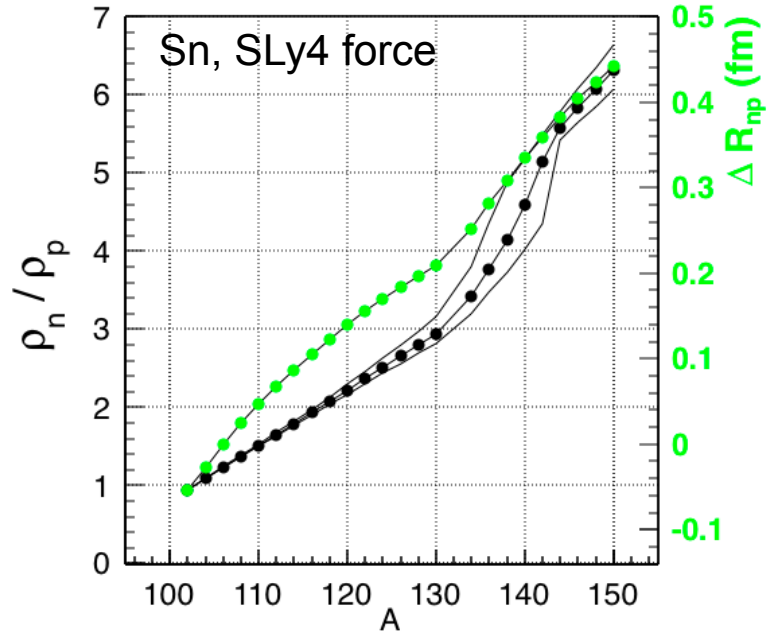


S. Typel *et al.*, Phys. Rev. C **89**, 064321 (2014)

Antiproton annihilation: a probe for the nuclear density tail



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

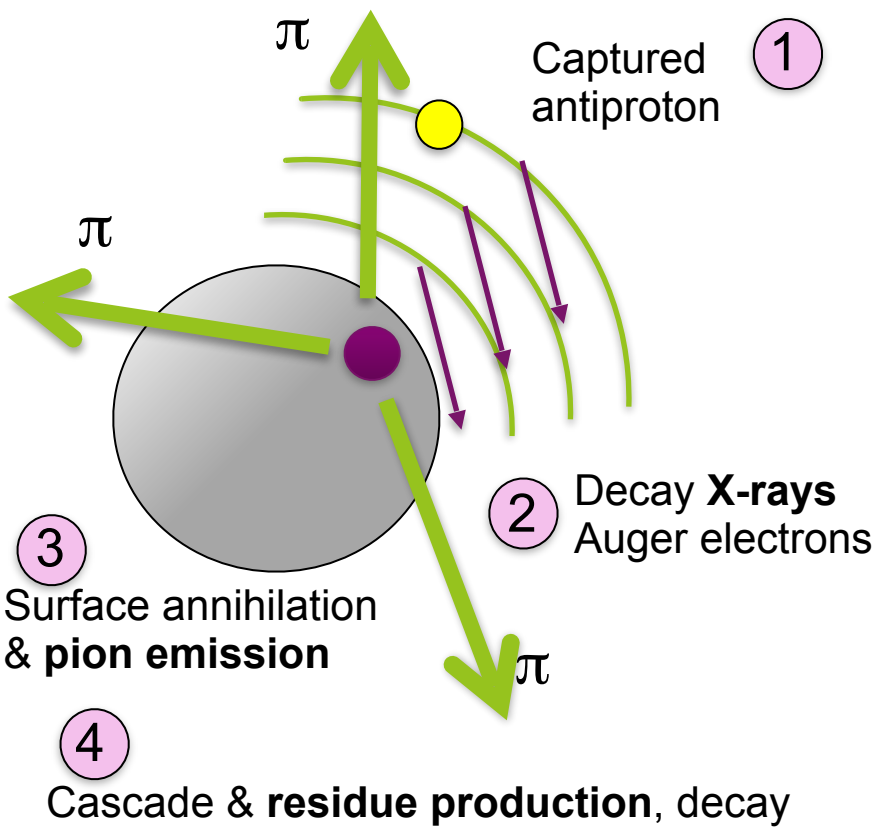


What would be an ideal probe?

- ❑ isospin sensitivity: selectivity of protons and neutrons
- ❑ sensitivity to the tail of the nuclear density, where the skin/halo are
- ❑ usable for short-lived and low-rate production nuclei

… **low-energy antiprotons as a probe** 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)

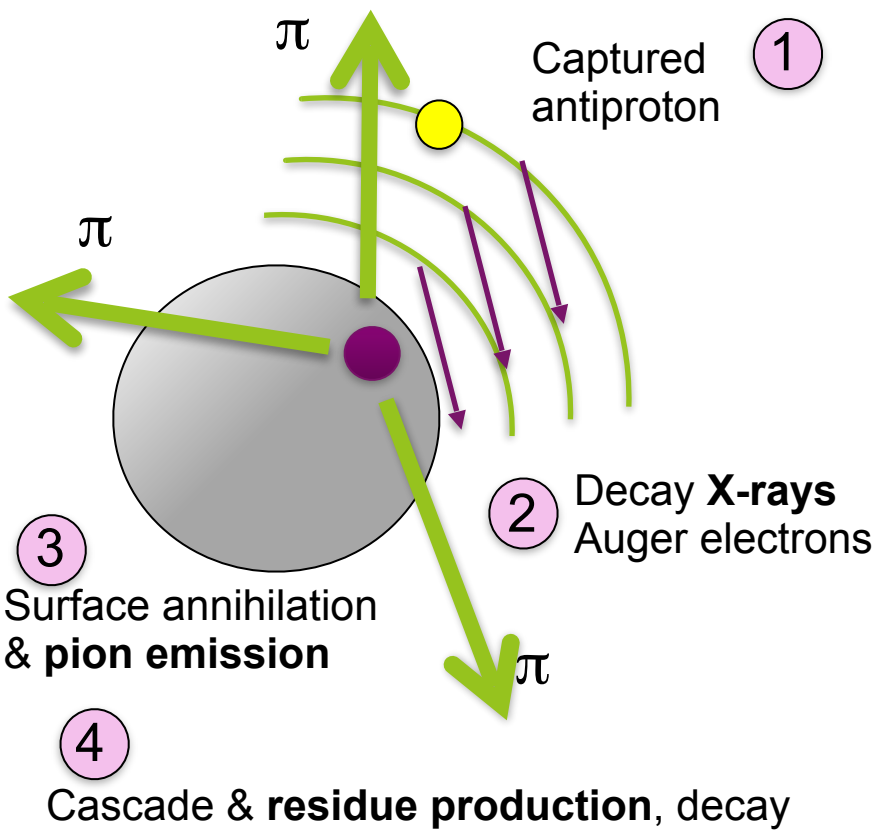
Antiproton-proton, $\overline{p}p$ [43]

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

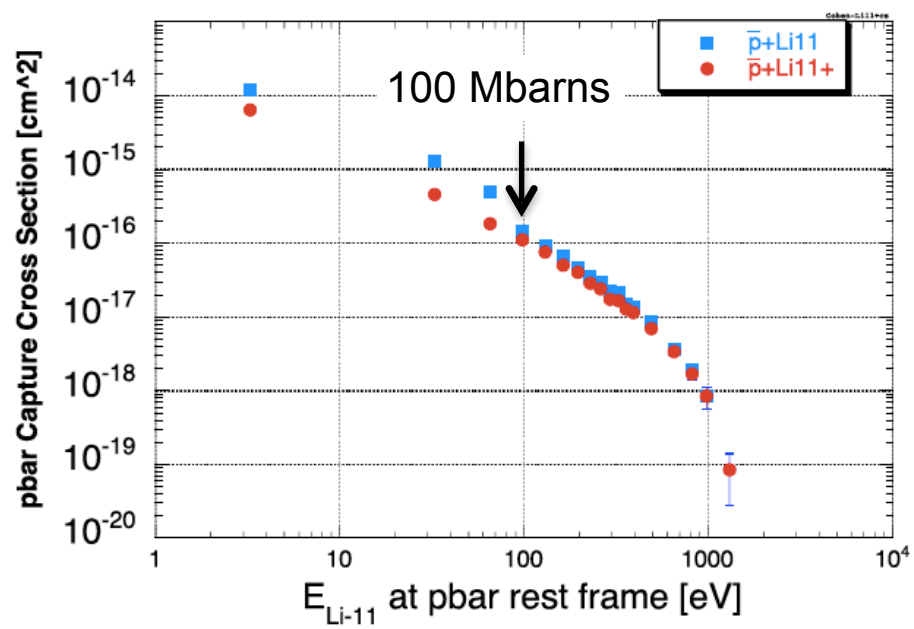
Antiproton-neutron, $\overline{p}n$ [46]

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



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



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

Antiproton annihilation: a probe for the nuclear density tail

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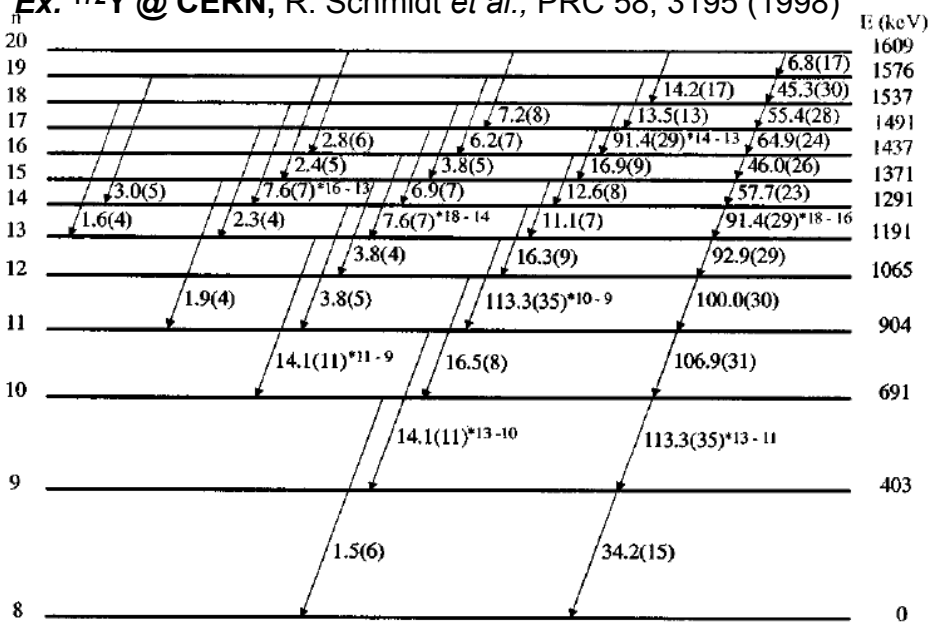
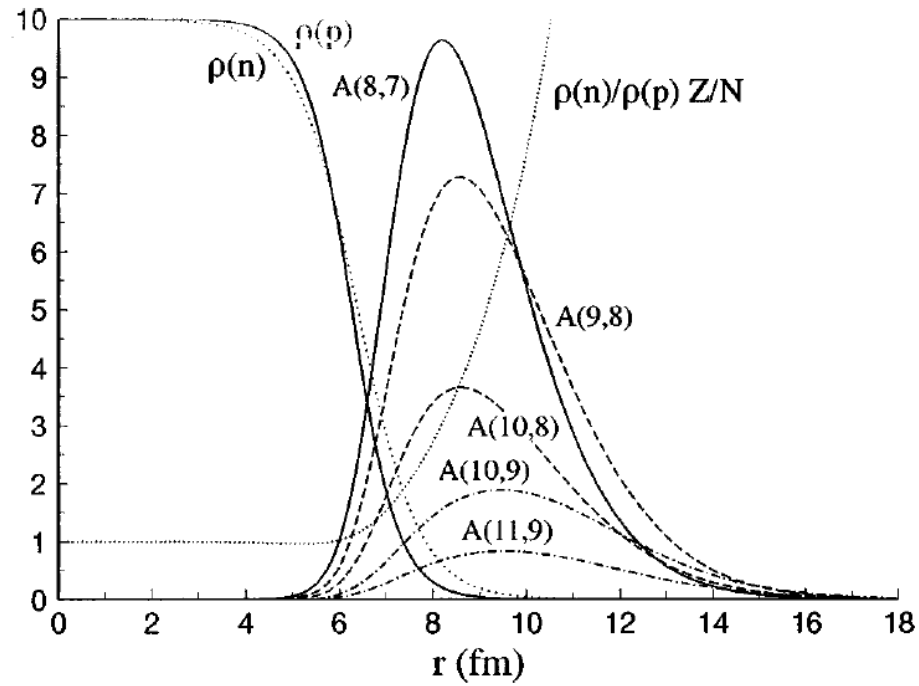
Ex. **^{172}Y @ CERN,** R. Schmidt *et al.*, PRC 58, 3195 (1998)





Γ reaction probability

Φ_{nl} antiproton radial wave function

V(r) antiproton-nucleus potential

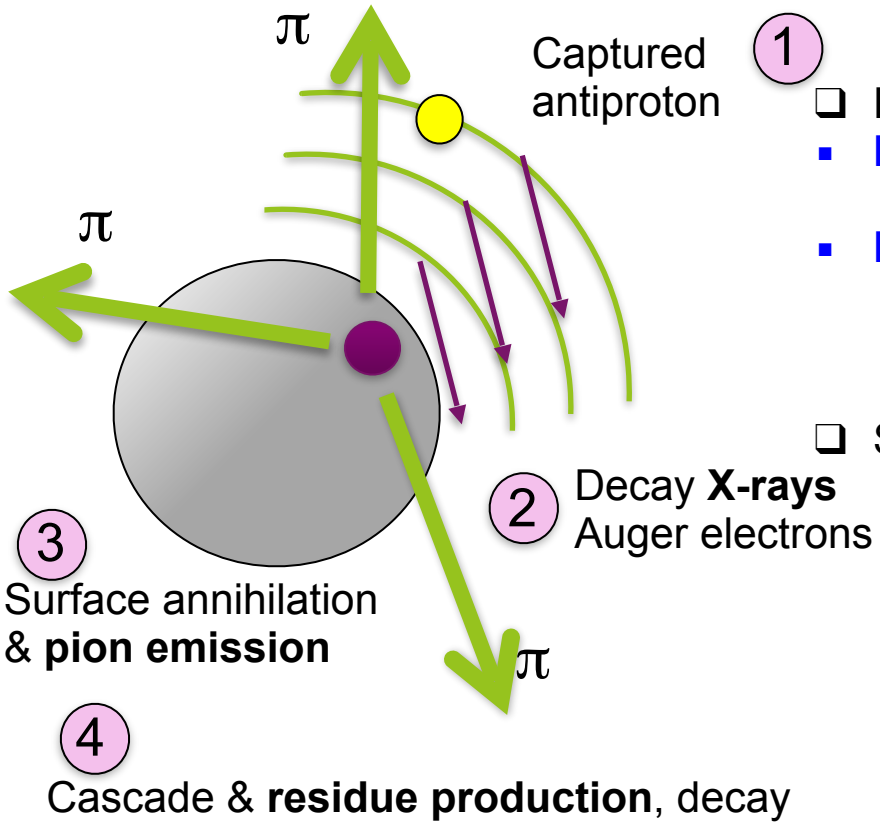
a effective N-antiproton scattering length
ex. a=-1.53 – 2.5 ***i*** fm (Batty, NPA 1997)

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

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

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

Antiproton annihilation: a probe for the nuclear density tail



- 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

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

Extracted from data

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

Sensitivity to final state interactions

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- 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:

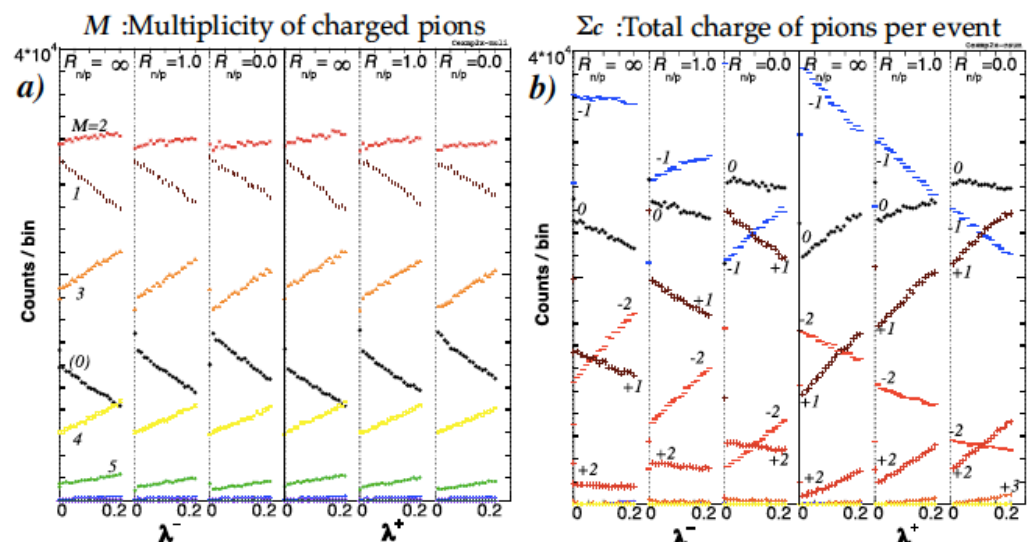
λ^+: $\pi^0 + p \rightarrow \pi^+ + n$
λ^-: $\pi^0 + n \rightarrow \pi^- + p$
ω^+: $\pi^- + p \rightarrow \pi^0 + n$
ω^-: $\pi^+ + n \rightarrow \pi^0 + p$

- 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



PUMA: Pbar Unstable Matter Annihilation

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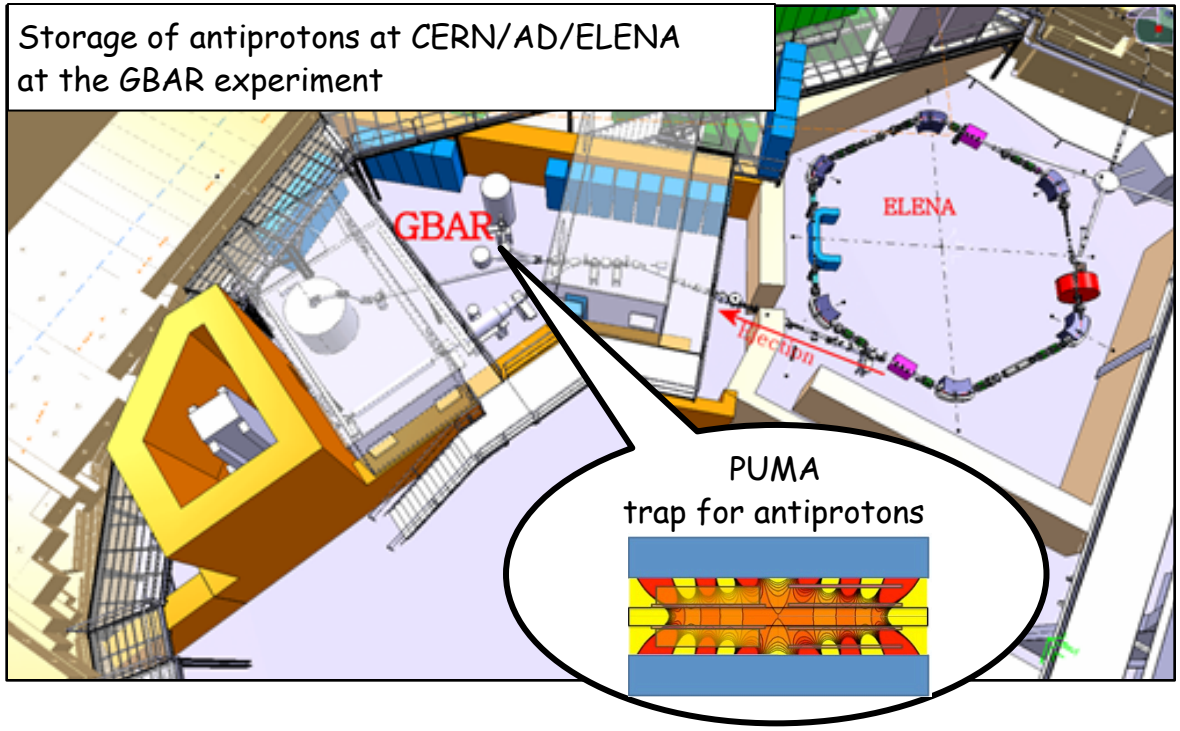
- Transport antiprotons from ELENA (CERN) to ISOLDE
- Device to be build (funded from 01/2018, for 5 years)
- First experiment at ISOLDE foreseen in 2022
- Pioneer experiment with antiprotons as a probe for short-lived nuclei



The GBAR experiment at CERN / ELENA

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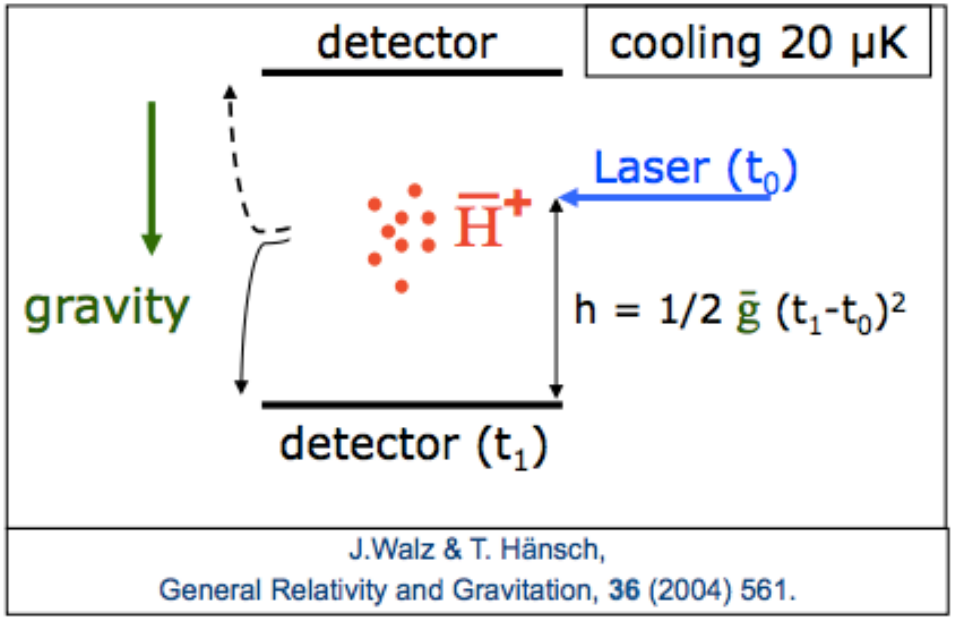
How does antimatter falls in the gravitational field?

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

Main perturbation

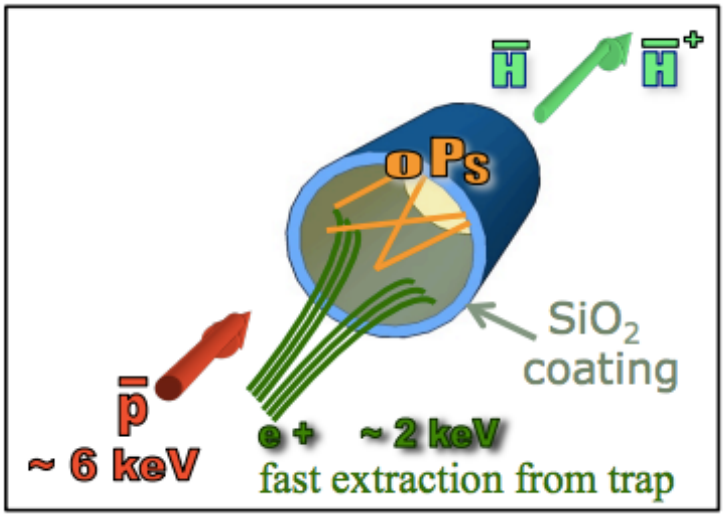
- Produce ion $\bar{H}^+$
- Sympathetic cooling 20 μK
- Photodetachment of e^+
- Time of flight

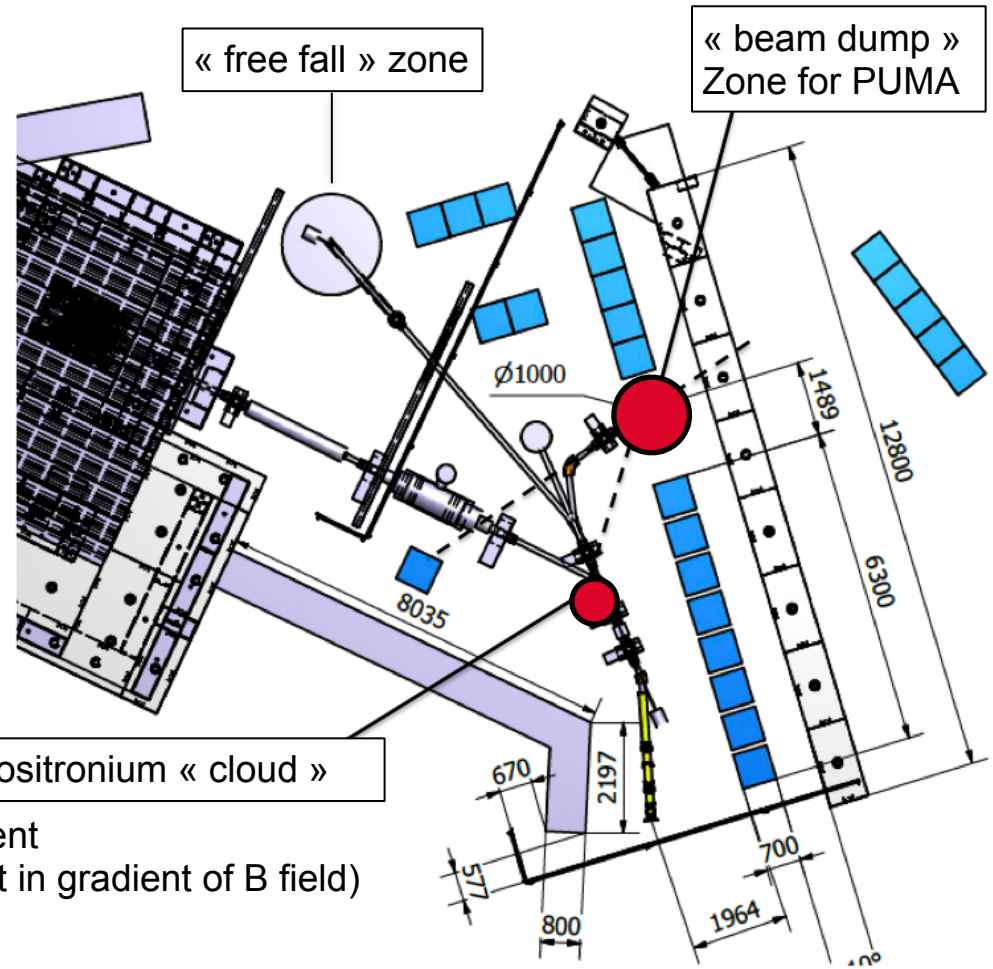
Error dominated by temperature of $\bar{H}^+$



Spokesperson: P. Pérez (CEA/IRFU)

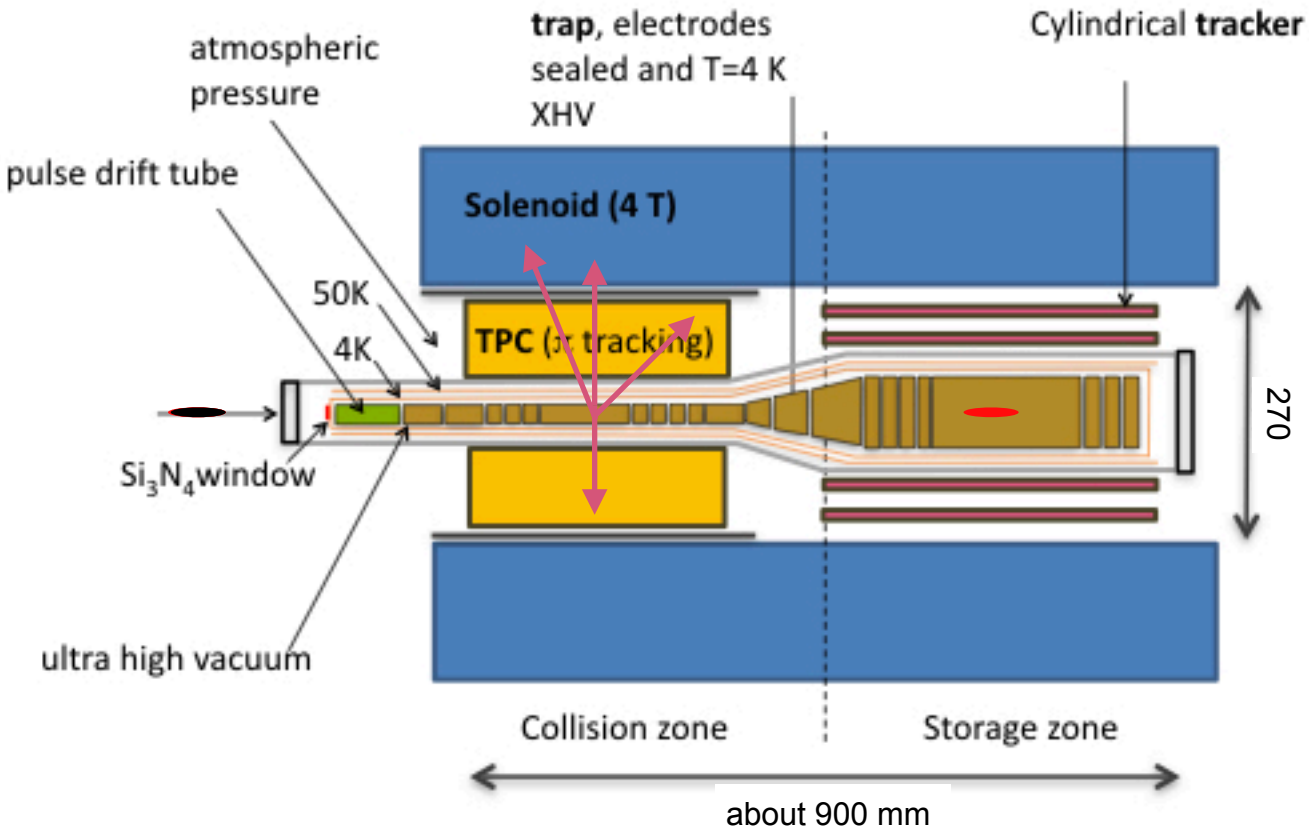
The GBAR experiment

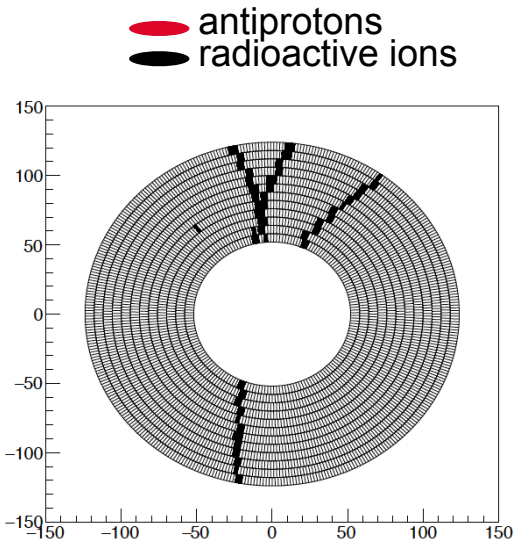




GBAR requires limitations on the fringe field gradient
at the free fall region (force from magnetic moment in gradient of B field)
dB/B < 0.02 G / m (0.1% precision fro gbar)

PUMA: a magnetic bottle for antiprotons

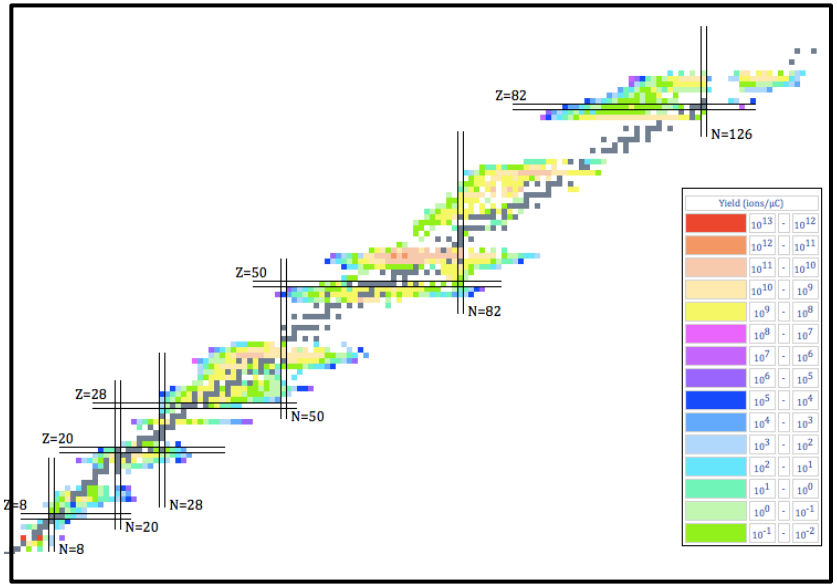




Technical challenges:

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

“Day one” physics cases



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
$^{104\text{-}138}$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)**

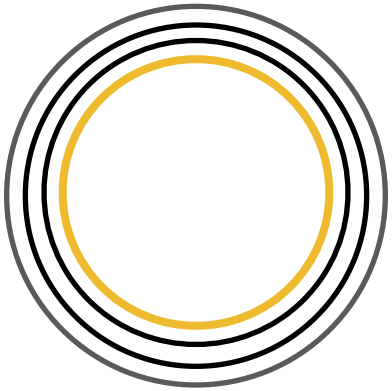
Dimensions

- Main assumption: about 10^7 charges / cm^3 is feasible with limited space charge effect

- **Collision trap (C trap):** 10^7 antiprotons
- **L=100** mm: (i) size of magnet, (2) detection
- Volume of antiprotons: a cylinder with R=2 mm, L=100 mm: 1.2 cm^3 (ISOLDE low-E beams)
- Trap radius could be taken as R**=10 mm** for manipulation before radius reduction

- **Storage zone (S trap):** 10^9 antiprotons
- Trap radius of **R=50 mm** (for a cloud of R= 40 mm) and a length **L=150 mm**
- Cloud volume is: 750 cm^3

C trap:
Ri=10 mm
Rext=33 mm



S trap:
Ri=50 mm
Rext=71 mm

Tracking and solenoid dimensions

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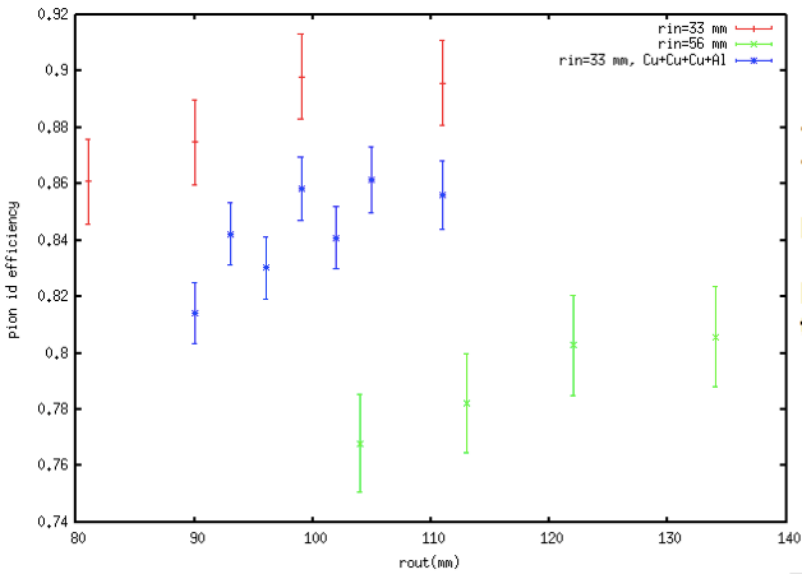
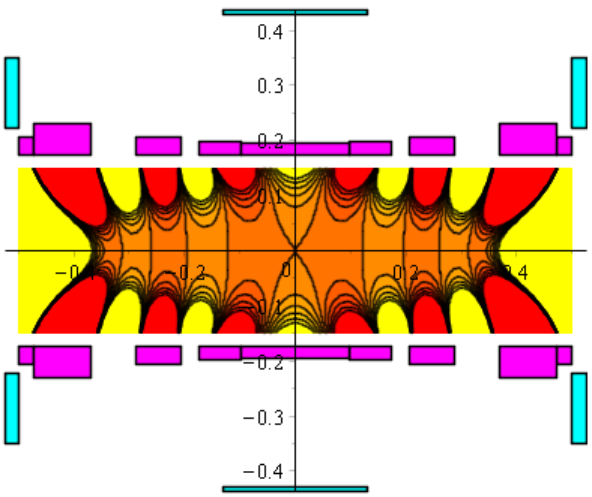
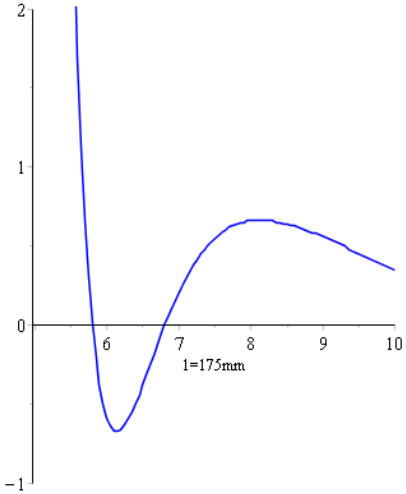
- TPC dimensions set to optimise tracking
- Inner radius set by C-trap radius: 56 mm
- Ext. radius: optimized for pion charge ID
- Simulations give 110 mm
- 80% efficiency (detection + ID)



- Supraconducting solenoid to be built
- Bore radius: 130mm, length: 700 mm
- 4T, active shielding
- 0.1% homogeneity in trapping region
- about 1% in tracking region
- Initial design G. Aubert (CEA), now TU Darmstadt





Along symmetry axis
1 meter from solenoid
5 mT (50 gauss)

Status of the development & timelines

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- **Magnet**: design at TU Darmstadt, Prof. De Gersem
  4T, active shielding, homogeneity: 0.1% in trap regions, <3% in tracking region
  Bore radius: 130 mm, effective length: 700 mm
  Call for tender to be sent around April 2018

- **Tracking**: TPC and scintillator barrels, design at CERN (R. Olivera), collaboration with CEA
  About 4000 pads (3*1 mm^2), to be fine tune with extended simulations
  Electronics: not decided yet. Several options considered
  System can be ready for tests mid-2019

- **Trap**: TU Darmstadt, MPI Heidelberg, RIKEN (T. Uesaka, S. Naimi, S. Ulmer), Isolde
  Call open for a 2-year postdoc + extension, one PhD student from next year

- **Trap cryostat**: see next slides. Starting discussions with TU Munchen, RIKEN (S. Ulmer)

4-5 people team at TU Darmstadt (to be built): 1 staff, 10 years of postdoc, 3 PhD over the next 5 years.

Trapping challenges

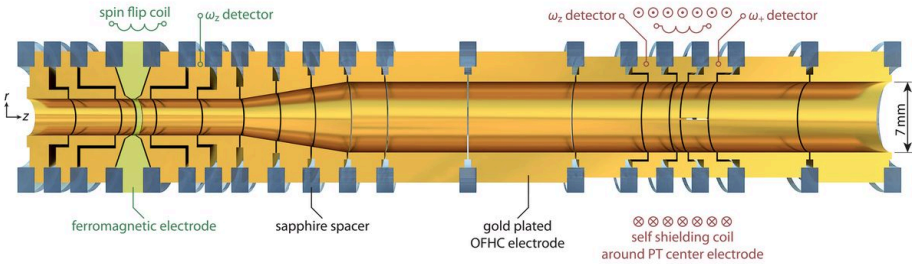
- **Transporting** charges in a Penning trap
  In 1993, trapped electrons from West to East coast in the US
  C.H. Tseng and G. Gabrielse, Hyperfine Interactions **76**, 381 (1993)

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

- Trapping antiprotons for a **long time**
  Today, BASE experiment: about 10 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

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- Lifetime of antiprotons determined by the vacuum

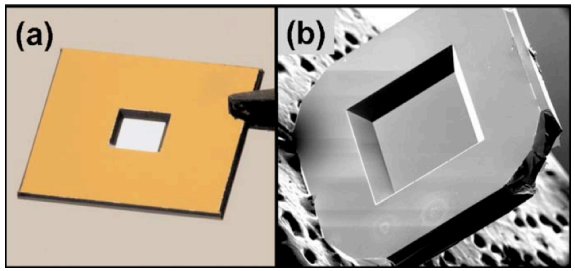
$$P_H(mbar) = 6\times10^{-16}\, T(K)/\tau(jours)$$

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

- « routinely » done at CERN for antiproton physics: $P<10^{-17}$ mbar
  Ex. G. Gabrielse, BASE experiment

- PUMA: **thin sealing window** needed for ion insertion
  - Material candidate: Si3N4. Well known properties, highly used membranes.
  - Membranes commercially available from 8 nm
  - Dimensions from 100 μm to few mm (depends on thickness)

Example:
1 mm^2
50 nm thick
200 mm Si substrat



Si_3N_4 thin windows

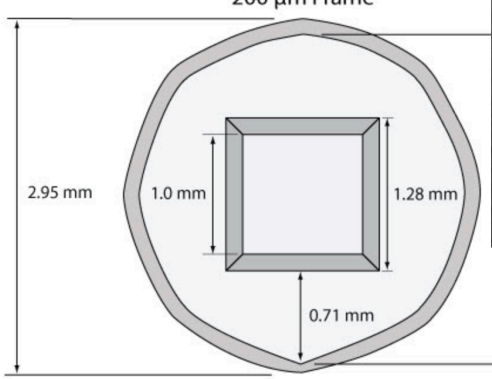
- Silicon nitrite spread in industry
- Preferred material for TEM windows
- Stands pressure difference of 1 bar
- 4 mm^2 for 10 nm remains a challenge

Ex. OCTALAB, Singapore, created in 2008

Film Thicknesses Available
on 200 micron thick frames

	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

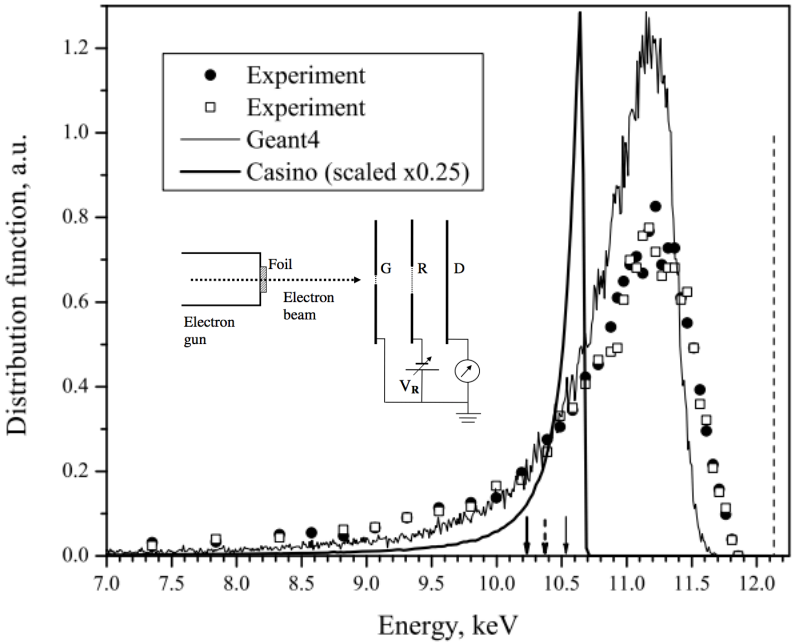
Single Square - 1mm² Window
200 µm Frame



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



Other potential physics opportunities with PUMA

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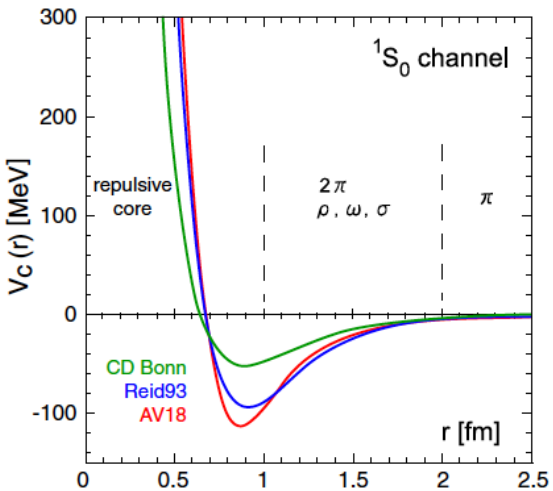
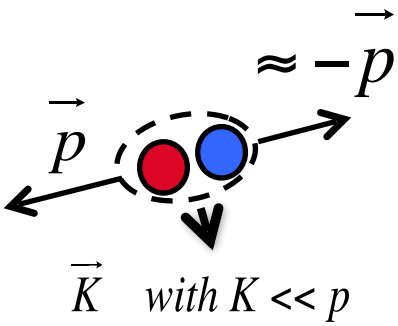
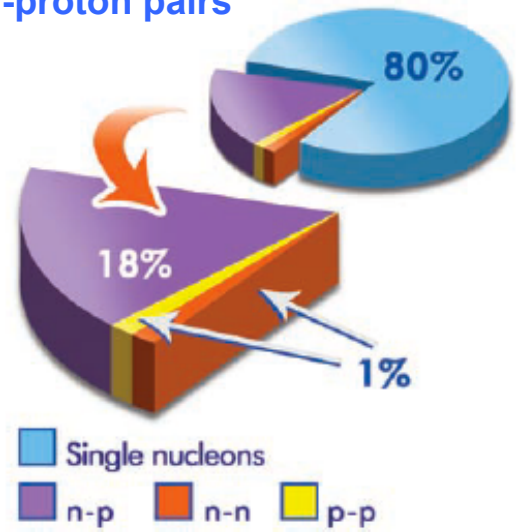
- Repulsive hard-core + tensor of the nuclear interaction induces **high-momentum correlations**
- Stable nuclei: **20% of nucleons** are concerned with **90% of neutron-proton pairs**







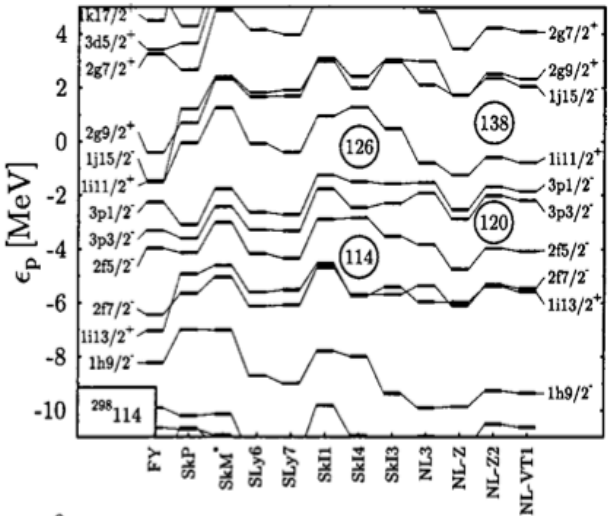
Subedi *et al.*, Science **320** (2008)

NOT in the current physics program:
PUMA can measure any **high-momentum charged partner after nucleon annihilation** (efficiency=10%, to be improved by **additional detection inside the trap;** F. Flavigny, IPN Orsay, application ongoing (2018))

- short range correlations at **the very surface of nuclei**
- high-momentum pair **proportion in proton-neutron asymmetric matter**

Other potential physics opportunities with PUMA

- **nucleon stripping from (super) heavy elements** at rest, gamma spectroscopy (S3, GANIL) low production yields compensated by long life time



- **precision measurement** experiments in low-background environment
- low-energy antiproton **capture process**
- in medium **meson** production (phi-meson study proposed by RCNP, Japan)

Summary

- **PUMA**: new program at **CERN / ELENA and ISOLDE** (official start on 02.01.2018)
- antiprotons as a new probe for the nuclear density tail of short-lived nuclei
- halos and thick neutron skins searched in medium mass short-lived nuclei
- transport trapped antiprotons from ELENA to ISOLDE
- trap and cryostat to be designed and built (not started)
- first physics experiments expected in 2022