PUMA: antiProton Unstable Matter Annihilation

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ISOLDE Collaboration Committee (ISCC), November 5th, 2019

erc

Alexander von Humboldt
Stiftung / Foundation

Neutron excess in nuclei

- ☐ Neutron excess develops at the nuclear surface, as a “neutron skin”
- ☐ Sensitive to saturation properties, symmetry energy (EOS) and correlations

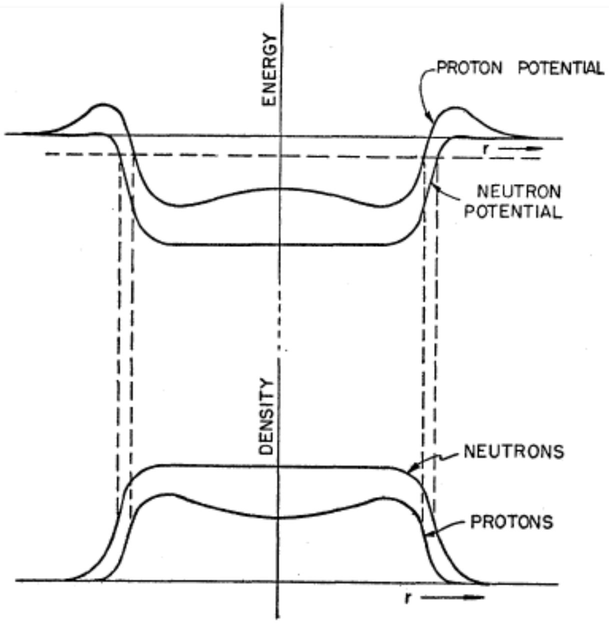
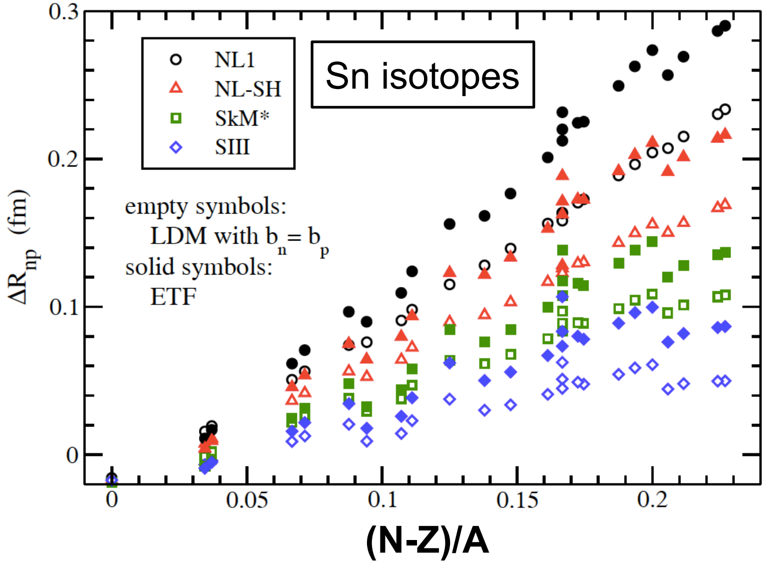


FIG. 1. Potentials and densities for protons and neutrons inside the nucleus.

M.H. Johnson and E. Teller, Phys. Rev. 93 (1954)

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



X. Vinas *et al.*, EPJA 50 (2014)

Measuring a skin thickness

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

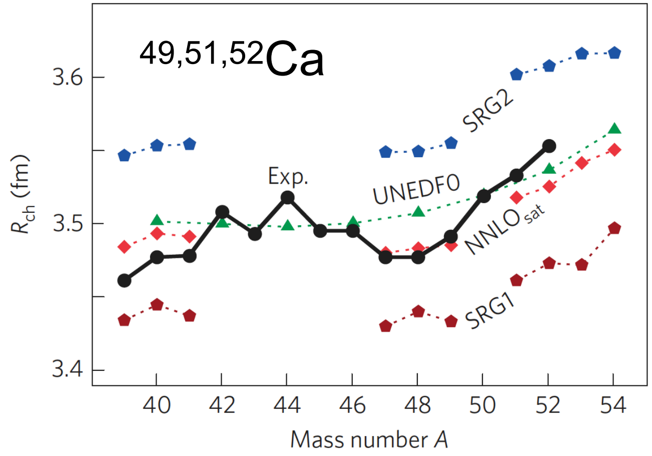
Charge radii:

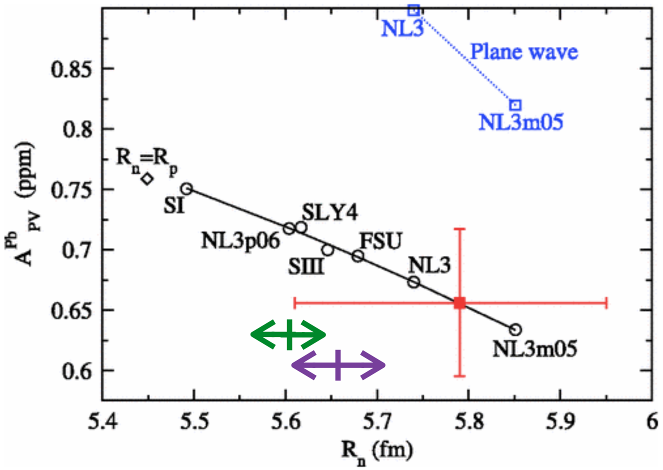
- ❑ charge densities from (e,e') for stable nuclei
  B. Frois and C.N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37 (1987)
- ❑ Relative charge radius from laser spectroscopy
  R. F. Garcia Ruiz et al., Nature Physics 12 (2016)

Neutron / matter radii:

- ❑ Parity-violating scattering (PREX), coherent pion photoproduction, polarised proton scattering require high statistics
  S. Abrahamyan et al., PRL 108 (2012)
  C.M. Tarbet et al., PRL 112 (2014)
  A. Tamii et al., PRL 107 (2011)
- ❑ not possible for short-lived nuclei

R. F. Garcia Ruiz et al., Nature Physics 12 (2016)





Modified from S. Abrahamyan et al., PRL 108 (2012)

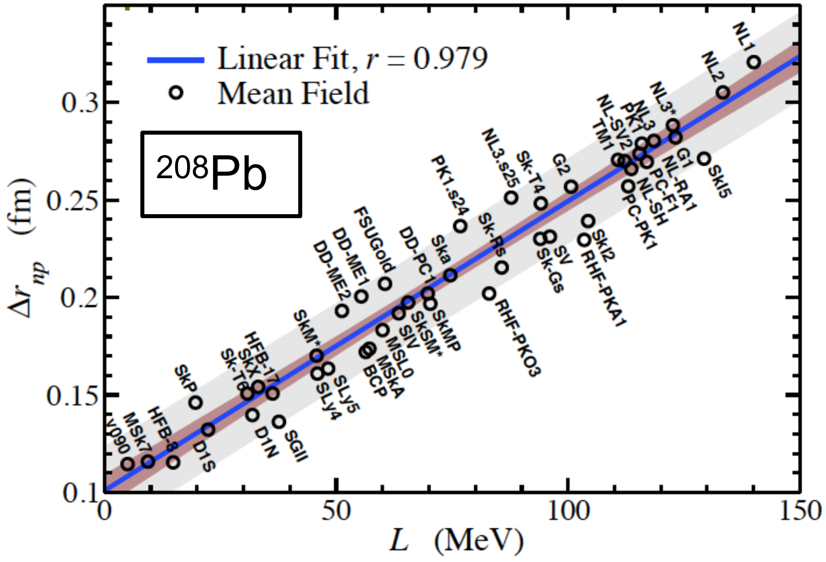
Neutron stars and neutron skins

- ❑ Neutron stars under active study
- ❑ Observations of neutron stars of more than two solar masses, recent discovery of NS mergers
  Abott et al. (LIGO, Virgo), PRL 119 (2017), Nobel 2017
- ❑ Connected to the symmetry energy of EOS

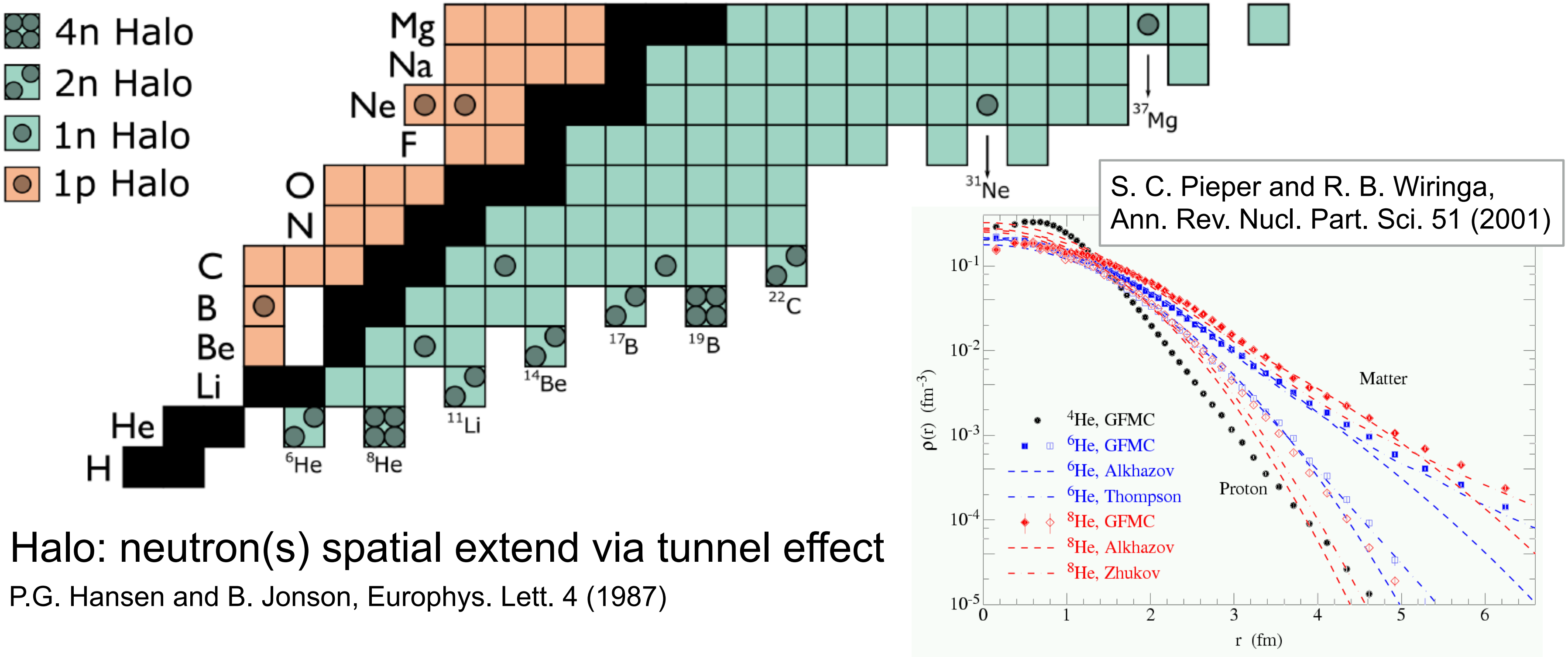
$$\frac{E}{A}(\rho_n,\rho_p)=\frac{E_0}{A}(\rho)+S(\rho)\left(\frac{\rho_n-\rho_p}{\rho}\right)^2 \qquad L\propto\left.\frac{\partial S(\rho)}{\partial\rho}\right|_{\rho_0}$$

Symmetry energy:
energy cost to separate protons and neutrons

X. Roca-Maza *et al.*, PRL 106 (2011)



Evolution towards the neutron drip line



S. C. Pieper and R. B. Wiringa, Ann. Rev. Nucl. Part. Sci. 51 (2001)

- ❑ Halo: neutron(s) spatial extend via tunnel effect

  P.G. Hansen and B. Jonson, Europhys. Lett. 4 (1987)

- ❑ Evidenced in light dripline nuclei only

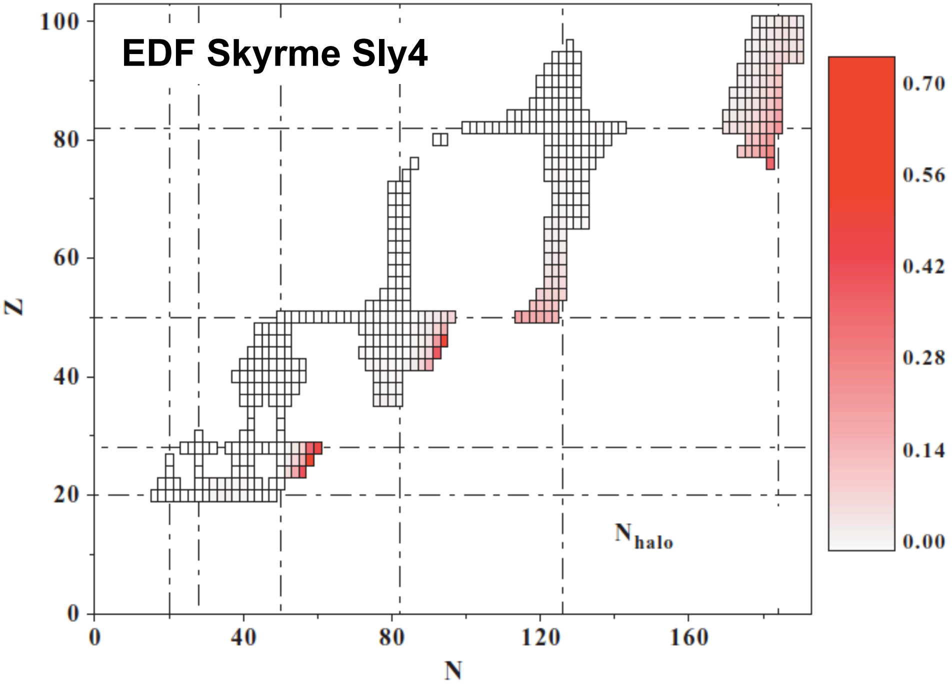
  I. Tannihata et al., PRL 55 (1985)

- ❑ Indirect observations for in medium mass nuclei (Ne, Mg)

  T. Nakamura et al., PRL 112 (2014)

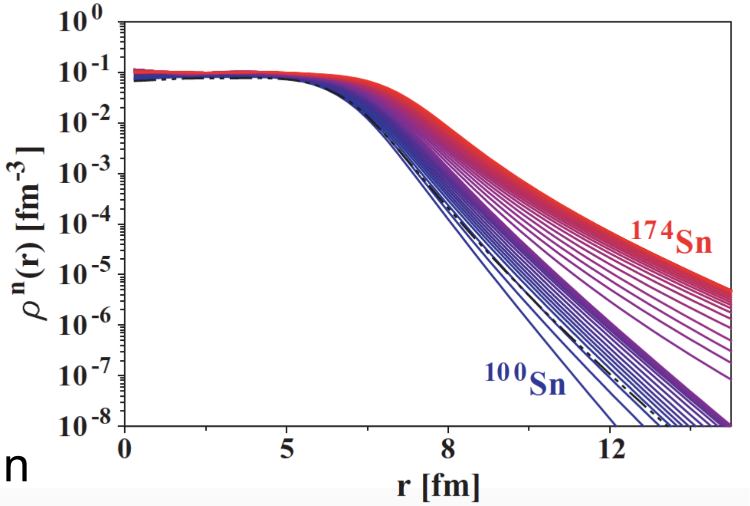
Evolution towards the neutron drip line

V. Rotival, K. Bennaceur and T. Duguet, PRC 79 (2009)



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

Beyond the radius r_0 : core density is one order of magnitude smaller than the halo one.

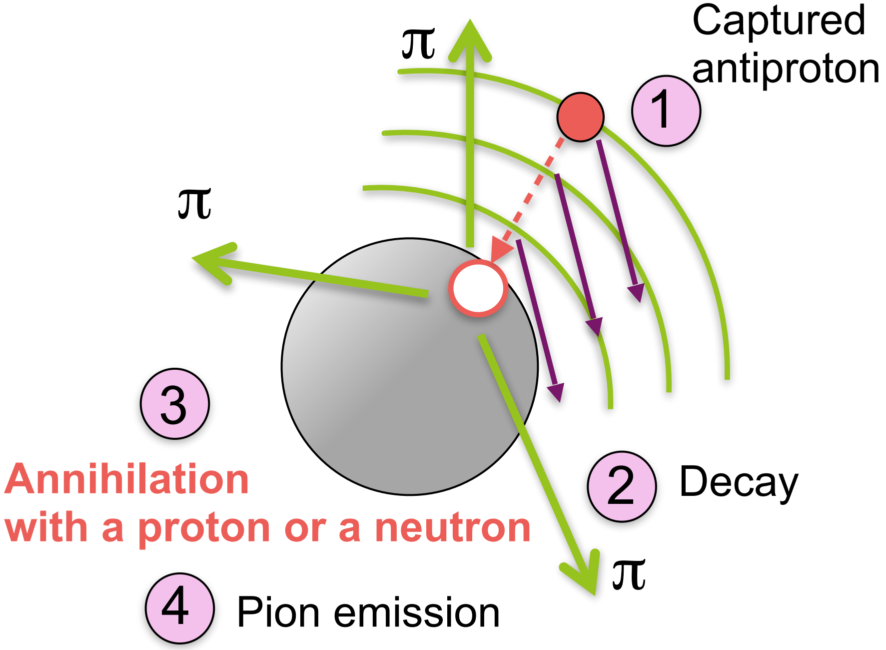


- ❑ role of deformation is an open question
  I. Hamamoto, PRC 95 (2017)

- ❑ correlations expected to affect the neutron skin
  S. Typel, PRC 89 (2014)

Low-energy antiprotons and nuclear physics

- ❑ Past works at BNL and CERN on antiproton annihilation from stable nuclei
  W. N. Bugg et al., PRL 31 (1973), J. Eades and F.J. Hartmann , Rev. Mod. Phys. 71 (1999).

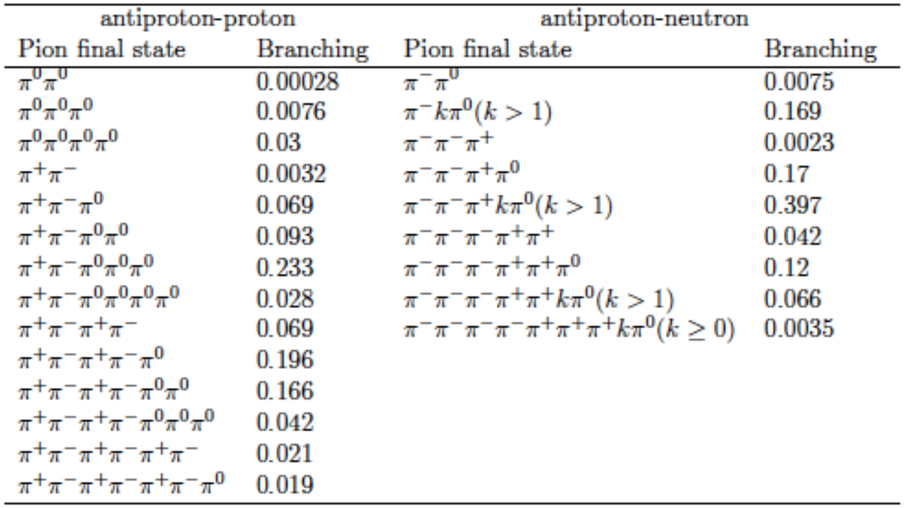


① Captured antiproton

② Decay

③ Annihilation with a proton or a neutron

④ Pion emission



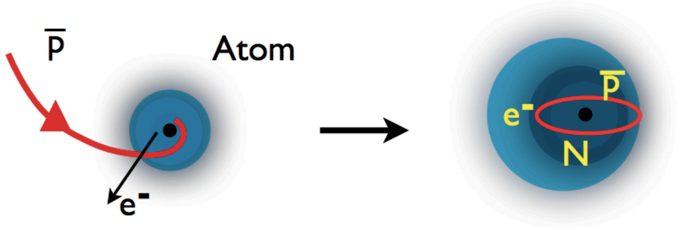
antiproton-proton		antiproton-neutron	
Pion final state	Branching	Pion final state	Branching
$\pi^0\pi^0$	0.00028	$\pi^-\pi^0$	0.0075
$\pi^0\pi^0\pi^0$	0.0076	$\pi^- k\pi^0 (k > 1)$	0.169
$\pi^0\pi^0\pi^0\pi^0$	0.03	$\pi^-\pi^-\pi^+$	0.0023
$\pi^+\pi^-$	0.0032	$\pi^-\pi^-\pi^+\pi^0$	0.17
$\pi^+\pi^-\pi^0$	0.069	$\pi^-\pi^-\pi^+ k\pi^0 (k > 1)$	0.397
$\pi^+\pi^-\pi^0\pi^0$	0.093	$\pi^-\pi^-\pi^-\pi^+\pi^+$	0.042
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233	$\pi^-\pi^-\pi^-\pi^+\pi^+\pi^0$	0.12
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028	$\pi^-\pi^-\pi^-\pi^+\pi^+ k\pi^0 (k > 1)$	0.066
$\pi^+\pi^-\pi^+\pi^-$	0.069	$\pi^-\pi^-\pi^-\pi^-\pi^+\pi^+\pi^+ k\pi^0 (k \geq 0)$	0.0035
$\pi^+\pi^-\pi^+\pi^-\pi^0$	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		

Electric charge conserved:

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

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

The antiproton capture

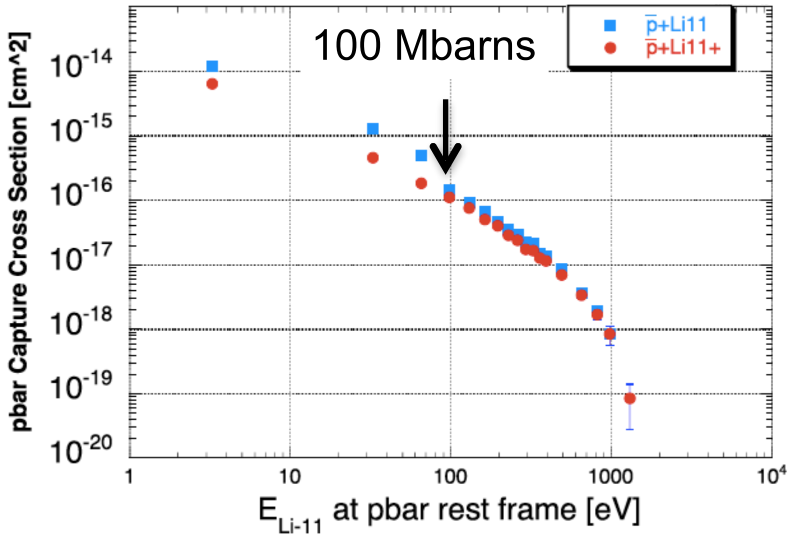


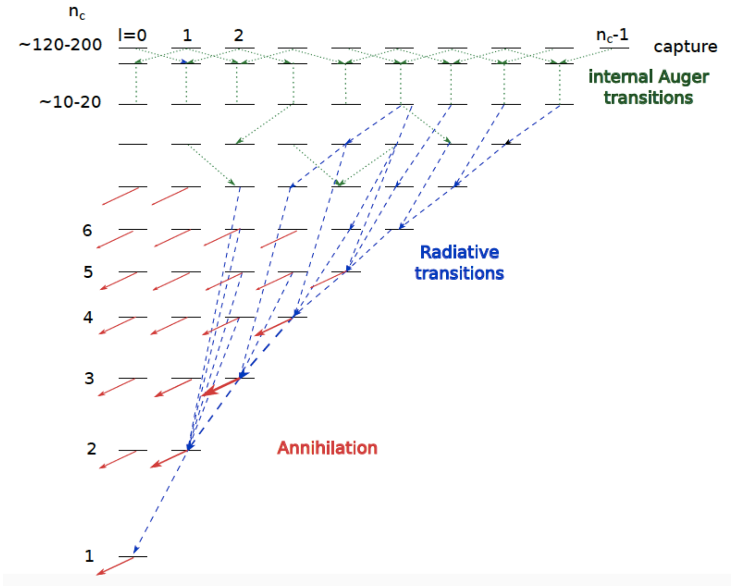
$$n_c \sim n_0 = \sqrt{M^*/m_e}\, n_e$$

M* reduced mass (antiproton - nucleus)
m_e electron mass
n_e electron principal quantum number

$$N(\ell) = (2\ell + 1)e^{\alpha\ell}$$

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





Antiprotons and the density tail of nuclei

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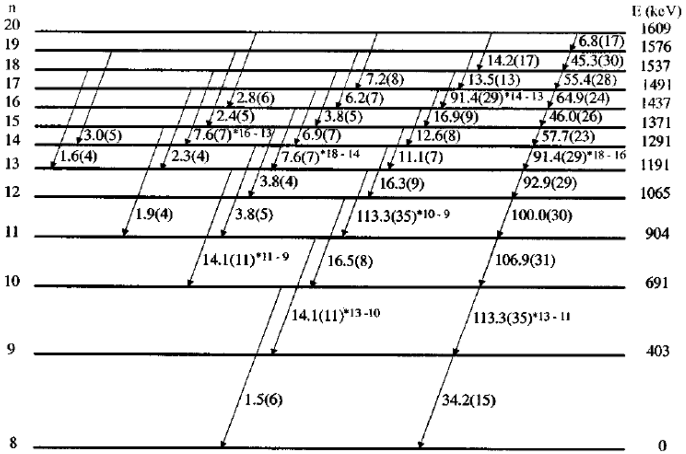
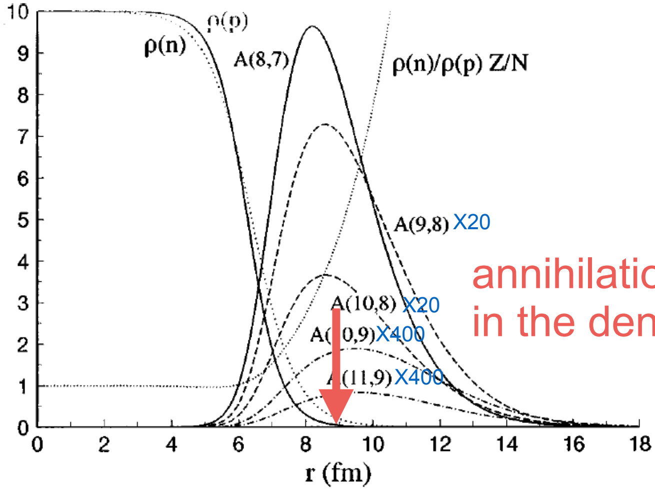
^{172}Y @ CERN, R. Schmidt *et al.,* PRC 58 (1998)





annihilation occurs in the density tail

Γ reaction probability

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)

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

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

Probing the neutron skin with antiprotons

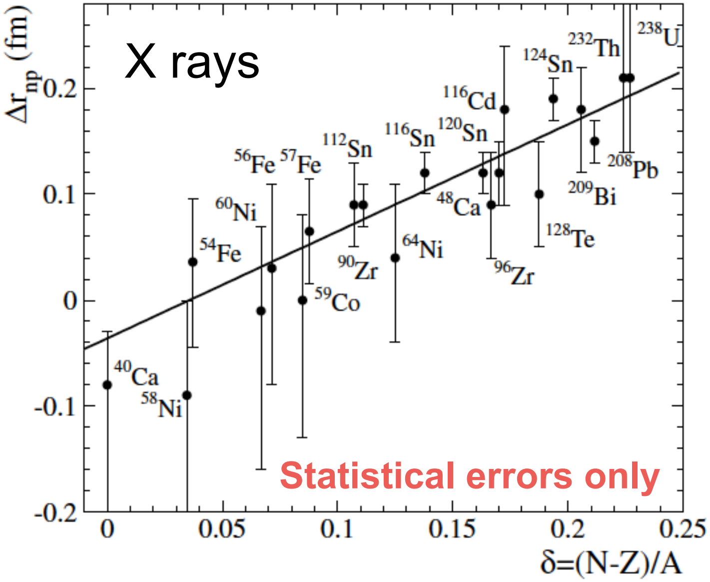
- First experiment at BNL: **charged pions to determine the ratio of neutron-to-proton at surface**
  W. N. Bugg et al., PRL 31 (1973)

- PS209 at LEAR: stable nuclei from ^{40}Ca to ^{238}U

- Neutron distributions « deduced » from :
  1) Antiprotonic **X rays** (energy shift)
  2) Annihilation on **n / p** (radiochemical method)

- Both method model dependent in case of neutron radius extraction but concluded to be consistent
  A. Trzcinska et al., PRL 87 (2001)
  B. Klos et al., PRC 76 (2007)
  A. Trzcinska et al., Hyperfine Interact 194 (2009)

A. Trzcinska et al., PRL 87 (2001)



Statistical errors only

$$\rho_{n,p}(r) = \frac{\rho_0}{1 + e^{\frac{r - c_{n,p}}{a_{n,p}}}}$$

Summary of advantages of antiprotons for skins and halos

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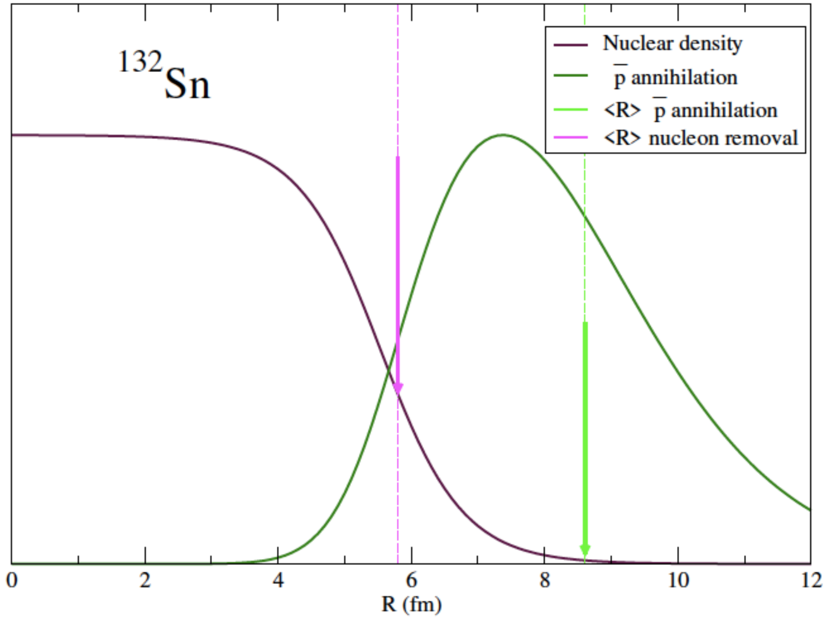
❑ Annihilation occurs in the tail of the radial density (+2 fm from surface), where skins and halos take place.

❑ Annihilation is sensitive to isospin: distinction between p / n annihilation

❑ Atomic cross sections at low energy

❑ **Radioactive nuclei ?**

FLAIR TDR - E. Widmann et al., Physica Scripta 72 (2005)
M. Wada and Y. Yamazaki, NIMB 214 (2004)

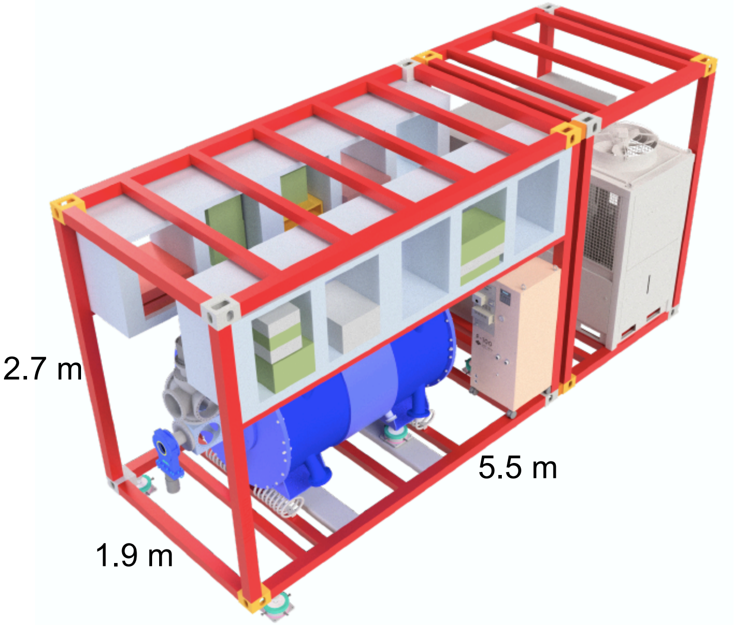


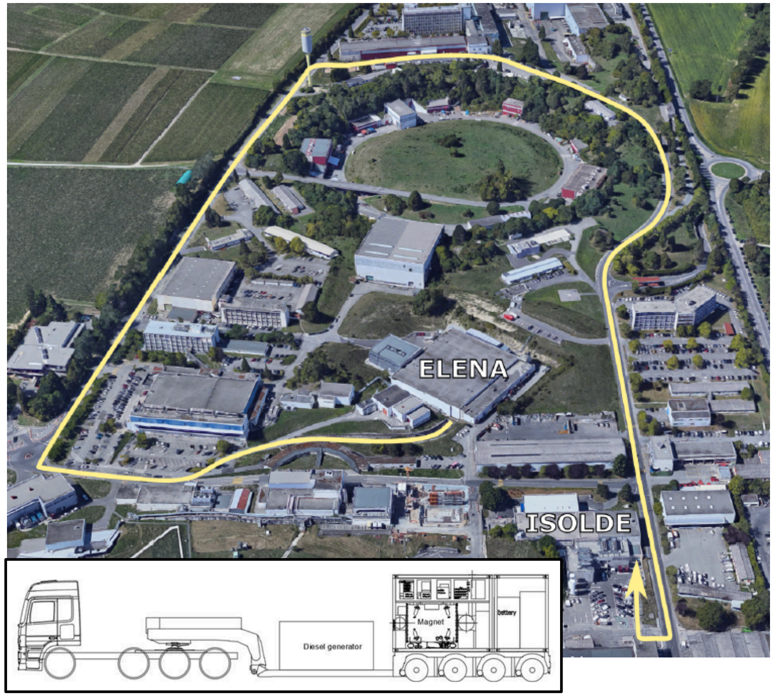
Calculations by S. Wycech (Warsaw), M. Gomez (TUDa)

Using antiprotons with radioactive nuclei

- Transport antiprotons from ELENA to ISOLDE at CERN
- Letter of Intent to CERN (2017) and proposal to CERN (2019)
  PUMA: first use of antiprotons as a probe for short-lived nuclei

- First experiment at ISOLDE foreseen in 2022





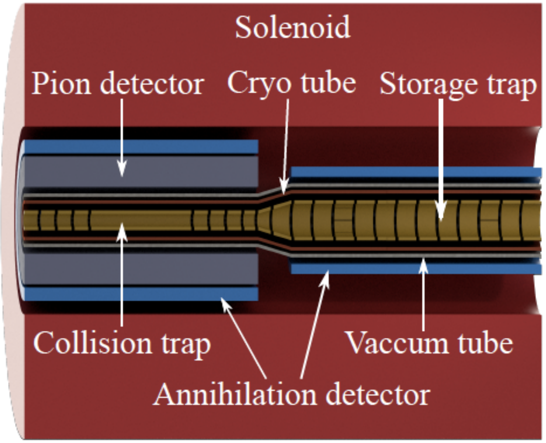
PUMA in a nutshell

☐ Penning-Malmberg trap for antiprotons and radioactive ions
4 T, superconducting, passive and active shielding, bore = 28cm

☐ Storing **10^9 antiprotons** at **ELENA**
☐ Extreme high vacuum of **10^{-17} mbar**, lifetime > 50 days

☐ Introduce low energy (<100 eV) ions at **ISOLDE**

☐ Measure charged pions resulting from annihilations
☐ Charge conservation determines the neutron-to-proton annihilation ratio

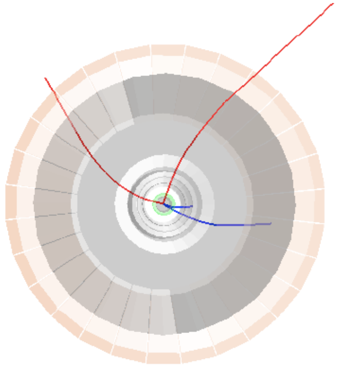


Extracted from data

Emitted pions
Multiplicity M
Total charge Σ

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

M. Wada, Y. Yamazaki, NIMB 214 (2004)

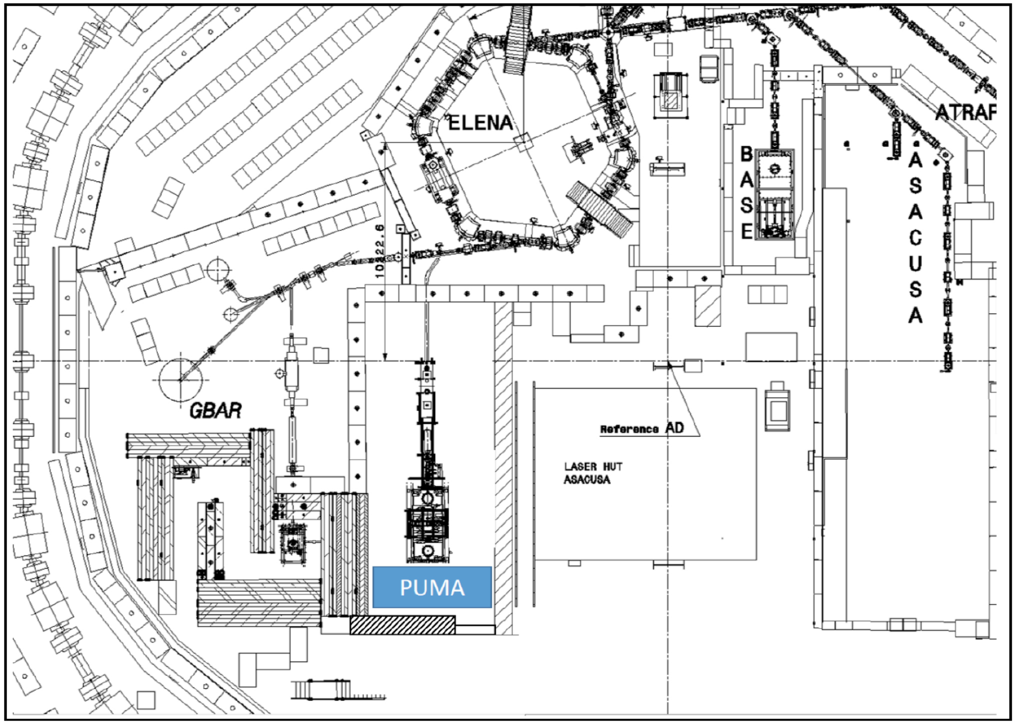


TPC + plastic barrel
Pion efficiency:78%

Simulations by S. Zacarias (TUDa)

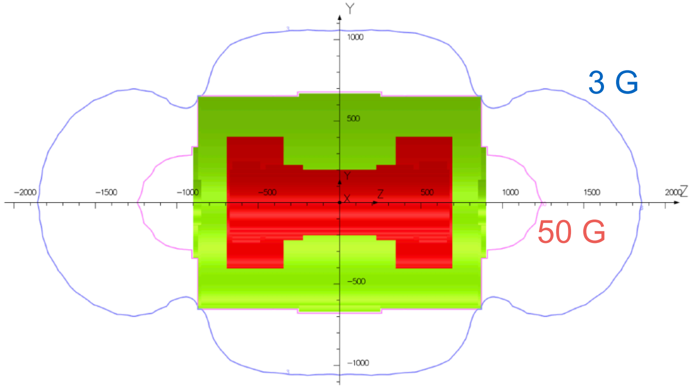
PUMA at ELENA

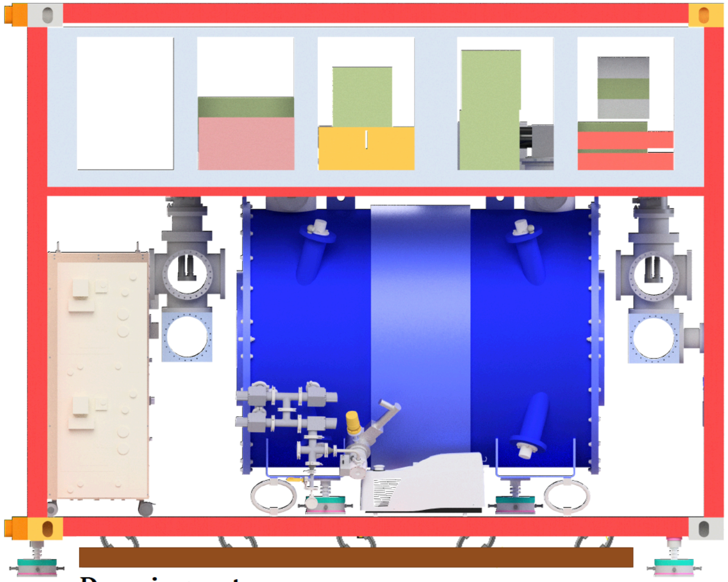
- ☐ One suitable location at ELENA: the LNE51 beam line (new)
- ☐ Engineering Change Request (ECR) produced
- ☐ Transfer via powered-crane operation
- ☐ in 2018: 5 power cuts longer than 500 ms, 3 longer than 2 hours
- ☐ plateform for diesel generator under discussion

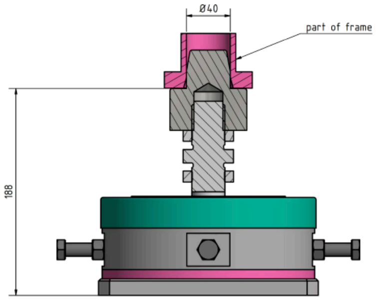


Status of the PUMA solenoid

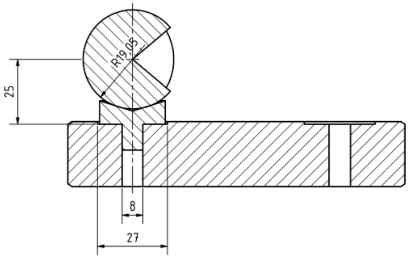
- ☐ manufactured by Noell-Bilfinger (Germany)
- ☐ to be delivered in May 2020
- ☐ design finalised
- ☐ superconducting wire to be received soon
- ☐ frame being finalised
- ☐ project on tracks, weekly meetings







positioning foot



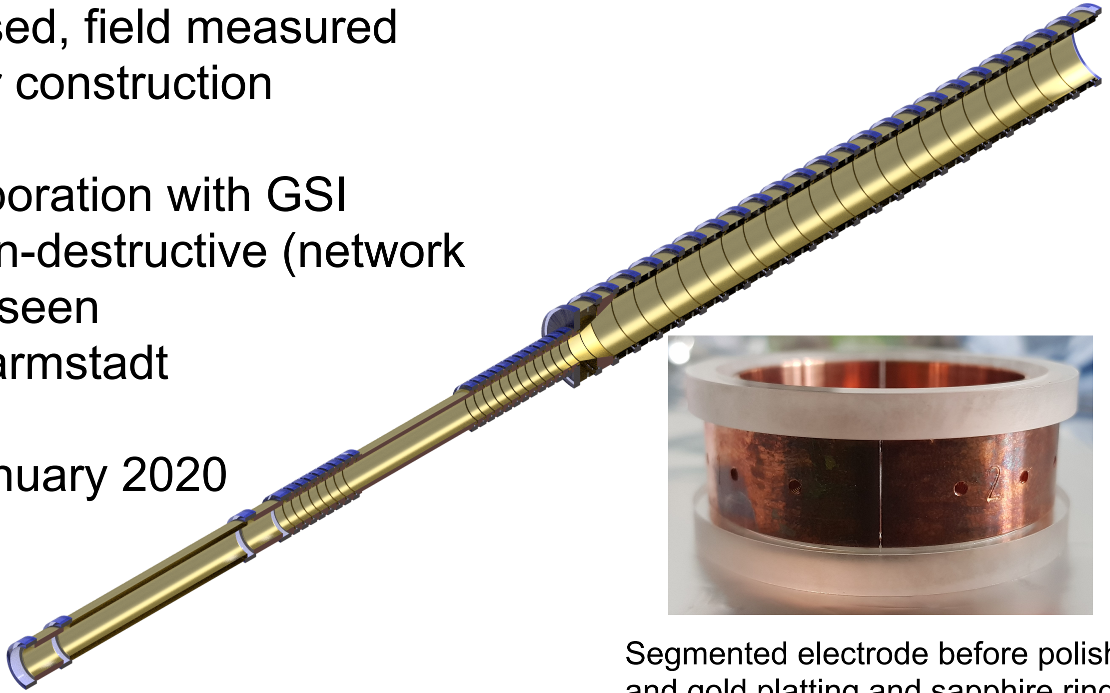
alignment compatible with CERN standards

Status of the PUMA trap

- Prototype under construction
- electrodes received, gold platting underway
- field-emission electron gun under development
- ion source (SPECS) purchased
- test solenoid (3T) purchased, field measured
- mechanical support under construction

- control command in collaboration with GSI
- destructive (MCP) and non-destructive (network analyzer) diagnostics foreseen
- laboratory space at TU Darmstadt

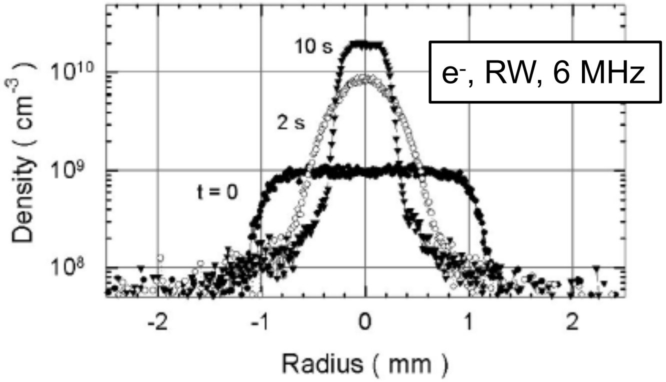
- First measurements in January 2020



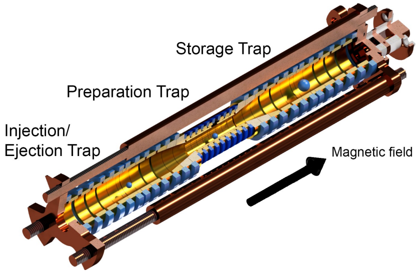
Segmented electrode before polishing and gold platting and sapphire rings

Transportable traps and trapping records

Danielson, Surko, PRL 94 (2005)

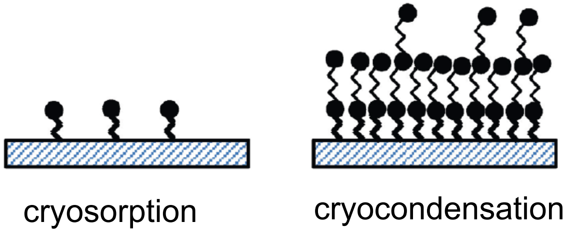


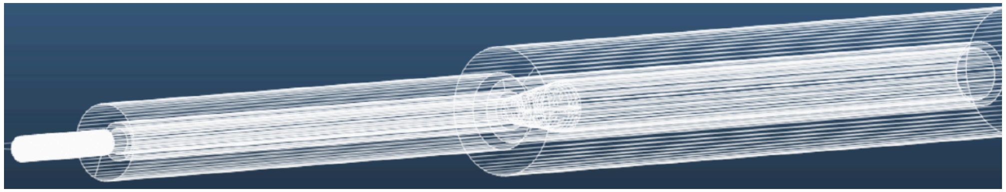
- ❑ Rotating wall and sympathetic cooling
  Hall and Gabrielse, PRL 77 (1996)
  Anderegg, Hollman, Driscoll, PRL 81 (1998)
- ❑ Storing 10^9 electrons at 2. 10^8 cm^{-3}
  Hollman, Anderegg, Driscoll, Phys. Plasmas 7 (2000)
- ❑ Storing antiprotons at BASE (CERN)
  Sealed trap, lifetime > 30 years (about 20 antiprotons)
- ❑ Transporting electrons in a Penning trap by truck over 5000 km
  Tseng and Gabrielse, Hyperfine Int. 76 (1993)
- ❑ Other project to transport antiprotons within the BASE experiment
  C. Smorra, ERC Starting Grant 2019



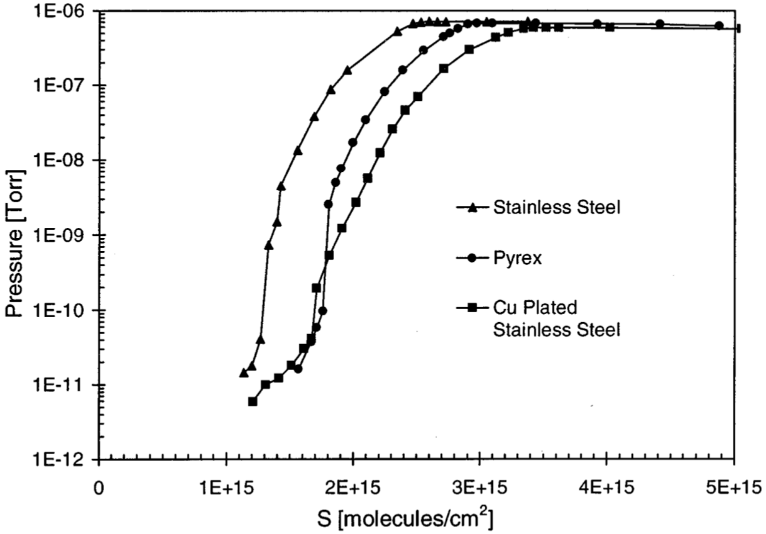
Cryopumping to achieve XHV

- Extreme vacuum reached by cryosorption of residual gas molecules until monolayer on cold surface is reached. Driven by **H_2 isotherms**.
- Trap and cryostat at **4 Kelvin**
- PUMA: the objective is to minimise the amount of residual gas entering the trap





Wallen, Jour. Vac. Sci. Tech. 15 (1997)



Cryopumping to achieve XHV

- ❑ COMSOL simulations by J. Ferreira Somoza (CERN)

- ❑ Preliminary design of cryostat

- ❑ Isotherm extrapolated from data

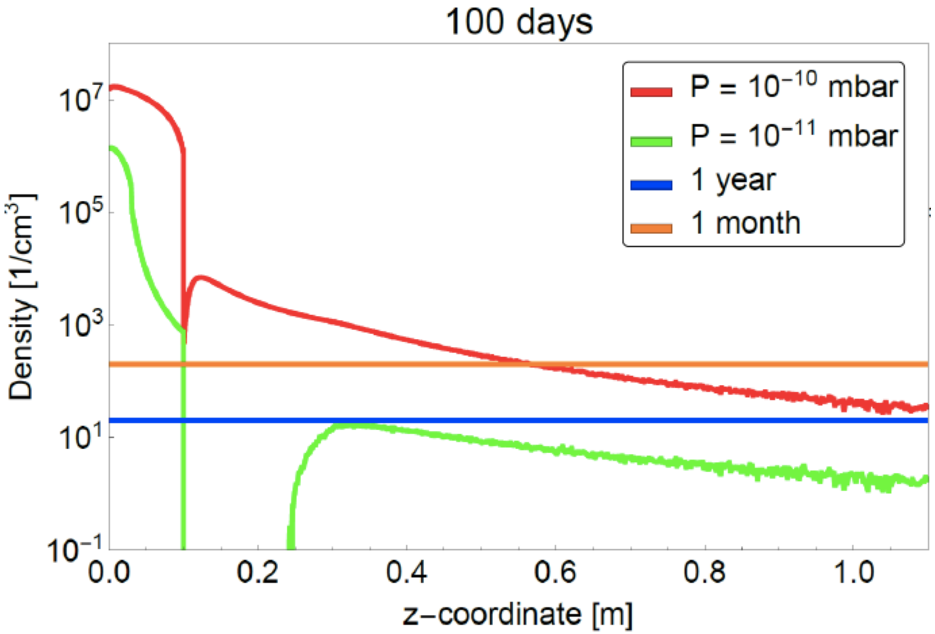
DRK parameterisation

$$P = P_0 \cdot \exp\left[-\frac{\sqrt{-\ln(S/S_\mathrm{m})}}{\sqrt{D} \cdot k_\mathrm{B} \cdot T}\right]$$

P_0 vapour pressure (4.2 10^{-7} mbar)

S_m monolayer density (6. 10^{14} cm^{-2})

D = 1.29 10^{41} J^{-2}



- ❑ Result: extreme vacuum kept for **100 days**, storage time (half life) > 100 days

Final state interactions

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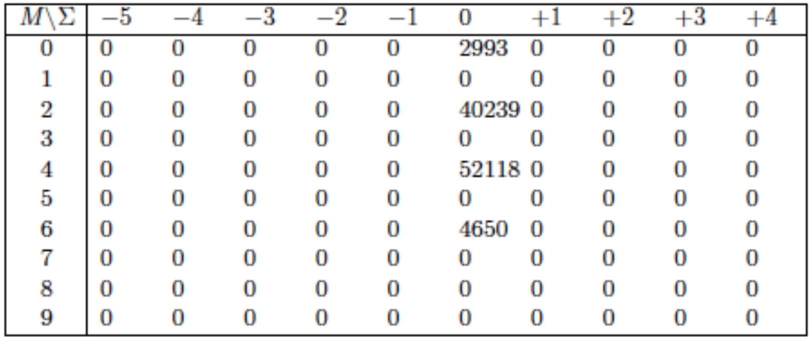
- ❑ Pions from annihilation have a probability to interact with the residual nucleus
- ❑ Several elementary processes can occur:

$$\omega^+ : \pi^+ + n \rightarrow \pi^0 + p \qquad \lambda^+ : \pi^0 + p \rightarrow \pi^+ + n$$

$$\omega^- : \pi^- + p \rightarrow \pi^0 + n \qquad \lambda^- : \pi^0 + n \rightarrow \pi^- + p$$

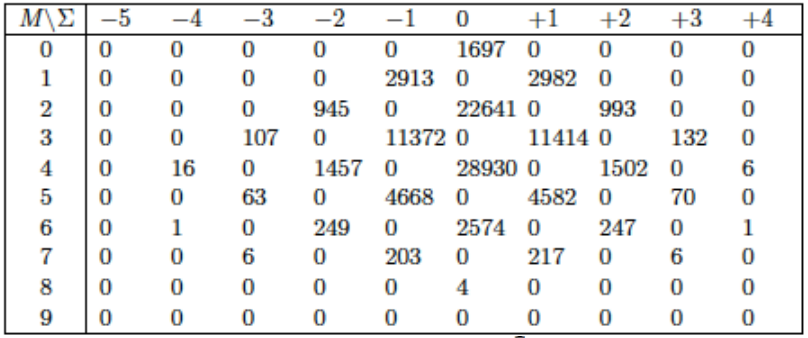
- ❑ Final State Interactions (FSI) need to be accounted for

antiproton - proton annihilation (no FSI)



$M\backslash\Sigma$	-5	-4	-3	-2	-1	0	$+1$	$+2$	$+3$	$+4$
0	0	0	0	0	0	2993	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	40239	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	52118	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	4650	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0

antiproton - proton annihilation (with FSI)



$M\backslash\Sigma$	-5	-4	-3	-2	-1	0	$+1$	$+2$	$+3$	$+4$
0	0	0	0	0	0	1697	0	0	0	0
1	0	0	0	0	2913	0	2982	0	0	0
2	0	0	0	945	0	22641	0	993	0	0
3	0	0	107	0	11372	0	11414	0	132	0
4	0	16	0	1457	0	28930	0	1502	0	6
5	0	0	63	0	4668	0	4582	0	70	0
6	0	1	0	249	0	2574	0	247	0	1
7	0	0	6	0	203	0	217	0	6	0
8	0	0	0	0	0	4	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0

Assuming $\omega^+ = \omega^- = \lambda^+ = \lambda^- = 0.1$

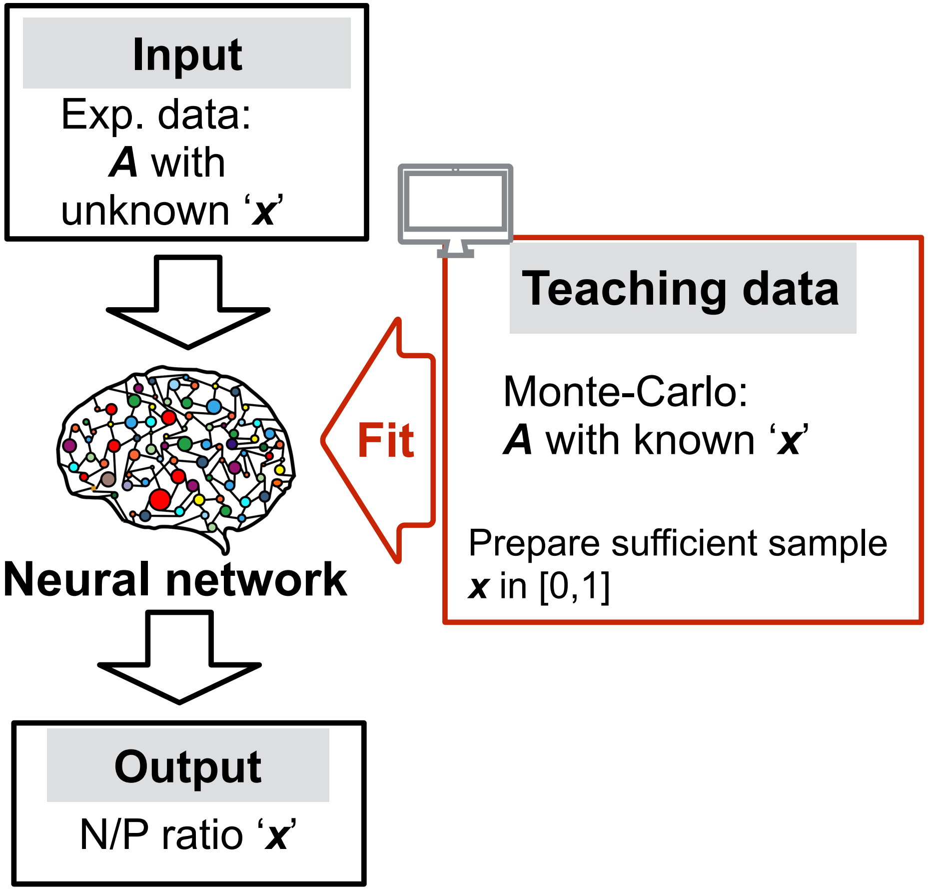
Expected uncertainties:

5% on Nn/Np for 10^5 events M. Wada, Y. Yamazaki, NIMB 214 (2004)

Analysis method

- Analyse the $M-\Sigma$ matrices
- Use their redundancy to estimate final state interactions and the ratio of neutron-to-proton annihilations
- FSI parameterised with

  $\omega^+, \omega^-, \lambda^+, \lambda^-$
- Neural network



Input

Exp. data:
A with
unknown ‘***x***’

Teaching data

Monte-Carlo:
A with known ‘***x***’

Prepare sufficient sample
x in [0,1]

Fit

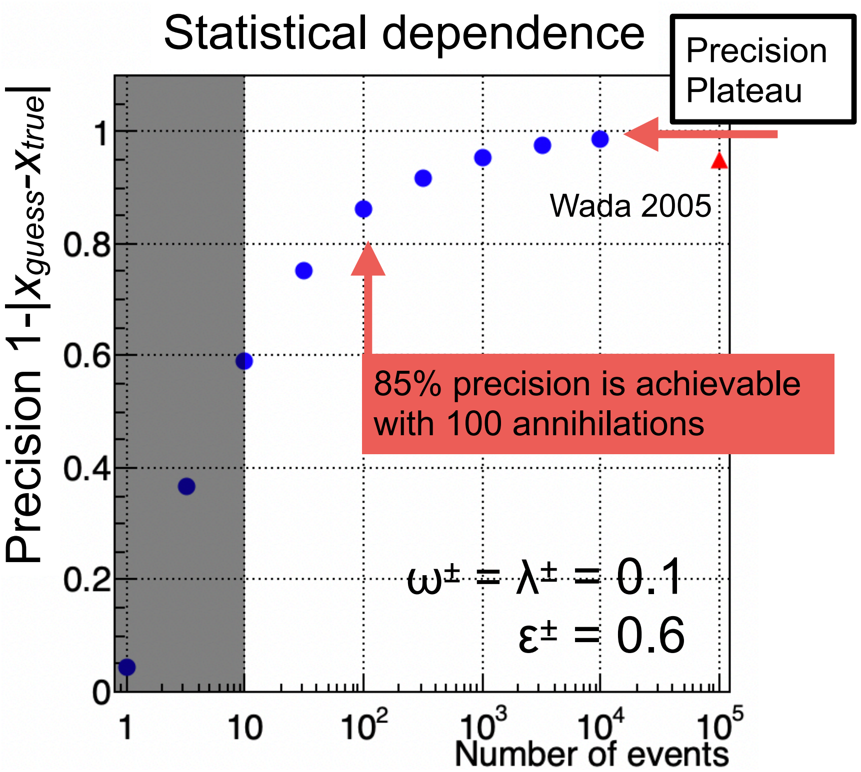
Neural network

Output

N/P ratio ‘***x***’

Analysis method developed by Y. Kubota (TUDa)

Analysis benchmark and accuracy


Statistical dependence

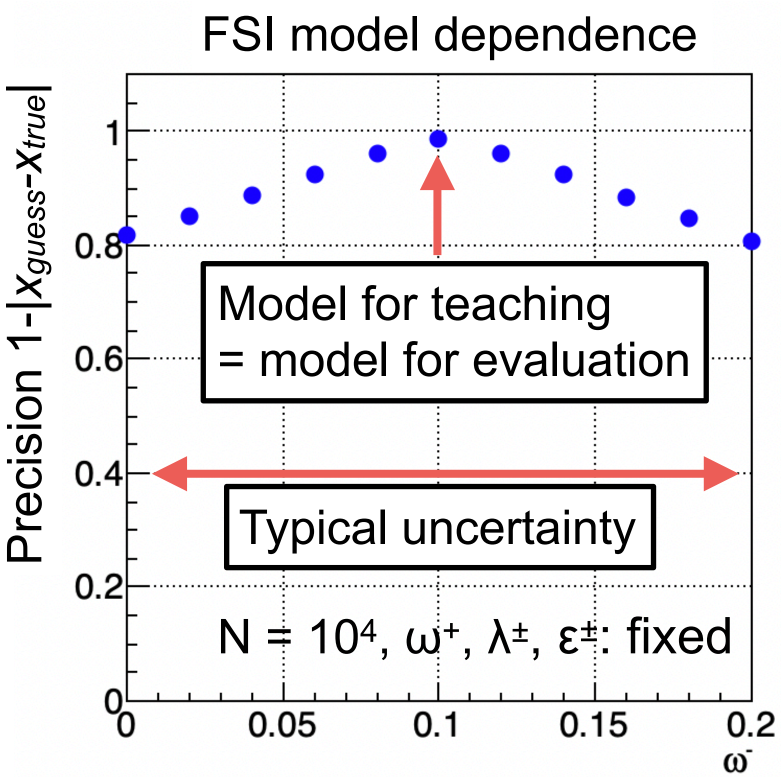
Precision Plateau

Wada 2005

85% precision is achievable with 100 annihilations

$\omega^\pm = \lambda^\pm = 0.1$

$\varepsilon^\pm = 0.6$


FSI model dependence

Model for teaching = model for evaluation

Typical uncertainty

N = 10^4, ω^+, $\lambda^\pm$, $\varepsilon^\pm$: fixed

Typical uncertainty (with the simplest model) is ~20%

Analysis method developed by Y. Kubota (TUDa)

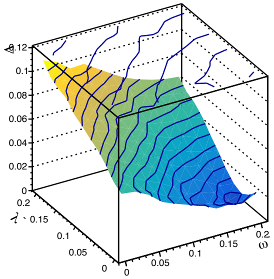
Analysis benchmark and accuracy

- ❑ Neural network to fit all together $\omega^+, \omega^-, \lambda^+, \lambda^-$ and $x = n/p$
- ❑ Model parameters estimated on data with precision of 10%
- ❑ Accuracy on the neutron-to-proton ratio better than 5%

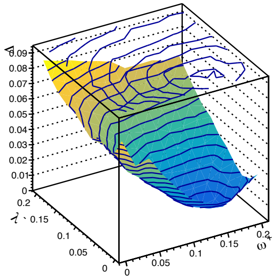
- ❑ Method will be benchmarked on **intra-nuclear cascade** events, not based on the model used to train the neural network. Ongoing work.

- ❑ **We expect an accuracy better than 10 % with this method**

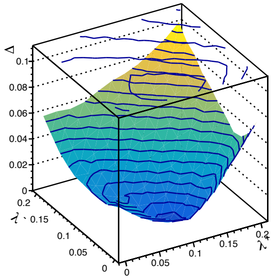
λ^- vs ω^-



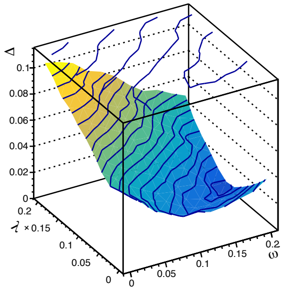
λ^- vs ω^+



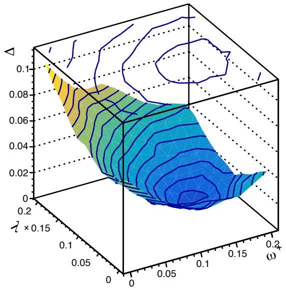
λ^- vs λ^+



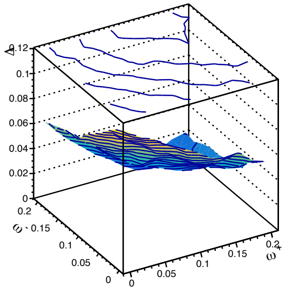
λ^+ vs ω^-



λ^+ vs ω^+



λ^+ vs λ^-



Objectives: neutron skin evolution and halos

Example 1: ^{132}Sn isotopes at 10^5 pps

$\sigma = 10^{-16}$ cm^2 at 100 eV

"antiproton thickness" $= 10^8$ cm^2

Beam intensity $= 10^5$ s^{-1}

100 eV $\rightarrow 10^4$ m.s^{-1} $\rightarrow 10^5$ cycles in 1 s

100 annihilations per second expected

8. 10^6 in one day

Example 2: ^{11}Li isotopes at 2000 pps

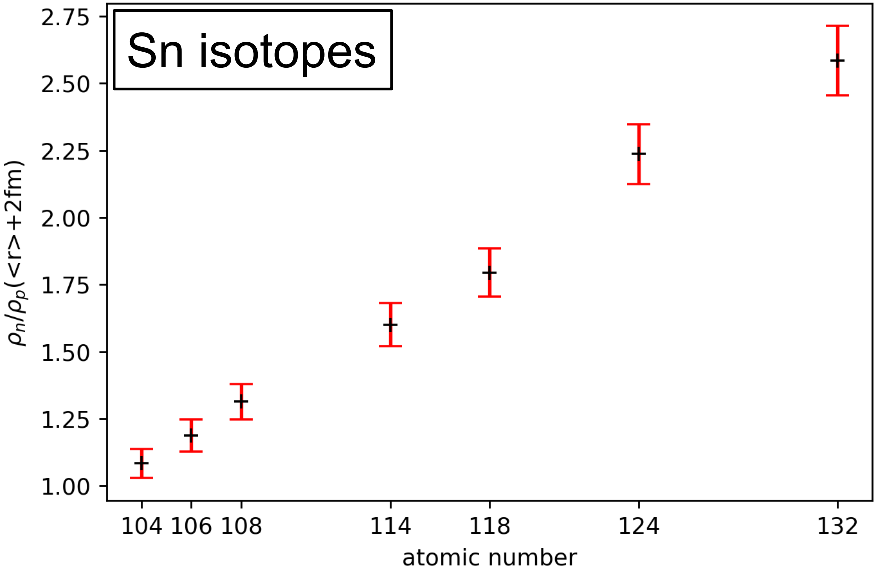
Beam intensity $= 2000$ s^{-1}

100 eV $\rightarrow 4 \times 10^4$ m.s^{-1} $\rightarrow 4 \times 10^3$ cycles in 10 ms

5 annihilations per minute expected

Few 10^3 in one day

Neutron skin evolution with isospin



Preliminary estimates: C. Klink, S. Zacarias (TUDa)

PUMA might offer other physics opportunities (hypernuclei, X rays from neutron-rich antiprotonic atoms,…)

Beam requirements at ISOLDE

Isotopic purity	$> 95\ \%$
Beam diameter	< 5 mm
Transverse emittance at 30-60 keV	$< 50\ \pi$ mm mrad
Energy	1 - 2 keV
Energy spread	± 30 eV
Bunch length	< 15 cm
Longitudinal emittance (^{18}Ne@2 keV)	< 30 us $\cdot$ eV

physics measurement

conductance pipe and luminosity

in-trap drift tube from <2 keV to 100 eV

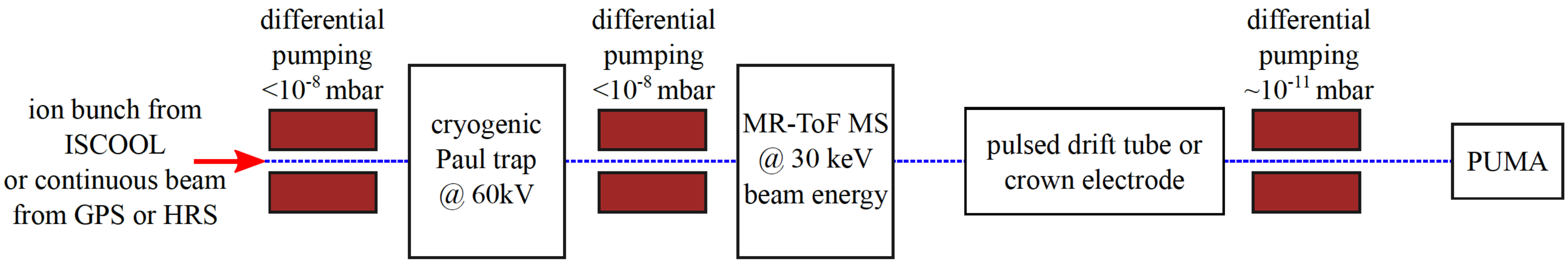
Nuclei	Yield (ions/μC)	Target
^{6,8}He	5.4×10^7 / 4.7×10^5	BeO - UC$_x$
^{7,9,11}Li	8.2×10^9 / 3.9×10^6 / 1.4×10^3	UC$_x$
^{8}B	300	C
^{17,18}Ne ... ^{26,27}Ne	4.5×10^3 / 3.5×10^6 ... 4.9×10^4 / 200	MgO ... UC$_x$
$^{28,...,33,34}$Mg	3.6×10^7 / ... / 3×10^3 / 140	SiC$_x$ / UC$_x$
$^{19-22}$O	1.3×10^5 / 3.4×10^4 / 7×10^3 / 1.3×10^3	UC$_x$
^{105}Sn ... ^{136,137,138}Sn	8×10^4 ... 4×10^3 / 100 / 2.5	LaC ... UC$_x$

PUMA at ISOLDE

Requirements for operations at ISOLDE:

☐ footprint necessary for the experiment (WxLxH: 4m x 6m x 3m)
☐ > 90 kW electrical power
☐ power on site and during crane operation
☐ cooling water (max. 28 degrees, 40 litres / minute)
☐ vacuum better than 10^{-9} mbar
(differential pumping in front pf PUMA from 10^{-9} mbar to 10^{-11} mbar)

MR-TOF based beam preparation is the best option (purity, timing, emittance)



ion bunch from ISCOOL or continuous beam from GPS or HRS

differential pumping $<10^{-8}$ mbar

cryogenic Paul trap @ 60kV

differential pumping $<10^{-8}$ mbar

MR-ToF MS @ 30 keV beam energy

pulsed drift tube or crown electrode

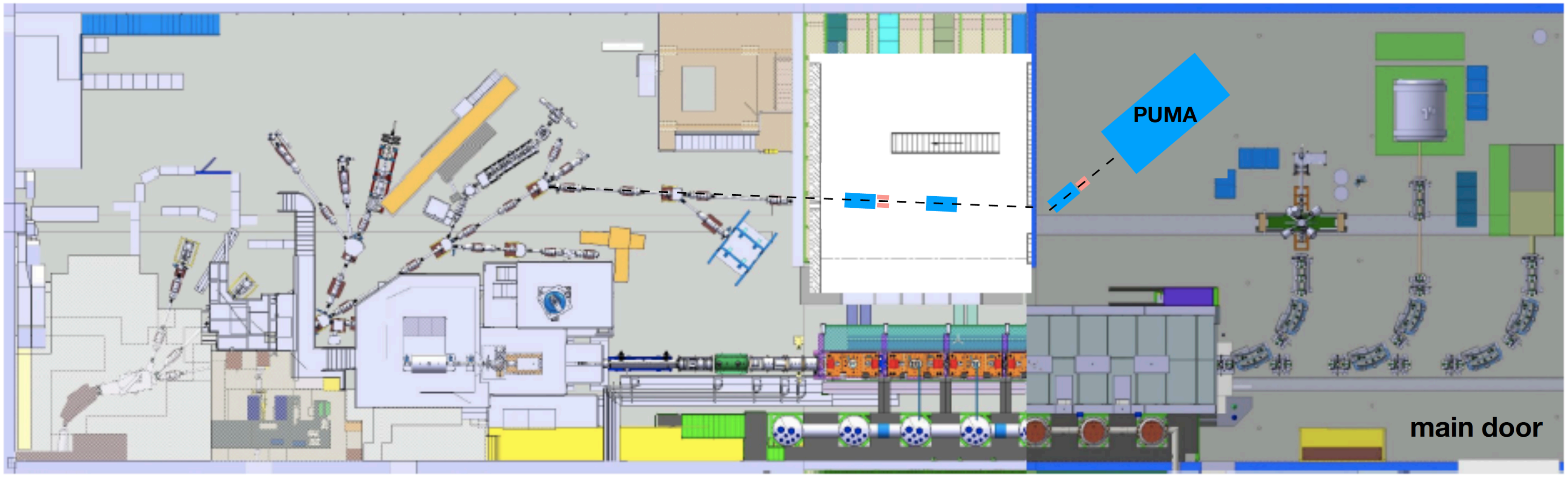
differential pumping $\sim10^{-11}$ mbar

PUMA

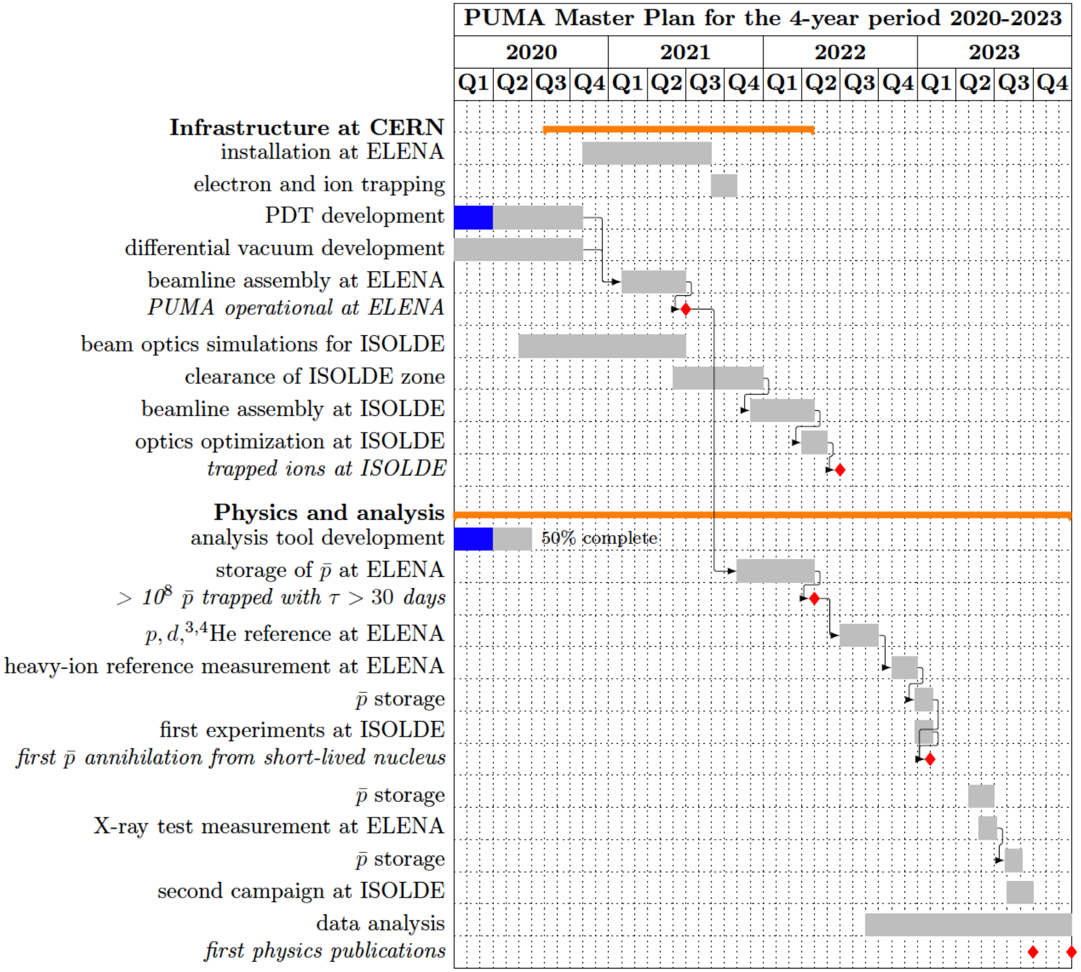
Collaboration with MIRACLS and university of Greifswald foreseen

PUMA at ISOLDE

- ❑ not many options can provide the necessary footprint for the experiment (WxLxH: 4m x 6m x 3m) and optics and MR-TOF
- ❑ no available site today: could either be in the high-energy zone (see below) or on (a) platform(s).



ECR in preparation, foreseen early 2020.


PUMA Master Plan for the 4-year period 2020-2023
2020
2021
2022
2023
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Infrastructure at CERN
installation at ELENA
electron and ion trapping
PDT development
differential vacuum development
beamline assembly at ELENA
PUMA operational at ELENA
beam optics simulations for ISOLDE
clearance of ISOLDE zone
beamline assembly at ISOLDE
optics optimization at ISOLDE
trapped ions at ISOLDE
Physics and analysis
analysis tool development
50% complete
storage of $\bar{p}$ at ELENA
$> 10^8$ $\bar{p}$ trapped with $\tau > 30$ days
$p, d, {}^{3,4}$He reference at ELENA
heavy-ion reference measurement at ELENA
$\bar{p}$ storage
first experiments at ISOLDE
first $\bar{p}$ annihilation from short-lived nucleus
$\bar{p}$ storage
X-ray test measurement at ELENA
$\bar{p}$ storage
second campaign at ISOLDE
data analysis
first physics publications

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UNIVERSITÄT
DARMSTADT

Summary

- ❑ **Halos, thick neutron skins** in medium mass nuclei predicted but not observed
- ❑ Key for the nuclear many-body problem and the nuclear EoS

- ❑ **PUMA : use antiprotons to probe the density tail of radioactive nuclei**
- ❑ **Neutron-to-proton annihilation ratio** from the detection of **charged pions**
- ❑ Proposed experiment (2019) at CERN (SPSC)
- ❑ First physics experiments at ISOLDE targeted in **2022** (proposals in 2021)

- ❑ Main technical challenge in XHV (feasibility proven from simulations)
- ❑ Final state interactions to be accounted for

Collaboration

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