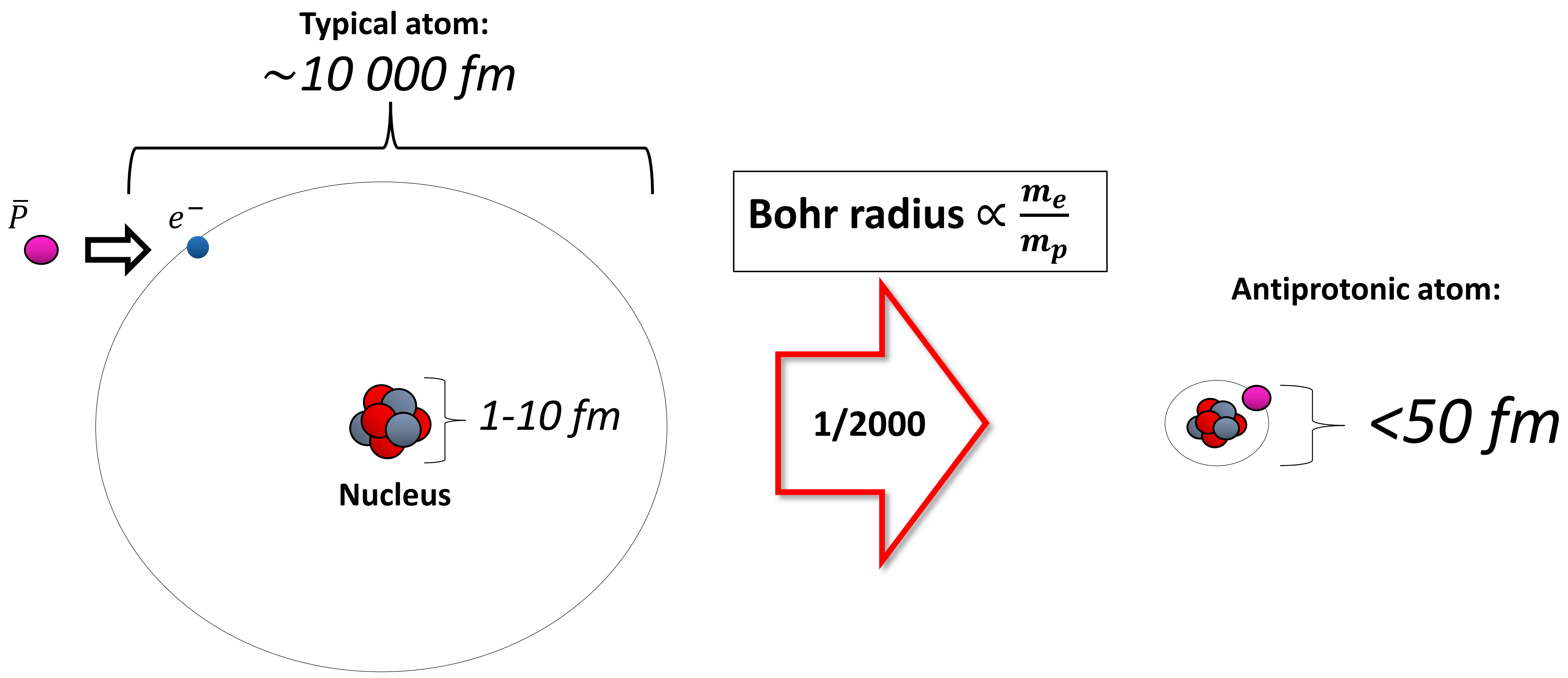
Synthesis of antiprotonic atoms and highly charged nuclear fragments in a Penning-Malmberg trap

Dr. Fredrik Parnefjord Gustafsson
On behalf of the AEgIS Collaboration
27-August-2024

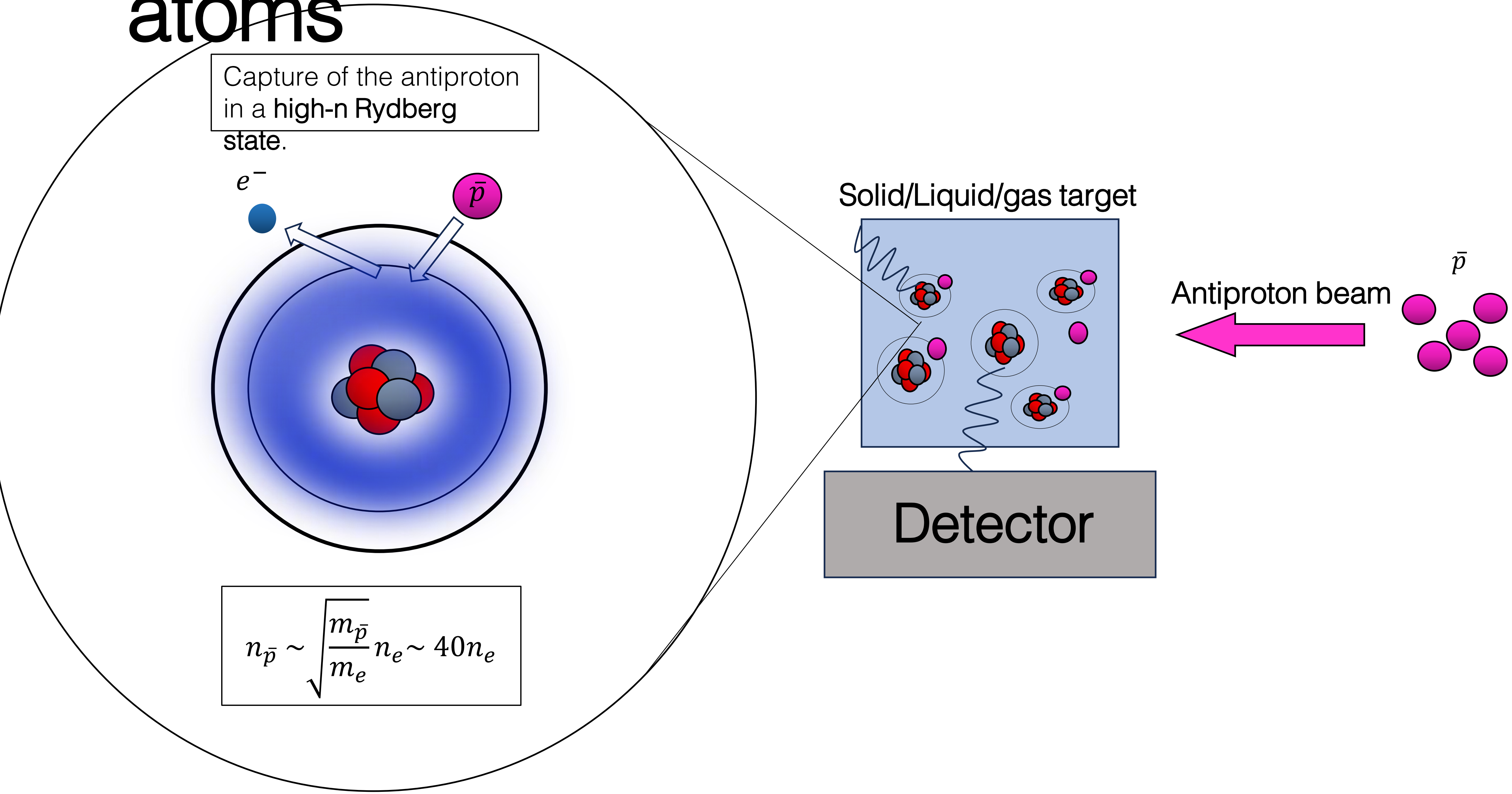
EXA2024

The antiprotonic atom



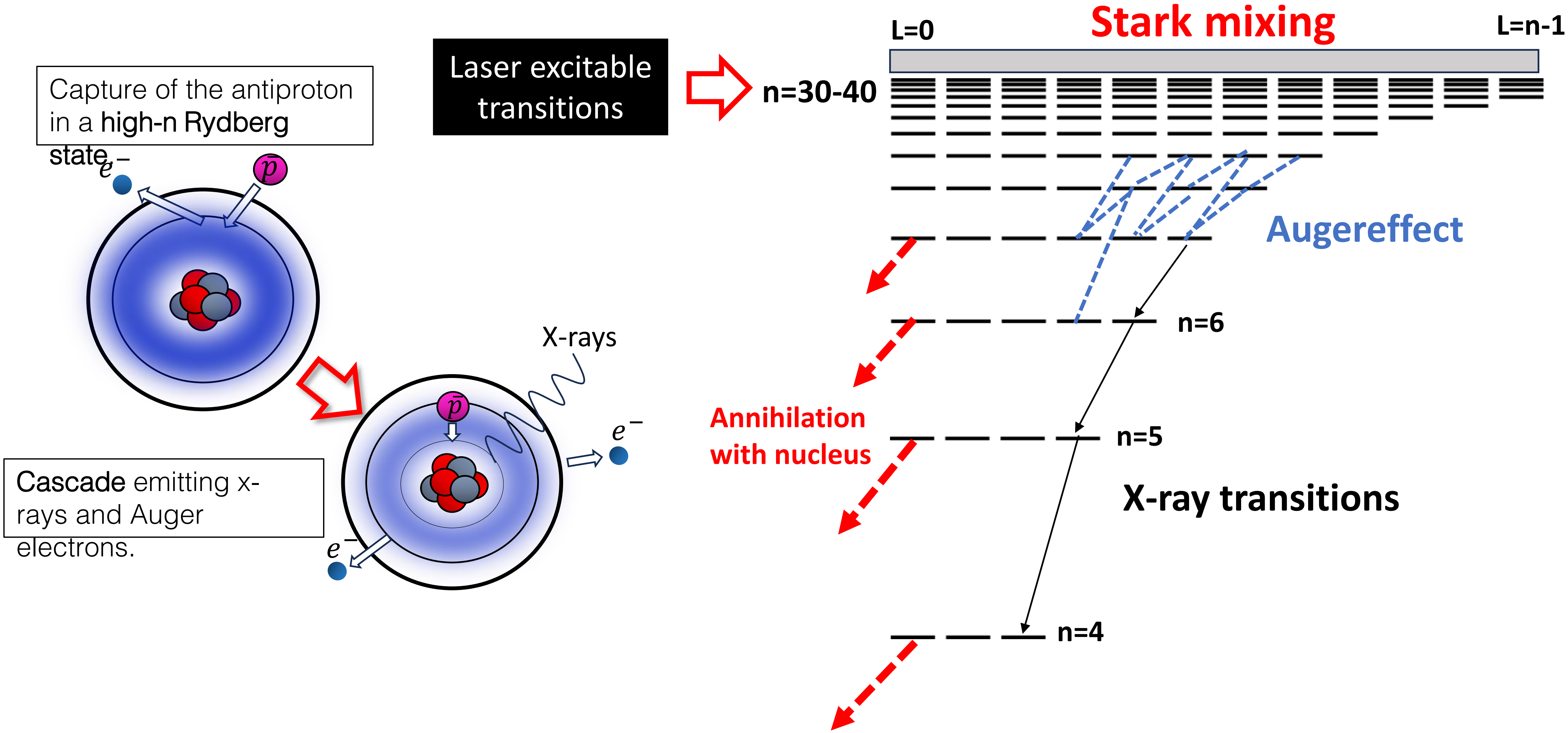
<u>Sensitive system for benchmarking both QED and QCD.</u>

Typical synthesis of antiprotonic atoms



$$n_{\bar{p}} \sim \sqrt{\frac{m_{\bar{p}}}{m_e}} n_e \sim 40 n_e$$

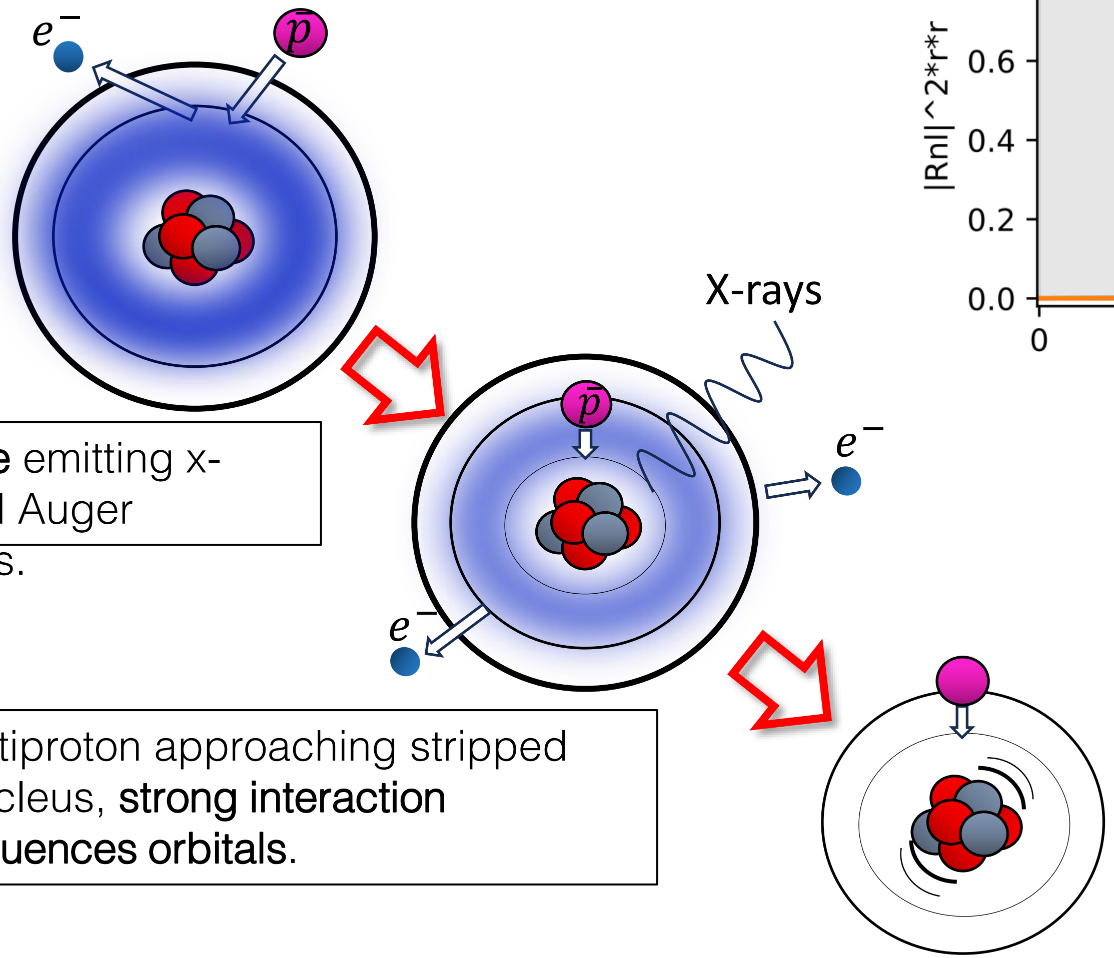
The life of an antiprotonic atom



In target spectroscopy limited to n<43 due to stark mixing.

The life of an antiprotonic atom

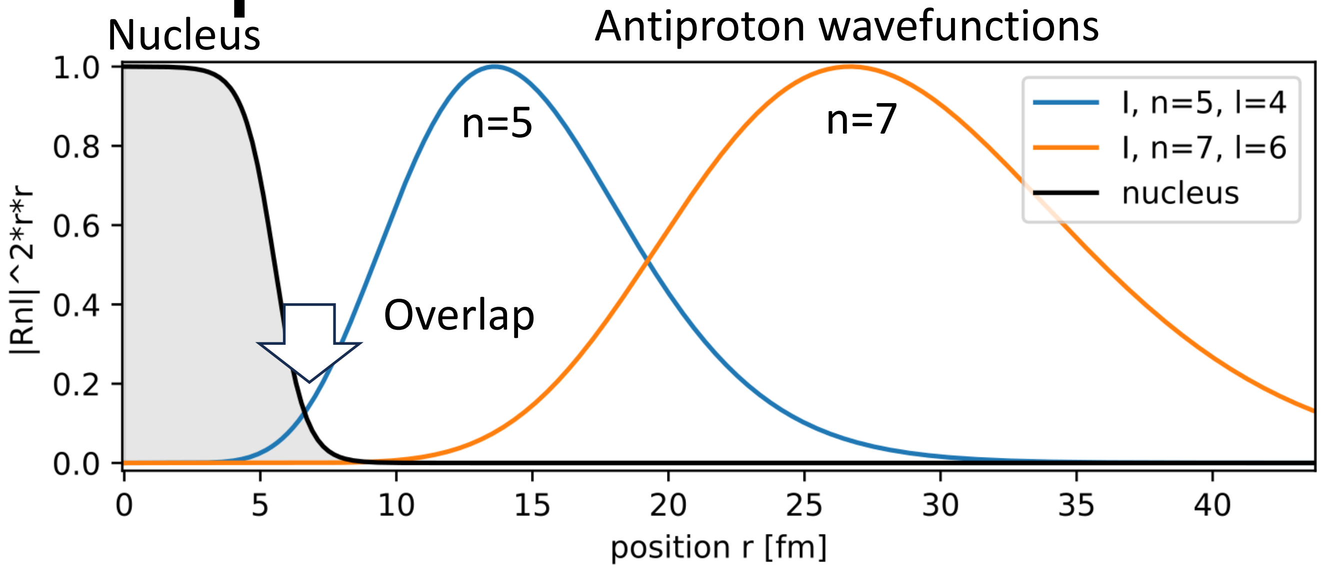
Capture of the antiproton in a **high-n Rydberg state**.

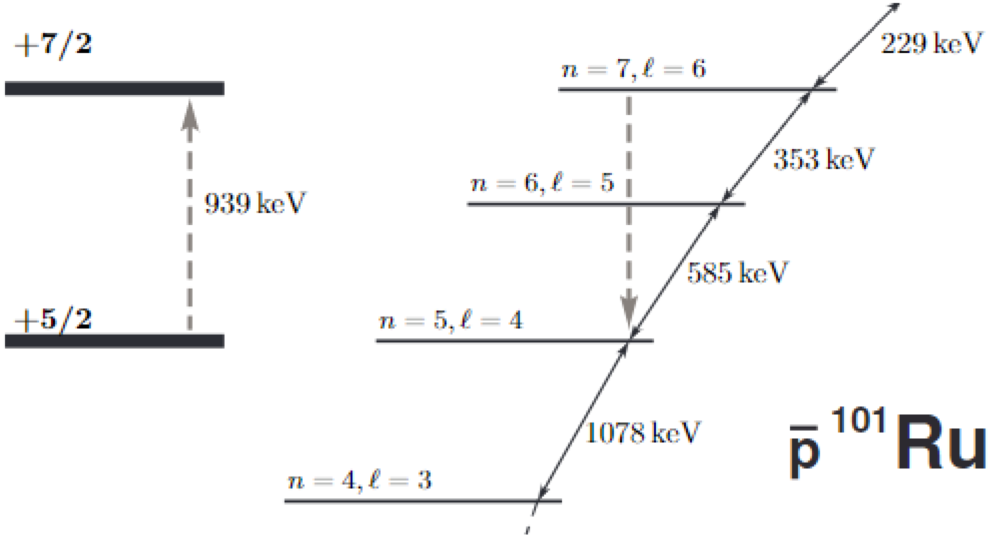


Cascade emitting x-rays and Auger electrons.

Antiproton approaching stripped nucleus, **strong interaction influences orbitals.**

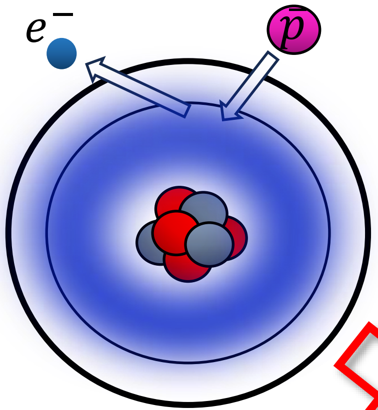
X-ray linebroadening caused by **annihilation with nuclear perifery.**



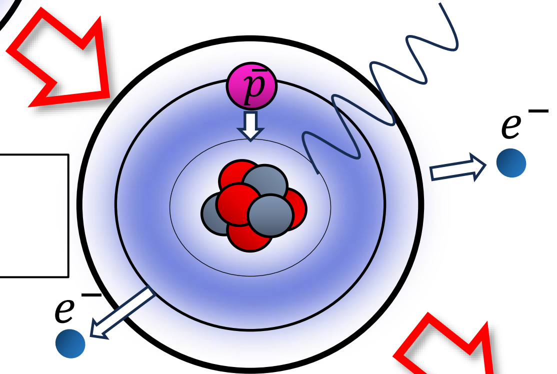


Gustafsson, Fredrik P., Daniel Pęcak, and Tomasz Sowiński. *Physical Review C* 109.6 (2024): 064320.

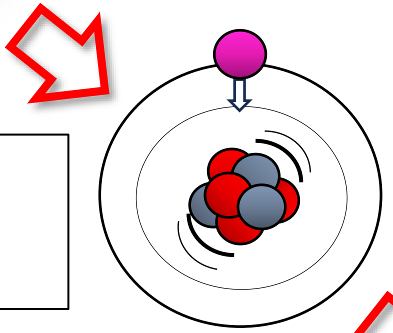
The life of an antiprotonic atom



Capture of the antiproton in a **high-n Rydberg** state.



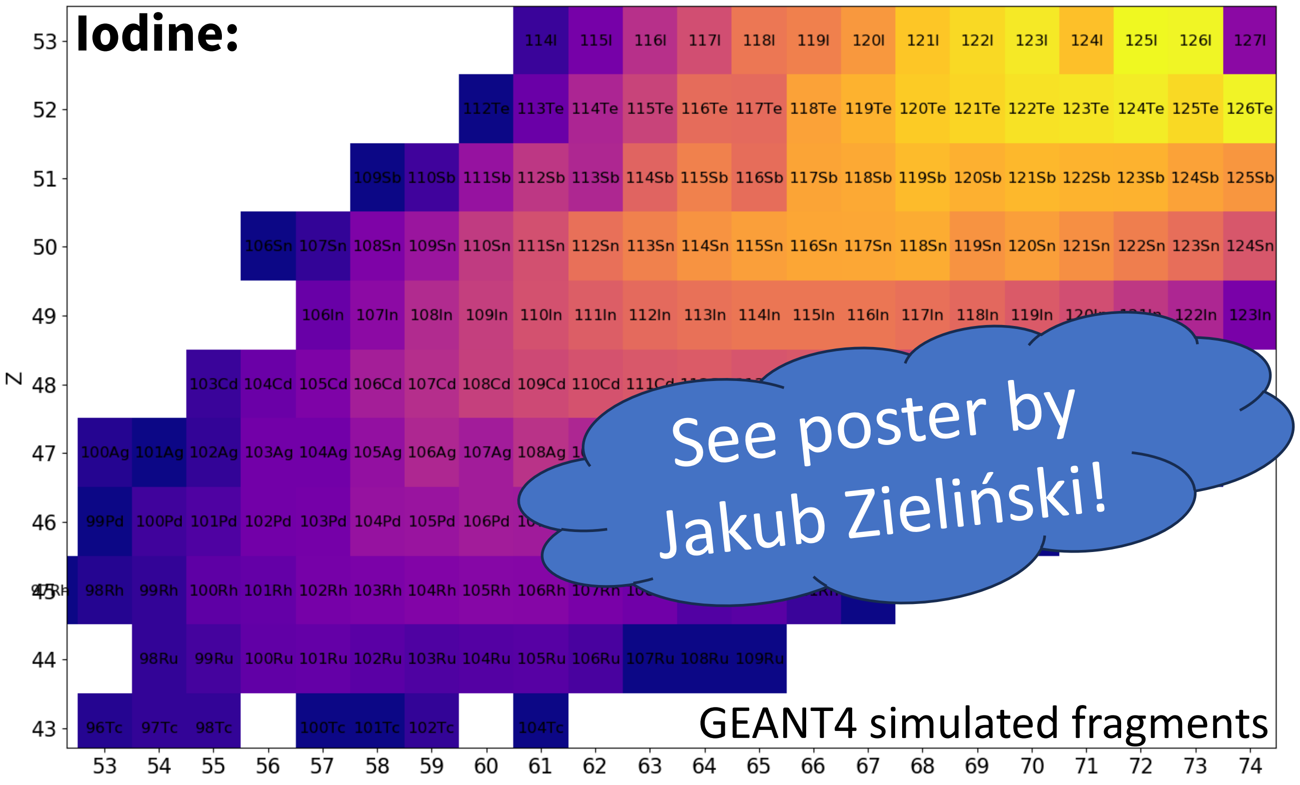
Cascade emitting x-rays and Auger electrons.



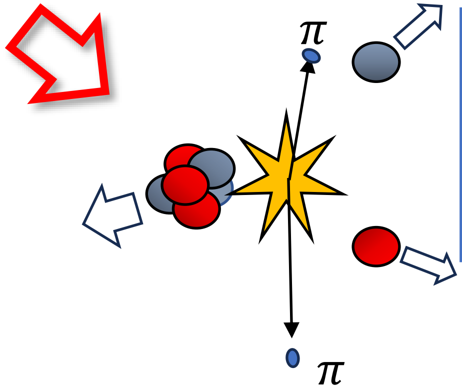
Antiproton approaching stripped nucleus, **strong interaction influences orbitals.**

X-ray linebroadening caused by **annihilation with nuclear perifery.**

Antiproton-induced nuclear fragmentation on Iodine:



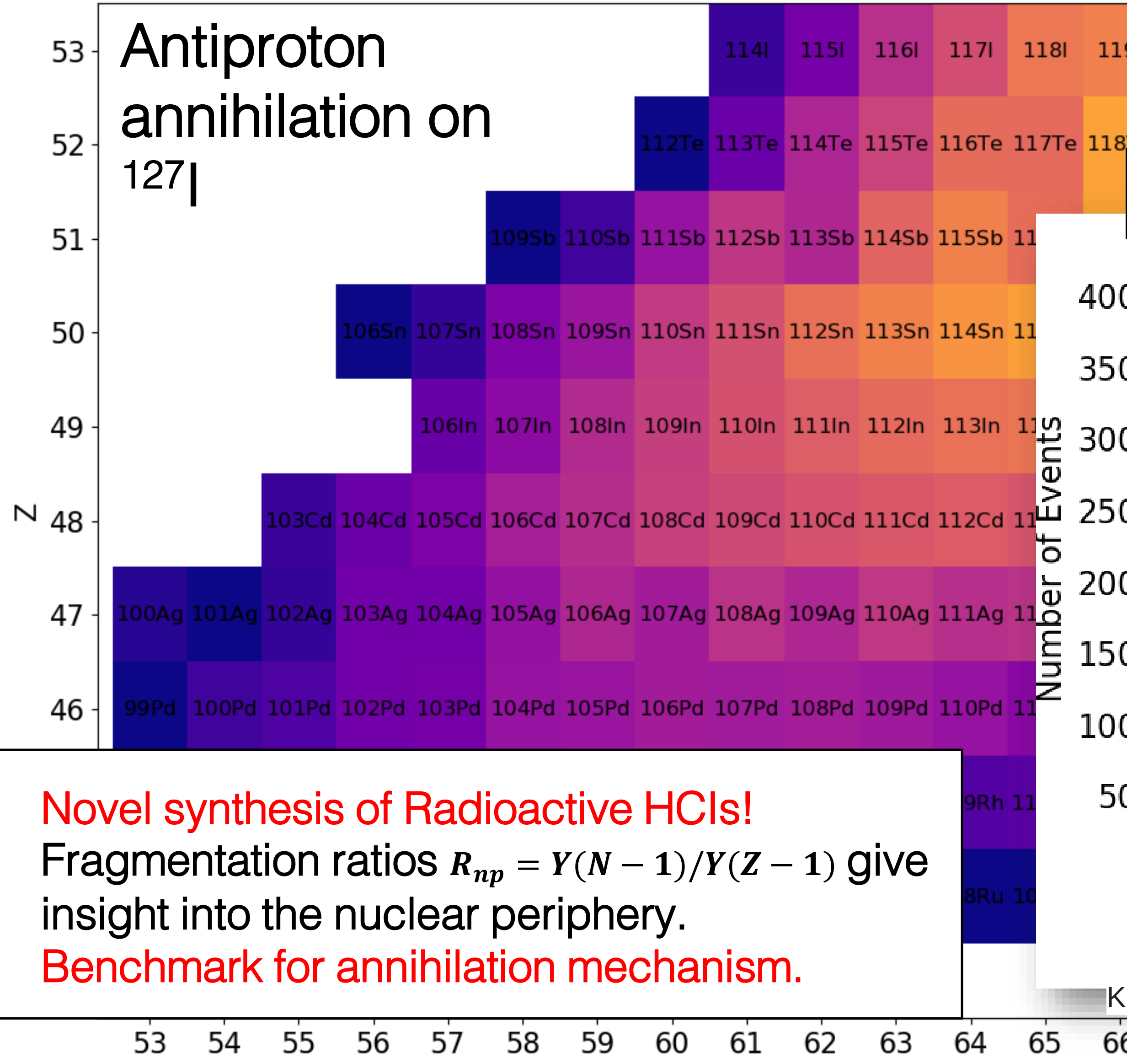
See poster by Jakub Zieliński!



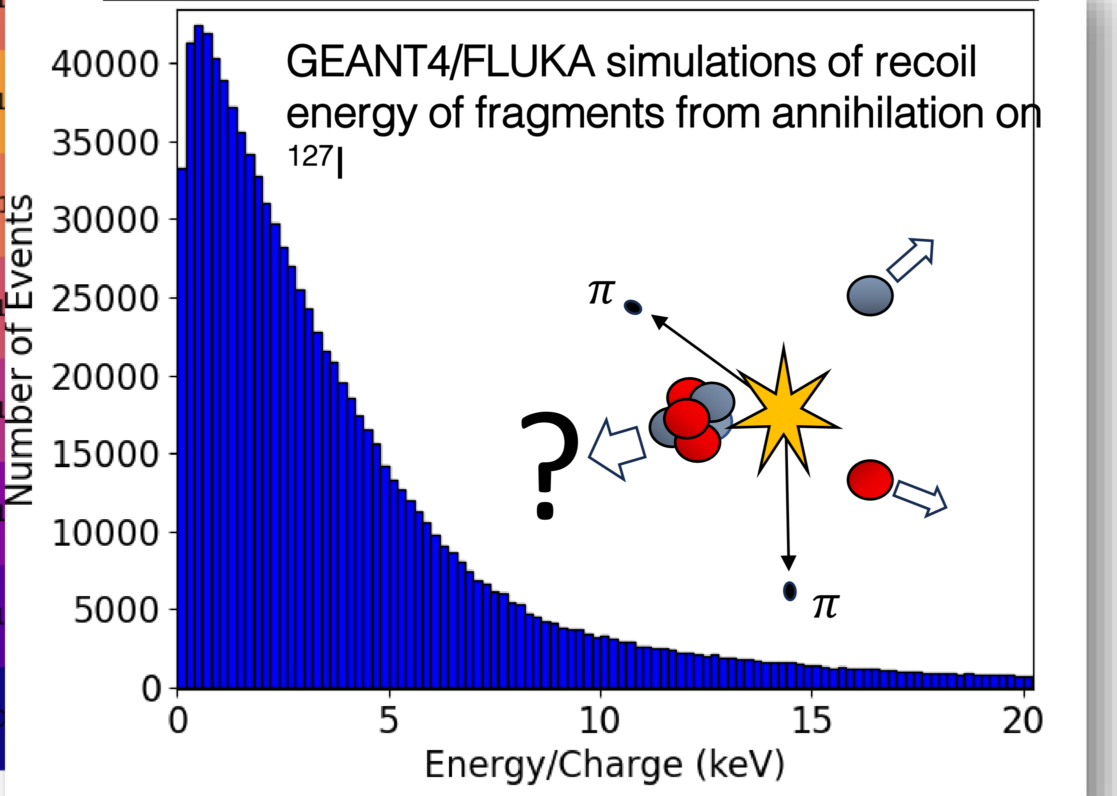
Annihilation on nucleus results in the formation of Highly Charged (radioactive) Ions (HCIs)

What about the resulting nuclear fragments?

$R_{np} = Y(N-1)/Y(Z-1)$



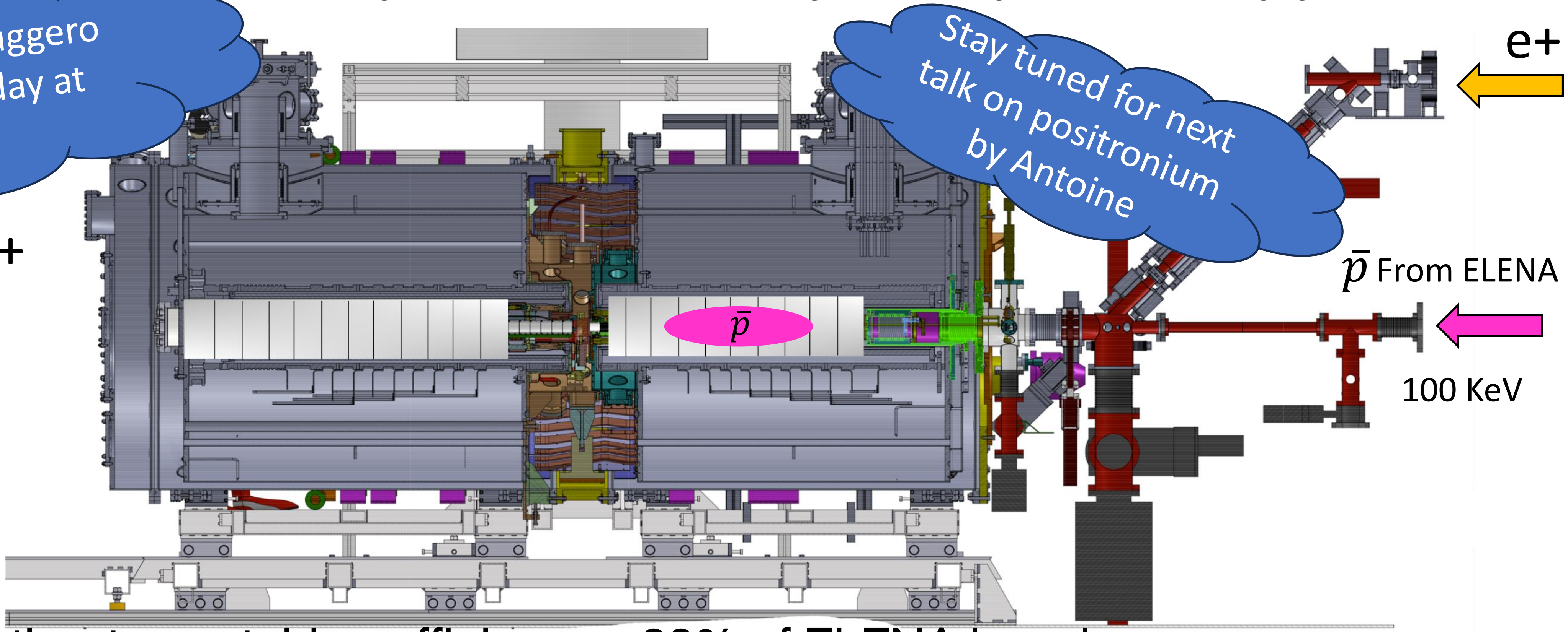
Can we capture these fragments?



Kornakov, Georgy, et al *Physical Review C* 107.3 (2023): 034314.

- Novel synthesis of Radioactive HCIs!
- Fragmentation ratios $R_{np} = Y(N-1)/Y(Z-1)$ give insight into the nuclear periphery.
- Benchmark for annihilation mechanism.

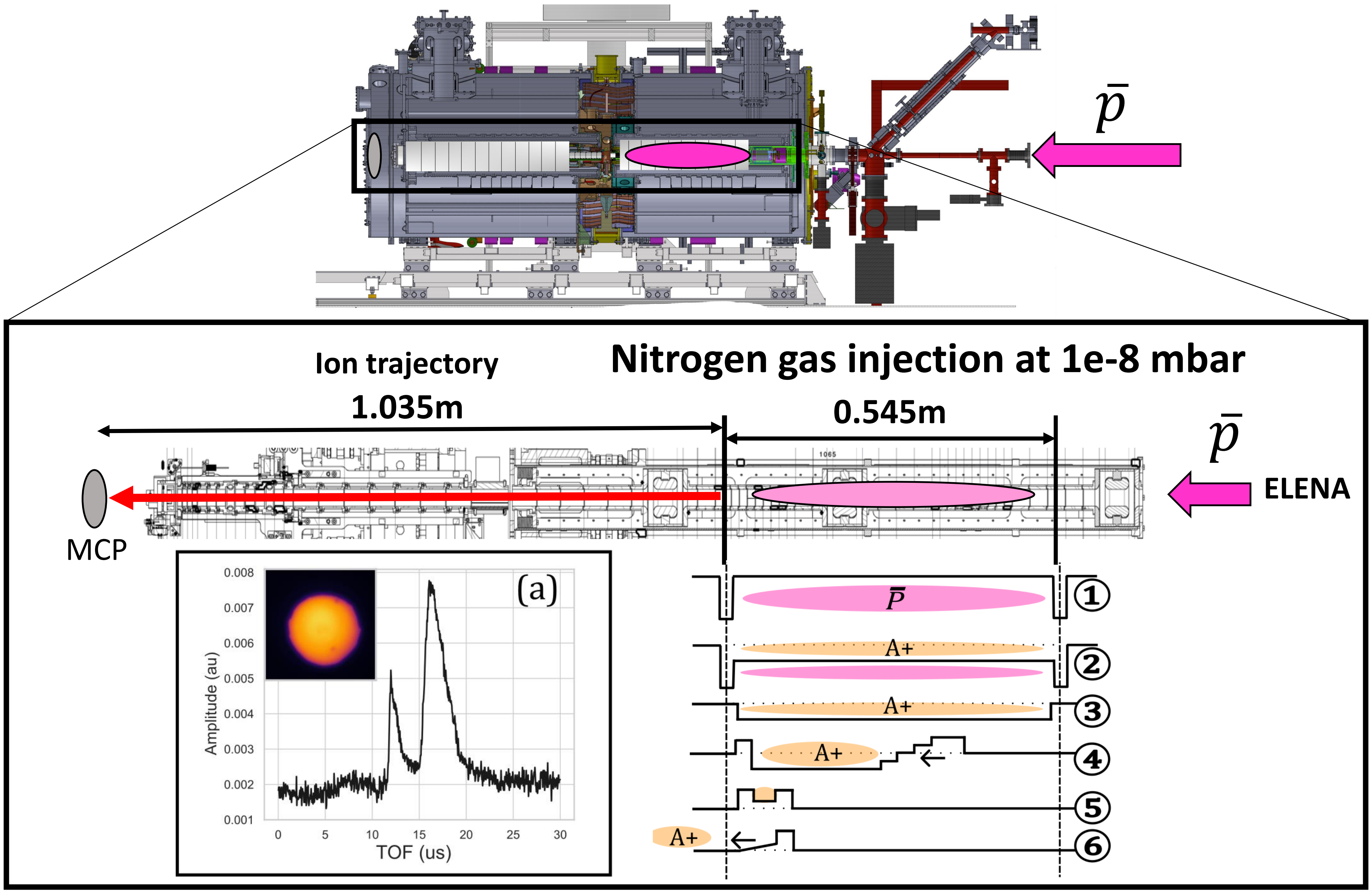
The Antimatter Experiment: Gravity, Interferometry and spectroscopy



- Record antiproton catching efficiency >80% of ELENA bunch.
- Research focus: Gravitational influence on anti-hydrogen, positronium physics and recently antiprotonic atoms.

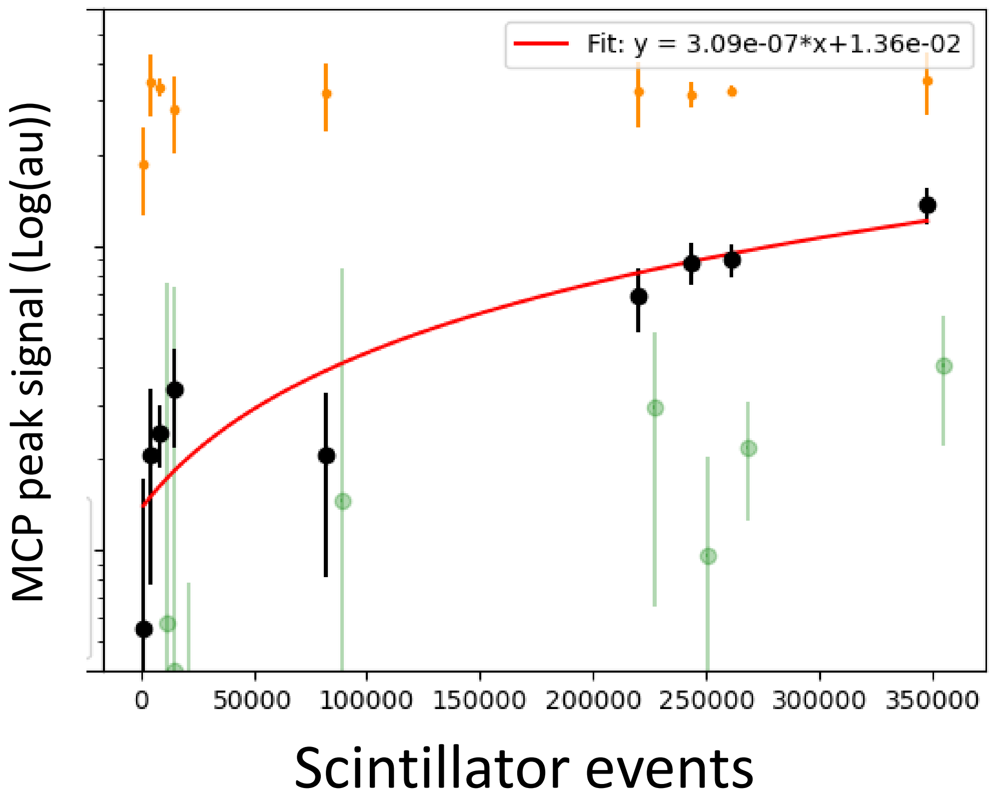
Can we capture and study the annihilation fragments using AEgIS?

Capturing positive ions formed from antiproton annihilations

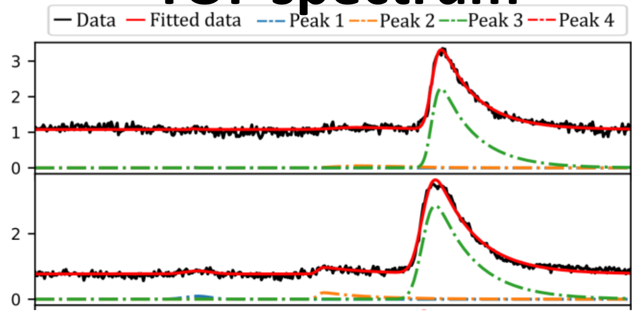


TOF spectrum vs scintillator signal

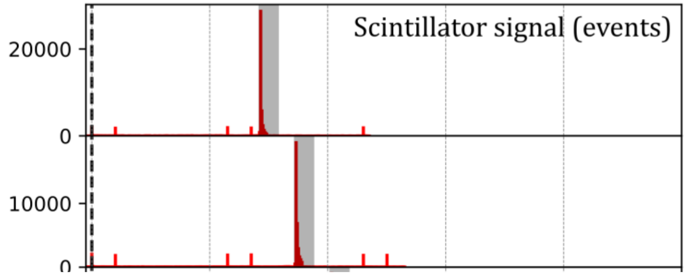
- Observation of a **TOF signal vs antiproton annihilation events** on nitrogen.
- Signal observed for **low energy antiprotor <1 keV**.



TOF spectrum



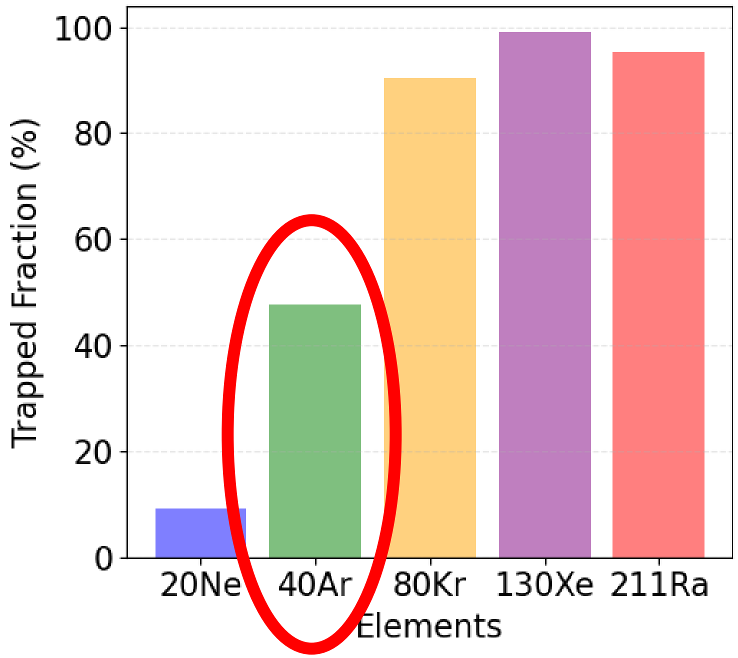
Pion events

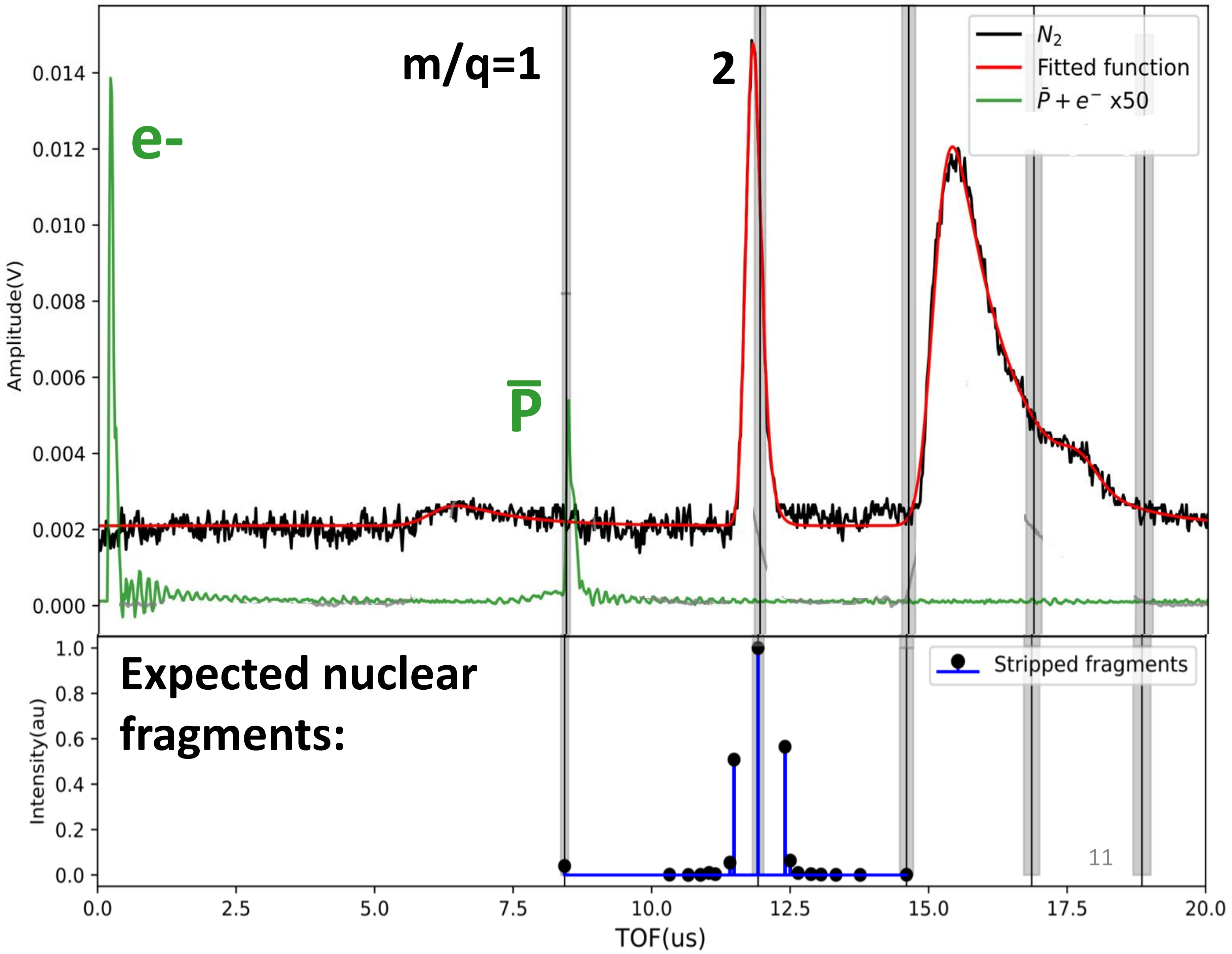


Identification of trapped ions formed from antiproton annihilation

- TOF spectrum calibrated using e-, $\bar{p}$ and H+.
- Ions trapped with m/q=2.0(1)
- Expected fragments from GEANT4 simulations: ($^{14}N^{7+}$) ,$^{12}C^{6+}$, $^{10}B^{5+}$, $^{6}Li^{3+}$, $^{4}He^{2+}$,..

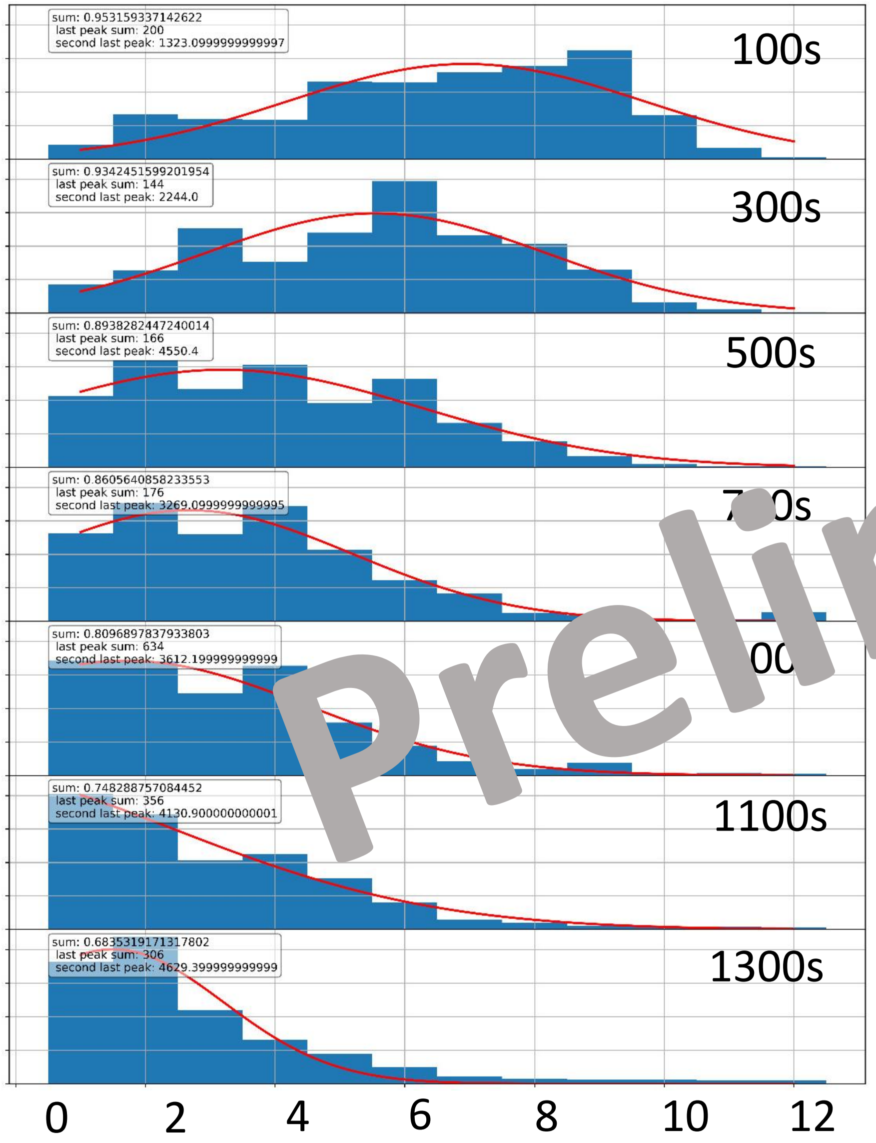
Heavier nobel gases:



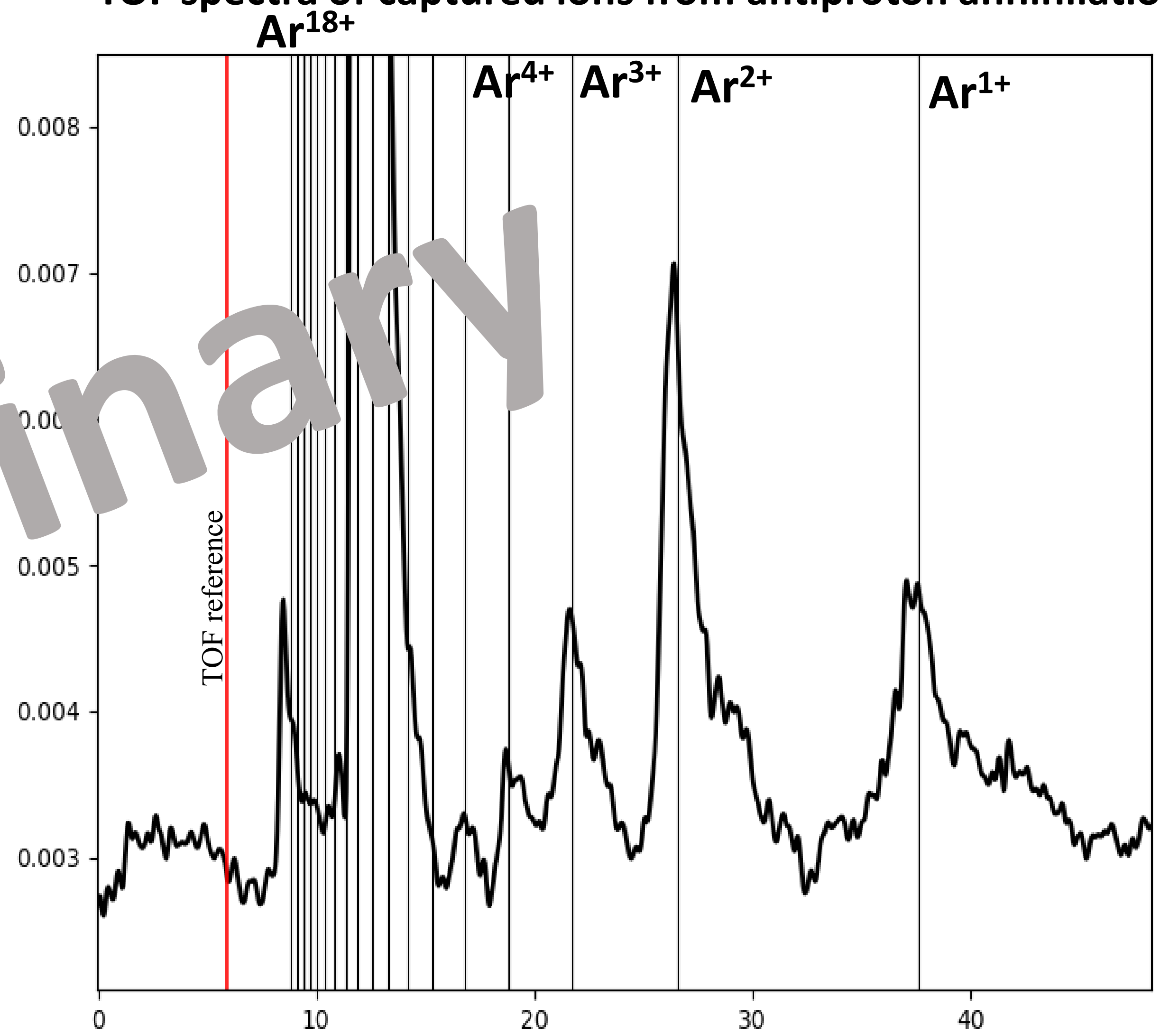


Argon campaign

Measurement of antiproton energy loss

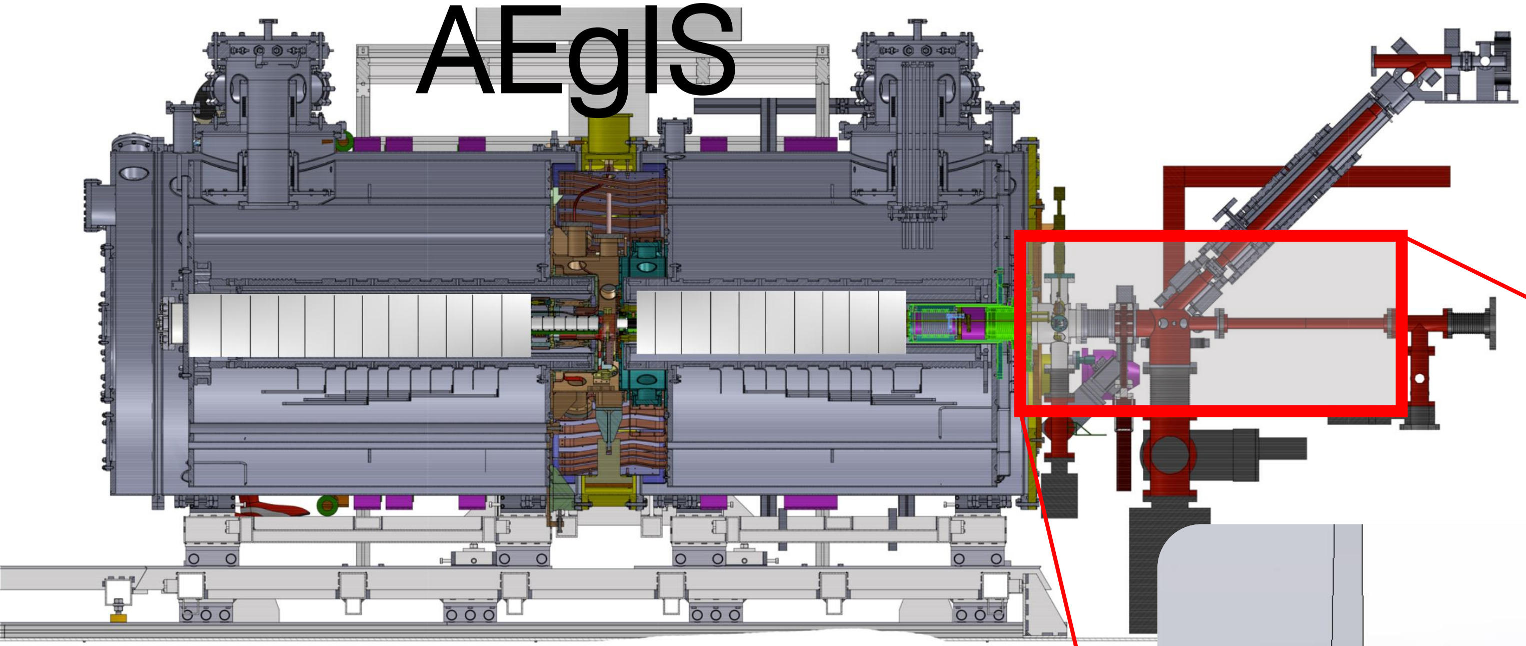


TOF spectra of captured ions from antiproton annihilation

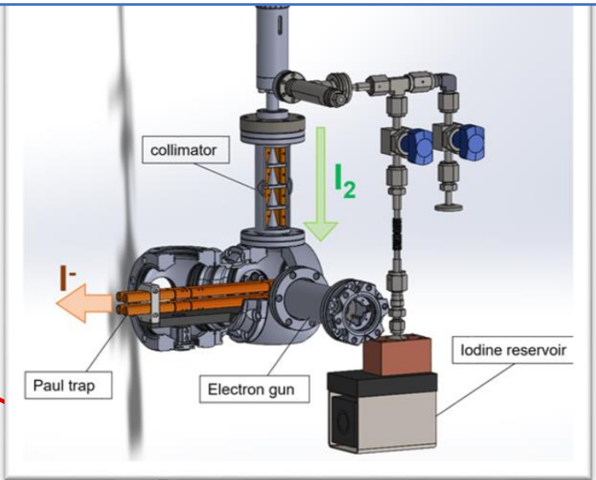


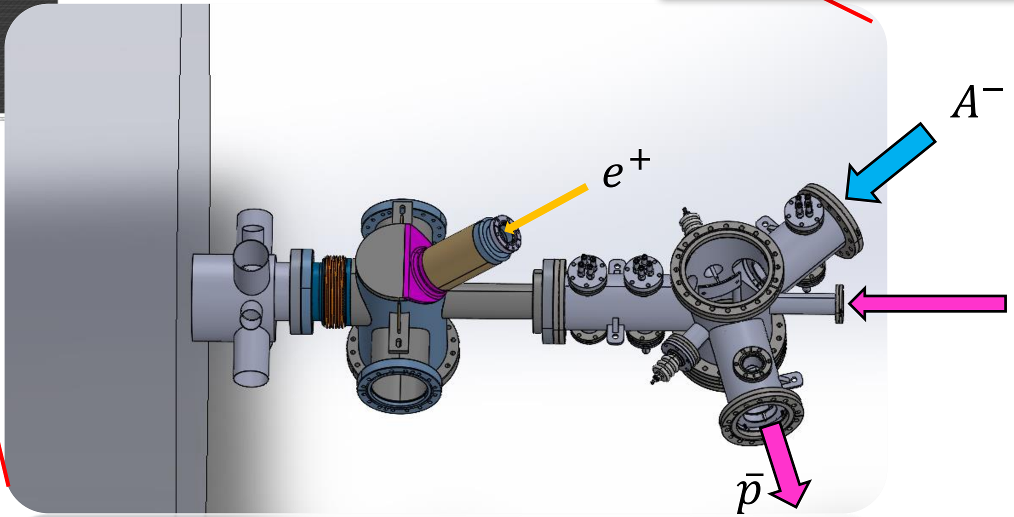
Analysis by Krzysztof Calik and Inkyu Hwang

Ongoing developments at AEgIS



Iodine anion source to be installed



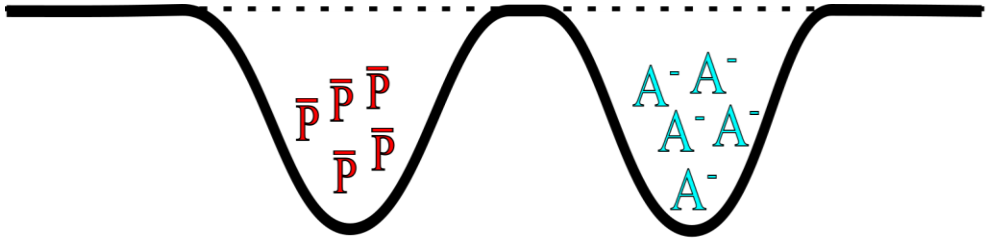


- Refining nested-trap ion TOF procedure (improving TOF resolution)
- MR-TOF
- Cooling of HCIs (positrons, laser cooled ions)
- RF mass spectroscopy

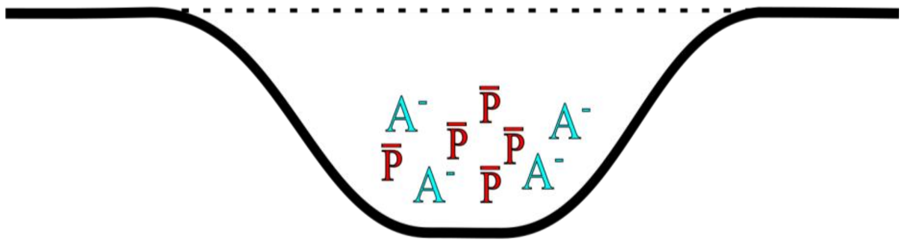
Slow extraction for **antiprotonic atom x-ray spectroscopy**, detector testing etc.

Outlook: Towards the laser triggered synthesis

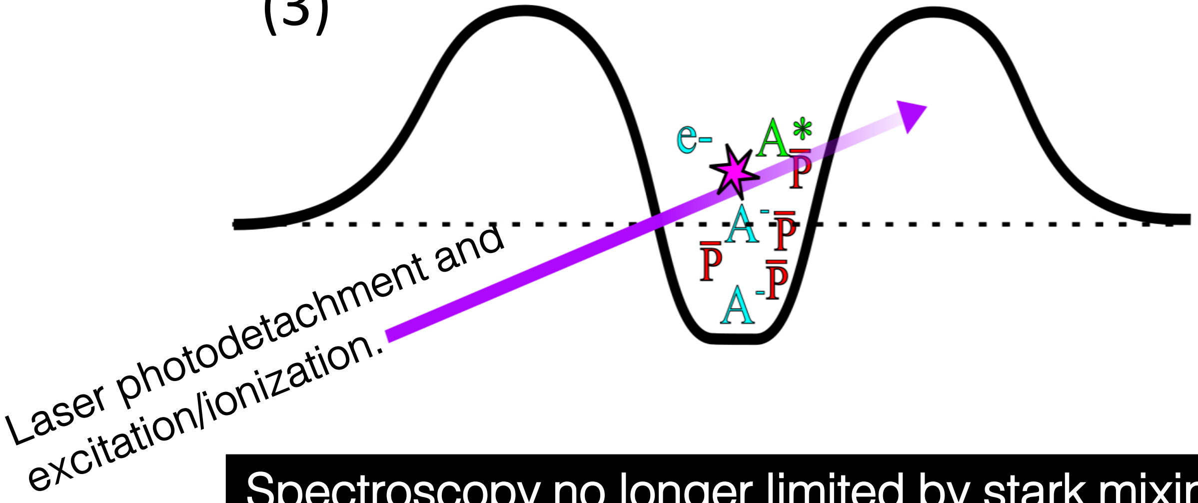
(1) Cotrapping of anions and antiprotons cooled using electrons.



(2) Mixing anions with antiprotons.

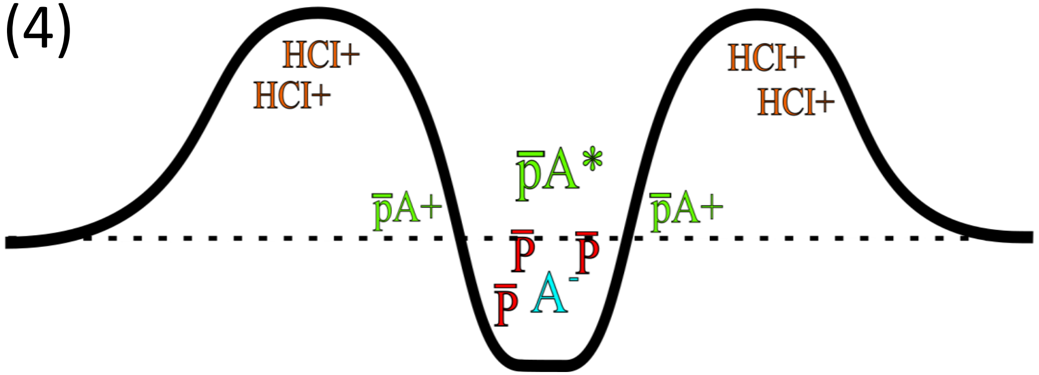


(3) Nested trap is created.



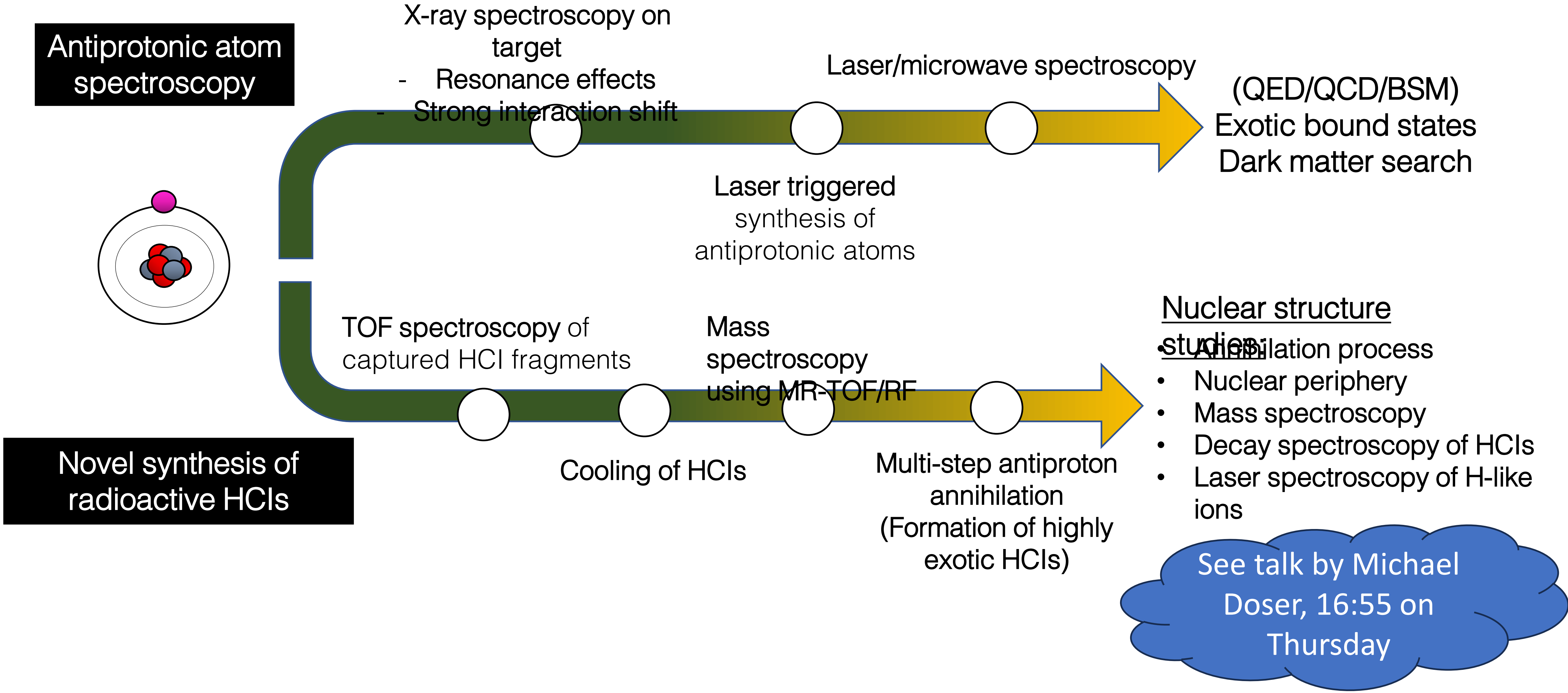
Spectroscopy no longer limited by stark mixing!

(4) Capture of HCI fragments after annihilation.



Summary and outlook:

New program at AEgIS focusing on the controlled synthesis and study of antiprotonic atoms and novel formation of HCIs:



Thank you for your attention

On behalf of the AEGIS collaboration

INFN

PAN

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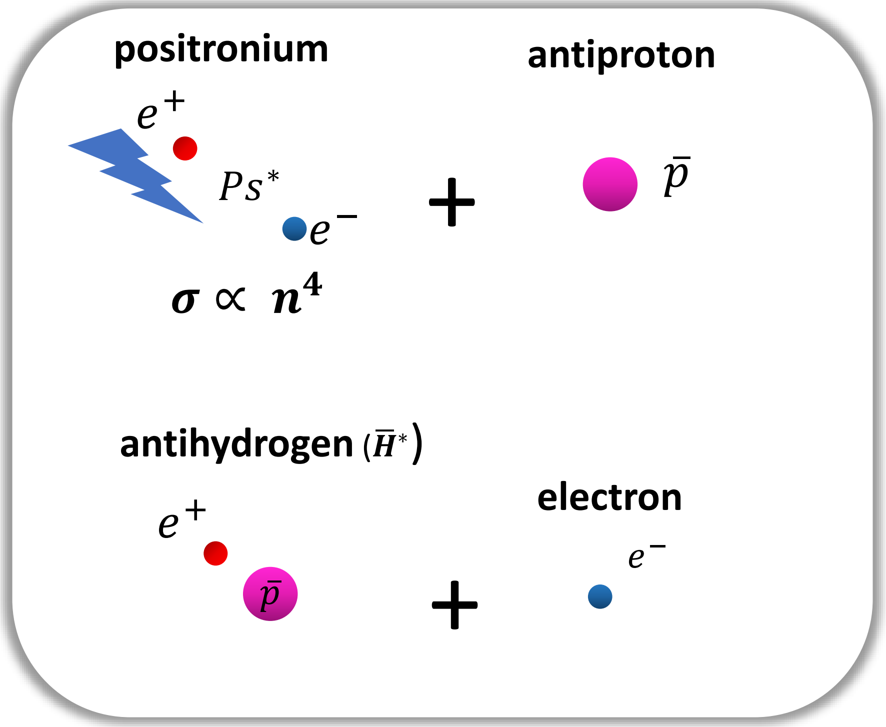
Lyon 1

TIFPA Trento Institute for Fundamental Physics and Applications

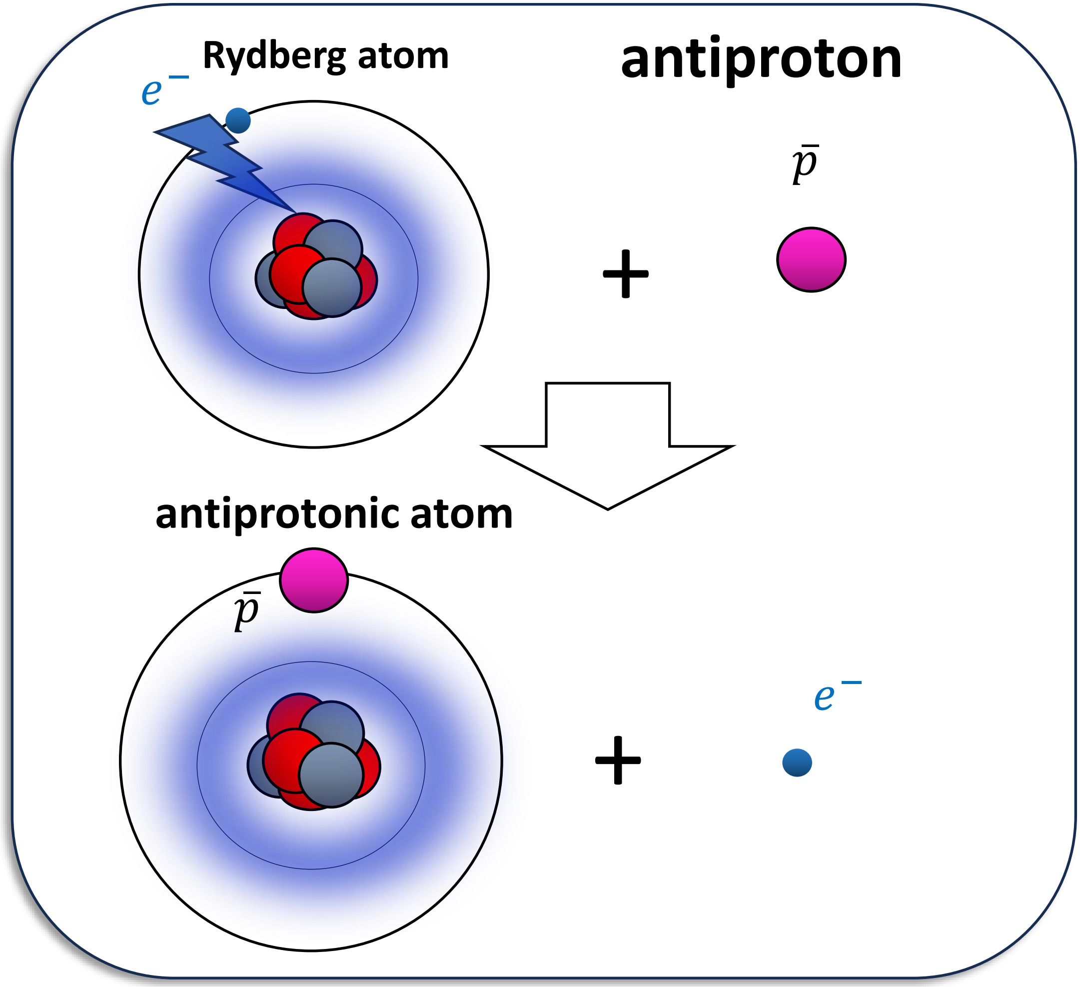
Outlook: Controlled synthesis of antiprotonic atoms using charge-exchange with Rydberg atoms

Charge exchange reaction:

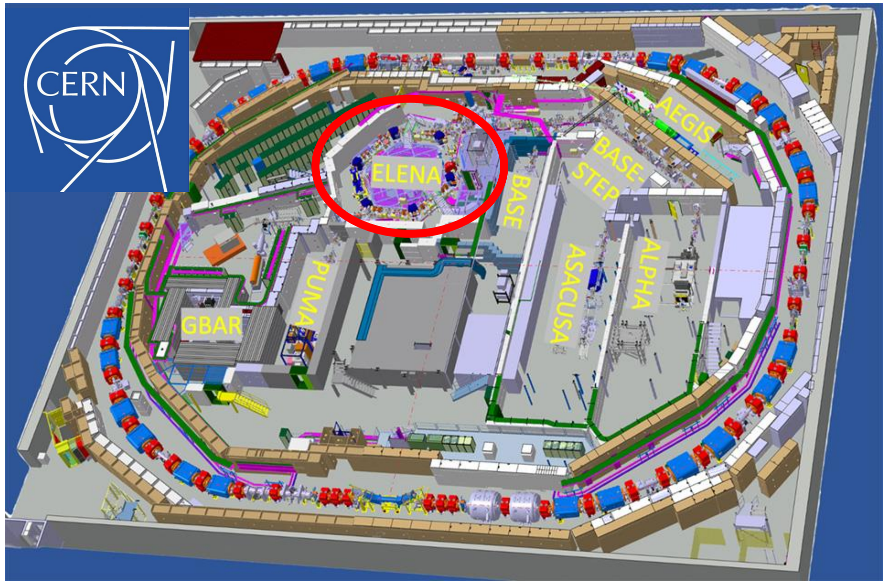
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

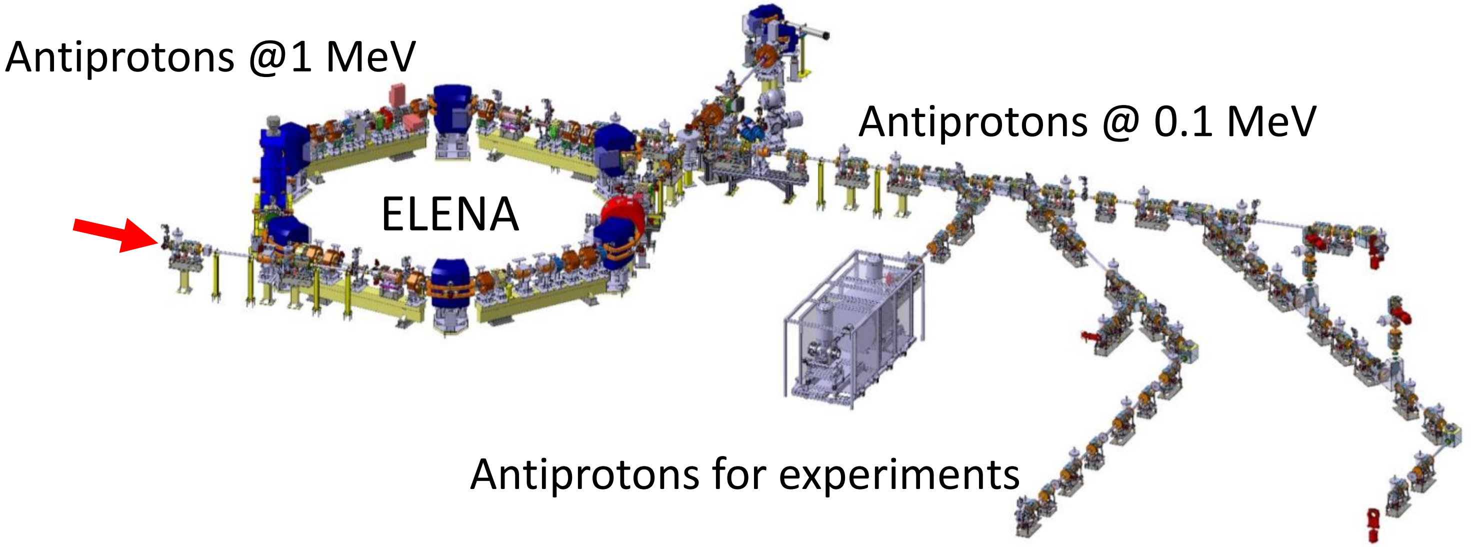


Charge-exchange with Rydberg atom



Experiements at the Antimatter factory





ALPHA

Trap
Antihydrogen trapping
Spectroscopy
Gravity

ASACUSA

Beam
Antiprotonic atoms
Collisions
Antihydrogen
Spectroscopy

AEGIS

Beam
Pulsed production
of antihydrogen
Gravity
Positronium
Antiprotonic atoms+HCIs

BASE

Trap
Mass spectroscopy
$\bar{p}$ magnetic moment

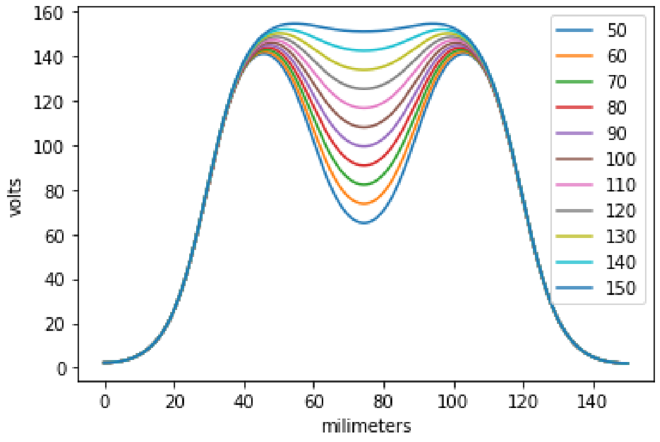
GBAR

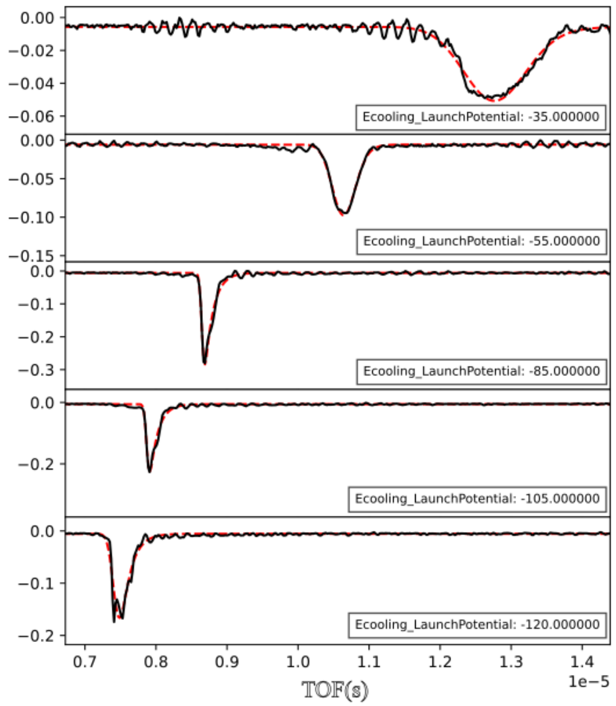
Trap
Gravity
Lamb-shift

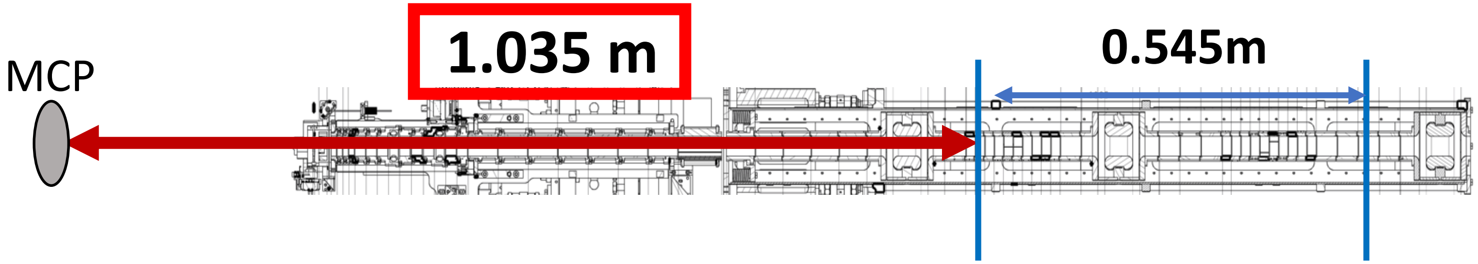
PUMA

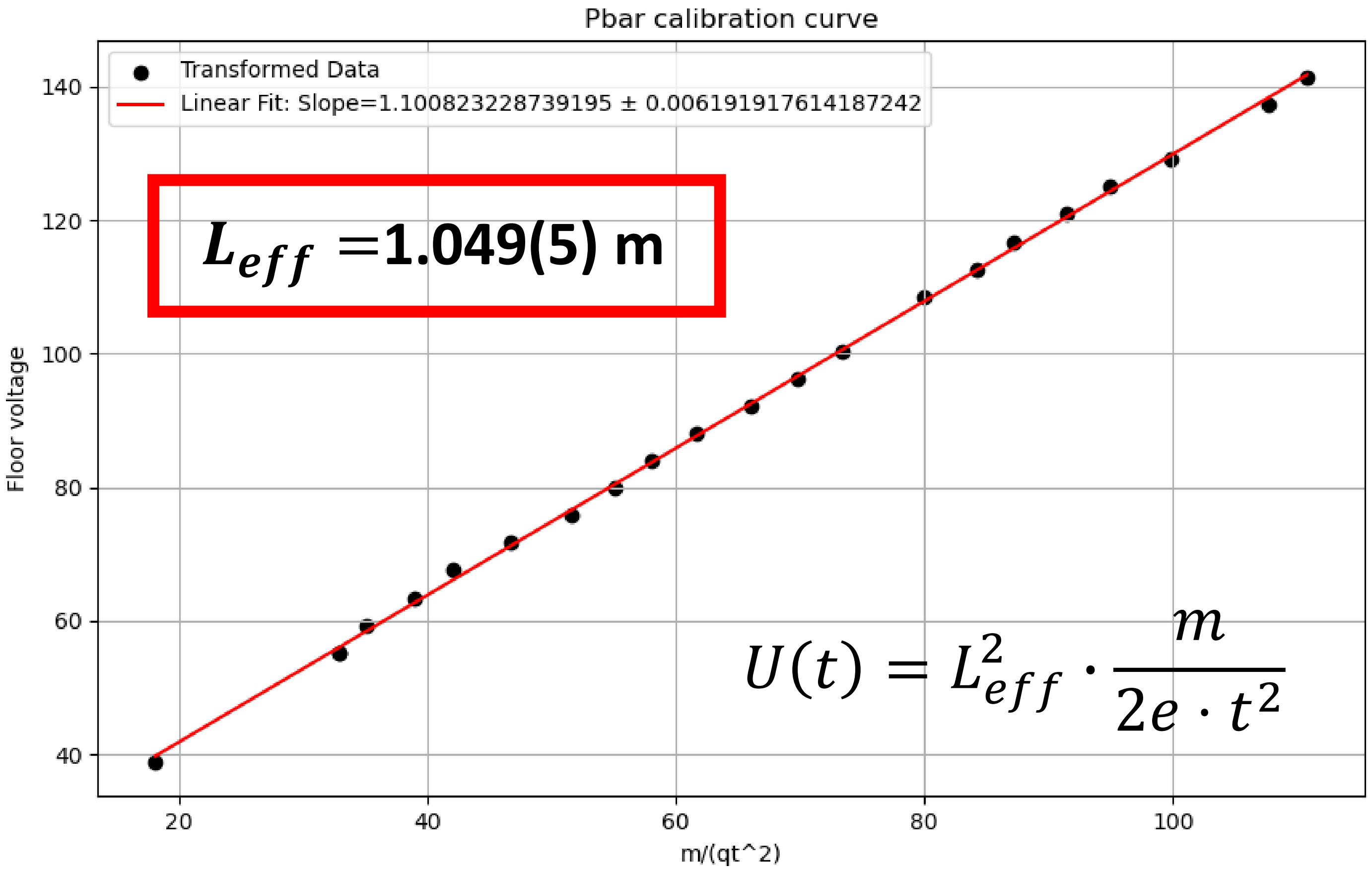
Movable trap
for antiprotons
Study of exotic nuclei

TOF calibration

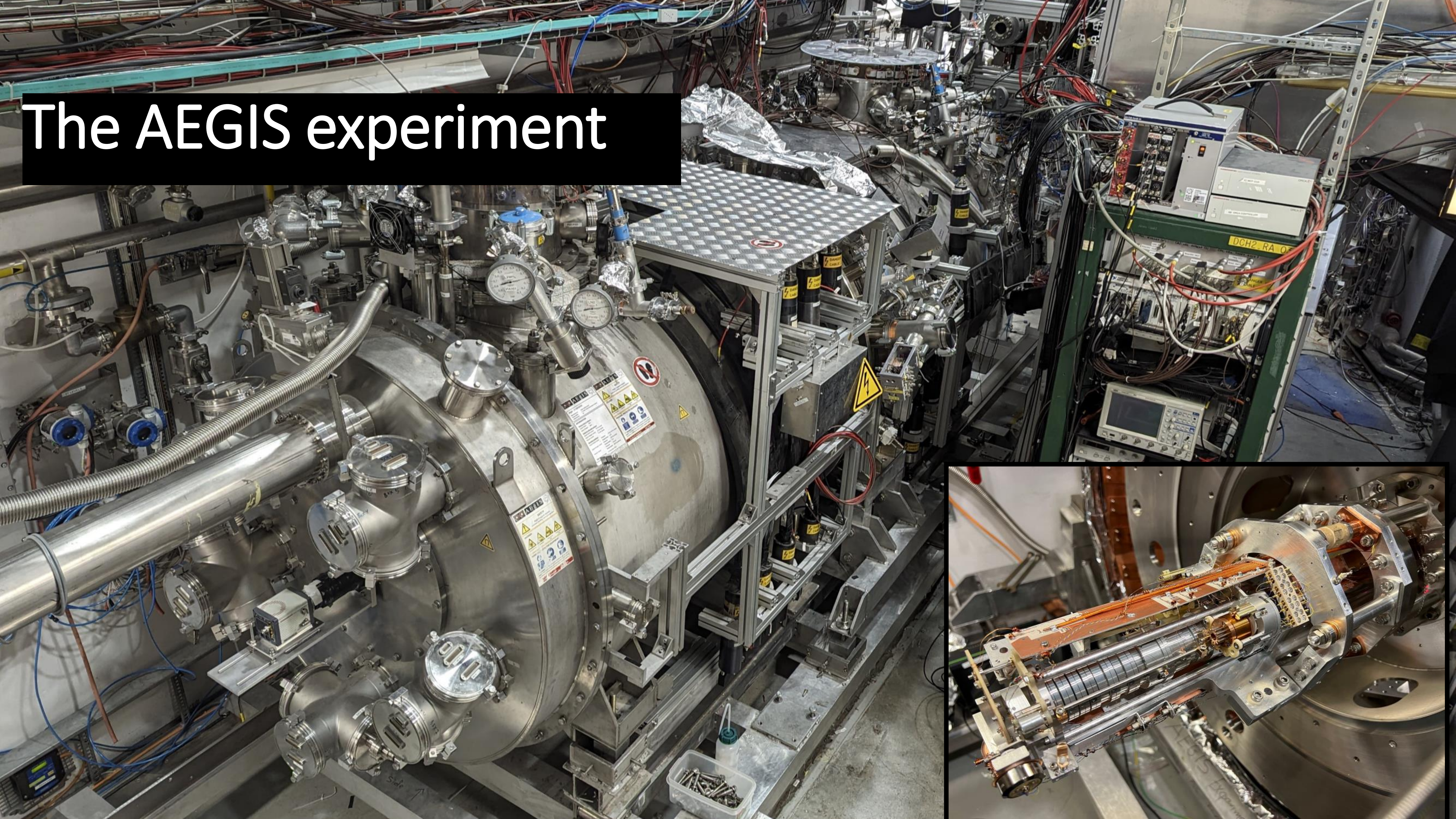






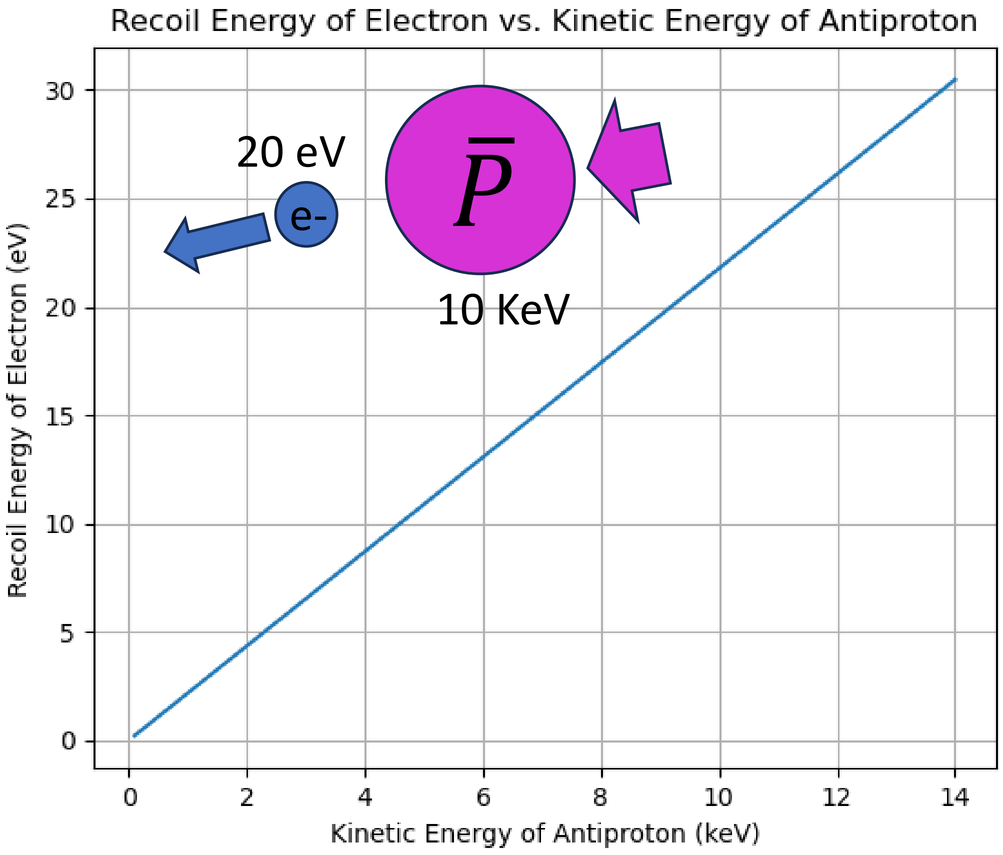


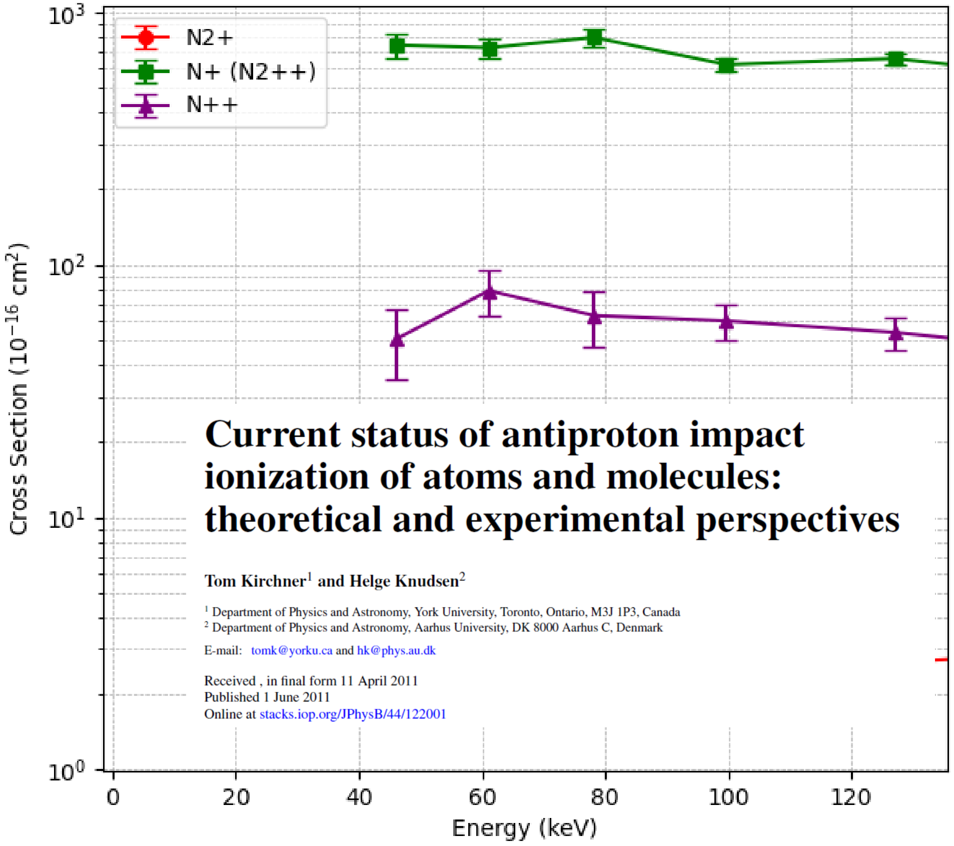
The AEGIS experiment



Collissional ionization with antiprotons?

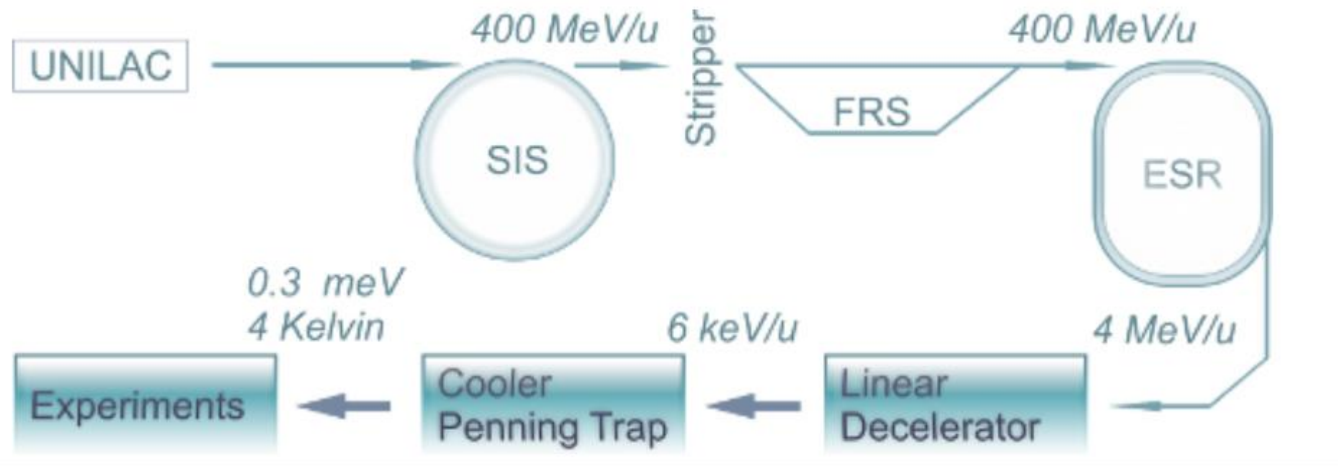
3000 eV is required to form N^{7+} from the N_2 molecule





Traditional HCI formation at radioactive beam facilities:

High energy beam through stripper foil:



Electron beam ionization:

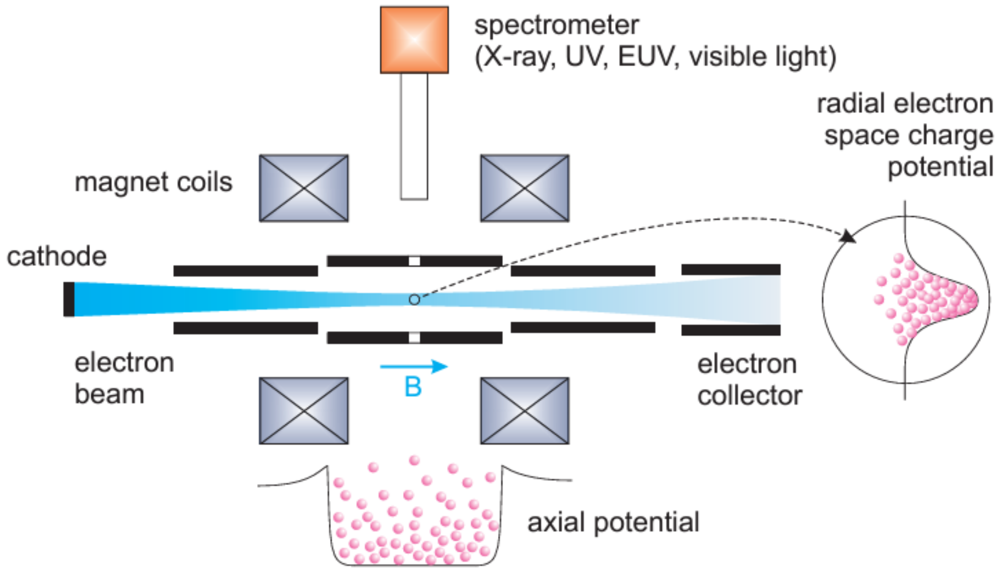
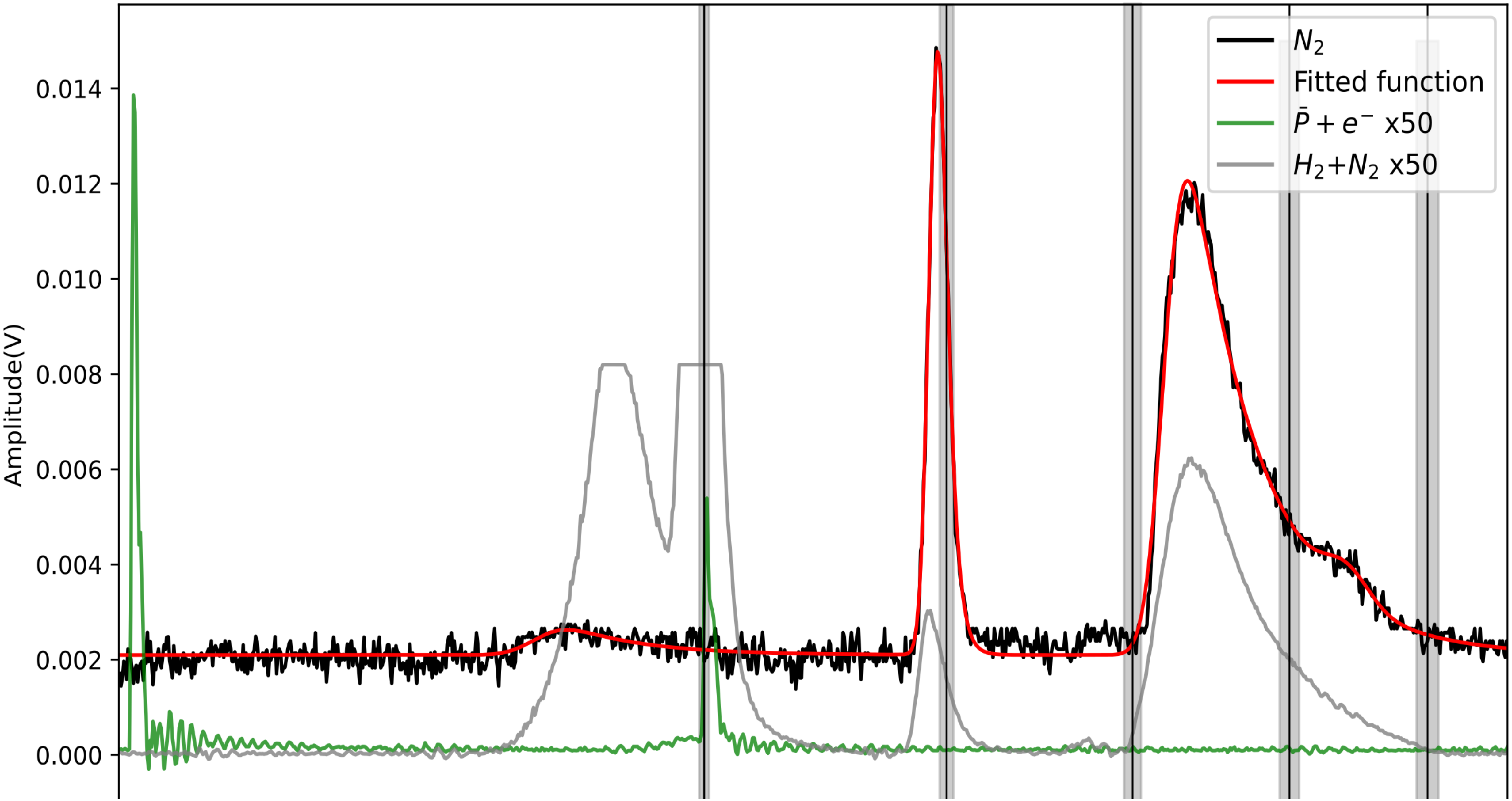


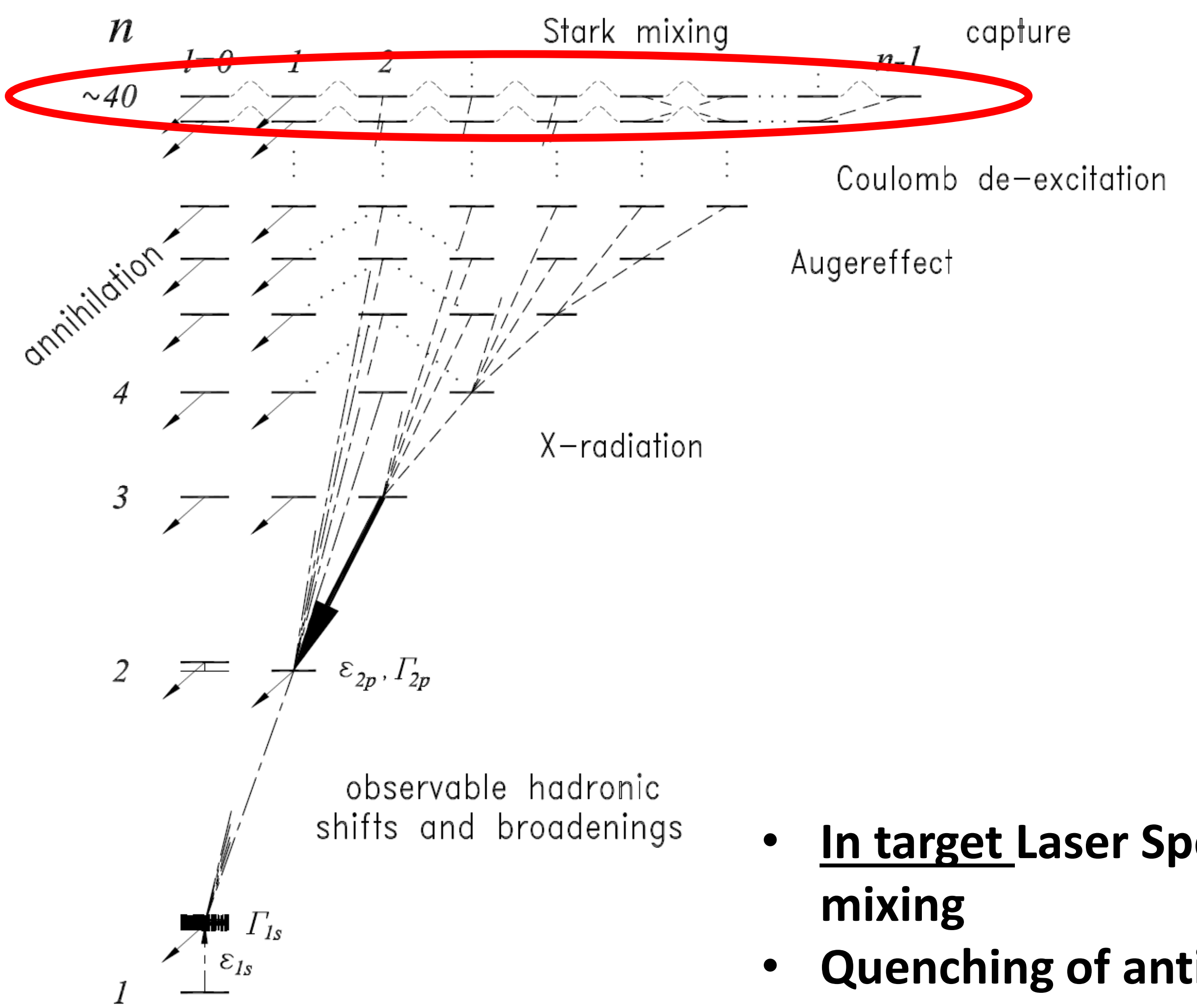
Fig. 2: Principle of operation of an EBIS

Zschornacka, G., M. Schmidt, and A. Thorn. "Electron beam ion

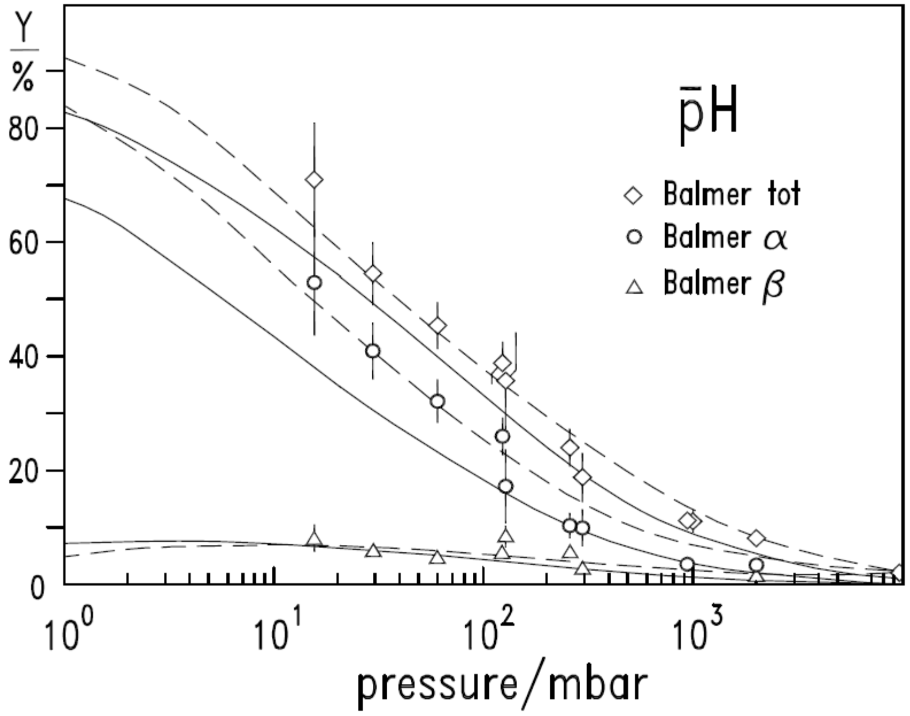


Amplitude(V)
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
N_2
Fitted function
$\bar{P} + e^-$ x50
H_2+N_2 x50

The life of an antiprotonic atom



Gotta, Detlev. "Light antiprotonic atoms." *Physics with Ultra Slow Antiproton Beams* 793 (2005): 169-182.



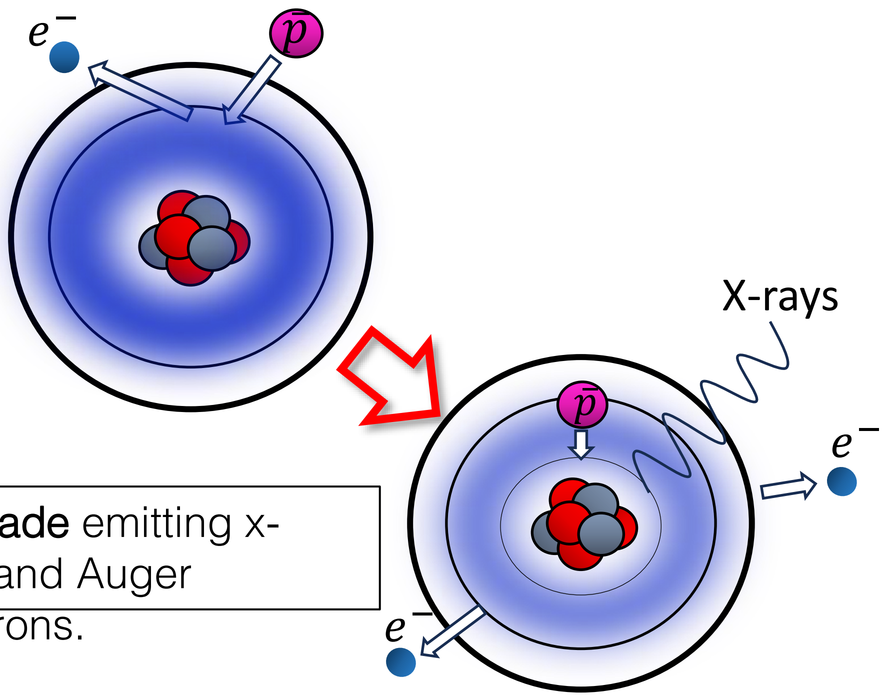
- **<u>In target</u> Laser Spectroscopy <u>limited to n<40</u> states due to stark mixing**
- **Quenching of antiprotonic Rydberg states in material prevent studies of medium to heavy antiprotonic nuclei**

Lower pressure needed to reduce quenching of Rydberg states

The life of an antiprotonic atom

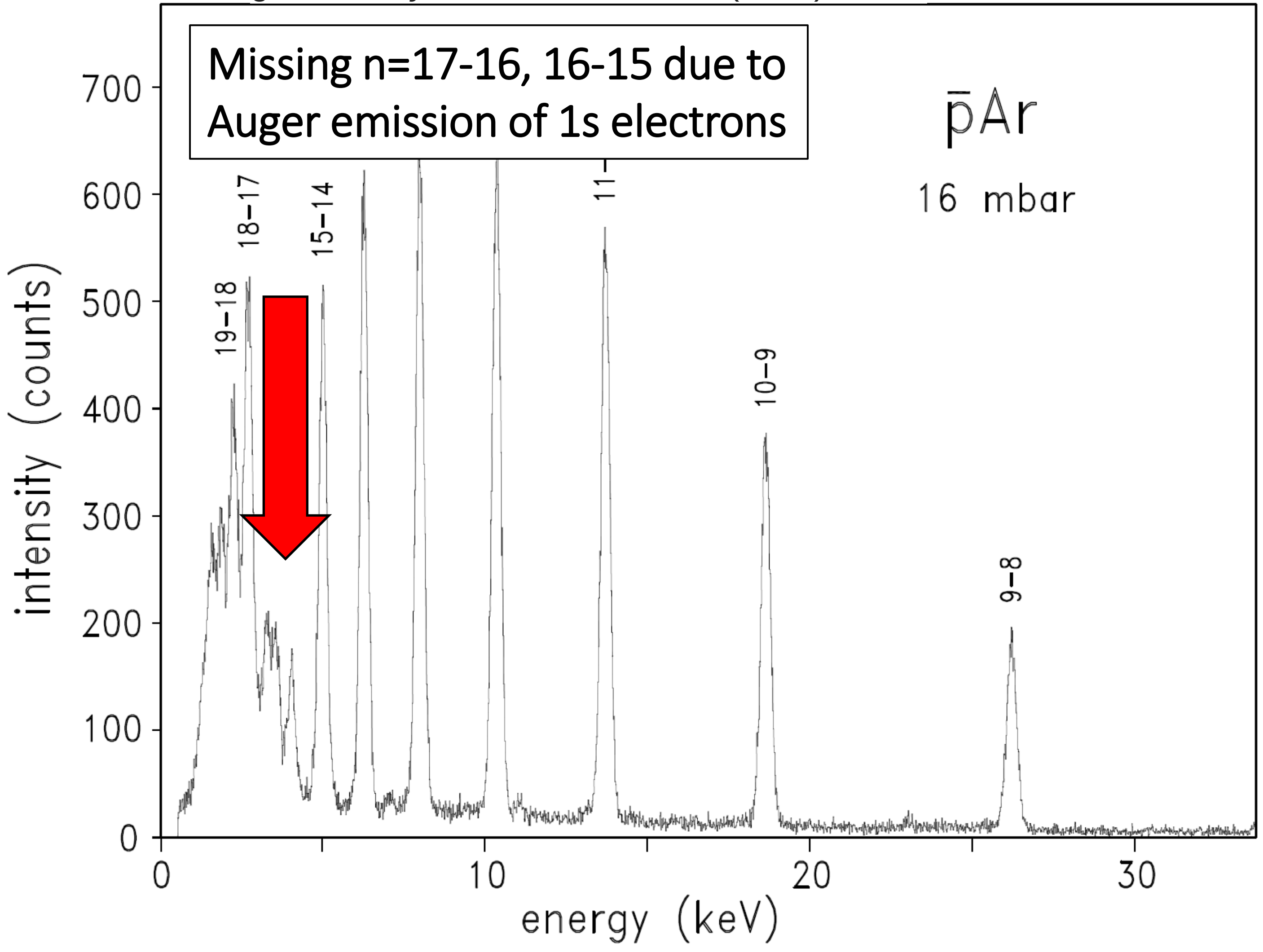
Capture of the antiproton in a **high-n Rydberg state**.

Cascade emitting x-rays and Auger electrons.

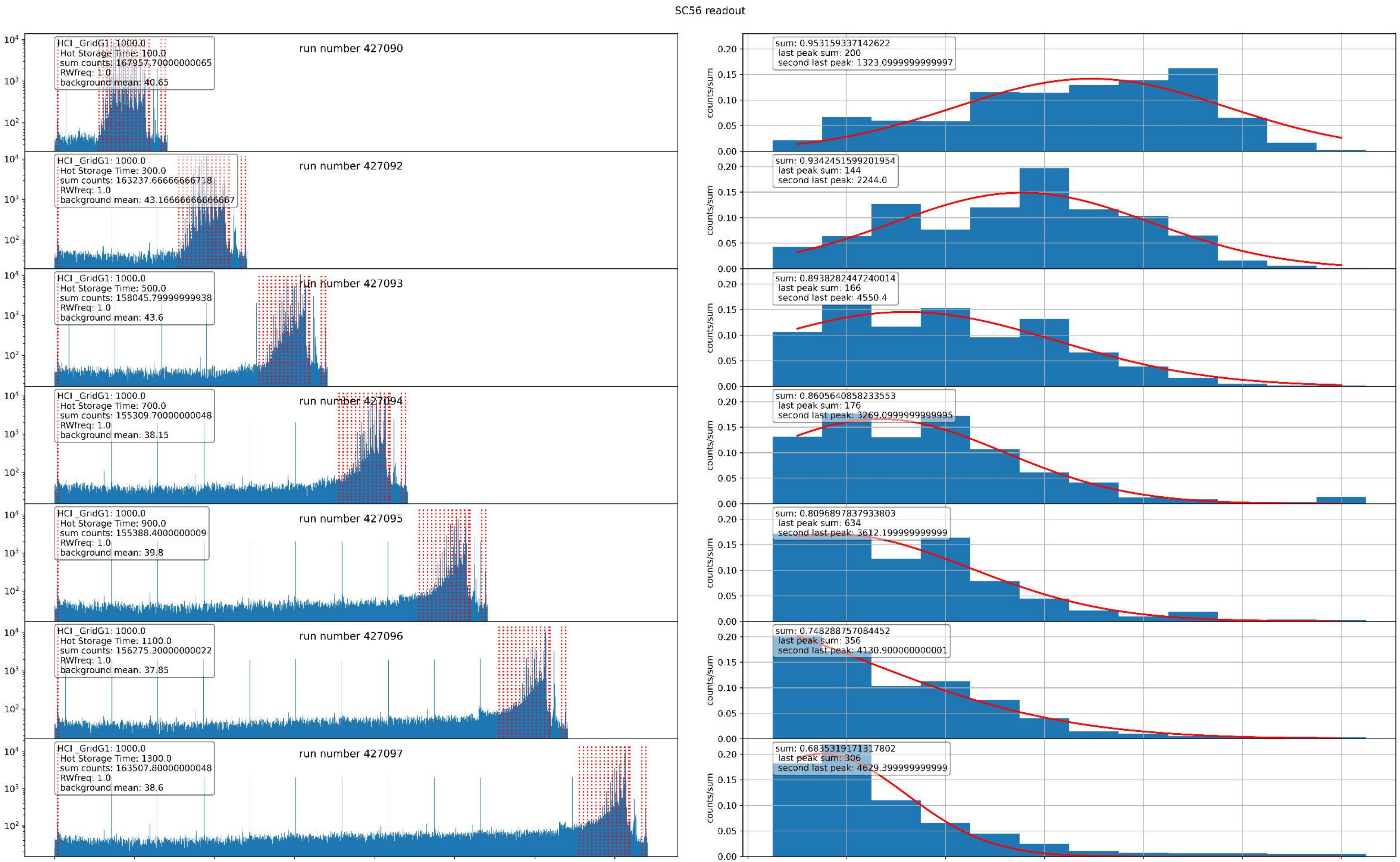


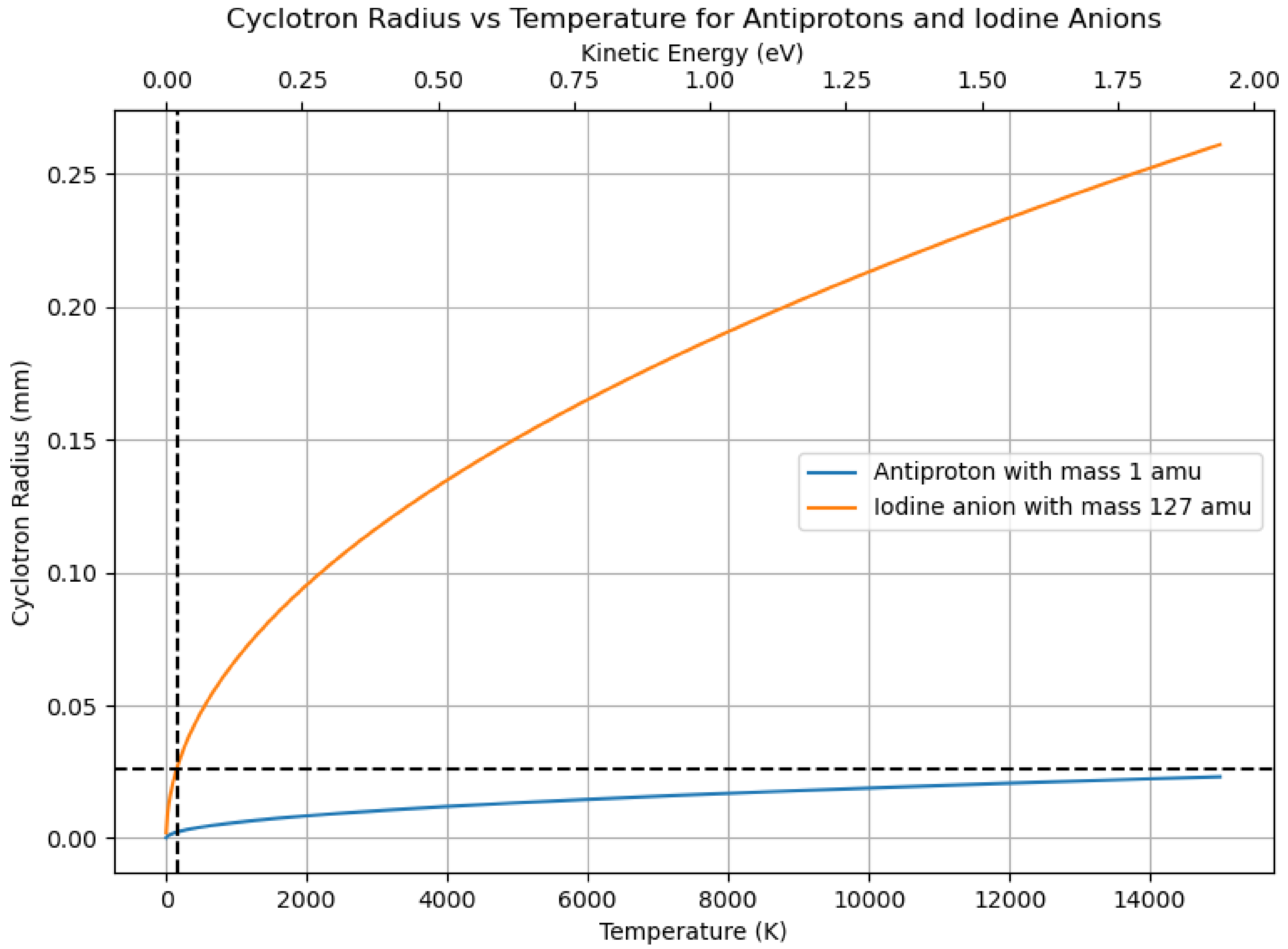
Auger ejected electrons

Bacher, R., et al. "Degree of ionization in antiprotonic noble gases." *Physical Review A* 38.9 (1988): 4395.



Auger ejection during cascade stripps the atom of electrons

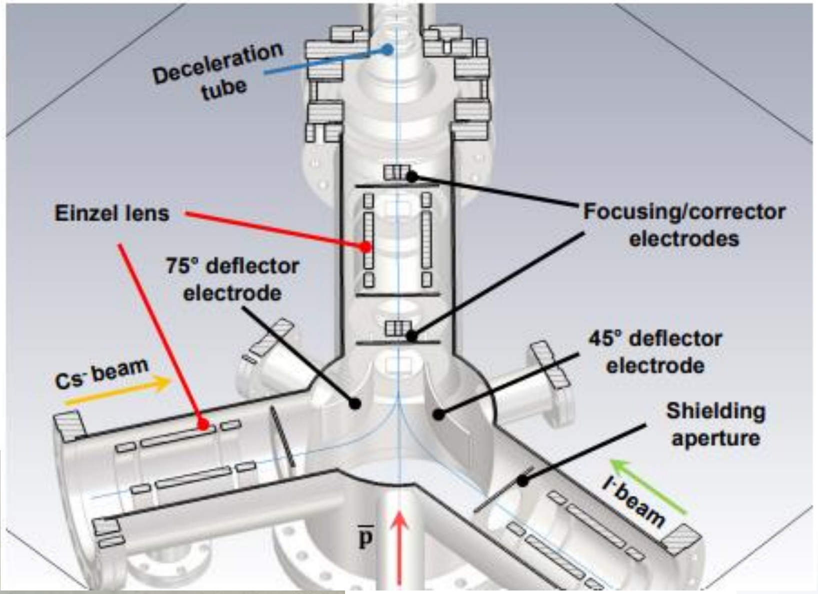

SC56 readout
HCI _GridG1: 1000.0
Hot Storage Time: 100.0
sum counts: 167957.70000000065
RWfreq: 1.0
background mean: 40.65
run number 427090
sum: 0.953159337142622
last peak sum: 200
second last peak: 1323.0999999999997
HCI _GridG1: 1000.0
Hot Storage Time: 300.0
sum counts: 163237.66666666718
RWfreq: 1.0
background mean: 43.16666666666667
run number 427092
sum: 0.9342451599201954
last peak sum: 144
second last peak: 2244.0
HCI _GridG1: 1000.0
Hot Storage Time: 500.0
sum counts: 158045.79999999938
RWfreq: 1.0
background mean: 43.6
run number 427093
sum: 0.8938282447240014
last peak sum: 166
second last peak: 4550.4
HCI _GridG1: 1000.0
Hot Storage Time: 700.0
sum counts: 155309.70000000048
RWfreq: 1.0
background mean: 38.15
run number 427094
sum: 0.8605640858233553
last peak sum: 176
second last peak: 3269.0999999999995
HCI _GridG1: 1000.0
Hot Storage Time: 900.0
sum counts: 155388.4000000009
RWfreq: 1.0
background mean: 39.8
run number 427095
sum: 0.8096897837933803
last peak sum: 634
second last peak: 3612.199999999999
HCI _GridG1: 1000.0
Hot Storage Time: 1100.0
sum counts: 156275.30000000022
RWfreq: 1.0
background mean: 37.85
run number 427096
sum: 0.748288757084452
last peak sum: 356
second last peak: 4130.900000000001
HCI _GridG1: 1000.0
Hot Storage Time: 1300.0
sum counts: 163507.80000000048
RWfreq: 1.0
background mean: 38.6
run number 427097
sum: 0.6835319171317802
last peak sum: 306
second last peak: 4629.399999999999
counts/sum
0.00
0.05
0.10
0.15
0.20
10^2
10^3
10^4

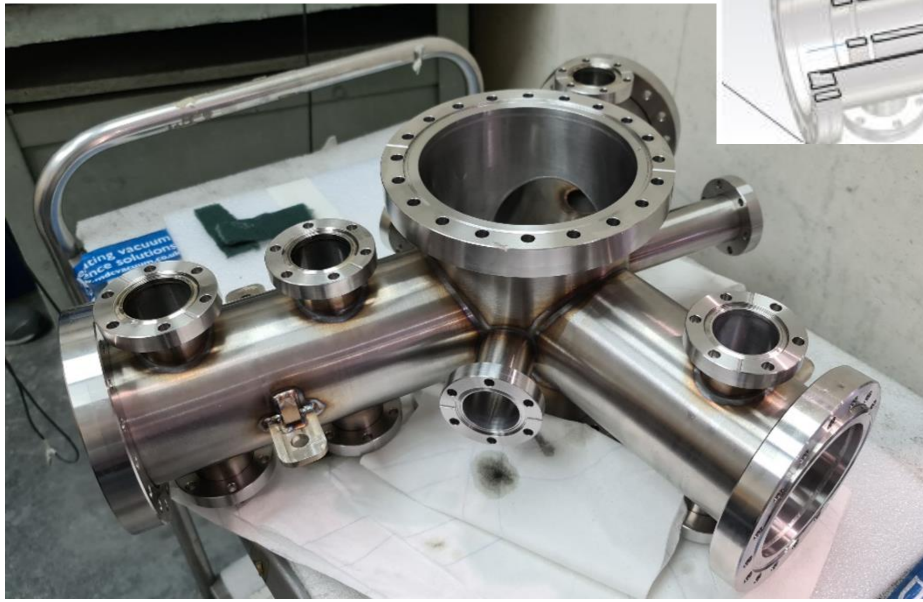

Cyclotron Radius vs Temperature for Antiprotons and Iodine Anions
Kinetic Energy (eV)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Cyclotron Radius (mm)
0.00
0.05
0.10
0.15
0.20
0.25
Antiproton with mass 1 amu
Iodine anion with mass 127 amu
0
2000
4000
6000
8000
10000
12000
14000
Temperature (K)

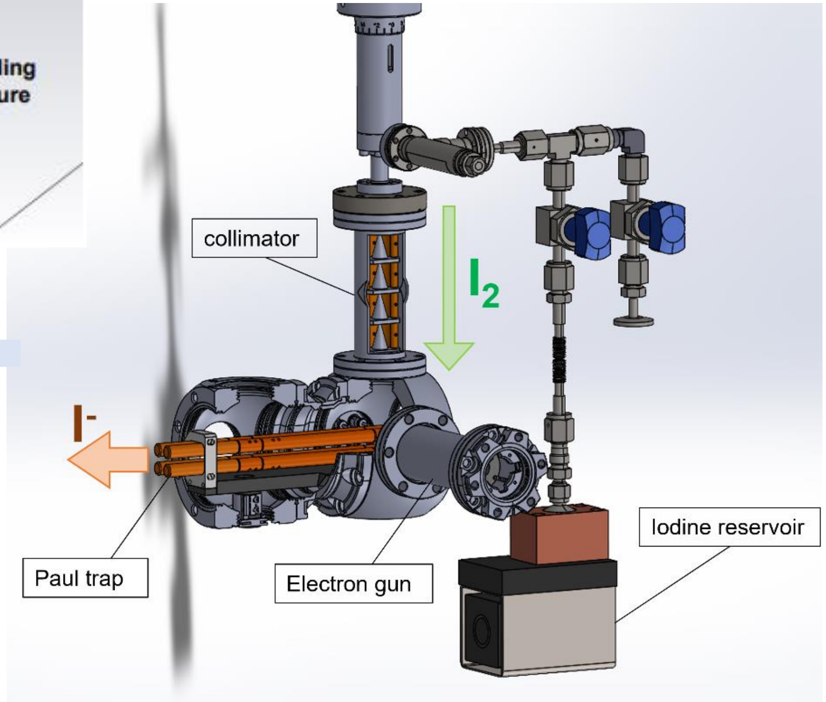
Antiprotonic atoms: setup of the ion injection beamline

Goal of the R&D: establish the techniques to form antiprotonic bound states.

On track for 2023

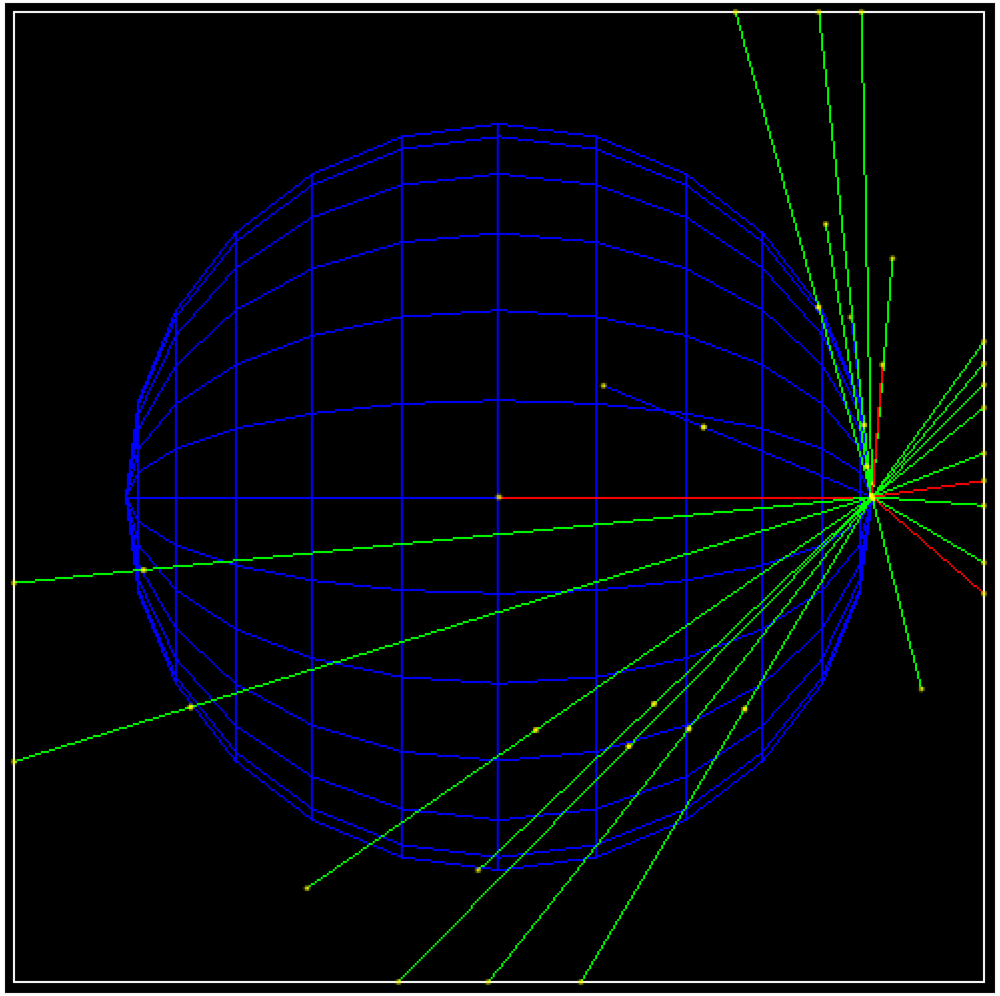






Simulation – Geant4 set up

- Antiproton is created inside a hollow sphere of 500 nm thickness of target material
- Target defined according to data from a config file (N,Z, density)
  - Simulation ran for different isotopes (over 3000 isotopes)
- 1M antiprotons with E=1 keV
- Physics List:
  - FTFP_BERT_HP



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