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University of Genova

University of Brescia

University of Pavia

ÖAW SMI Stefan Meyer Institute, Vienna

Pulsed Production of Antihydrogen in AEgIS

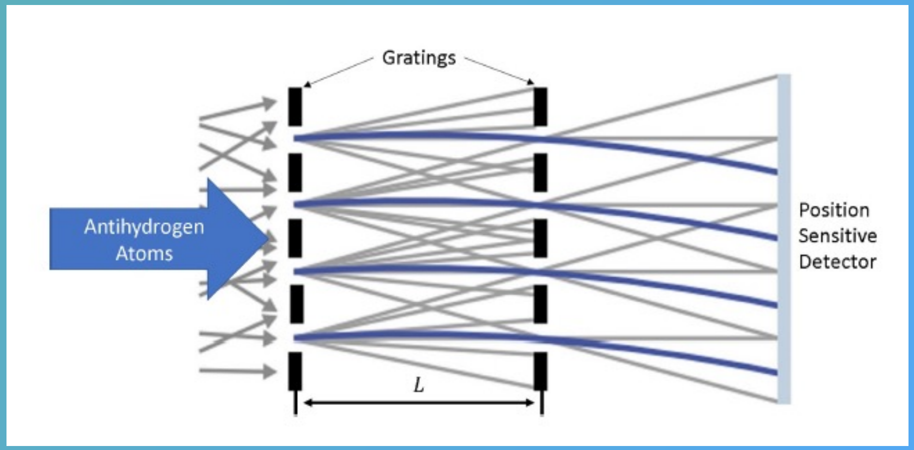
Nicola Zurlo [University of Brescia & INFN Pavia]
on behalf of the AEgIS Collaboration

AEgIS (Antimatter Experiment Gravity Intereferometry Spectroscopy) goals

Test the validity of fundamental principles with antihydrogen : WEP – CPT

g measurement on anti-H:
vertical shift of a cold beam travelling through a grating system coupled with a position sensitive detector (classical deflectometer or interferometer)

Proof of principle of tiny vertical force measurement with the grating system with pbars in
Nature Comm. 5, 4538 (2014) AEgIS Coll,
"A moiré deflectometer for antimatter"



THE WEAK EQUIVALENCE PRINCIPLE

- **Universality of free fall** (UFF) established by Galileo and Newton

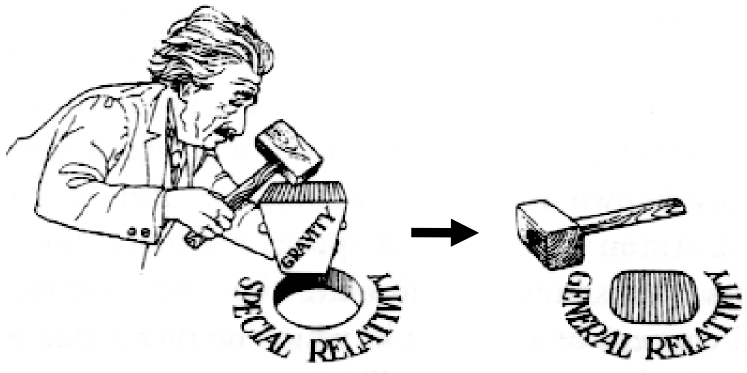
$$m_i = m_g$$

Weak equivalence principle (WEP)

- Unique behavior:

electric field:	gravitational field:
$\mathbf{F} = q \cdot \mathbf{E}$	$\mathbf{F} = m \cdot \mathbf{G}$
$\lvert\mathbf{E}\rvert \propto \frac{Q}{r^2}$	$\lvert\mathbf{G}\rvert \propto \frac{M}{r^2}$
$\lvert\mathbf{a}\rvert \propto q$	$\lvert\mathbf{a}\rvert$ = const

- **Einstein Equivalence Principle**:
  - WEP
  - Local Lorentz Invariance (LLI)
  - Local Position Invariance (LPI)



TEST OF THE EEP

- EEP is the *"heart and soul"* of **General Relativity (GR)**:
  - EEP valid → gravity is governed by a *"metric theory of gravity"*

R. Dicke, **Les Houches Summer School of Theoretical Physics: Relativity, Groups and Topology**, pp. 165–313, CNUM: C63-07-01 (1964)

- EEP extensively tested experimentally:

C. Will, **Living Rev. Relativity** 17 (2014)

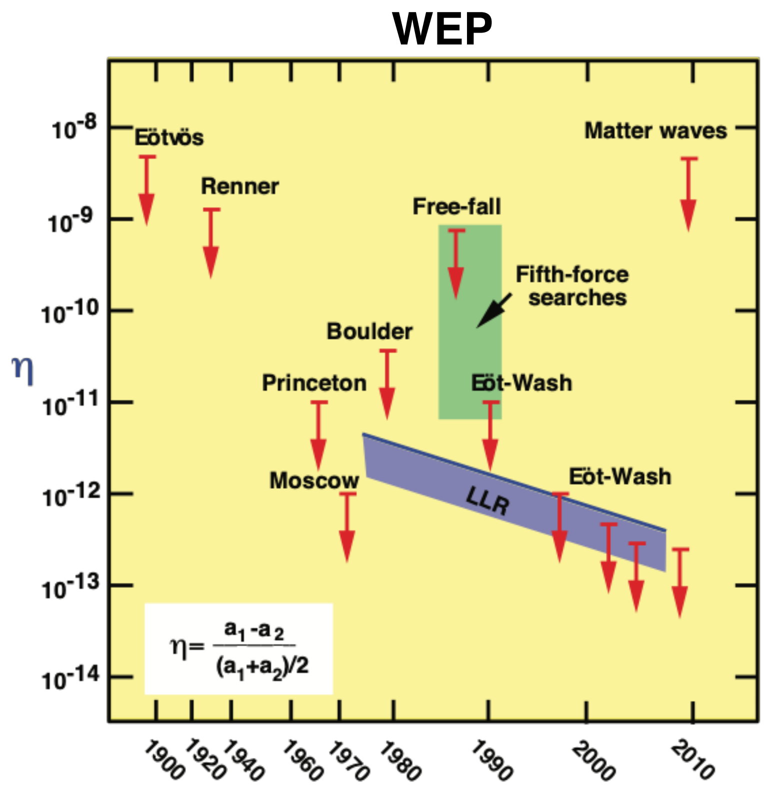
LLI Isotropy of atomic energy levels: $\delta = |c^{-2} - 1| > 10^{-23}$

LPI Gravitational red shift:

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2} > 10^{-6}$$

WEP Torsion balance:

$$\eta = \frac{a_1 - a_2}{(a_1 + a_2)/2} > 10^{-13}$$



WEP FOR ANTIMATTER: THE CURRENT PICTURE

- Some arguments *would* suggest the WEP holds for antimatter
- Strong theoretical arguments only apply to the idea of *antigravity*
  - **Morrison (1958), Schiff (1958), Good (1961), etc…**
  - **none of them *necessarily* requires $m_i^{anti-matter} = m_g^{matter}$**
- On the experimental side:
- neutrinos detected from Supernova 1987A

S. Pakvasa *et al.*, **Phys. Rev. Lett. D.** 39, 6 (1989)

  - **Shapiro delay of relativistic particles not a test for the EEP**

C.S. Unnikrishnan and G. T. Gillies, **Class. Quantum Grav.** 29 (2012)

- $p - \bar{p}$ cyclotron frequency comparisons: $(\omega_c - \overline{\omega}_c)/\omega_c < 9 \cdot 10^{-11}$

G. Gabrielse *et al.*, **PRL** 82 (3198) (1999)

  - **Model dependent, CPT assumption, absolute potentials, …**
- and others…but none of them is conclusive

WEP FOR ANTIMATTER: WHY TO TEST IT?

- Our attempts for a quantum theory of gravity typically result into new interactions which violate the WEP (ex. **KK theory**)

Int. J. Mod. Phys. D18, 251–273 (2009)

- Some open questions (like *dark matter* and *baryogenesis*) could benefit from a direct measurement

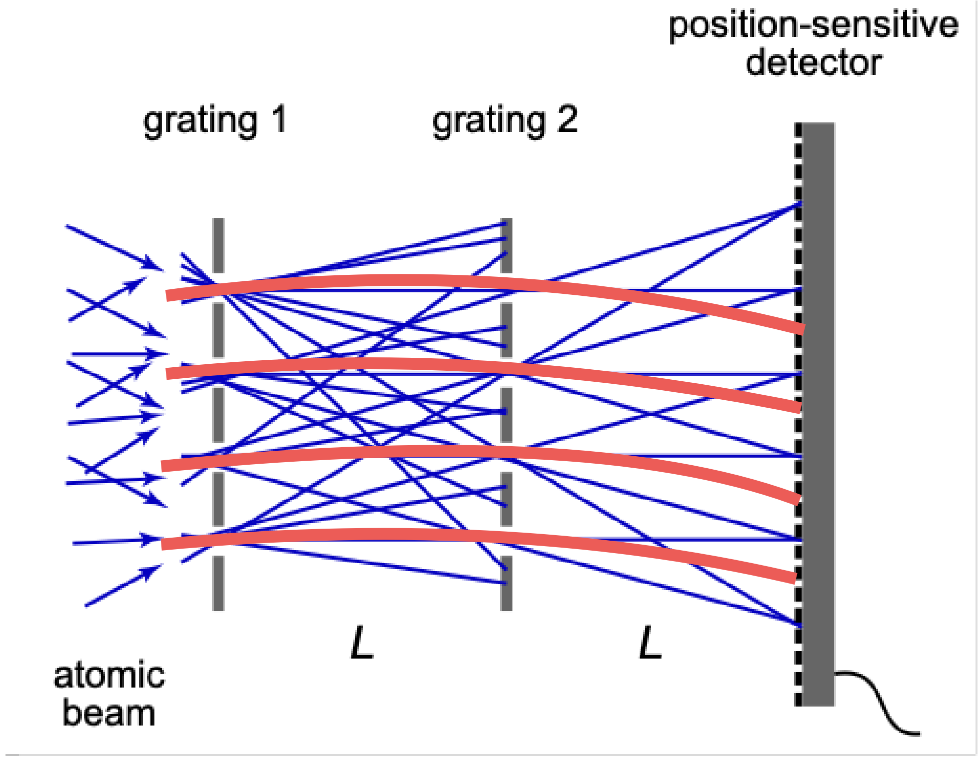
Astrophys. Space Sci. 334, 219–223 (2011)
JHEP 1502, 076 (2015)

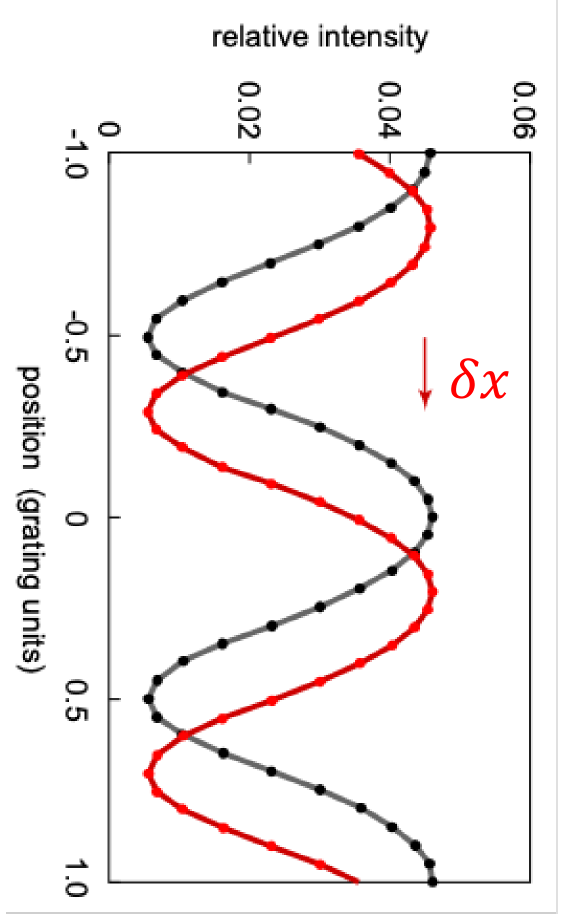
- Because *it's possible* and no direct measurements are available

- Previous attempts:
  - **1967**: **Fairbank** and **Witteborn** tried to use positrons
    Phys. Rev. Lett. 19, 1049 (1967)
  - **1989**: PS-200 experiment at CERN tried to use $(4\ K)\ \bar{p}$
    Nucl. Instr. and Meth. B, 485 (1989)
  - Both **unsuccessful** because of stray $\vec{E}$ and $\vec{B}$ fields
  - **2013**: ALPHA experiment at CERN set limit on m_g/m_i for $\overline{H}$
    Nature Communications 4, 1785 (2013)
    - $m_g/m_i > 110$ excluded at 95% CL

GRAVITY MEASUREMENT WITH AEḡIS EXPERIMENT

- Main goal of **AEḡIS:** a direct measurement of the Earth's local gravitational acceleration g on a "cold" beam of $\overline{H}$ atoms using a **moiré deflectometer**





$$\delta x = -g\left(\frac{L}{v}\right)^2$$

- For $\overline{H}$ at very low temperature a precision of the order of few percent could be reached

AEgIS Method

Capture of antiprotons from the CERN-AD
Cooling of the trapped antiprotons

Positronium (e^+e^-) production by e^+ on SiO_2
Ps laser excitation to Rydberg state

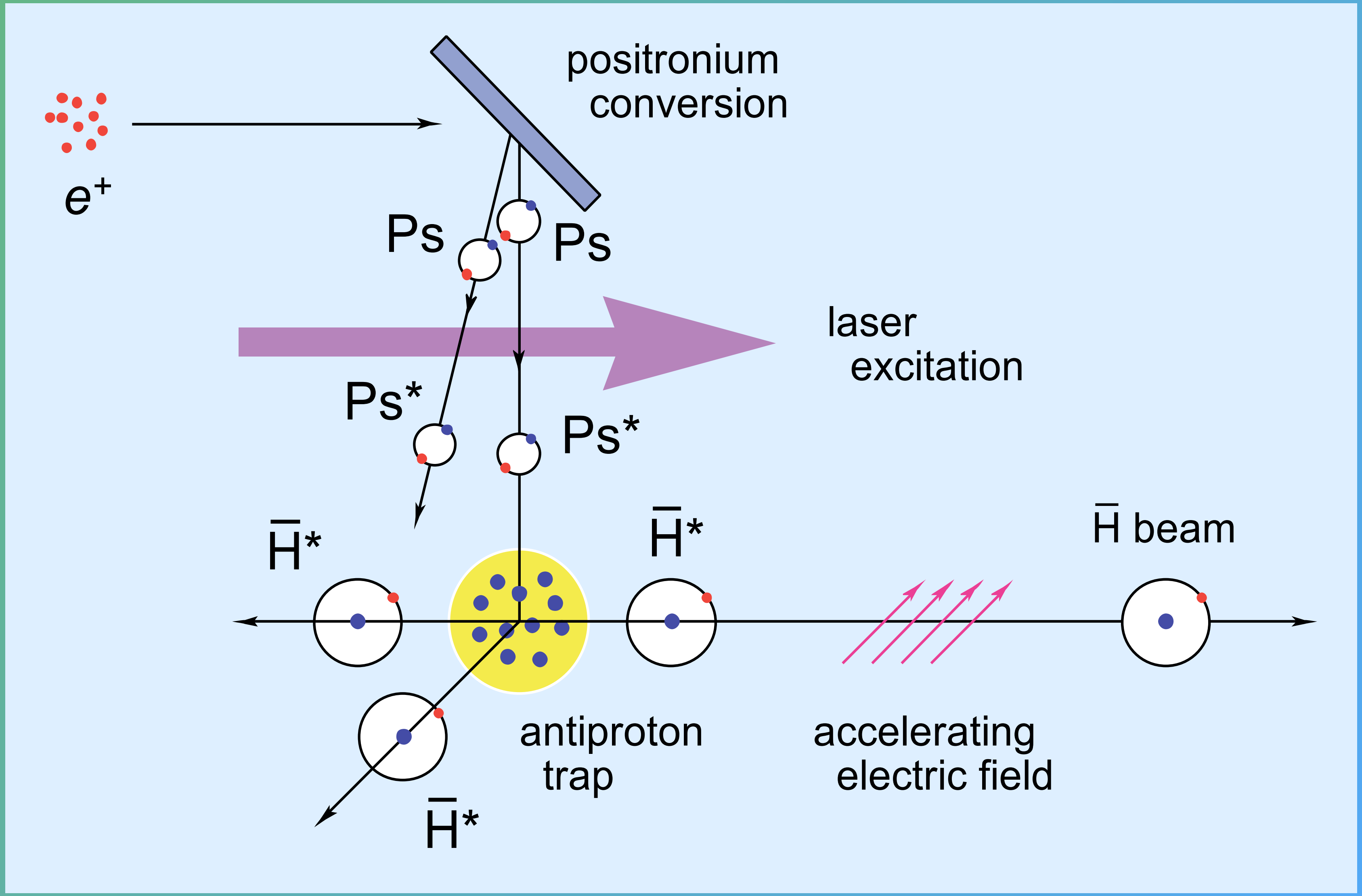
Interaction of Ps* with the antiproton cloud

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

Positronium charge exchange reaction

First proposed by B.I. Deutch et al., Proceedings of The First Workshop on Antimatter Physics at Low Energy, 371 (1986).
same charge exchange reaction with a similar technique based on Rydberg cesium performed by ATRAP: C. Storry et al., Phys. Rev. Lett. 93 (2004)

ADVANTAGES
- Large cross section $\sigma \propto (n_{Ps})^4$
- Narrow and well defined band of final states ($n_{\overline{H}} \approx \sqrt{2} n_{Ps}$, with a rms of few units)

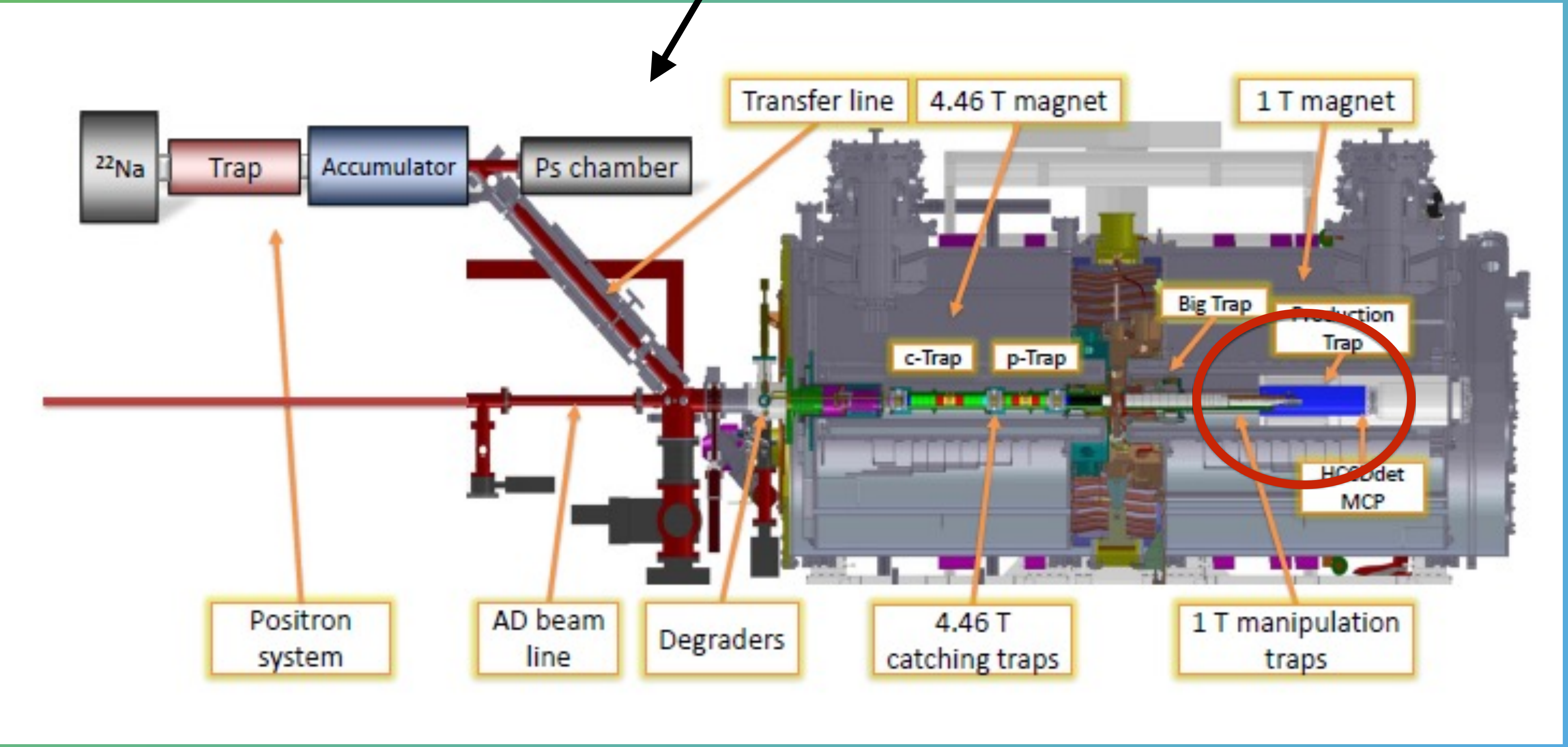


Antihydrogen will eventually be accelerated and fly toward a "moiré deflectometer"

AEgIS Apparatus

- Accumulator for e+
- Magnetic transfer line for e+
- Superconducting magnetic fields (5T, 1T)
- Cryogenic traps (105 electrodes)
- antiH detector (scintillating fibers)
- External plastic scintillators
- Internal (MCP+phosphor screen & Faraday cups in cryogenic UHV)
- lasers
- Additional detectors
- POSITRON MEASUREMENT setup

Ps test setup
used for measurements with Ps (excitation etc.)



Positronium

$$e^+ + e^- \longrightarrow Ps \longrightarrow (Ps)^*$$

Positronium [o-Ps] formation through a nanoporous silica target

Ps production efficiency $\simeq 27\%$

Mariazzi et al. Phys. Rev. Lett. 104, 243401 (2010)

e^+ implantation energy $\simeq 5$ keV

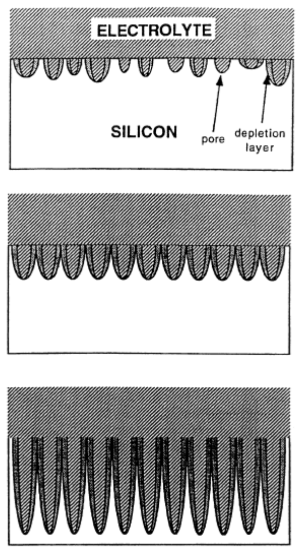
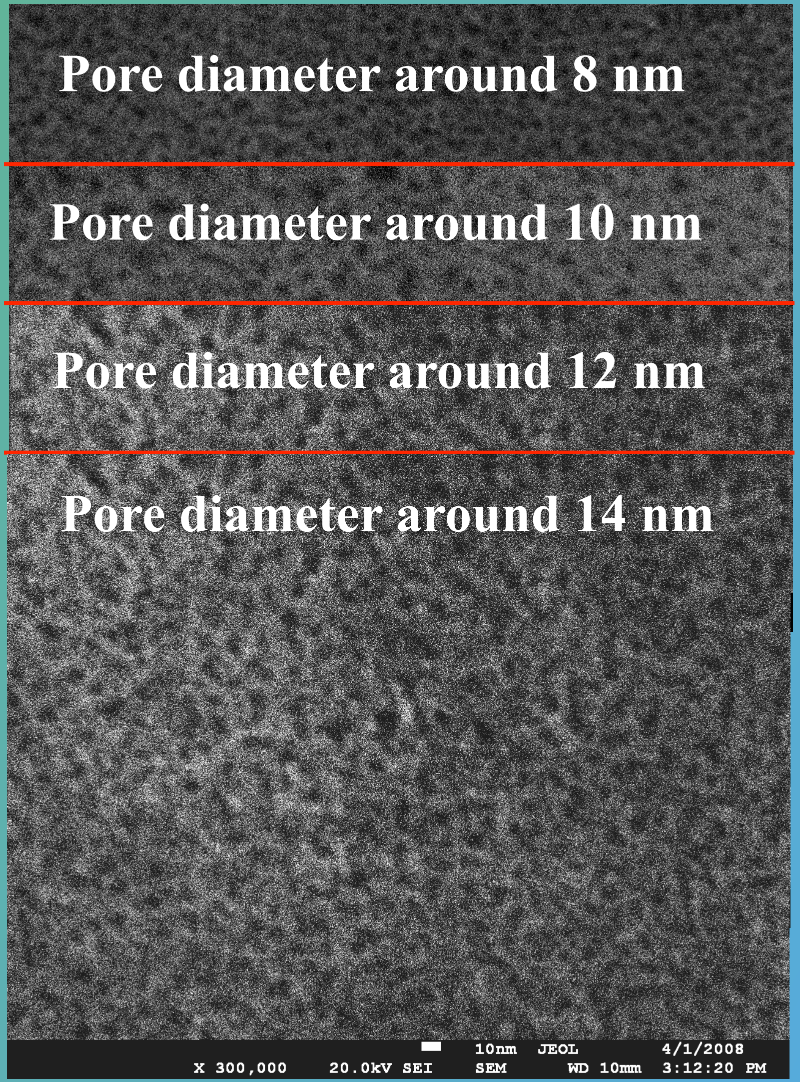


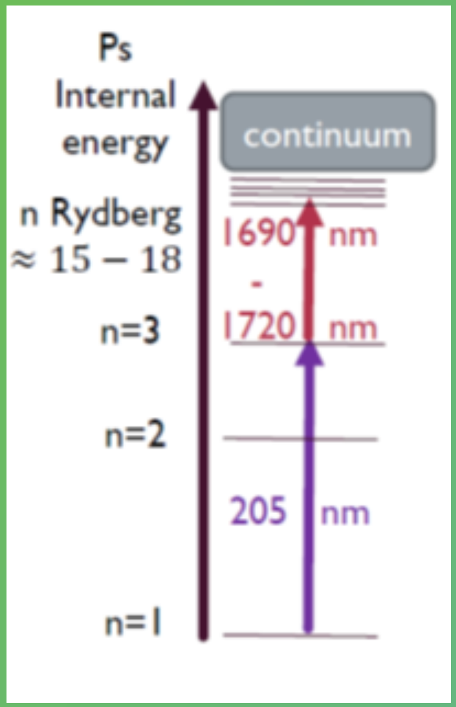
Fig. 6. Mechanism of pore formation in PS. Random pore initiation on the Si surface (top panel), formation of depletion layers and directional growth of pores (middle panel) and dissolution advance only at the pore tips (bottom panel).

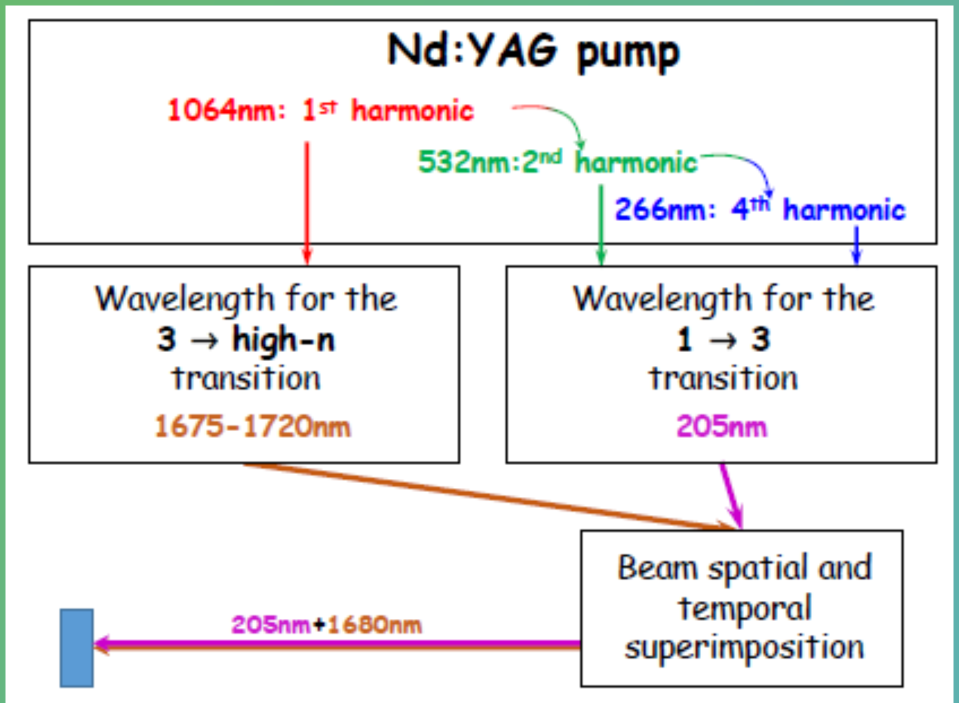


Positronium

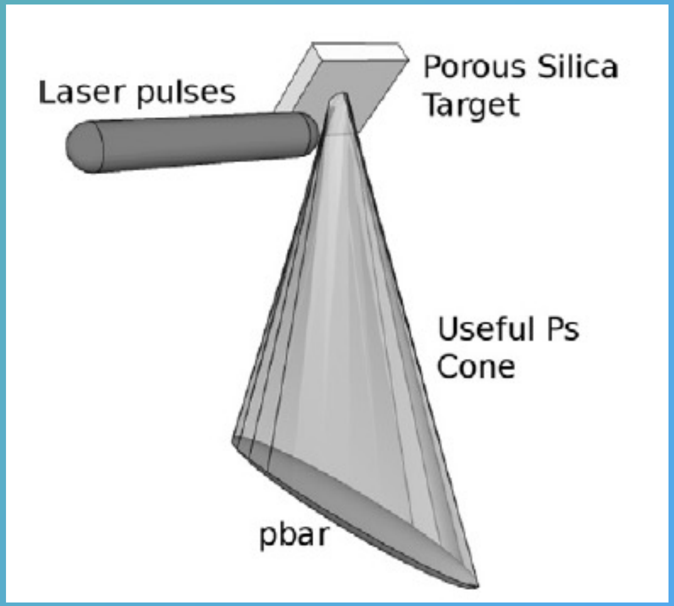
$$e^+ + e^- \longrightarrow Ps \longrightarrow (Ps)^*$$

2 steps Positronium laser excitation





UV 205.047 nm	IR 1680-1715 nm
1.5 ns	5 ns (2 ns delay with respect to UV)
3mm FWHM	3.5 mm FWHM
90 µJ	1 mJ



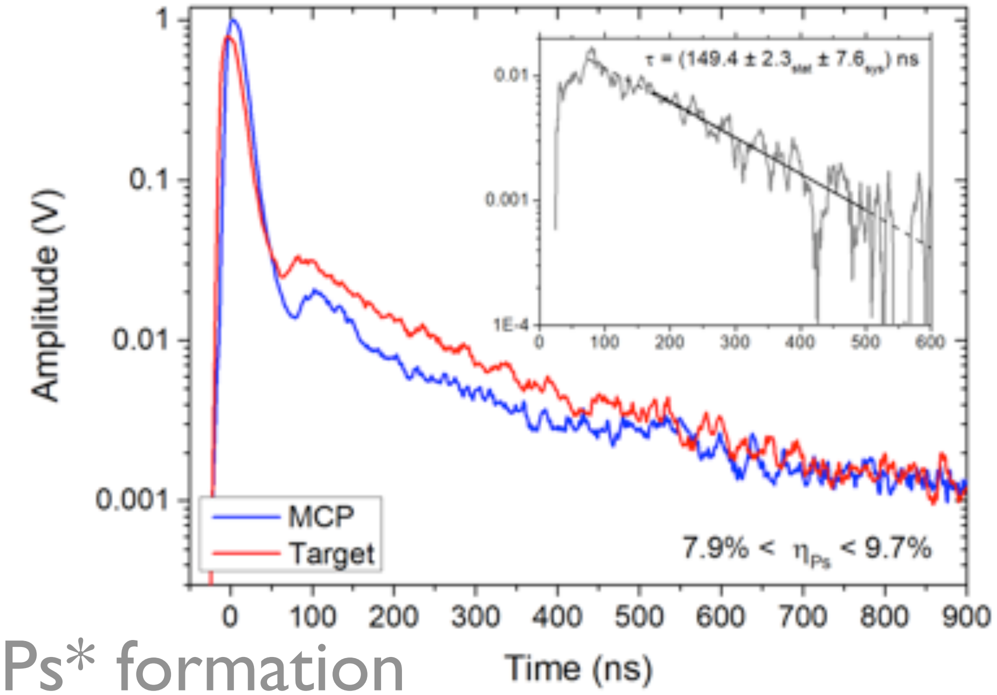
Already demonstrated by us in the e^+ test setup

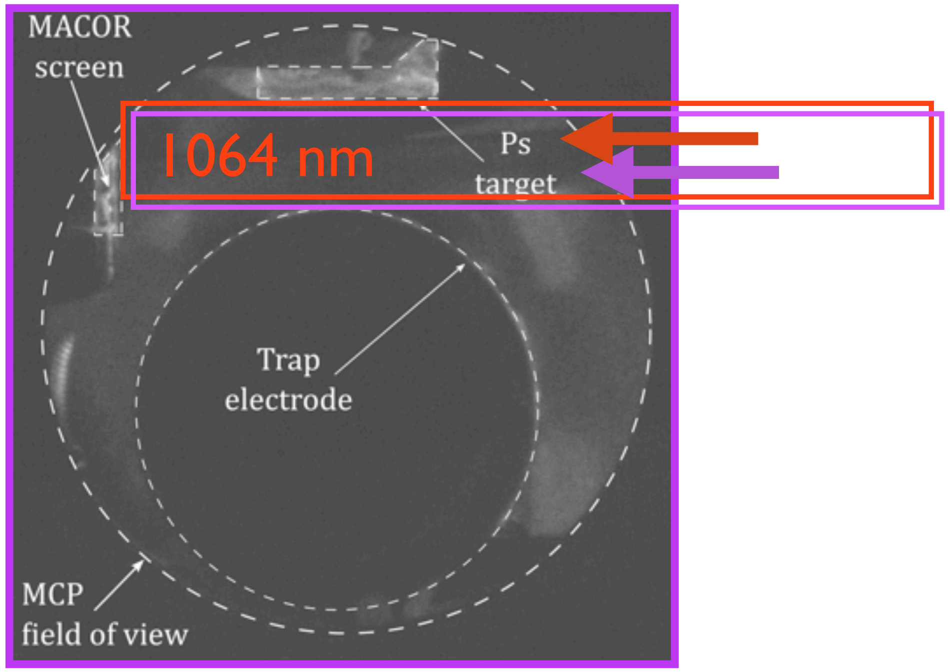
"Laser excitation of the n=3 level of positronium for antihydrogen production"
Phys. Rev. A 94 (2016) 012507 AEgIS Coll.

Positronium: Ps & Ps* excitation and detection (B=1T)

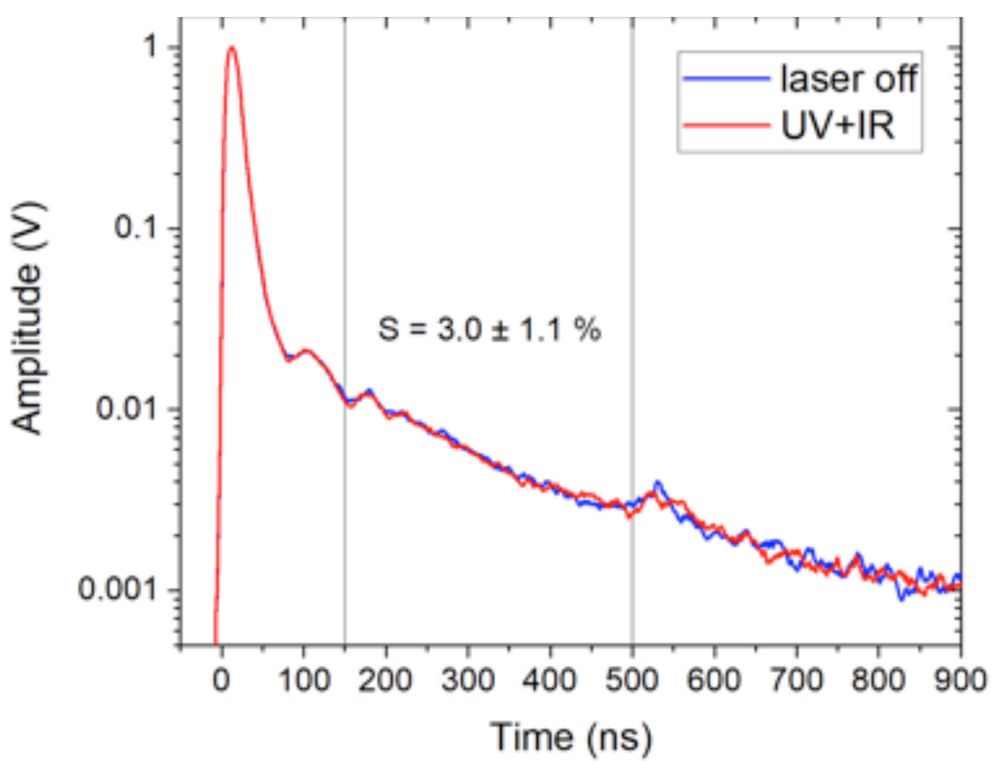
before: SSPALS (100's of shots) now: photo-ionization (few shots)

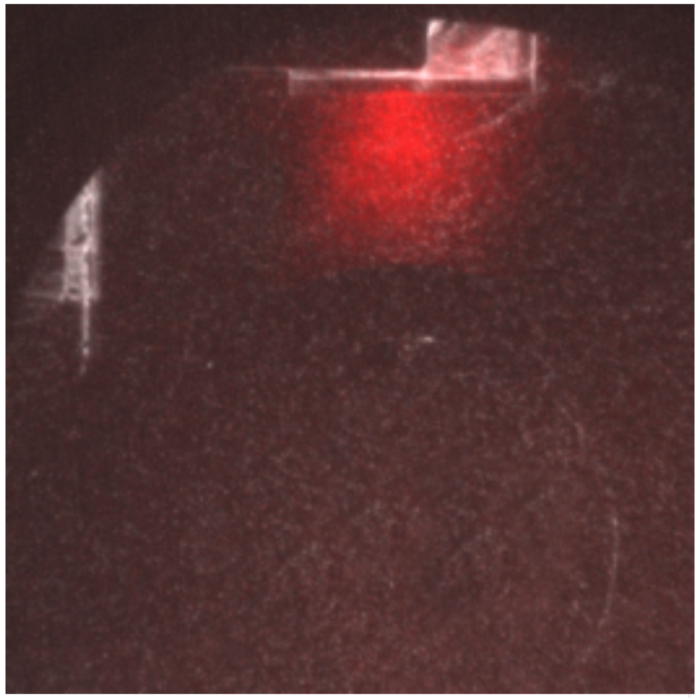
Ps formation



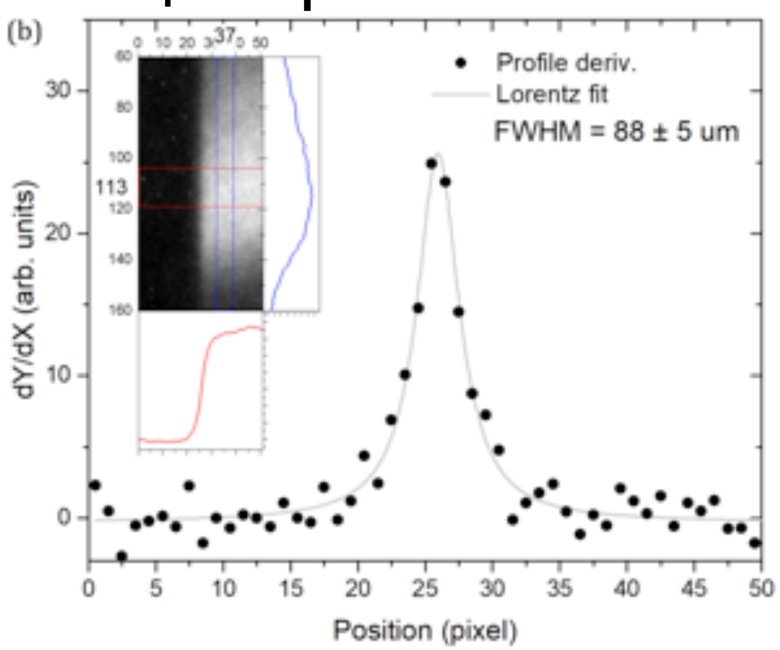


Ps* formation



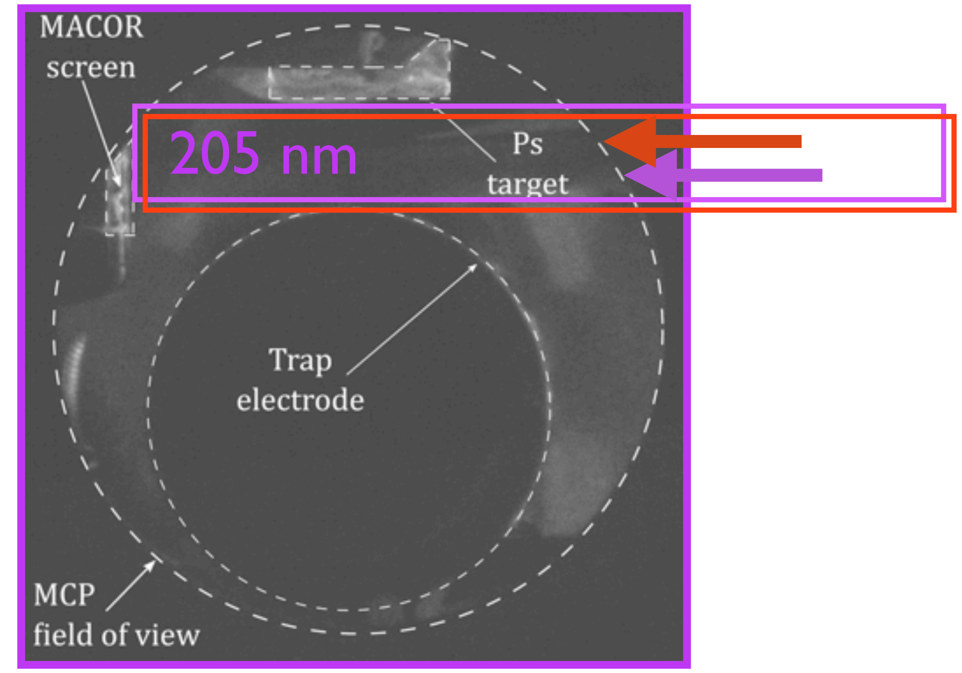


90 µm spatial resolution

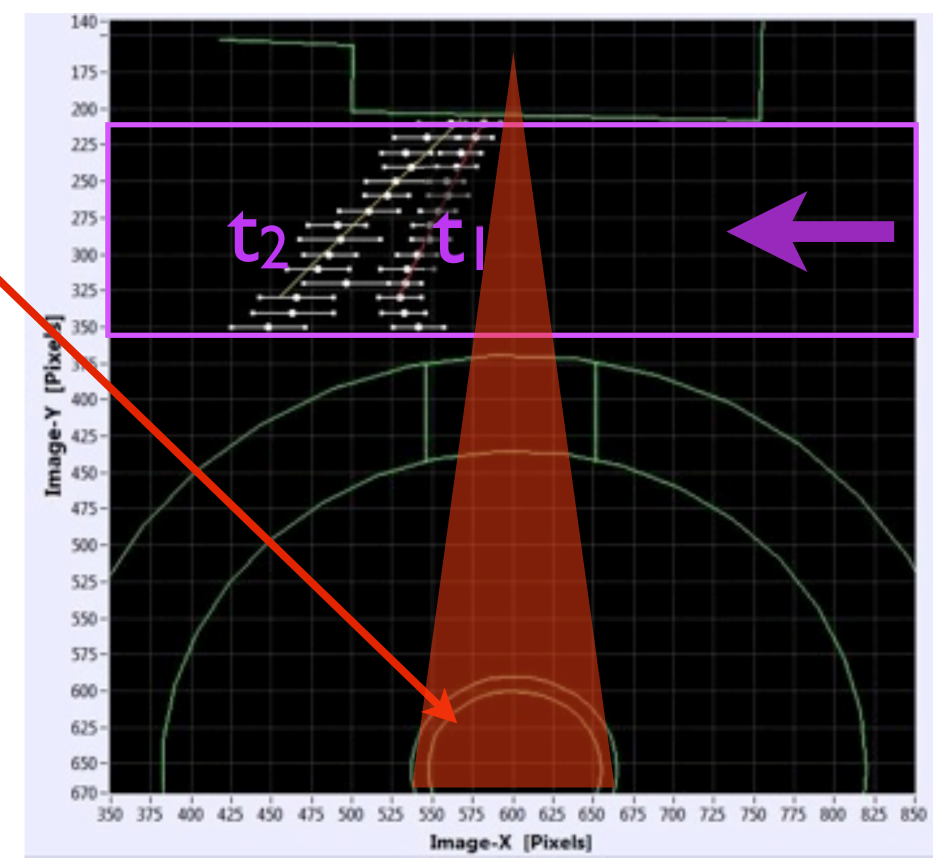


Positronium: optimization (direction, velocity)

Doppler selectivity in $Ps_{//}$ velocity vector



Tune UV laser central wavelength (fired at different times) such that the intersect does not move with time, and Ps* propagates in the direction of the <u>antiproton cloud</u>

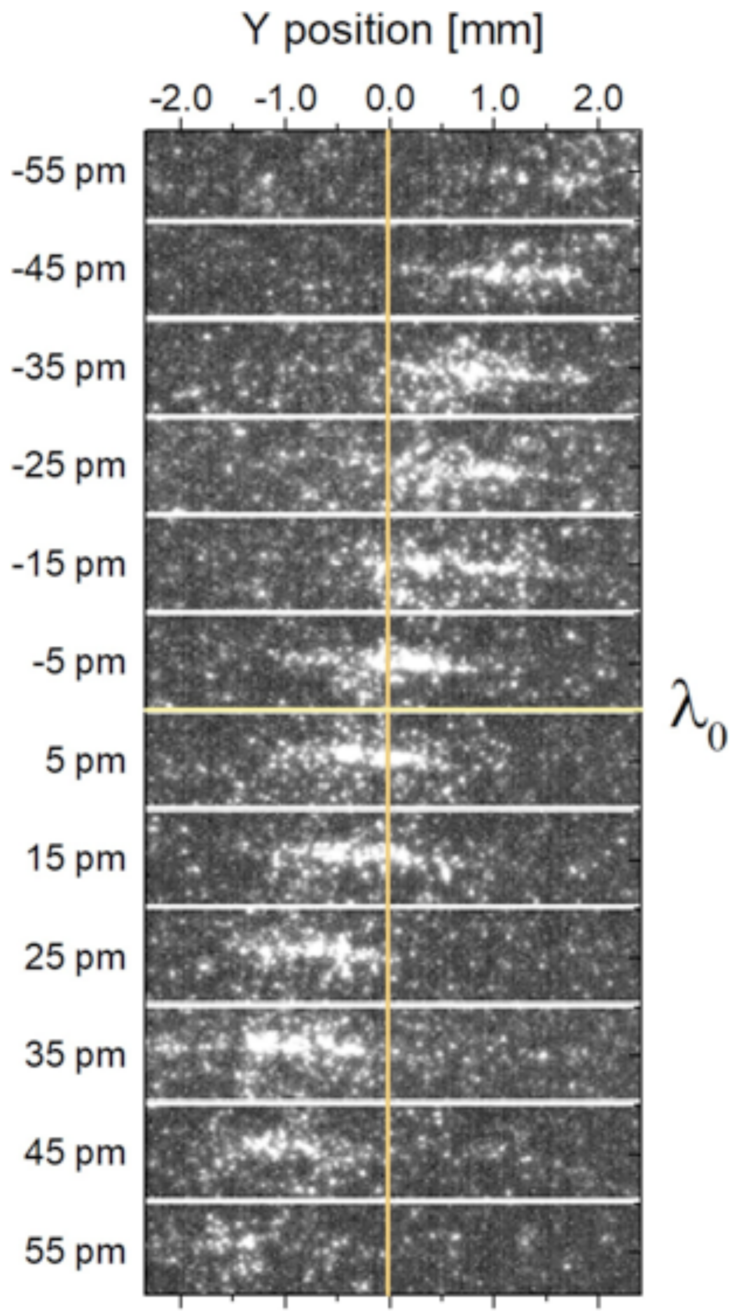


<u>Final tuning</u>: select laser firing time to maximize the fraction of useful ($v_{axial} < 10^5$ m/s) towards $\overline{p}$

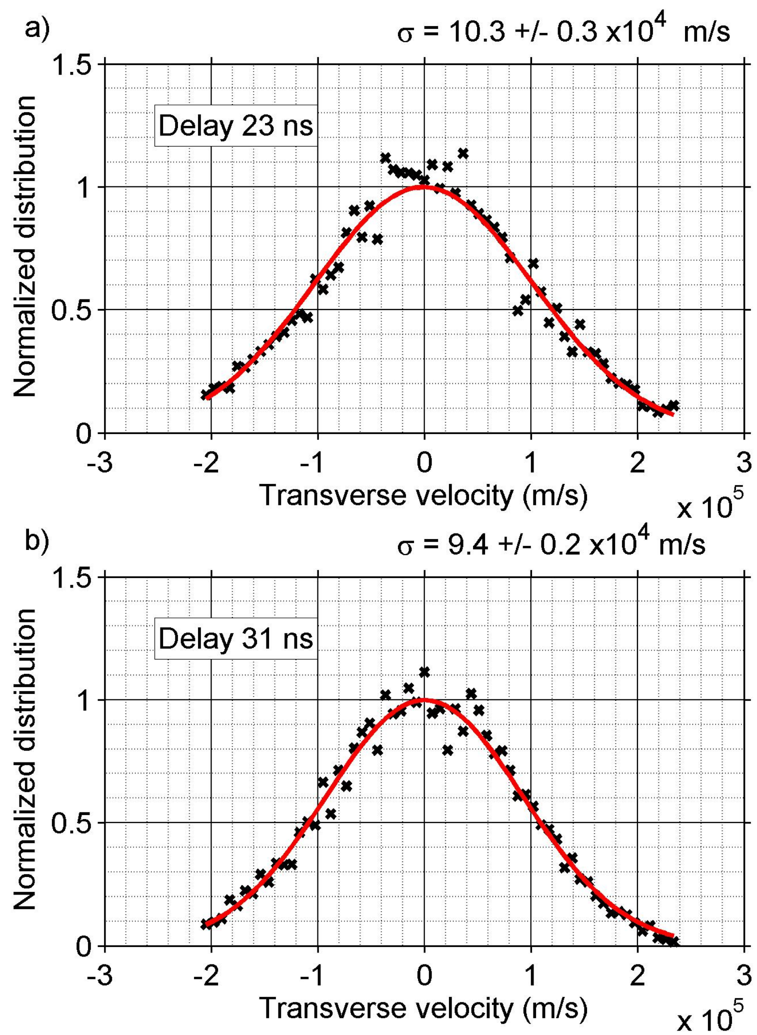
<u>Final tuning</u>: select IR frequency to maximize cross-section & minimize field ionization of Ps*

Ps* velocimetry

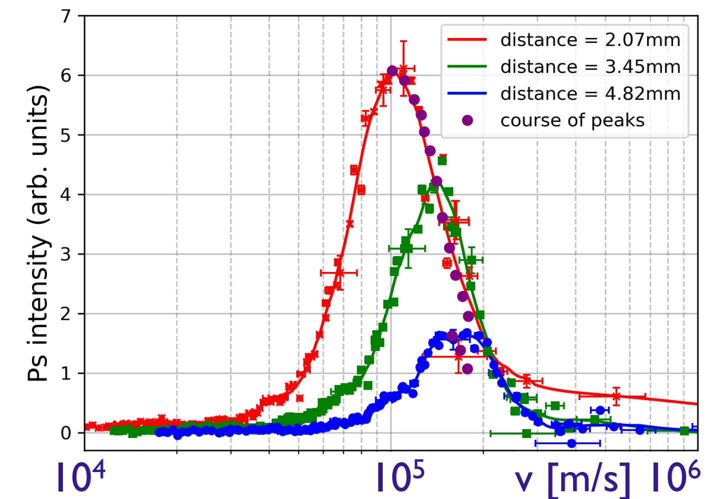
Scan 1→3 laser wavelength *(at fixed time)*

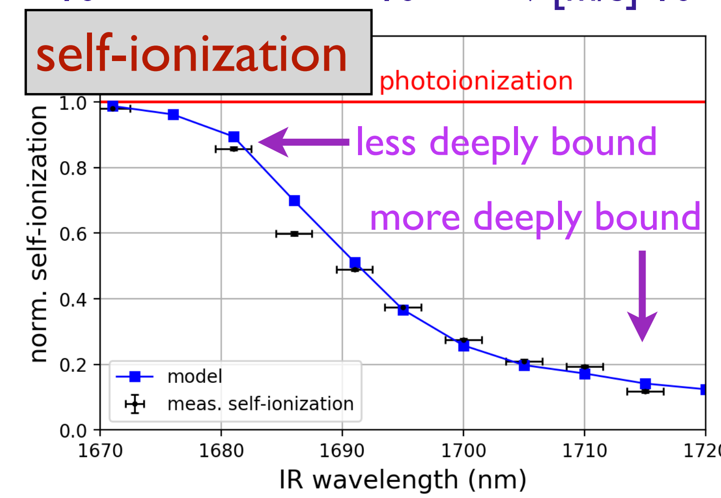


transverse velocity ($\sigma \sim 1 \times 10^5$ m/s)



axial velocity ~ 1.6×10^5 m/s





Doppler velocimetry in 0.01 nm steps

NIM B, Volume 457, 15 October 2019, 44-48

Doppler broadening ⊗ laser bandwidth

subm. Phys. Rev. A

Charge Exchange cross section

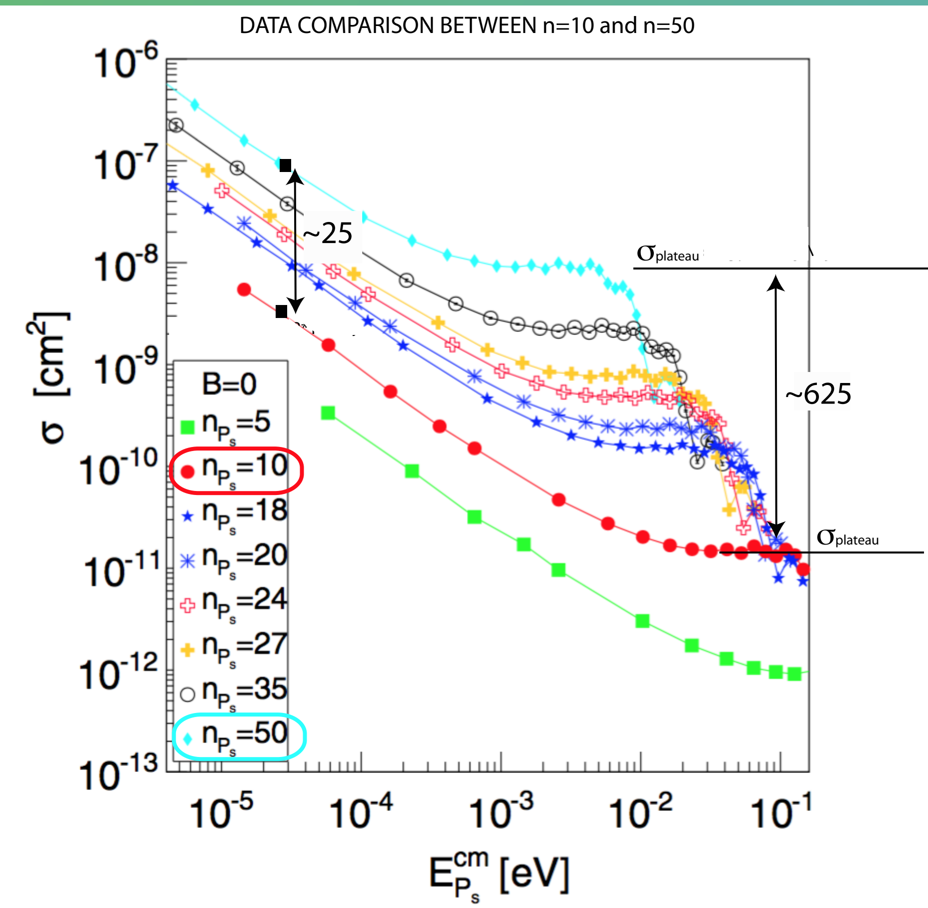


FIG. 3. Charge-exchange cross section σ as a function of the P_s center-of-mass energy. The plot shows the same points of Fig. 2. The lines simply connect the points to help the graphical interpretation.

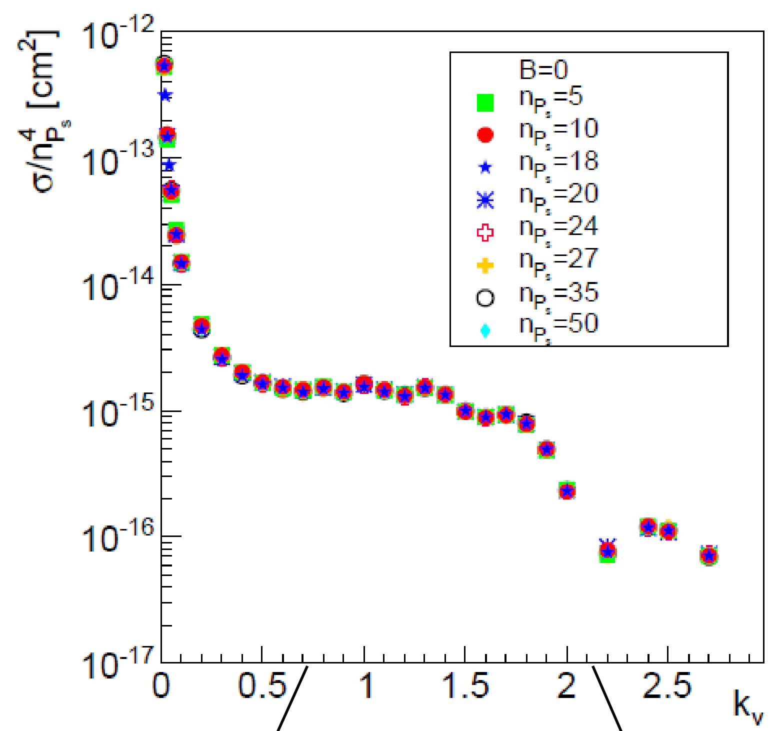


FIG. 2. Charge exchange cross section divided by $n^4_{P_s}$ ($\sigma/n^4_{P_s}$) as a function of k_v with B=0. The results obtained for the various principal quantum number shown in the legend collapse into a universal curve and they cannot be distinguished in the plot. For each n_{P_s} the l_{P_s} and m_{P_s} values are sampled from a canonical ensemble as described in section II.

$$v_{Ps} = 3\ 10^4\, m/s$$

if nPs=17

$$v_{Ps} = 1.2\ 10^5\, m/s$$

if nPs=17

D. Krasnicky, C. Canali, R. Caravita, G. Testera
Phys. Rev. A 94, 022714 (2016)

Classical Calculation

$$\sigma \propto n^4$$

$$\left(v^{Ps}_{cm}\right)_{m/s} = \frac{k_v}{2\, n_{Ps}} 2.19\ 10^6\, m/s$$

A.S. Kadyrov et al.
Nature Comm. 8, 1544 (2017)

Quantum calculation

Classical regime restored if

$$\lambda_{dB} < 2 a_0 n^2_{Ps}$$

that is:

$$n_{Ps} k_v > 3.3$$

Plateau regime correct in our range of nPs
Low k_v region and low nPs: σ scales as n^2......

Charge Exchange cross section

Recent developments on this topic:

D.Krasnicky, G.Testera and N.Zurlo 2019 J. Phys. B: At. Mol. Opt. Phys. 52 115202
Comparison of classical and quantum models of anti-hydrogen formation through charge exchange

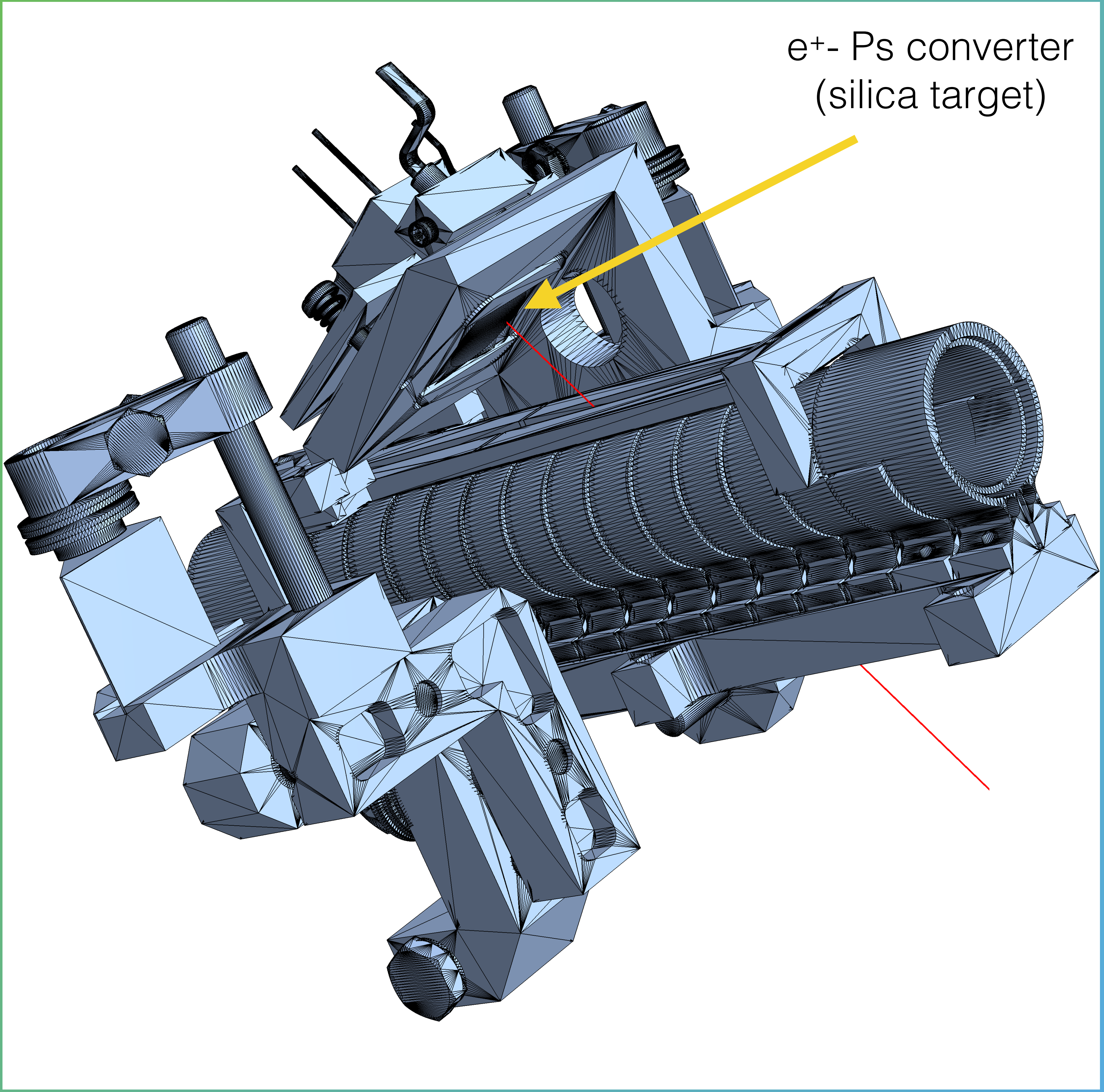
↓

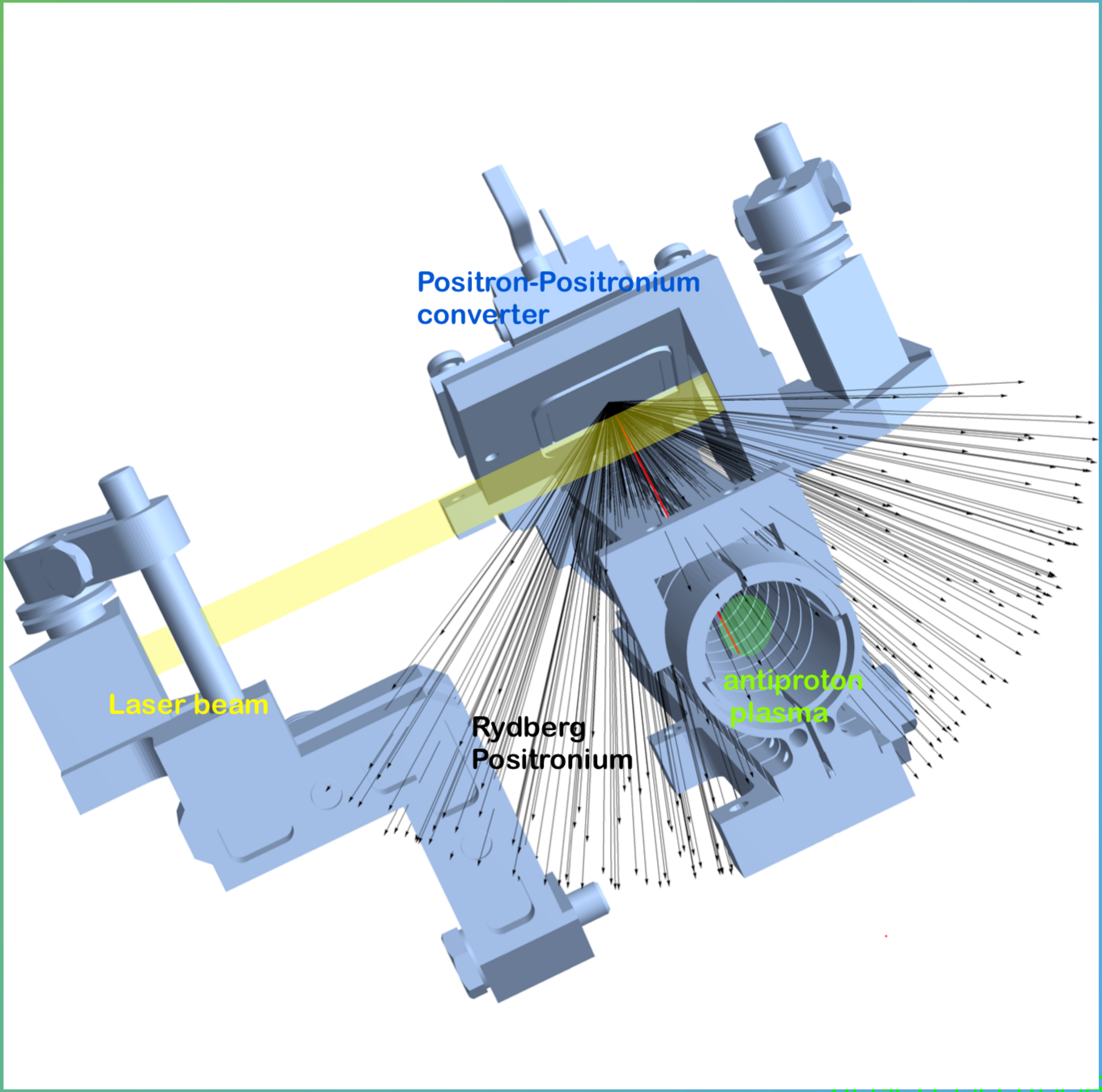
CLASSICAL CALCULATION RESULTS ARE FULLY COMPATIBLE WITH QUANTUM MECHANICAL RESULTS, (APART FOR VERY LOW n's OBVIOUSLY, where classical limit is not USABLE), ESPECIALLY FOR WHAT CONCERNS THE SCALING LAWS!

H. B. Ambalampitiya, D.V. Fursa, A.S. Kadyrov, I.Bray and I.I.Fabrikant, J. Phys. B: At. Mol. Opt. Phys. 53 155201
Charge transfer in positronium–proton collisions: comparison of classical and quantum-mechanical theories

↓

QUANTUM MECHANICAL CROSS SECTION IS SMALLER THAN THE CLASSICAL ONE FOR n=4 and n=5, BUT THE EFFECT IS NOT LARGE


e+- Ps converter
(silica target)

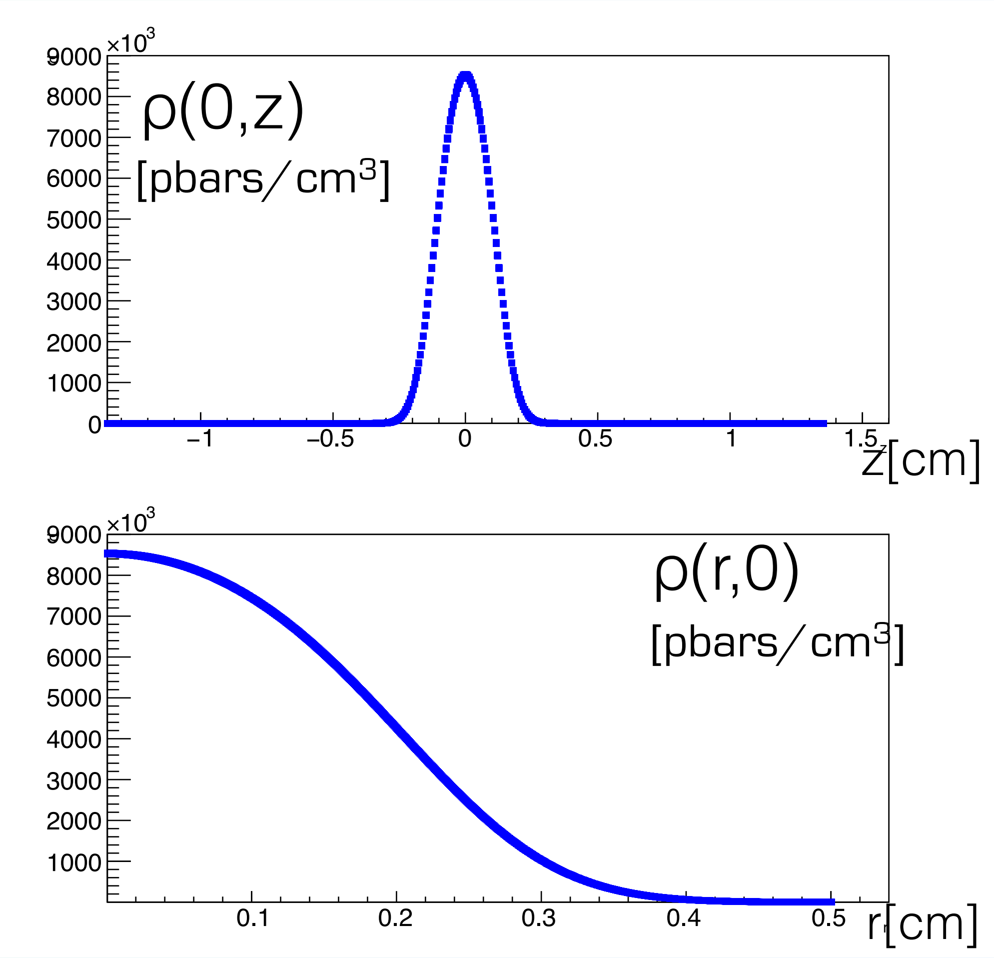

Positron-Positronium
converter
Laser beam
Rydberg
Positronium
antiproton
plasma

From the experimental side, we measure the integrated density along the trap axis $\int \rho(r,z)dz$ through a MCP detector coupled to a phosphor screen

S. Aghion et al. (AEGIS COLLABORATION)
"Compression of a mixed antiproton and electron non-neutral plasma to high densities"
Eur. Phys. Journal D, in press

and the total number of antiprotons by external calibrated scintillators.

Number of pbars : ~3,5 x 10^5
Central plasma density: ~9 x 10^6 pbars/cm^3
Plasma size: radius ~2mm, z length ~1 mm
Plasma Temperature : in the ~100 K—1000 K range



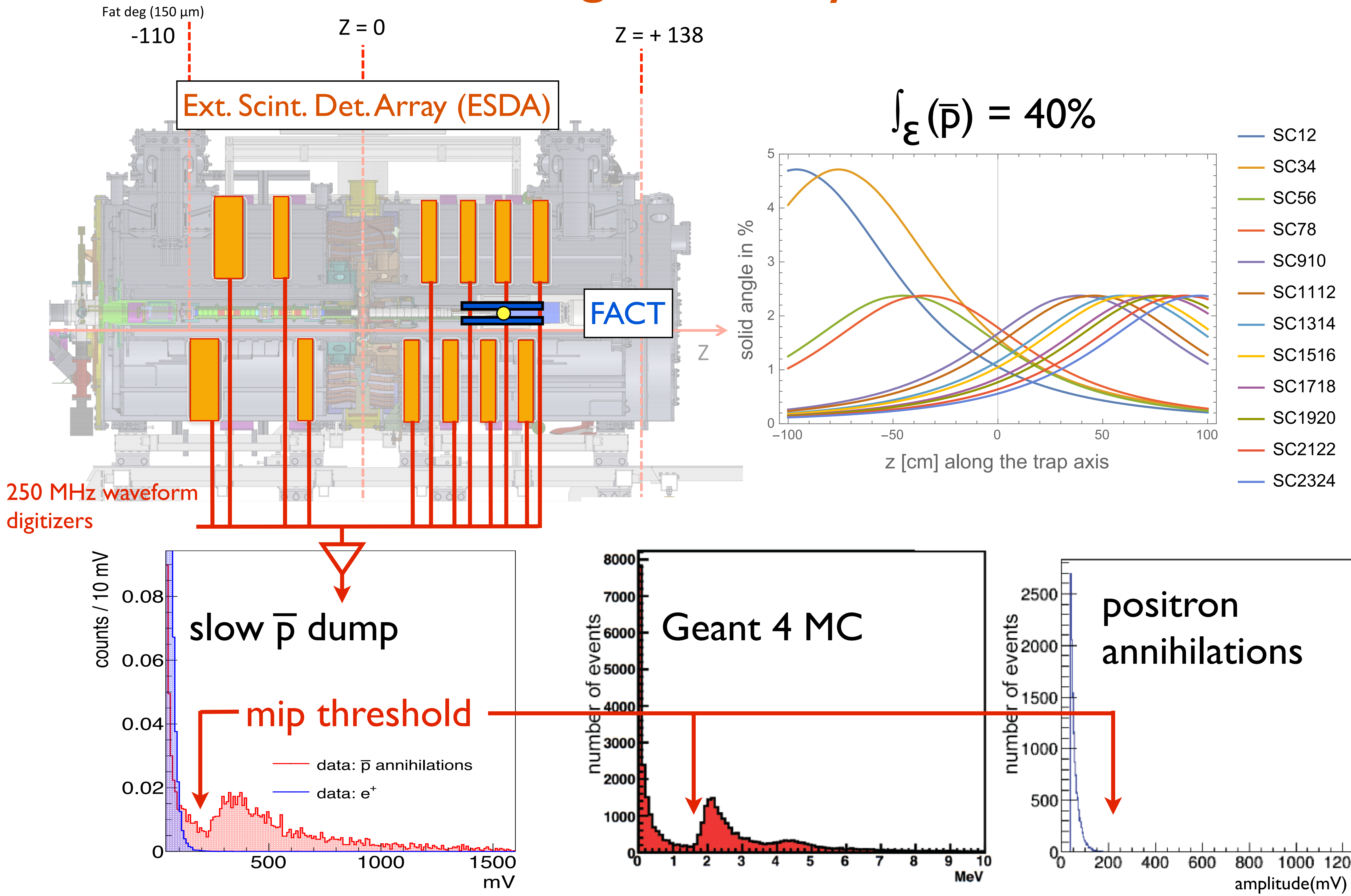
From these data and the analytical model we infer:

Pbar Thermal Velocity: $v_{th} \lesssim$ 4'000 m/s

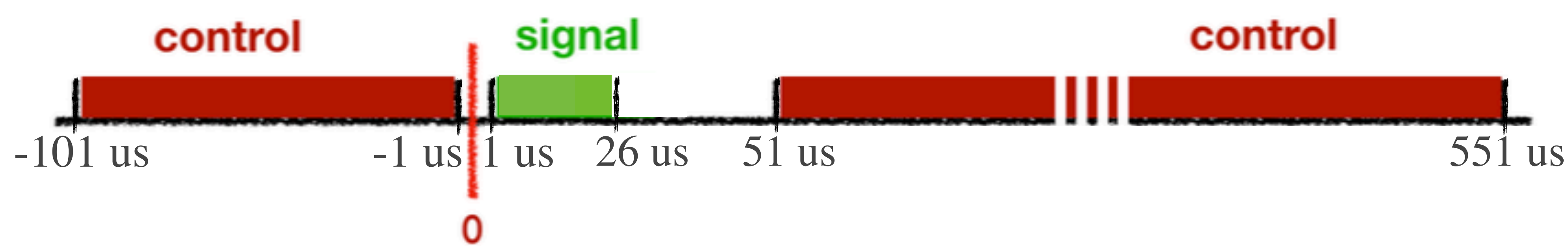
Pbar Rotational Velocity: $v_{rot} \ll$ 1'000 m/s

So, the pbar velocity is negligible compared to the Rydberg positronium velocity and we can consider only the latter for the cross section calculations!

$\overline{\mathrm{H}}$ detectors: scintillating slab array (mips), FACT (vertex tracker)



Protocol for pulsed antihydrogen production



NOT TO SCALE

injection of e^+ and formation of Ps

firing of UV and IR lasers and formation of Ps*

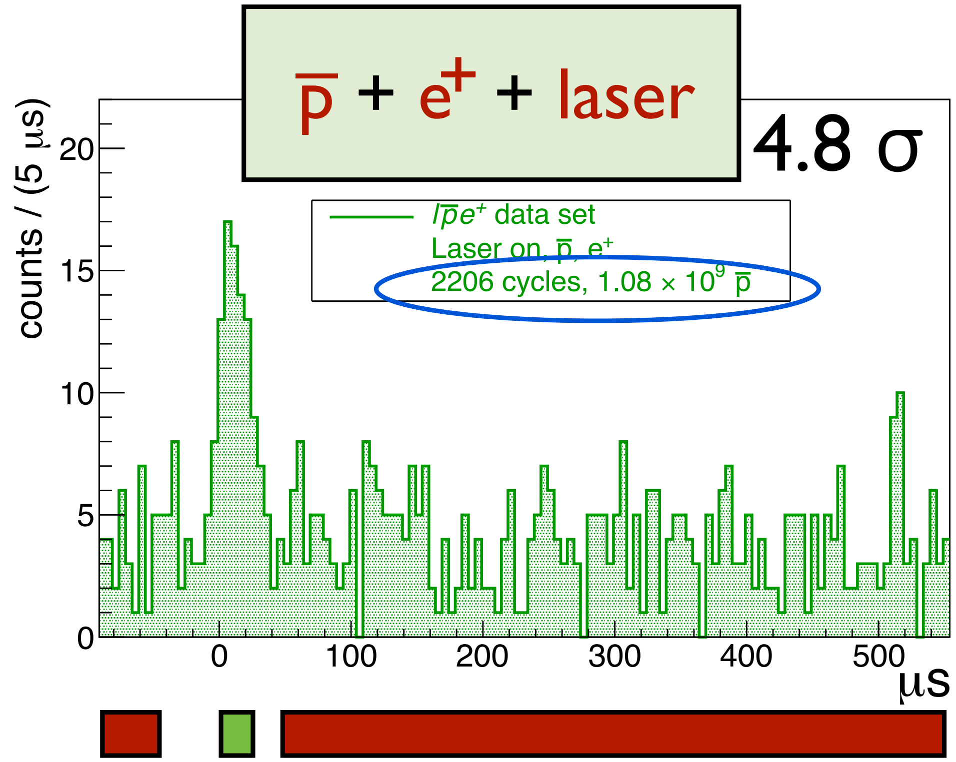
pulsed formation of $\bar{H}$

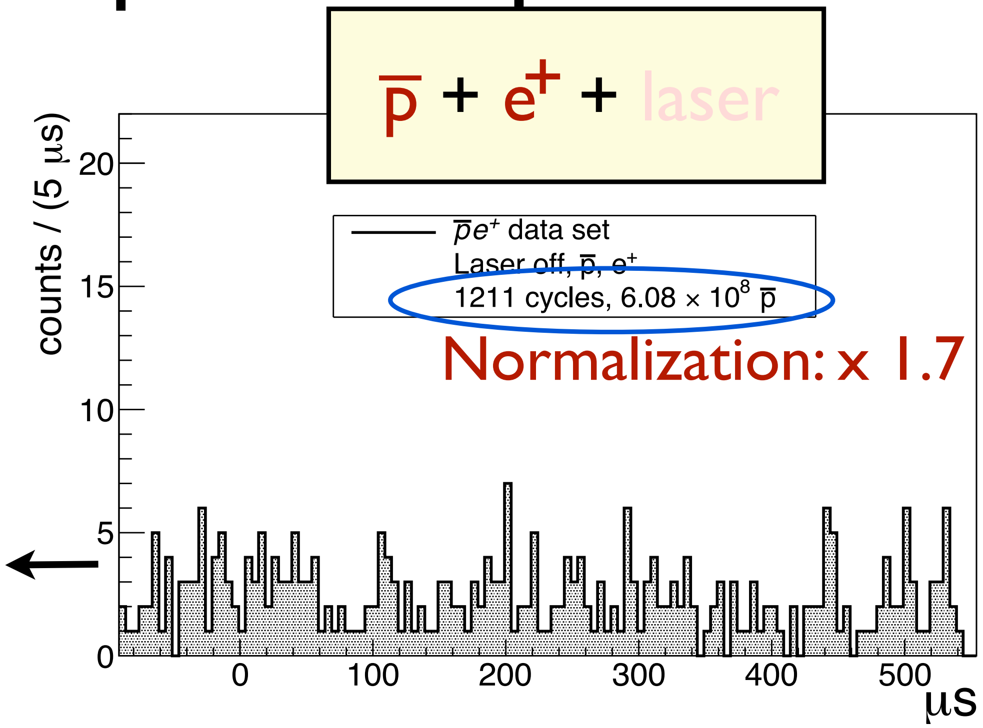
diffusion of formed $\bar{H}$ and annihilation with electrodes

Same protocol for several combinations:

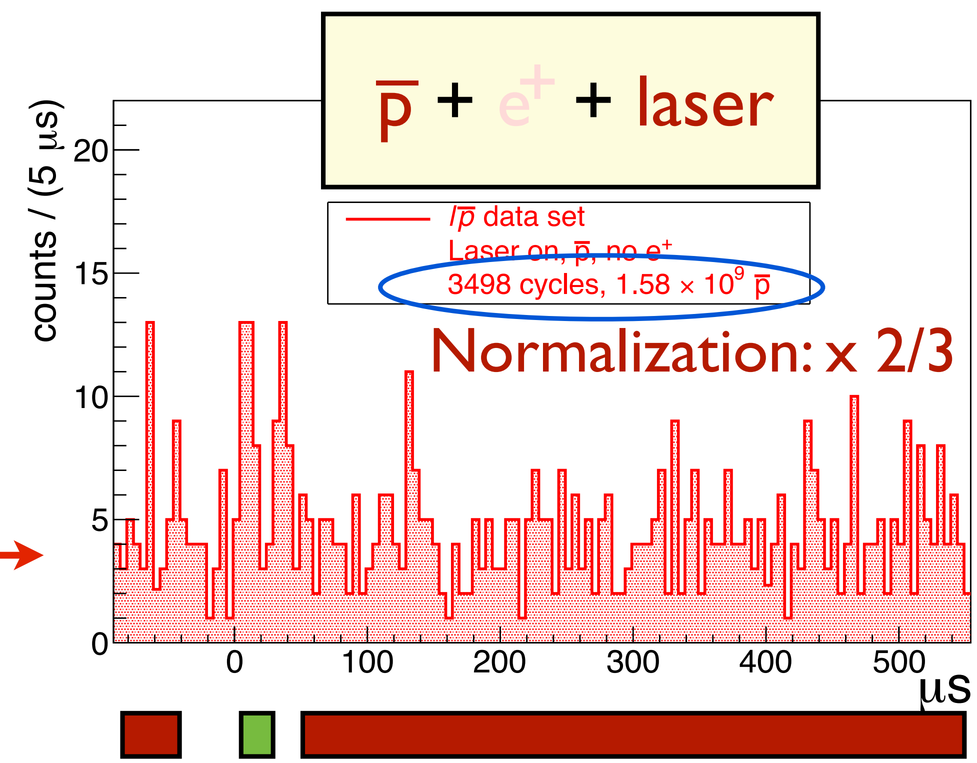
$\bar{p}$, e^+, lasers	nominal $\bar{H}$ prod.
$\bar{p}$, ~~e^+~~, lasers	no Ps, no $\bar{H}$
$\bar{p}$, e^+, ~~lasers~~	no Ps*, no $\bar{H}$
~~$\bar{p}$~~, e^+, lasers	no $\bar{H}$ prod.
cosmics	no $\bar{H}$ prod.

mip detection: search for pulsed $\bar{H}$ production





long time average rate compatible with cosmics rate



long time average rate compatible with cosmics rate

excess in signal region [1, 26 μs];

the absence of signal is rejected with 4.8 σ

(tiny excess in signal region in background [1, 26 μs] compatible with expected laser-induced desorption & subsequent annihilation with trapped antiprotons)

Amsler, C., Antonello, M., Belov, A. et al. Pulsed production of antihydrogen. Commun Phys 4, 19 (2021).
https://doi.org/10.1038/s42005-020-00494-z

Conclusions

Pulsed production of antihydrogen established

Major advances in techniques but much remains to be done: temperature, rate, beam formation; modifications ongoing

Radical improvement in the apparatus : geometry, Ps/Ps* converter efficiency,…

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Thank you to the organisers