Pulsed production of antihydrogen

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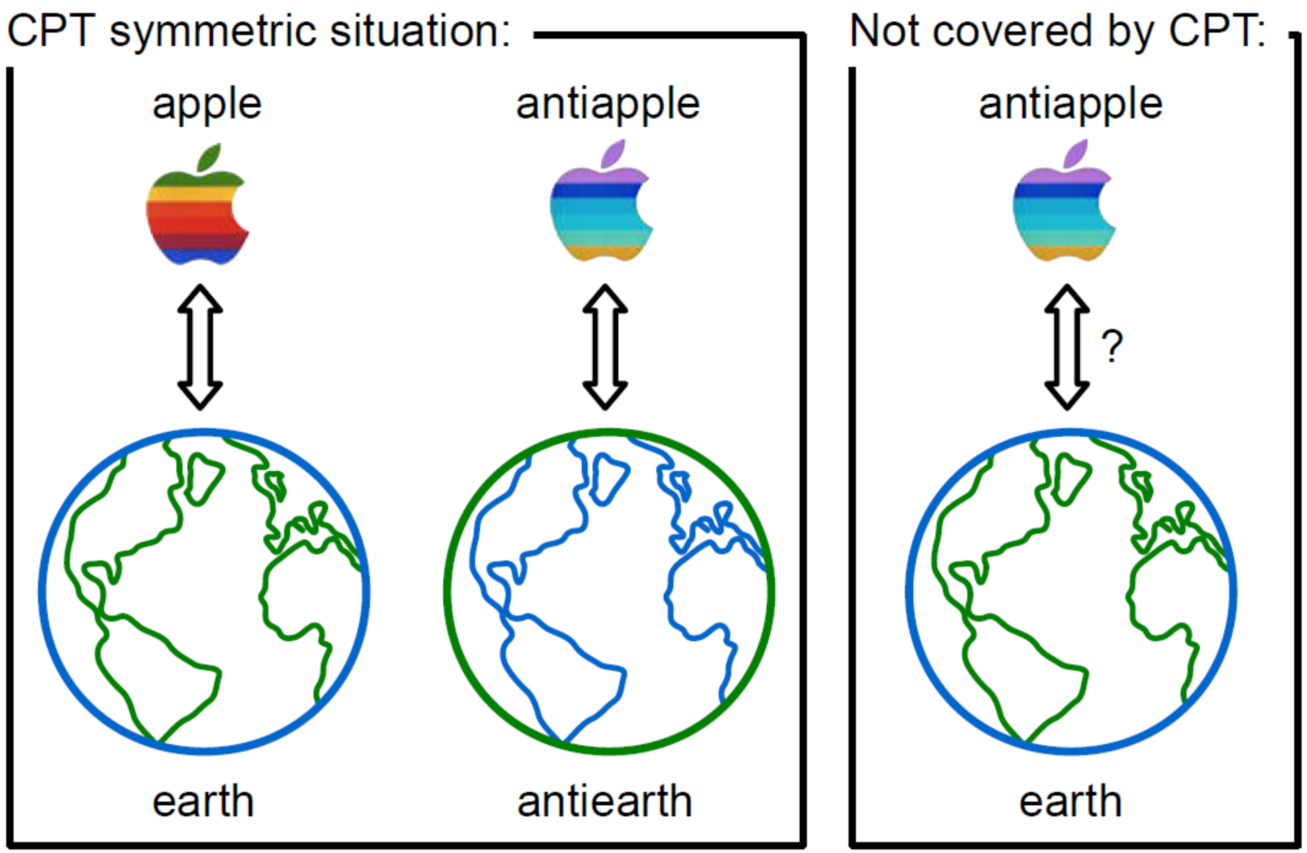
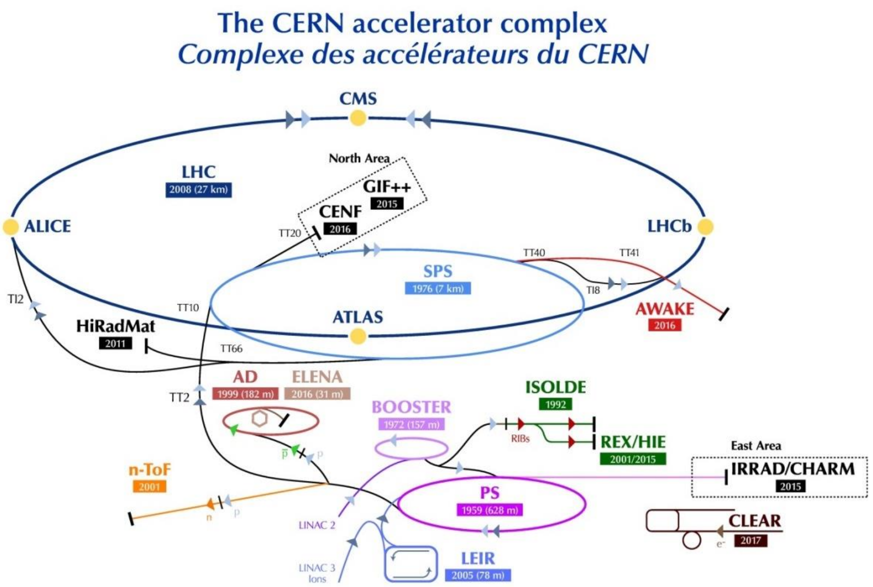
On behalf of the AEgIS collaboration

The Weak Equivalence Principle (Universality of free fall, General relativity)

$$V = -\frac{G m_1 m_2}{r}\left(1 \pm a\, e^{-\frac{r}{v}} + b\, e^{-\frac{r}{s}}\right) \quad (a, b \geqslant 0)$$





INFN

TIFPA Trento Institute for Fundamental Physics and Applications

UNIVERSITÀ DI TRENTO

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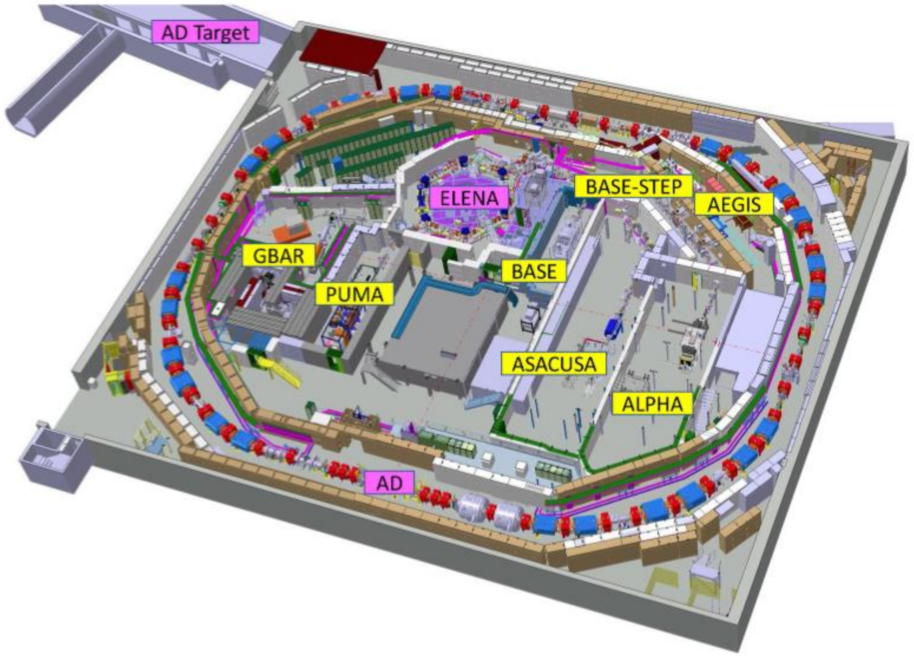
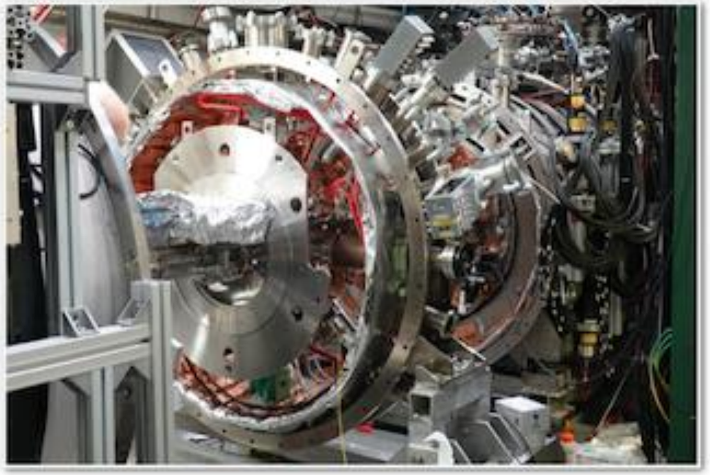
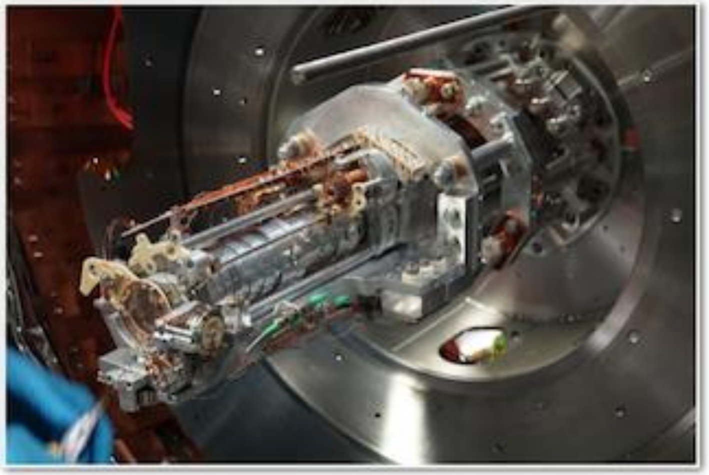
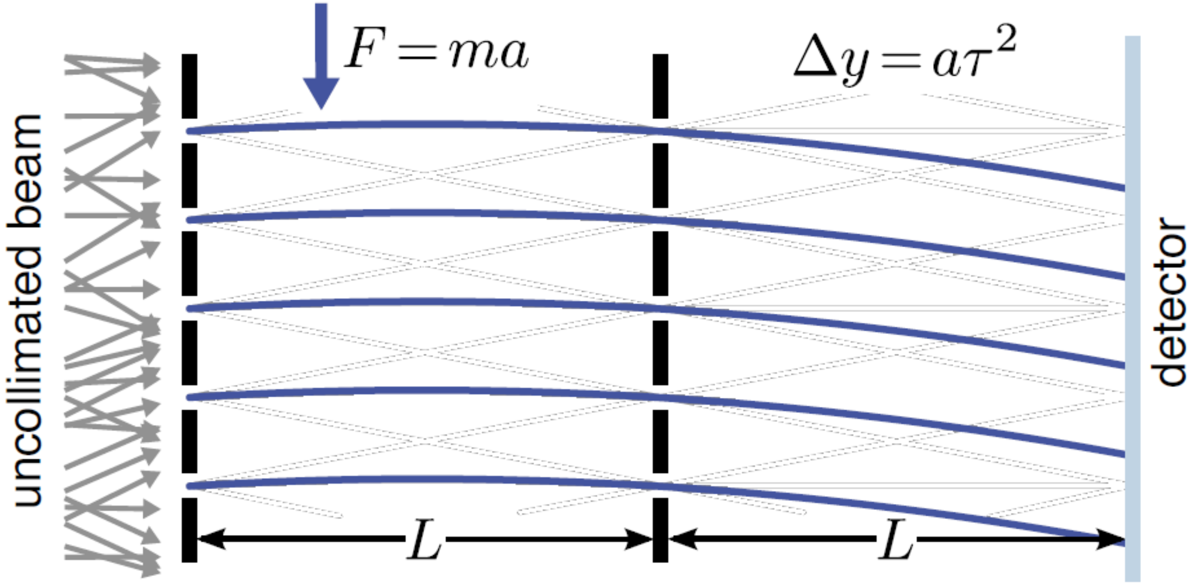
RRI







Antimatter moiré deflectometer



Aghion S. et al (AEgIS collaboration), *Nat Comm 5:4538* (2014)

Velocity 350 m/s (T = 5K)

Length 0.5m

$\tau \sim 10^{-3}$s

d = 10^{-4} m

$$\varphi = \frac{2\pi}{d}\Delta y = \frac{2\pi}{d} a\,\tau^2$$

Resolution $R_{acc} = \frac{d\varphi}{da} = 2\pi\frac{\tau^2}{d} \sim \frac{2\pi}{100}$

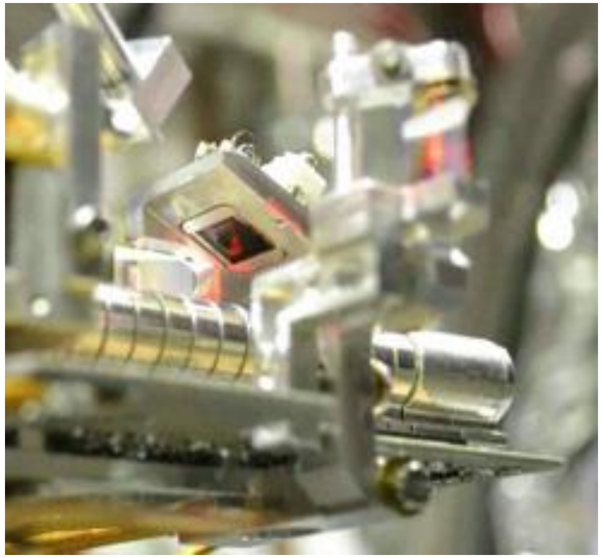
Minimal detectable acceleration

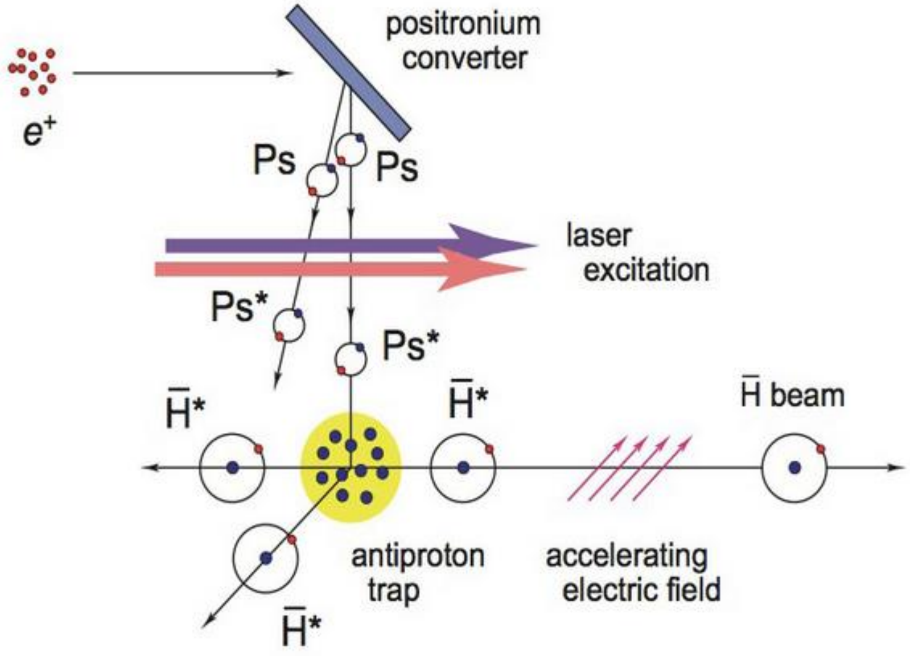
$$a_{min} = \frac{1}{R_{acc} C \sqrt{N}}$$

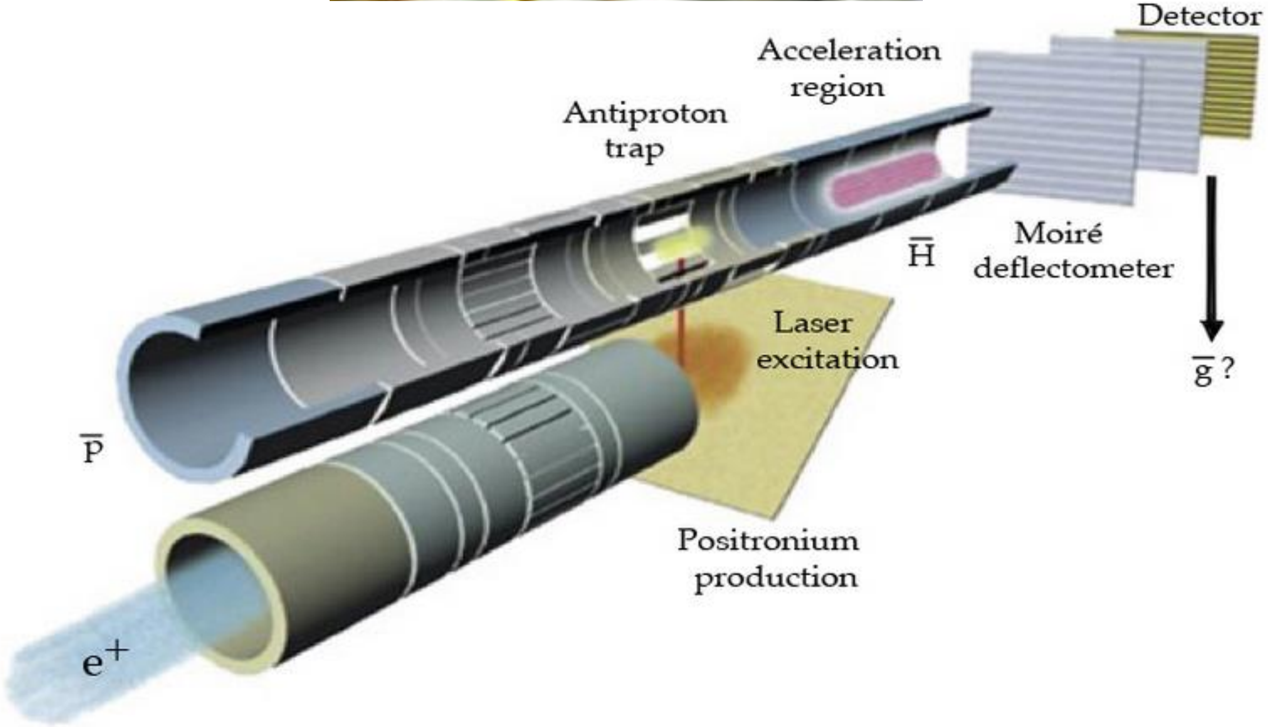
a_{min} = 1 m/s^2 for N = 10^4 and C = 0.16

Antihydrogen production

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

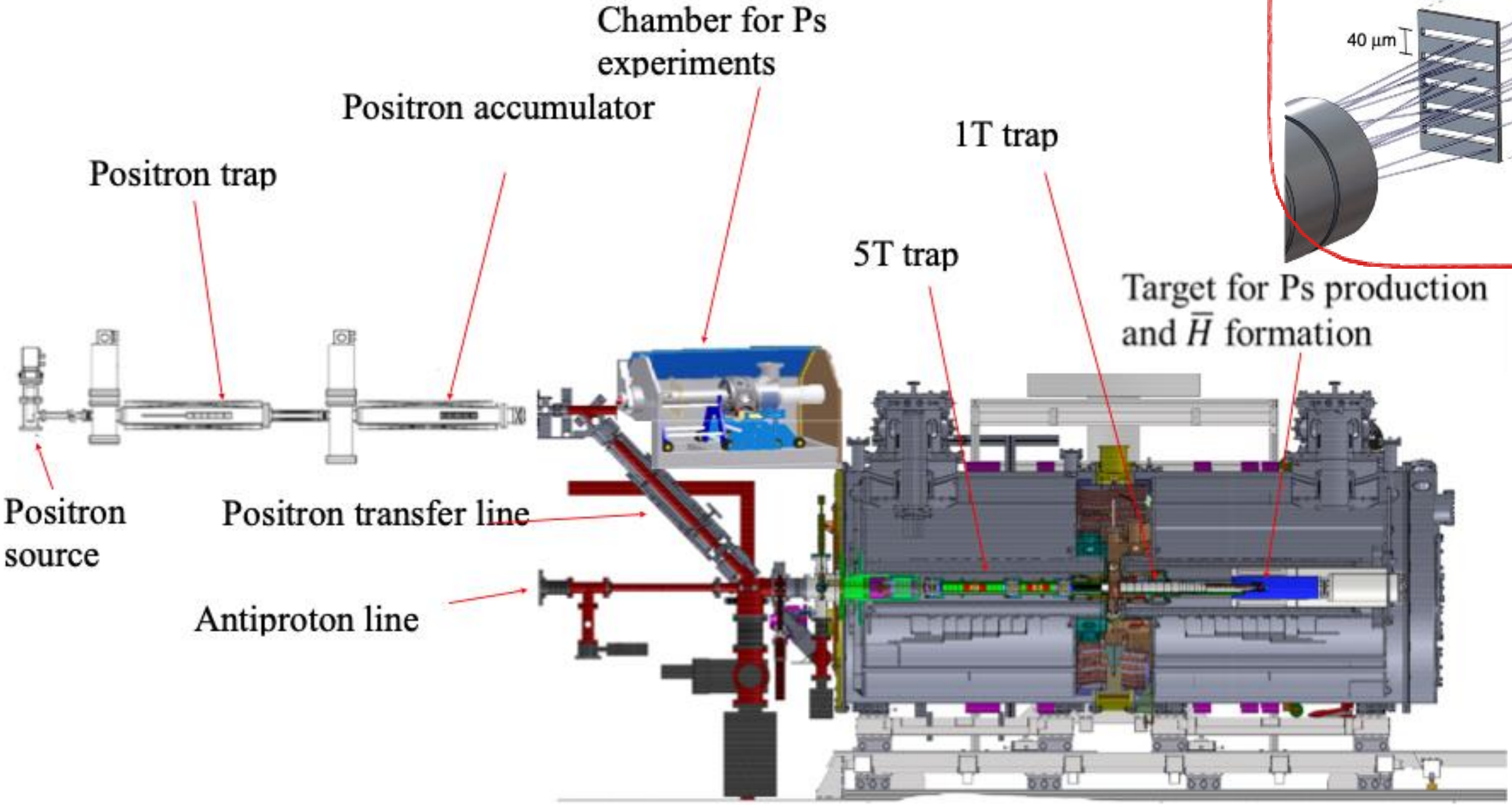


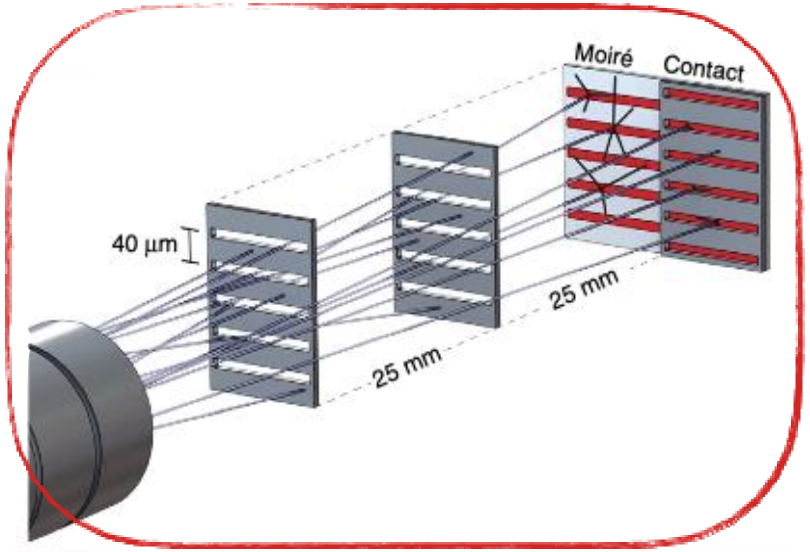




Kellerbauer A. et al (AEgIS collaboration), *NIM B* 266 (2008) 351-356
Krasnicky D., Caravita R., Canali C., Testera G., *PRA* 94 (2016) 022714

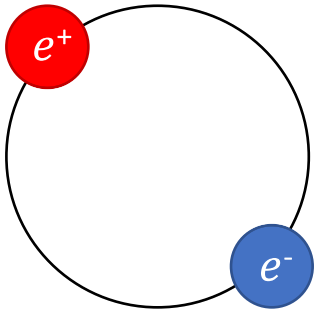
The AEgIS setup



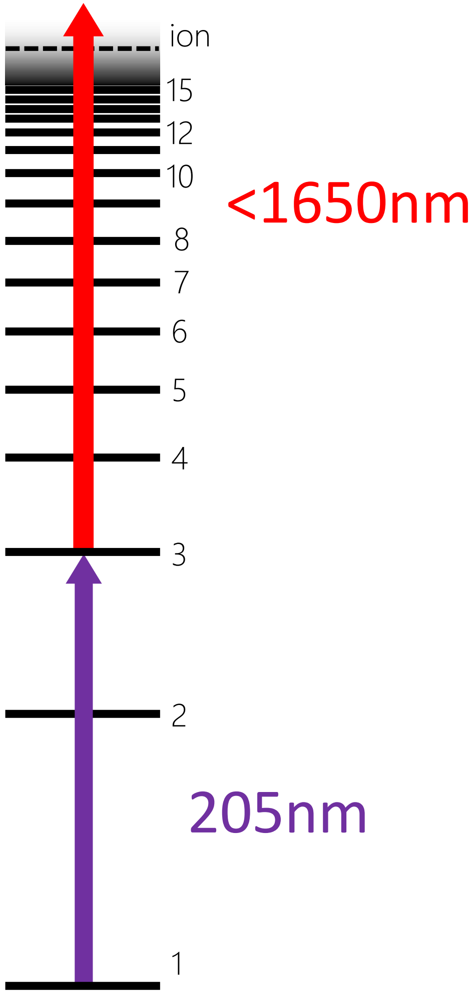


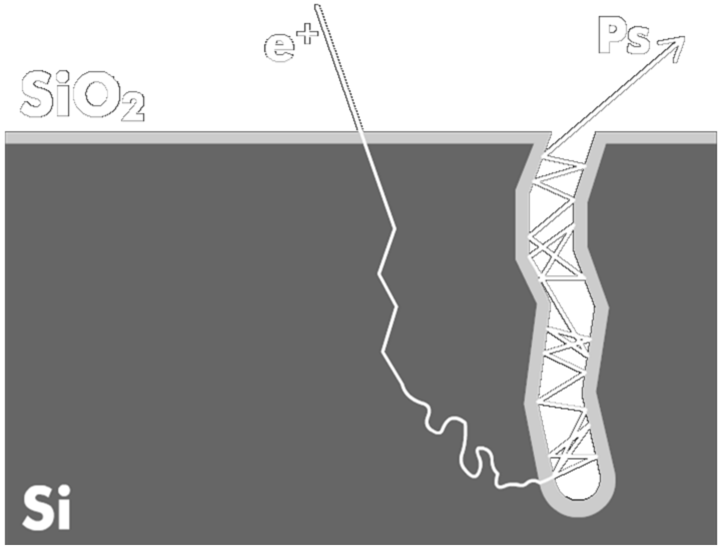
Positronium production

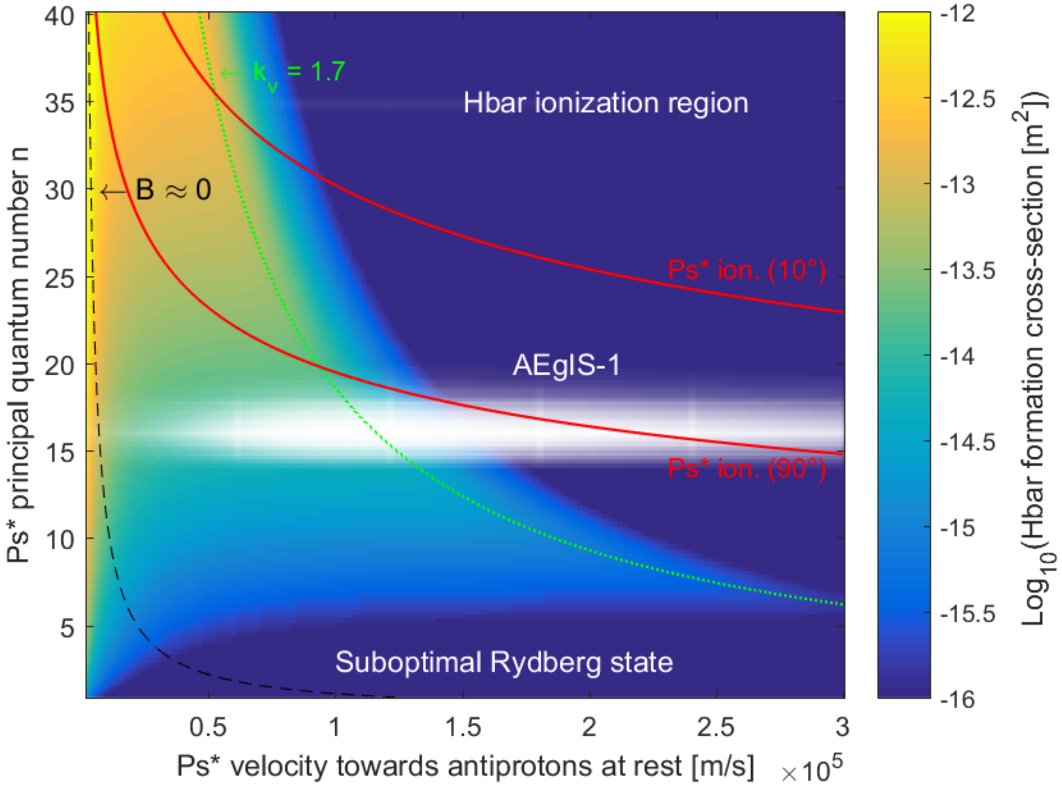
Positronium (Ps)



142 ns lifetime







SSPALS positronium Doppler velocimetry

Methodology

Excite the 1^3S – 3^3P transition (**UV**)

Photoionize 3^3P atoms (**IR**)

o-Ps signal reduction at later times

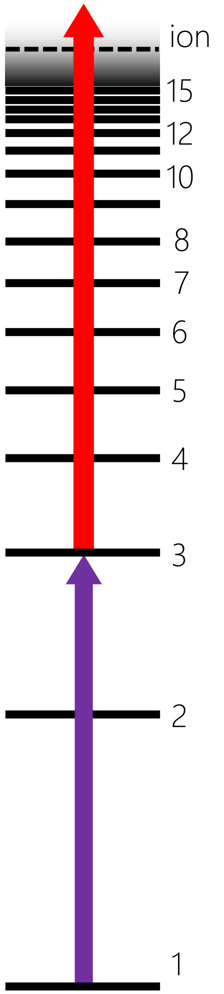
Results

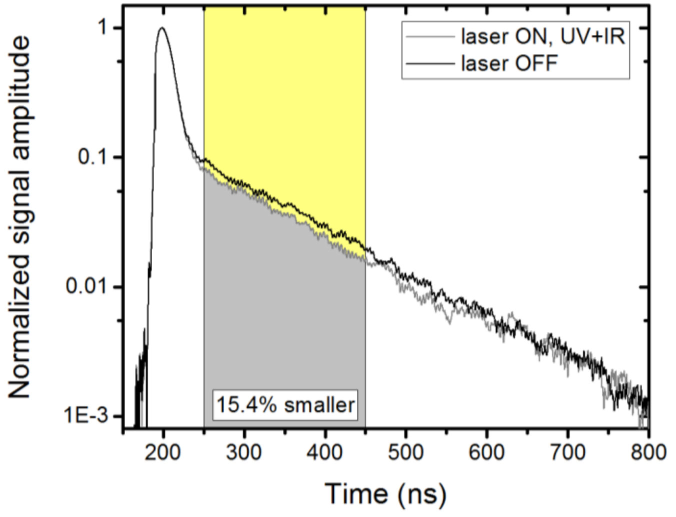
First spectroscopy of Ps n = 3

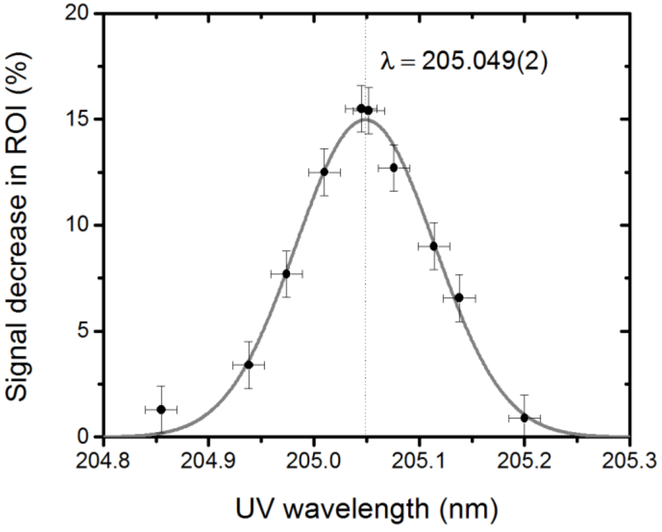
Doppler temperature ~1200K

16 % max. excitation efficiency

- 20 % Doppler coverage
- 80 % geometrical efficiency

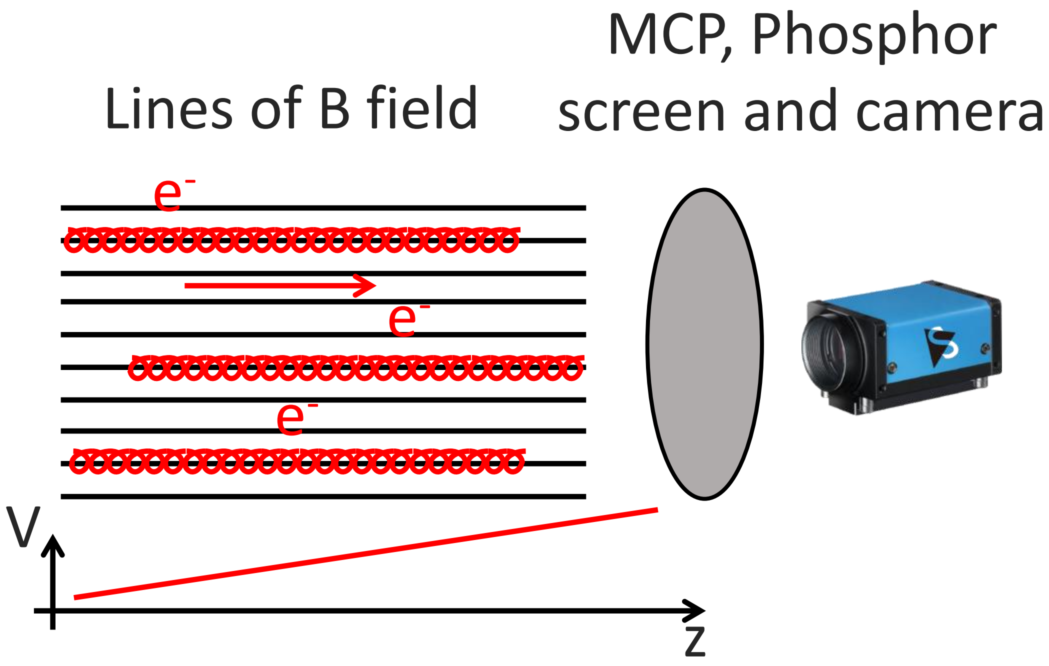


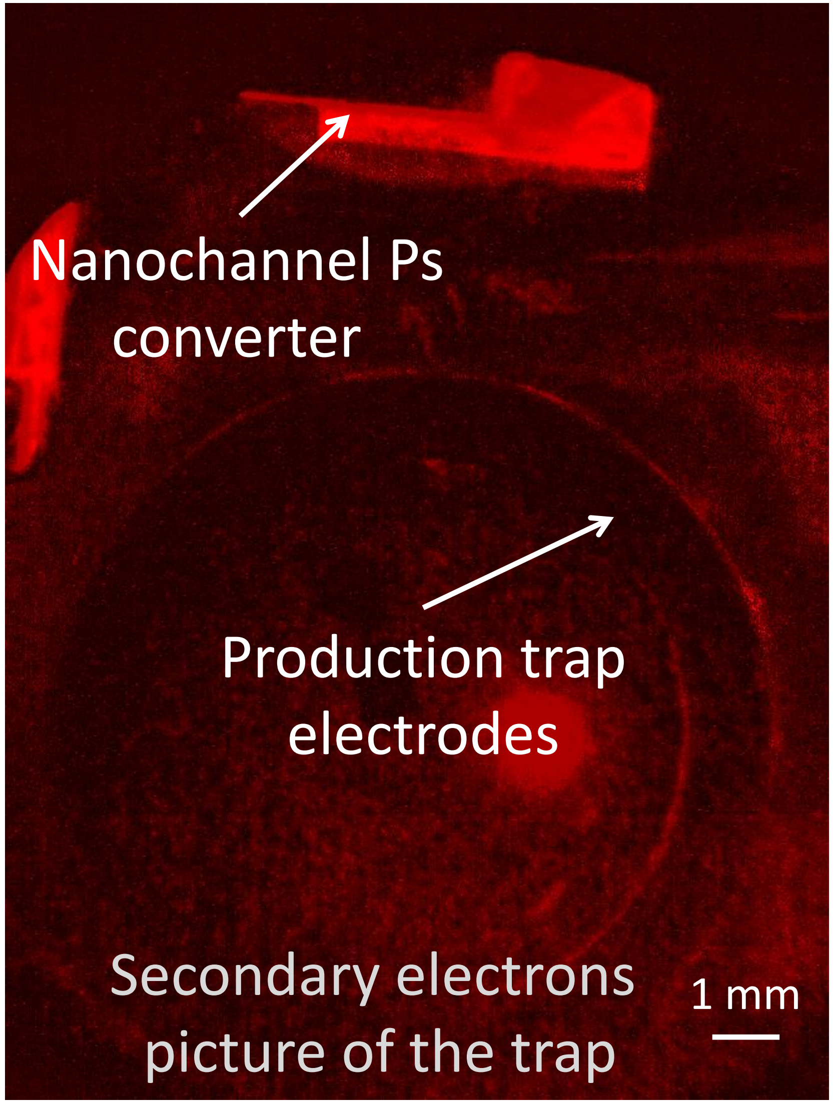




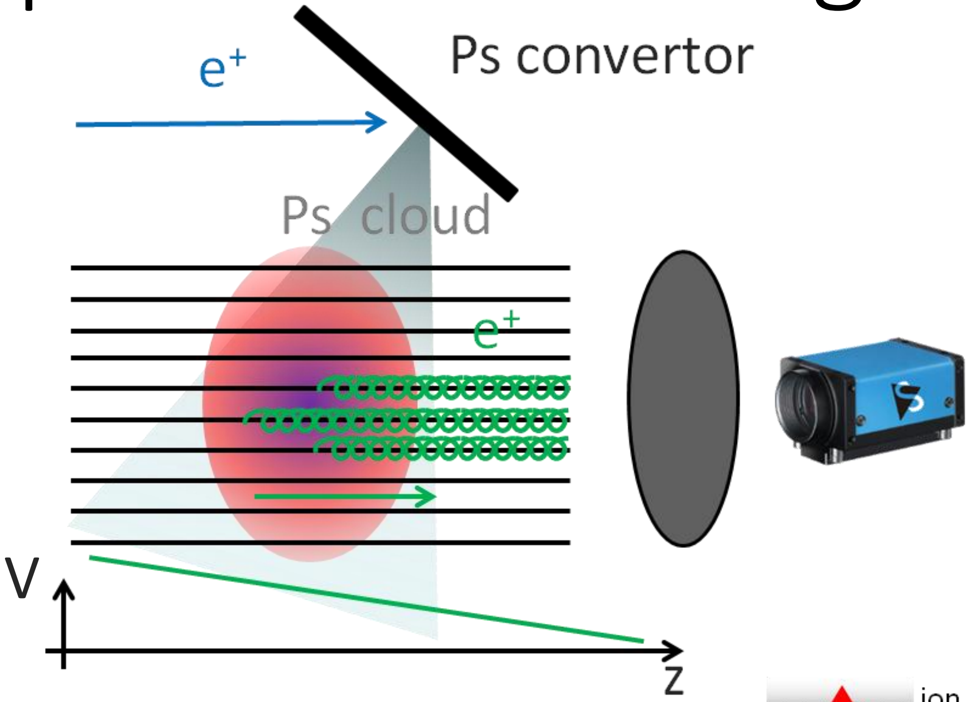
Aghion S. et al (AEgIS collaboration), *Physical Review A 94 (2016) 012507*

Photoelectron imaging

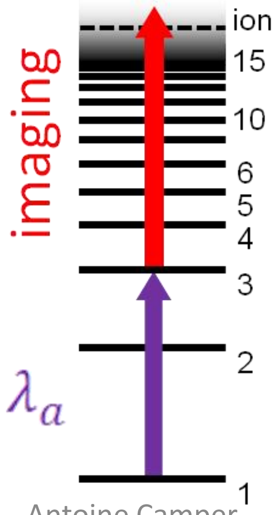


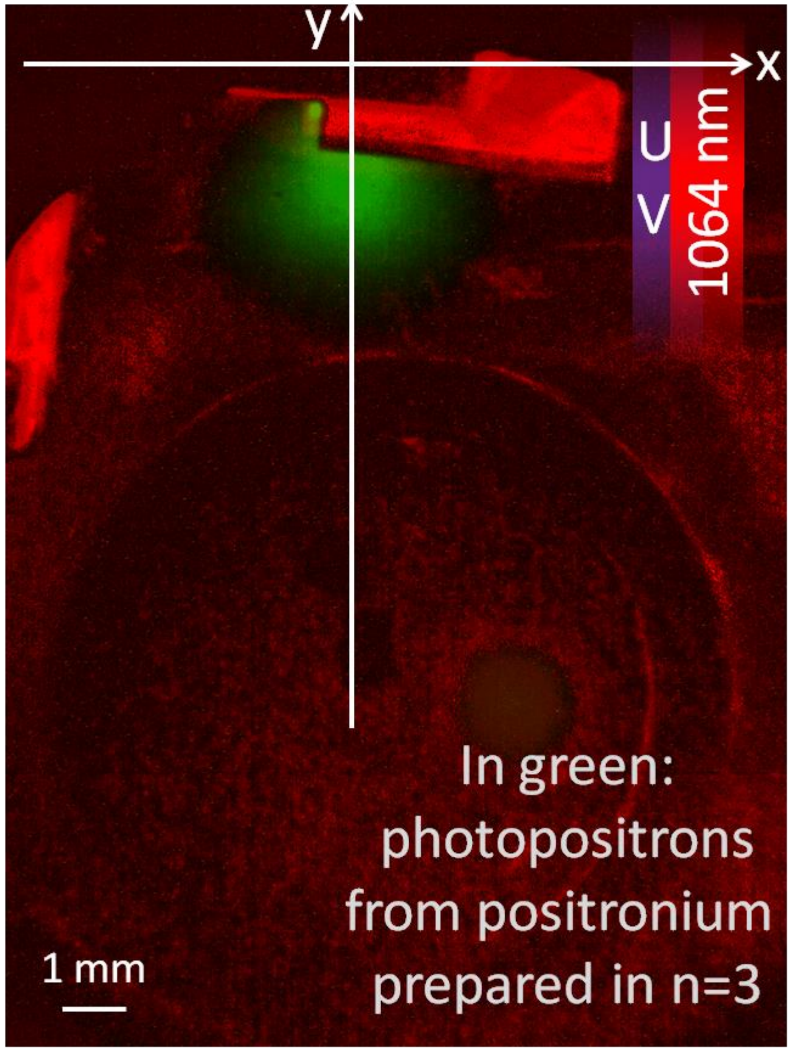


Photopositrons: a background free signal



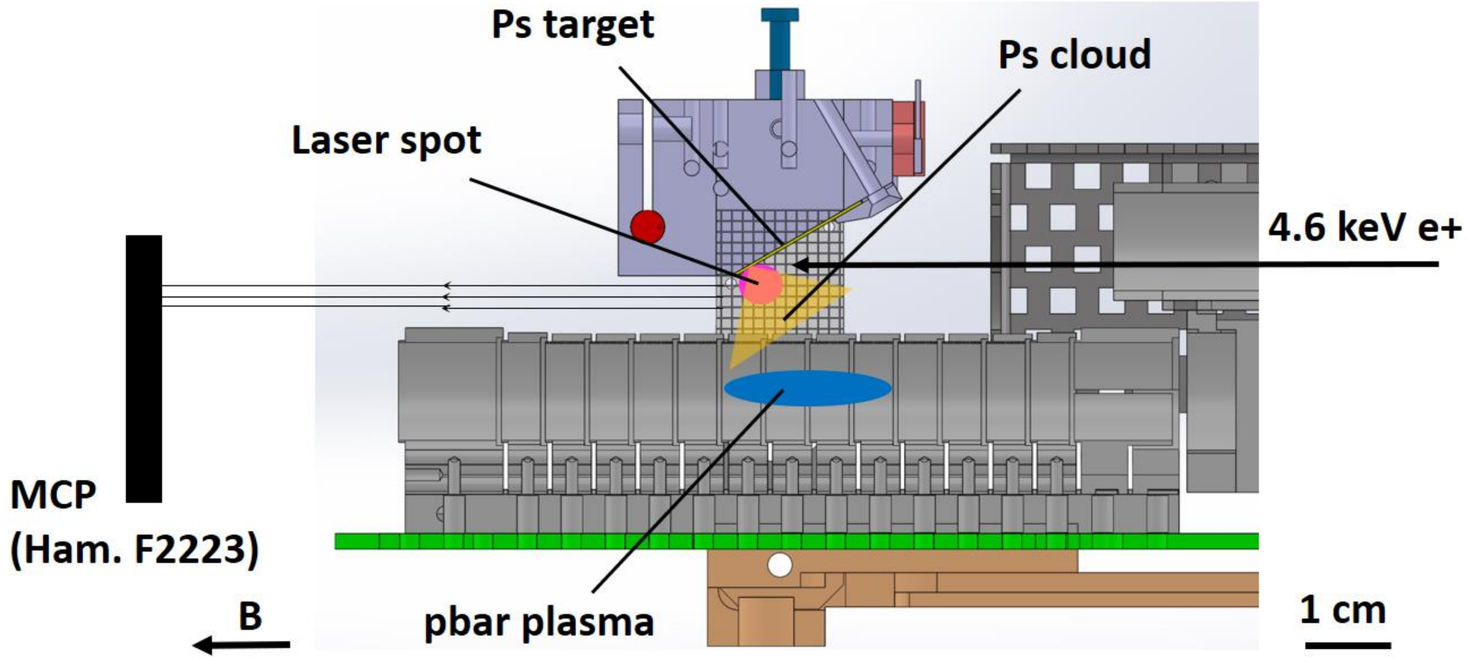
$$\lambda^D = \lambda_a\left(1 + \frac{v_\parallel}{c}\right)$$
$$\simeq \lambda_a\left(1 + \frac{x}{\mathrm{c} \times \Delta \mathrm{t}}\right)$$

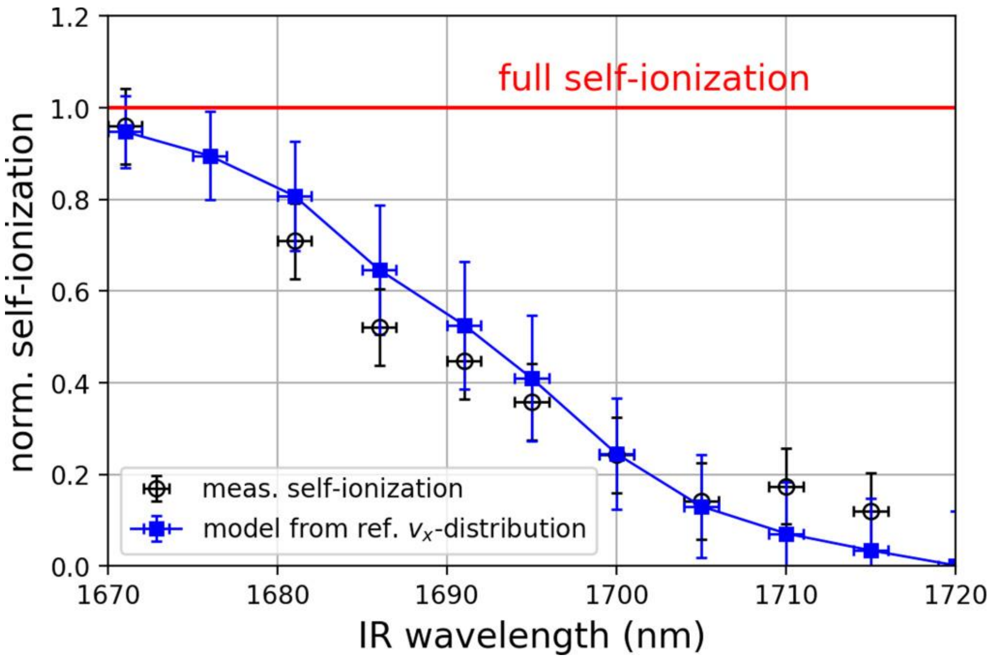




Motional Stark effect self-ionization

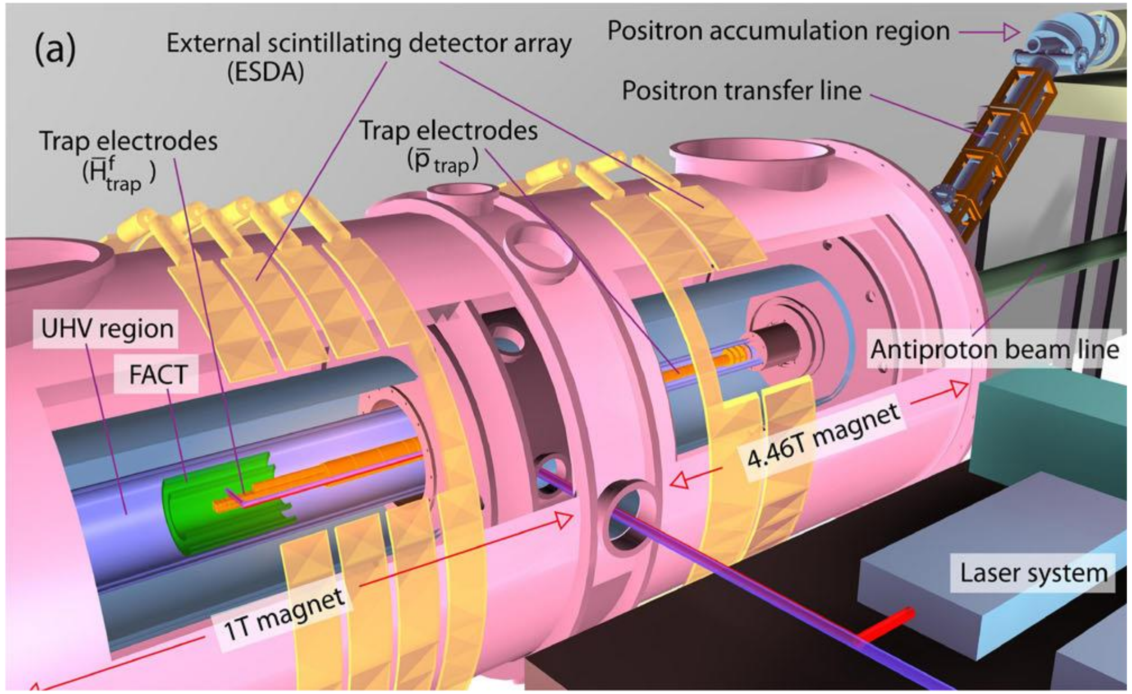
$$\vec{F}_{mot} = \vec{v} \times \vec{B}$$

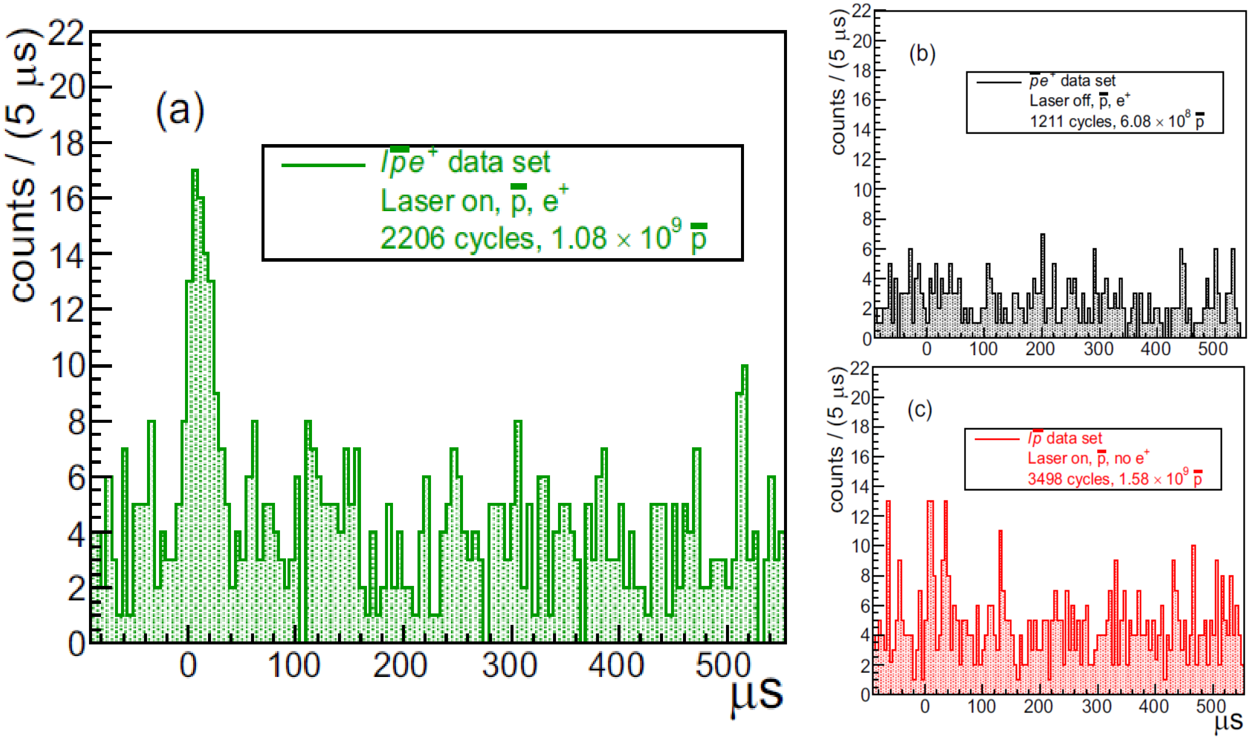




Antonello M. et al (AEgIS collaboration), *Phys Rev A* 102, 013101 (2020)

Pulsed production of antihydrogen

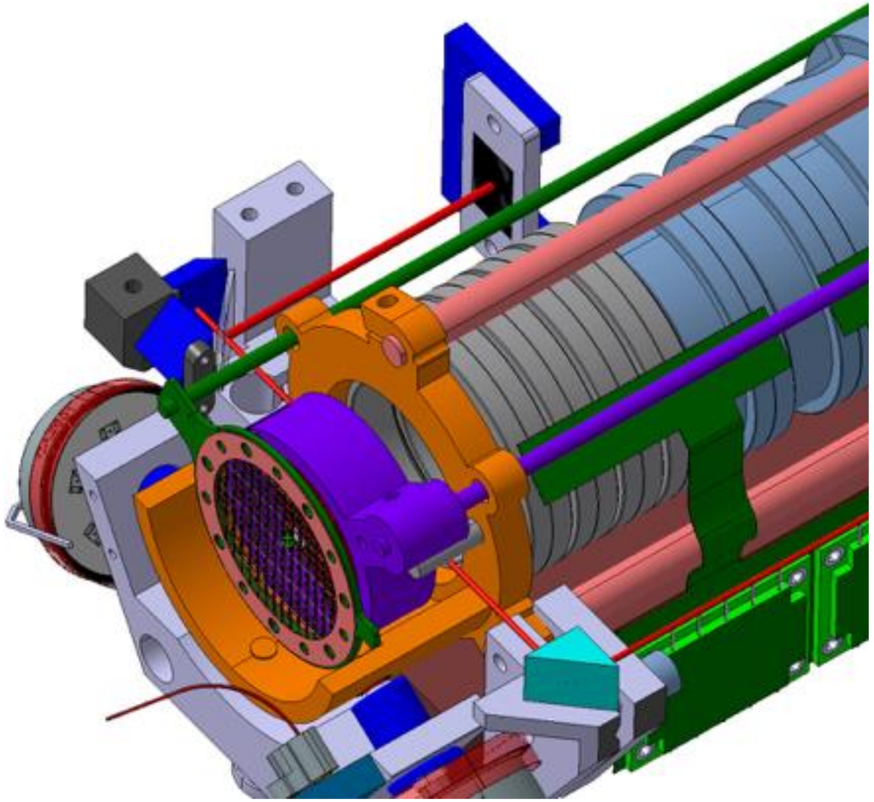




Key finding: 0.05 $\bar{H}^*$ produced every 2 mins (with $1.0{\cdot}10^6$ antiprotons)
$\bar{H}^*$ produced in a time window of 250ns

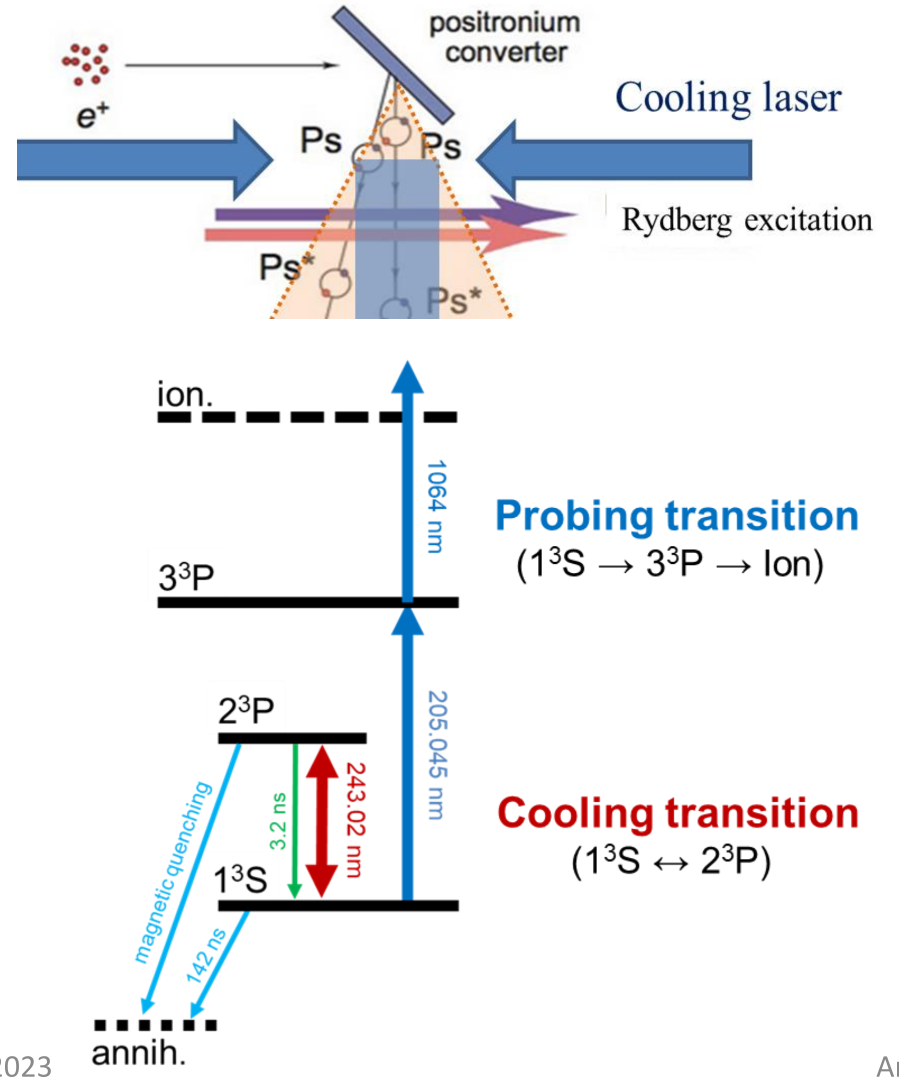
Amsler C. et al (AEgIS collaboration), *Com Phys* 4:19 (2021)

Recent developments



- Connection to ELENA (new degrader scheme)
- On axis Ps production (higher Rydberg states)
- Fiber bundle multispectral imaging system

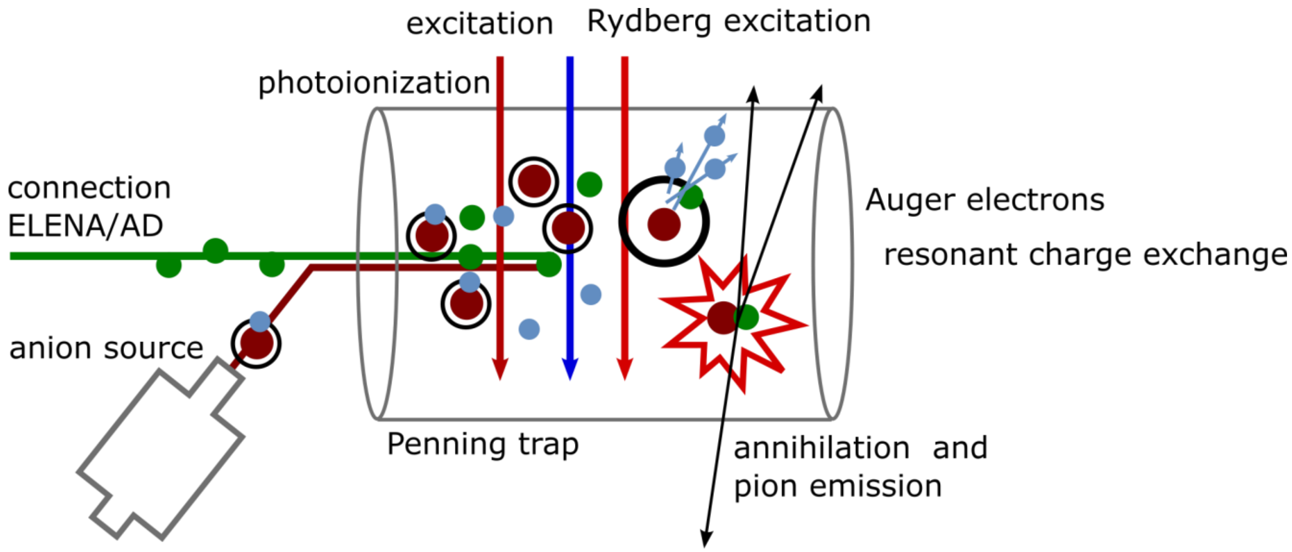
Positronium laser cooling



- Short annihilation lifetime (142 ns) pulsed cooling with long intense UV pulse → alexandrite laser
- Broad initial distribution (10^5 m/s)
- Short decay time of n=2 (3ns)
- Huge recoil (15 km/s)
- Quenching in E and B field

Zimmer C. et al, *Phys Rev A* 104, 023106 (2021)

Formation of cold antiprotonic atoms



1. Precise laser spectroscopy of Rydberg antiprotonic atoms
2. Trapping of cold and trapped highly charged radioisotopes produced after annihilation of antiprotons on the surface.

Conclusions and perspectives

- Antimatter deflectometer
- Pulsed production of antihydrogen
- Ps velocimetry

- Enhanced production of antihydrogen
- Directional beam of antihydrogen
- Ps laser cooling
- Antiprotonic atoms

Thank you for your attention!

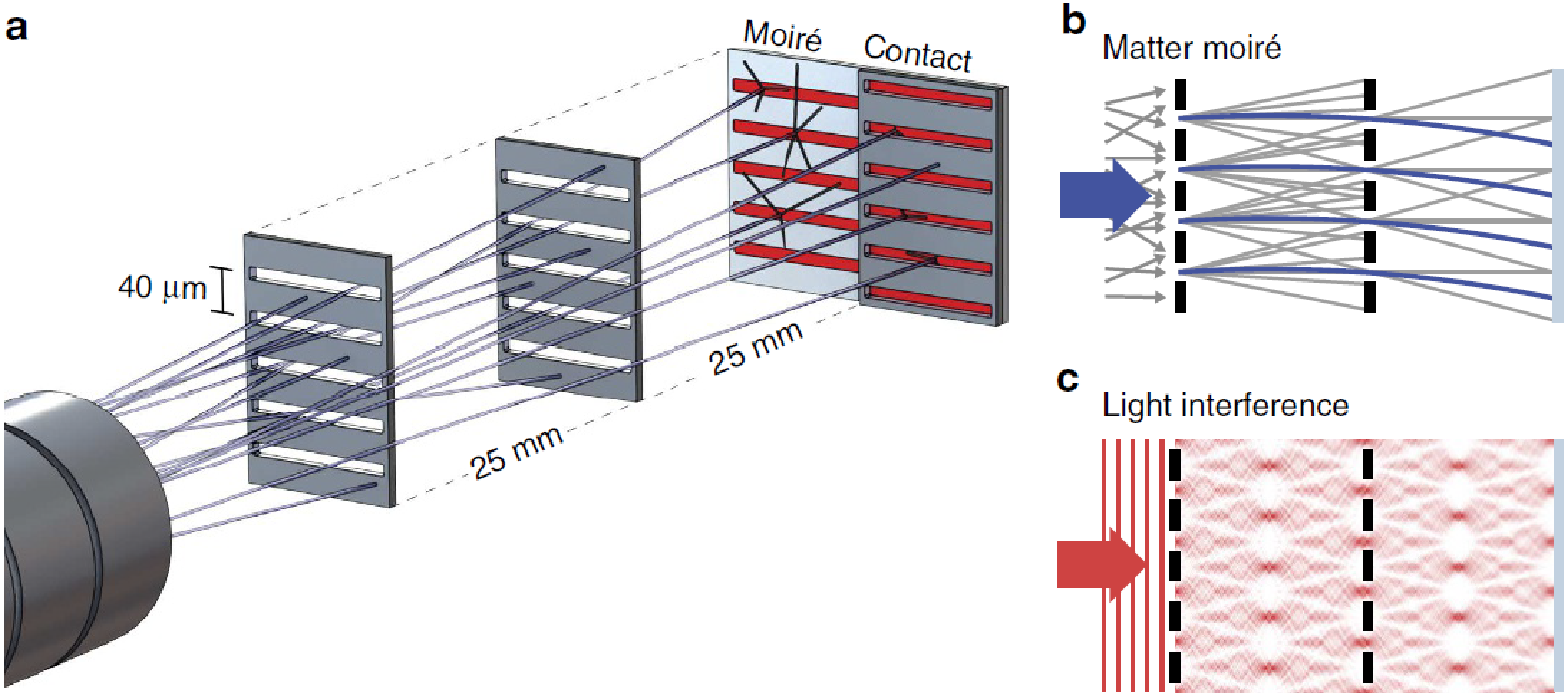
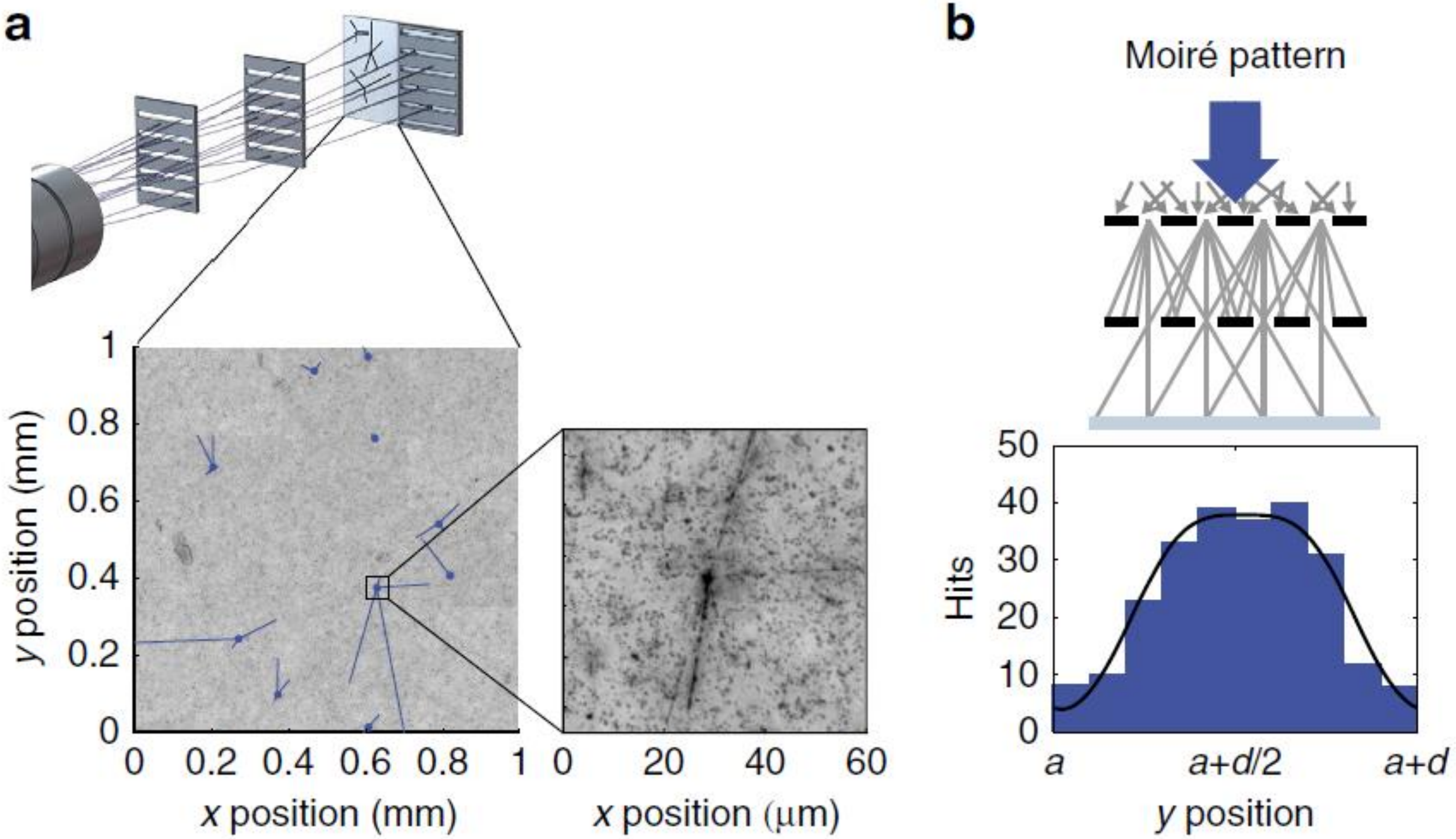
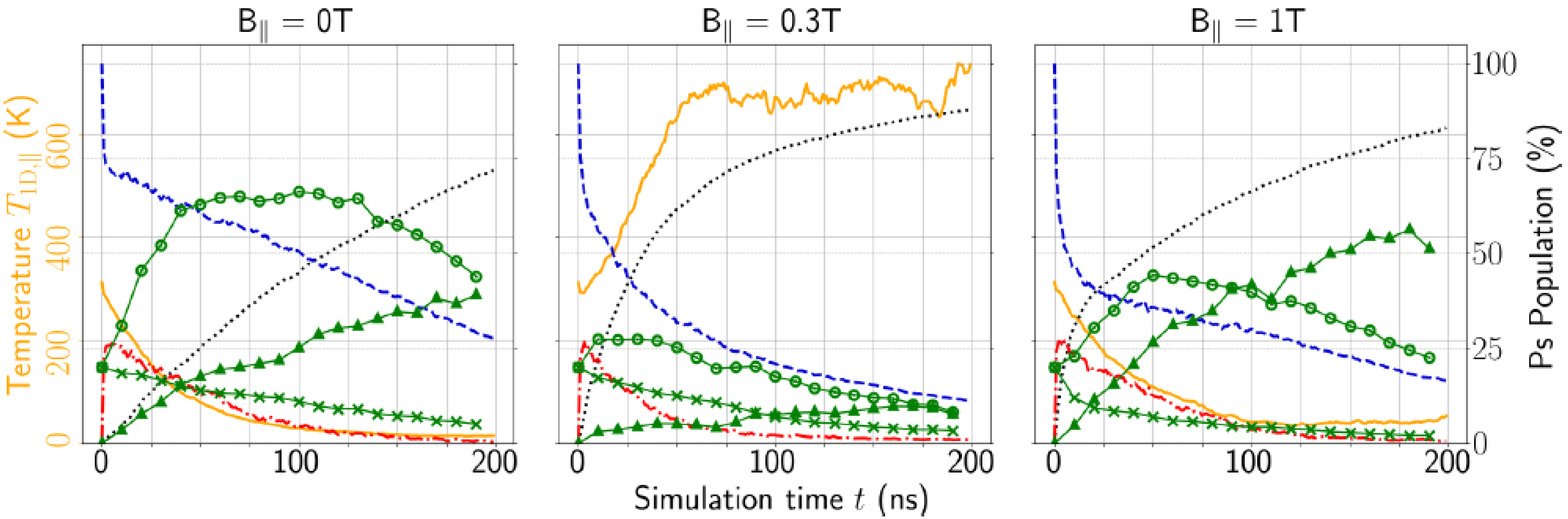


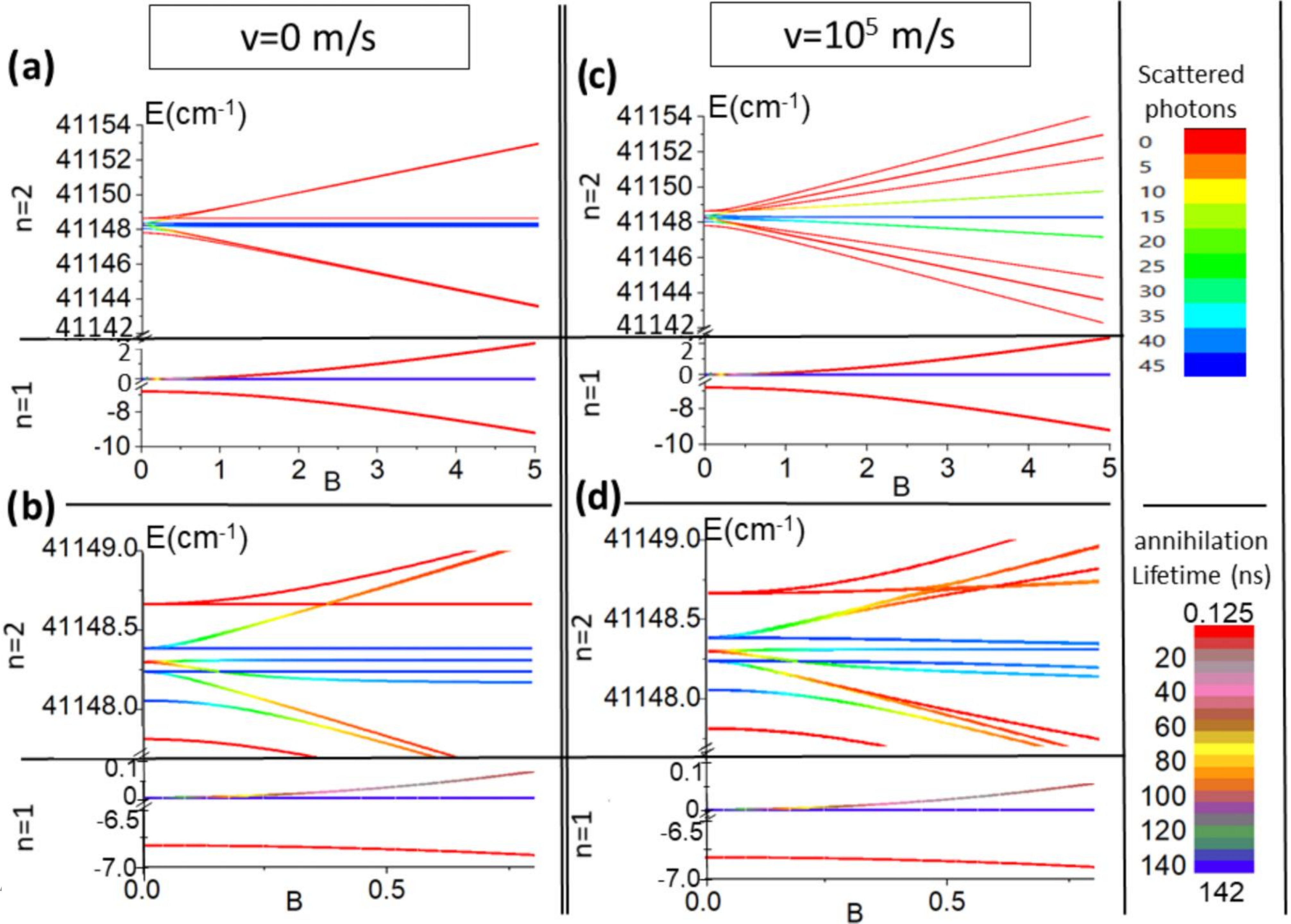
Figure 1 | Moiré deflectometer for antiprotons. (**a**) A divergent antiproton beam impinges on two subsequent gratings that restrict the transmitted particles to well-defined trajectories. This leads to a shadow fringe pattern as indicated in **b**, which is shifted in the presence of a force (blue trajectories). Finally, the antiprotons are detected with a spatially resolving emulsion detector. To infer the force, the shifted position of the moiré pattern has to be compared with the expected pattern without force. (**c**) This is achieved using light and near-field interference, the shift of which is negligible. A grating in direct contact with the emulsion is used to reference the antimatter and the light measurements.



a
1
0.8
0.6
0.4
0.2
0
y position (mm)
0
0.2
0.4
0.6
0.8
1
x position (mm)
0
20
40
60
x position (μm)
b
Moiré pattern
50
40
30
20
10
0
Hits
a
a+d/2
a+d
y position
c
Contact pattern
60
50
40
30
20
10
0
Hits
0
d/2
d
y position



B$_\parallel$ = 0T
B$_\parallel$ = 0.3T
B$_\parallel$ = 1T
Temperature $T_{1D,\parallel}$ (K)
0
200
400
600
0
100
200
Simulation time t (ns)
Ps Population (%)
0
25
50
75
100


v=0 m/s
v=10^5 m/s
(a)
(b)
(c)
(d)
E(cm-1)
n=2
n=1
B
Scattered photons
0
5
10
15
20
25
30
35
40
45
annihilation Lifetime (ns)
0.125
20
40
60
80
100
120
140
142