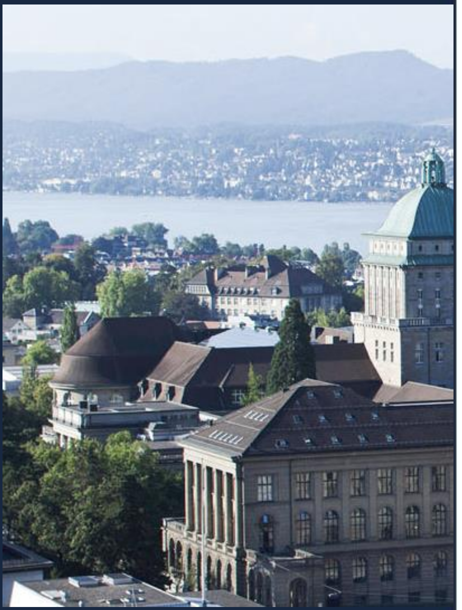
THE ANTIMATTER EXPERIMENT
Gravity | Interferometry | Spectroscopy

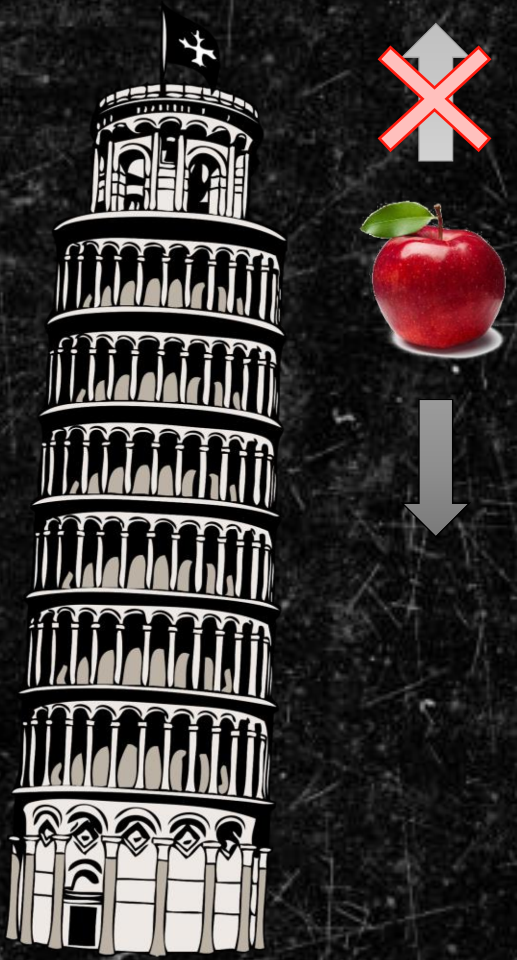
AEgIS
THE WEIGHT OF ANTIMATTER



PSAS'2024: Broadband Positronium Laser Cooling

Speaker: Benjamin Rienäcker

How does gravity affect antimatter?



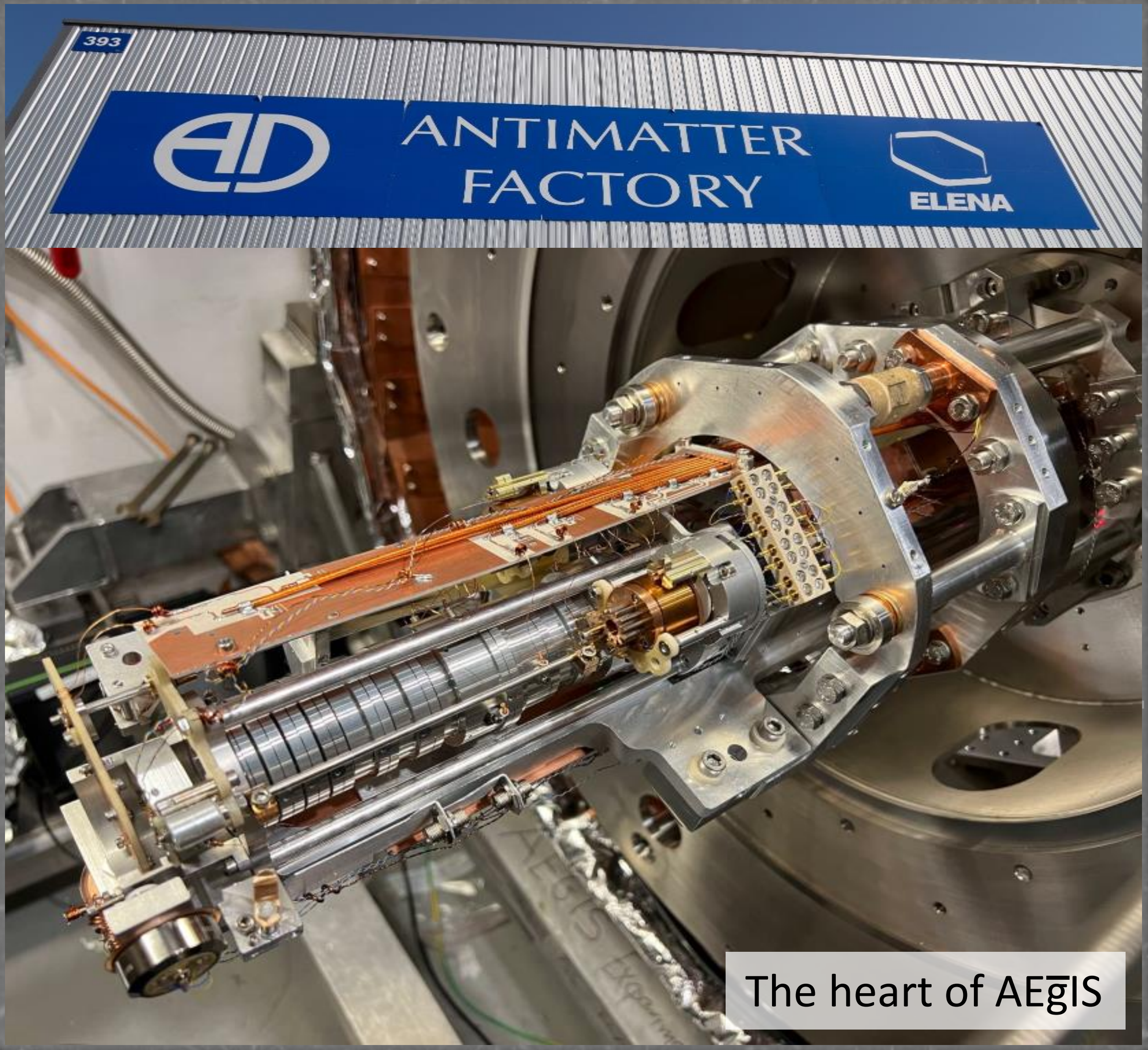
- Exact value of $\bar{g}$ unknown
  (ALPHA-g 2023: $a_{\bar{g}}/a_g = 0.75 \pm 0.16 \pm 0.13$)

- Low precision on WEP tests for antimatter
  (Normal matter: precision 10^{-15}, **MICROSCOPE 2022**)

- Other observations limit possible anomalies
  (e.g. neutrinos from **SN1987A**, **BASE 2022**)

- Direct free-fall type experiments with antimatter are very challenging!

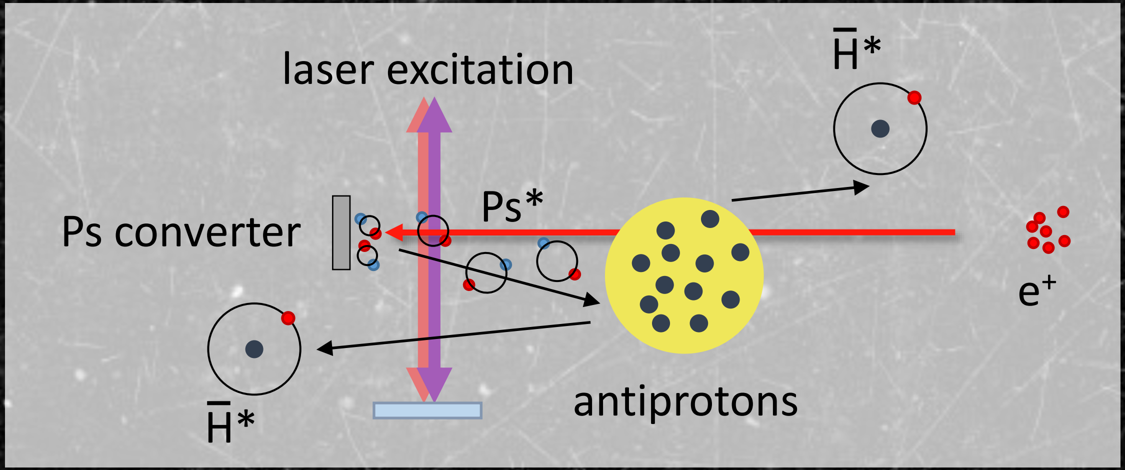
Production of antihydrogen



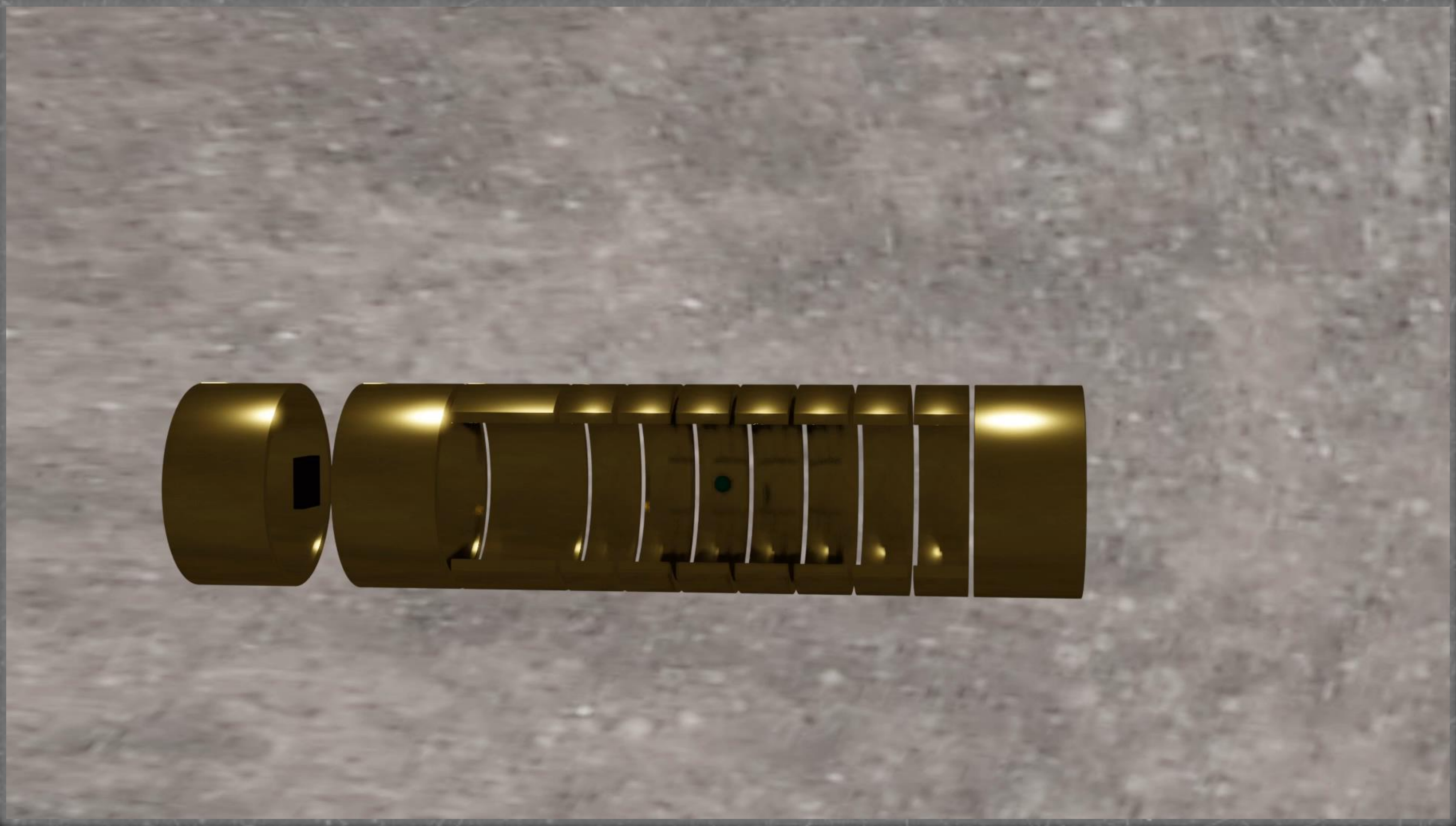
The heart of AEg̅IS

Charge exchange reaction:

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

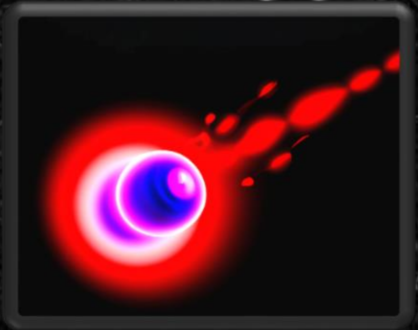


Production of antihydrogen



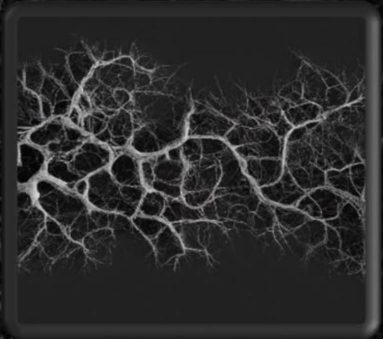
- antiproton
- positron
- electron
- positronium
- antihydrogen

How to get positronium?



The ^{22}Na isotope emits positrons (e^+)

Cooling

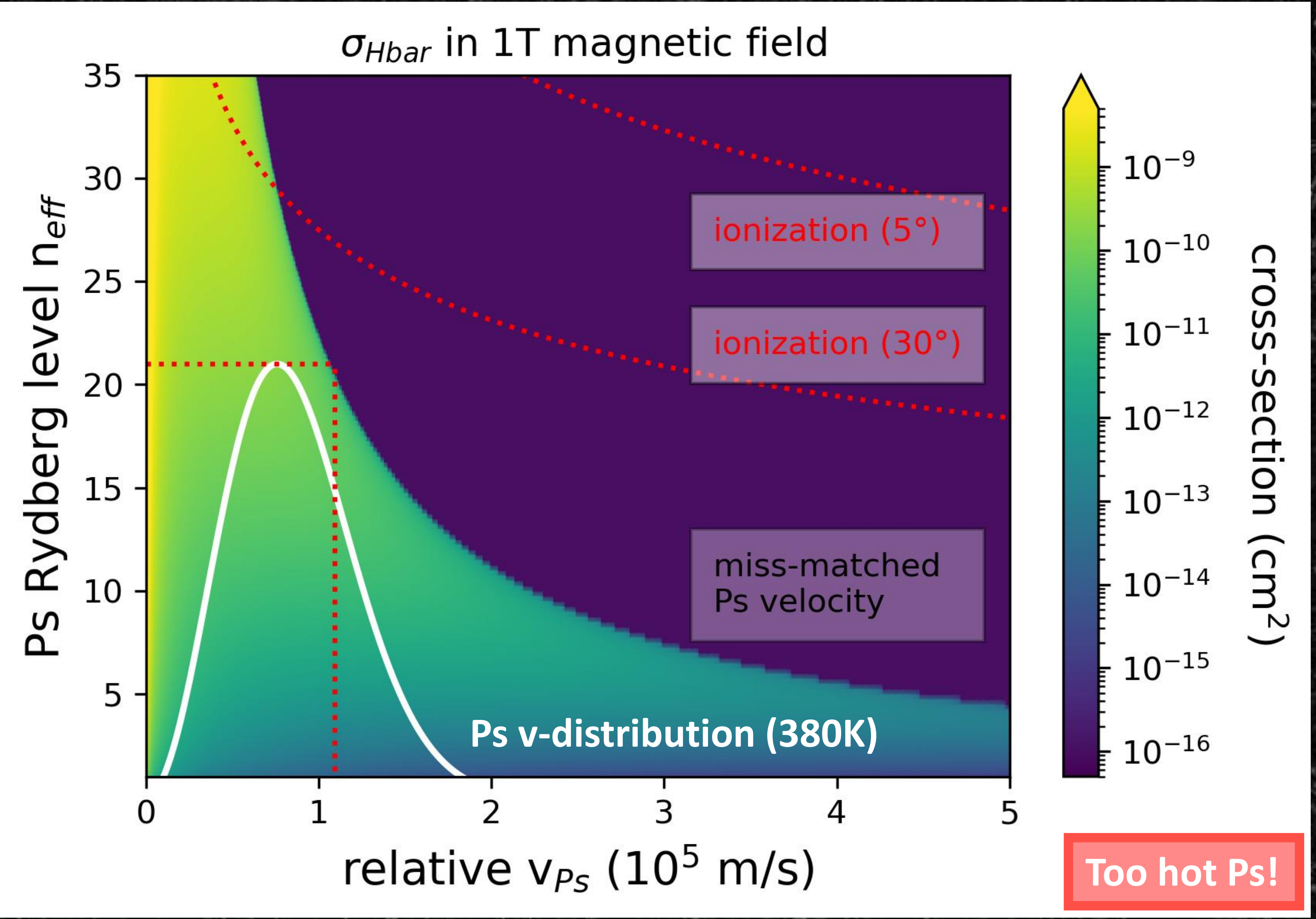


Injecting e^+ into nanoporous **Si**

… e^- meets e^+

Thermal emission (300K or 10^5 m/s)

Hbar cross-section 2023



Too hot Ps!

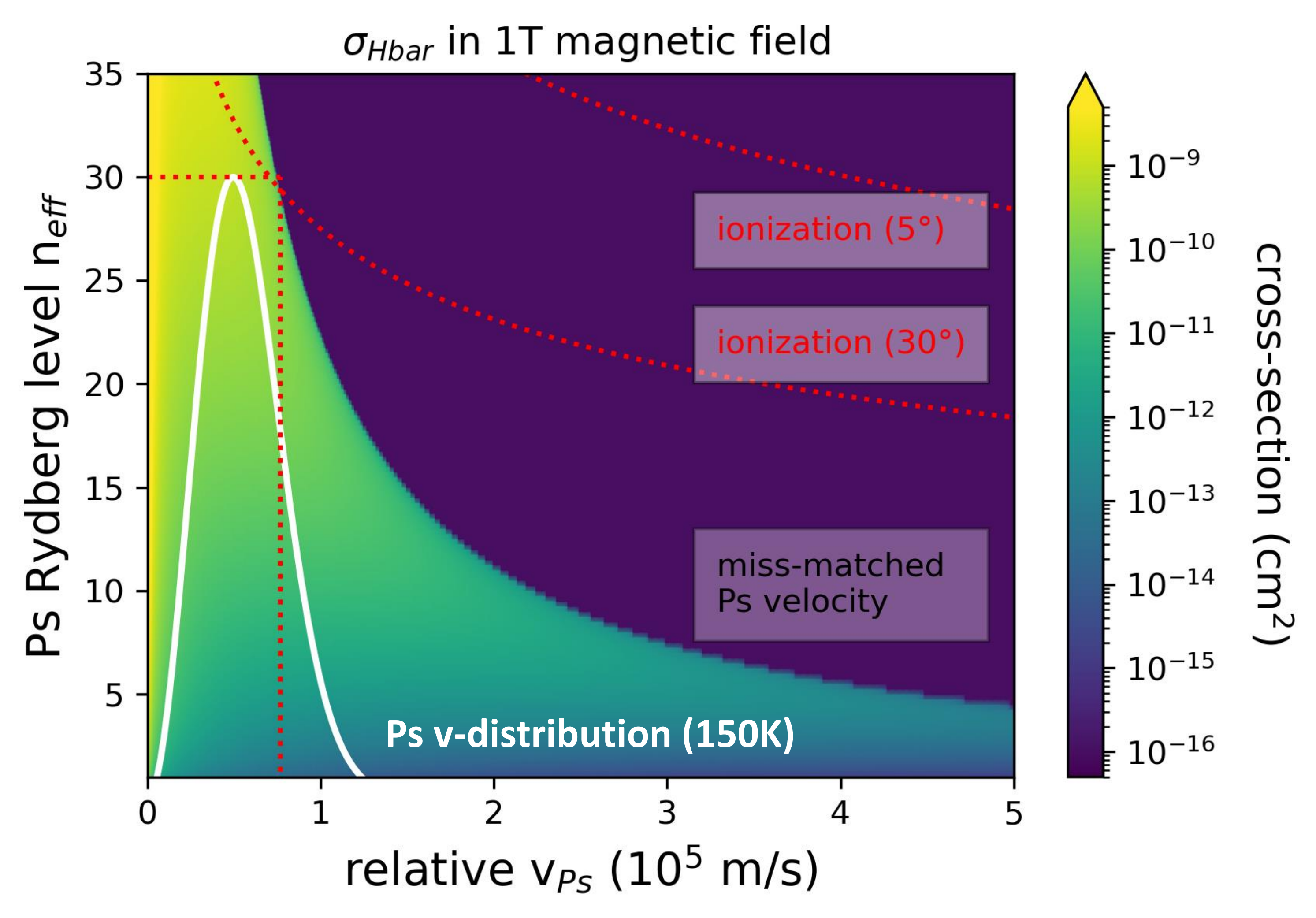
$$\sigma_{\bar{H}} \sim n^4$$

$$E_{ion} = v_{Ps} \times B = \frac{6.8}{9 a_0 n^4}$$

Phys. Rev. A ***94***, *022714 (2016)*
https://doi.org/10.1103/PhysRevA.94.022714

Commun. Phys ***4***, *19 (2021)*
https://doi.org/10.1038/s42005-020-00494-z

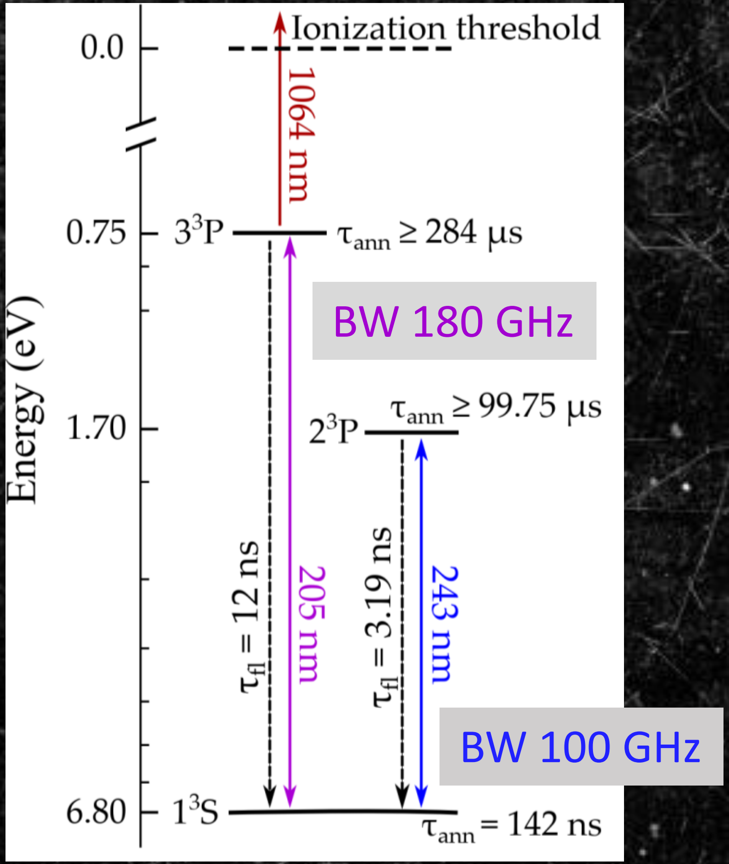
Hbar cross-section **ideal**

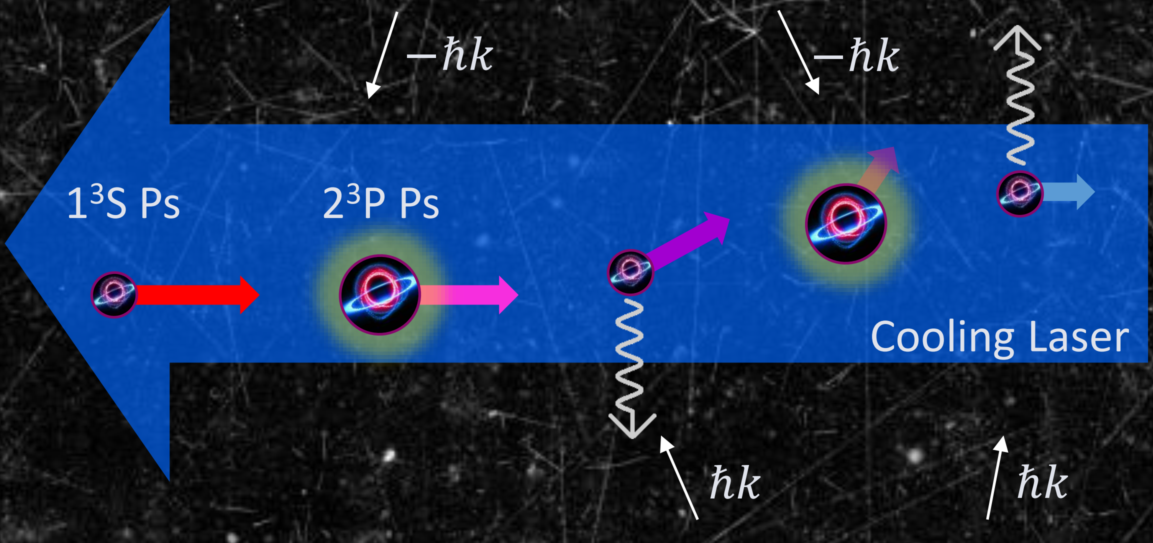


$$\sigma_{\overline{H}} \sim n^4$$

$$E_{ion} = v_{Ps} \times B = \frac{6.8}{9 a_0 n^4}$$

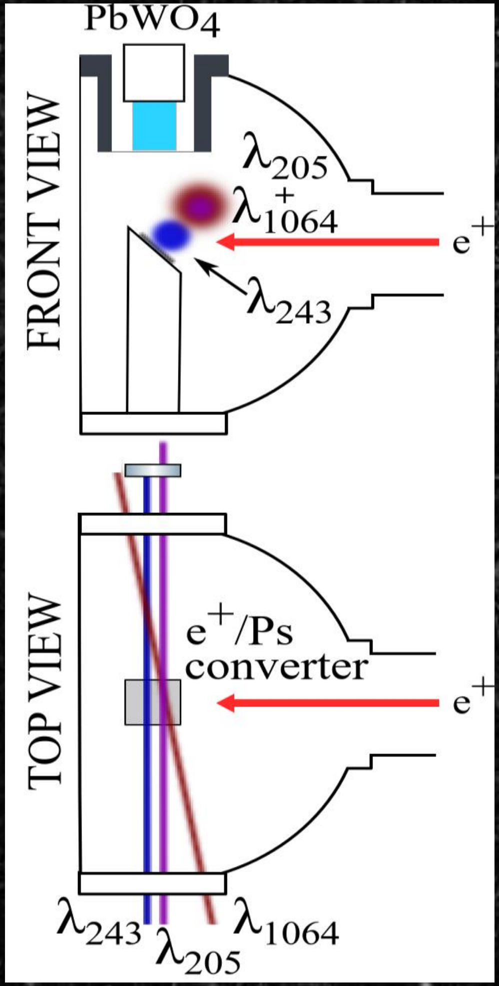
AEgIS positronium laser cooling scheme

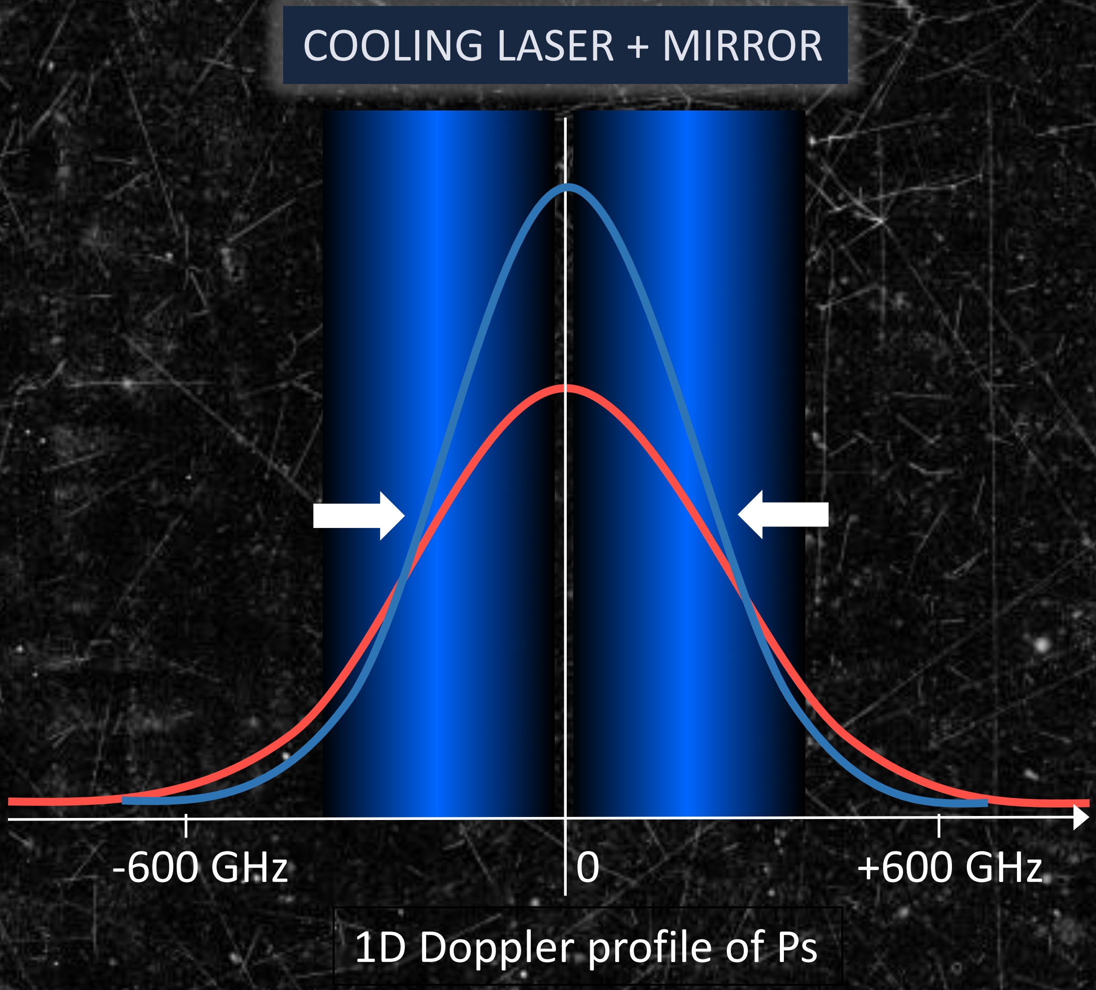




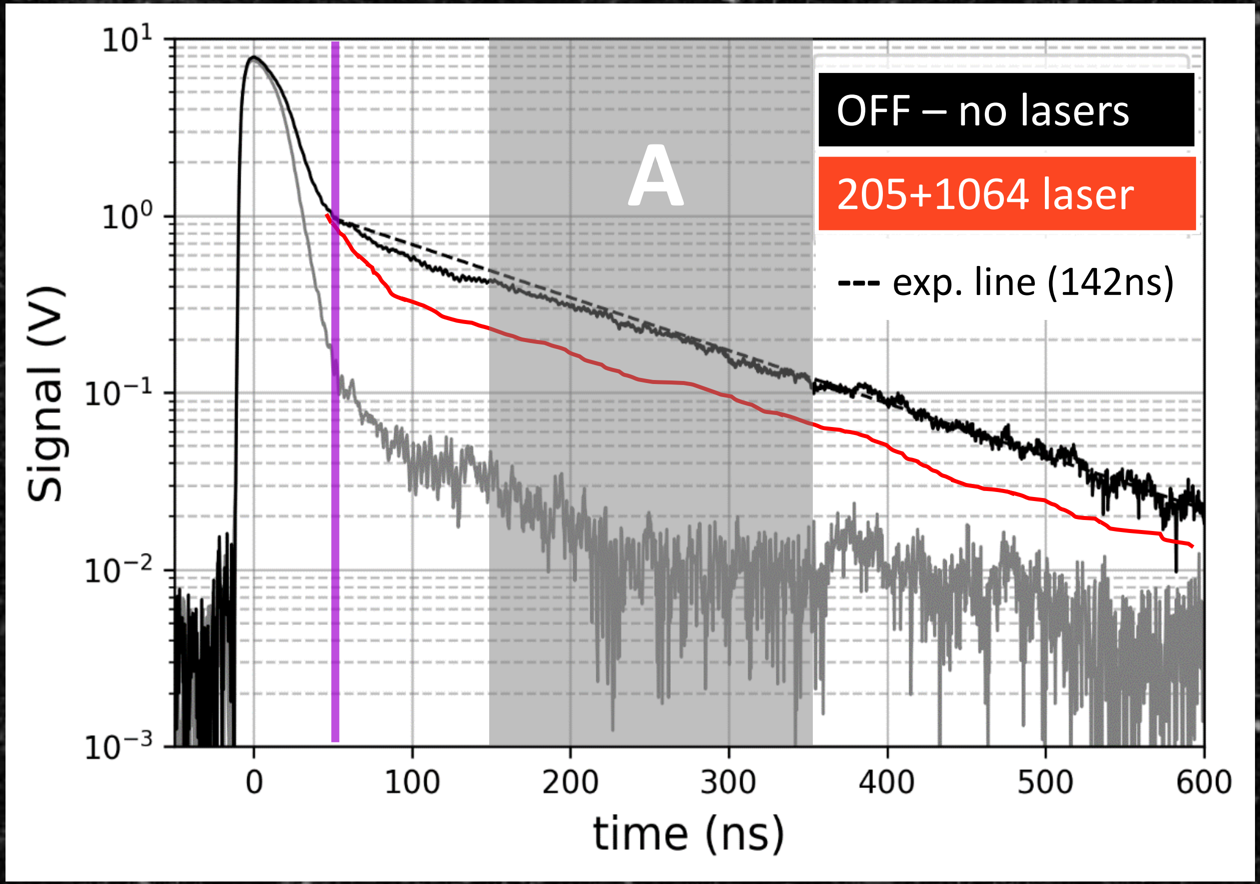
Technical paper submitted to **Optics and Laser Technology**
"An alexandrite laser system for positronium laser cooling"

AEgIS choice: Broadband 70ns laser pulse





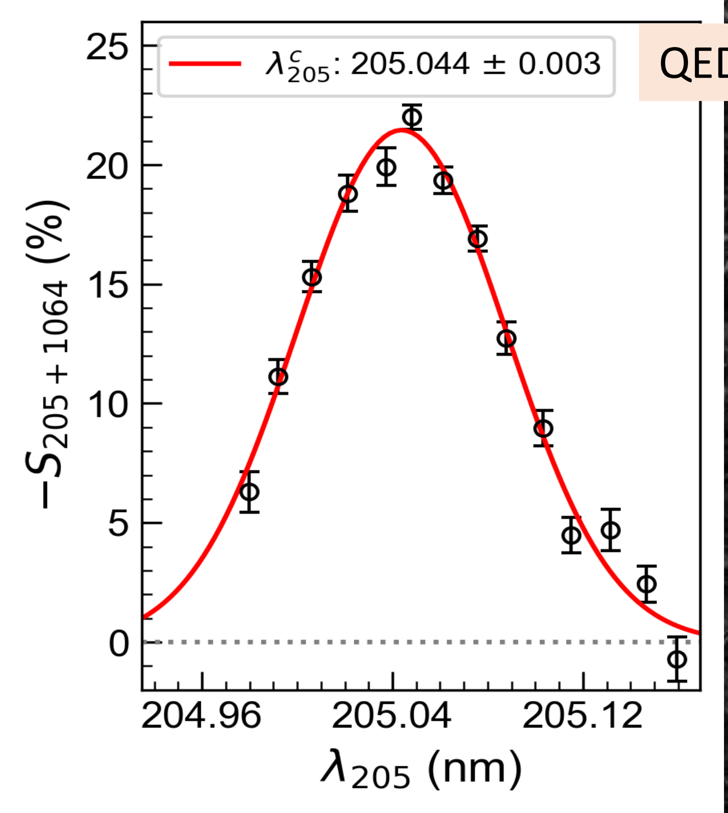
SSPALS reference by 205 probing laser



$$S_{205+1064} = \frac{A_{205+1064} - A_{\text{off}}}{A_{\text{off}}} < \mathbf{0}$$

Result for the 205nm probing laser alone

Ps Doppler Scan on the $1^3S - 3^3P$ transition



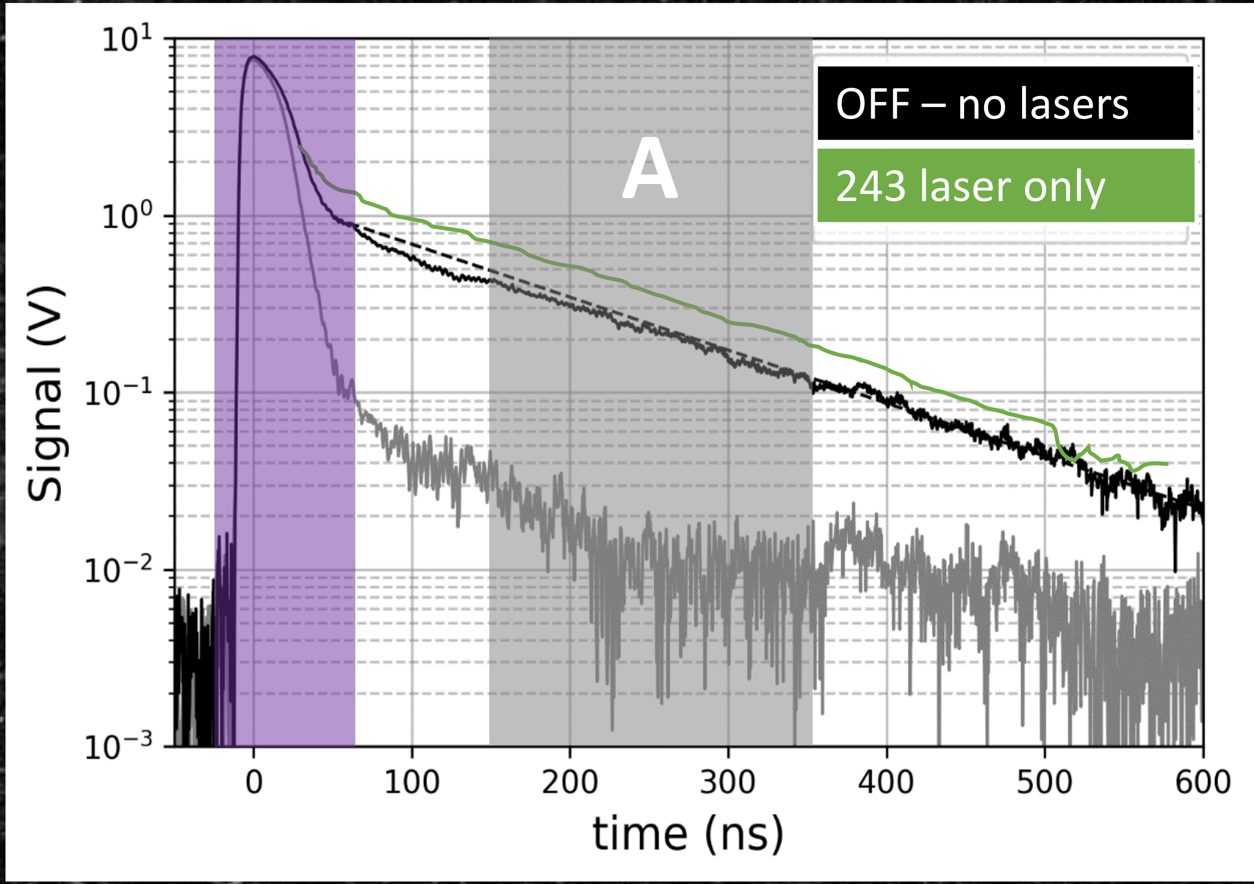
QED: 205.047 nm, B = 0

From the width of a Gaussian fit and the 205 BW (180 GHz):

v_{rms}= (5.4 ± 0.2)·10^4 ms^{-1}

T= (380 ± 20) K

SSPALS with 243 cooling laser alone



$$S_{243} = \frac{A_{243} - A_{\text{off}}}{A_{\text{off}}} > \mathbf{0}$$

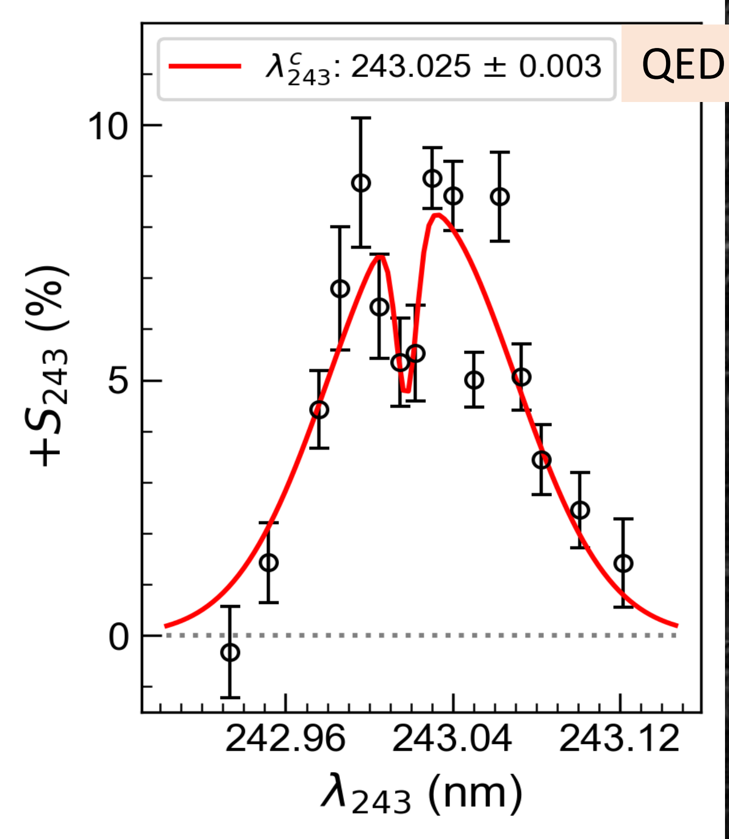
First experimental observation:

"Laser-induced preservation of decaying atoms"

The average lifetime of the excitable Ps fraction during the interaction with the cooling laser pulse is ≈**284ns**

Result for the 243nm cooling laser alone

Ps Doppler Scan on the $1^3S – 2^3P$ transition



QED: 243.022 nm, B = 0

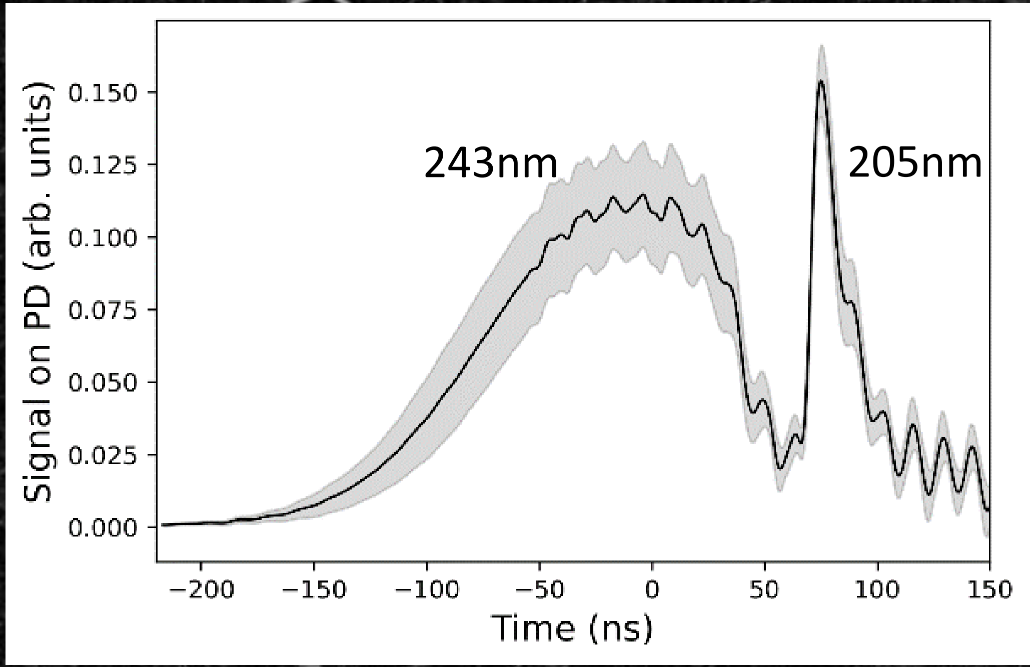
From a 2-Gaussian fit and the 243 BW (100 GHz):

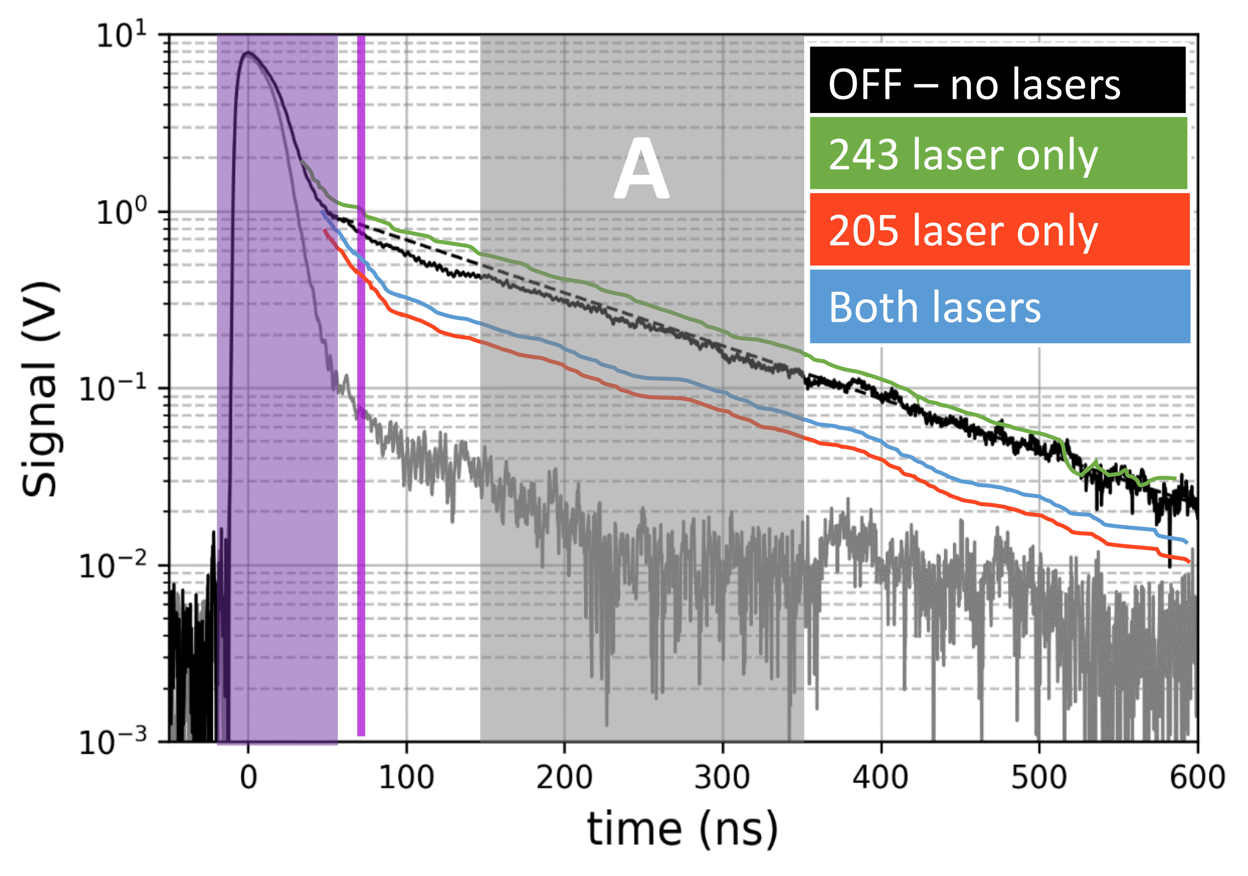
v_{rms} = (4.9 ± 0.4)·10^4 ms^{-1}

T = (*320* ± *50*) K

Timing synchronisation between 243 and 205 lasers

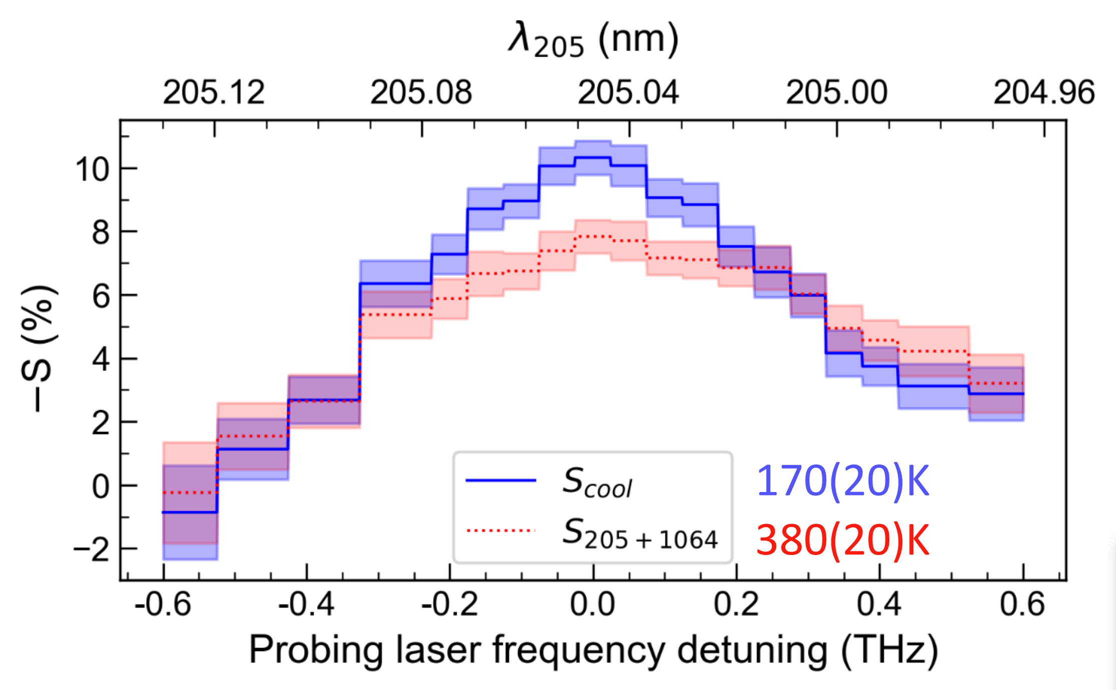
$$S_{cool} = S_{243+205+1064} - S_{243}$$

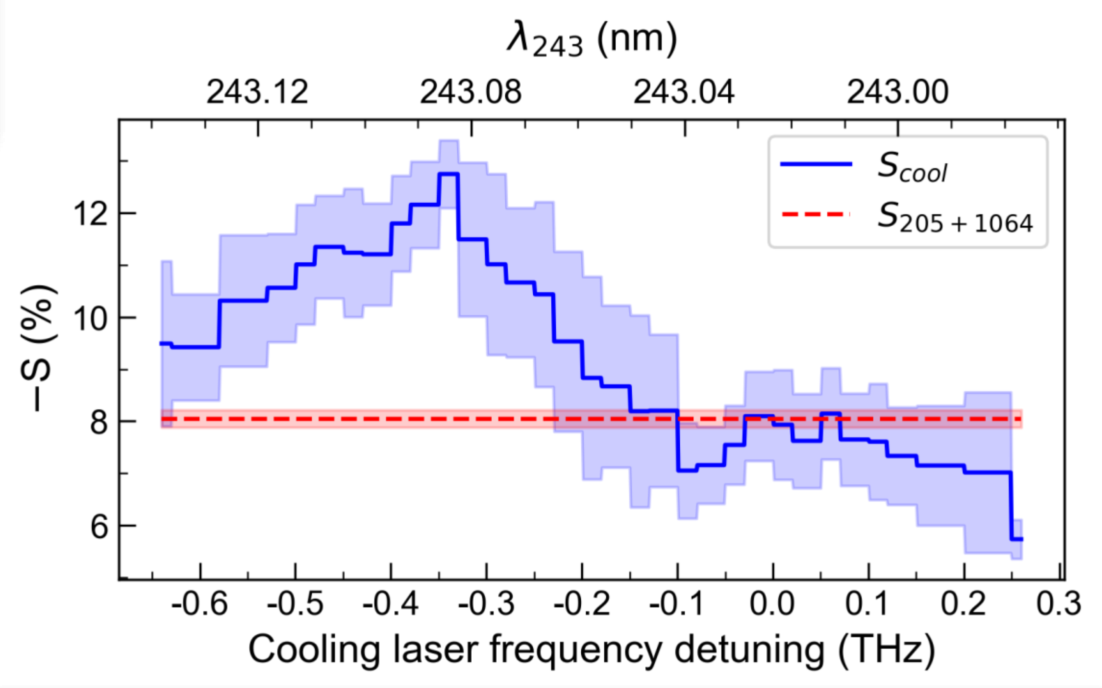




Positronium laser cooling: result

1D rms-velocity reduces from
$5.4 \cdot 10^4 \, \frac{m}{s}$ to $3.7 \cdot 10^4 \, \frac{m}{s}$

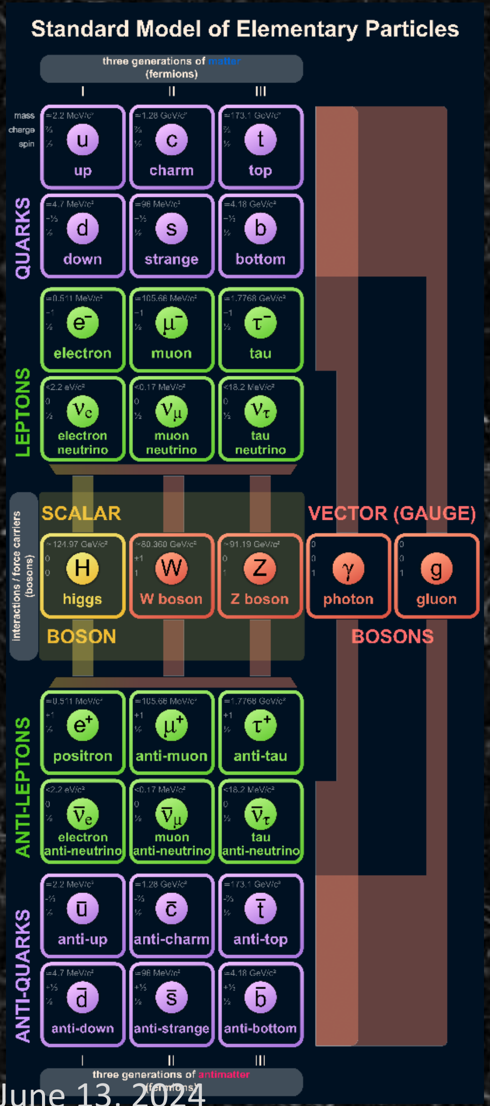




A maximum increase **of 58(9)%** of Ps with |v|< 3.7e4 at -0.35 THz red-detuning

Phys. Rev. Lett. ***132***, *083402 (2024)*
https://doi.org/10.1103/PhysRevLett.132.083402

Gravitational tests with Ps?



$$E_{0+g} = mc^2 + U(x)$$

The absolute gravitational potential U(x) affects energy levels and transition frequencies (clocks)

Savely G Karshenboim 2016
J. Phys. B: At. Mol. Opt. Phys. **49** 144001
https://doi.org/10.1088/0953-4075/49/14/14400

The gravitational redshift of clocks is a measure for U(x)

⬇

If you know U(x) for a matter system from spectroscopic measurements, you can measure and compare the redshift of an antimatter system

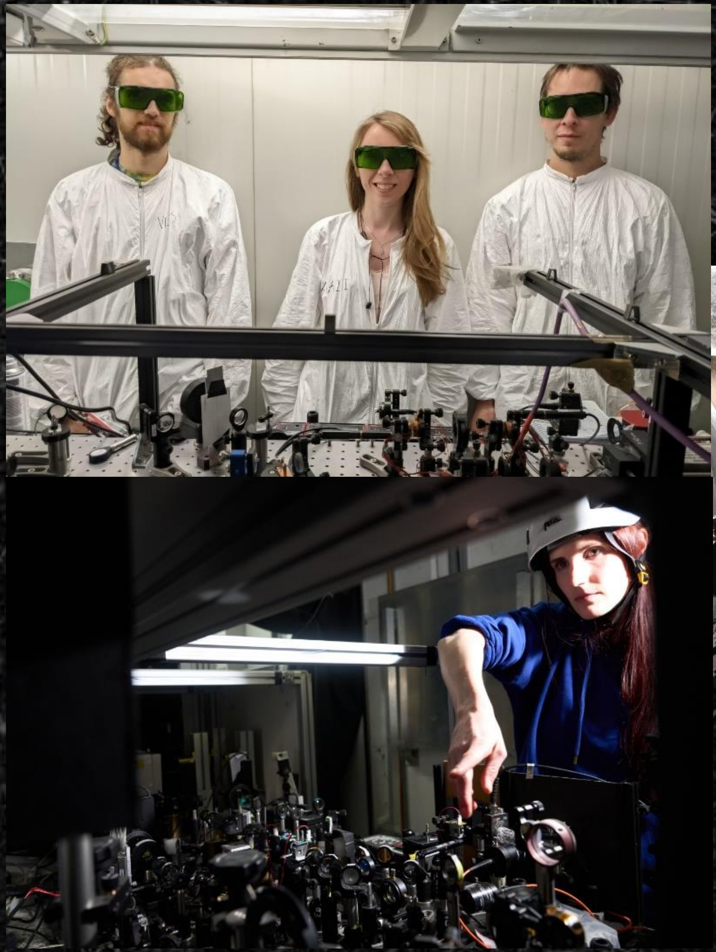
⬇

Ps has no nucleus, theory well described by QED -> Tests for (W)EP are very interesting … but are limited by the second order Doppler shift by the Ps velocity

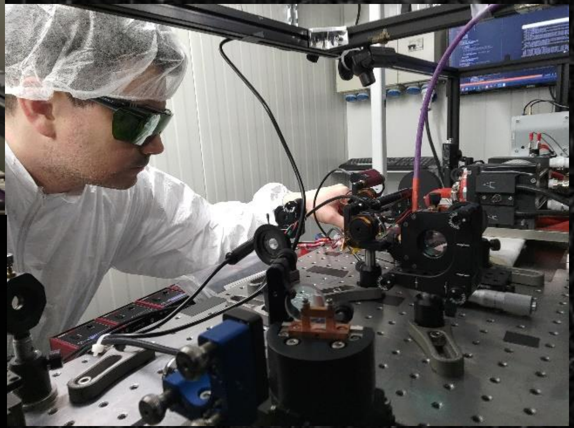
Cool Ps further!

Summary

- 1D Ps laser cooling with broadband 70ns long laser pulse along the $1^3S \rightarrow 2^3P$ transition achieved
- Cooling by 200K or 1.7e4 ms^{-1}, i.e. maximum momentum transfer that can be achieved within 70ns
- Next steps: 2D (3D) laser cooling; using cryogenically precooled Ps; applying the technique to AEgIS‘ antihydrogen production scheme



Thank



You

Backup: The cooling laser

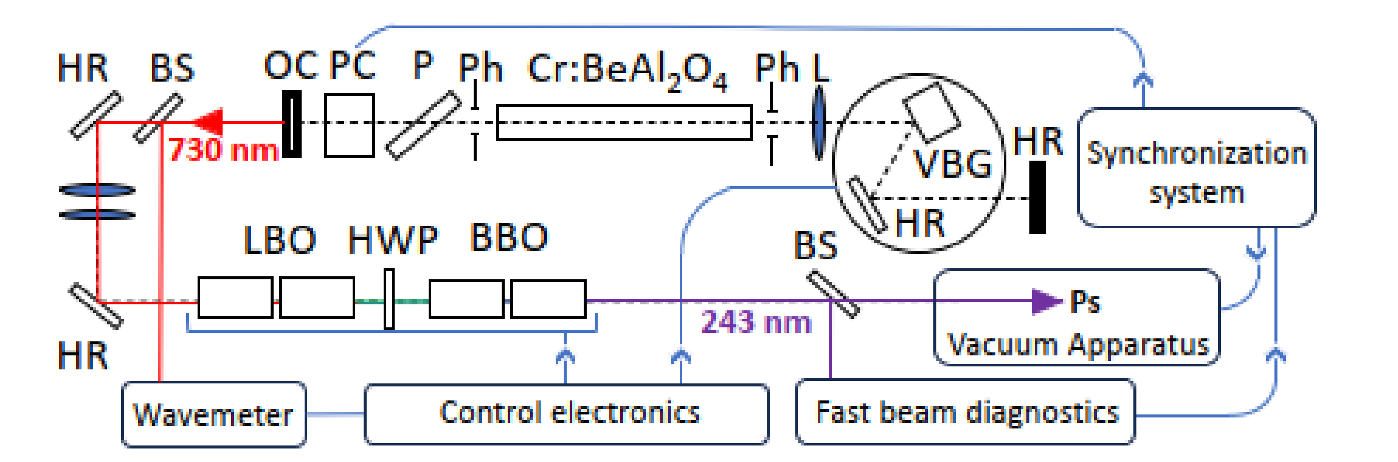


Table 1: Laser parameters

Energy at 729 nm	up to 40 mJ
Energy at 243 nm	up to 2 mJ
Spectral bandwidth at 730 nm (σ)	130(15) GHz
Spectral bandwidth at 243 nm (σ)	101(3) GHz
Pulse duration at 730 nm (FWHM)	266 ns
Pulse duration at 243 nm (FWHM)	203 ns