Status and plans of the AEgIS experiment

152th meeting of the SPSC
February 6th, 2024

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on behalf of the **AEgIS Collaboration**

The AEgIS collaboration

57 members from 15 institutes from 10 countries

Switzerland	France
Poland	Latvia
Italy	India
Germany	Czech Republic
Norway	UK

Main physics goals

Tests of the Weak Equivalence Principle
Spectroscopy and tests of CPT
Beyond the Standard Model searches

Systems

antihydrogen, positronium, antiprotonic atoms

Main tools

Laser-controlled charge-exchange reactions
Spectroscopy and laser cooling with pulsed lasers
Moiré deflectometry and atom interferometry

New groups (MoU signed in 2023)

- Jagiellonian University, Poland
  1 senior + 1 post.doc + 1 student

New groups (MoU in discussion)

- Siegen University, Germany
- Technical University of Munchen, Germany

AEgIS research lines

Shared dev + **$\bar{H}$** + **Ps** + **p̄ atoms** + **R&D**

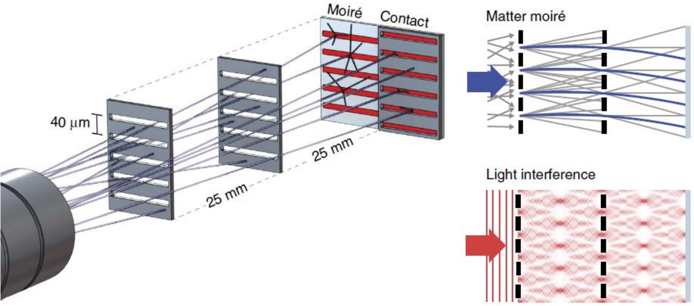
PROPOSAL — 2008

Construction began — 2012

2014

Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

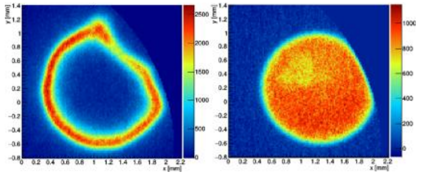
A moiré deflectometer for antimatter



2016

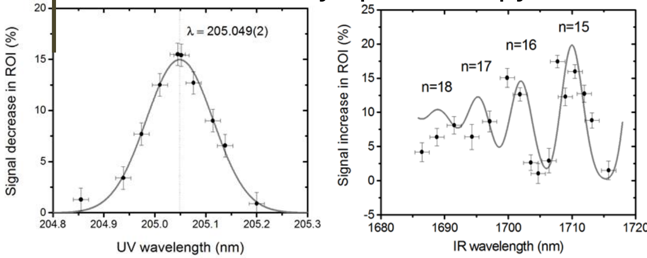
2017

Pbar compression to mm radius



S. Aghion et al., Eur. Phys. J. D (2018) 72: 76

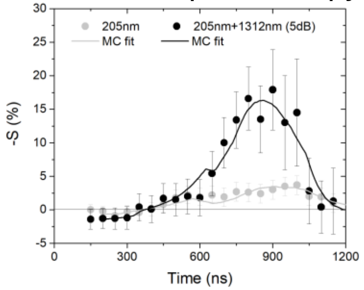
Ps 1S-3P-Ry spectroscopy



S. Aghion et al., PRA **94,** 012507 (2016)

2018

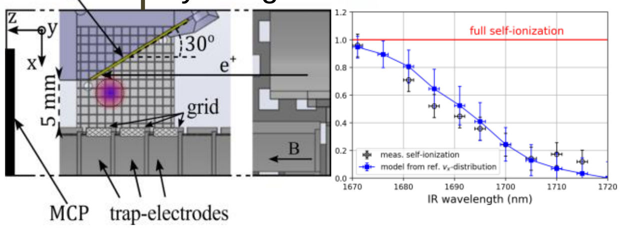
Ps 2S-3P spectroscopy



M. Antonello et al., PRA **100,** 063414 (2019)

2019

Rydberg Ps in 1T

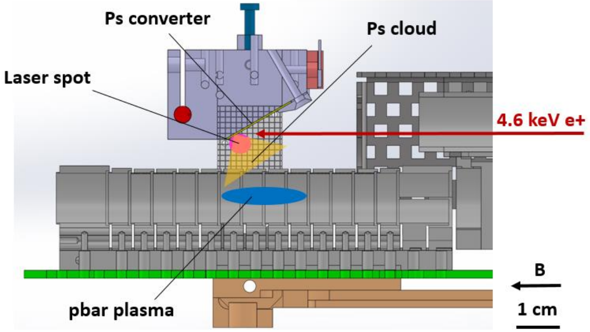


M. Antonello et al., PRA **102,** 013101 (2020)

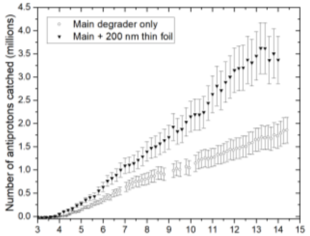
2020

https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen

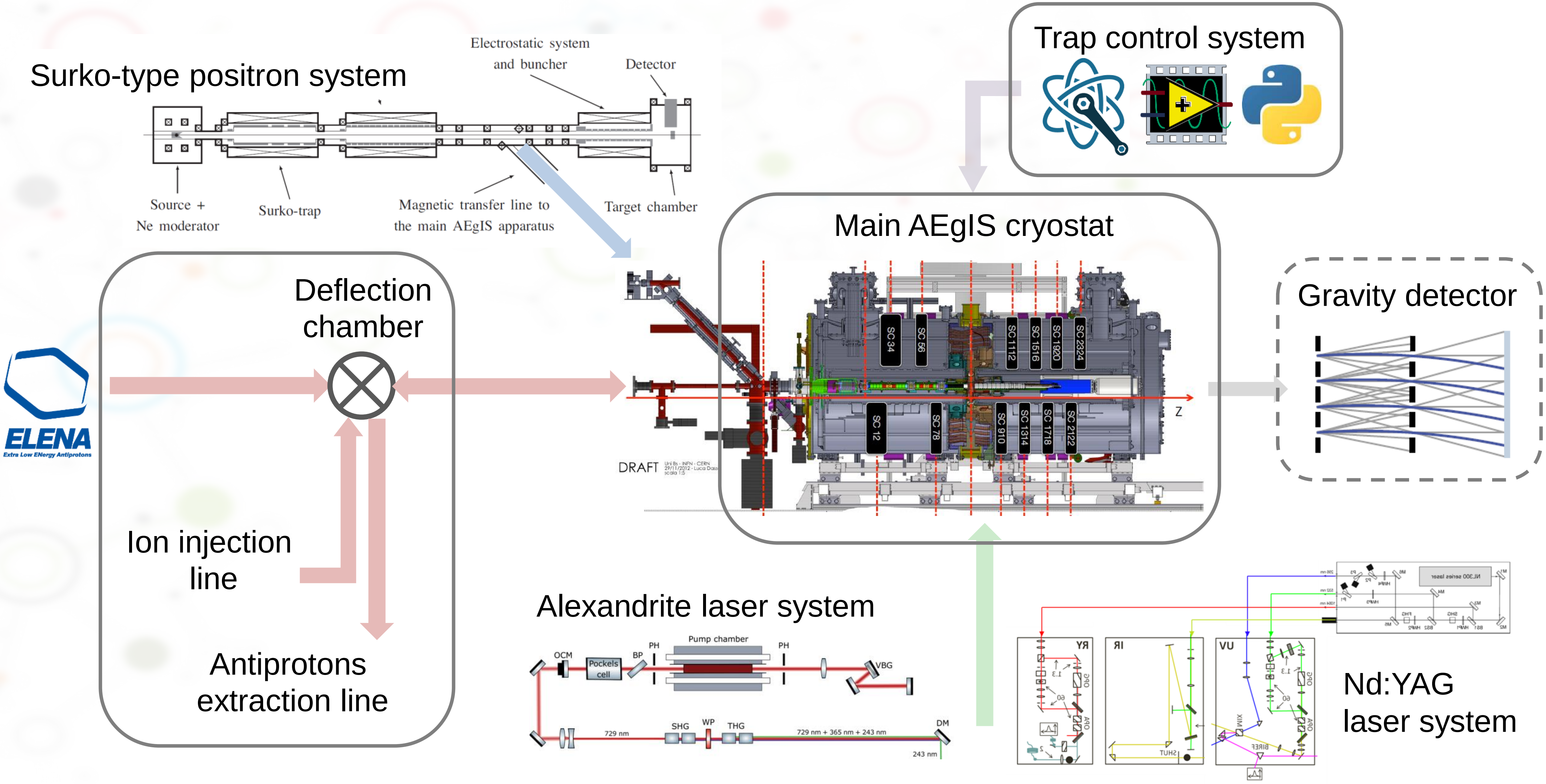


2023



Efficient catching from ELENA

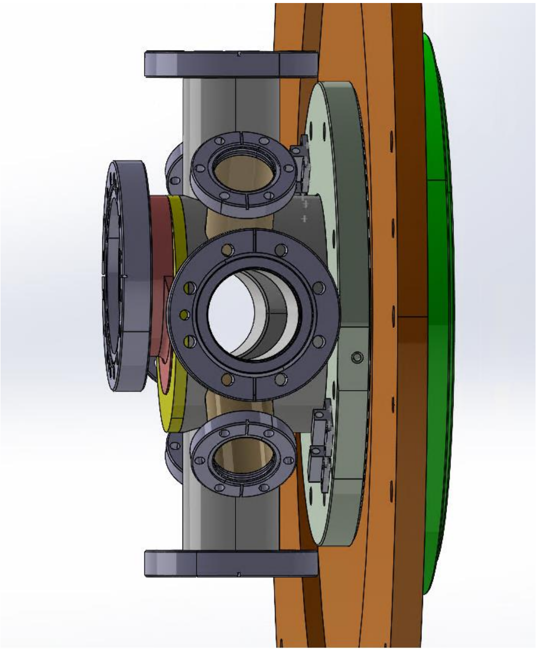
Shared developments in 2023: apparatus upgrade areas



Shared developments in 2023: investments on hardware

Central flange long-term consolidation

- Improved indium seal and closure procedure
- Invidivual flanges leak-testing campaign

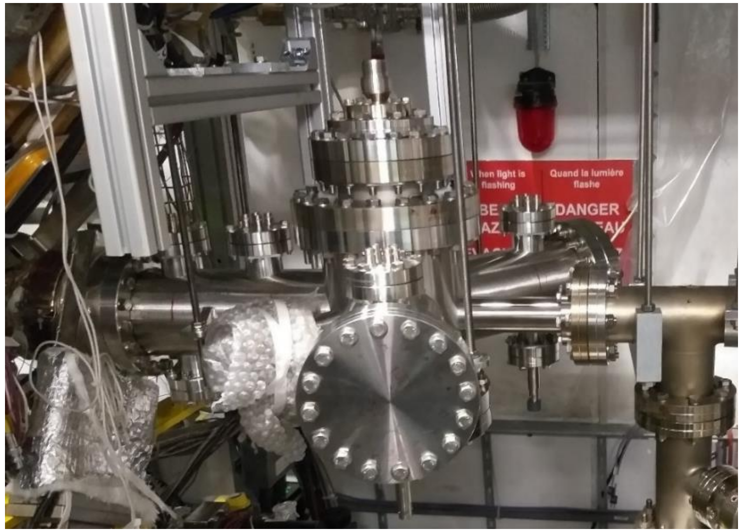


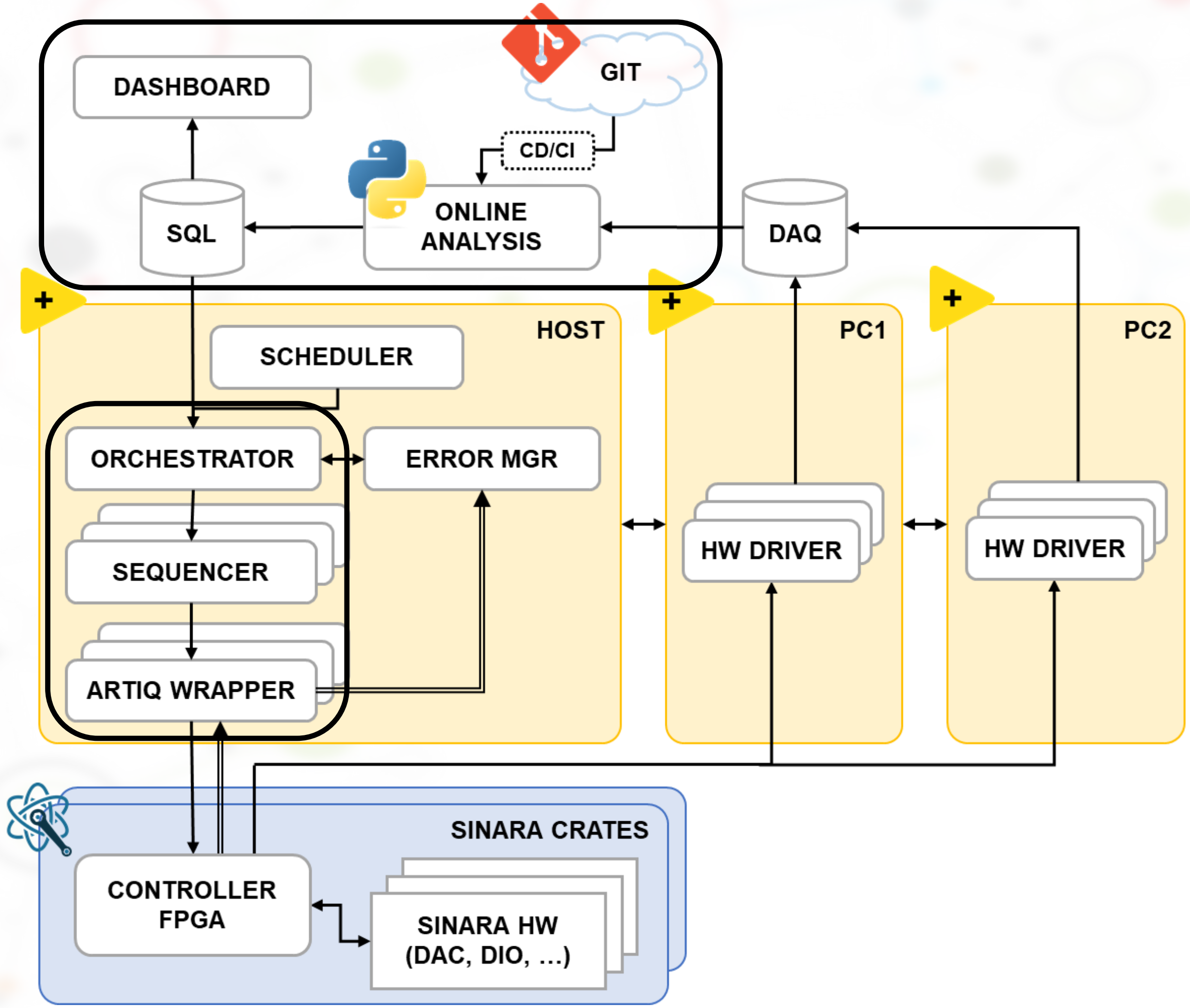
Entrance flange long-term consolidation

- Vacuum jacket for 2023 run to remove structural leak
- Rebuilt the whole chamber for replacement (YETS)

Deflection chamber commissioning

- Testing, installation and alignment
- Commissioning with HV and particles





Automatic online analysis and data quality check

- CD/CI deploy via GIT for in-vivo upgrades
- Feedback loop to orchestrator to automate data quality checks and data re-acquisition

Bayesian optimizer for automatic optimization

- Automatic optimizes any ask/tell experiment
- Used for automatic beam steering (5 dimensions)

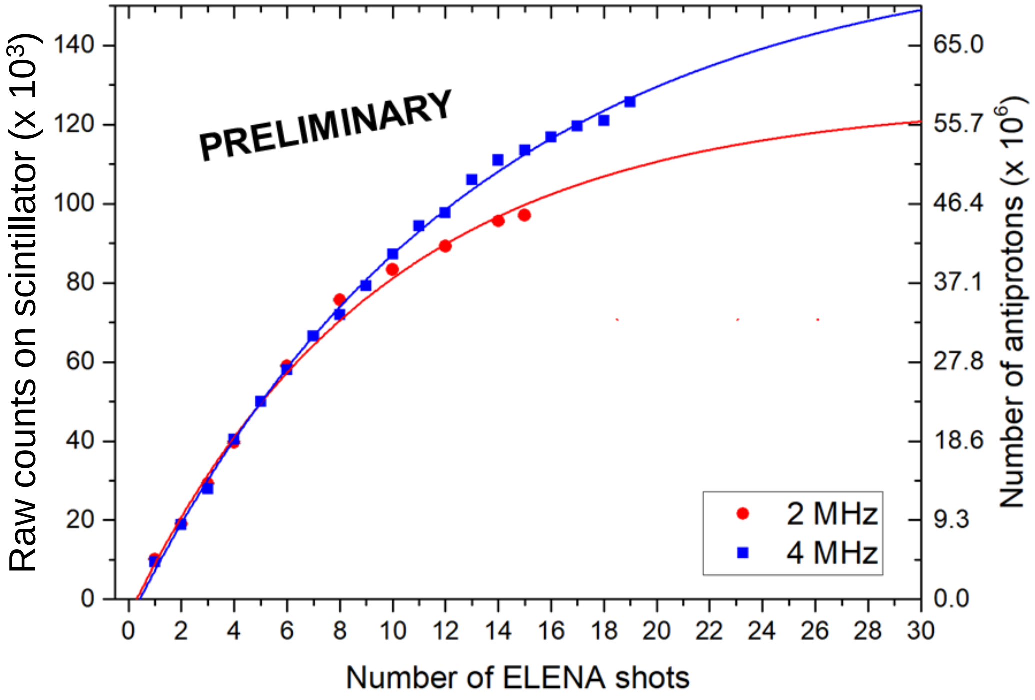
Concurrent multi-controller running modality

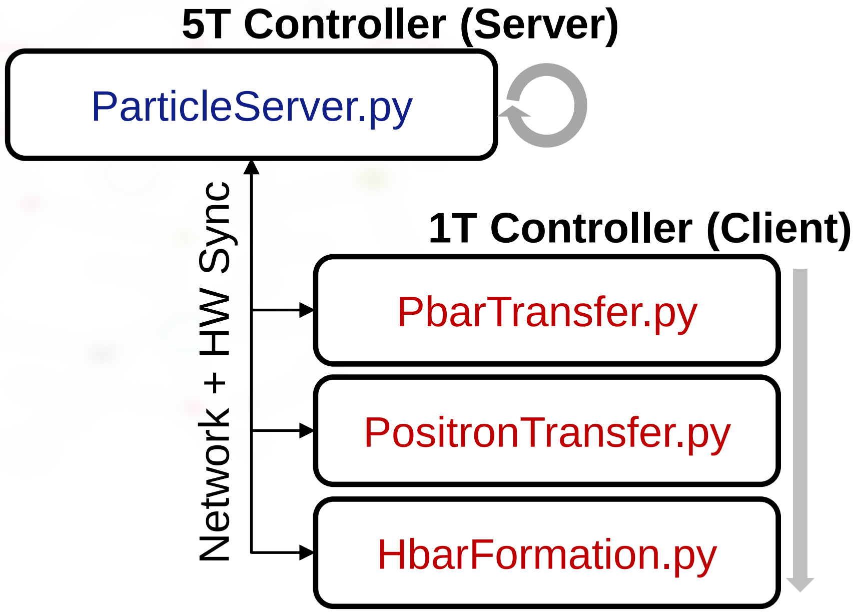
- Support for multiple Sinara FPGA controllers
- Flexible user-selectable synchronous or asynchronous operation
- Nanosecond re-synchronization routines

M. Volponi, S. Huck et al. (AEgIS collaboration), accepted on EPJ Quantum Technologies (2024)

Client-Server asynchronous architecture

- 5T catching trap controller in a continuous accumulation and listen for messages loop
- 1T interaction trap controller runs custom experimental sequences and allows debugging

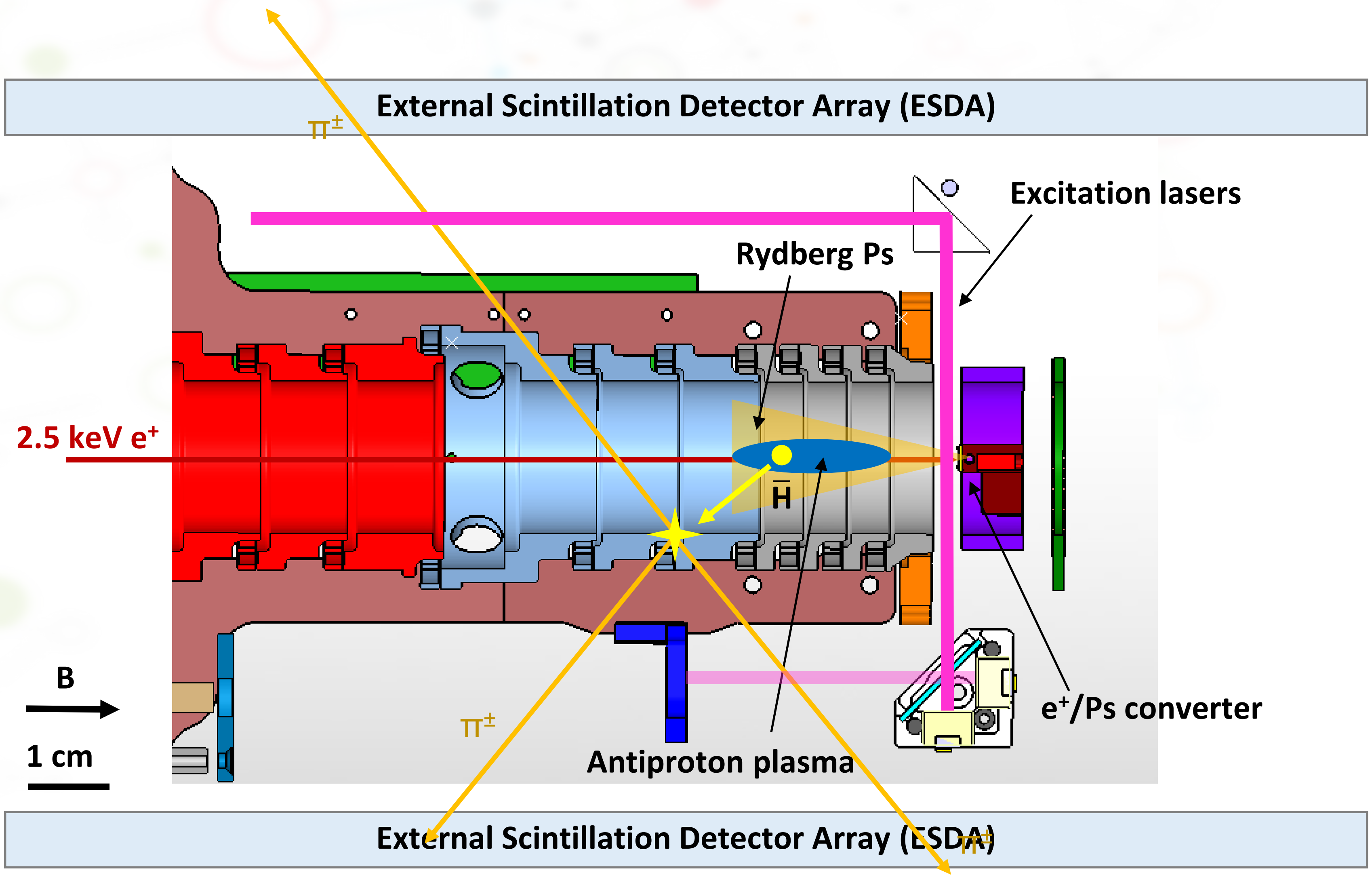




Achievements

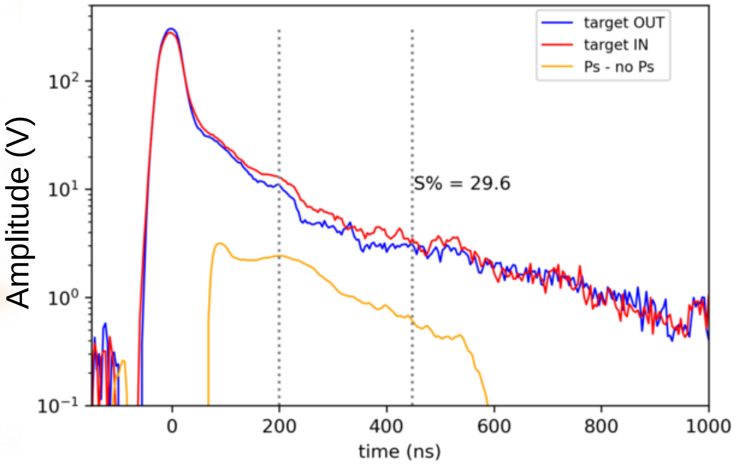
- Stable operation for weeks in constant accumulation
- While constantly accumulating, we reached up to **~100 million antiprotons** in our traps

Collinear antihydrogen production scheme

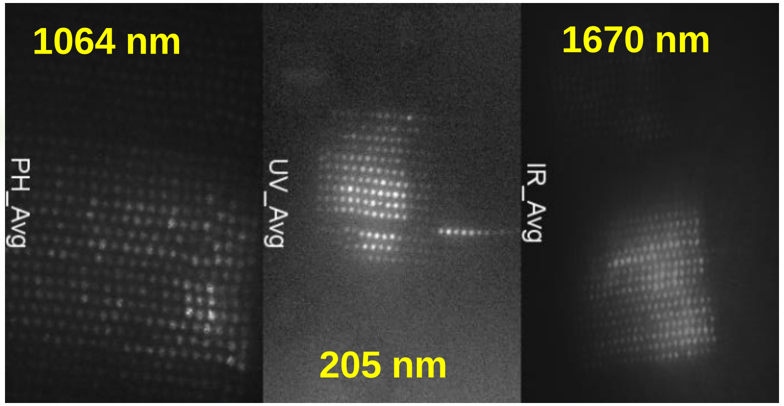


Positronium run achievements

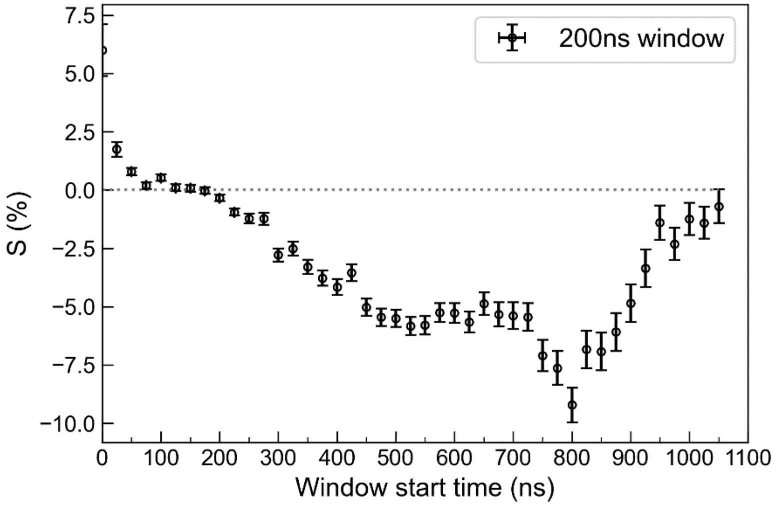
Digitized scintillator spectra with and without Ps production



Realtime diagnostics of laser intensity and alignment from fiber array



Difference scintillator spectrum with and without Rydberg excitation



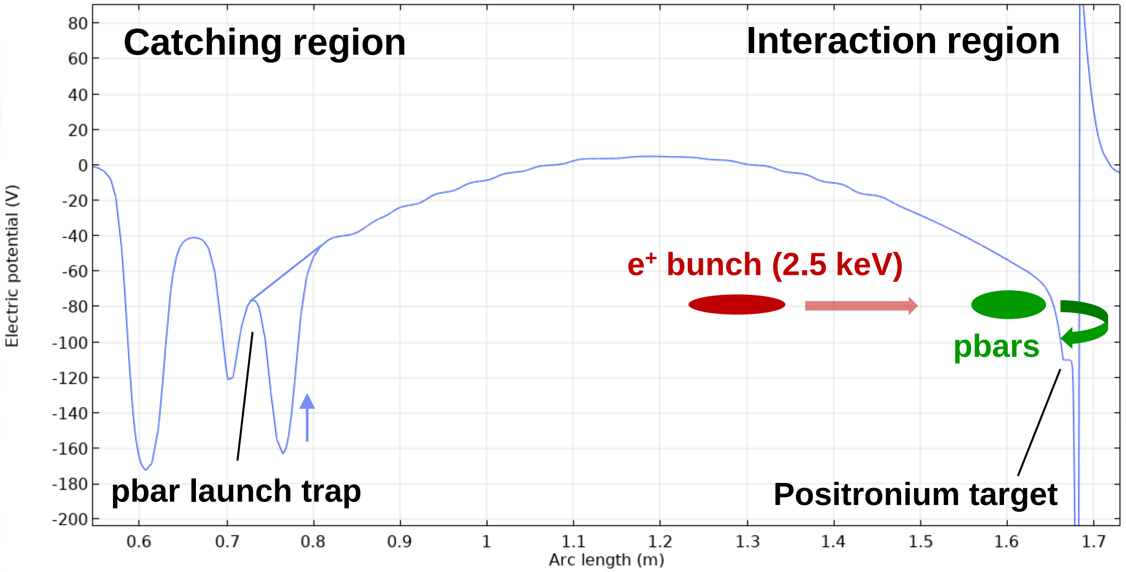
Achievements

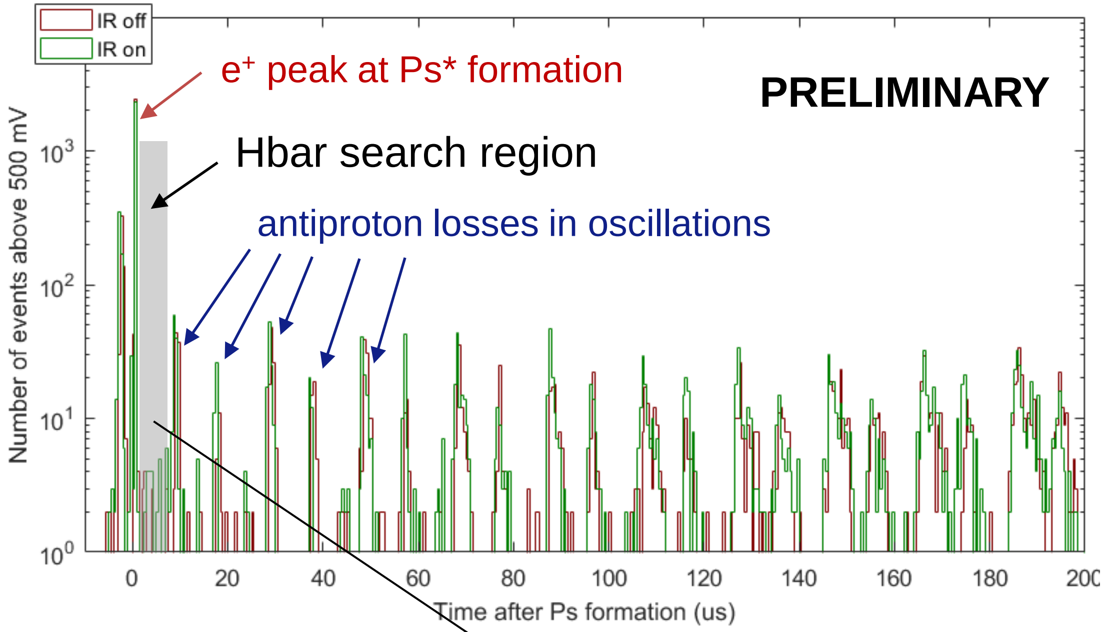
- Ps formation from on-axis target observed with scintillators
- Lasers' diagnostics fully consolidated: individual beam monitoring
- Established Rydberg Ps excitation to n = 21 (formerly n = 17)

Despite

- Low Ps target yield (2.5% Ps/e^+) – under investigation
- Old ^{22}Na source – new one delivery had 1 year delay (Nov '23)

Antihydrogen run achievements



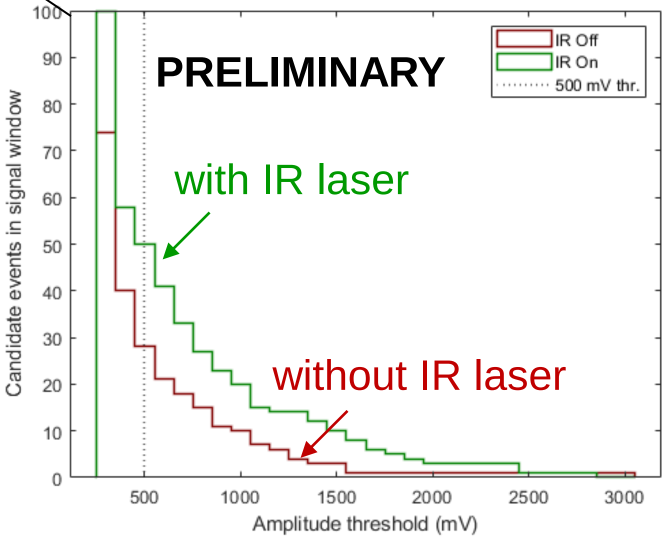


Achievements

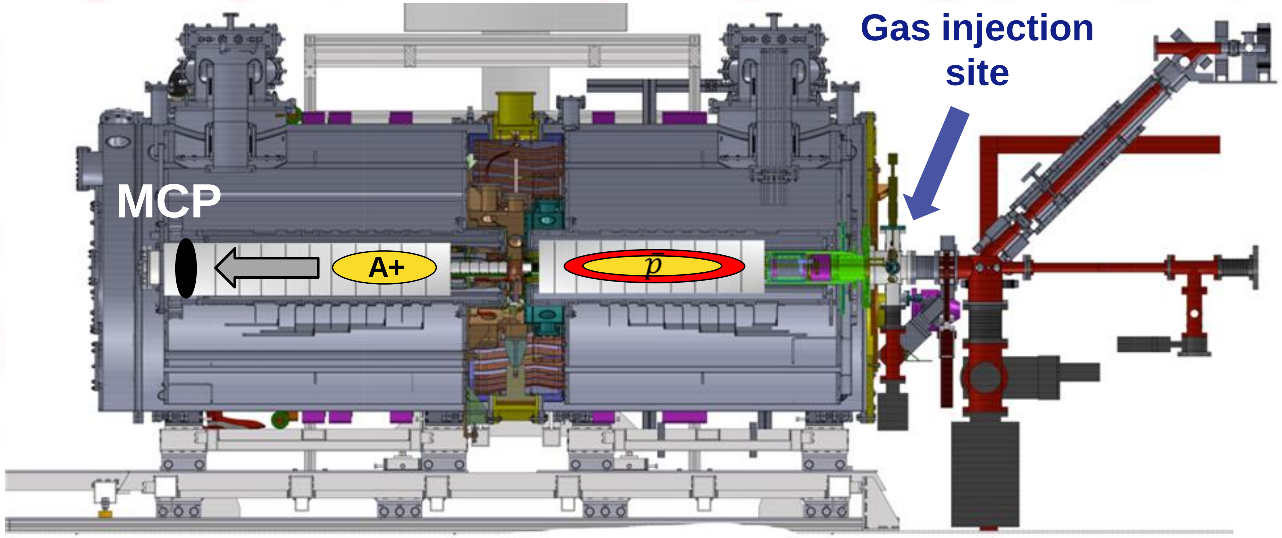
- Antiproton transfer with fine time control and minimal time dispersion
- No observed effect from to the e$^+$ bunch passage through the antiprotons
- Evidence of antihydrogen production with Ps excited to n = 21

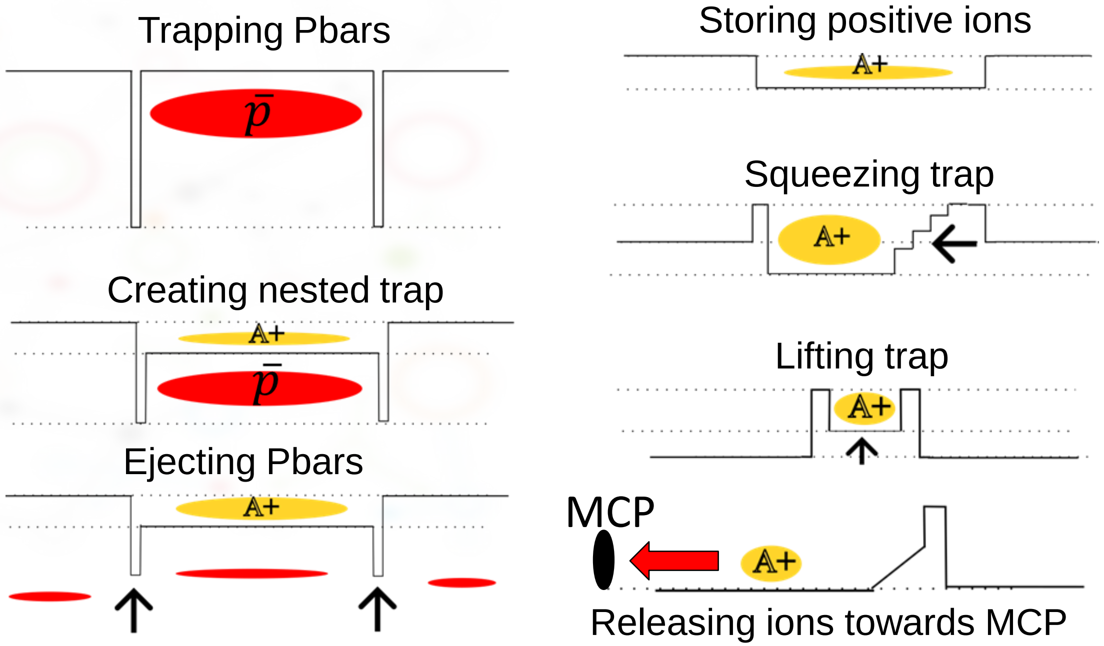
Despite

- Background due to antiproton cloud oscillations in the transfer potential
- Nearly catastrophic abrupt failure of the Surko trap magnet

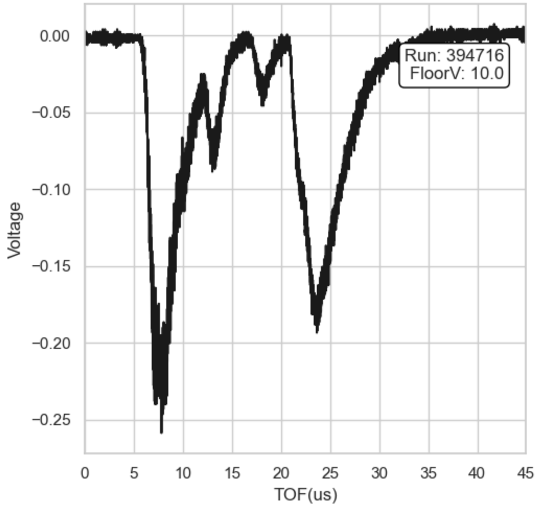


Antiprotonic atoms run achievements

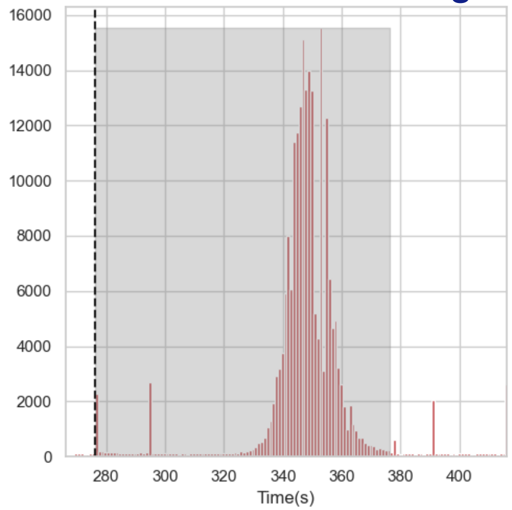




MCP TOF spectrum



Scintillator monitoring



Achievements

- Procedure for controlled gas injection and cleaning
- Technique to trap the positive ions resulting from antiproton interactions with the rest gas target
- Time-of-flight spectroscopy of trapped positive ions

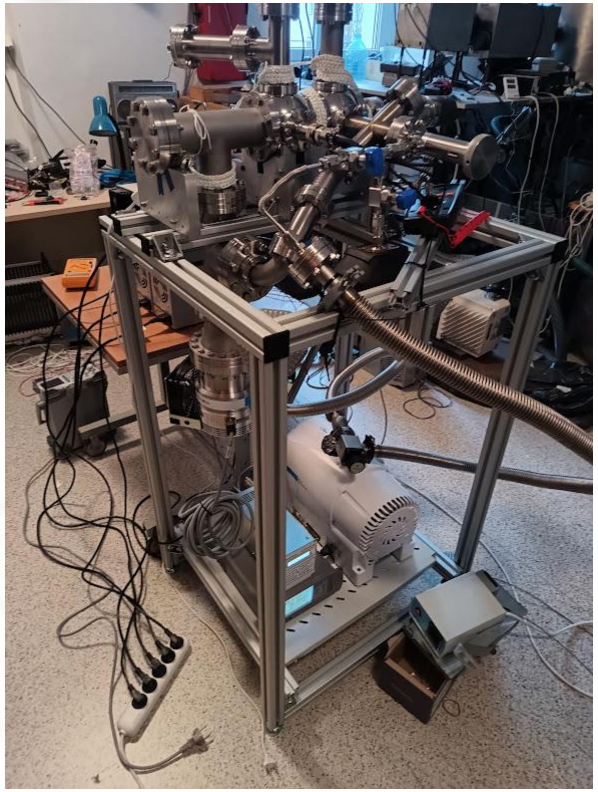
This technique can lead to

- Fully stripped and highly charged ions in Penning traps
- TOF spectroscopy of annihilation fragments
- Produce short-lived nuclei directly in Penning traps

Ongoing R&D activities: anionic system

Construction of a negative iodine source

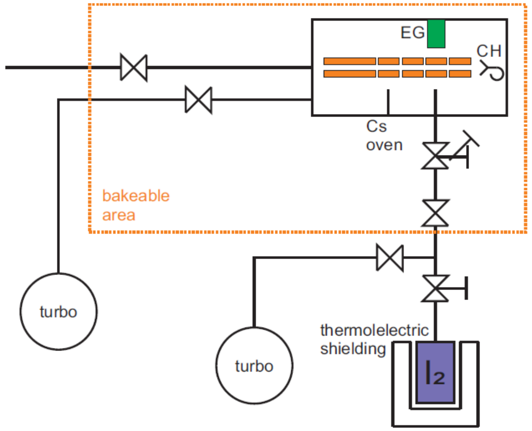
via electron dissociative attachment for «clean» antiprotonic iodine production



The I^- source at KL-FAMO

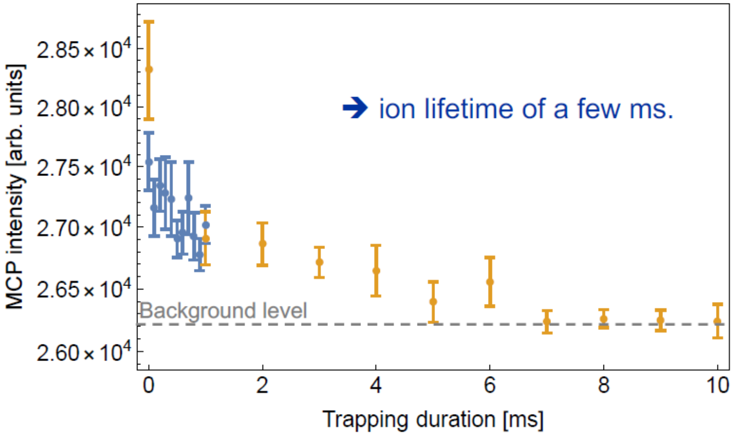
$$I_2 + e \rightarrow I + I^-$$

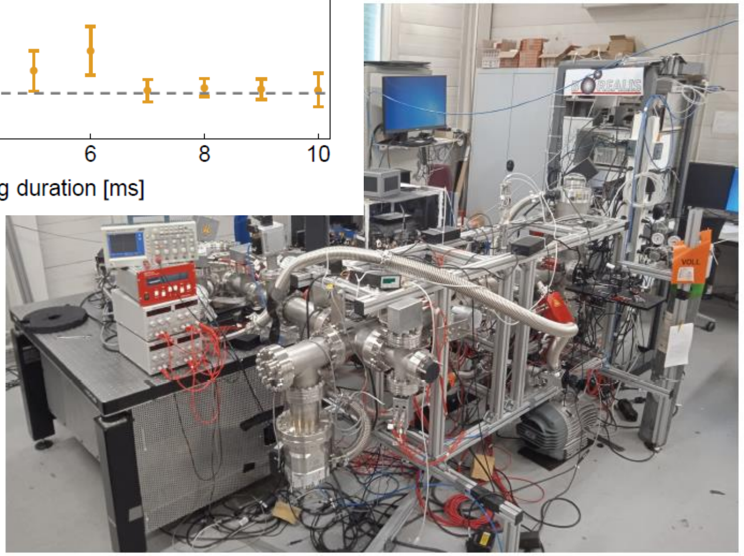
$$I_2 + e \rightarrow I^+ + I^- + e$$



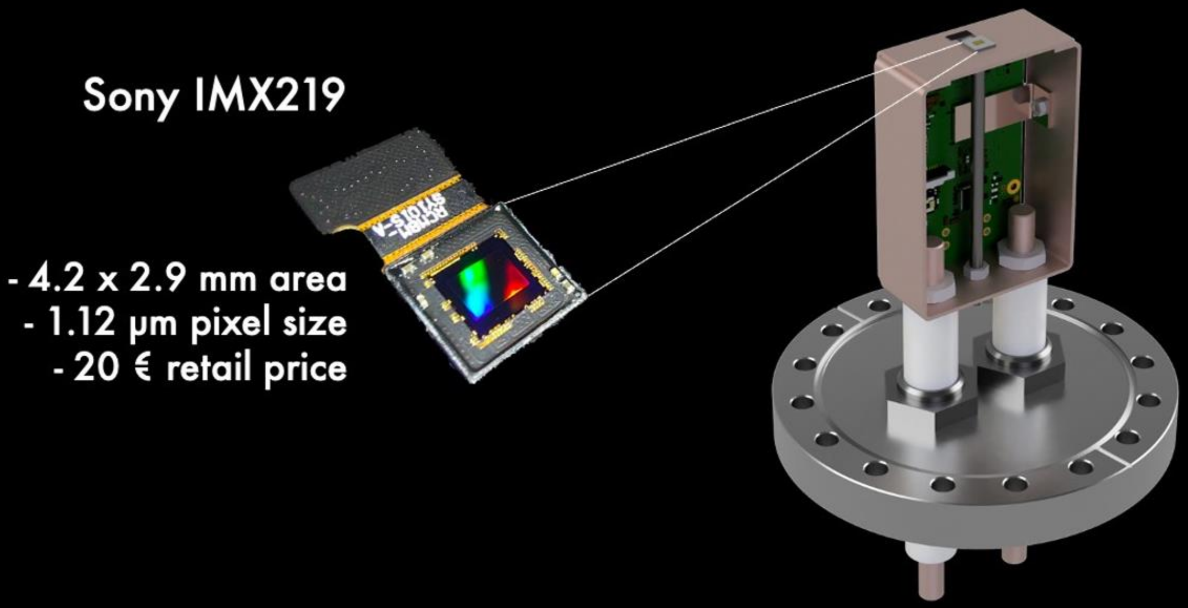
C_2^- trapping in Paul trap for spectroscopy

towards establishing laser cooling of anionic molecules to sympatetically cool antiprotons





The C_2^- cooling setup at CERN



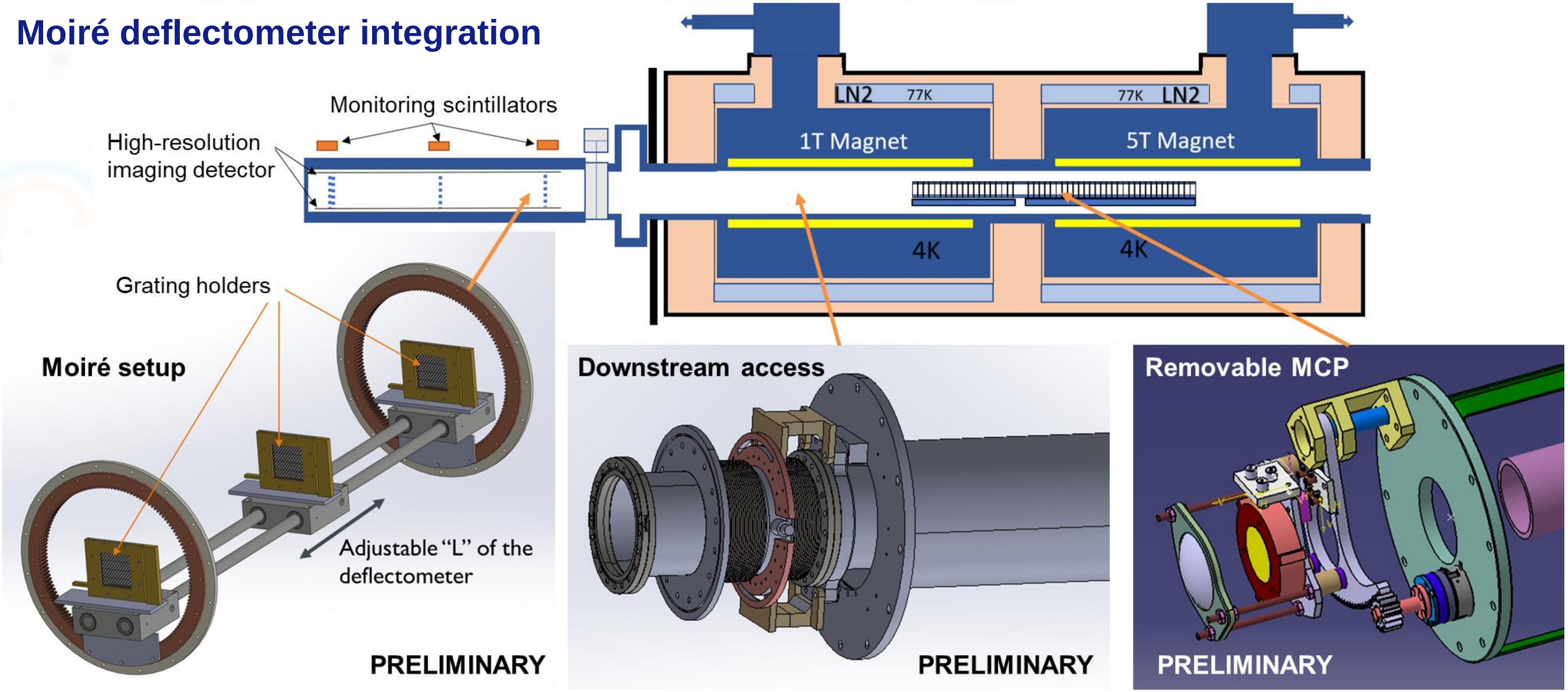
Sensitive to photons

Resolution to antiproton vertices < 2.0 μm

In collaboration with: Technical University of Munich

Agenda for 2024: antiproton recapture in catching traps: recycling and background removal
replace aged ^{22}Na source and replace malfunctioning Ps target
increase Rydberg Ps principal quantum number up to n = 30

Moiré deflectometer integration



Medium and long term plans

Before LS3

Dec. 2025

During LS3

Jun. 2027

After LS3

Antihydrogen source flux to 1 Hbar min^{-1} or higher

First WEP test with antihydrogen in null magnetic field

Establishing laser cooling of positronium

Cryogenic Ps transmission targets

Form Rydberg antiprotonic ions in traps

Time-of-flight spectroscopy of trapped nuclear isotopes

Apparatus upgrade for Ps transmission targets in antihydrogen setup

Ps 1^3S-2^3P and 1^3S-3^3P spectroscopy with a laser-cooled source

Ps n=3 hyperfine RF spectroscopy

Two-photon spectroscopy of Ps n^3S Rydberg states

Positron affinity of neutralized anions via charge-exchange

Precise antihydrogen WEP test in a null magnetic field

Atom interferometry with antihydrogen

Precision Ps 1^3S-2^3S and 1^3S-3^3S spectroscopy with laser cooling

Spectroscopy of Rydberg antiprotonic atoms

Inertial s

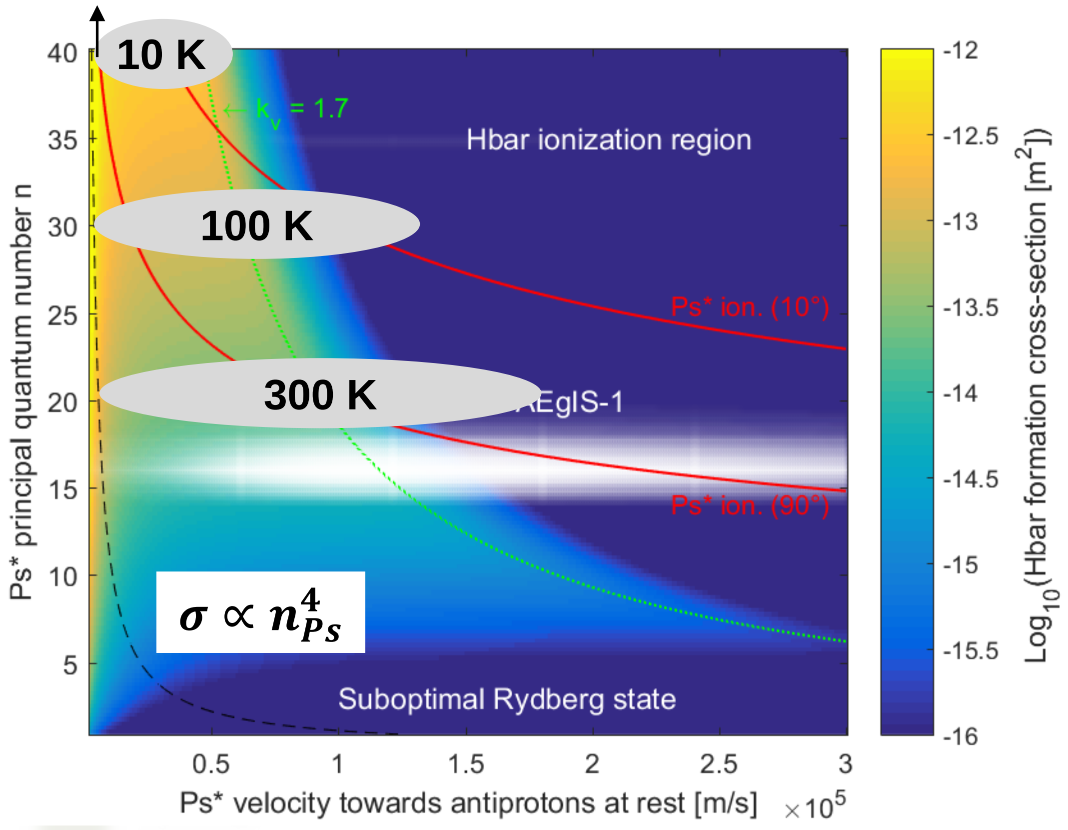
Sea

antipr

Search of hexaquark DM candidate via pbar-^{3}He in traps

Antideuteronic atoms formation and measurement of X-ray cascade

Anti-^{3}He and Anti-T synthesis by antideuteron fusion in Penning traps



We need colder Ps sources …

1. A colder Ps source in a reflection geometry
2. An efficient cold Ps source in transmission

D. Krasnicky, R. Caravita, C. Canali, G. Testera, Phys. Rev. A **94** (2016) arXiv:1608.02785v1

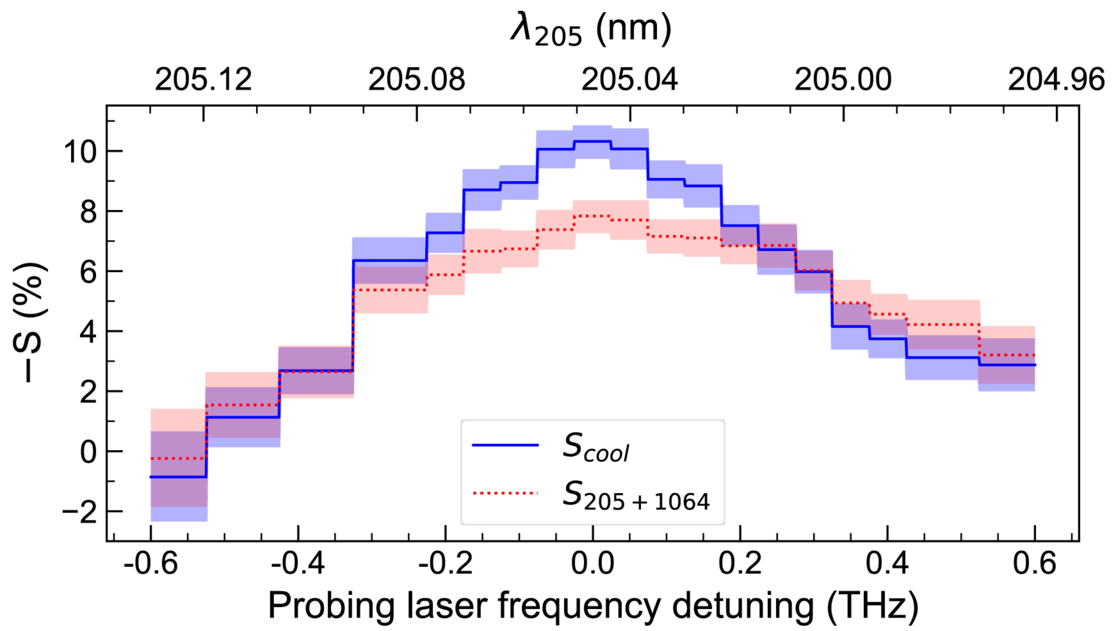
“The ultimate reduction in the positronium temperature would, of course, be achieved by laser cooling the atoms”

M. S. Fee, S. Chu, A. P. Mills et al. (1993)

“Ps laser cooling has been discussed for many years but has not been experimentally demonstrated, even in a proof-of-principle measurement”

D. B. Cassidy (2018)

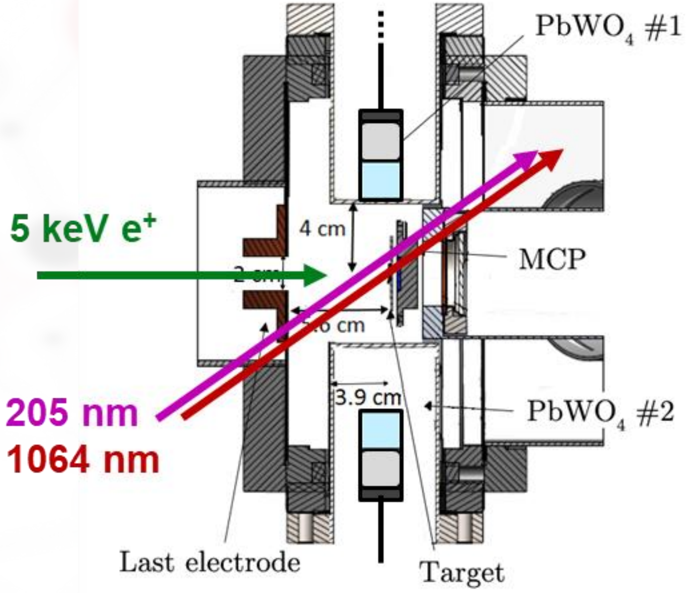
Laser Cooling of Positronium

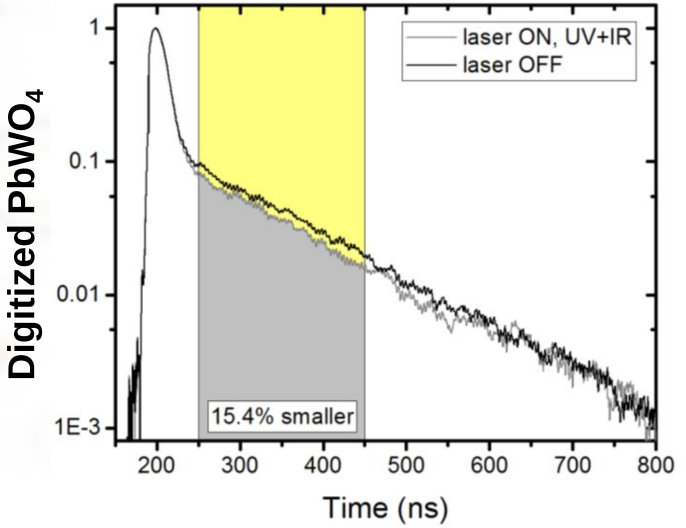


In 2023, we laser cooled Positronium for the first time

Accepted on Physical Review Letters with Editors' suggestion
Expected publication date: end of February

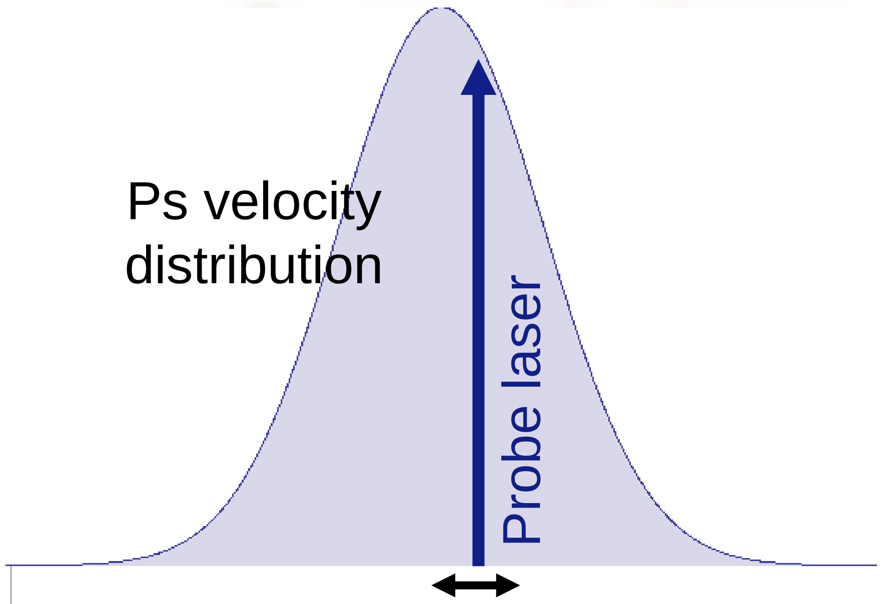
How? Starting from Ps 1^3S-3^3P Doppler velocimetry





PHYSICAL REVIEW A 94, 012507 (2016)

Laser excitation of the $n = 3$ level of positronium for antihydrogen production

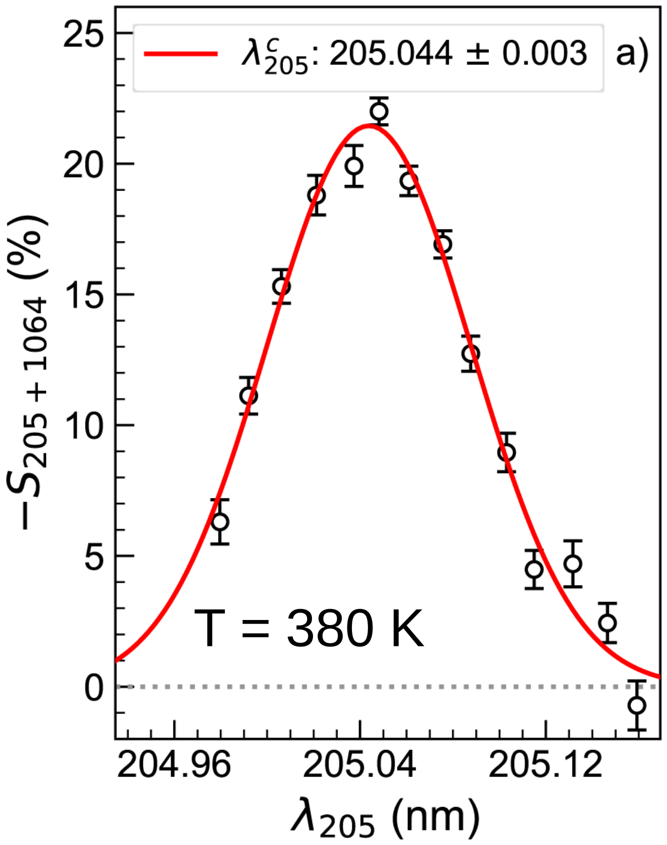


Doppler effect

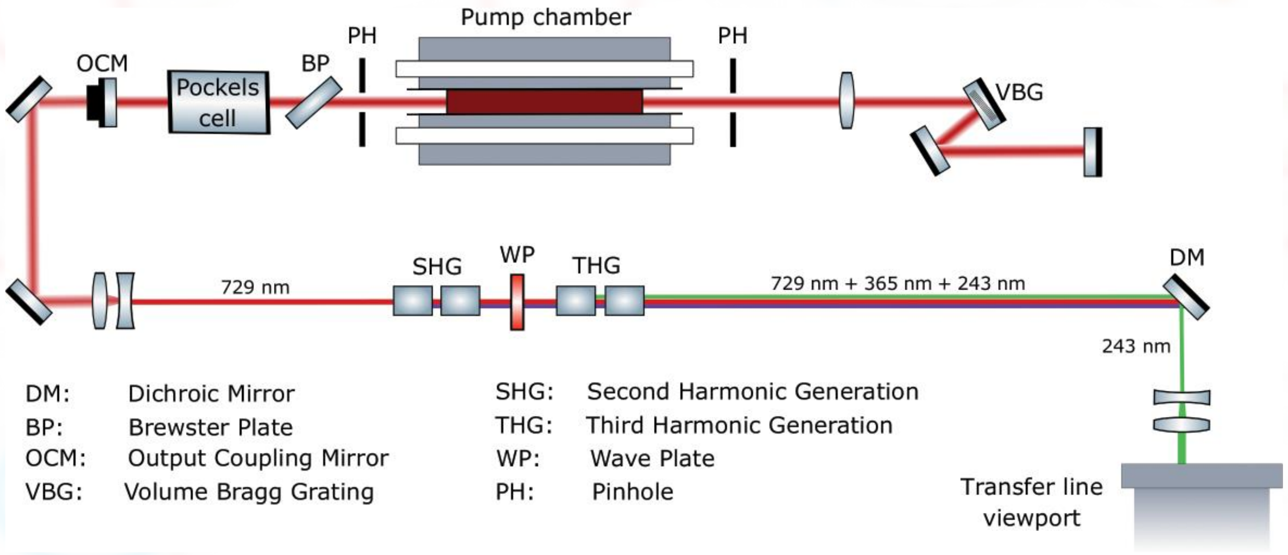
Ps velocity along laser axis

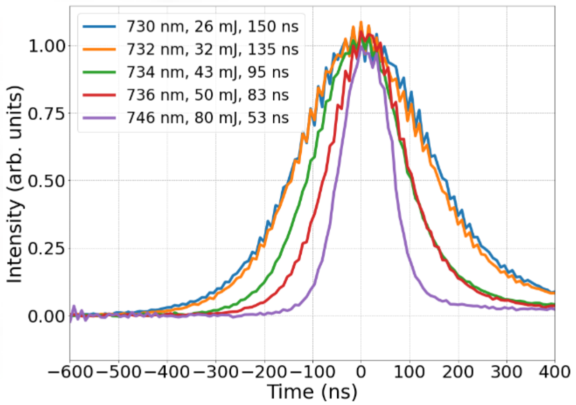
⬄

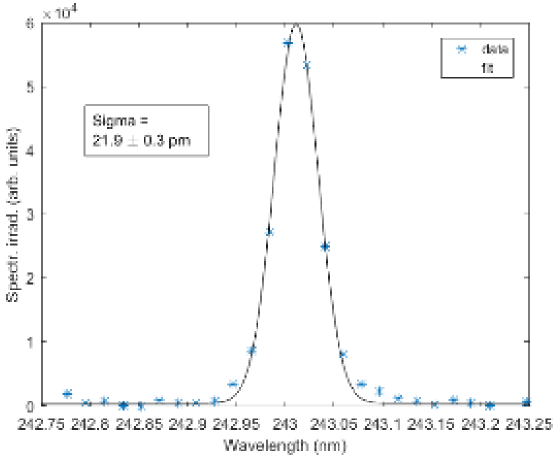
Choice of laser detuning



How? Developing a broadband Q-switched alexandrite laser system



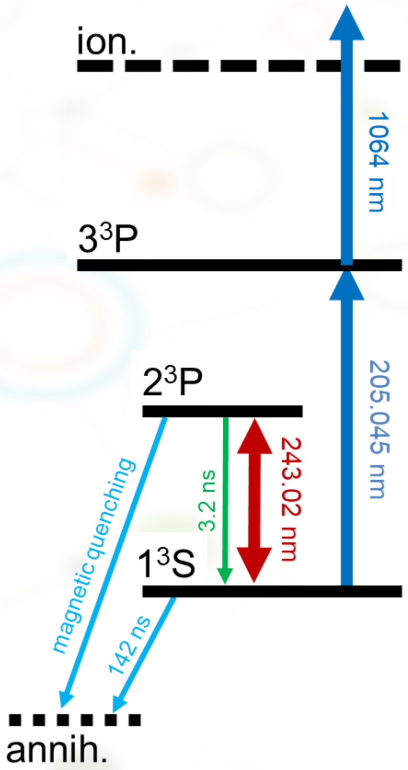




Designed for broadband Ps cooling

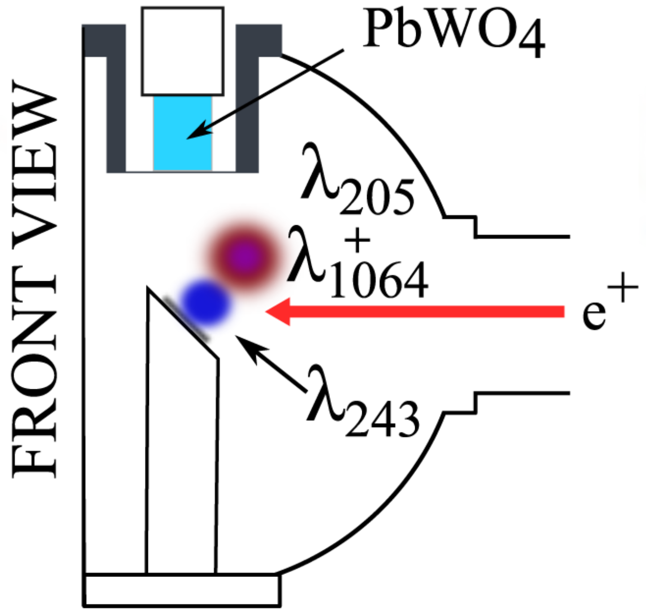
70 ns, 243 nm pulses, 3 mJ, 120 GHz

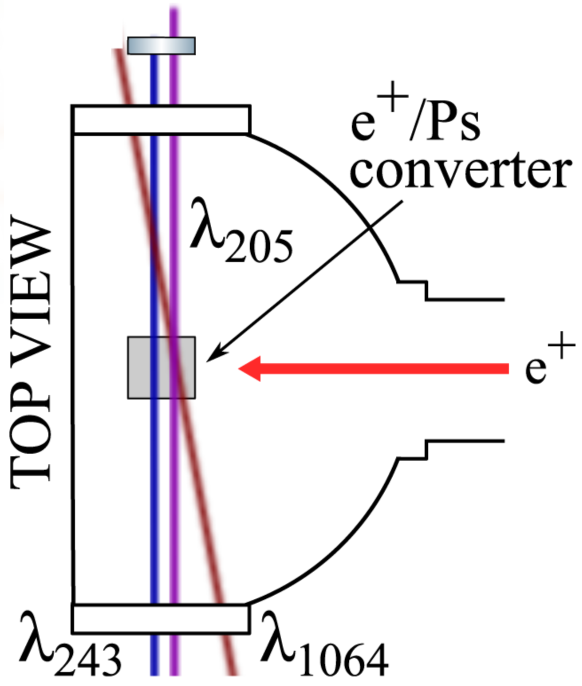
How? Introducing the retroreflected cooling laser



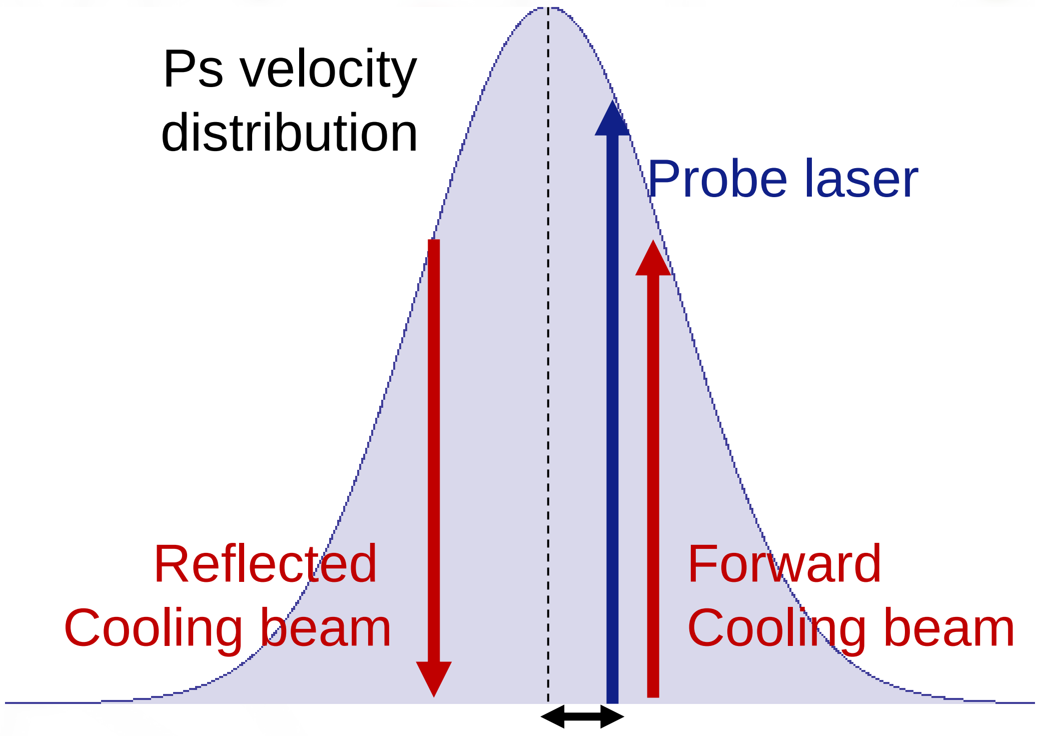
Probing transition
($1^3S \rightarrow 3^3P \rightarrow$ Ion)

Cooling transition
($1^3S \leftrightarrow 2^3P$)

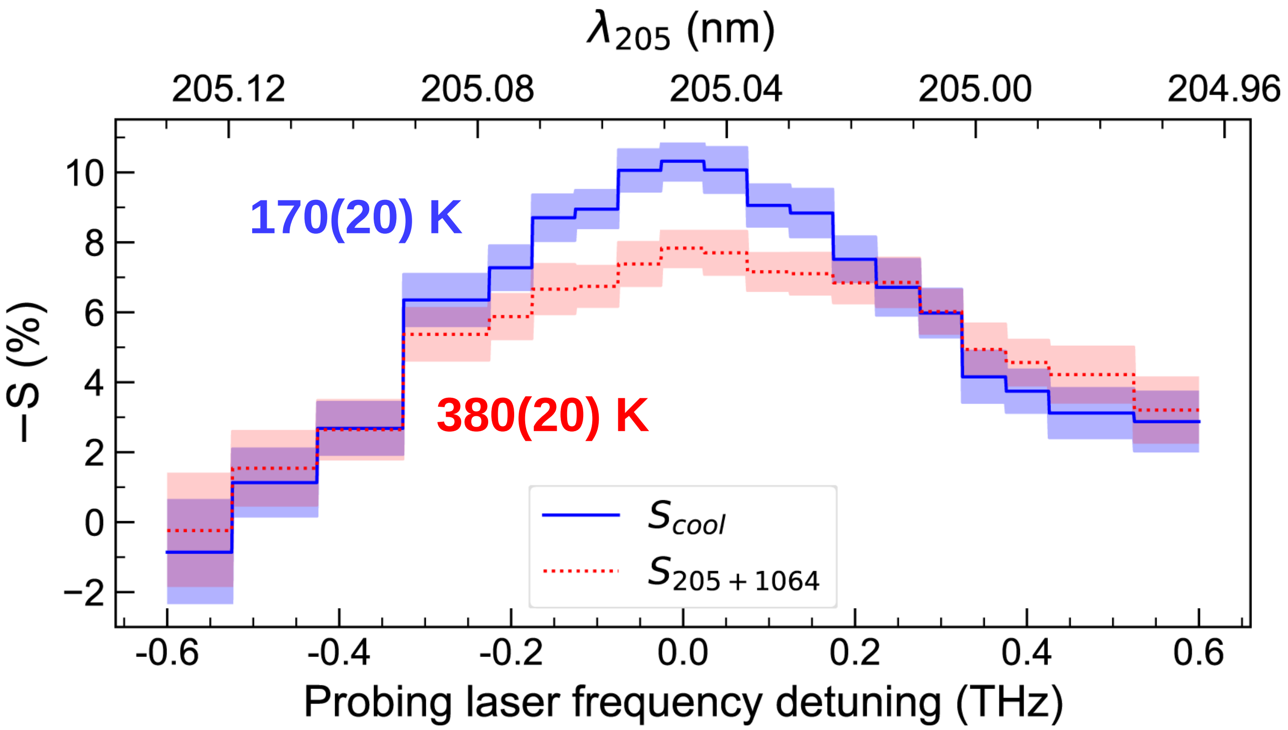




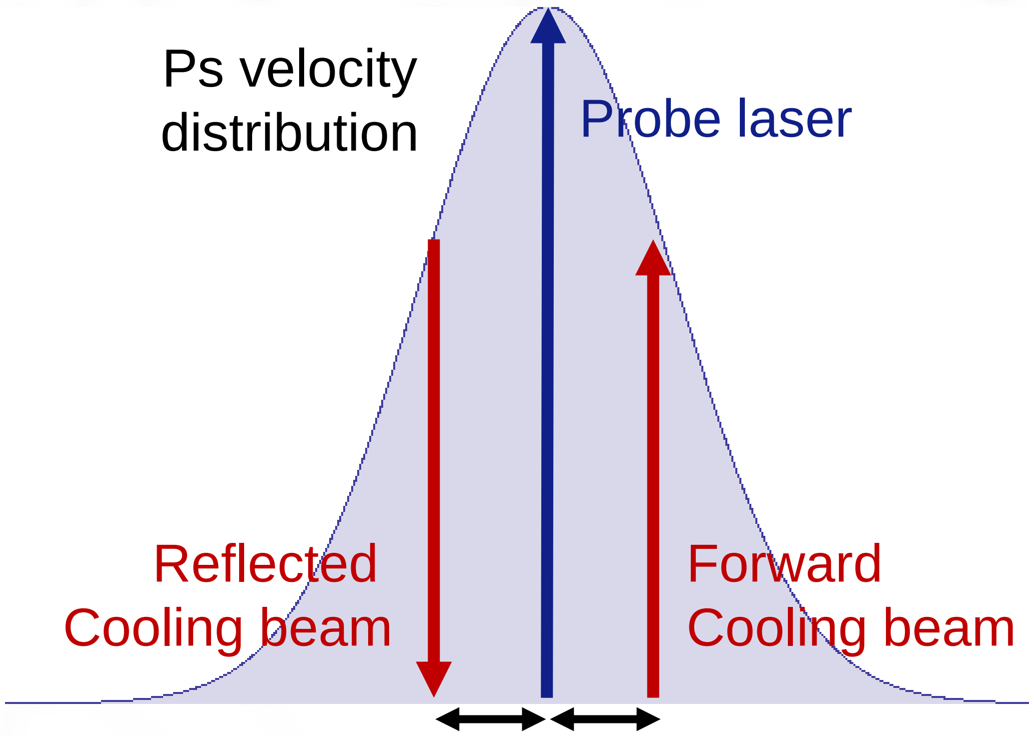
How? Measuring the temperatures with and without cooling



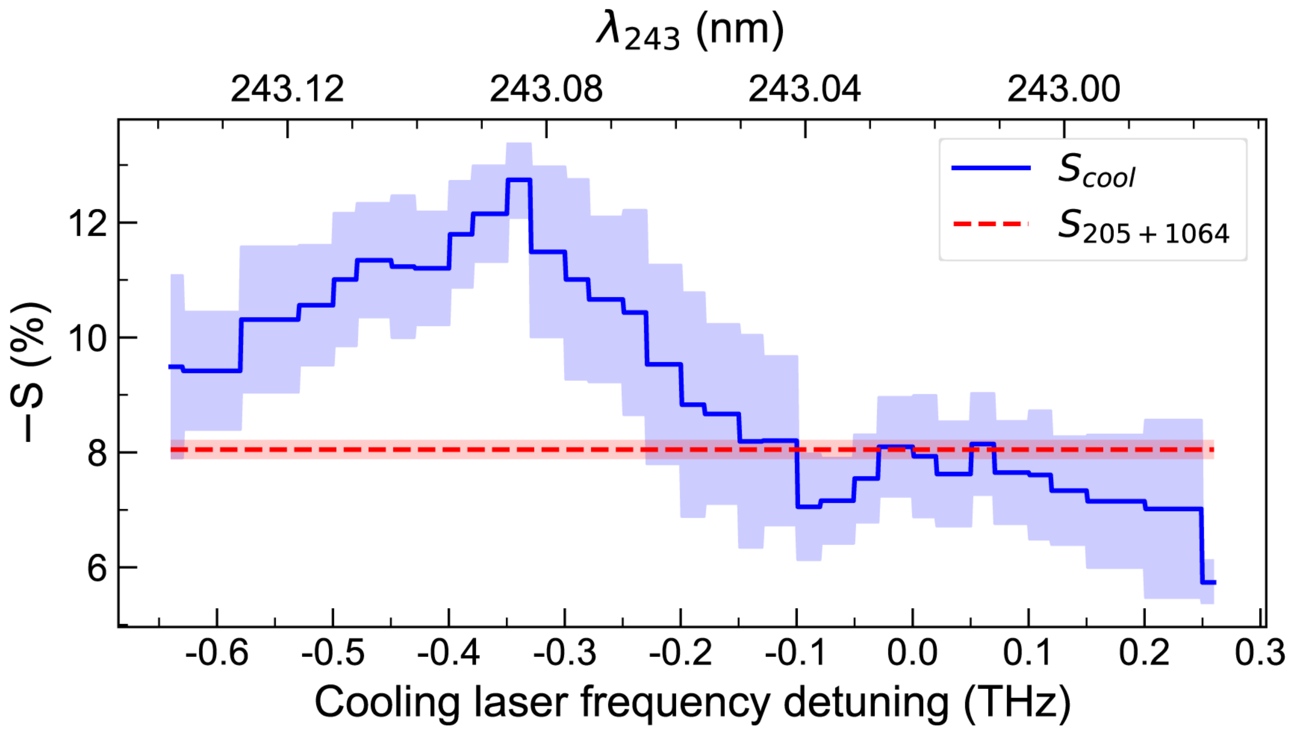
Scanning the probe laser detuning



How? Measuring an increase in the cold atoms' fraction

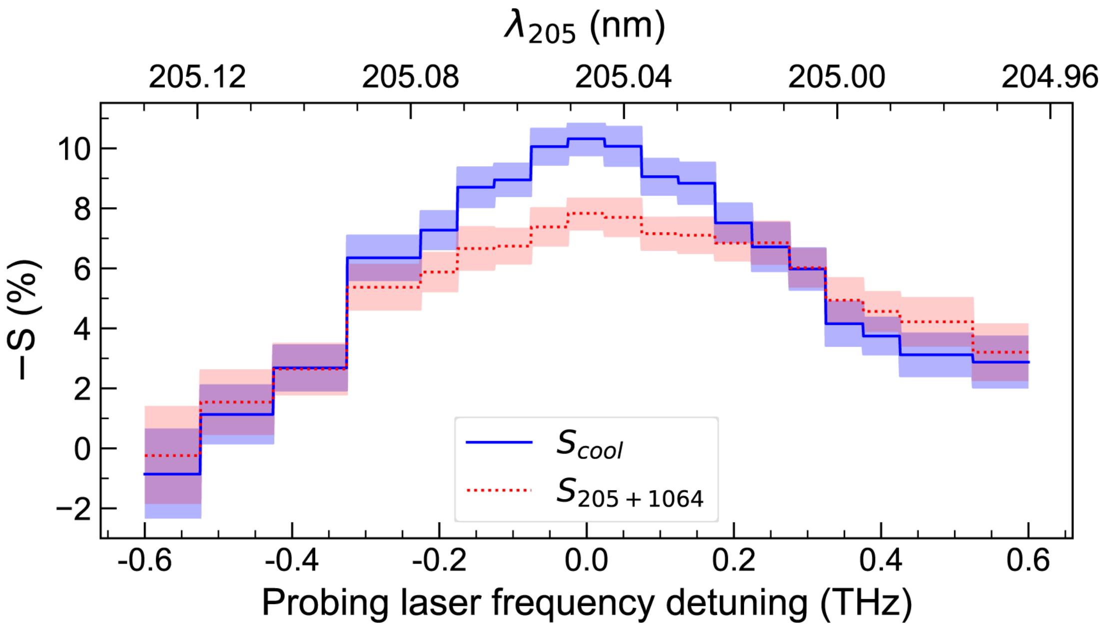


Scanning the cooling laser detuning

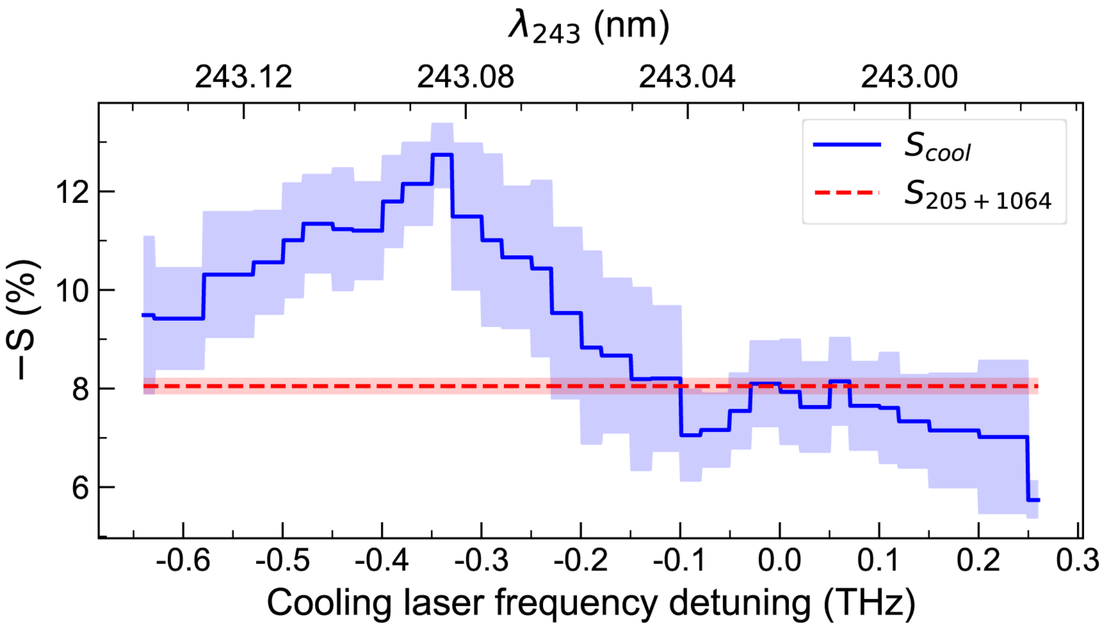


Wrapping it up

Narrowing of the $1^3S – 3^3P$ line



Increase of the number of atoms in the probe laser BW



> we cooled the Ps cloud from 380(20) K to 170(20) K <

> we reached the maximum cooling efficiency allowed by Doppler laser cooling <

The impact of this result goes beyond antihydrogen production:
opens the way for precision spectroscopy, clock tests of the WEP with Ps, and Bose-Einstein condensation

Thank you for your attention