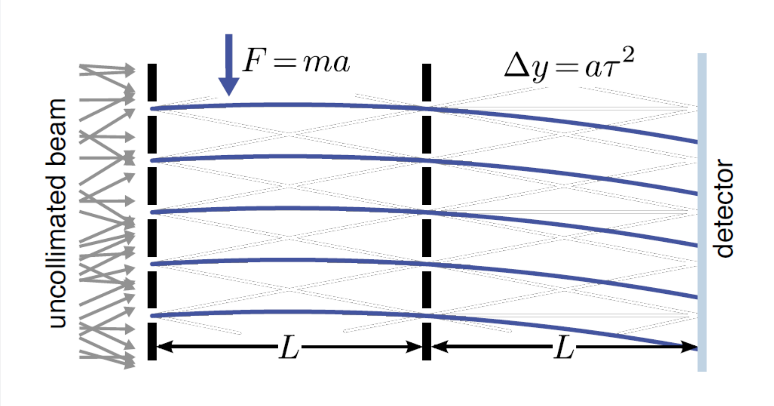
LASER COOLING OF UNSTABLE SPECIES: THE CASE OF POSITRONIUM

Antoine Camper
University of Oslo, Norway
On behalf of the AEgIS collaboration

Physics with laser cooled Ps

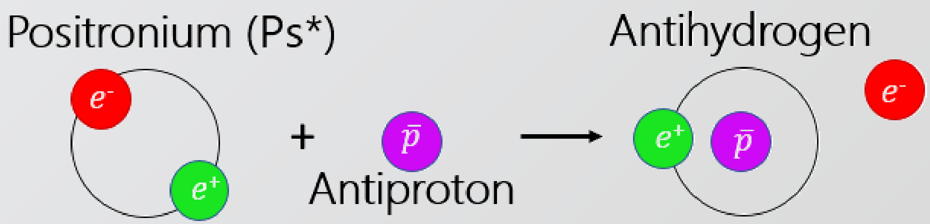
1. Antihydrogen moiré deflectometer

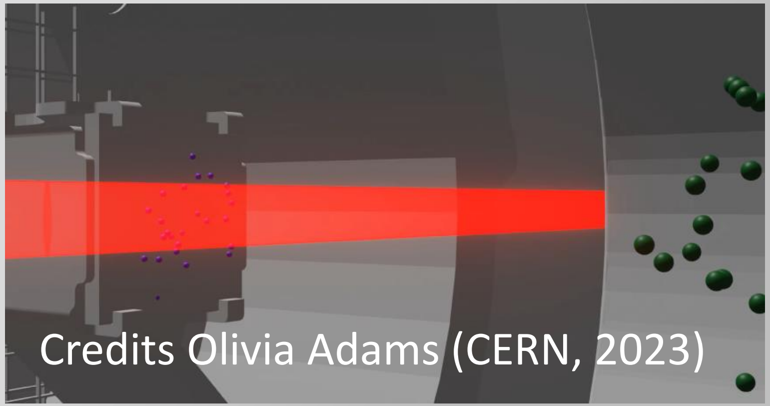


Aghion S. et al (AEgIS collaboration), Nat Comm 5:4538 (2014)

2. Pulsed production of antihydrogen by charge exchange

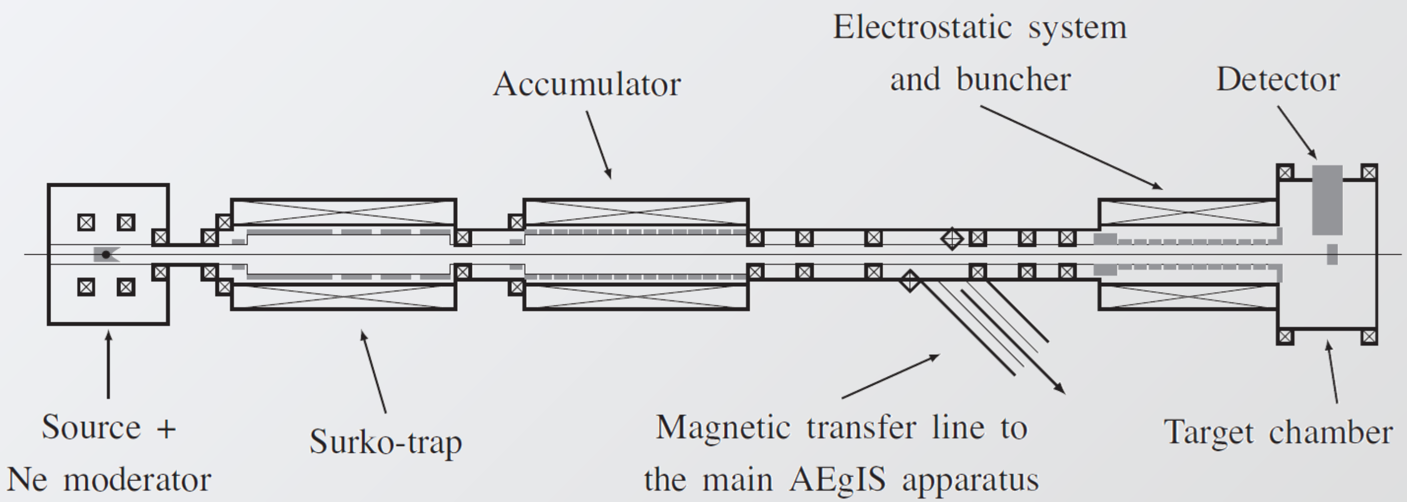
Amsler et al. (AEgIS)
Comm Phys 4:19 (2021)





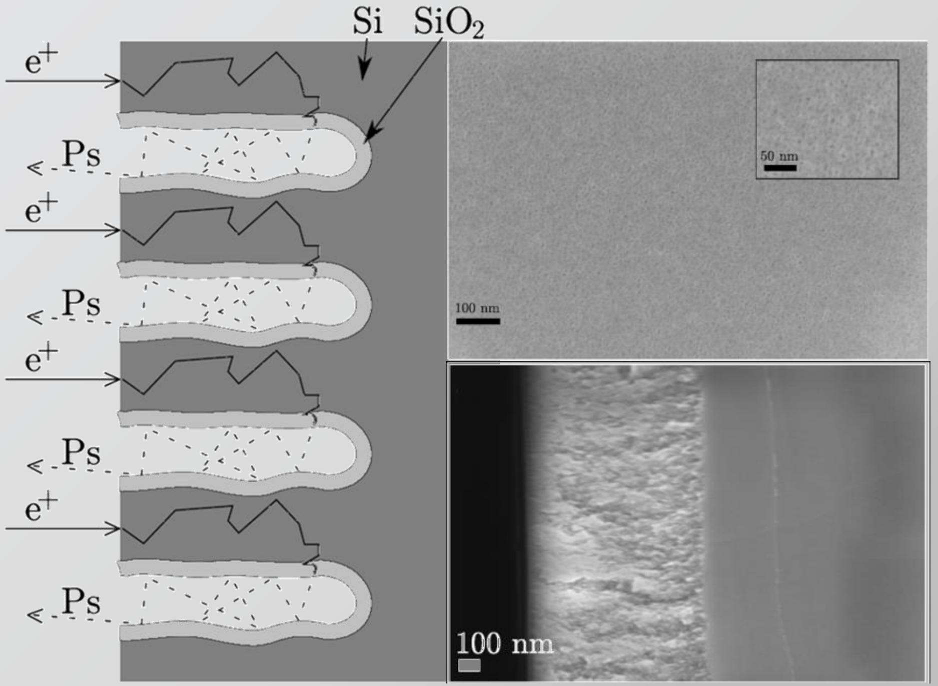
Pulsed positronium production

1. The AEgIS positron beam line



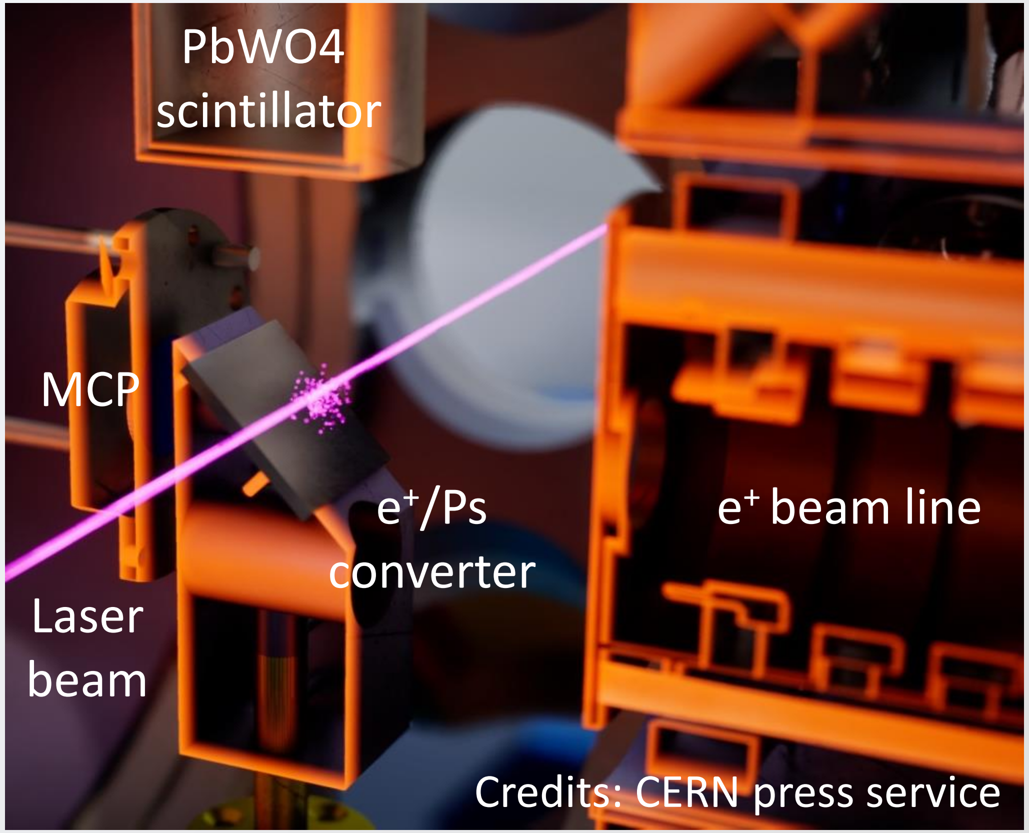
Aghion S. et al (AEgIS collaboration), NIM B 362 (2015) 86-92

2. Nanochannel Si converter targets

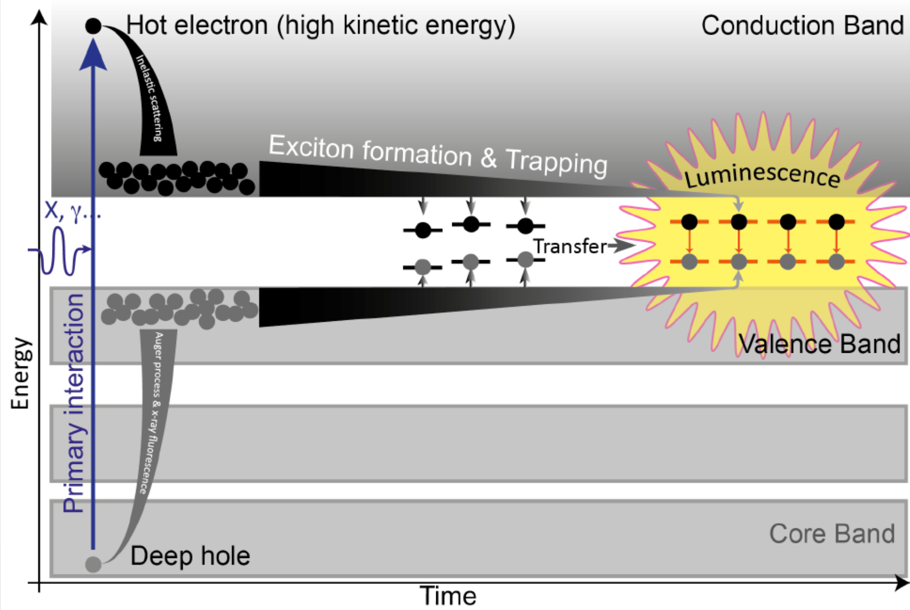


Mariazzi S. Bettotti P. Brusa R. S.,
PRL 104, 243401 (2010)

Experimental scheme

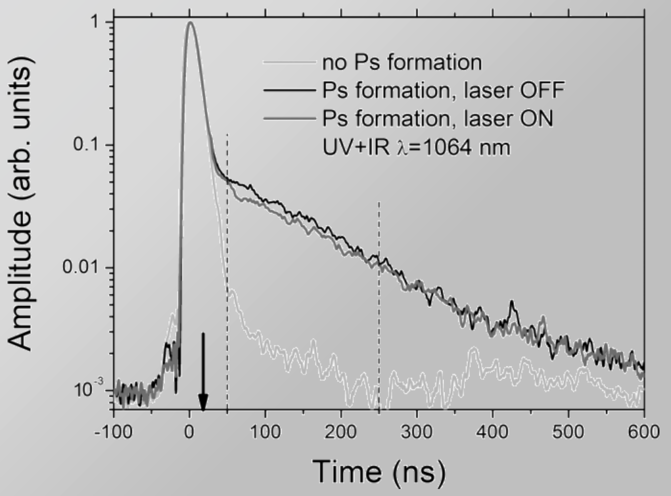


1. Scintillator for gamma-ray detection



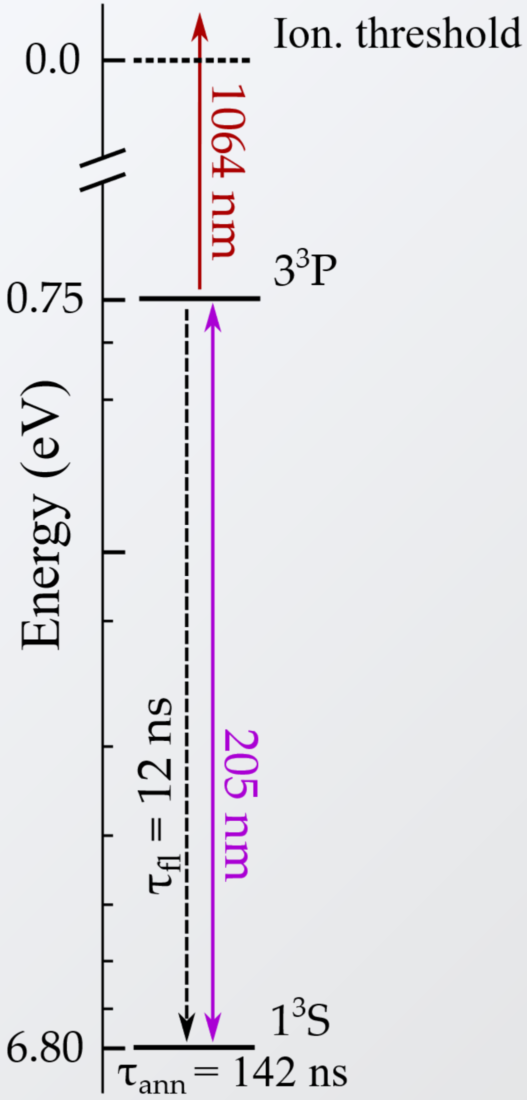
2. Single Shot Positron Annihilation Lifetime Spectroscopy (SSPALS)

Annihilation gamma-rays recorded as a function of time using a digitized scintillator

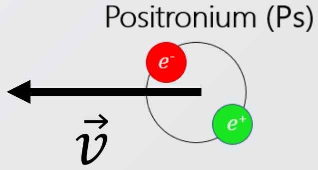


Aghion et al. (AEgIS collaboration)
PRA 94, 012507 (2016)

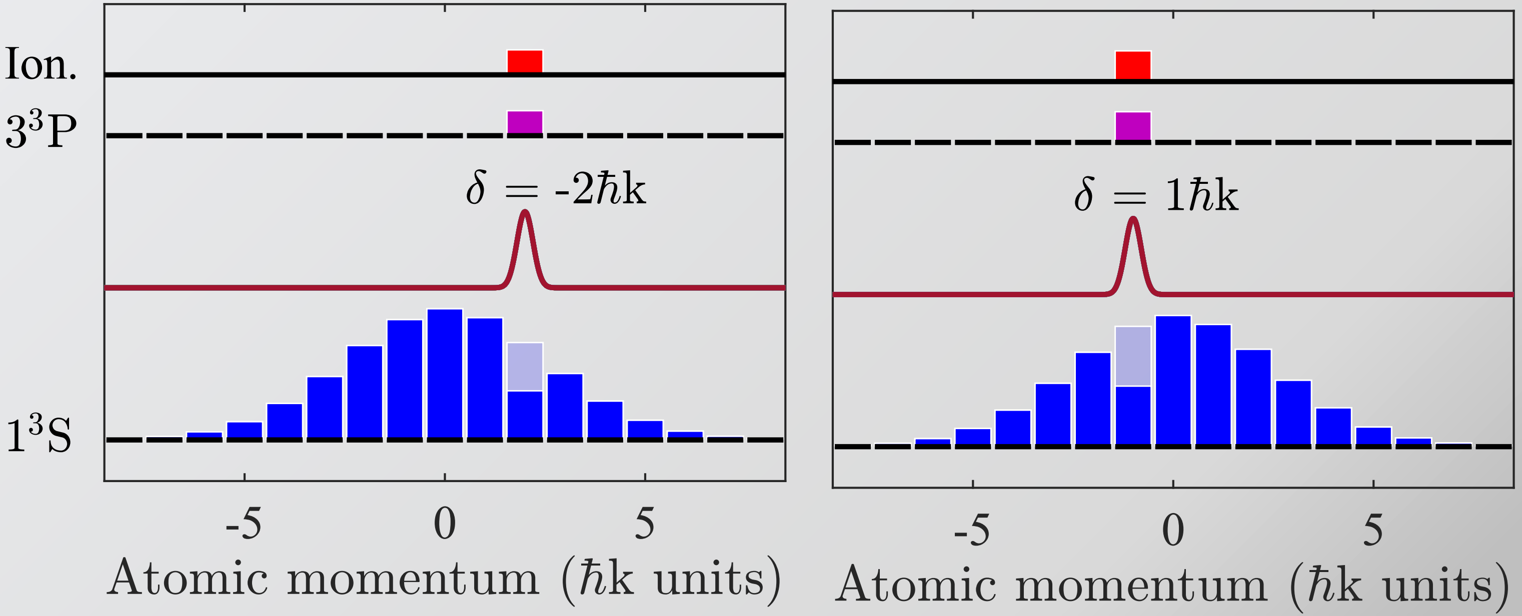
Doppler velocimetry



1. Doppler selection



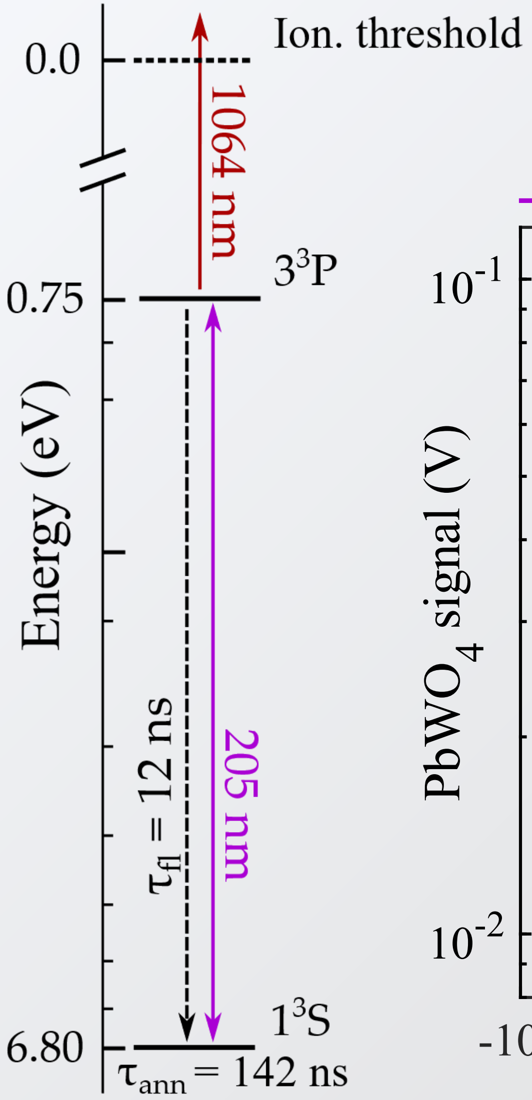
$$\nu = \nu_0 \left(1 - \frac{v}{c}\right)$$



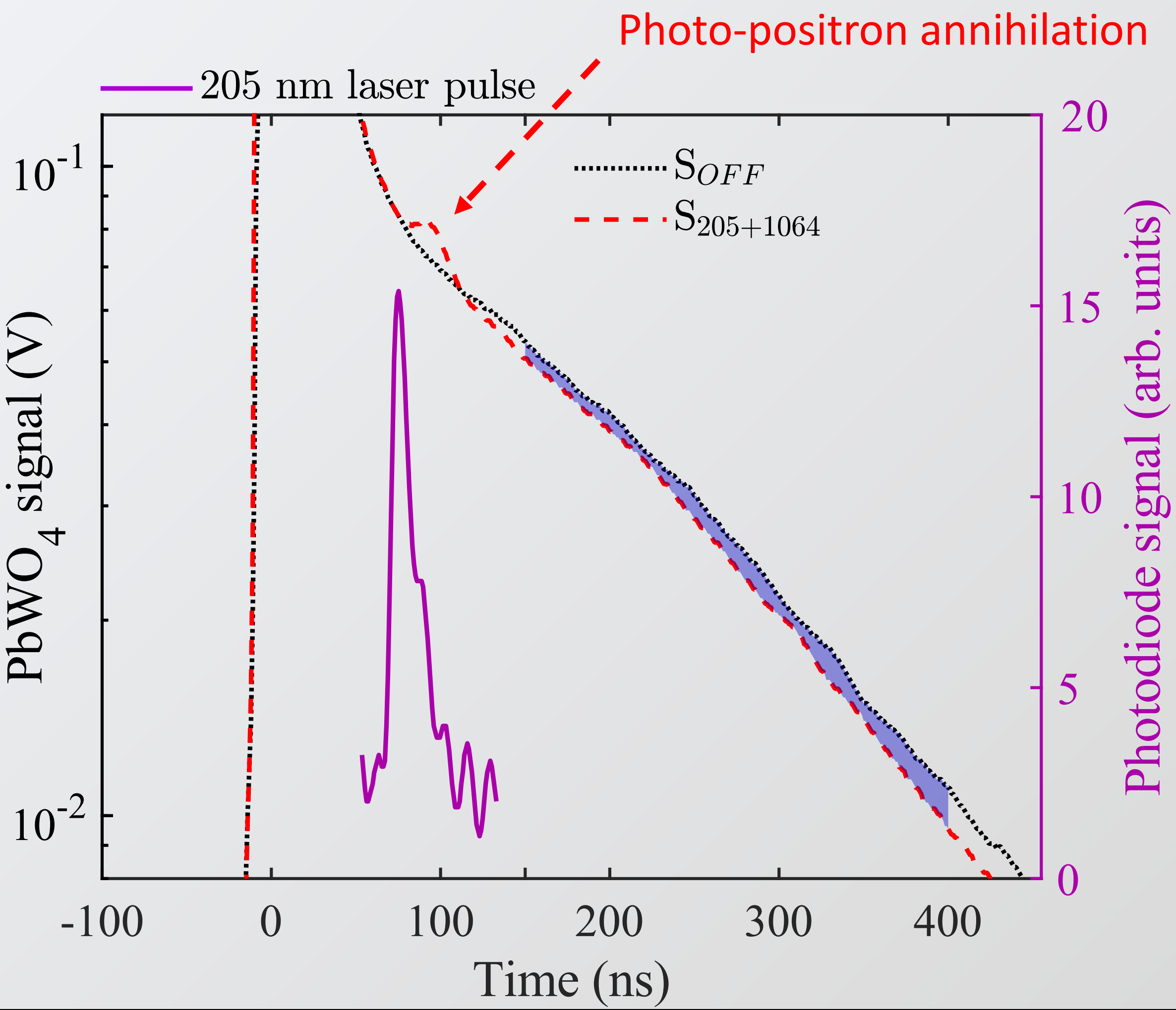
2. Two-photon resonant ionization

$$Ps^*(n = 3) + h\nu \longrightarrow e^+ + e^-$$

SSPALS Doppler velocimetry

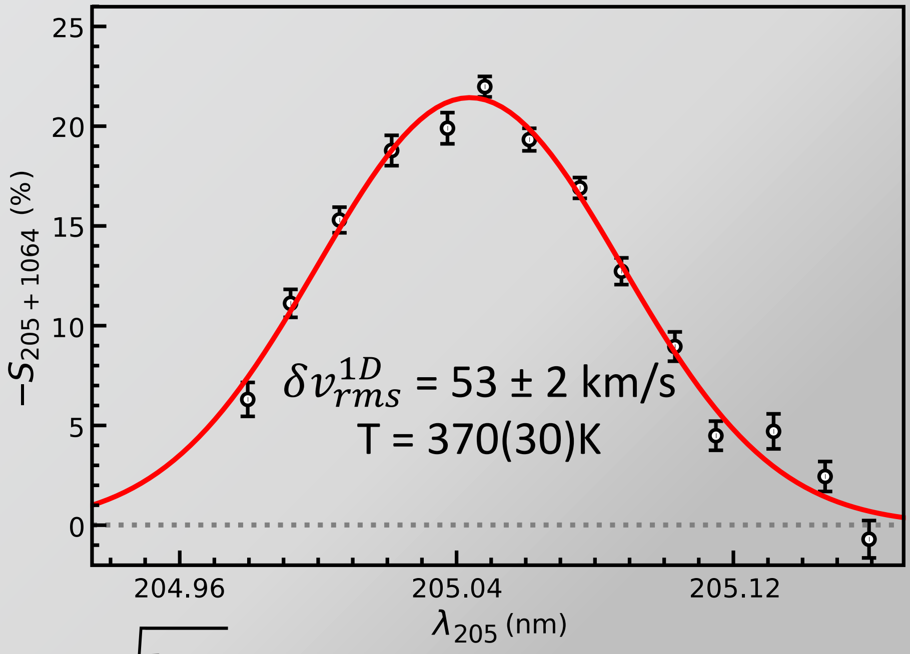


1. SSPALS photoionization spectrum



2. $1^3S \rightarrow 3^3P$ Doppler broadened linewidth

$$-S_{205+1064} = \frac{f_{OFF} - f_{205+1064}}{f_{OFF}}$$



$$\sqrt{\frac{k_B T}{m_{Ps}}} = \delta v_{rms}^{1D}$$

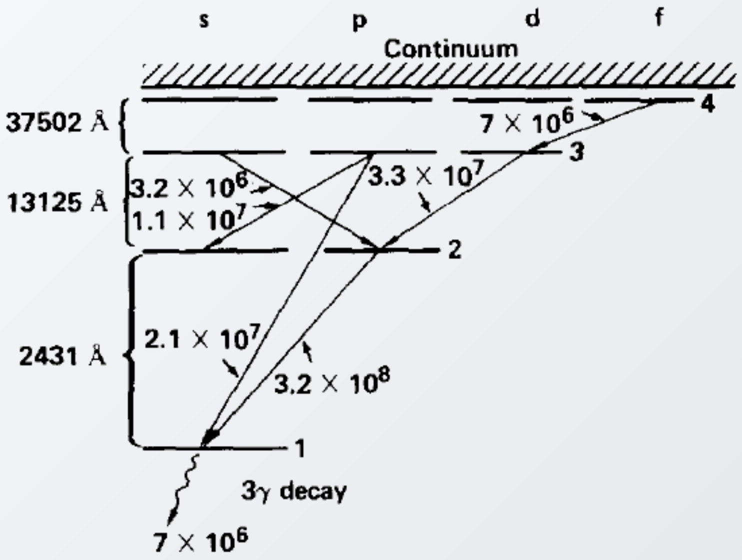


Fig. 2. Energy levels and radiative decay rates of the lowest lying states of ortho-positronium.

Liang and Dermer, OPTICS COMMUNICATIONS **65**, 6 (1988) 419-424

This requires that the laser frequency be swept rapidly so that all Ps in the Doppler wing are effectively "snowploughed" to lower velocities. In practice such rapid frequency sweeps (at rates >> 109 GHz/s) are difficult to achieve. A technically more feasible approach is to use a stationary broadband laser with negative detuning.

PHYSICAL REVIEW LETTERS **132,** 083402 (2024)

Editors' Suggestion | Featured in Physics

Positronium Laser Cooling via the 1^3S-2^3P Transition with a Broadband Laser Pulse

physicsworld TOP 10 BREAKTHROUGH 2024

Article | Open access | Published: 11 September 2024

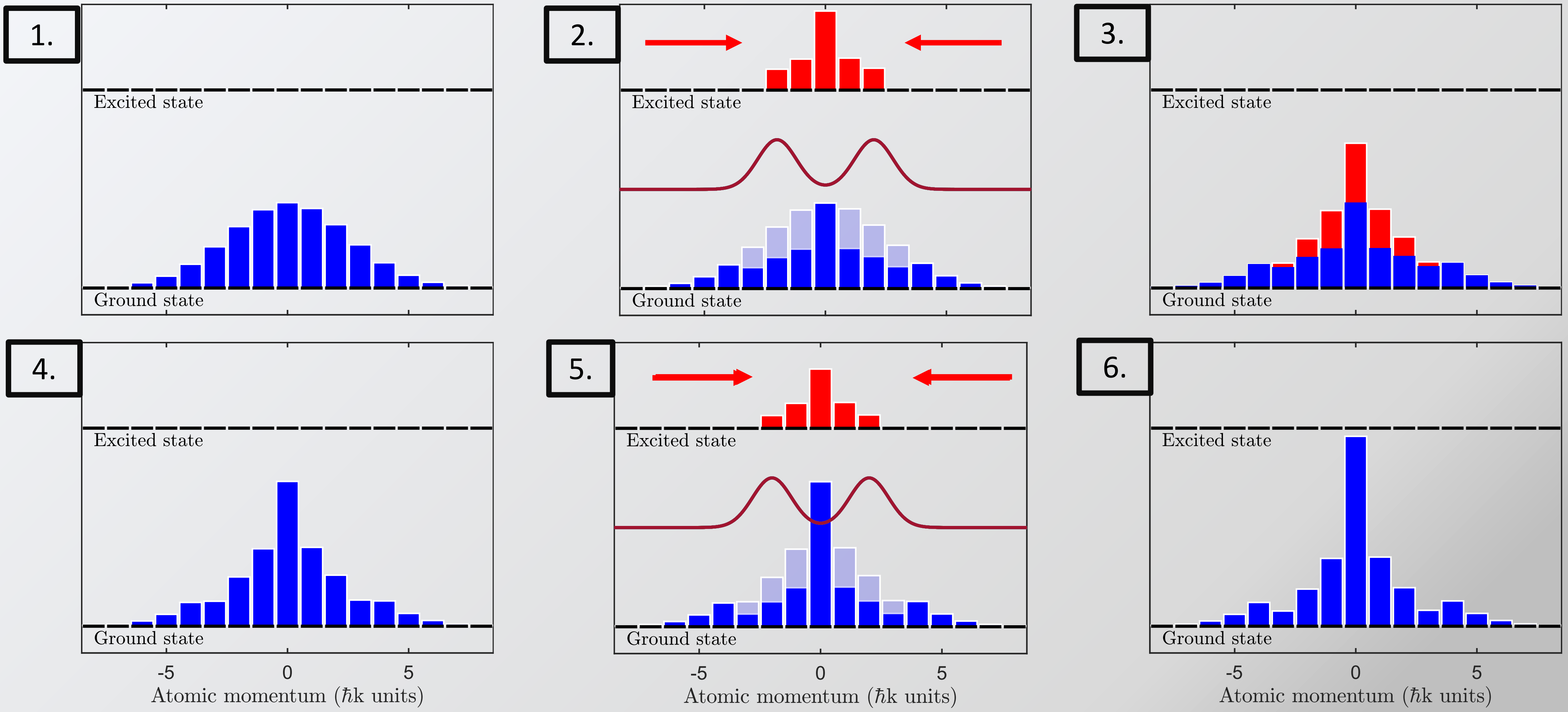
Cooling positronium to ultralow velocities with a chirped laser pulse train

K. Shu, Y. Tajima, R. Uozumi, N. Miyamoto, S. Shiraishi, T. Kobayashi, A. Ishida, K. Yamada, R. W. Gladen, T. Namba, S. Asai, K. Wada, I. Mochizuki, T. Hyodo, K. Ito, K. Michishio, B. E. O'Rourke, N. Oshima & K. Yoshioka

Nature **633**, 793–797 (2024) | Cite this article

Broadband Doppler laser cooling

Traditional Doppler cooling maximum reduction rate : 1ħk (6.17 GHz) per $2\tau_{SE}$ (6.38 ns) or 970 GHz/μs for Ps



Margaret K. Brown "Long-pulse broadband 243-nm source based on a Cr:LiSAF laser operating at 972 nm", Proc. SPIE 3613, Solid State Lasers VIII, (4 May 1999).

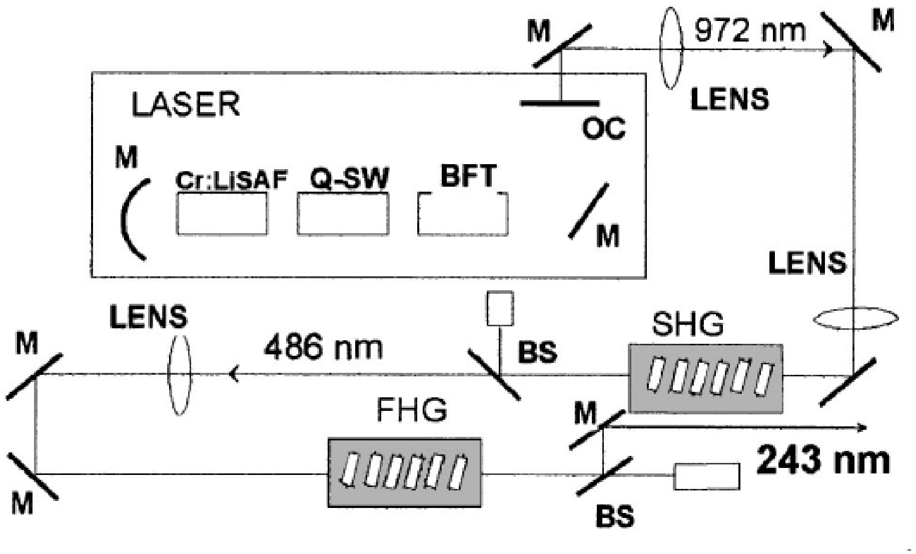


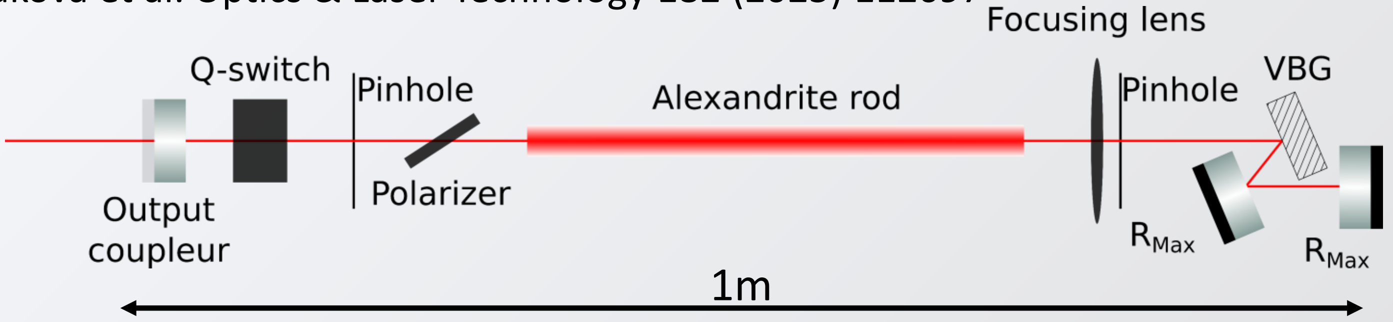
Fig. 1. Schematic of the 243-nm source. A Cr:LiSAF *Q*-switched laser (Q-SW) is used to generate radiation at 972 nm. The broadband 972-nm radiation is then frequency quadrupled in two successive multicrystal type I BBO SHG processes. M's, mirrors; OC, output coupler; BFT, birefringent tuner; BS's, beam splitters.

Cassidy et al., AIP Conference Proceedings **1037**, 66 (2008)
Cold Antimatter Plasmas and Applications to Fundamental Physics
Okinawa 2008

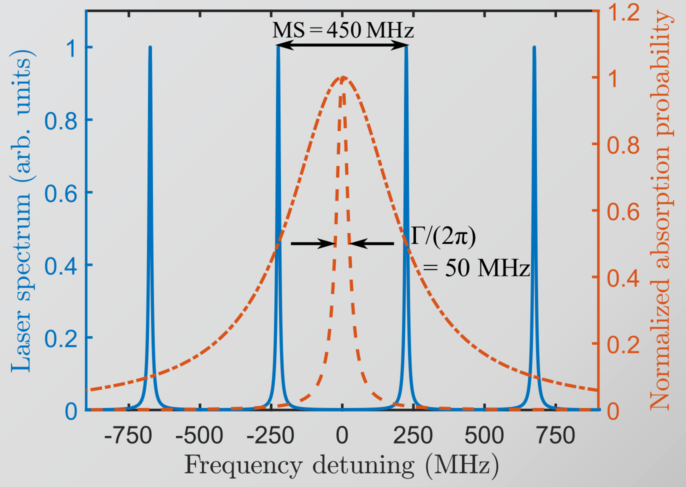
The spontaneous lifetime of 2P Ps is 3.2 ns but at high optical intensities the fastest the atom can be recycled is 6.4 ns. Thus the minimum time for 30 absorptions is ~200 ns. We will use 300 ns duration, 243 nm, 40 GHz linewidth pulses, made by third harmonic generation of a ~ 500 ns duration 729 nm pulse from a Q-switched and pulse-stretched alexandrite laser, producing at least 20 mJ/pulse at 243 nm. When focused to a Gaussian diameter of 3 mm, the peak intensity in the 3-d cooling beams will each reach 580 KW/cm2 over a 40 GHz linewidth, which is 580 times the saturation intensity.

Strong saturation regime

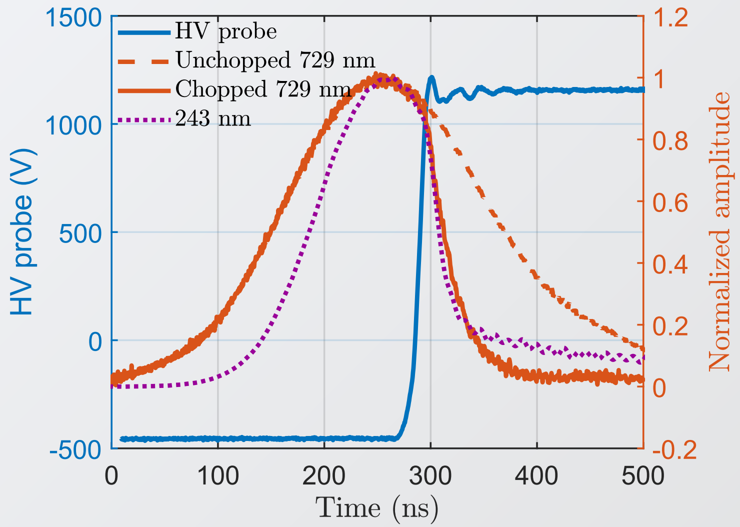
Gusakova et al. Optics & Laser Technology 182 (2025) 112097



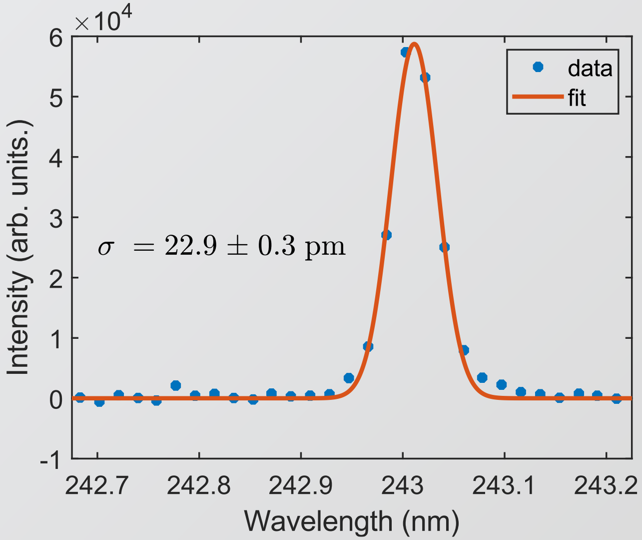
3. E_{243} = 700µJ on 7 mm² yields 100kW.cm⁻²
(I_{sat} = 0.45 W/cm² per 50 MHz)

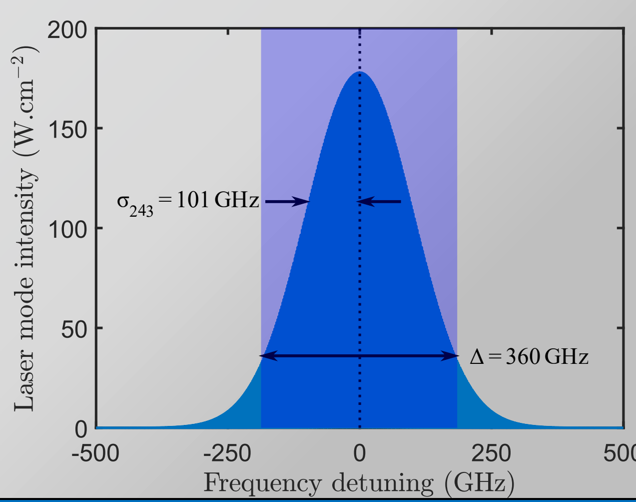


1. 70 ns laser-Ps interaction



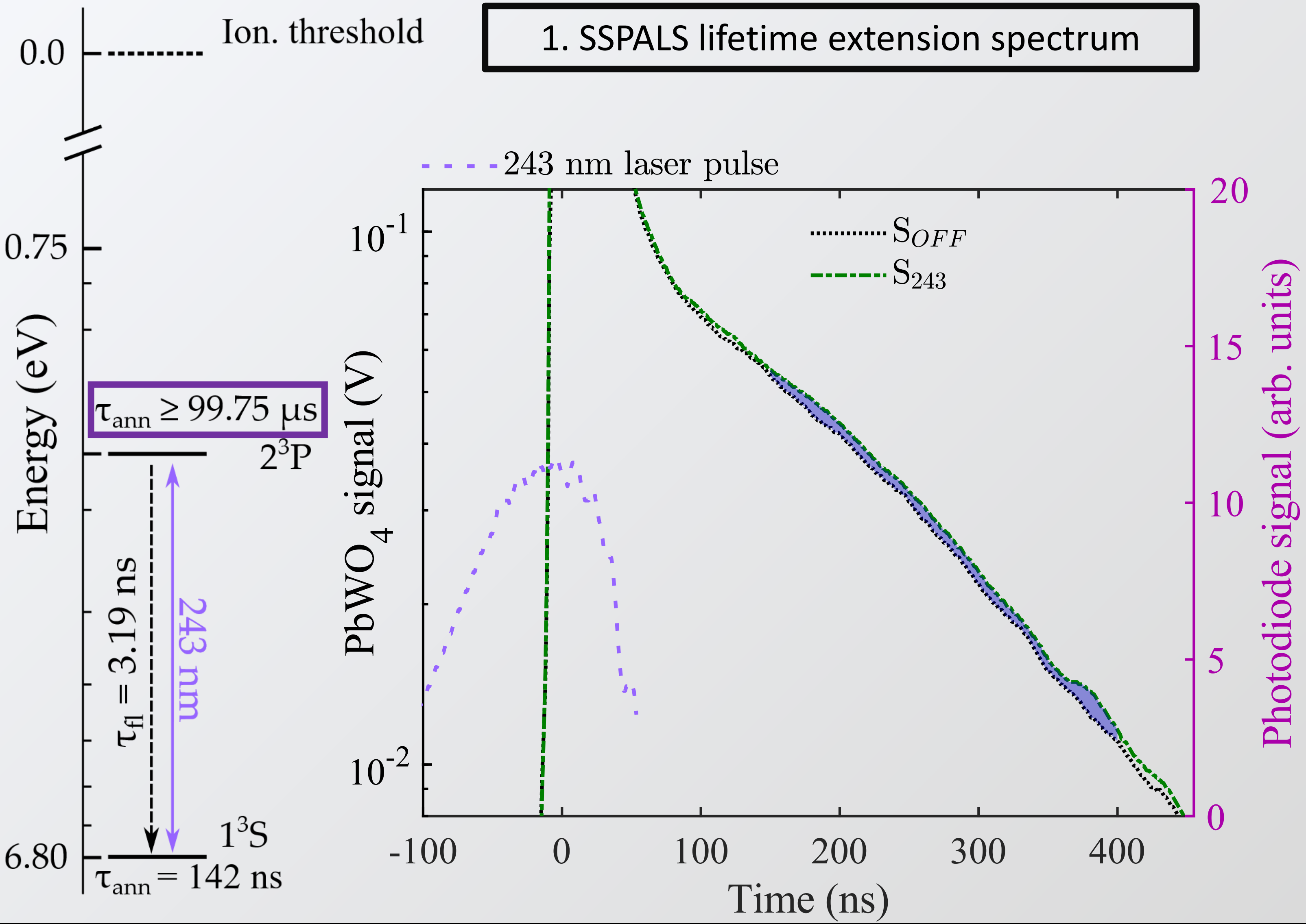
2. σ_{243} = 101 GHz





450 MHz mode spacing at 243 nm but transition linewidth only 50 MHz

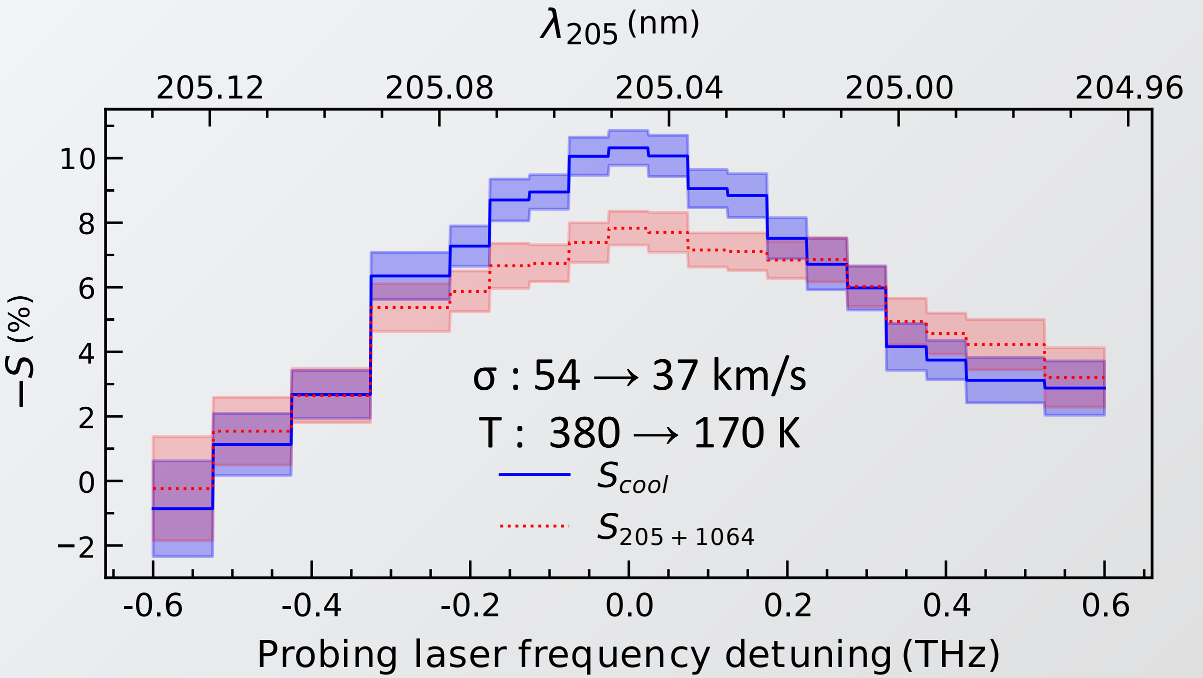
SSPALS lifetime extension spectroscopy

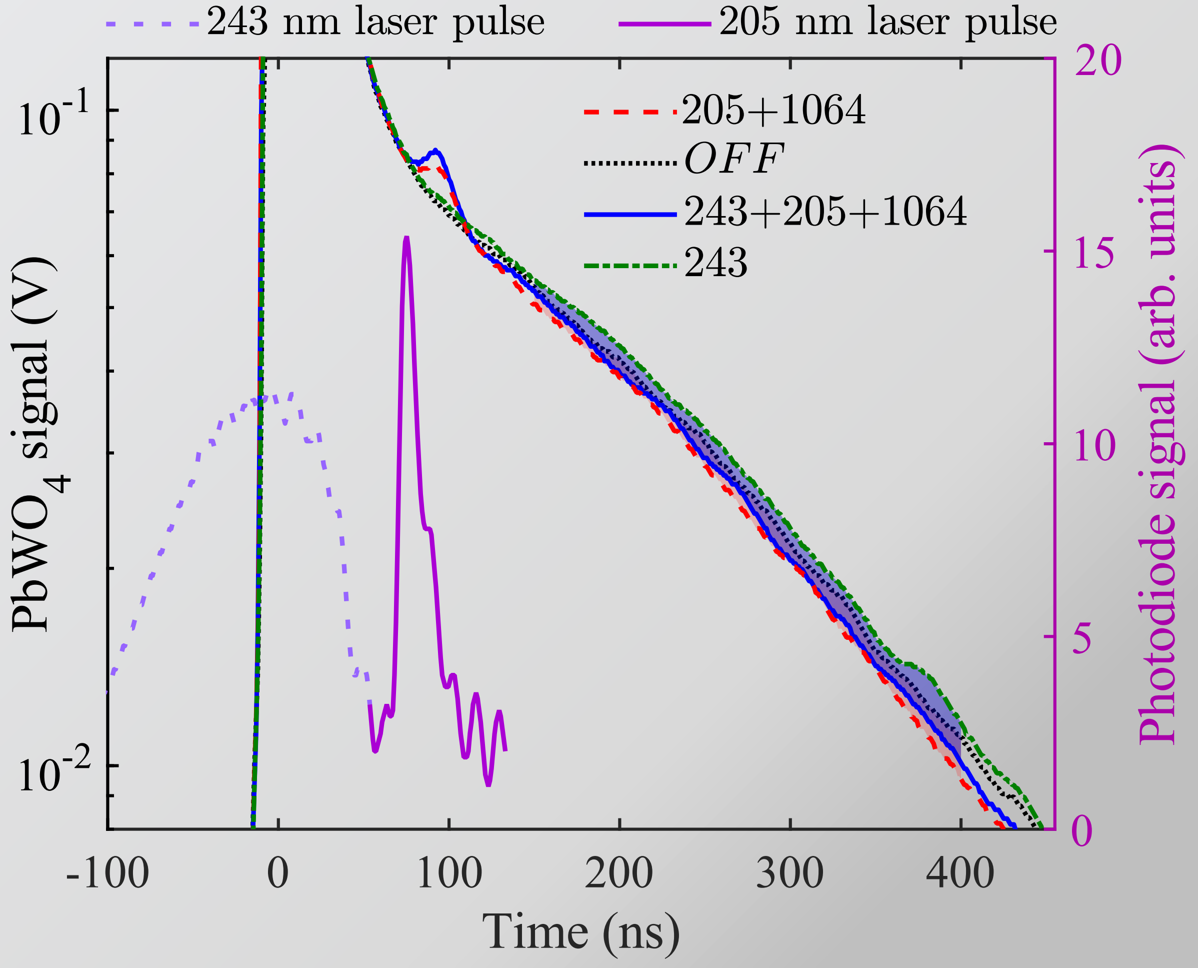


Doppler profile narrowing

$$-S_{205+1064} = \frac{f_{OFF} - f_{205+1064}}{f_{OFF}}$$

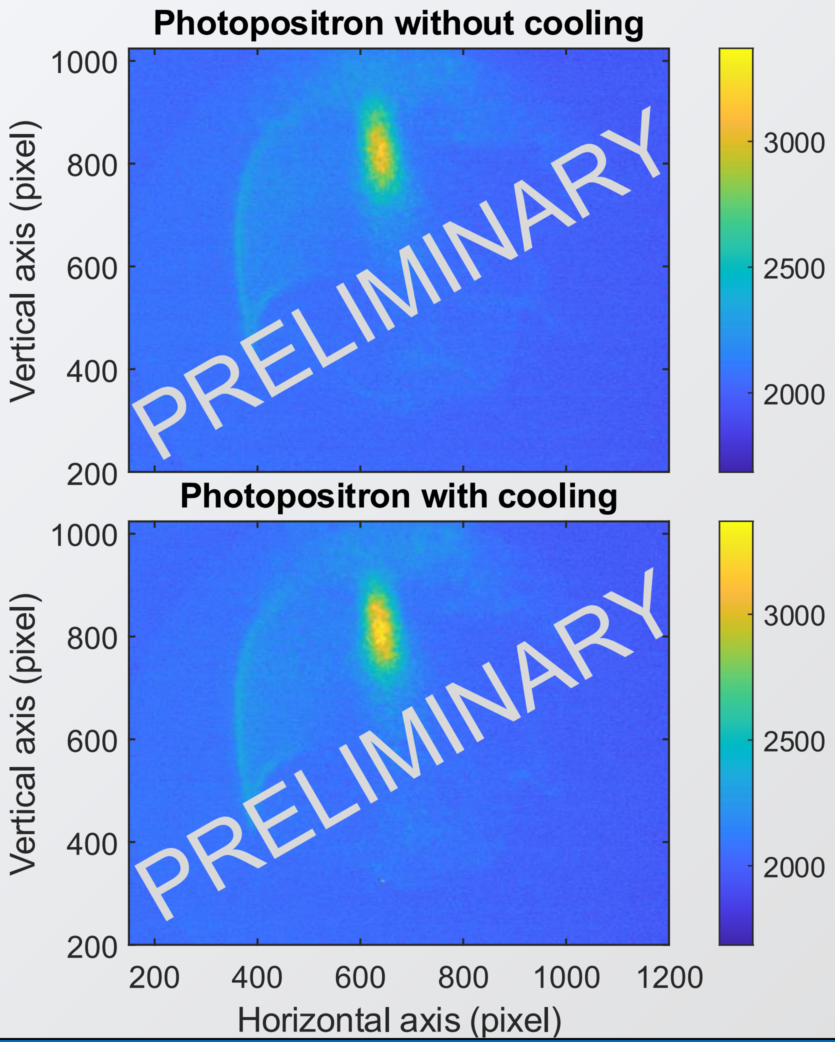
$$-S_{cool} = S_{243+205+1064} - S_{243} = \frac{f_{OFF} - f_{243+205+1064}}{f_{OFF}} - \frac{f_{OFF} - f_{243}}{f_{OFF}}$$



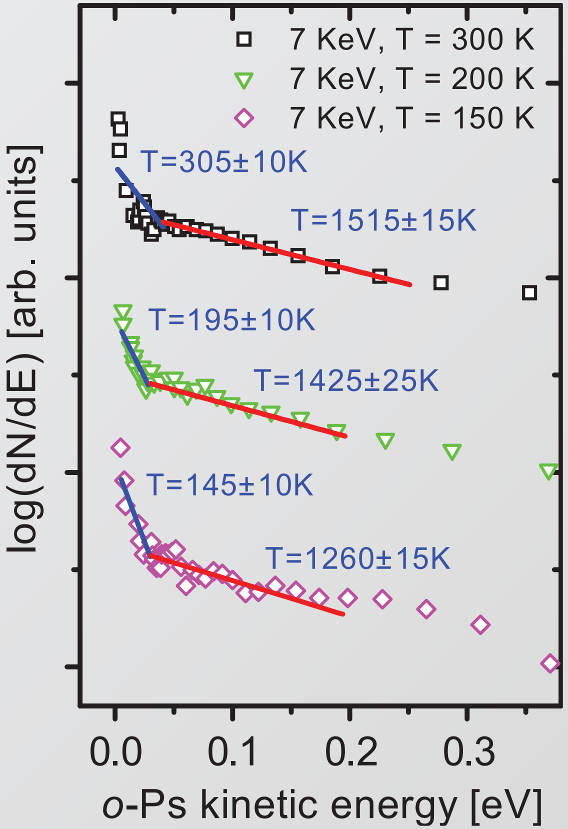


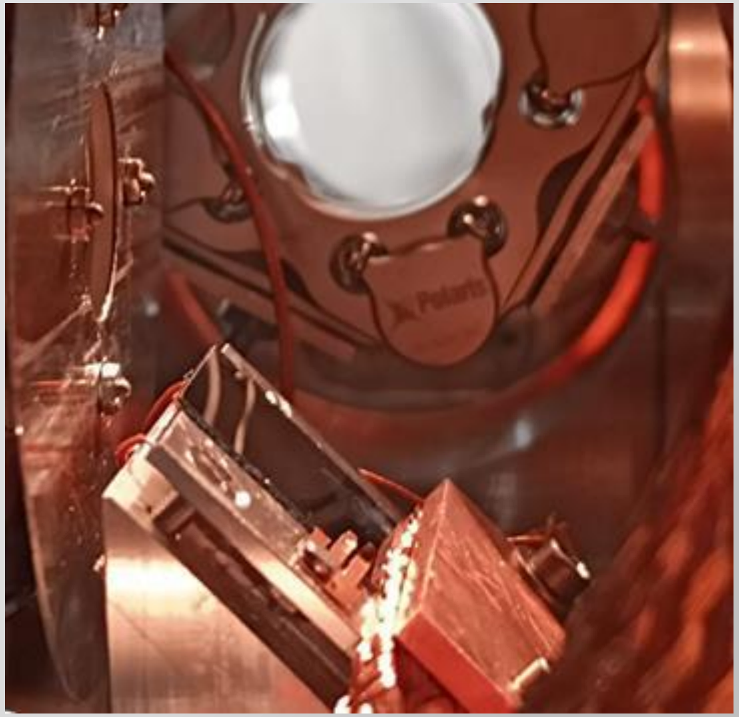
Current developments

1. MCP photo-positron imaging



2. Cryocooler for 100 K target cooling

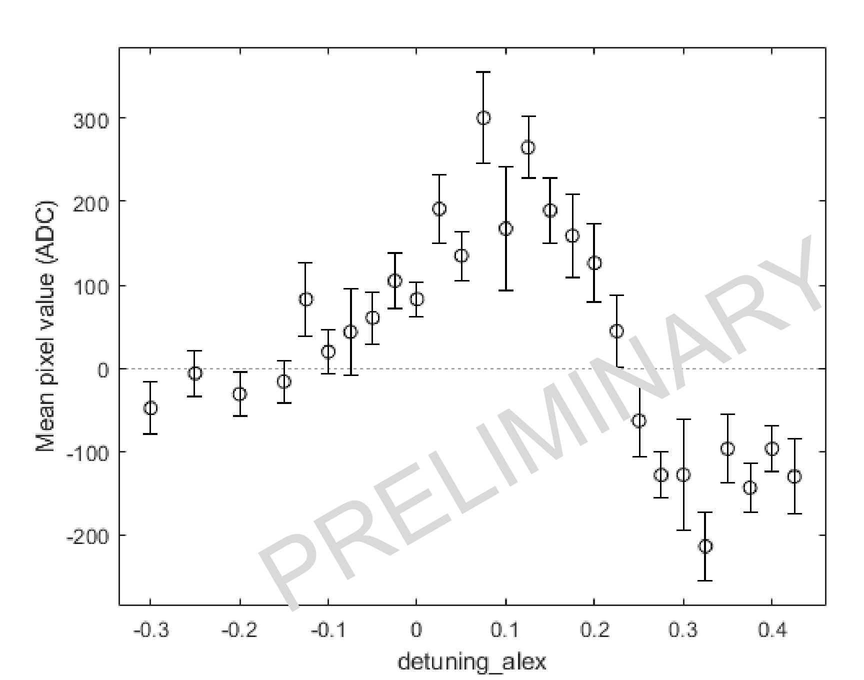




Mariazzi et al. PRL 104, 243401 (2010)

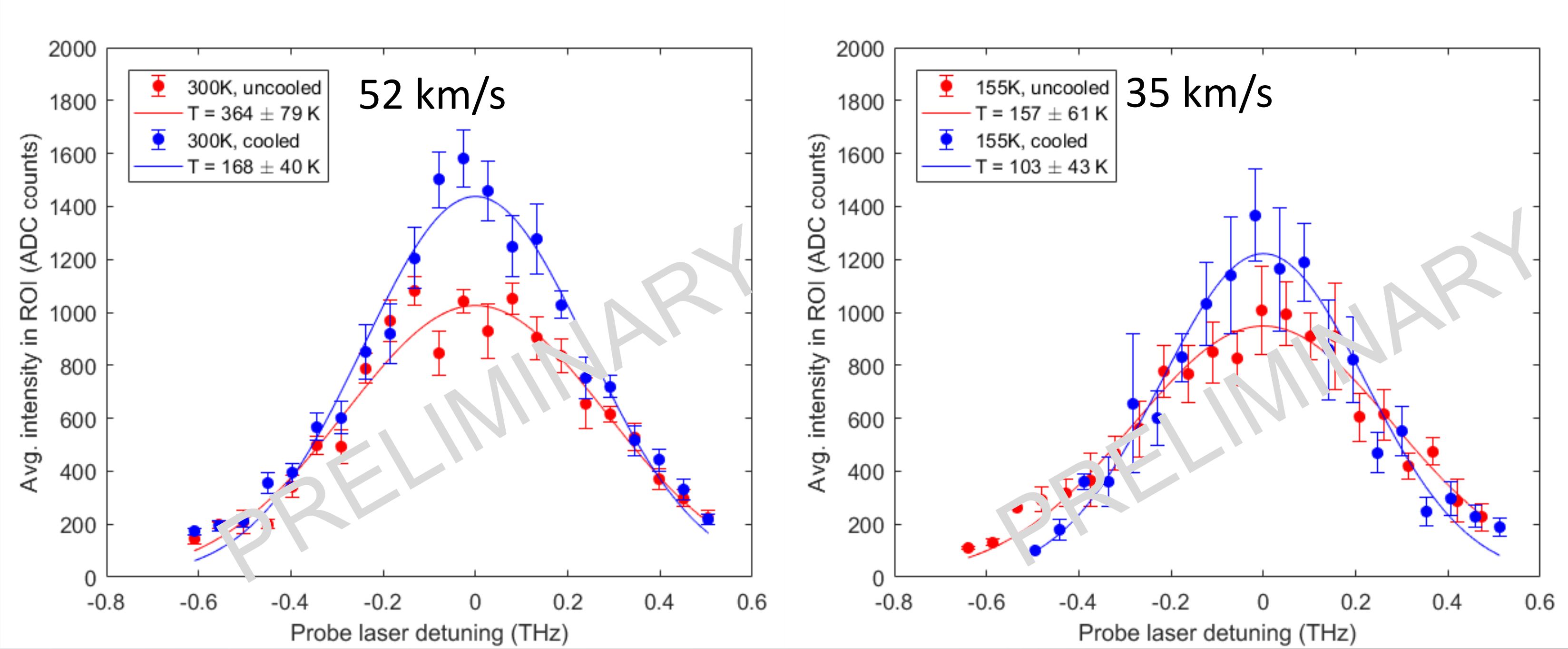
Preliminary results

1. Optimization of the cooling detuning



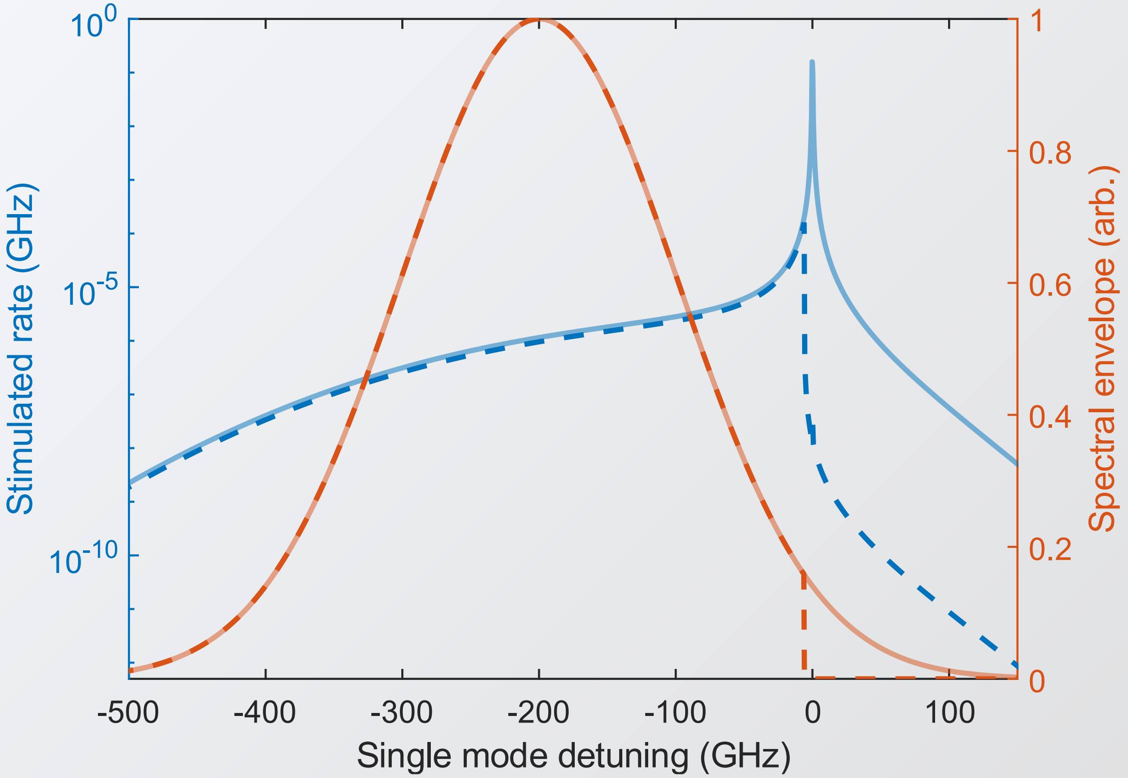
The 205nm pulse ionizes Ps at resonance.

2. MCP photo-positron imaging



The Doppler broadening measurement is limited by the bandwidth of the 205nm. (potentially 50 K after laser cooling)

Scattering rate at resonance (v = 0 m/s)



E_{243} = 700µJ on 7 mm^2 yields 100kW.cm^{-2}

σ_{243} = 101 GHz

MS = 450 MHz (mode spacing at 243 nm)

1. No spectral cut

$$\Gamma_n = \frac{\Omega_n^2}{4}\frac{(\Gamma+\Gamma_{mode})}{\left(\omega_{eg}-\omega_{\mathcal{L}}-nMS\right)^2+\left(\frac{\Gamma+\Gamma_{mode}}{2}\right)^2}$$

where $\Omega_n^2 = \frac{d^2}{h^2}\frac{2P_n}{\epsilon_0 c} = \frac{d^2}{h^2}\frac{2P\,MS}{\epsilon_0 c\sigma_{243}\sqrt{2\pi}}e^{-\frac{(nMS-\omega_{\mathcal{L}})^2}{2\sigma_{243}^2}}$

2. With spectral cut

$$\Gamma_n = \frac{\Omega_n^2}{4\pi^2}\int_{-\infty}^{\omega_c} d\omega\,\frac{\Gamma}{\left(\omega-\omega_{eg}\right)^2+\left(\frac{\Gamma}{2}\right)^2}\frac{\Gamma_{mode}}{(\omega-\omega_{mode})^2+\left(\frac{\Gamma_{mode}}{2}\right)^2}$$

$\sum_n \Gamma_n$ = 320 MHz with no spectral cut

$\sum_n \Gamma_n$ = 3 MHz with spectral cut at -6 GHz

Towards faster cooling?

1. Traditional Doppler laser cooling

$1\hbar k/2\ \tau_{SE}$ with τ_{SE} = 3.2 ns

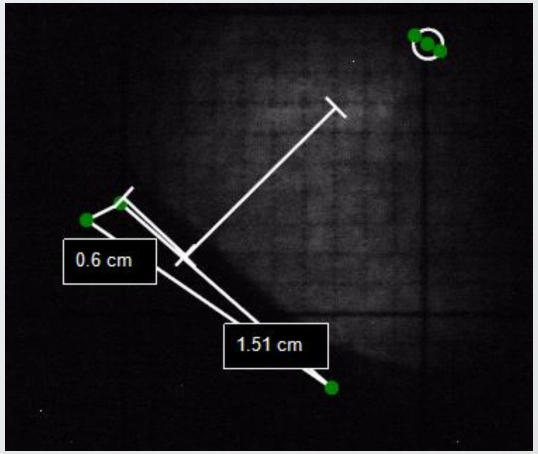
50 km/s = 33*1.5 km/s

33*2*3.2ns = 211 ns

$\tau_{ann.}$ = 142 ns

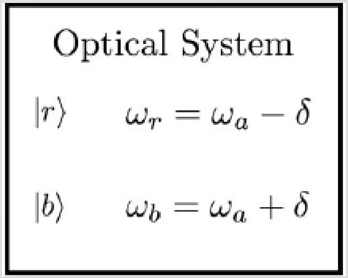
Current limitation:

laser-Ps interaction time (70 ns)

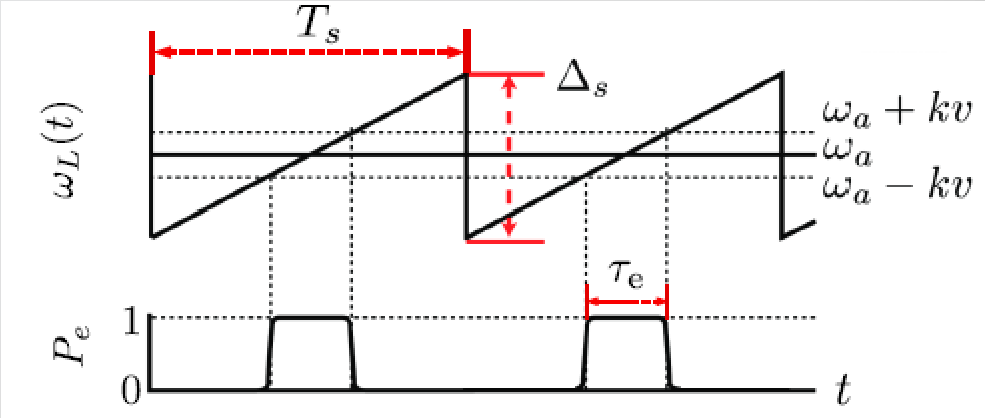


2. Coherent laser cooling

"Laser cooling without spontaneous emission using the bichromatic force"
C. Corder, et al. JOSA B 32, 5 (2015).



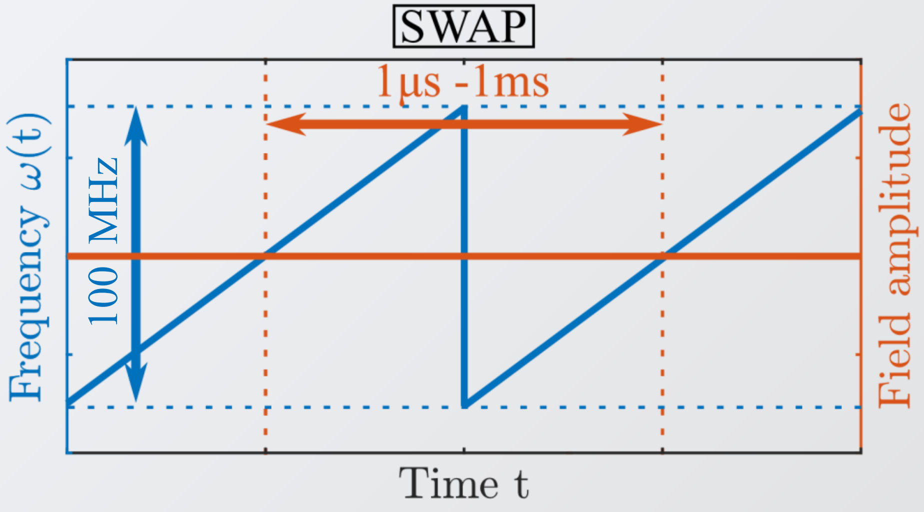
"Laser cooling by sawtooth-wave adiabatic passage"
J. Bartolotta, et al. PRA 98, 023404 (2018).

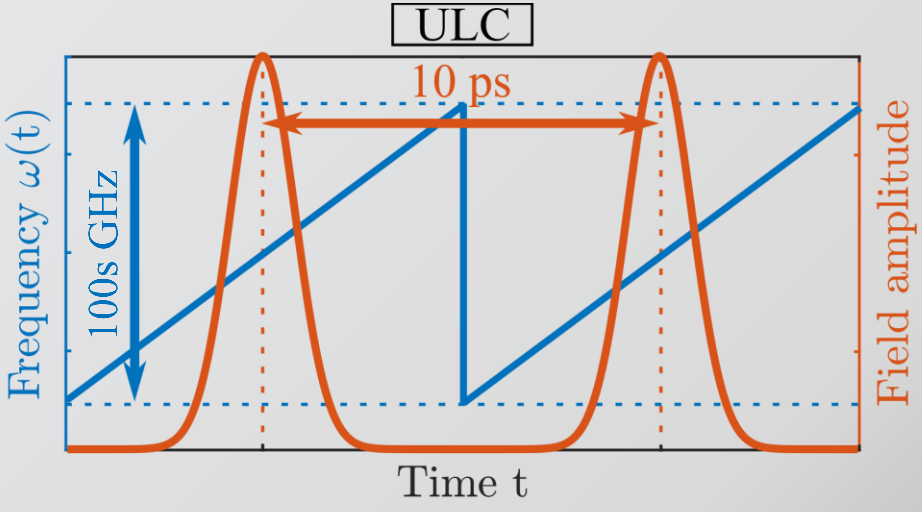


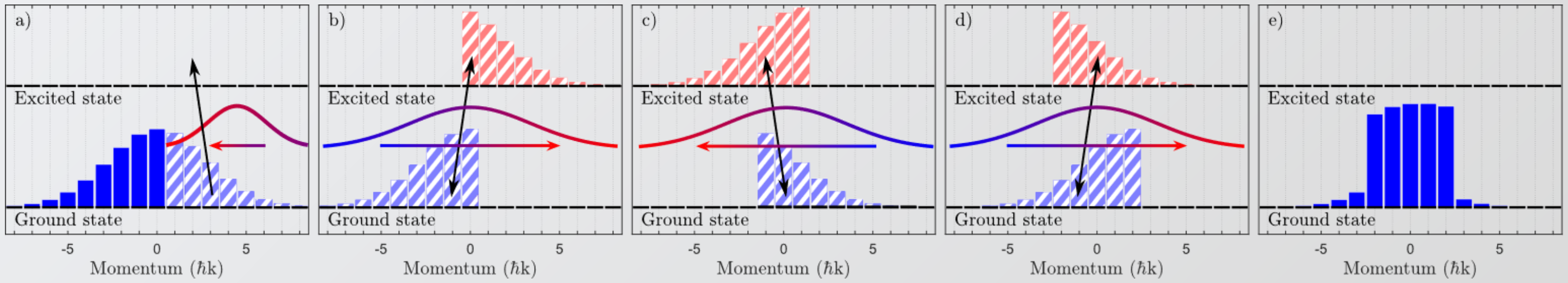
Difficult to transpose directly to Ps

Coherent laser cooling applied to Ps

1. Benefit of using ultrashort pulses





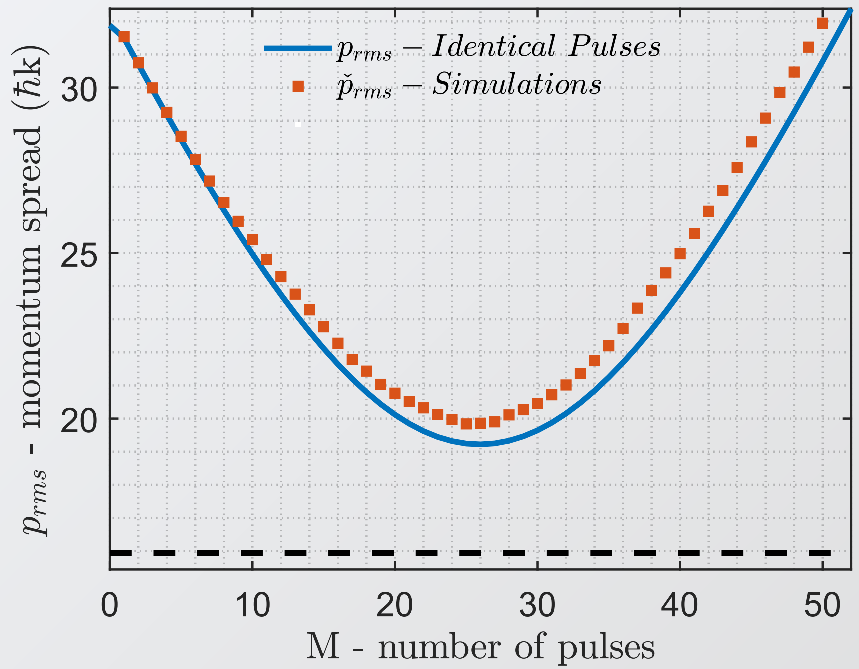


2. Trains of counter propagating pulses

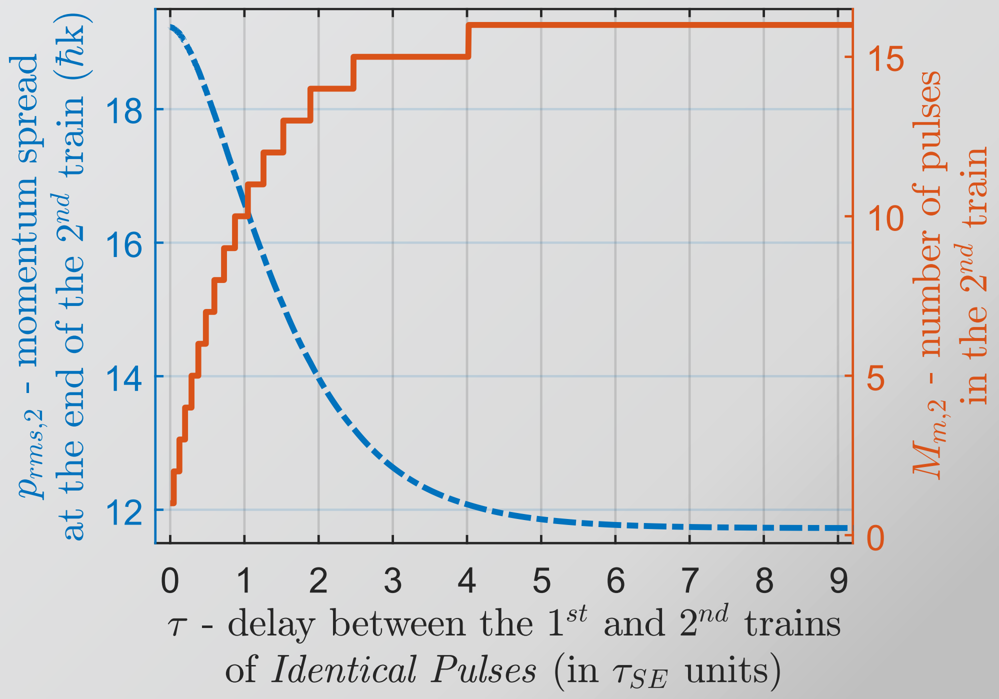
Malamant et al. PRA 110, 013109 (2024).

Limits of the train of identical pulses approach

1. Optimal number of pulses in a train



2. Trains of trains of pulses



Malamant et al. PRA 110, 013109 (2024).

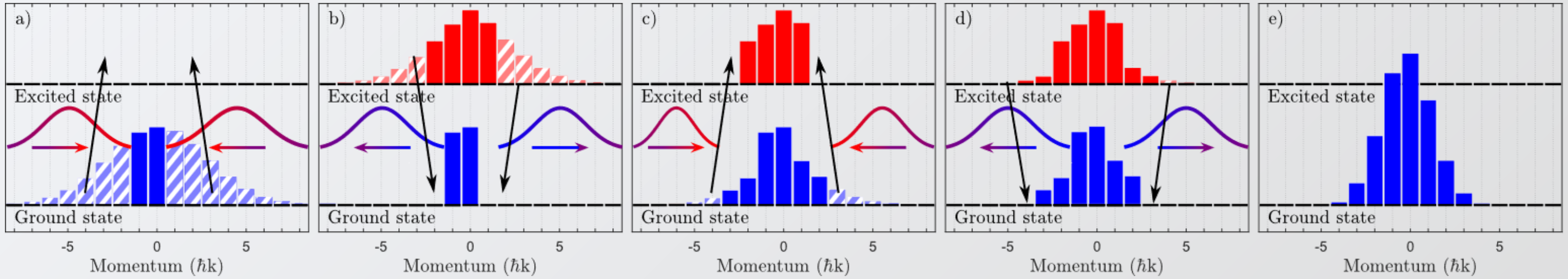
A Monge Kantorovich problem

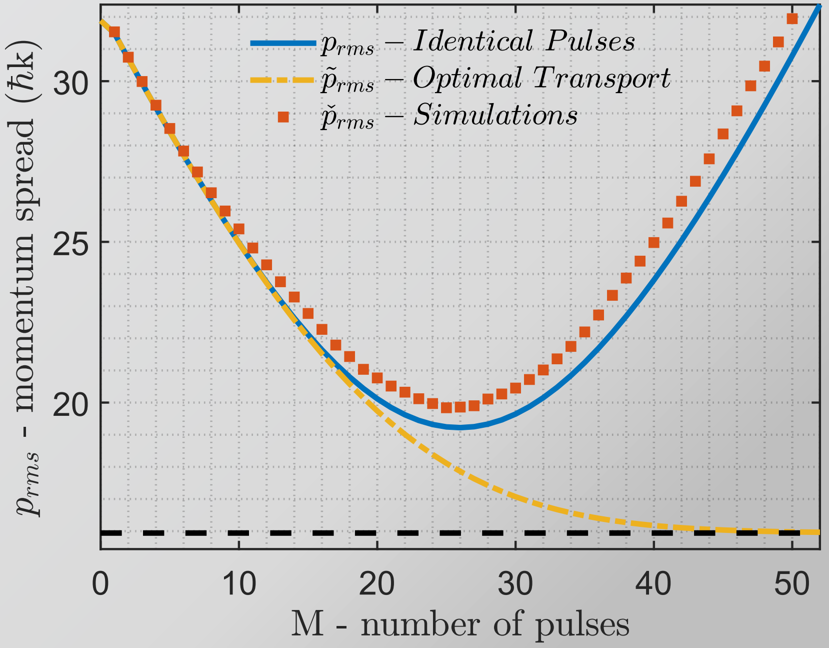
1. For a 2-level system, σ of a Maxwell Boltzmann distribution can at best be halved in the absence of SE.

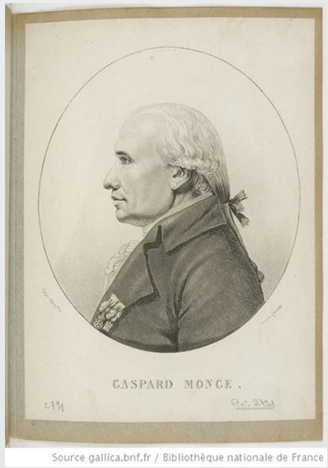
Chanelière et al. PRA 98, 063432 (2018).

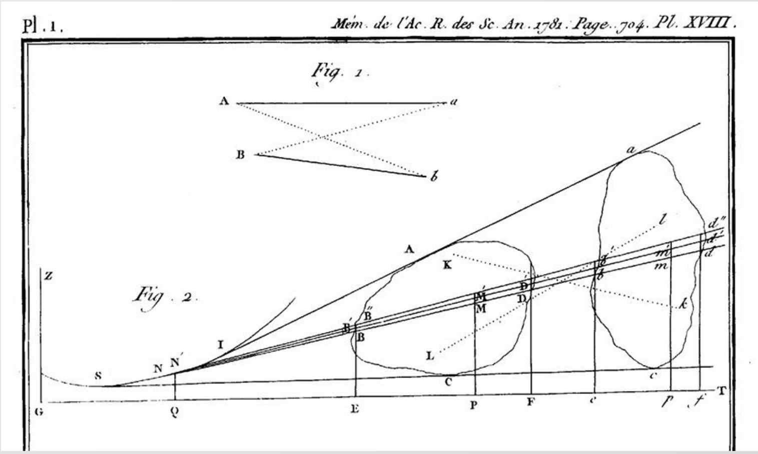
2. Optimal transport scheme

Malamant et al. PRA 110, 013109 (2024).



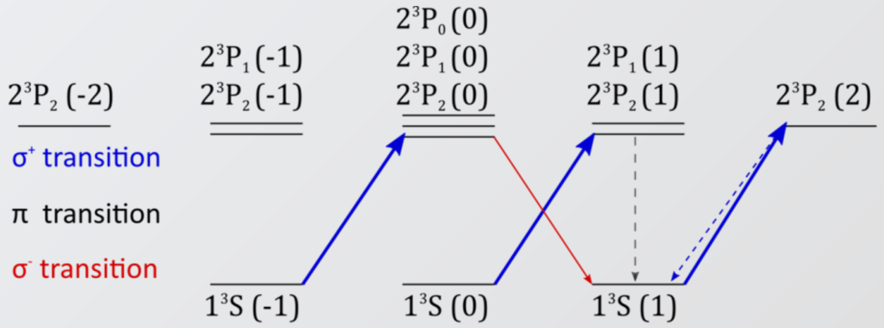




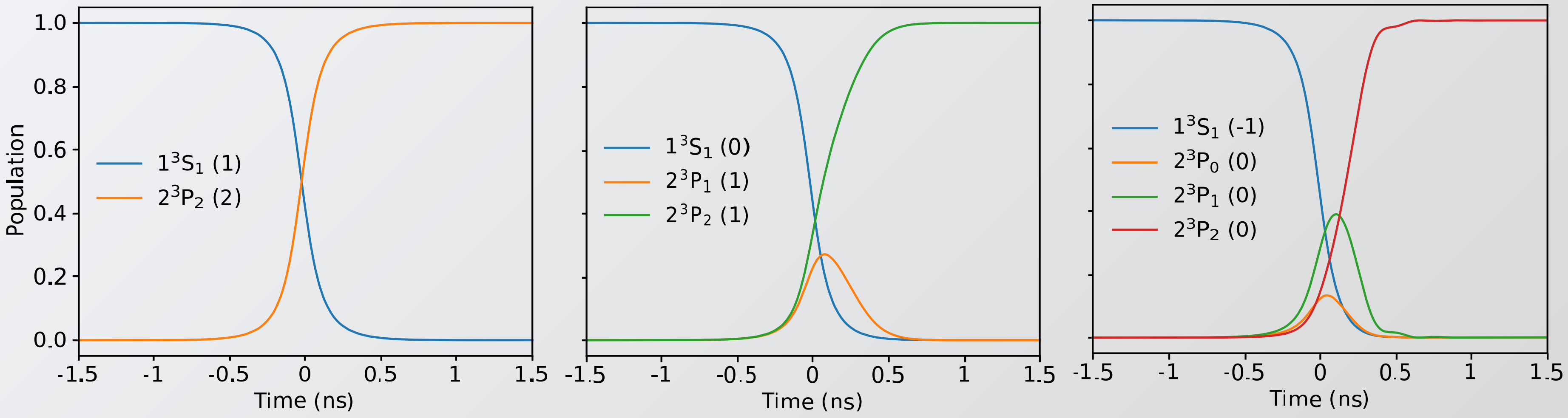


Turning Ps into a 2-level system

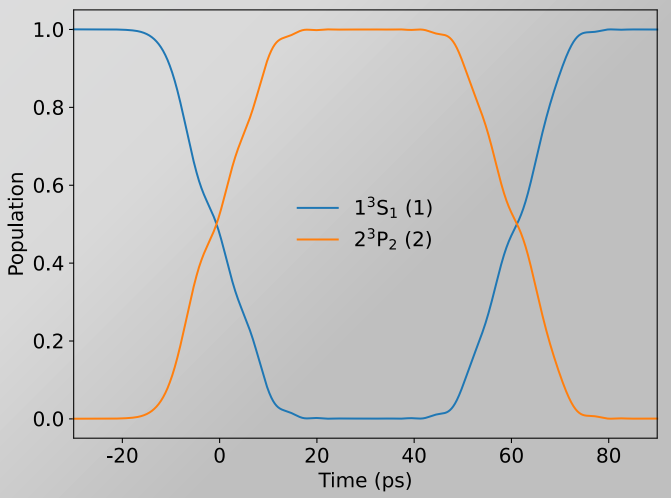
1. Ps is produced in 3 ground states



2. Coherent population transfer speed limited by energy splitting energy in the excited state



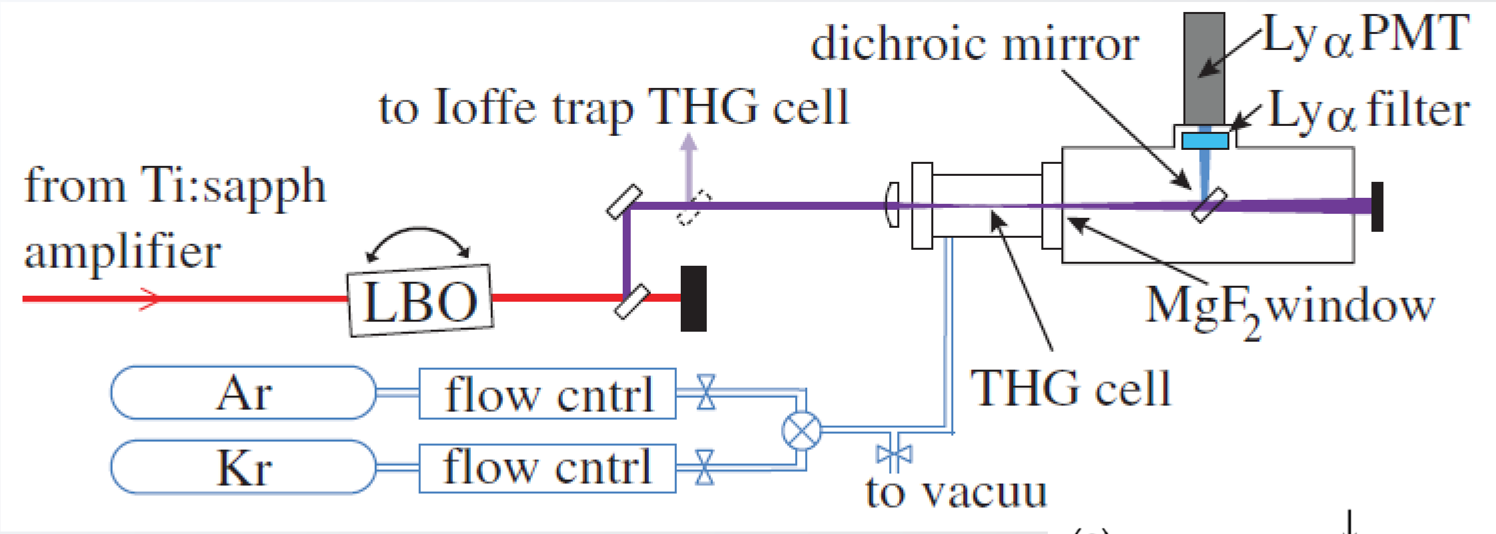
3. Two-level ultrafast transfer



J. S. Melinger et al. Phys. Rev. Lett. 68, 13 (1992)

A. Camper et al. (AEgIS collaboration) "Positronium Doppler laser cooling : results and perspectives" *POS* **480** (2025) [10.22323/1.480.0047](10.22323/1.480.0047)

Reaching Ly-α for hydrogen / muonium?

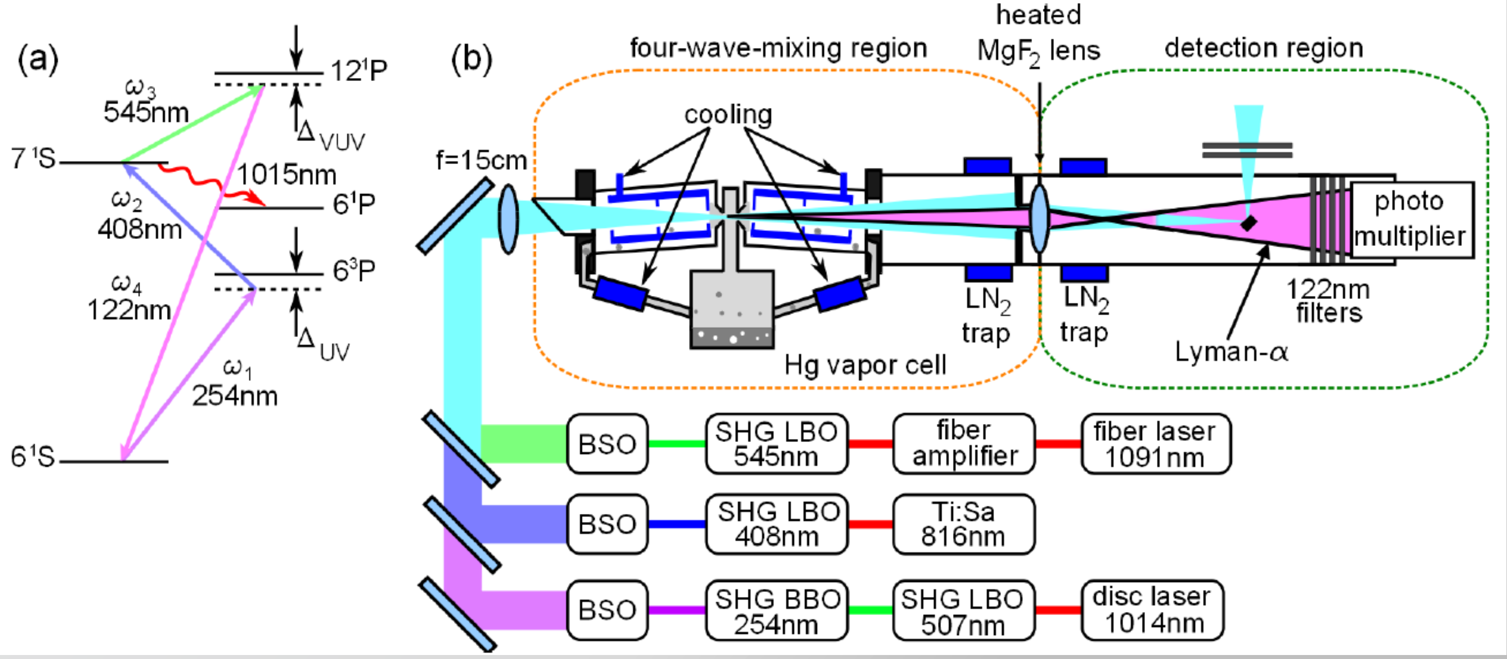


P. Bakule et al. *App. Phys. B* **71**, 11-17 (2000)
Alexandrite laser for muonium 1S-2S spectroscopy

K. Eikema et al. *Phys. Rev. Lett.* **83**, 19 (1999).
D. Kolbe et al. *Hyp. Int.* **212**, 213-220 (2012).

L. Cabaret, et al. *Opt. Comm.* **61**, 2 (1987).
G. Gabrielse et al. *Opt. Lett.* **43**, 12 (2018).

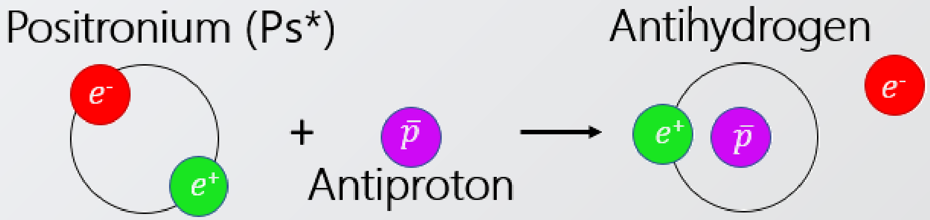
Compared to positronium:
- 121 nm instead of 243
- narrower Doppler profile
- longer pulses (2.2 µs vs 243 nm)
- Need to scatter way more photons (the recoil per photon is much smaller)

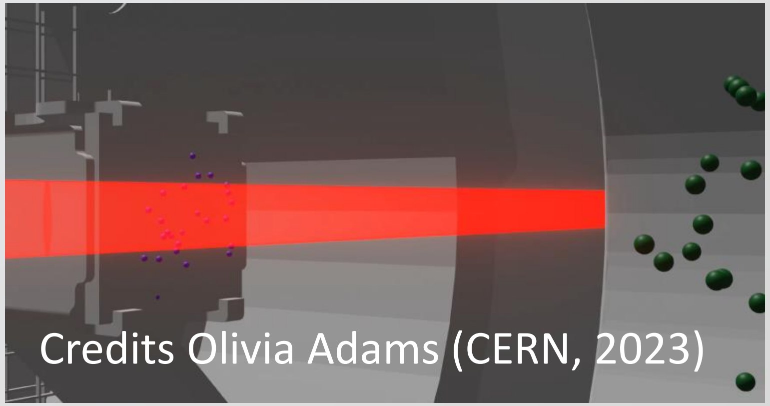


Perspectives

1. Pulsed production of antihydrogen by charge exchange

Amsler et al. (AEgIS)
Comm Phys 4:19 (2021)





2. Ps high precision spectroscopy

Fee et al. Phys. Rev. Lett. 70, 10 (1993)

$1S$-$2S$ transition frequency	$616\,803\,608.2 \pm 1.6$ MHz
$1S$-$2S$ interval	$1\,233\,607\,216.4 \pm 3.2$

TABLE I. Summary of uncertainties and results.

Te_2 reference line	$616\,803\,544.4 \pm 0.6$ MHz
AOM offset	55.0 ± 0.0
Model fit to line center	10.0 ± 1.5

3. Ps Bose-Einstein condensation

Platzman and Mills Phys. Rev. B 49, 1 (1994)

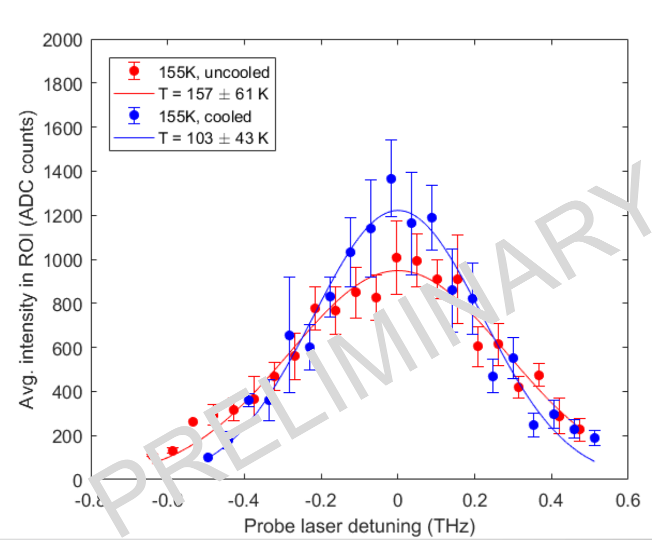
$$n\lambda_D^3 = 2.65\ , \tag{1}$$

where the de Broglie wavelength is given by

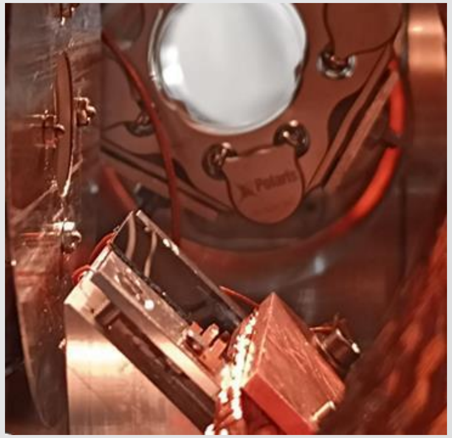
$$\frac{\lambda_D}{2\pi} \equiv k_D^{-1} = (2mT)^{-1/2}\ . \tag{2}$$

Conclusion

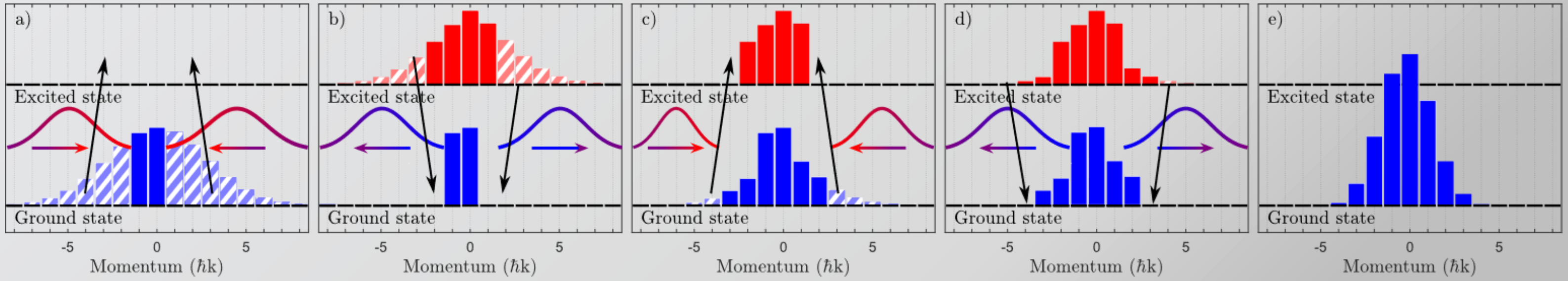
- Traditional Doppler cooling of Ps works well at the momentum transfer speed limit and with lifetime extension.



- Use of cryogenic target cooler.



- Benefits of short pulses for positronium physics
- Polarization
- Cooling
- Deceleration



Thanks for your attention!