Development of nanoporous materials to form dense and cold positronium for Bose-Einstein condensation

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Ps-BEC

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https://tabletop.icepp.s.u-tokyo.ac.jp/psbec_en/

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Acknowledgement

創発的研究支援事業
Fusion Oriented REsearch for disruptive Science and Technology

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- JSPS KAKENHI Grant Numbers JP16H04526, JP17H02820, JP17H06205, JP17J03691, JP18H03855, JP19H01923, JP23H05462,
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https://tabletop.icepp.s.u-tokyo.ac.jp/psbec_en/

Contents

- Motivations for positronium Bose-Einstein Condensation (Ps-BEC)
- Overview of the current status of our Ps-BEC project:
  - A) High-density Ps formation
    1. Positron focusing
    2. Ps formation material
  - B) Rapid Ps cooling
    3. Thermalization
    4. Laser cooling

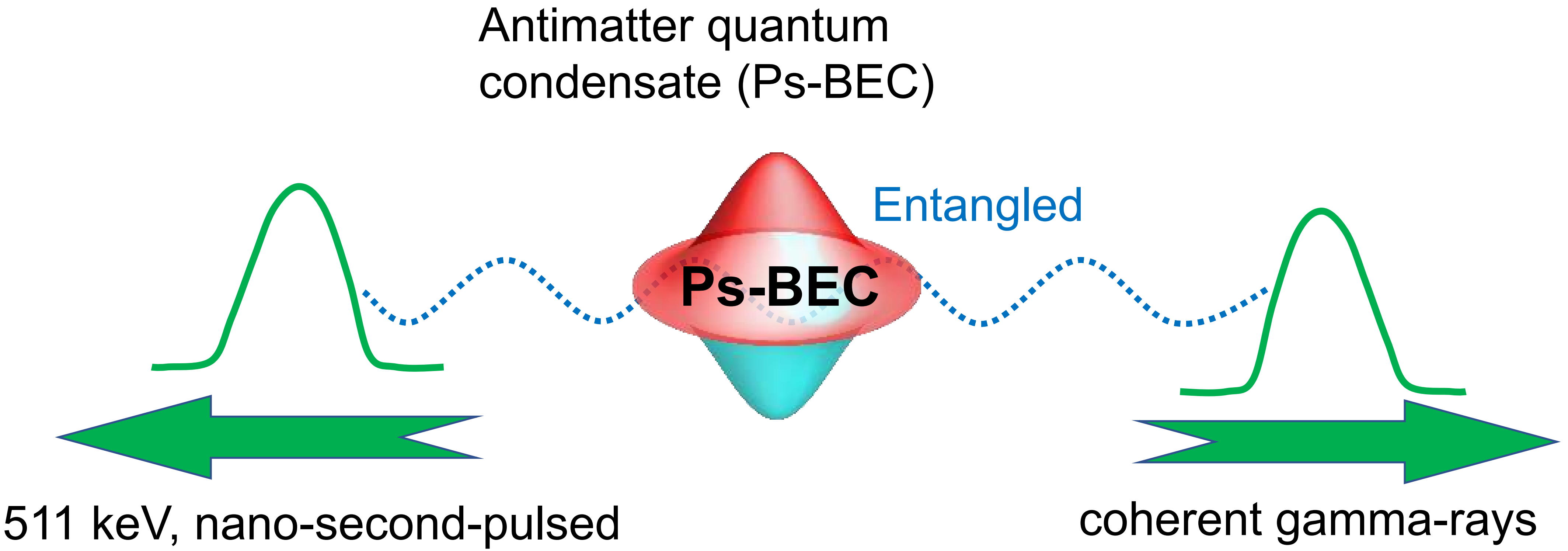
Goals:

10^{18} cm^{-3}

10 K

in ~100 ns

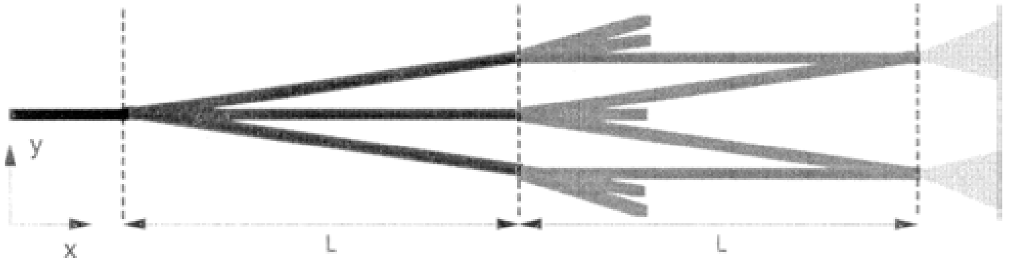
We want to realize an **antimatter quantum condensate** = positronium Bose-Einstein condensate (Ps-BEC). **Gamma-ray lasers** may be realized using Ps-BEC as a source.



Ps-BEC for antimatter gravity measurements

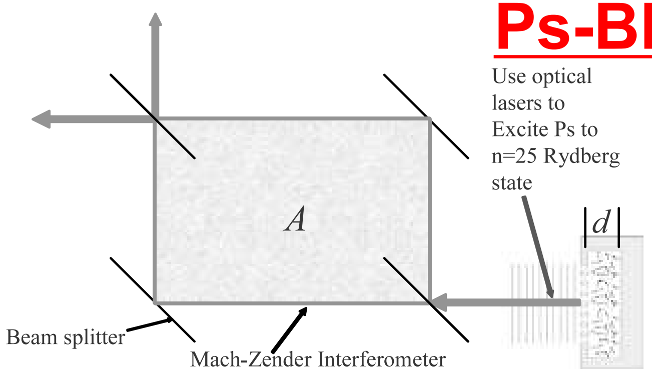
Interferometry

coherence will be increased by cooling Ps

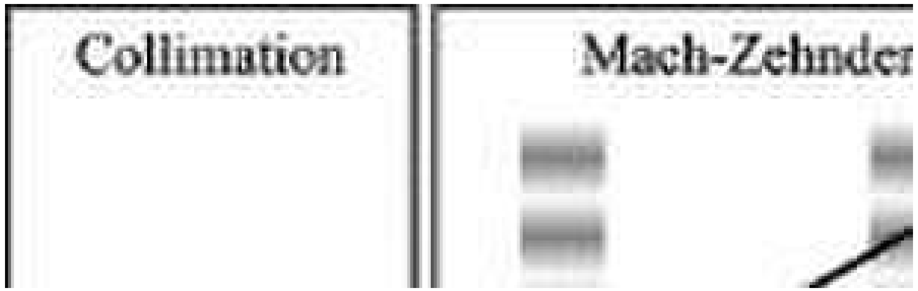


T. J. Phillips, Hyperfine Interactions **109**, 357 (1997).

Ps-BEC

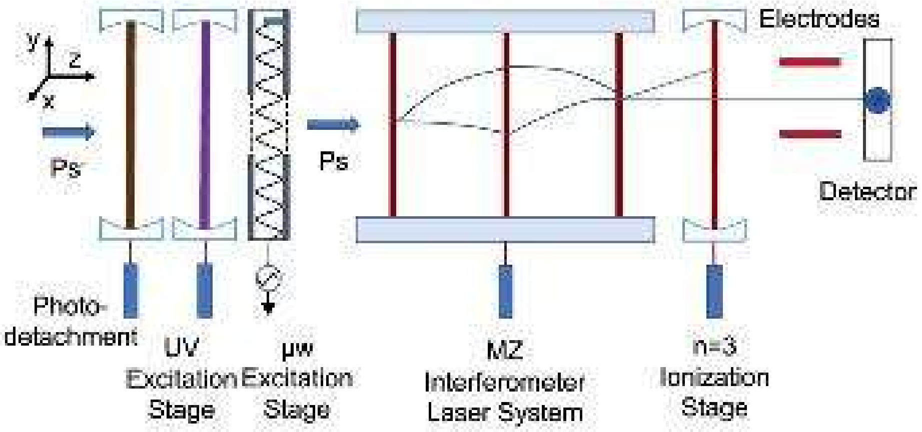


D. B. Cassidy and A. P. Mills, Jr., phys. stat. sol. (c) **4**, 3419 (2007).



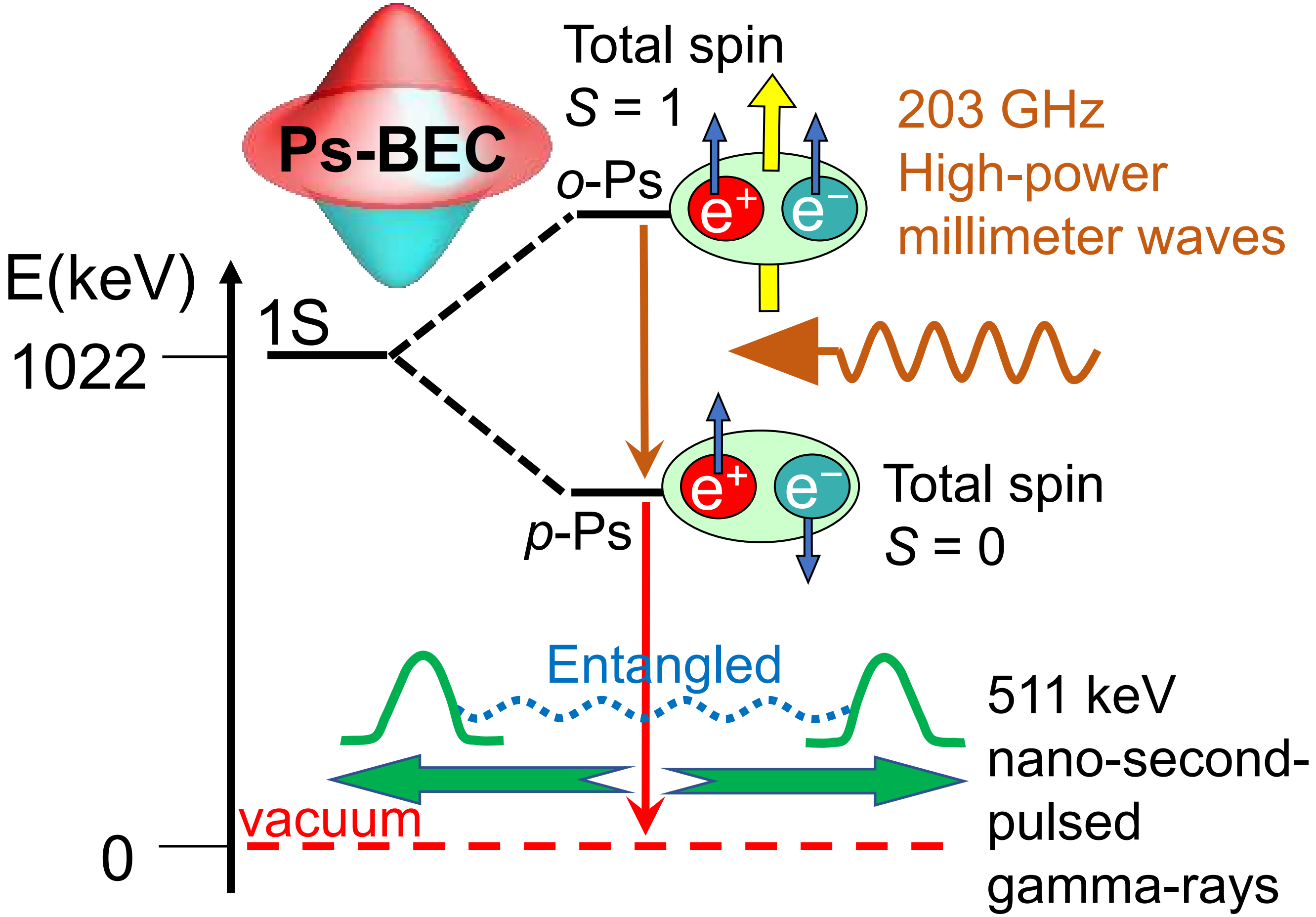
M.K. Oberthaler / Nucl. Instr. and Meth. in Phys. Res. B **192** (2002) 129–134

Utilizing Ps^{-}



G Vinelli *et al* 2023 *Class. Quantum Grav.* **40** 205024

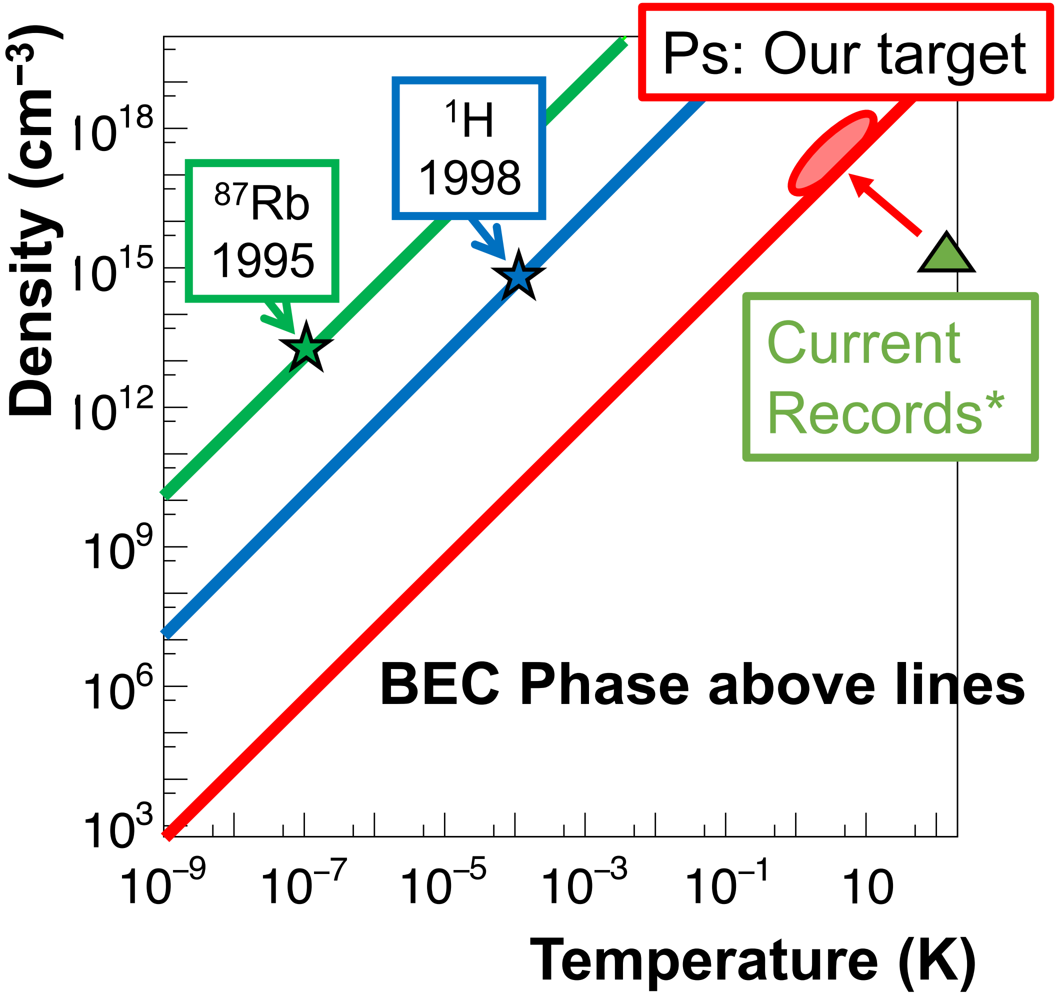
Self-annihilations of Ps-BEC can generate 2 coherent and entangled gamma-rays: Realization of **gamma-ray lasers**



H. K. Avetissian *et al.*, Phys. Rev. A **92**, 023820 (2015).

Our Target:

Positronium Bose-Einstein condensate (Ps-BEC)



* : S. Mariazzi *et al.*, Phys. Rev. Lett. **104**, 243401 (2010)
* : D. Cassidy *et al.*, physica status solidi **4**, 3419 (2007)

- Ps must be dense and cold
- High critical temperature because of Ps light mass (14 K at 10^{18} cm^{-3})
- One of the best candidates for the first antimatter BEC
- BEC is "Atomic laser". We would like to make the first antimatter laser and perform new experiments using the coherency of Ps-BEC.

Two challenges to realize Ps-BEC

Main problem

Ps lifetime is only 142 ns

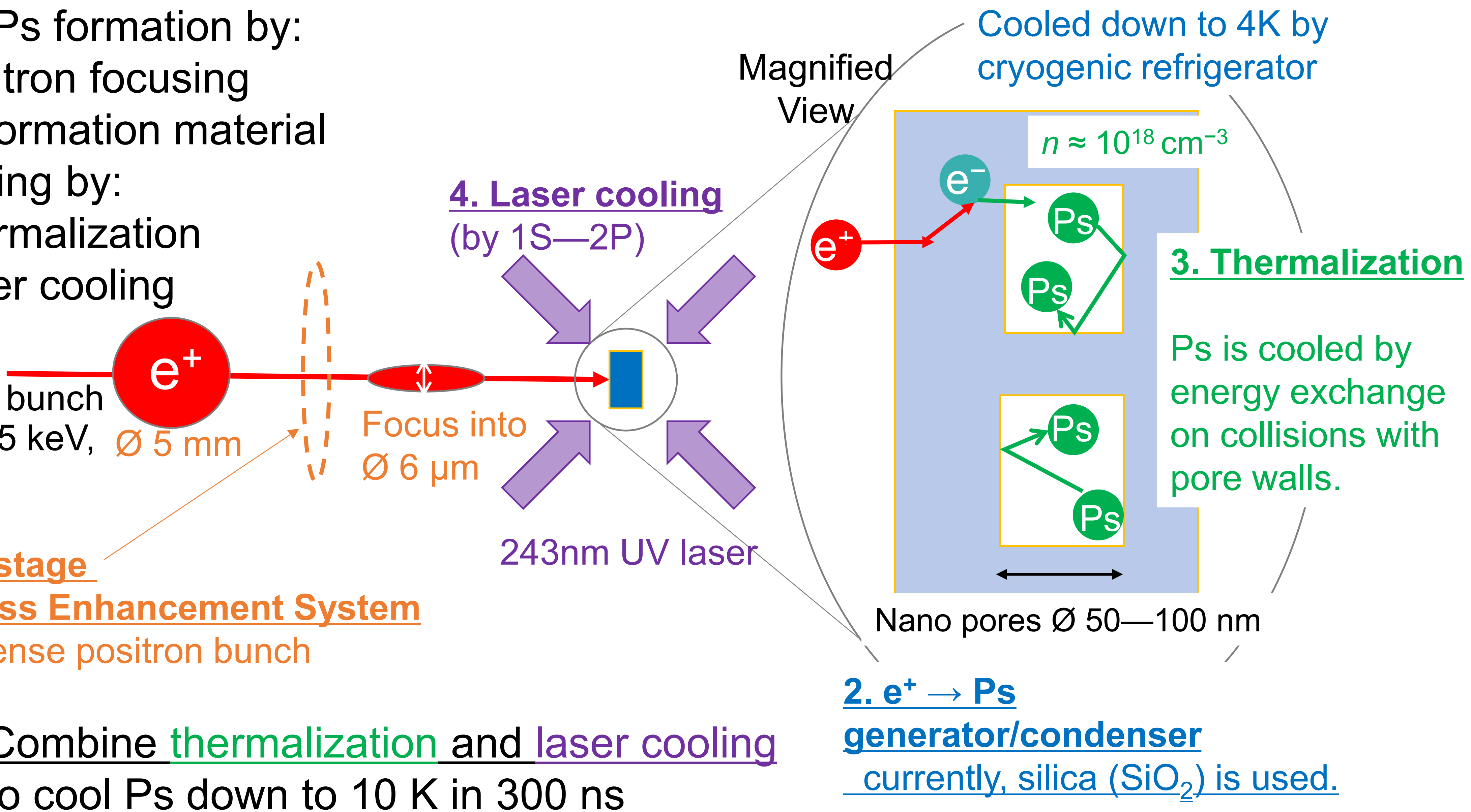
Two challenges

1. Instant creation of dense Ps
   $> 10^{18}$ cm^{-3} in < 50 ns
2. Rapid cooling of Ps
   < 10 K in ~300 ns

Our idea to realize Ps-BEC

A) Dense Ps formation by:
   1. Positron focusing
   2. Ps formation material

B) Ps cooling by:
   3. Thermalization
   4. Laser cooling

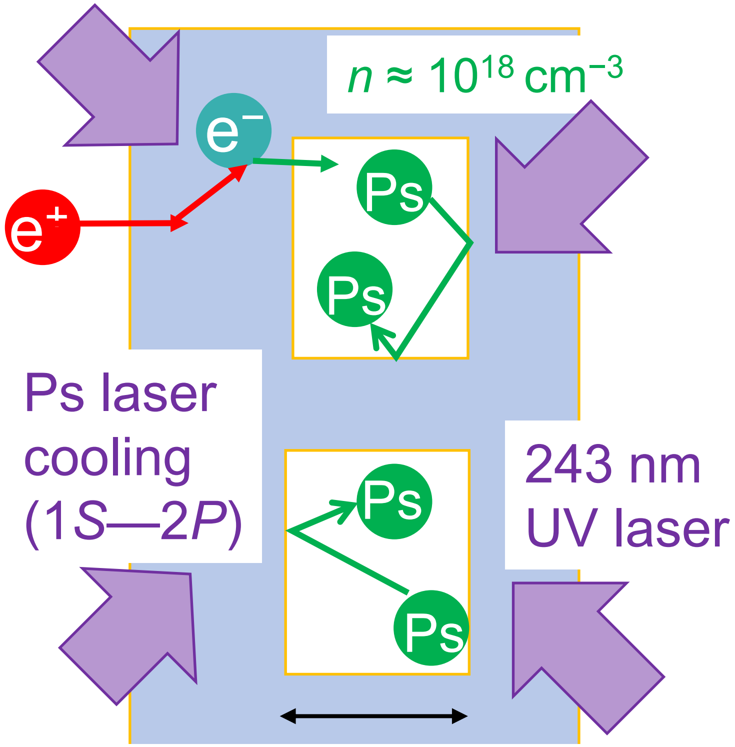


Combine thermalization and laser cooling
to cool Ps down to 10 K in 300 ns

K. Shu *et al.* J. Phys. B 49, 104001 (2016)

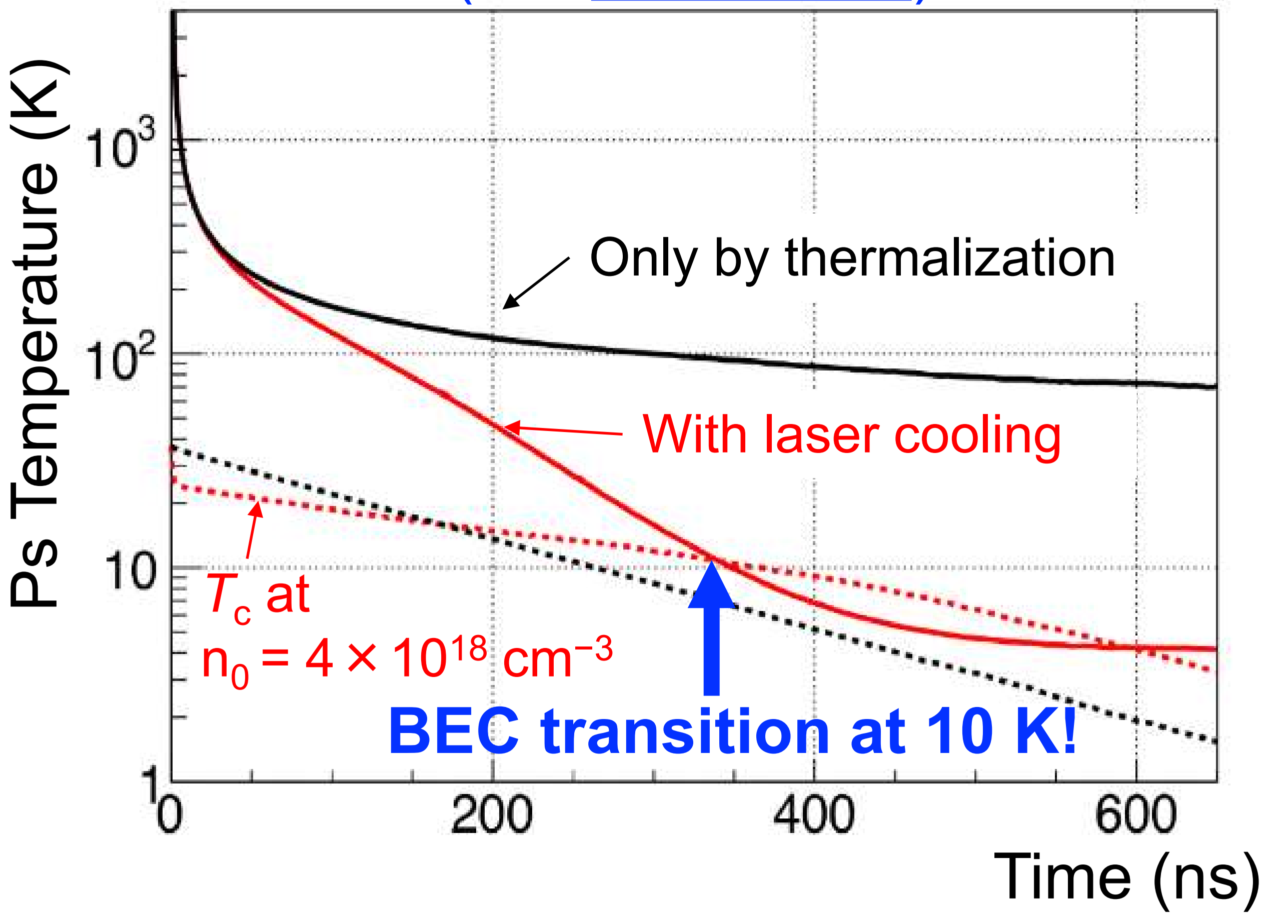
Combination of Thermalization and Laser cooling is suitable for fast Ps cooling to realize Ps-BEC.

1. Ps formation
2. Thermalization (nanopores)
3. Laser cooling (UV-transparent)



Nano pores Ø 50—100 nm

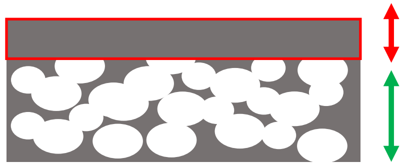
Ps temperature evolution (MC ***simulation***)

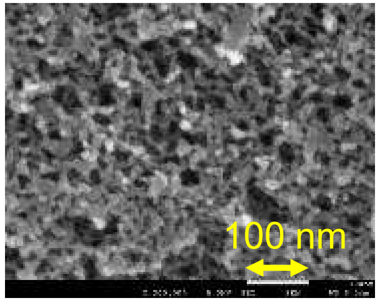


K. Shu *et al.*, J. Phys. B **49**, 104001 (2016), A. Ishida *et al.*, JJAP Conf. Proc. **7**, 011001 (2018).

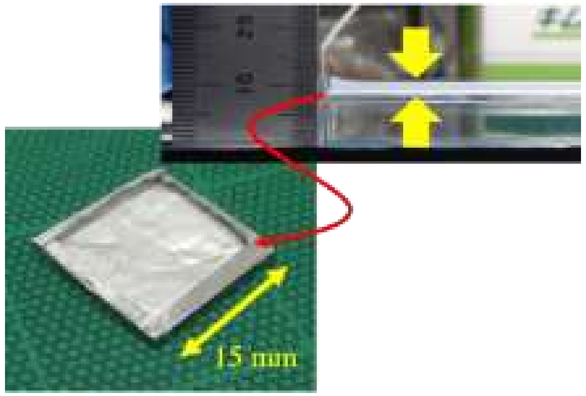
Silica (SiO_2) aerogel was a good candidate for Ps formation and cooling material. The surface of the aerogel capped with an amorphous silica thin film by plasma-enhanced chemical vapor deposition (CVD).

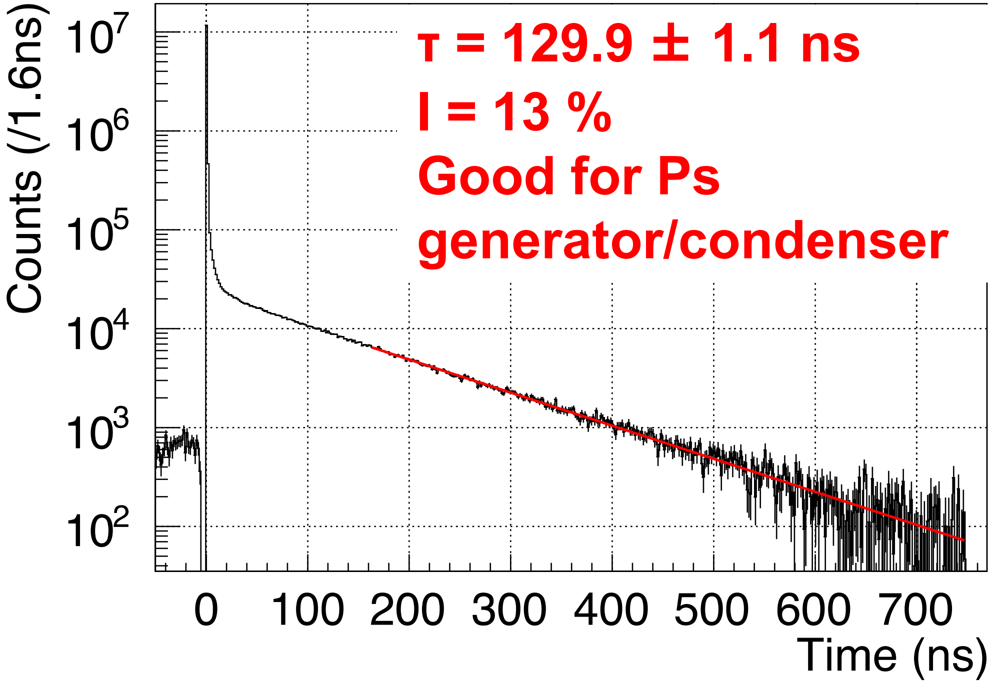
Silica aerogel 0.12 g cm^{-3}
45 nm pores



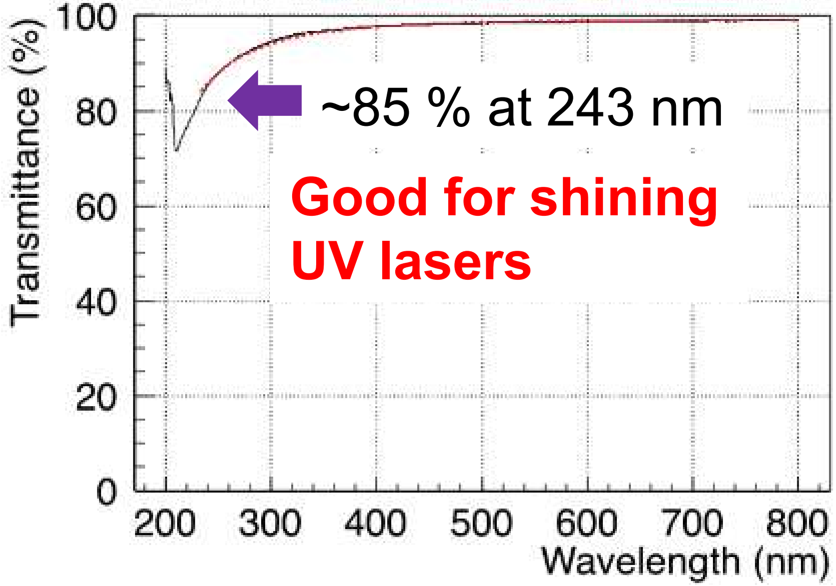


×200,000



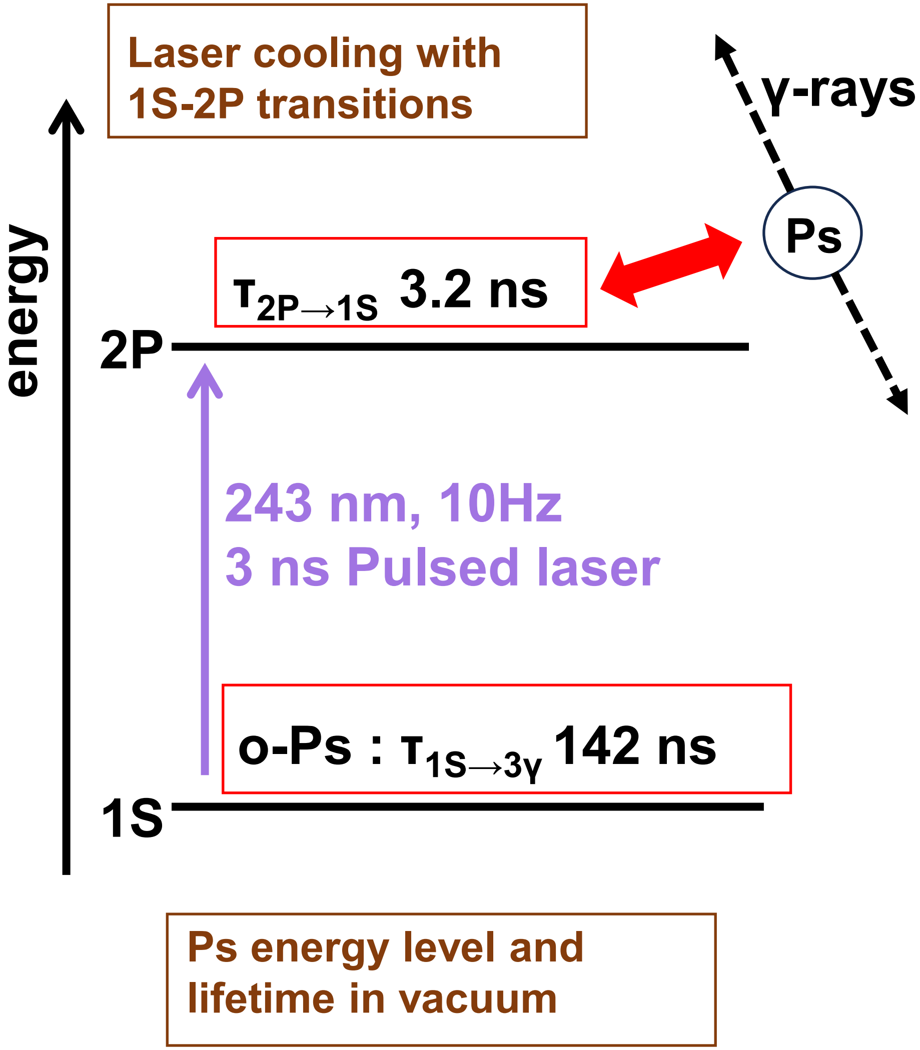


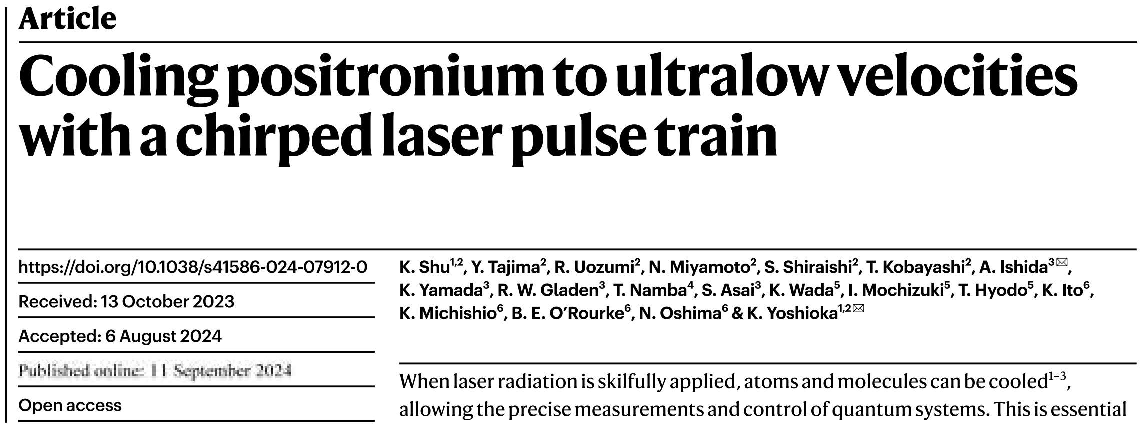
Timing spectrum of bulk-PALS measurement using ^{22}Na with t = 1 mm silica aerogel



Parallel light transmittance measured by spectrophotometer with t0.5 mm silica aerogel

Ps Laser Cooling and Its Challenges




Article

Cooling positronium to ultralow velocities with a chirped laser pulse train

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When laser radiation is skilfully applied, atoms and molecules can be cooled[1–3], allowing the precise measurements and control of quantum systems. This is essential

Ps is laser cooled by irradiating a 243 nm UV laser corresponding to the transition between 1S-2P and repeating excitation and de-excitation between 1S-2P.

We have succeeded in Ps laser cooling in vacuum.
(Nature **633**, 793–797 (2024))

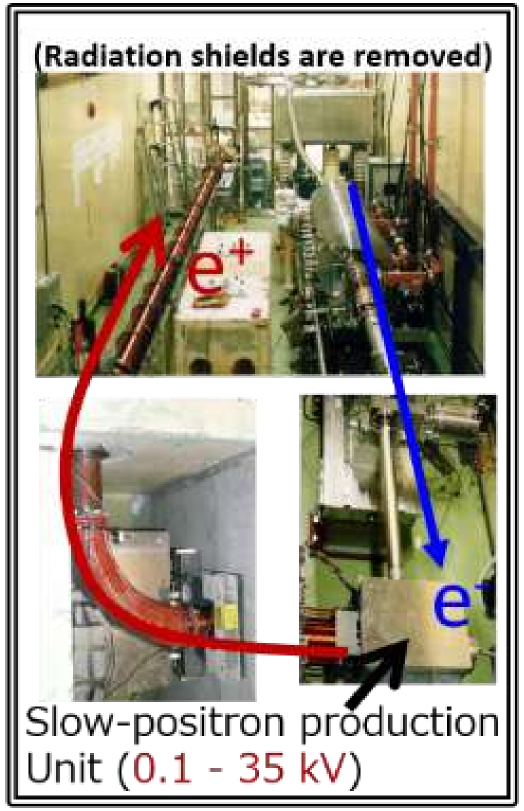
Achieved 1 K in vacuum (1D cooling)!

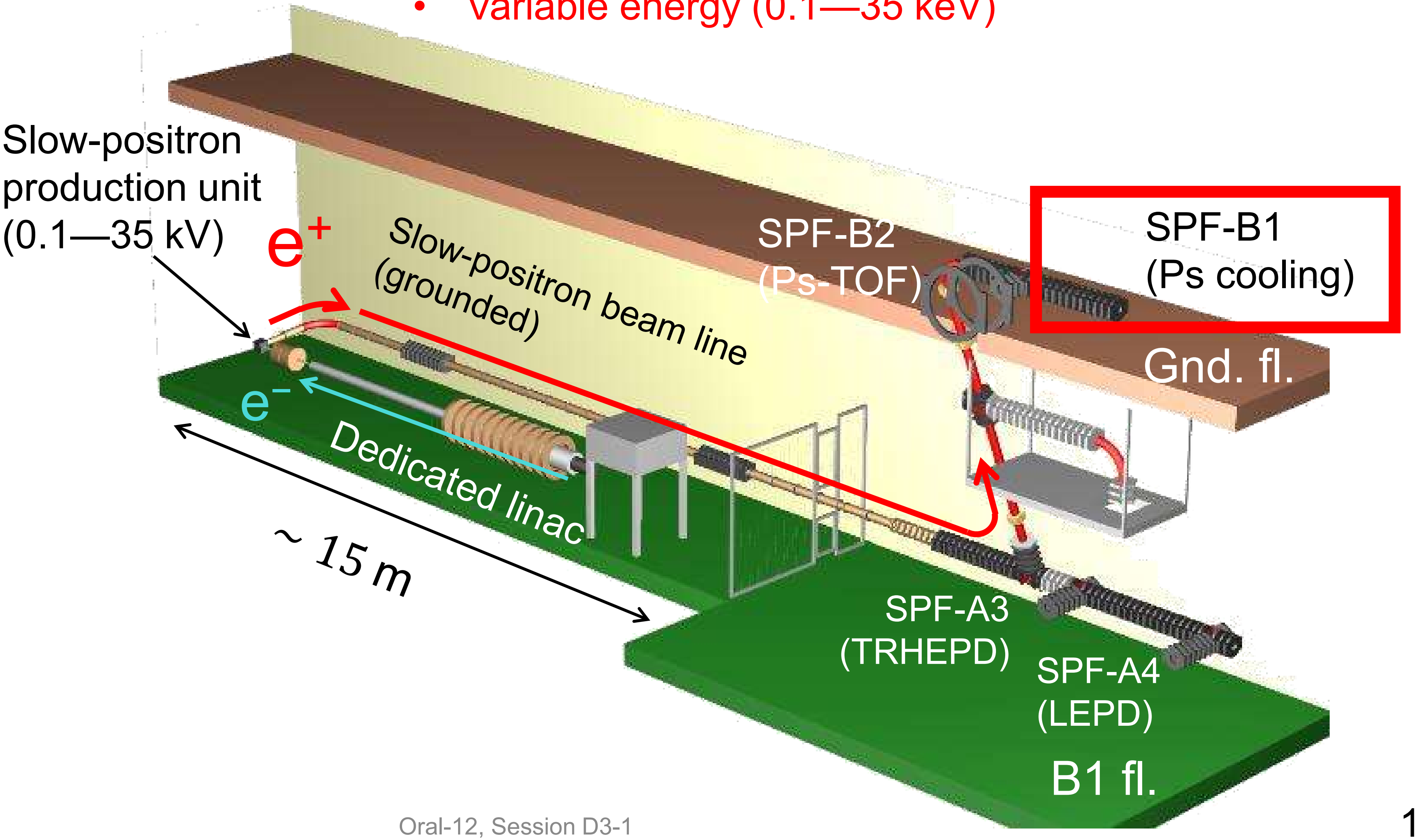
↕

In silica aerogel, when Ps is excited 1S→2P with lasers, it immediately annihilates into γ-rays (in a time well shorter than 2P→1S's spontaneous deexcitation life of 3.2 ns).
The mechanism is not yet clear.

We performed a test experiment at KEK IMSS Slow Positron Facility (SPF), Tsukuba, Japan.

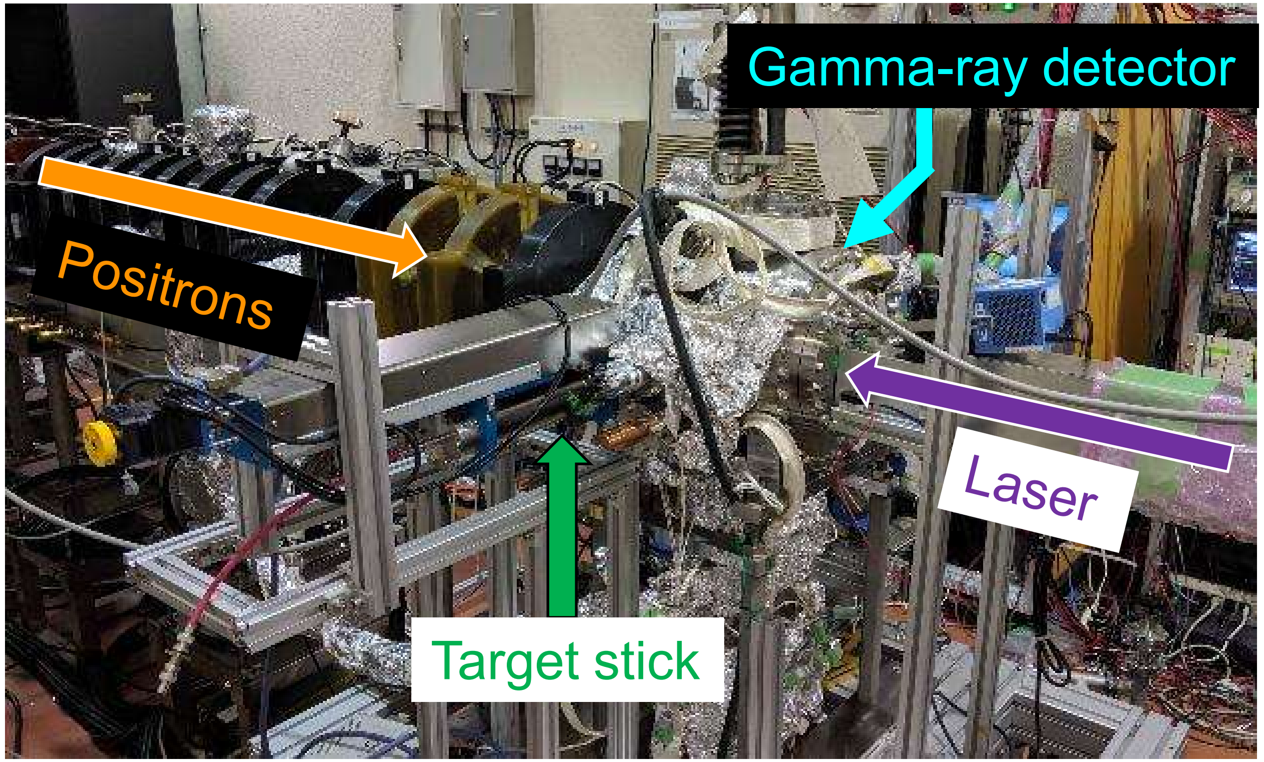
- Highest intensity (5×10^7 slow e^+ s^{-1})
- Variable energy (0.1—35 keV)



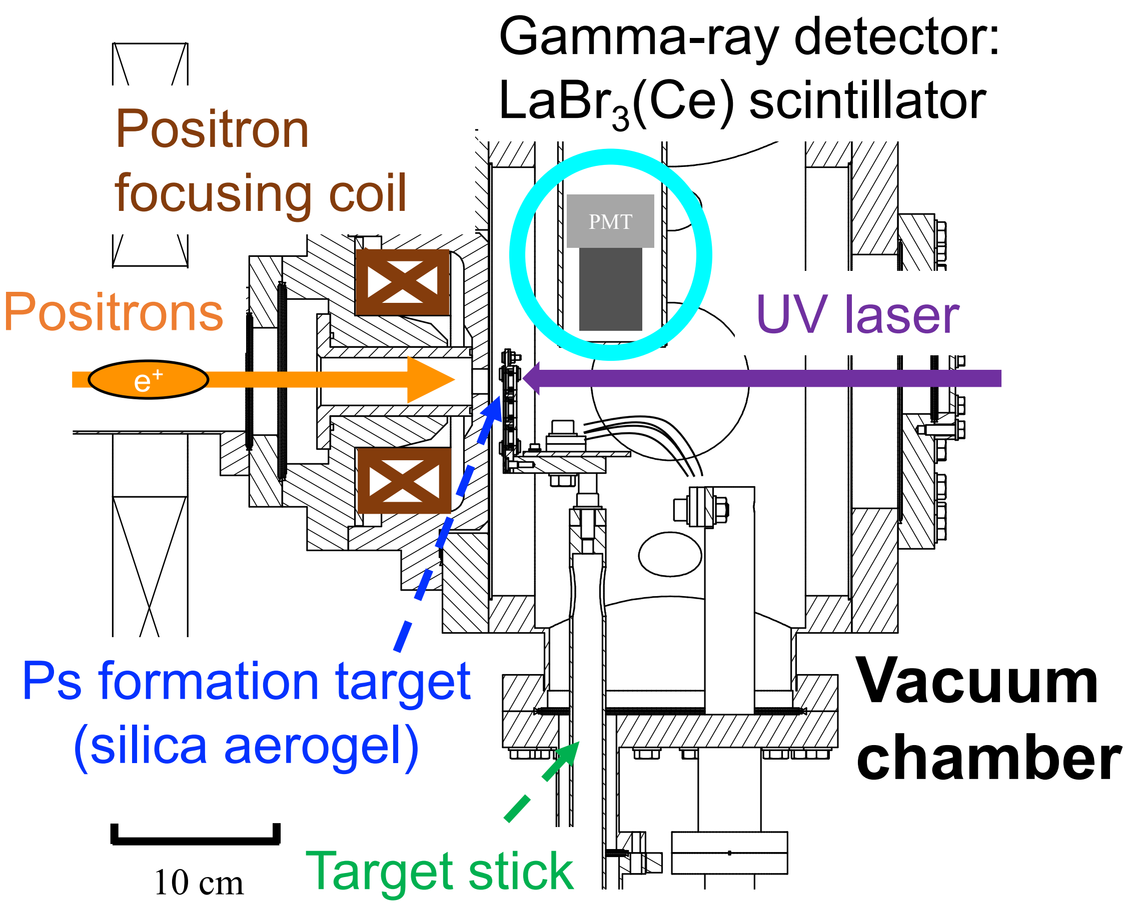


Experimental setup at KEK-SPF

KEK-SPF B1 beamline



Energy	5 keV
Intensity	～10^4 e^+/ pulse
Repetition	50 Hz
Pulse width	16 ns
Size	Ø～10 mm



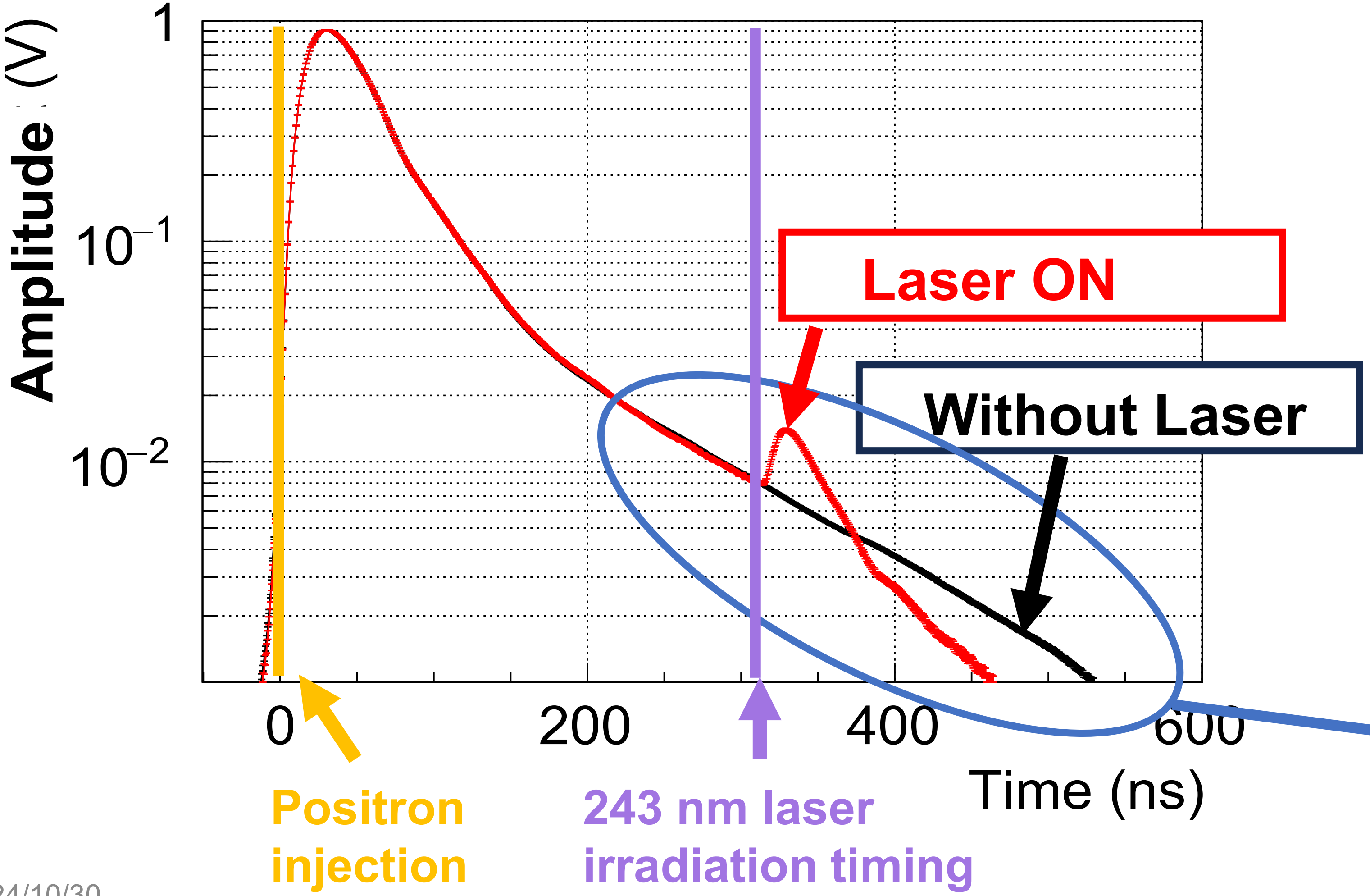
Positrons were focused to 3 mm so that it matched the laser size.

K. Shu, Ph.D. thesis (UTokyo, 2020).

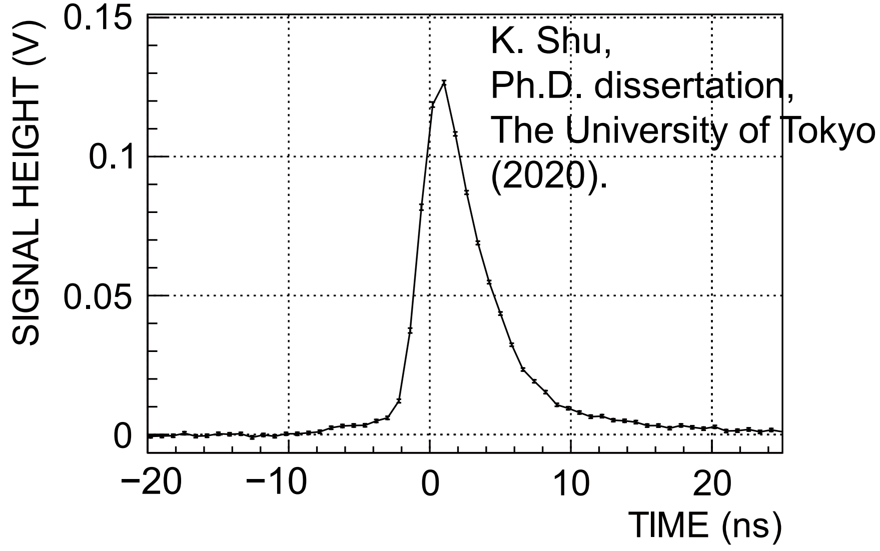
Ps annihilation was observed after laser irradiation

Comparison of the average waveform of the signal detected by the scintillator with and without a 243 nm laser after about 300 ns of positron beam injection on silica aerogel

Average waveforms of the scintillator signals



Time profile of the UV laser.
Laser pulse width: 2 ns–5 ns (including a rise time of a digitizer)

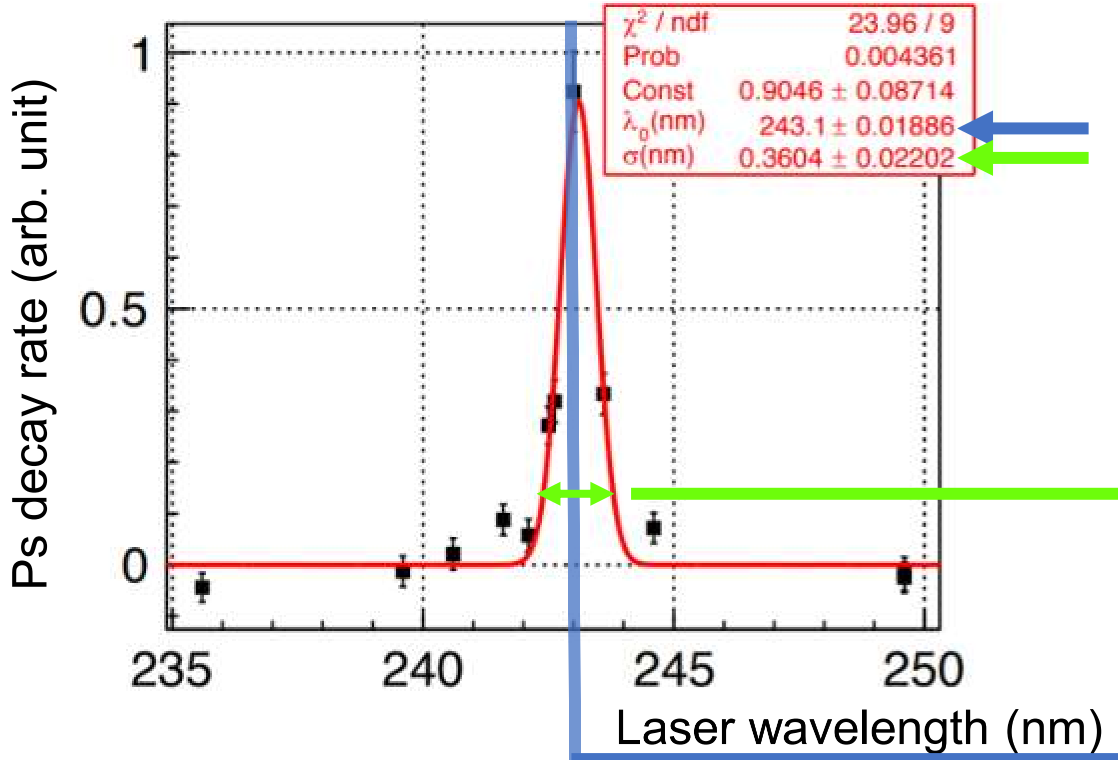


Ps decayed into γ-rays due to laser irradiation.

Decay occurs only at around the wavelength of 243 nm
Immediately after 1S-2P transition; 2P-Ps decays.

Laser wavelength dependence of the Ps decay rate

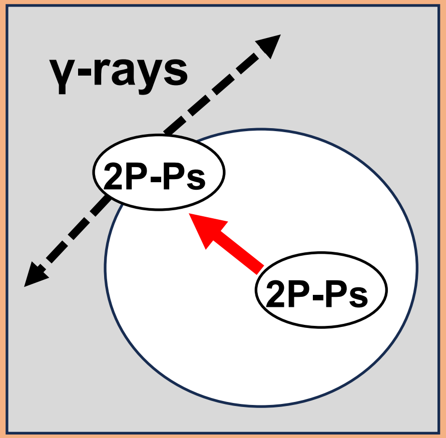
■ Data —— Lorentzian Fit



2P-Ps lifetime calculated from the width ~ 100 fs

To the same extent?

Mean free time of Ps collisions with silica aerogel walls inside pores ~100 fs



2P-Ps annihilates when it collides with a pore wall in silica aerogel?

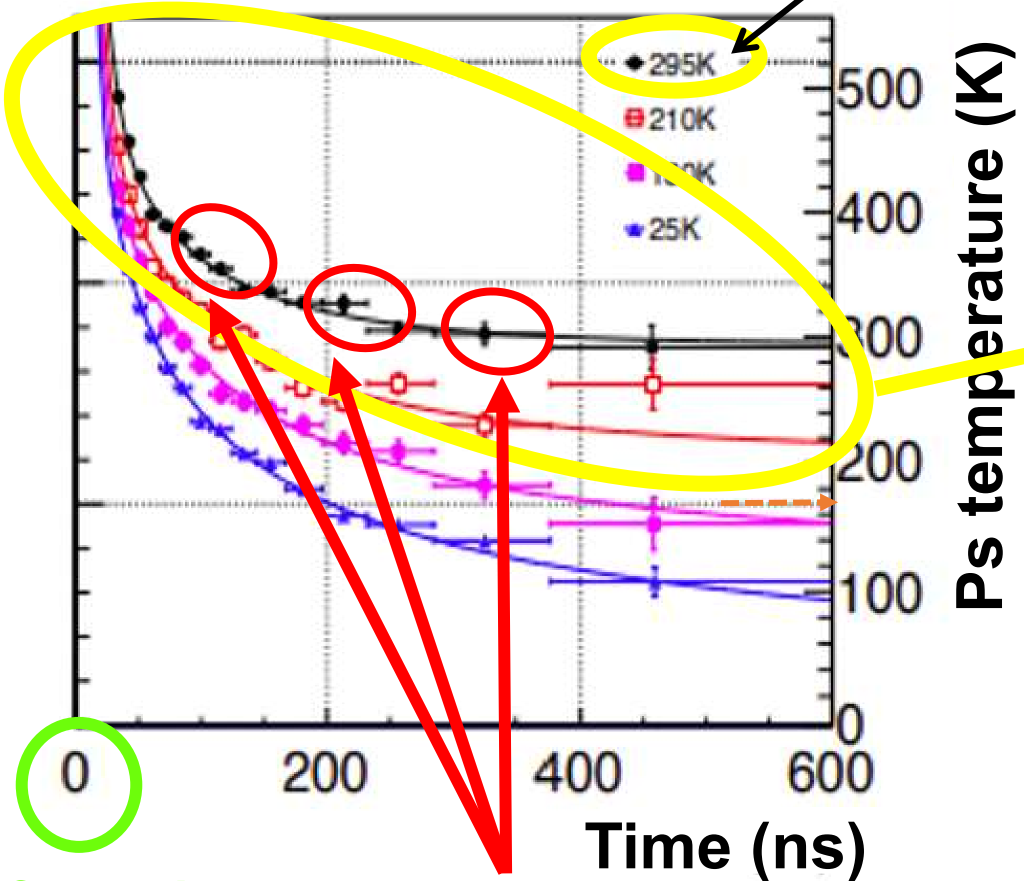
Does 2P-Ps decay rate depend on Ps temperature?

Ps decay rate is maximum at 243 nm, which corresponds to the 1S-2P transition energy of Ps

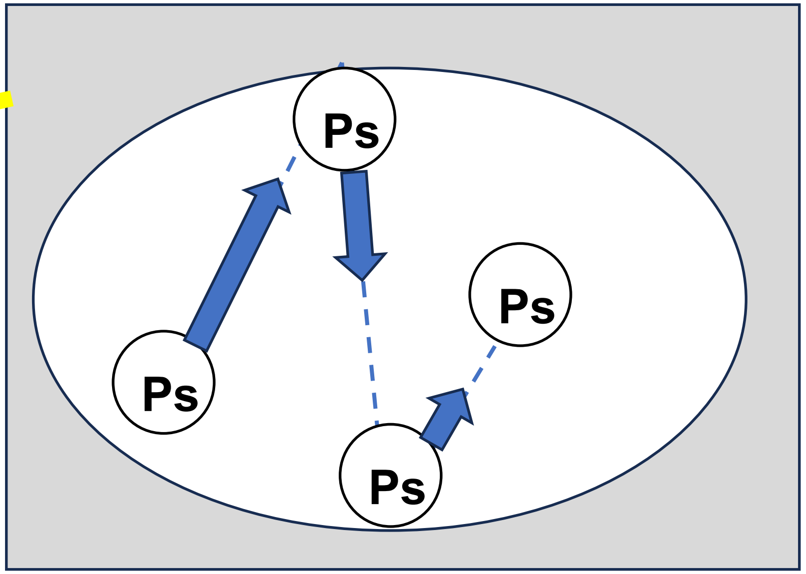
Ps in silica aerogel is cooled by thermalization

K. Shu, A. Ishida, T. Namba, K. Ito *et al.*:
Phys. Rev. A, **104** (2021) L050801.

Temperature of
the silica aerogel



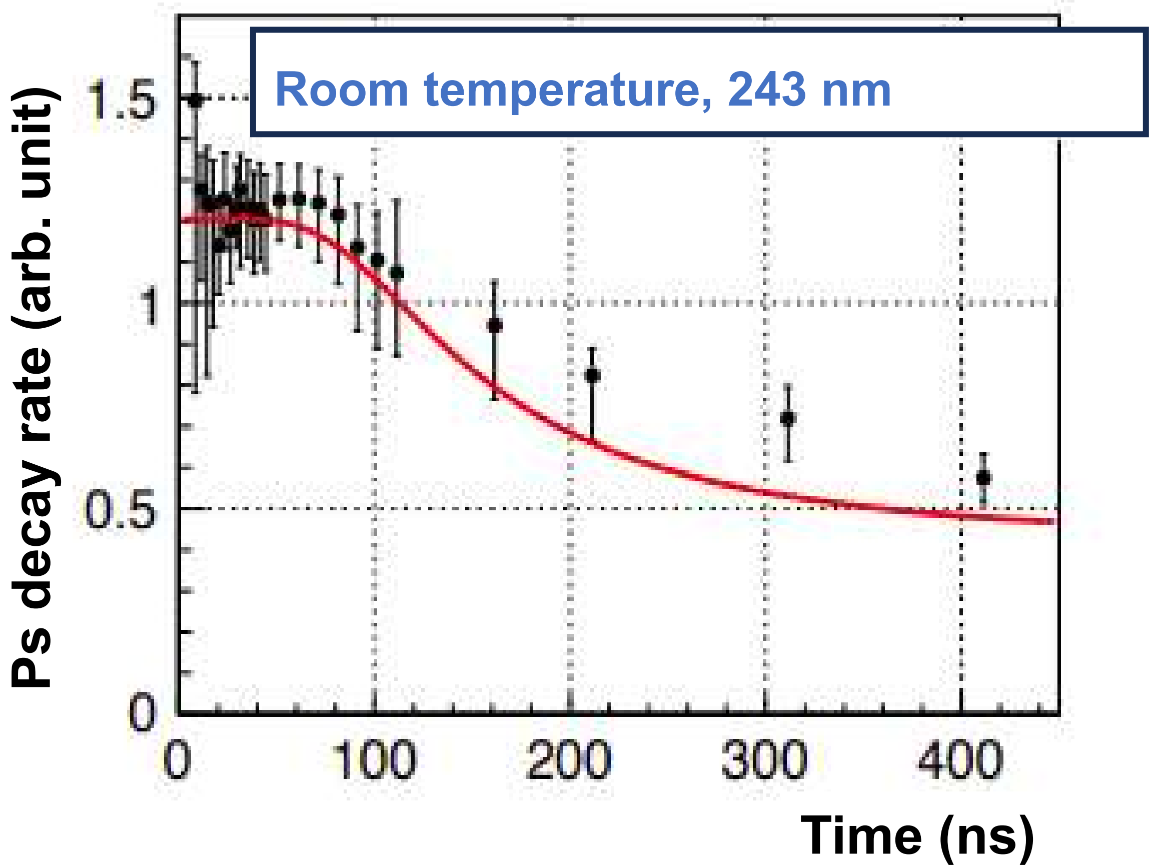
Ps formation

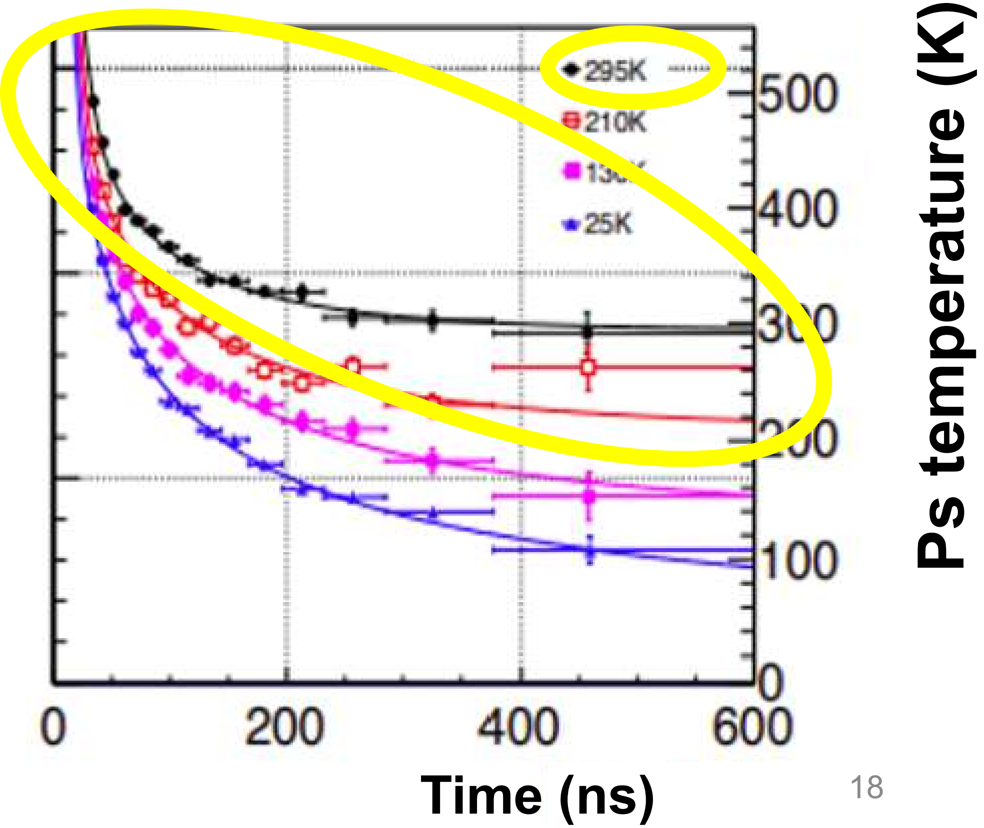


With laser irradiation at different timings,
does the 2P-Ps decay rate change?

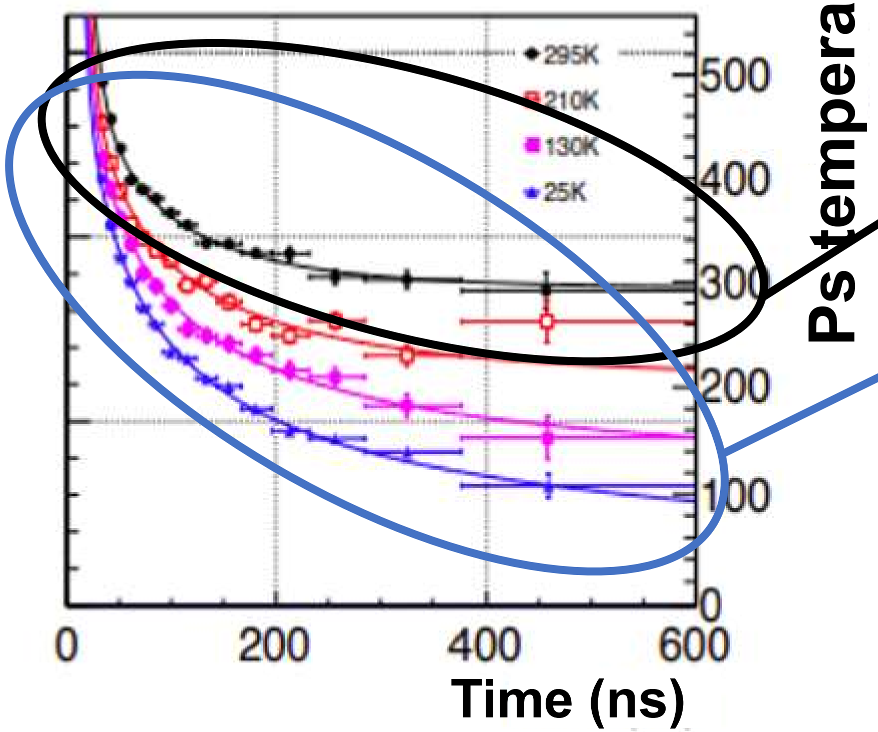
The later the irradiation timing, the lower the 2P-Ps decay rate.

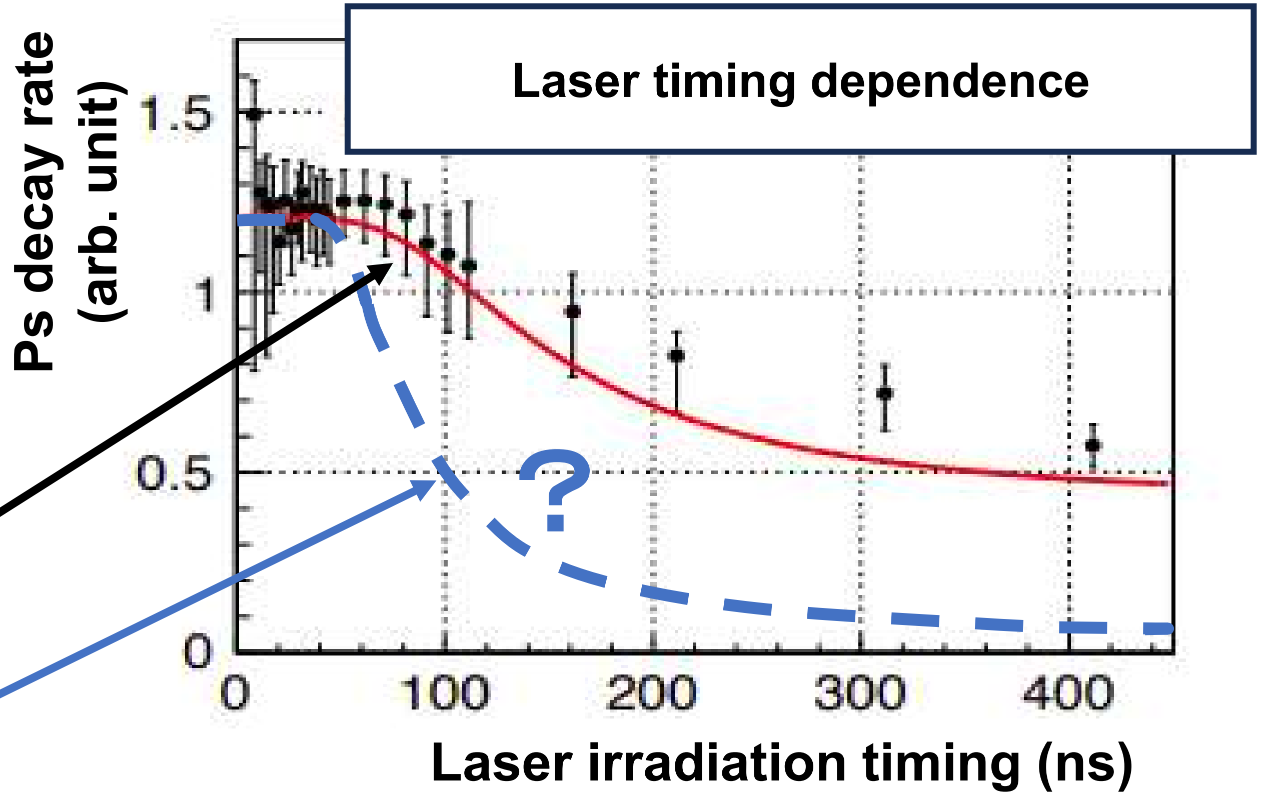
2P-Ps decay rate decreases by Ps thermalization cooling?





We are currently testing with cold silica aerogel.

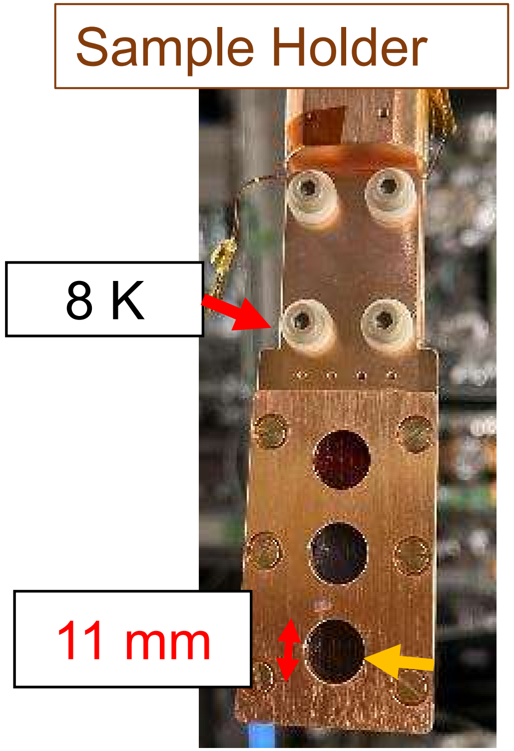


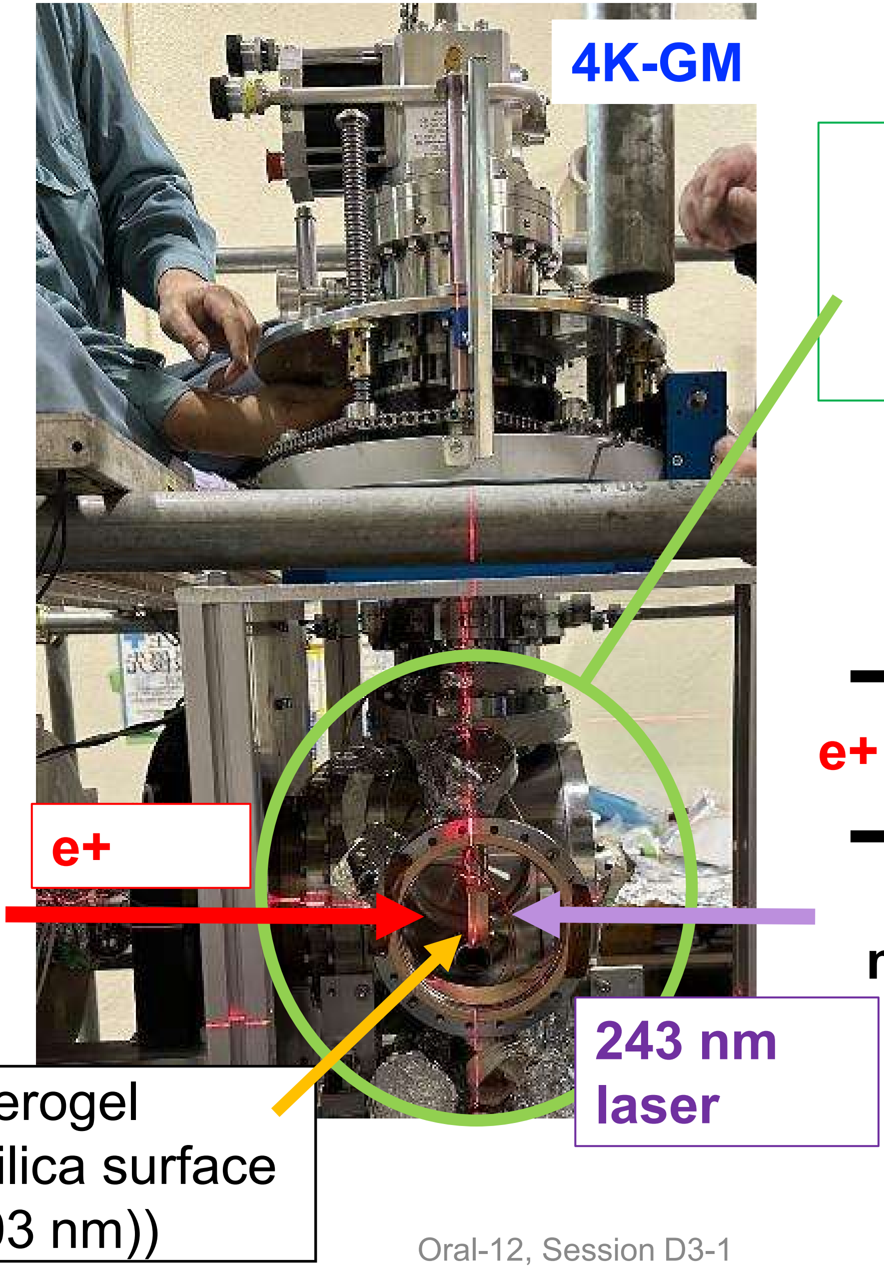


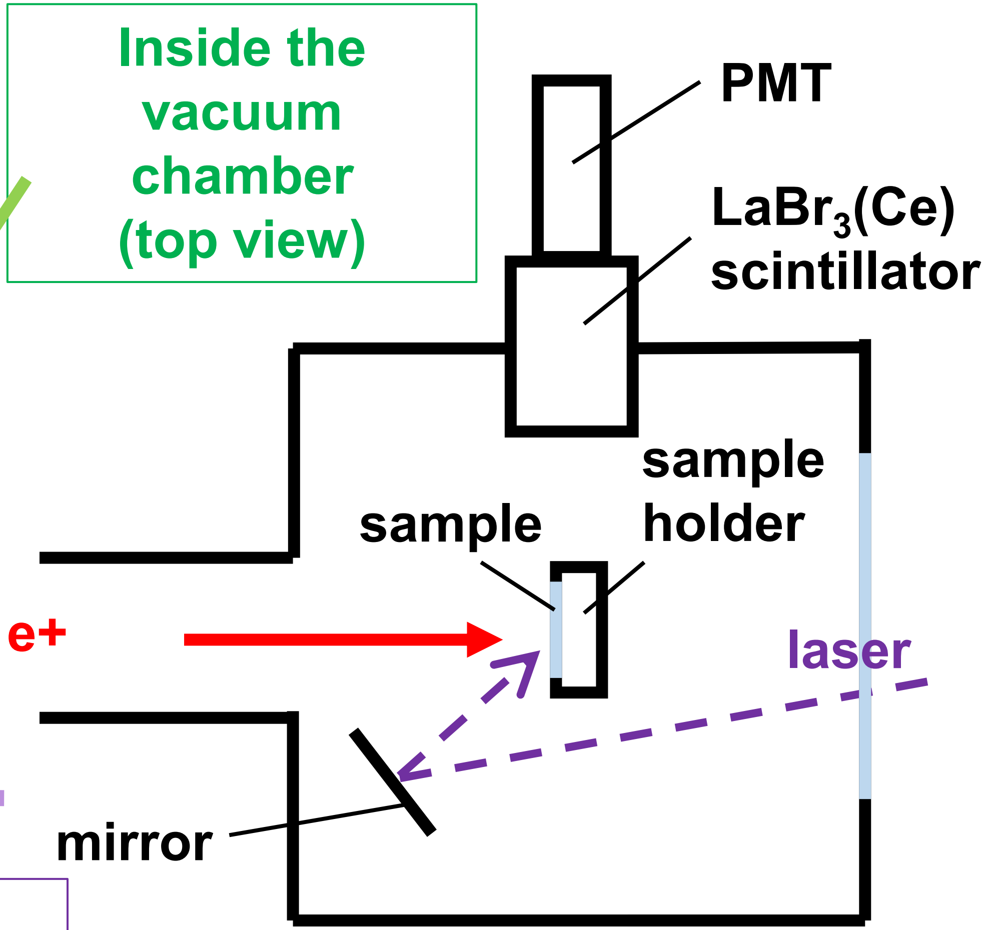
Ps is cooler when formed in cold silica aerogels.

Does the 2P-Ps decay rate get lower when the silica aerogel is cooled by a 4K-GM refrigerator?

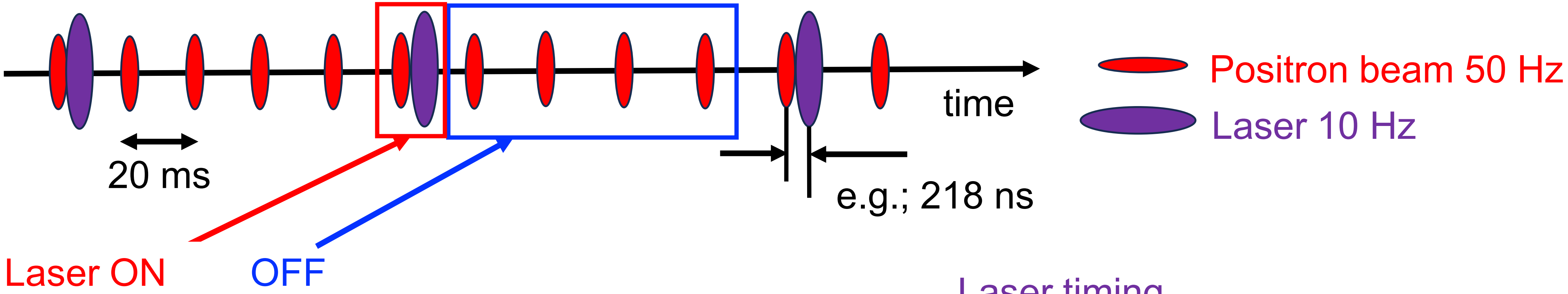
Ps laser transition experiment inside silica aerogel cooled by a refrigerator (June 2024 @ KEK-IMSS-SPF-B1, 7.5 keV)



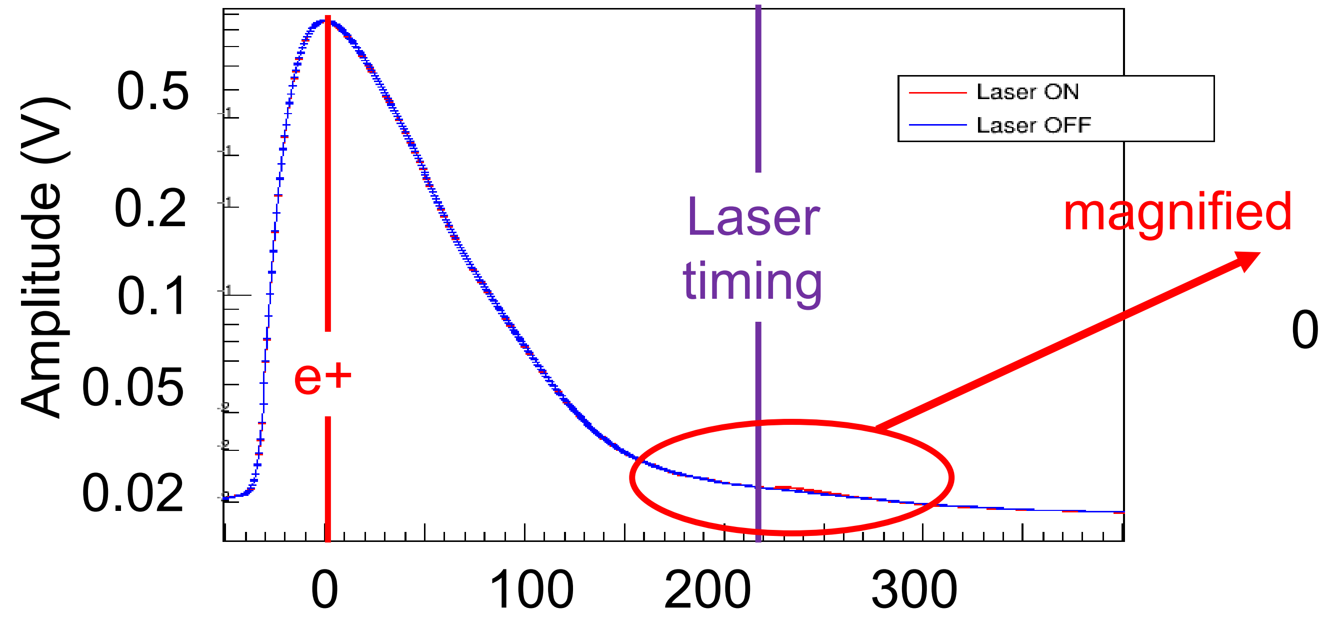


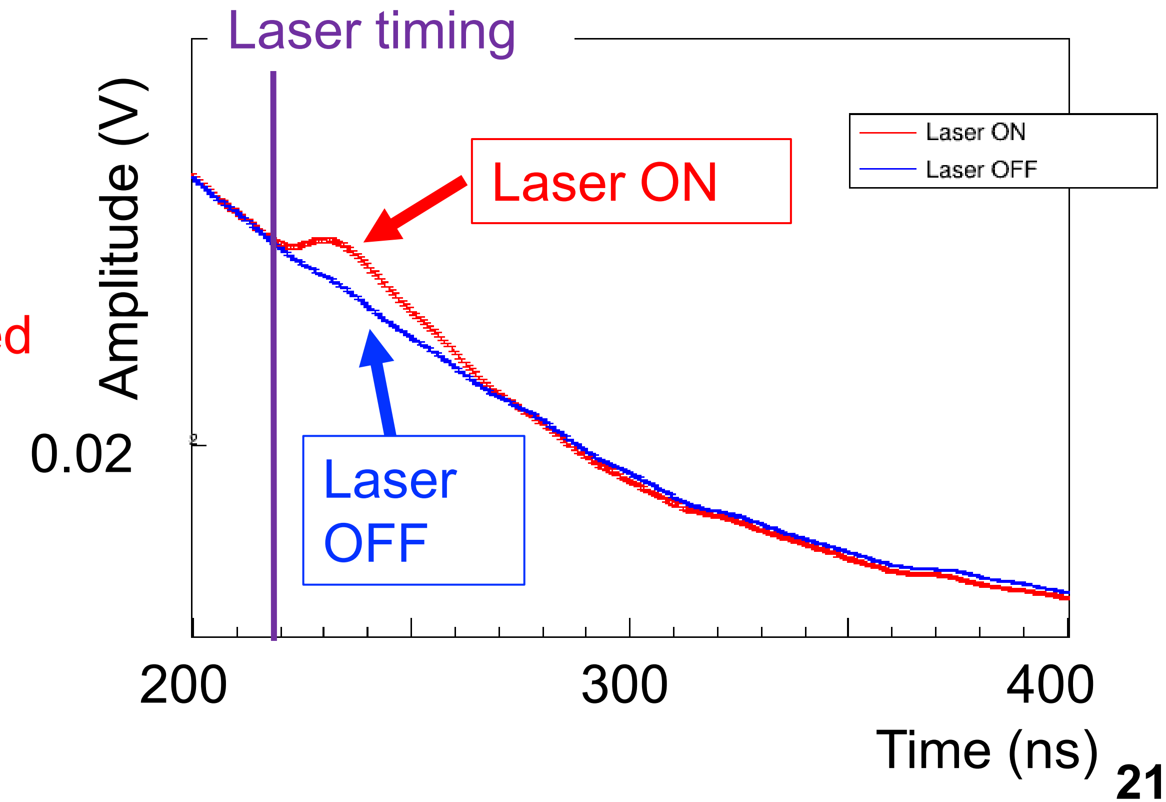


Confirmed decay of 2P-Ps into gamma rays by 243 nm.
Analysis is ongoing to check the reproducibility of room temperature data and see the temperature dependence.



Average waveform of the scintillator signal.





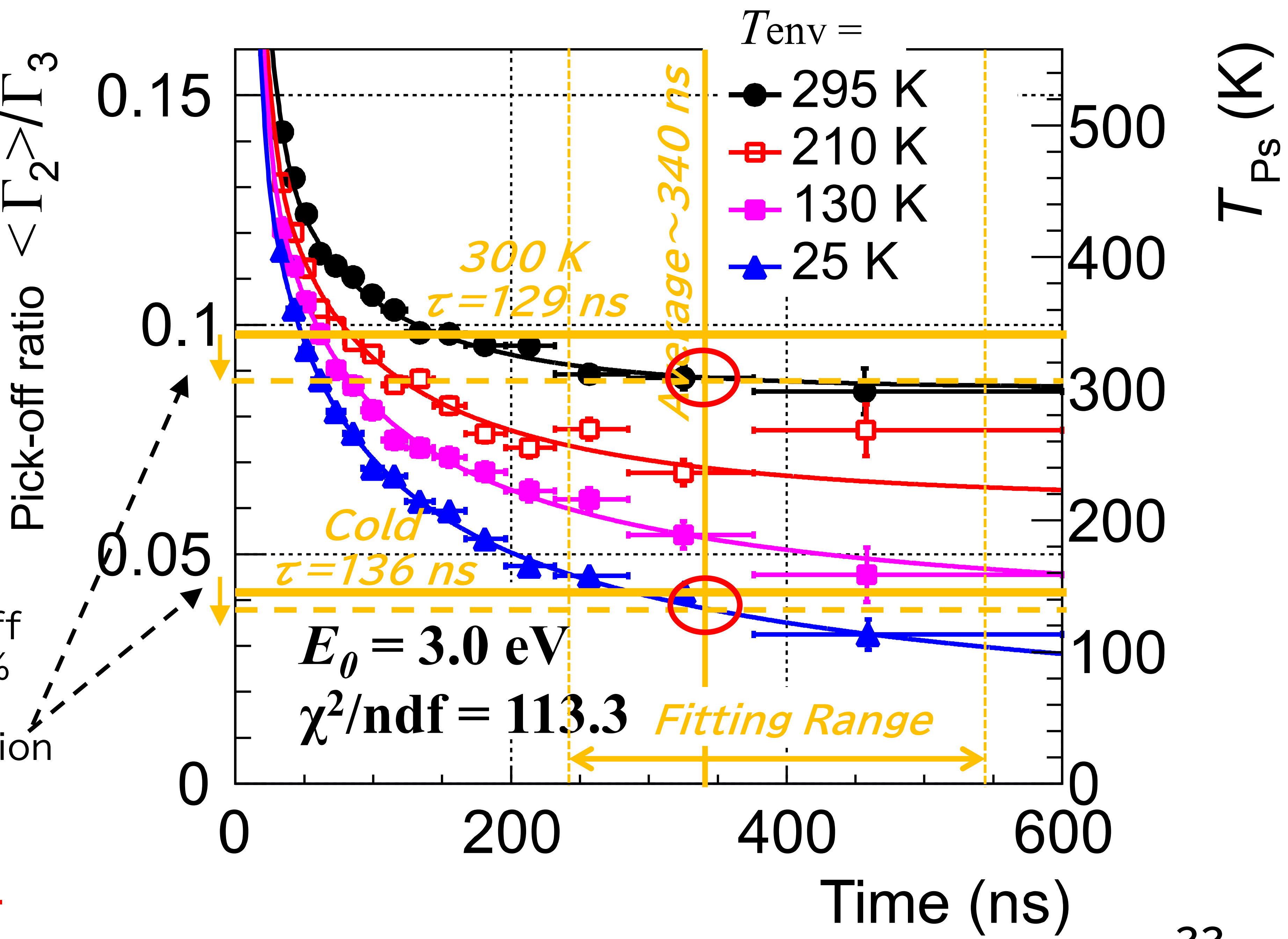
2024/10/30

Ps lifetime at room and low temperatures

Mean free path of silica aerogel when measuring the thermal curve 38.5 nm

Mean free path of silica aerogel used this time 34.0 nm

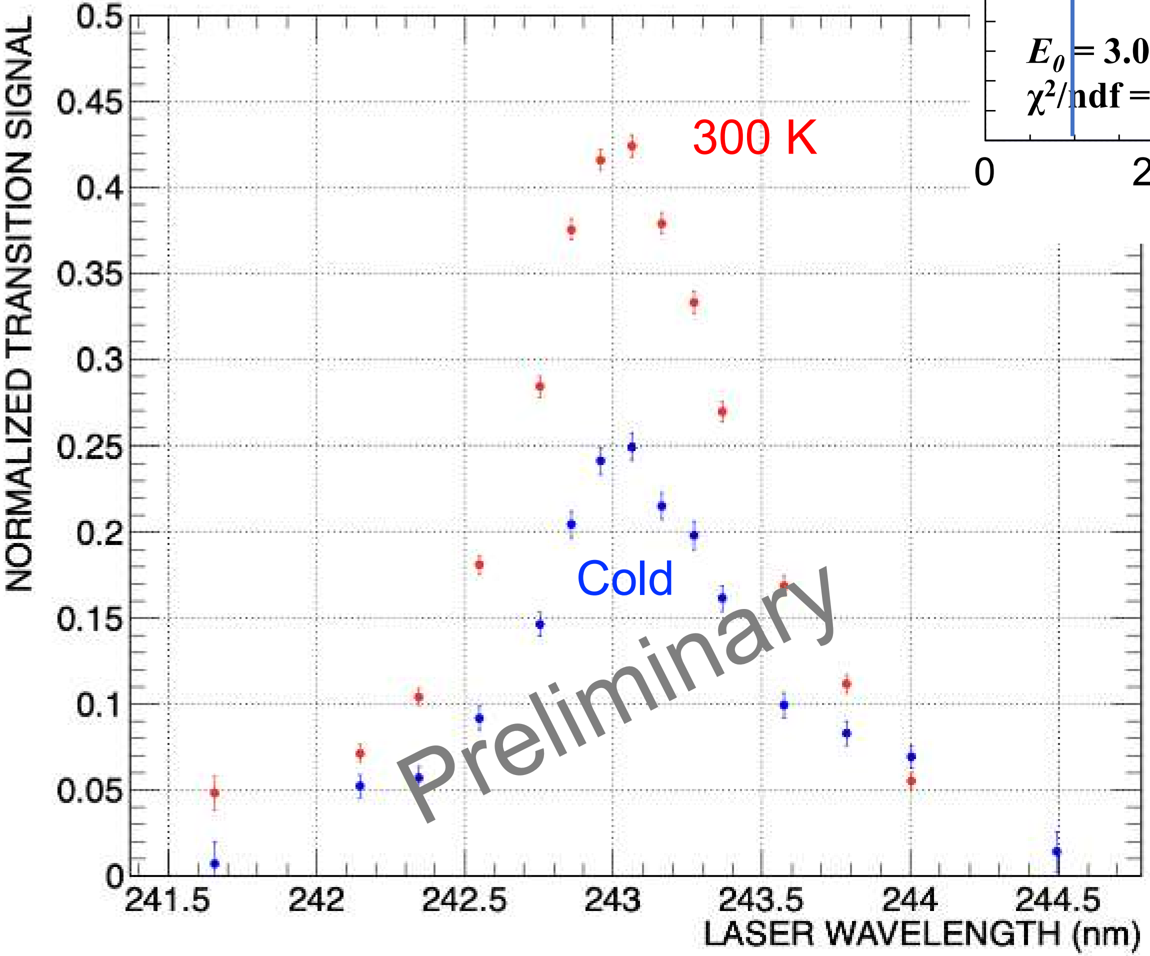
This time the pick-off should be about 12% bigger
→ when that correction is added, it matches (dashed line)

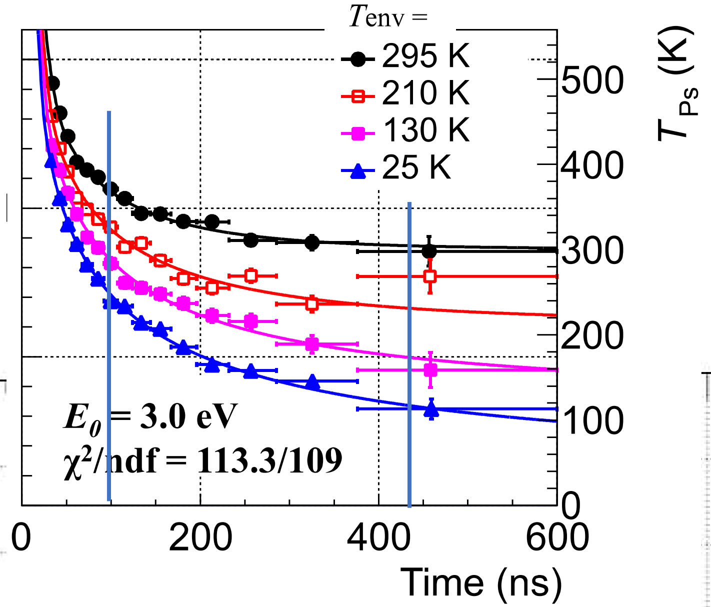


We have cooled Ps.

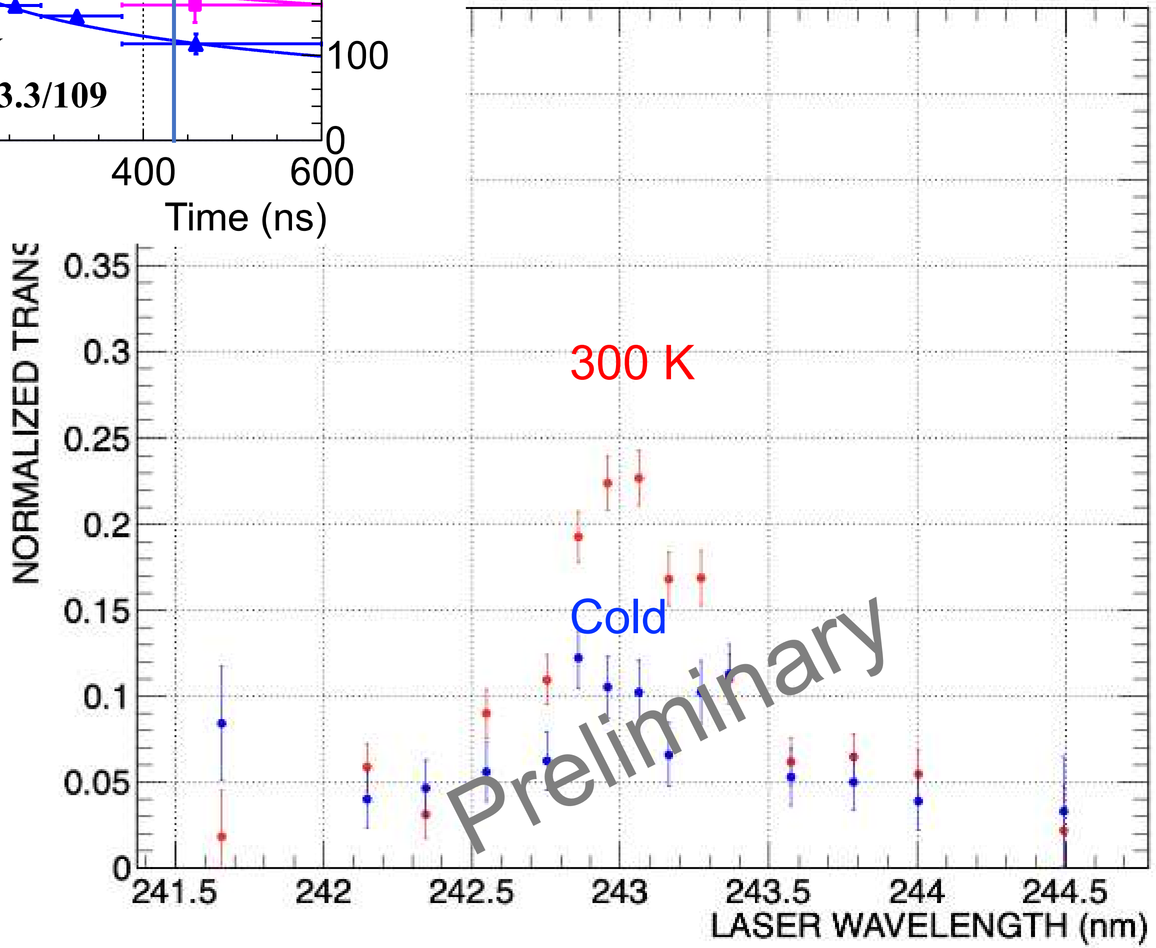
Some preliminary results (by simple analysis)

Laser timing = 110 ns

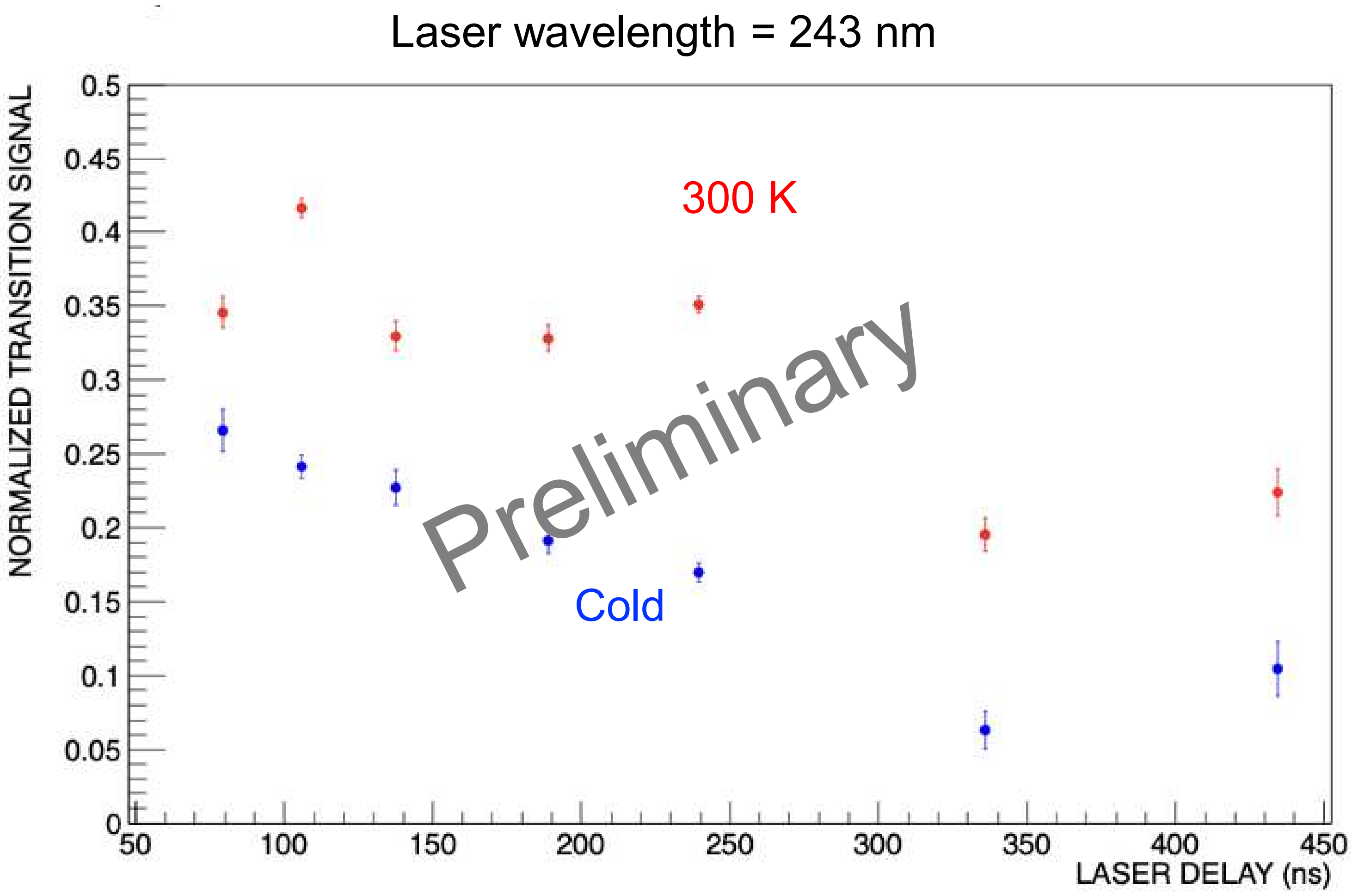


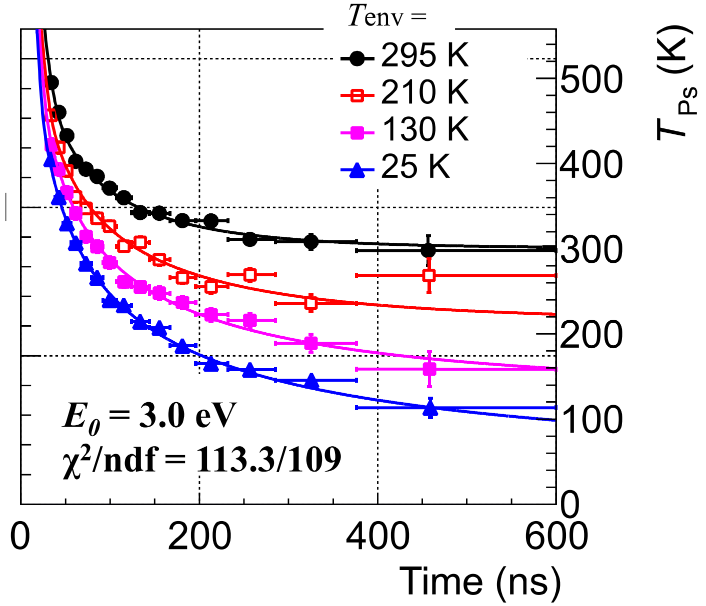


Laser timing = 430 ns



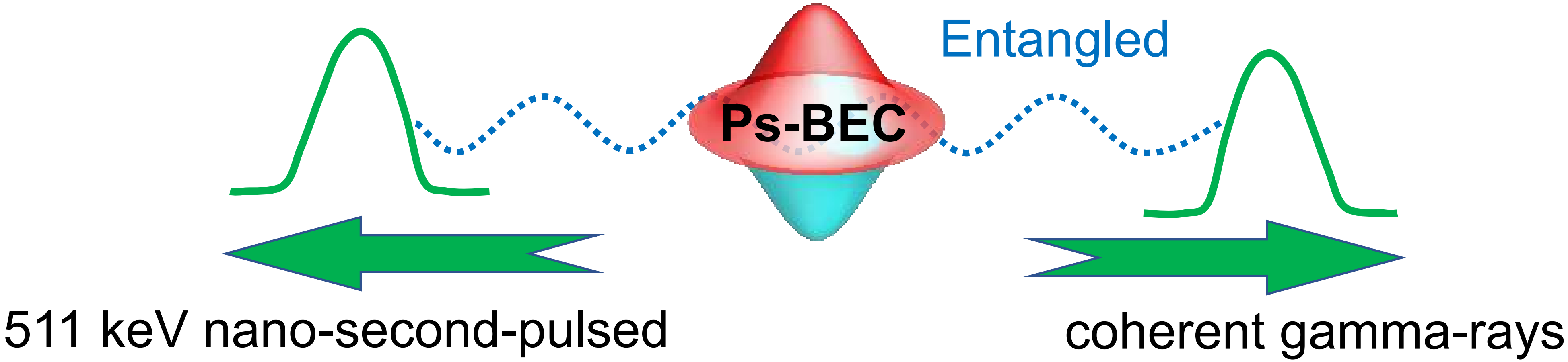
Some preliminary results (by simple analysis)





Summary

We want to realize an **<u>antimatter quantum condensate</u>** = positronium Bose-Einstein condensate (Ps-BEC).
<u>Gamma-ray lasers</u> may be realized using Ps-BEC as a source.



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   1. Positron focusing
   2. Ps formation material
B) Rapid Ps cooling
   3. Thermalization
   4. Laser cooling