Recent progress towards positronium Bose-Einstein condensation

Ps-BEC

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6 AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)
7 GIC
8 KEK
9 JAEA
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創発的研究支援事業
Fusion Oriented REsearch for disruptive Science and Technology

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- MEXT Q-LEAP JPMXS0118067246.

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- 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

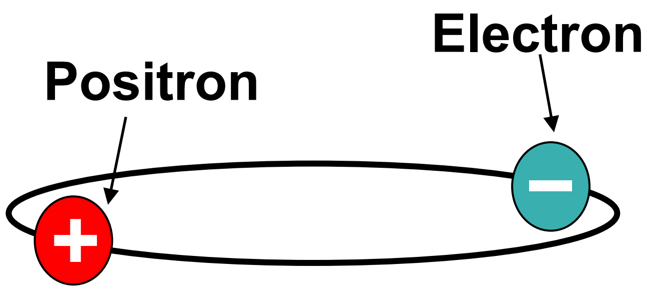
Goals:

$\boxed{10^{18}\ \mathrm{cm}^{-3}}$

$\boxed{10\ \mathrm{K}}$

$\boxed{\text{in} \sim 100\ \text{ns}}$

Positronium (Ps) is a good probe for fundamental physics

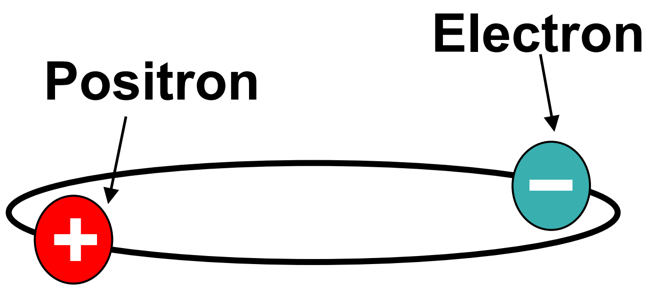


Bound state of an electron (e^-) and its **antiparticle** positron (e^+)

The Lightest and Exotic Atom

- ✓ Exotic atom with antiparticle
  - ➢ Good to explore the mystery of antimatter
- ✓ Purely leptonic system
  - ➢ Experiments and theoretical calculations can be compared in high precision without uncertainties of hadronic interactions.

Positronium (Ps) is a good probe for fundamental physics

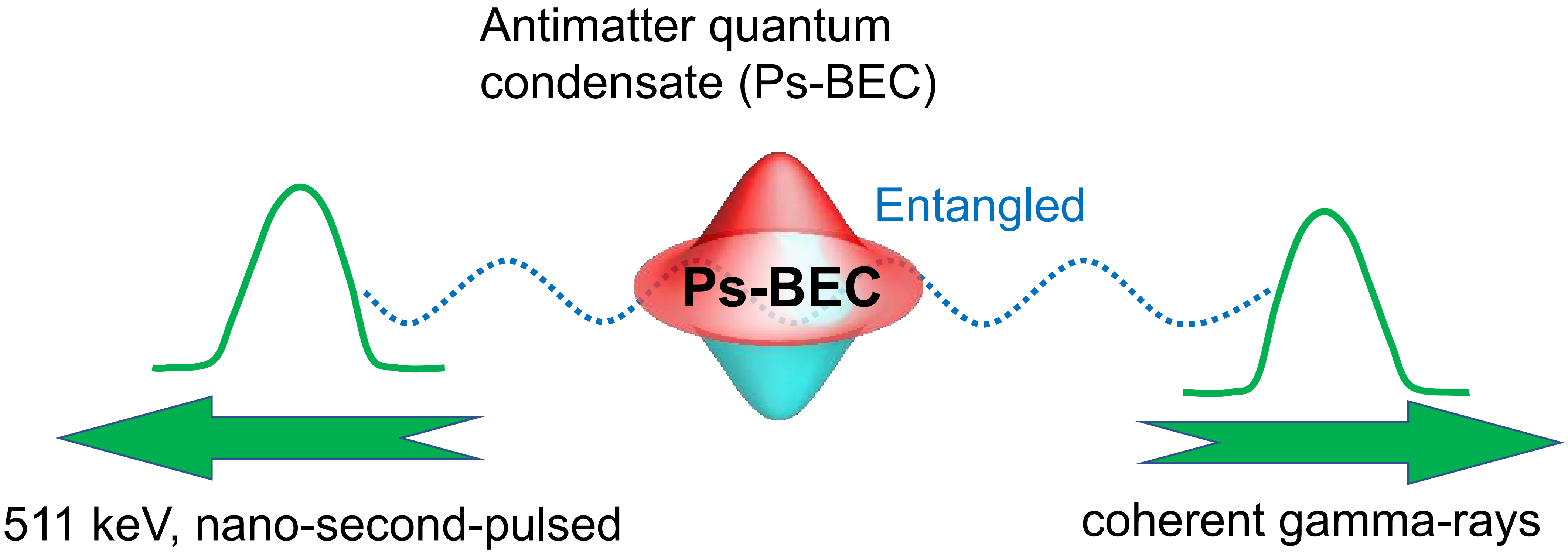


Bound state of an electron (e^-) and its **antiparticle** positron (e^+)

The Lightest and Exotic Atom

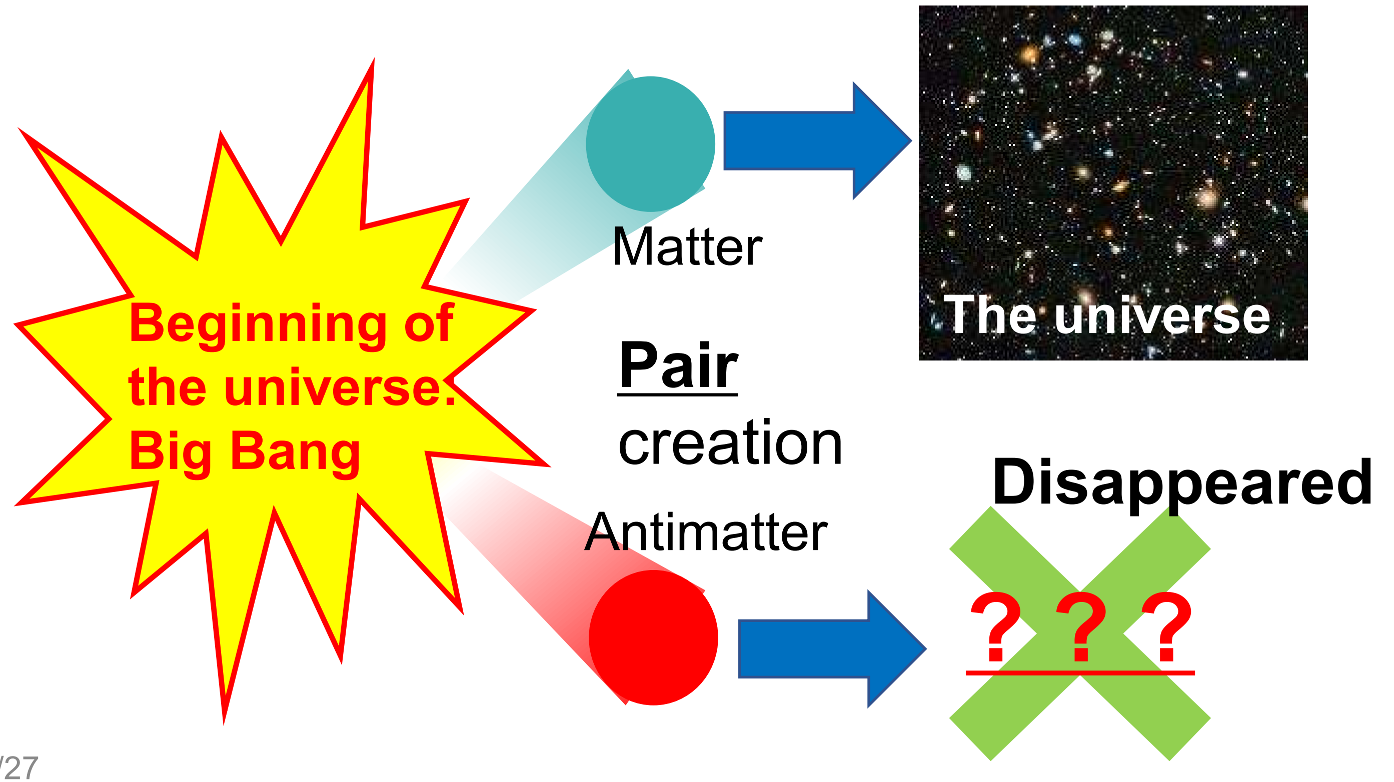
In this talk, we focus on the ground-state *ortho*-positronium (*o*-Ps), the spin-triplet state with a lifetime of 142 ns.
o-Ps has much longer lifetime than the spin-singlet *para*-positronium (*p*-Ps), which has a lifetime of 125 ps.

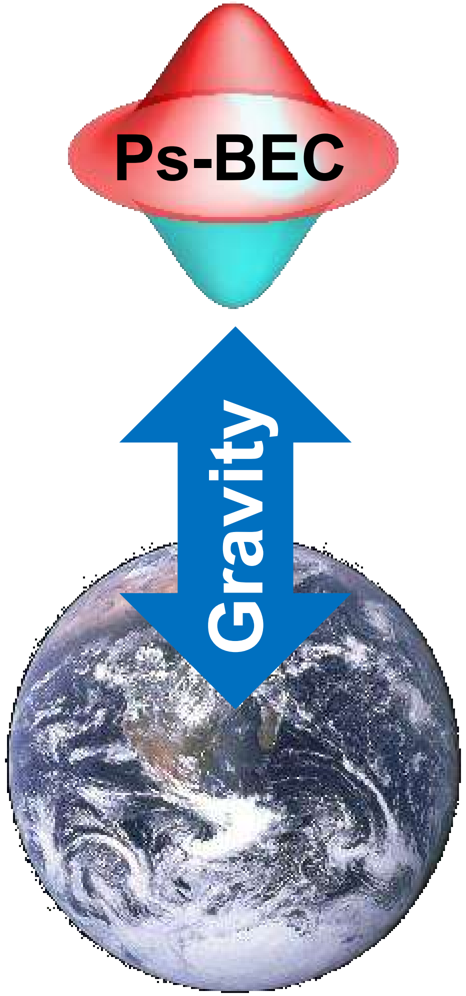
We want to realize an **antimatter quantum condensate** = positronium Bose-Einstein condensate (Ps-BEC). **Gamma-ray lasers** may be realized using Ps-BEC as a source.



Ps-BEC may answer the great mystery of the matter-dominated universe

Game change in particle physics, atomic physics, and cosmology

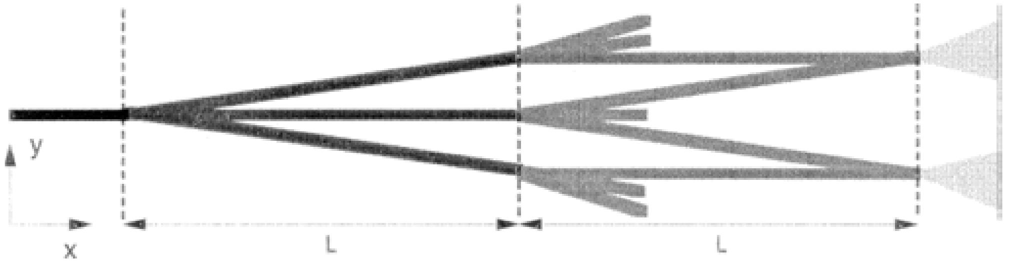




Proposed Ps antimatter gravity measurements

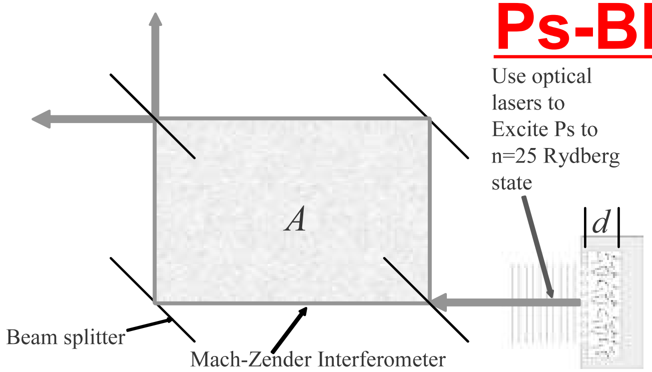
Interferometry

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).

Spectroscopy

precision will be improved by cooling Ps

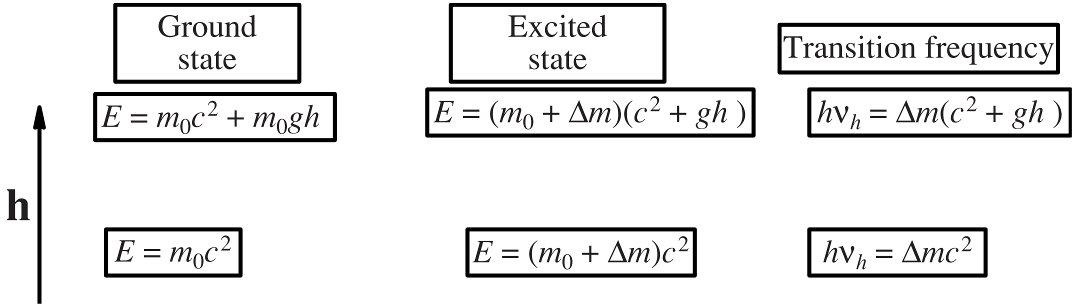


Fig. 1. Derivation of the gravitational red shift.

S. G. Karshenboim, Astron. Lett. **35**, 663 (2009).

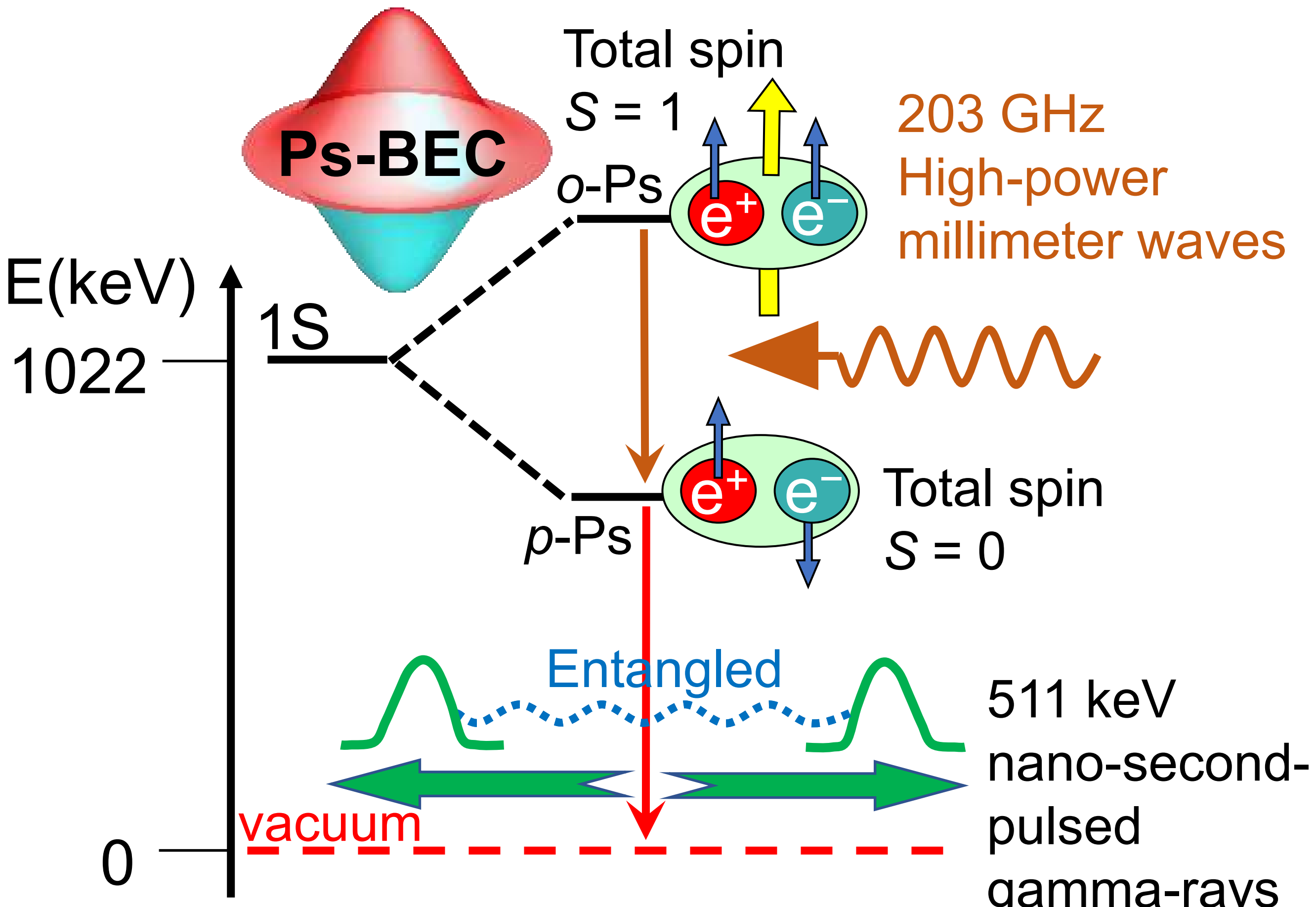
Different distance from the Sun:

$$\frac{\Delta U(r_{\max}) - \Delta U(r_{\min})}{c^2} \simeq 3.2 \times 10^{-10}.$$

(0.32 ppb)

cf. Ps 1*S*—2*S* : 2.6 ppb

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



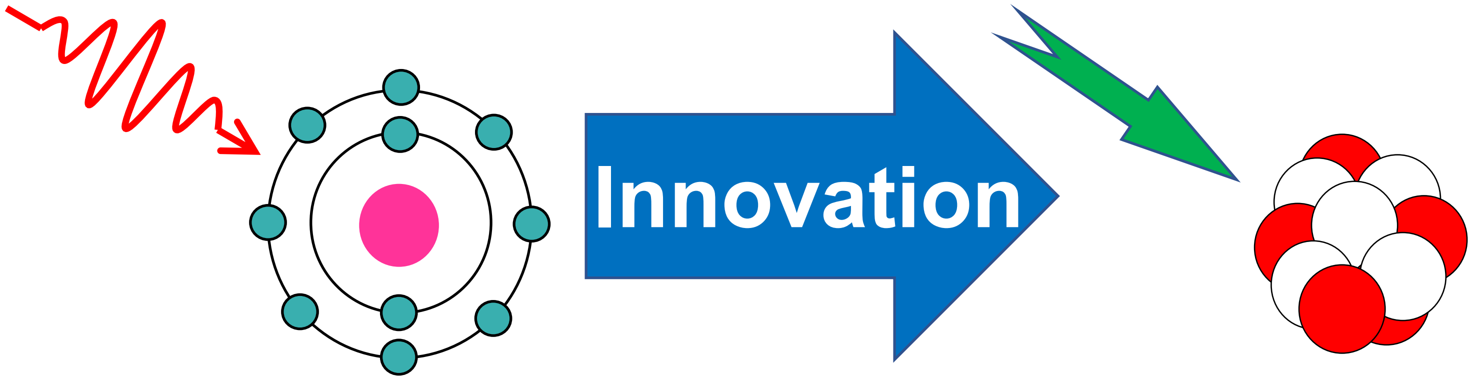
H. K. Avetissian *et al.*, Phys. Rev. A **92**, 023820 (2015).

Motivation

Exploration of unknown energy regions in all quantum optics research

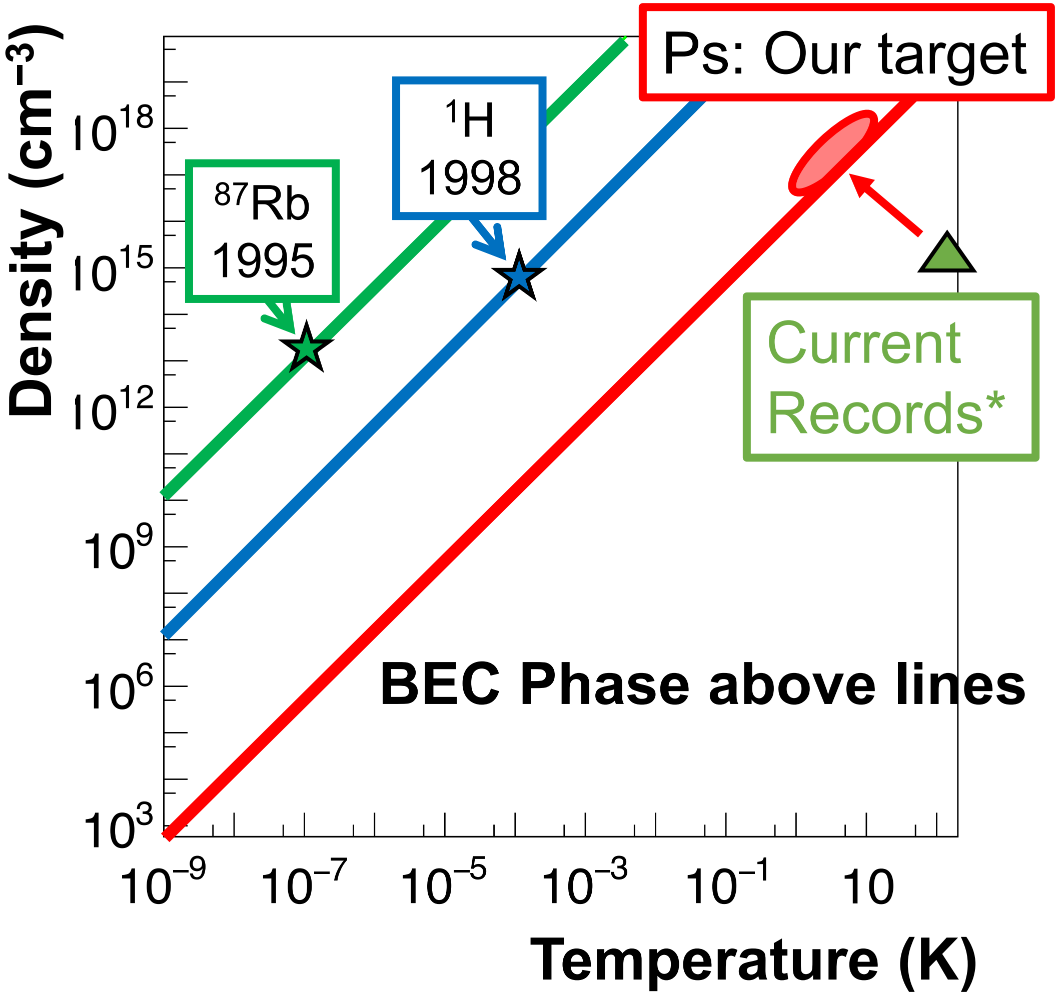
Game change in the fields of optics, atomic physics, and nuclear physics

Visible laser & **atom** **Gamma-ray laser** & **nucleus**



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

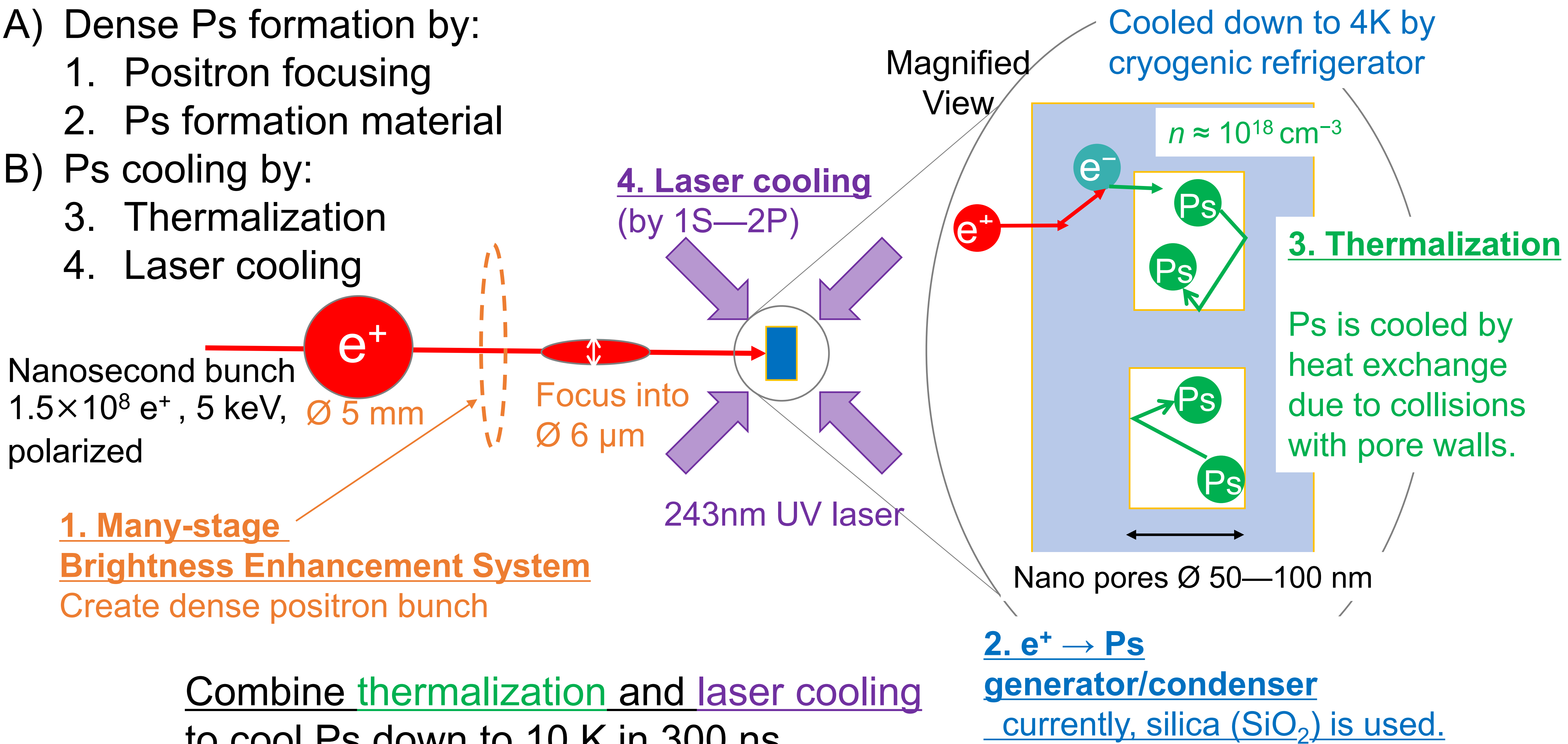
Two challenges

1. Instant creation of dense Ps
   $> 10^{18}\ \mathrm{cm^{-3}}$ 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)

Our idea to realize Ps-BEC

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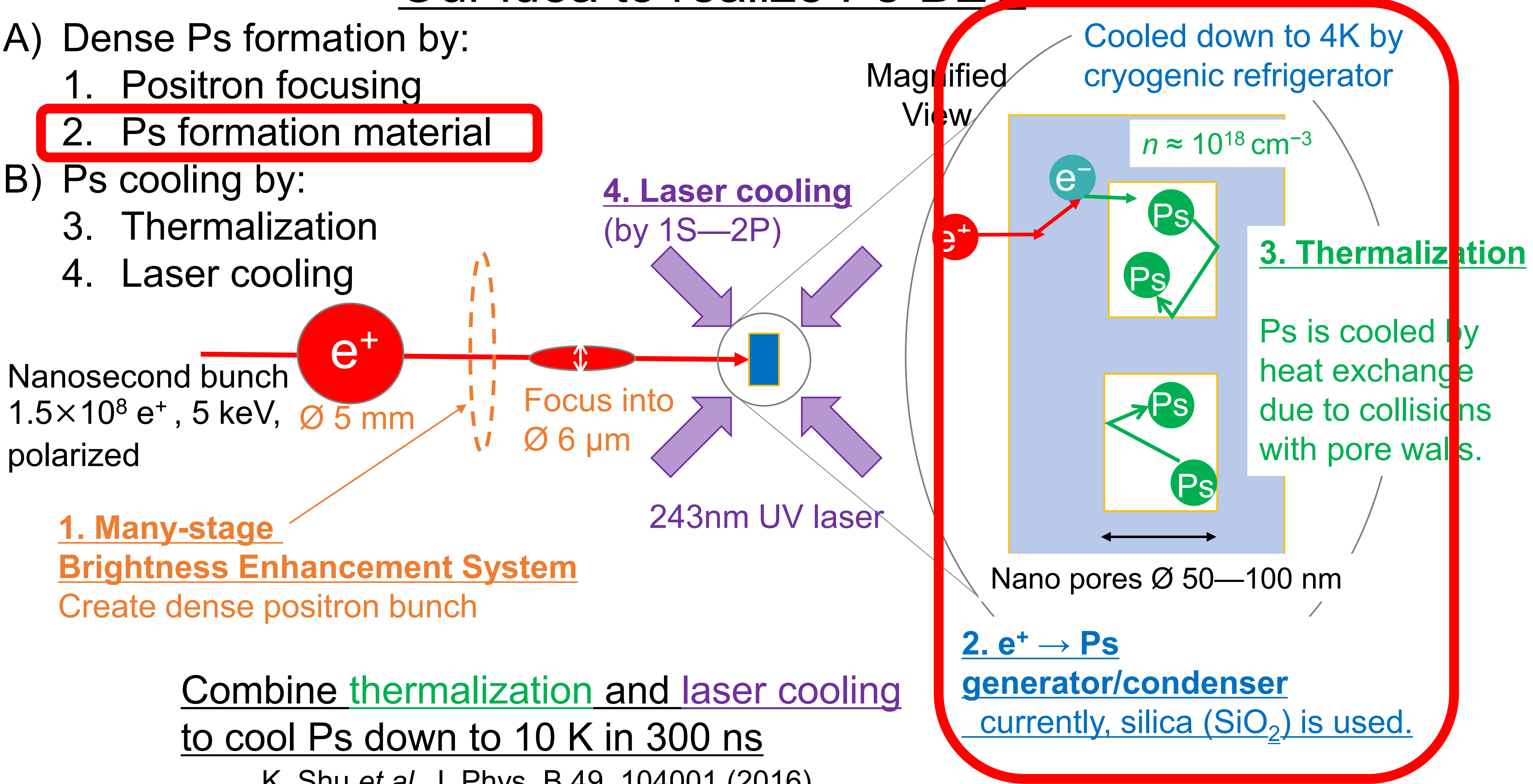
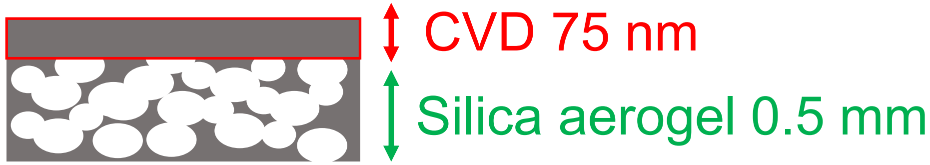


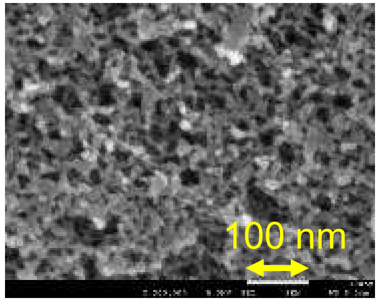
Combine thermalization and laser cooling
to cool Ps down to 10 K in 300 ns

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

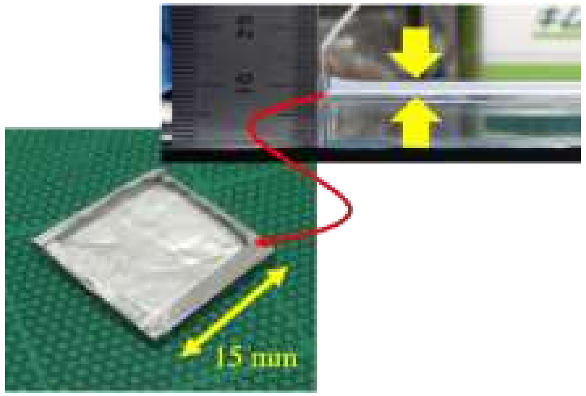
Silica (SiO_2) aerogel was a good candidate.
Capped the surface of the aerogel with an amorphous silica thin film by plasma-enhanced chemical vapor deposition (CVD).

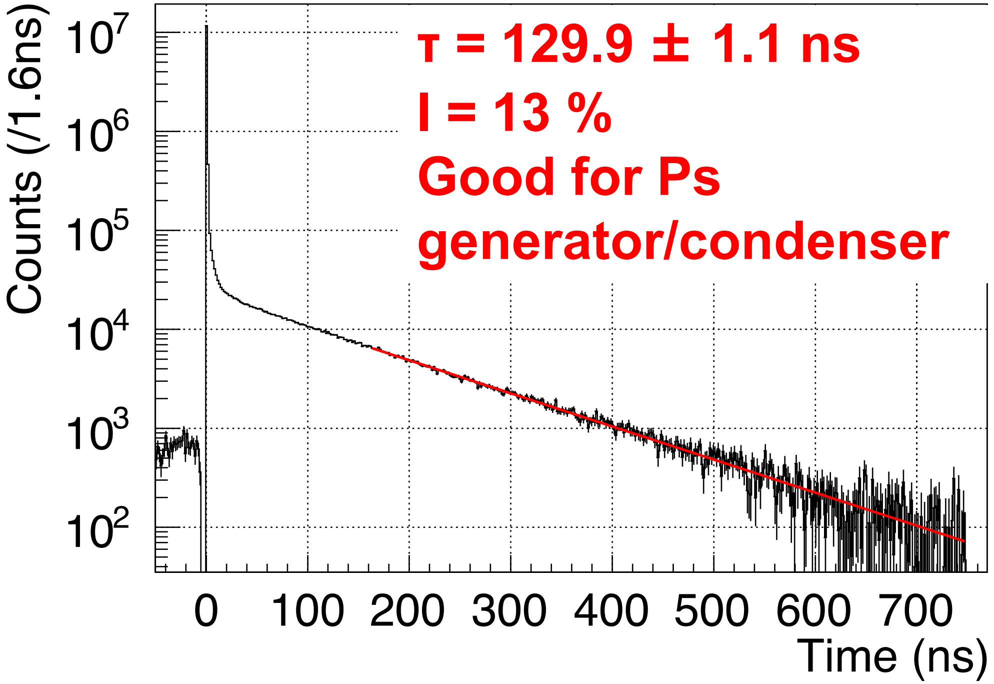
Silica aerogel 0.12 g cm^{-3}
45 nm pores



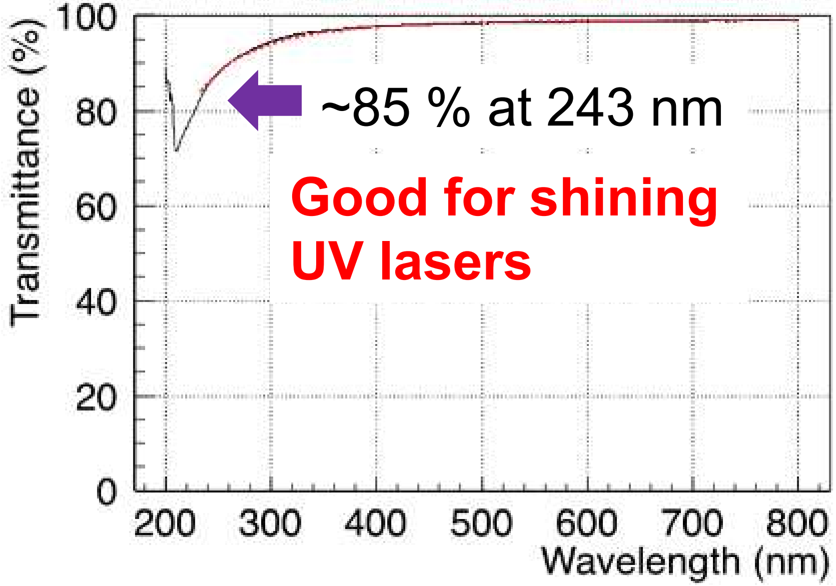


×200,000





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

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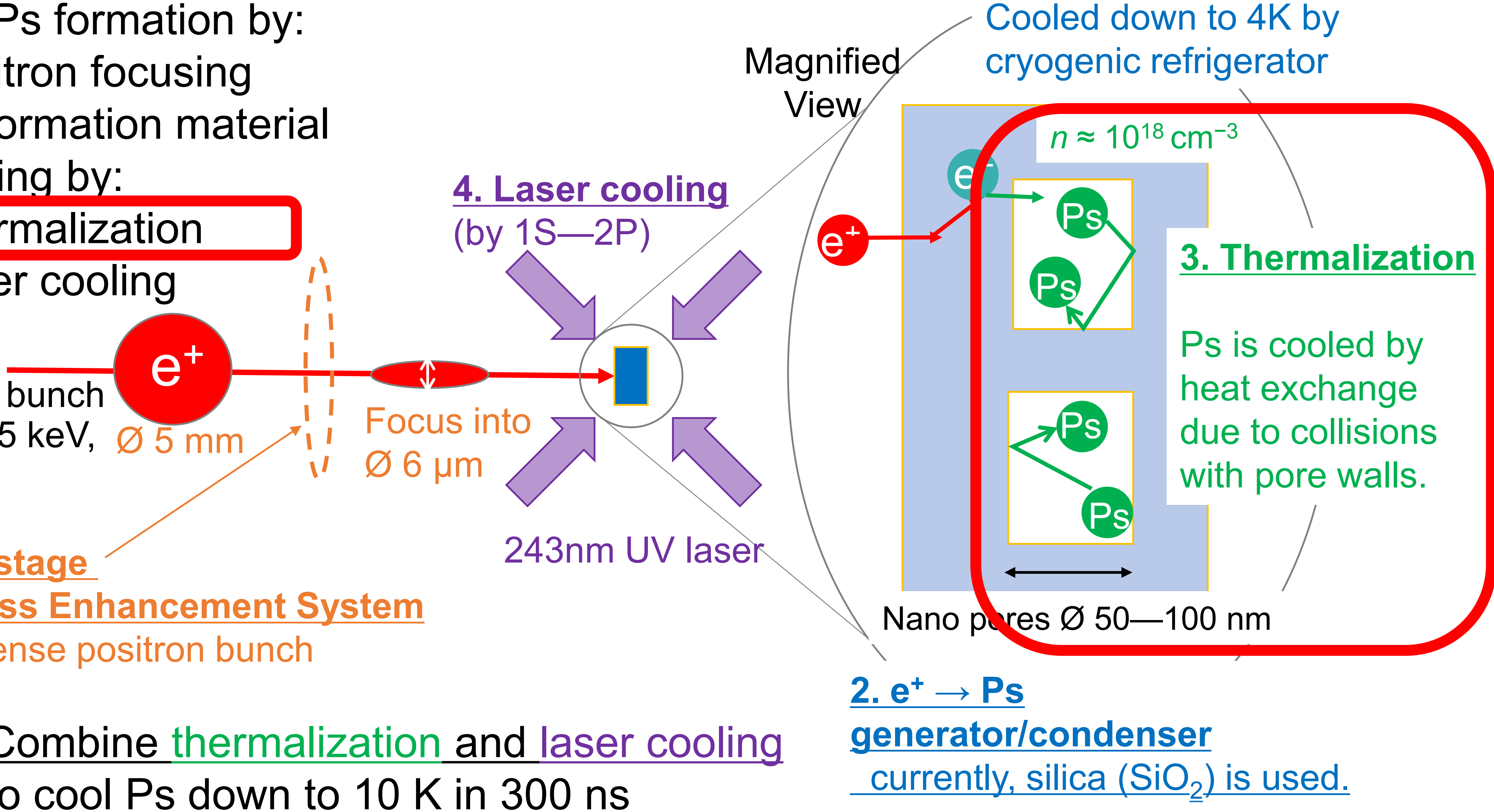
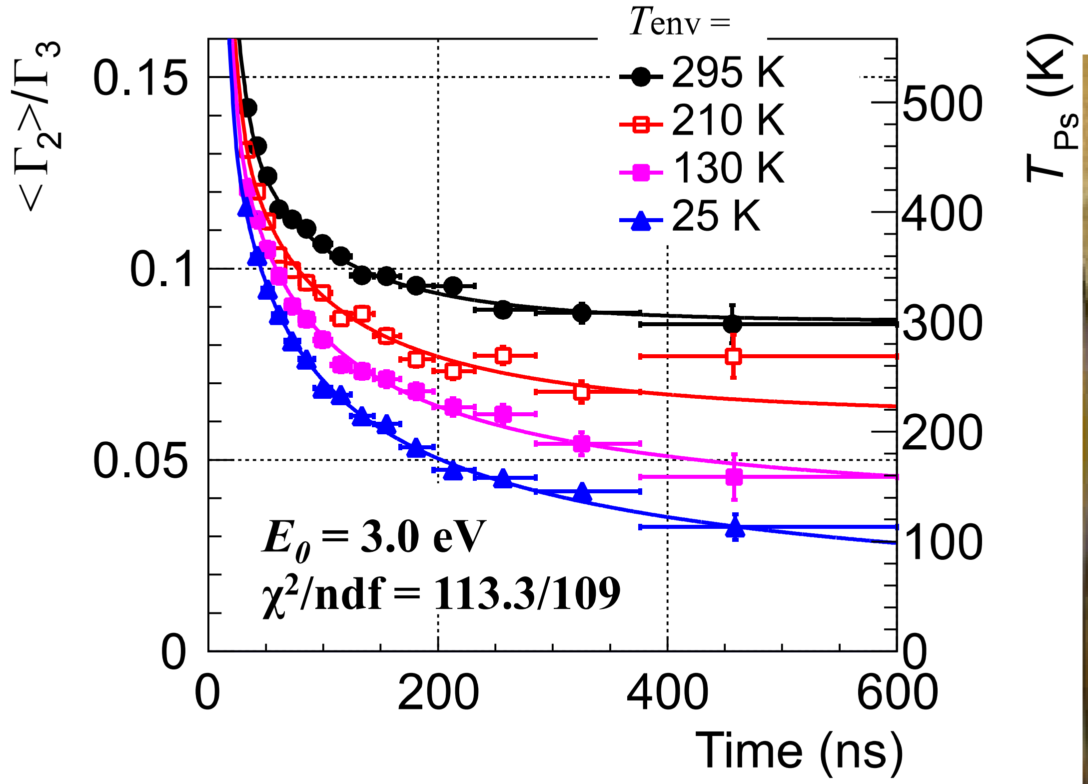
4. Laser cooling

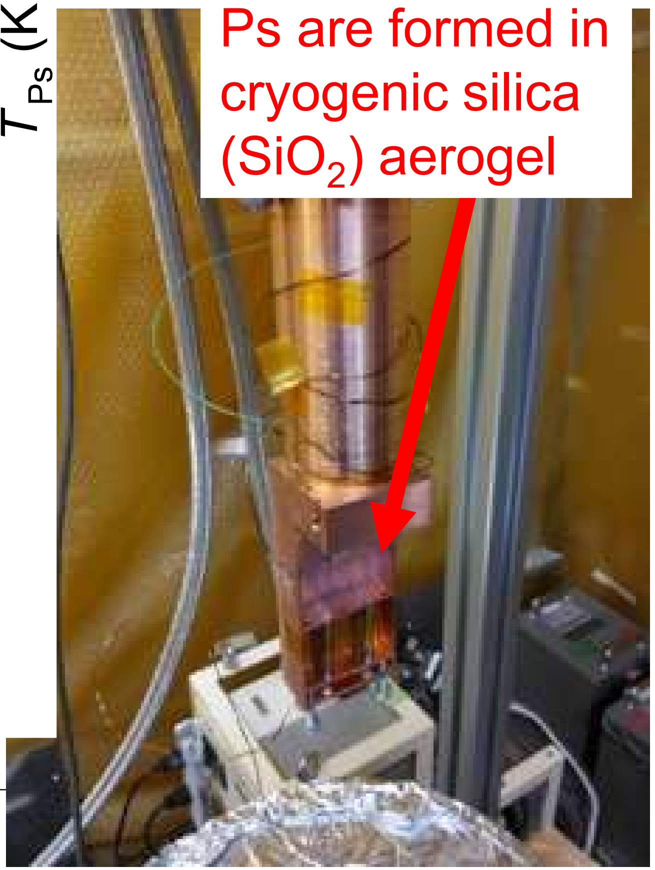


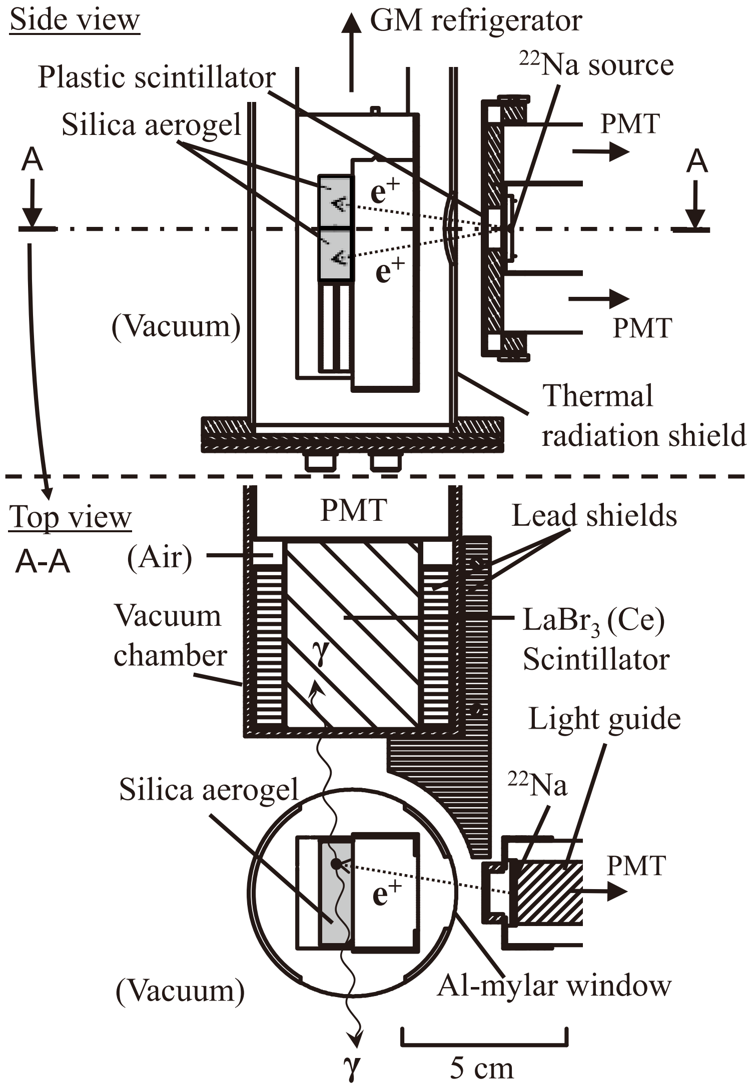
Combine thermalization and laser cooling to cool Ps down to 10 K in 300 ns

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

Ps thermalization down to 100 K was observed with 25 K silica aerogel. However, the observed thermalization cooling was too slow to get 10 K.







PHYSICAL REVIEW A **104**, L050801 (2021)

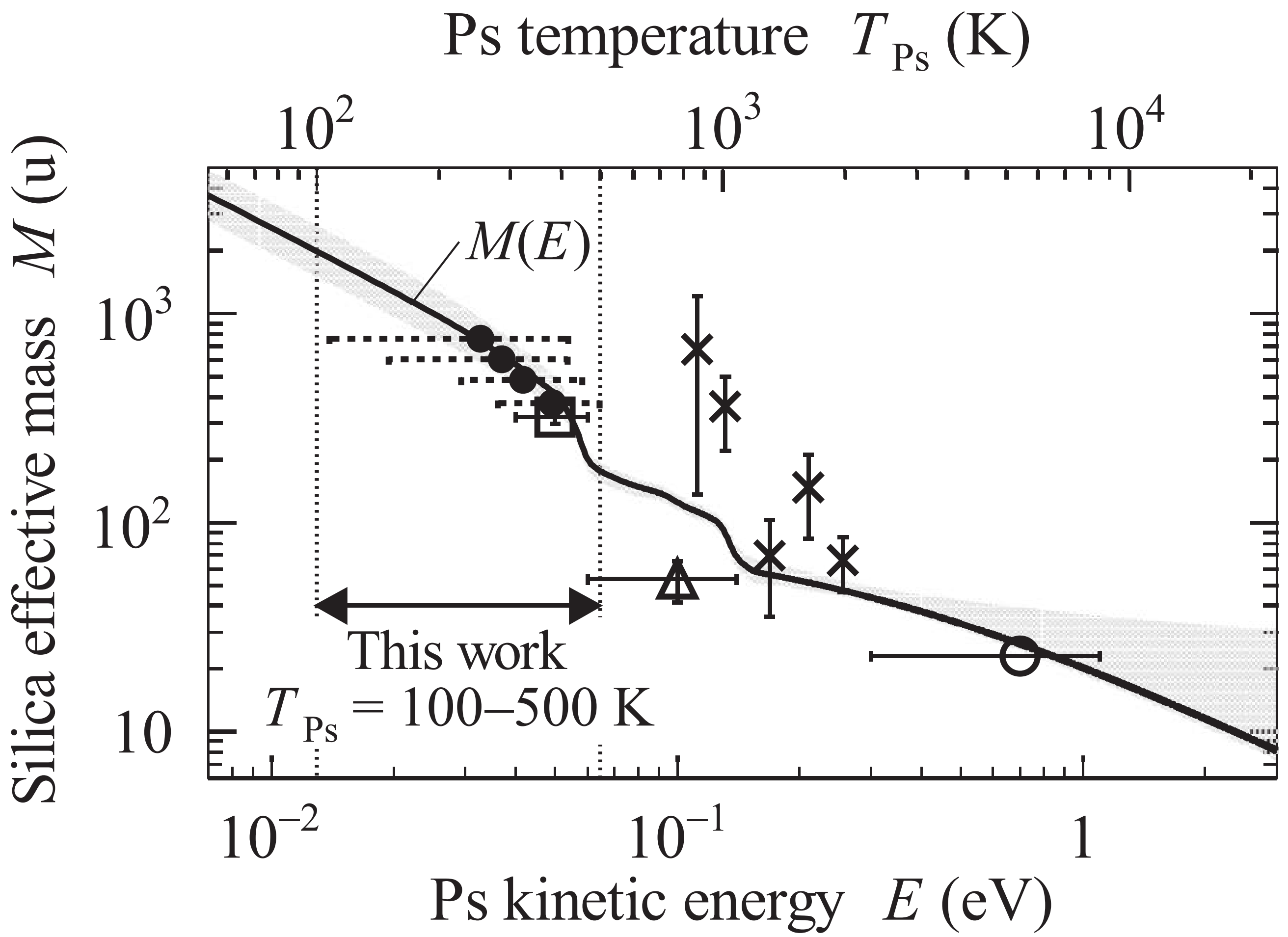
Letter

Observation of orthopositronium thermalization in silica aerogel at cryogenic temperatures

Kenji Shu,* Akira Ishida,† Toshio Namba, and Shoji Asai
Department of Physics, Graduate School of Science, and International Center for Elementary Particle Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Nagayasu Oshima, Brian E. O'Rourke, and Kenji Ito
National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba-Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Ps thermalization slows down at lower Ps kinetic energy

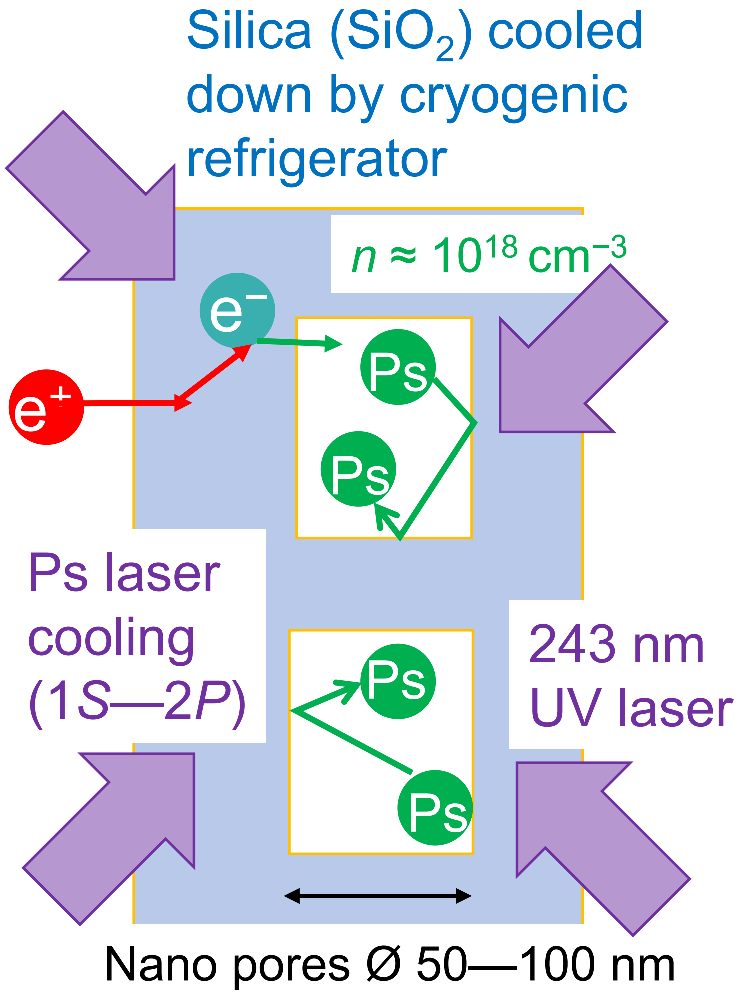


K. Shu *et al.*, Phys. Rev. A **104**, L050801 (2021).

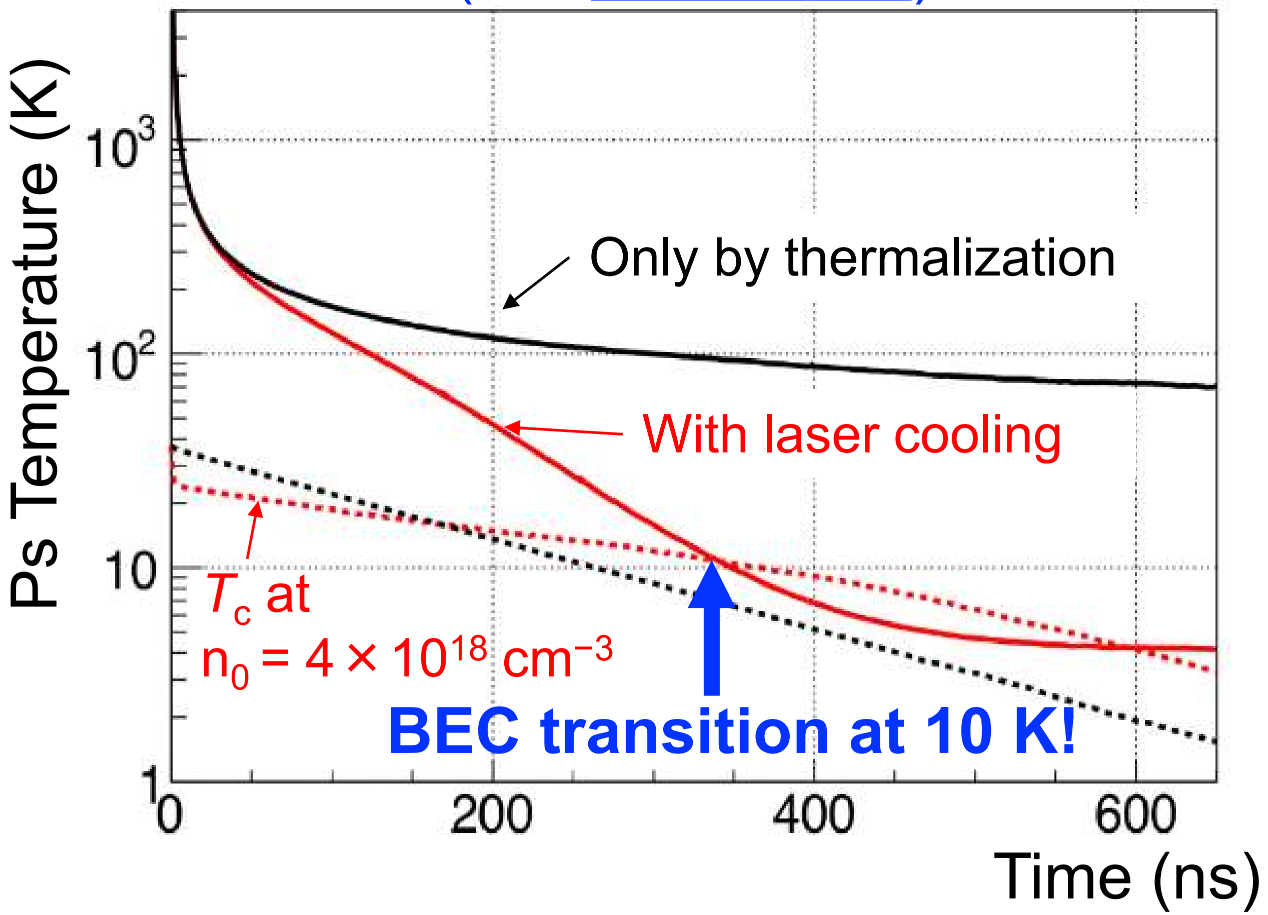
$$\frac{dE(t)}{dt} = -\frac{2}{LM}\sqrt{2m_{Ps}E(t)}\left[E(t) - \frac{3}{2}k_B T_{env}\right].$$

- Consistent with older experiments at higher temperatures.
- The dependence of the silica effective mass *M* on the Ps kinetic energy can be explained by the de Broglie wavelength of the Ps atoms ($M \propto \left(\lambda_{Ps}^{dB}\right)^2 \propto E^{-1}$).
- Thermalization can cool Ps down to 100 K, but not enough for Ps-BEC.
- Next cooling: <u>Laser cooling down to 10 K.</u>

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



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).

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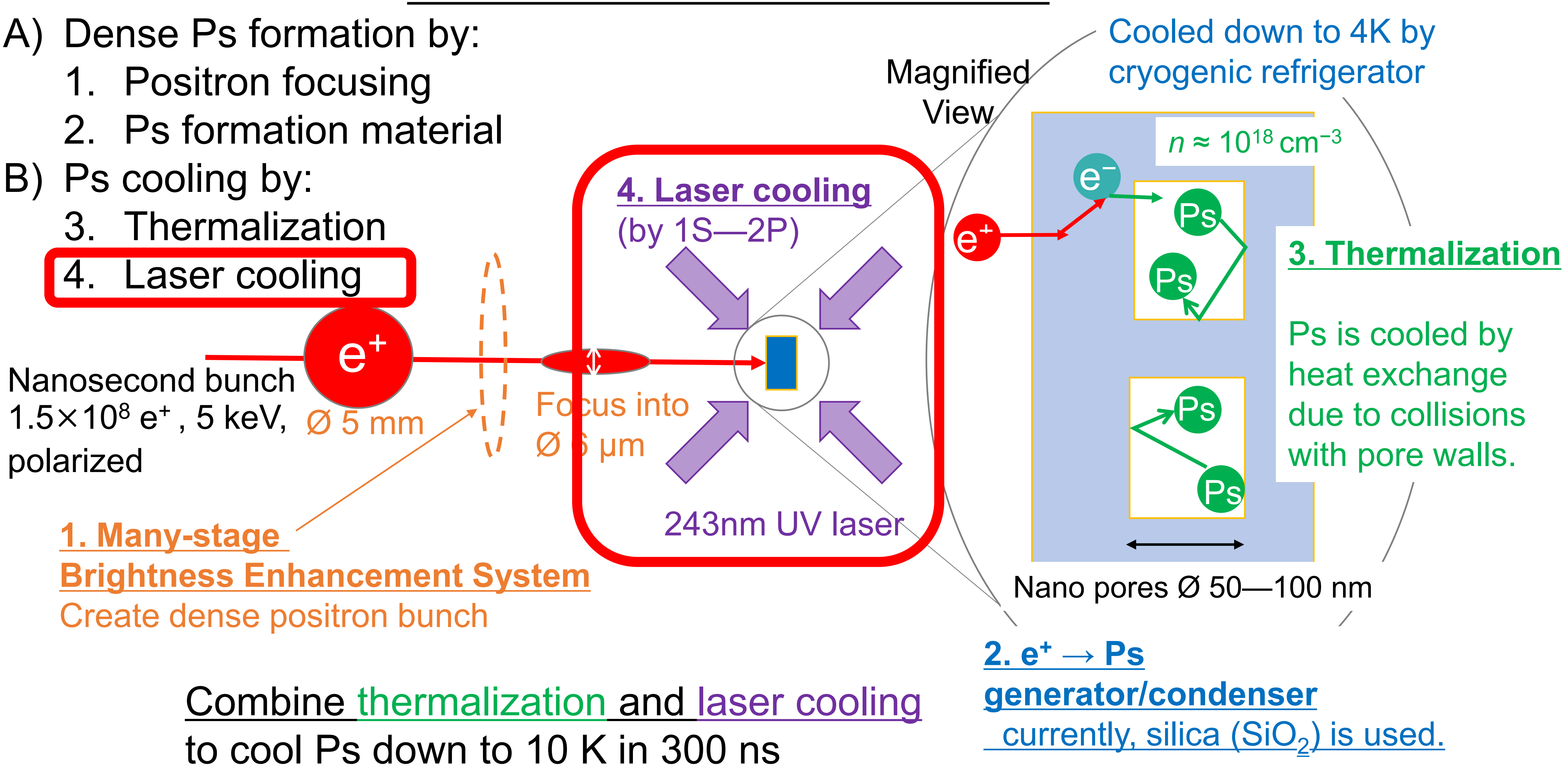
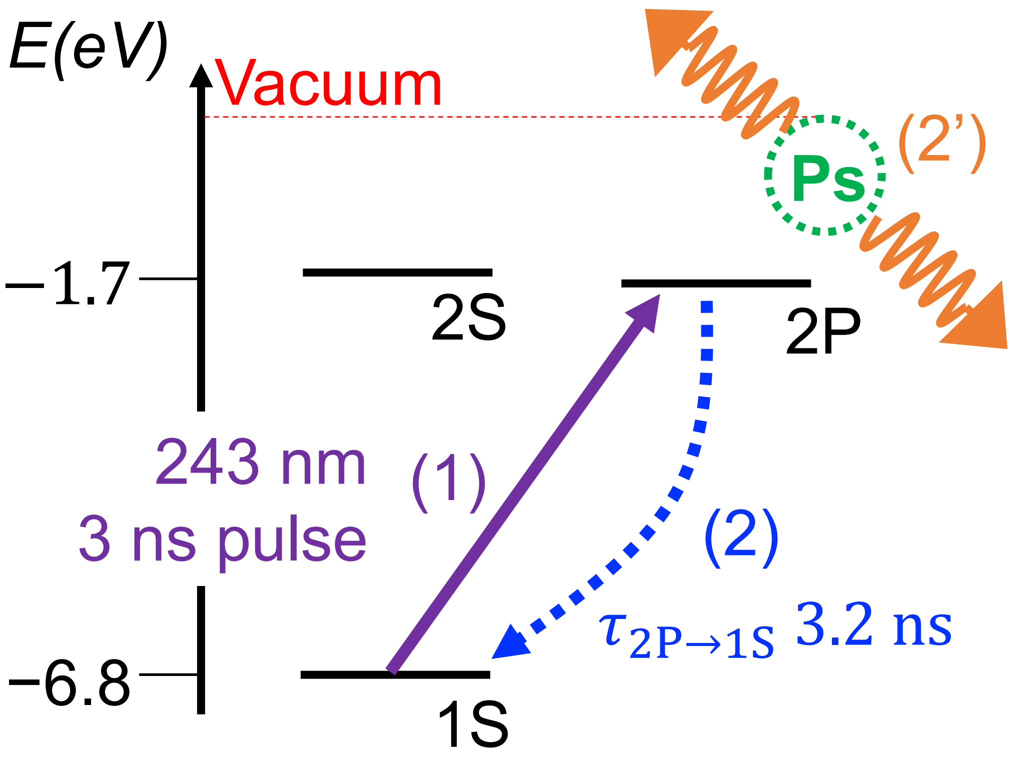


Combine thermalization and laser cooling
to cool Ps down to 10 K in 300 ns

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

Test experiment to excite 1S-Ps inside the silica aerogel pores to 2P state by shining 243 nm, 3 ns pulsed UV laser.



Ps energy levels

Core process of the Ps laser cooling

(1) Excite Ps to 2P state by shining 243 nm UV laser.

(2) If nothing special happens...

- Ps is de-excited to 1S state with lifetime of 3.2 ns (Lyman-alpha).

→***Good for laser cooling***

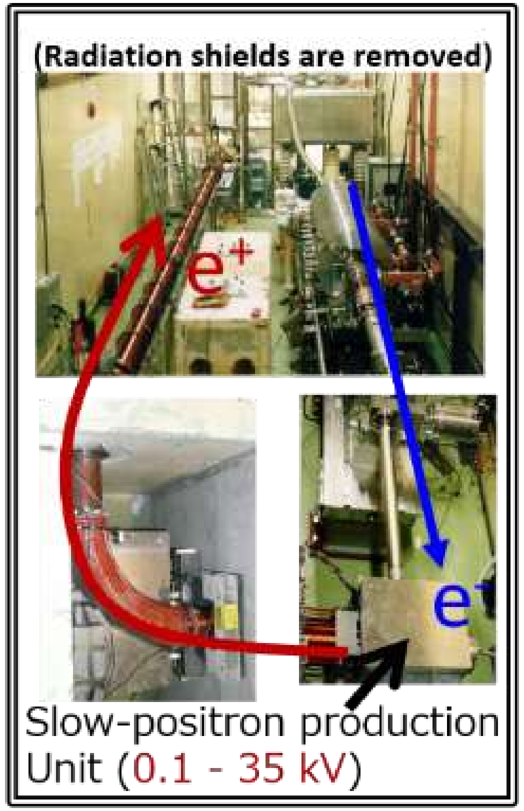
(2') If lifetime of 2P-Ps inside pores is short (as reported in B. S. Cooper et al. PRB 97, 205302 (2018).)**...**

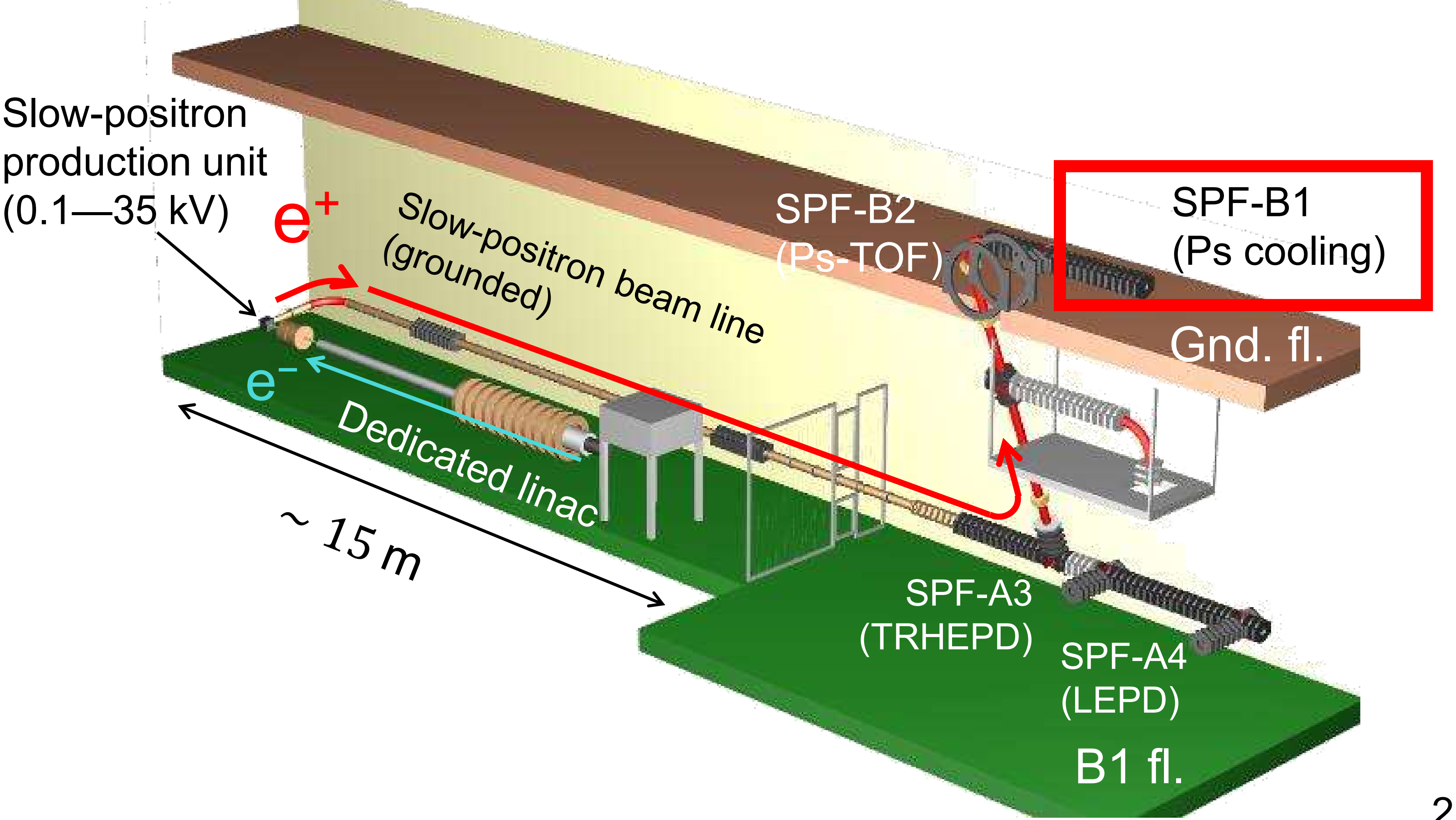
- Annihilation rate to gamma-rays is increased.

→***Bad for laser cooling***

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

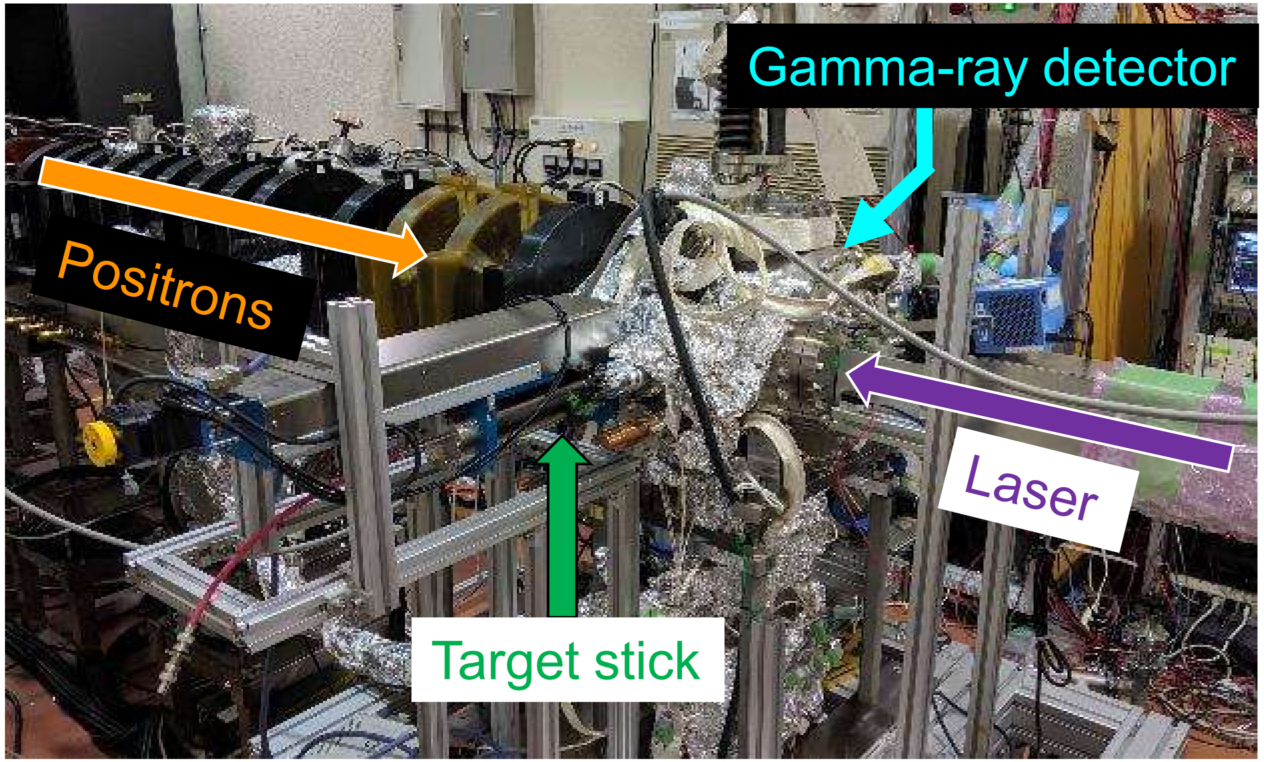
- Highest intensity (5×10^{7} slow e^{+} s^{-1})
- Variable energy (0.1—35 keV)



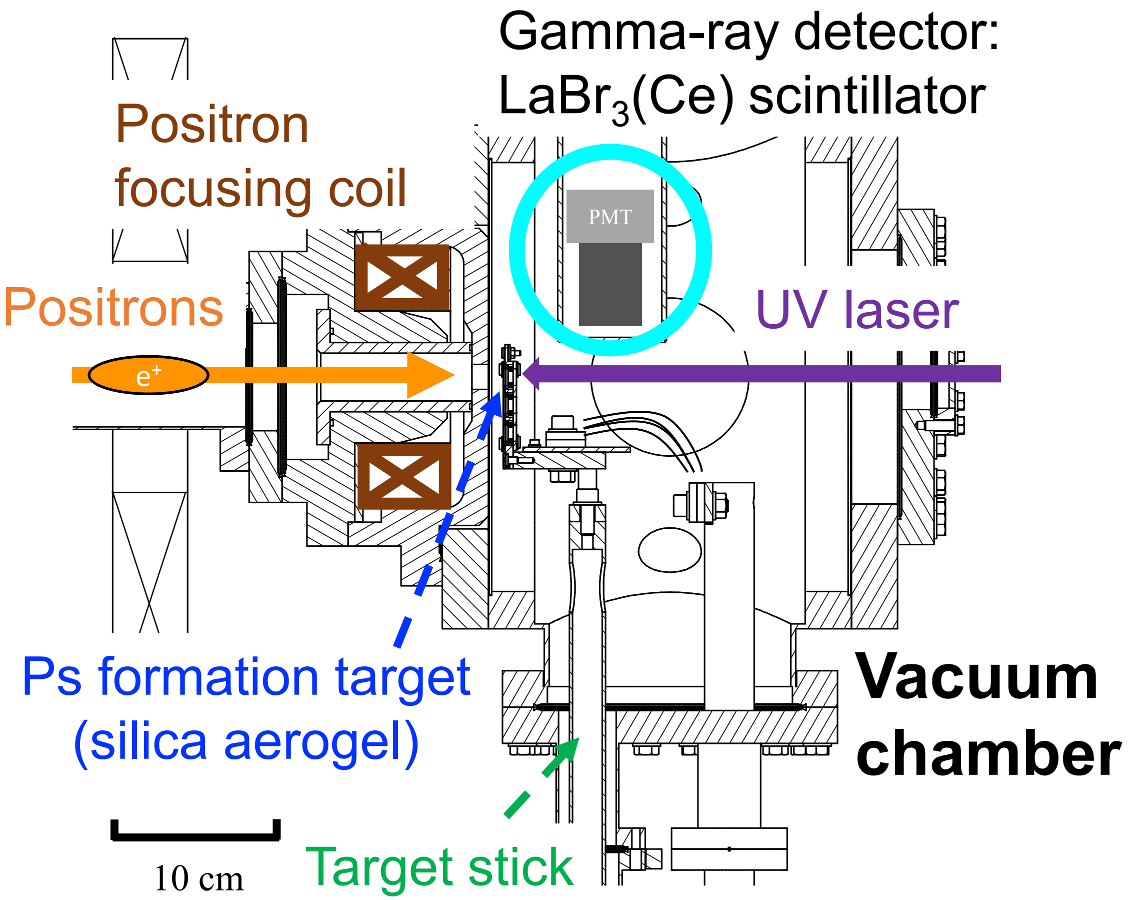


Experimental setup at KEK-SPF

KEK-SPF B1 beamline



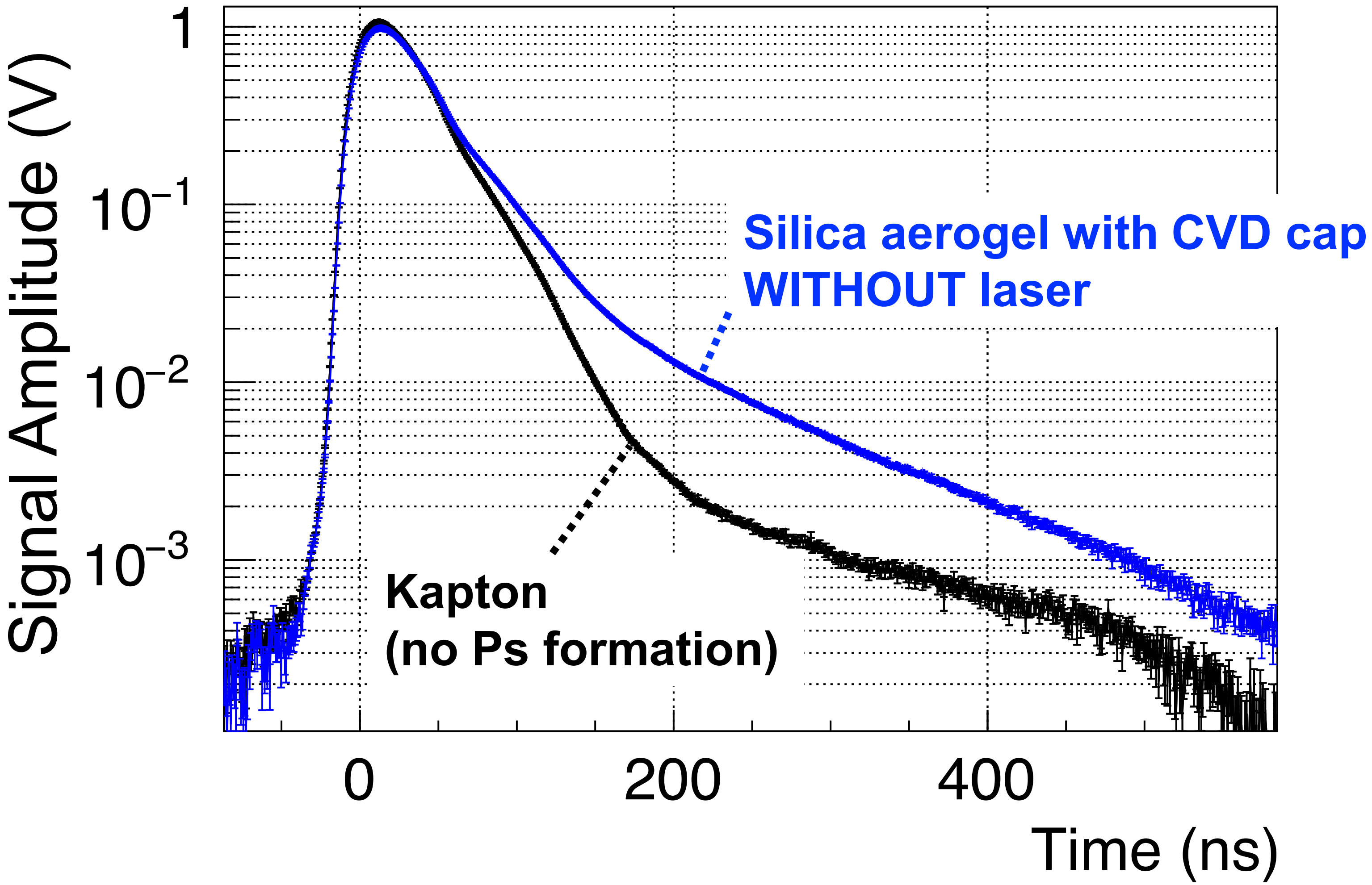
Energy	5 keV
Intensity	～10^4 e^+/ pulse
Repetition	50 Hz
Pulse width	16 ns
Size	Ø～10 mm



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

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

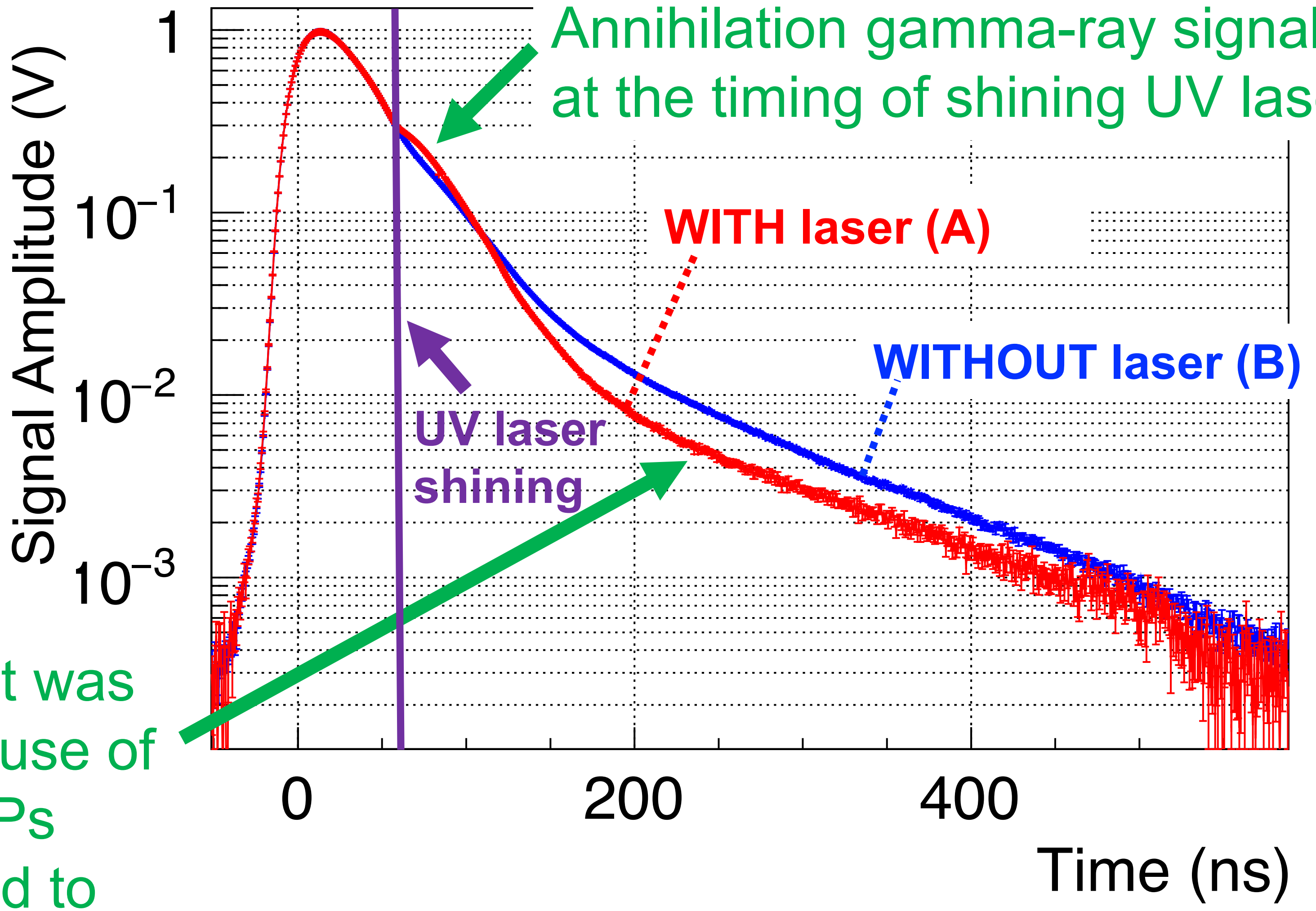
Slow component of *o*-Ps annihilations was confirmed in silica-aerogel timing spectrum without shining UV laser.



PMT signals made by annihilation gamma-rays detected by $LaBr_3(Ce)$ scintillator

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

2P-Ps annihilates into gamma-rays immediately in silica aerogel.



Long component was decreased because of annihilations of Ps which are excited to 2P state.

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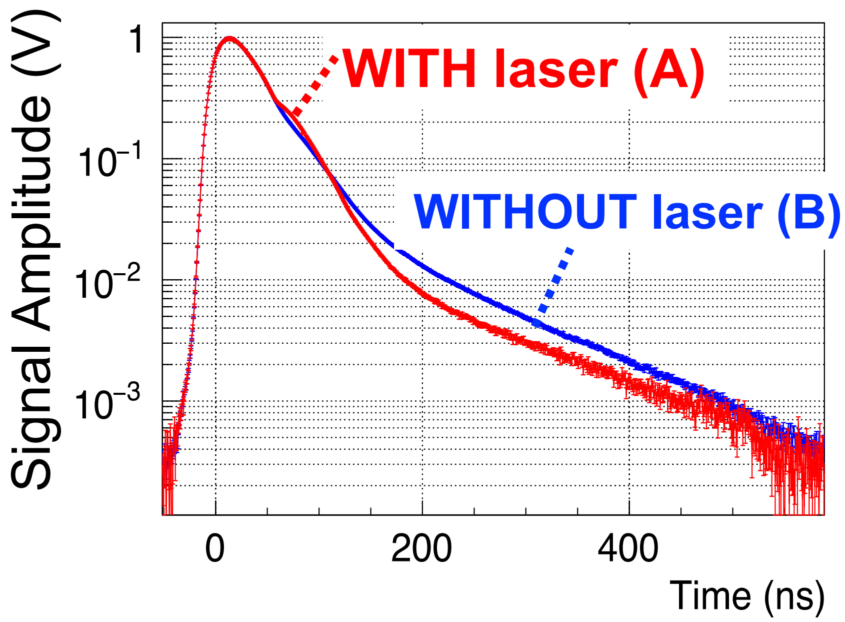

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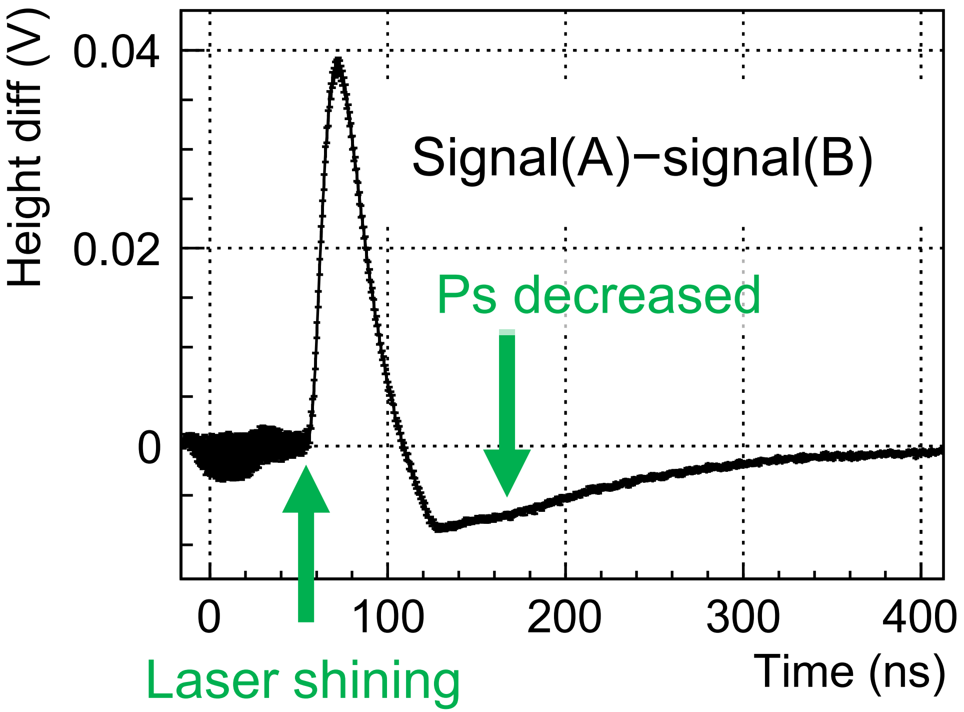
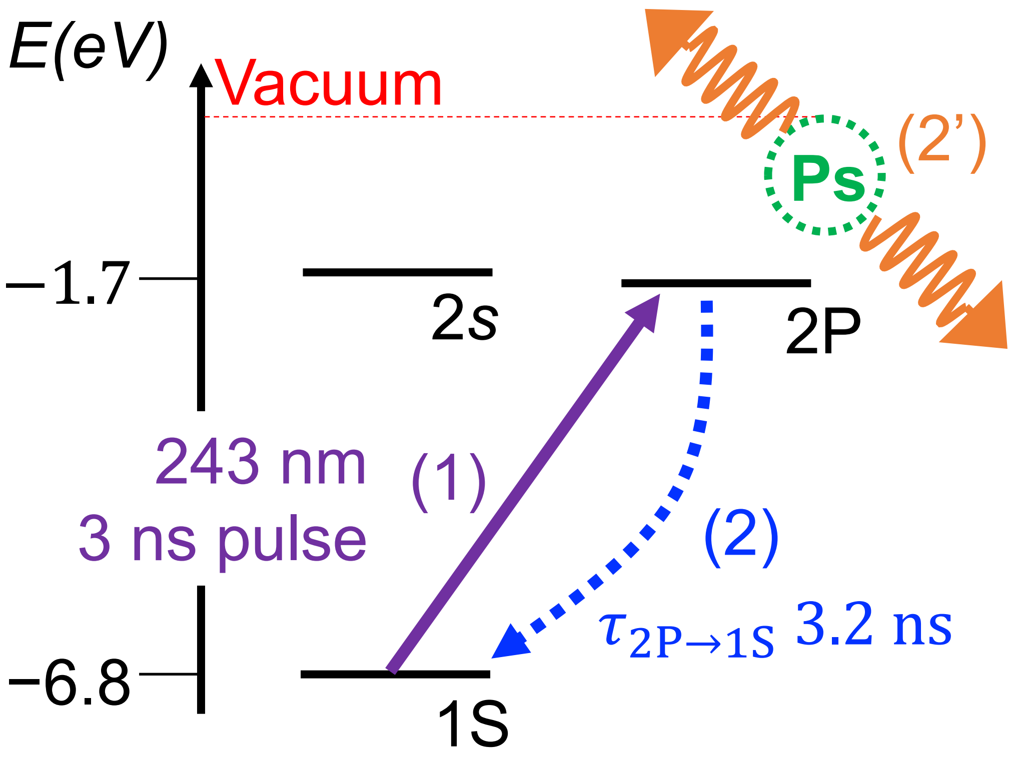


Signal difference caused by shining UV laser

Only UV laser of 300 μJ pulse caused Ps annihilations to gamma-rays.
Lifetime of 2P-Ps is short in silica aerogel.
This means **<u>Ps laser cooling inside the silica aerogel pores is very difficult.</u>**

Test experiment to excite 1S-Ps inside the silica aerogel pores to 2P state by shining 243 nm, 3 ns pulsed UV laser.



Ps energy levels

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  →***Good for laser cooling***

(2') If lifetime of 2P-Ps inside pores is short (as reported in B. S. Cooper et al. PRB 97, 205302 (2018).)**...**

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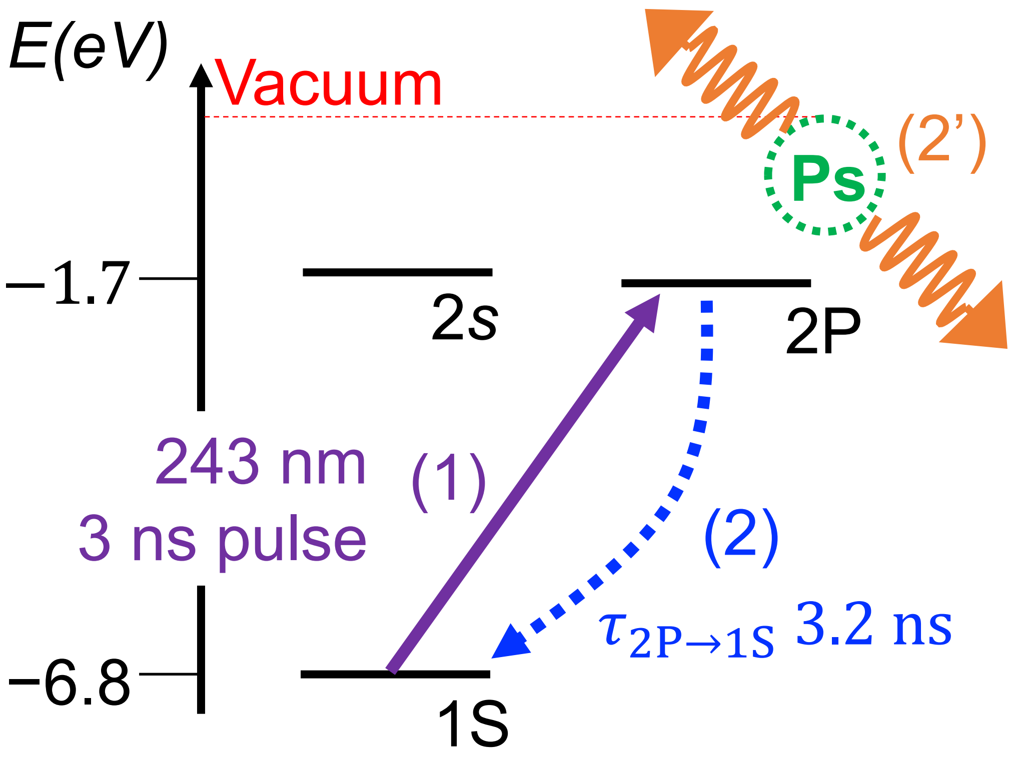


Ps energy levels

R&D of Ps formation material other than silica aerogel is also ongoing.

Unfortunately, (2') was the case.

Ps laser cooling inside the silica aerogel pores is very difficult.

We are currently trying a Ps laser cooling in vacuum.

(2') If lifetime of 2P-Ps inside pores is short (as reported in B. S. Cooper et al. PRB 97, 205302 (2018).)**...**

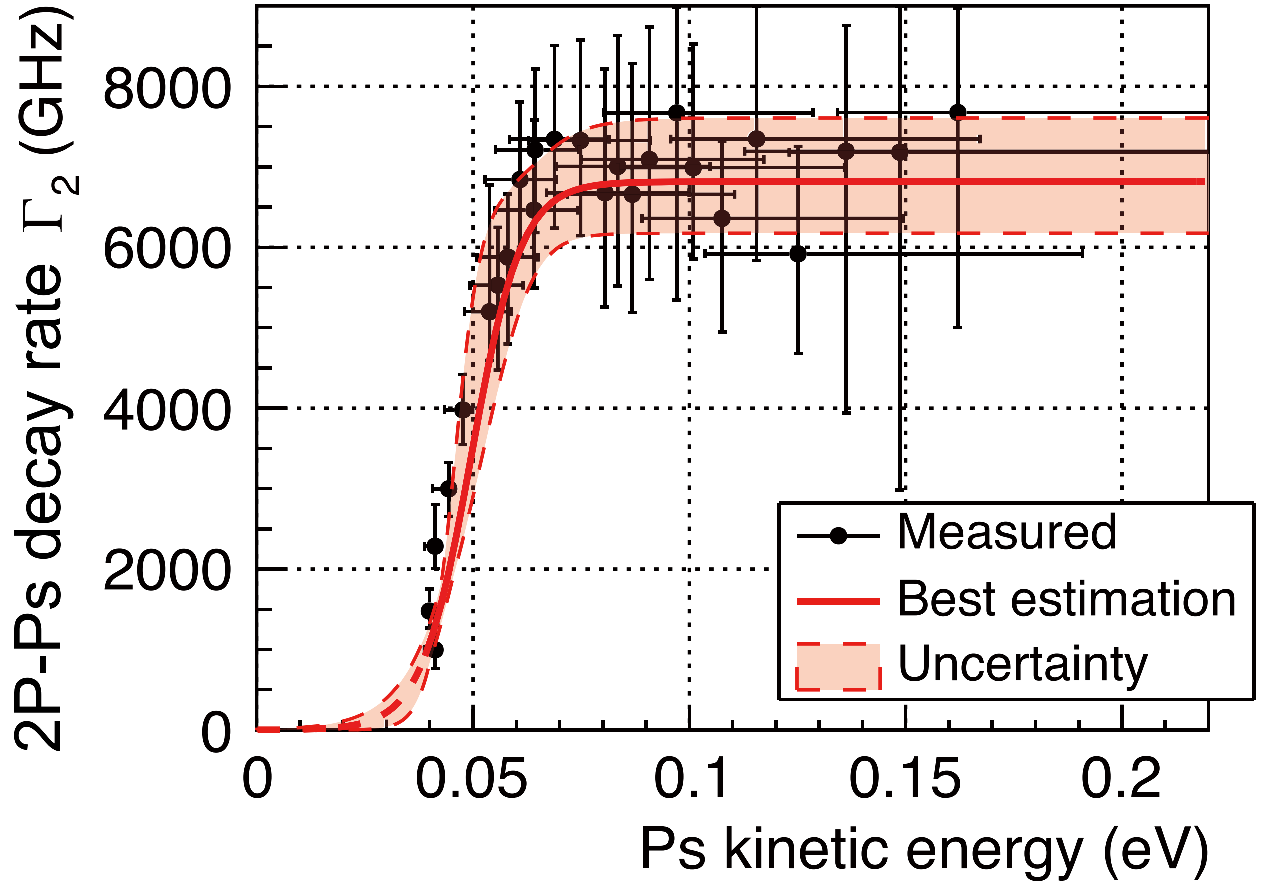
- Annihilation rate to gamma-rays is increased.

  →***Bad for laser cooling***

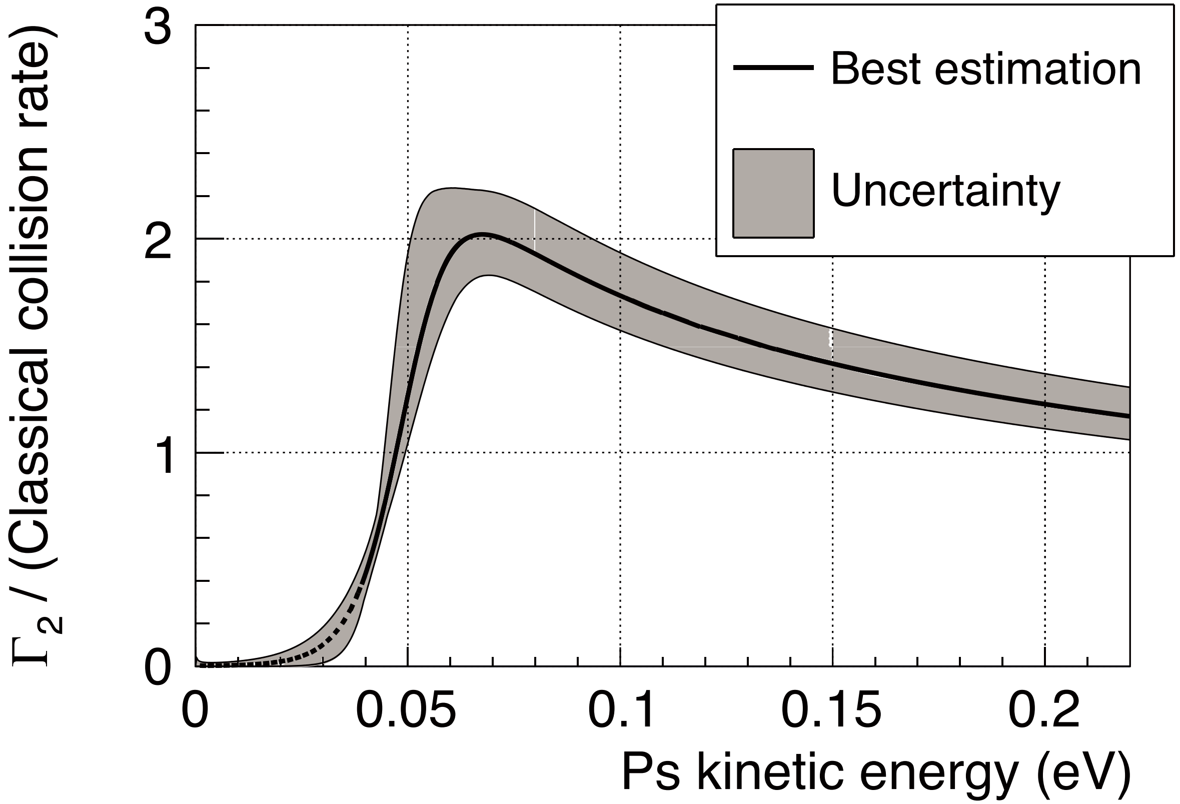
There is an indication that the 2P-Ps decay rate at low Ps temperature might be low enough for Ps laser cooling.

We measured the 2P-Ps decay rate at different laser irradiation timings.

Ps temperature depends on the timing because of the Ps thermalization.



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

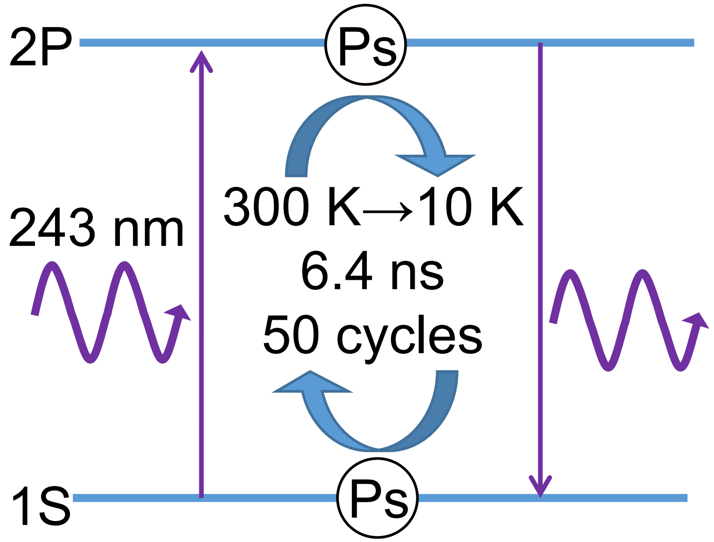


We are planning to measure the 2P-Ps decay rate at cryogenic temperatures this winter.

Requirements for Ps cooling laser

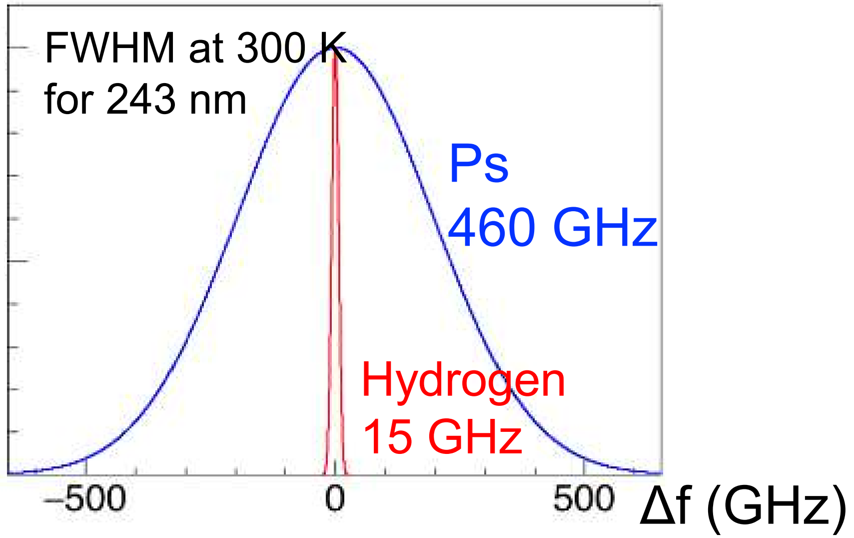
→ 243 nm sub-μs pulsed, broadband, and frequency-chirped laser

1. <u>Long pulse duration and sufficient pulse energy</u> ← Ps lifetime: 142 ns



- 1S—2P (243 nm)
- 6.4 ns × 50 ≈ 300 ns → Cool down Ps with 300-ns single pulse
- Pulse energy ≥ 40 μJ

2. <u>Broadband and frequency-chirped</u> ← Ps light mass: $2m_e$



- Doppler broadening is **30 times larger than hydrogen**.
- To follow the change in the Doppler profile by cooling (300 K to 10 K in 300 ns) → Broadband (≥ 10 GHz) and Frequency chirp ≥ +0.2 GHz ns^{-1}

Chirped Pulse-Train Generator (CPTG)

PHYSICAL REVIEW APPLIED **16,** 014009 (2021)

Theoretical Analysis and Experimental Demonstration of a Chirped Pulse-Train Generator and its Potential for Efficient Cooling of Positronium

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M. Kuwata-Gonokami,[1] E. Chae,[2,4,5] K. Shu,[1,2,4] and K. Yoshioka[2,4,*]

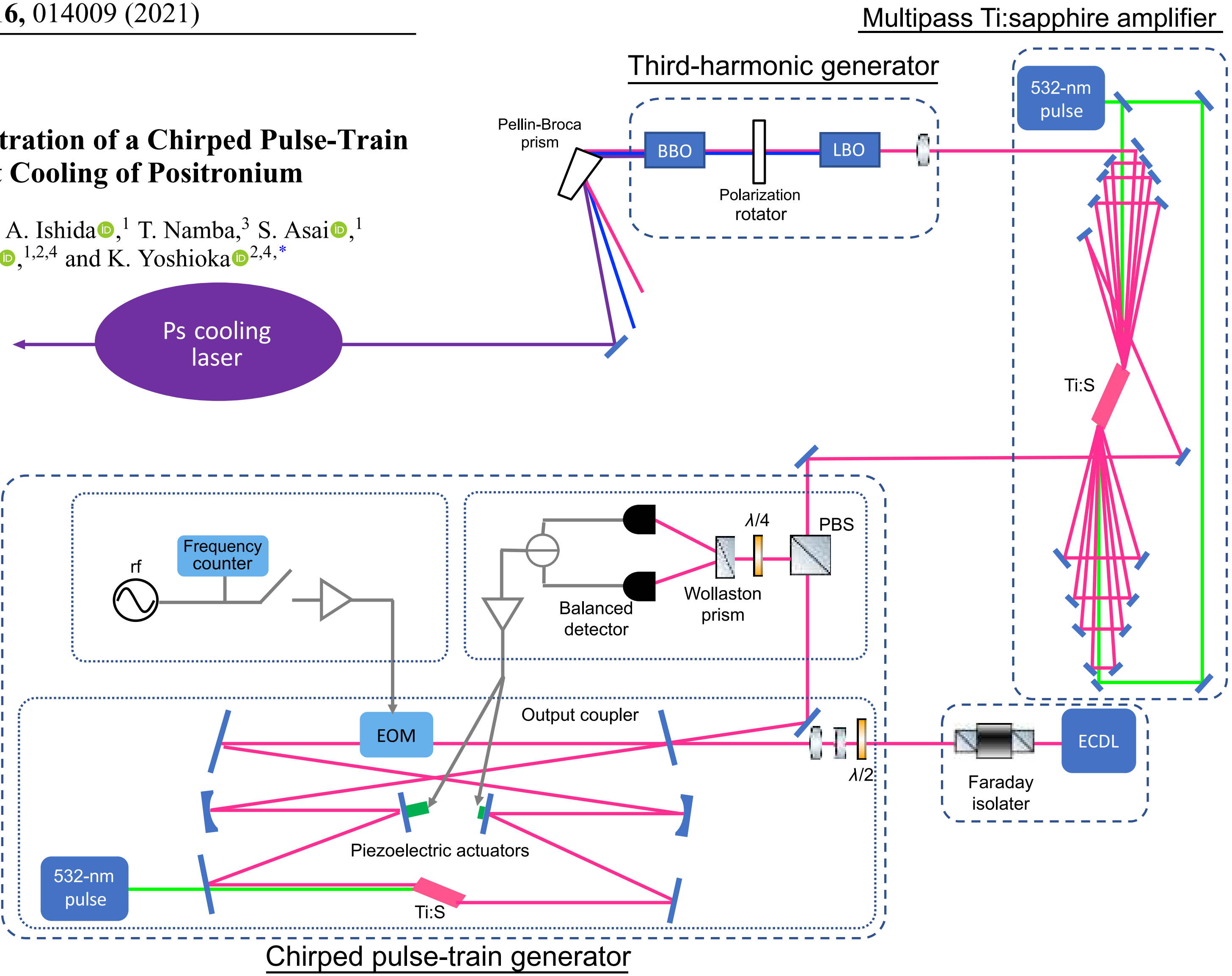
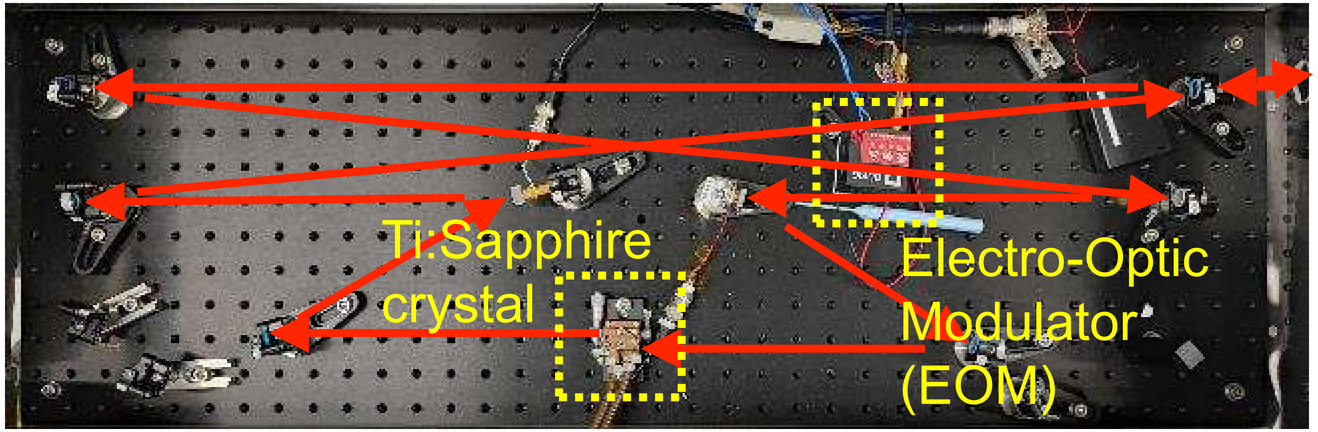
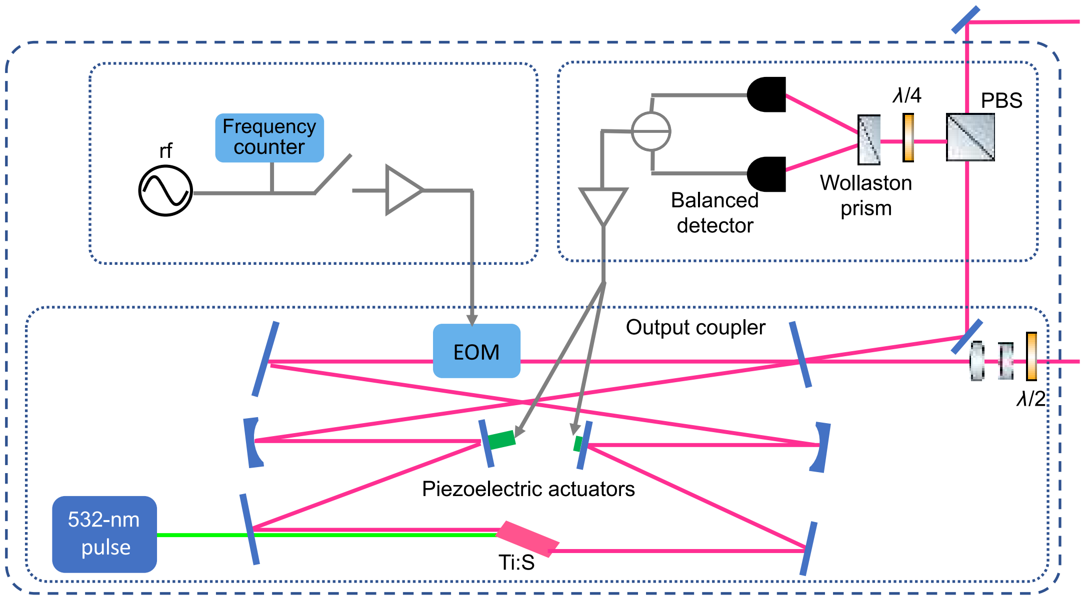


FIG. 1. Schematic of the prototypical cooling laser system. ECDL, external-cavity diode laser; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; EOM, electro-optic phase modulator; rf, driving radio frequency; Ti:S, Ti:sapphire crystal; PBS, polarizing beam splitter; LBO, lithium triborate crystal; BBO, β-barium borate crystal.

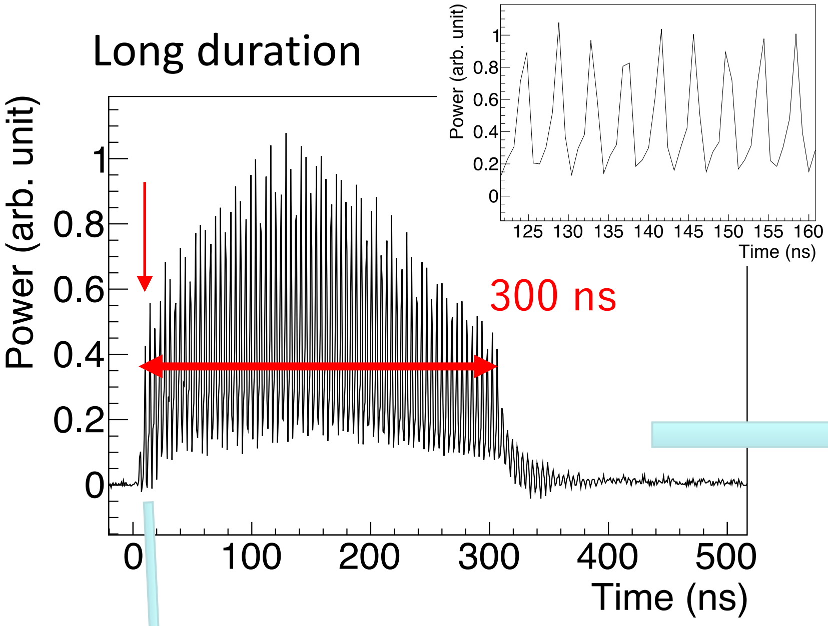
Ps cooling laser





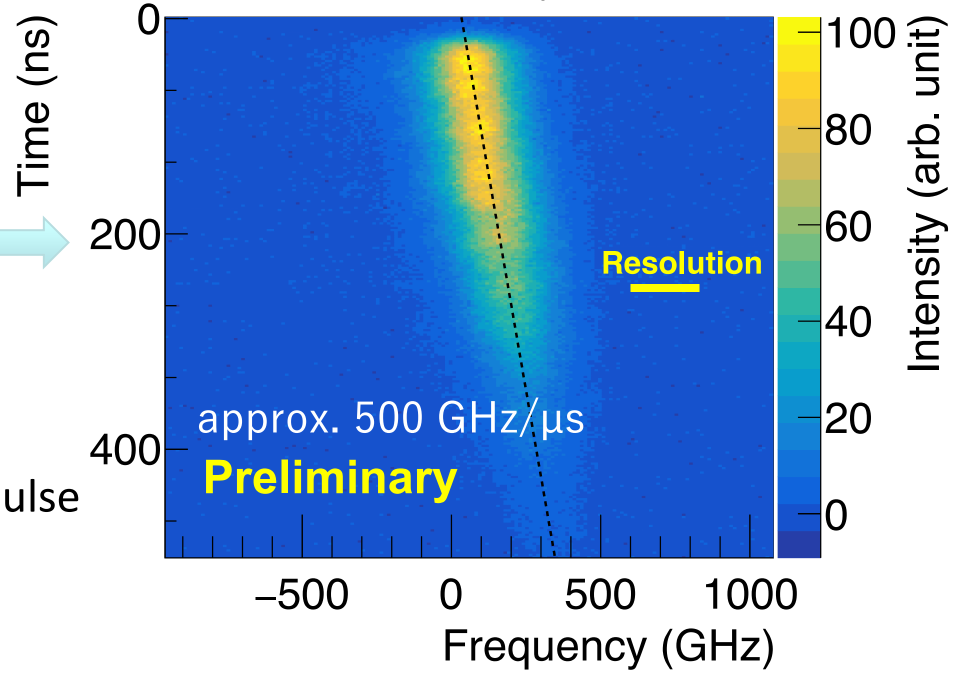
Chirped pulse-train generator

Using a chirped train of optical pulses (Yoshioka group)

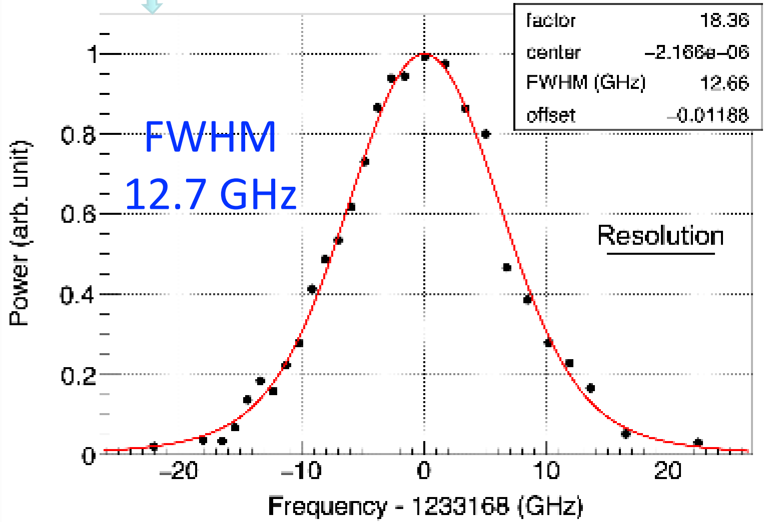


A laser for efficient laser cooling of Ps
K. Shu *et al.*, submitted

Fast chirp



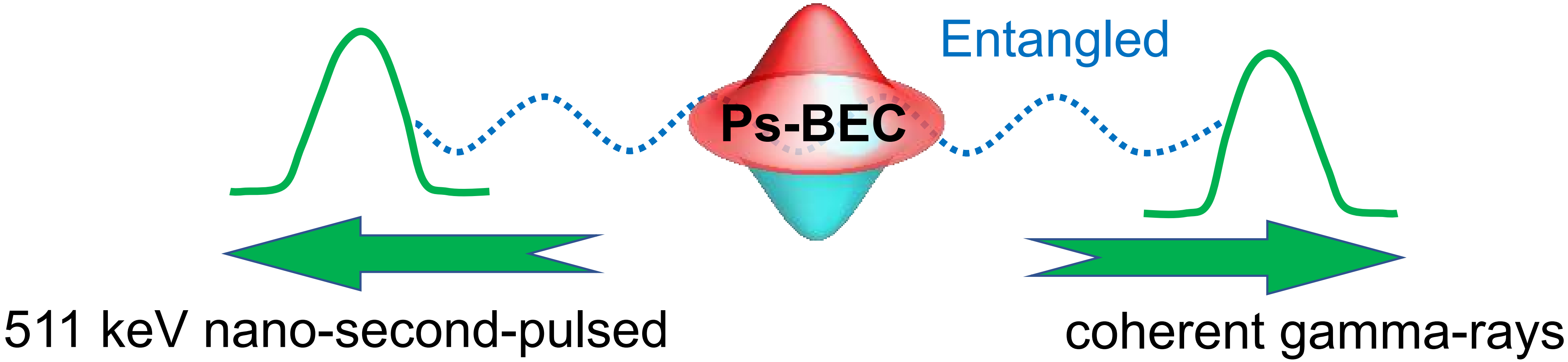
Broadband spectrum of a selected pulse



POSMOL 2023, August 5
talk by K. Yoshioka
(The University of Tokyo)

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.



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