Excitation of positronium by laser for efficient cooling

Kenji Shu[1,3],

K. Yamada[1], K. Hashidate[1,3], A. Ishida[1], T. Namba[1], S. Asai[1], M. Kuwata-Gonokami[1],

Y. Tajima[2], E. Chae[2], K. Yoshioka[2], N. Oshima[3], B. E. O'Rourke[3], K. Michishio[3],

K. Ito[3], K. Kumagai[3], R. Suzuki[3], S. Fujino[4], T. Hyodo[5], I. Mochizuki[5], K. Wada[6] and T. Kai[7]

1 SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO ICEPP The University of Tokyo 2 APSA Advanced Photon Science Alliance UT-PSC

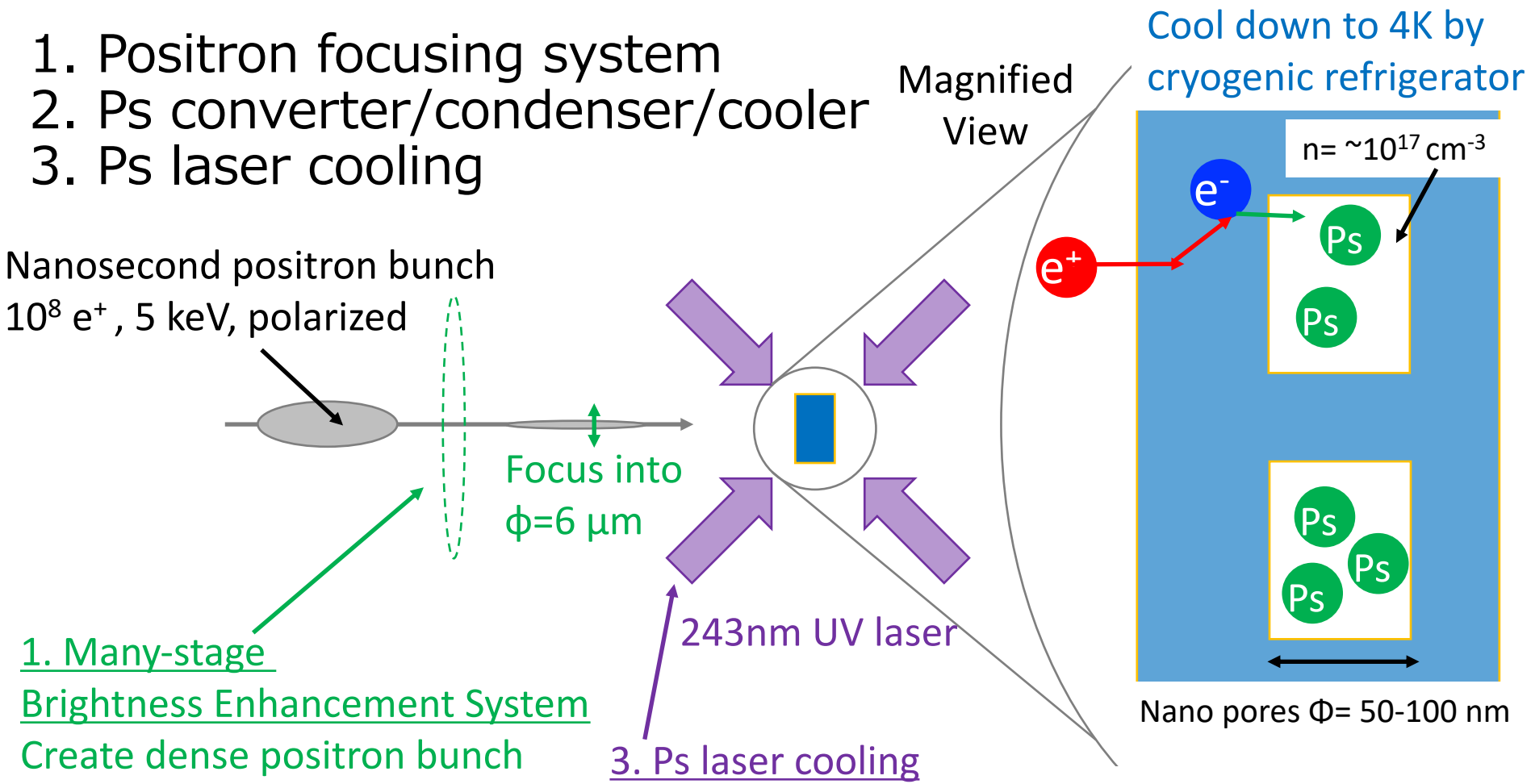
3 AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST) 4 GIC 5 KEK 6 QST 7 JAEA

Supported by JSPS KAKENHI Grant Numbers JP16H04526, JP17H02820, JP17H06205, JP17J03691, JP18H03855, JP19H01923, MATSUO FOUNDATION, Mitutoyo Association for Science and Technology (MAST), Research Foundation for Opto-Science and Technology, and TIA Kakehashi TK17-046, TK19-016.

https://tabletop.icepp.s.u-tokyo.ac.jp/?page_id=365

Our new idea to realize Ps-BEC

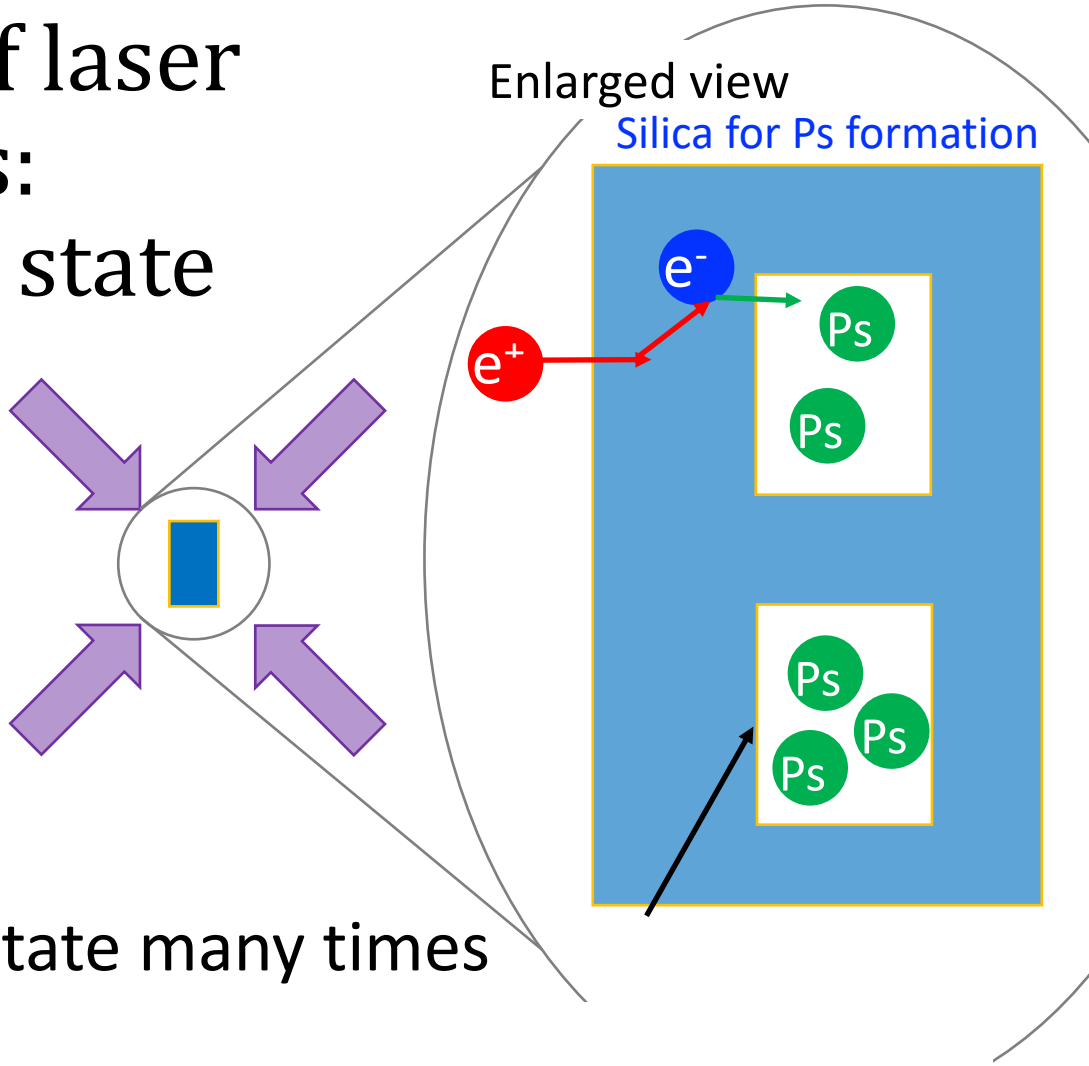
1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling



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)

Key technology of laser cooling of Ps: Exciting Ps to 2P state

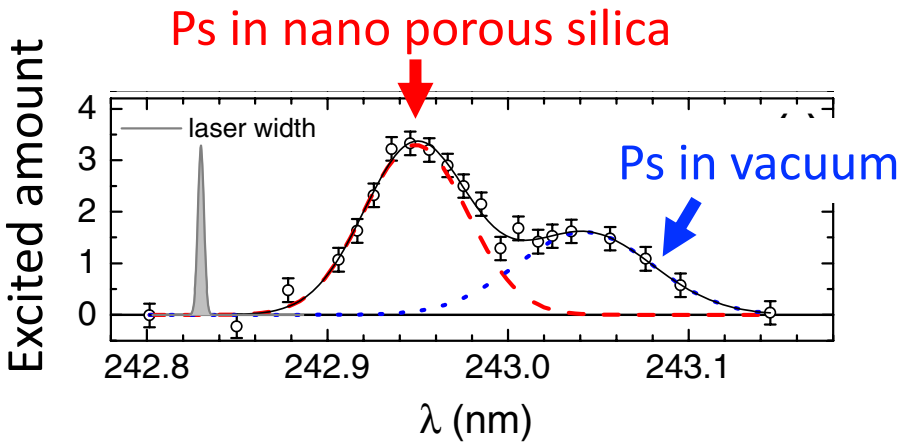


Ps will be excited into 2P-state many times during laser cooling

Interactions of 2P-state Ps with materials are not well known.

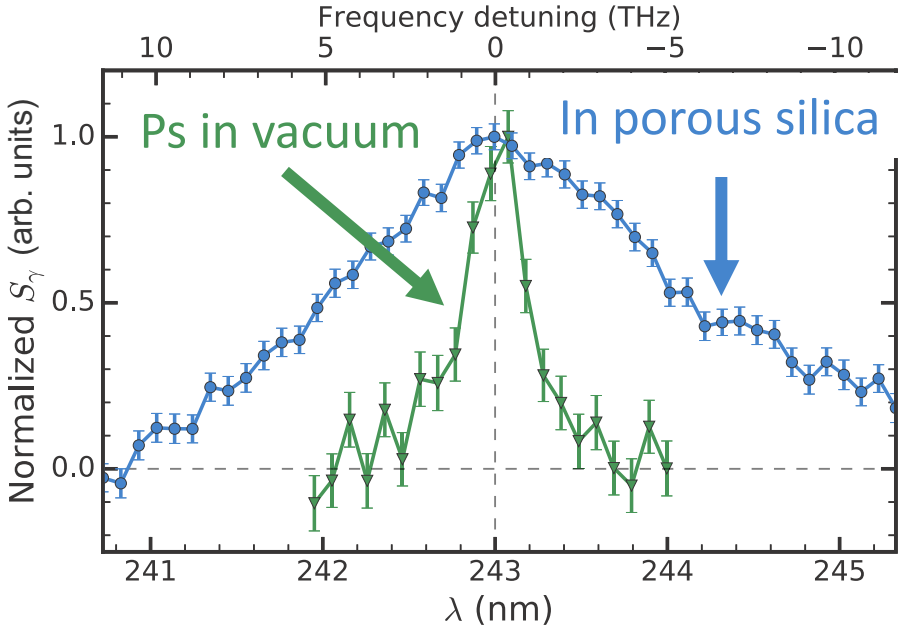
2P-Ps were reported to be strongly affected by material

Excited amounts to 2P-Ps were measured against excitation laser wavelength



D. B. Cassidy et al. PRL 106, 023401 (2011).

- Resonance frequency shifted
- Width narrowed

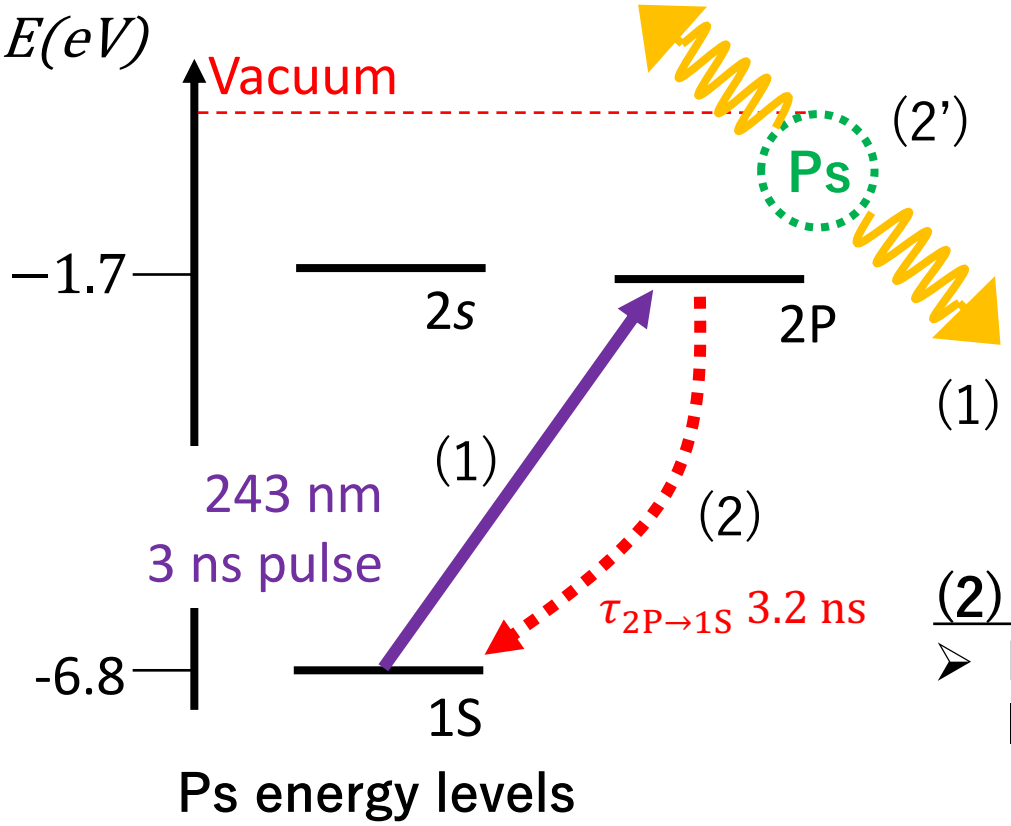


B. S. Cooper et al. PRB 97, 205302 (2018).

- Width broadened
- 2P-Ps decays in very short lifetime

Contradicting effects have been reported. These effects make laser cooling difficult.
We manufactured well-characterized silica cavity and observed 2P-Ps behavior.

Exciting Ps to 2P state by shining 243 nm, 3 ns pulsed UV laser.



Ps energy levels

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

(2) If nothing special happens...

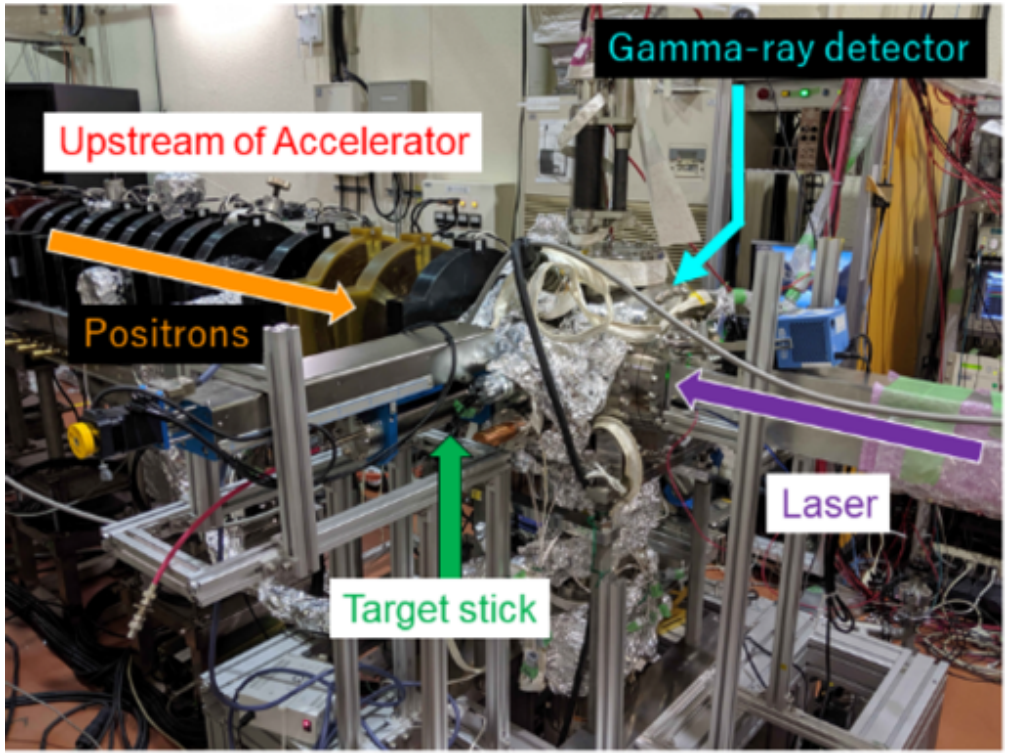
- Ps is de-excited to 1S state with lifetime of 3.2 ns (Lyman-alpha).

(2') If lifetime of 2P-Ps inside pores is short as reported...

- Annihilation gamma-rays will be increased.

Experimental setup at KEK slow positron facility (KEK-SPF) in Tsukuba, Japan

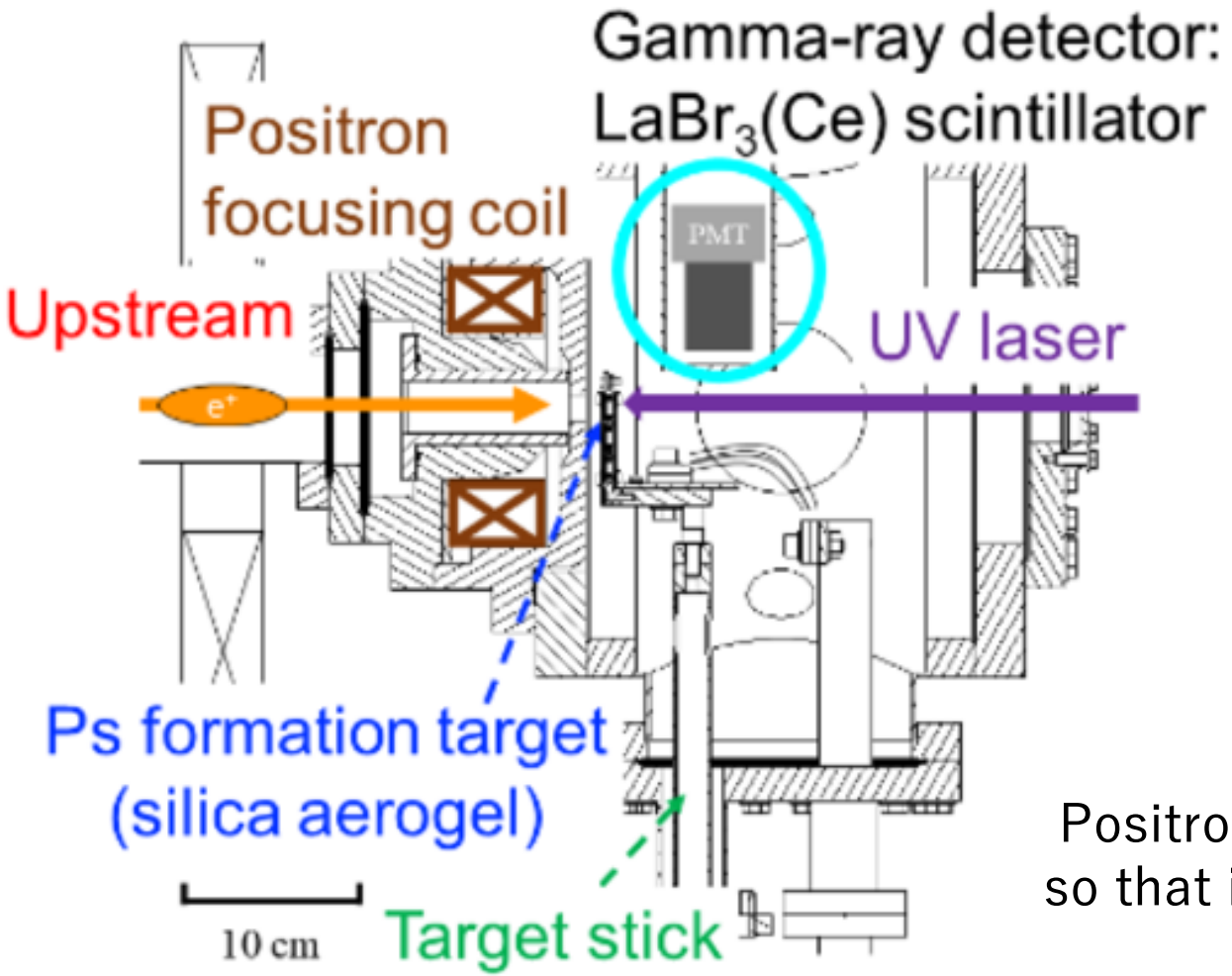
KEK-SPF B1 beamline



Energy	5 keV
Highest Intensity	10^5 e^+/ pulse
Repetition	50 Hz
Time width	16 ns
Size	Φ ～10 mm

Operated in short pulse mode to synchronize with the pulse laser

Experimental setup at KEK slow positron facility (KEK-SPF) in Tsukuba, Japan

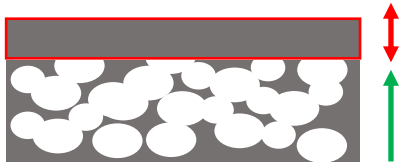


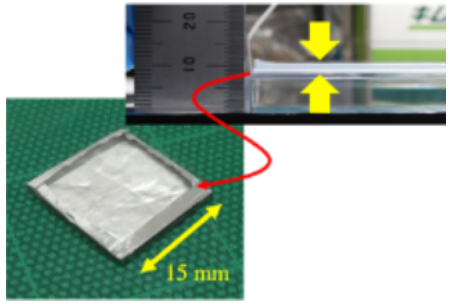
Vacuum chamber cross section

Positrons are focused to 4 mm so that it matches the laser size.

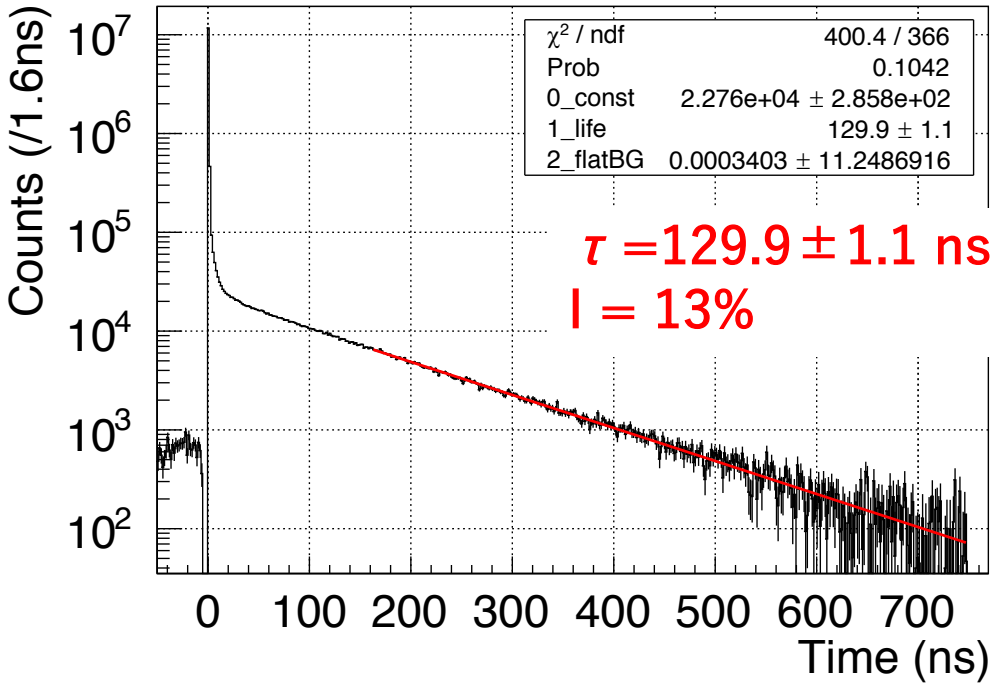
We used silica aerogel as silica cavity. Capped the surface of the aerogel by amorphous silica thin film using plasma CVD.

Silica aerogel 0.1 g cm^{-3}
50 nm pores
0.5 mm thick





CVD thickness 75 nm



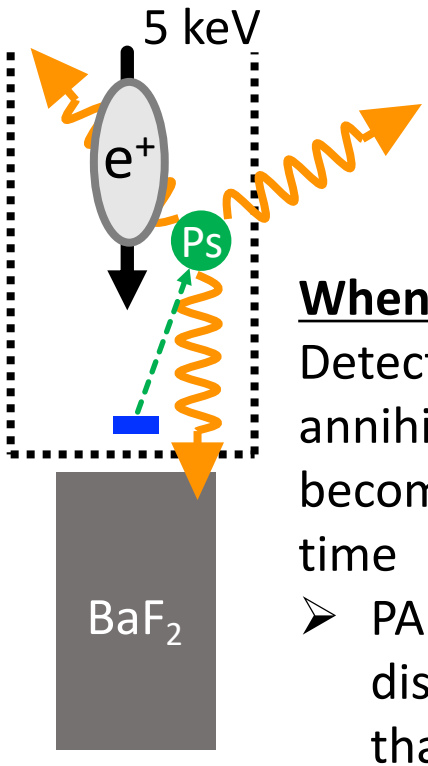
Timing spectrum of bulk-PALS measurement using ^{22}Na with t=1 mm silica aerogel

- Consistent with the lifetime expected in 50 nm pores.
- High Ps formation fraction (50% of stopped positrons)

➢ We obtain *o*-Ps in the pores as expected.

Confining of Ps in pores was observed by the blocking cap

- PALS measurement by slow positron beam was conducted to confirm Ps confinement in pores

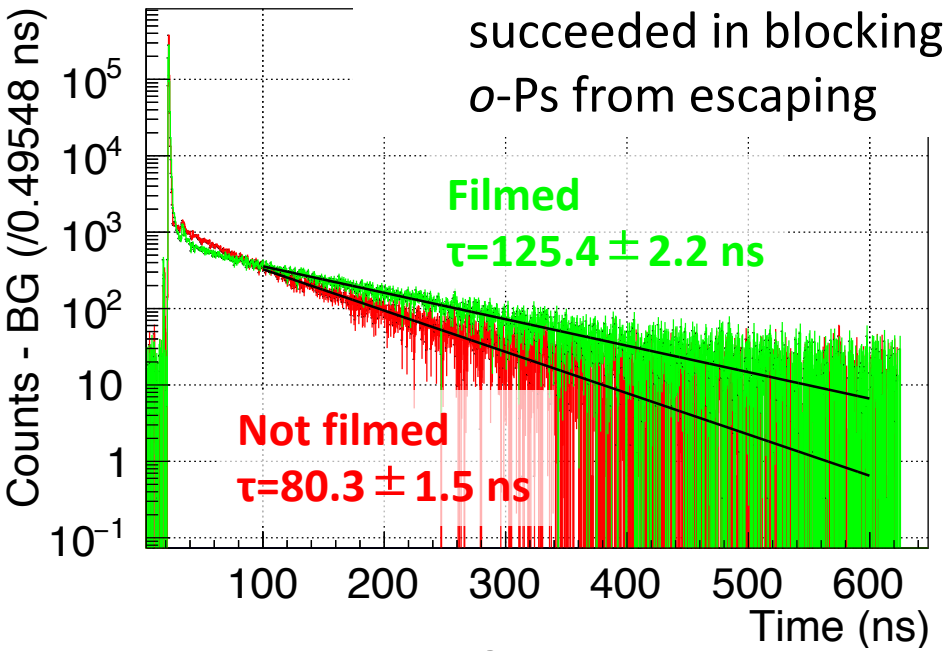


When *o*-Ps escaped …

Detection efficiency of annihilation gammas becomes less and less by time

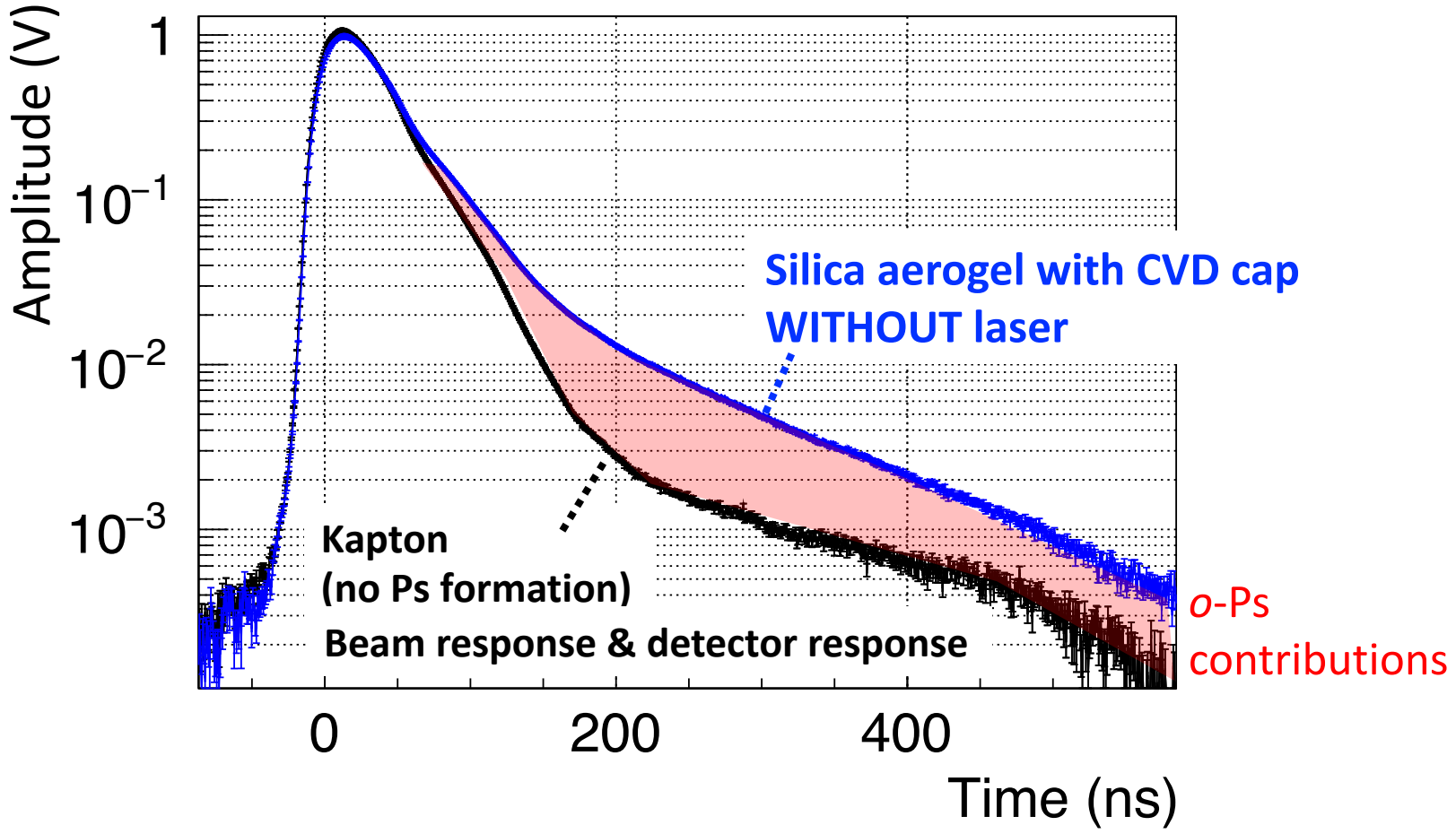
- ➢ PALS spectrum will be distorted to pretend that *o*-Ps has short lifetime

- ✓ By non-porous film, succeeded in blocking *o*-Ps from escaping



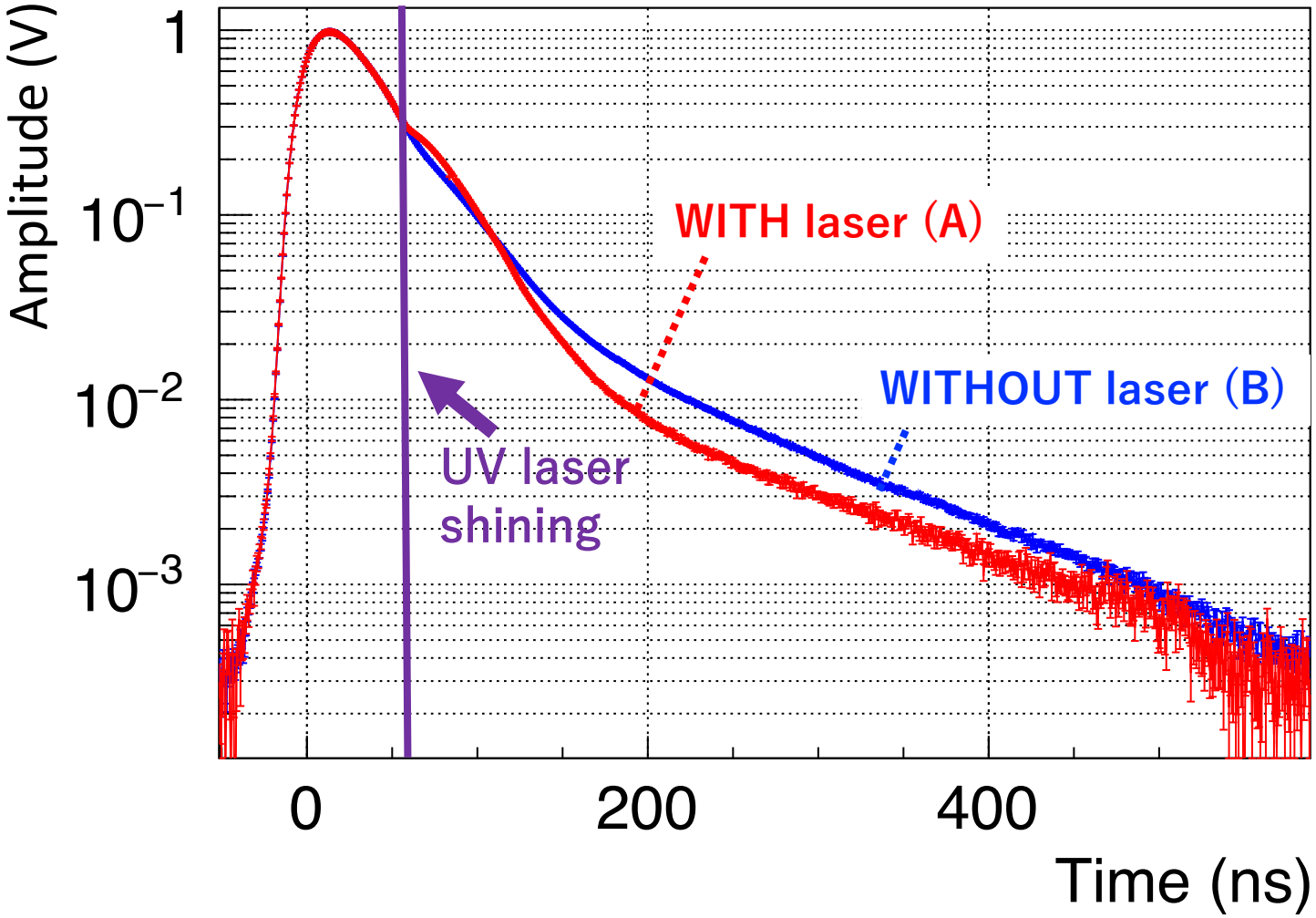
PALS spectra

o-Ps were observed by delayed gamma-rays



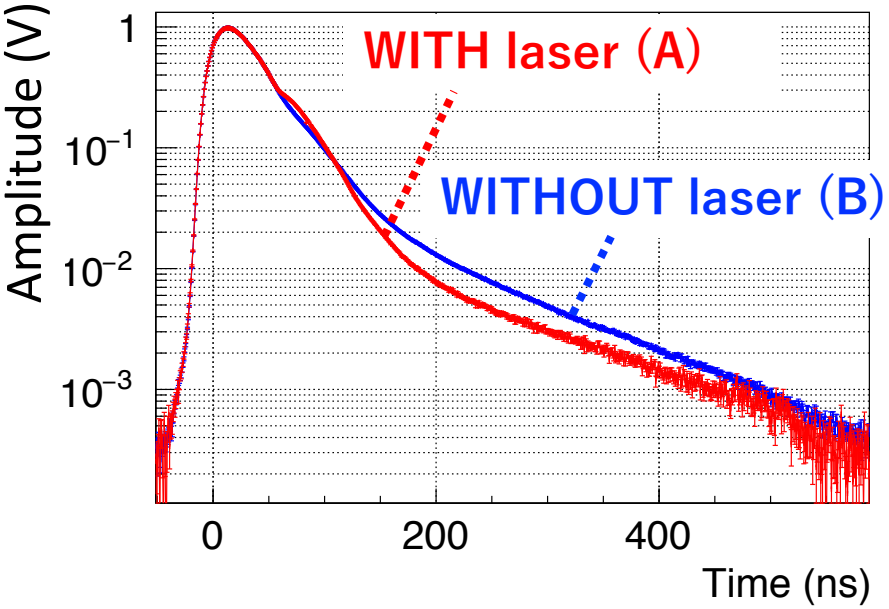
PMT signals made by annihilation gamma-rays detected by $LaBr_3$(Ce) scintillator (signal amplitude)

2P-Ps decays into gamma-rays immediately in silica aerogel

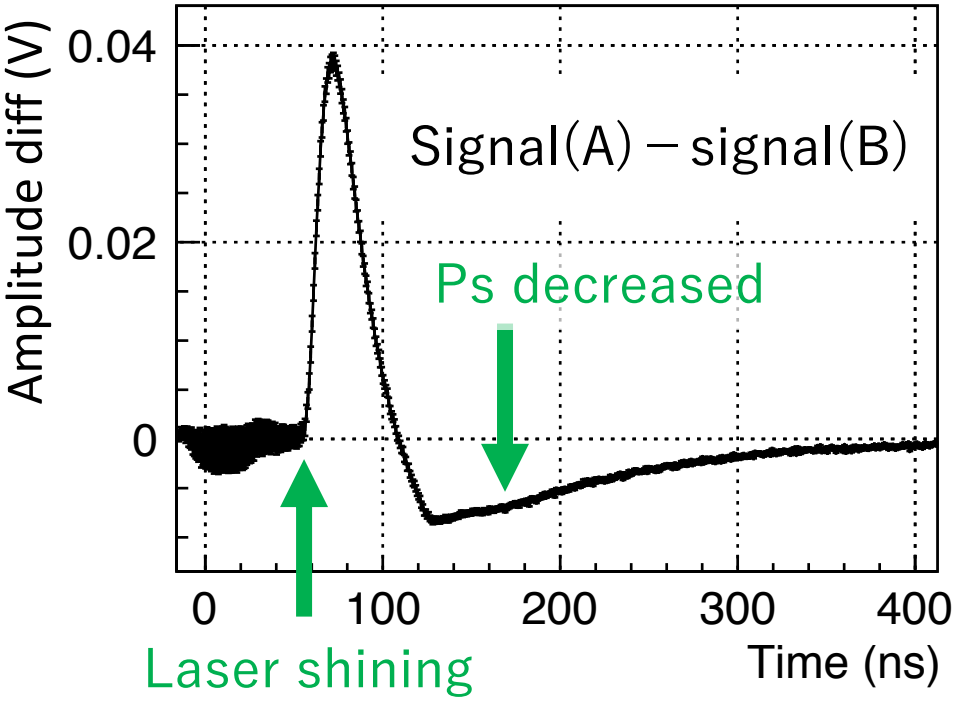


PMT signals made by annihilation gamma-rays detected by $LaBr_3(Ce)$ scintillator (signal amplitude)

2P-Ps decays into gamma-rays immediately in silica aerogel



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

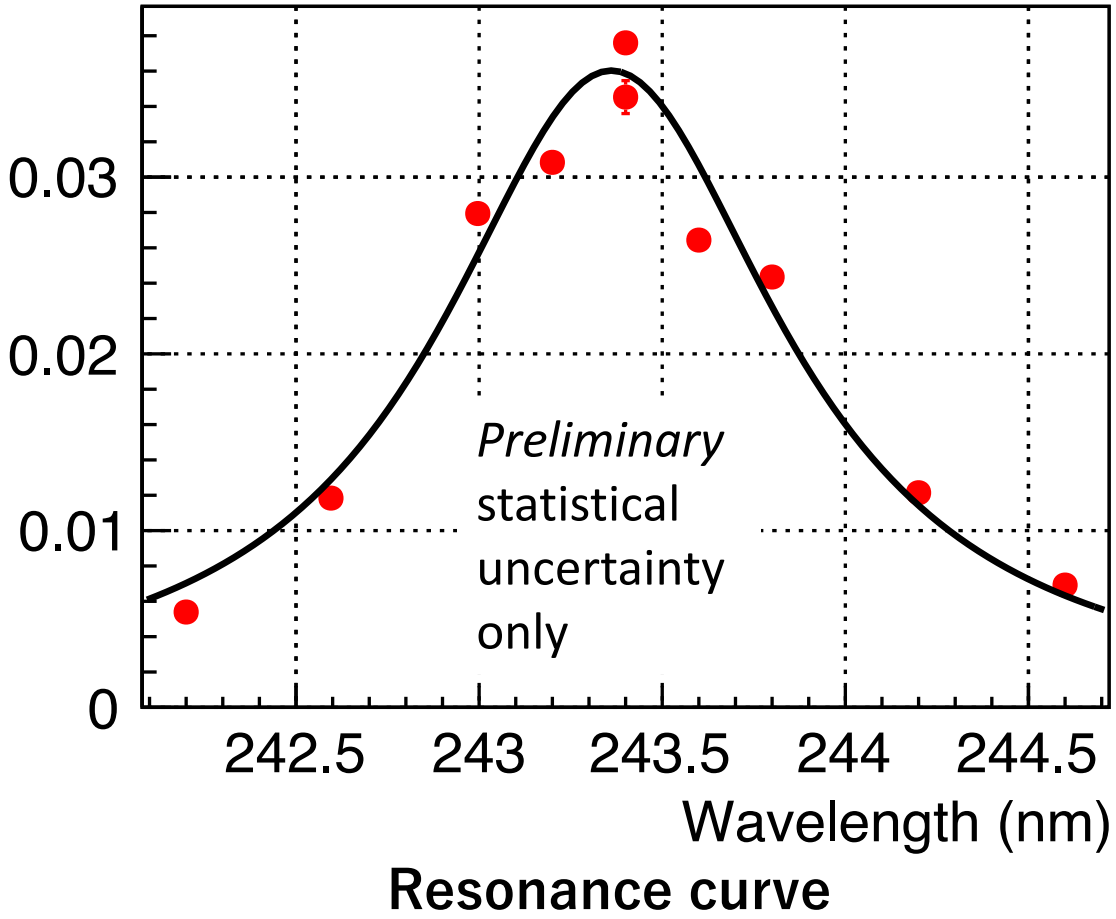


Signal difference caused by shining UV laser

Only UV laser of 300 μJ pulse induced Ps decay to gamma-rays.
Lifetime of 2P-Ps is short in silica aerogel.

Broad resonance (1 nm)
Lifetime or something else?

2P-Ps decay rate was scanned against UV laser wavelength



Broad resonance: 1 nm

cf.)

Natural width: 0.06 pm

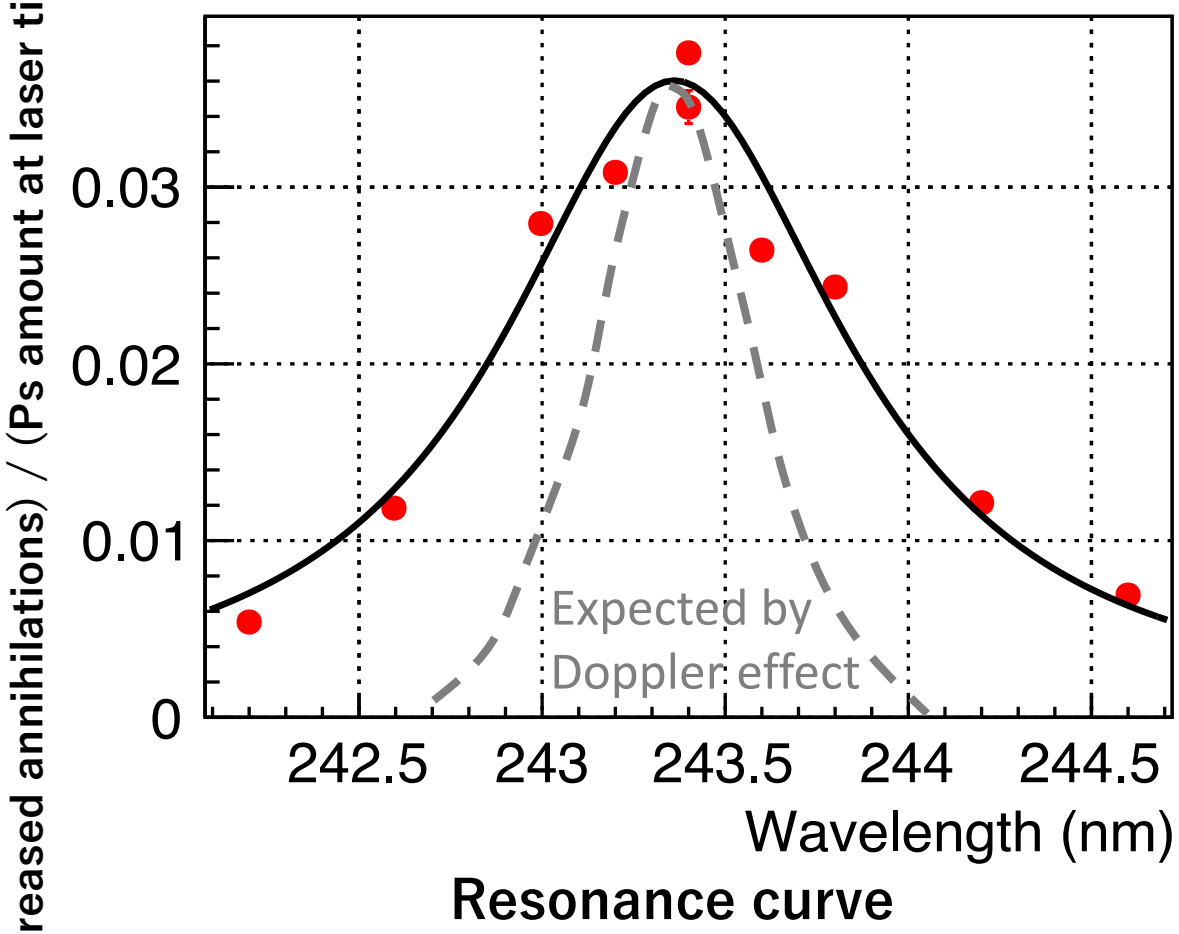
Doppler broadening at 1 eV:
0.5 nm

- Equivalent lifetime is 30 fs (< mean free time in the silica pores ~*O*(100 fs))
- Other reason?
  ex) Stark effect
  (Prof. Saito)

Laser cooling of Ps in silica aerogel seems to be very difficult....

Broad resonance (1 nm)
Lifetime or something else?

2P-Ps decay rate was scanned against UV laser wavelength



Broad resonance: 1 nm

cf.)

Natural width: 0.06 pm

Doppler broadening at 1 eV: 0.5 nm

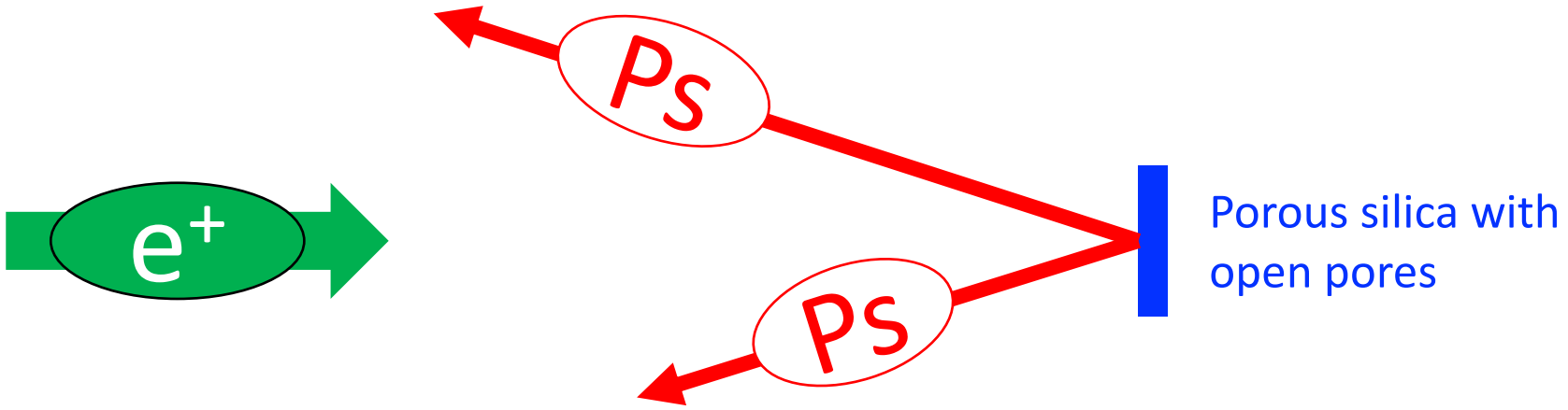
- Equivalent lifetime is 30 fs (< mean free time in the silica pores ~*O*(100 fs))
- Other reason?
  ex) Stark effect
  (Discussed with Prof. Saito)

Laser cooling of Ps in silica aerogel seems to be very difficult....

Next steps

1. Mechanisms of annihilation and broadening will be studied
   - Other porous silica
   - Different materials. Tungsten, Zeolite, Zirconia, …
   - Any idea?

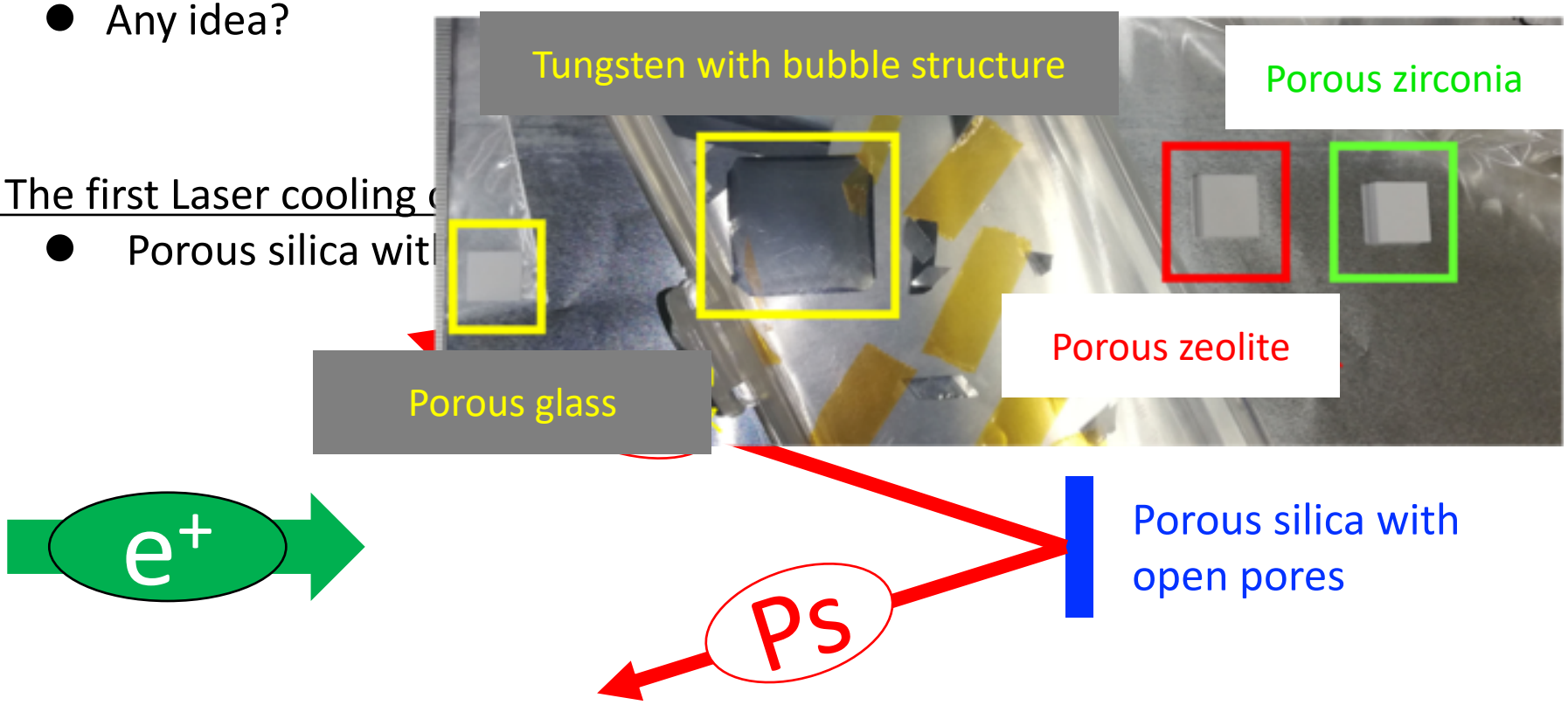
2. The first Laser cooling of Ps in vacuum will be conducted to measure its efficiency
   - Porous silica with open pores will be used



Next steps

1. Mechanisms of annihilation and broadening will be studied
   - Other porous silica
   - Different materials. Tungsten, Zeolite, Zirconia, …
   - Any idea?

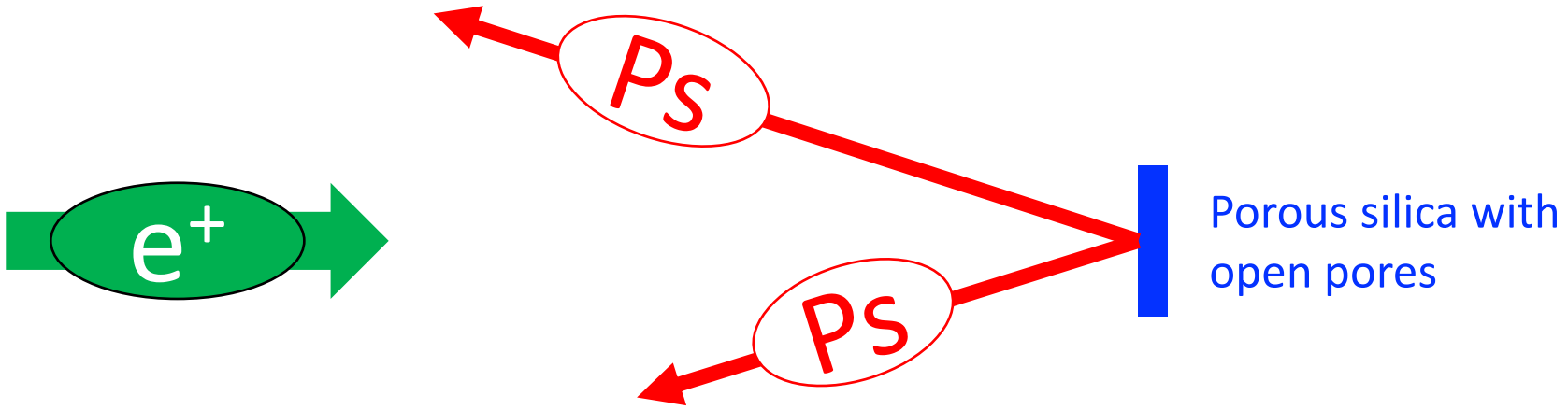
2. The first Laser cooling o
   - Porous silica wit



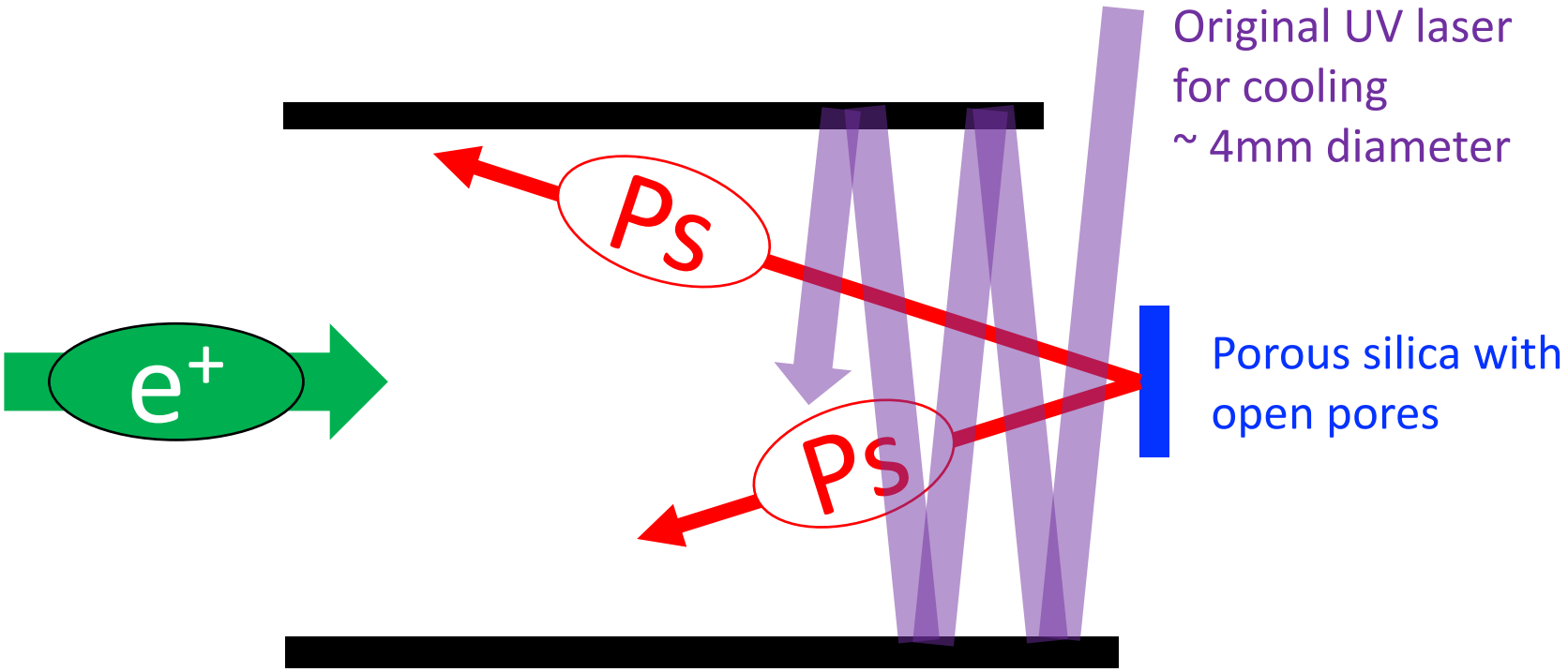
Next steps

1. Mechanisms of annihilation and broadening will be studied
   - Other porous silica
   - Different materials. Tungsten, Zeolite, Zirconia, …
   - Any idea?

2. The first Laser cooling of Ps in vacuum will be conducted to measure its efficiency
   - Porous silica with open pores will be used



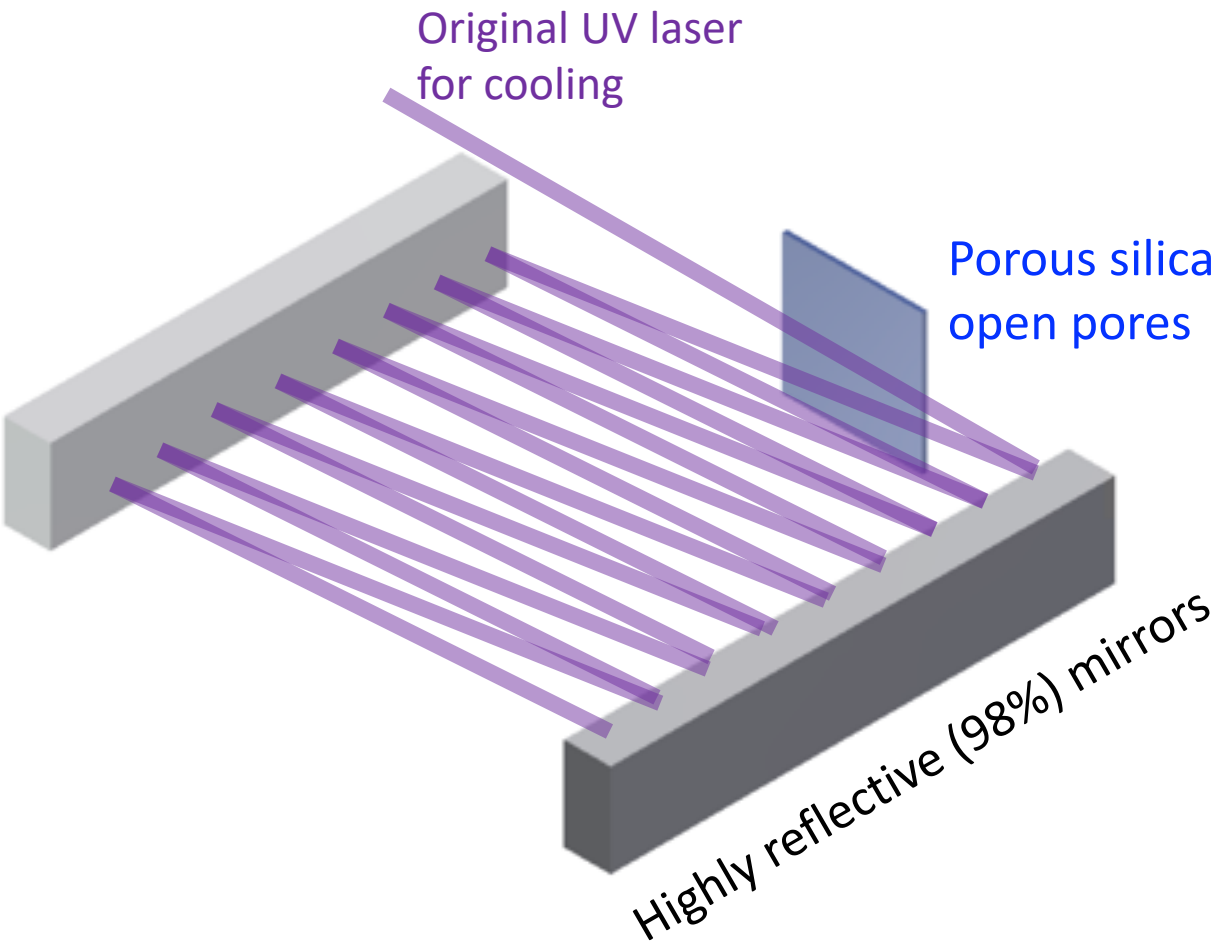
Ps - laser interaction regions will be enlarged



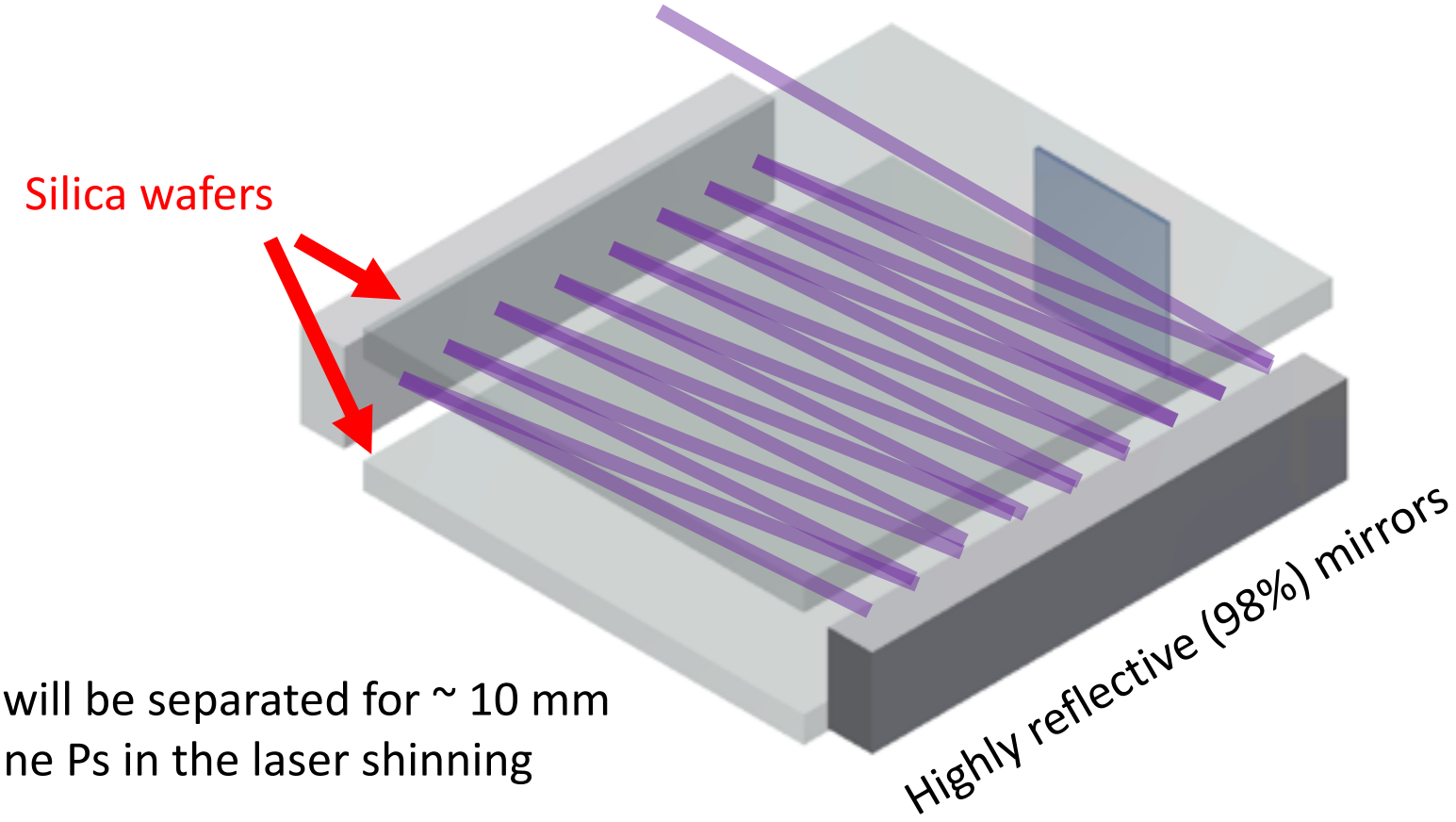
Highly reflective (98%) mirrors

- Ps will travel 50 mm during the laser cooling process
- UV laser will be reflected ~ 20 times

Ps will be confined in vertical direction to the laser

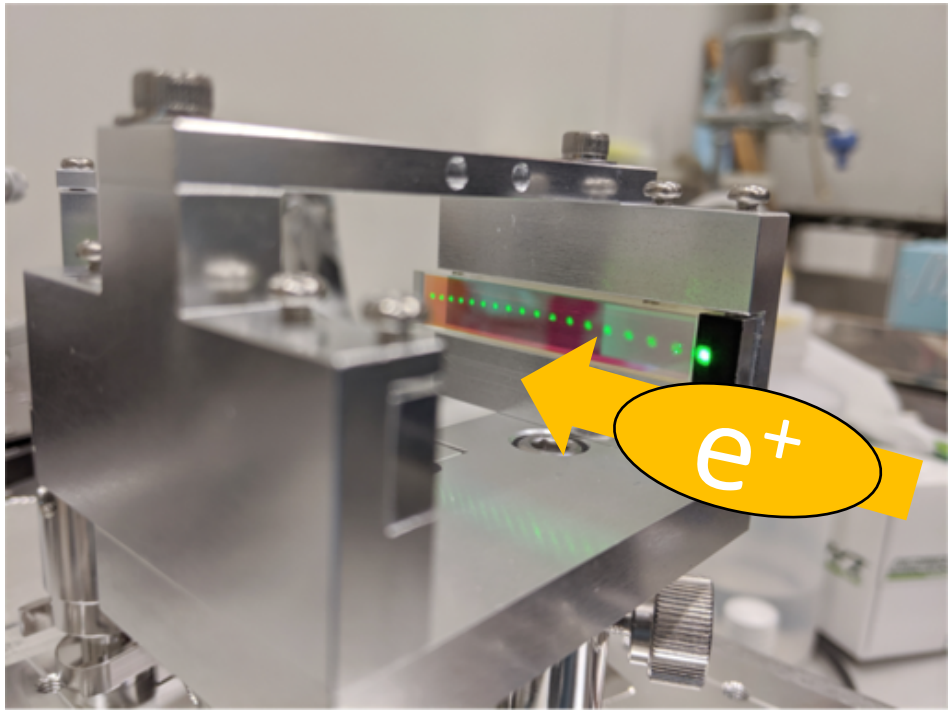


Ps will be confined in vertical direction to the laser

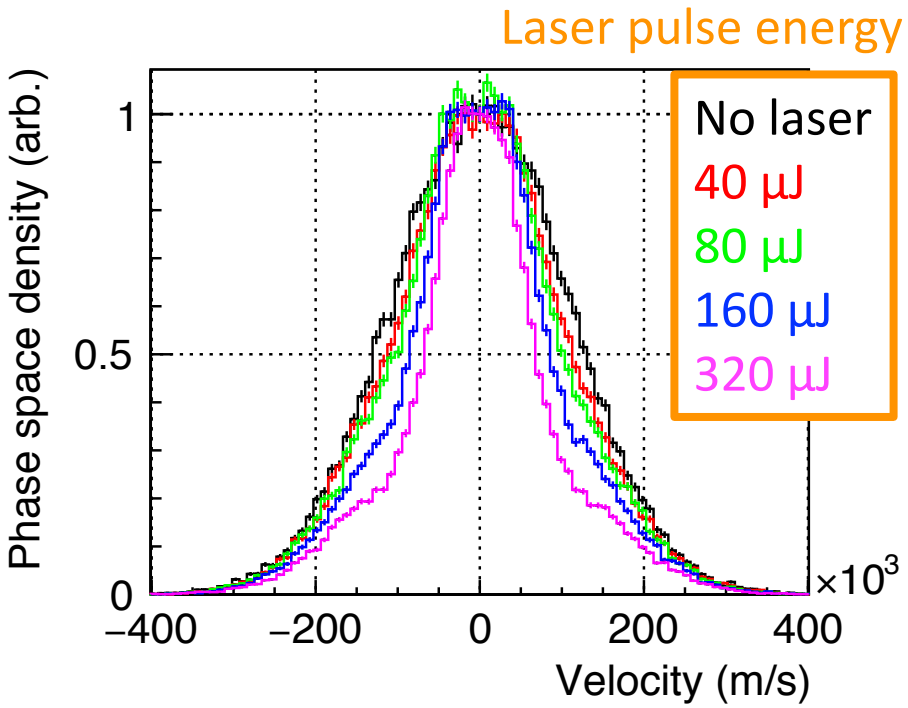


- Wafers will be separated for ~ 10 mm to confine Ps in the laser shinning region
- The distance ensures only 1S-Ps will be reflected by the wafers

Preparations are ongoing



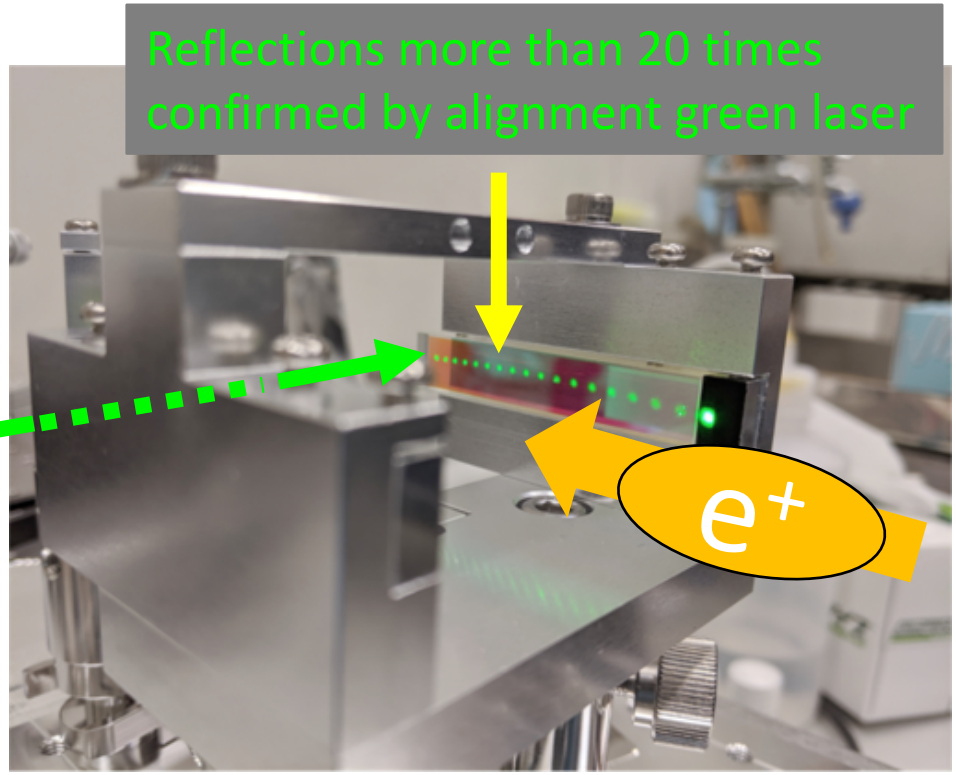
Laser reflector setup



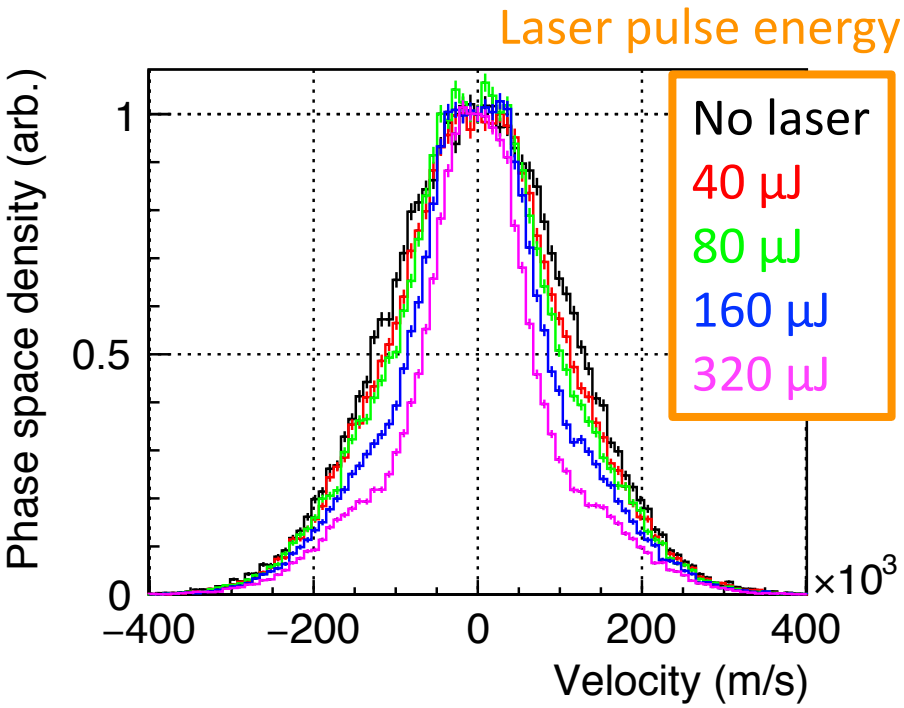
Expected velocity distributions

The first laser cooling will be conducted by 2020 Apr.

Preparations are ongoing



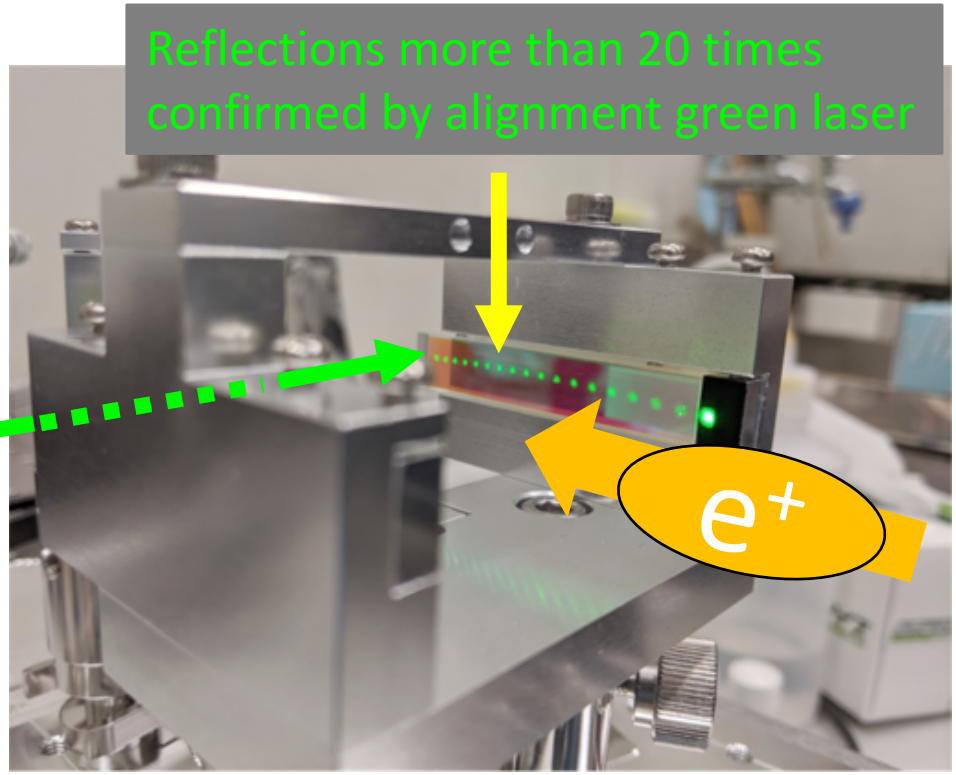
Laser reflector setup



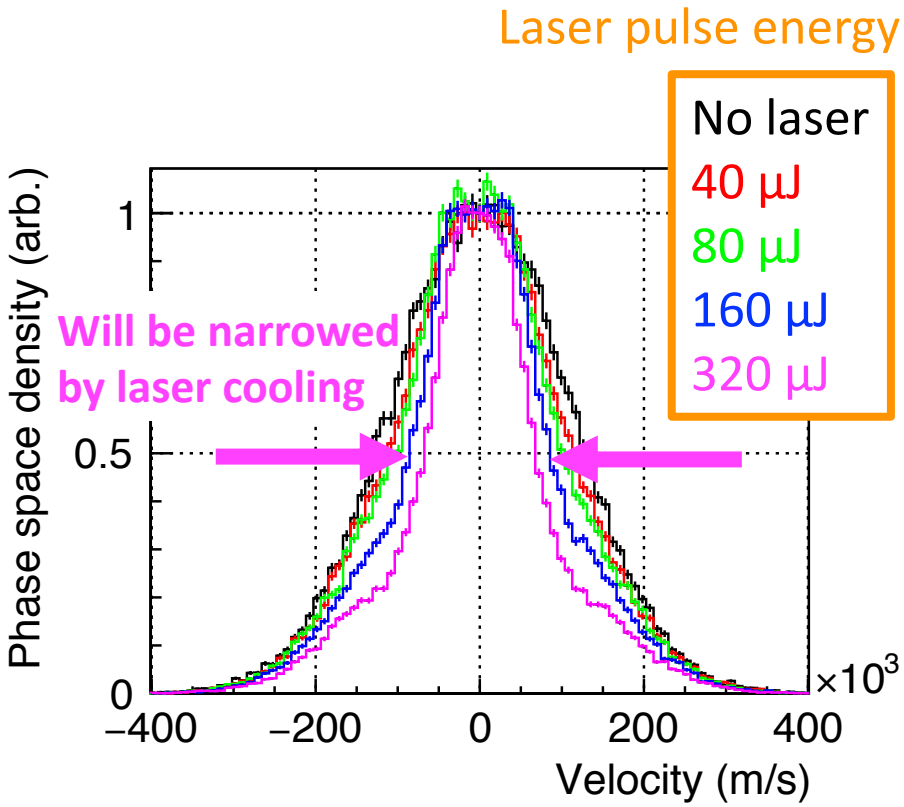
Expected velocity distributions

The first laser cooling will be conducted by 2020 Apr.

Preparations are ongoing



Laser reflector setup

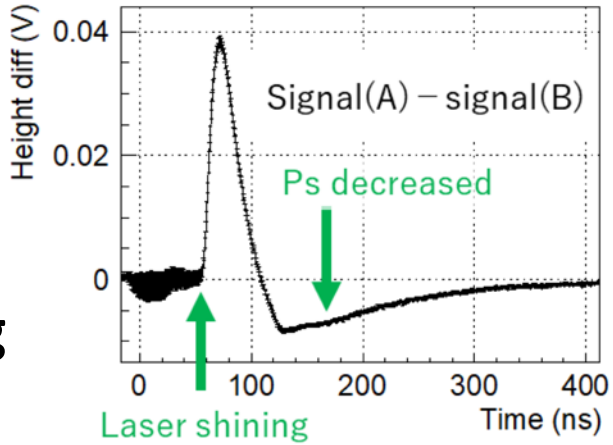


Expected velocity distributions

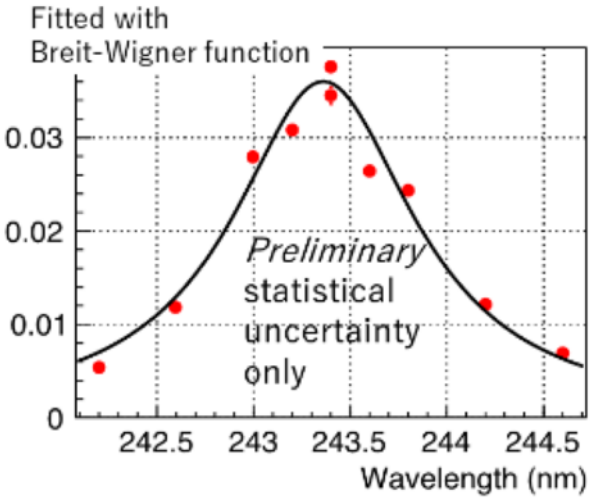
The first laser cooling will be conducted by 2020 Apr.

Summary

1. **2P-Ps annihilates into gamma-rays immediately in silica aerogel pores. Studies on annihilation and broadening are planned.**

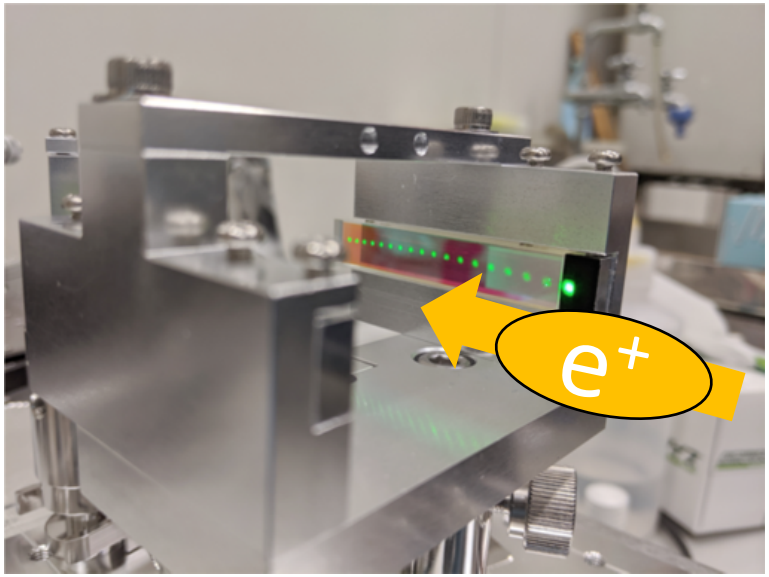


Signal difference caused by shining UV laser



Resonance curve

2. **Ps laser cooling in vacuum will be conducted with enhancing laser - Ps interactions. In order to realize Ps-BEC, we will develop new silica cavity without 2P-Ps decay and apply laser cooling tested in vacuum.**



https://tabletop.icepp.s.u-tokyo.ac.jp/?page_id=365