Recent progress towards positronium Bose-Einstein condensation

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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

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https://tabletop.icepp.s.u-tokyo.ac.jp/Tabletop_experiments/English_Home.html

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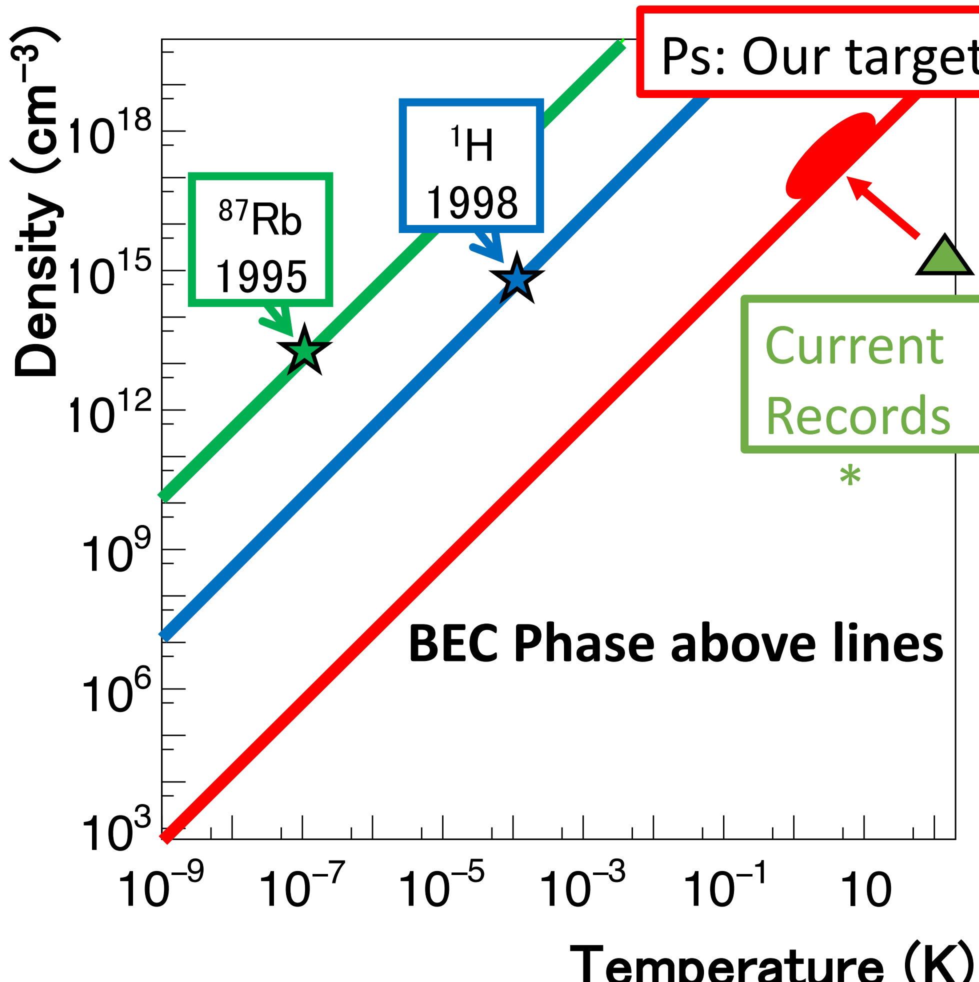
Contents

- Motivation for Ps-BEC: Good candidate for the first antimatter laser.
- Our new idea to realize Ps-BEC
- 1S-2P Ps excitation experiment by shining 243 nm UV laser

Our Target: Positronium Bose-Einstein Condensation (Ps-BEC)

- Ps must be dense and cold
- High critical temperature because of Ps light mass ($14K$ 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.

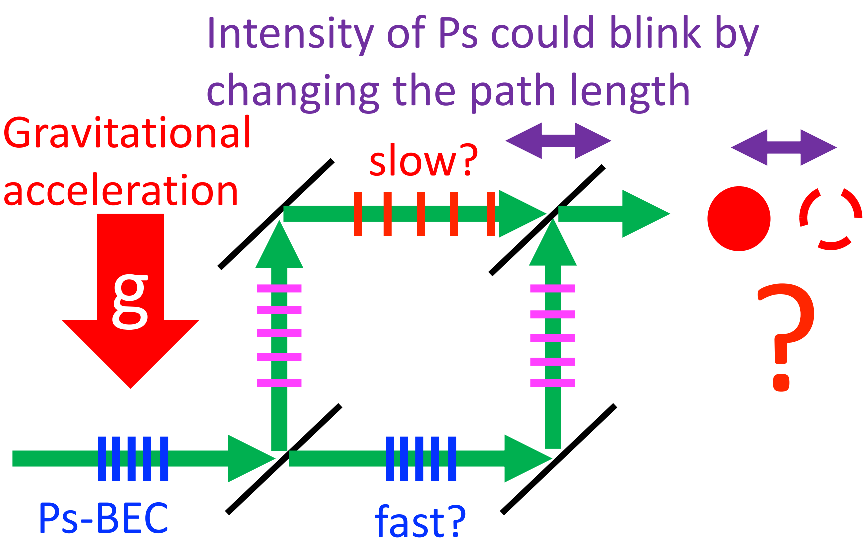


* : S. Mariazzi *et al.* Phys. Rev. Lett. 104, 243401 (2010)
* : D. Cassidy *et al.* physica status solidi 4, 3419 (2007)

Applications of Ps-BEC

1. Antimatter gravity:

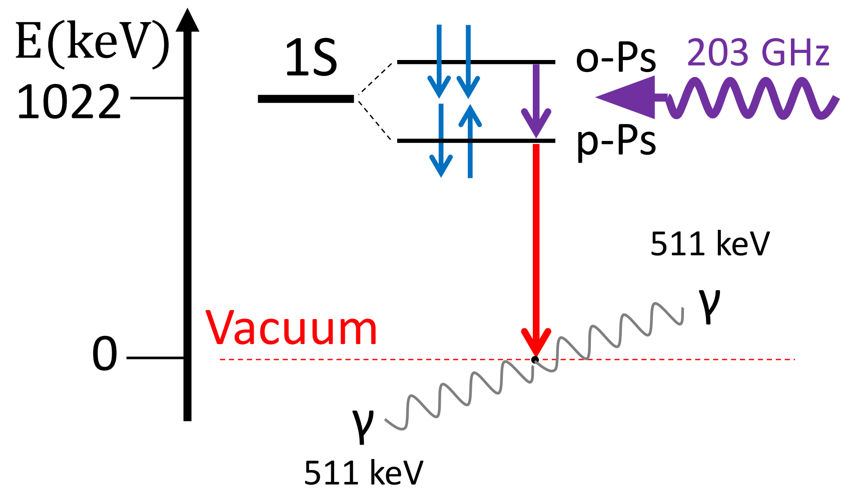
Build Ps-BEC atomic interferometer to see gravitational effect on antimatter.



- Gravity shifts phase of Ps in different paths

Phys. stat. sol. 4, 3419 (2007)

2. 511 keV γ-ray laser



Phys. Rev. A 92, 023820 (2015)

- *o*-Ps BEC to *p*-Ps by 203 GHz RF
- *p*-Ps BEC collectively decays into coherent 511 keV gamma-rays

Two challenges to realize Ps-BEC

Main problem

Ps lifetime is only 142 ns

Two challenges

1. Instant creation of dense Ps
   $> 10^{17}$ cm^{-3} in < 50 ns
2. Rapid cooling of Ps
   < 10 K in ~300 ns

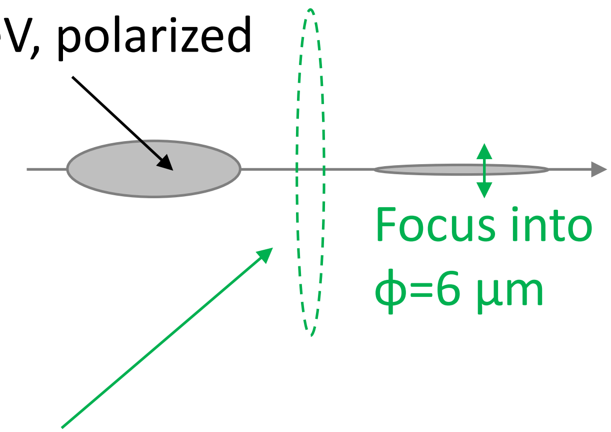
Our new idea:

3 technologies to realize Ps-BEC

Our new idea to realize Ps-BEC

1. Positron focusing system

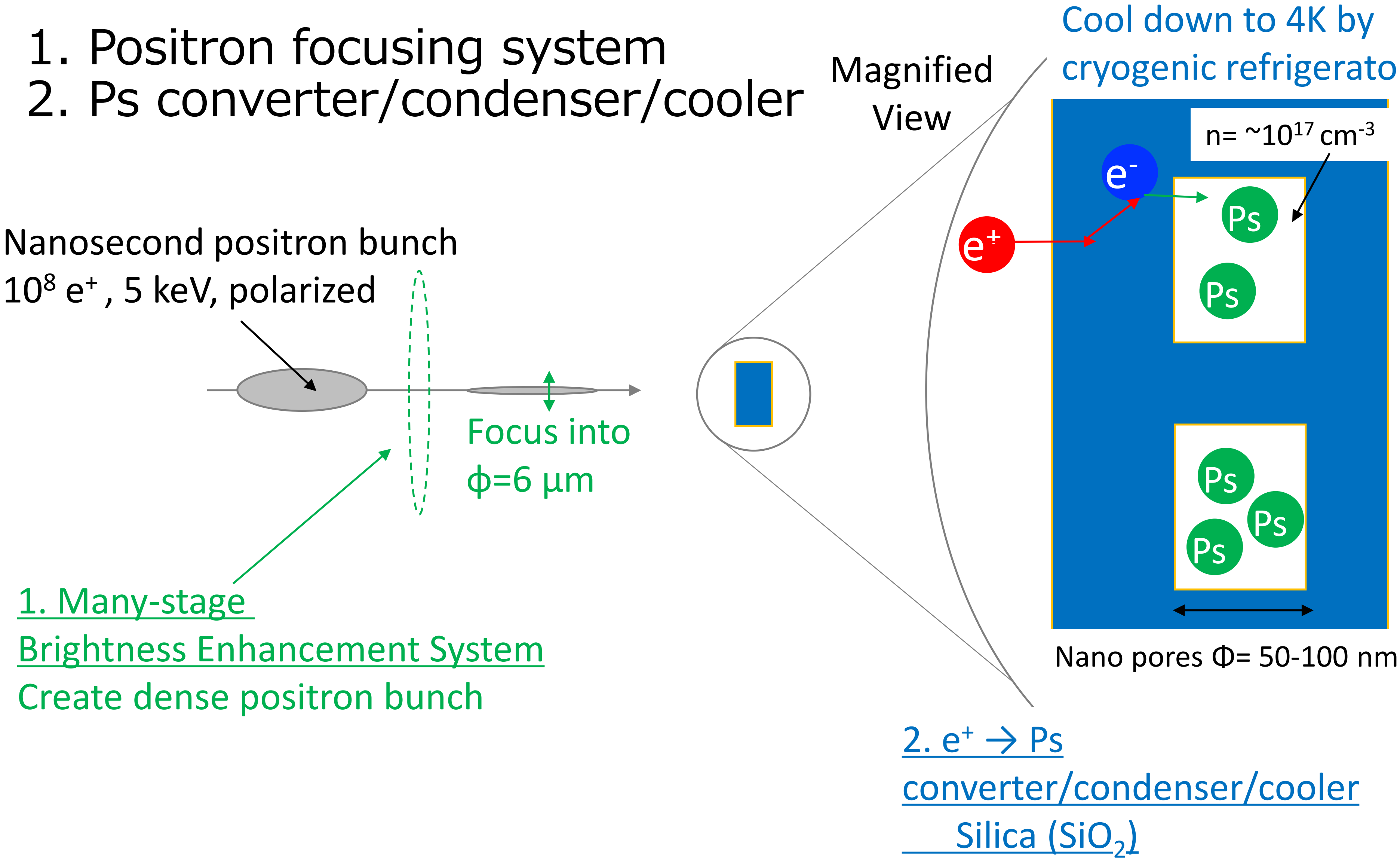
Nanosecond positron bunch
10^8 e^+, 5 keV, polarized



<u>1. Many-stage</u>
<u>Brightness Enhancement System</u>
Create dense positron bunch

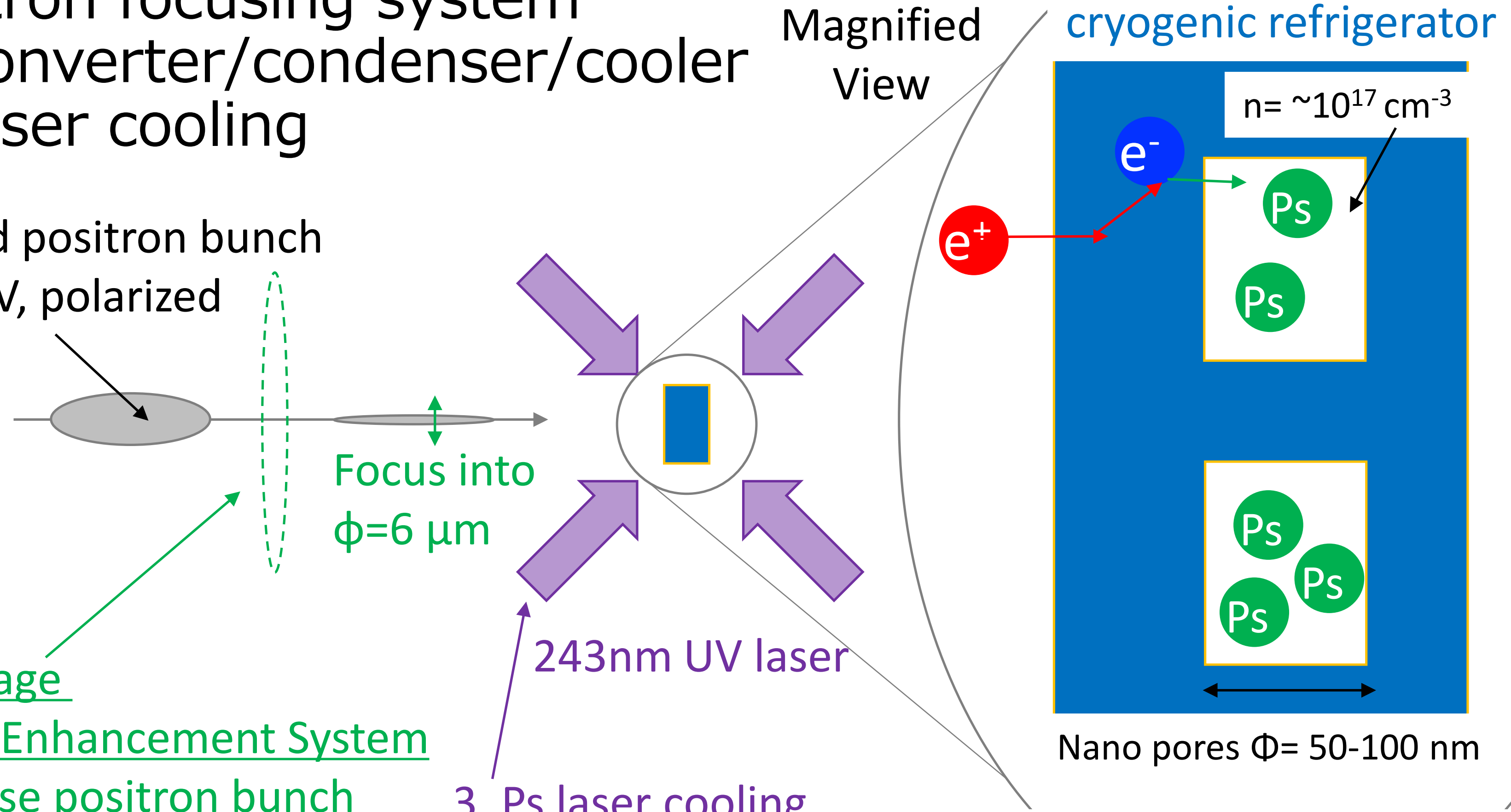
Our new idea to realize Ps-BEC

1. Positron focusing system
2. Ps converter/condenser/cooler



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)

Combination of Thermalization and Laser cooling is efficient enough to realize Ps-BEC

1.Thermalization

- Efficient at > 200 K

Initial Ps energy is 0.8 eV = 6000 K.
Cooling Ps down to 100 K

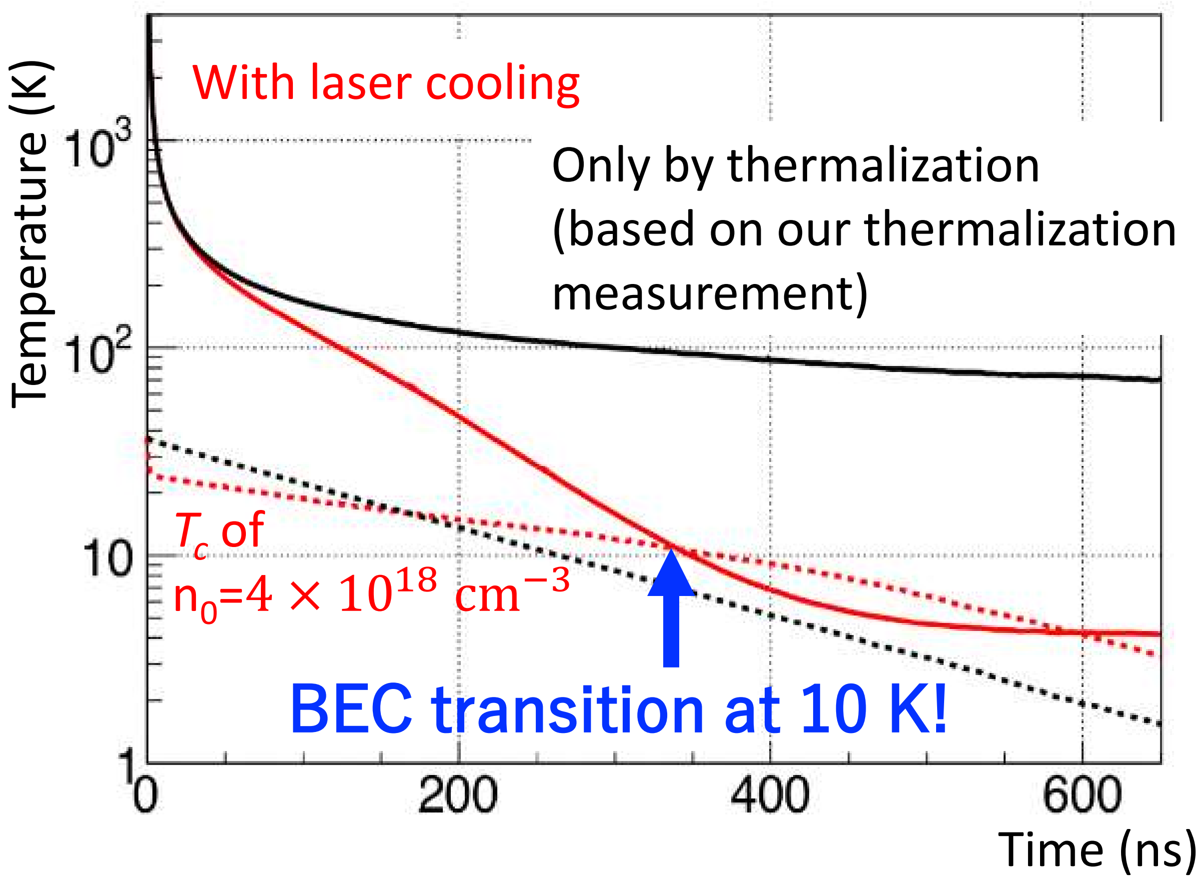
2.Laser cooling

- Efficient at < 200 K

Cooling Ps down to < 10 K is possible

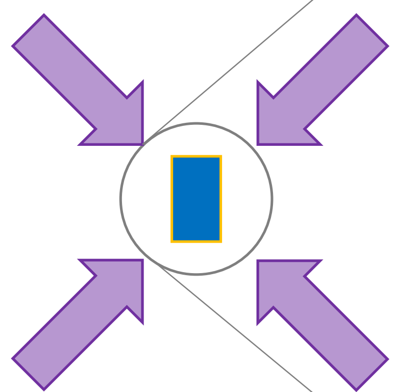
✓ Combining these two methods is essentially important

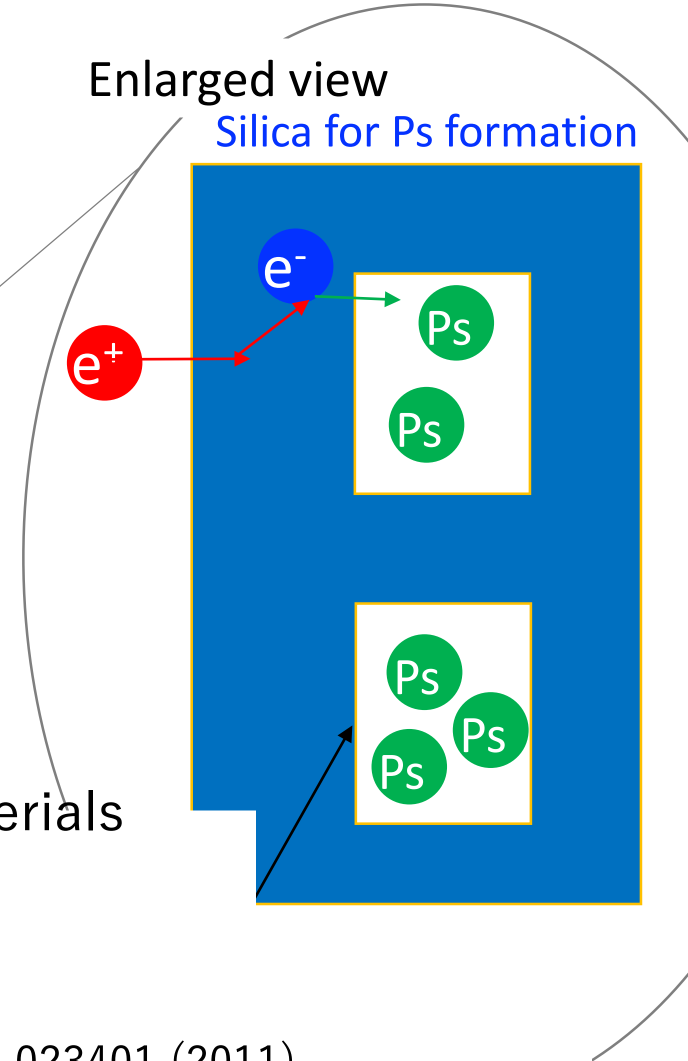
MC simulated temperature evolution



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

→ Shining UV laser to Ps inside the silica pores





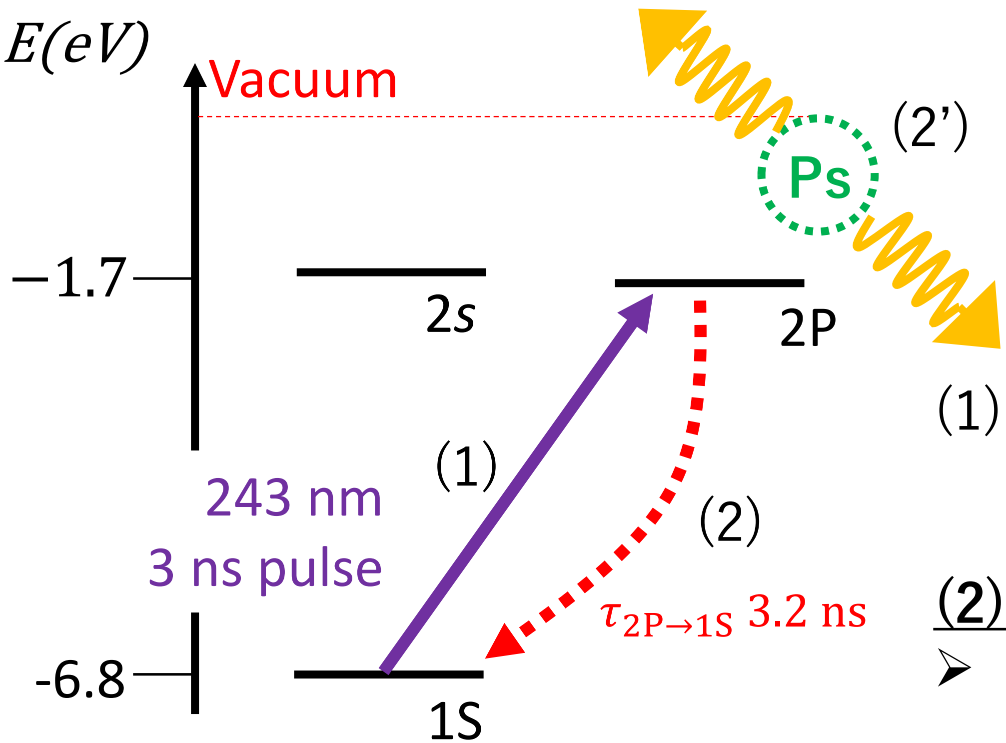
Interactions of 2P-state Ps surrounded by materials are not well known.

<u>Previous reports using nanoporous silica</u>

- Frequency shift and narrow resonance:
  D. B. Cassidy et al. PRL 106, 023401 (2011).
- Immediate annihilation of 2P-Ps and broad resonance:
  B. S. Cooper et al. PRB 97, 205302 (2018).

➢ These phenomena make laser cooing of Ps difficult.
We have tested it using our silica aerogel sample (pore size = 50 nm).

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.

<u>(2) If nothing special happens…</u>

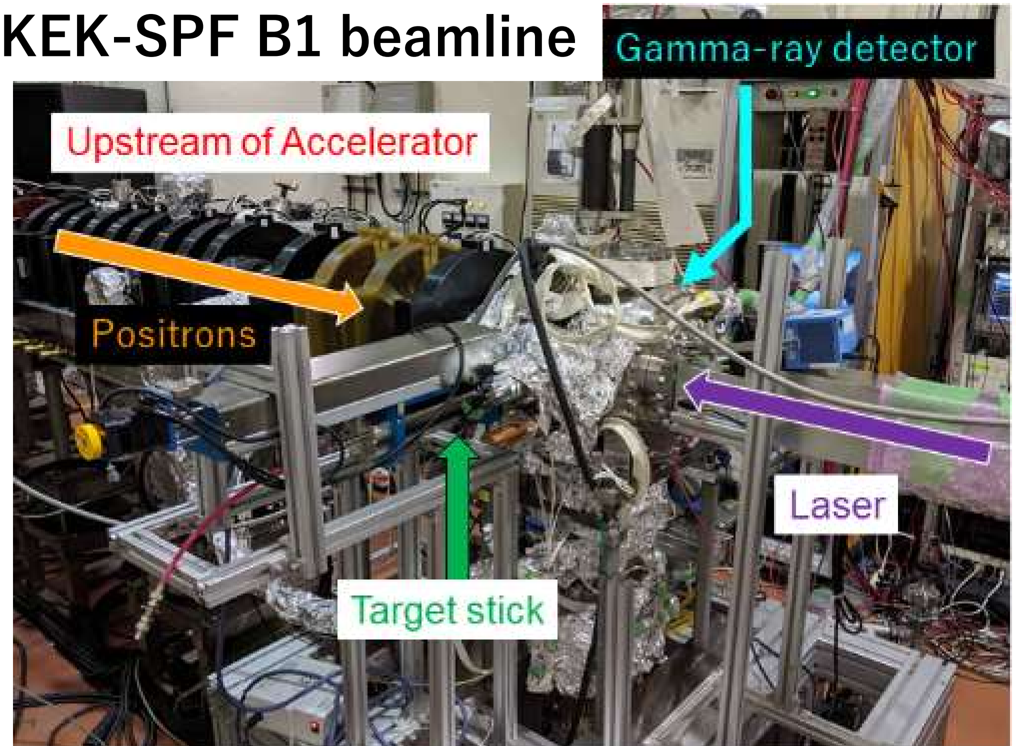
- Ps is de-excited to 1S state with lifetime of 3.2 ns (Lyman-alpha).

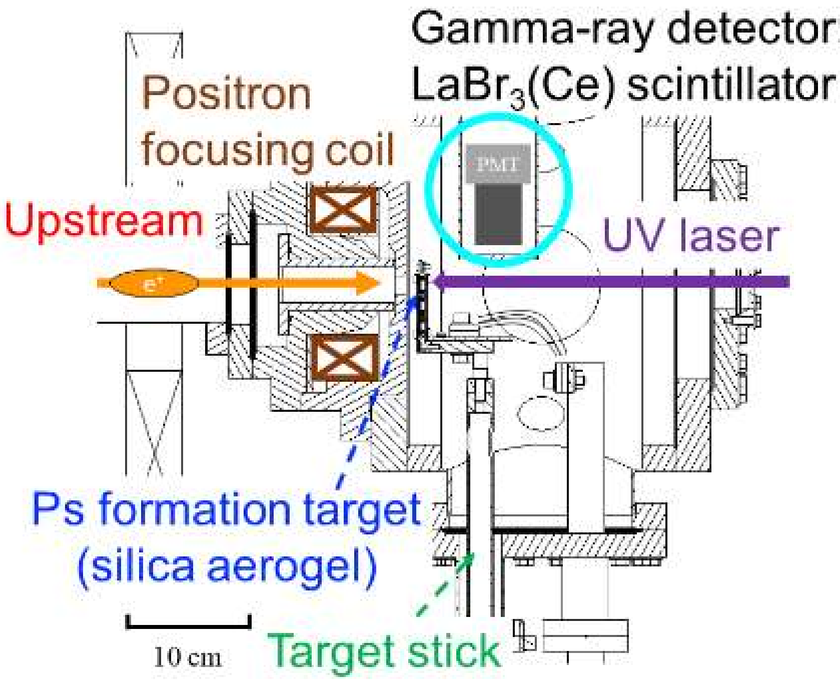
<u>(2') If lifetime of 2P-Ps inside pores is short as reported…</u>

- Annihilation rate to gamma-rays is increased.

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

KEK-SPF B1 beamline





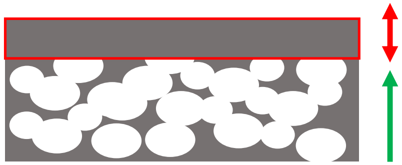
Energy	5 keV
Highest Intensity	10^5 e^+/ pulse
Repetition	50 Hz
Time width	16 ns
Size	Φ ～10 mm

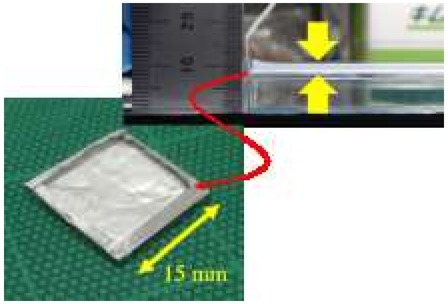
Vacuum chamber

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

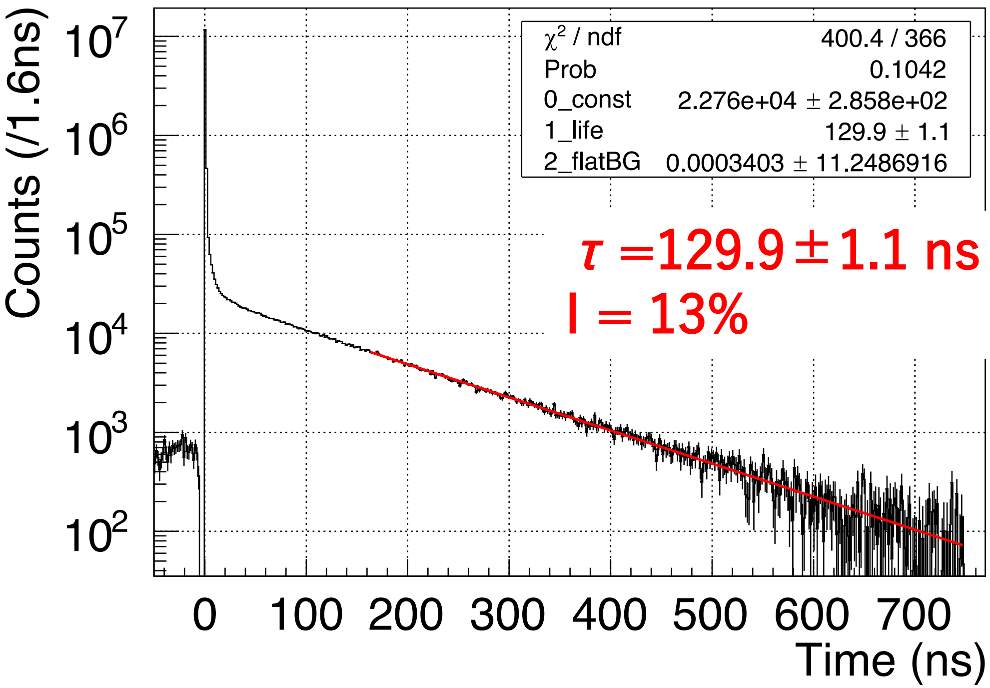




CVD thickness 75 nm

- 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.

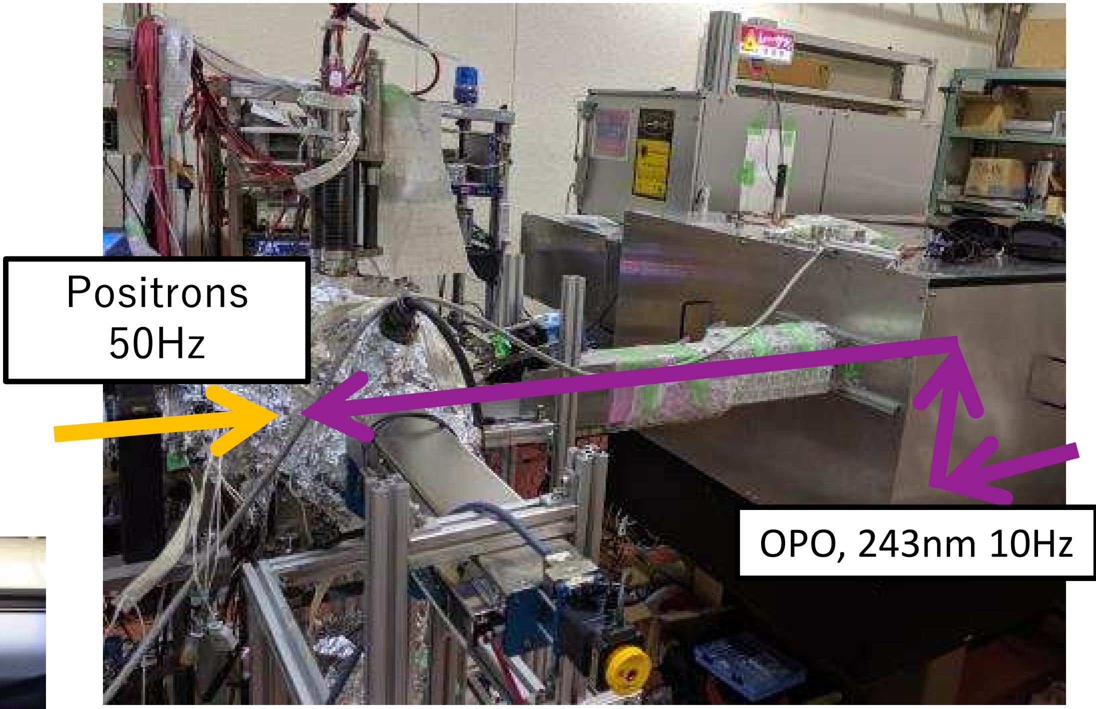


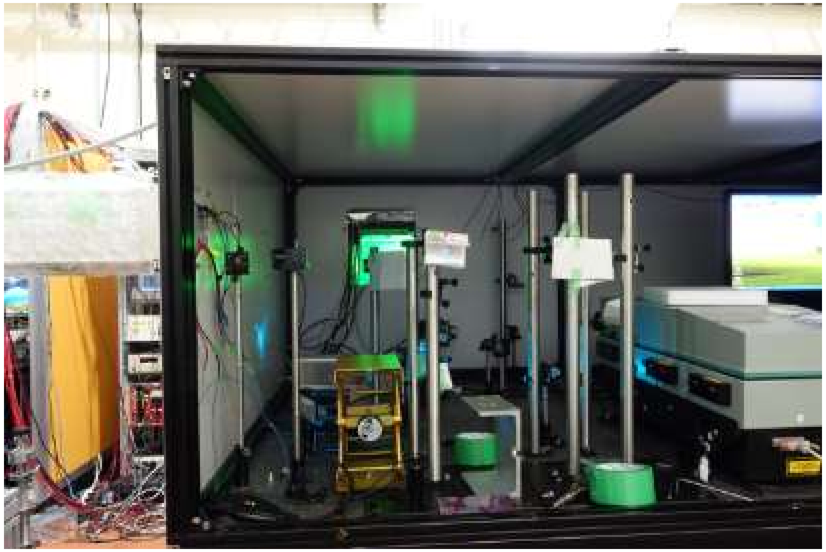
Timing spectrum of bulk-PALS measurement using ^{22}Na with t=1 mm silica aerogel

UV laser was produced using optical parametric oscillator (OPO) pumped by Nd:YAG laser

Laser specifications

Pulse energy	300 µJ
Linewidth (243 nm)	0.06 nm
Beam diameter	5 mm
Pulse width	3 ns
Repetition	10 Hz

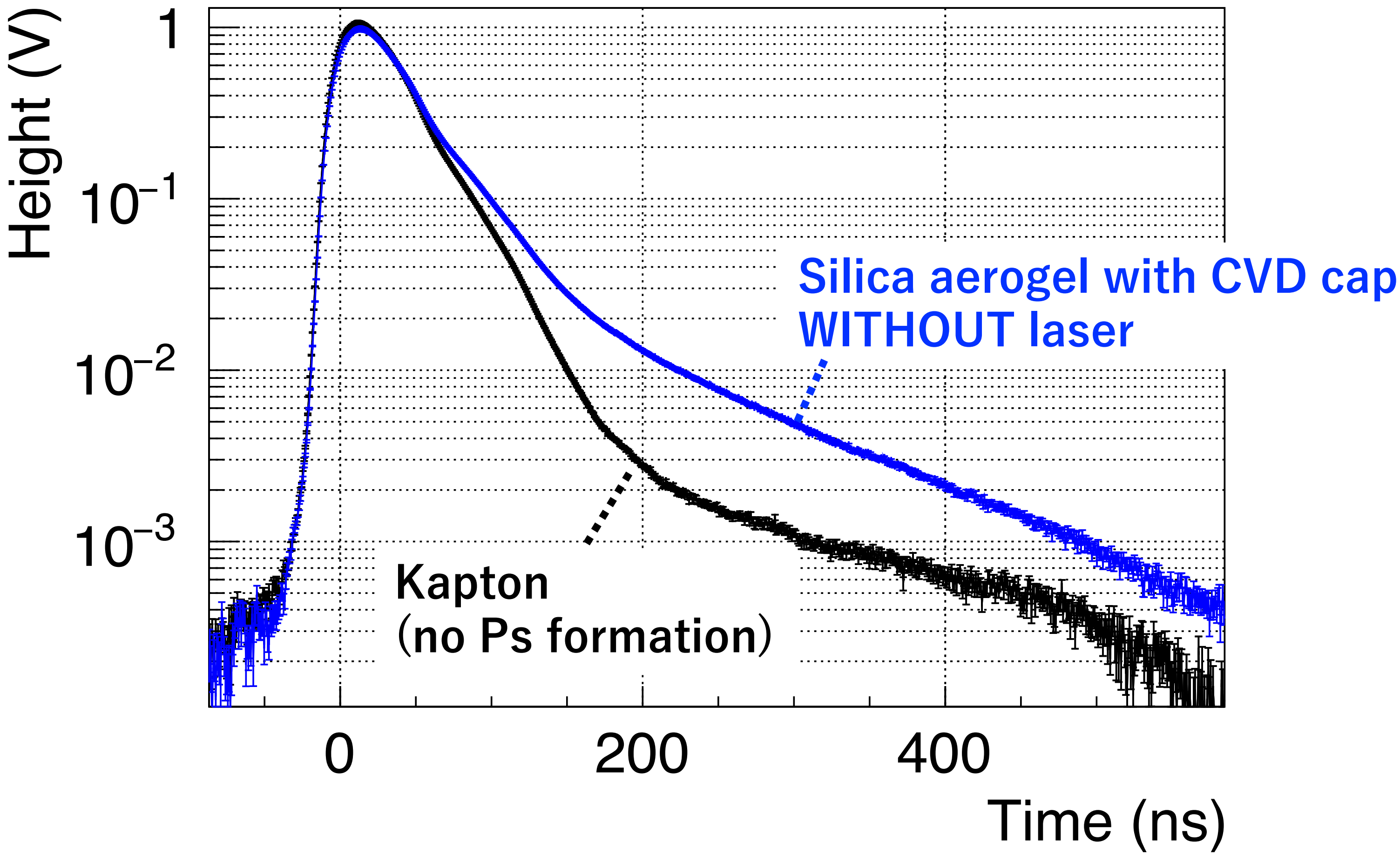




↑← Photos of laser system

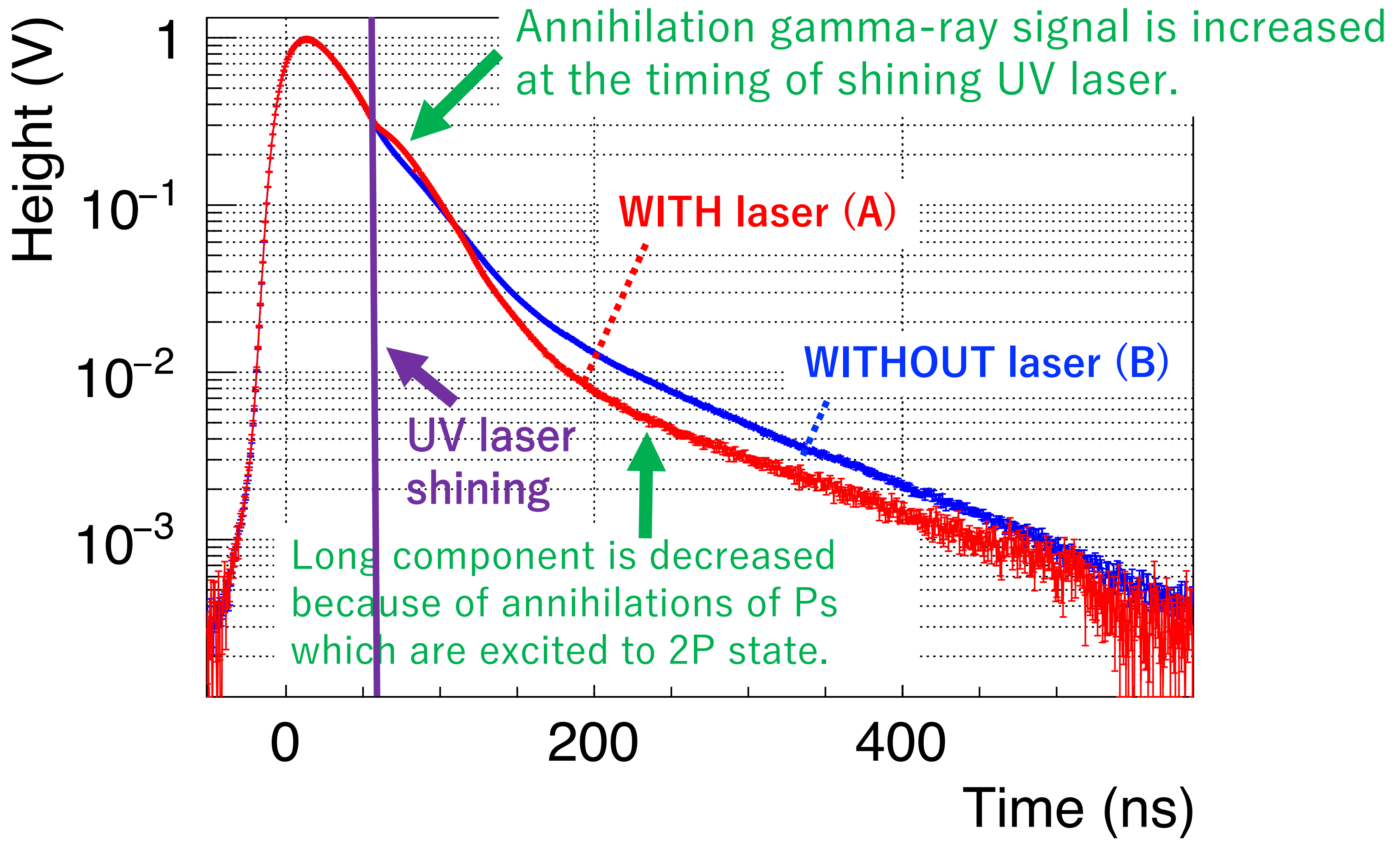
OPO is borrowed from Yoshimura group in Okayama University.
We appreciate it.

Slow component of o-Ps annihilations is observed in silica-aerogel timing spectrum without shining UV laser.



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

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



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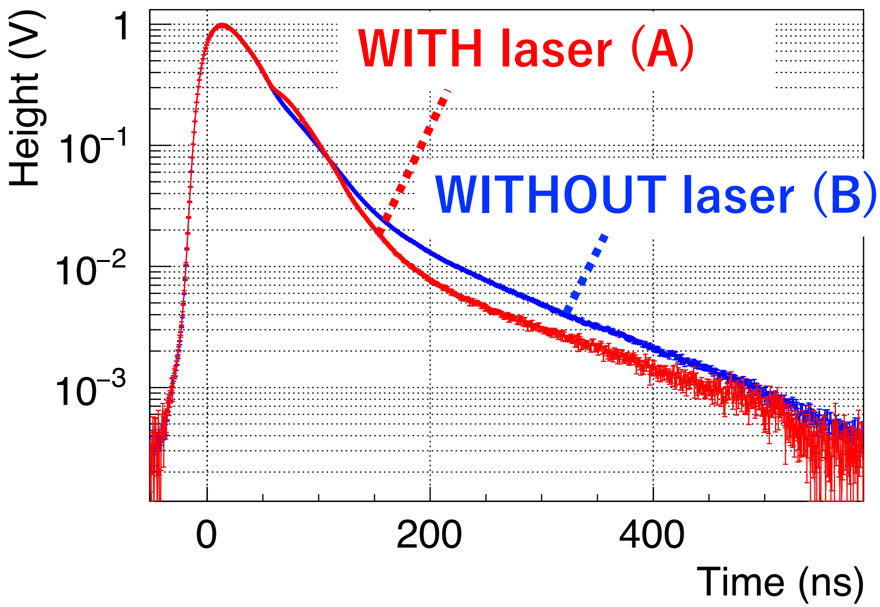

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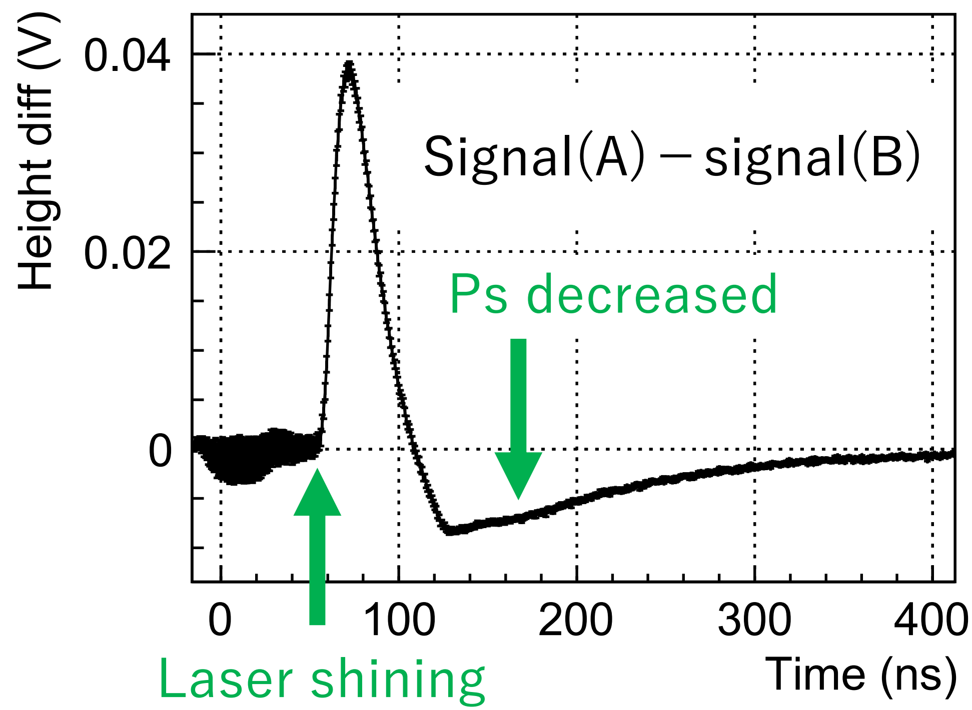
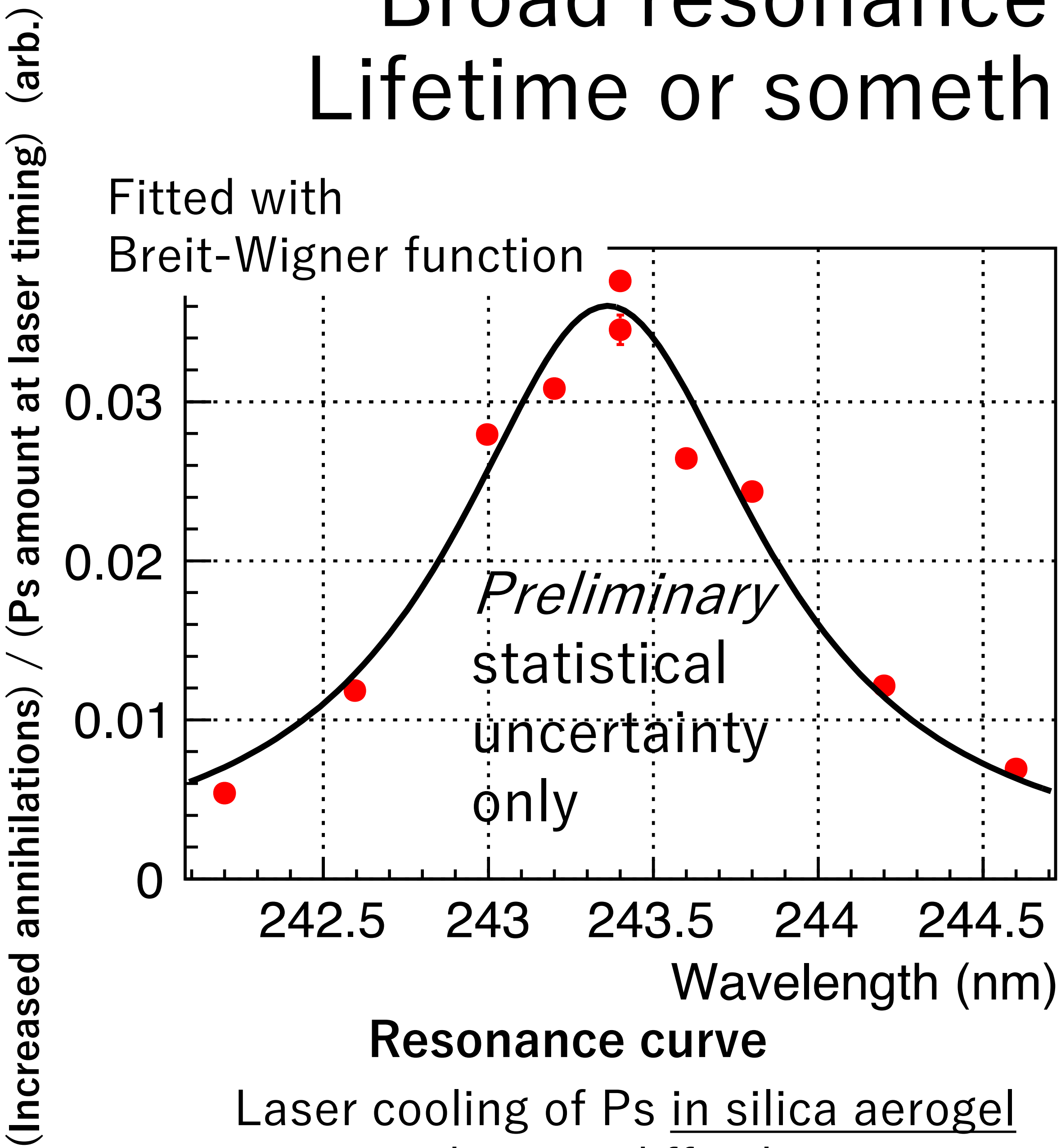


Signal difference caused by shining UV laser

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

Broad resonance (1 nm) Lifetime or something else?

Fitted with
Breit-Wigner function



Resonance curve

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

Scanned the increase of gamma-ray annihilations by changing the wavelength of the UV laser.

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)

Next step: Laser cooling of Ps in vacuum

As a proof-of-concept of our method to cool Ps efficiently enough for realizing Ps-BEC.

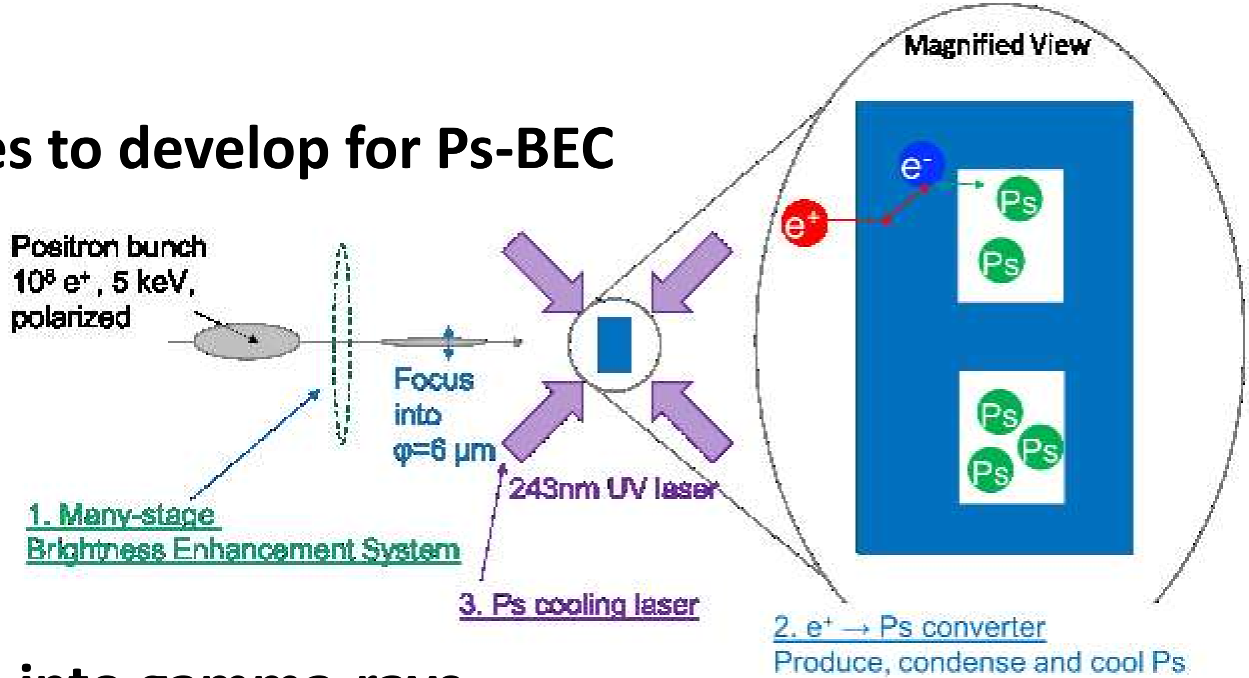
For the problem of short lifetime of 2P-Ps in silica aerogel pores, we will investigate some hypotheses.

- There is chemically unstable structure on the surface of the silica aerogel.
- Positrons of Ps are absorbed in silica particles because the binding energy of 2P-Ps is small.

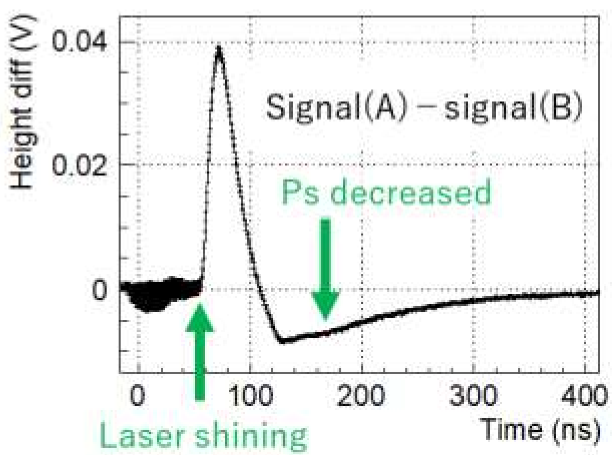
➢ We will try nano-size cavities other than silica aerogel.

Summary

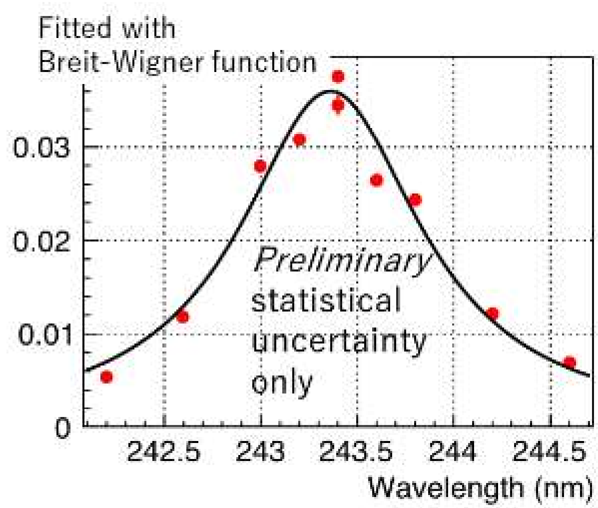
1. **Three technologies to develop for Ps-BEC**



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



Signal difference caused by shining UV laser



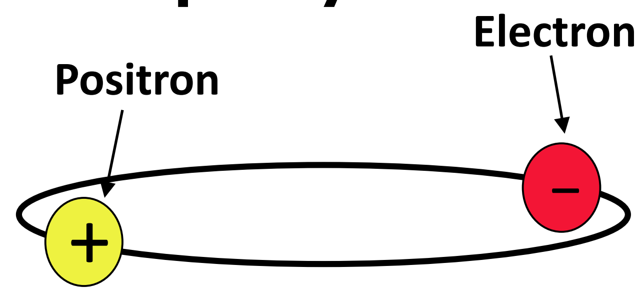
Resonance curve

3. **Next step: Laser cooling of Ps in vacuum**

Backup

Positronium (Ps) is a good probe for fundamental physics

Bound state of an electron (e^-) and a positron (e^+)



Lightest and Exotic Atom

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

Why the 2P-Ps lifetime so short?

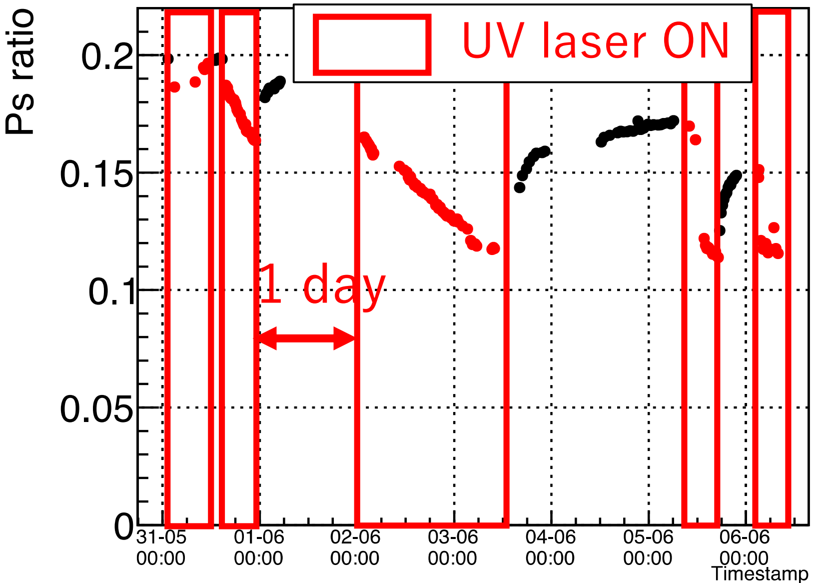
Hypotheses

1. Interaction between 2P-Ps and paramagnetic radicals formed by UV laser shining is strong.
   - ➢ Checked experimentally.

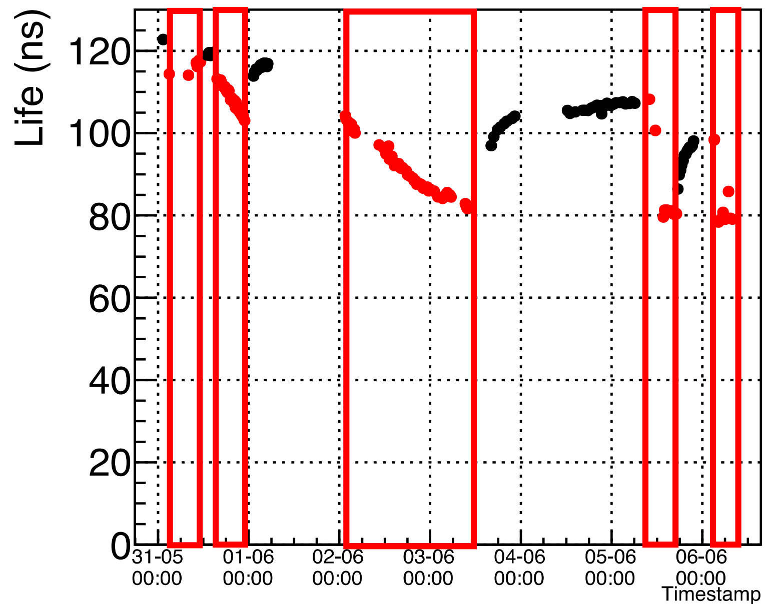
2. There is chemically unstable structure on the surface of the silica aerogel.

3. Positrons of Ps are absorbed in silica particles because the binding energy of 2P-Ps is small.

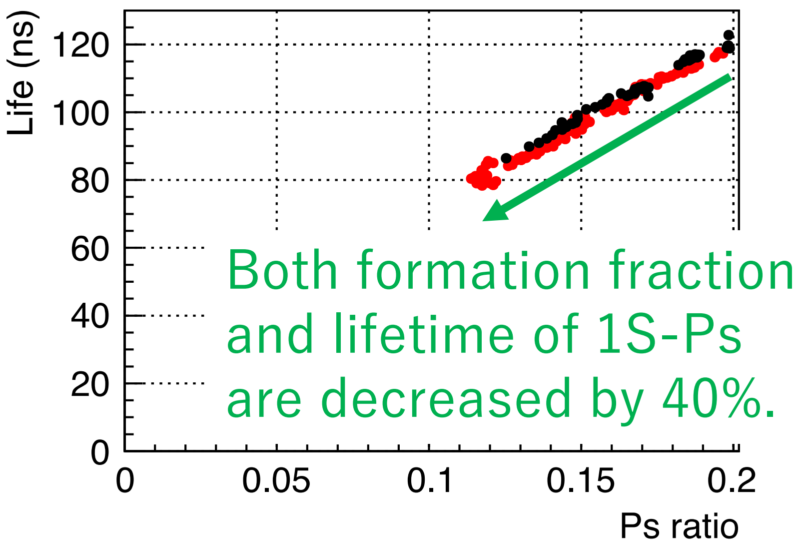
Are paramagnetic radicals formed by shinning UV laser the reason?



Ps formation fraction



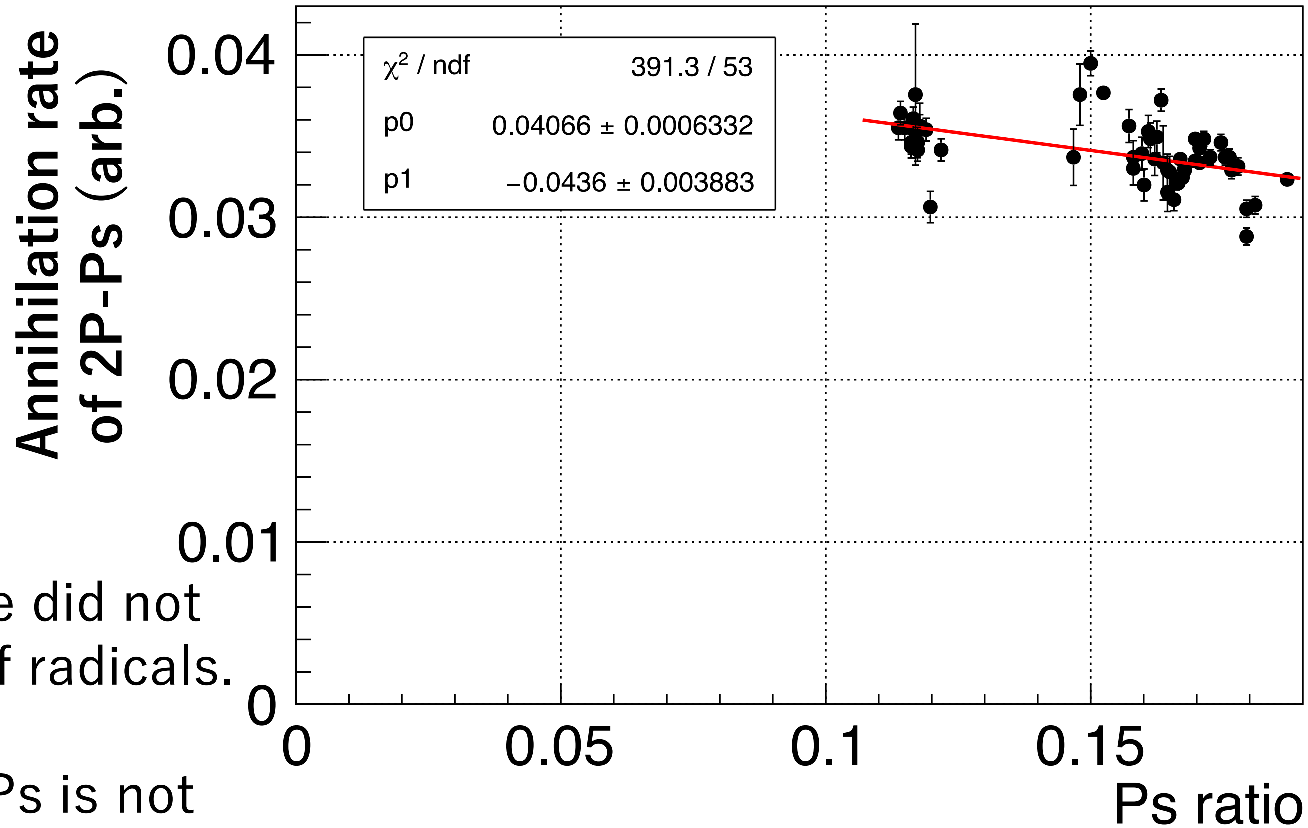
***o*-Ps lifetime**



Both formation fraction and lifetime of Ps are decreased by shining UV laser.
Paramagnetic radicals are thought to be formed at hydrophobic methyl group on surface of the silica aerogel.

Correlation between Ps lifetime and formation fraction

Annihilation rate of 2P-Ps does not depend on the amount of paramagnetic radicals.



Annihilation rate of 2P-Ps vs. Ps formation fraction

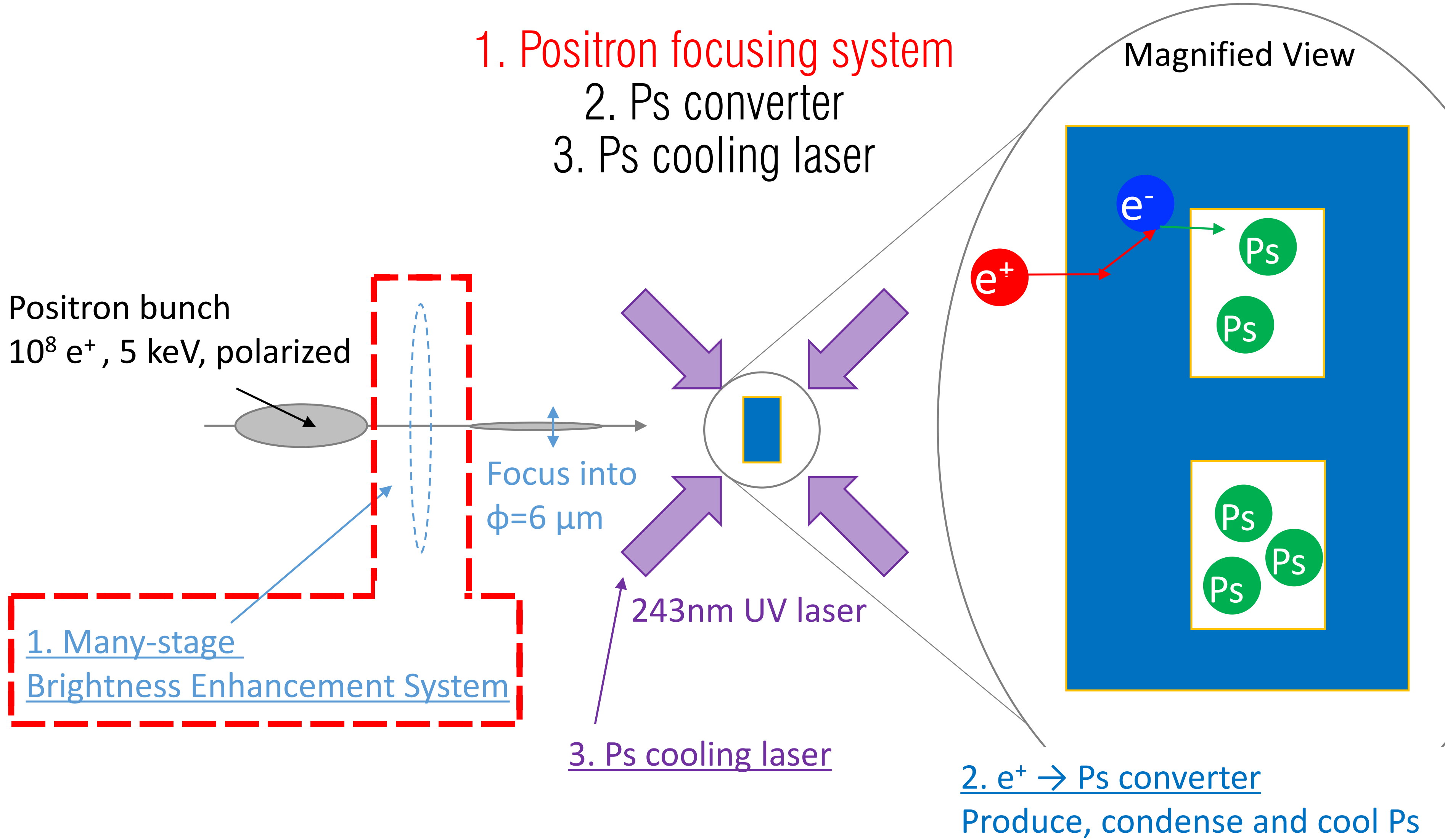
2P-Ps annihilation rate did not change with amount of radicals.

- Annihilation of 2P-Ps is not caused by paramagnetic radicals formed by UV laser.

Annihilation of 2P-Ps was observed also in the sample annealed in dry air in order to remove surface methyl group.

Three technologies to develop for Ps-BEC

1. Positron focusing system
2. Ps converter
3. Ps cooling laser

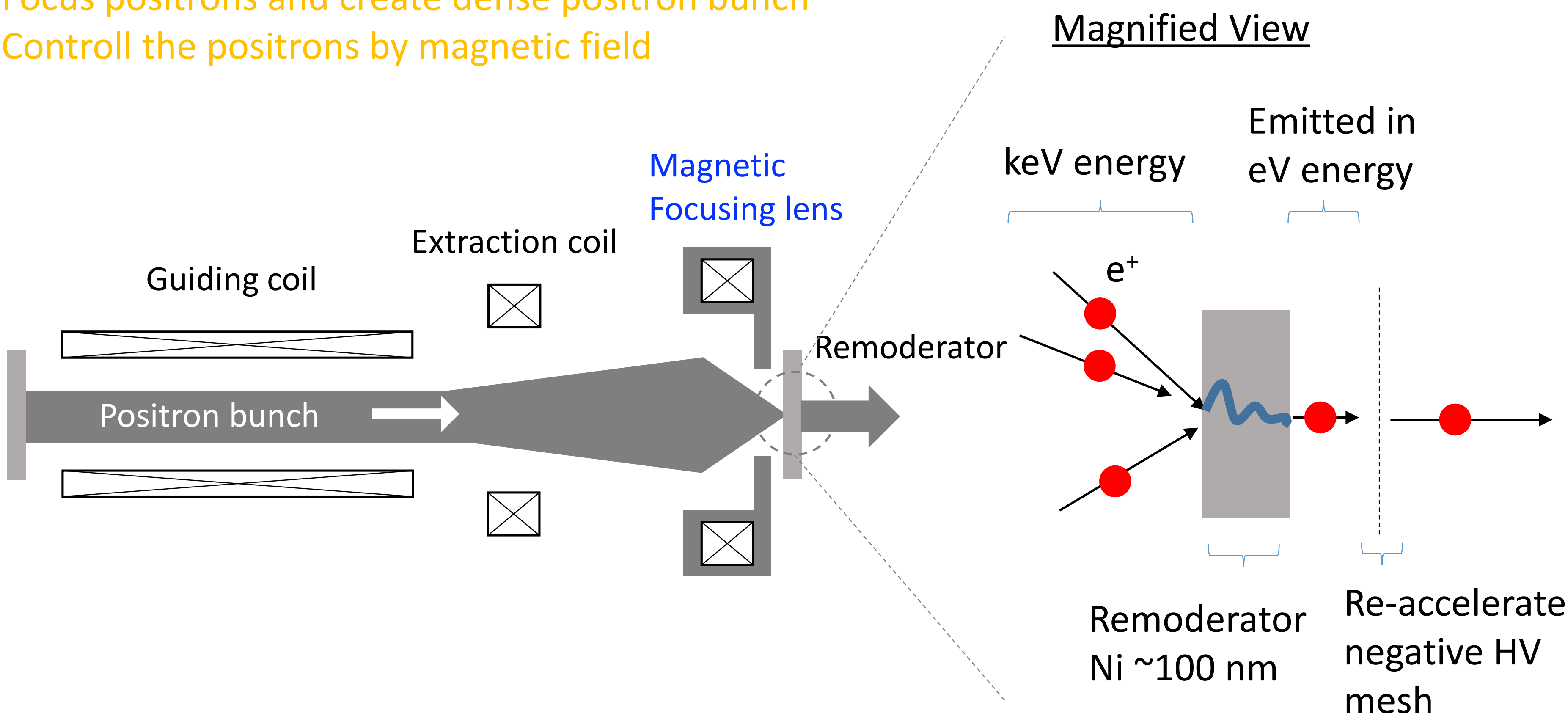


Positron Focusing

Brightness Enhancement System

Focus positrons and create dense positron bunch

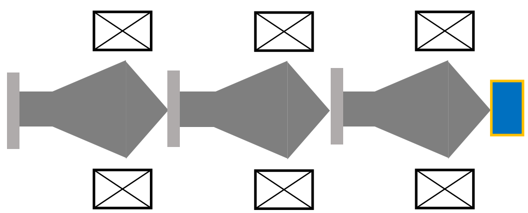
Controll the positrons by magnetic field



Narrow and low-emittance positron beam can be created

Many-Stage Brightness Enhancement System
1.Positron focusing system

Many-Stage Brightness Enhancement System



- Repeat the Brightness Enhancement multiple times and gradually focus the positrons.
- Currently focusing into 30 μm* is possible by this method so we consider improving this technique
- Now studying and designing beam optics

*N. Oshima *et al.* Materials Science Forum 607, 238(2008)

Calculation

BE BE Focus only

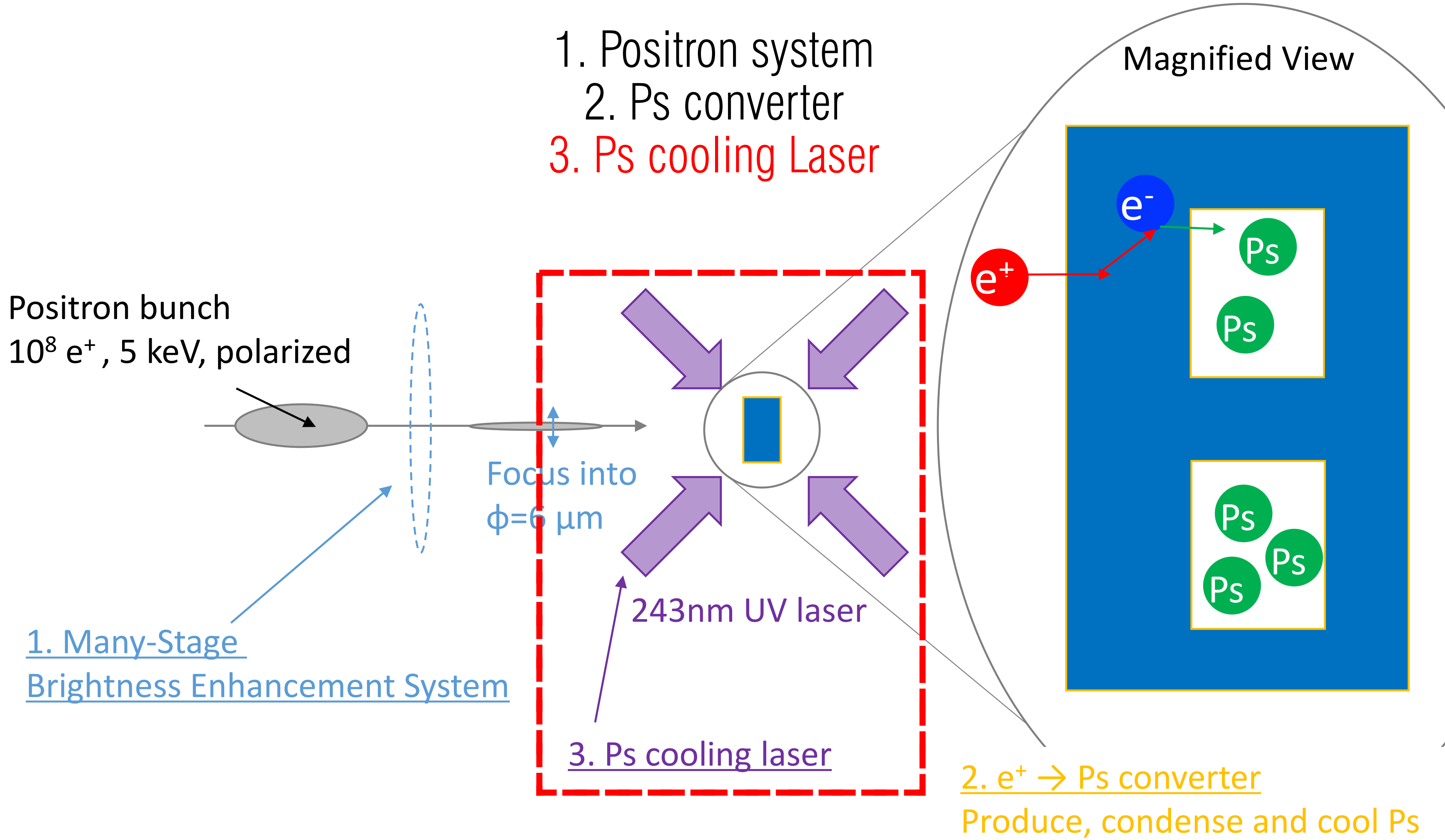
Beam Parameter	1 st	2 nd	3 rd	final
Ps Density* (cm^{-3})	2.5×10^{12}	4.9×10^{13}	6.8×10^{14}	6.8×10^{16}
Diameter	5 mm	500 μm	60 μm	6 μm
e^{+} Number	1×10^{8}	2×10^{7}	4×10^{6}	4×10^{6}

Positronium density 6.8×10^{16} cm^{-3} is achievable

*Positronium Production rate 10% is assumed

Three technologies to develop for Ps-BEC

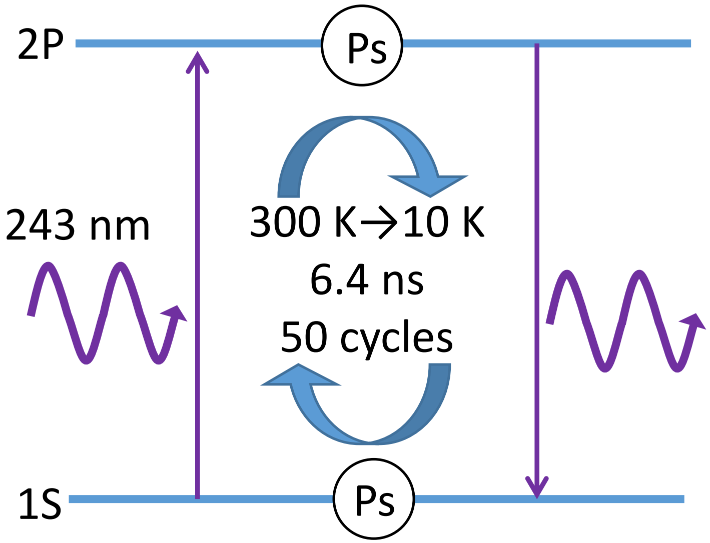
1. Positron system
2. Ps converter
3. Ps cooling Laser



Two Challenges for Ps Laser Cooling

1. Rapid cooling

∵ Short Ps lifetime: 142ns

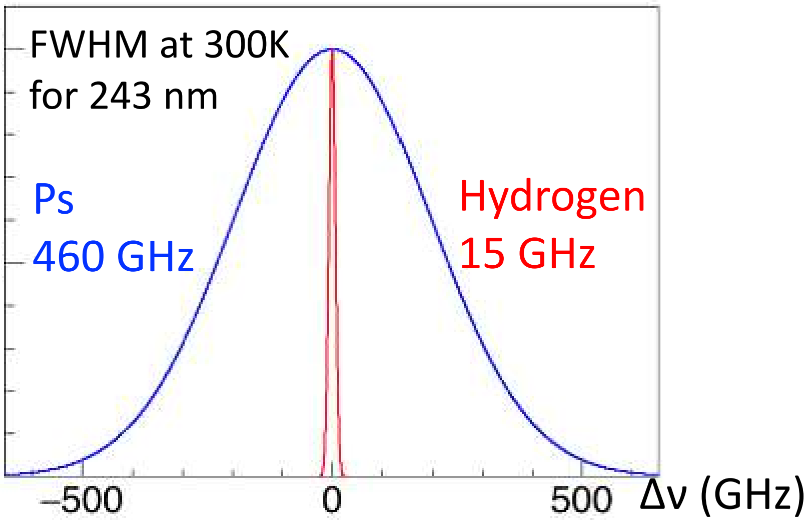


- Largest energy gap: 1S-2P (243 nm)
- 6.4 ns × 50 ~ 300 ns

→ Cool down Ps with single long pulse

2.Broadband laser

∵ Ps light mass: $2m_e$



- Doppler broadening is 30 times larger than Hydrogen

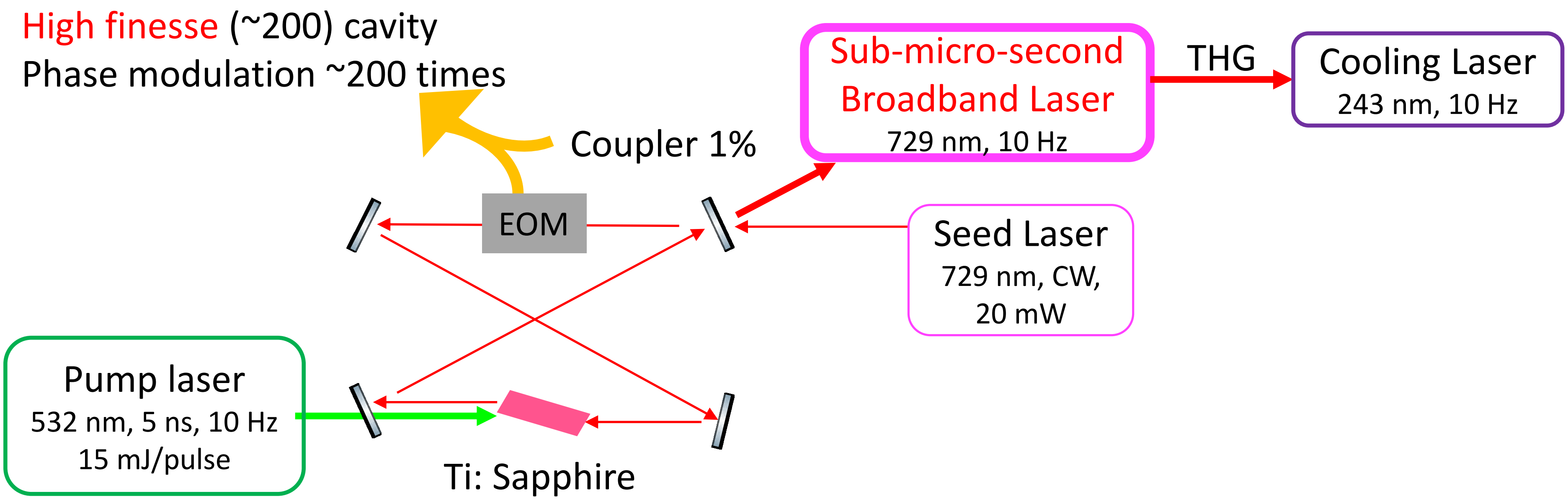
→ Broadband (150 GHz) laser is necessary to cool down all the Ps

243 nm broadband CW laser with enough power is difficult

→243 nm sub-micro-second pulsed broadband laser

Commercially unavailable → Build cooling laser system ourselves

Production of sub-micro-second pulsed broadband laser



Sub-micro-second long pulse

→long photon decay time

1. long cavity (3.8 m)
2. High finesse cavity

   loss/cycle = 1%(coupler)+0.6%

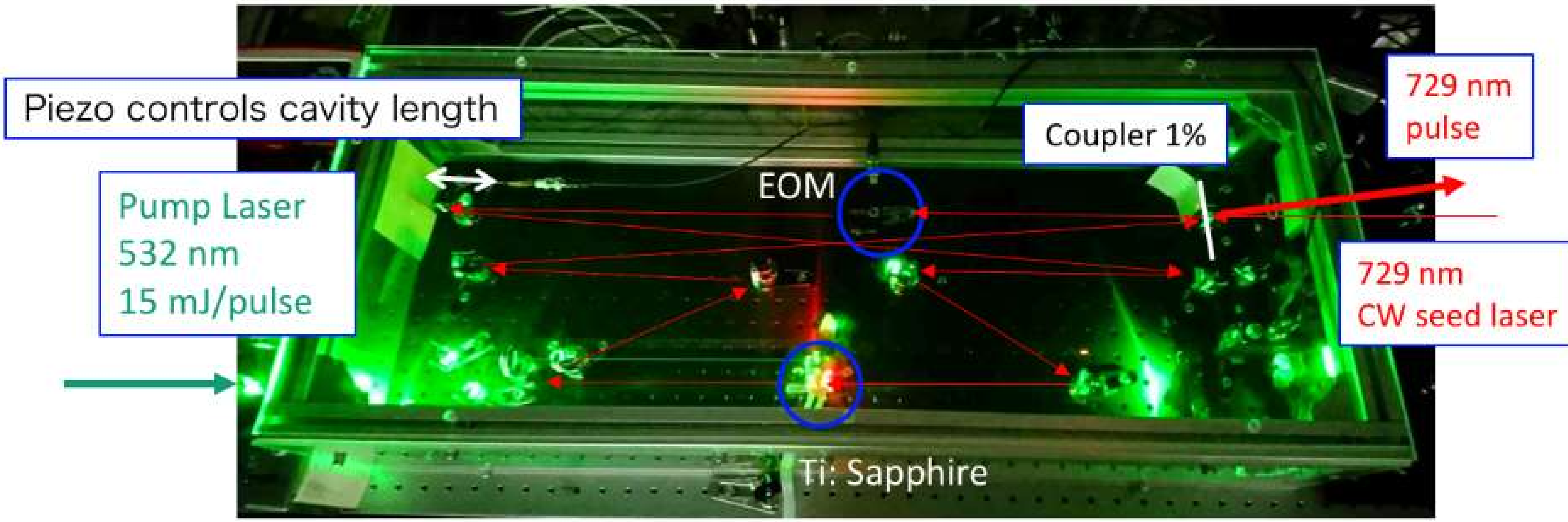
Broadening of pulsed laser

1. EOM: sideband generation
2. High finesse (~200) cavity

EOM modulates the laser ~200 times and creates sidebands up to high order .

→Broaden the laser spectrum effectively

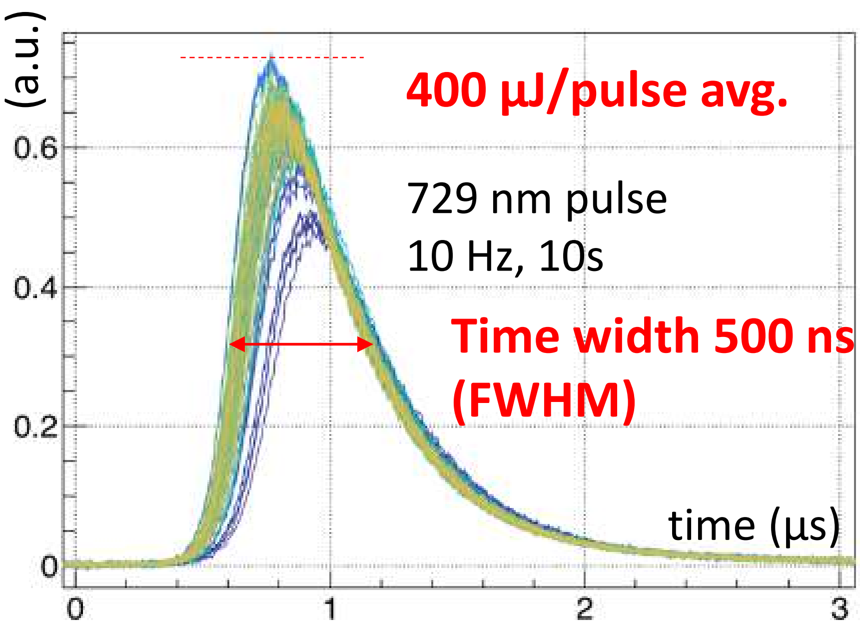
Long and high finesse cavity
A core of the cooling laser system



1. Long cavity (3.8 m) Folded with 8 mirrors (96 × 36 cm^2)
2. High finesse (~200)

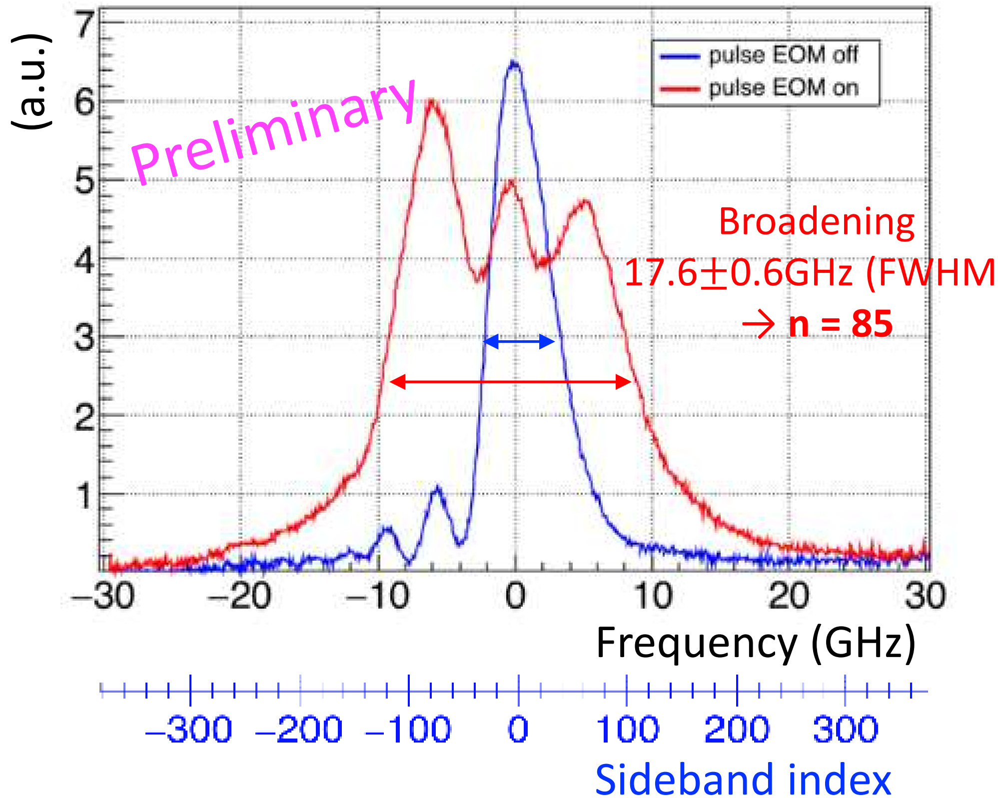
Ps cooling laser is almost ready

Time profile of 729 nm pulse



- ✓ Long pulse: 500 ns
- ✓ Enough pulse energy: 400 μJ

Spectral profile of 729nm pulse



First high order sidebands generation with pulsed laser

- ✓ ±n = 85 has achieved (FWHM)

✓ Most difficult and important part of cooling laser is done. Almost ready for laser cooling.

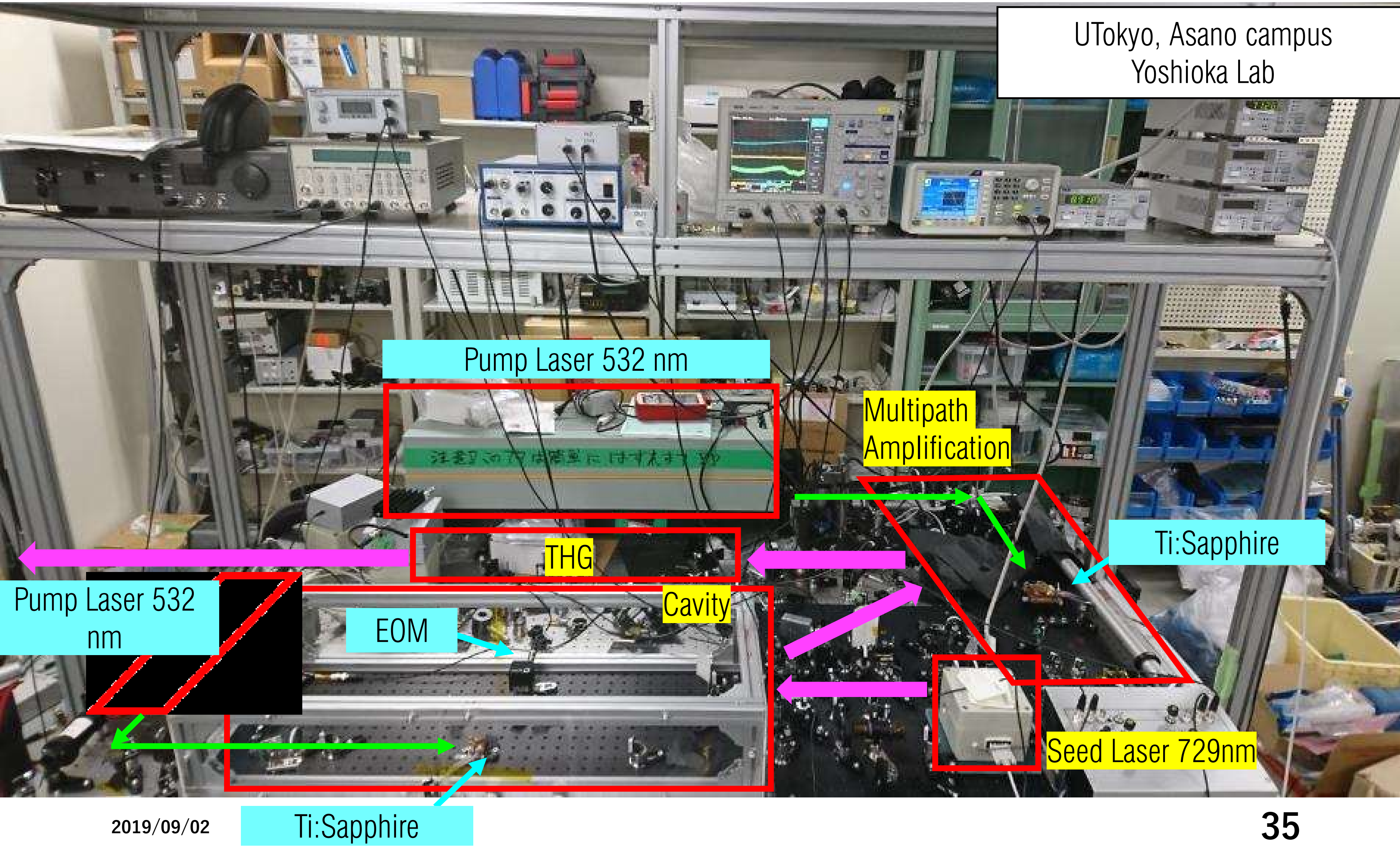
Overview of the cooling laser system

Compact system (2.0 m $\times$ 1.1 m) will be moved to KEK-SPF (Slow e^{+} Facility)

Construction of Cooling laser system will be finished soon.

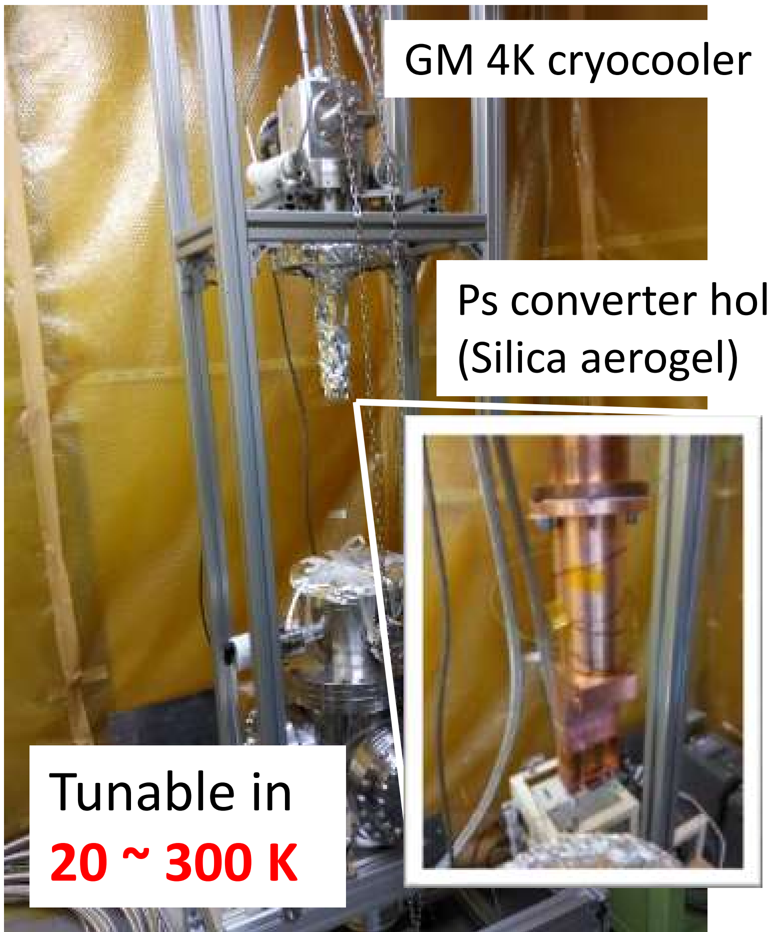
Overview of the cooling laser system

Compact system (2.0 m$\times$1.1 m) will be moved to KEK-SPF (Slow e^+ Facility)

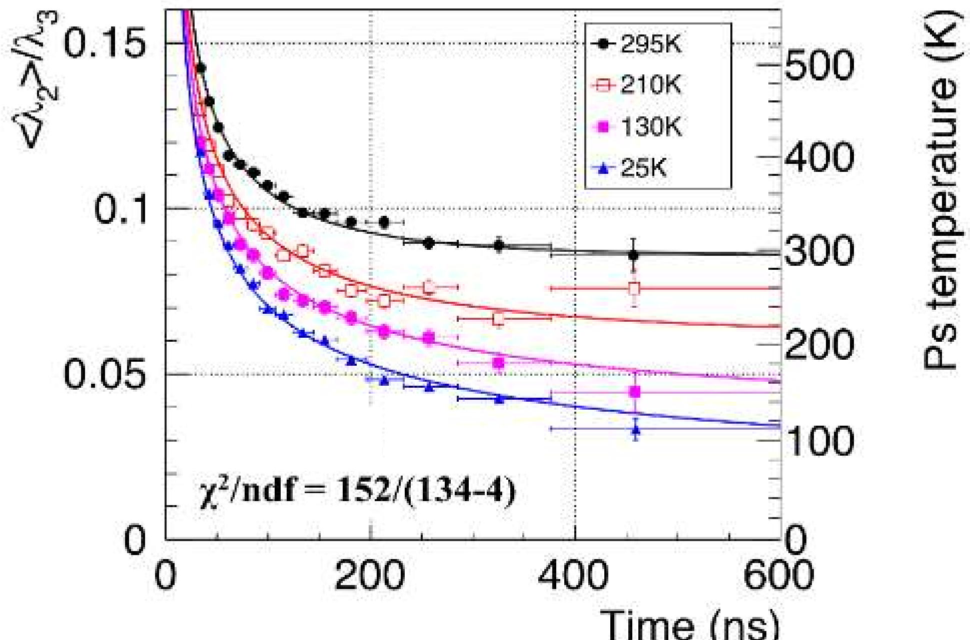


Ps thermalization down to 100 K was observed

We confirmed if Ps can be thermalized in its short lifetime (142 ns).



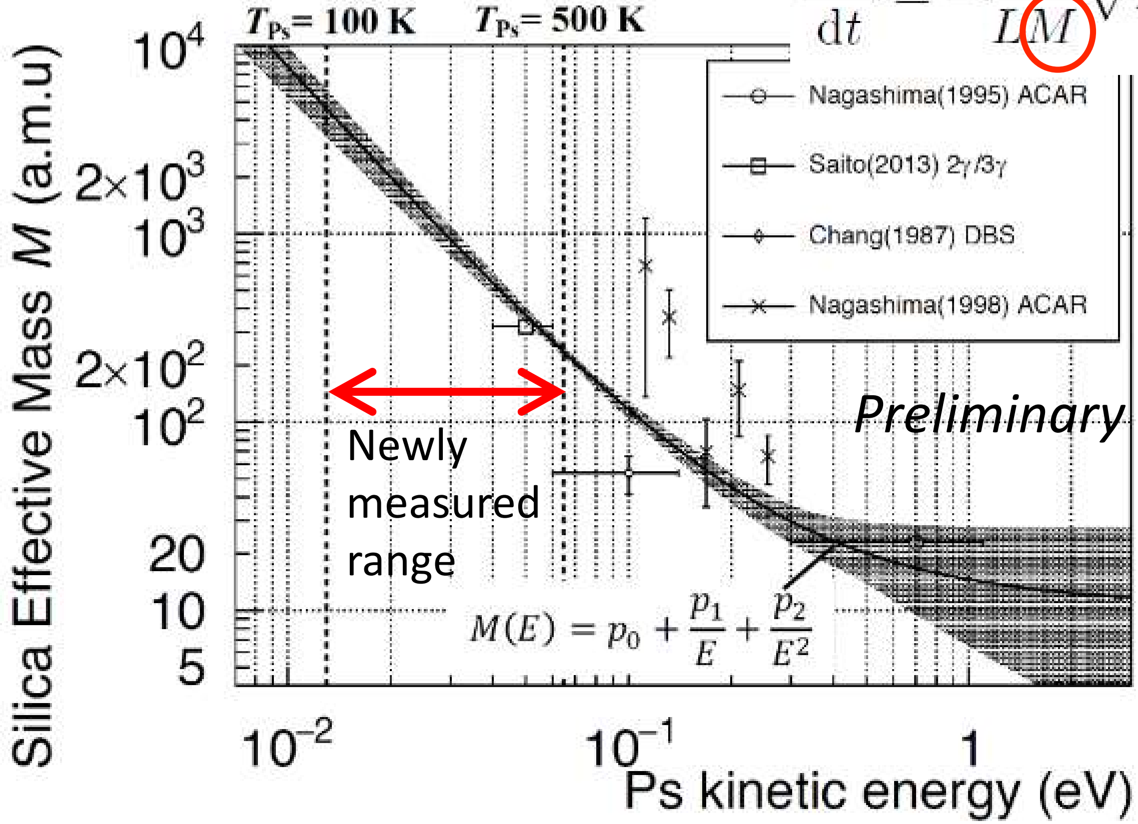
Thermalization curves of Ps in various silica temperature



- ✓ Thermalization into cryogenic temperature was clearly observed
- ➢ Next, Laser cooling and cool Ps down to 10 K

Ps thermalization slows down at lower Ps kinetic energy

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{2}{LM}\sqrt{2m_{\mathrm{Ps}}E}\left(E - \frac{3}{2}k_B T\right)$$



p_0 = 10.6 u
p_1 = 3.3 u eV
p_2 = 0.73 u eV^2

χ^2/ndf = 152/130

Band: 1σ uncertainty

- Consistent with older experiments at high temperatures.
- Thermalization can cool Ps down to 100 K, but not enough for Ps-BEC. Next cooling: Laser cooling down to 10 K.

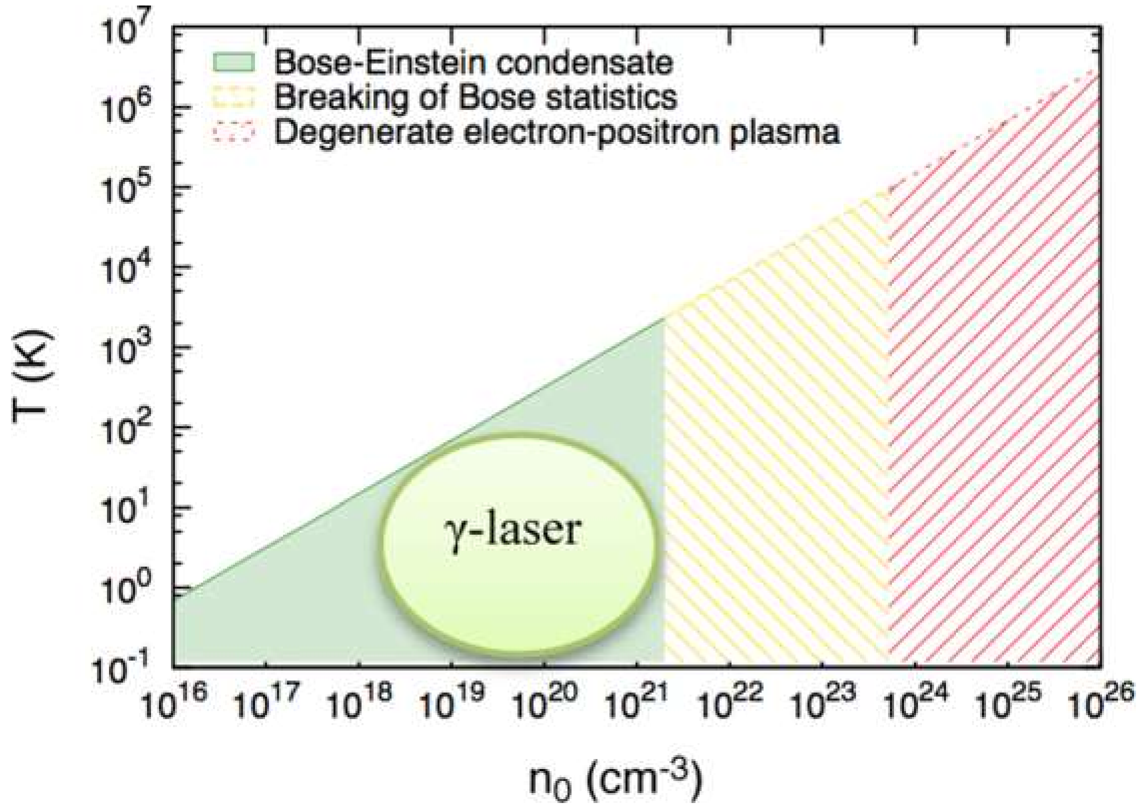
511 keV gamma-ray Laser

Decay from the BEC state (macroscopically occupied) enhances corrective decay

- Directive
- Coherent

BEC shape should be long in one direction (cigar shape) to have long interacting time between Ps and 511 keV photons

Ps-BEC will be formed in *ortho*, then stimulated into *para* by 203 GHz photon



511 keV photon density vs BEC density from Ref

1.5 cm x ϕ10 μm Ps-BEC

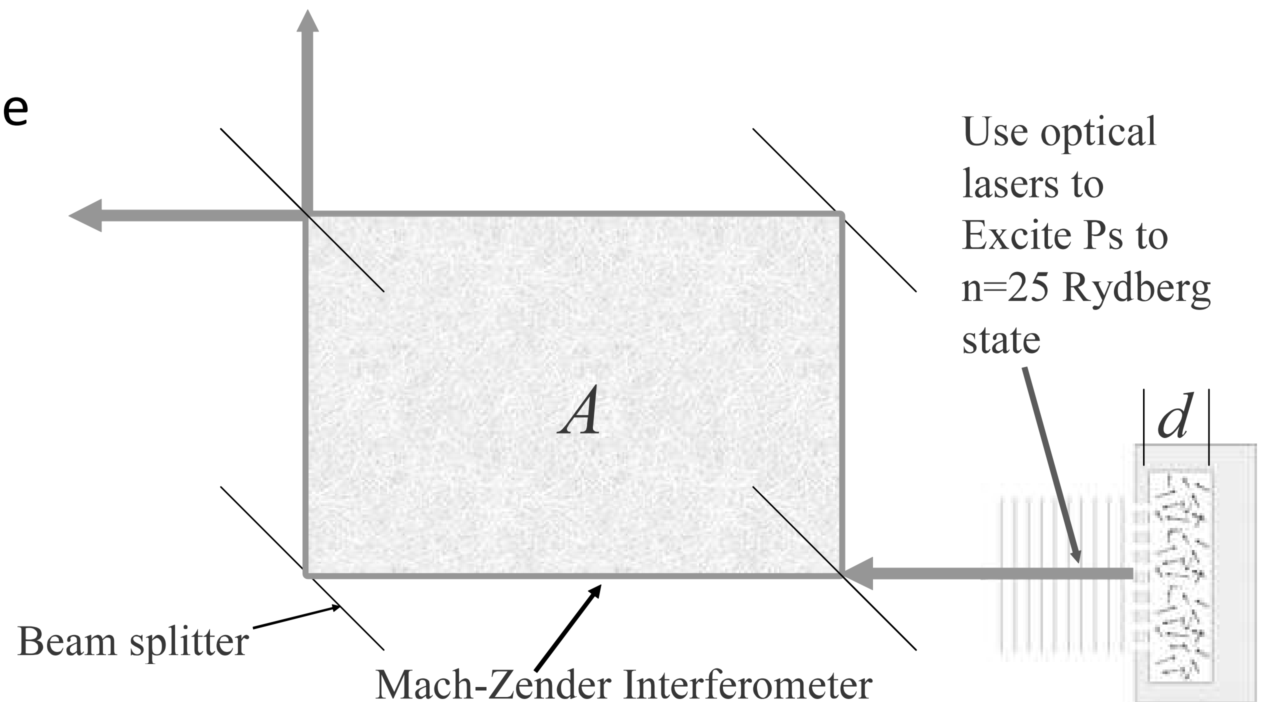
H. K. Avetissian *et al.* Phys. Rev. A 92, 023820 (2015).

Anti-matter Gravity Measurement

Difference of the paths will rotate relative phase between splited beams

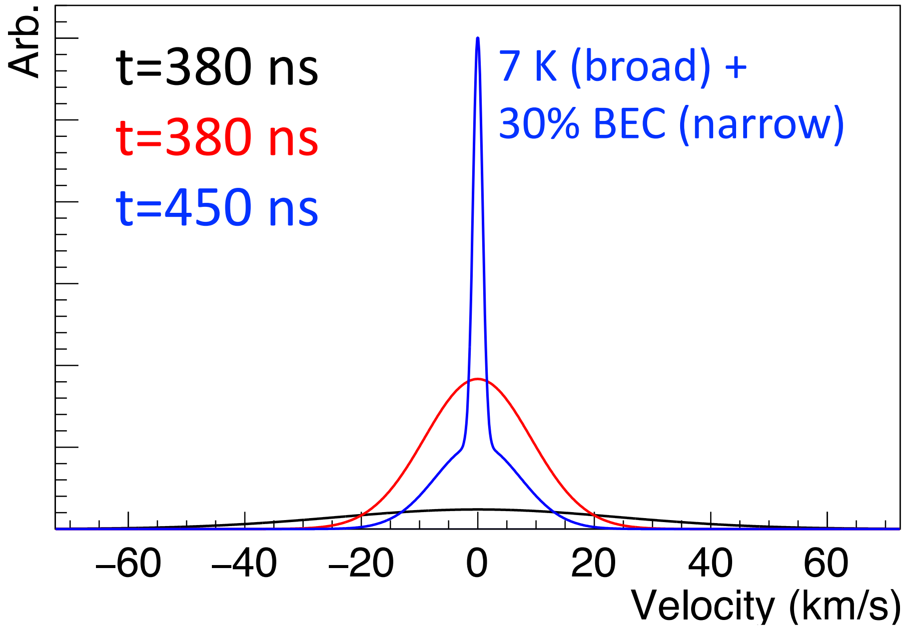
It is said that in Ref: 20 cm legs would be enough to see anti-matter gravity's effect

Ps must be excited into Rydberg state to be long-lived (~miliseconds)



Interferometer experiment with Ps-BEC from Ref.

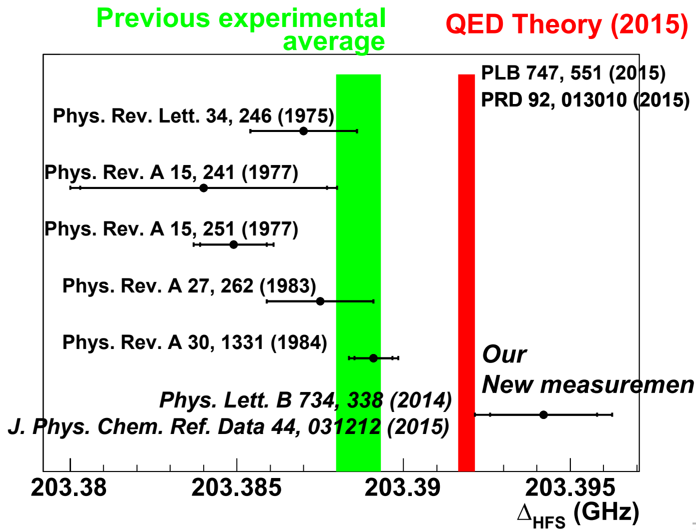
D. B. Cassidy et al. phys. stat. sol. (c) 4, No. 10 (2007)

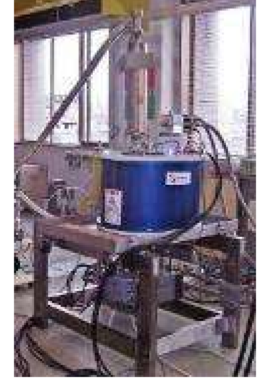


Arb.
t=380 ns
t=380 ns
t=450 ns
7 K (broad) +
30% BEC (narrow)
−60
−40
−20
0
20
40
60
Velocity (km/s)

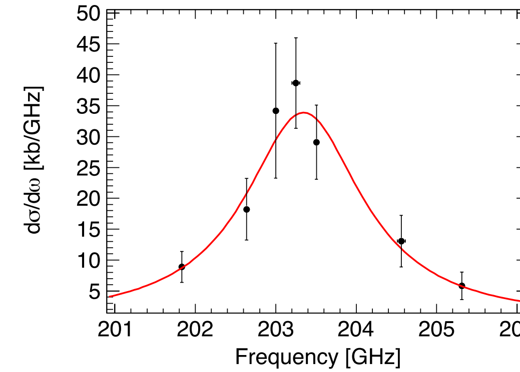
Our works

Hyperfine splitting ($E_{o\text{-}Ps}$-$E_{p\text{-}Ps}$) *(planning to improve)*





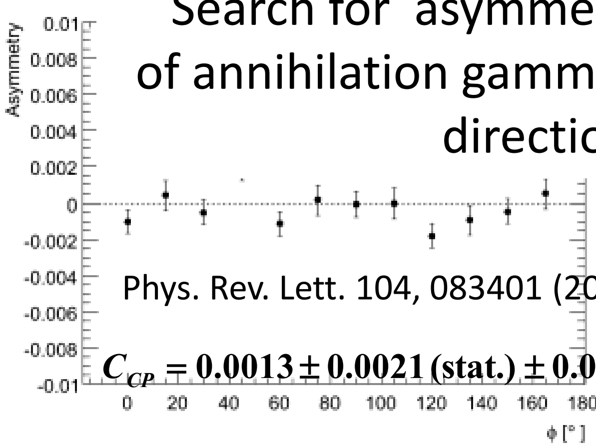
First direct transition o-Ps → p-Ps



Prog. Theor. Exp. Phys. 2015, 011C01

CP violation in lepton sector

Search for asymmetry of annihilation gammas' directions



Phys. Rev. Lett. 104, 083401 (2010)

$$C_{CP} = 0.0013 \pm 0.0021\,(\text{stat.}) \pm 0.0006\,(\text{sys.})$$

o-Ps lifetime

Phys. Lett. B 671(2009)219