Study on positronium Bose-Einstein condensation

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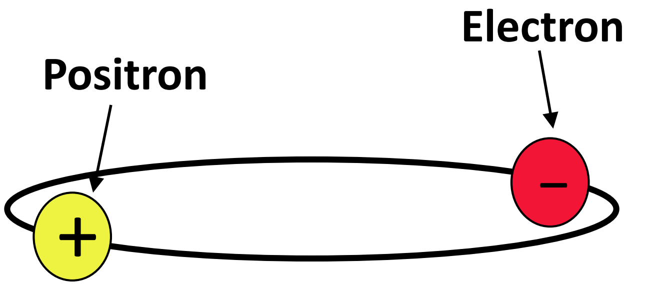
Contents

- Introduction – Motivation for Ps-BEC
  - matter-antimatter asymmetry
  - gamma-ray laser
- Our new idea to realize Ps-BEC
  - pulsed dense positron beam + SiO_2 cavity
  - thermalization + laser cooling
- Ps themalization measurement in cryogenic environment
- Laser development for Ps cooling

Positronium (Ps)

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



Lightest and Exotic Atom

◆ Sensitive probe for fundamental physics

✓ Exotic atom with antiparticle

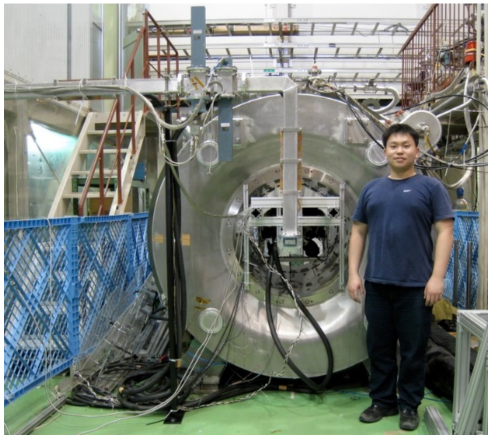
➢ Suitable for exploring the mystery of antimatter

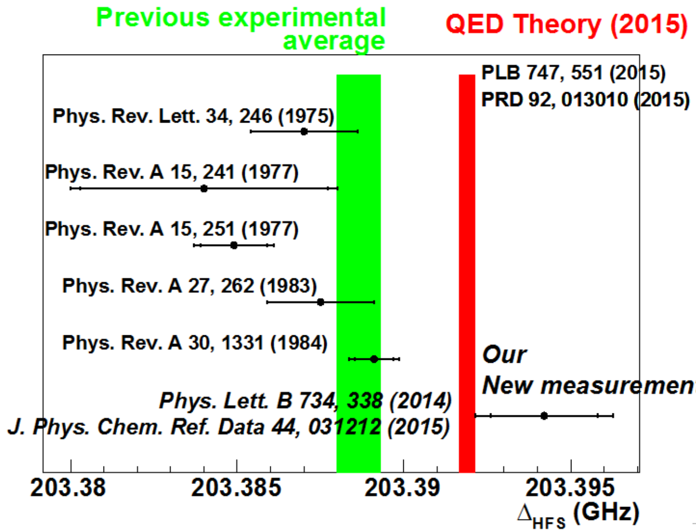
✓ Pure leptonic system

➢ Experiments and theoretical calculations can be compared in high precision (*ppm* level)

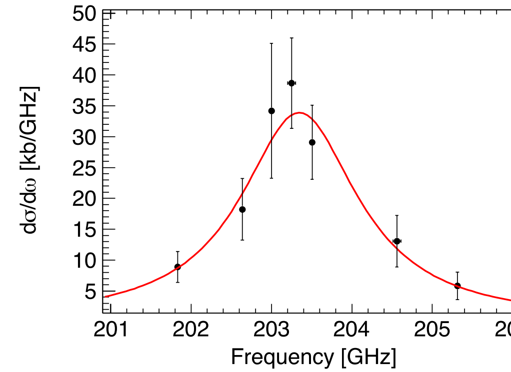
Our works

Hyperfine splitting ($E_{o\text{-}Ps}$-$E_{p\text{-}Ps}$) *ppm* precision!





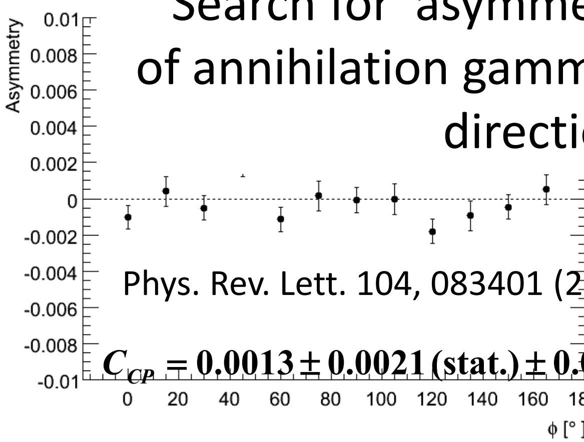
First direct transition o-Ps → p-Ps



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

CP violation in lepton sector

Search for asymmetry of annihilation gammas' directions

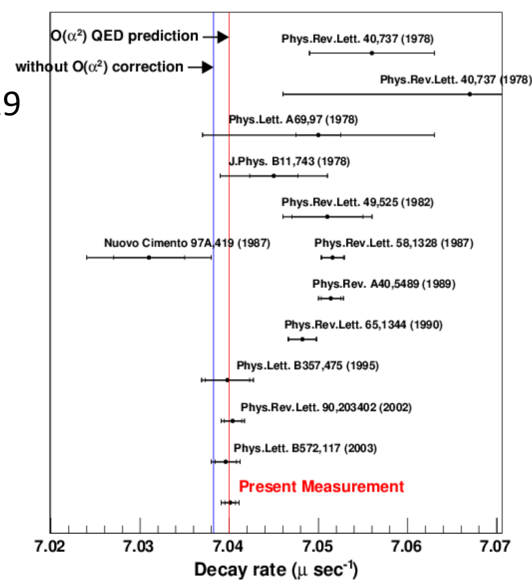


Phys. Rev. Lett. 104, 083401 (2010)

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

o-Ps lifetime

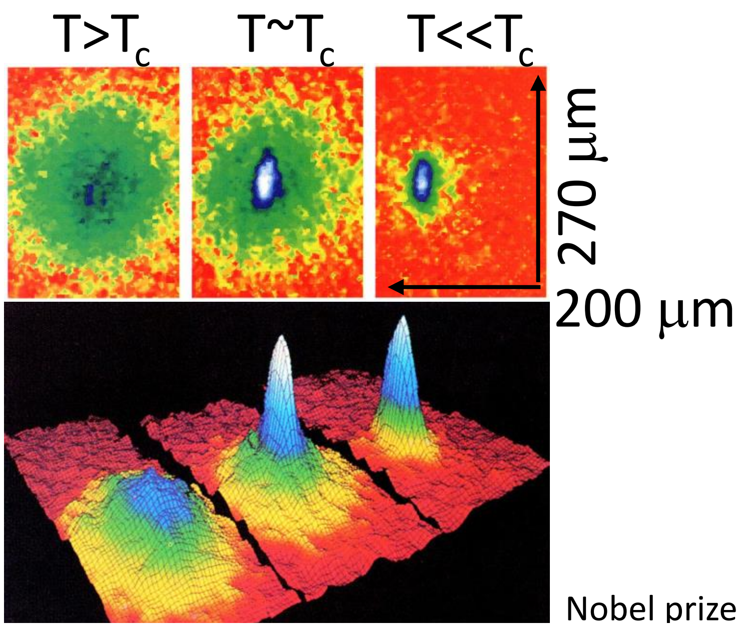
Phys. Lett. B 671(2009)219



Next target : Positronium Bose-Einstein condensation

<u>Bose-Einstein condensation (BEC)</u>

- Almost all of atoms in a cloud occupy a single quantum state
- Atoms must be dense and cold



Nobel prize

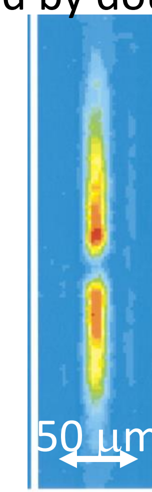
Spatial image of dense rubidium-87 around T_c (critical temperature) of BEC

... group. The upper left sequence of pictures shows the shadow created by absorption in the expanding atomic cloud released from the trap. Below, the same data are shown in another representation, where the distribution of the atoms in the cloud is depicted. In the first frame to the left, we see the situation just before the condensation sets in,

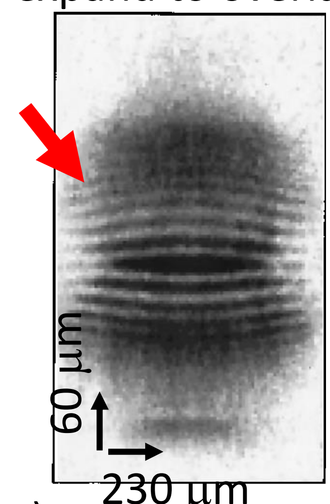
<u>Important feature</u>

- BEC is "Atom laser"
- Quiet and coherent: Microscopic quantum effect in macroscopic such as matter-wave interference
- Breakthrough to study microscopic world

Before release trapped by double-well



After release expand to overlap

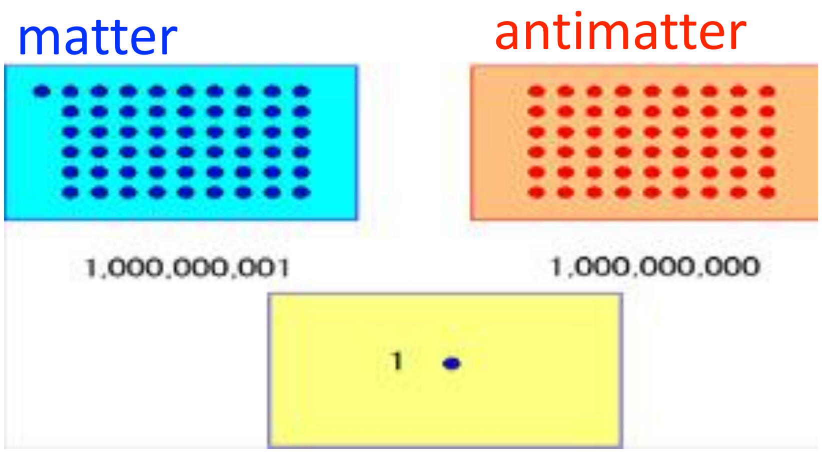


Science 275, 637 (1997)

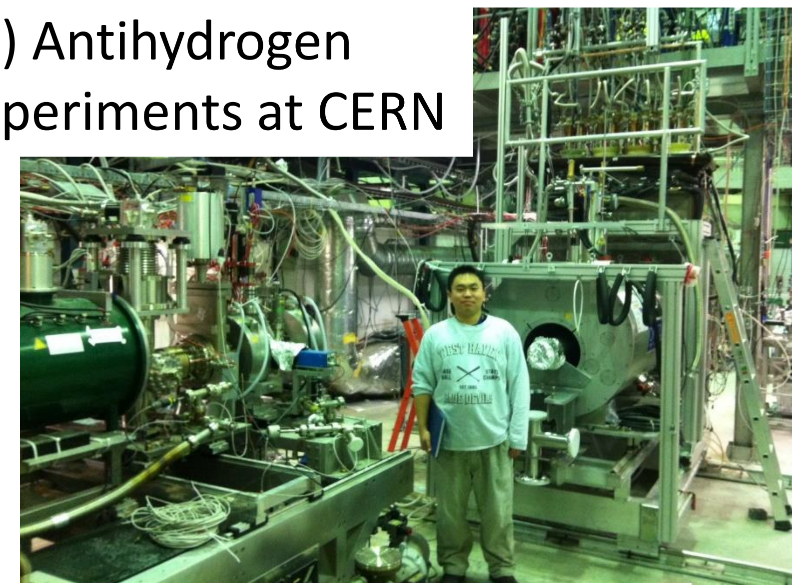
BEC of Positronium
- Antimatter -

◆ First BEC with antimatter. ➢ <u>Hot topic in particle physics and cosmology</u>

Antimatter should not be the same as matter to explain why matters are left in the universe. ⇨ Many experiments are searching for matter-antimatter asymmetry



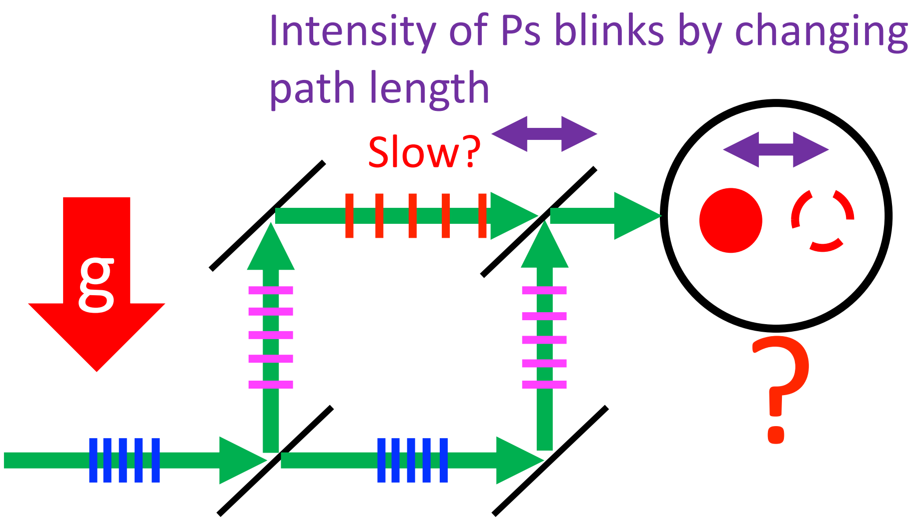
Ex) Antihydrogen experiments at CERN



➢ <u>BEC with antimatter can be a good tool to search on this hot topic by using coherency</u>

Applications of Ps-BEC

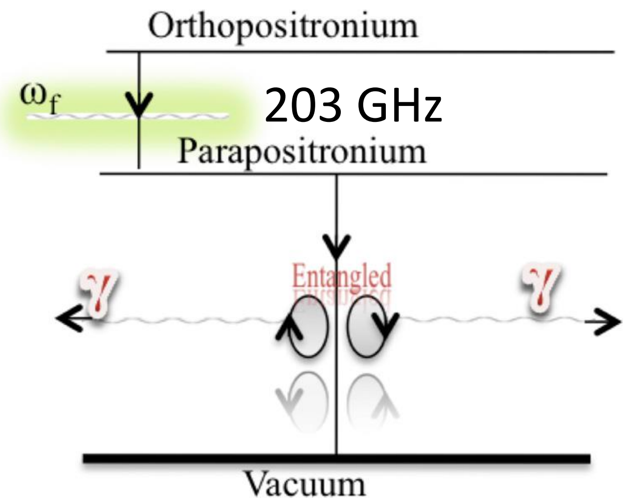
1. Measure anti-matter gravity by atom-interferometer



- Deceleration by gravity shift phase of Ps in different paths
- Path length 20 cm to see gravity effects with weak-equivalent principle

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

2. 511 keV gamma-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

☐ High-resolution imaging with x10 shorter wavelength than current X-rays

☐ Macroscopic entanglement

The challenge:
Dense and cold Ps in a short time

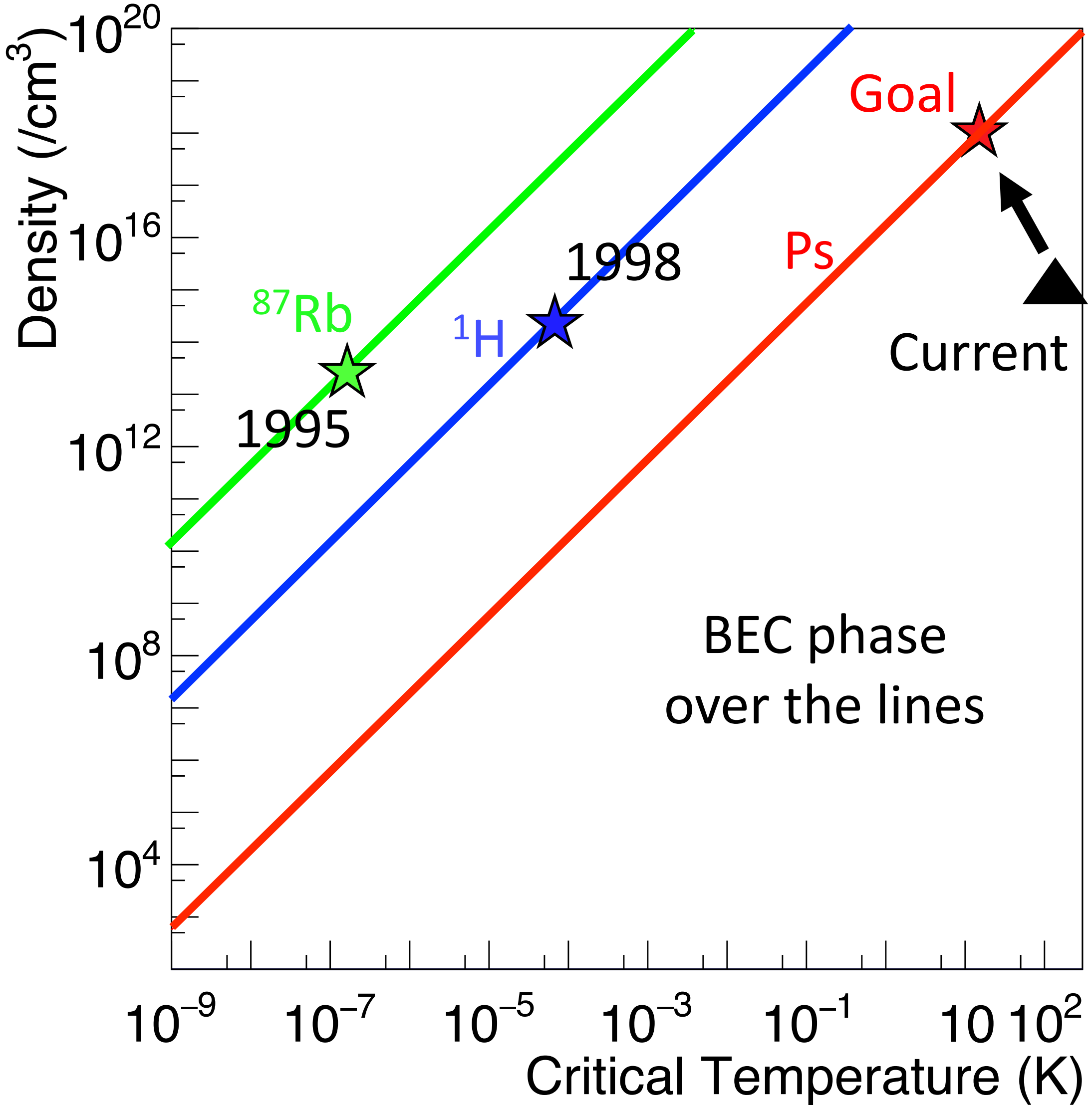
<u>Conditions to realize Ps-BEC</u>

- High density
- Low temperature
- ➢ For Ps, 14 K at 10^{18} cm^{-3}

- Critical temperature (T_C) is very high due to Ps light mass
- × Ps annihilation life time is only 142 ns (o-Ps)

<u>Necessary techniques</u>

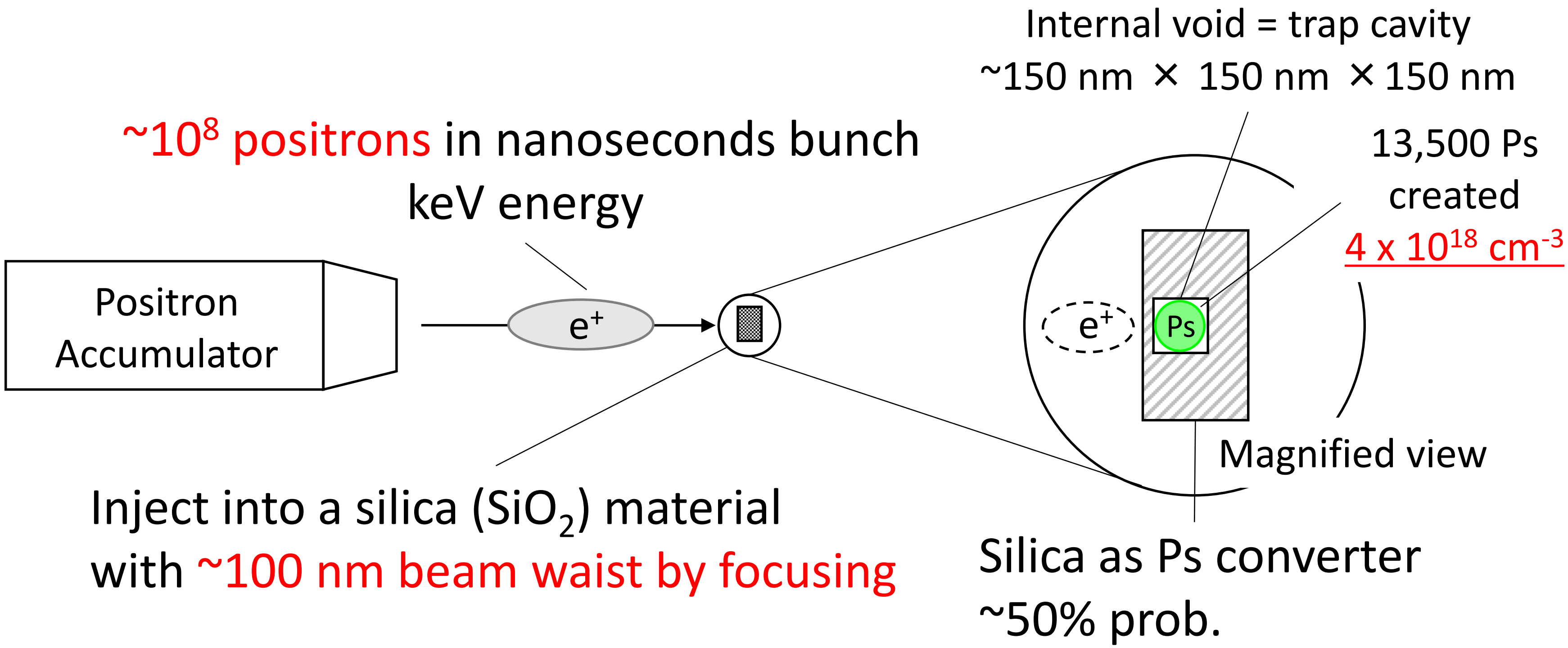
1. Instance (around 10 ns) creation of dense Ps
2. Fast cooling of Ps to 10 K in around 100 ns



Method to realize Ps-BEC

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

1. Create dense positrons and convert into dense Ps at once

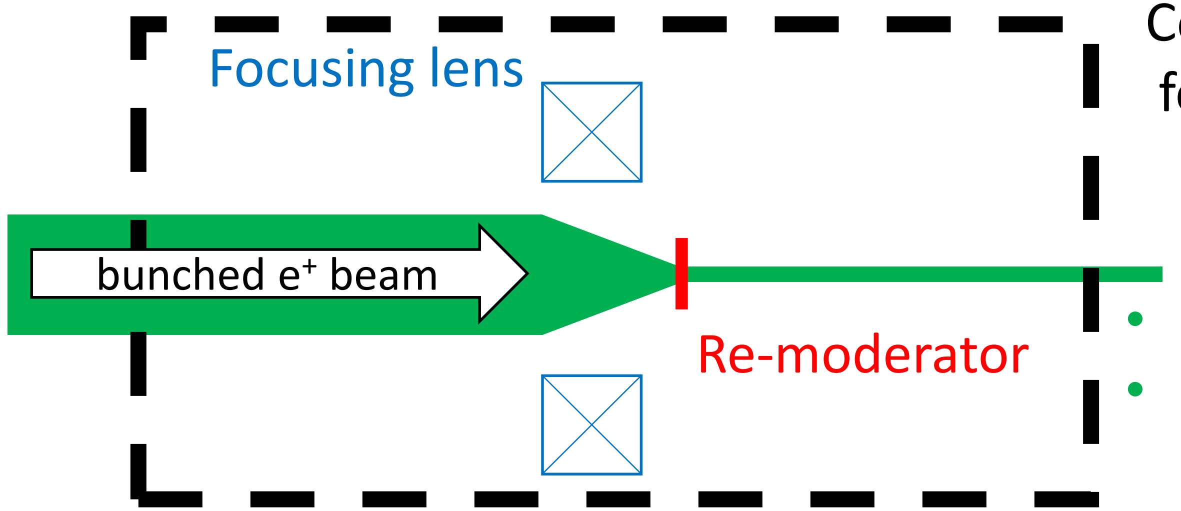


- 10^9 positron accumulation was achieved elsewhere. We are studying new focusing system to achieve 100nm beam waist.

Positron focusing – Basic Idea

State-of-the-art: a few μm waist **→ 100 nm waist for BEC**

Principle of Positron focusing:



Continue this process for several stages

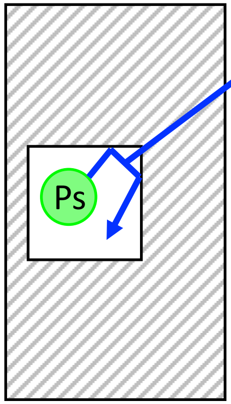
- Pararell
- Monochromatic Energy

N. Oshima *et al.* J. Appl. Phys. 103, 094916 (2008).

Problems to be solved : Space charge (beam),
Discharge, charging up, heating up (target)

→ Basic study is ongoing. Measurement of beam-density dependence on target using bunched positron beam is important!

1st Ps cooling: thermalization process



Cold Silica < 10 K

1st step

By collisions with cold silica cavity wall
= Thermalization process

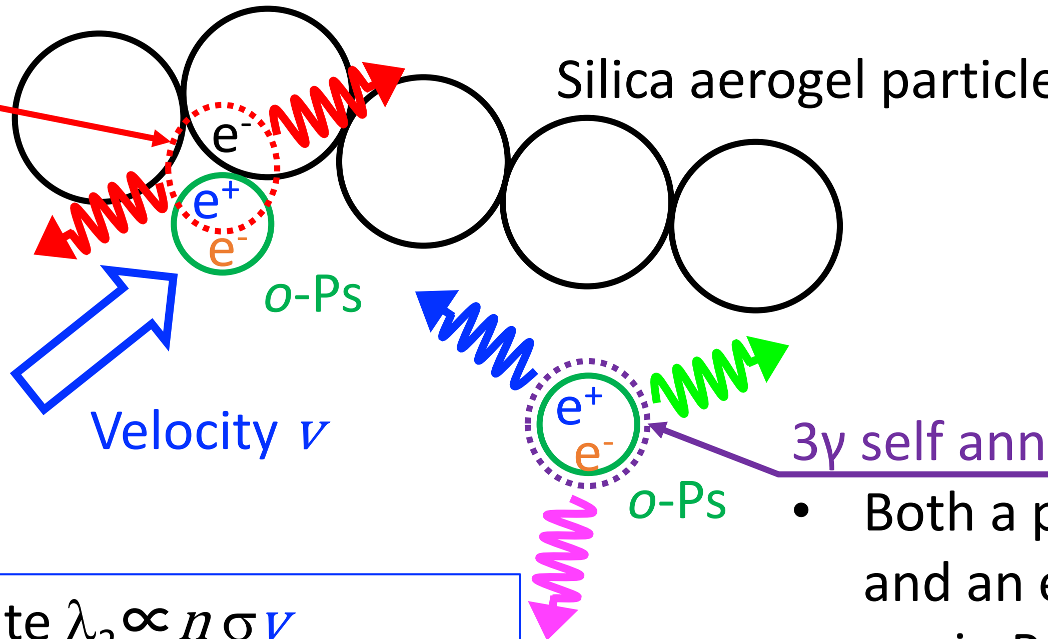
No measurement of Ps thermalization process in cryogenic environment

→ We are measuring it for the first time.

Observation of Ps thermalization process in cryogenic environment

Pick-off 2γ annihilation

- A positron in Ps and an electron in silica by collisions
- 511 keV mono energy



3γ self annihilation

- Both a positron and an electron are in Ps
- 0 ~ 511 keV continuous energy spectrum

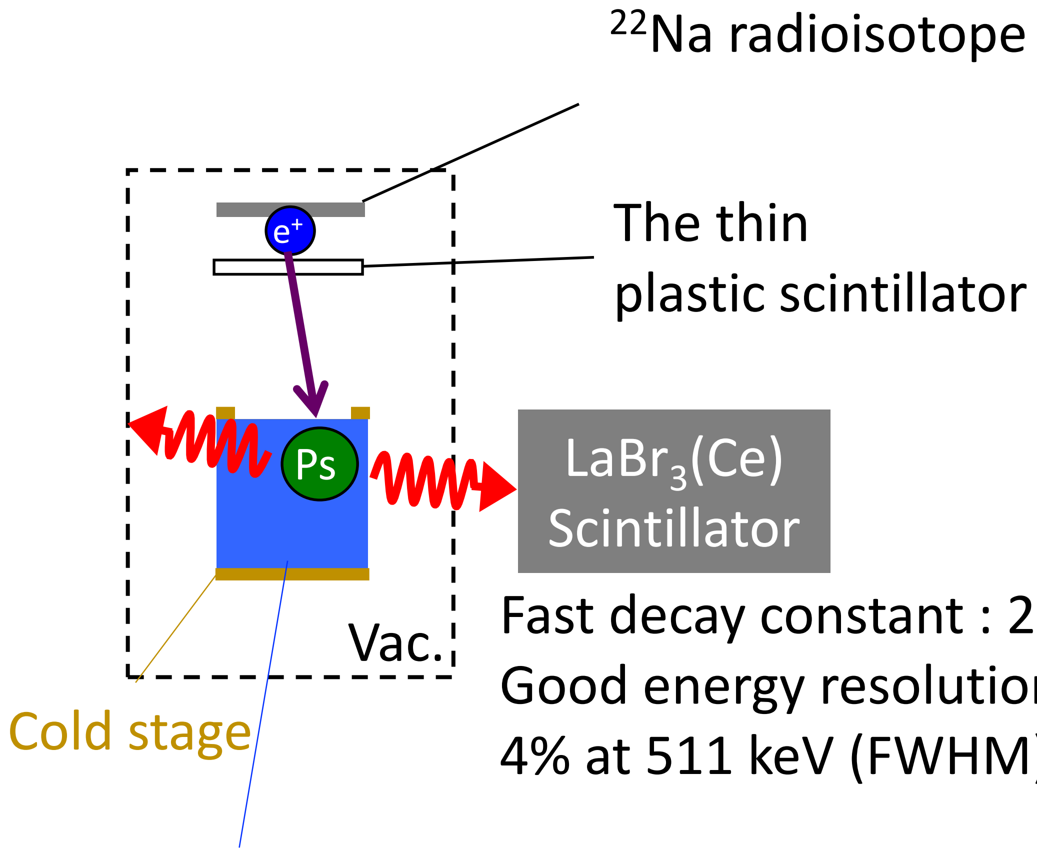
Pick-off annihilation rate $\lambda_2 \propto n \sigma v$

n: Density of electrons in silica particle

σ: Cross section of Pick-off annihilation

→ <u>By measuring λ_2 vs Ps life, temperature evolution of Ps can be measured</u>

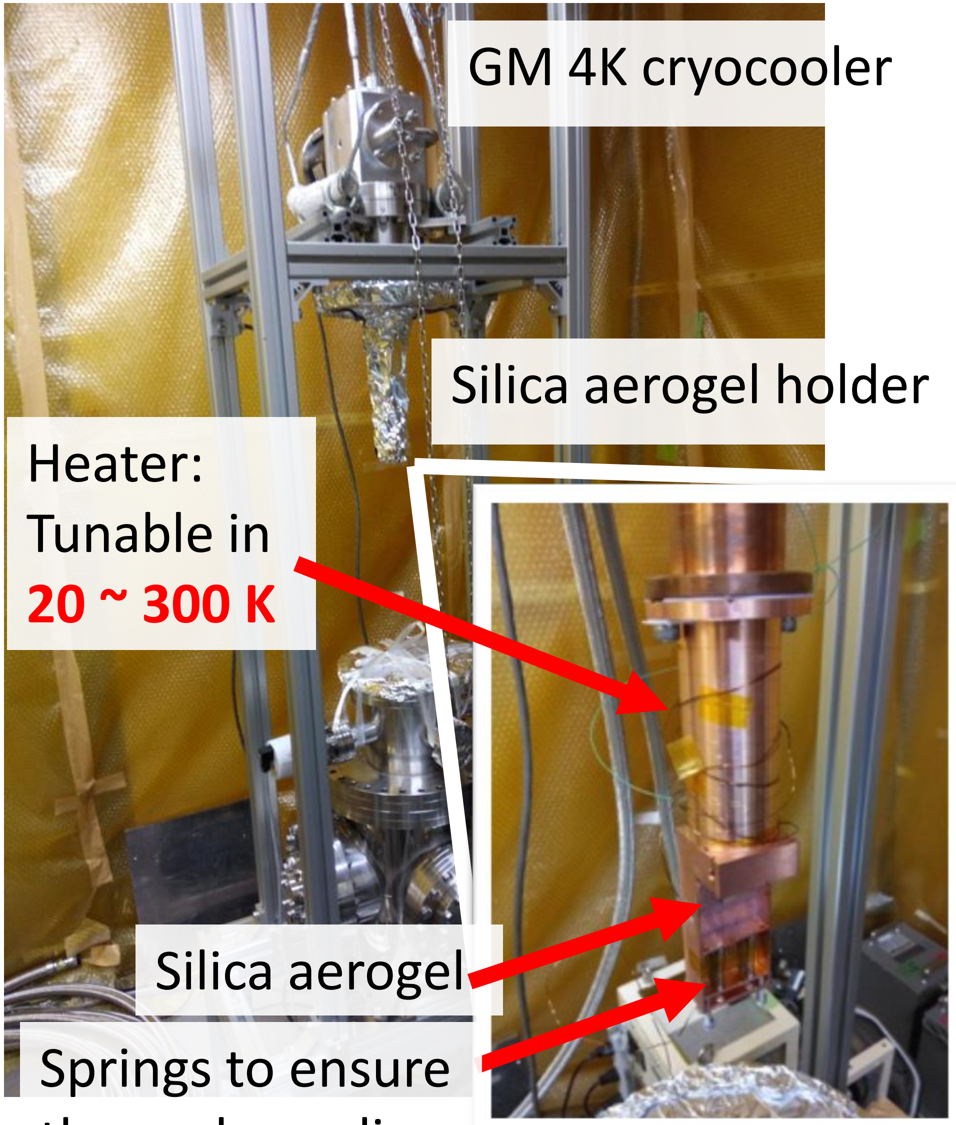
Experimental Setup

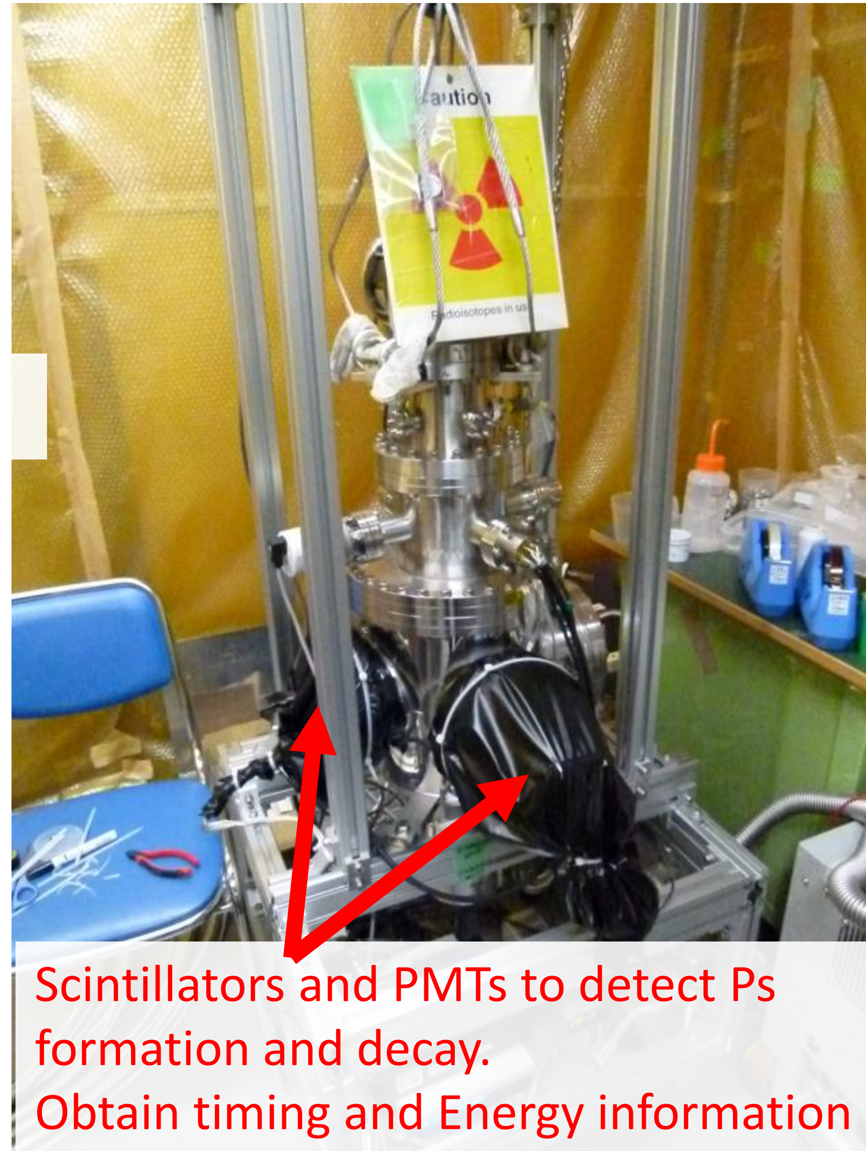


Fast decay constant : 20 ns
Good energy resolution :
4% at 511 keV (FWHM)

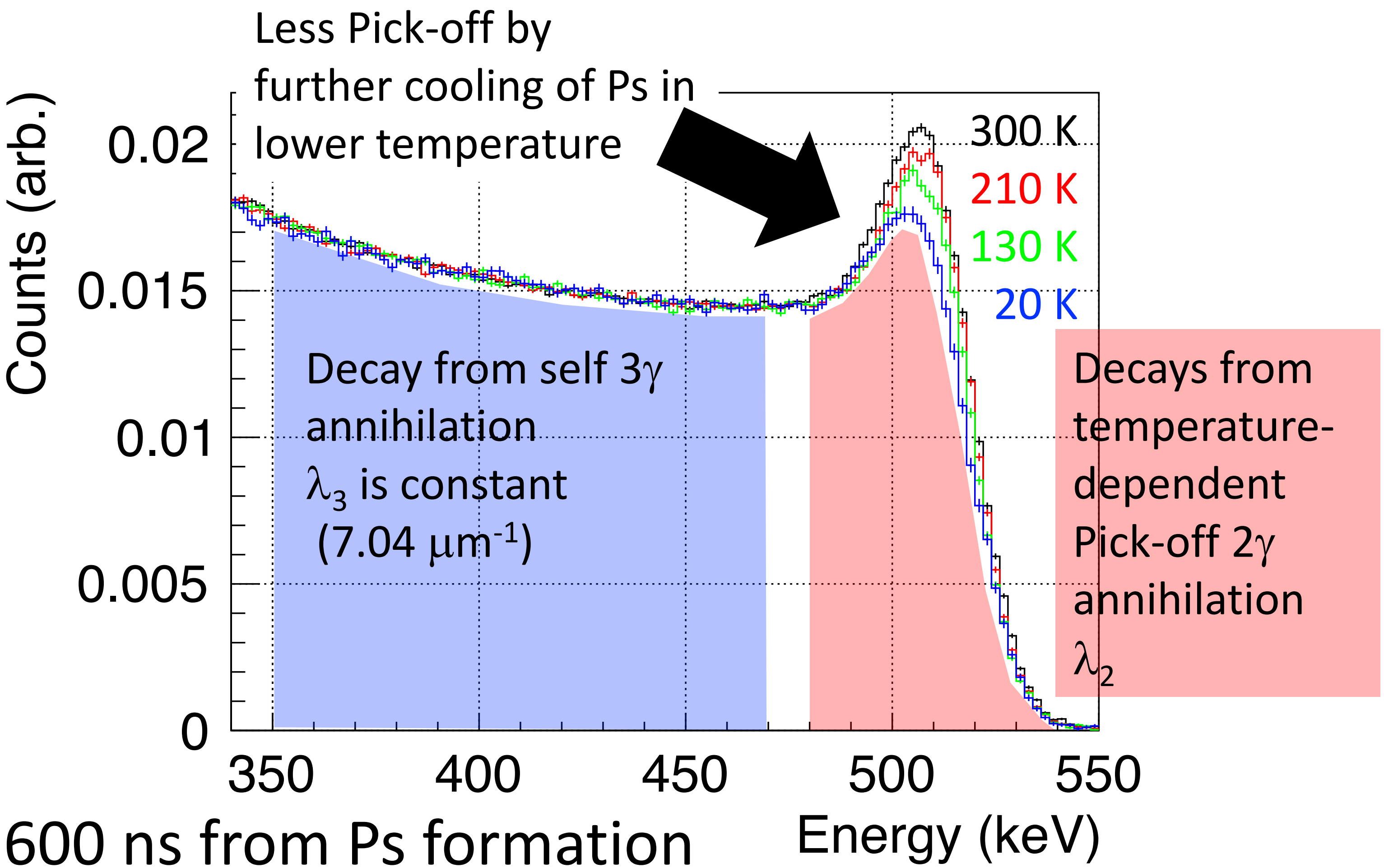
Silica aerogel : porous material made by silica
Density: 0.11 g/cm^3 → Mean free path 60 nm

Photos


GM 4K cryocooler
Silica aerogel holder
Heater:
Tunable in
20 ~ 300 K
Silica aerogel
Springs to ensure
thermal coupling


Scintillators and PMTs to detect Ps
formation and decay.
Obtain timing and Energy information

Annihilation γ-rays' energy spectra



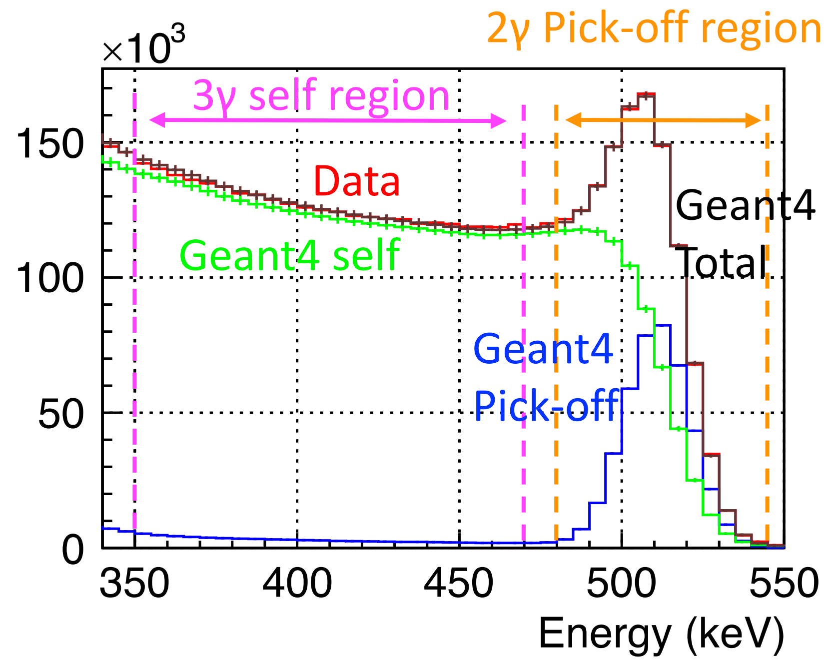
30 - 600 ns from Ps formation

Deducing Pick-off annihilation rate using MC simulation

- Use difference between energy spectra of Pick-off 2γ/Self 3γ

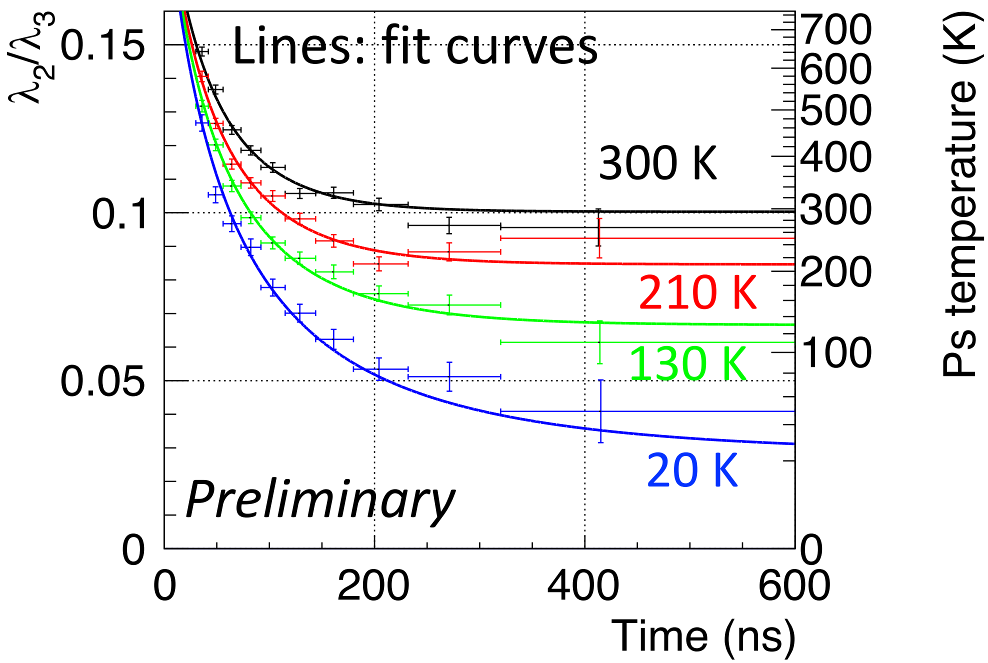
  Pick-off 2γ : 511 keV peak

  Self 3γ : Continuous
- Define energy regions to enhance each annihilation event
- Detection efficiencies and contamination fractions are estimated by Geant4 MC simulation.



Recorded energy spectrum (Ps life 30 - 300 ns)
Accidental events are subtracted by energy spectrum in 1200 - 1500 ns

Result of the measurement



Thermalization curves of Ps in various silica temperature

- Thermalization into cryogenic temperature was clearly observed

Temperature evolutions of Ps are well fitted by the elastic-scattering model

$$\frac{dE}{dt} = -\frac{2}{LM} v \left(E - \frac{3}{2} k_B T\right),$$

$$v = \sqrt{\frac{2E}{m_{Ps}}},$$

$$\lambda_2(t) = \frac{C}{L} \times v$$

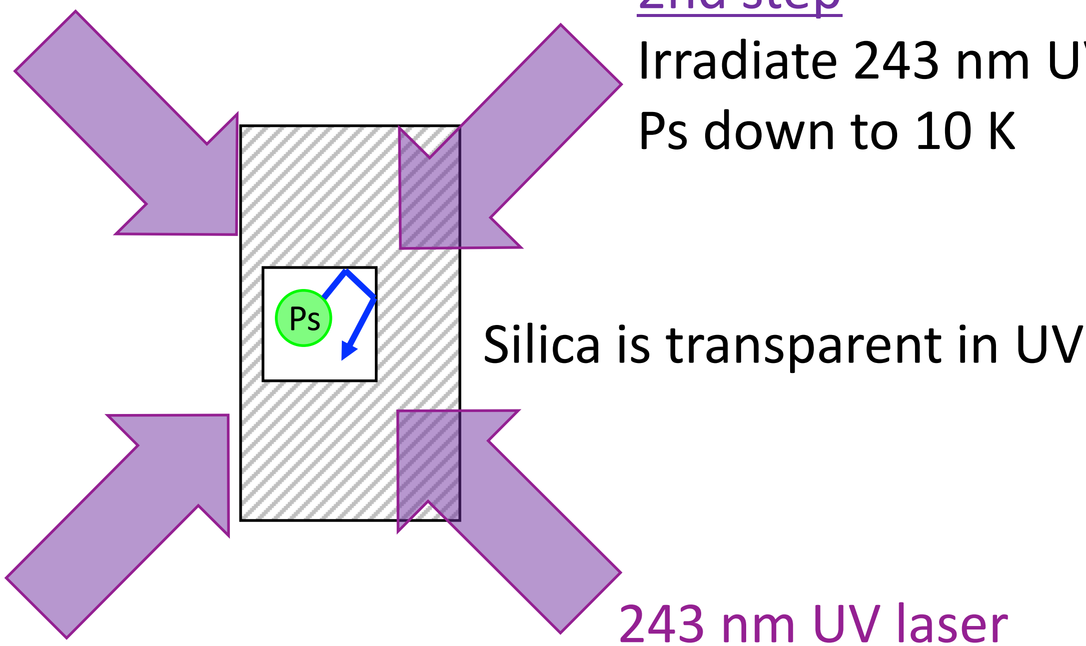
<u>Important parameter M:</u>

Effective mass of silica for elastic collision with Ps

Measured M = 170±10 a.m.u

✓ Smaller (thermalize faster) than other experiments in high T or with gases

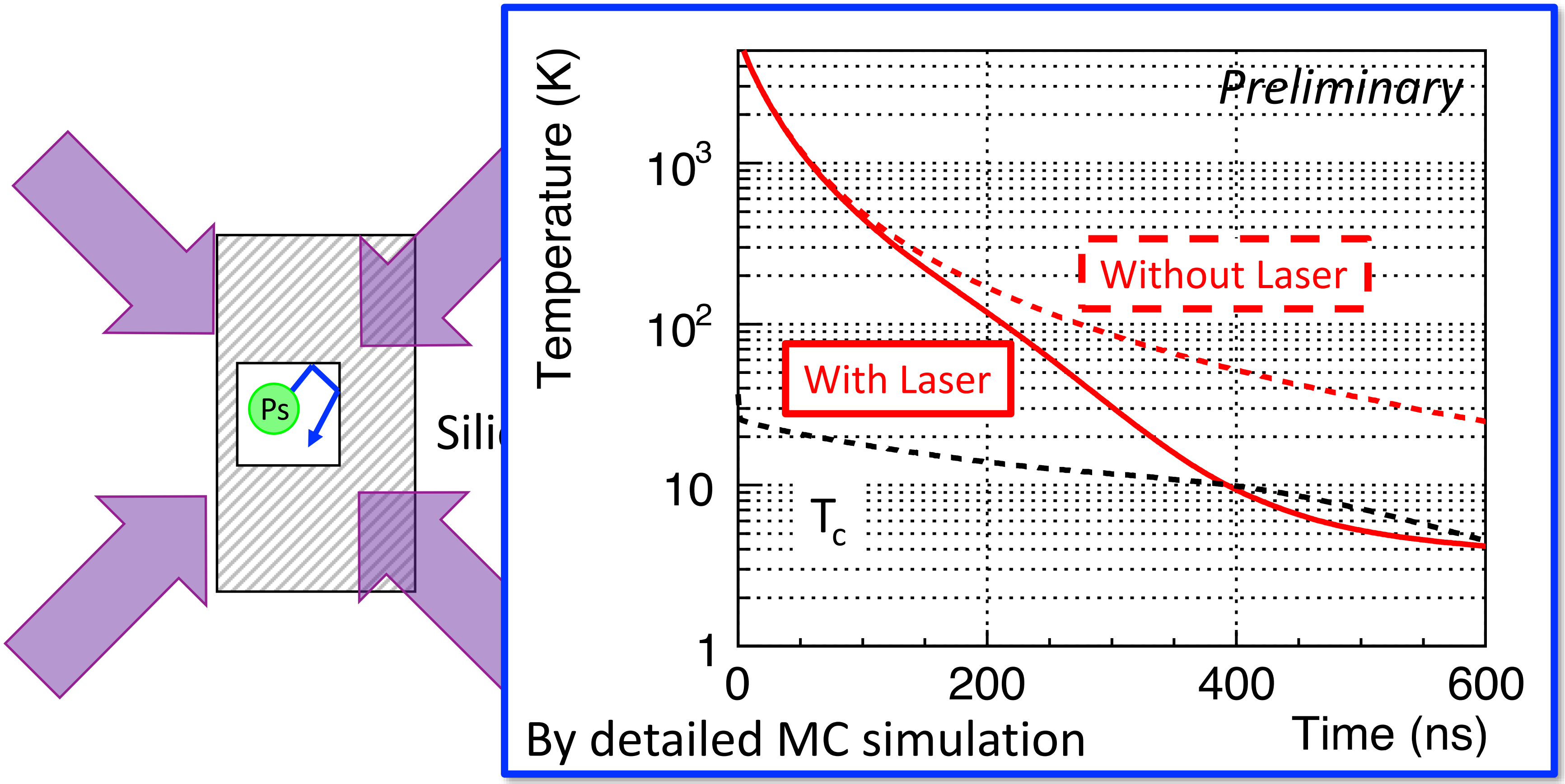
2nd Ps cooling: Laser cooling



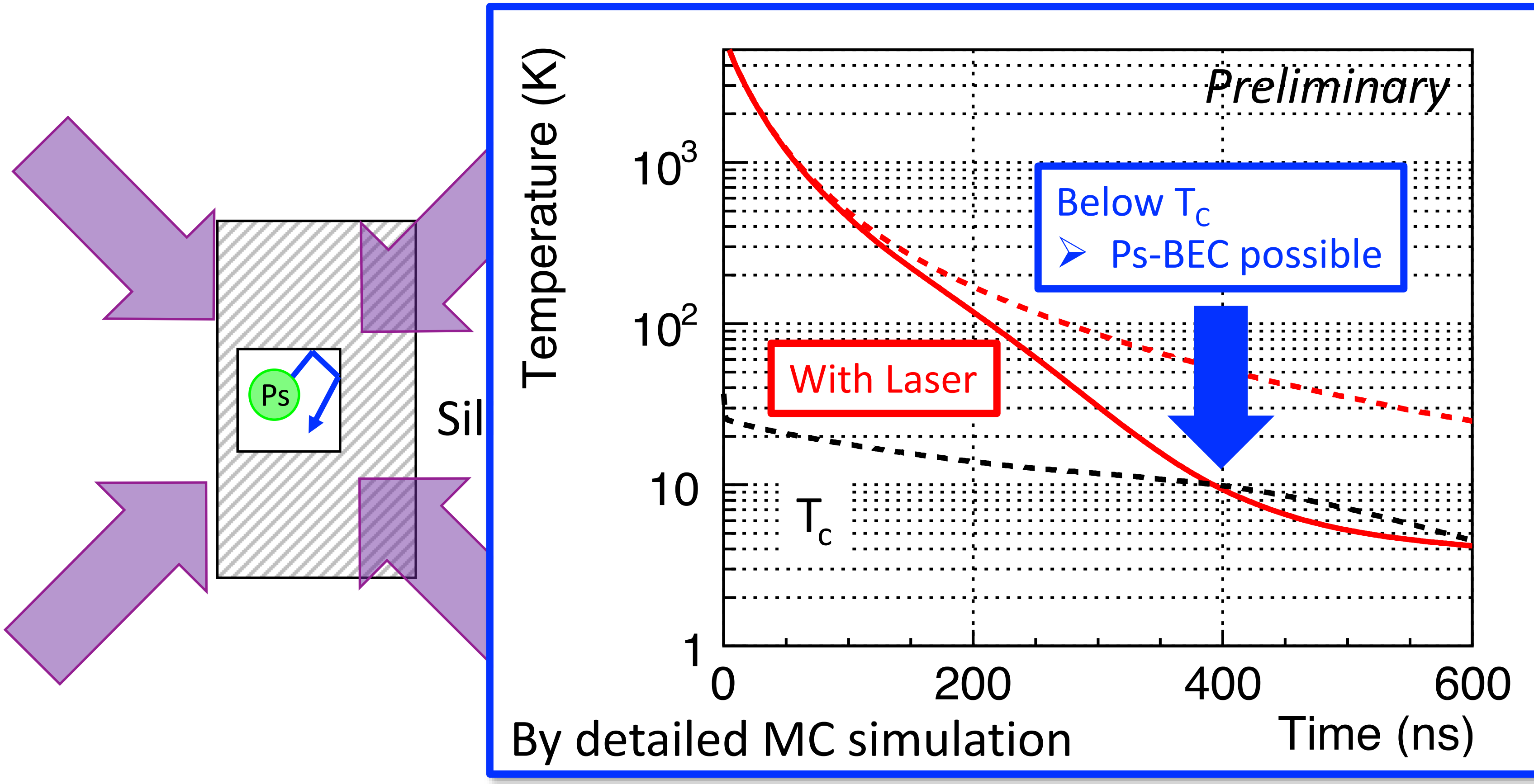
2nd step

Irradiate 243 nm UV laser to cool Ps down to 10 K

Ps laser cooling

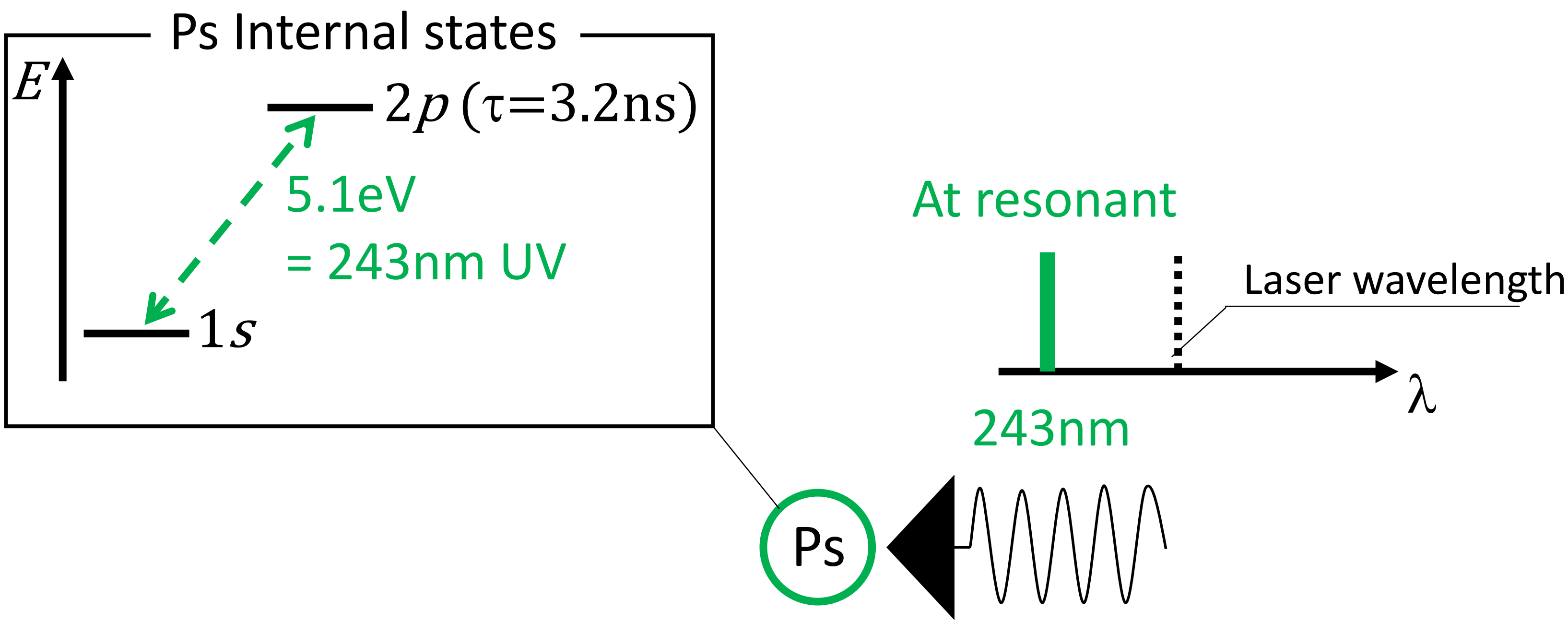


Ps laser cooling



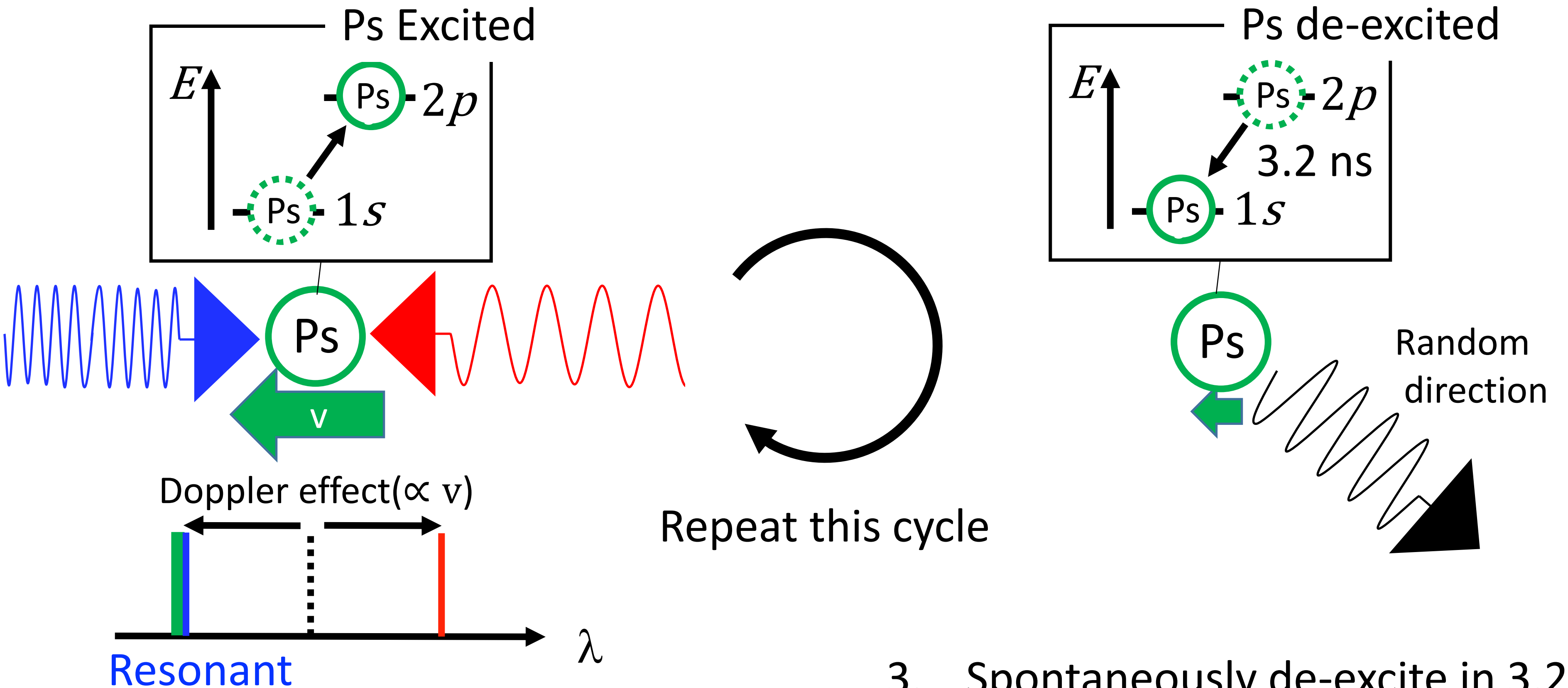
Principle of Laser Cooling

Laser cooling: Cool atoms by absorptions of photons' momenta



- To let Ps absorb photon, use 1s - 2p transition
- Incident laser wavelength is detuned slightly longer than resonance

Ps Laser Cooling Cycle



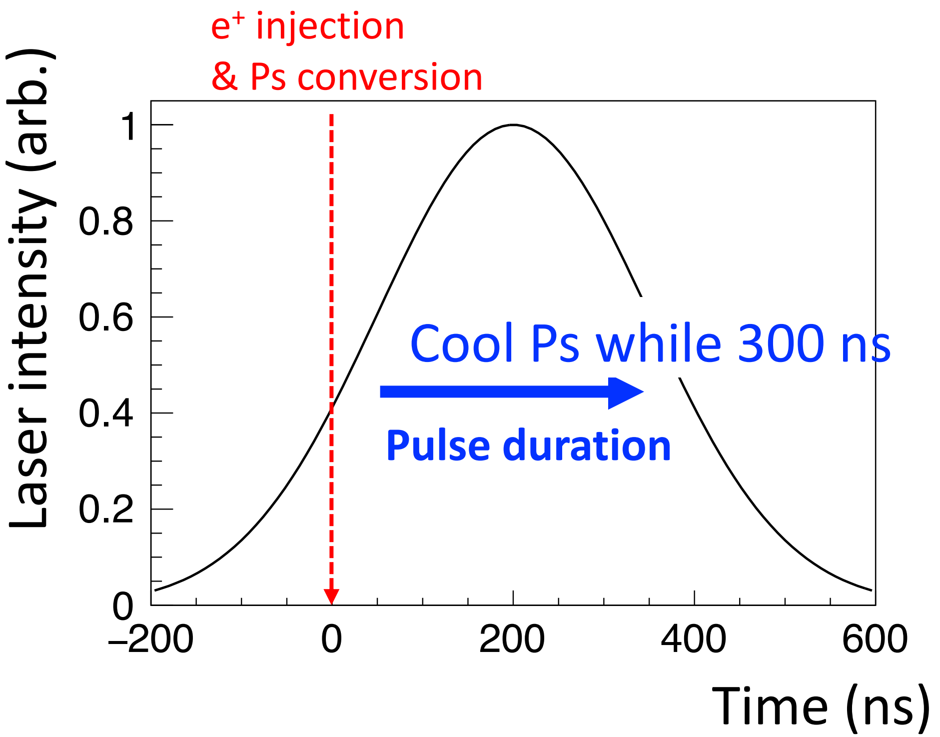
1. Only counter-propagating photons are absorbed by Doppler effect
2. Decelerate by photon's momentum
3. Spontaneously de-excite in 3.2 ns with random direction photon
(no effect on Ps temperature)

Requirements for Cooling Laser

First laser cooling of Ps (anti-matter systems)

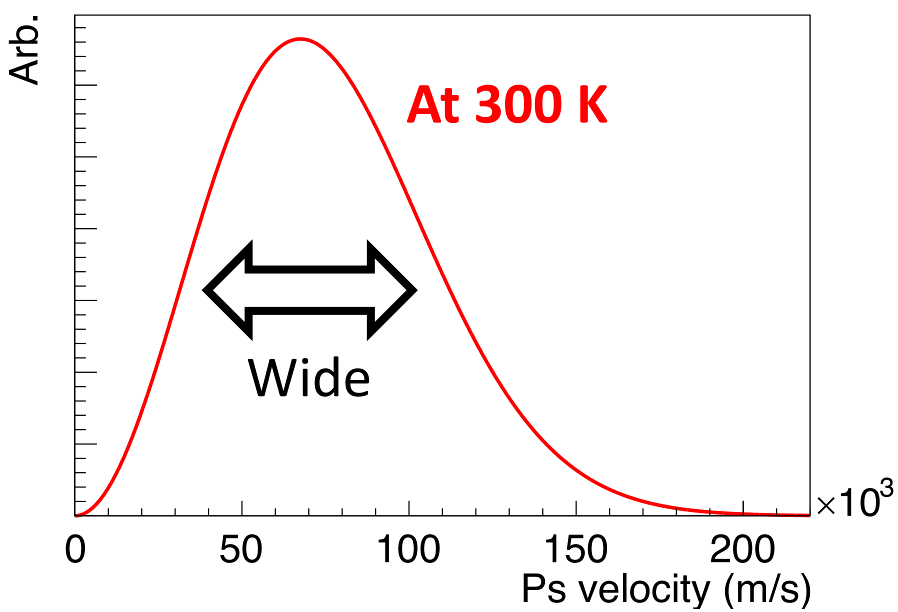
For Ps, several special features are necessary

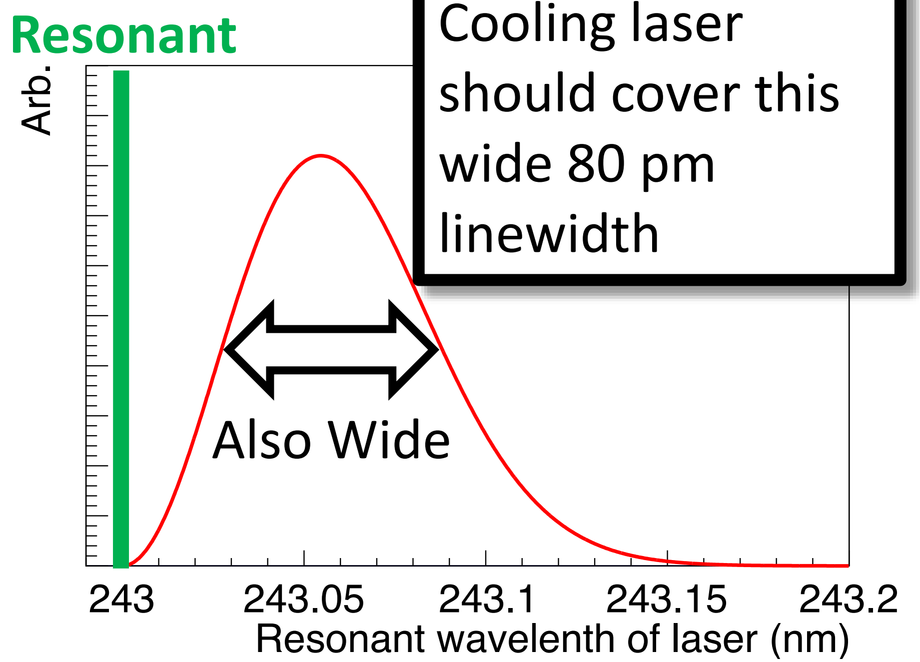
1. <u>Long time duration pulse</u>
   - Cooling of Ps takes around 300 ns (~ Ps life)



Requirements for Cooling Laser

2. Wide linewidth
   - Doppler effect is large due to Ps light mass, so laser linewidth must cover wide Doppler width

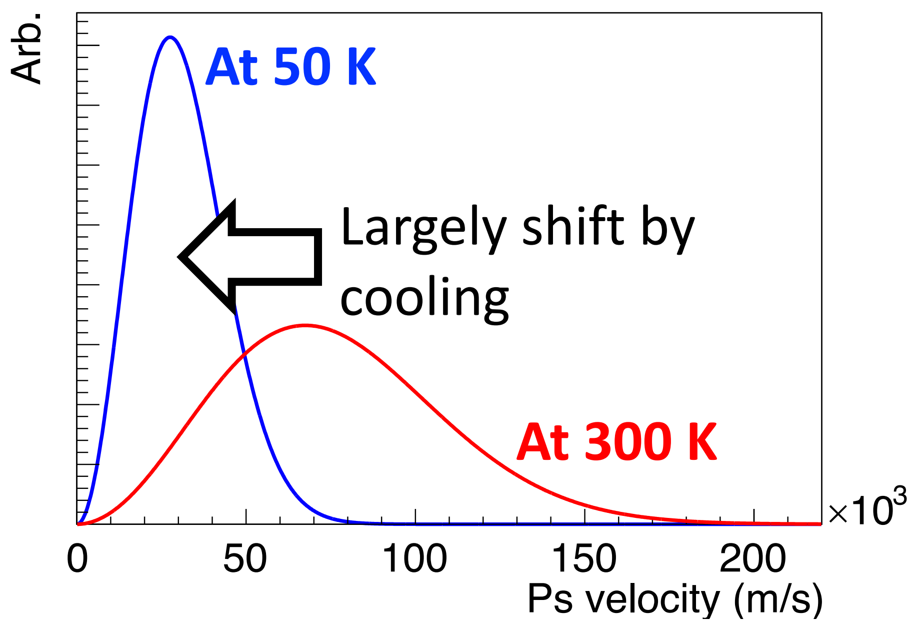


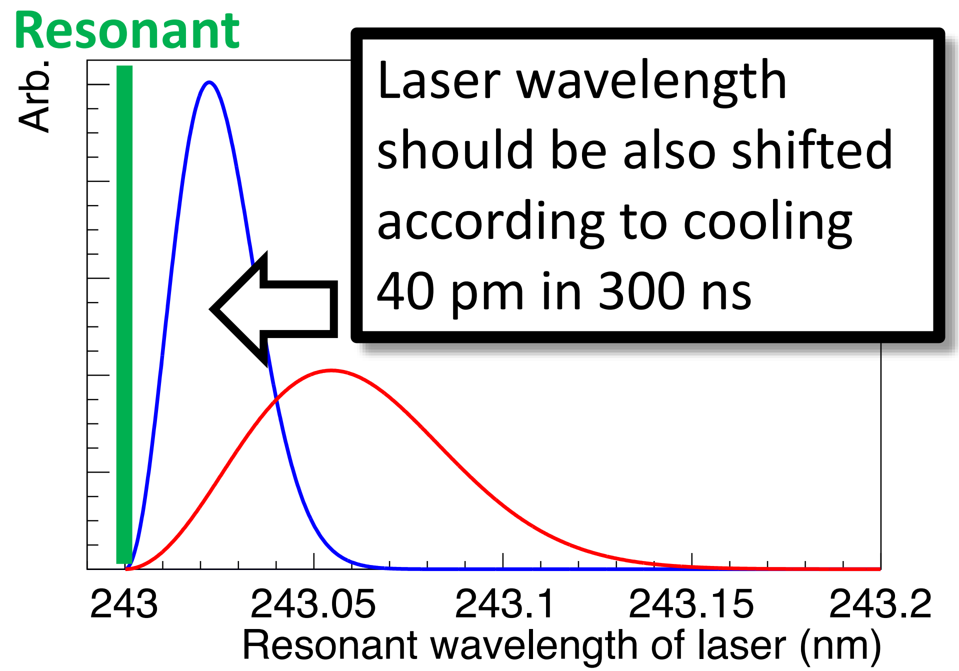


Cooling laser should cover this wide 80 pm linewidth

Requirements for Cooling Laser

3. <u>Fast shift of wavelength</u>
   - ➢ Resonant wavelength shifts as Ps atoms get cold
   - ✓ Fast shift (40 pm in 300 ns) of pulse laser has never been achieved





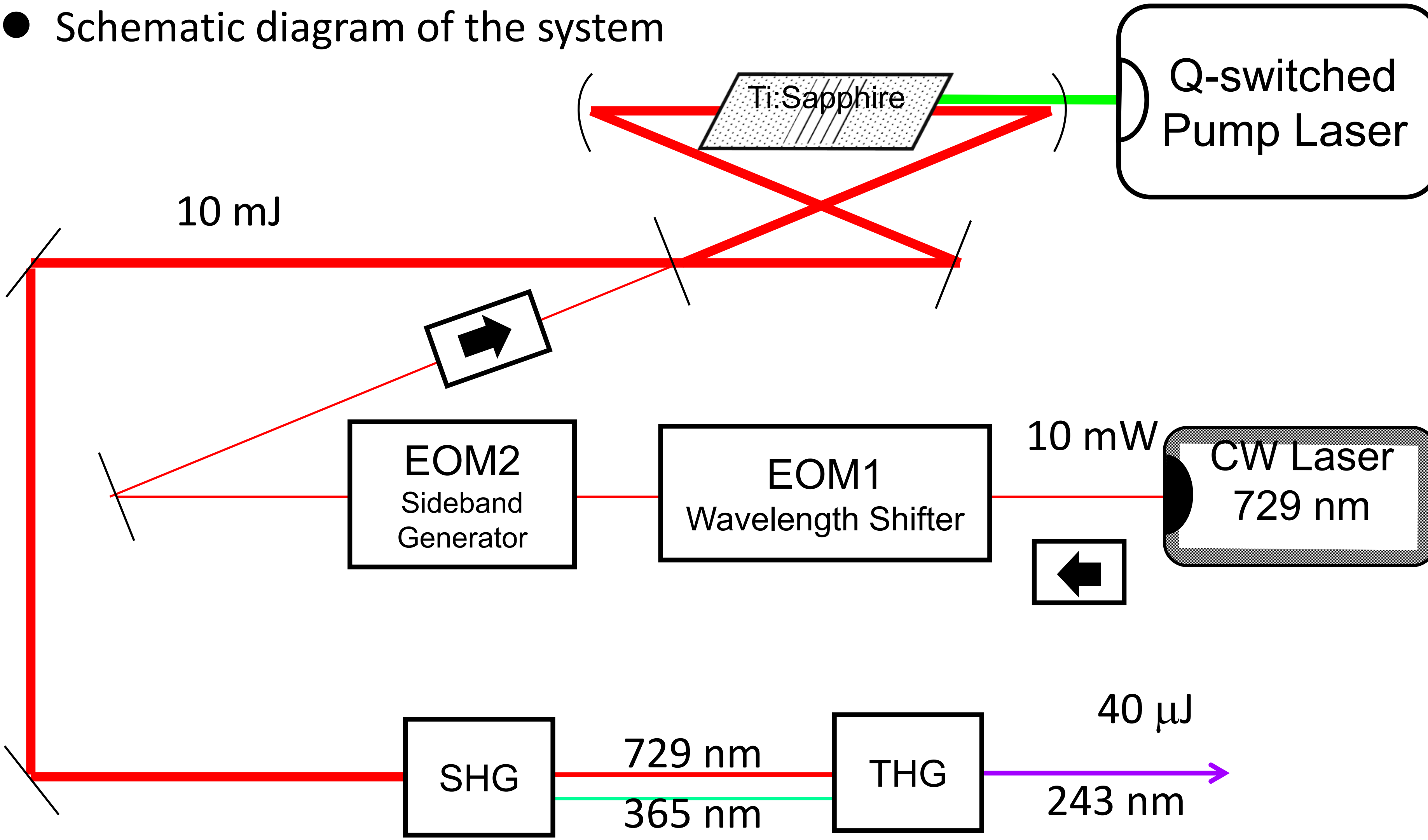
How special is laser?

	Ps cooling laser	Common laser
Time duration	300 ns	CW or Pulse with 10ns or 100 fs
Linewidth	80 pm	< 2 pm or > 10 nm
Wavelength shift	40 pm in 300 ns	No example in my knowledge

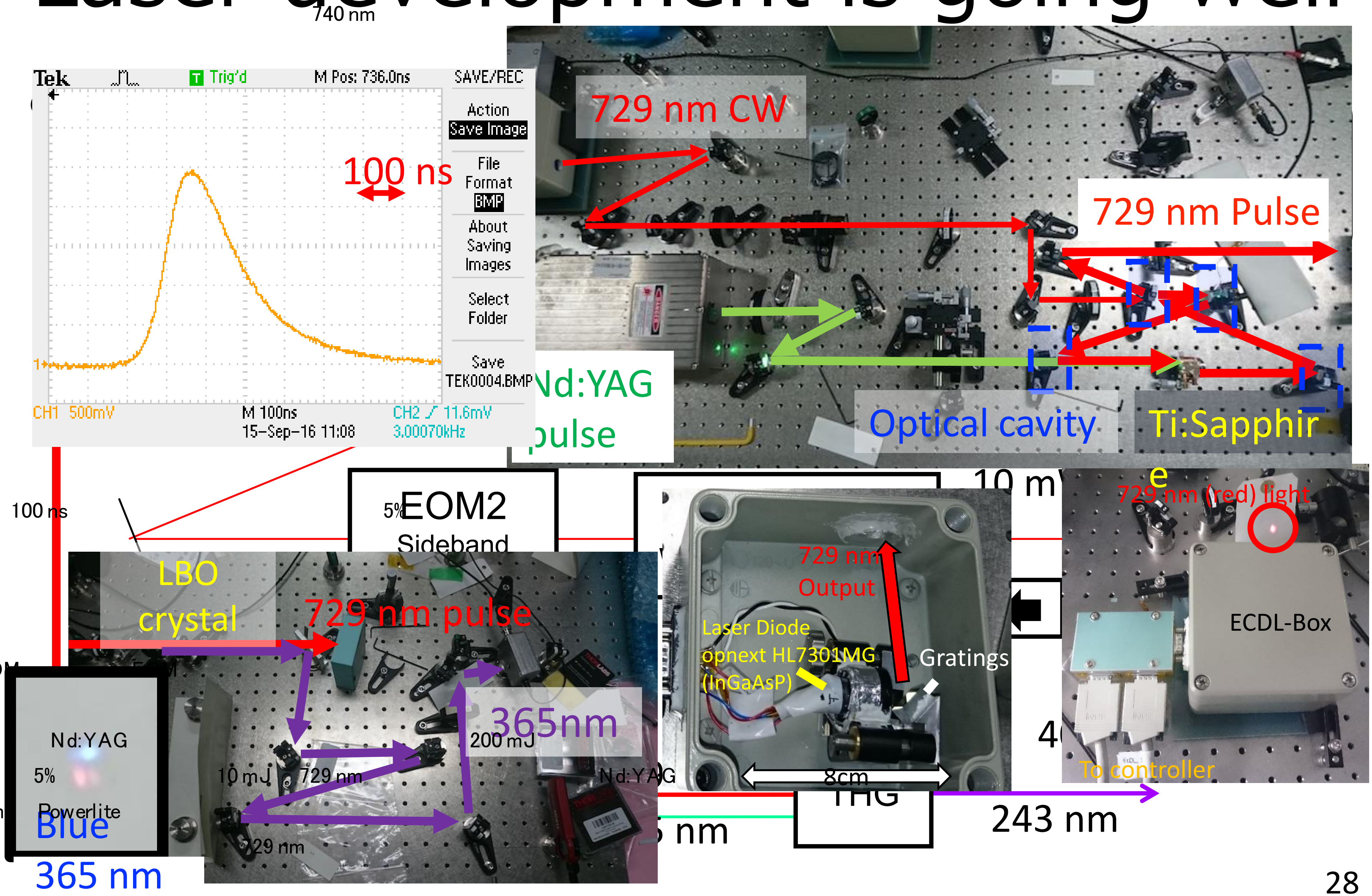
- Even though laser optics are deeply developed, many features which Ps requires are special because laser cooling of Ps is a new challenge
- New design has been considered by combining sophisticated the-state-of-the-arts optics technologies

Special home-made laser system

- Schematic diagram of the system



Laser development is going well



Summary

- Ps-BEC is a good candidate for the first BEC with antimatter, which has a rich potentials on both fundamental and application physics
- A new method has been proposed using dense positrons and cooling by the thermalization process and laser cooling.
- Ps Thermaliztion process in cryogenic environment has been measured for the first time. The result indicates that it is efficient enough to realize BEC with laser cooling
- Cooling laser for Ps requires very special optics, so new system is currently under development. Prototype long pulse mode is confirmed to be possible.
- Developments on creating dense, focused positrons is also under study in parallel
- We will do Ps laser cooling firstly and then go to BEC!