Recent progress in positronium experiments for Bose-Einstein condensation

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1 ICEPP The University of Tokyo

2 APSA Advanced Photon Science Alliance

3 AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

4 GIC Global Innovation Center グローバルイノベーションセンター 九州大学

5 KEK

6 QST

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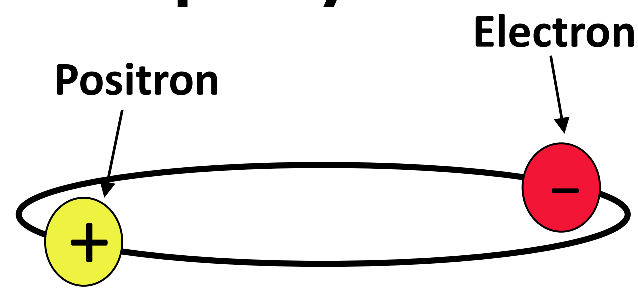
Contents

- Introduction – Motivation for Ps-BEC
  - Matter-antimatter asymmetry
    (gravity measurement)
  - 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
- Ps laser cooling
  - Development of special home-made laser system
  - Planned to be performed at KEK-SPF

Positronium (Ps) is a good probe for fundamental physics

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

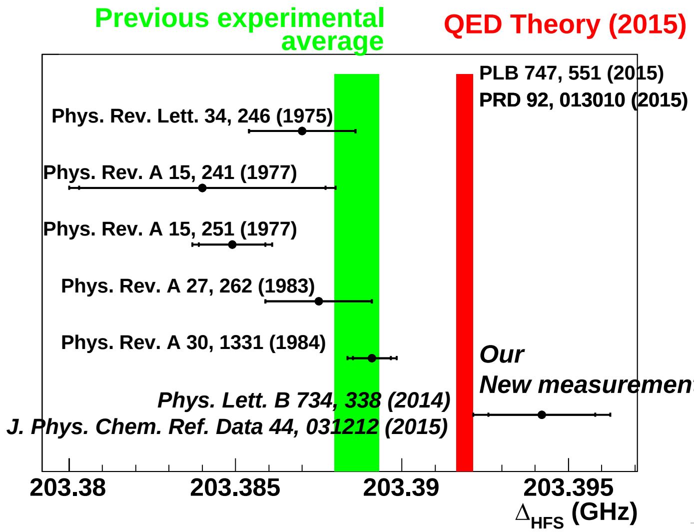


Lightest and Exotic Atom

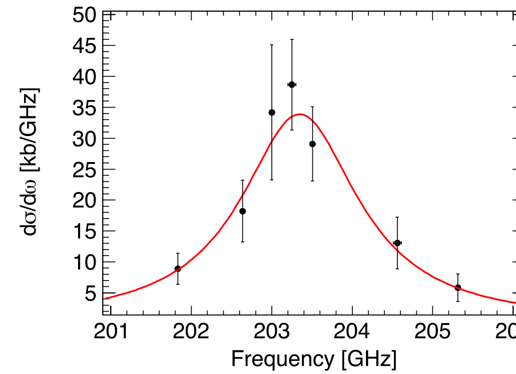
- ✓ <u>Exotic atom with antiparticle</u>
  - ➢ Good for exploring the mystery of antimatter
- ✓ <u>Pure leptonic system</u>
  - ➢ Experiments and theoretical calculations can be compared in high precision without uncertainties of hadronic interactions.

Our works

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



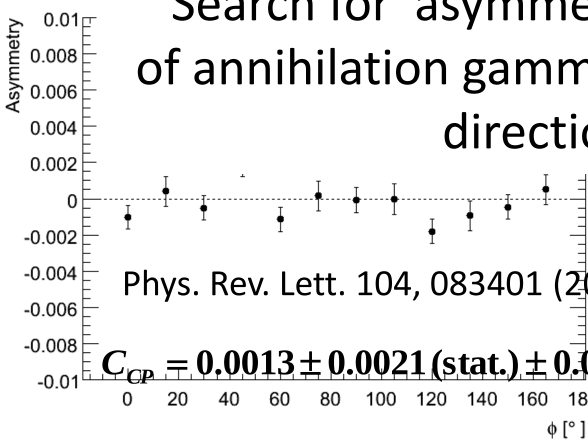
First direct transition o-Ps → p-Ps



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

CP violation in lepton sector

Search for asymmetry of annihilation gammas' directions

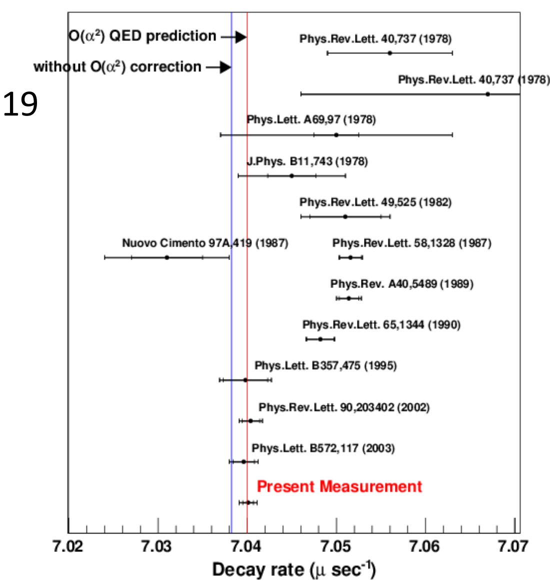


Phys. Rev. Lett. 104, 083401 (2010)

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

o-Ps lifetime

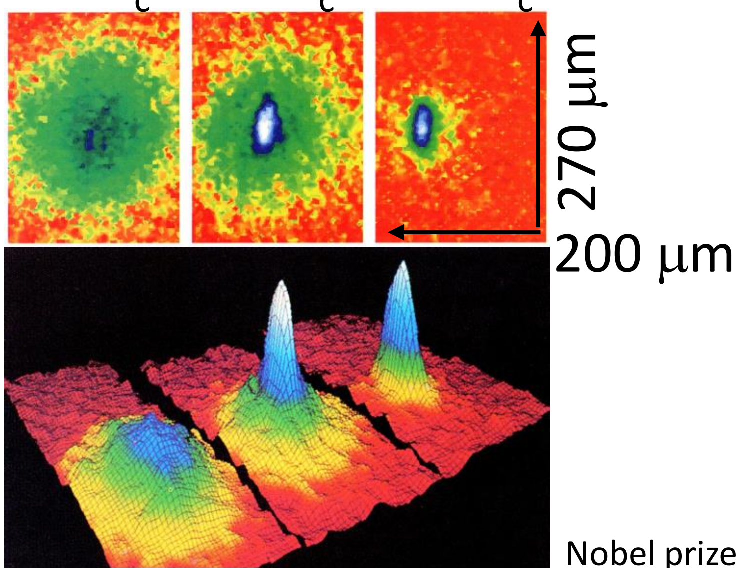
Phys. Lett. B 671(2009)219



Next target :
Positronium Bose-Einstein condensation

Bose-Einstein condensation (BEC)

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



Nobel prize

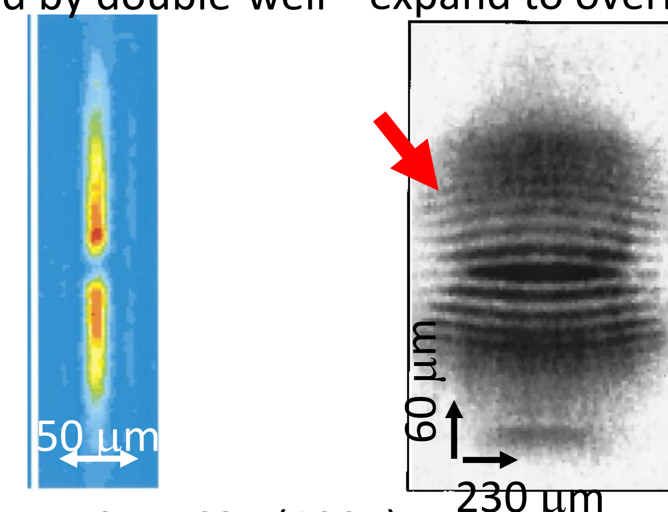
Spatial image of dense rubidium-87 around T_c (critical temperature) of BEC

Important feature

- 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

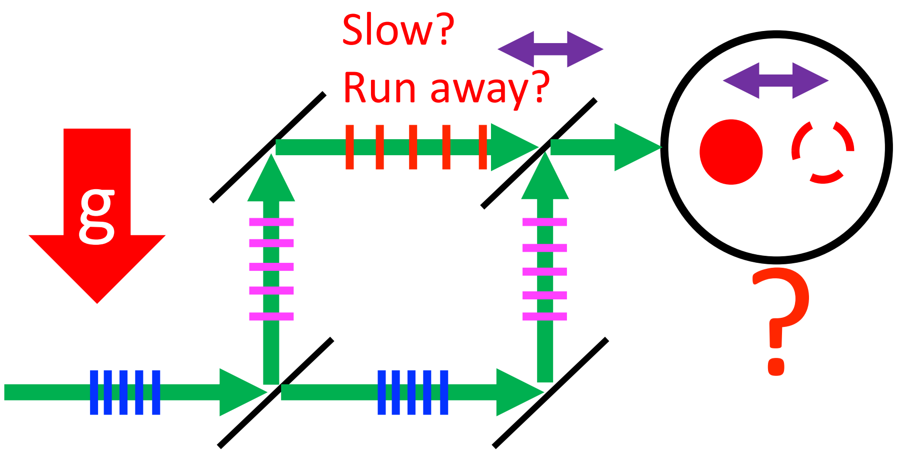


Science 275, 637 (1997)

Applications of Ps-BEC

1. Measure anti-matter gravity by atom-interferometer

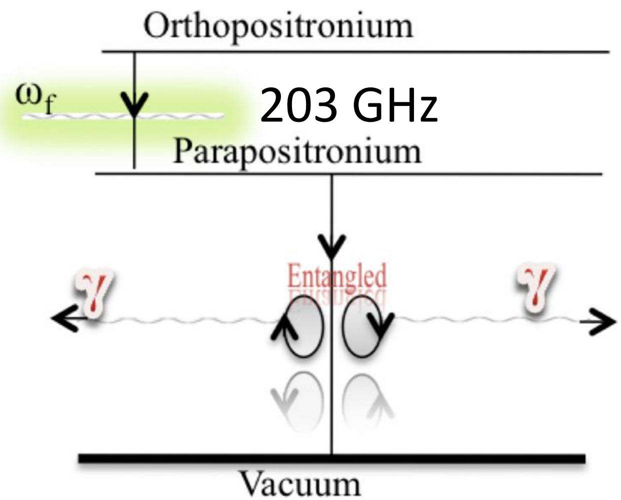
Intensity of Ps blinks by changing path length



- 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

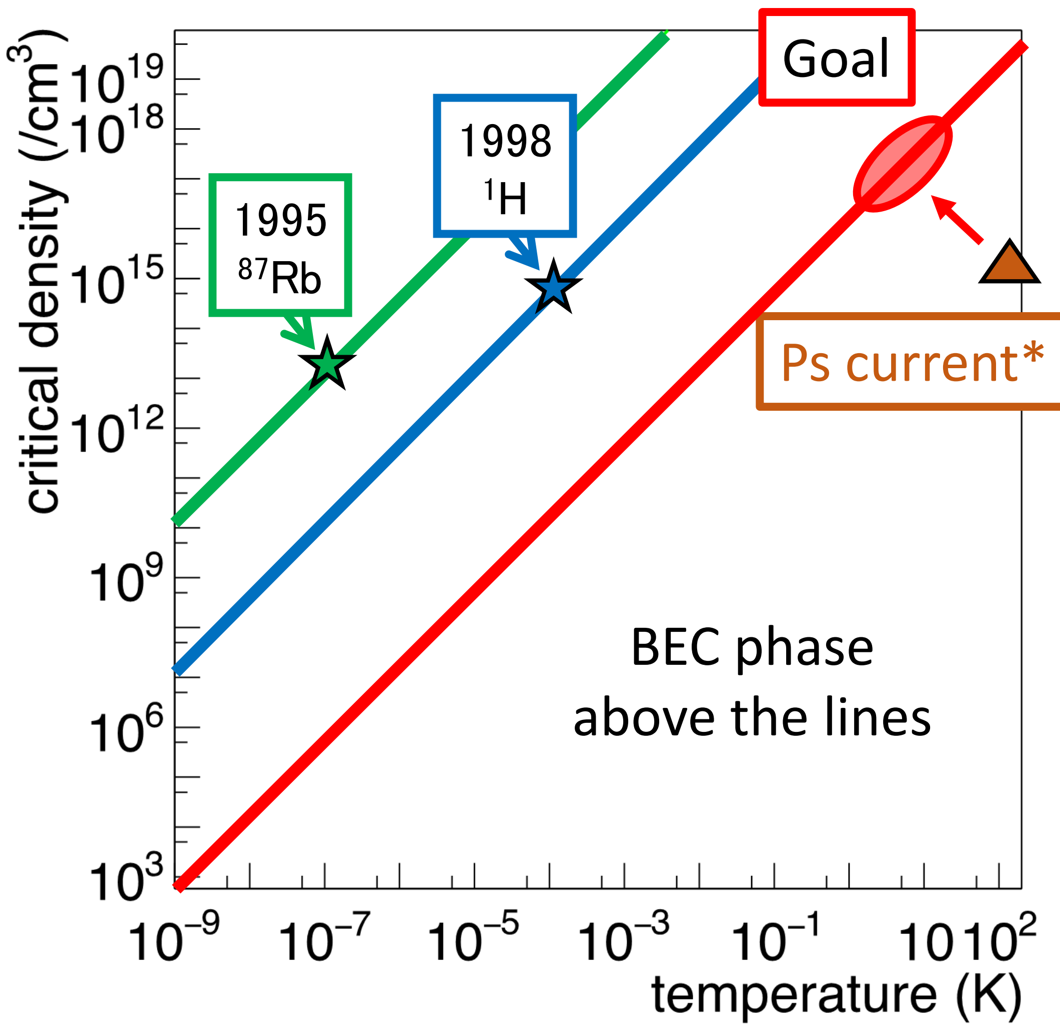
<u>Conditions to realize Ps-BEC</u>

- High density
- Low temperature
- ➢ For Ps, $T <$ 10 K at
  $n > 10^{17}$ cm^{-3}

- Critical temperature (T_C) is very high due to Ps light mass, but 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 a short time of ~100 ns



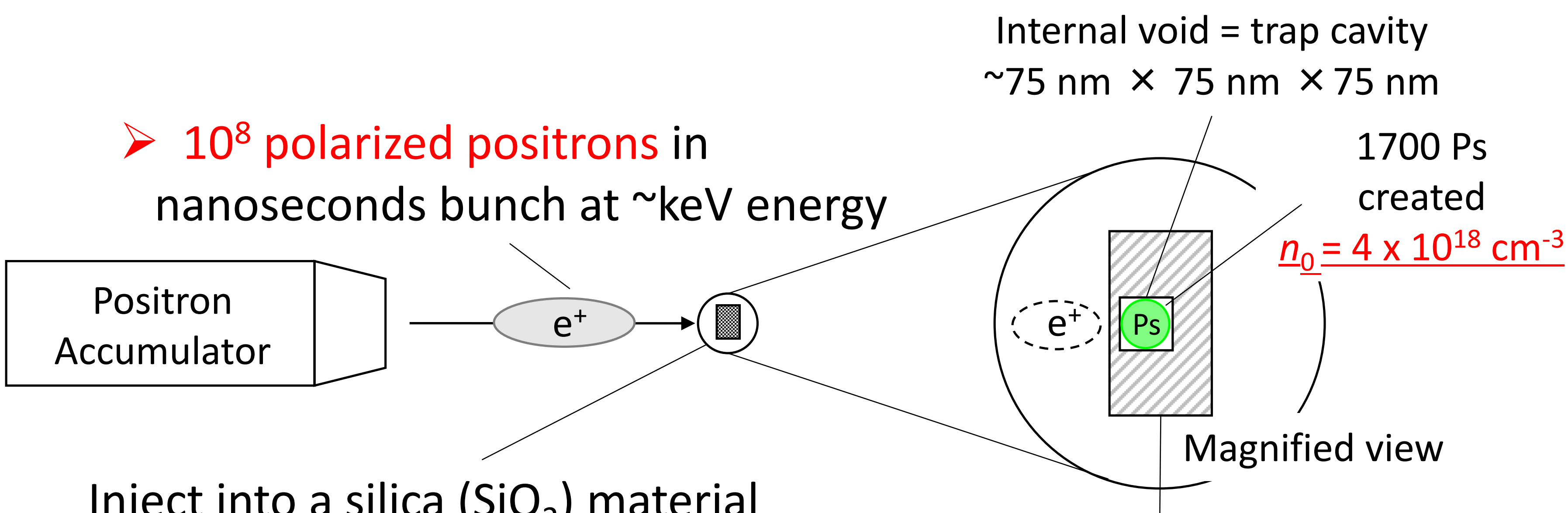
* : S. Mariazzi *et al.* Phys. Rev. Lett. 104, 243401 (2010)
* : D. Cassidy *et al.* physica status solidi 4, 3419 (2007)

Method to realize Ps-BEC

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

First Step for Ps-BEC:
Create dense positrons and convert into dense Ps at once

- 10^8 polarized positrons in nanoseconds bunch at ~keV energy



Inject into a silica (SiO_2) material with sub-μm beam waist by focusing

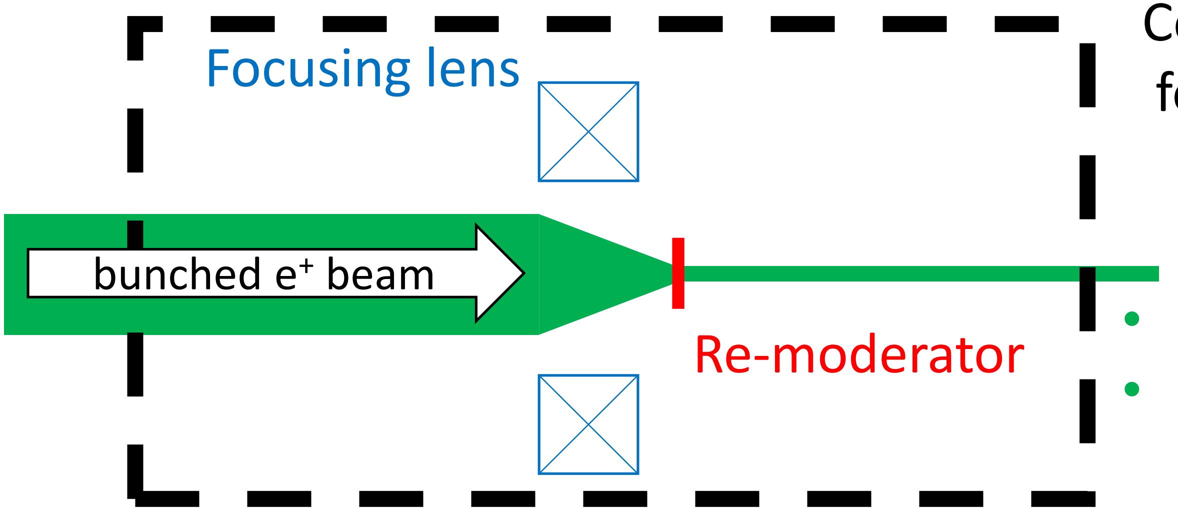
Silica as Ps converter ~50% prob.

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

Positron focusing by repeating brightness enhancement for several times

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

Principle of Positron focusing:



Continue this process for several stages

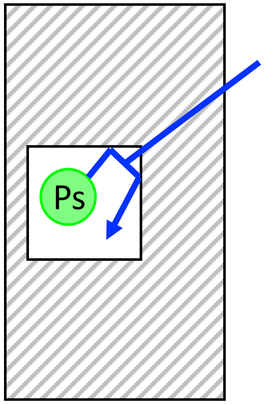
- Pararell
- Monochromatic Energy

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!

Second step for Ps-BEC:
Ps Cooling
1. Thermalization process



1st cooling

By collisions with cold silica cavity wall
= Thermalization process

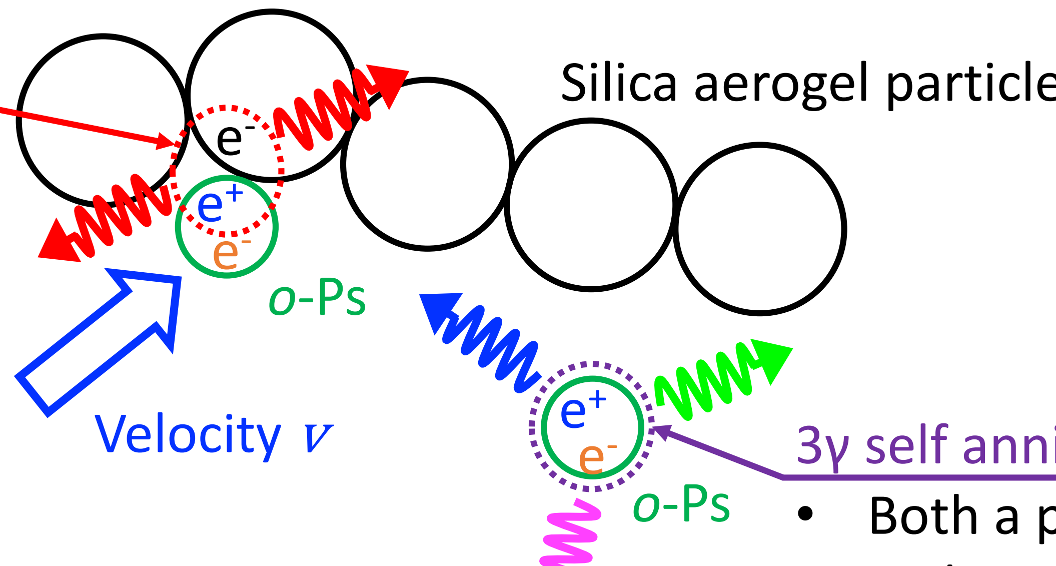
No measurement of Ps thermalization process in cryogenic environment

→ We have measured it for the first time.

Pick-off annihilation rate is used to measure Ps thermalization process

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

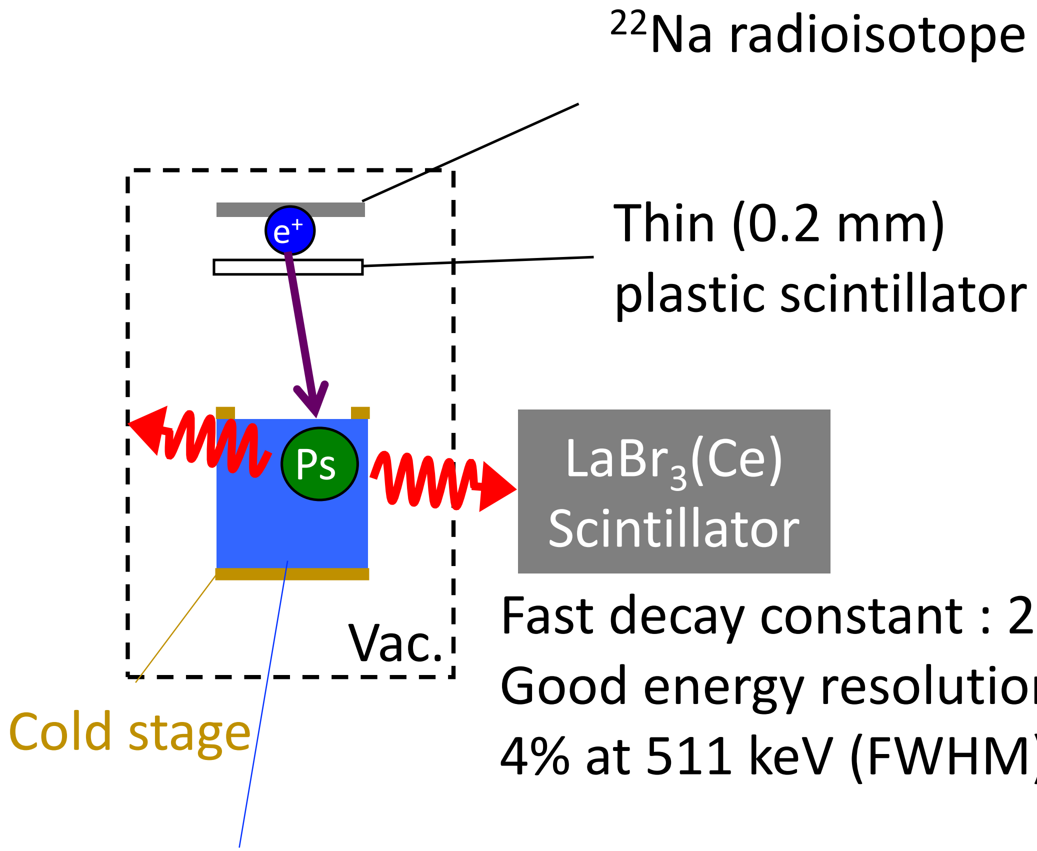
Pick-off annihilation rate $\lambda_2 \propto n\,\sigma\,v$

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

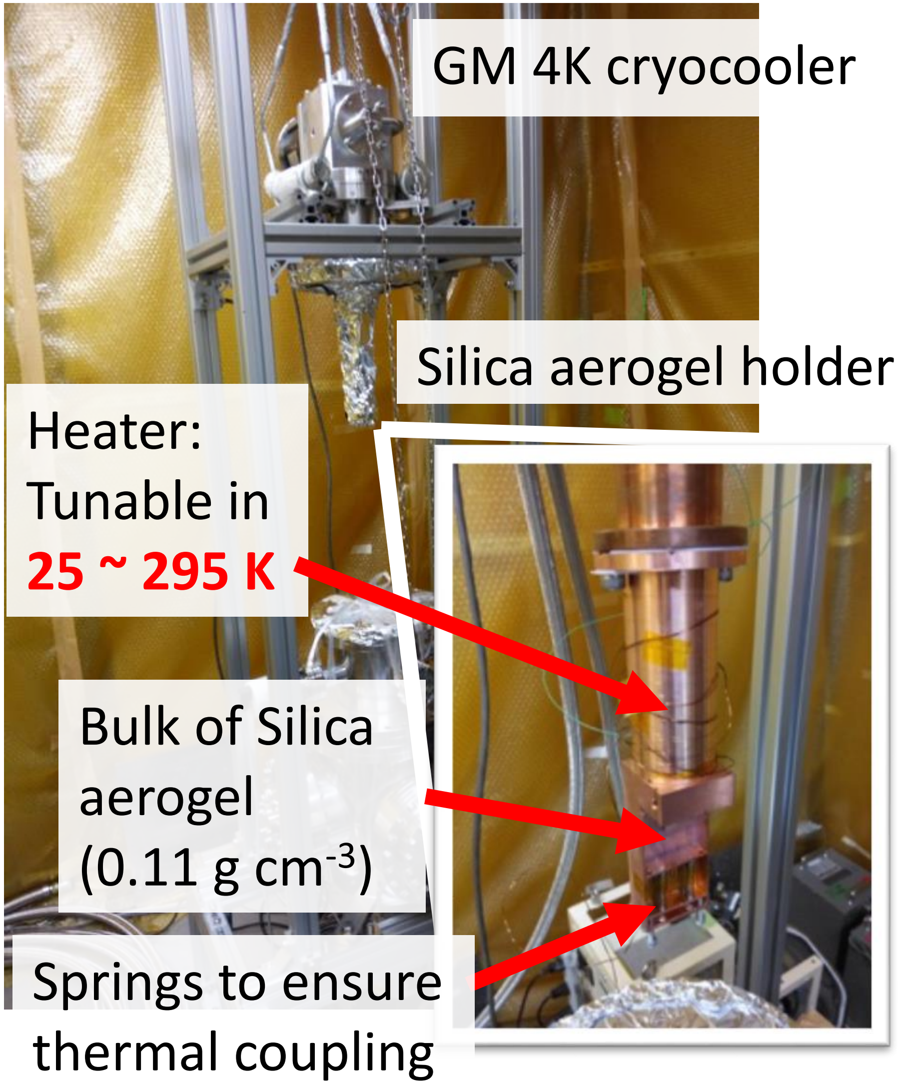


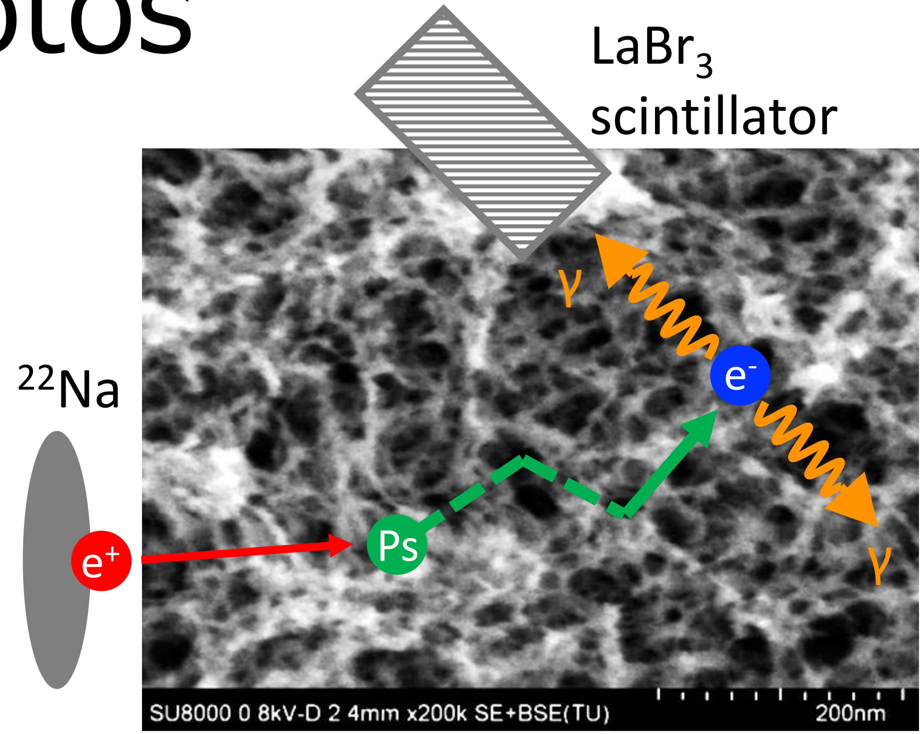
Fast decay constant : 20 ns
Good energy resolution :
4% at 511 keV (FWHM)

Silica aerogel : porous material made by silica to trap and thermalize Ps

Density: 0.11 g cm^{-3} → Mean free path L = 38 nm

Photos

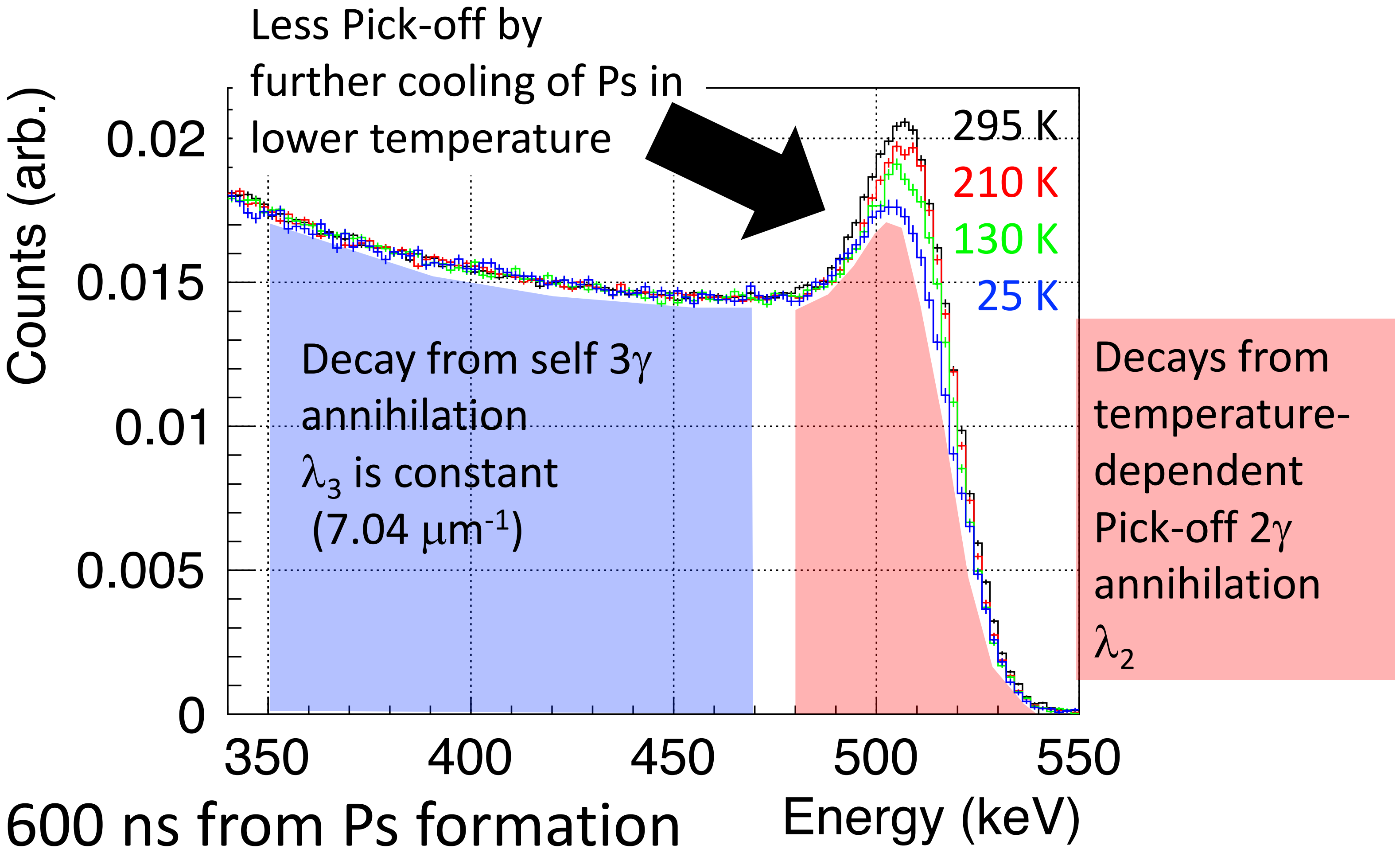




SEM image of used silica aerogel

- Ps formed inside pores are cooled by collisions with pore walls.
- Ps temperature can be estimated by pick-off annihilation rate.

Energy information is used to identify 2γ / 3γ annihilations



30 - 600 ns from Ps formation

Deduction of Pick-off annihilation rate using MC simulation

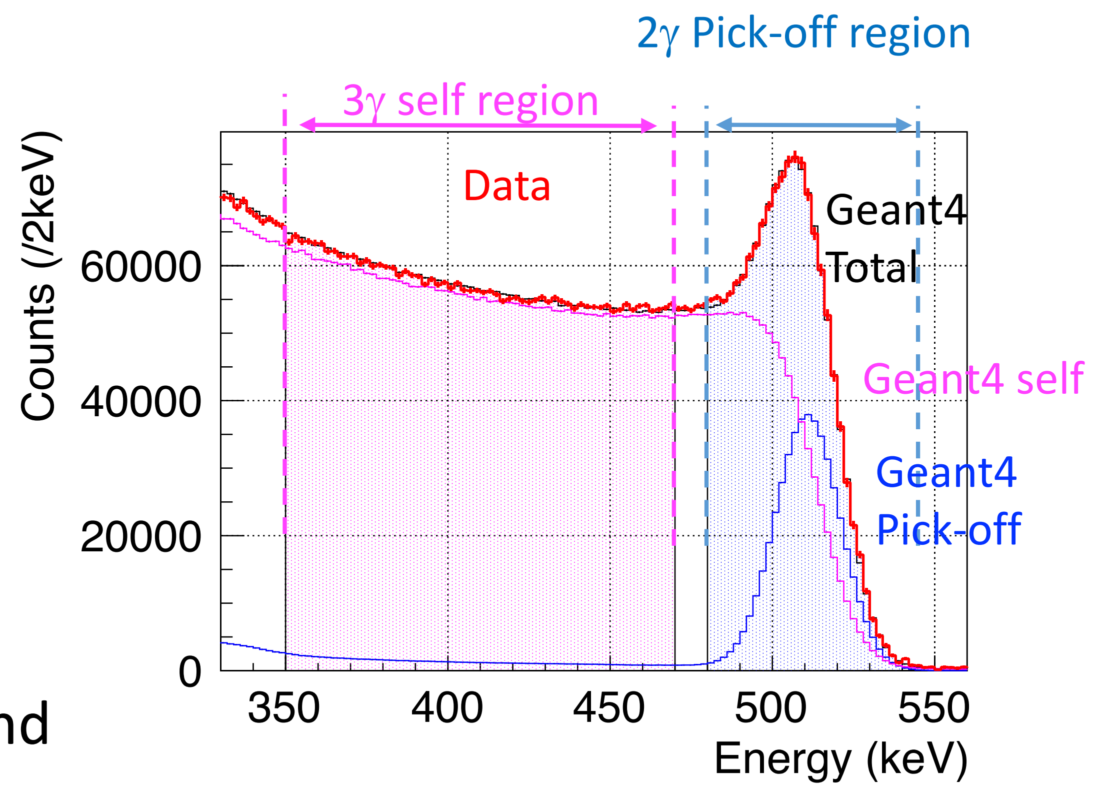
- Use difference between energy spectra of Pick-off 2γ/Self 3γ

Pick-off 2γ : 511 keV peak

Self 3γ : Continuous

- <u>Define energy regions to enhance each annihilation event</u>

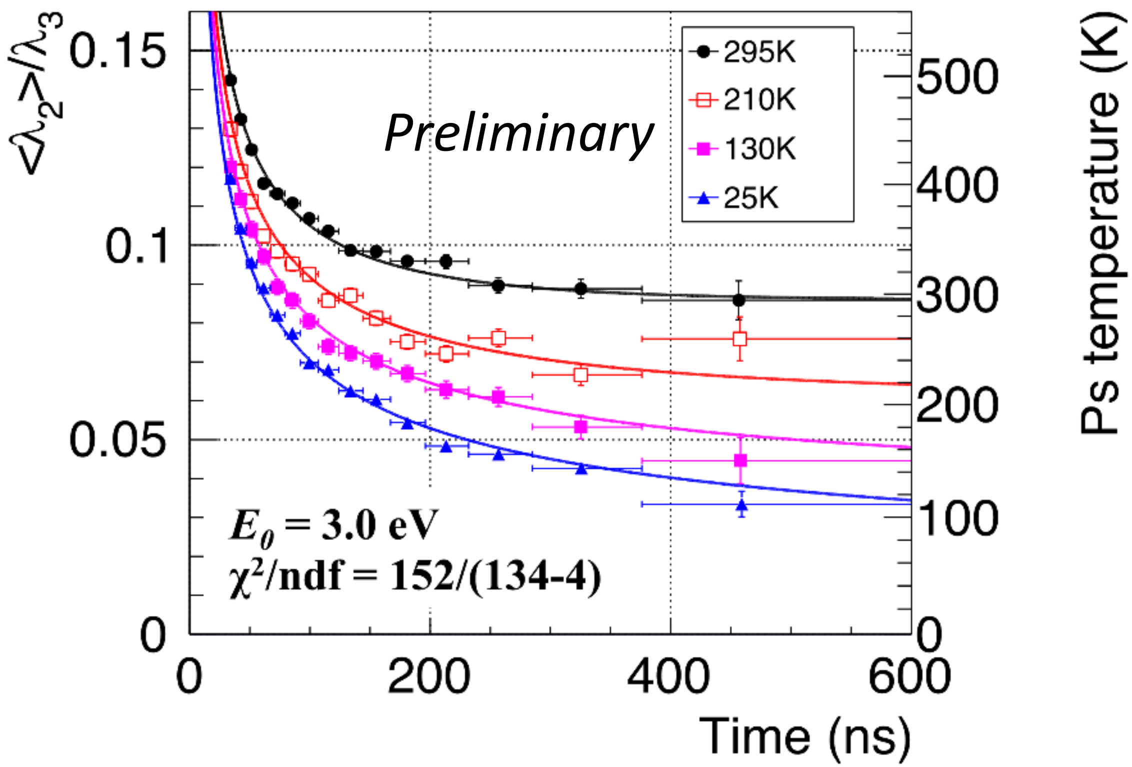
- Detection efficiencies and contamination fractions are estimated by Geant4 Monte Carlo simulation.



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

Ps thermalization down to 100 K was observed.

Thermalization curves of Ps in various silica temperature



- Thermalization into cryogenic temperature was clearly observed

Conversion from pick-off rate to temperature by RTE model. (T. L. Dull *et al.*, *J. Phys. Chem. B* **105**, 4657 (2001).)

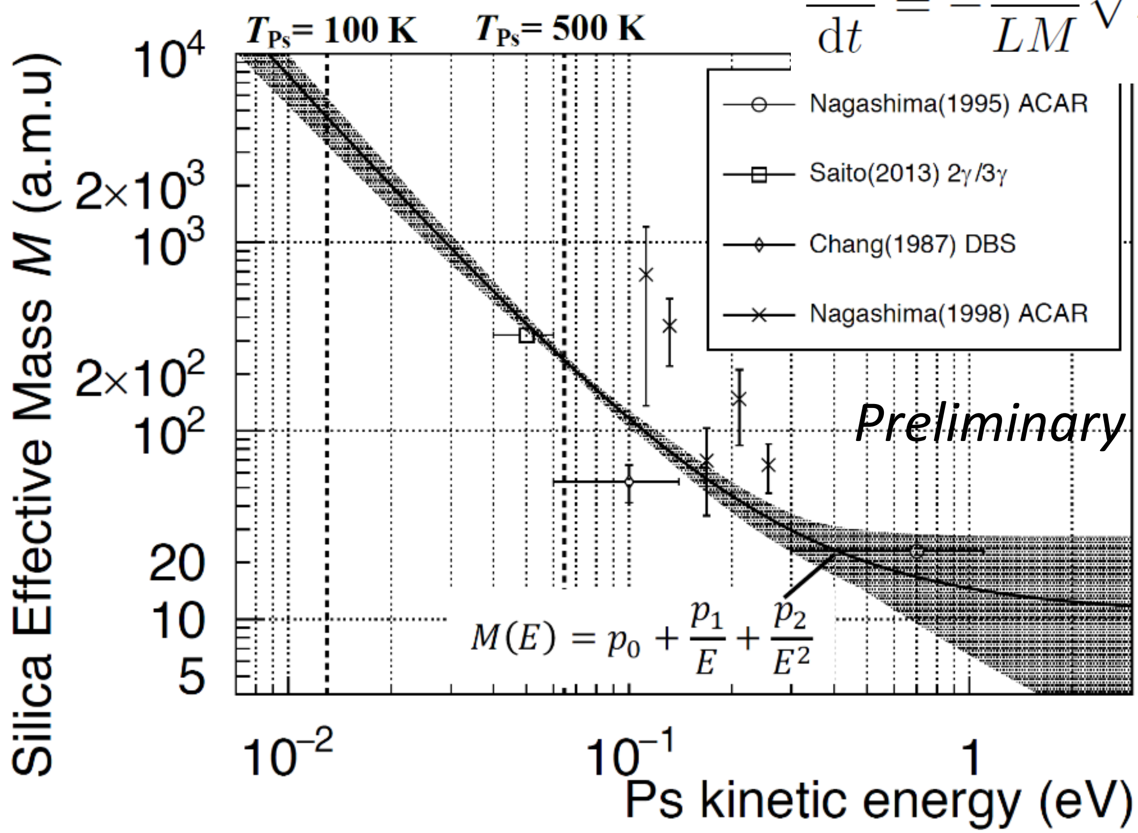
Fitted by the elastic-scattering model (Y. Nagashima *et al.*, PRA **52**, 258 (1995)) with energy-dependent *M* (silica effective mass)

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

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

Ps thermalization slows down at lower Ps kinetic energy

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

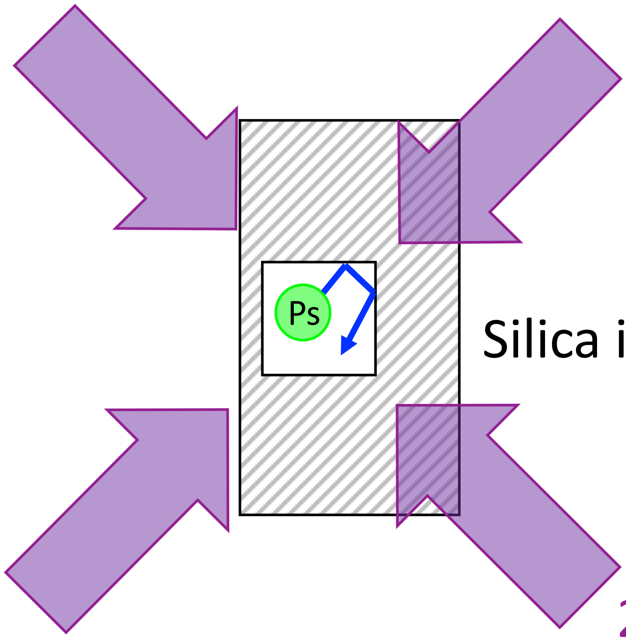


$p_0 = 10.6$ u
$p_1 = 3.3$ u eV
$p_2 = 0.73$ u eV^2

$\chi^2/\mathrm{ndf} = 152/130$

- 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.

Second step for Ps-BEC: Ps Cooling 2. Laser cooling



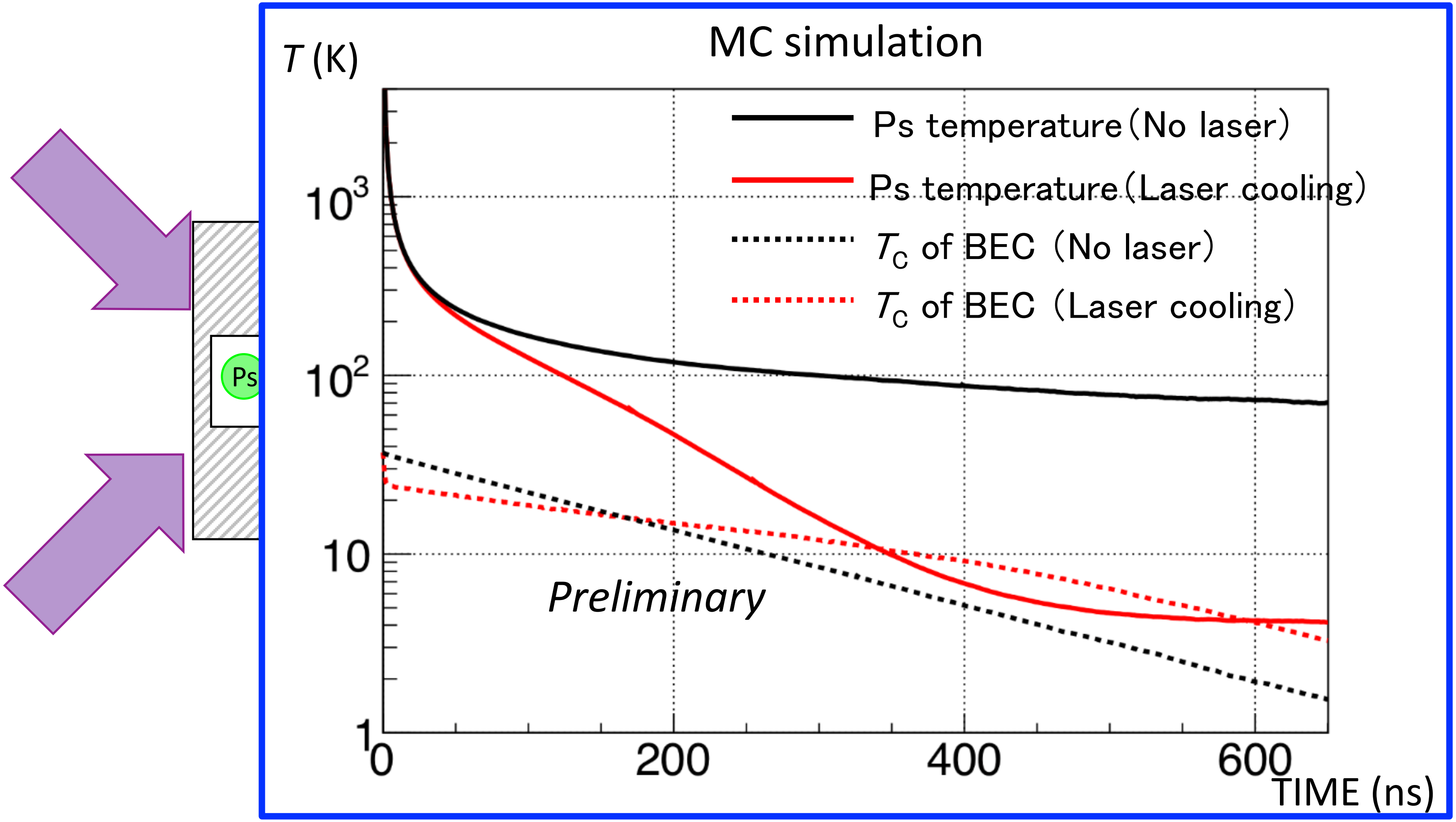
2nd cooling

Irradiate 243 nm UV laser to cool
Ps down to 10 K
Use 1S-2P transitions

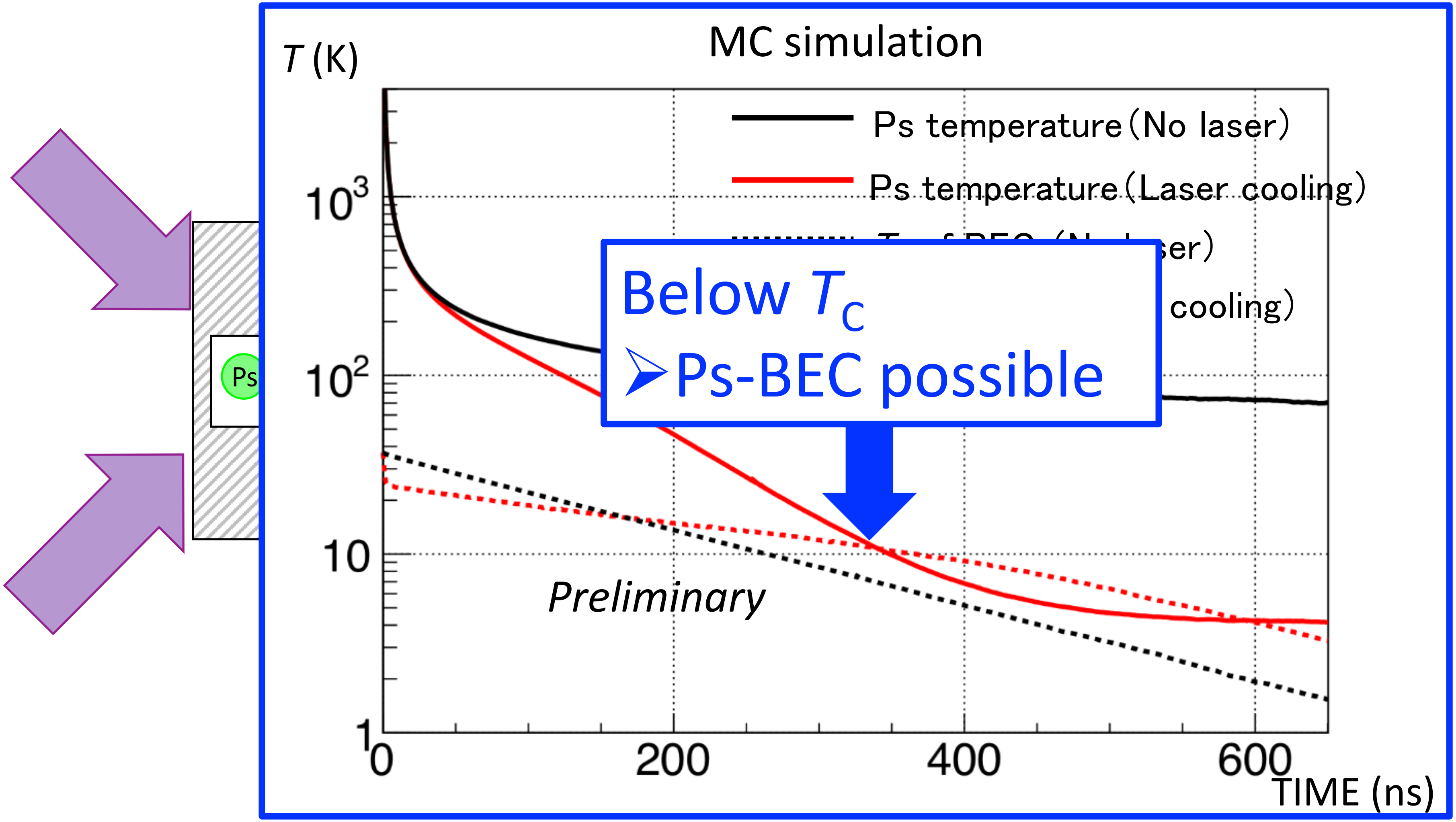
Silica is transparent in UV

243 nm UV laser

Ps laser cooling



Ps laser cooling

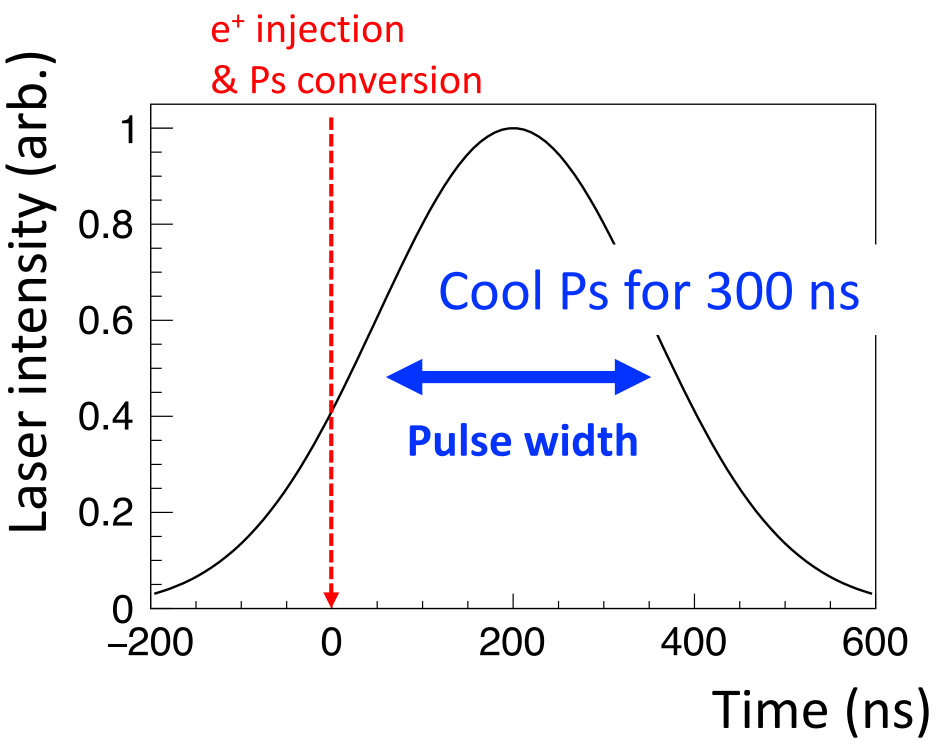


Requirements for Cooling Laser
1. Long pulse width

First laser cooling of Ps (antimatter systems)

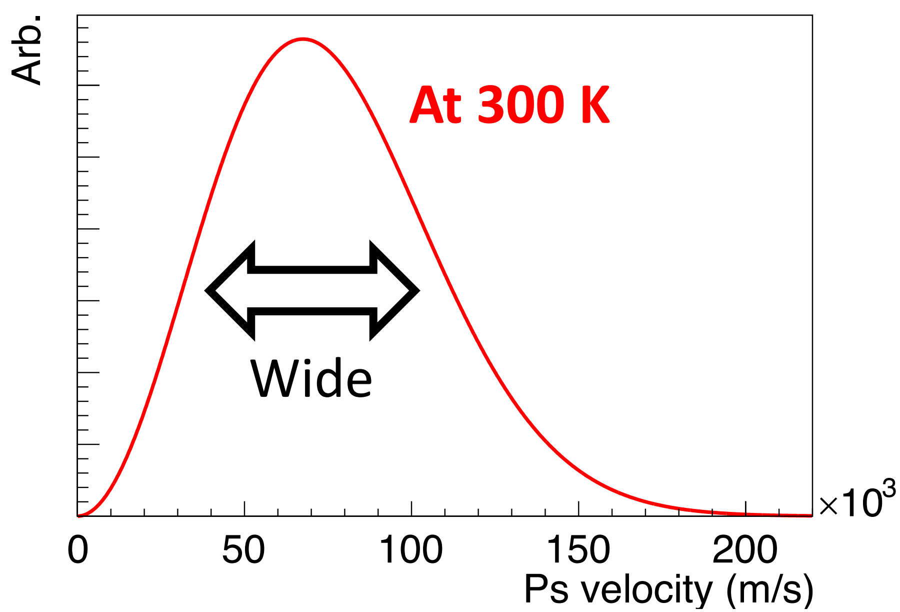
For Ps (light, short lifetime), several special features are necessary

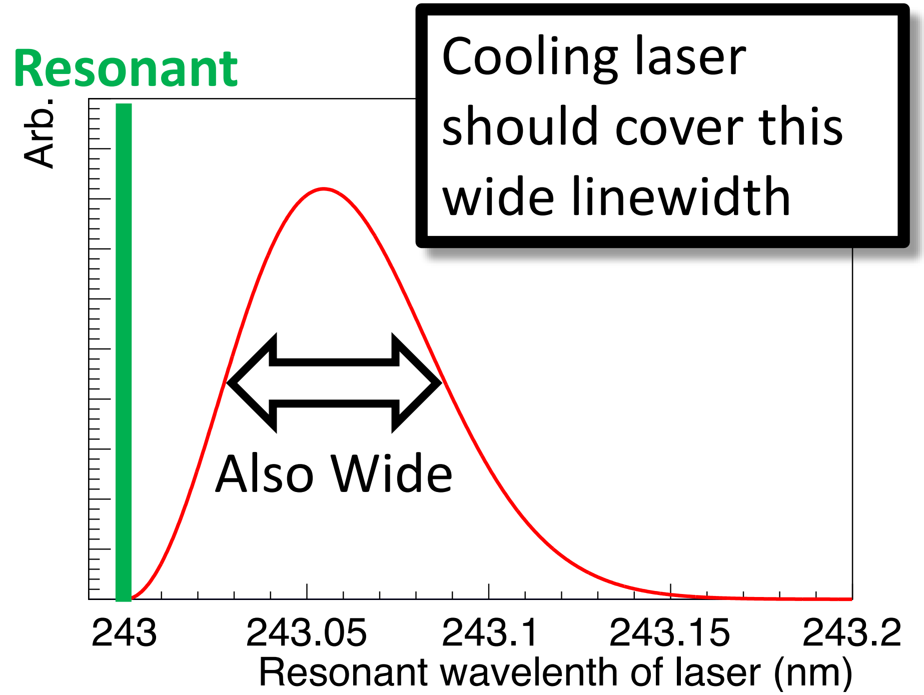
- Cooling of Ps takes around 300 ns
  (~ Ps lifetime when 1S-2P transitions are saturated)



Requirements for Cooling Laser
2. Wide linewidth

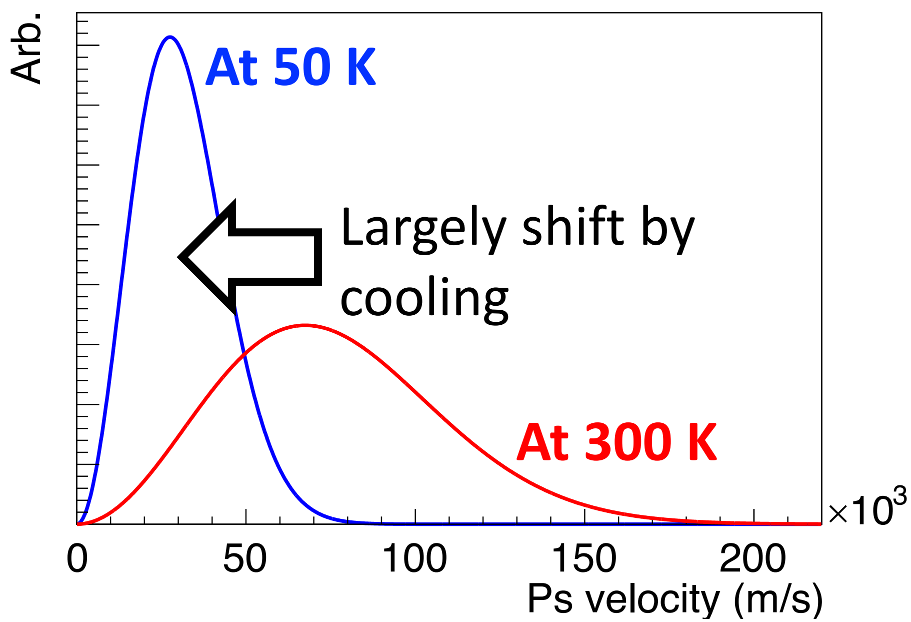
- Doppler effect is large due to Ps light mass, so laser linewidth must cover the wide Doppler width.

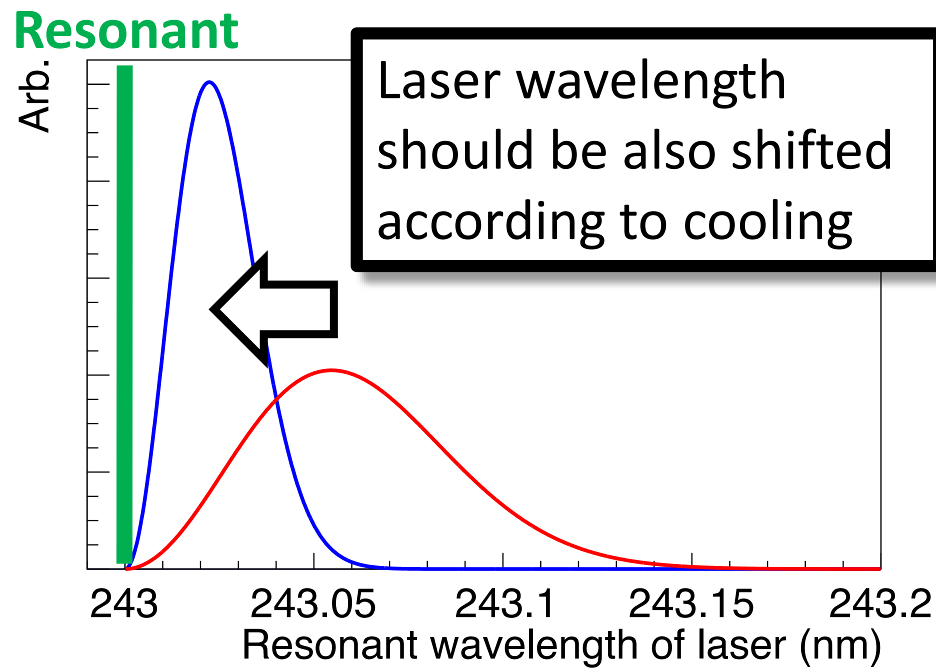




Requirements for Cooling Laser
3. Fast frequency chirp

➢ Resonant wavelength shifts as Ps atoms get cold.
Fast frequency chirp of pulsed laser has never been achieved





Ps cooling laser is special

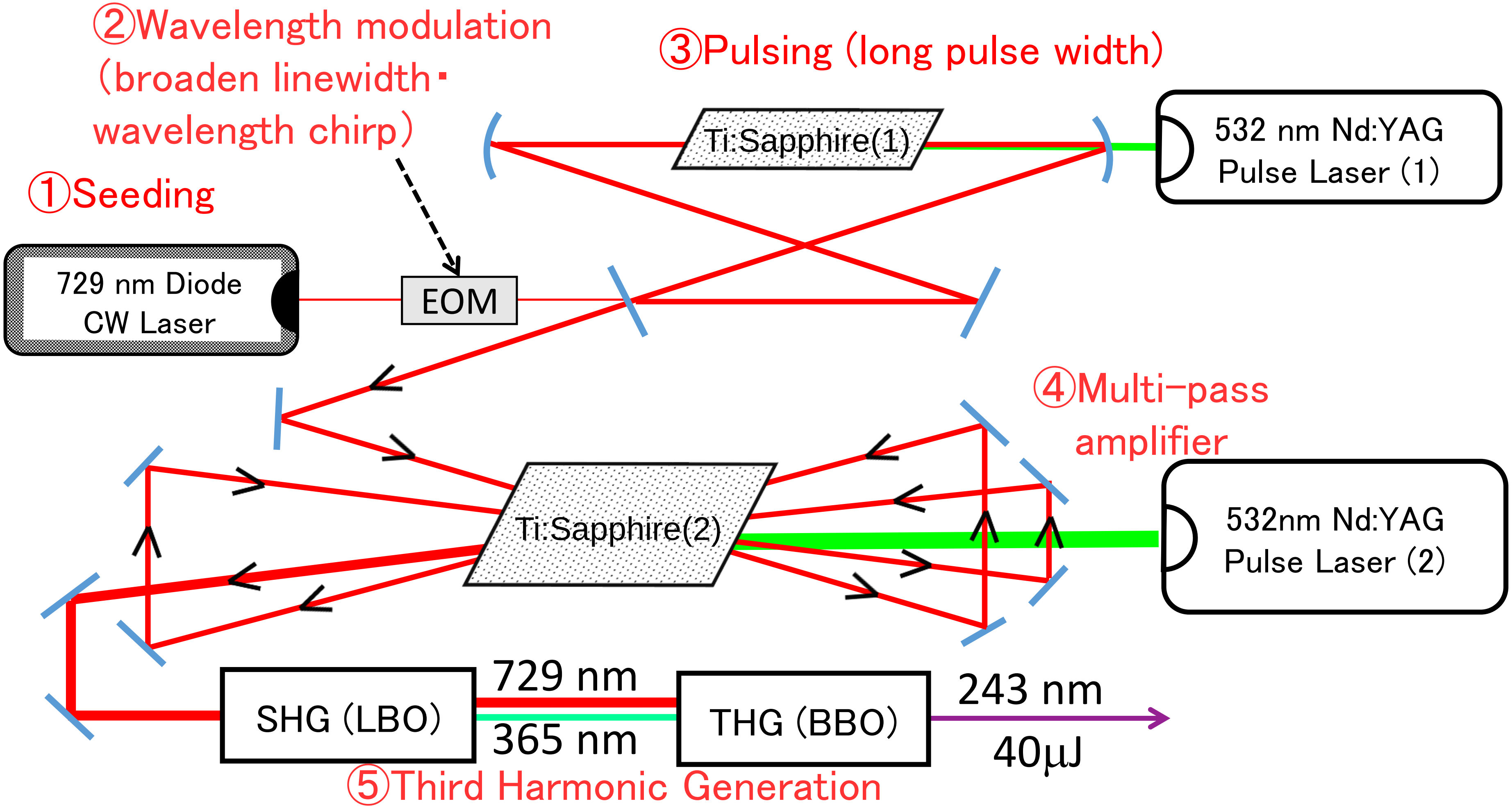
	Ps cooling laser	Common laser
Pulse width	300 ns	CW or Pulse with 10ns or 100 fs
Linewidth	28 pm	< 2 pm or > 10 nm
Wavelength shift	12 pm in 300 ns	No example in my knowledge

- Even though laser optics are deeply developed, many features required for Ps cooling are special.
- New design has been considered by combining sophisticated state-of-the-art optics technologies

Special home-made laser system

5 steps to make Ps cooling laser:

①Seeding (729 nm)→②Wavelength modulation→③Pulsing→
④Amplification→⑤Third Harmonic Generation



Special home-made laser system

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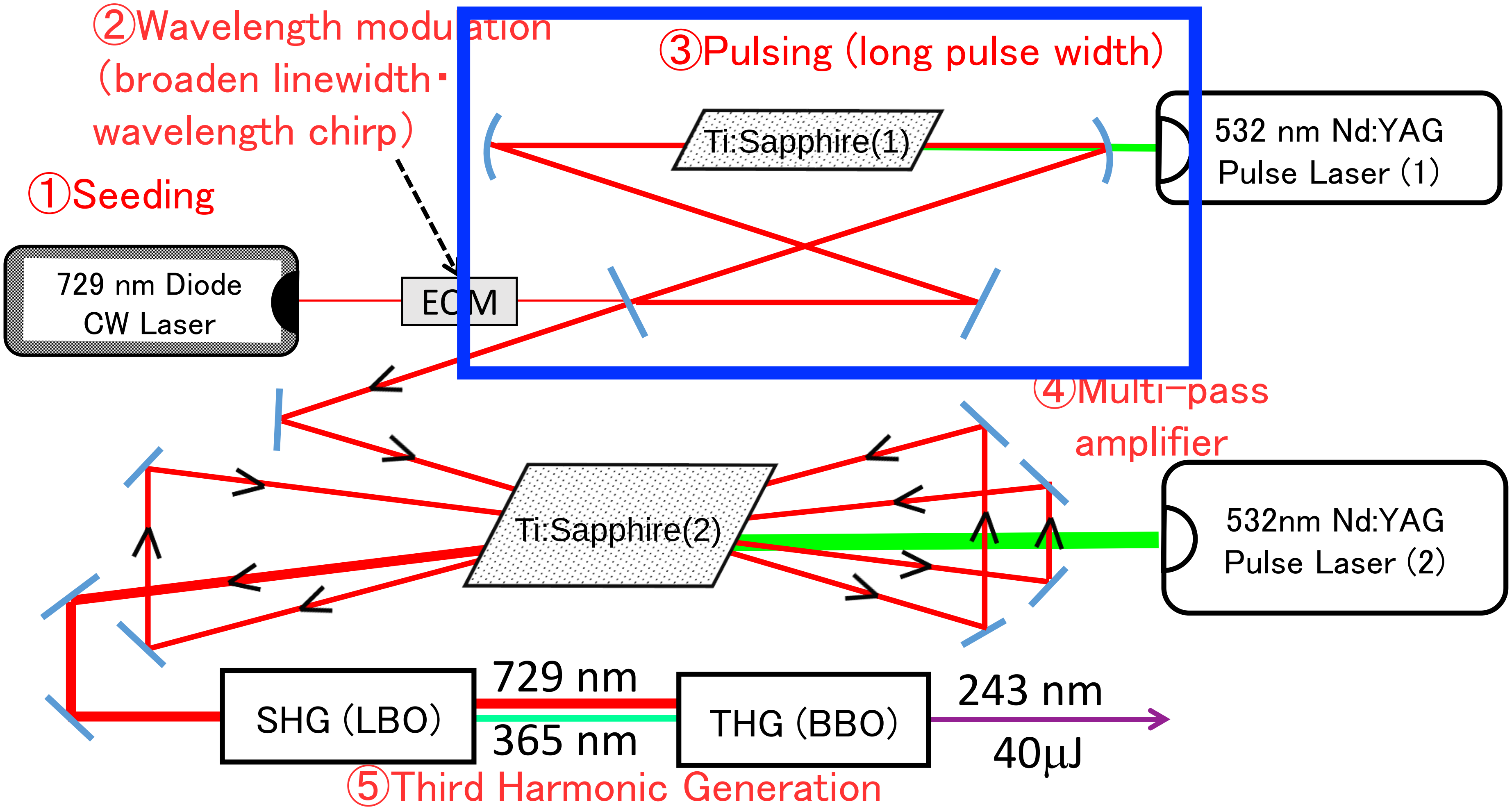
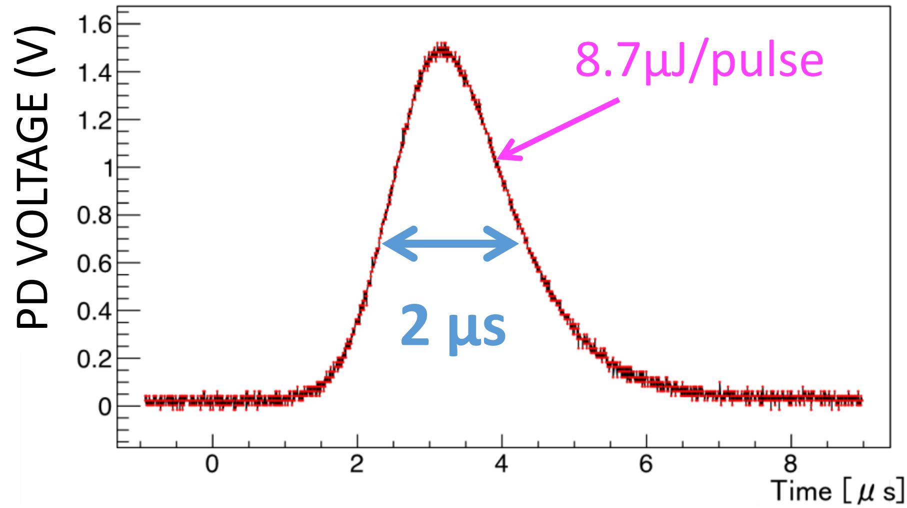
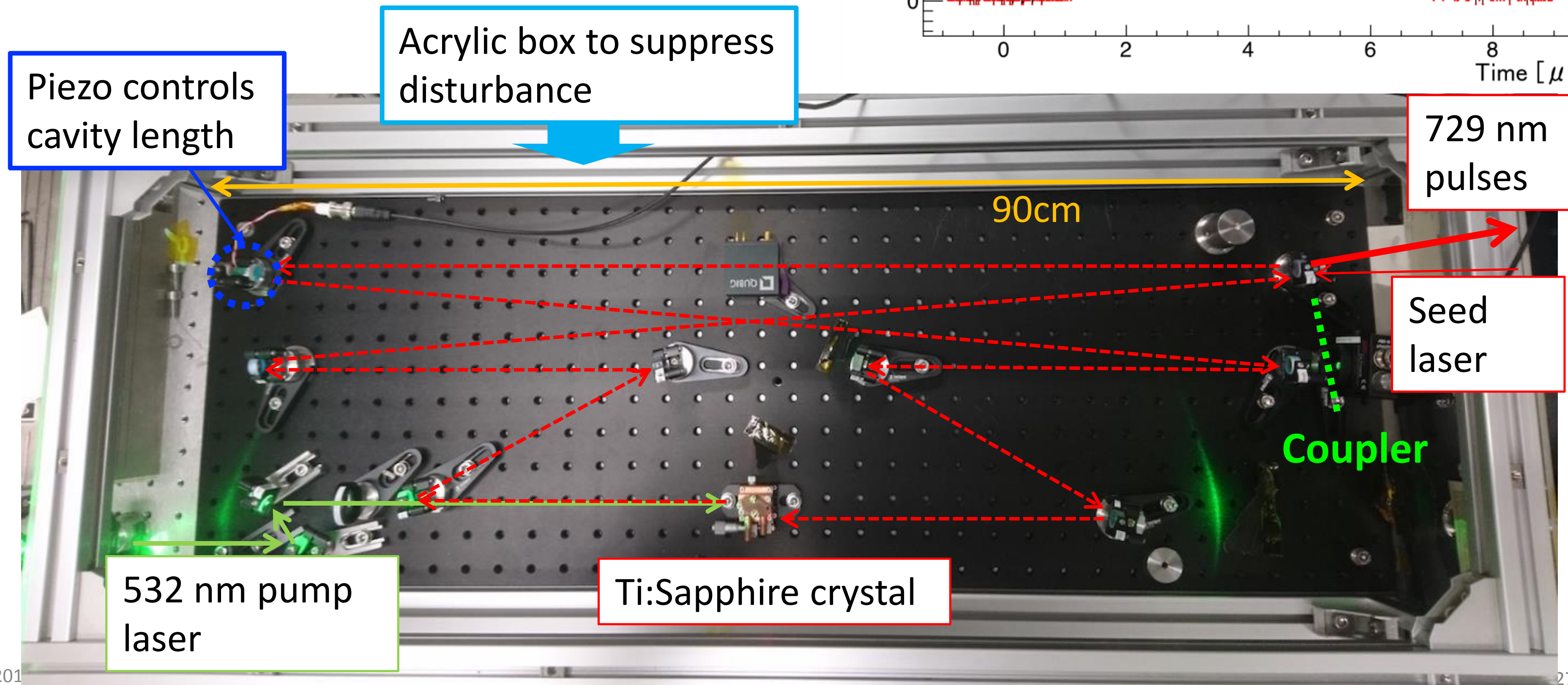


Ps cooling laser ③ Pulsing: Prototype Ti:Sapphire cavity provides 2 μs pulses

- Cavity length = 3.8 m long.
- Only 1.4% round-trip loss.
- Wavelength-selective mirror makes 729 nm lights resonate.

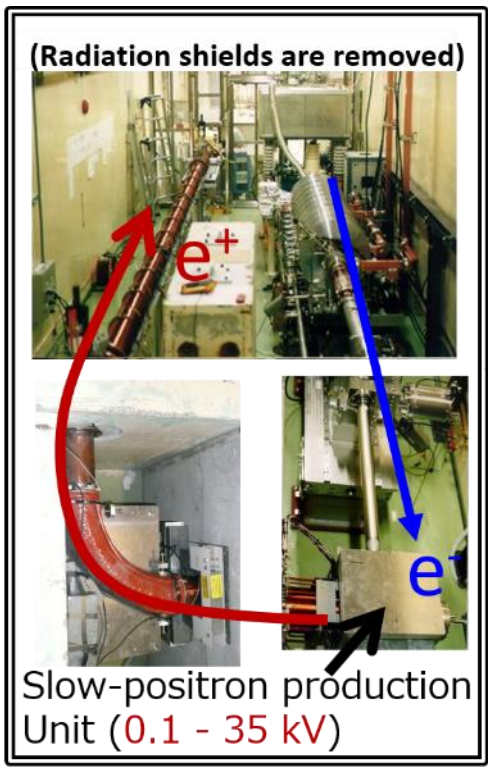


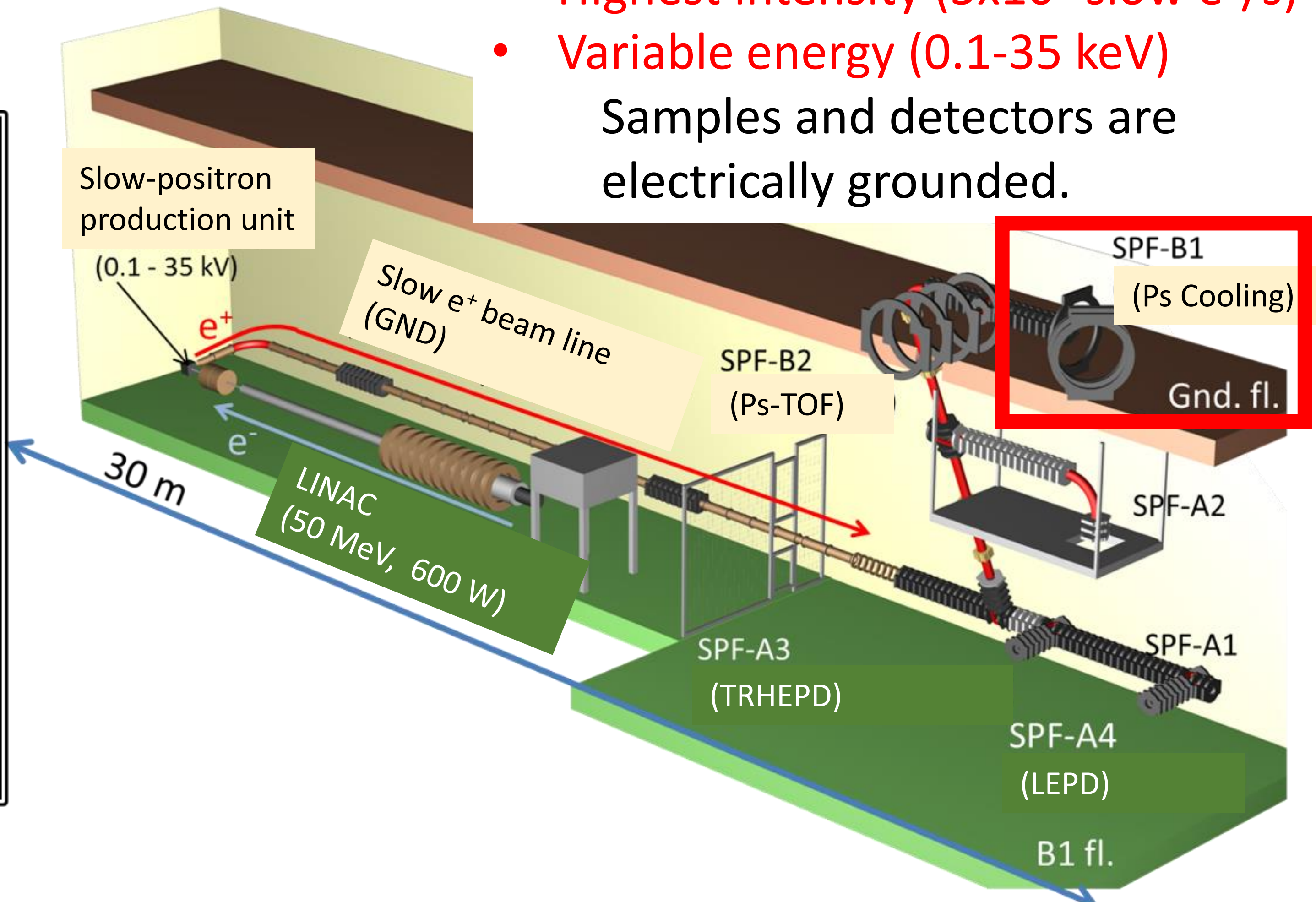


Ps laser cooling experiment will be performed at KEK-SPF (Slow Positron Facility) (within 2 years).

- Highest intensity (5x10^7 slow e^+/s)
- Variable energy (0.1-35 keV)

  Samples and detectors are electrically grounded.

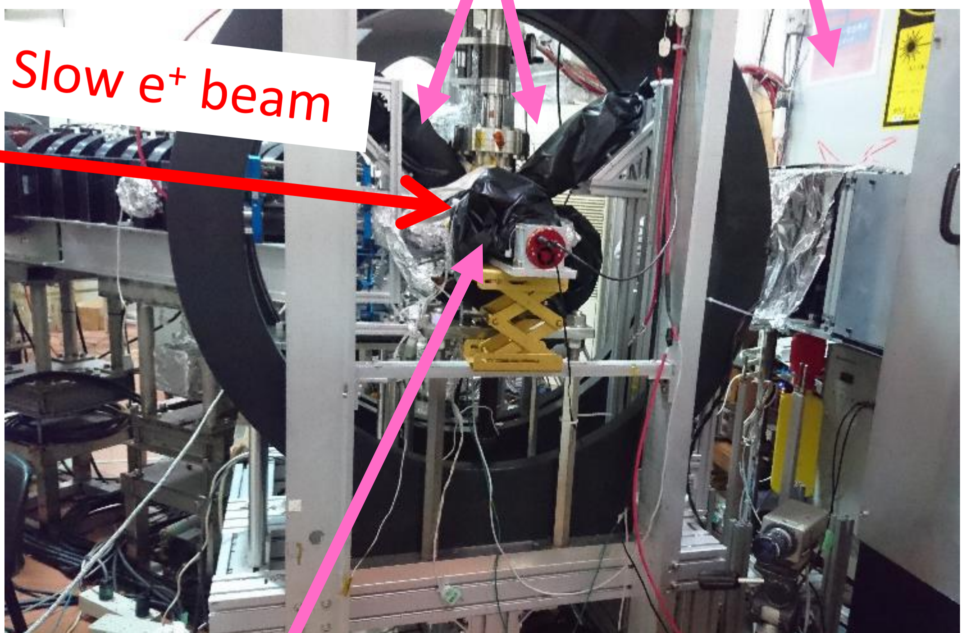




Testing silica targets and γ-ray detectors

γ-ray detectors
$LaBr_3(Ce)$ / Plastic
scintillators + PMT

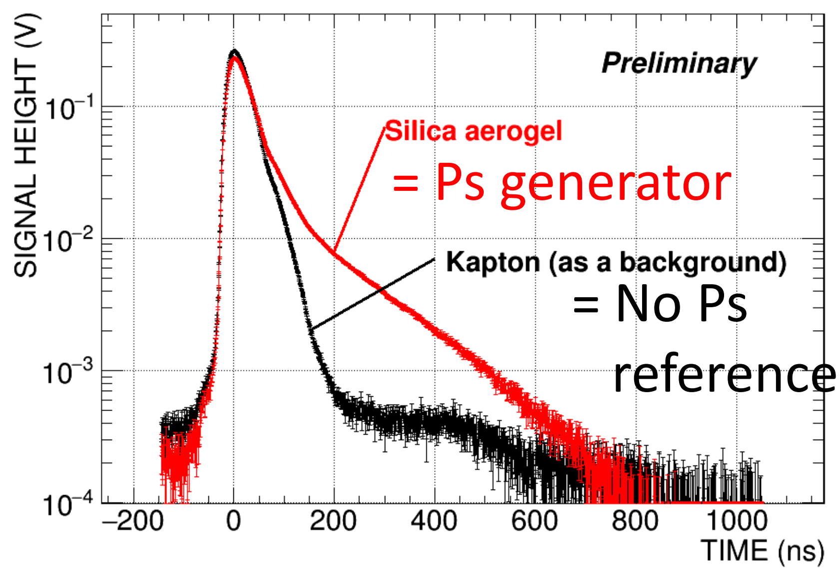
Nd:YAG laser
(not yet in
operation)



Silica targets
inside

Beam test
@KEK-SPF
(6-9/3)

SSPALS
(Single-Shot Positron Annihilation Lifetime Spectroscopy) data obtained by $LaBr_3(Ce)$ scintillator
E_{e+} = 5 keV, 16 ns pulse, 50 Hz, 10 min.
We have tested if silica aerogel can be used for Ps mass-producer.



γ-ray detection system will be improved for next measurement.

Summary

- Ps-BEC is a good candidate for the first BEC with antimatter, which has 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.
- Developments of creating dense, focused positrons is under study.
- Ps Thermalization process in cryogenic environment has been measured for the first time. The result indicates that it is efficient enough to realize BEC if it is combined with laser cooling.
- Cooling laser for Ps requires very special optics, so new system is currently under development. Prototype 2-μs-long 729-nm pulse laser has been confirmed to be possible.
- We plan to perform Ps laser cooling firstly at KEK-SPF within 2 years and then go to BEC!