Positron focusing system and positronium thermalization measurement for realizing positronium Bose-Einstein condensation

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Contents

- Our new idea to realize Ps-BEC
  - Pulsed dense positron beam + SiO_2 cavity
  - Thermalization + laser cooling
- Ps thermalization measurement in cryogenic environment

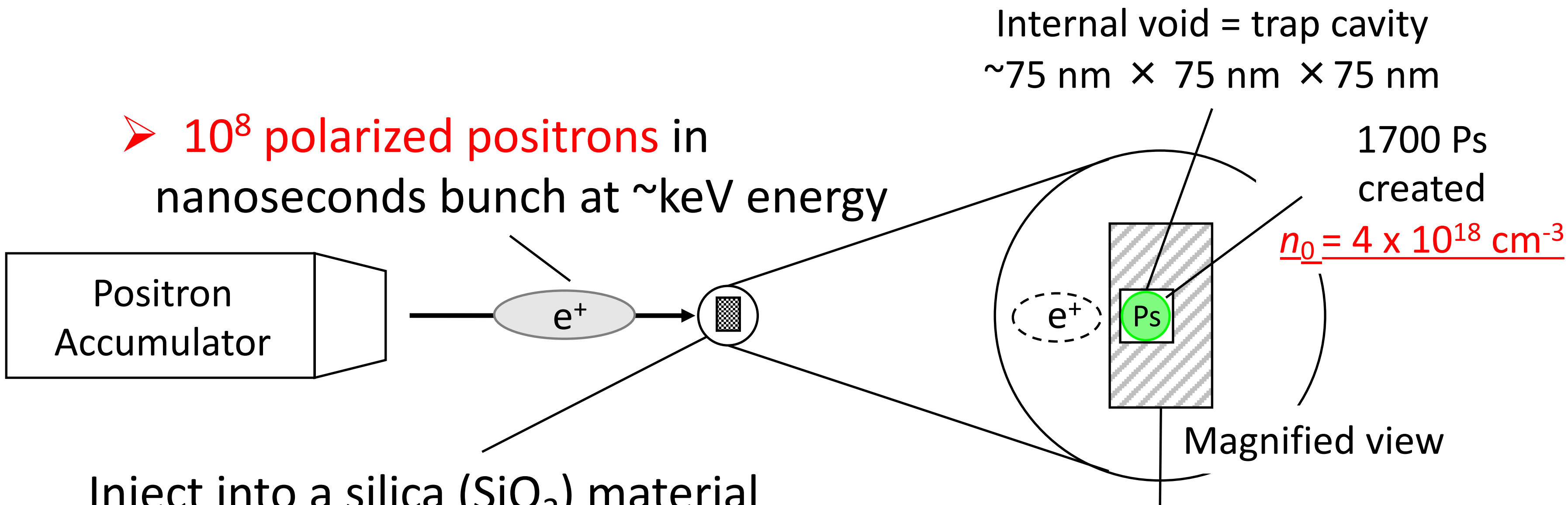
Method to realize Ps-BEC

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



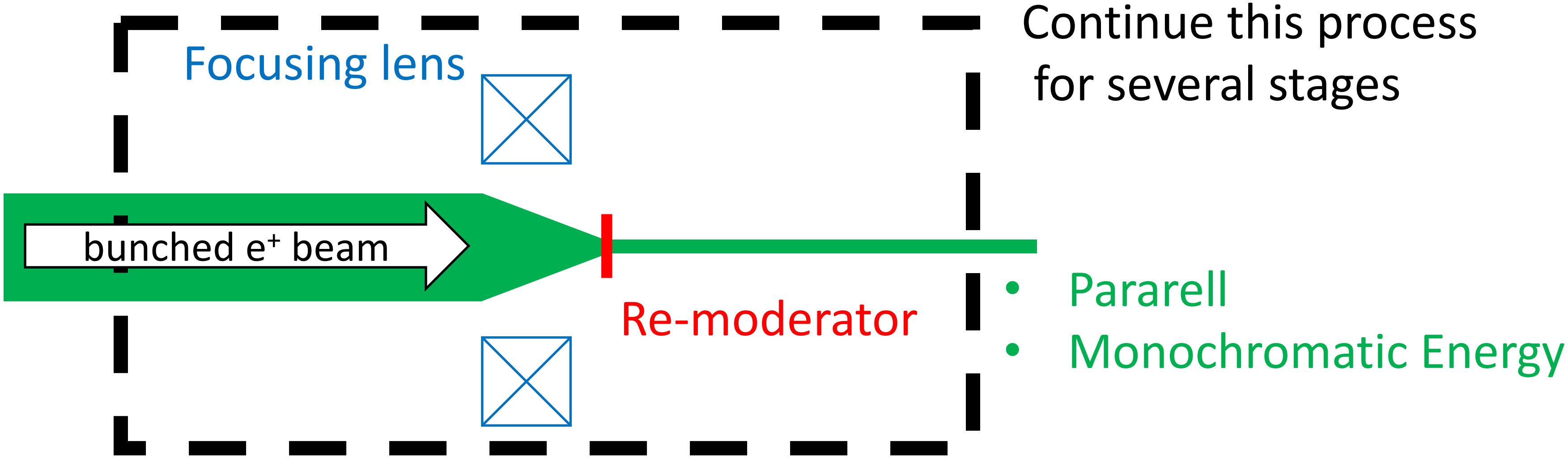
Inject into a silica (SiO_2) material with sub-μm beam waist by focusing

Silica as Ps converter
~50% prob.
(-> Talk by K. Shu)

- 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

Principle of Positron focusing: (Details: talk by N. Oshima (Monday))

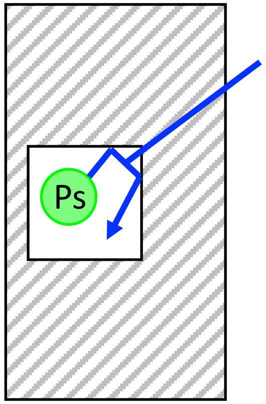


N. Oshima *et al.* J. Appl. Phys. 103, 094916 (2008).

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



Cold Silica < 10 K

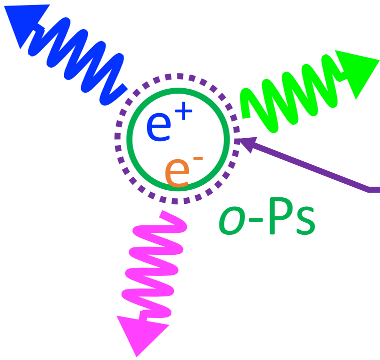
1st cooling

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



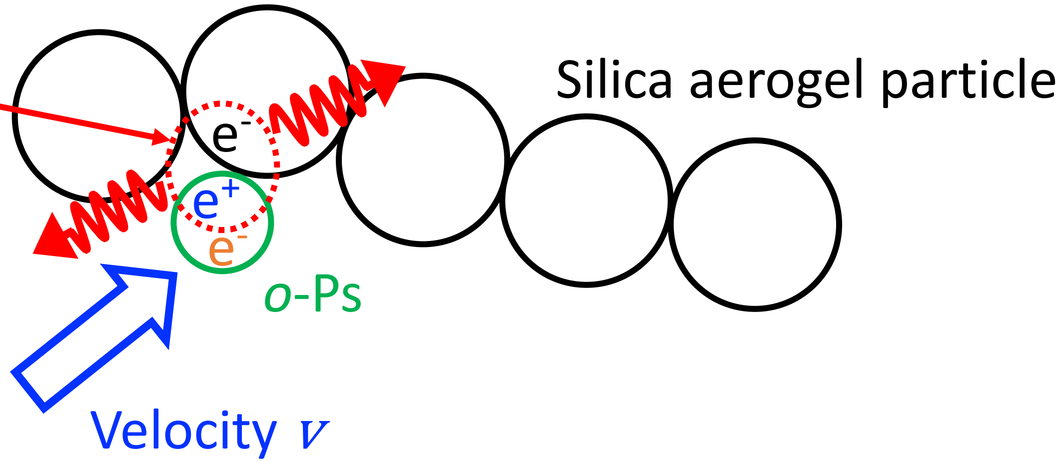
3γ self annihilation

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

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



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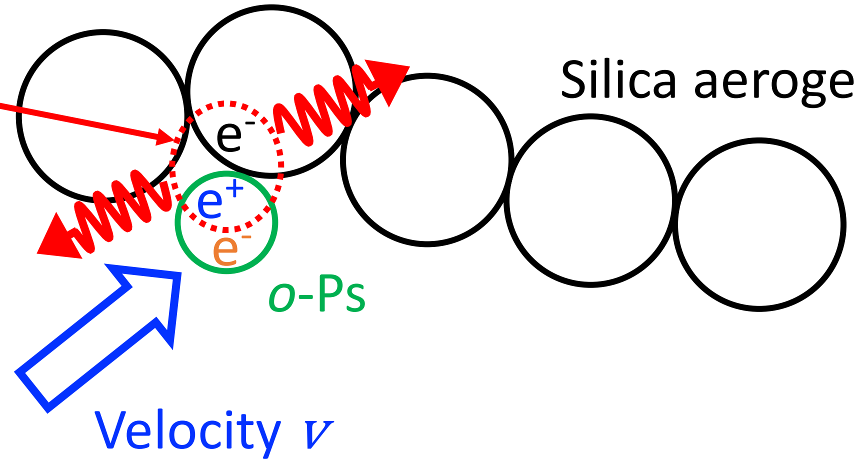

Pick-off annihilation rate $\lambda_2 \propto n \sigma v$

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>

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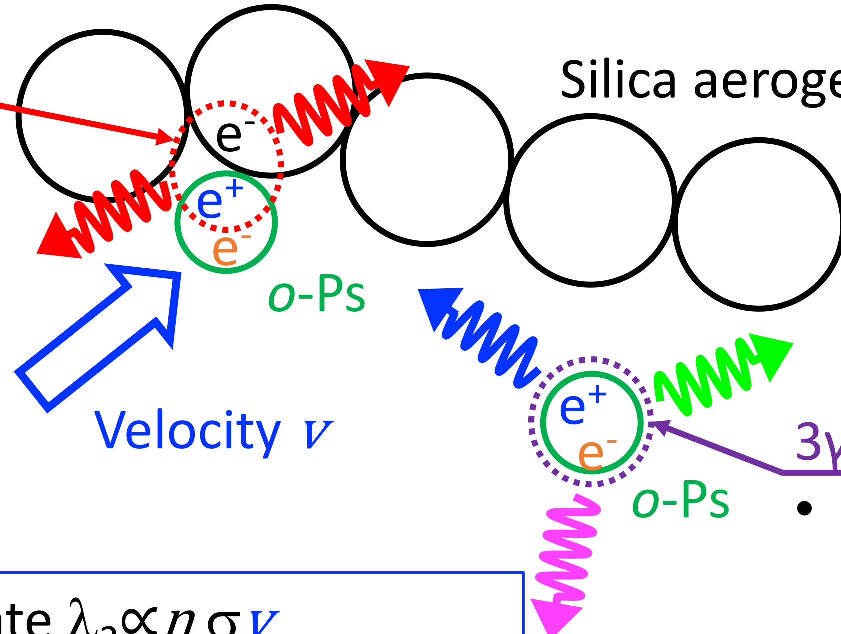

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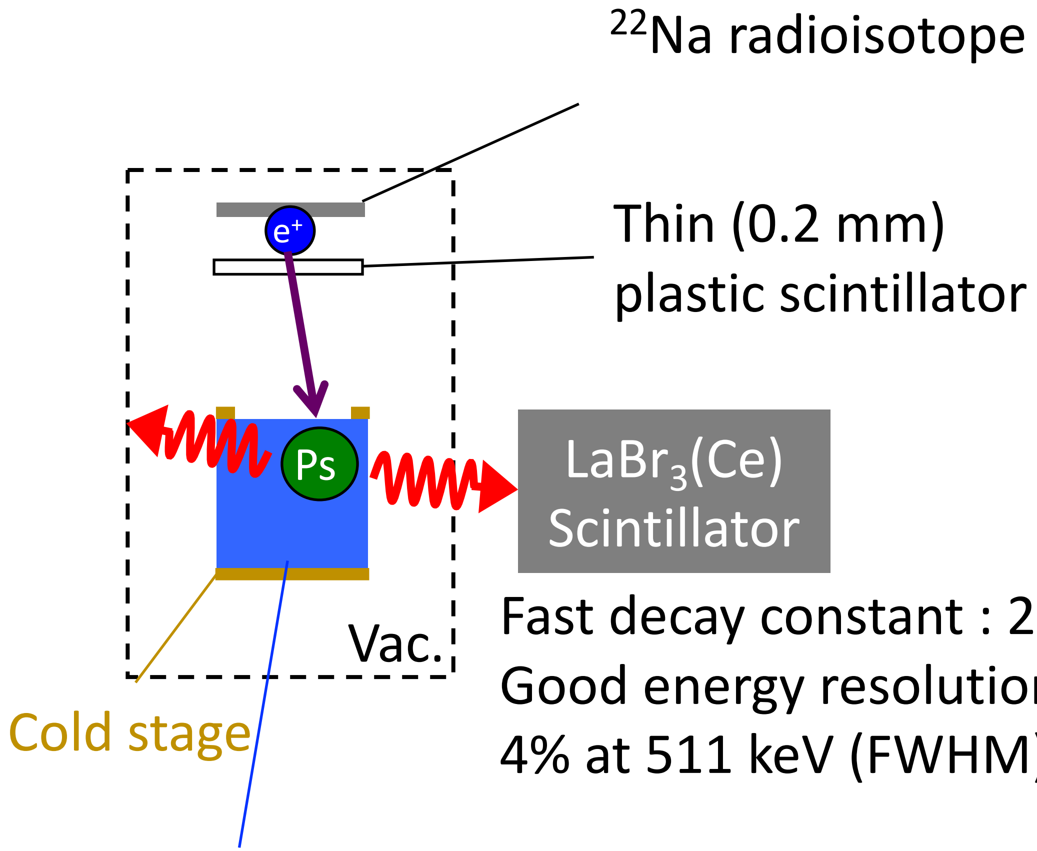
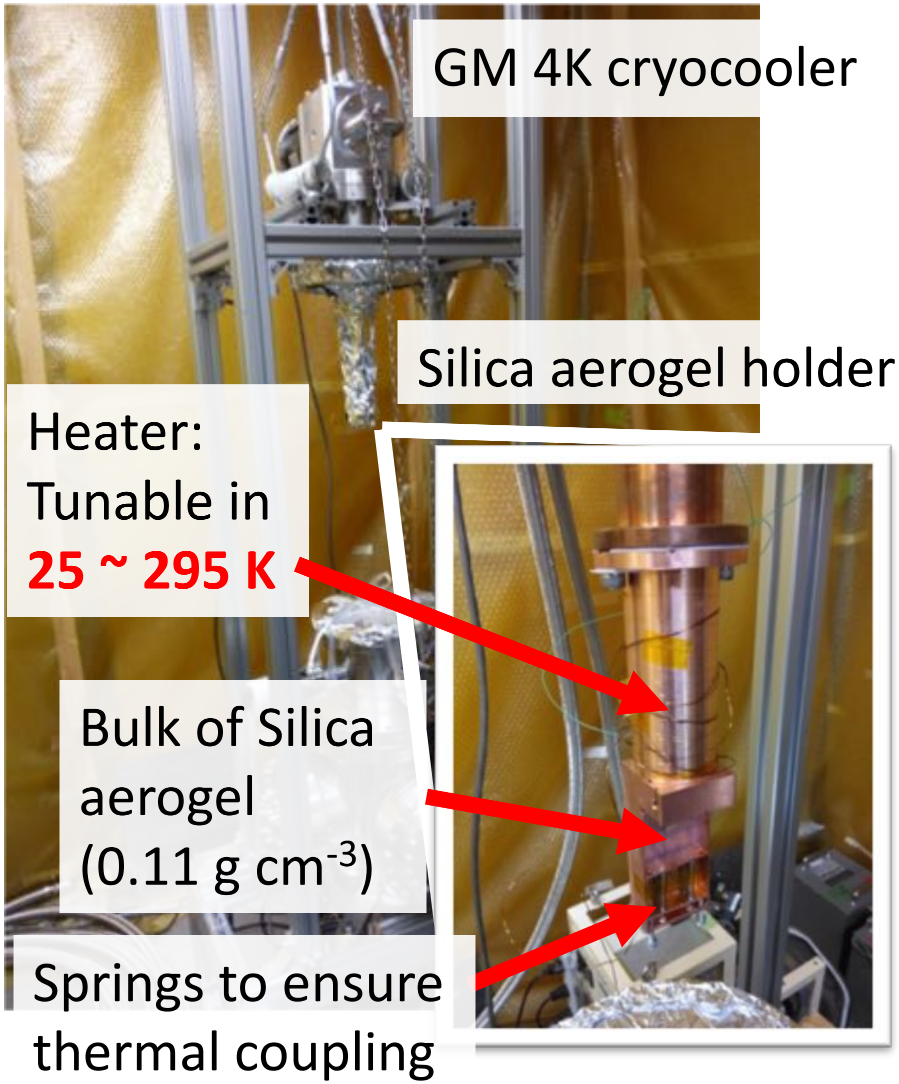
Experimental Setup

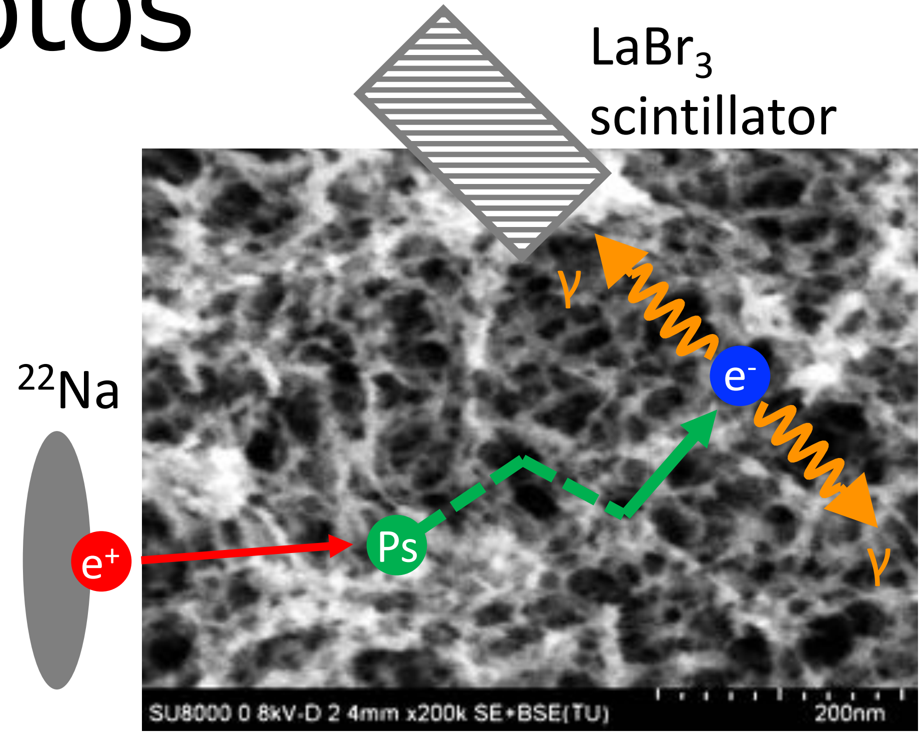


Fast decay constant : 20 ns
Good energy resolution :
4% at 511 keV (FWHM)

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

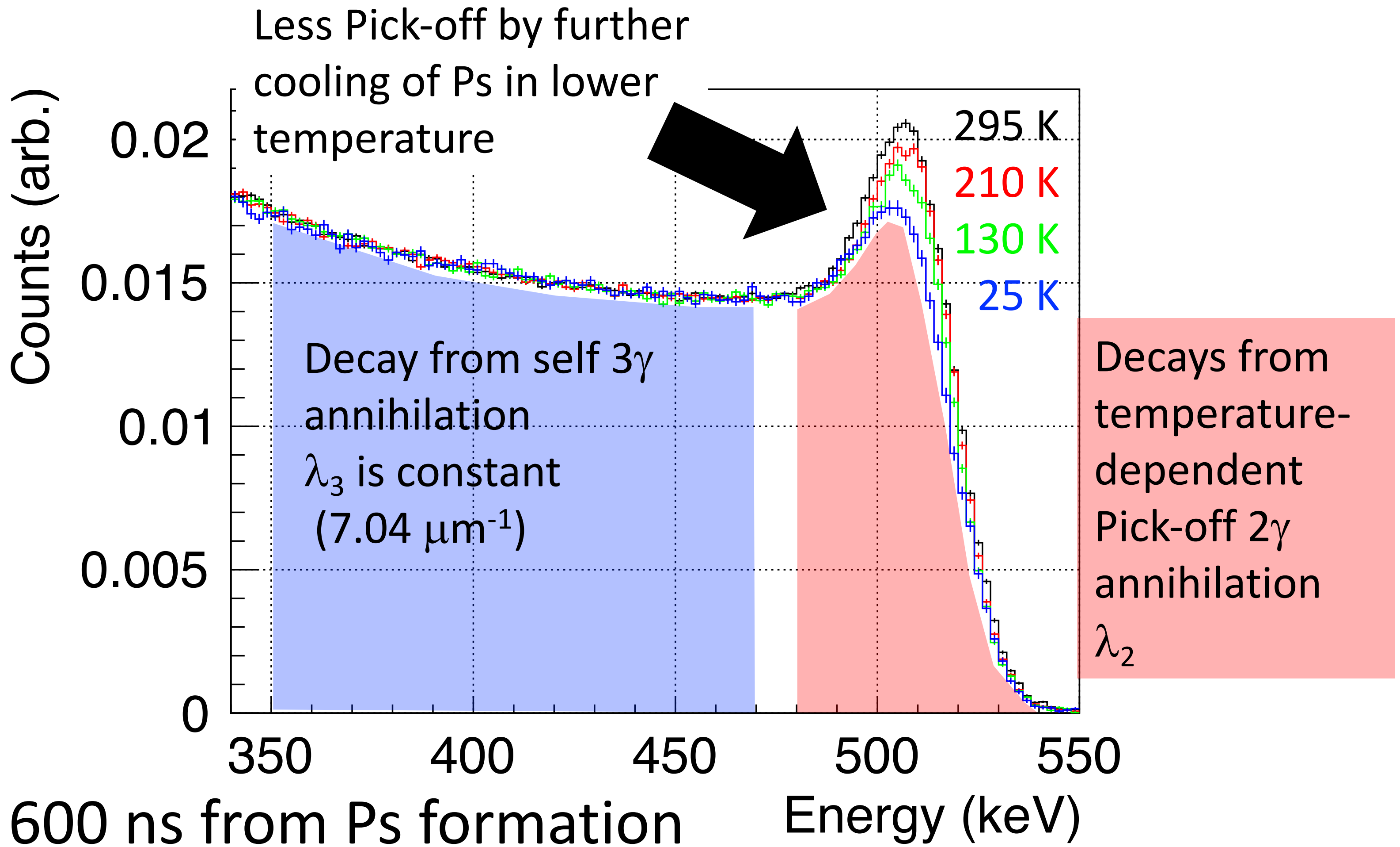




SEM image of used silica aerogel

- 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

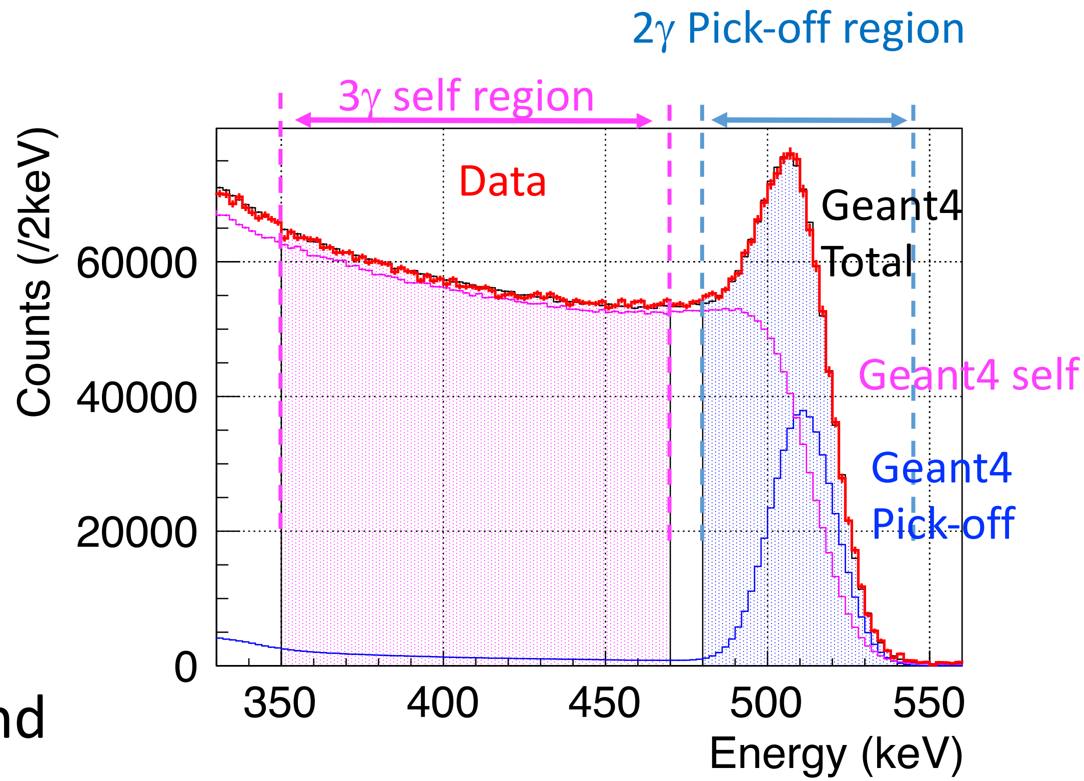
Deduction of Pick-off annihilation rate using MC simulation

- 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>

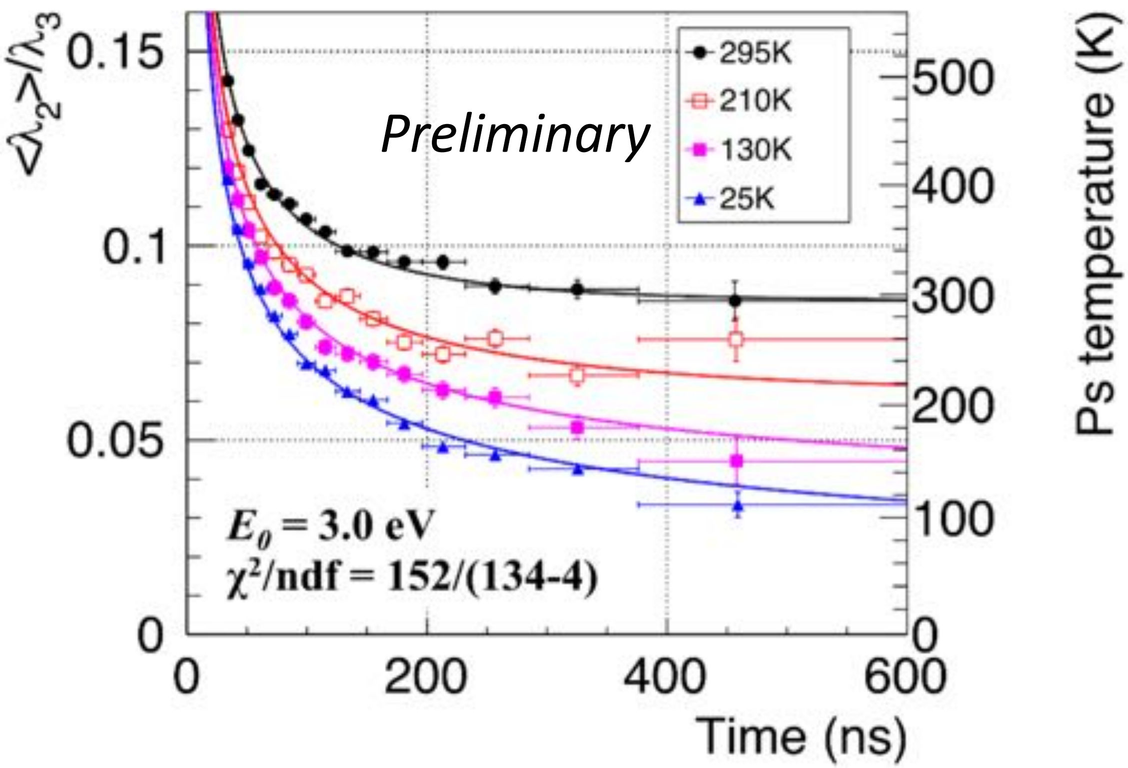
- Detection efficiencies and contamination fractions are estimated by Geant4 Monte Carlo simulation.



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).)

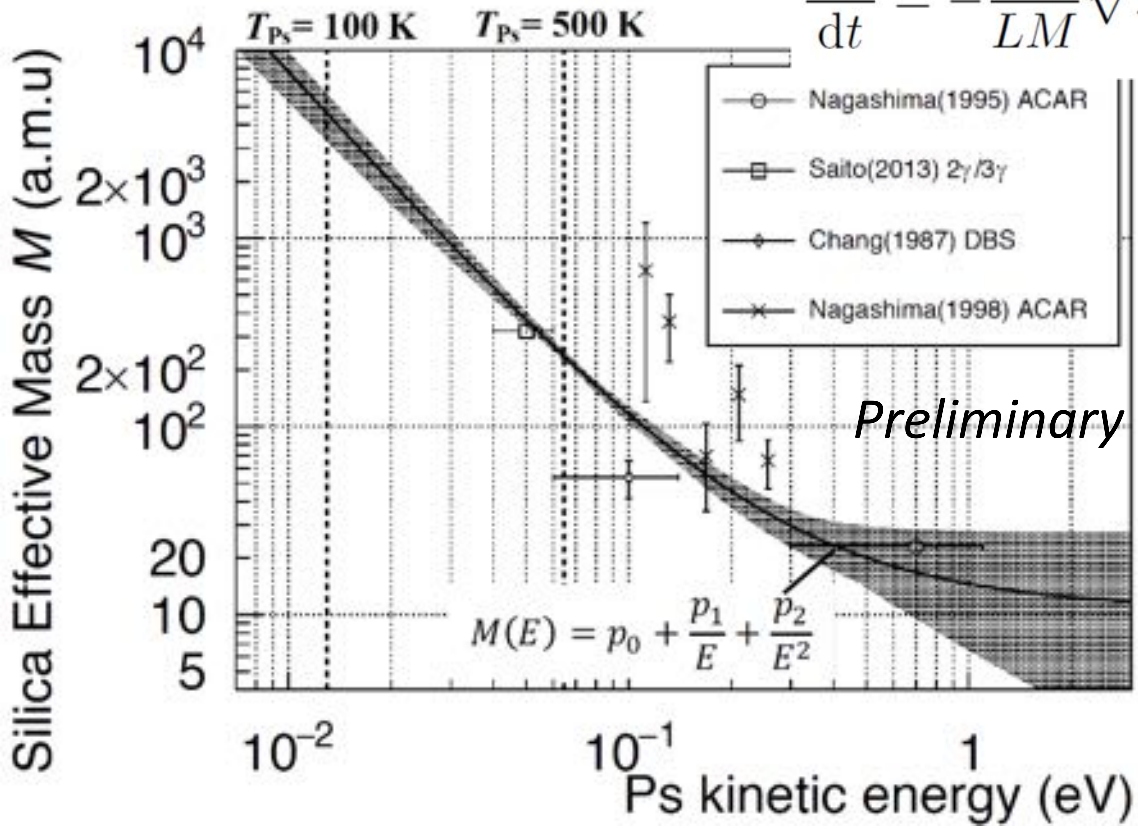
Fitted by the elastic-scattering model (Y. Nagashima *et al.*, PRA **52**, 258 (1995)) with energy-dependent *M* (silica effective mass)

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

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

Ps thermalization slows down at lower Ps kinetic energy

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

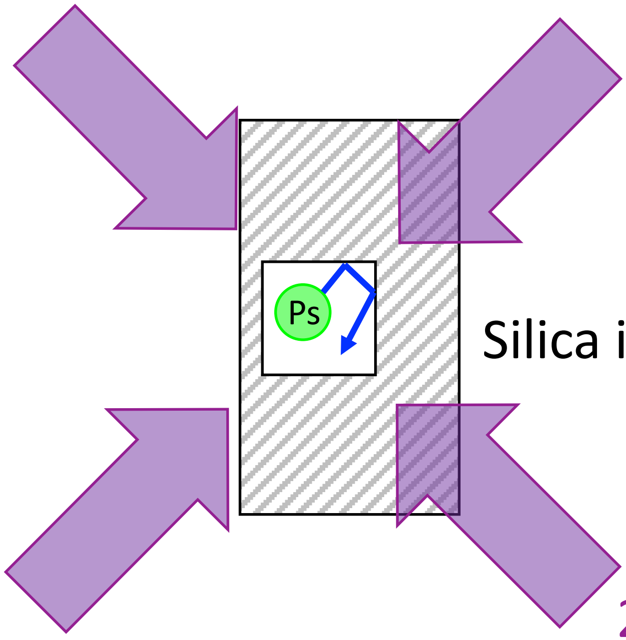


$p_0 = 10.6$ u
$p_1 = 3.3$ u eV
$p_2 = 0.73$ u eV^2

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

- 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

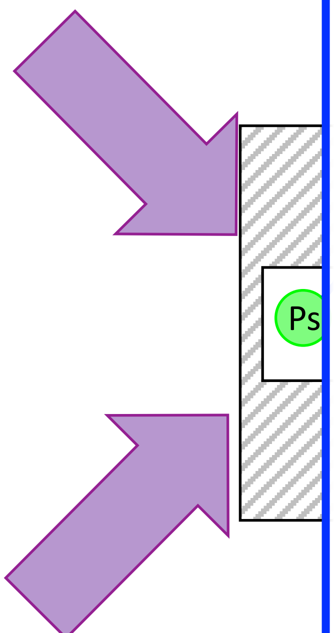
Irradiate 243 nm UV laser to cool Ps down to 10 K

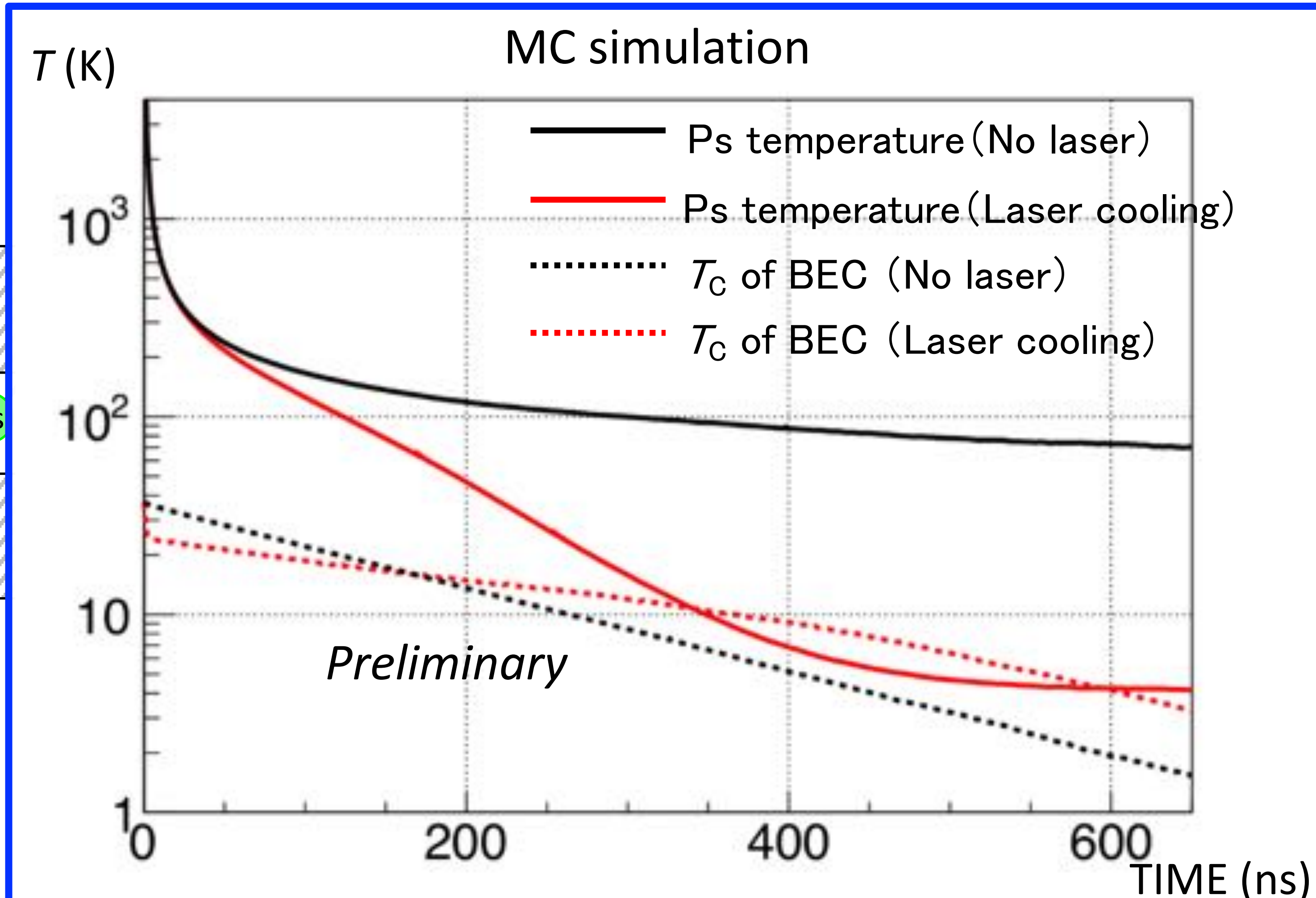
Use 1S-2P transitions

Silica is transparent in UV

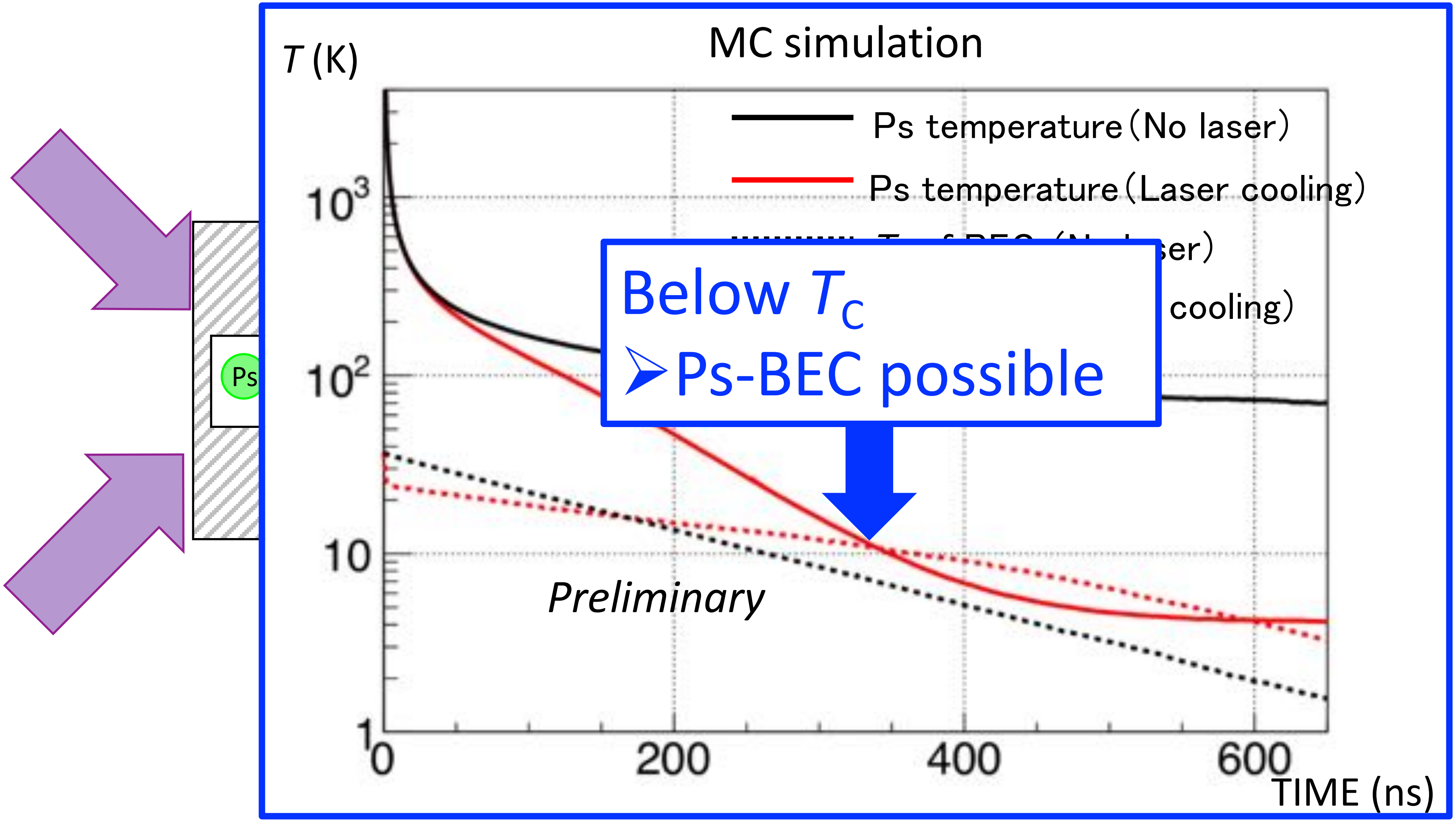
243 nm UV laser

Ps laser cooling





Ps laser cooling



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.
- We plan to perform Ps laser cooling firstly within 2 years and then realize Ps-BEC in 5 years!