Development of cooling system for positronium

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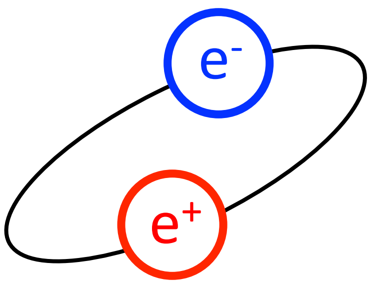
18th International Conference on Positron Annihilation
Orlando, USA

Positronium: Probe on Fundamental Physics

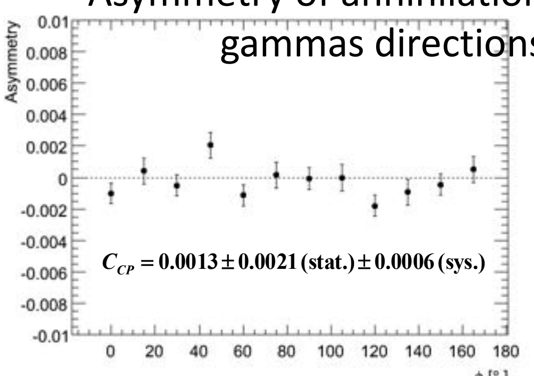


- ◆ Sensitive probe on fundamental physics
- ✓ Exotic atom with anti-particle
  - ➢ Suit for exploring the mystery of anti-matter
- ✓ Pure leptonic system
  - ➢ Experiments and theory calculations can be compared in high precision (*ppm* level)

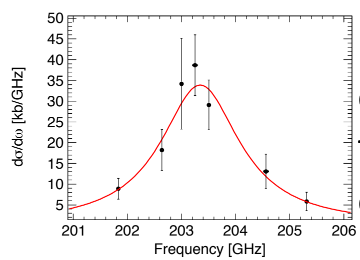
Our works:

CP violation in lepton sector

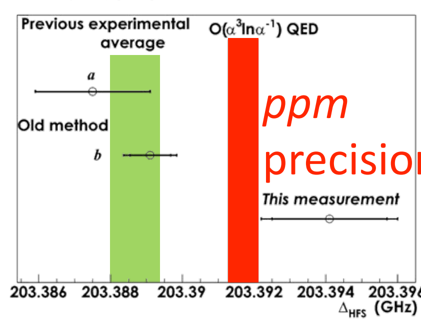
Asymmetry of annihilation gammas directions



Hyperfine structure ($E_{o\text{-}Ps}$-$E_{p\text{-}Ps}$)

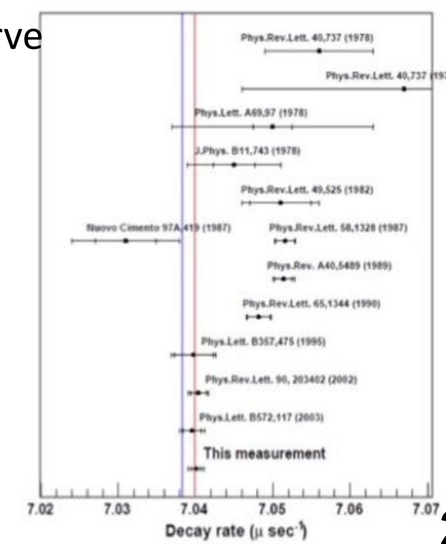


Breit-Wigner curve of First direct transition o-Ps → p-pS



ppm precision!

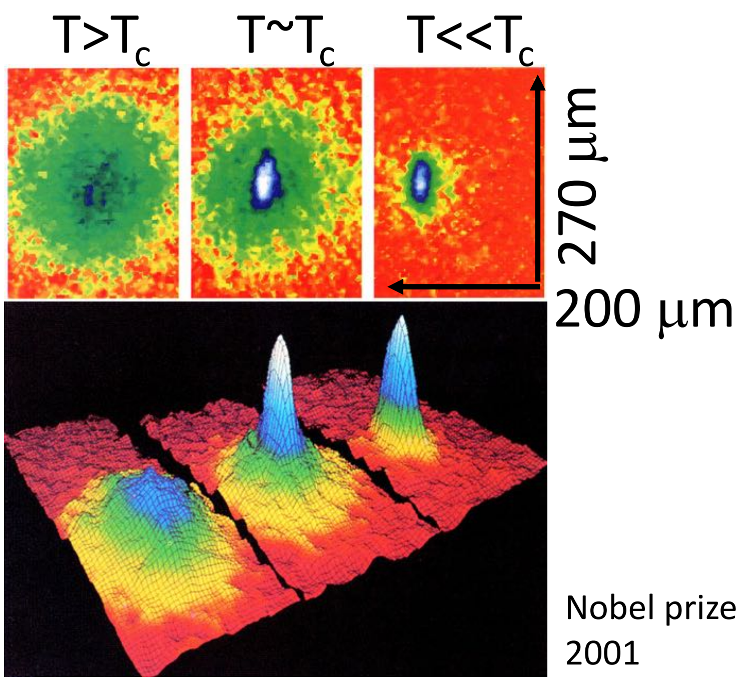
o-Ps life



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



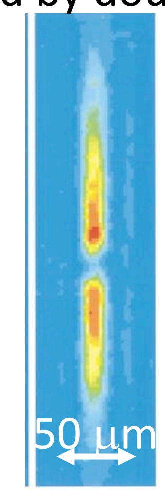
Nobel prize 2001

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

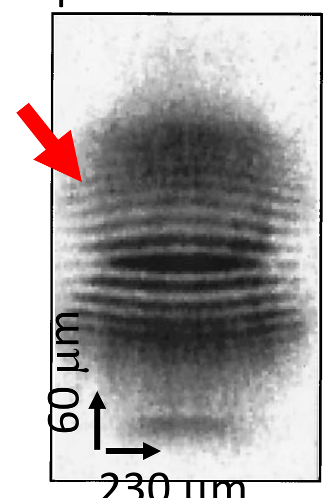
Important feature

- 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



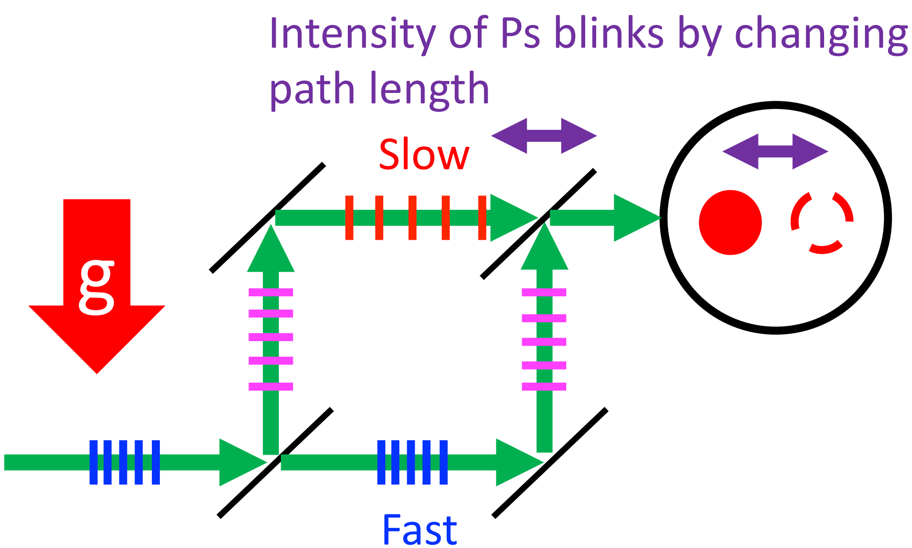
After release expand to overlap



Science 275, 637 (1997)

Applications of Ps-BEC

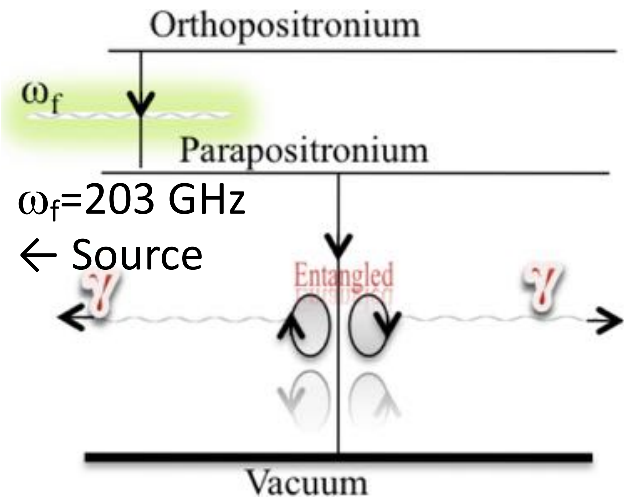
1. Measure anti-matter gravity by atom-interferometer



- 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

☐ Probe with x10 shorter wavelength than current x-rays

☐ Macroscopic entanglement

Challenges to realize Ps-BEC

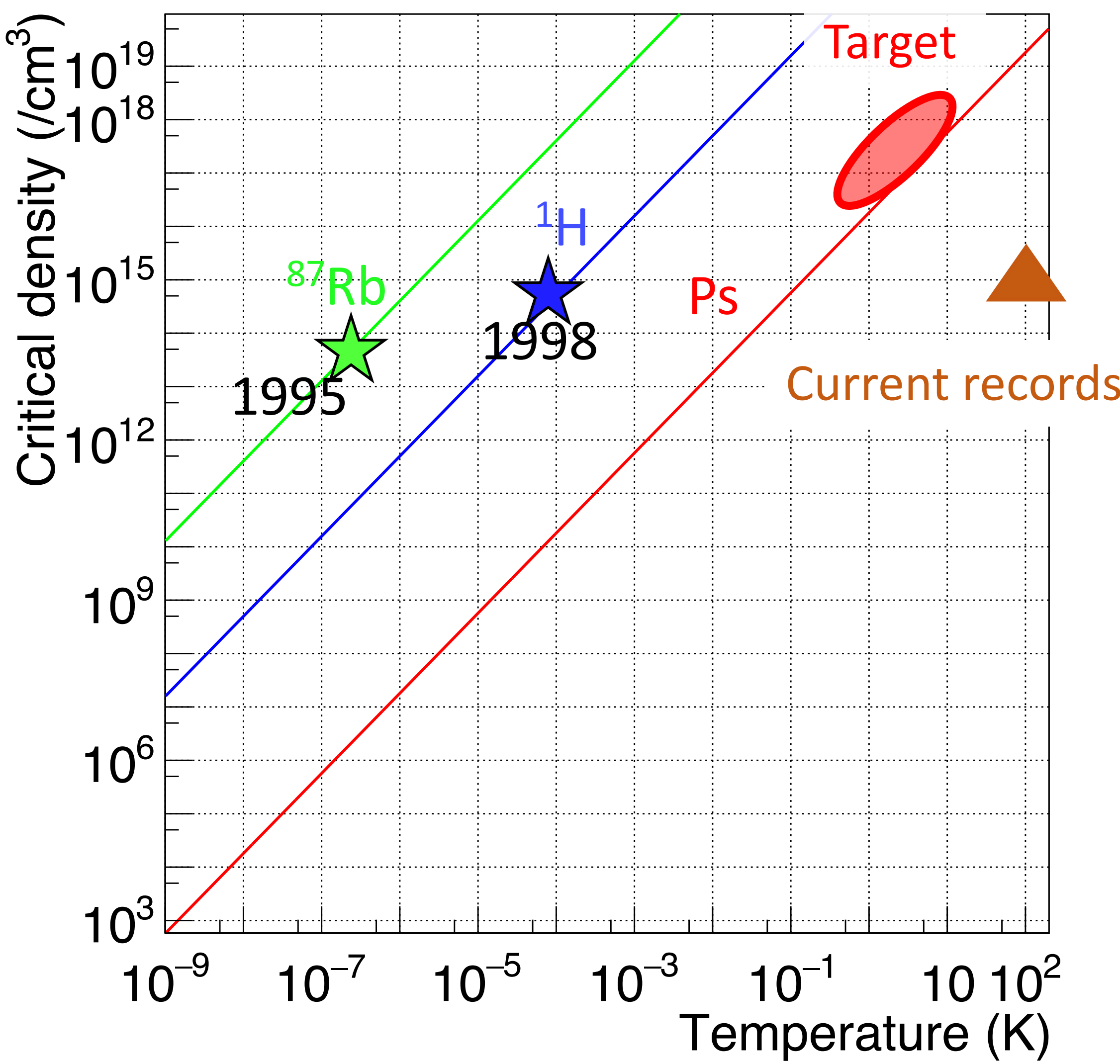
<u>Conditions to realize Ps-BEC</u>

- 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

<u>Necessary techniques</u>

1. Instance creation of dense Ps
2. Fast cooling of Ps



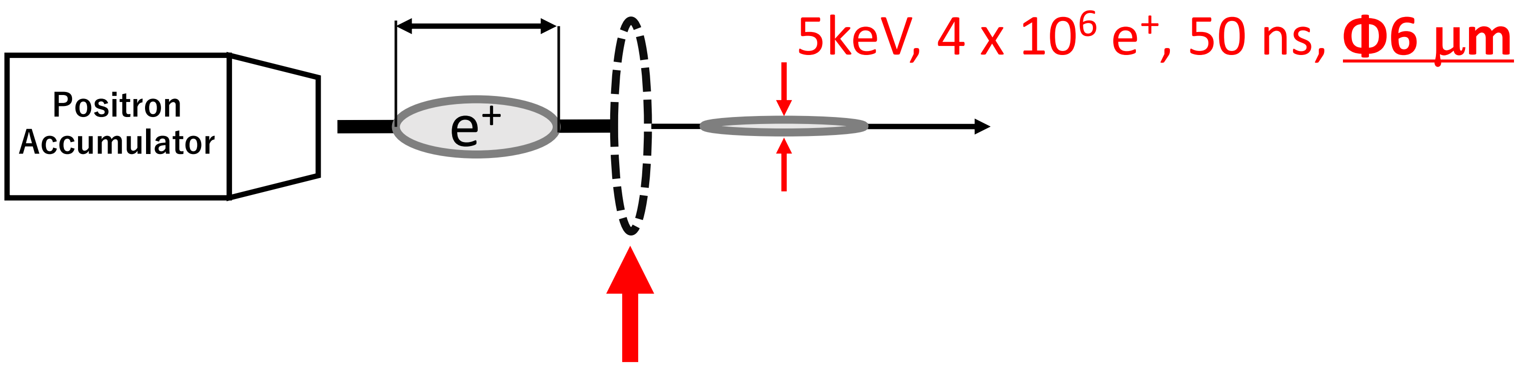
New method to realize Ps-BEC

Many-stages brightness enhancement & hybrid Ps cooling

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

1. Create dense positron bunch by repeating brightness enhancement in many stages

5 keV, 10^8 e^+, 50 ns, Φ 5 mm

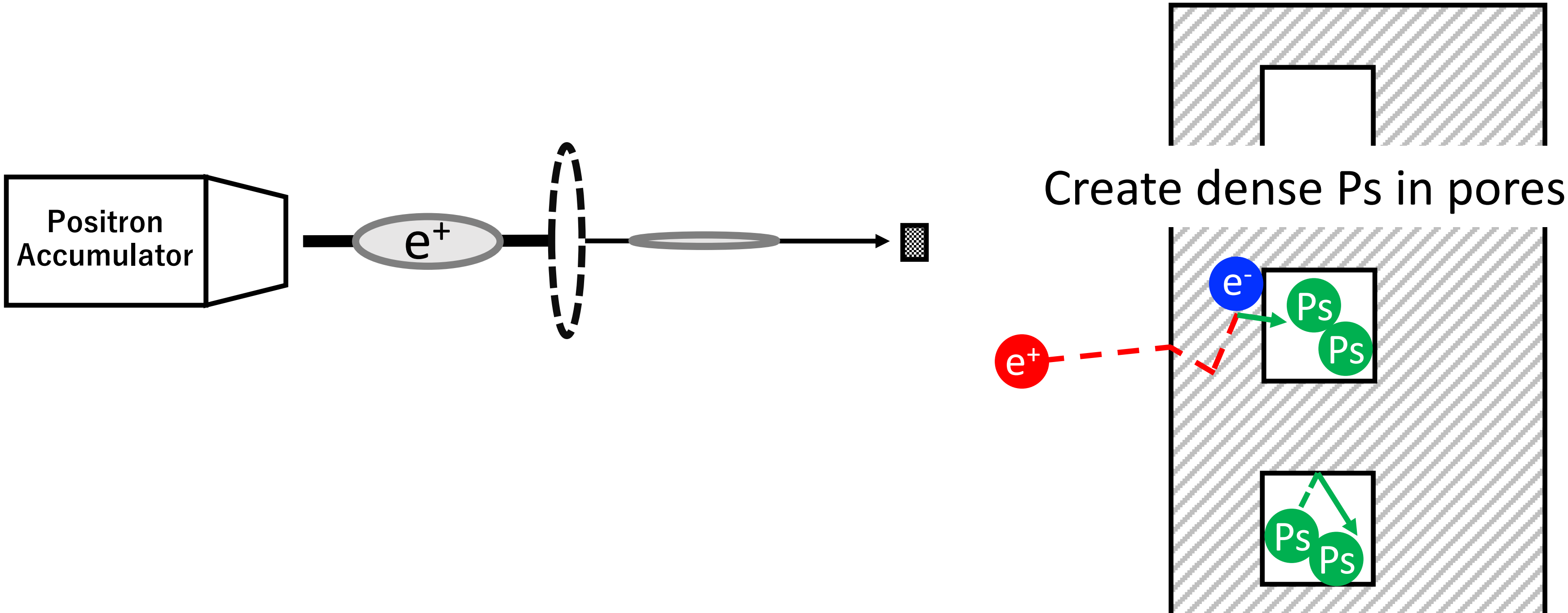


Many-stages brightness enhancement
Details in the next and N. Oshima’s talk

New method to realize Ps-BEC
Many-stages brightness enhancement & hybrid Ps cooling

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

2. Inject dense positron into a porous material to convert $e^+ \rightarrow$ *o*-Ps



New method to realize Ps-BEC

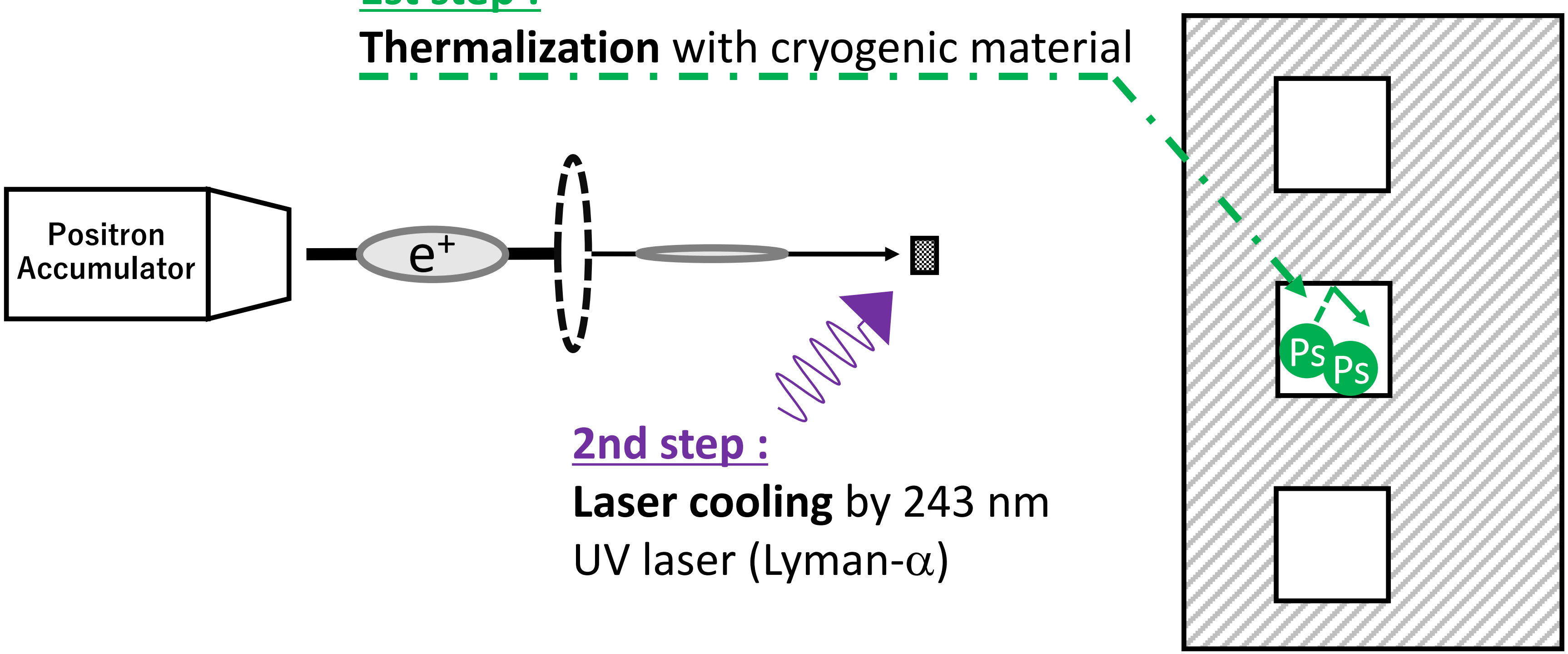
Many-stages brightness enhancement & hybrid Ps cooling

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

3. Cooling of Ps by hybrid cooling :
   Combination of thermalization and laser cooling

Cooling to 4 K by cryo-refrigerator

1st step :
Thermalization with cryogenic material

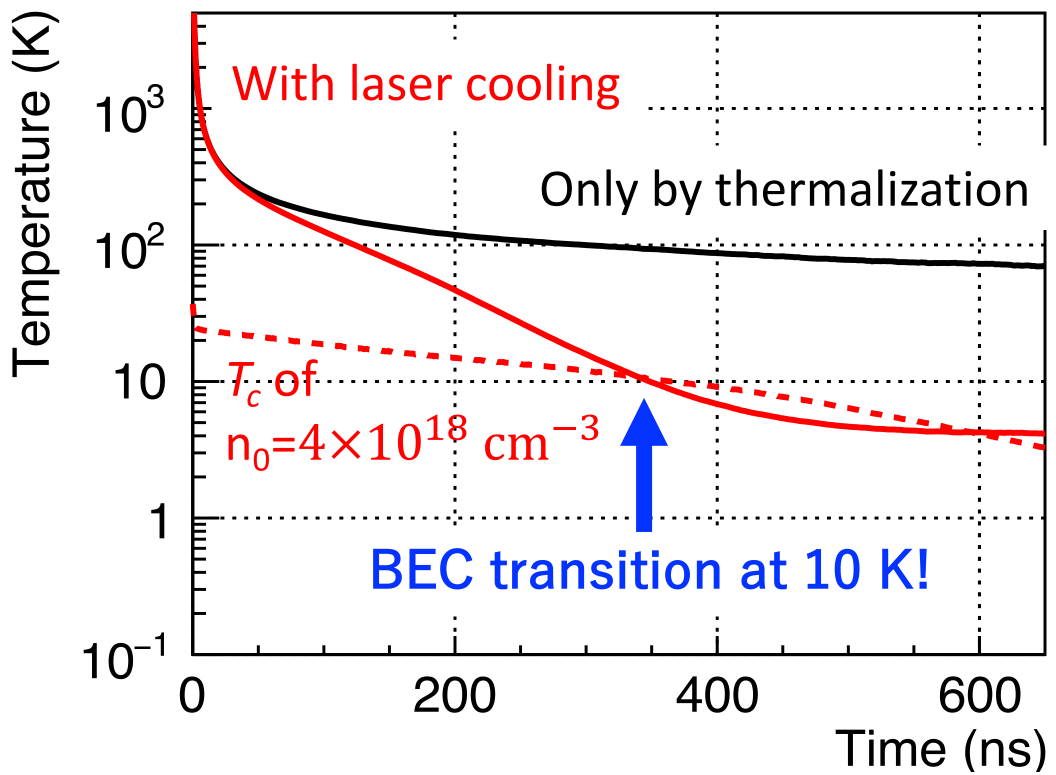


2nd step :
Laser cooling by 243 nm UV laser (Lyman-α)

Cooling efficiency will be efficient enough
Both of cooling mechanism are necessary

Temperature evolution was simulated.

- Cooling down less than 10 K will be possible
- Efficient to realize Ps-BEC with $n_0 = 4\times10^{18}\ \mathrm{cm}^{-3}$



Simulated temperature evolution

<u>Thermalization</u>

Efficient at hotter than 200 K
(We used measure data whose detail in the next talk)

<u>Laser cooling</u>

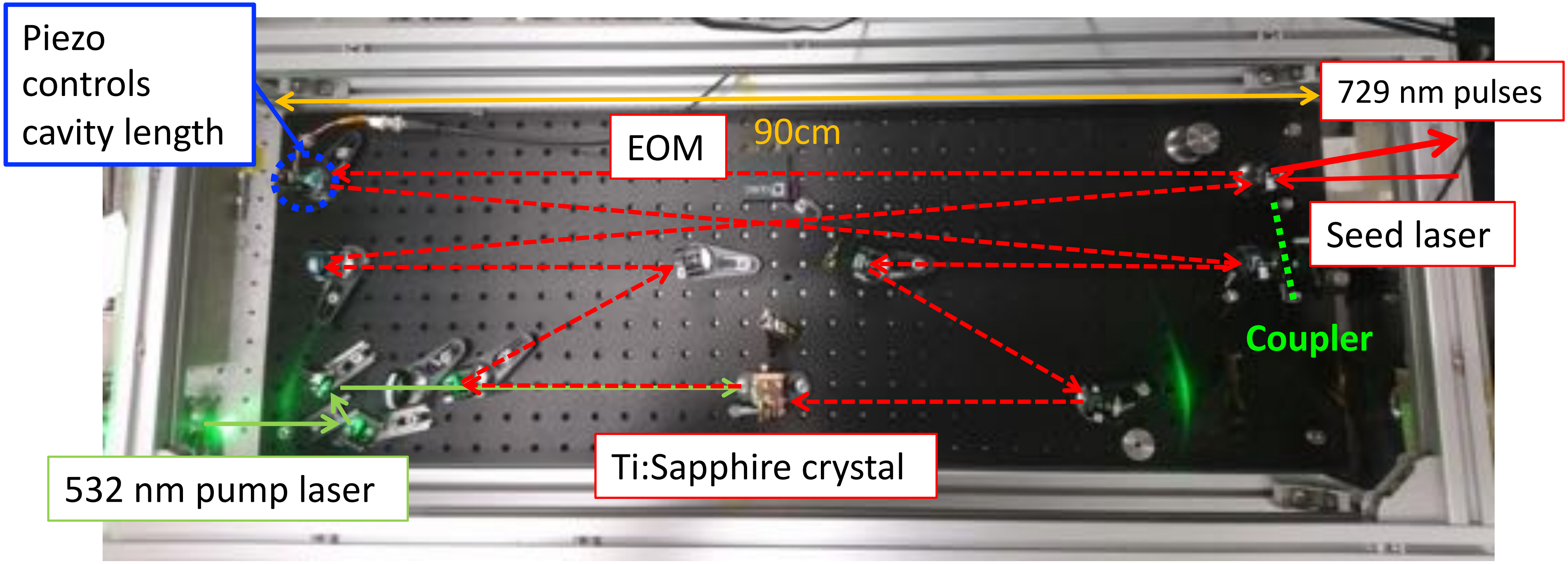
Efficient at colder than 200 K

- Combination of two methods are essentially important

Two new technologies to develop
1. Cooling laser

Ps laser cooling requires some special features
we are developing original system. Will be available in 2018.

1. Long pulse duration : Already done.
2. Broad linewidth : Elements are ready, now in testing.



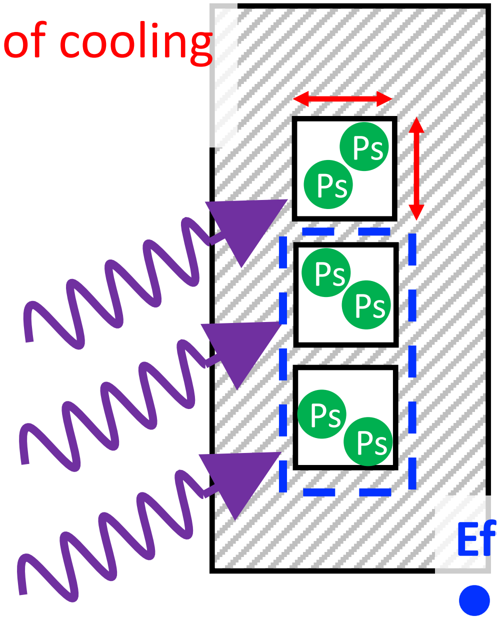
Home-made laser cavity (A core of the system)

Two new technologies to develop
2. Ps converter

3 Requirements

Optimized void size 50-100 nm to

- Make thermalization rapid
- Reduce pick-off annihilation
- Avoid quantum limit of cooling and Dicke narrowing



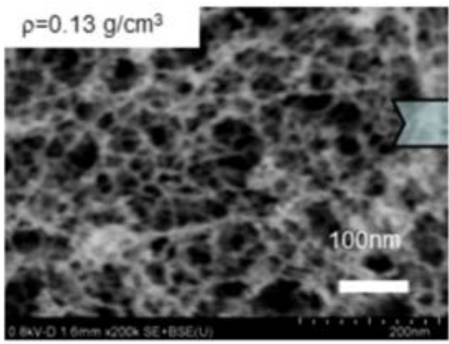
High transparency at UV

Efficient Ps trap by

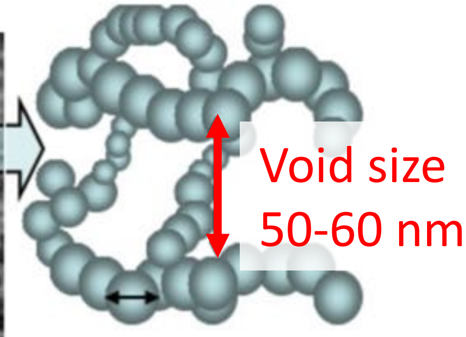
- Material of high Ps conversion efficiency
- High porosity

2 ideas of converters made by SiO_2 (silica)
Thin aerogel & Nano-processing

Idea 1 : Thin aerogel



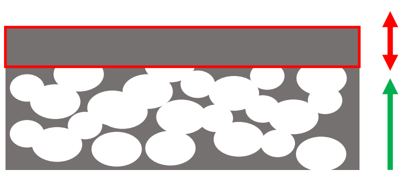
SEM image of aerogel



Schematic of structure

Porous material made by sol-gel method

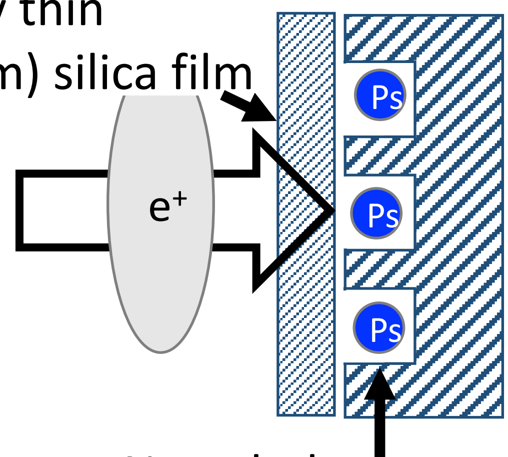
supplied by Japan Fine Ceramics Center (JFCC)



Good points :

- High Ps production ~50%
- High porosity >90% and best void size
- High transparency in thin film shape

Idea 2 : Nano-processing by on silica glass wafer



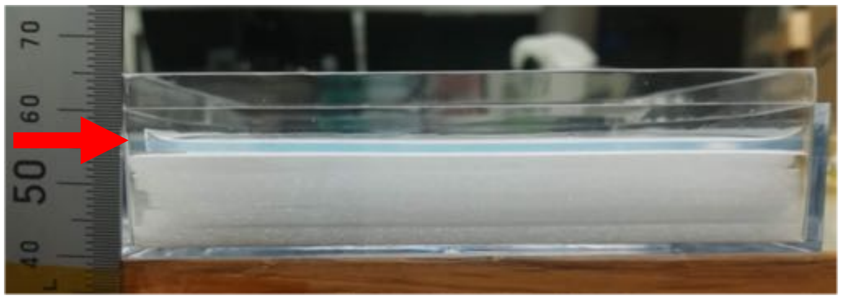
Good points :

- High UV transparency > 95%
- Fully-controllable void structure to optimize its size and porosity

2 ideas of converters made by SiO_2 (silica)
Thin aerogel & Nano-processing

Both idea have its own pros and cons, so developing in parallel

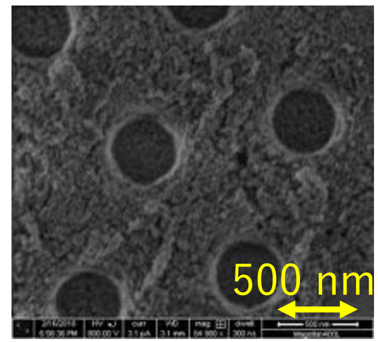
Idea 1 : Thin aerogel



1 mm thick silica aerogel by JFCC

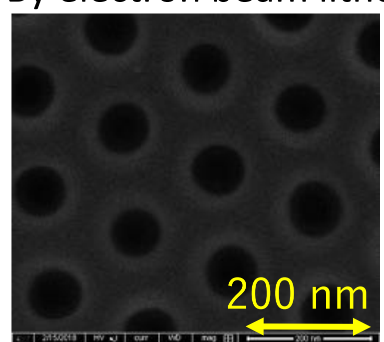
For aerogel, Basic features were tested and requirements were fulfilled.

Idea 2 : Nano-processing



By imprinting on SiO_2-PVA composite and sintering

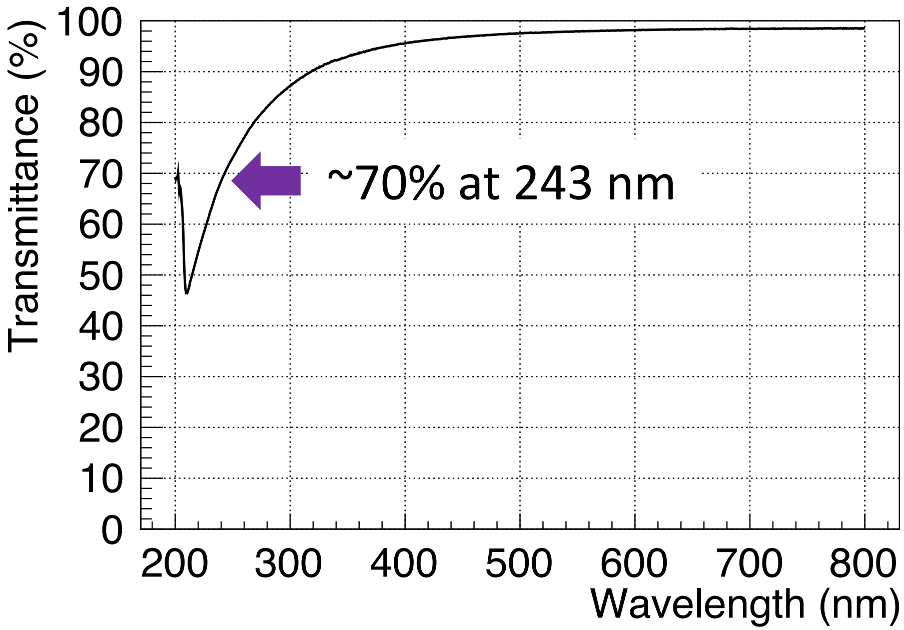
By electron beam lithography



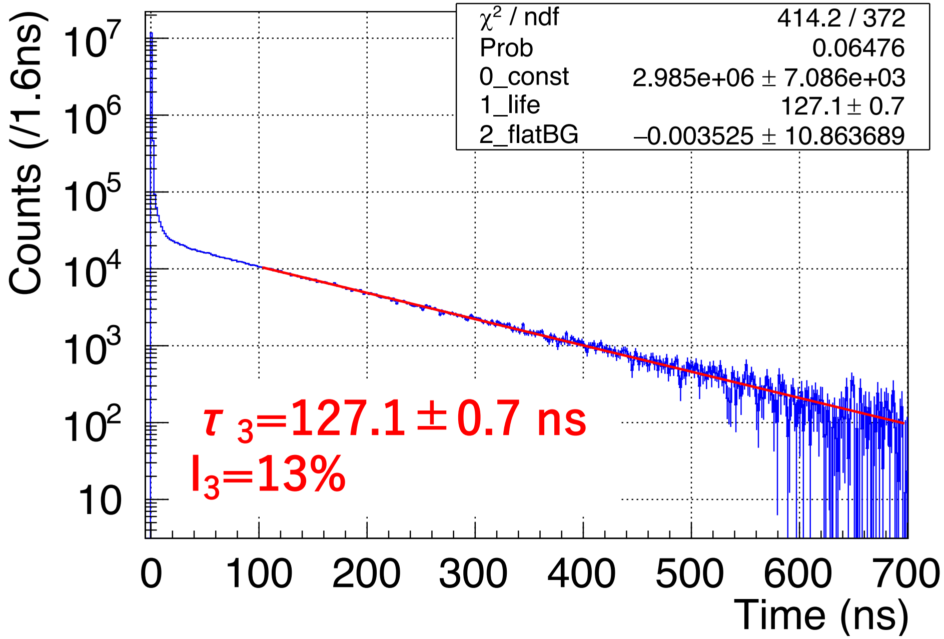
Two prototype devices are created
Now in testing

Test of thin silica aerogel : Enough transparency & Efficient Ps conversion

- Void structure of aerogel results in Rayleigh scattering
- Transmittance of 70% is enough for the first laser cooling experiment
- Now working on t0.5mm size



Transmittance of t1mm aerogel by spectrophotometer

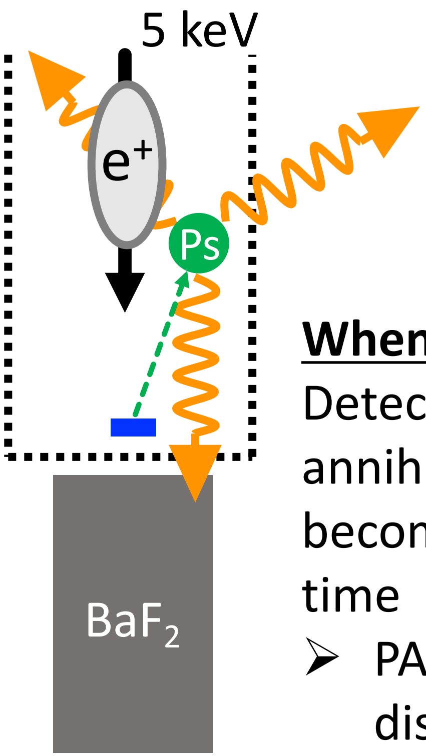


Na-22 Bulk PALS spectrum

- Confirmed trapped *o*-Ps in 50 nm voids (⇔ τ_3=130 ns by RTE model)
- I_3=13% ⇔ ~50% of stopped e^+ were converted to *o*-Ps

Test of thin silica aerogel : Trapping of *o*-Ps close to the aerogel surface

- Experiments with laser will use slow-positron
- o-Ps created at near surface was confirmed to be trapped by PALS measurement

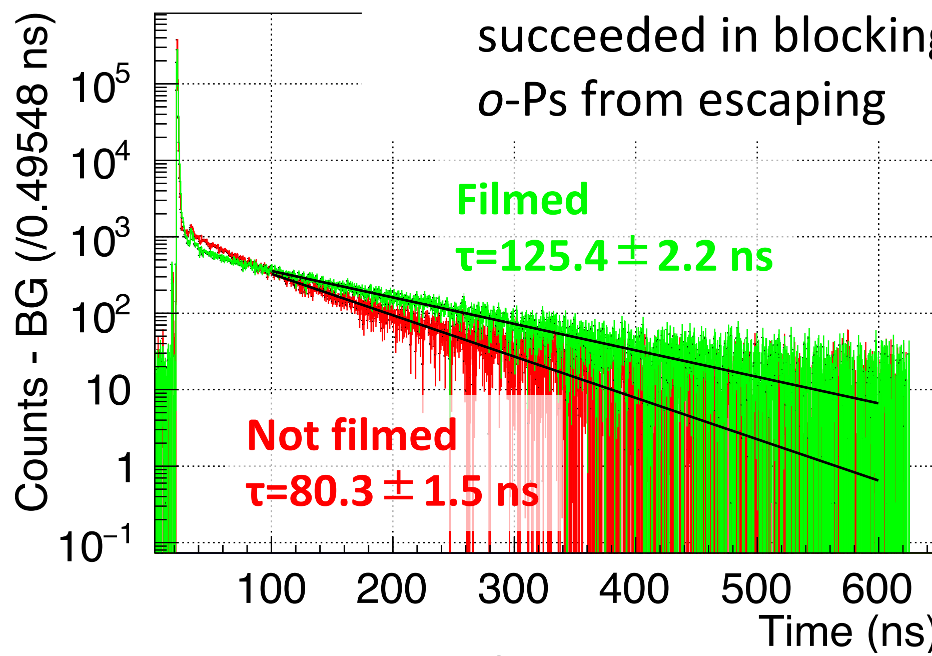


<u>When *o*-Ps escaped …</u>

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

<u>Thin aerogel is ready for experiment with laser on trapped *o*-Ps</u>

1st step : Doppler spectroscopy in early 2019

Current achievement & Plans of the developments

For laser cooling at KEK-SPF
In ~ 1 year

Ps converter (Silica aerogel)

- ✓ Efficient Ps conversion and trapping
- ✓ High transparency
- ✓ Optimized void size
- ➢ Test in cryogenic & UV radiated environment
- ➢ Test of thinner aerogel for higher transparency (t 1 → 0.5mm)

Cooling laser

- ✓ Long duration pulsing
- ➢ Wavelength broadening by driving EOM in the cavity
- ➢ Wavelength shift by out EOM
- ➢ Amplification & THG (conventional techniques)

For Ps-BEC
In ~ 5 years

Ps converter

- ➢ Heat and charge up problem by dense positron

Cooling laser

- ➢ Further optimization of the wavelength structure to achieve 1 K Ps temperature

Positron systems

c.f. talk of N. Oshima and A. Ishida

- ➢ Many stage brightness enhancement
- ➢ Spin-polarized positron buncher

Summary

- Ps-BEC is a good candidate of the first BEC with anti-matter, which has a rich potentials on both fundamental and application physics.

- A new method of cooling has been proposed using both of the thermalization process and laser cooling.

- Cooling laser for Ps requires very special optics, so new system is currently under development. The development will be finished in 2018.

- New Ps converters which enables the hybrid cooling are in development. One of the types, thin silica aerogel, has been tested to have good features and be used for the laser cooling experiment.

- We plan to perform Ps Doppler spectroscopy in early 2019, and then laser cooling in 2019.