Experimental progress in physics of cold positronium

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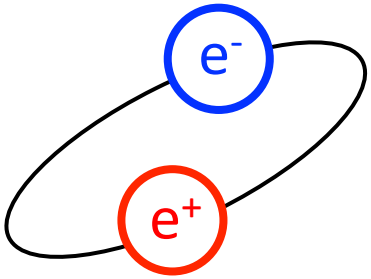
VIRTUAL FPUA 2021

Fundamental Physics Using Atoms

Positronium
A good probe on fundamental physics

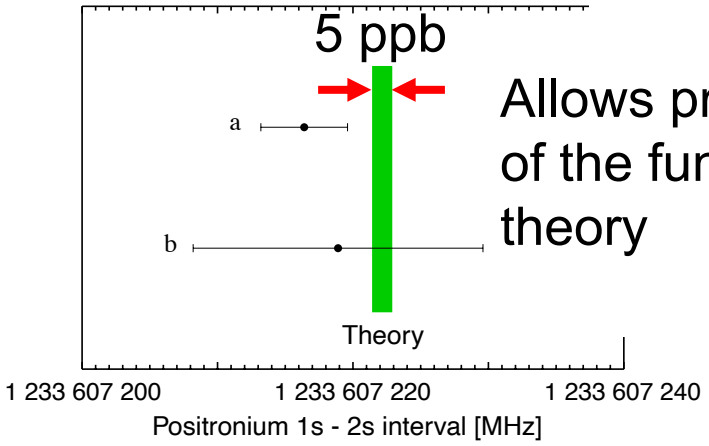
Positronium (Ps)

An exotic hydrogen-like atom consisting of an electron and a positron



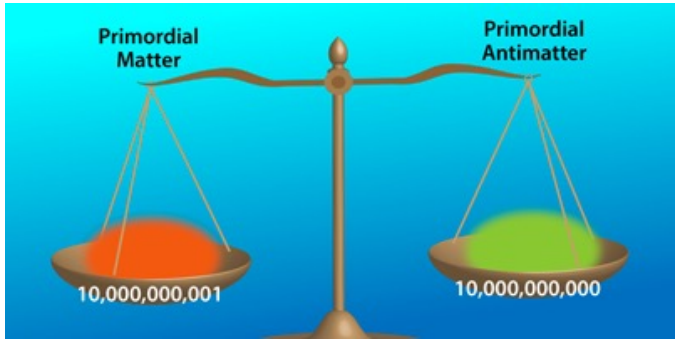
Two useful features

1. Pure leptonic structure



Allows precise test of the fundamental theory

2. Including antimatter



From Alan Stonebraker

Search for matter – antimatter asymmetry to solve the mystery of disappeared antimatter

S. G. Karshenboim, Phys. Rep. 422, 1 (2005).

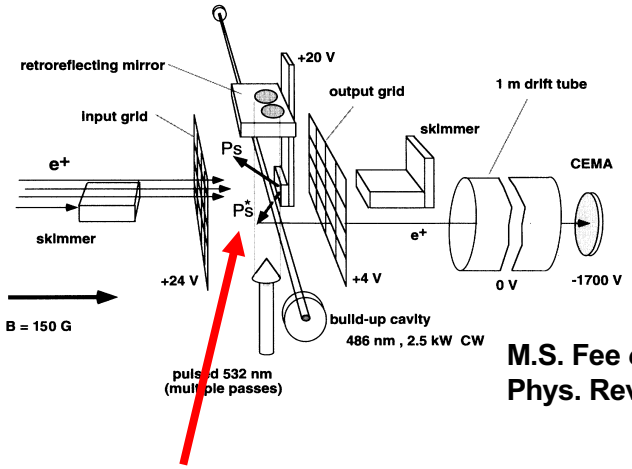
[a] M.S. Fee *et al.*, Phys. Rev. Lett. 70 (1993) 1397.

[b] K. Danzmann *et al.*, Phys. Rev. A 39 (1989) 6072.

Cold positronium in a few Kelvin is a key resource for next steps

For precise spectroscopy

Reducing systematic uncertainties arising from the large velocity



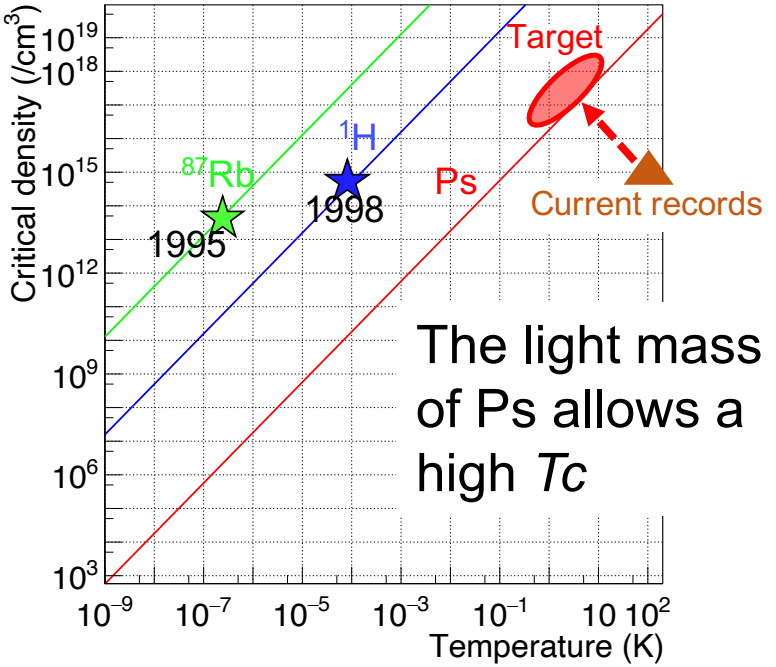
M.S. Fee *et al.*,
Phys. Rev. Lett. 70 (1993) 1397.

Ps was around 600 K

Cooling of Ps to a few Kelvin will improve to 10 times more precision

To realize Bose-Einstein condensation

The first BEC, which is a coherent matter wave, with an antimatter

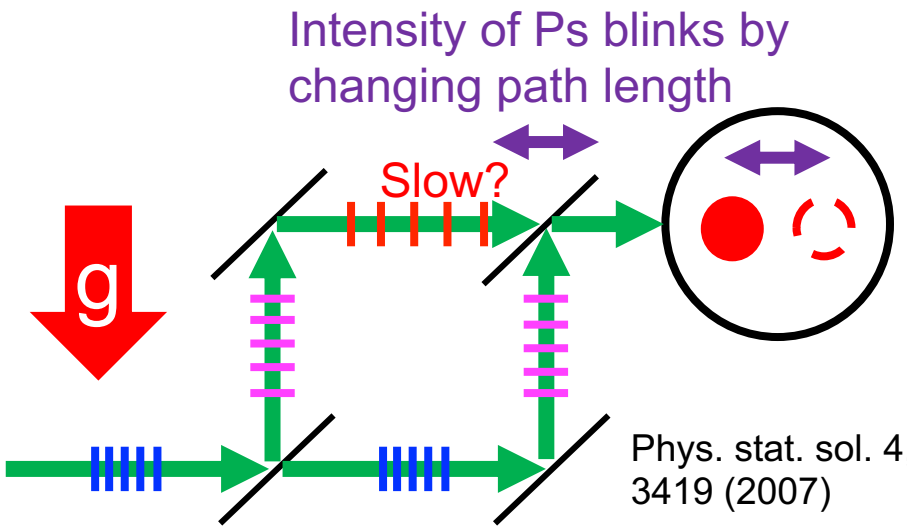


The light mass of Ps allows a high *Tc*

Phase diagram for BEC transition

Ps-BEC has impacts on both fundamental and applied physics

High-contrast antimatter interferometer to measure gravity

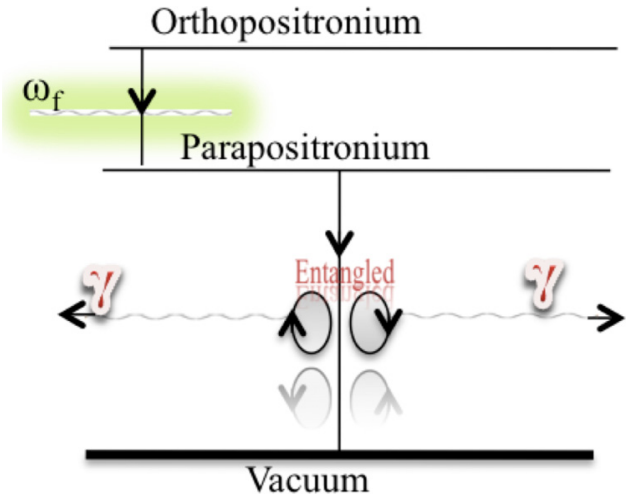


Phys. stat. sol. 4, 3419 (2007)

Can be a key to explain why only matters are left in the current universe

Under intense study in many experiments

511 keV gamma-ray laser



Phys. Rev. A 92, 023820 (2015)

Ps decays into spin-entangled γ rays through the pair annihilation

γ ray laser will be realized by BEC coherence

★ High energy for many applications

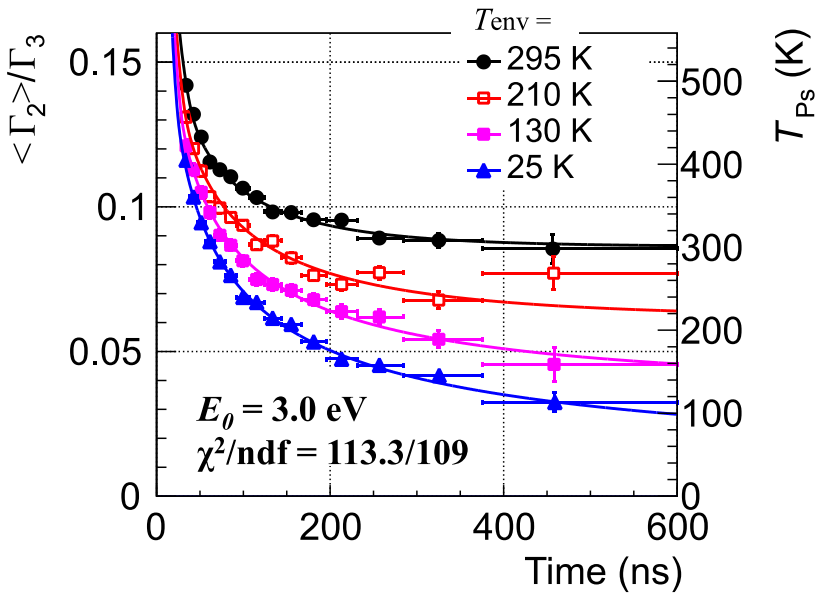
★ Macroscopic entanglement

Cooling of Ps requires a breakthrough: we use laser cooling

Short lifetime as 142 ns* requires **a rapid cooling**

* For the long-lived *ortho*-Ps (*Spin* = 1)

Conventional technique using thermalization in cryogenic nanopores



We showed the limit was around 100 K (in preparation)

Laser cooling (Doppler cooling)

Photon recoil velocity : 1.5 km s^{-1}

$\sigma_v \sim 50\ \mathrm{km\ s^{-1}}$ at 300 K

Recoil cooling limit : 100 mK

$\tau_{2P\rightarrow 1S} = 3.2\ \mathrm{ns}$

Ps will be cooled to a few Kelvin in 300 ns

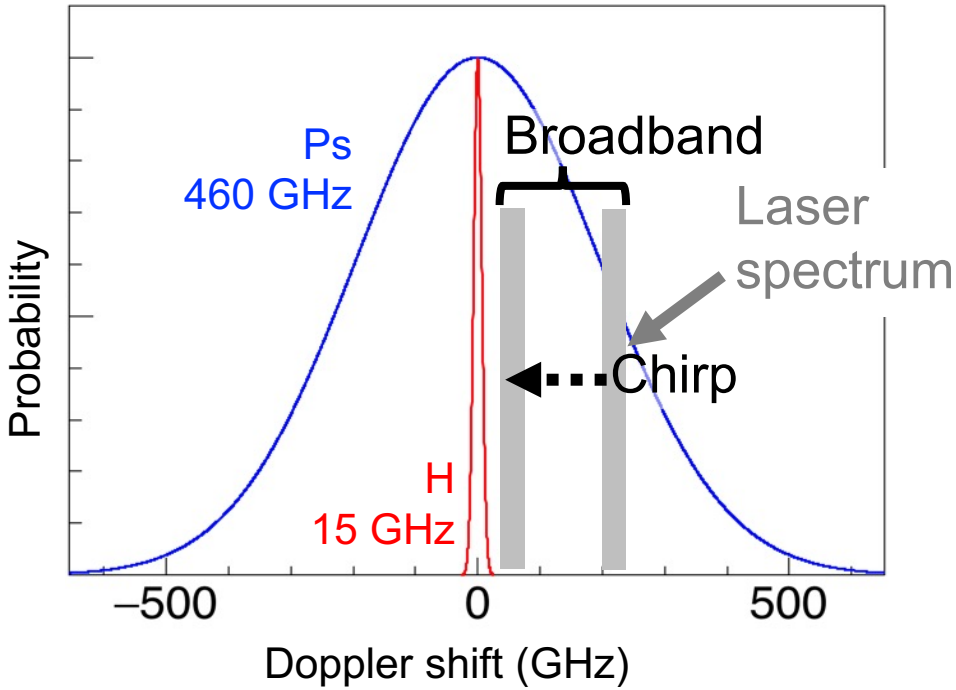
Broad spectral profile is necessary for the cooling laser

The light mass of Ps leads to a large Doppler shift

Laser should be broadband with a chirp follow decreasing Doppler shift by the cooling
Desired chirp rate :

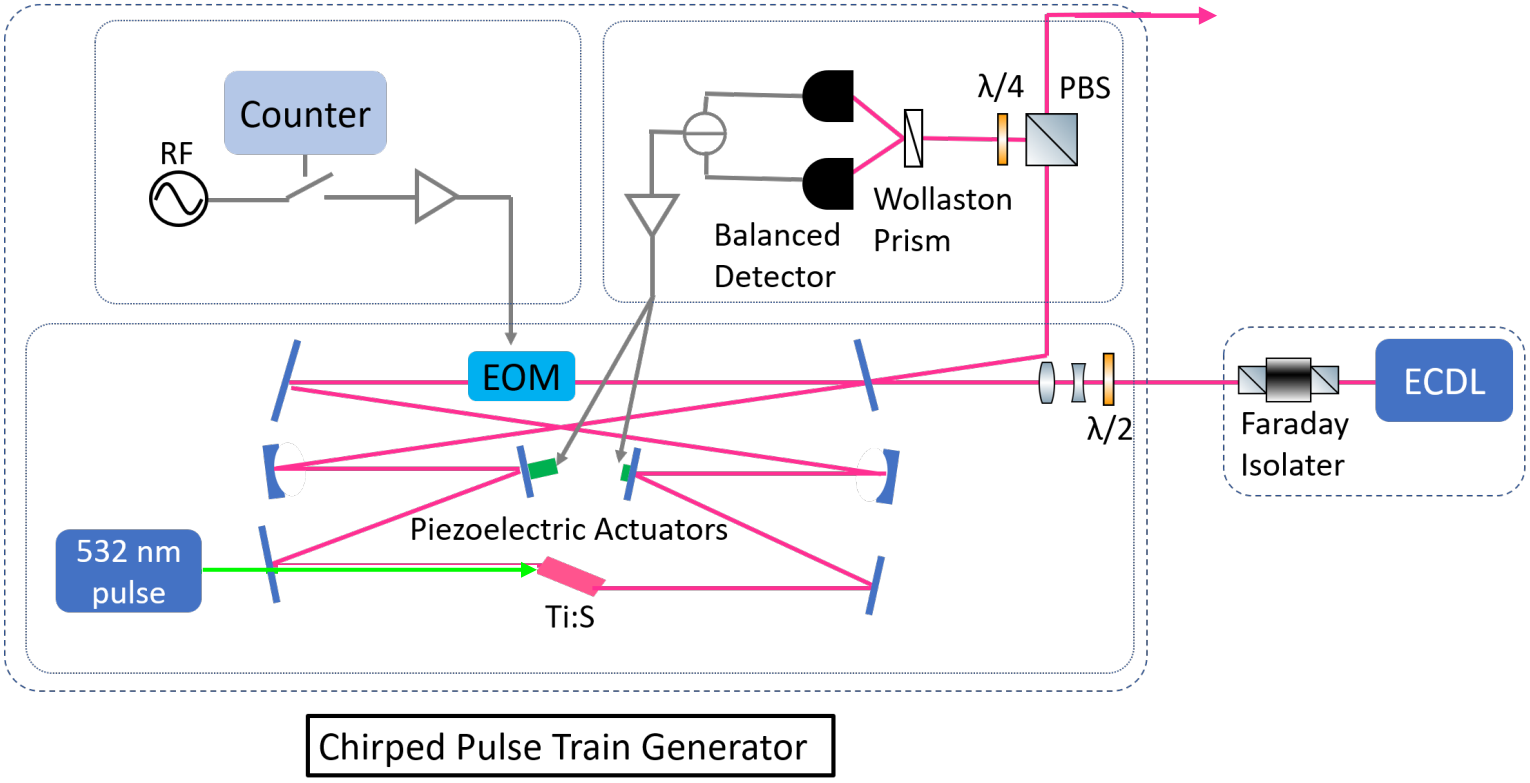
$$1.23\ \mathrm{PHz}/_{2\pi\times 3.2\ \mathrm{ns}} \times\ 1.5\ \mathrm{km\ s^{-1}}/_{c}$$
$$\approx 300\ \mathrm{GHz}\ /\ \mu\mathrm{s}$$

Duration should be long enough (300 ns) to complete the cooling



Doppler profile for atoms in the room temperature

We designed and built a home-made laser to realize Ps cooling



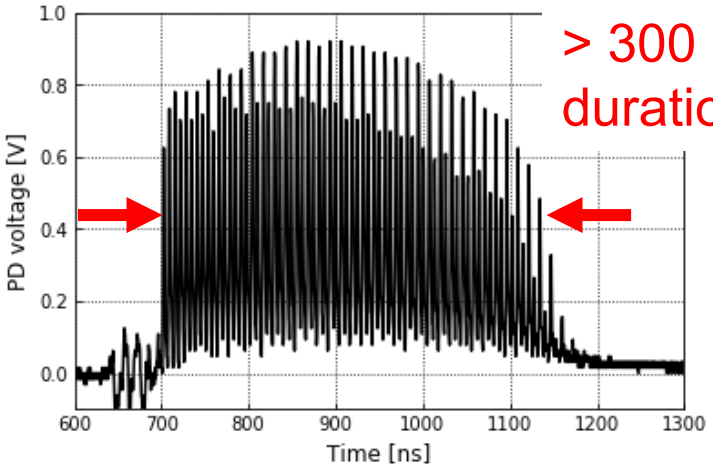
Chirped Pulse Train Generator

Published in K. Yamada *et al.*, Phys. Rev. Applied **16**, 014009 (2021).

We found and demonstrated a rapid chip occurs by modulating pulsed laser inside the cavity

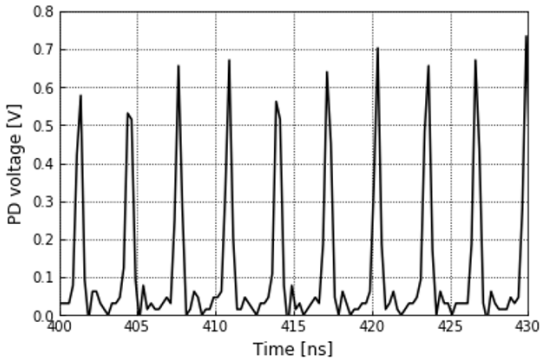
Long duration and broadband were confirmed

Laser properties



> 300 ns duration

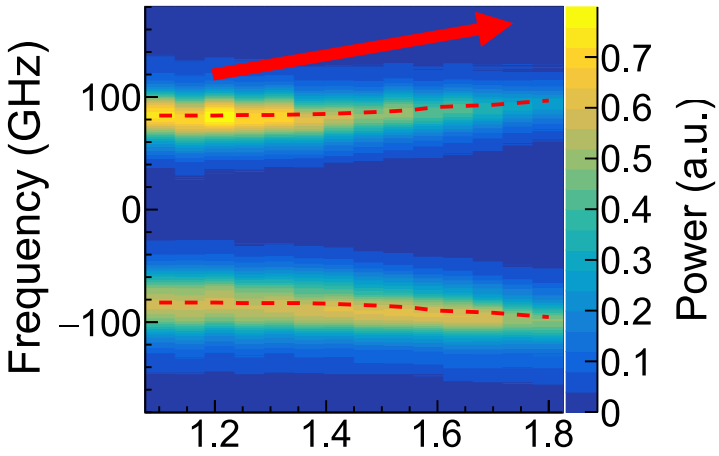
Timing profile



(Enlarged)

Consist of pulse train

45 GHz / μs chirp

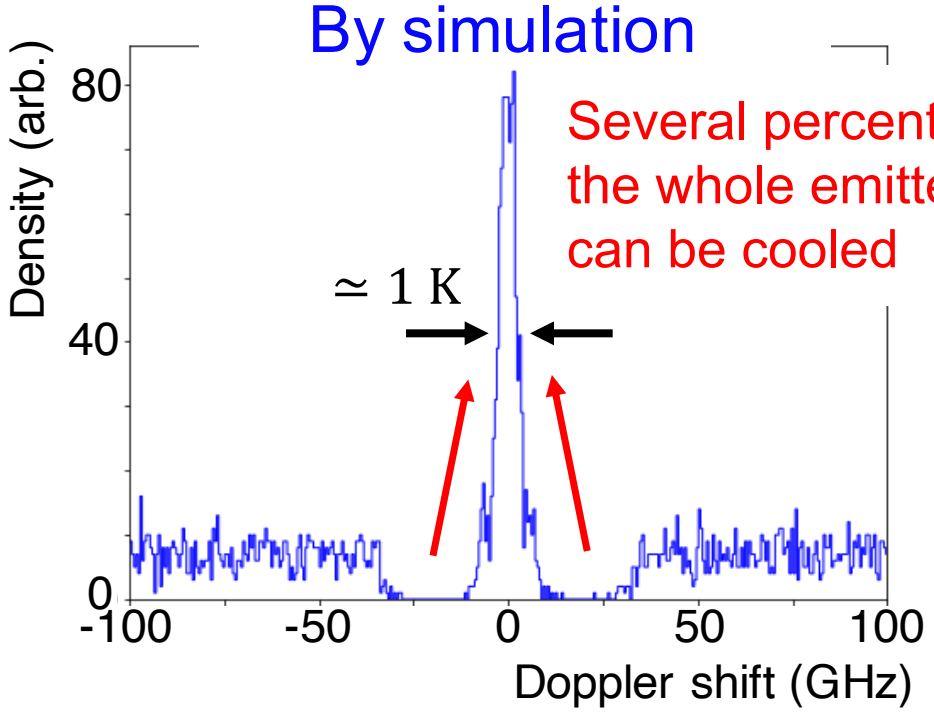


Intensity map of Integrated spectrum

★ Enough duration for Ps cooling

★ Rapid chirp consistent with a theoretical calculation based on the prototypical design of the laser

Demonstration of laser cooling and upgrade for more broadband are ongoing



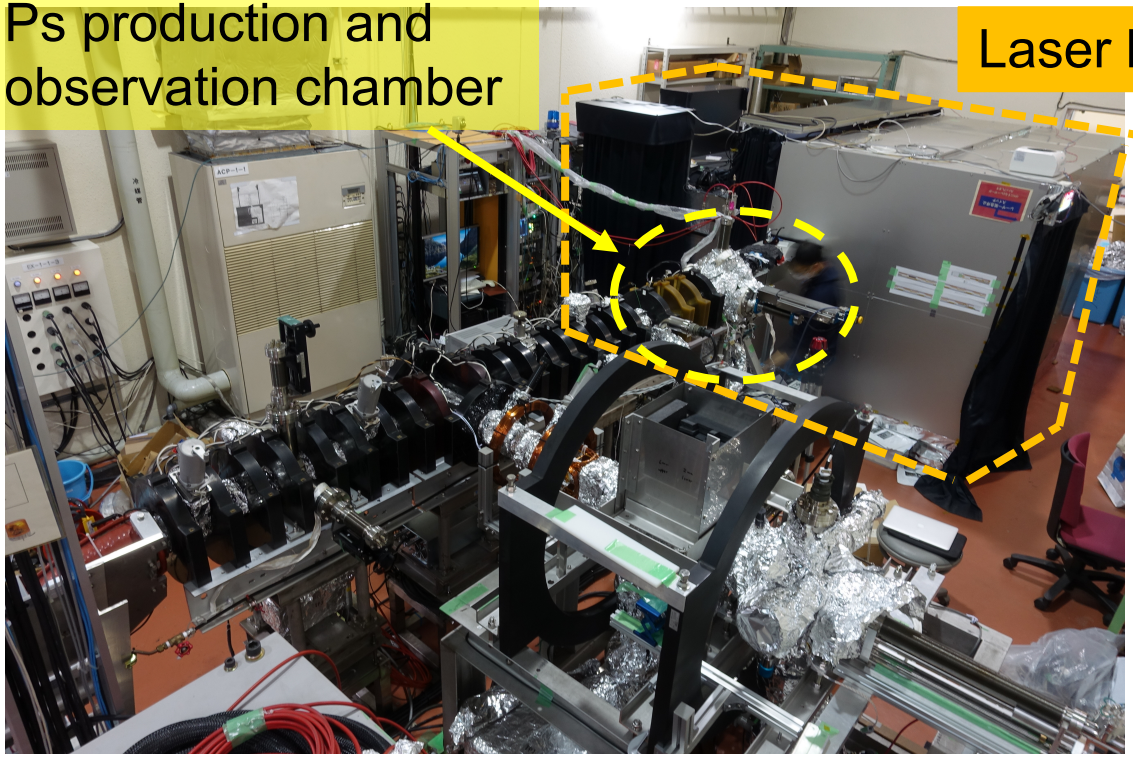
Simulated Doppler shift after laser cooling by the prototypical laser

We are doing experiment to demonstrate laser cooling using the prototypical laser

Cooled fraction is not expected to be so large but assumed to be detectable by Doppler spectroscopy

Upgrade to increase laser bandwidth ~10 times more is also ongoing by replacing the Electro-optical modulator

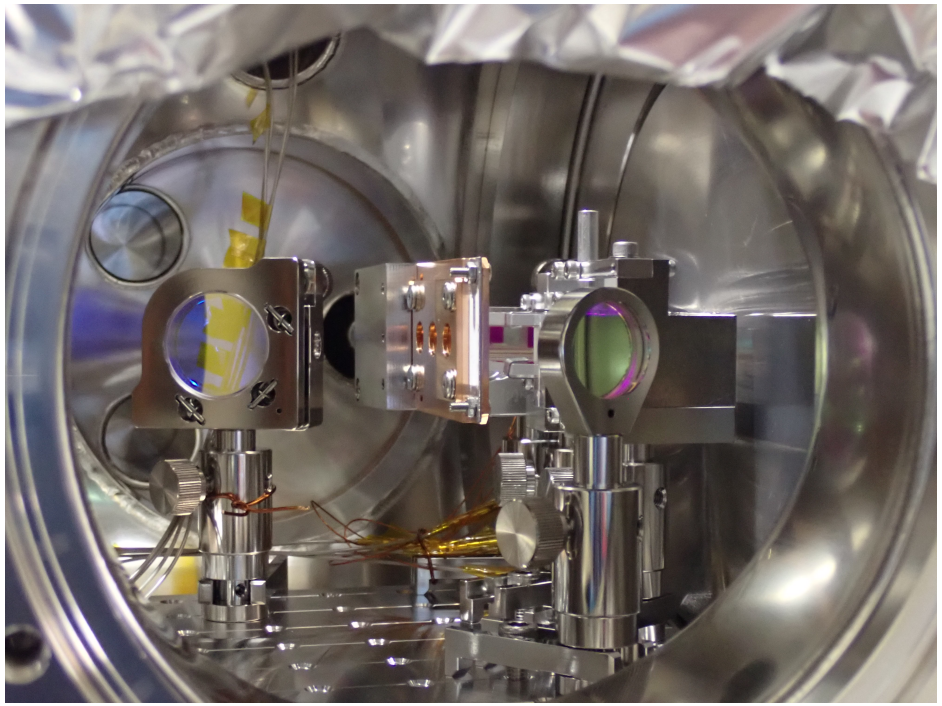
Experiment is conducted at KEK-SPF



Lasers to profile velocity distribution of Ps are also installed

We built a specialized system to demonstrate laser cooling at KEK Slow Positron Facility

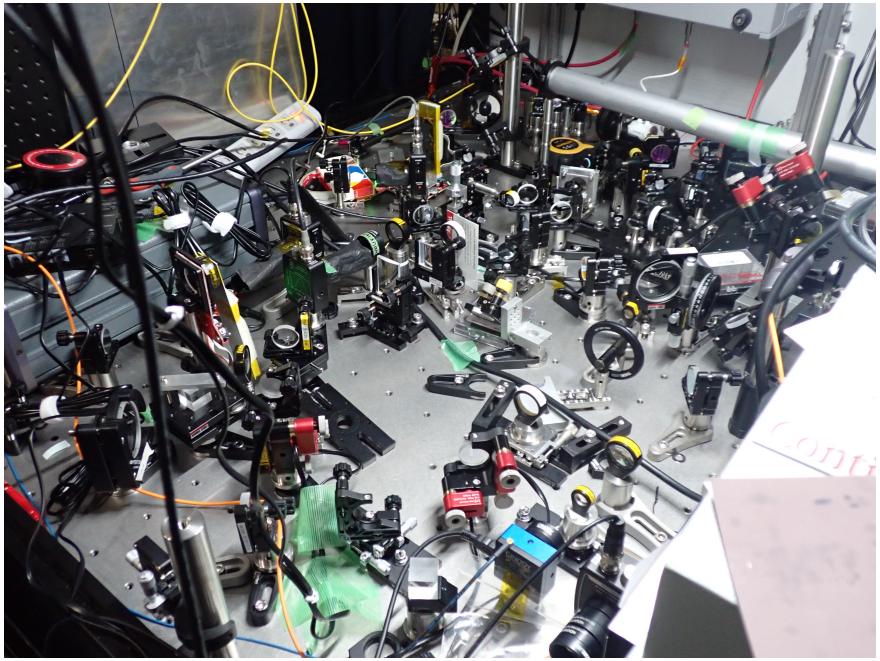
Experiment is conducted at KEK-SPF



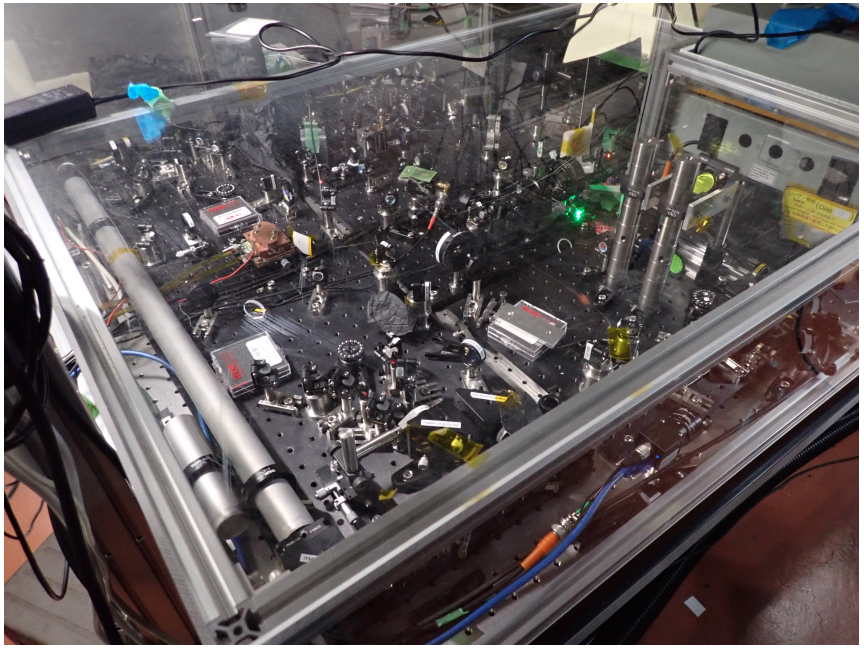
Inside the chamber (from detector side)

Inside the laser booth

Experiment is conducted at KEK-SPF

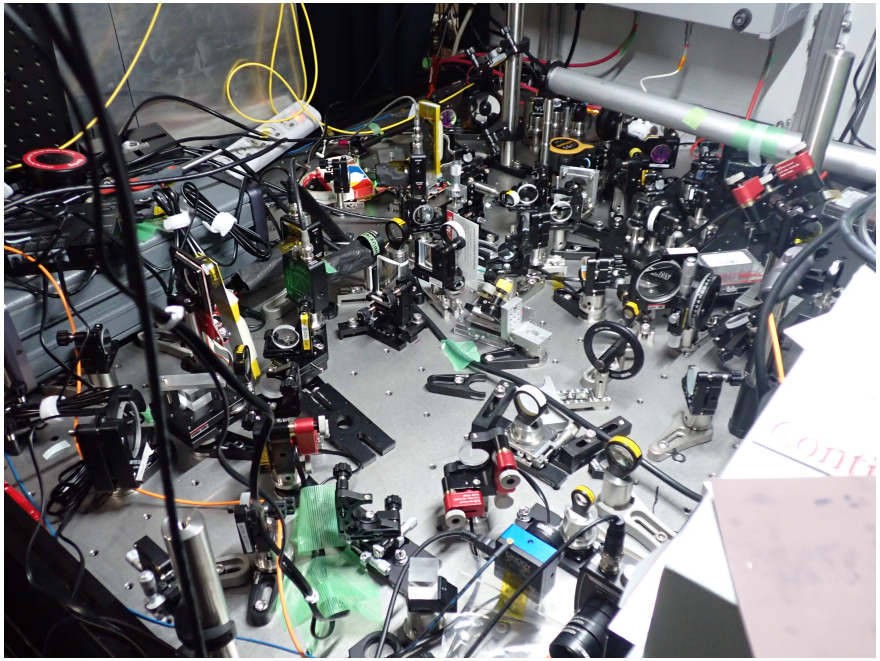


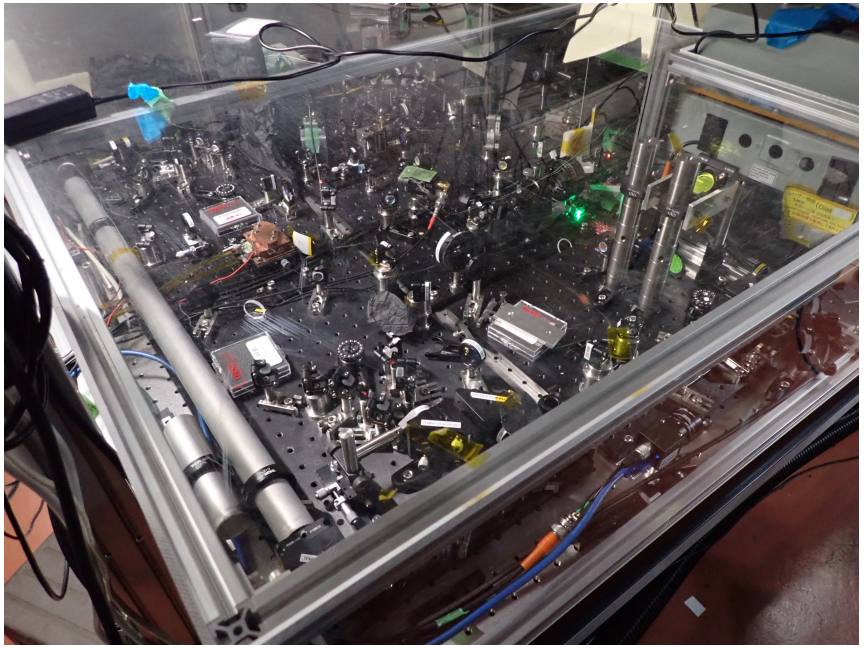
Wavelength-variable laser optics to measure Doppler profile



Cooling laser at KEK-SPF

Experiment is conducted at KEK-SPF





Wavelength-varia… … at KEK-SPF
to measure Dopp…

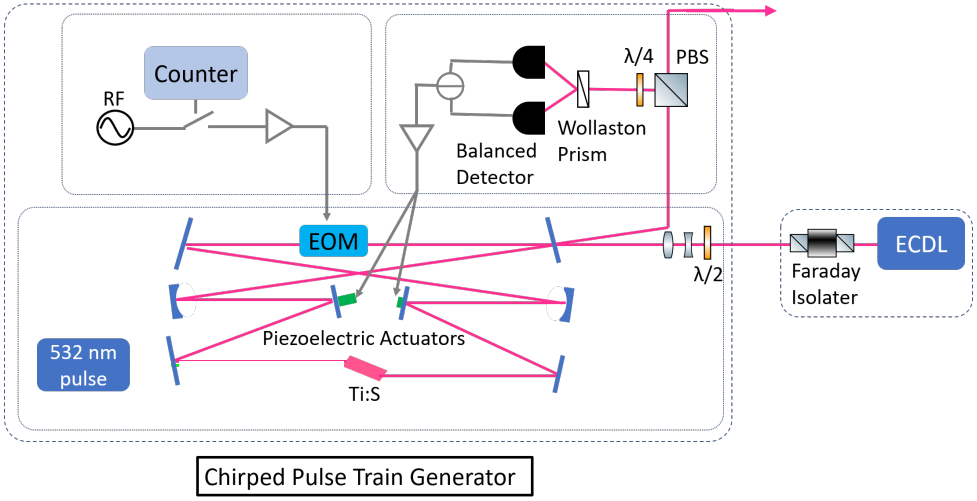
We studied :

- Velocity distribution measurements
- Background effects from irradiating the cooling laser

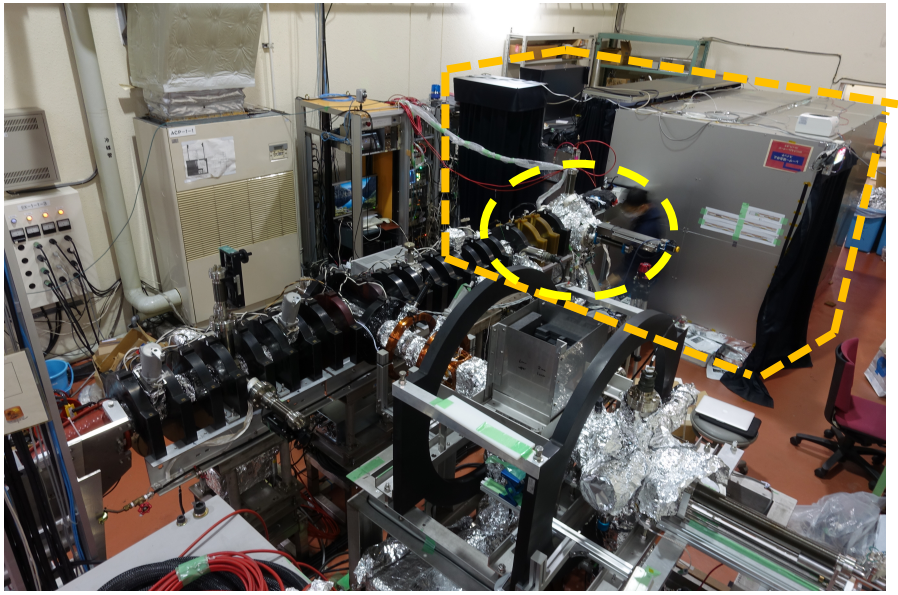
We plan laser cooling will be demonstrated in 2021 FY

Summary

- Ps is a unique system suitable for studying fundamental physics
- Cooling of Ps is a breakthrough for precise spectroscopy and Ps-BEC
- We cool Ps by laser cooling



Built an optimized laser with long duration and broadband by an original configuration



Conduct demonstration experiment at KEK-SPF