Development of cooling laser for positronium Bose-Einstein condensation

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ICEPP The University of Tokyo

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d Global Innovation Center

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f QST

g JAEA

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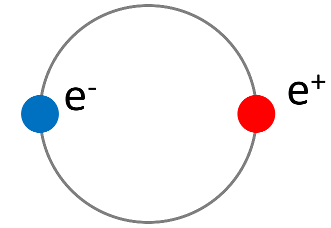
positronium



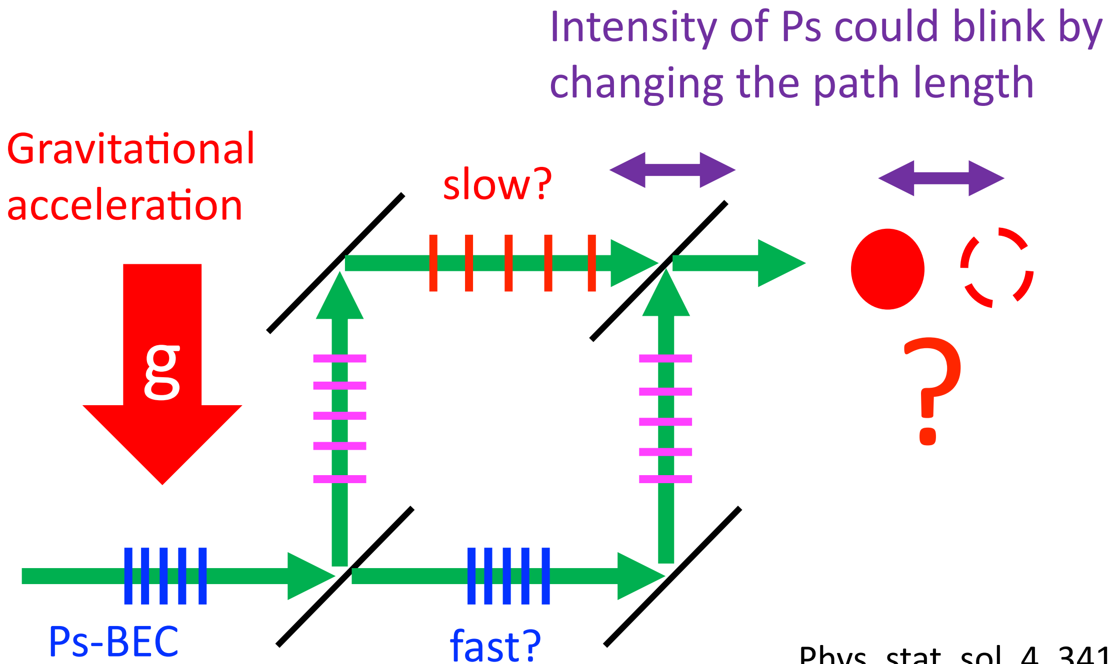
Our Goal:
Realize the first "antimatter laser" and perform a new experiment with antimatter

- Target: Positronium Bose-Einstein Condensation (Ps-BEC)
- Dense and cold atoms form BEC state.
  BEC is "Atomic laser"
- Ps is easy to produce, and its BEC critical temperature is high (14K at 10^{18} cm^{-3})
- Ps is one of the best candidates for the first antimatter BEC

Applications of Ps-BEC

1. Precision test of matter-antimatter symmetry

Build Ps-BEC atomic interferometer to see tiny effect on antimatter: such as gravity

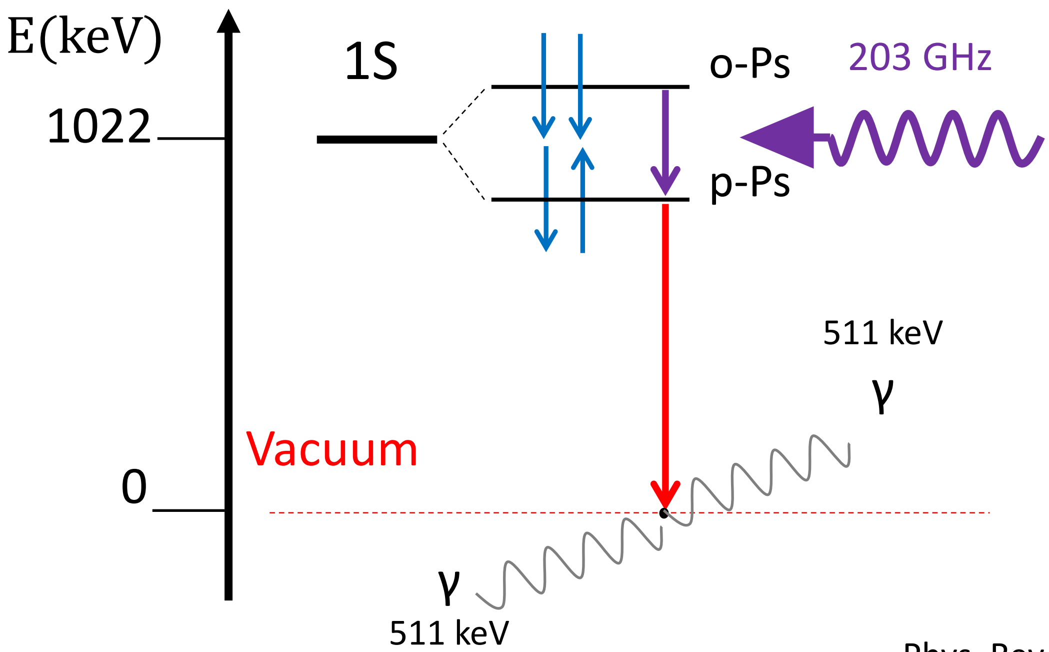


Phys. stat. sol. 4, 3419 (2007)

- Gravity shifts phase of Ps in different paths
- Path length is 20 cm to see gravity effect

Applications of Ps-BEC

2. <u>511 keV γ-ray laser</u>



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
- 10 times finer probe than current X-rays

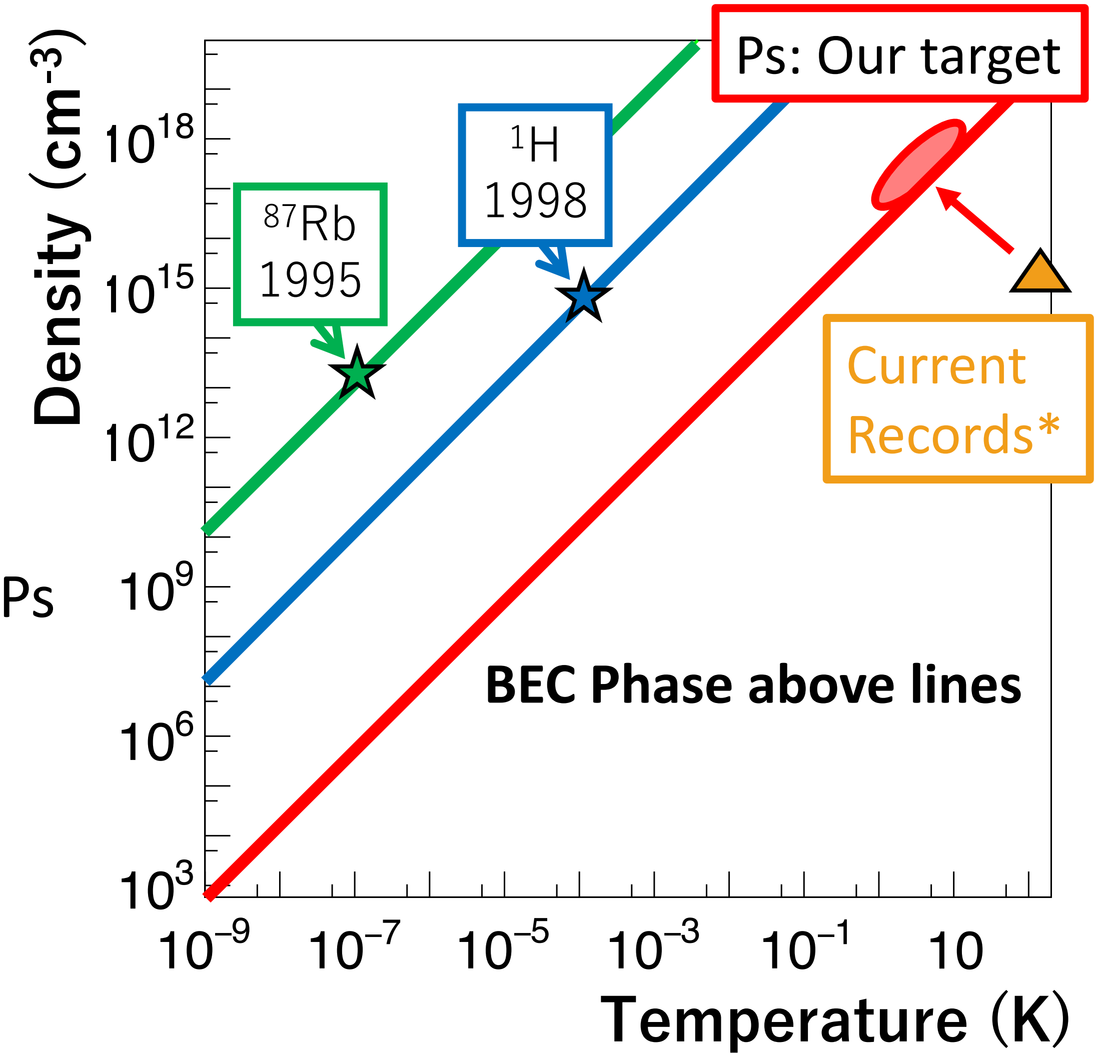
Two challenges to realize Ps-BEC

Main problem

Ps lifetime is only 142 ns

Two challenges

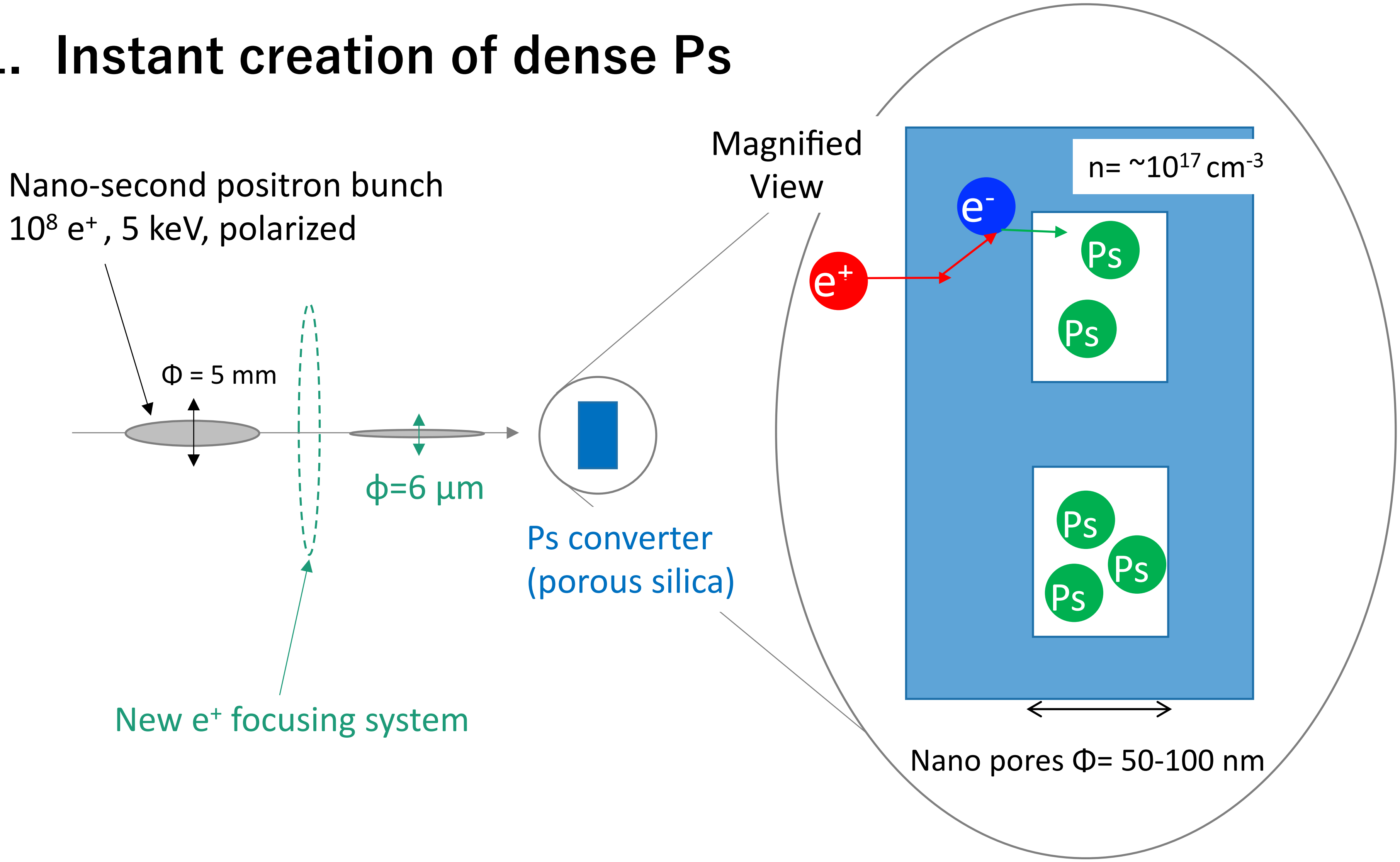
1. Instant creation of dense Ps
   $> 10^{17}$ cm^{-3} in < 50 ns
2. Rapid cooling of Ps
   < 10 K in ~300 ns



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

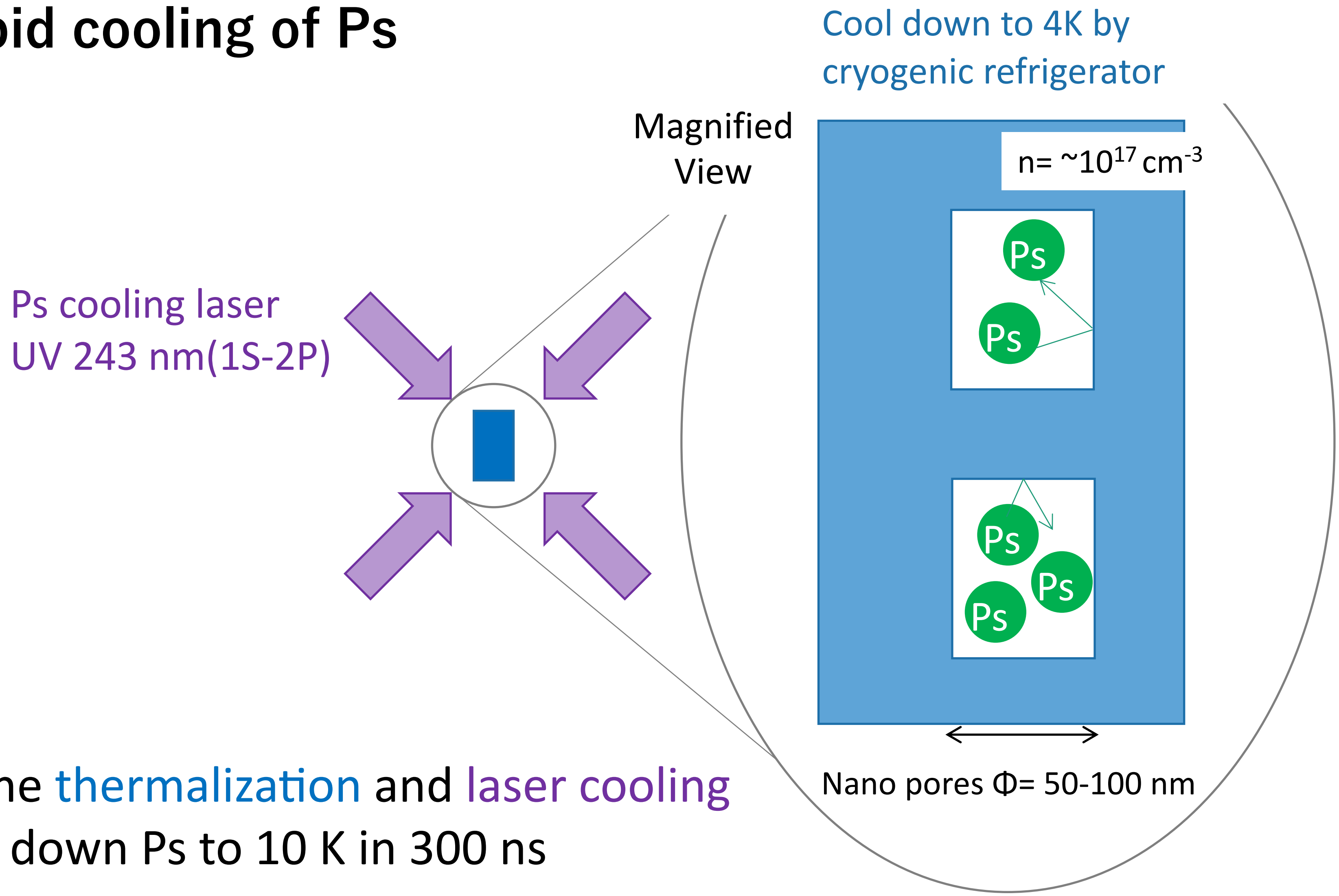
New method to realize Ps-BEC

1. Instant creation of dense Ps



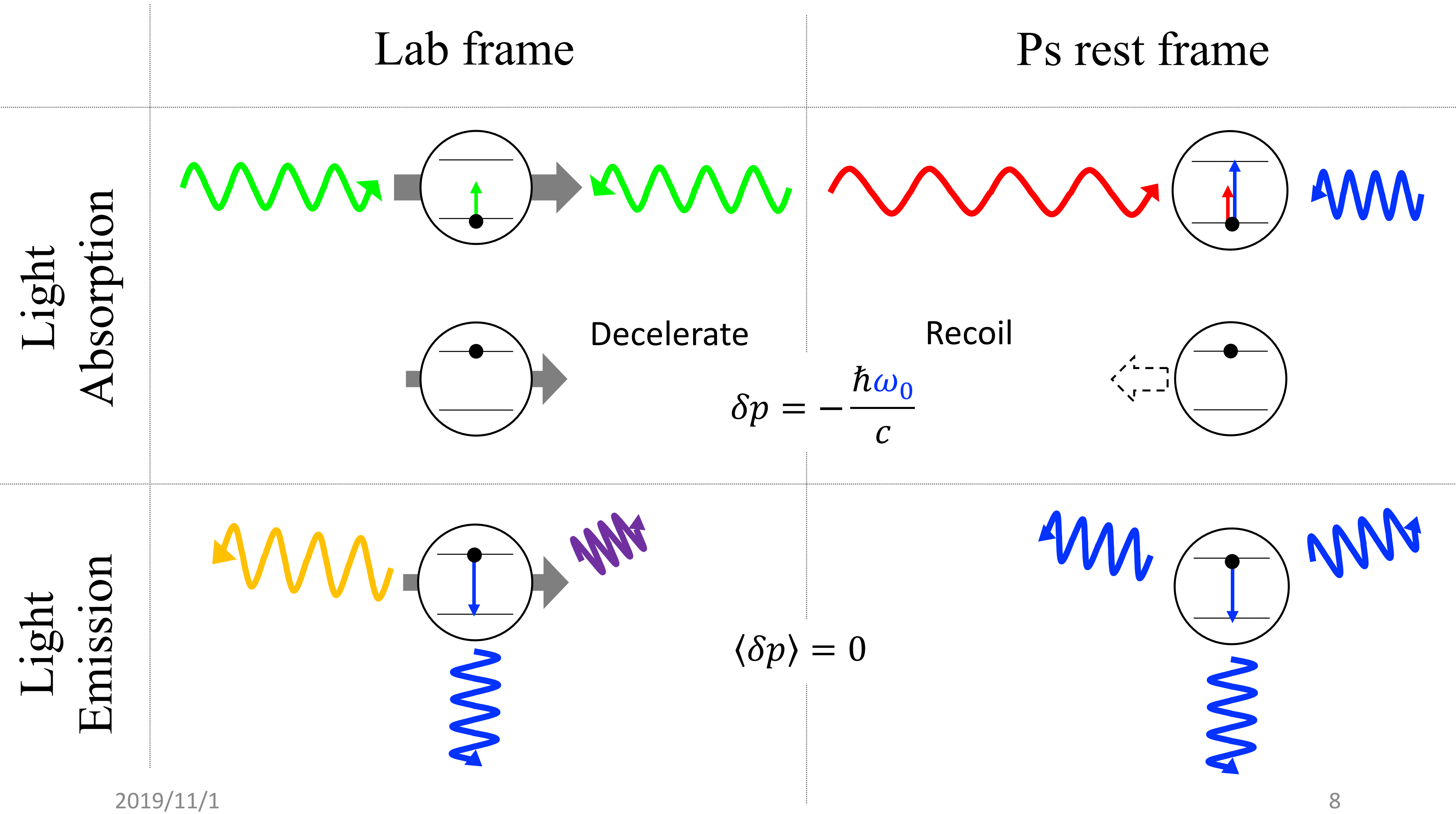
New method to realize Ps-BEC

2. Rapid cooling of Ps



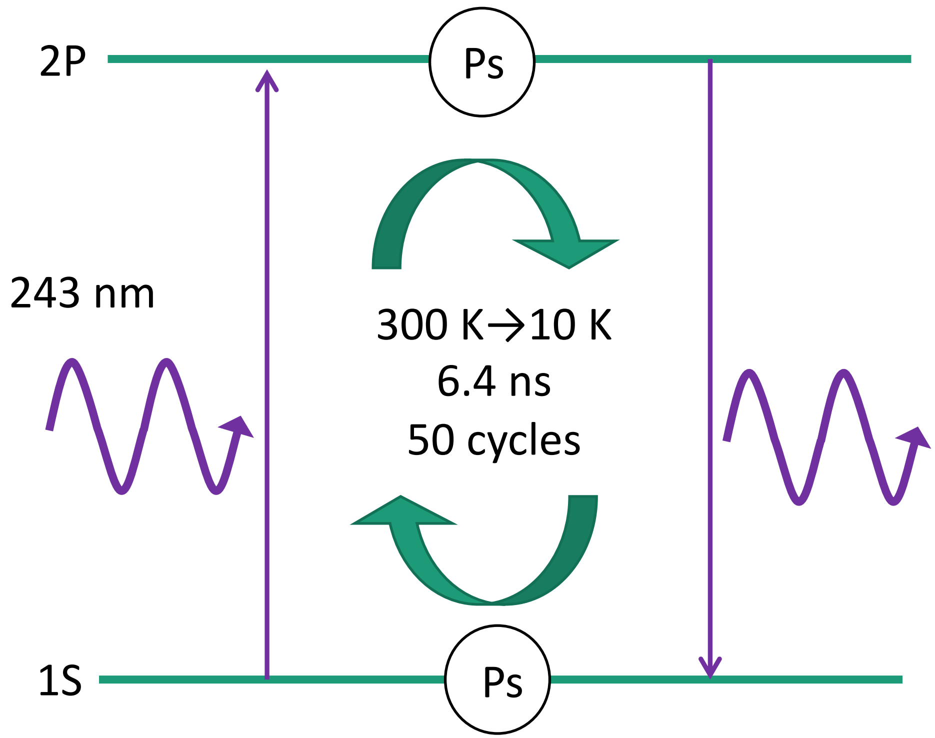
Combine thermalization and laser cooling
to cool down Ps to 10 K in 300 ns

Principle of Laser Cooling
(Doppler cooling)



Two Requirements for Ps Laser Cooling

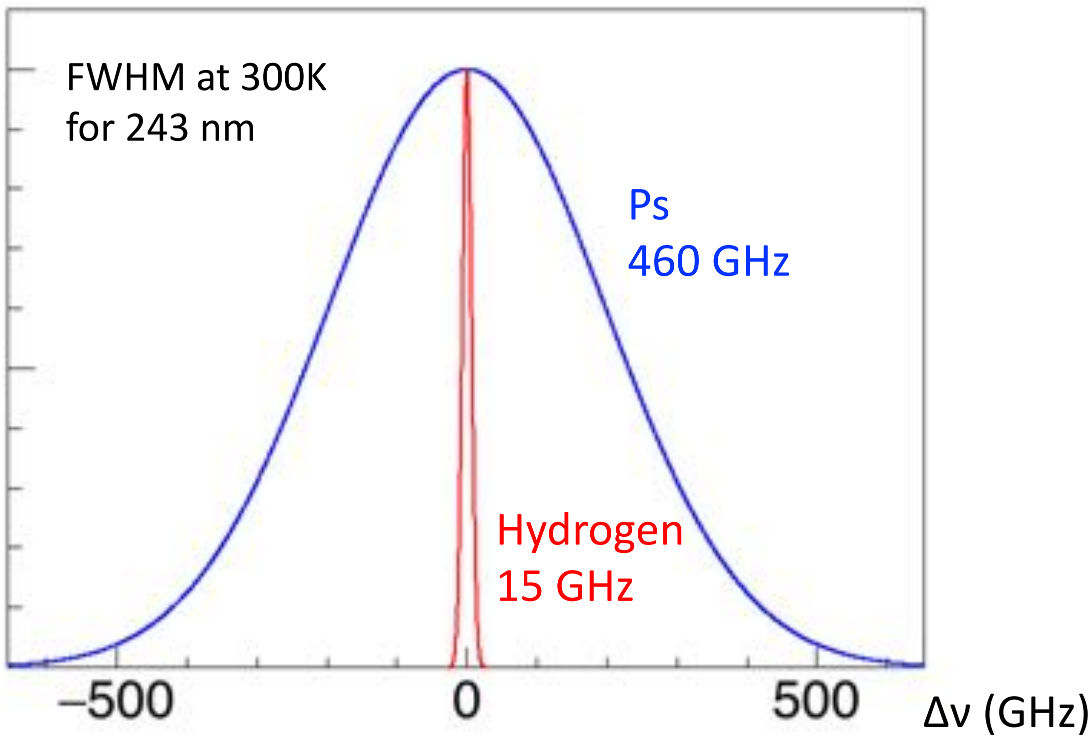
1. Long-pulsed laser



- 6.4 ns × 50 ~ 300 ns
- Complete the laser cooling within a single 300 ns long pulse (~ Ps lifetime 142 ns)

Two Requirements for Ps Laser Cooling

<u>2.Broadband laser</u> ∵ Ps light mass: $2m_e$



- Doppler broadening is 30 times larger than Hydrogen
- Broadband (150 GHz) laser is necessary to cool down all the Ps

How to realize the Ps cooling laser

Laser system which fulfills the 2 requirements
is commercially unavailable
We are building a cooling laser system ourselves

UV laser (243 nm 1S - 2P) is not easy to handle.

- Many of the materials absorbs UV light.
- Laser technologies are well developed in visible light region.

729 nm laser
①long-pulsed (500 ns)
②broadband (50 GHz)
③high-energy (5 mJ)

Wavelength transformation
$\lambda \times \frac{1}{3}$ by crystal

Cooling Laser : 243 nm
①long-pulsed (300 ns)
②broadband (150 GHz)

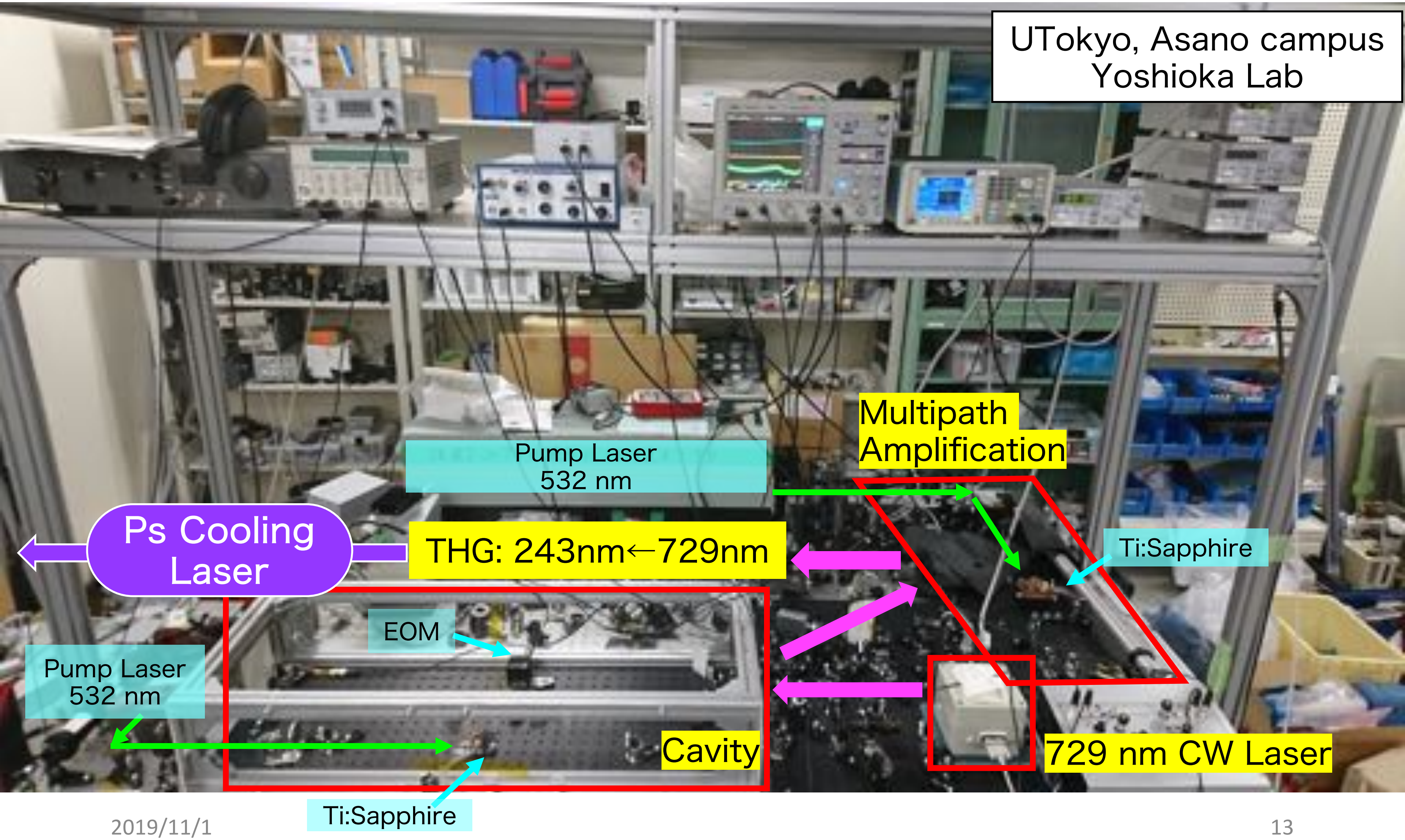
Overview of the cooling laser system

Compact system (2.0 m×1.1 m) will be moved to KEK-SPF (Slow e+ Facility)

UTokyo, Asano campus
Yoshioka Lab

Overview of the cooling laser system

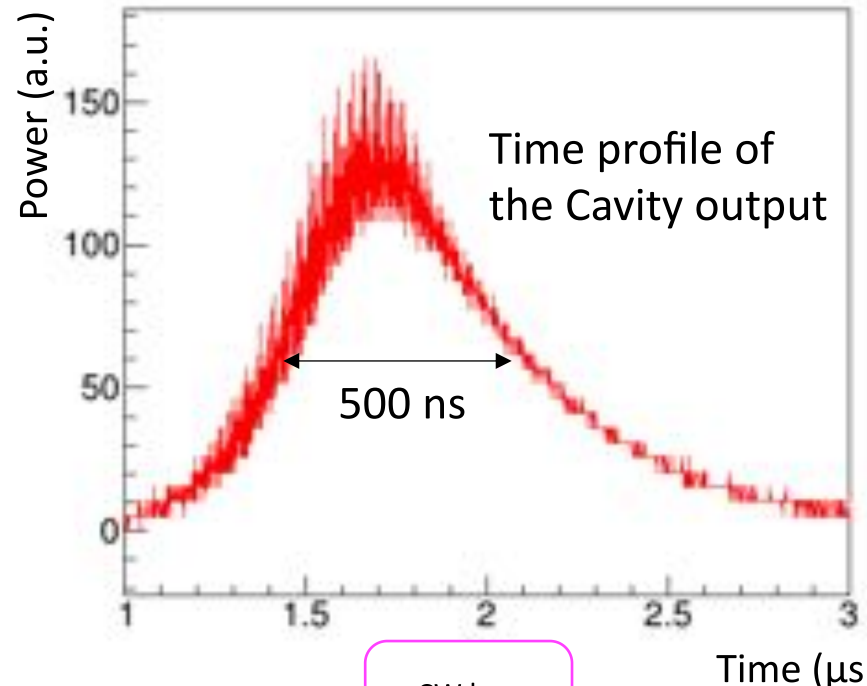
Compact system (2.0 m×1.1 m) will be moved to KEK-SPF (Slow e+ Facility)

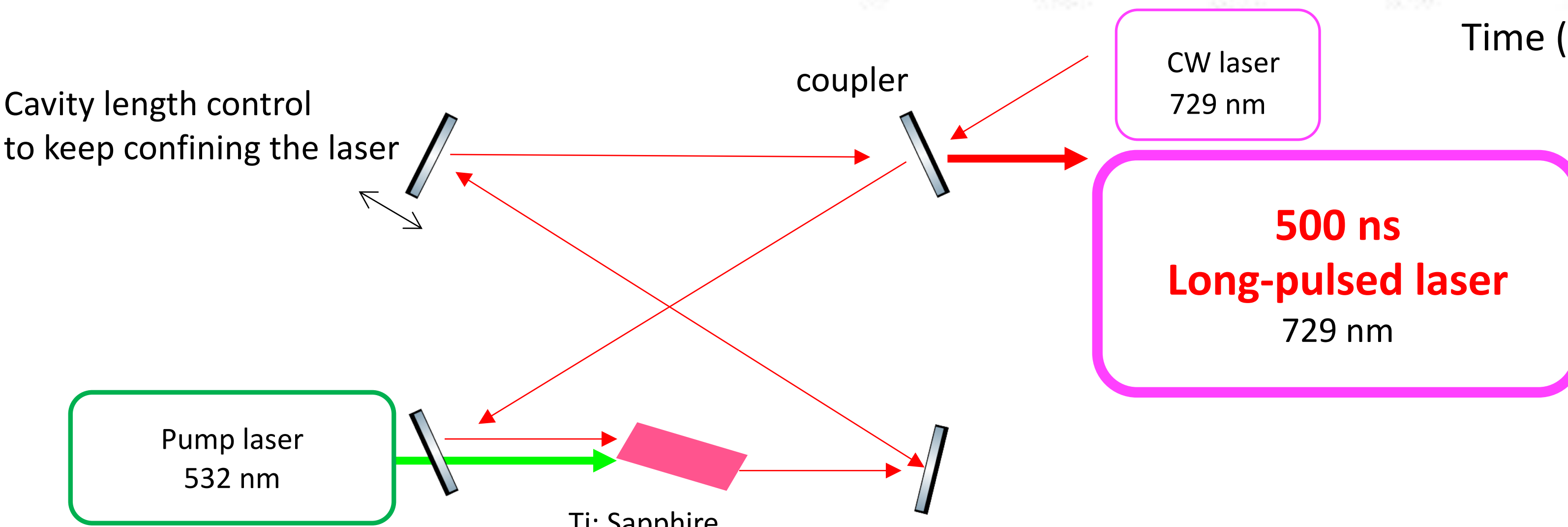


Realization of ①500 ns long-pulsed laser

Ti:Sapphire Optical Cavity

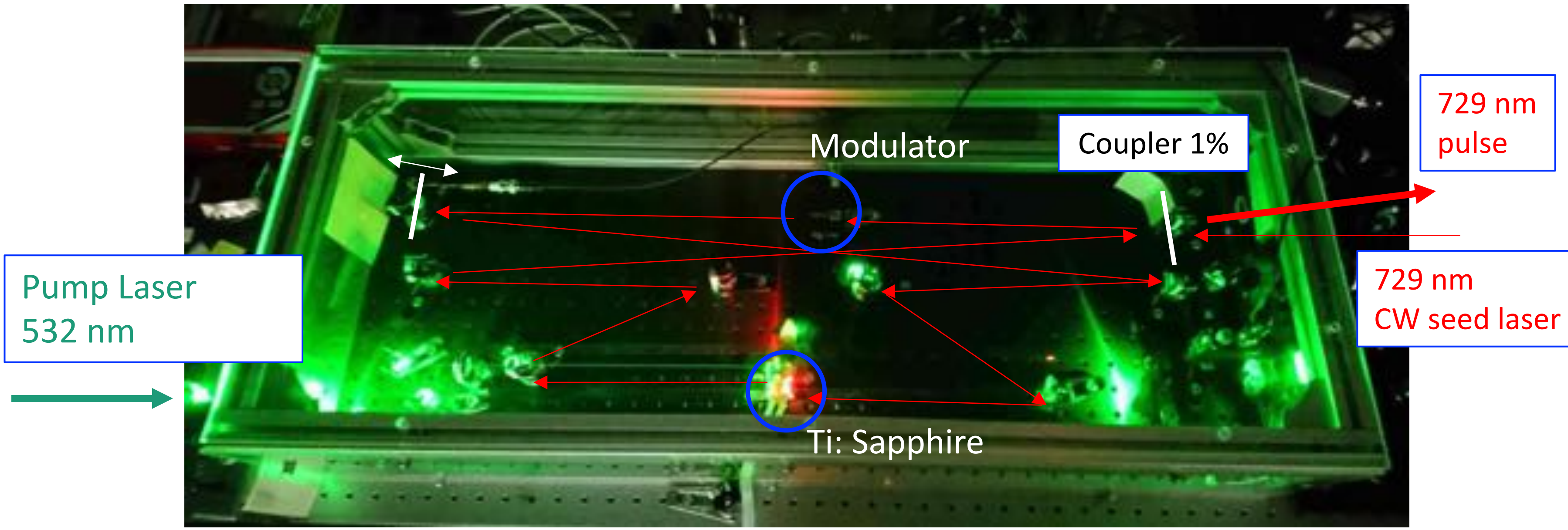
Confine the seed-laser inside the long-lifetime cavity





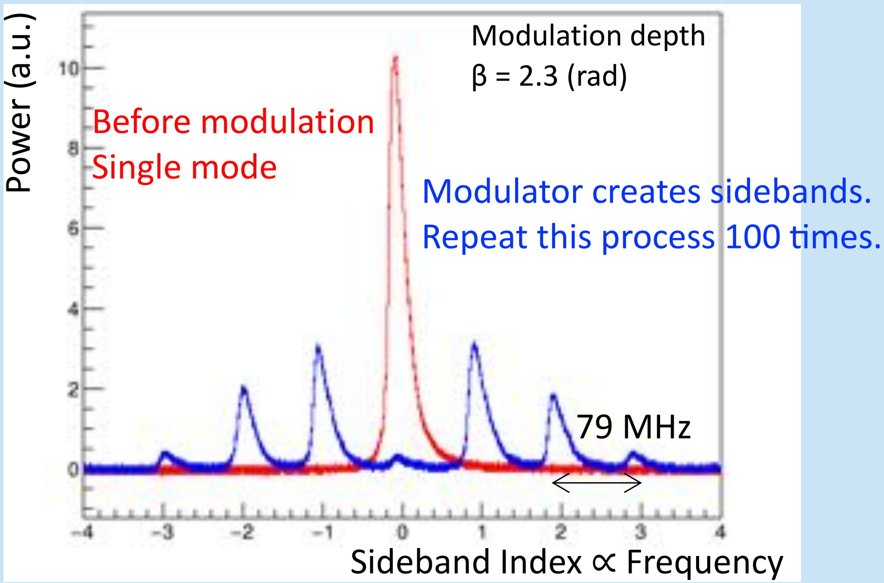
Long-lifetime cavity

A core of the cooling laser system

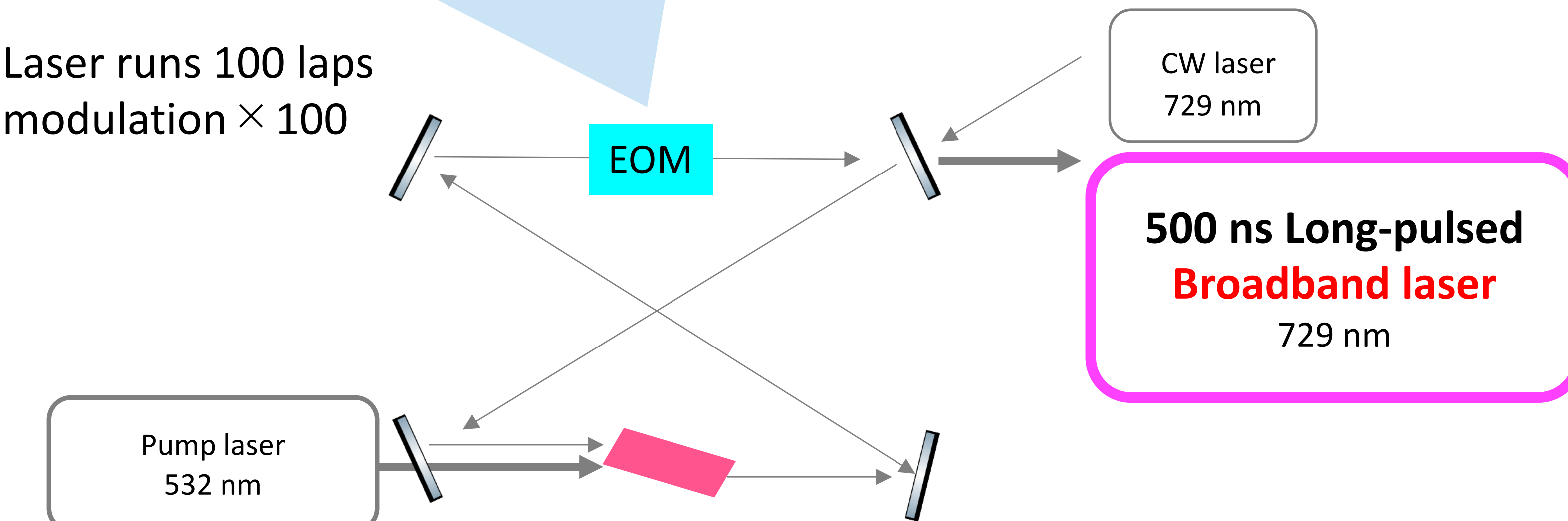


1. Long cavity (3.8 m) Folded with 8 mirrors (96 × 36 cm^2)
2. High reflectivity (laser runs ~ 100 laps inside the cavity)

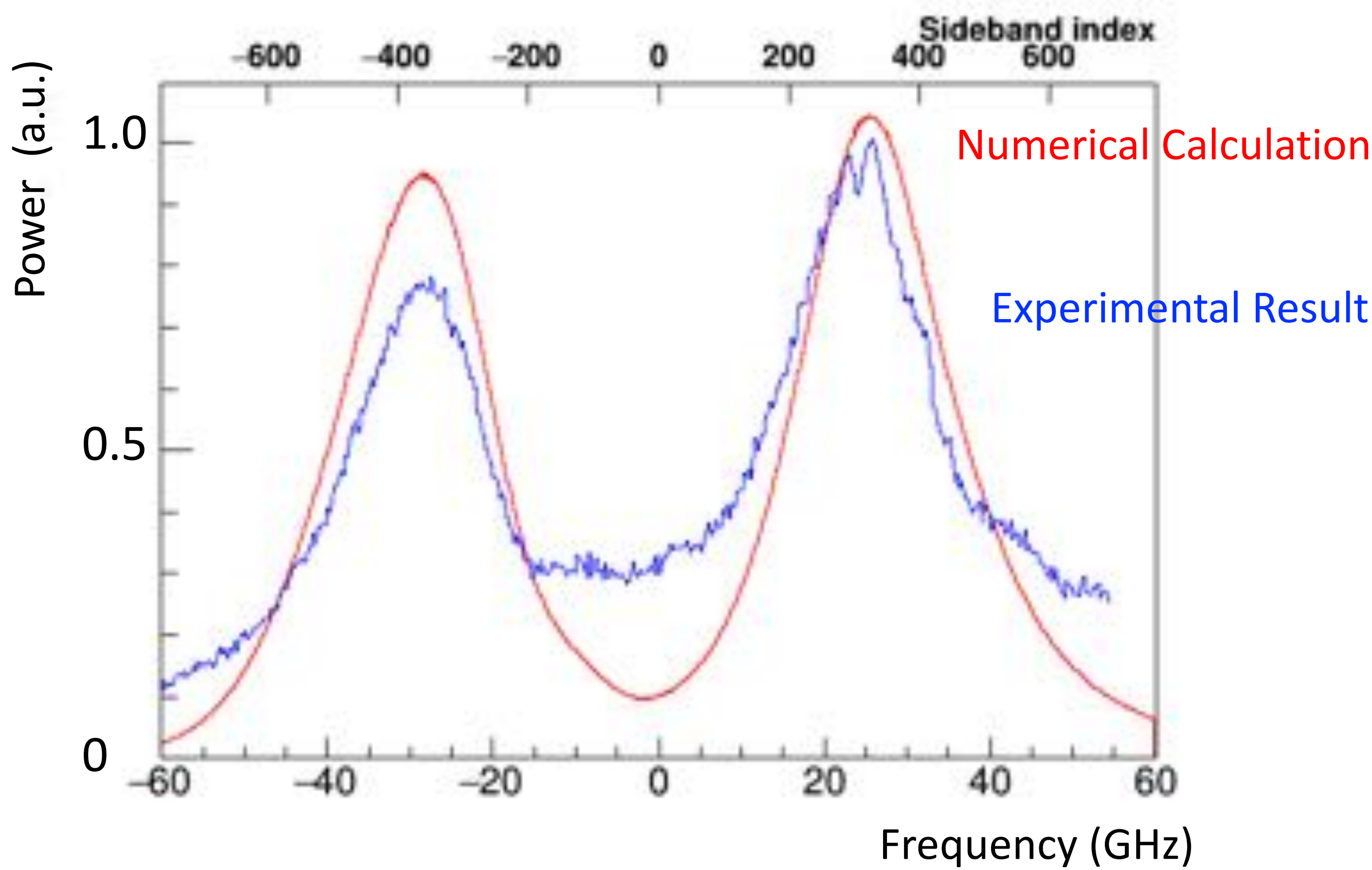
Realization of ②50 GHz broadband laser



Spectral broadening by optical modulator in cavity



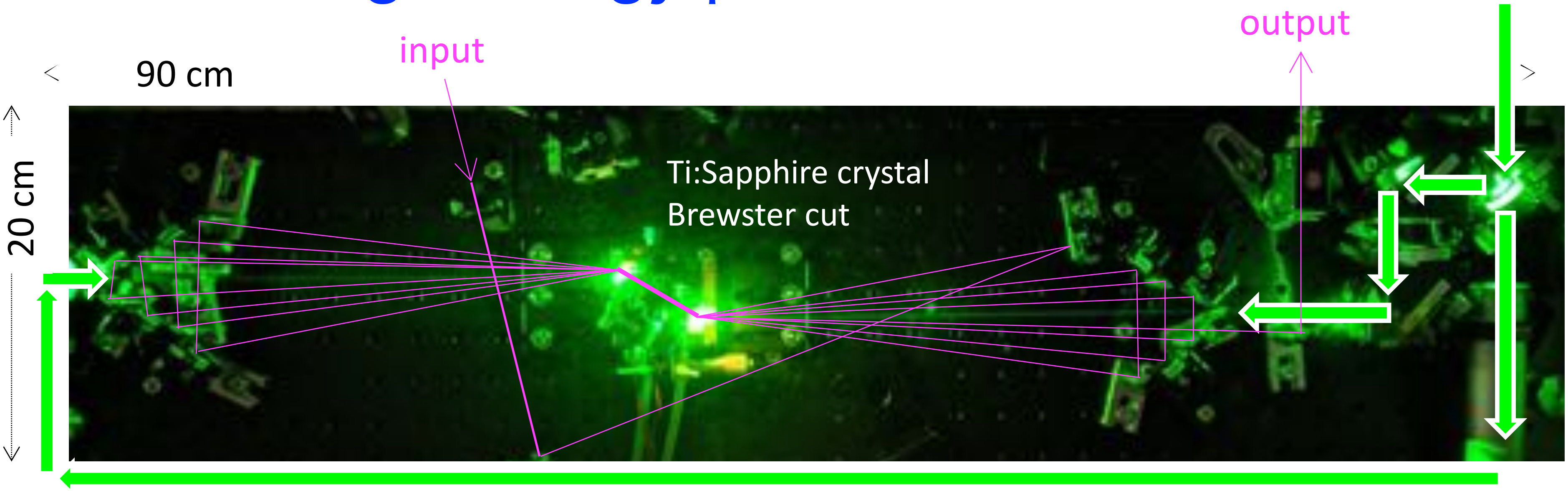
Spectral broadening by modulator in optical cavity was observed



- Generated sidebands up to over 300th orders.
- Experiment and numerical calculation show reasonable match.

Multipath Ti:Sapphire Amplification

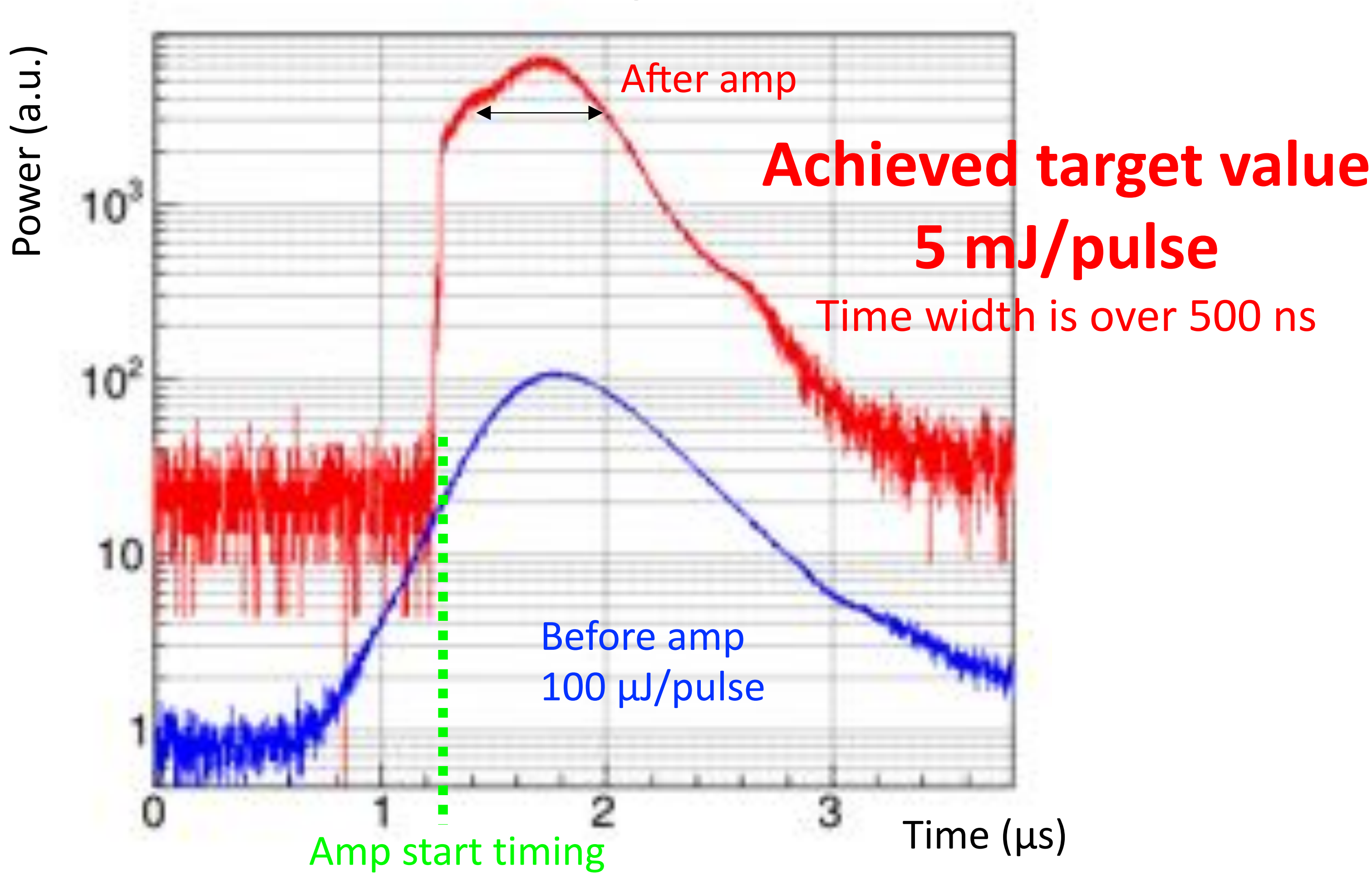
③ 5 mJ high energy pulse



Pump Ti:Sapphire crystal by pump laser(220 mJ, 532 nm, 5 ns, 10Hz, Nd:YAG SHG)
Amplify the 729 nm pulse 8 times by stimulated emission

Split pump laser and pump from 2 ways to reduce pump laser damage on Ti:S crystal

Achieved enough energy to realize 243nm 40 uJ cooling laser



Time Profile is modulated at modulation frequency (79 MHz).
This modulation corresponds to the sidebands in the frequency domain.

Development of Ps cooling laser is almost done
The final step is wavelength transformation

		Required value	Achieved value
Seed laser		power 10 mW linewidth < 1 GHz frequency drift < 1 GHz	20 mW <50 kHz <0.8 GHz
cavity	pulse	Time width >500 ns Pulse energy 100 μJ	500 ns 100 μJ
	broadening	linewidth 50 GHz	~ 50 GHz
Pulse amplification		Pulse energy 5 mJ	5.7 mJ
Wavelength transformation		365 nm 500 μJ 243 nm 40 μJ	365 nm 600 μJ 243 nm -------

Summary

- Ps-BEC is the best candidate for the first antimatter BEC.
- Three technologies to realize Ps-BEC.

1. Ps cooling laser: Rapidly cool Ps
2. Many-stage brightness enhancement system: Create dense e^+
3. $e^+ \rightarrow$ Ps converter: Produce, trap, cool and condense Ps

- Original Ps cooling laser is under development.
- 729 nm, high energy, long-pulsed and broadband laser is achieved. Ps cooling laser is almost ready. The final step is the wavelength transformation (729 nm → 243 nm).
- We are going to perform a Ps laser cooling experiment at KEK slow positron facility (SPF) hopefully by April 2020.