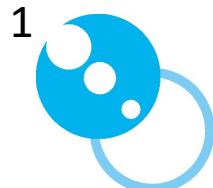


Development of a High-Resolution Probing Laser Suited for Cold Positronium Spectroscopy

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グローバルイノベーションセンター



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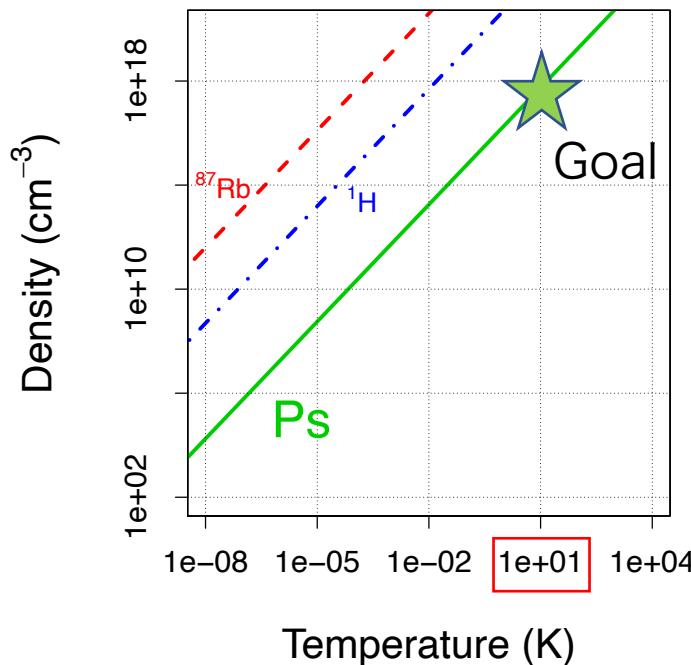
6
JAEA



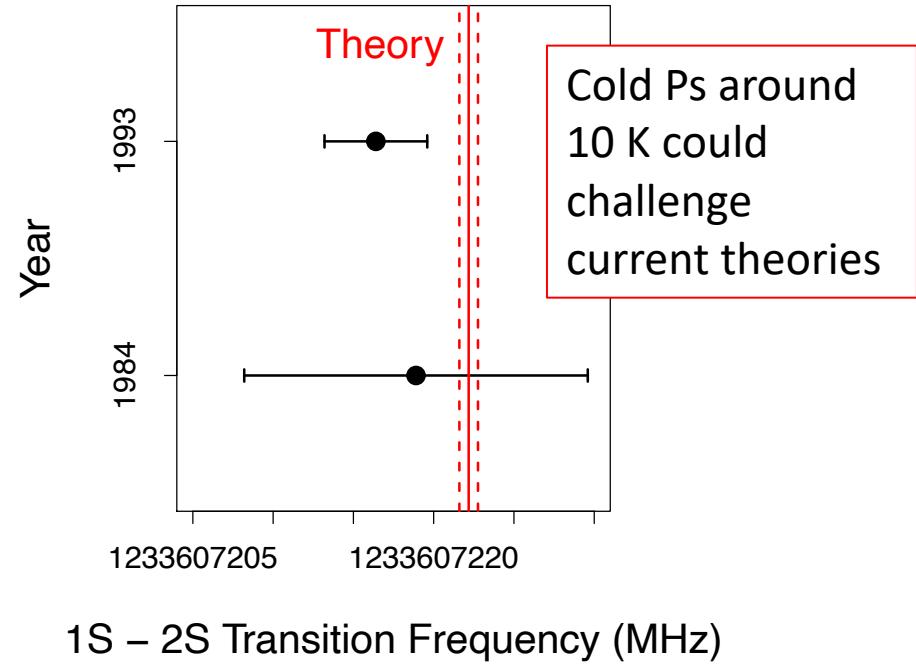
7
KOREA
UNIVERSITY

Significance of Cold Ps

Realization of
the first Bose-Einstein Condensation
by an antimatter containing atom



Precision spectroscopy of
transition frequencies



Realizing cold Ps around 10 K is of great importance

Temperature Measurement Methods of Cold Ps needs to be Established

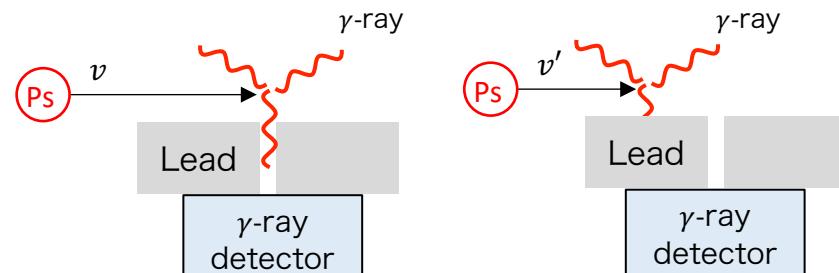
Typical Temperature measurement methods

- Time-of-flight (TOF)

Ps mean velocity:

1.4×10^4 m/s @ 10 K

2.0×10^4 m/s @ 20 K



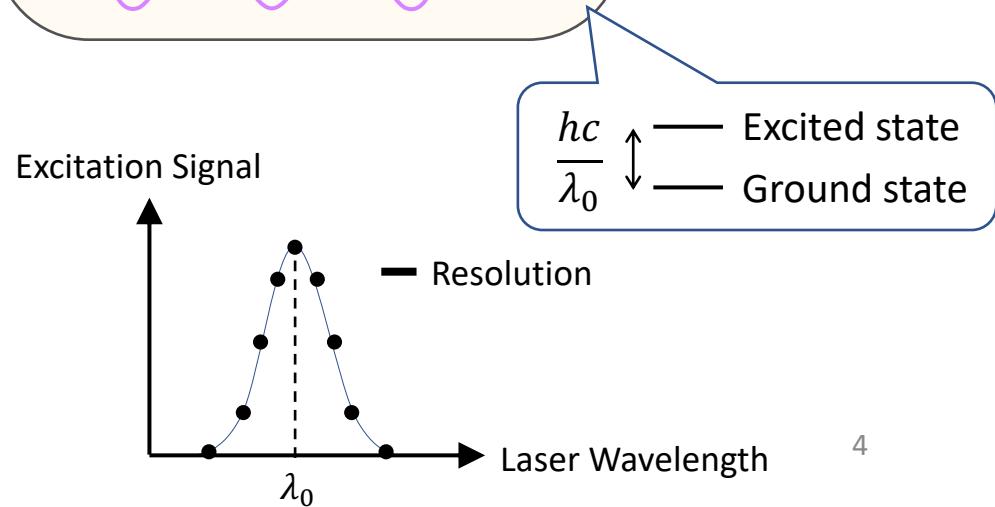
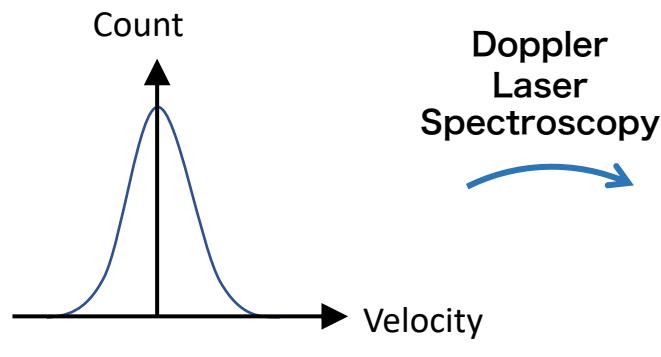
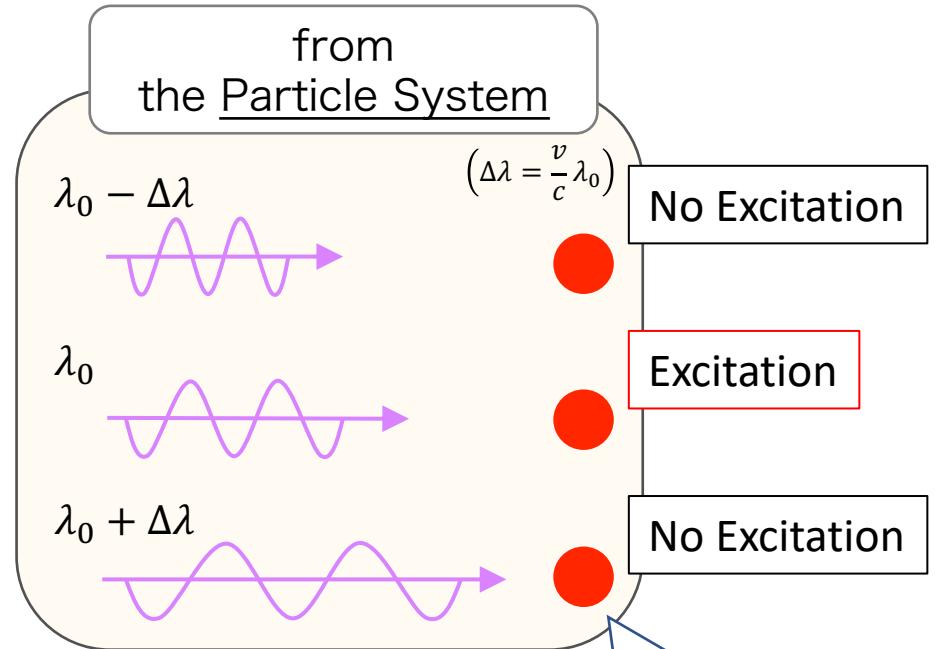
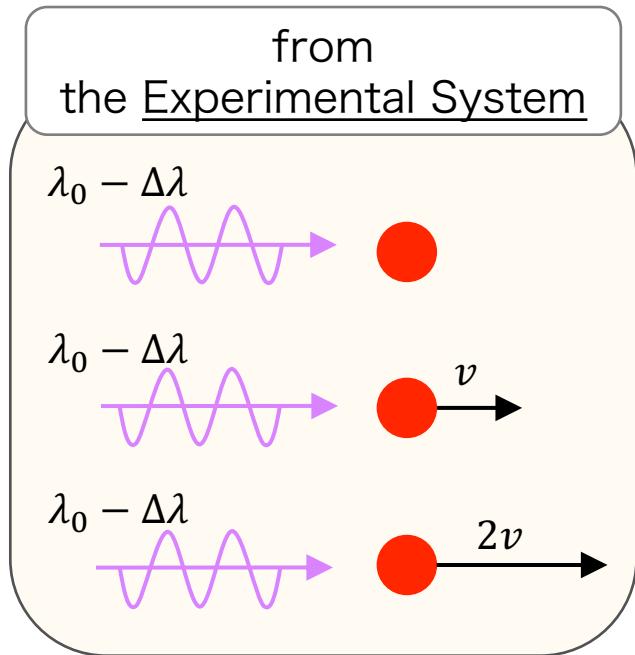
Spatial difference of 5 mm after flight of 800 ns

α -Ps decay time: 142 ns

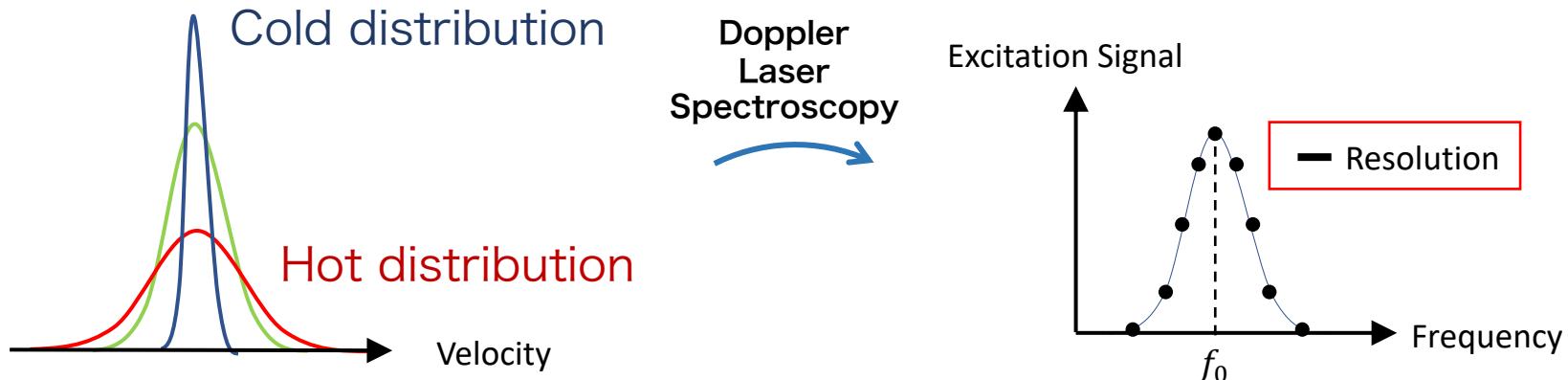
- Doppler broadening spectroscopy (DBS)
- Angular Correlation of Annihilation Radiation (ACAR)
- Laser Spectroscopy

Laser spectroscopy could be a suited method
for cold Ps temperature measurement

Concept of Doppler Laser Spectroscopy



Resolution (given by Laser Linewidth) will be Tunable

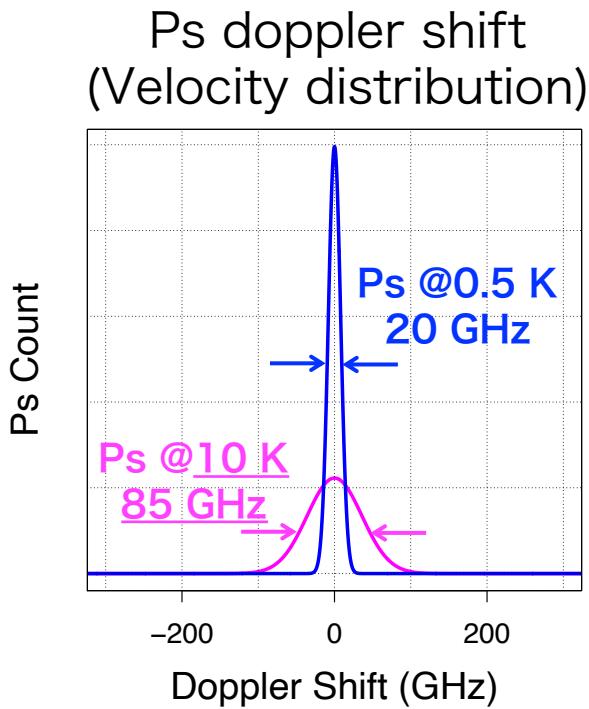


Resolution is determined by the linewidth of the probing laser (=how monochromatic the laser is)

With the laser technology of today, linewidth could be adjusted to a desired

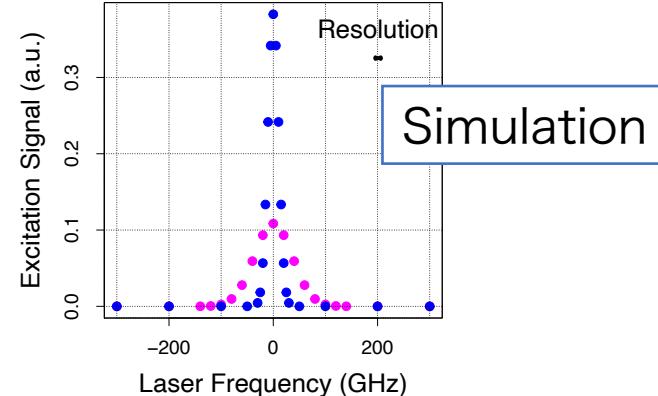
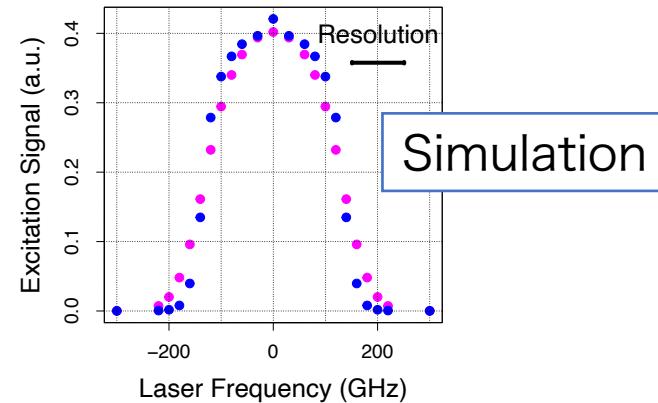
Laser spectroscopy by a laser with an optimized linewidth could suit temperature measurement of cold Ps

How Narrow should the Linewidth be?



Typical available laser^{*1}
Linewidth: **100 GHz**

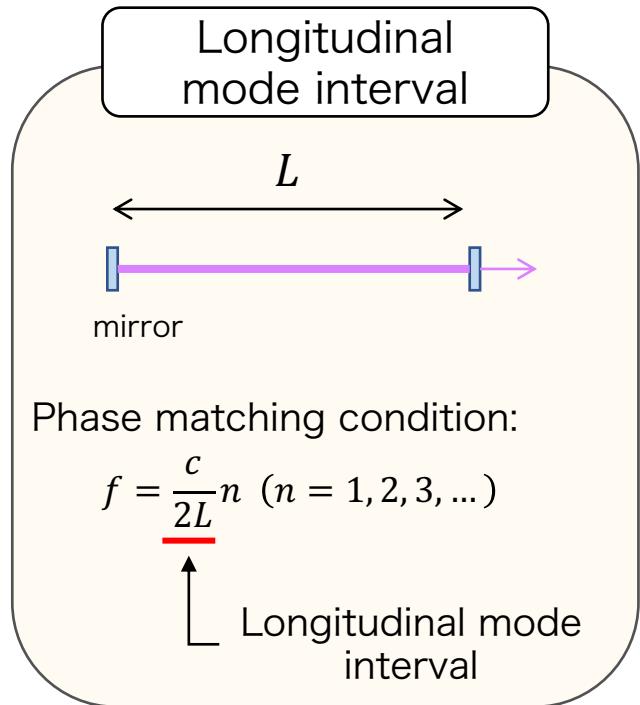
New laser
Linewidth: **10 GHz**



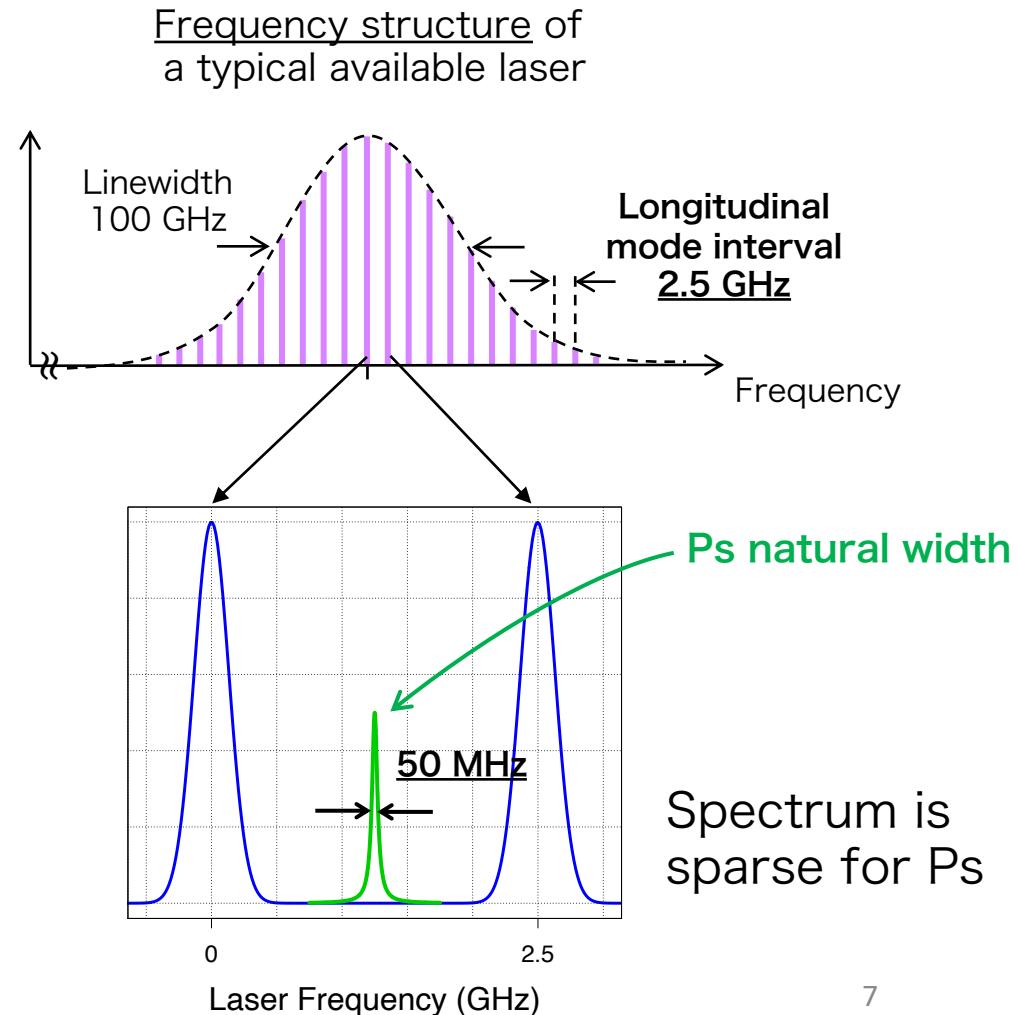
Optimized linewidth for Ps 10 K or below
would be 10 GHz

^{*1} laser intensity: 500 $\mu\text{J} / (1 \text{ cm}^2 \times 2 \text{ ns})$ @243 nm

Choosing an Appropriate Longitudinal Mode Interval

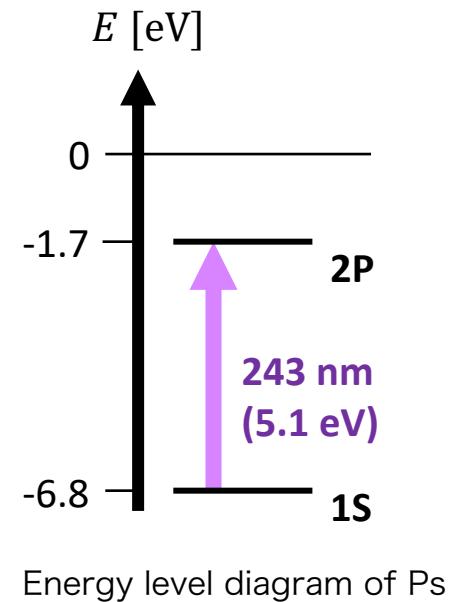


Longitudinal mode intervals
should be narrow enough
to be comparable to
the natural width of Ps (50 MHz)



Requirements for the Cold Ps Probing Laser

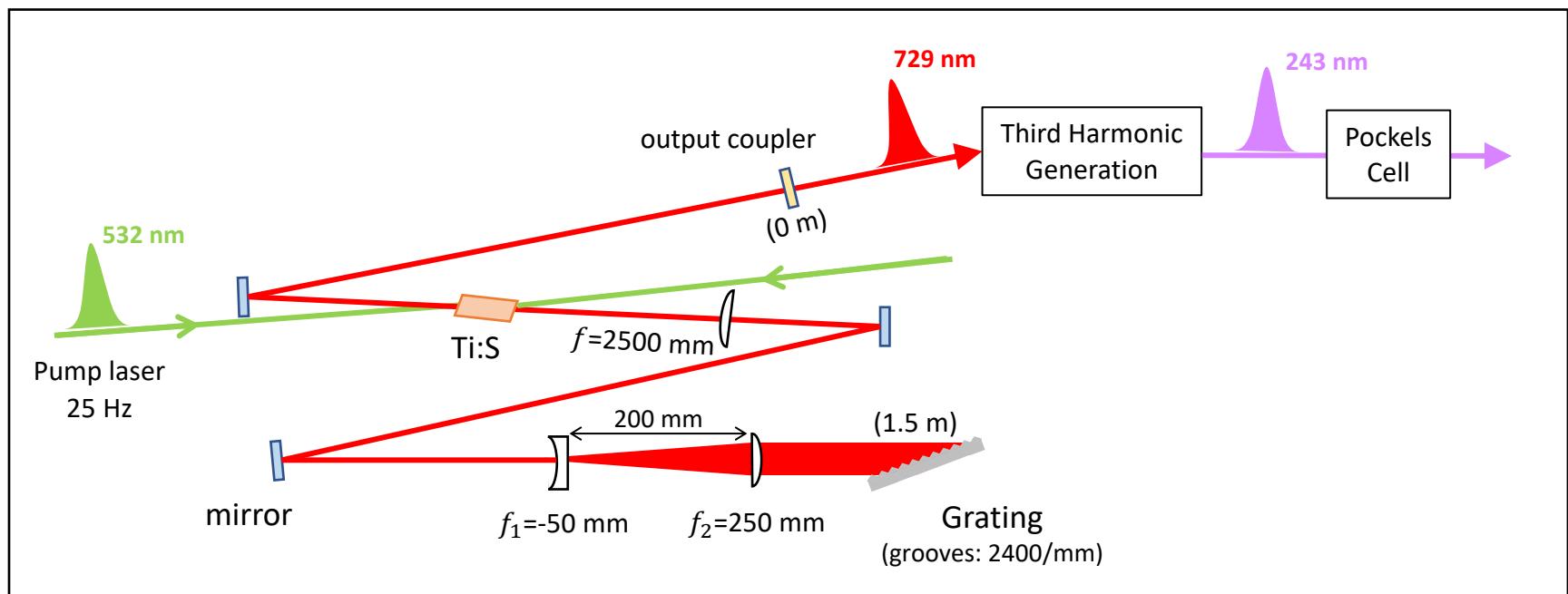
1. Optimized linewidth: around 10GHz
2. Appropriate longitudinal mode intervals:
near 50 MHz
3. Wavelength: Ultraviolet (243 nm)
4. Adequate pulse intensity
5. Frequency stability



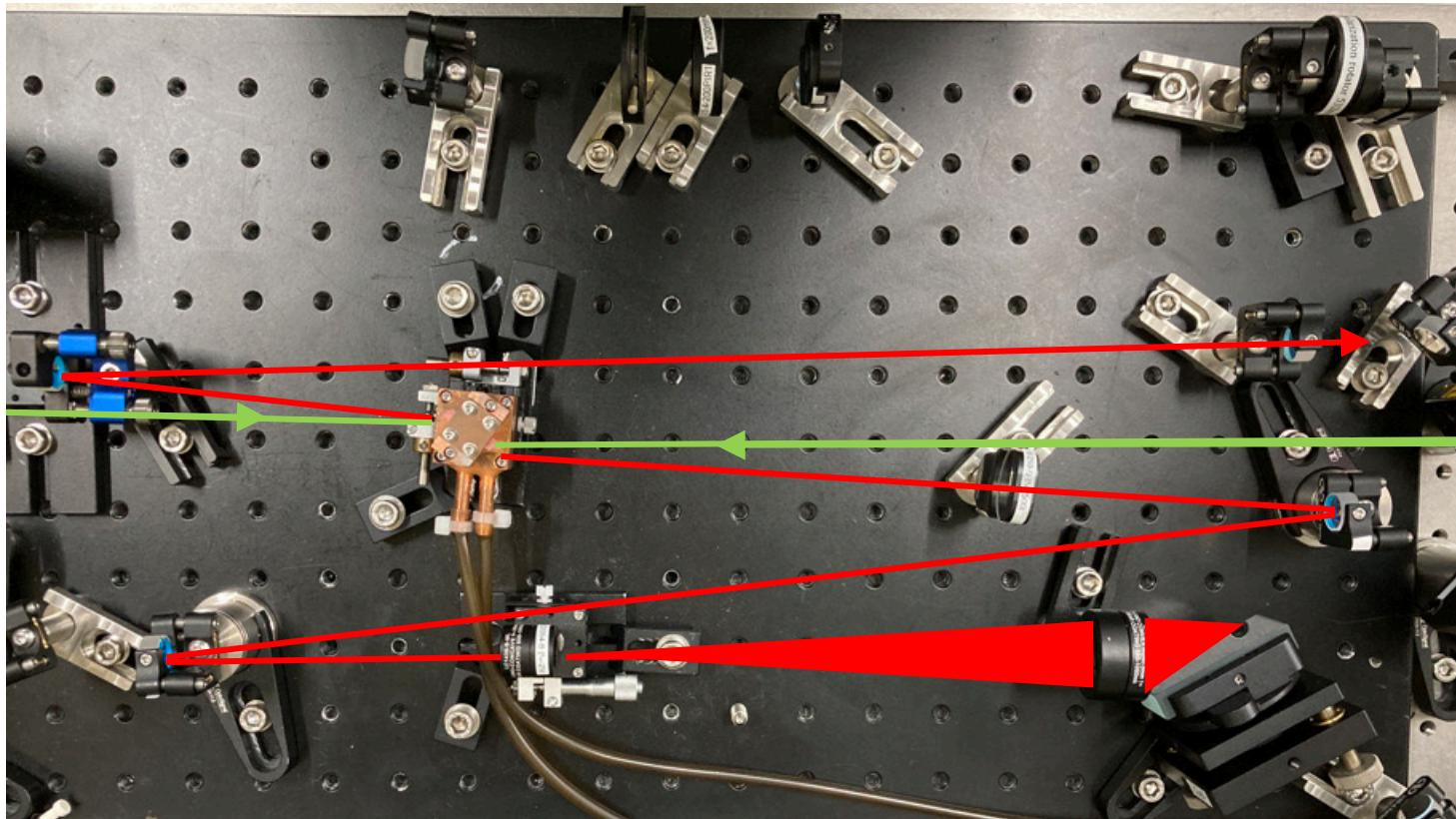
Energy level diagram of Ps

These requirements can not be achieved
by commercially available lasers

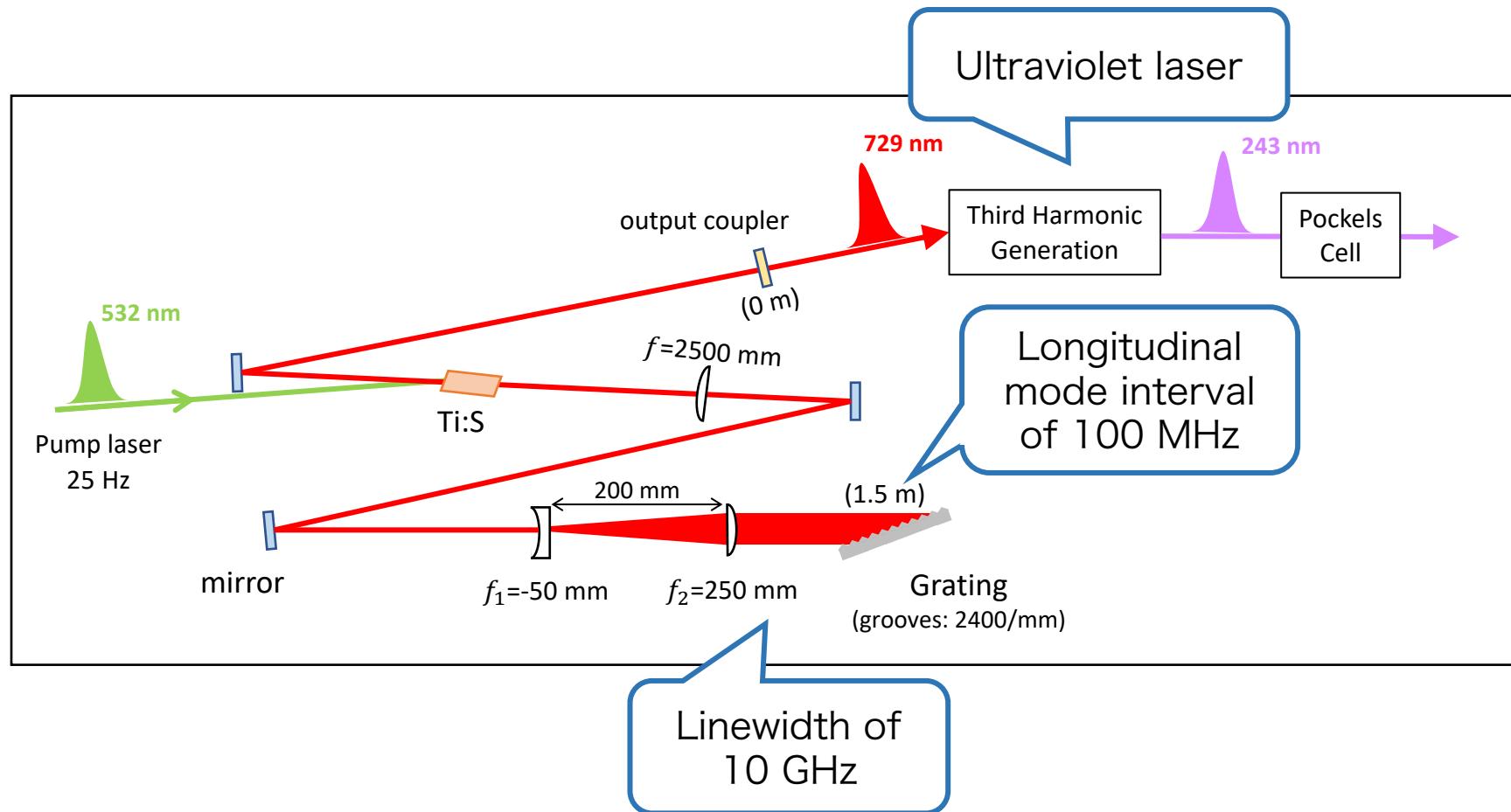
The Newly Developed High-Resolution Probing Laser



The Newly Developed High-Resolution Probing Laser

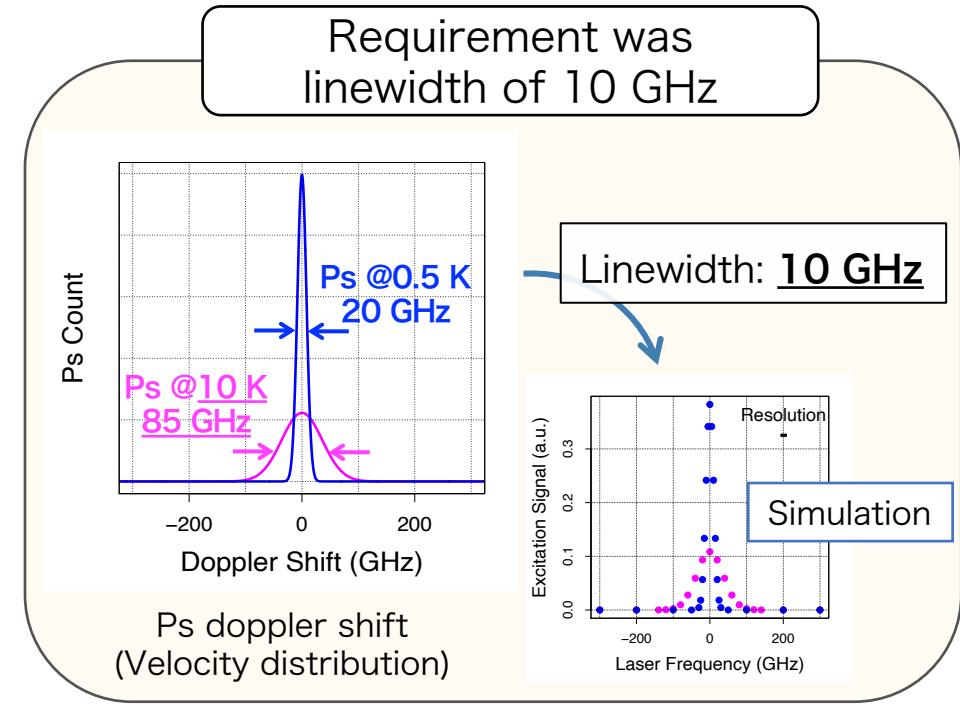
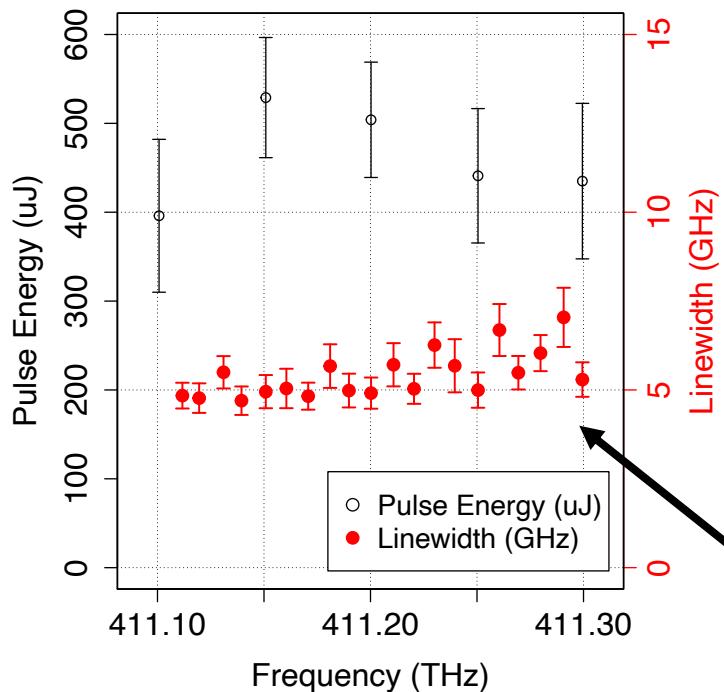


The Newly Developed High-Resolution Probing Laser



Linewidth

Linewidth measurement using Fizeau interferometer @729 nm

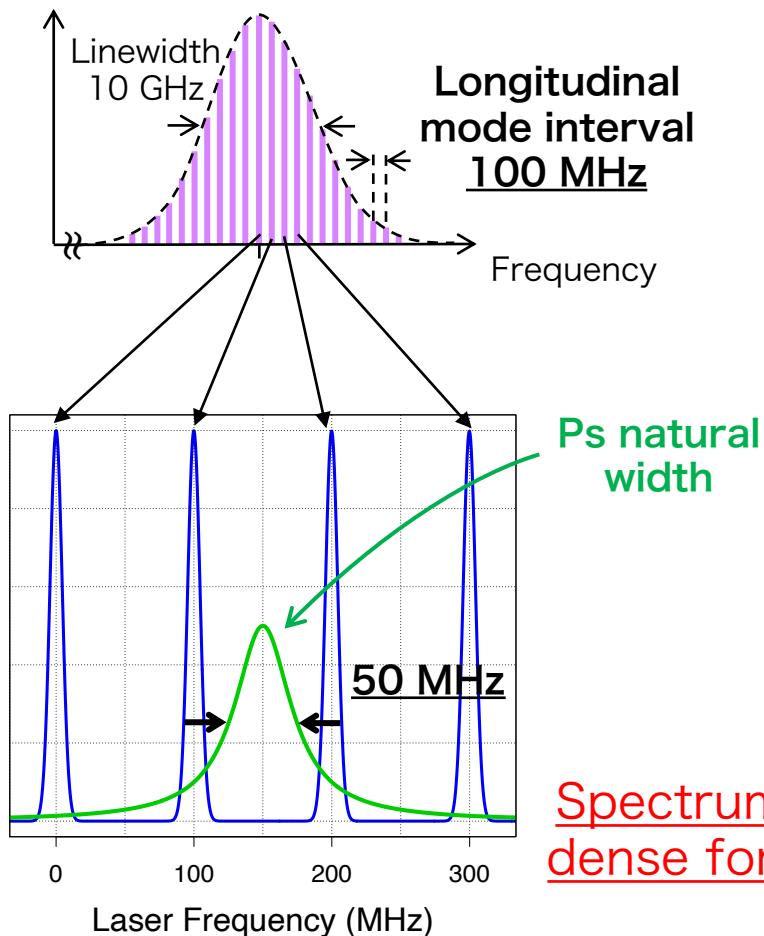


Linewidth of 6 GHz @729 nm
(10 GHz @243 nm)

Achieved the requirement of 10 GHz linewidth

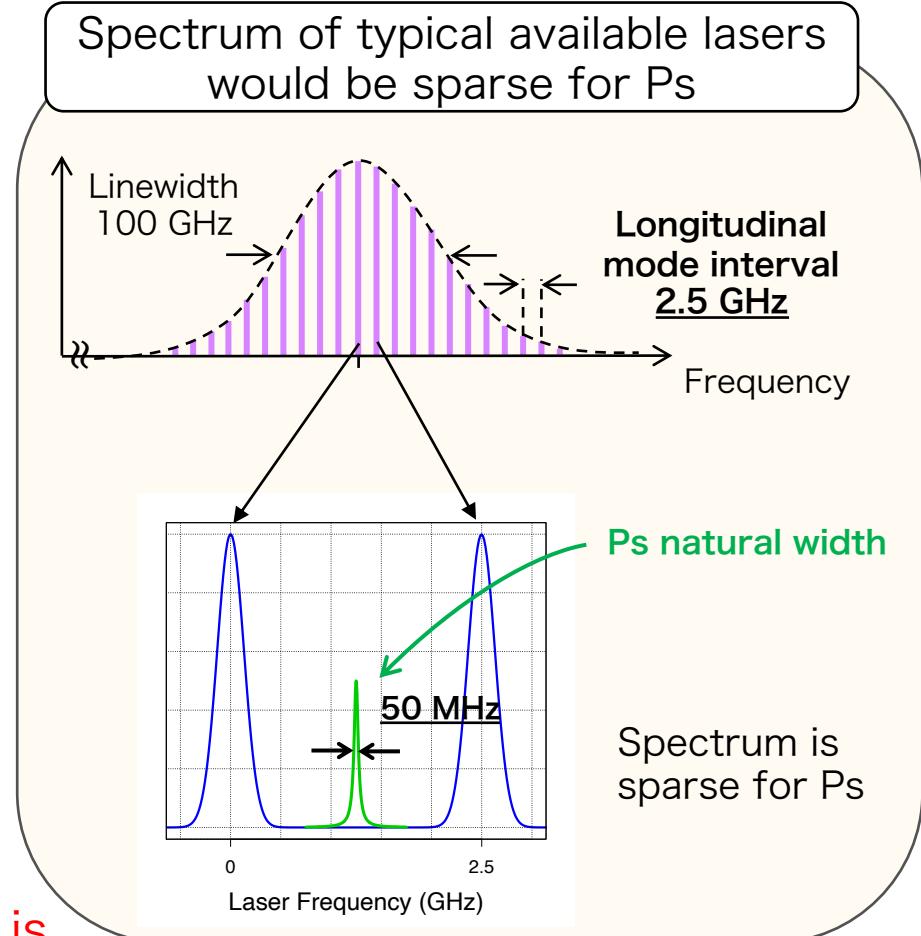
Longitudinal Mode Interval

Frequency structure of the newly developed laser



Spectrum is dense for Ps

Spectrum of typical available lasers would be sparse for Ps

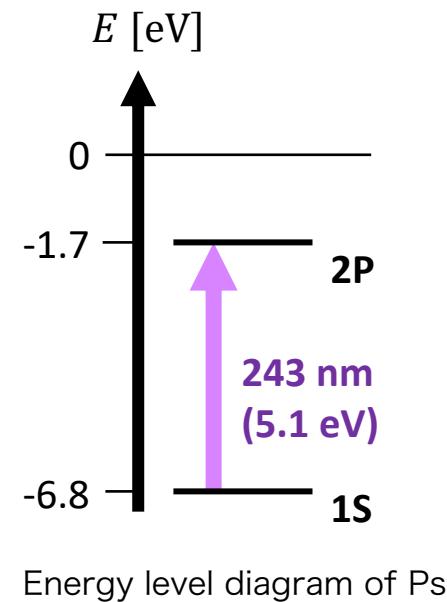


Requirements for the Cold Ps Probing Laser

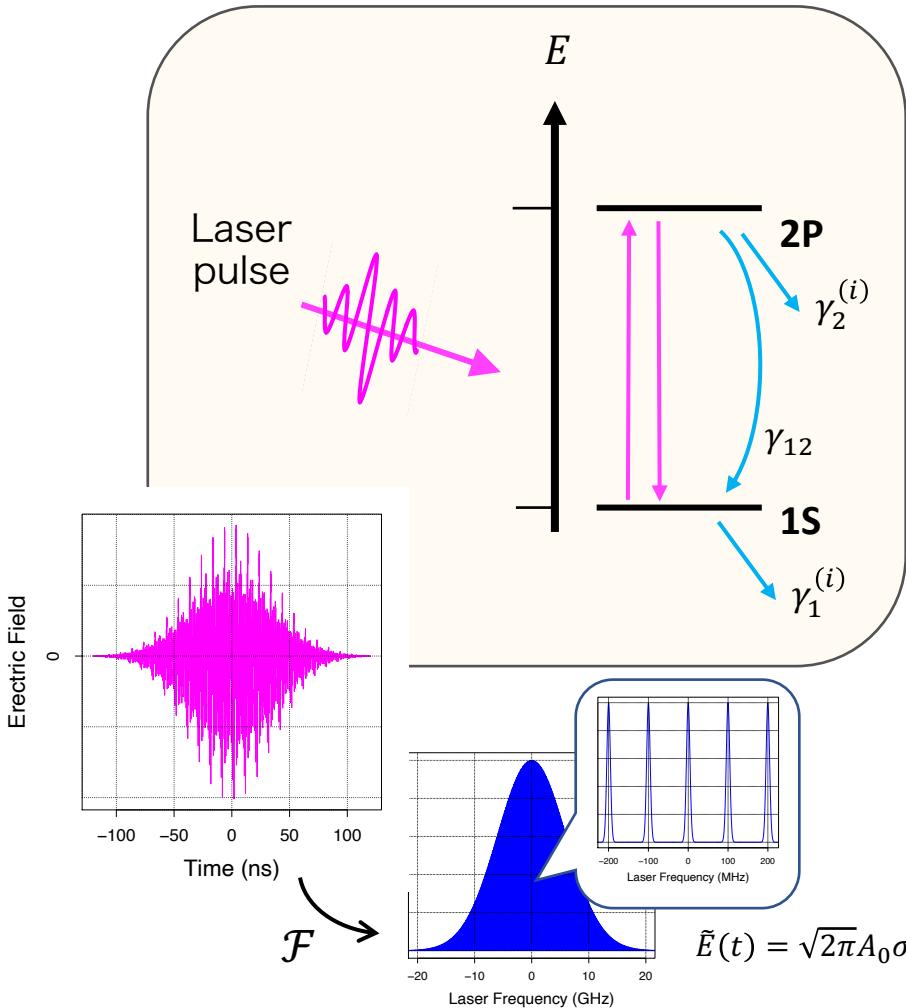
1. Optimized linewidth: around 10GHz
2. Appropriate longitudinal mode intervals:
near 50 MHz
3. Wavelength: Ultraviolet (243 nm)
4. Adequate pulse intensity
5. Frequency stability

Small fluctuation to endure long measurements

Excite enough Ps to 2P state



Numerical Simulation of Laser Induced Excitation



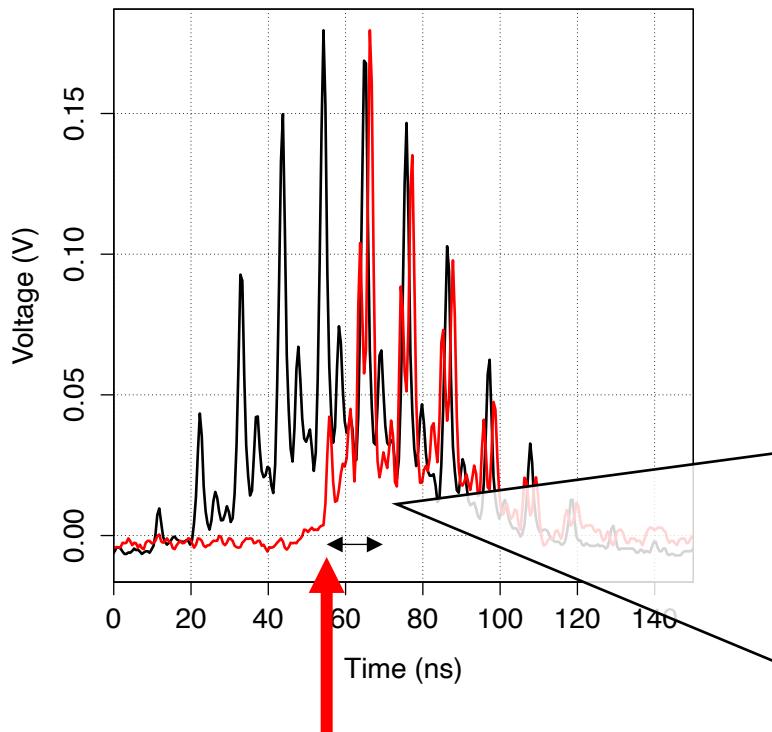
Track the density matrix elements

$$\begin{cases} \frac{d\rho_{11}}{dt} = -\frac{i}{2}(\Omega\tilde{\rho}_{12} - \Omega^*\tilde{\rho}_{21}) - \sum_i \gamma_1^{(i)}\rho_{11} + \gamma_{12}\rho_{22} \\ \frac{d\tilde{\rho}_{12}}{dt} = -\left(\frac{1}{T_2} - i\Delta\omega\right)\tilde{\rho}_{12} - \frac{i}{2}\Omega^*(\rho_{11} - \rho_{22}) \\ \frac{d\tilde{\rho}_{21}}{dt} = -\left(\frac{1}{T_2} + i\Delta\omega\right)\tilde{\rho}_{21} + \frac{i}{2}\Omega(\rho_{11} - \rho_{22}) \\ \frac{d\rho_{22}}{dt} = \frac{i}{2}(\Omega\tilde{\rho}_{12} - \Omega^*\tilde{\rho}_{21}) - \sum_i \gamma_2^{(i)}\rho_{22} - \gamma_{12}\rho_{22} \end{cases}$$

$$\tilde{E}(t) = \sqrt{2\pi}A_0\sigma_m \exp\left[-\frac{\sigma_m^2 t^2}{2}\right] e^{-i(\omega_c + \delta\omega)t} \sum_k \exp\left[-\frac{(k\omega_{\text{rep}} + \delta\omega)^2}{2\sigma^2}\right] e^{-i(k\omega_{\text{rep}}t - \phi(k,t))}$$

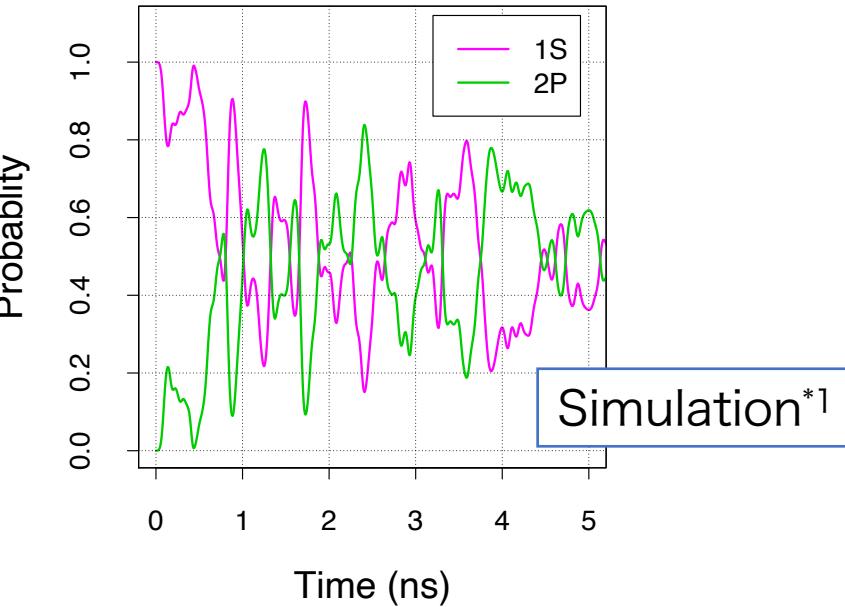
Adequate Pulse Intensity to Excite Ps to 2P State

Pulse waveform from a photodetector



Cut pulse using Pockels cell

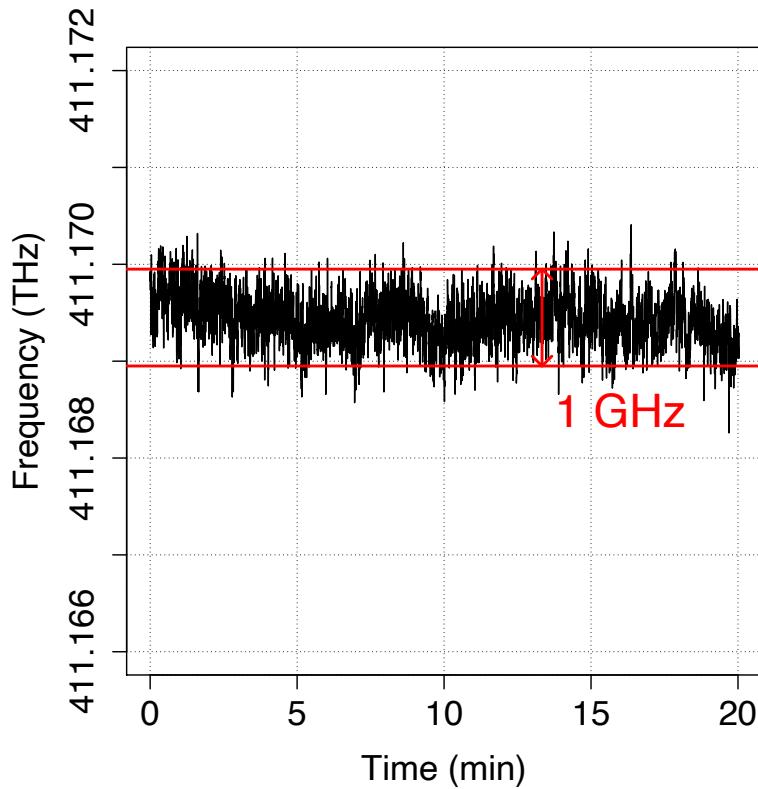
Time evolution of density matrix



*1 laser intensity: 25 uJ /(1 cm² × 60 ns)

Frequency Stability

Frequency measurement
using a wavemeter @729 nm



20 min frequency stability of
1 GHz @729 nm
(3 GHz @243 nm)

Sufficient frequency stability
to endure long measurements

Conclusion and Future Prospects

Conclusion

- Developed a new high-resolution probing laser.
- Achieved an optimized linewidth of 10 GHz which could probe Ps at 10 K or below.
- Narrow longitudinal mode interval of 100 MHz was achieved to efficiently excite Ps.
- The new laser has adequate pulse intensity to pump enough Ps to excitation state.

Future prospects

- Preparing for spectroscopy measurements using the new laser.
- Application of utilizing the new laser to observe proof of laser cooling.