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

<u>R. Uozumi[1]</u>, Y. Tajima[1], T. Kobayashi[1], K. Shu[1], E. Chae[1,7], K. Yoshioka[1], A. Ishida[2], T. Namba[2], S. Asai[2], M. Kuwata-Gonokami[2], N. Oshima[3], B.E. O'Rourke[3], K. Michishio[3], K. Ito[3], K. Kumagai[3], R. Suzuki[3], S. Fujino[4], T. Hyodo[5], I. Mochizuki[5], K. Wada[5] and T. Kai[6]

1 UT-PSC Photon Science Center of the University of Tokyo

2 ICEPP The University of Tokyo

3 AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

4 GIC Global Innovation Center グローバルイノベーションセンター 九州大学

5 KEK

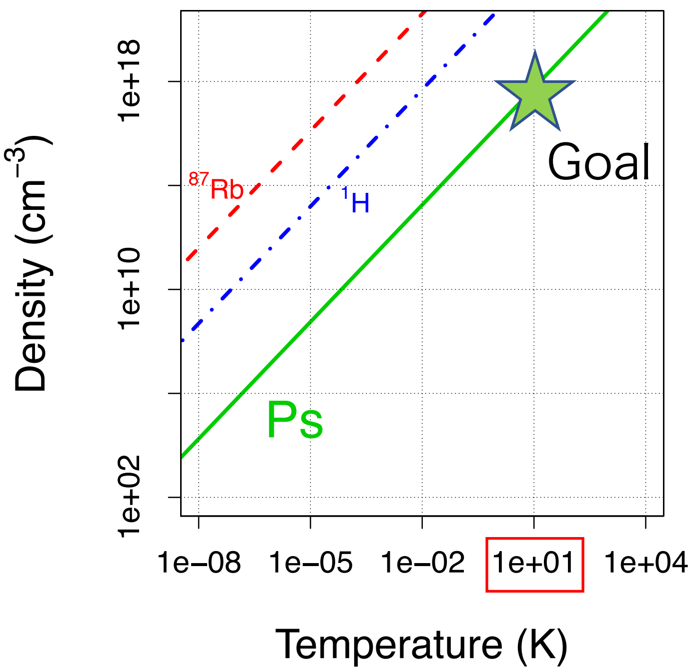
6 JAEA

7 KOREA UNIVERSITY

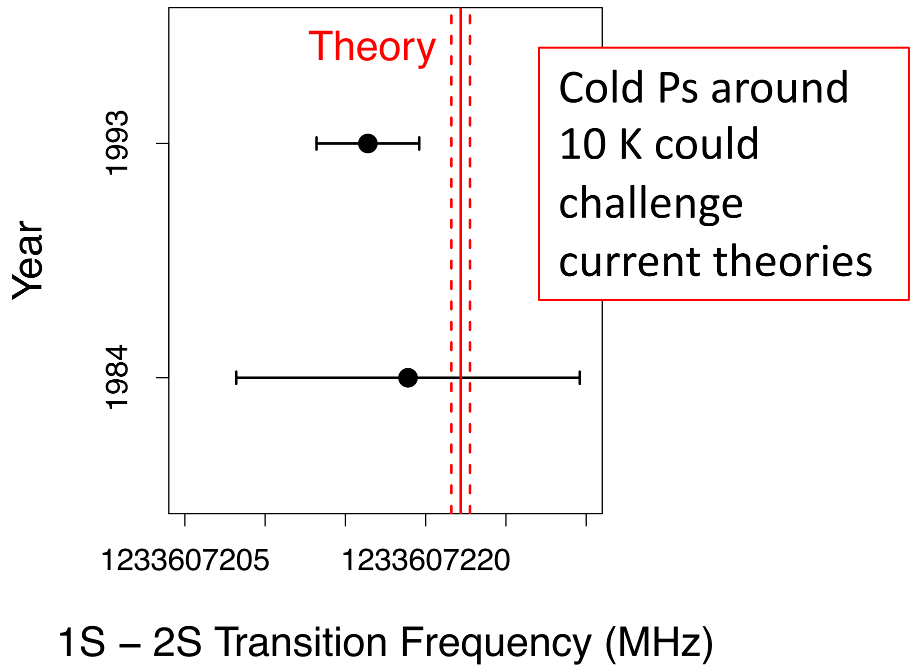
12.5th International Workshop on Positron and Positronium Chemistry (PPC 12.5)
31 August 2021

Significance of Cold Ps

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



Precision spectroscopy of
transition frequencies



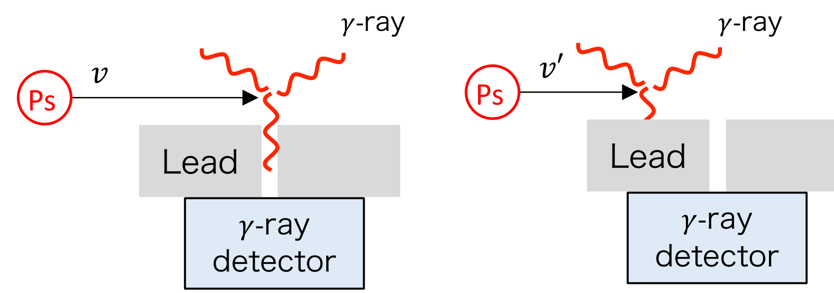
M. S. Fee *et.al*, Physical Review A **48**, 192 (1993).
K. Danzmann, M. S. Fee, and S. Chu, Physical Review A **39**, 6072 (1989)
A. Czarnecki, K. Melnikov, and A. Yelkhovsky, Physical Review A **59**, 4316 (1999).

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

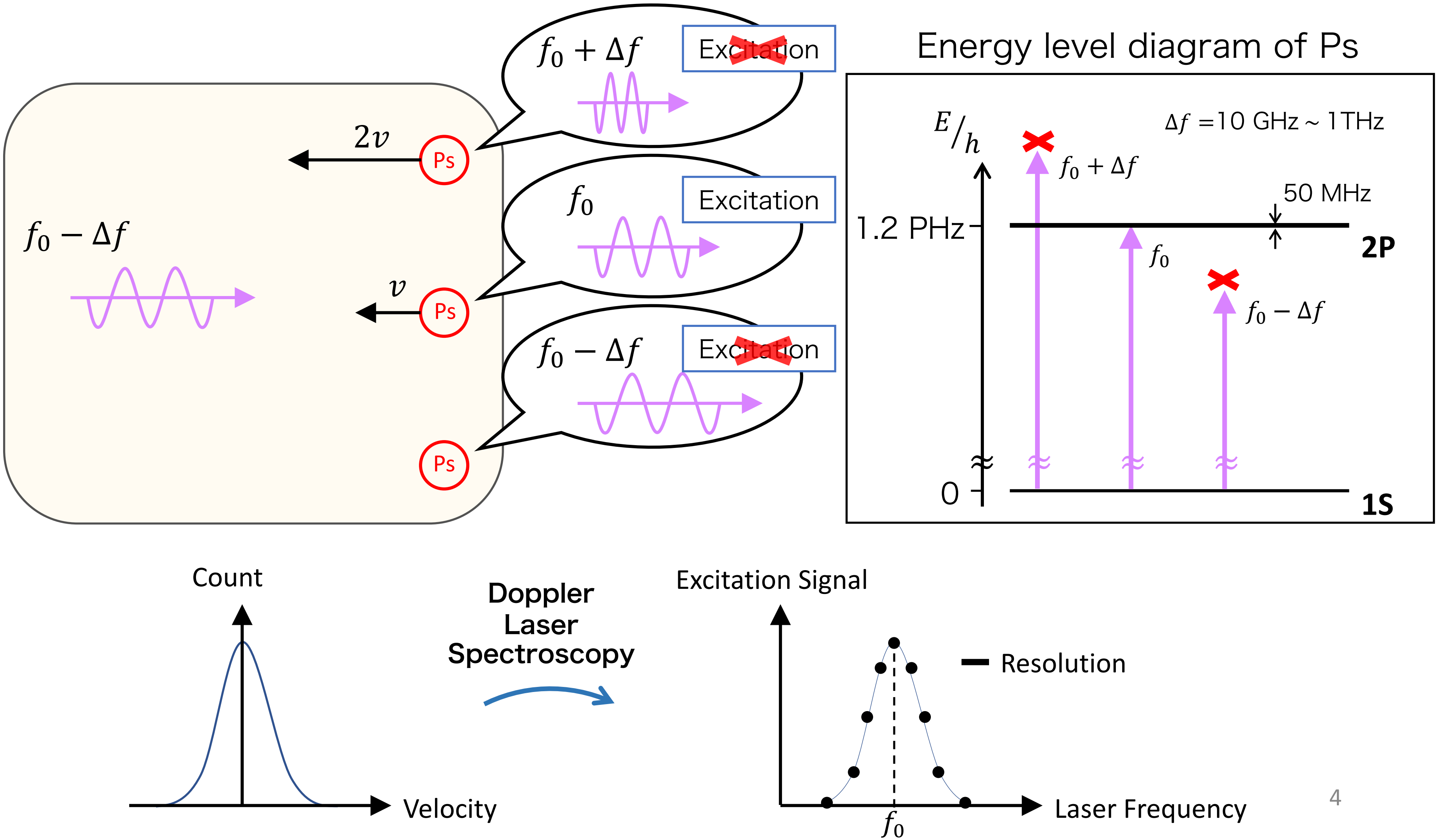
Spatial difference of 5 mm after flight of **800 ns**

o-Ps decay time: **142 ns**

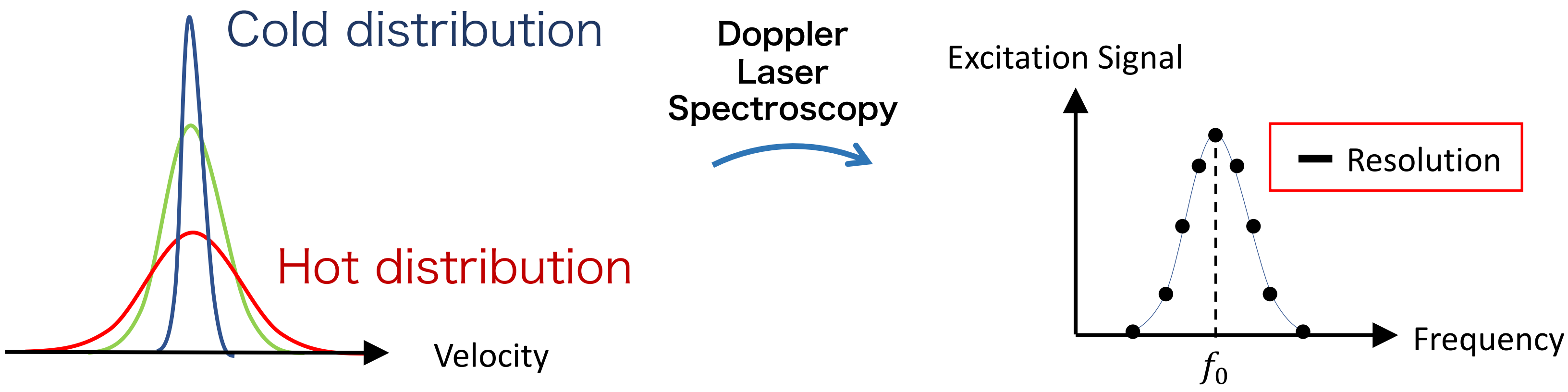
- Doppler broadening spectroscopy (DBS)
- Angular Correlation of Annihilation Radiation (ACAR)
- ★ Doppler Laser Spectroscopy

Doppler laser spectroscopy could be a suited method for cold Ps temperature measurement

Doppler Laser Spectroscopy of Ps



Resolution (given by Laser Linewidth) will be Tunable



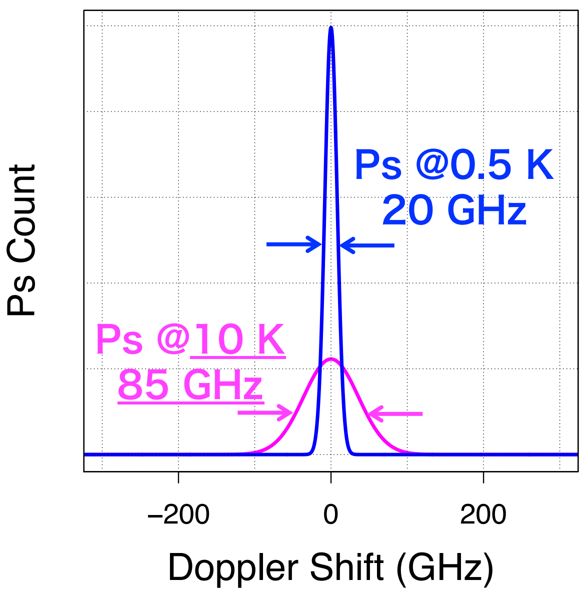
Resolution is determined by
the linewidth of the probing laser
(=how monochromatic the laser is)

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

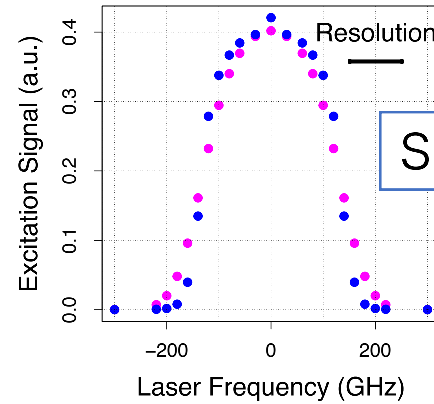
How Narrow should the Linewidth be?

Ps doppler shift
(Velocity distribution)



Typical available laser[*1]

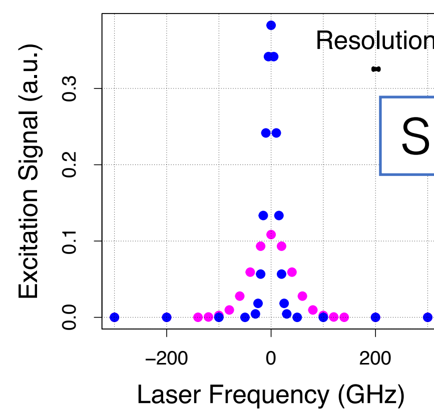
Linewidth: **100 GHz**



Simulation

New laser

Linewidth: **10 GHz**



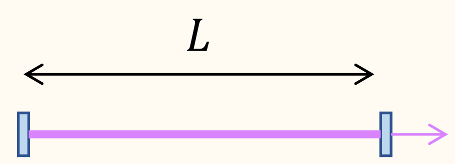
Simulation

Optimized linewidth for Ps @10 K would be 10 GHz

[*1] laser intensity: 500 uJ /(1 cm^2 × 2 ns) @243 nm

Choosing an Appropriate Longitudinal Mode Interval

Longitudinal mode interval

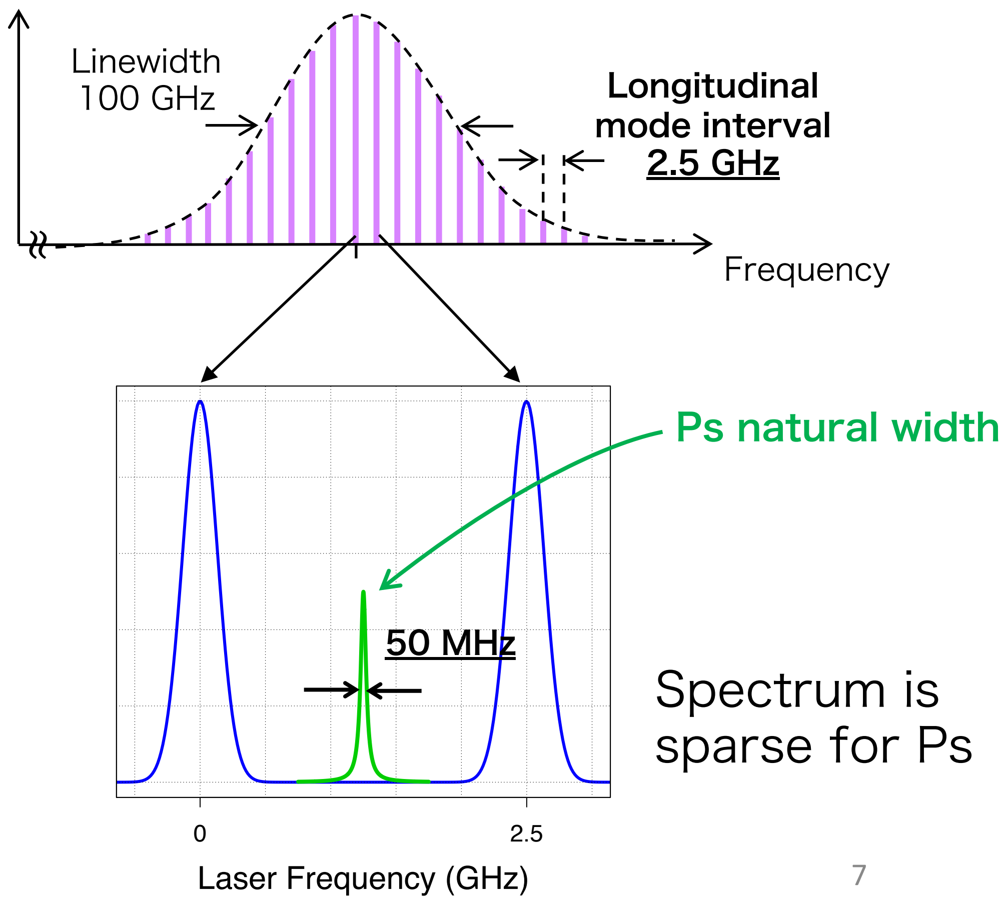


Phase matching condition:

$$f = \frac{c}{2L} n \quad (n = 1, 2, 3, \dots)$$

↑ Longitudinal mode interval ($\frac{c}{2L}$)

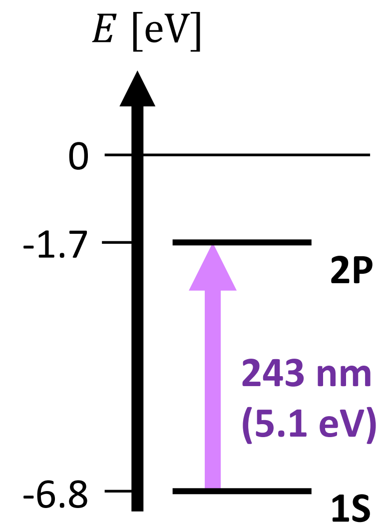
<u>Frequency structure</u> of a typical available laser



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

Requirements for the Cold Ps Probing Laser

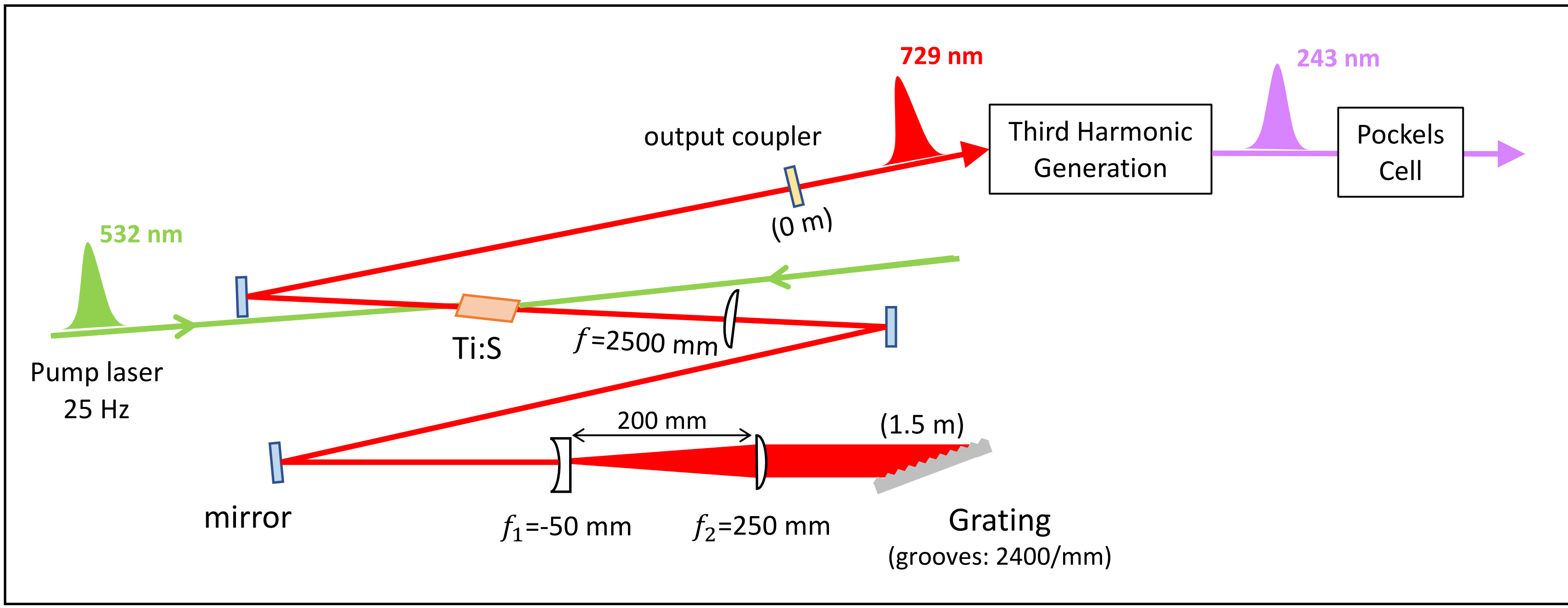
1. Optimized linewidth: around 10 GHz
2. Appropriate longitudinal mode interval: near 50 MHz
3. Wavelength: Ultraviolet (243 nm)
4. Adequate pulse intensity
5. Frequency stability



Energy level diagram of Ps

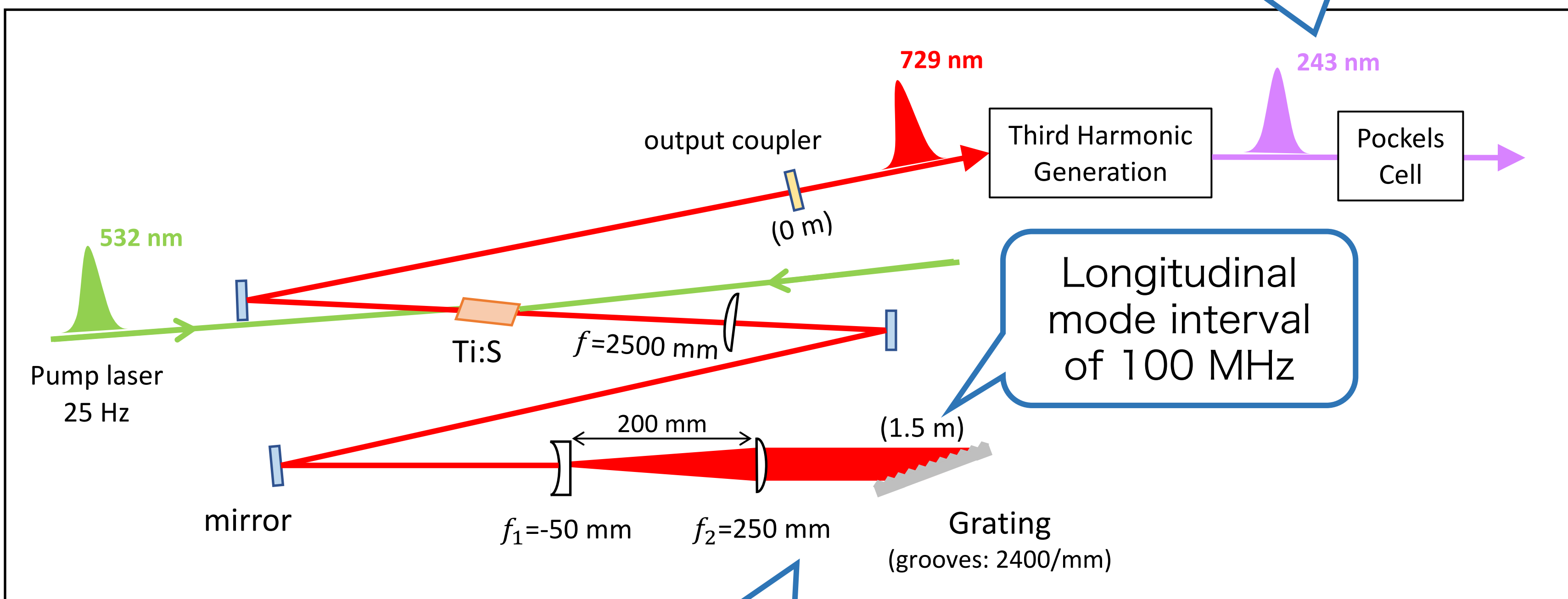
These requirements can not be achieved by commercially available lasers

The Newly Developed High-Resolution Probing Laser



The Newly Developed High-Resolution Probing Laser

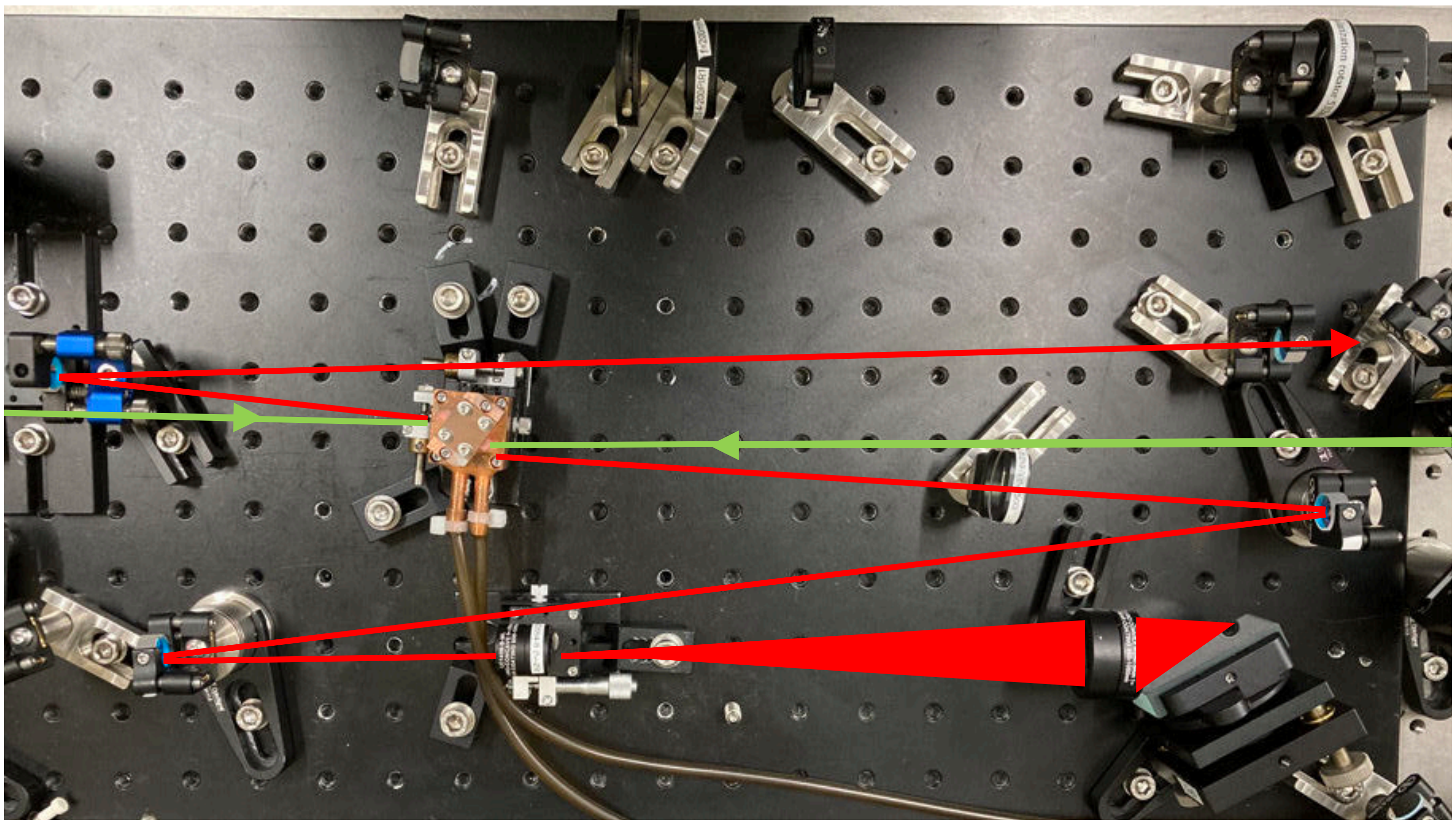
Ultraviolet laser



Longitudinal mode interval of 100 MHz

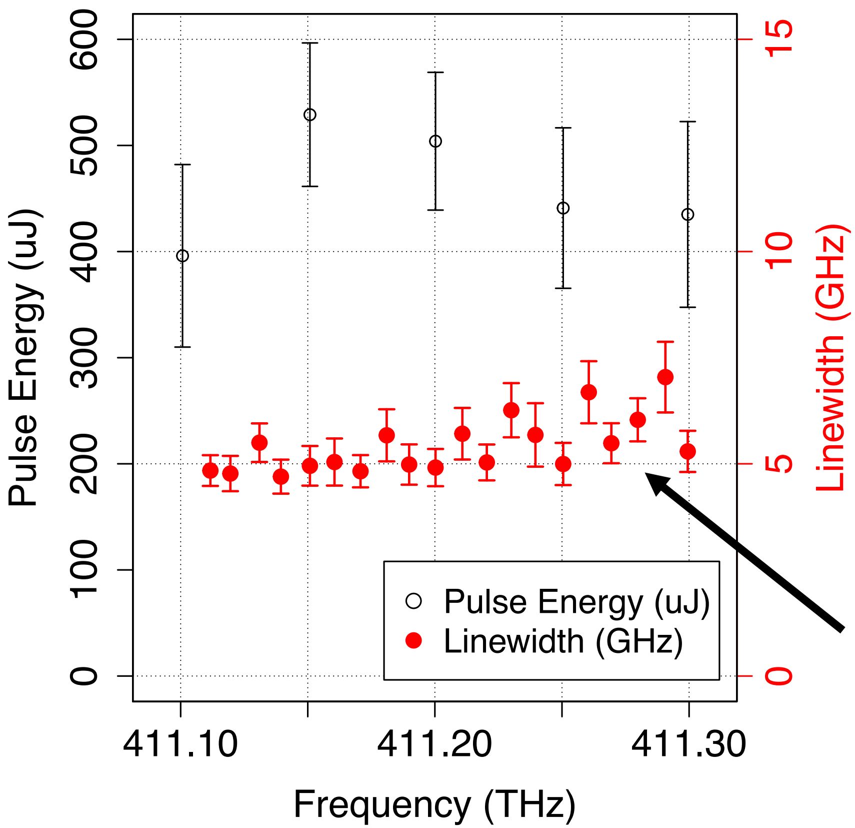
Linewidth of 10 GHz

The Newly Developed High-Resolution Probing Laser



Linewidth

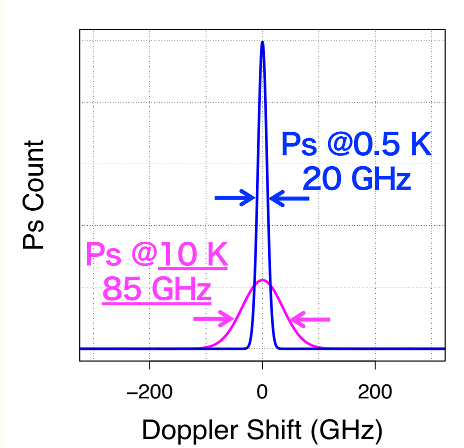
Linewidth measurement using
Fizeau interferometer @729 nm



Linewidth of 6 GHz @729 nm

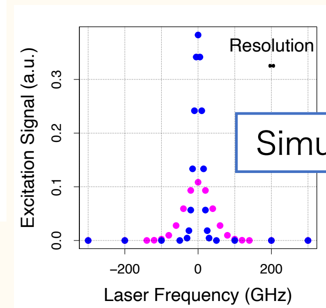
(**10 GHz** @243 nm)

Requirement was
linewidth of 10 GHz



Ps doppler shift
(Velocity distribution)

Linewidth: **10 GHz**

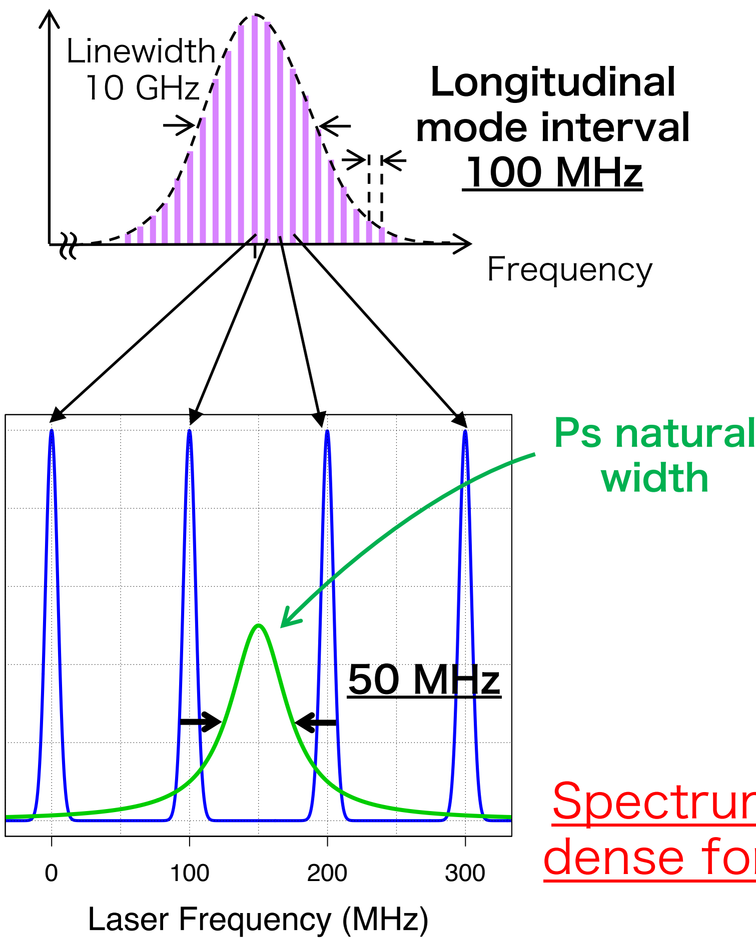


Simulation

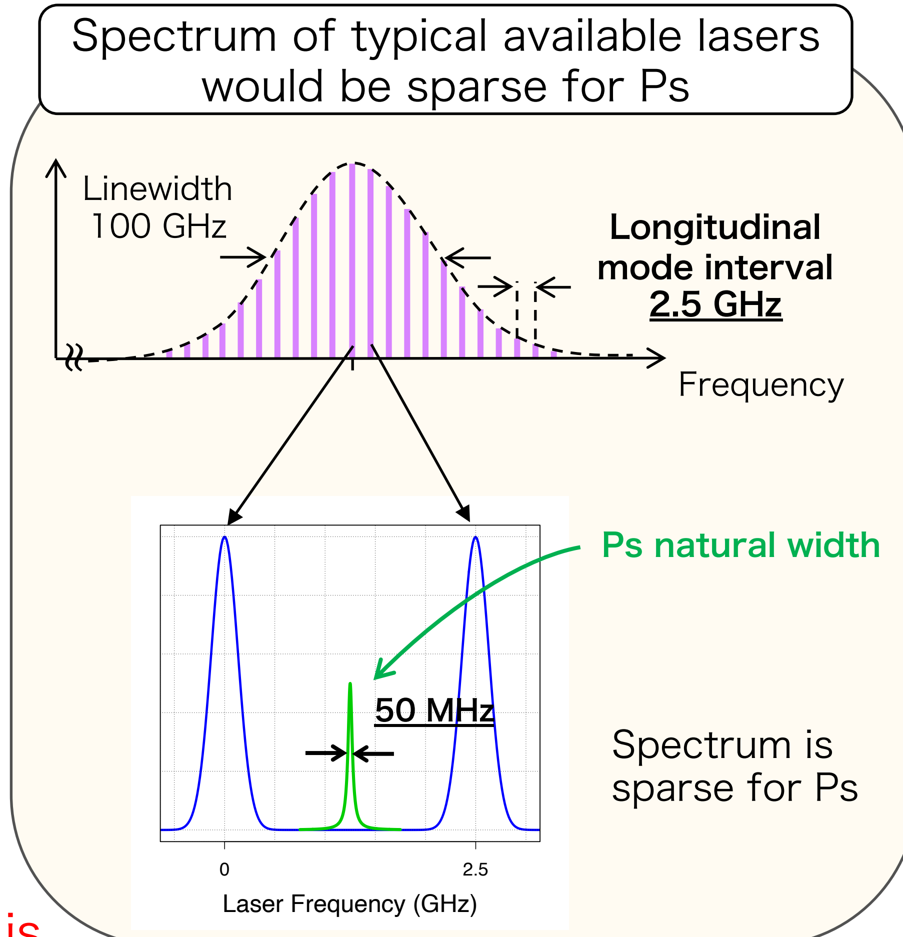
Achieved the requirement of 10 GHz linewidth

Longitudinal Mode Interval

Frequency structure of
the newly developed laser



Spectrum is
dense for Ps

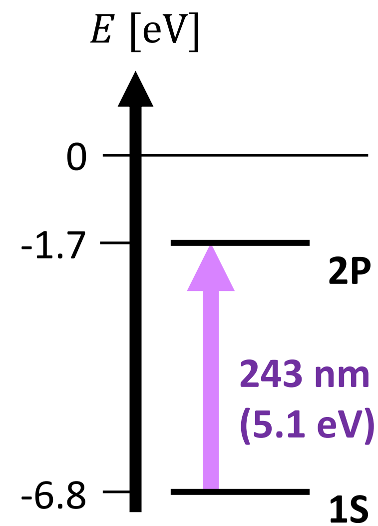


Requirements for the Cold Ps Probing Laser

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

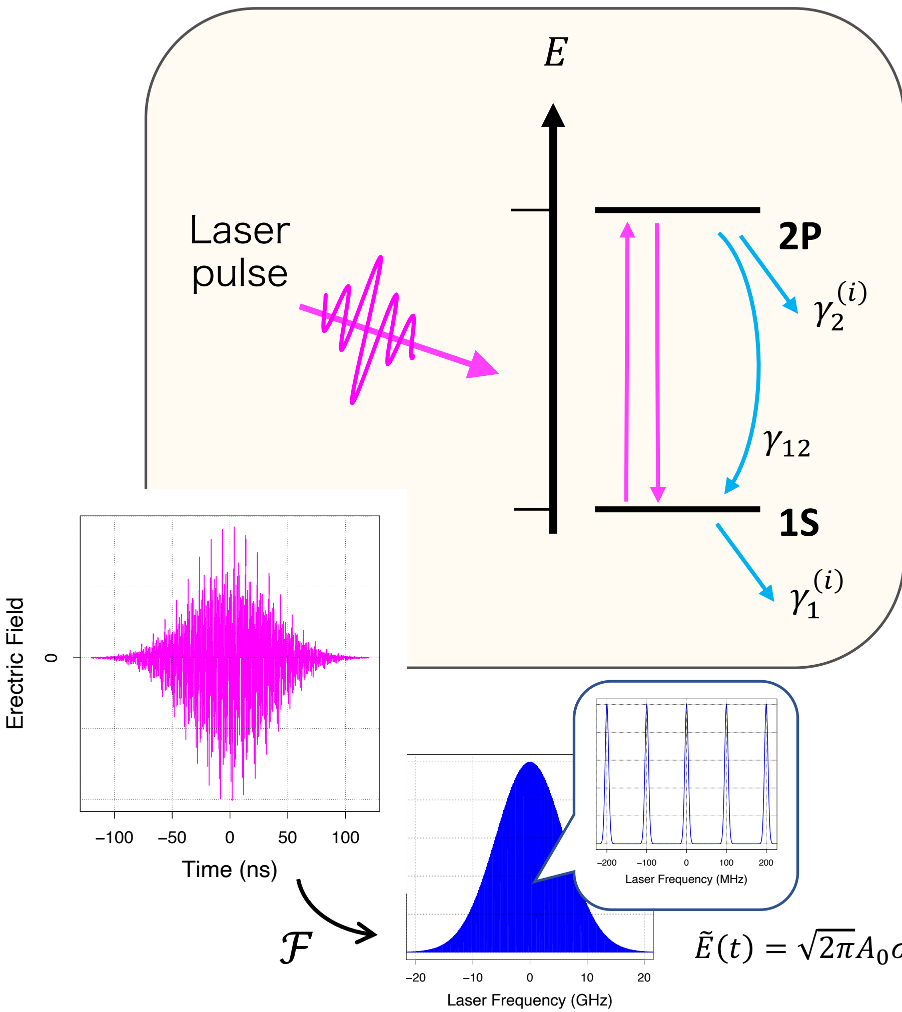
Small fluctuation to endure long measurements

Excite enough Ps to 2P state



Energy level diagram of Ps

Numerical Simulation of Laser Induced Excitation

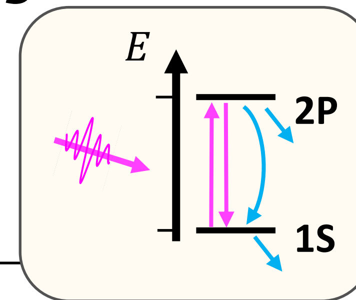


Track the density matrix elements

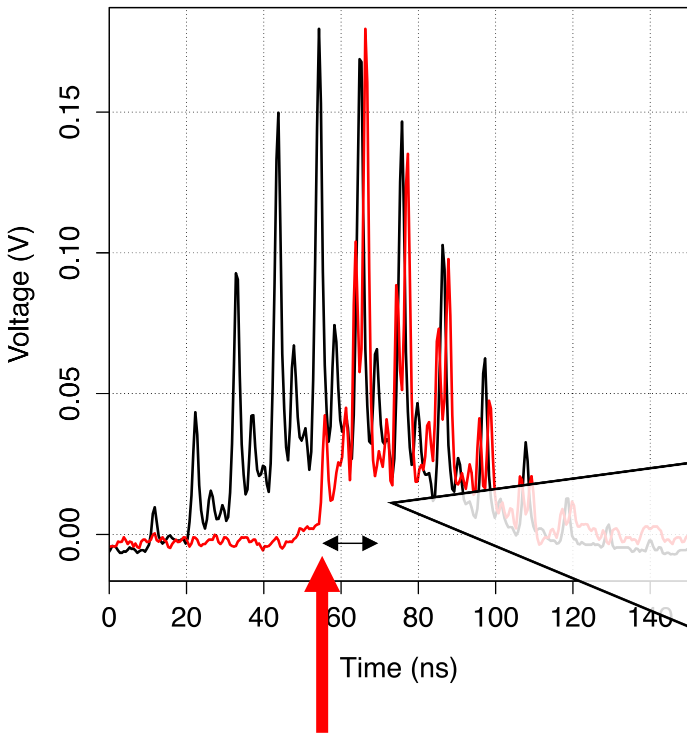
$$\begin{cases} \dfrac{d\rho_{11}}{dt} = -\dfrac{i}{2}(\Omega\tilde{\rho}_{12} - \Omega^*\tilde{\rho}_{21}) - \displaystyle\sum_i \gamma_1^{(i)}\rho_{11} + \gamma_{12}\rho_{22} \\ \dfrac{d\tilde{\rho}_{12}}{dt} = -\left(\dfrac{1}{T_2} - i\Delta\omega\right)\tilde{\rho}_{12} - \dfrac{i}{2}\Omega^*(\rho_{11}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

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

Adequate Pulse Intensity to Excite Ps to 2P State

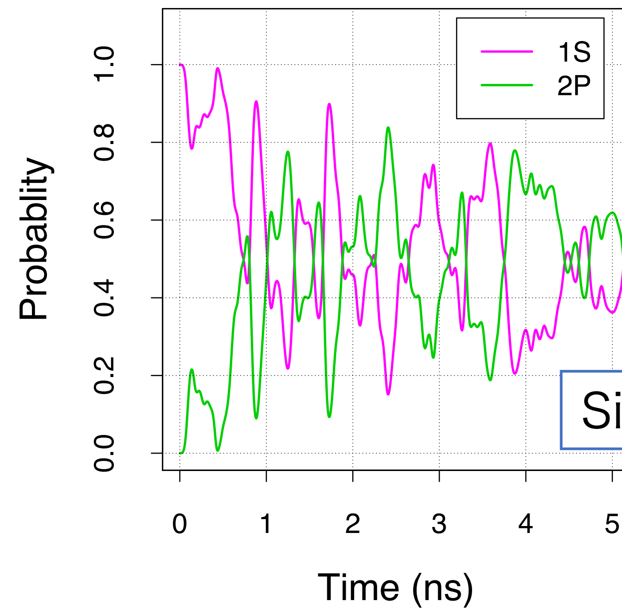


Pulse waveform from a photodetector



Cut pulse using Pockels cell

Time evolution of density matrix

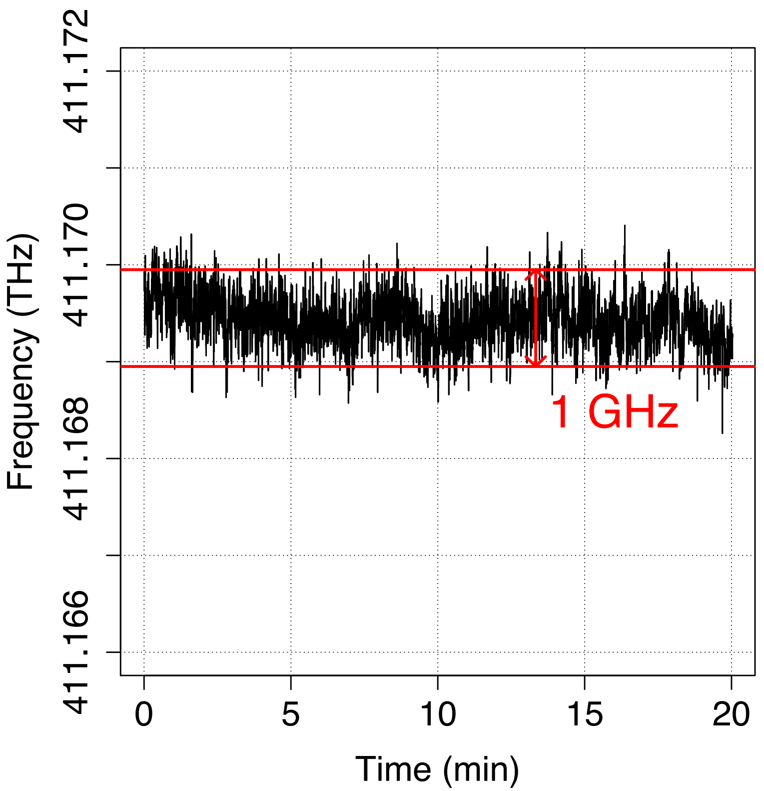


Simulation*1

*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.