# Coherently amplified multi-photon emission toward neutrino mass spectroscopy

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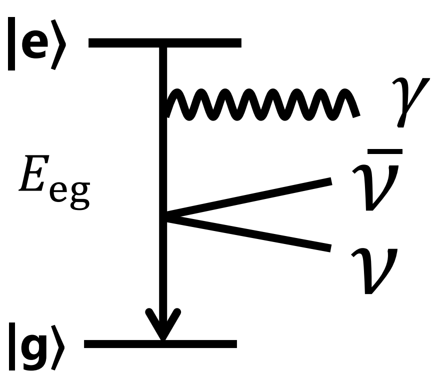
# Introduction

# SPectroscopy with Atomic Neutrino

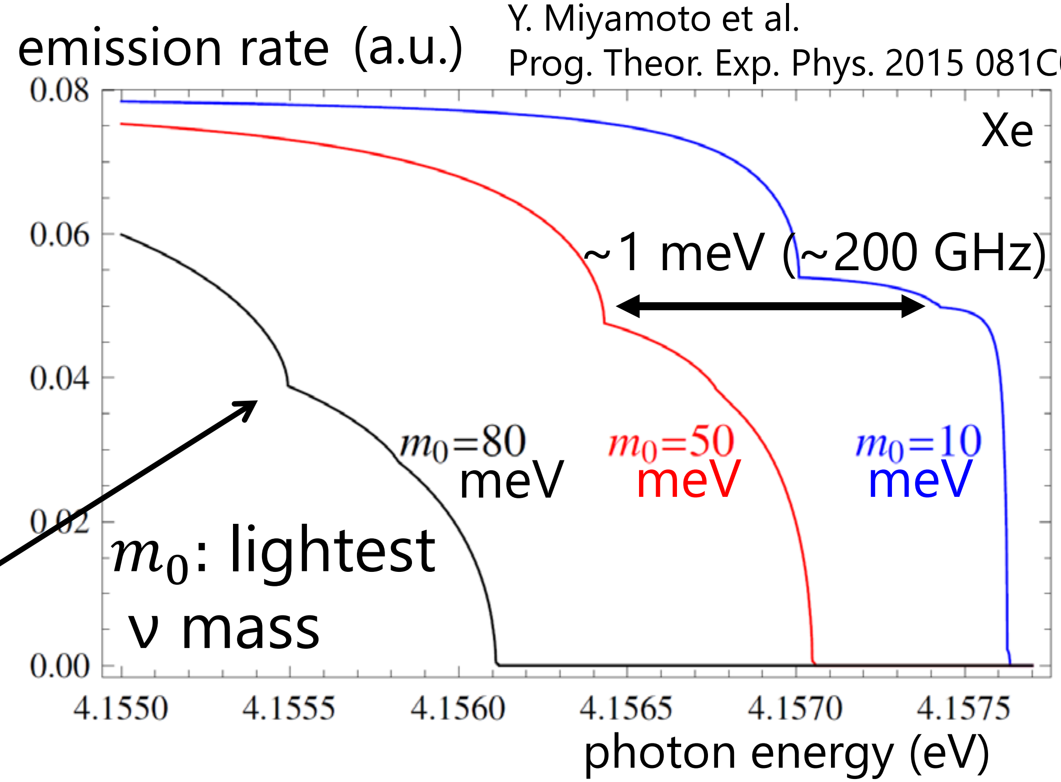
✓ determine unknown neutrino properties (ex. absolute masses) by using techniques of laser spectroscopy

- Radiative Emission of Neutrino Pair (RENP)




- Emission rate spectra (near endpoint)

Y. Miyamoto et al.
Prog. Theor. Exp. Phys. 2015 081C01




- threshold energy

$$E_{th} = \frac{E_{eg}}{2} - \frac{((m_\nu + m_{\bar{\nu}})c^2)^2}{2E_{eg}}$$

(no boost case)

# Rate Amplification

- De-excitation rate of RENP: extremely small

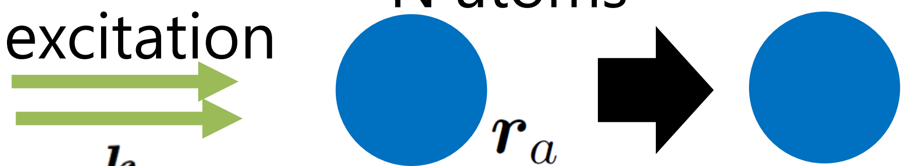
➡ Rate amplification using **atomic coherence**

**coherence generation**

lasers for excitation

N atoms

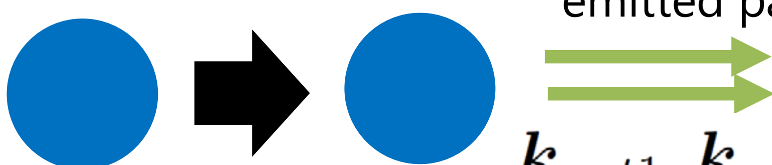
initial spatial phase



$\boldsymbol{k}_{in1}, \boldsymbol{k}_{in2}, \cdots$ $\boldsymbol{r}_a$

$$\sum_a \exp(i\boldsymbol{k}_{in} \cdot \boldsymbol{r}_a)$$

**De-excitation process**



emitted particles

$\boldsymbol{k}_{out1}, \boldsymbol{k}_{out2}, \cdots$

de-excitation rate ∝

$$|\sum_a \exp(i\Delta\boldsymbol{k} \cdot \boldsymbol{r}_a)\mathcal{M}_a|^2$$

$$\Delta\boldsymbol{k} = \boldsymbol{k}_{in} - \boldsymbol{k}_{out}$$

- If $\Delta\boldsymbol{k} = \boldsymbol{0}$ holds, the emission rate ∝ **$N^2$ (rate amplification)**
  - <u>momentum conservation among initial and emitted particles</u>

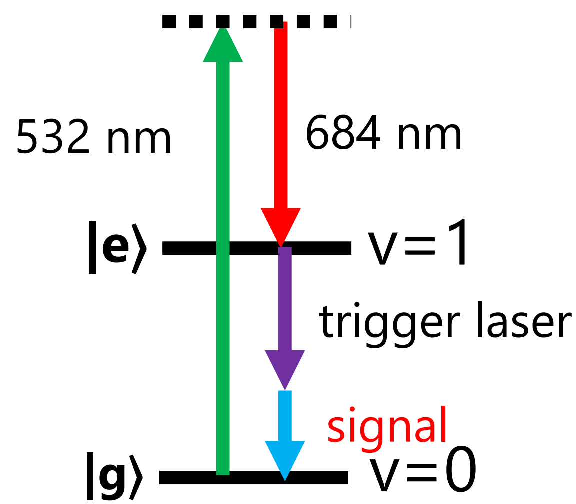
✓ study the mechanism using multi-photon emission processes

# Previous experiments

✓ Two-photon emission (TPE) process using vibrational states (v=0, J=0 ↔ v=1, J=0) of para-hydrogen ($pH_2$) molecules

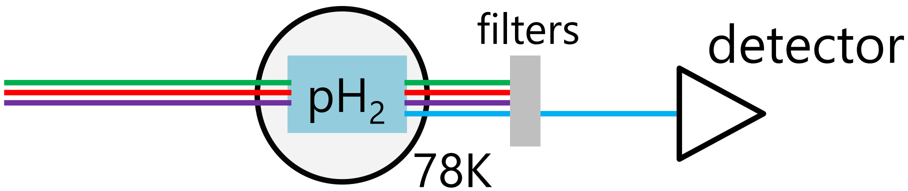
- 1-photon E1: forbidden, 2-photon E1×E1: allowed

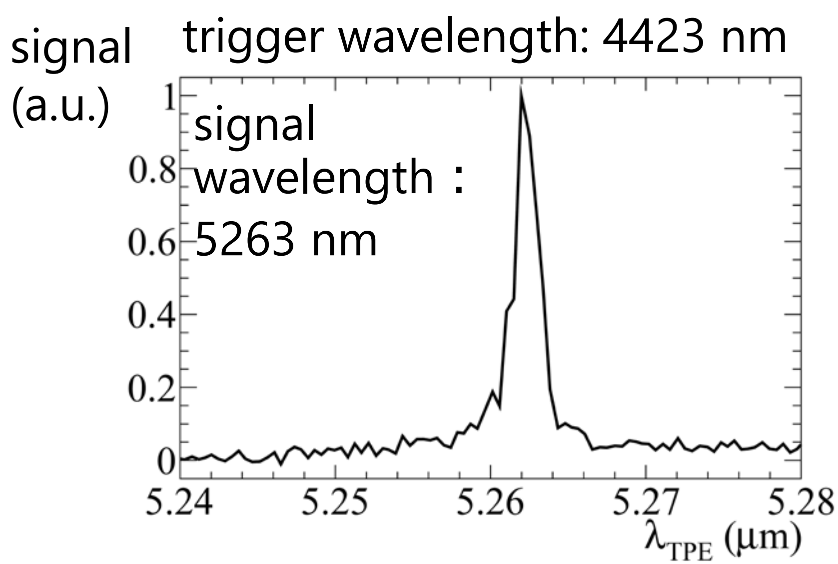
## $pH_2$ Energy diagram




- Coherence generation by stimulated Raman process
- 532 nm, 684 nm pulse lasers
- stimulate TPE process by a trigger laser
- injection from **the same direction**

## experimental setup




Rate amplification factor >$10^{18}$

Prog. Theor. Exp. Phys. **2014**, 113C01

**Current experiment:**

Two-photon emission from $pH_2$ molecules excited by **counter-propagating** lasers

# Coherent amplification condition

✓ Energy-momentum conservation among photons

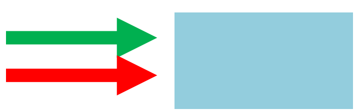
✓ Process: Two-photon emission (TPE)

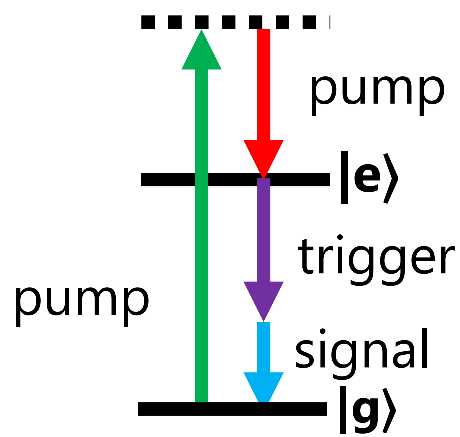
no dispersion case

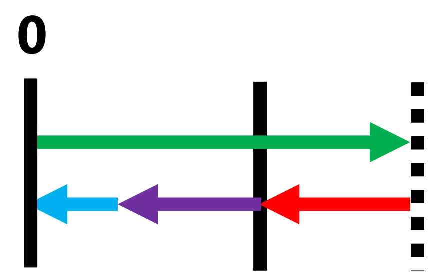
Energy

momentum

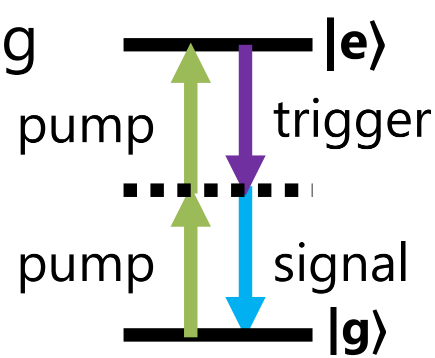
- one-side excitation

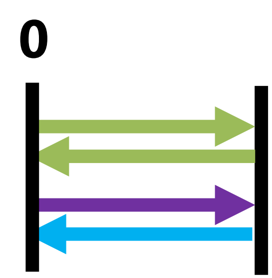





- counter-propagating excitation




The condition is satisfied in both cases

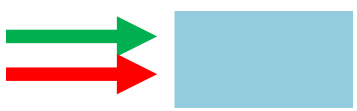
# Coherent amplification condition

✓ Energy-momentum conservation among photons+ν

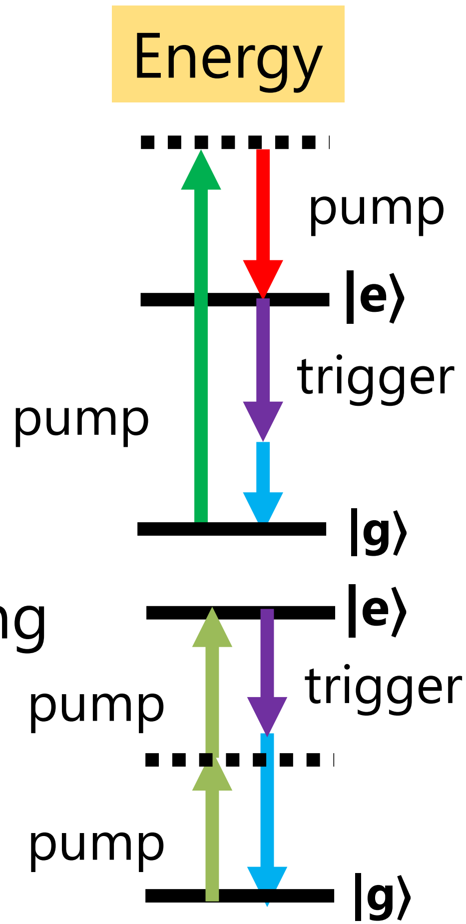
✓ Process: Radiative emission of neutrino pair (RENP)

no dispersion case

- one-side excitation



- counter-propagating excitation

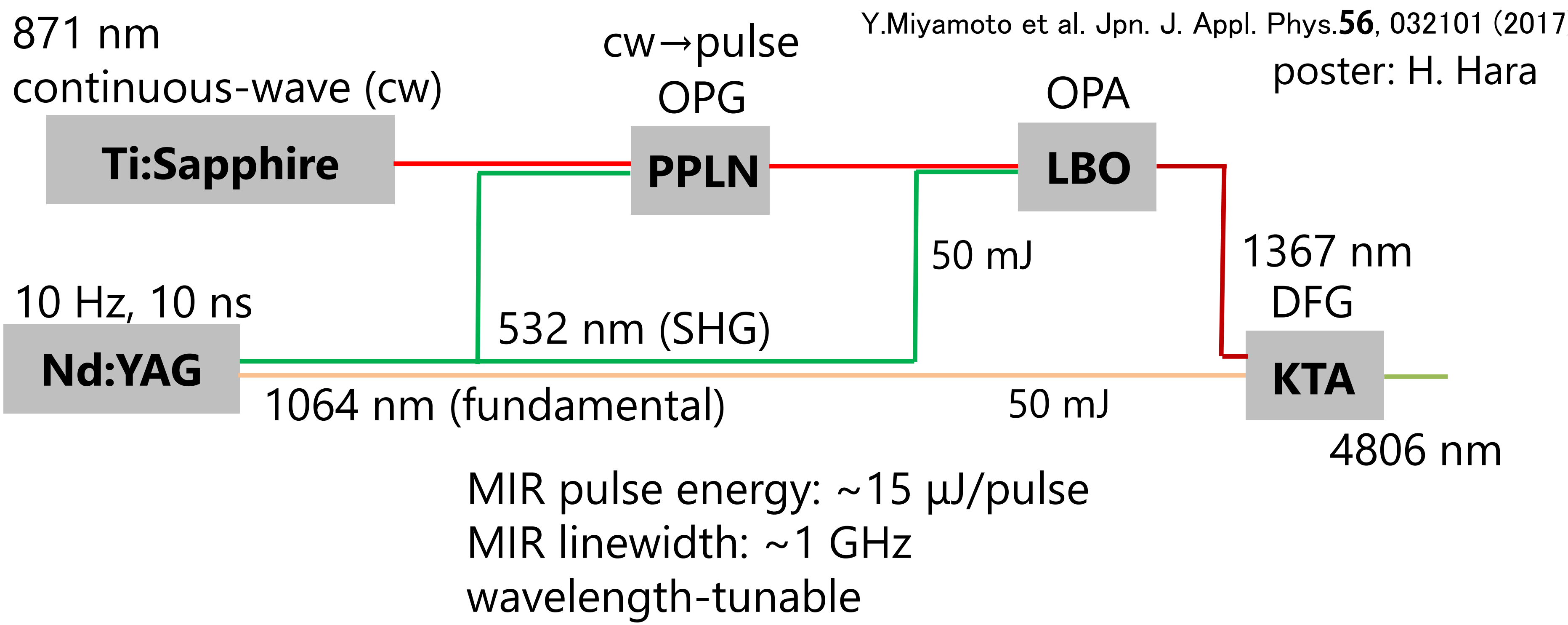




✓ High-quality mid-infrared (4806 nm) laser is required.

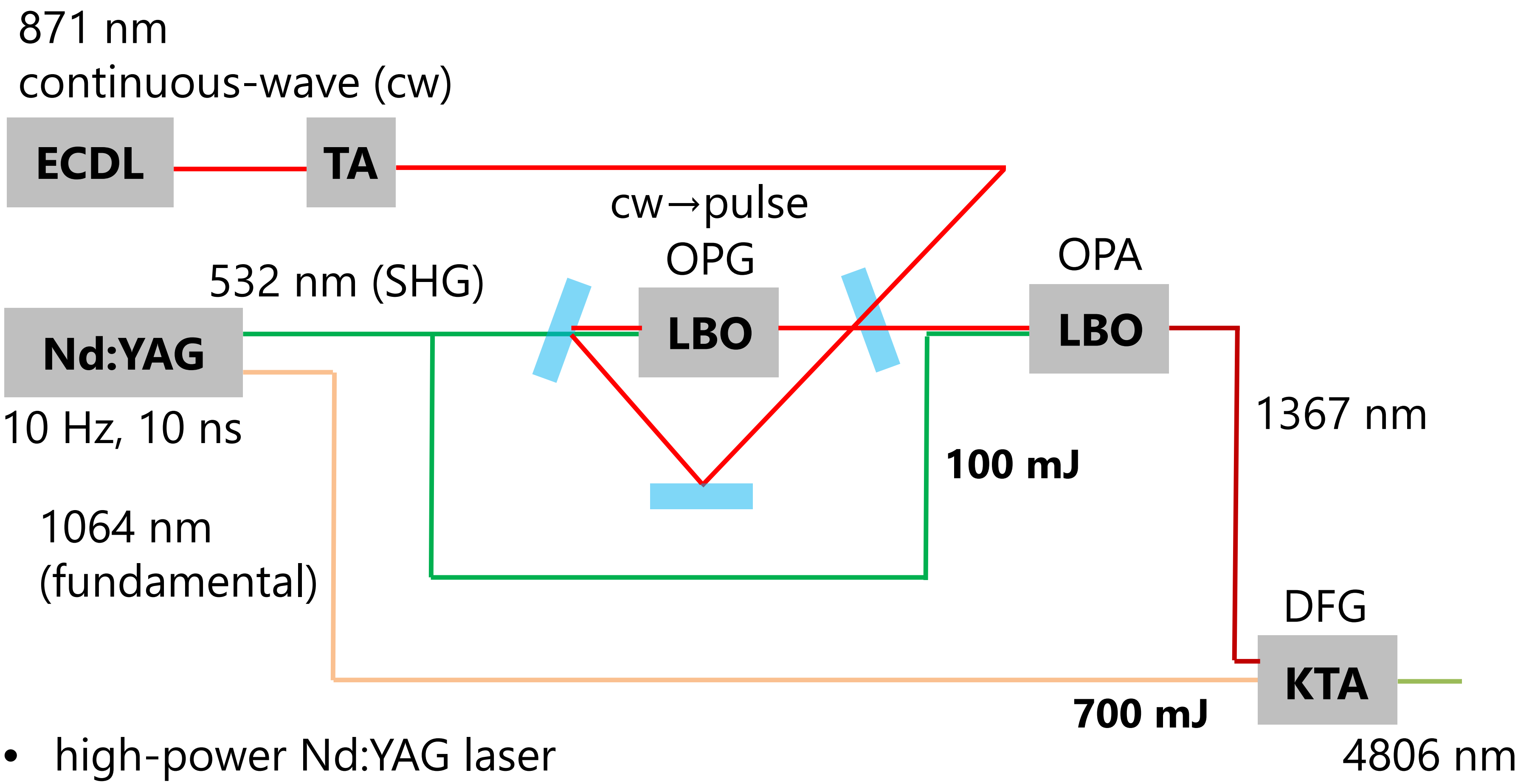
# Laser setup (previous experiment)

- We previously used a mid-infrared laser as the trigger.




- We use this laser as one of the trigger laser again.
- Intensity and linewidth of this laser are not enough for the excitation laser.

# Laser setup (new)

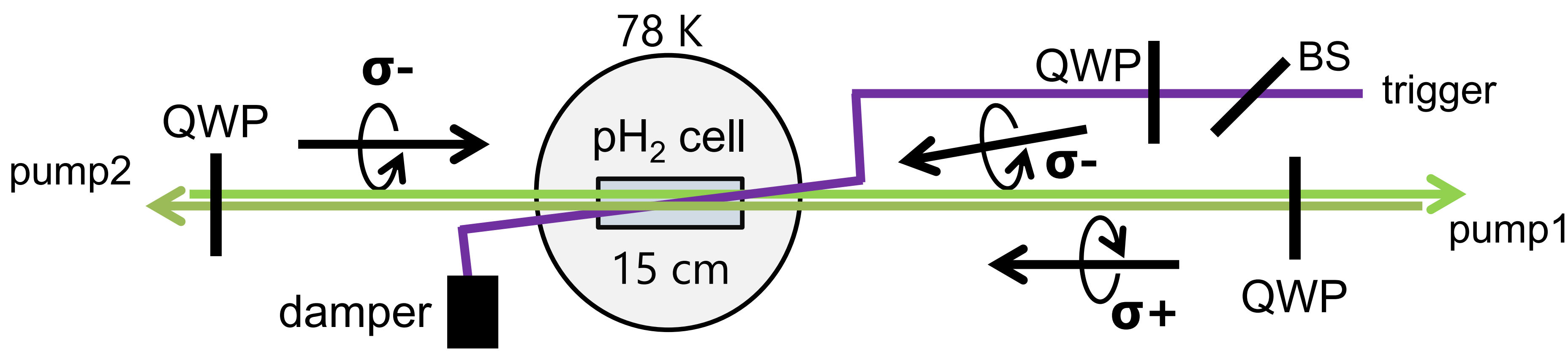


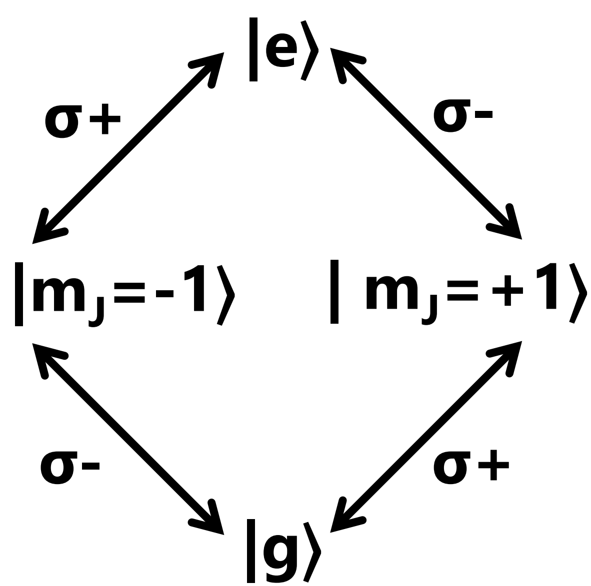

- high-power Nd:YAG laser
- adopt a cavity in the OPG section (effective injection seeder)

MIR pulse energy: ~5 mJ/pulse
MIR linewidth: ~150 MHz
MIR pulse duration: ~5 ns (FWHM)

significant improvement!

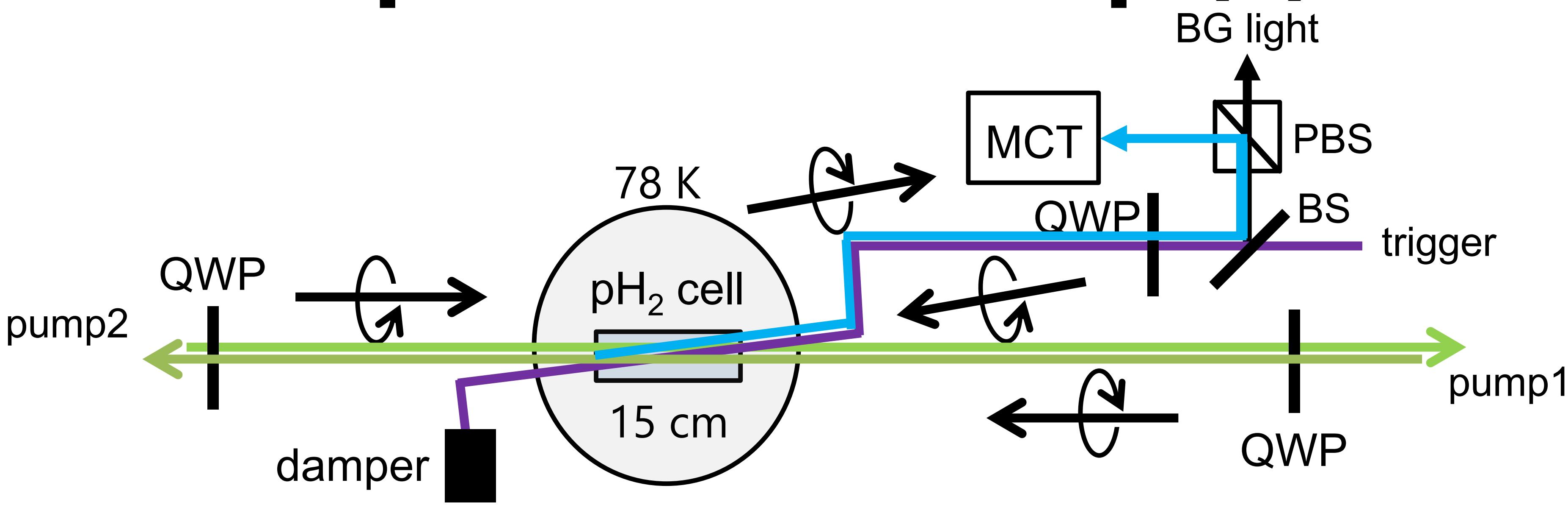
# Experimental setup (1)




- use circularly polarized beam
  - excitation by the single beam is not allowed
- inject pump and trigger beams simultaneously into the para-$H_2$ target

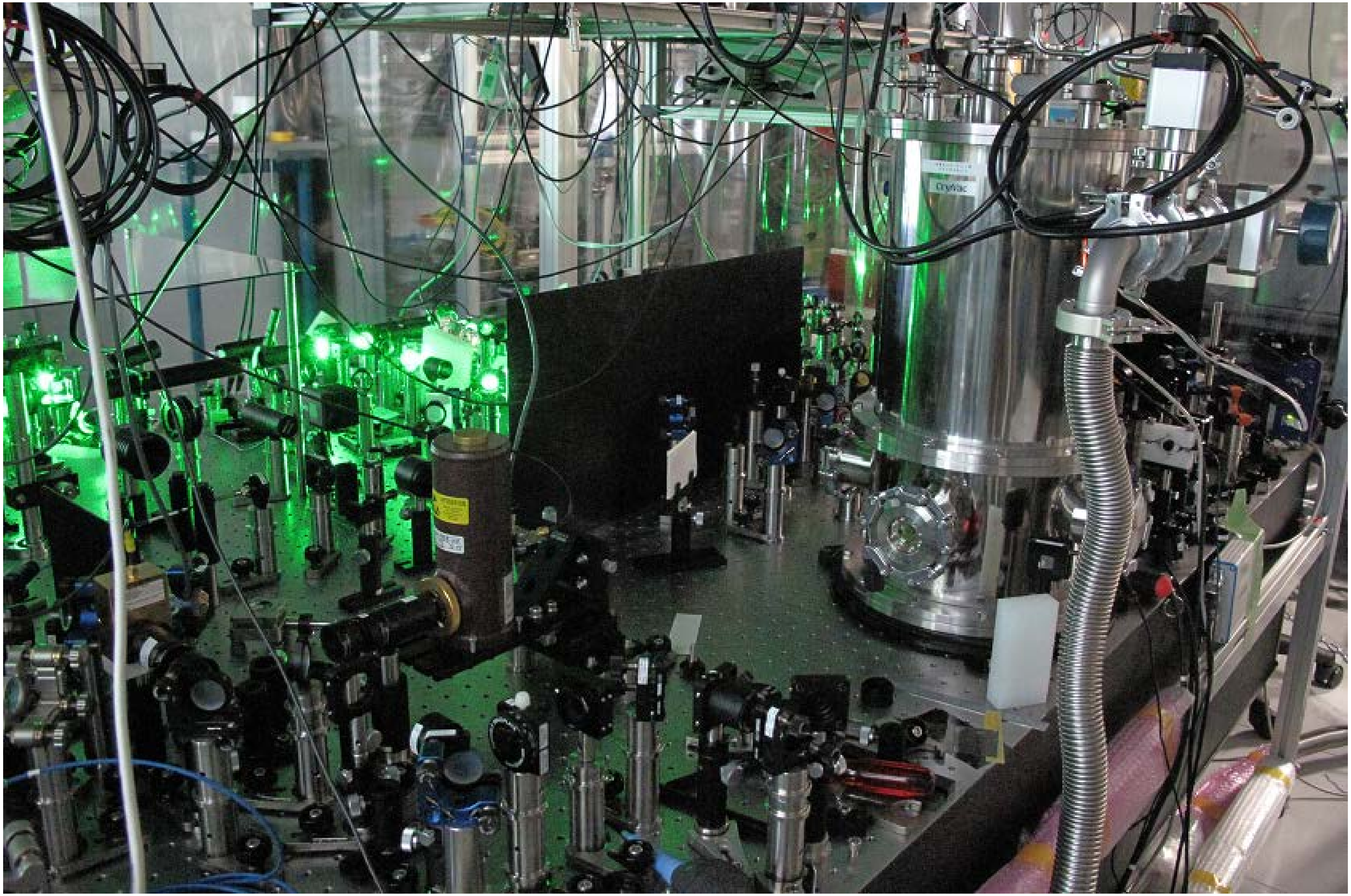
# Experimental setup (2)




- Signal light is generated by the trigger laser and advances in the backward direction
- amplification condition (momentum conservation)

- Wrong-polarization component of the background scattering light is reduced by using a polarized beam splitter.

# Experimental setup

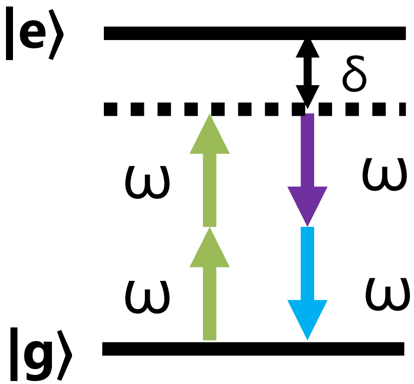


✓ Construction of the laser system was finished last year.

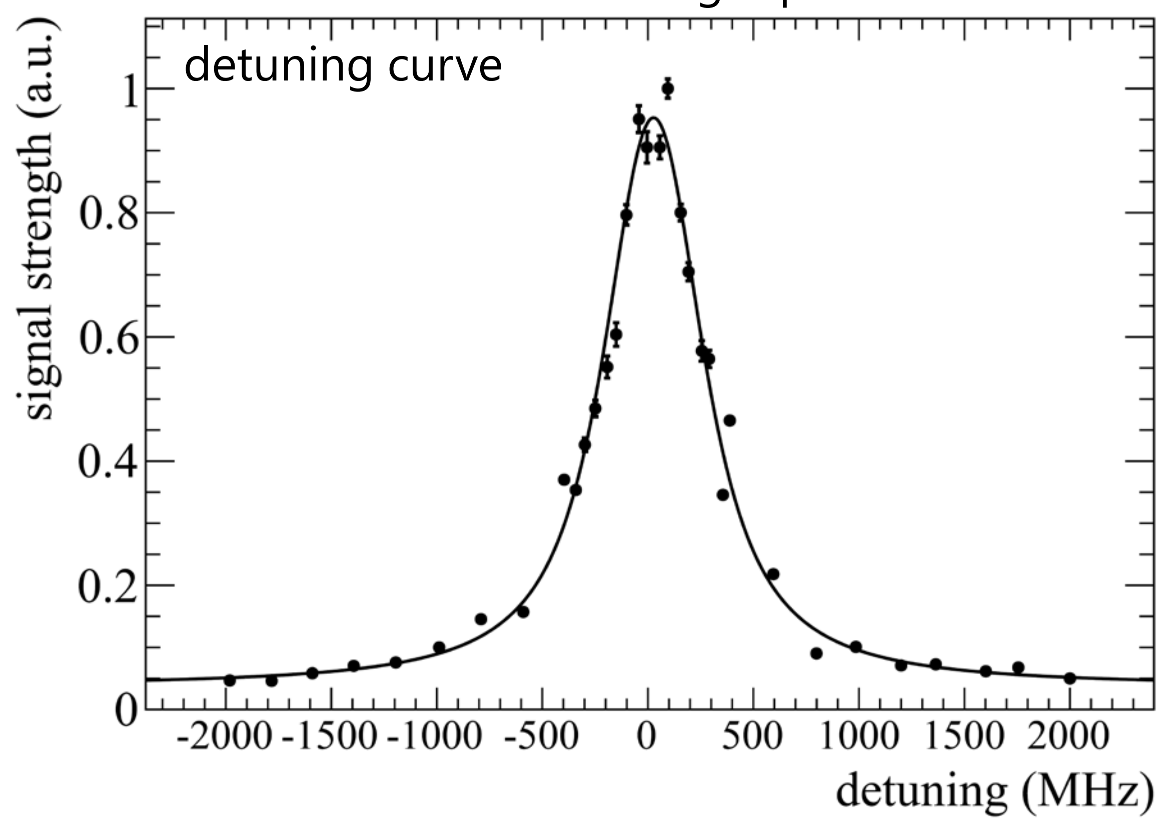
# Results: detuning dependence

- use the new mid-infrared laser as both pumps and trigger
  - pump energy: ~1 mJ/pulse, trigger energy: ~ 0.6 mJ/pulse

✓ vary the detuning δ




target pressure: 280 kPa

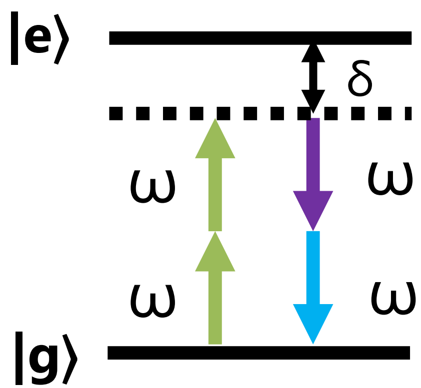


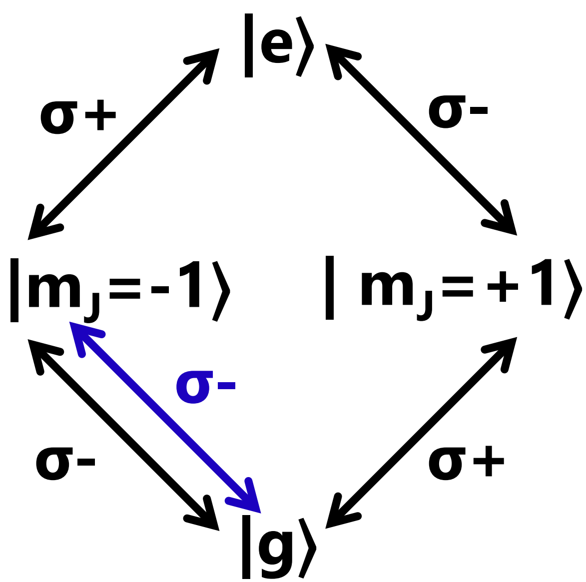

✓ Successfully observed a clear signal peak!

- Signal energy: ~20 nJ/pulse at δ=0

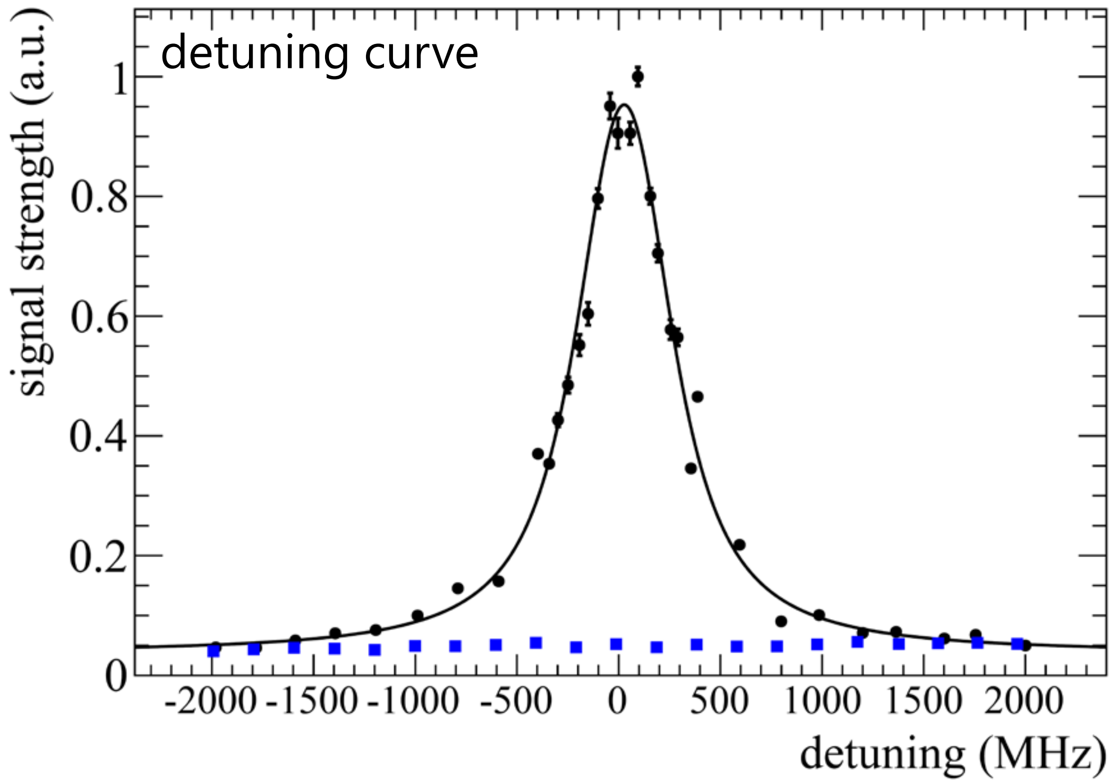
# Results: detuning dependence

- vary the detuning δ




target pressure: 280 kPa



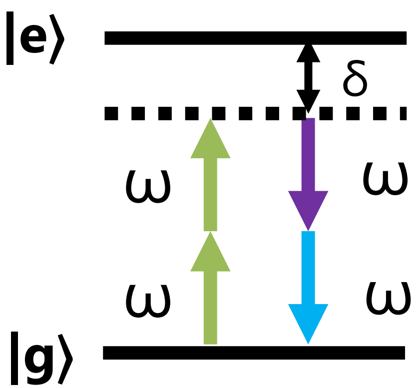

- Circular polarization of a pump is flipped.

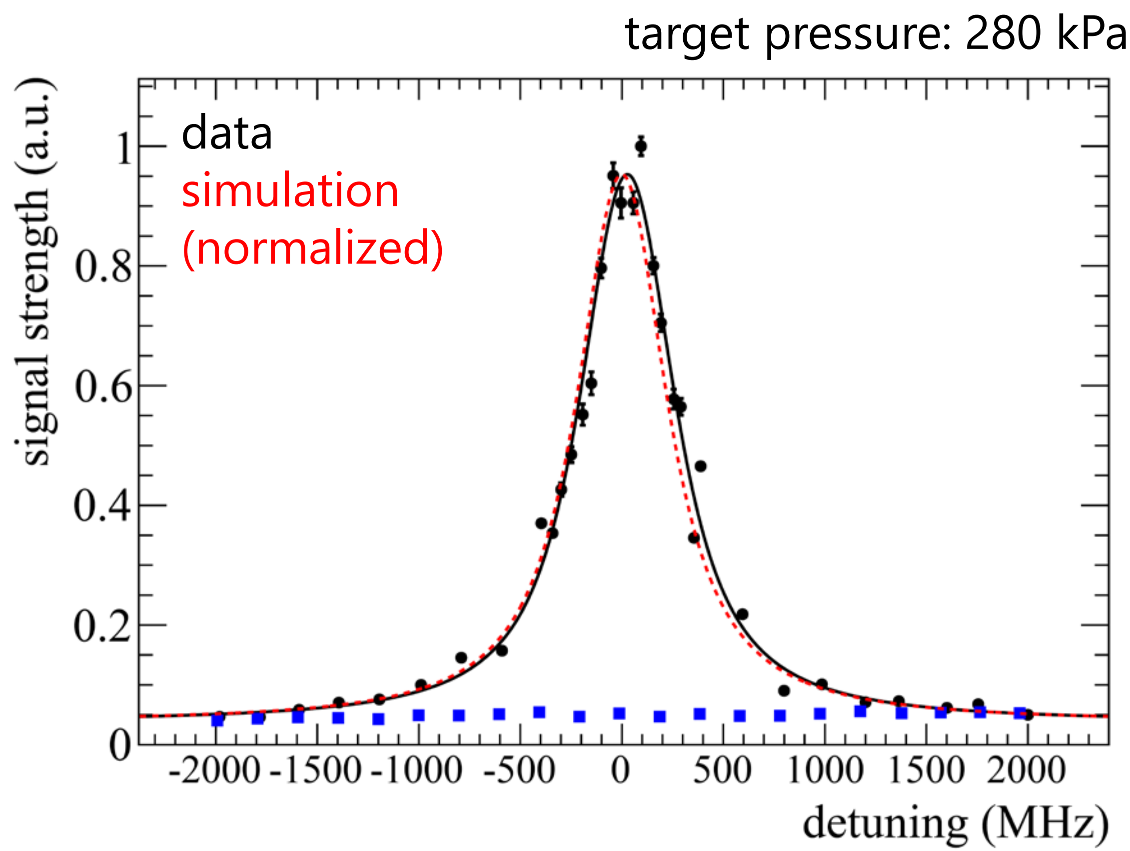
➡ no signal is observed.

- confirmation of the excitation by counter-propagating lasers

# Results: detuning dependence

- vary the detuning δ



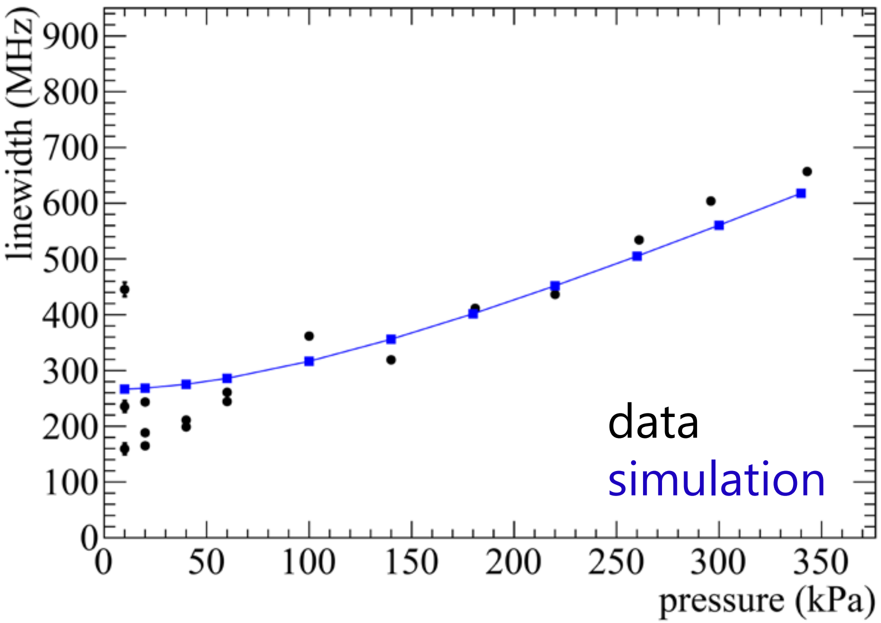




- comparison with simulation based on Maxwell-Bloch equations
- describe development of laser fields and coherence
- Though it is difficult to reproduce absolute signal intensity, curve shape is consistent between data and simulation.

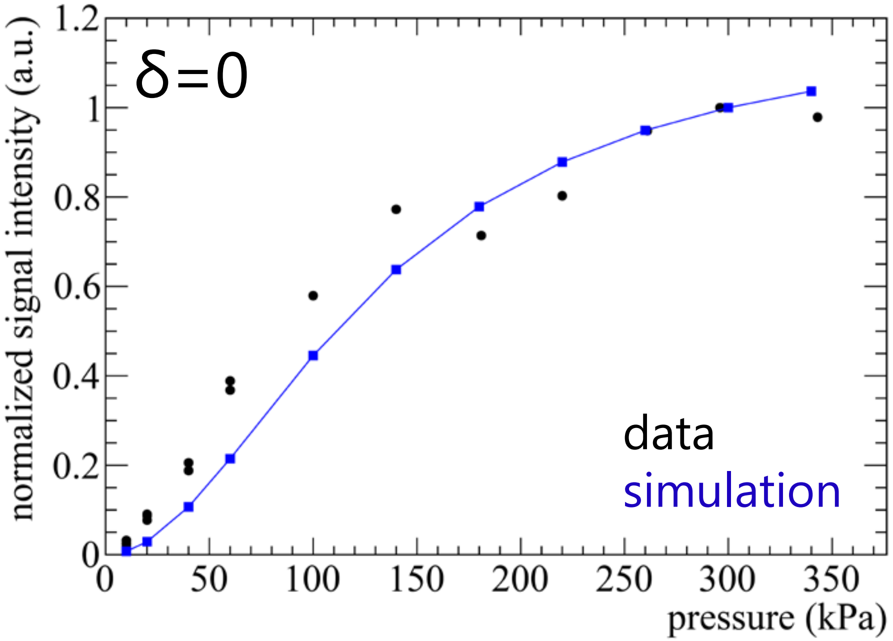
# Results: Pressure dependence

- vary the $pH_2$ target pressure

detuning curve width (FWHM)



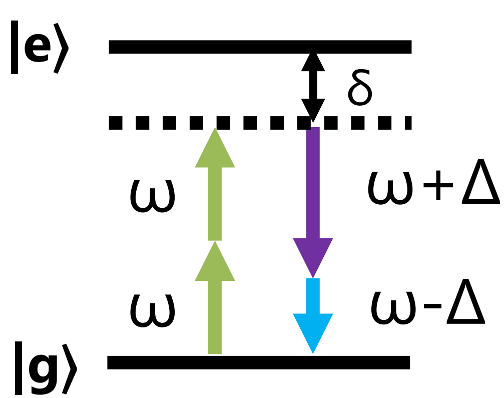

normalized intensity



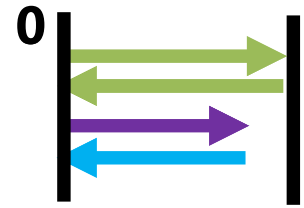

- Laser linewidth and pressure broadening determine the width
- Signal intensity increases as the target density larger.

✓ Consistent tendency is obtained between data and simulation.

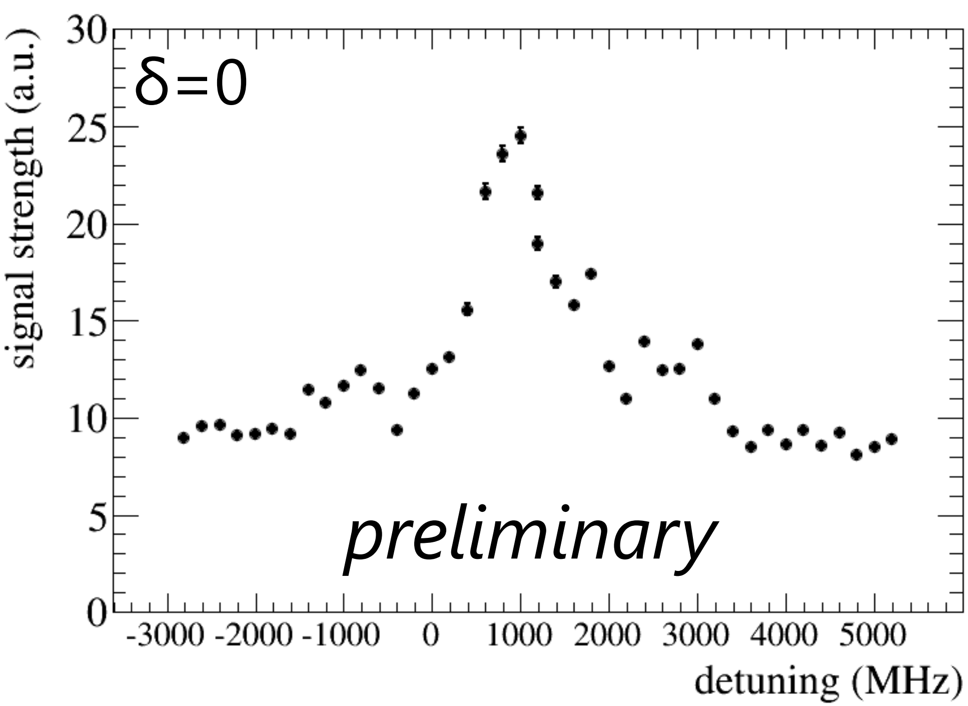
# trigger frequency dependence




- vary only the frequency of the trigger laser
- amplification condition requires Δ=0




- Setup construction is finished very recently




✓ A signal peak is observed
- obscure peak due to weaker trigger intensity

✓ Further studies (experiment/ simulation) will be conducted.

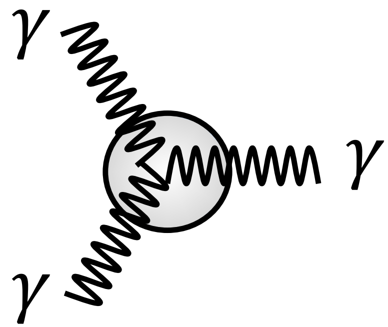
# Next step

# Higher QED process

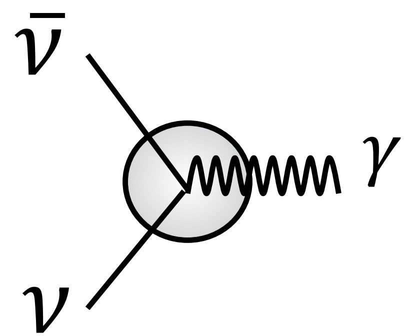
- study of coherent amplification of higher QED process
  - 2-photon E1×M1, 3-photon E1×E1×E1

Poster: K. Okai

**3-photon emission**




**RENP**

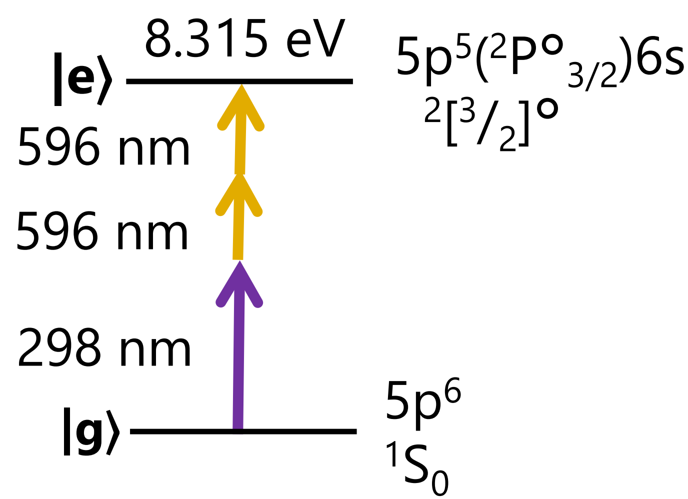



same kinematics

✓ Xe target:
one of the candidates
of the RENP experiment

- use metastable excited state
  - E1, E1×E1: forbidden
  - E1×M1, E1×E1×E1: allowed

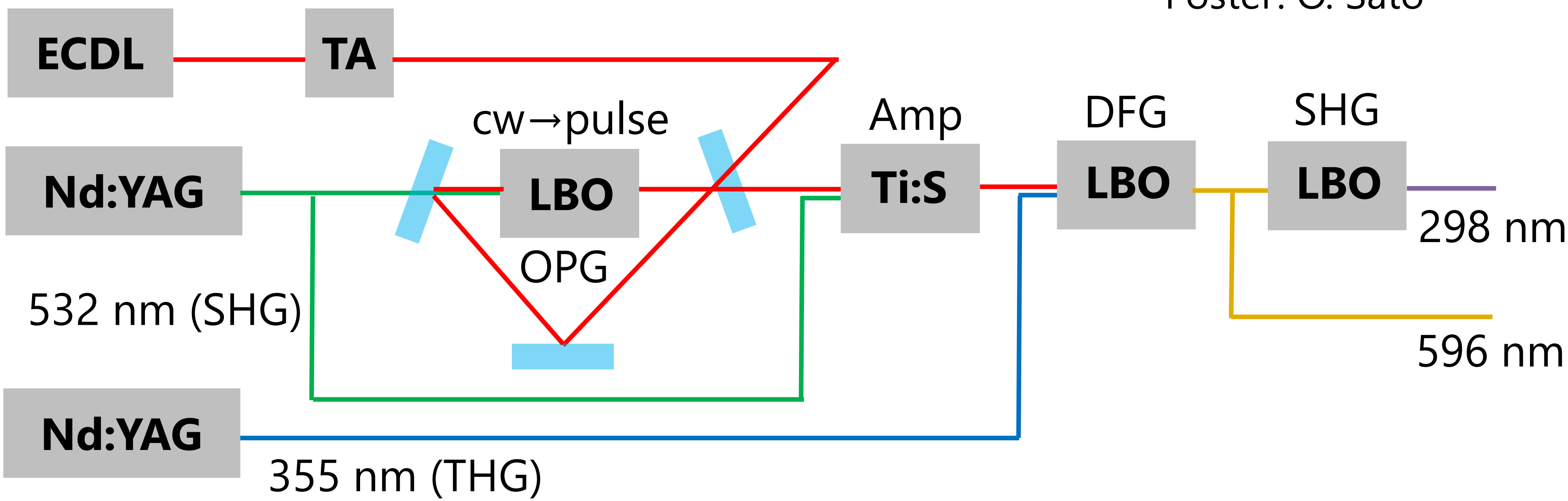
3-photon excitation



# Laser setup (Xe)

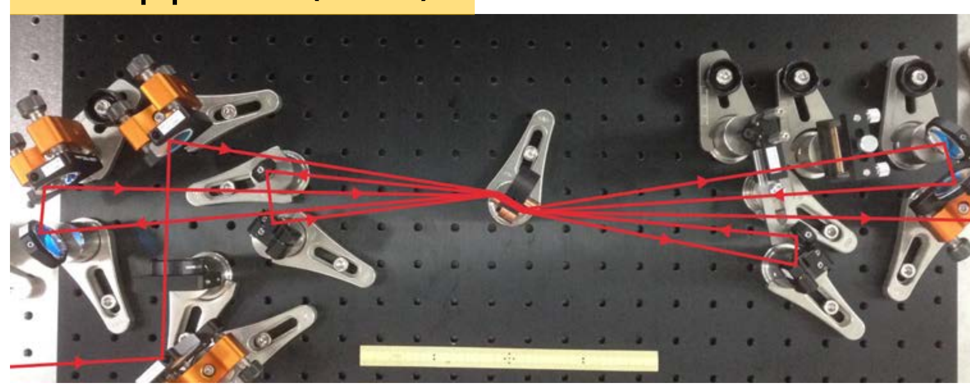
876 nm
continuous-wave (cw)

Poster: O. Sato




ECDL, LBO (OPG)

Ti:Sapphire (OPA)



✓ Experiment will start soon!

# Summary

## para-$H_2$ experiment

- coherence generation by counter-propagating laser
- observed two-photon emission signal
- further investigation ongoing

## Xe experiment

- coherent amplification of higher-order QED processes
- Laser system construction is almost finished and experiment will start soon.

# Back up

# Parahydrogen

ortho-$H_2$ | para-$H_2$

I (nuclear spin) =1

J=**1**, 3, 5…

I=0

J=**0**, 2, 4…

↖ dominant @ 78 K

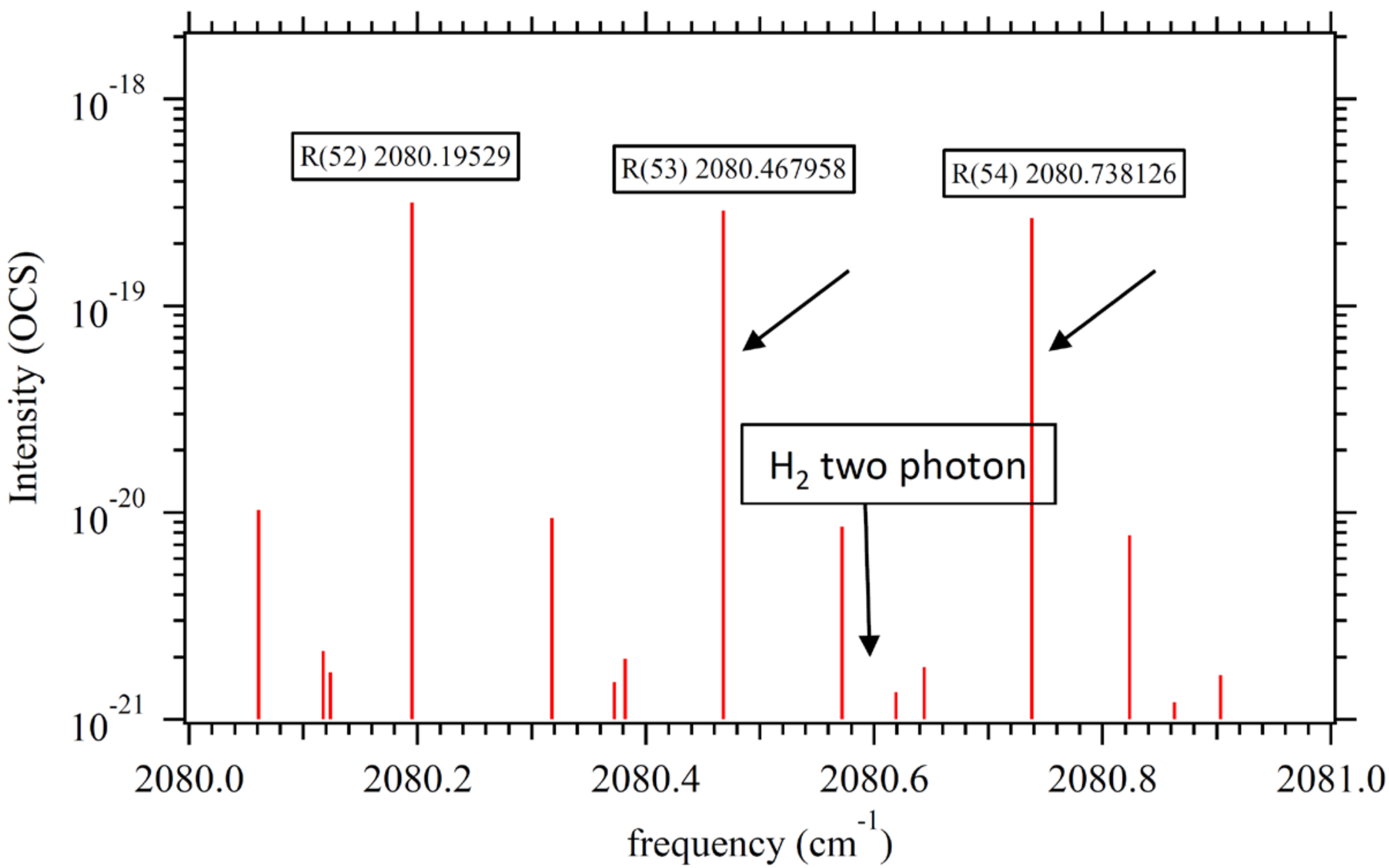
✓ J=0 (ground state) para-$H_2$: completely spherical wavefunction
➡ weak intermolecular interaction
➡ longer decoherence time

- generate high-purity (>99.9%) para-$H_2$ from normal $H_2$

- converter: cooled to 13.8 K, FeO(OH) as magnetic catalyst

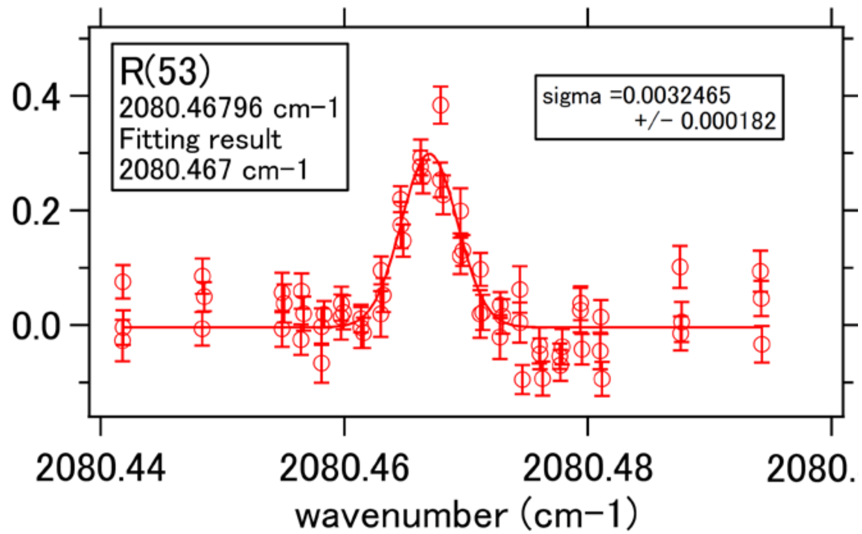
# Laser linewidth measurement

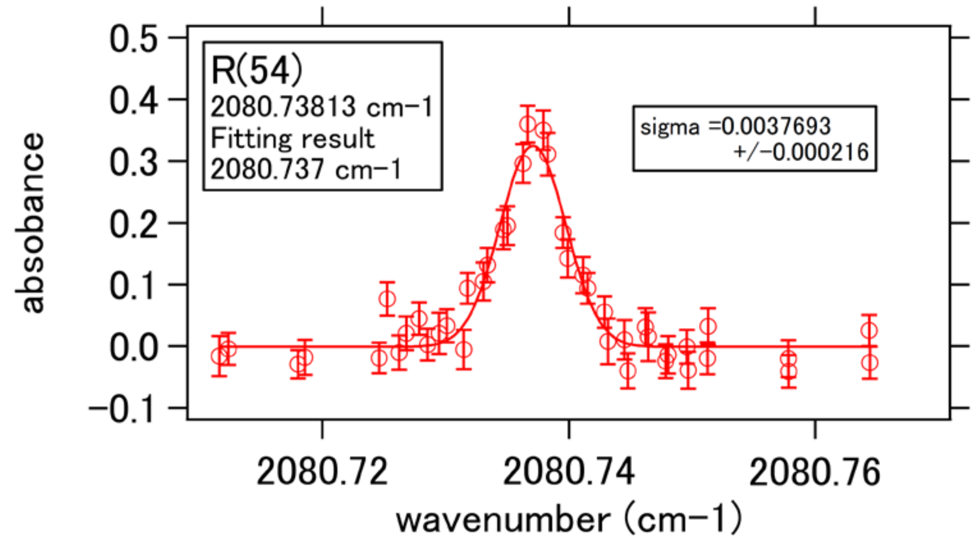
- measurement of the narrow-linewidth MIR laser
- method: absorption spectroscopy of carbonyl sulfide (OCS)



# Laser linewidth

- observed absorption spectra




| | width (FWHM) |
|---|---|
| Observed linewidth | 175 (13) |
| Doppler width | 99 |
| **MIR Laser linewidth** | **145 (16)** |

✓ narrow laser linewidth (~1.6×FT-limit ) is achieved.

# Maxwell-Bloch equations

## Development of the density matrix

$$\frac{\partial \rho_{gg}}{\partial t} = \mathrm{i}(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}) + \gamma_1 \rho_{ee},$$

$$\frac{\partial \rho_{ee}}{\partial t} = \mathrm{i}(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}) - \gamma_1 \rho_{ee},$$

$$\frac{\partial \rho_{ge}}{\partial t} = \mathrm{i}(\Omega_{gg} - \Omega_{ee} + \delta)\rho_{ge} + \mathrm{i}\Omega_{ge}(\rho_{ee} - \rho_{gg}) - \gamma_2 \rho_{ge}.$$

ρ: density matrix

$\Omega_{gg(ee)}$: two-photon Rabi frequency

$\Omega_{eg(ge)}$: AC Stark shift

$\gamma_1$, $\gamma_2$ :relaxation rates

δ: detuning

## Development of the electric fields

$$\left(\frac{\partial}{\partial t} - c\frac{\partial}{\partial z}\right) E_{\mathrm{p1}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{p1}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{p2}}\right),$$

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right) E_{\mathrm{p2}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{p2}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{p1}}\right),$$

$$\left(\frac{\partial}{\partial t} - c\frac{\partial}{\partial z}\right) E_{\mathrm{trig}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{trig}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{sig}}\right),$$

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right) E_{\mathrm{sig}} = \frac{\mathrm{i}\omega_l N_t}{2}\left((\alpha_{gg}\rho_{gg} + \alpha_{ee}\rho_{ee})E_{\mathrm{sig}} + 2\alpha_{eg}\rho_{eg}E^*_{\mathrm{trig}}\right).$$

$\omega_l$: laser frequency

$N_t$: target density

α: polarizability