Coherent Two-Photon Emission Towards Neutrino Mass Spectroscopy using Atoms

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RIKEN

Remaining Problems on Neutrino

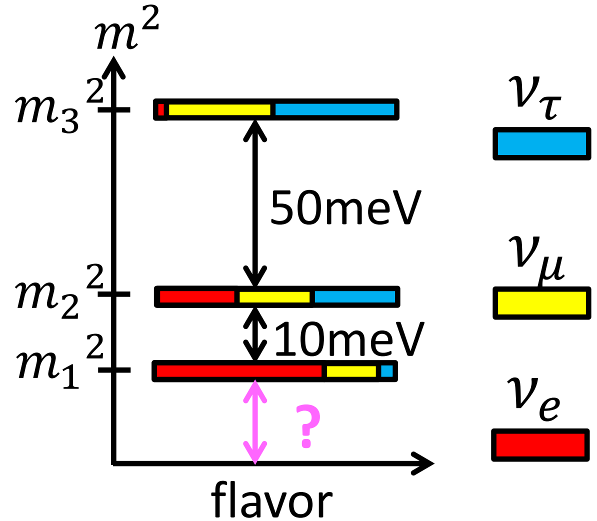
The Nobel Prize in Physics 2015 was awarded "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

$$|\nu_\alpha\rangle = \sum_{i=1,2,3} U_{\alpha i}|\nu_i\rangle$$

flavor eigenstate (α=e,μ,τ) mass eigenstate

remaining problems

absolute masses



normal hierarchy

$$m_1 < m_2 < m_3$$

inverted hierarchy

$$m_3 < m_1 < m_2$$

mass type (Dirac or Majorana) $\nu = \bar{\nu}$?

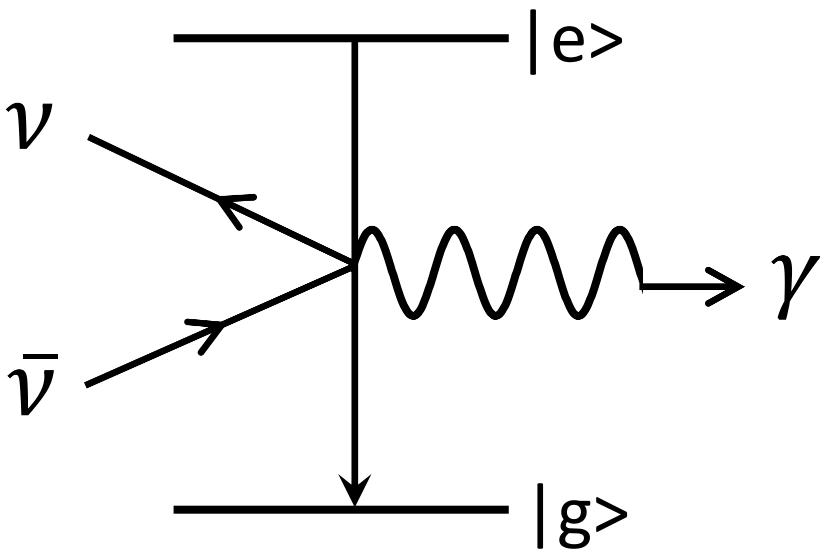
CP phase (α, β, δ)

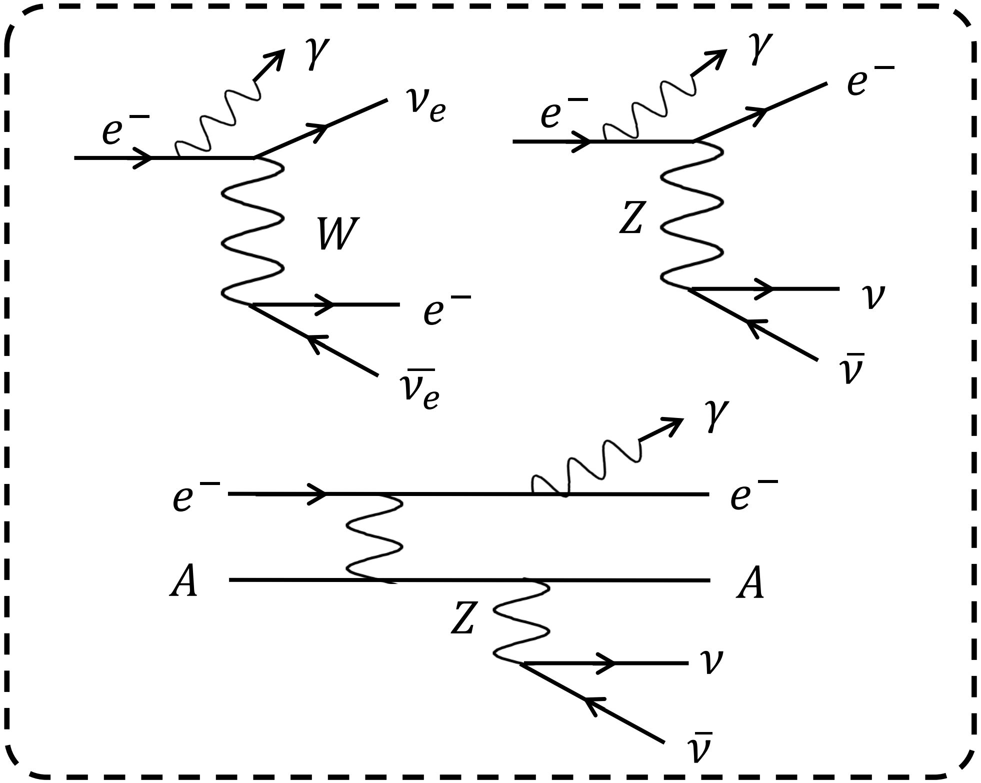
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Our Solution : RENP

Radiative Emission of Neutrino Pair with a photon

$$|e\rangle \rightarrow |g\rangle + \gamma\nu\bar{\nu}$$



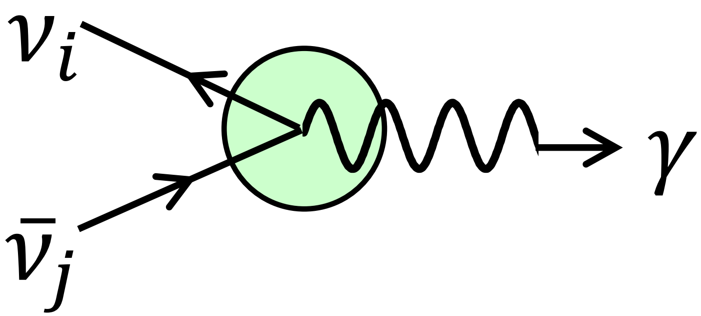


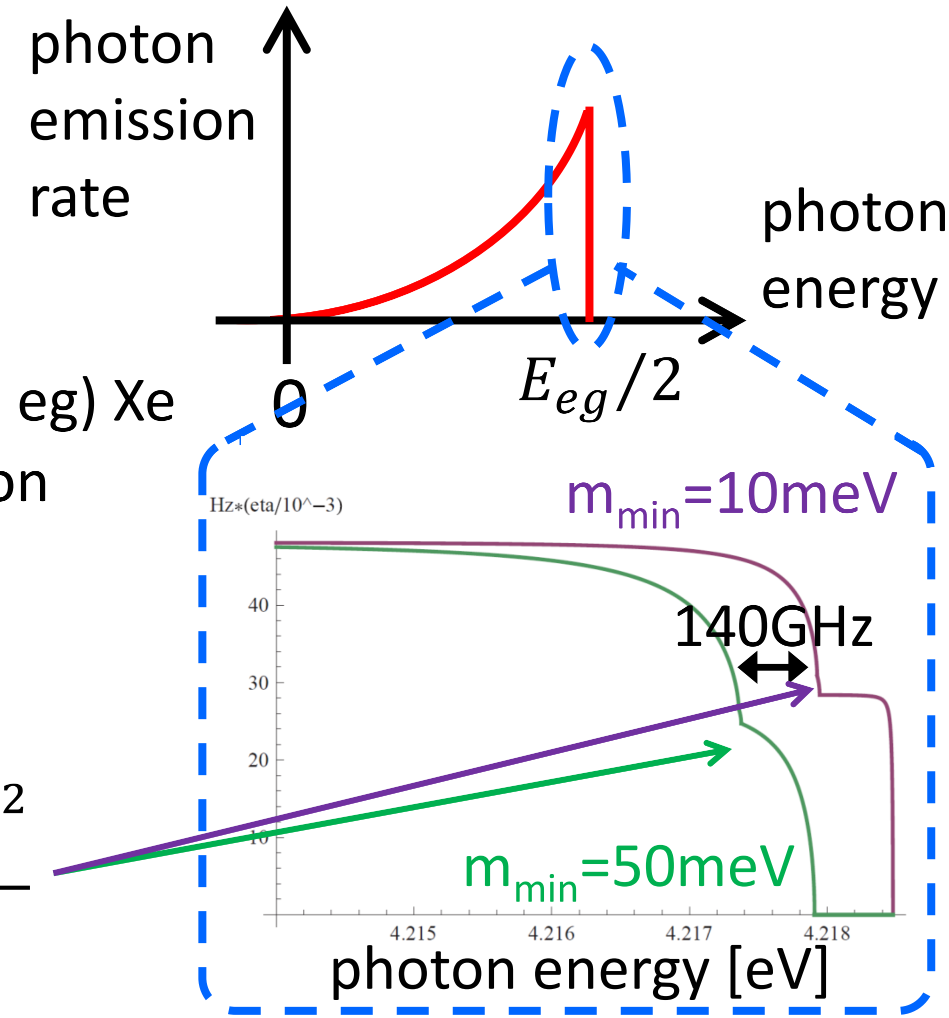
The emitted photon has information about parameters of neutrinos.

PTEP 2012, 04D002 (2012)

RENP spectrum

$$|e\rangle \rightarrow |g\rangle + \gamma\nu_i\bar{\nu}_j$$





energy and momentum conservation

$$E_{eg} = E_\gamma + E_i + E_j$$

$$0 = \vec{k}_\gamma + \vec{p}_i + \vec{p}_j$$

$$E_\gamma{}^{th} = \frac{E_{eg}}{2} - \frac{\{(m_i + m_j)c^2\}^2}{2E_{eg}}$$

Neutrino masses can be determined by laser spectroscopy!

Advantage and Disadvantage

Neutrino masses can be determined by laser spectroscopy!

- Energy scales are almost the same order.

  $E_{eg} \sim m_\nu c^2$ (~eV)

- Spectrum of RENP is sensitive to all of absolute mass, hierarchy, mass type, and CP phase.

RENP is very rare event.

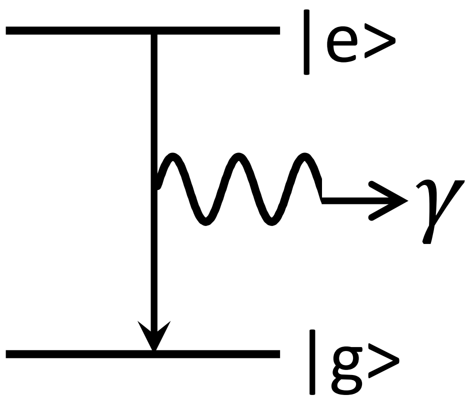
Γ_{RENP} ~ 10^{-34} Hz (1/10^{26} year) for E_{eg} ~ 1eV

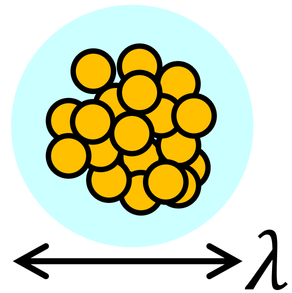
We will amplify such small rate by using **macro-coherence** among atoms.

Macro-Coherent Amplification

familiar example : **super radiance**

R. H. Dicke, PR 93, 99 (1954)

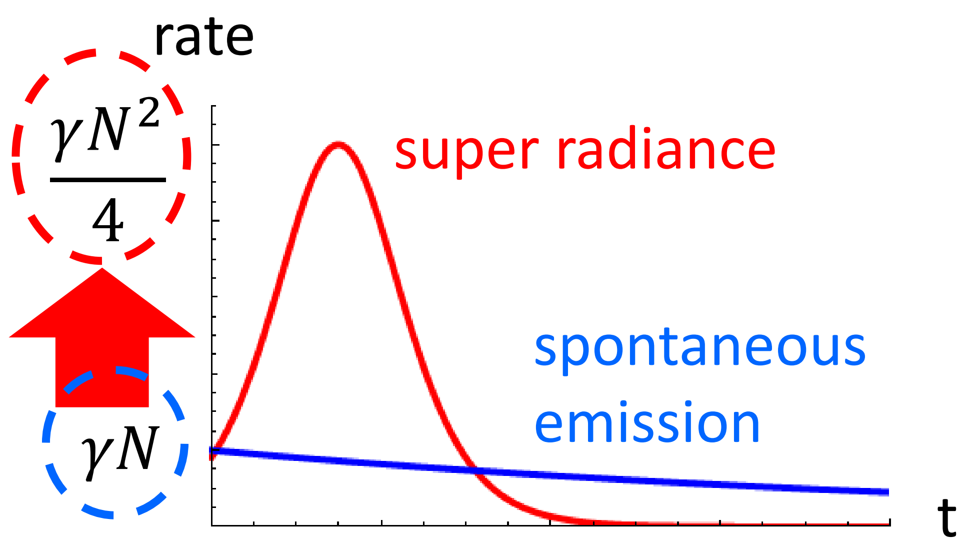




$r_a \ll \lambda$

rate

$$R_\gamma = \left|\sum_a^N \exp\left(\underbrace{i\vec{k}\cdot\vec{r}_a}_{=0}\right) M_a\right|^2 \approx N^2|M_a|^2$$



Rate ∝ N^2 (amplified)

Macro-Coherent Amplification

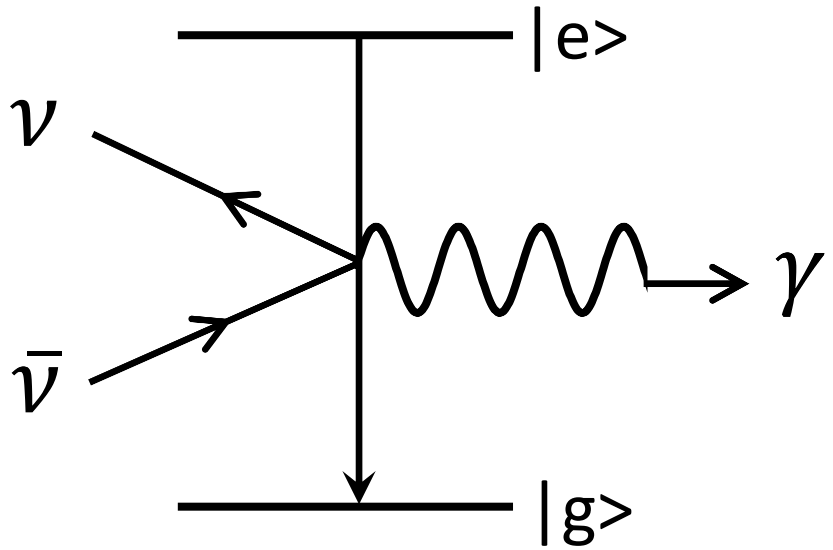
How about multi-particle emission cases?

Similar enhancement should occur
when the following momentum conservation law is satisfied.

$$R_{\gamma\nu\bar{\nu}} = \left|\sum_a^N \exp\left(i\underbrace{\left(\vec{k}_\gamma + \vec{k}_\nu + \vec{k}_{\bar{\nu}}\right)}_{=0} \cdot \vec{r}_a\right) M_a\right|^2 \propto N^2 |M_a|^2$$

energy and momentum conservation

$$E_{eg} = E_\gamma + E_i + E_j$$
$$0 = \vec{k}_\gamma + \vec{k}_i + \vec{k}_j$$



We call this mechanism "macro-coherent amplification".

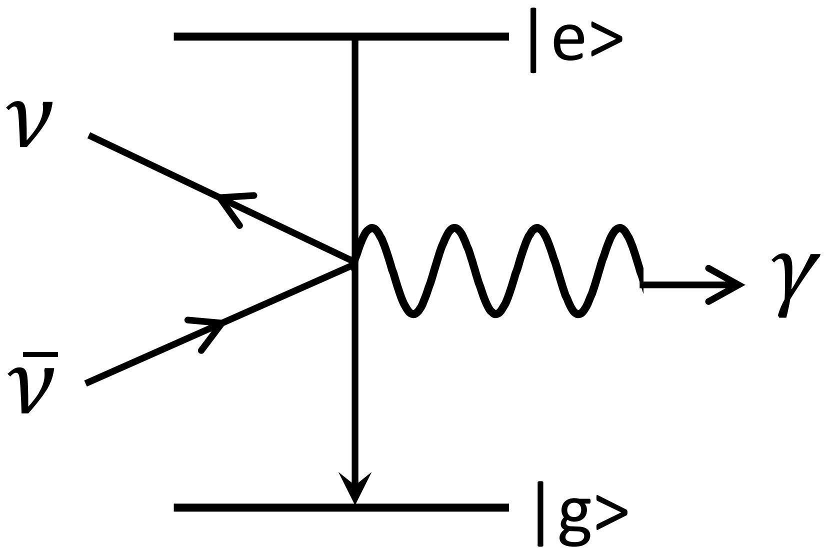
Is such enhancement possible?

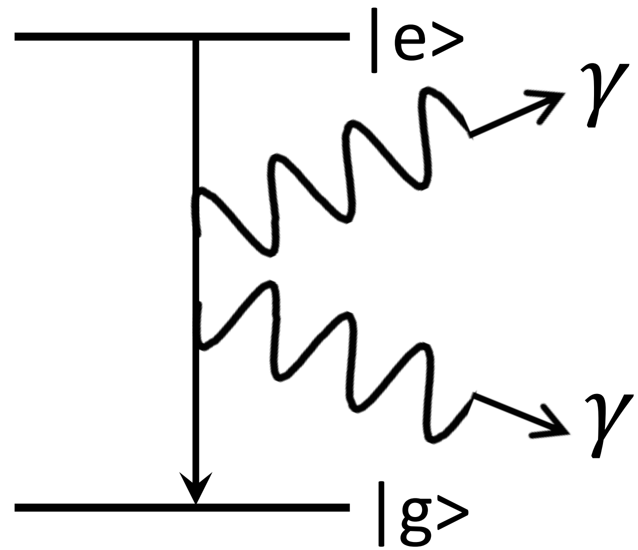
We demonstrate amplification of multi-particle emission process.

Macro-Coherent Amplification

our goal : RENP

this talk :
coherent two-photon emission





weak interaction
⇒ difficult to observe

QED process
⇒ easier to observe than RENP

Contents

① introduction

② experimental setup (target, laser, coherence)

arXiv:1511.00409
PTEP 2014, 113C01 (2014)

③ result (spectrum, parameter dependence)

PTEP 2015, 081C01 (2015)

④ future plan

Contents

Idea

$$|\psi\rangle = \cos\theta|g\rangle + \sin\theta\, e^{-i\varphi}|e\rangle$$

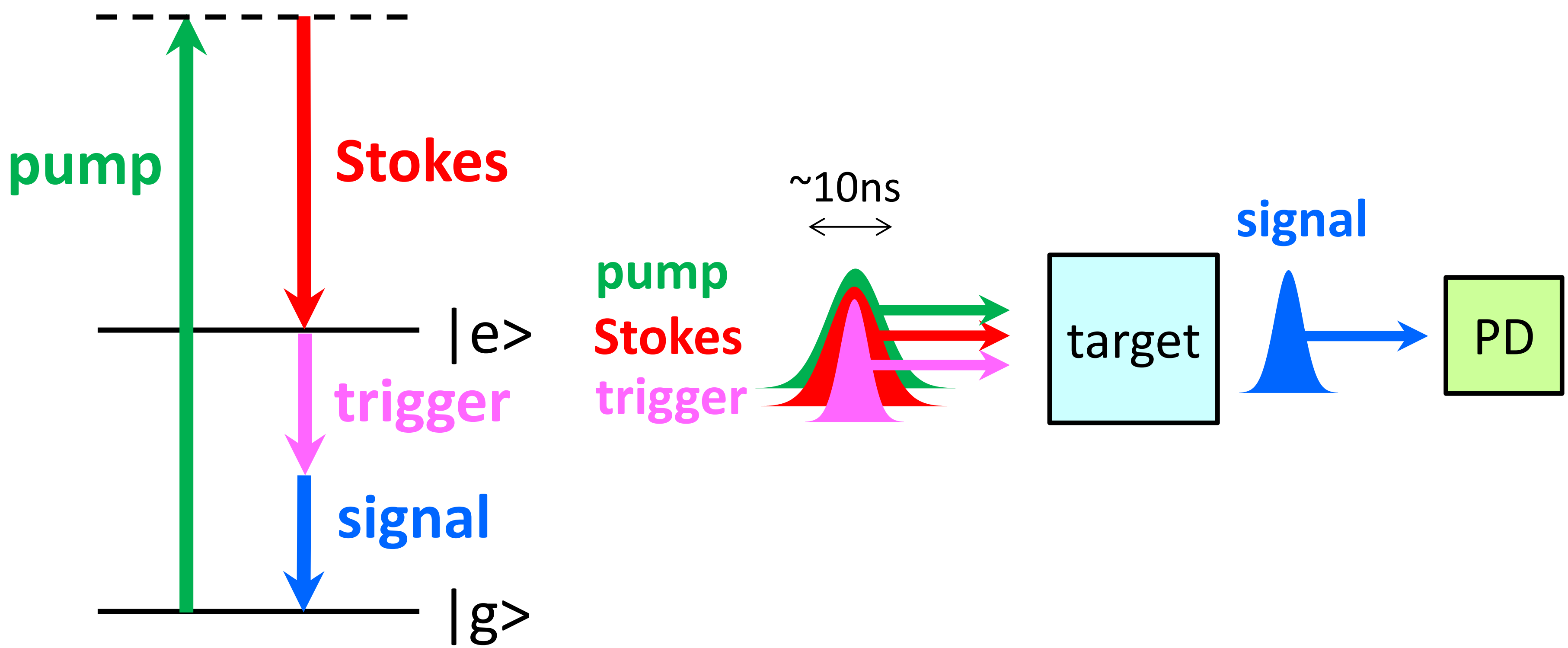
coherence :

$$\rho_{ge} = \frac{1}{2}\sin 2\theta\, e^{i\varphi}$$ (max 0.5)

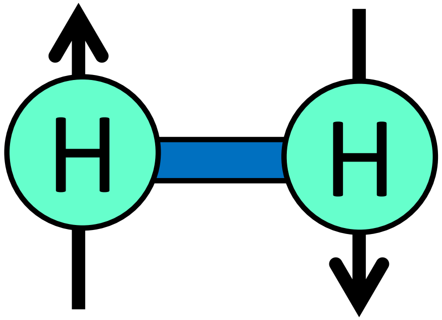
① generate coherence by adiabatic Raman transition

② irradiate trigger pulse

③ detect two-photon emission signal pulse energy

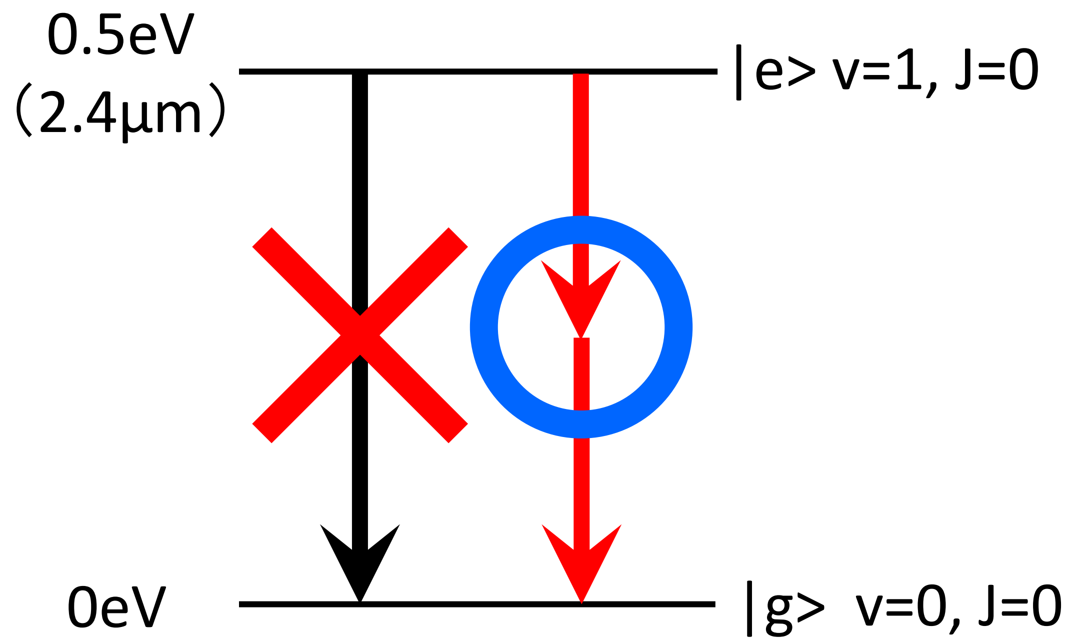


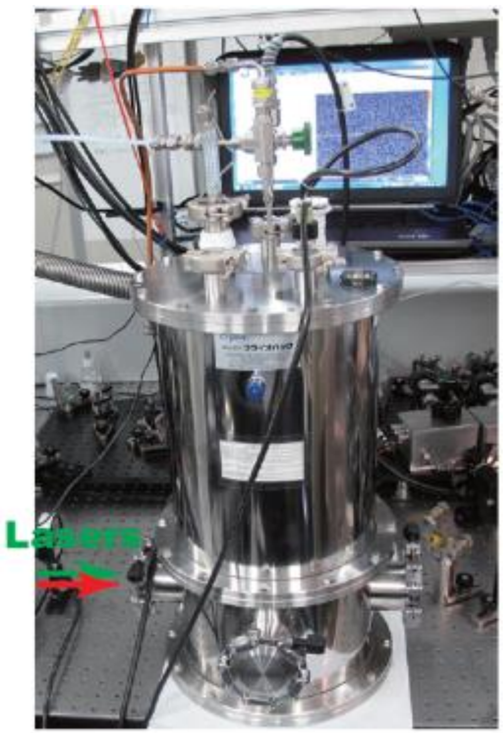
Target : Para-H_2



nuclear spin $I = 0$
rotation $J = 0, 2, 4, \cdots$

vibrational transition (of homonuclear molecule)
⇒ One-photon (E1) transition is forbidden.
Two-photon transition is allowed.

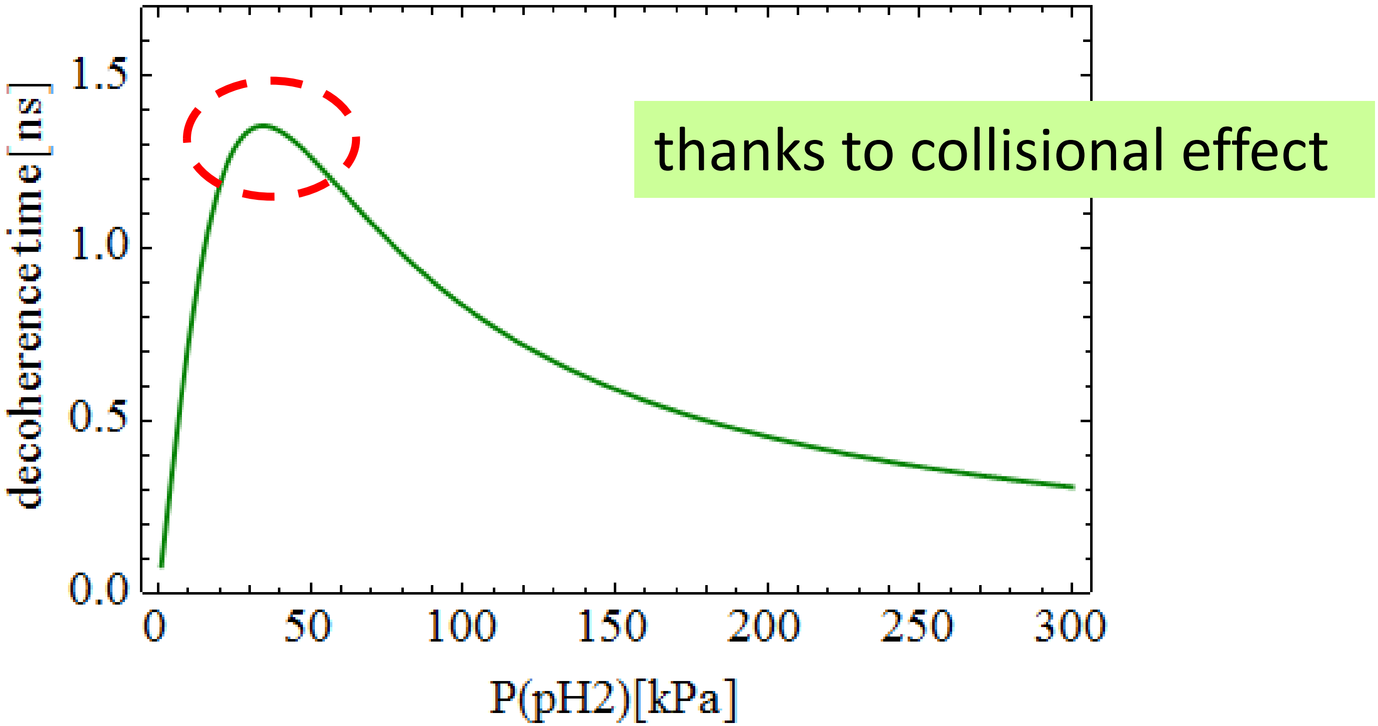




p-H2 gas in liquid N_2 cryostat [T=78K]
Almost all p-H_2 are in |g>.

Decoherence Time

In order to observe coherent phenomena, decoherence is undesirable.

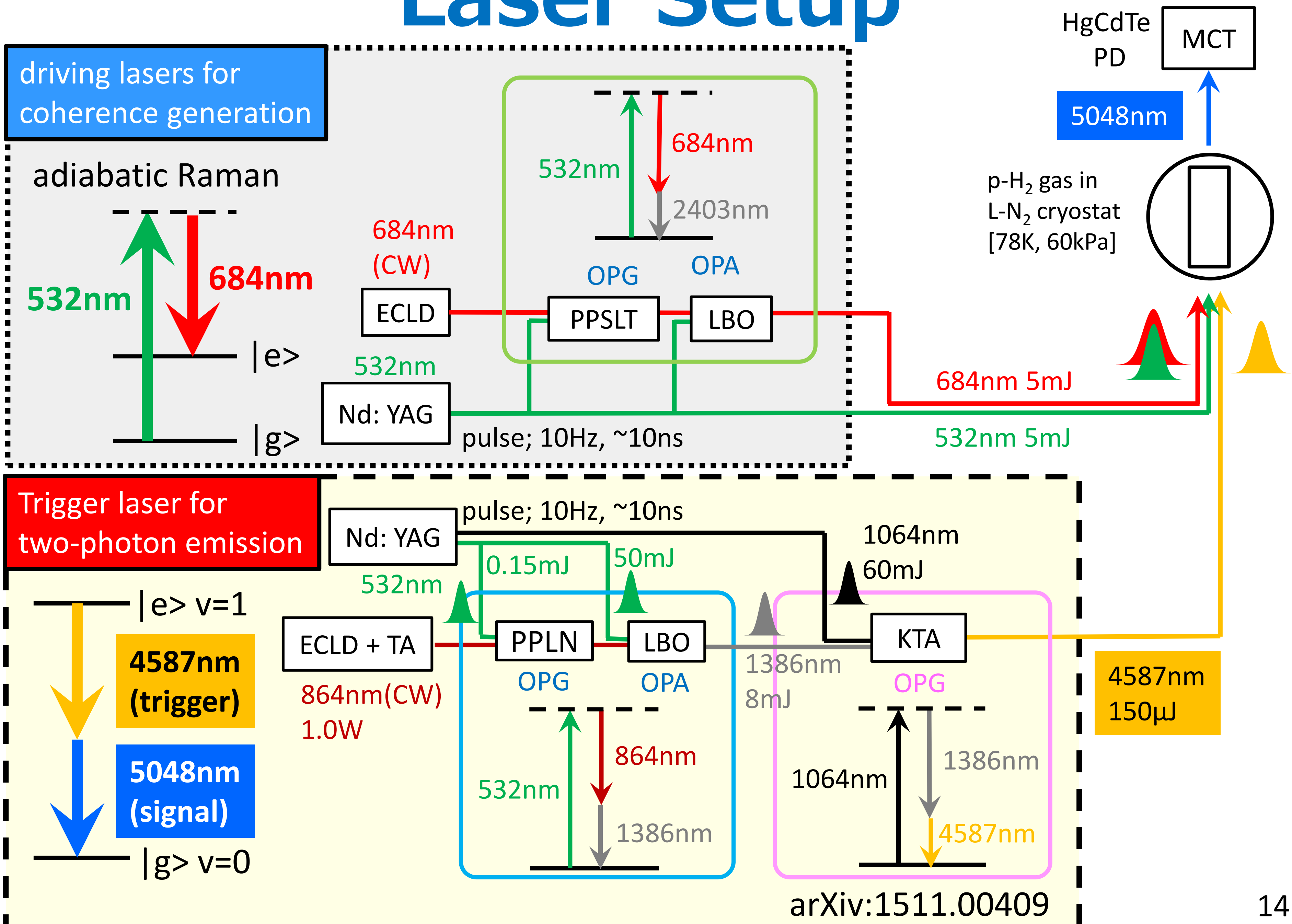


W. K. Bischel and M. J. Dyer , PRA 33, 3113 (1986)

[P=60kPa]

Decoherence time is relatively long.

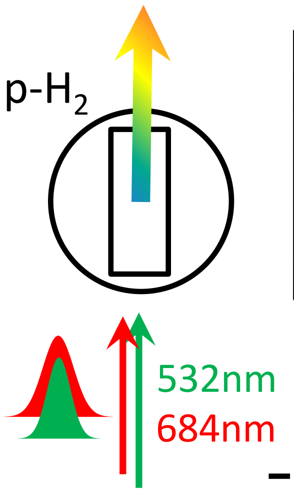
Laser Setup

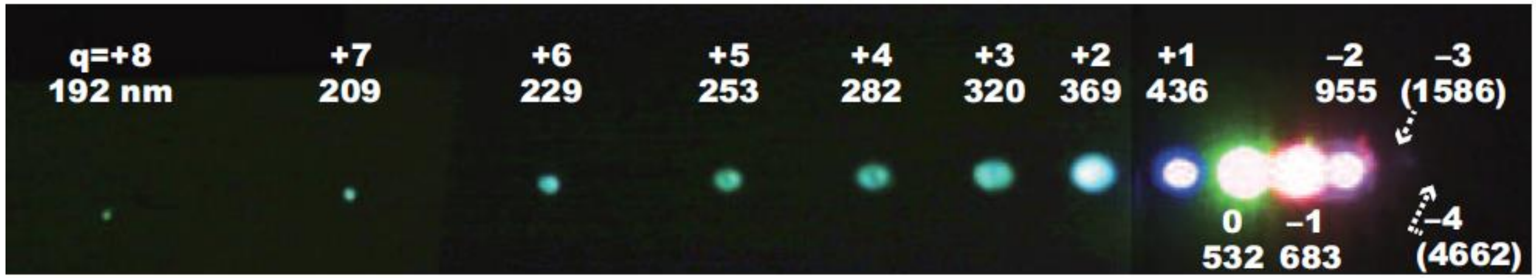


arXiv:1511.00409

Coherence

Coherence is estimated from Raman sidebands.

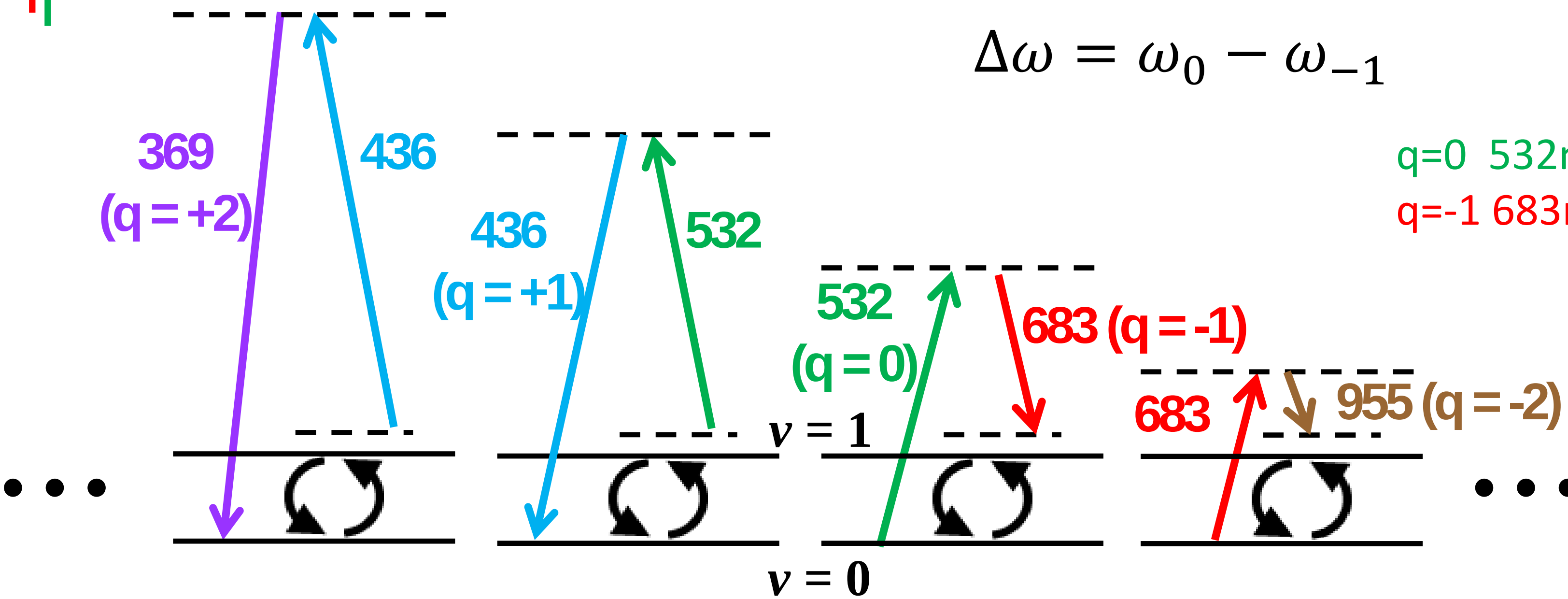




q-th sideband $\quad \omega_q = \omega_0 + q\Delta\omega$

$$\Delta\omega = \omega_0 - \omega_{-1}$$

q=0 532nm
q=-1 683nm



PTEP 2014, 113C01 (2014)

Maxwell-Bloch Equations

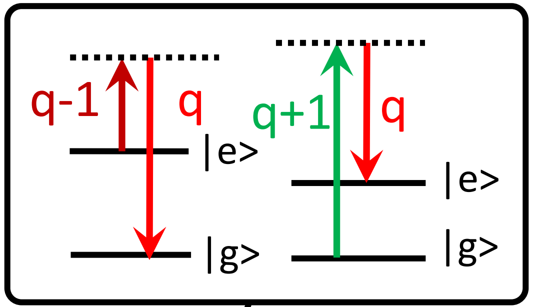
Bloch eq.(development of density matrix)

$$\frac{\partial \rho_{gg}}{\partial \tau} = i\left(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\right) + \gamma_1{}^{(g)}\rho_{ee}$$

$$\frac{\partial \rho_{ee}}{\partial \tau} = i\left(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}\right) - \gamma_1{}^{(e)}\rho_{ee}$$

$$\frac{\partial \rho_{ge}}{\partial \tau} = i\left(\Omega_{gg} - \Omega_{ee} + \delta\right)\rho_{ge} + i\Omega_{ge}\left(\rho_{ee} - \rho_{gg}\right) - \gamma_2\rho_{ge}$$

Raman sidebands

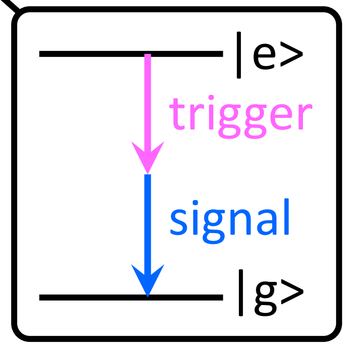


Maxwell eq.(propagation of Electric field)

$$\frac{\partial E_q}{\partial \xi} = \frac{i\omega_q n}{c}\left\{\left(\rho_{gg}a_q + \rho_{ee}b_q\right)E_q + \underline{\rho_{eg}d_{q-1}E_{q-1} + \rho_{ge}d_q{}^{*}E_{q+1}}\right\}$$

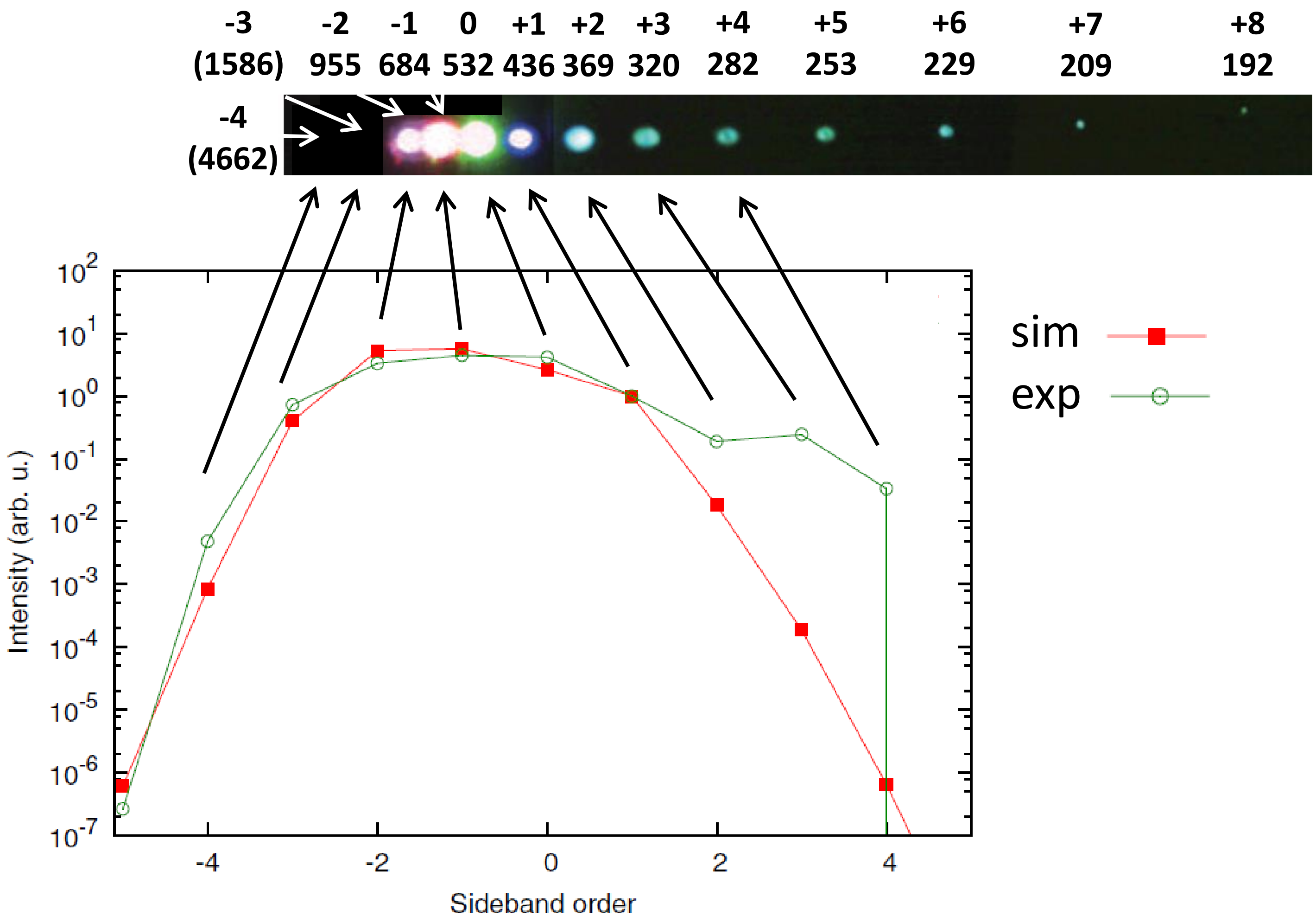
$$\frac{\partial E_{sig}}{\partial \xi} = \frac{i\omega_{sig} n}{c}\left\{\left(\rho_{gg}a_{sig} + \rho_{ee}b_{sig}\right)E_{sig} + \underline{\rho_{eg}\left(d_{trig} + d_{sig}\right)E_{trig}{}^{*}}\right\}$$

coherent
two-photon
emission



Coherence

compare the energies of the experiment and those of the simulation



coherence $|\rho_{ge}| \sim 0.04$
8% of maximum

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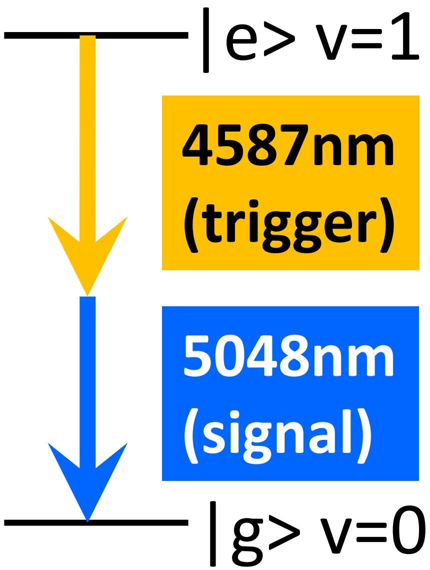
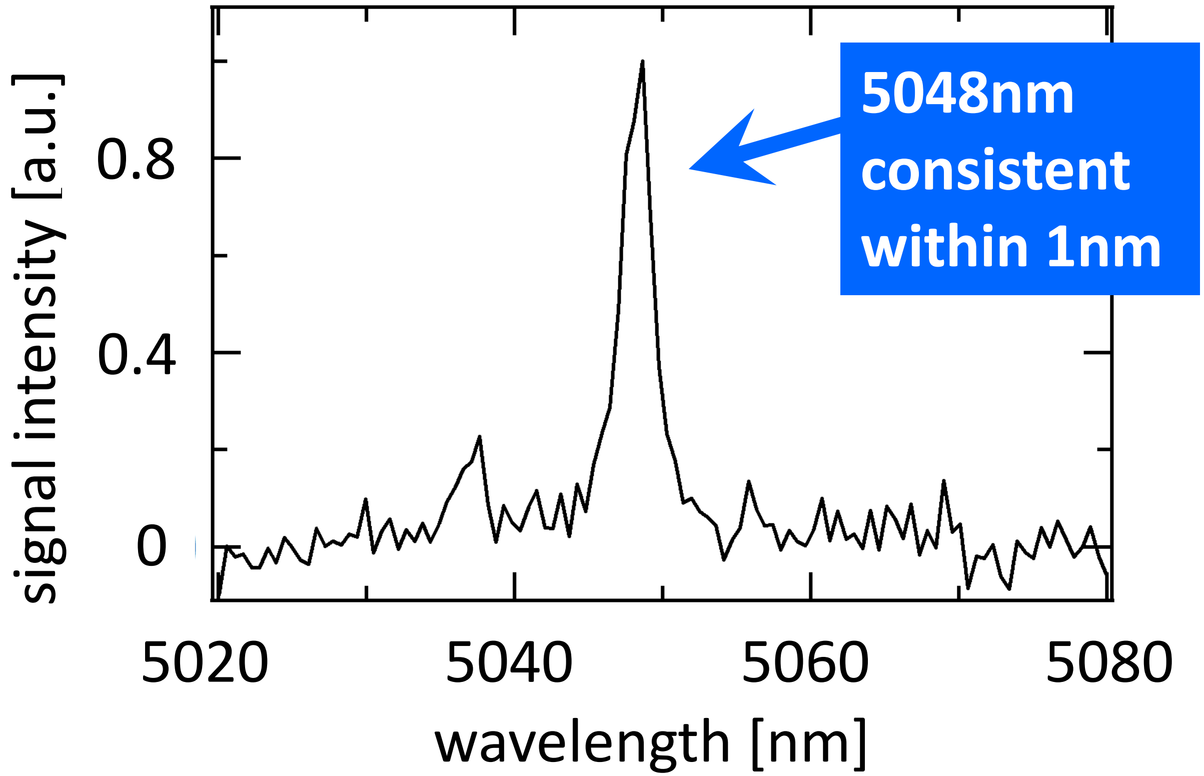
Observed Spectrum





signal pulse energy 24nJ/pulse

(**6.1×10^{11} photons/pulse**)

$$\text{enhancement} = \frac{\text{observed photon number}}{\text{spontaneous emission}} = \frac{6.1 \times 10^{11}}{2.4 \times 10^{-7}} = \mathbf{10^{18}}$$

PTEP 2015, 081C01 (2015)

Parameter Dependence

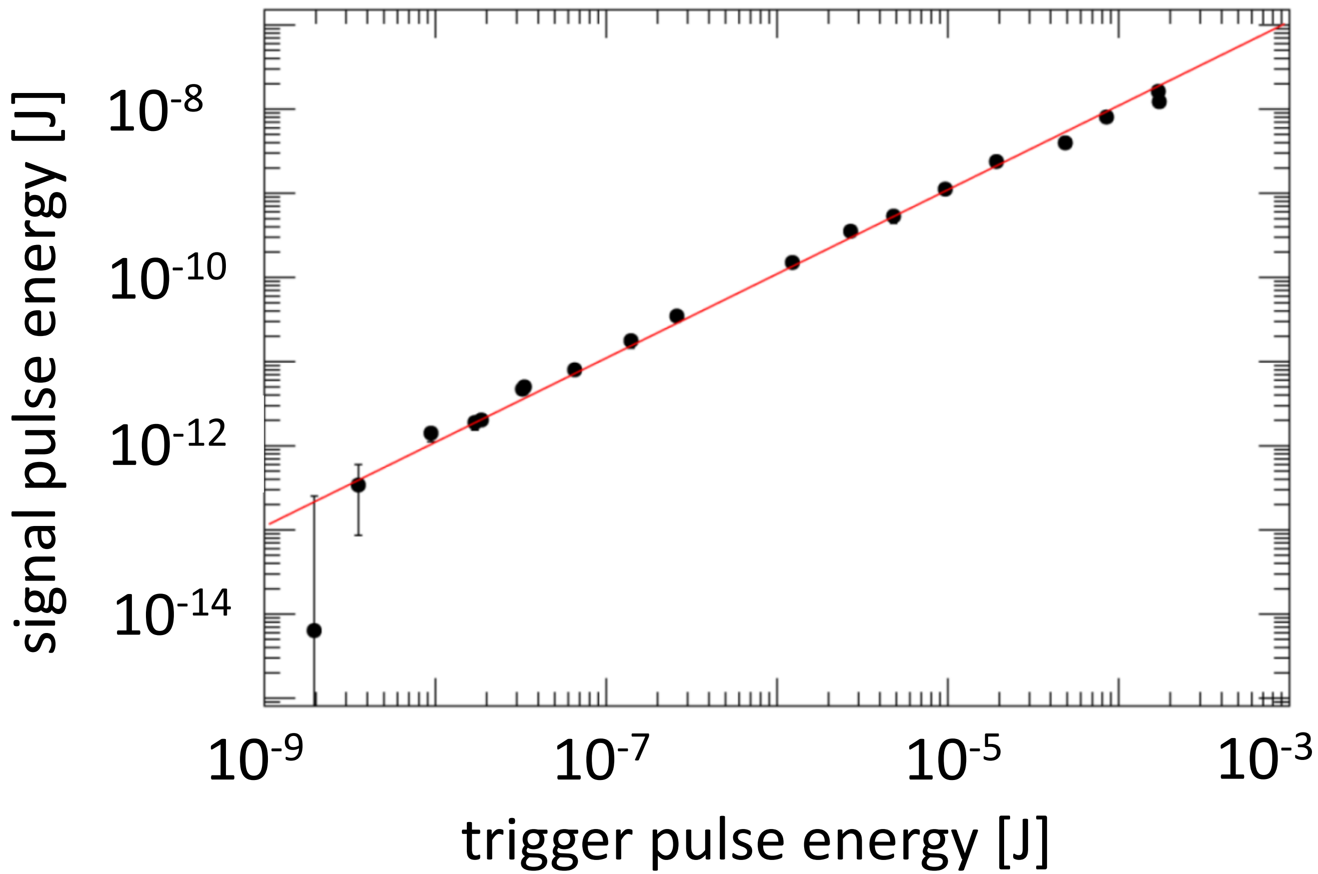
In order to check whether the experimental result is consistent with Maxwell-Bloch numerical simulation,
we measured parameter dependences of two-photon emission.

- trigger energy dependence

- trigger timing dependence

Trigger Energy Dependence

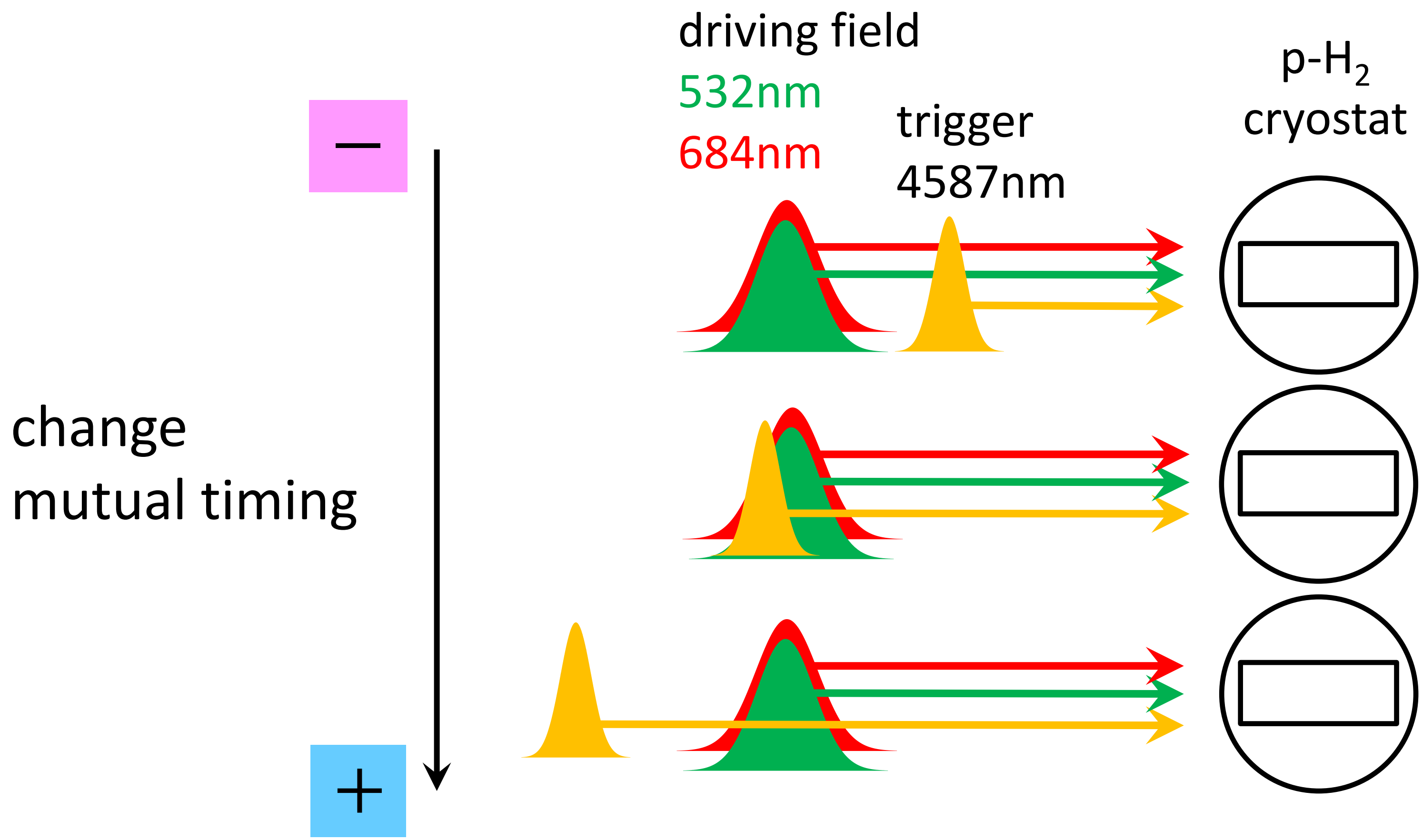
change the trigger energy 2nJ ～150μJ



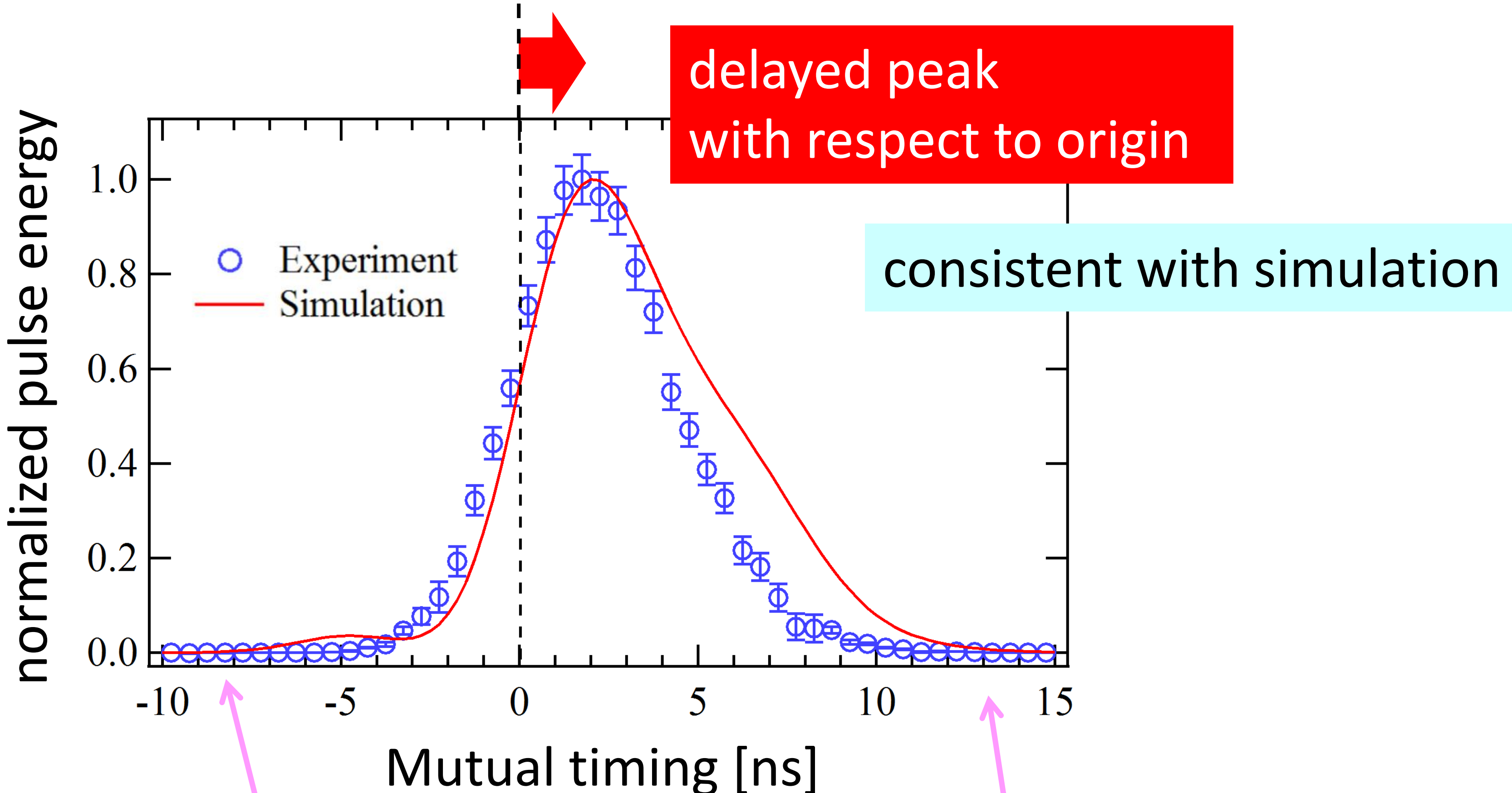
linear behavior consistent with Maxwell-Bloch eq.

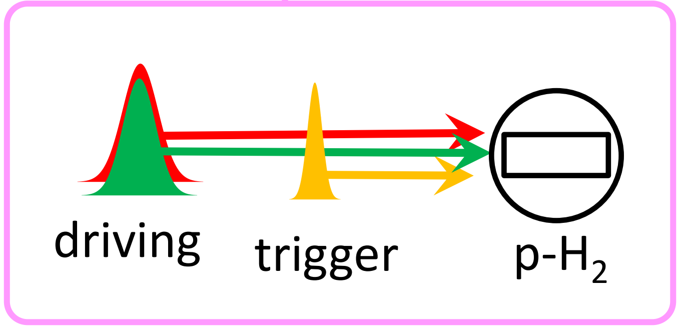
Trigger Timing Dependence

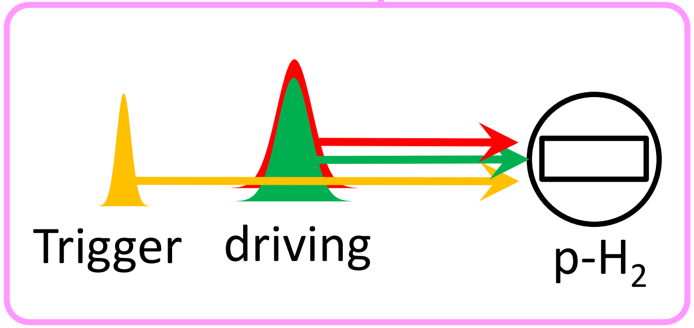
Two-photon emission signal can be used
as a monitor of coherence development.



Trigger Timing Dependence







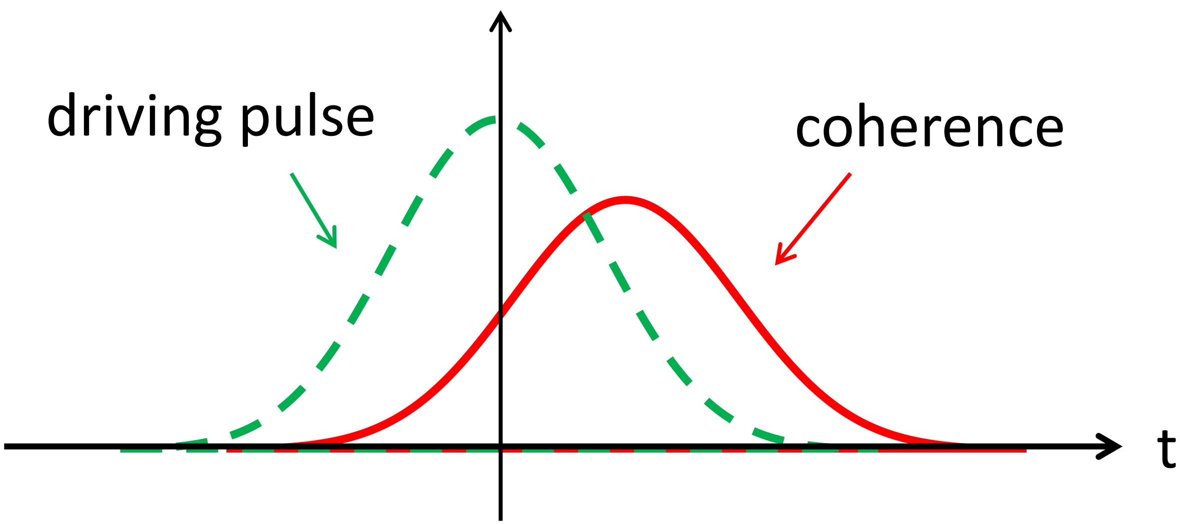
Trigger Timing Dependence

delayed peak with respect to origin

can be explained in a simple Bloch picture

Rabi oscillation period (> 100 ns) $\gg$ driving pulse duration (~ 7 ns)

⇒ State changes more slowly than driving pulse intensity.



Coherence reaches its maximum after the peak of the driving pulse, then decays due to the decreasing driving intensity and decoherence.

Summary of Result

- In the case of multi-particle emission process, rate amplification using coherence is demonstrated by p-H_2. enhance $\sim$ $\mathbf{10^{18}}$

- Coherence $\sim$ 0.04

- In order to check whether experiment and simulation are consistent, parameter dependences of two-photon emission are measured.

  - trigger energy dependence
  - trigger timing dependence

  → consistent with simulation

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④ future plan

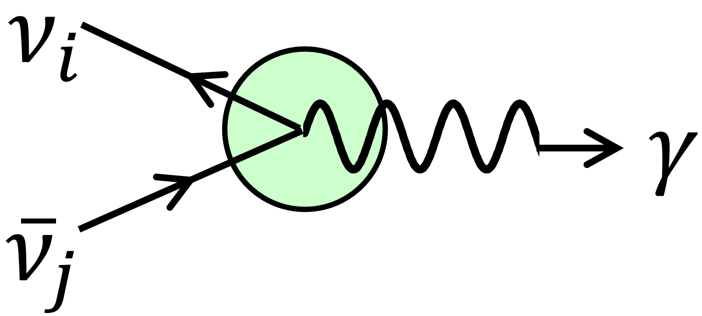
Future Plan ①

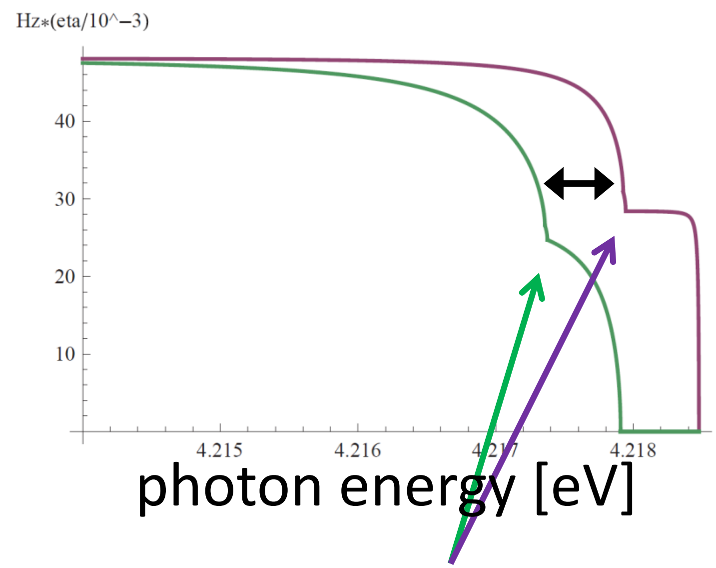
counter-propagating two-photon emission (p-H_2)

In order to realize successful RENP experiment,
counter-propagating excitation is the most basic configuration.

RENP

$$|e\rangle \rightarrow |g\rangle + \gamma \nu_i \bar{\nu}_j$$





energy and momentum conservation

$$E_{eg} = E_\gamma + E_i + E_j$$

$$0 = \vec{k}_\gamma + \vec{p}_i + \vec{p}_j$$

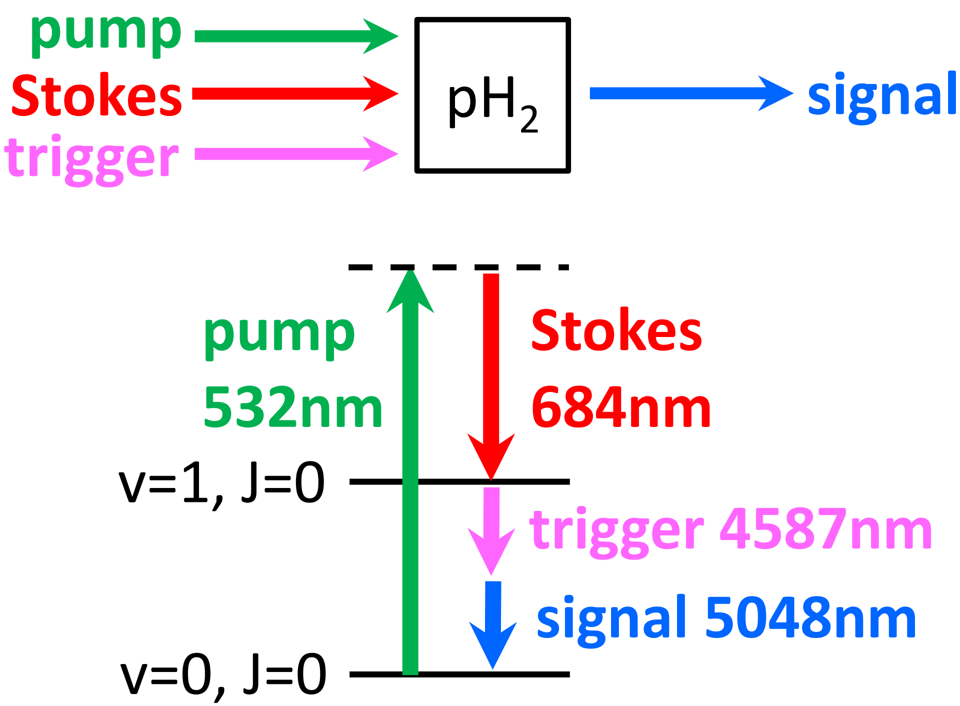
$$E_\gamma{}^{th} = \frac{E_{eg}}{2} - \frac{\{(m_i + m_j)c^2\}^2}{2E_{eg}}$$

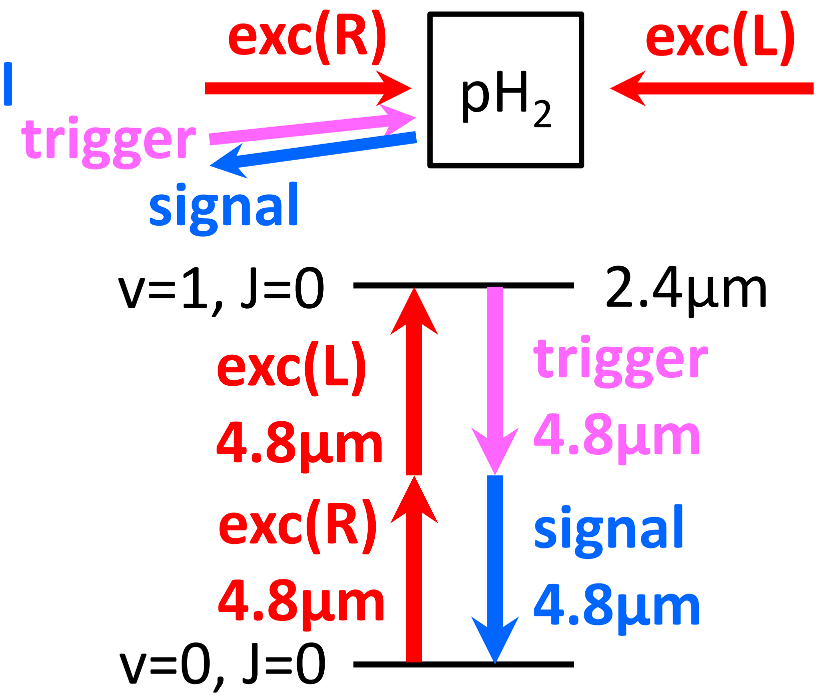
Future Plan ①

counter-propagating two-photon emission (p-H_2)

this talk :
Raman-type excitation
by unidirectional beams

next step :
Ladder-type excitation
by counter-propagating beams





preliminary simulation
coherence ~ 0.03 (I_{exc}=100MW/cm^2)

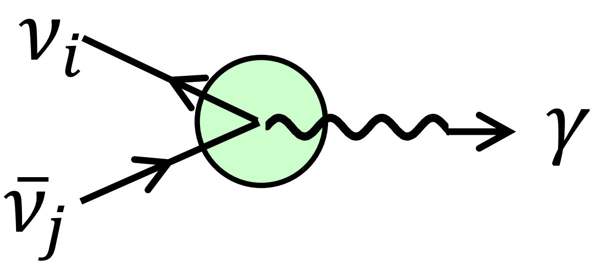
Future Plan ②

coherent amplification of three-photon emission

same kinematics

RENP

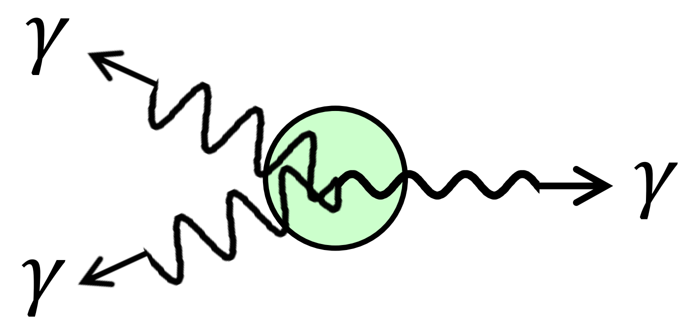
$$|e\rangle \rightarrow |g\rangle + \gamma\nu_i\bar{\nu}_j$$



Neutrinos cannot be detected.

three-photon emission

$$|e\rangle \rightarrow |g\rangle + \gamma + \gamma + \gamma$$



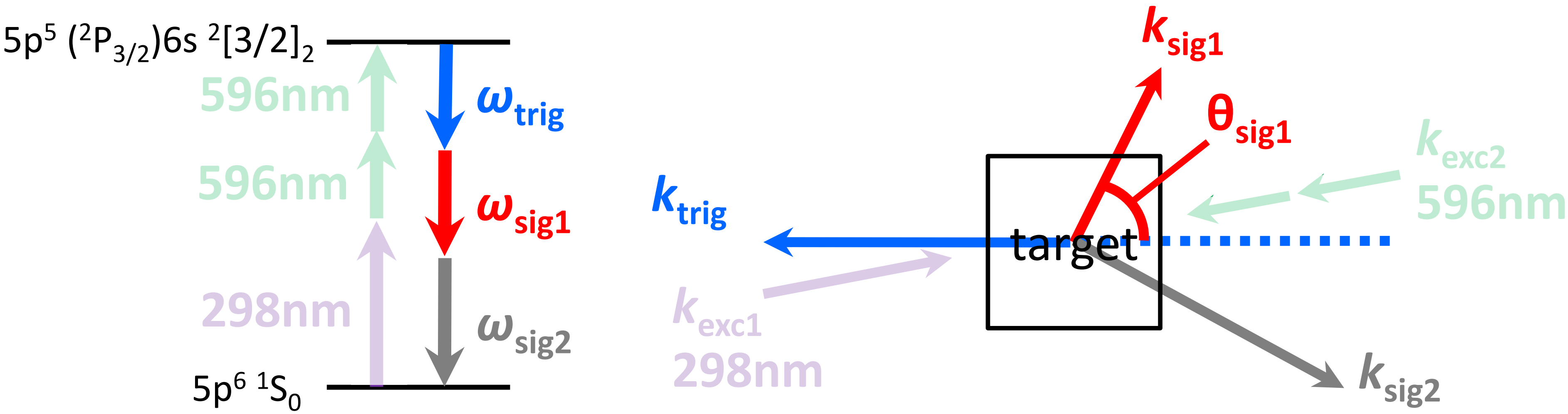
Photons can be detected.

- Detailed mechanism on coherent amplification of three-particle emission can be understood.
- Three-photon emission is also background of RENP.
  ⇒ This process should be understood for RENP.

next talk by M. Tanaka

Future Plan ②

coherent amplification of three-photon emission



Coherence is generated by three-photon excitation.

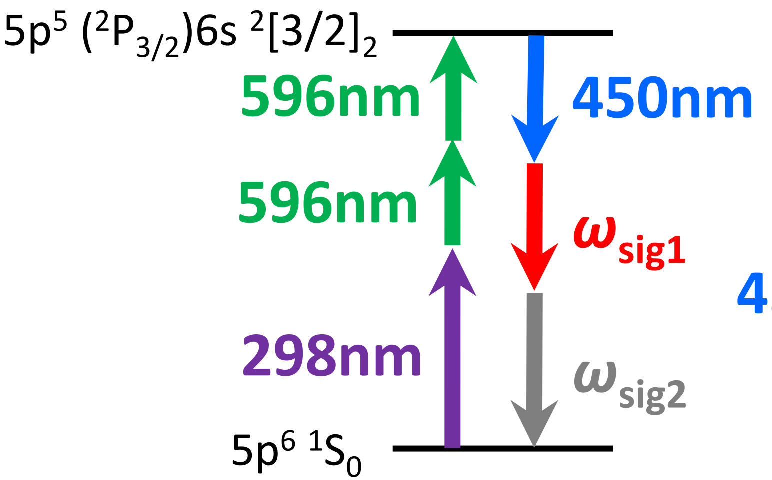
candidate target : Xe

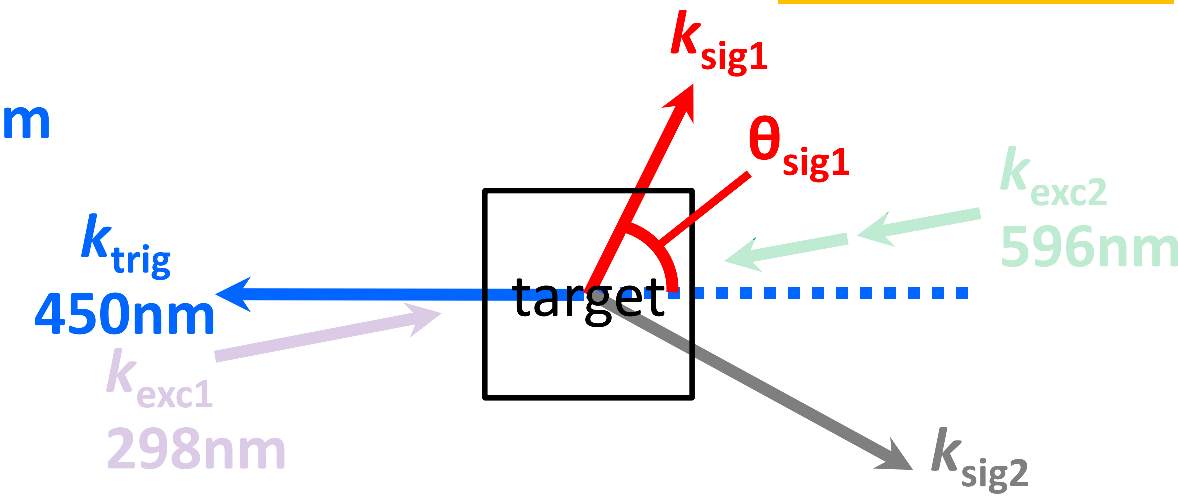
If trigger pulse is irradiated, two signal pulses are emitted to any directions satisfying energy and momentum conservation laws.

Future Plan ②

coherent amplification of three-photon emission

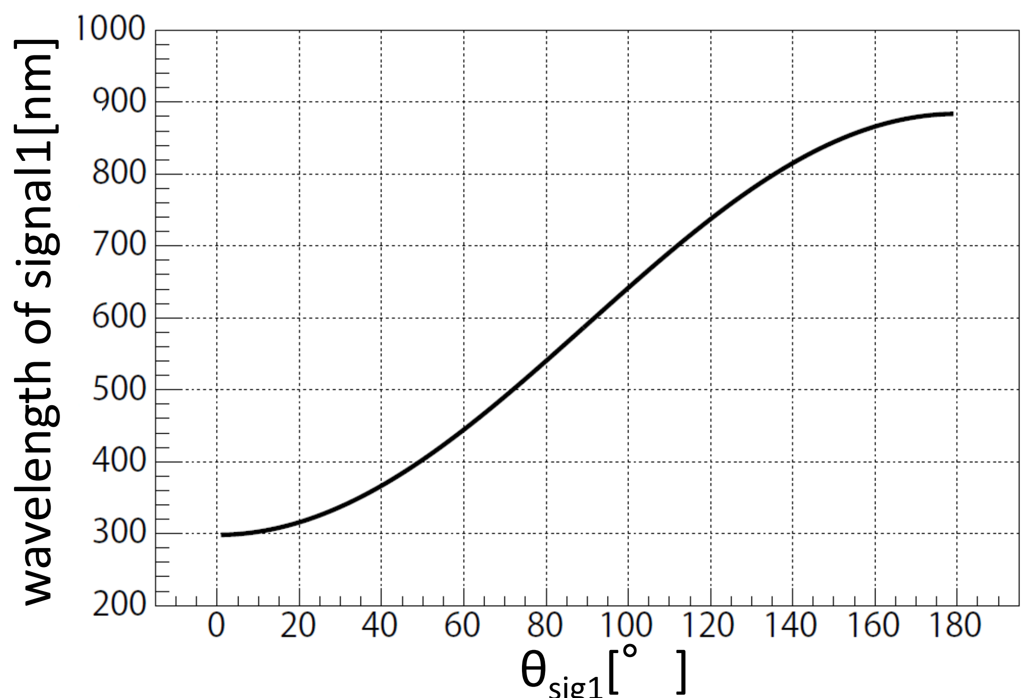
candidate Xe





For trigger frequency ω_{trig}, correlation exists between θ_{sig1} and ω_{sig1}.

We plan to measure emitted photon number at each angle θ_{sig1}.



Summary

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enhance $\sim$ $\mathbf{10^{18}}$

- Coherence $\sim$ 0.04

- In order to check whether experiment and simulation are consistent, parameter dependences of two-photon emission are measured.

  - trigger energy dependence
  - trigger timing dependence

  → consistent with simulation

- Future plan
  - counter-propagating two-photon emission (p-H_2)
  - three-photon background study (Xe)