ニュートリノ質量分光に向けた コヒーレンスによる二光子対超放射の観測

岡山大学　極限量子研究コア

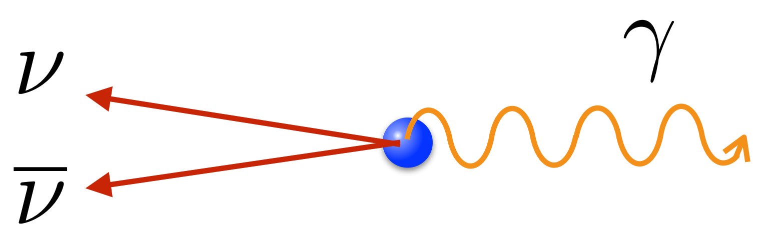
増田孝彦 on behalf of the SPAN collaboration

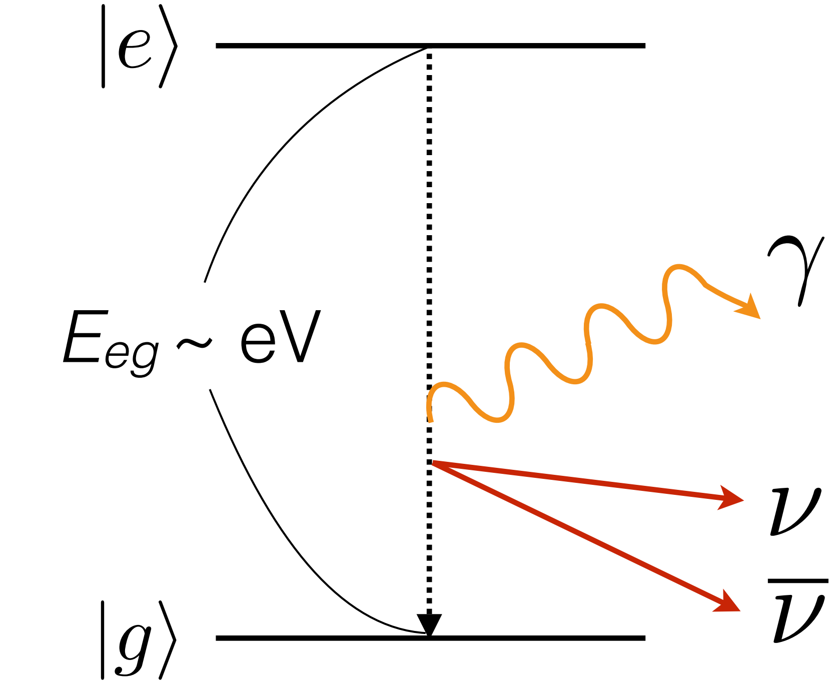
OKAYAMA UNIV.

SPAN Collaboration

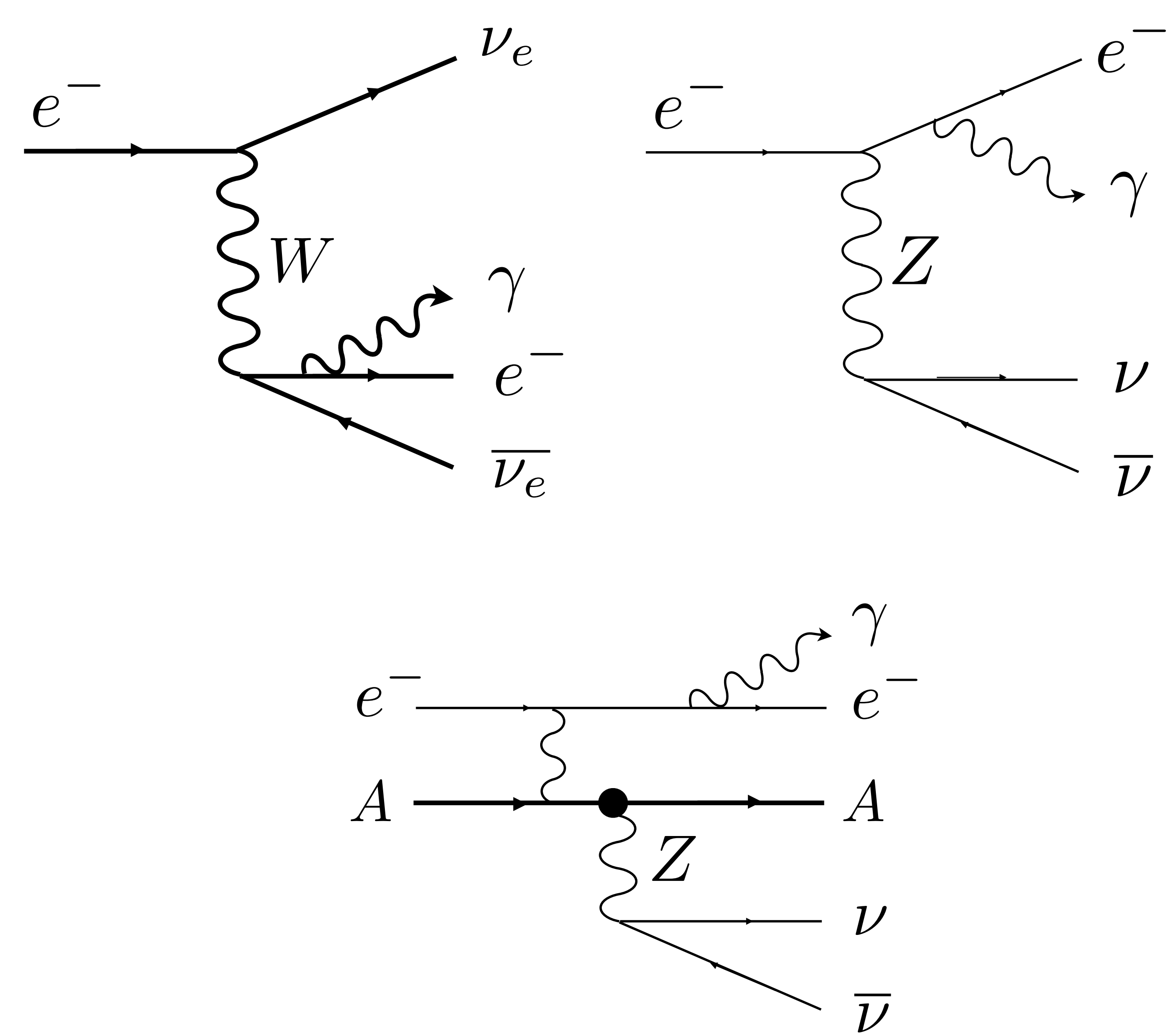
- *Motivation* :
  Neutrino absolute mass measurement using atomic de-excitation.

RENP
(Radiative Emission of Neutrino Pair)



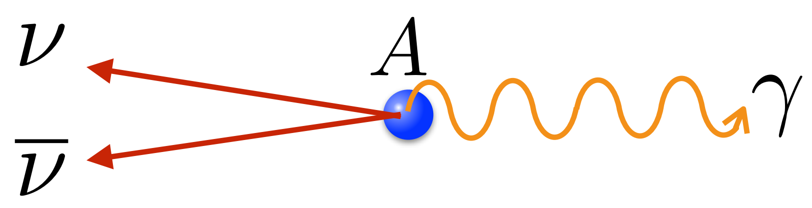


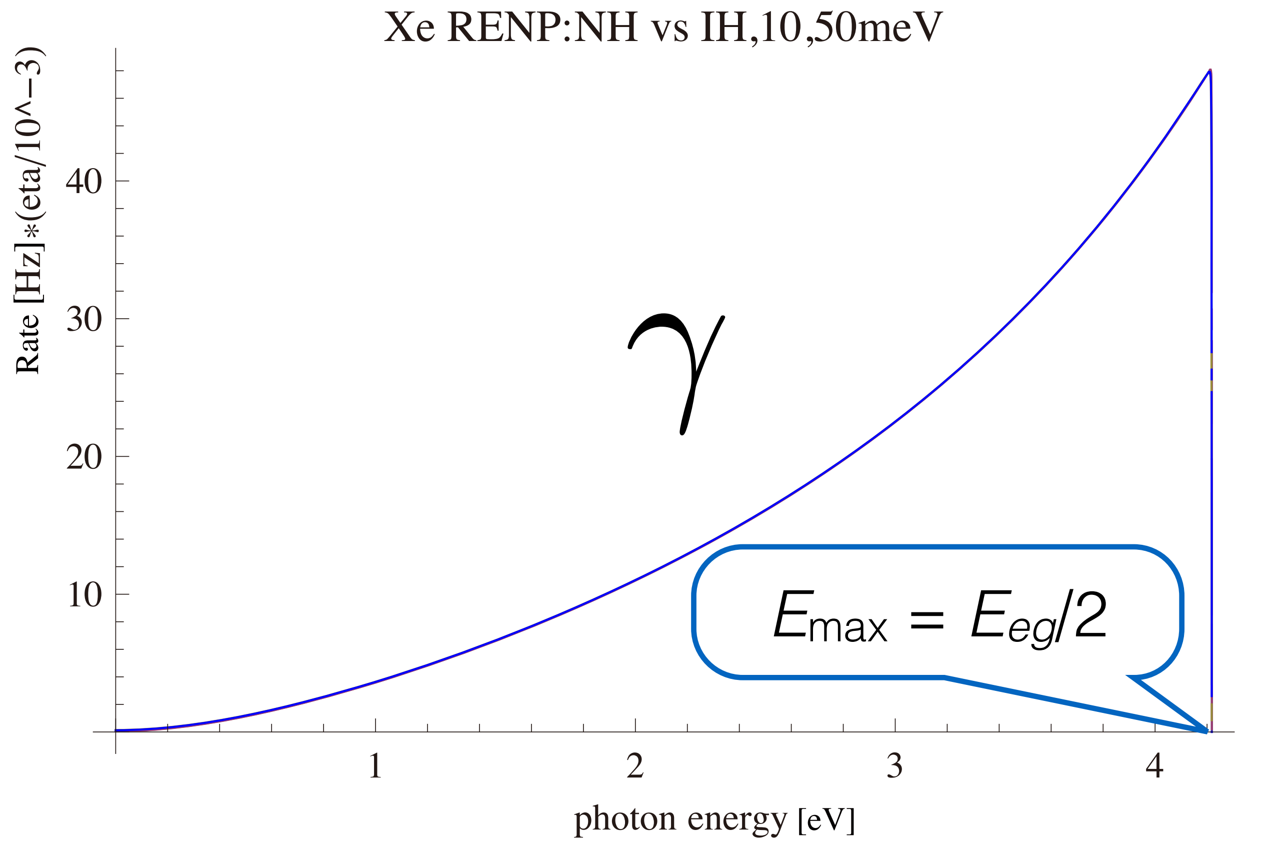
Diagrams of RENP



Energy spectrum of emitted photon

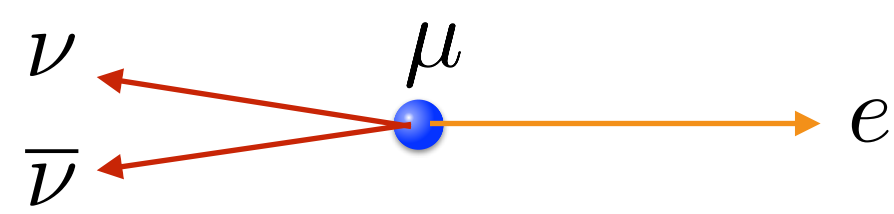
$$E_{eg} \rightarrow \gamma \nu_i \overline{\nu}_j$$

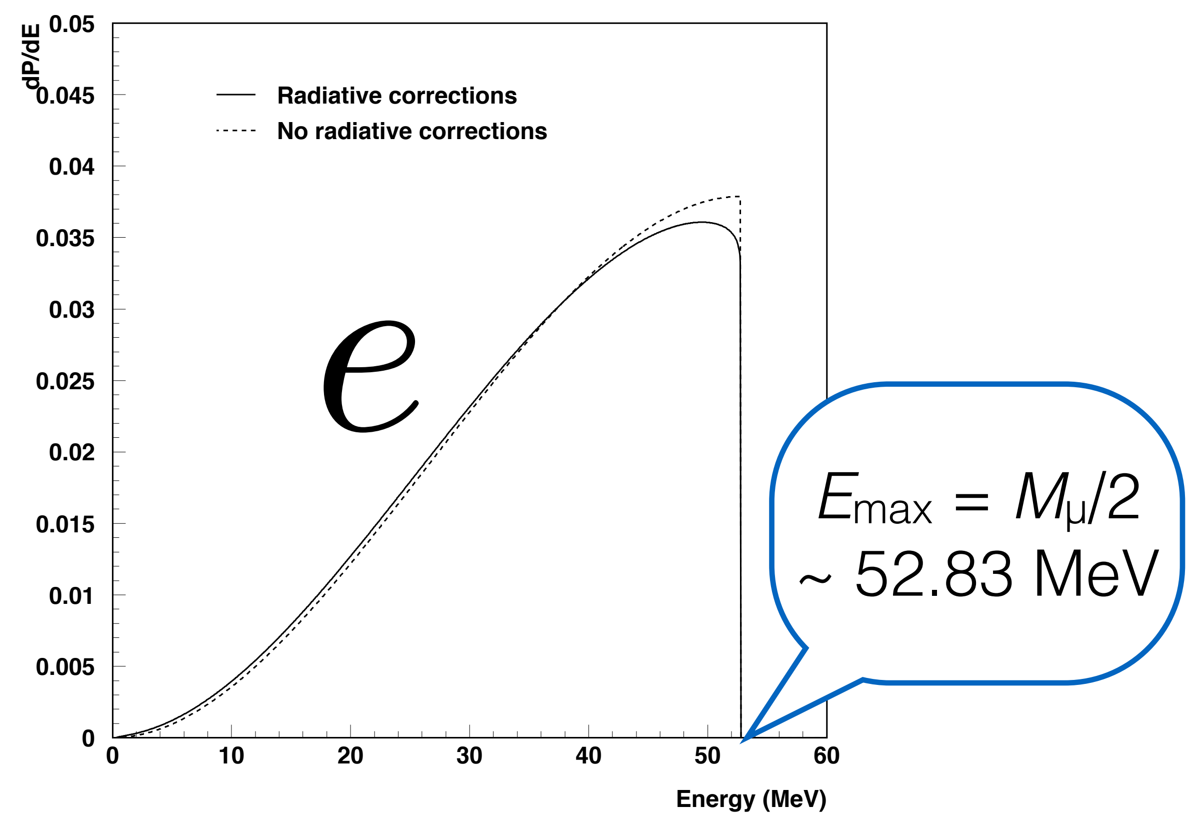




高エネルギーニュース **33** 2, 99-107 (2014)

$$\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$$





Eur. Phys. J. C **33** 233-241 (2004)

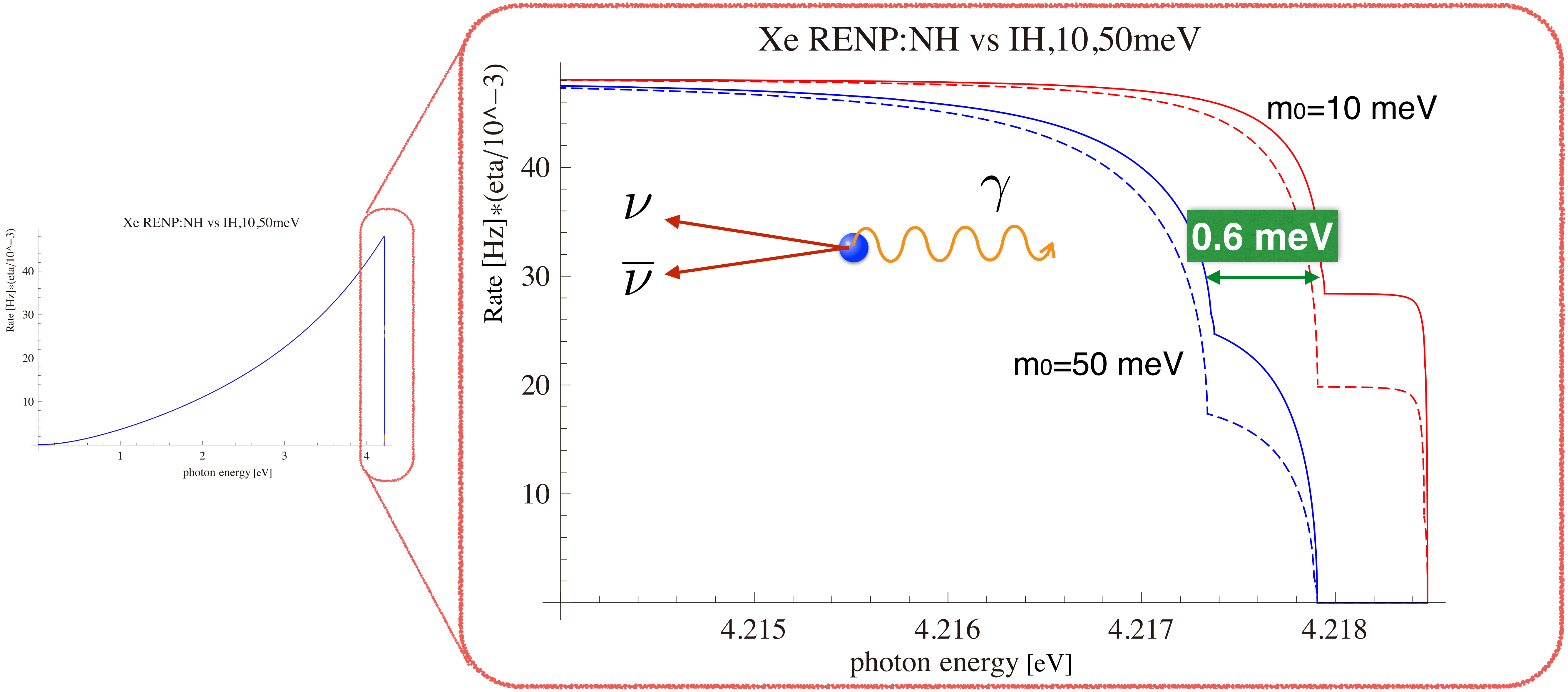
- Photon energy spectrum is similar to Michel Spectrum
  → Maximum value is q-value/2 based on **the massless assumption**

Energy spectrum of emitted gamma

End-points contain the mass information : $\omega_{ij} = \frac{\omega_{eg}}{2} - \frac{(m_i + m_j)^2}{2\omega_{eg}}$

- ☑ $\omega_{eg} \sim m_\nu$ → **Atomic transition**
- ☑ sub meV energy resolution → **Laser spectroscopy**

高エネルギーニュース **33** 2, 99-107 (2014)



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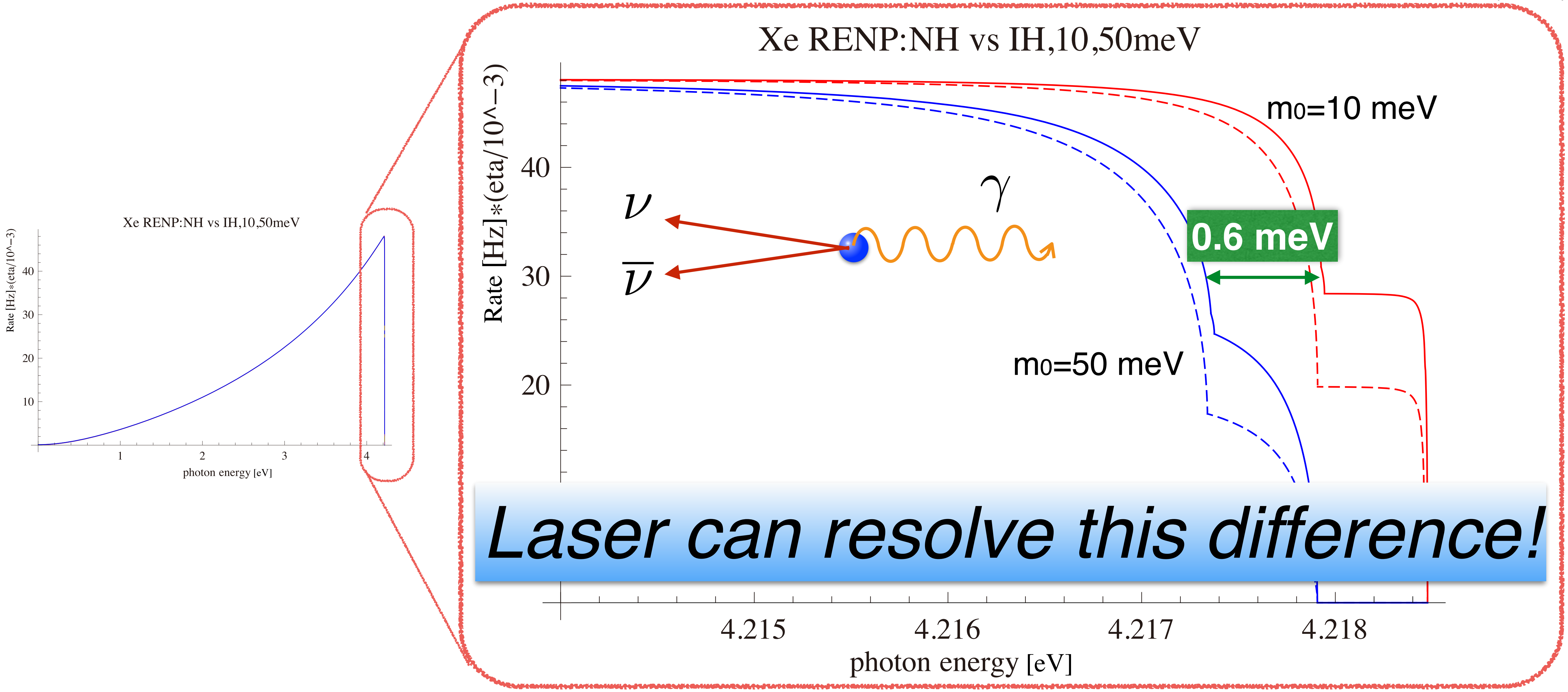


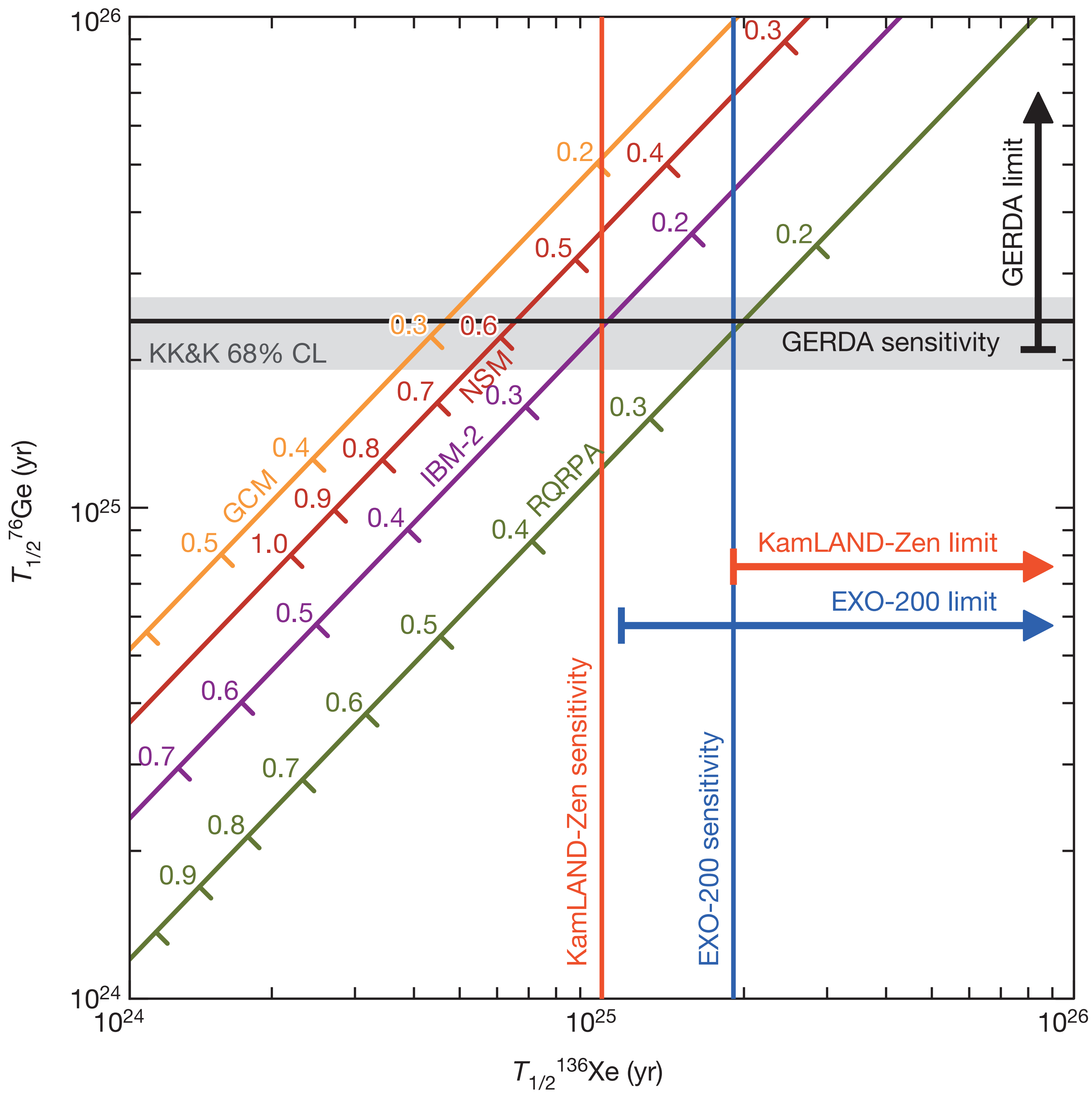
Laser can resolve this difference!

Problem

same as the current sensitivity of $0\nu\beta\beta$

- rare process

i.e. : E_{eg}=1 eV ⇒ $\boldsymbol{\Gamma_{\mathrm{RENP}}}$ **~ 1/(10[26] year)** for single atom



Nature **510** 229-234 (2014)

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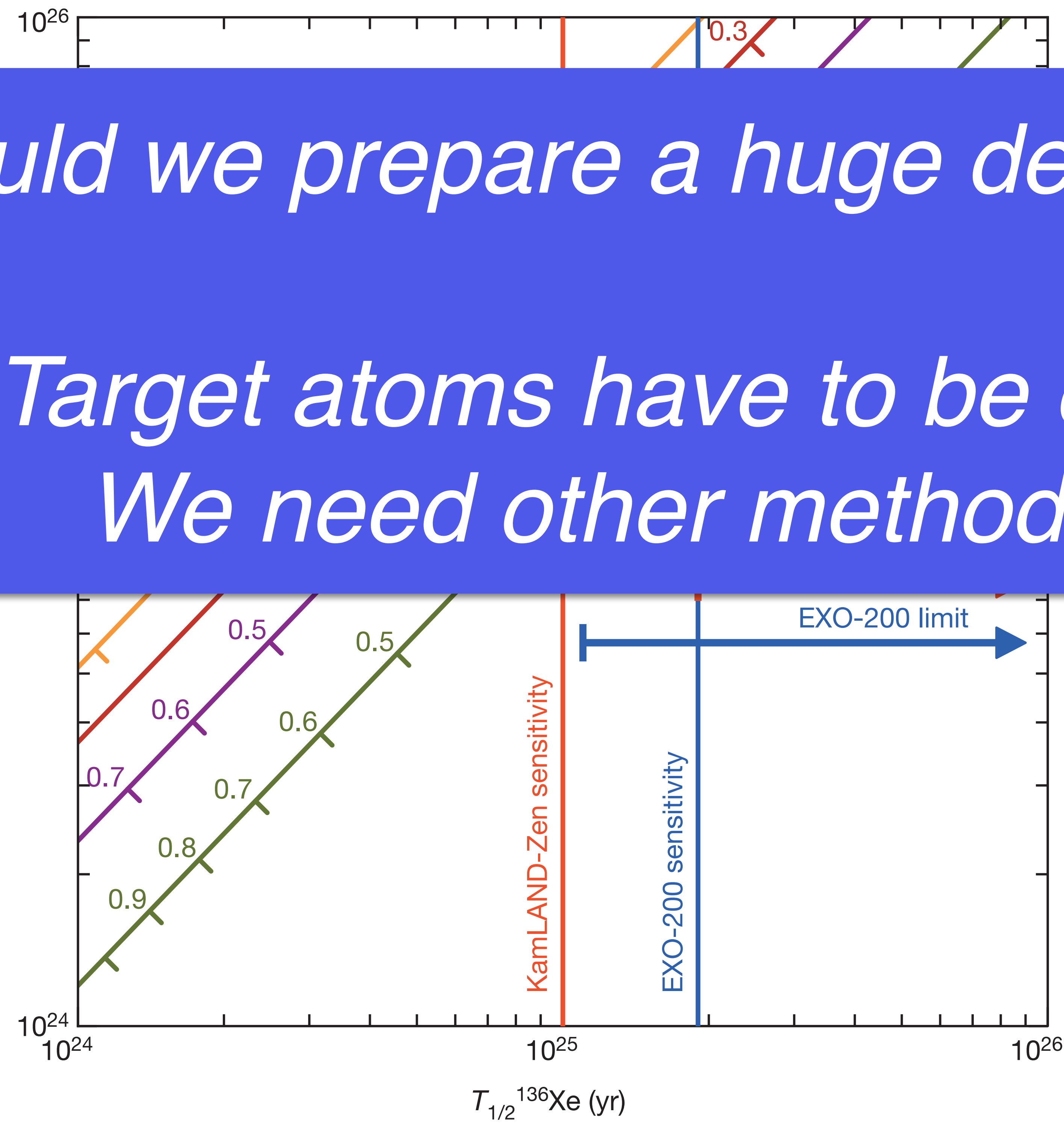


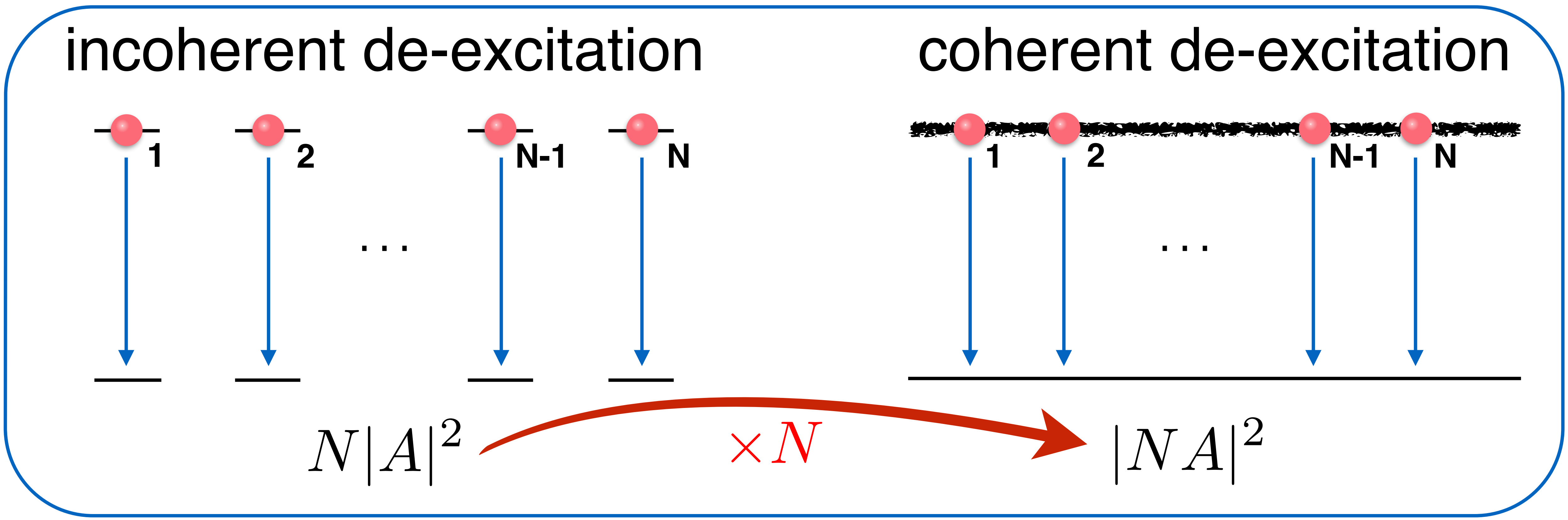
Nature **510** 229-234 (2014)

Should we prepare a huge detector?

No. Target atoms have to be excited.
We need other method.

Macro-coherent Amplification

- **Macro-Coherent Amplification**
  - Coherence in macroscopic size can *enhance* the rate of de-excitation.
    - *Not enlarge the amount of target atoms, but enlarge its transition rate.*



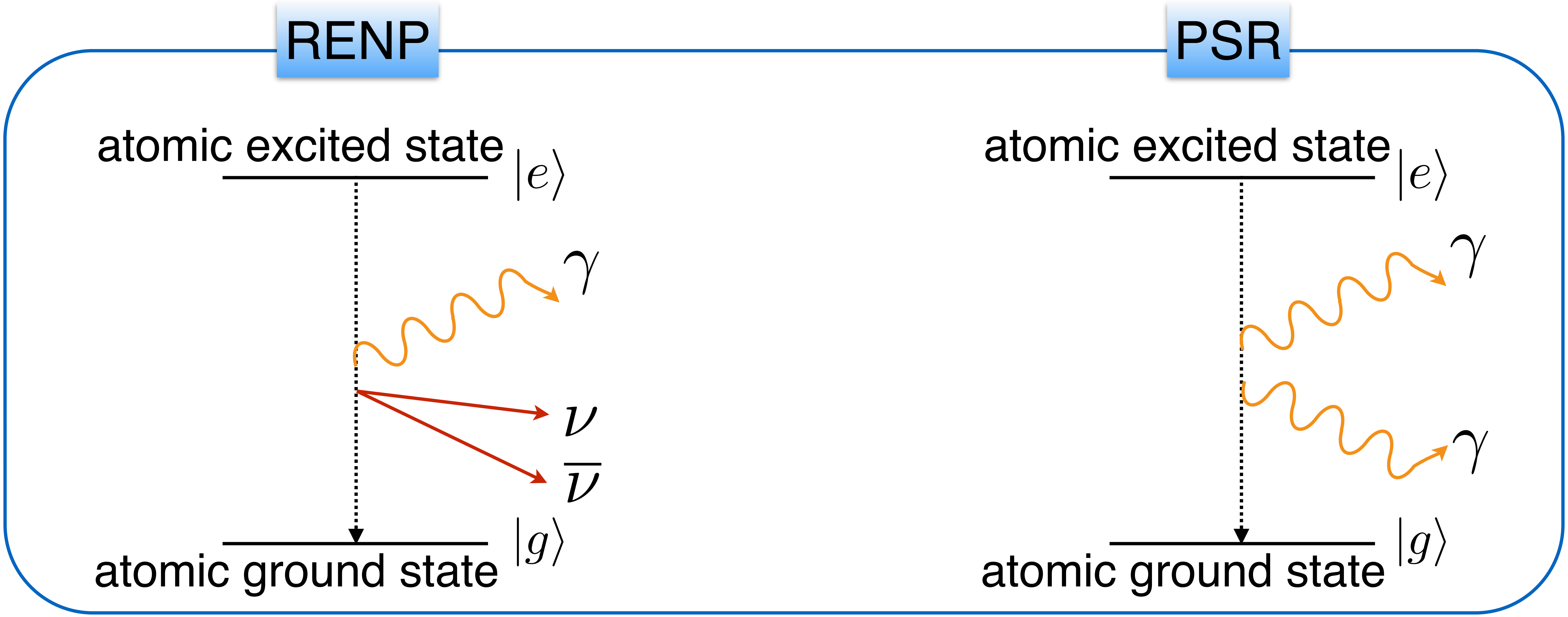
- The mutual phase among *N* atoms have to be same.
- Momentum of emitted particles should be conserved.

$$\left| \sum_a^N e^{-i\sum_i k_i r} \mathcal{M}_a \right|^2$$

Demonstration on the Macro-coherent Amplification

- Macro-coherent Amplification should be demonstrated experimentally.
  → Two photon emission version, named Paired Super-radiance (*PSR*), is a suitable example for this phenomenon.

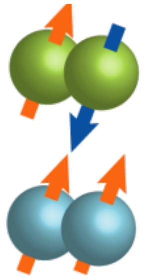
- Rare QED process. Macro-coherent amplification is needed to observe it.
- Easier than RENP.



PSR experiment using pH_2 molecule

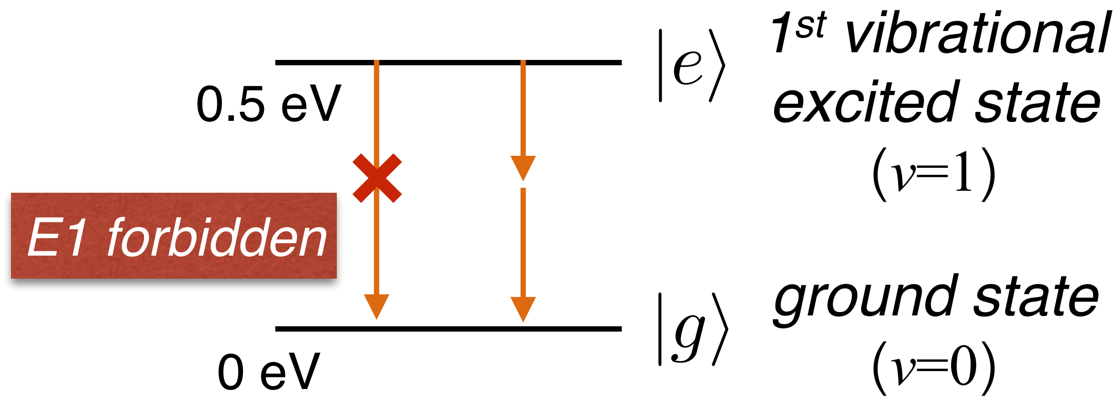
- Target : para-H_2 gas
  @ 77 K, 60 kPa (5.6×10^{19} cm^{-3})

para- & ortho- hydrogen

para-  I=0, J=0, 2, 4, …

ortho- I=1, J=1, 3, 5, …

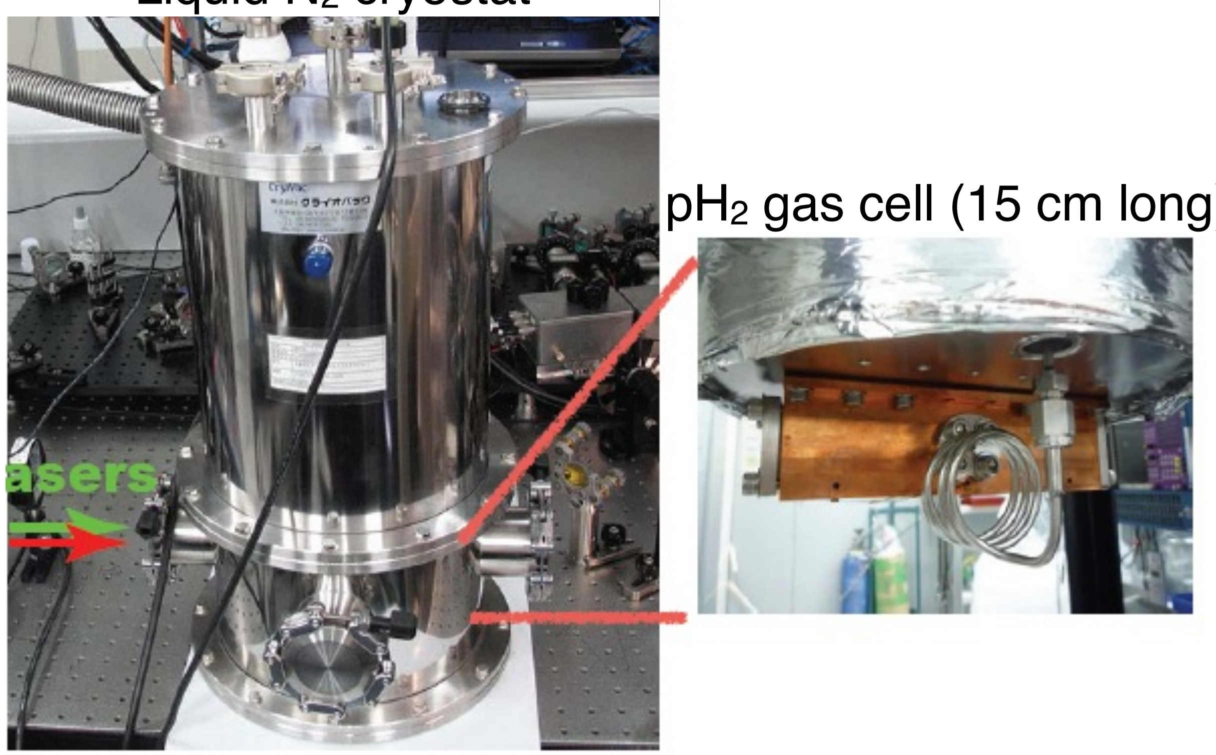
- **Two photon emission can be expected**
  - One photon (E1) transition is forbidden
  - Two photon (E1×E1) transition is allowed
    ※ Rate ~ 5×10^{-12} Hz



- **Initial coherence can be generated**
  - Previous researches have studied coherence generation methods.
    → Adiabatic Raman Excitation

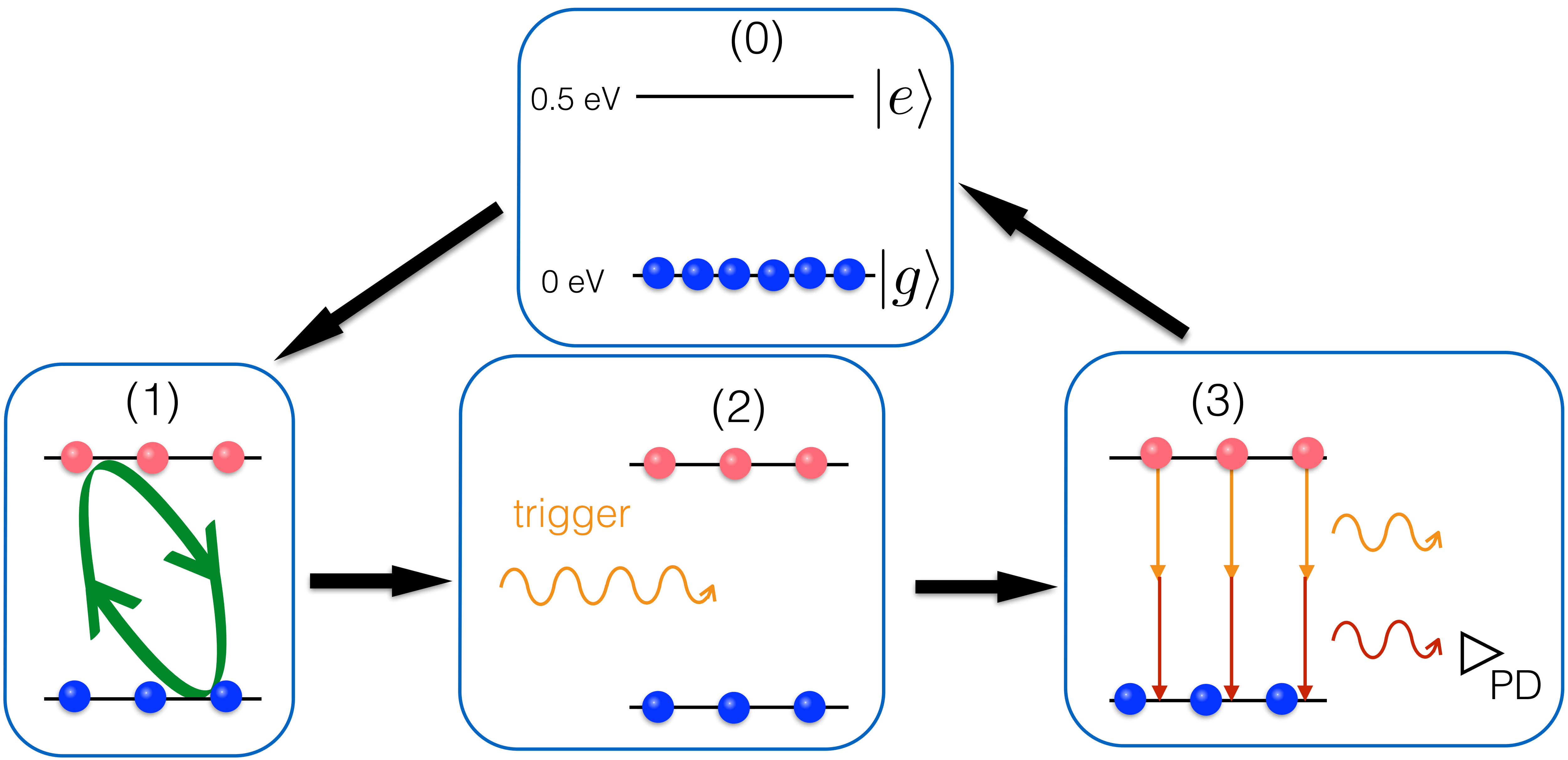
Liquid N_2 cryostat

pH$_2$ gas cell (15 cm long)



Experiment procedure

(1) Generate initial coherence in pH_2 medium using Adiabatic Raman Excitation
(2) Stimulate two photon emission by injecting trigger laser
(3) Measure the intensity of the other wavelength from two photon de-excitation
(4) Repeat (1)~(3) by 10 Hz



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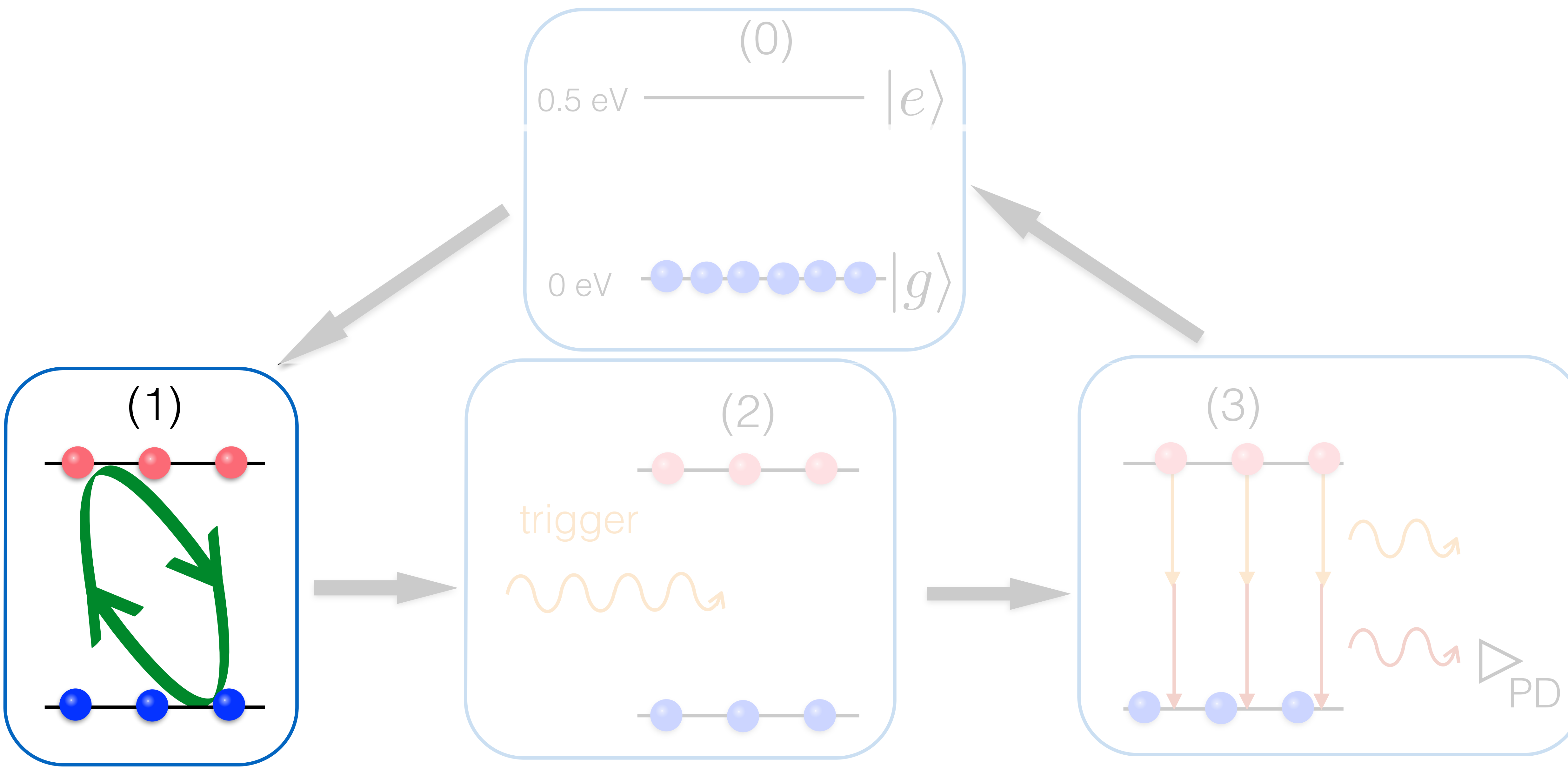


(1) Coherence preparation

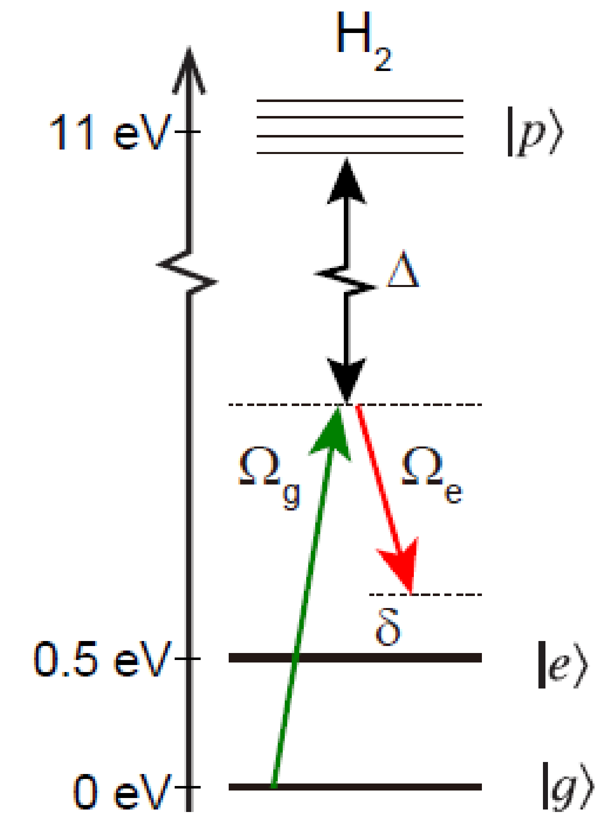
State w/ Laser Fields : $\psi(t) = \cos\frac{\theta(t)}{2}|g\rangle + \sin\frac{\theta(t)}{2}e^{i\phi(t)}|e\rangle$

Mixing angle : $\tan\theta(t) \simeq \frac{2|\Omega_{ge}(t)|}{\delta}$

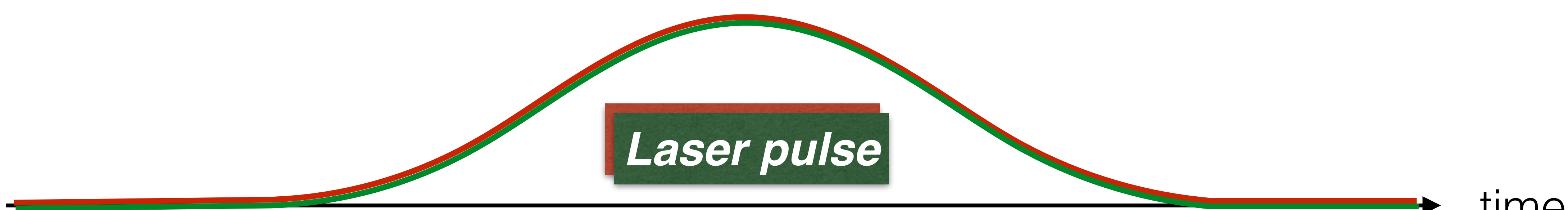
Coherence : $\rho_{ge}(t) = [|\psi(t)\rangle\langle\psi(t)|]_{ge} = \frac{1}{2}\sin\theta(t)$

$$\Omega_{ge}(t) \equiv \frac{\Omega_g(t)\Omega_e(t)}{\Delta} = \frac{(\vec{d}_{gp}\cdot\vec{E}_g(t))(\vec{d}_{pe}\cdot\vec{E}_e(t))}{\Delta}$$

$$e^{i\phi(t)} \equiv \frac{\Omega_{ge}(t)}{|\Omega_{ge}(t)|}$$



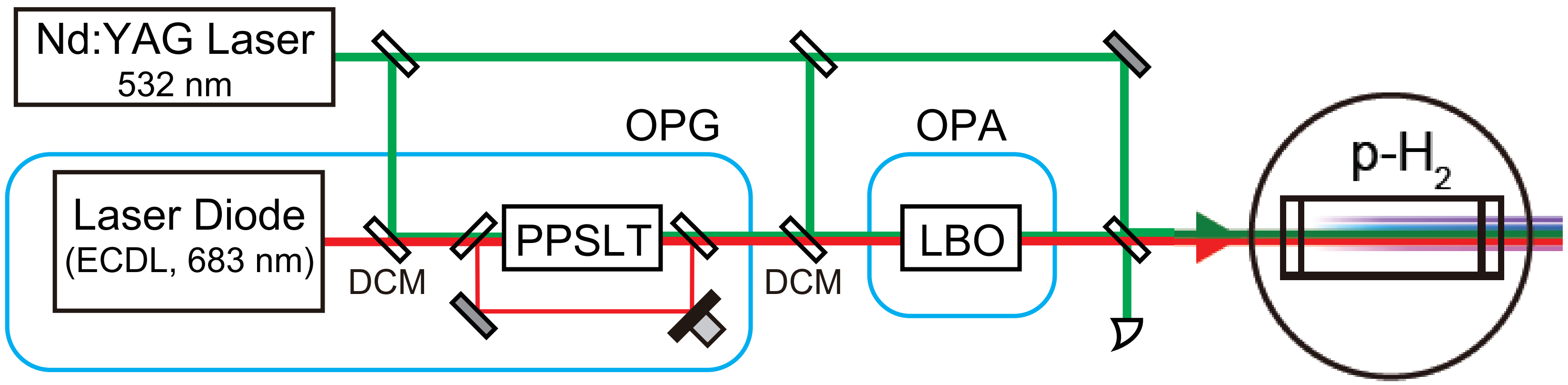
Theory: S.E. Harris & A.V. Sokolov, Phys. Rev. A 55, R4019 (1997)
Experiments: M. Katsuragawa et al., CLEO/QELS (1999), A.V. Sokolov et al., PRL 85, 562 (2000)

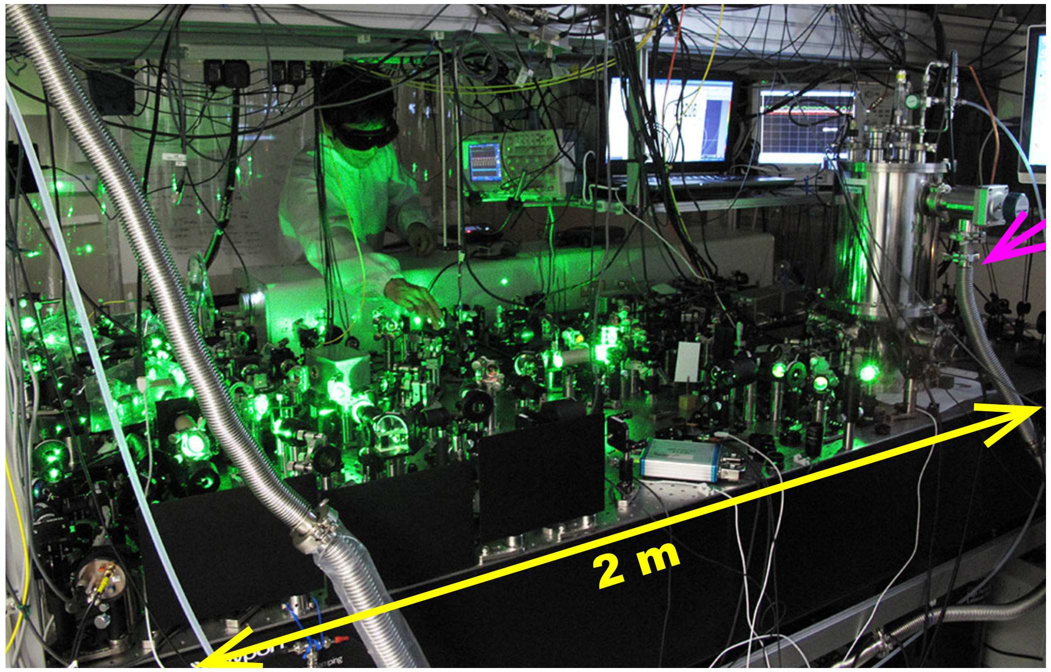


state	$\lvert g\rangle \quad (\theta = 0)$	$\frac{1}{\sqrt{2}}\lvert g\rangle + \frac{1}{\sqrt{2}}\lvert e\rangle \quad \left(\theta = \frac{\pi}{2}\right)$	$\lvert g\rangle \quad (\theta = 0)$
coherence	0	0.5	0

Strong two color lasers generate the initial coherence in the pH_2 medium

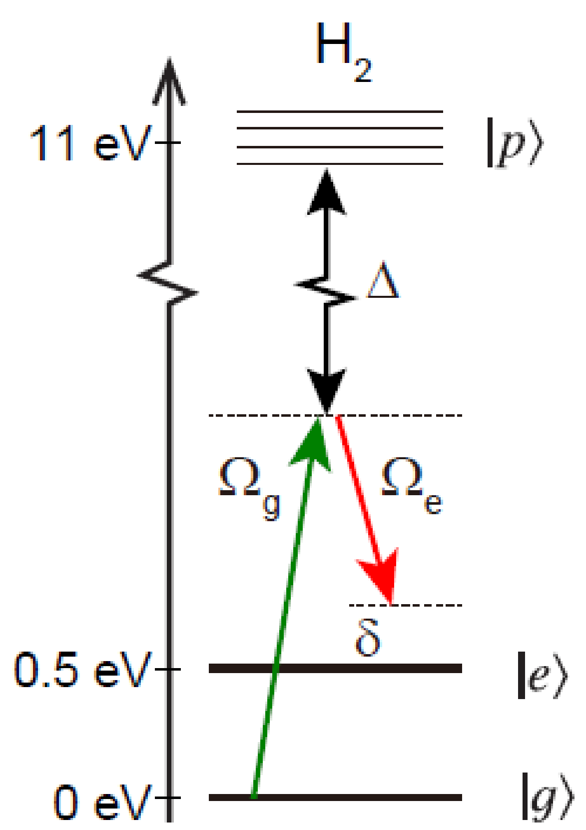
Driving laser system



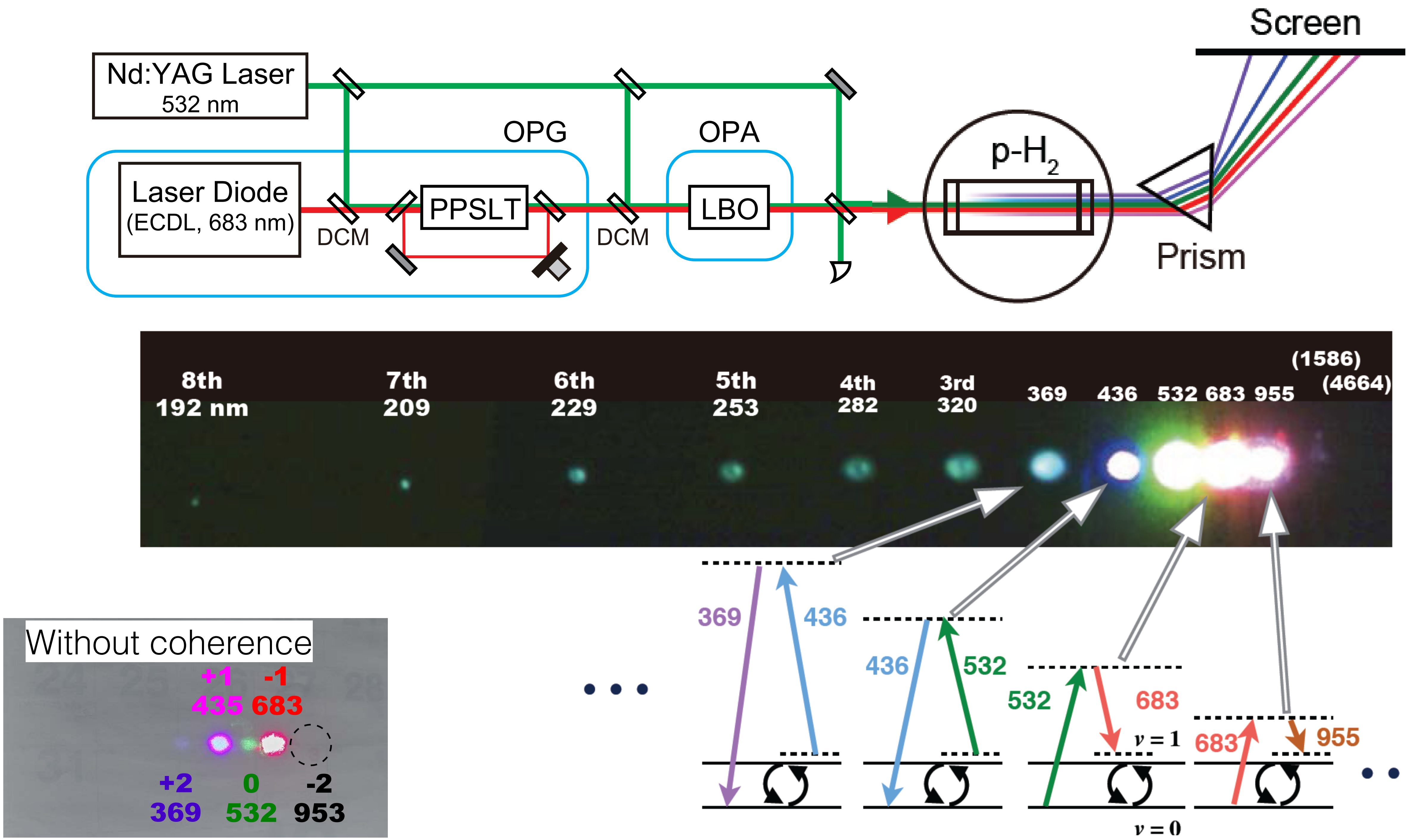


- Two driving Lasers

Light source	Nd:YAG	ECDL + Non-linear crystals
Wavelength	532 nm (green) ~ 2.3 eV	683 nm (red) ~ 1.8 eV
Pulse duration	8 ns	6 ns
Pulse energy*	4.3 mJ	4.3 mJ



Initial Coherence Generation



- The Raman side band in higher orders were observed.
  → Initial coherence was generated.

(ρ_{eg}=0.032 based on a numerical simulation)

Experiment procedure

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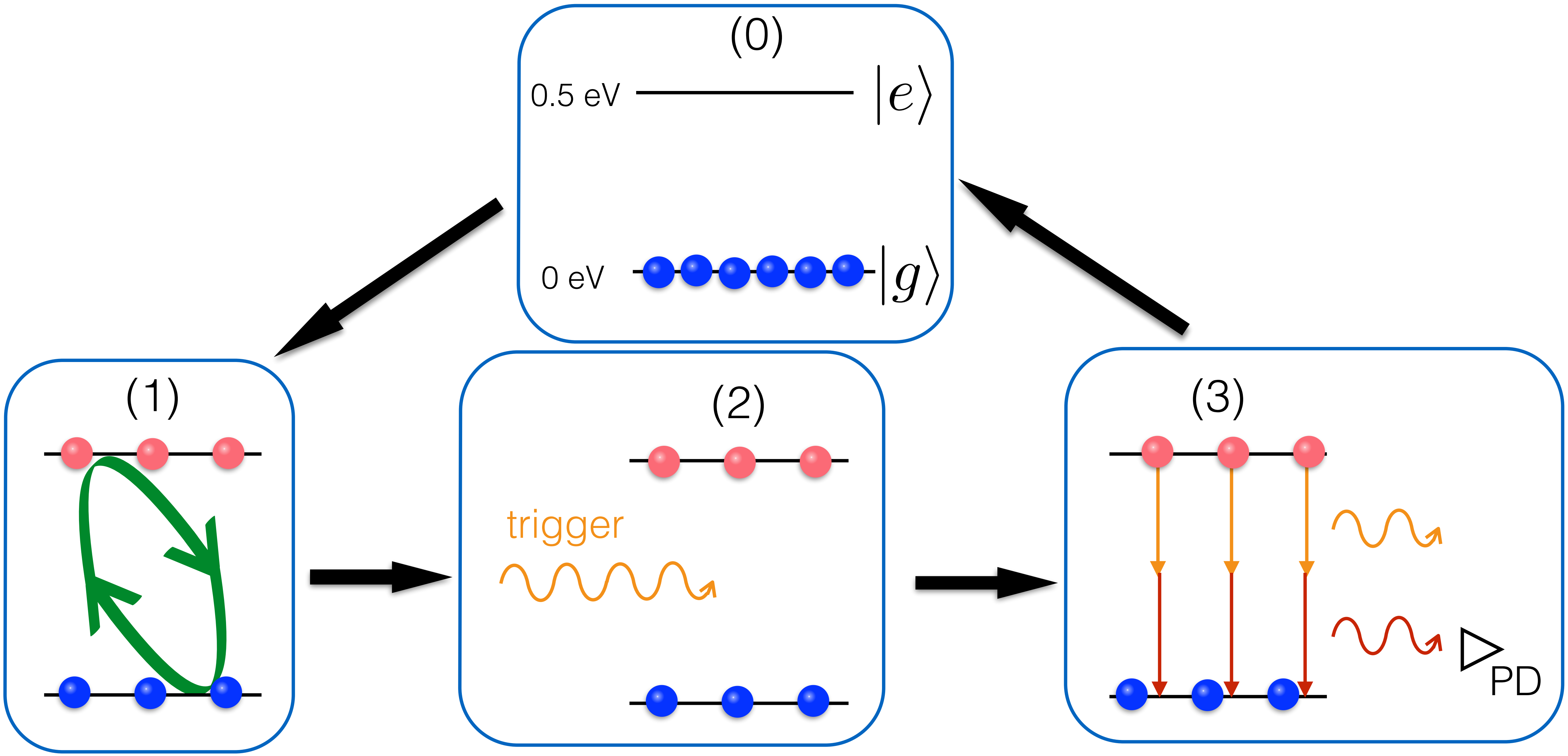

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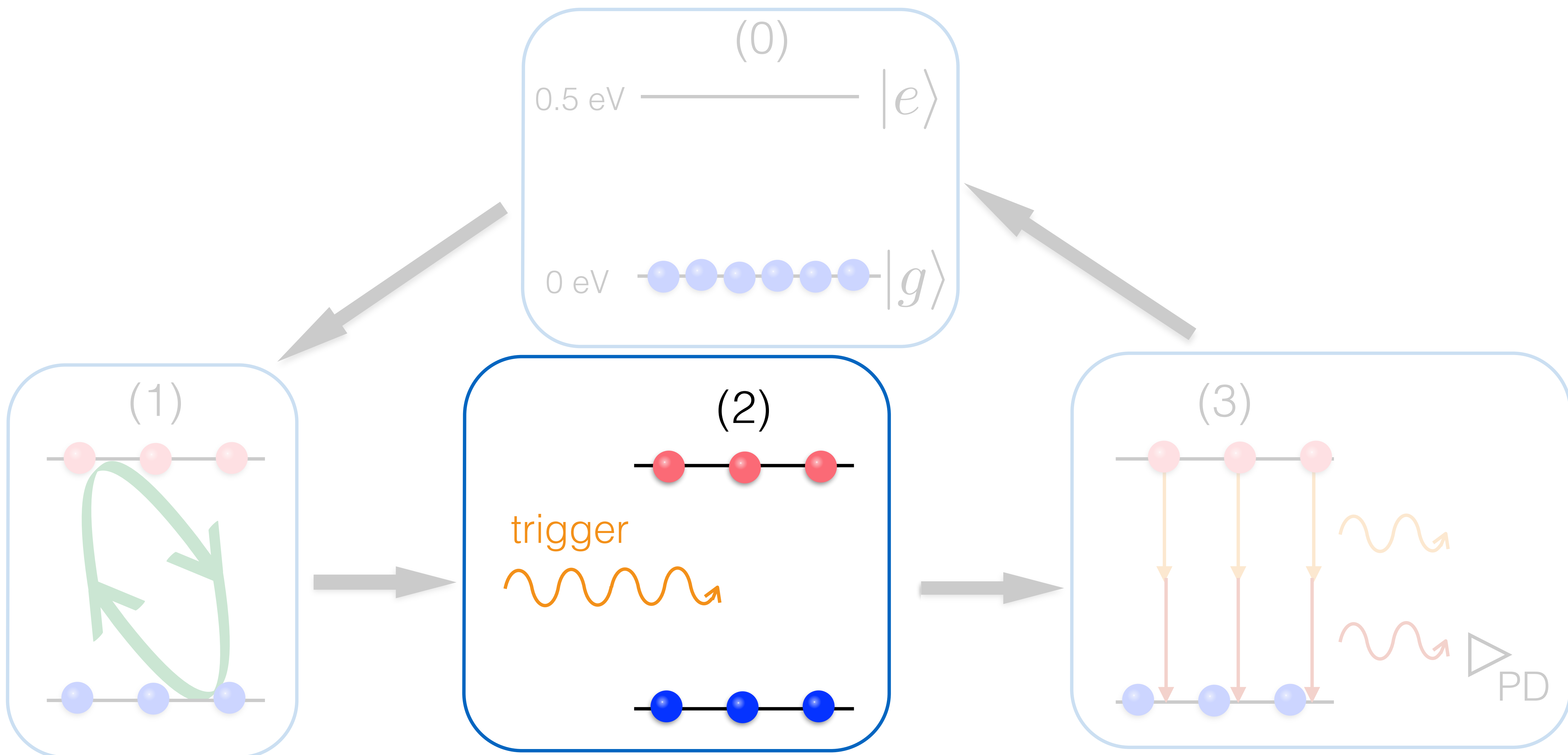
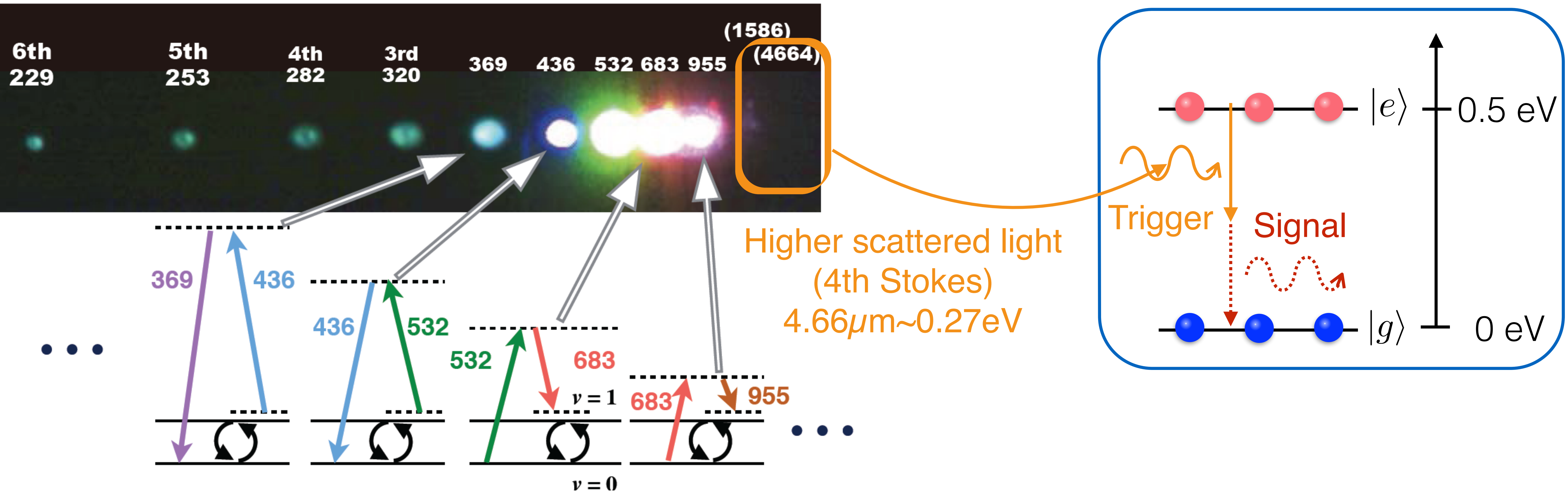


(2) Trigger



- The energy of 4th Stokes light (4.66 μm=0.27 eV) is almost a half of the transition energy (0.5 eV)
  →4th Stokes can be a trigger.

Trigger	4.66 *μ*m (Mid Infra Red)	0.27 eV
Signal	4.96 *μ*m (Mid Infra Red)	0.25 eV

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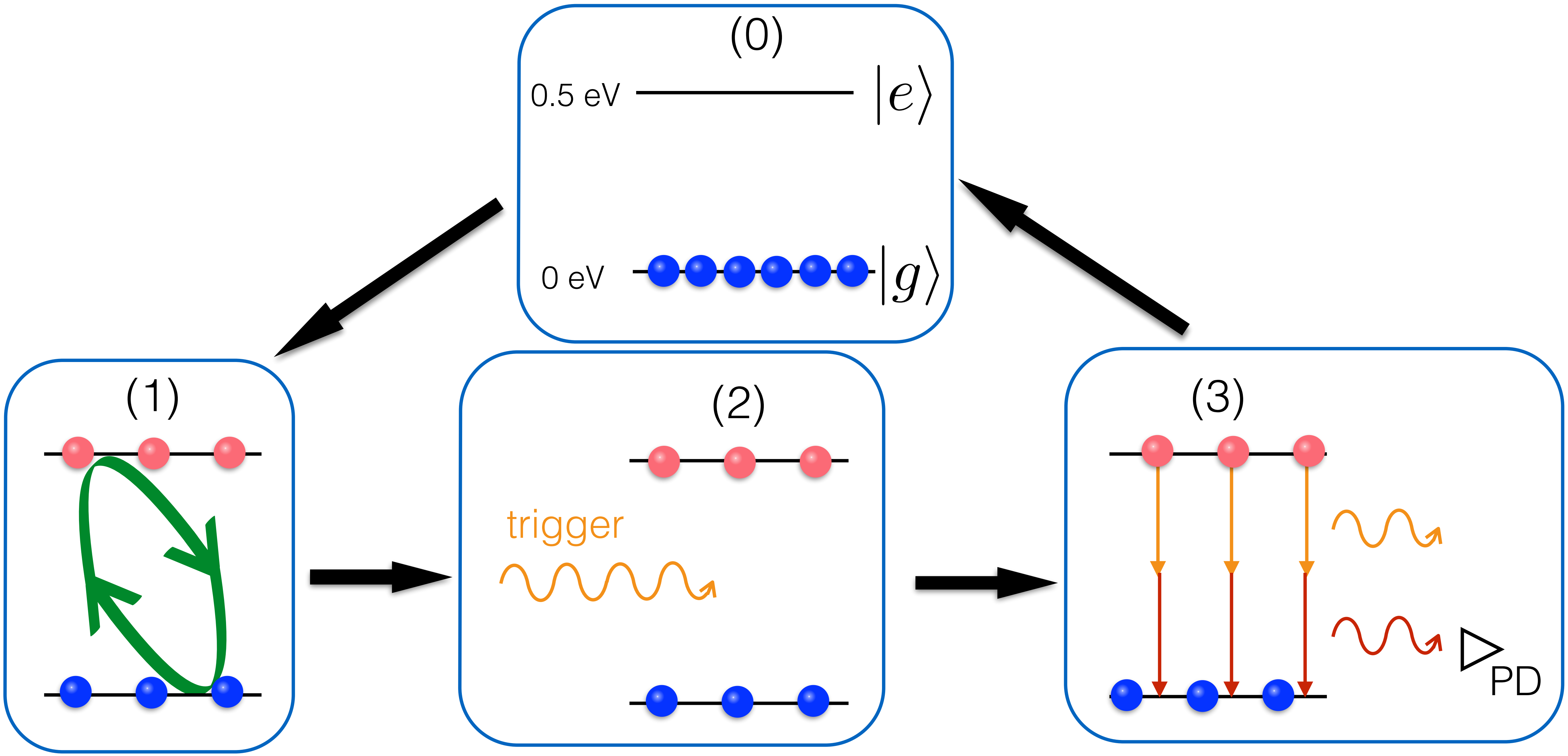

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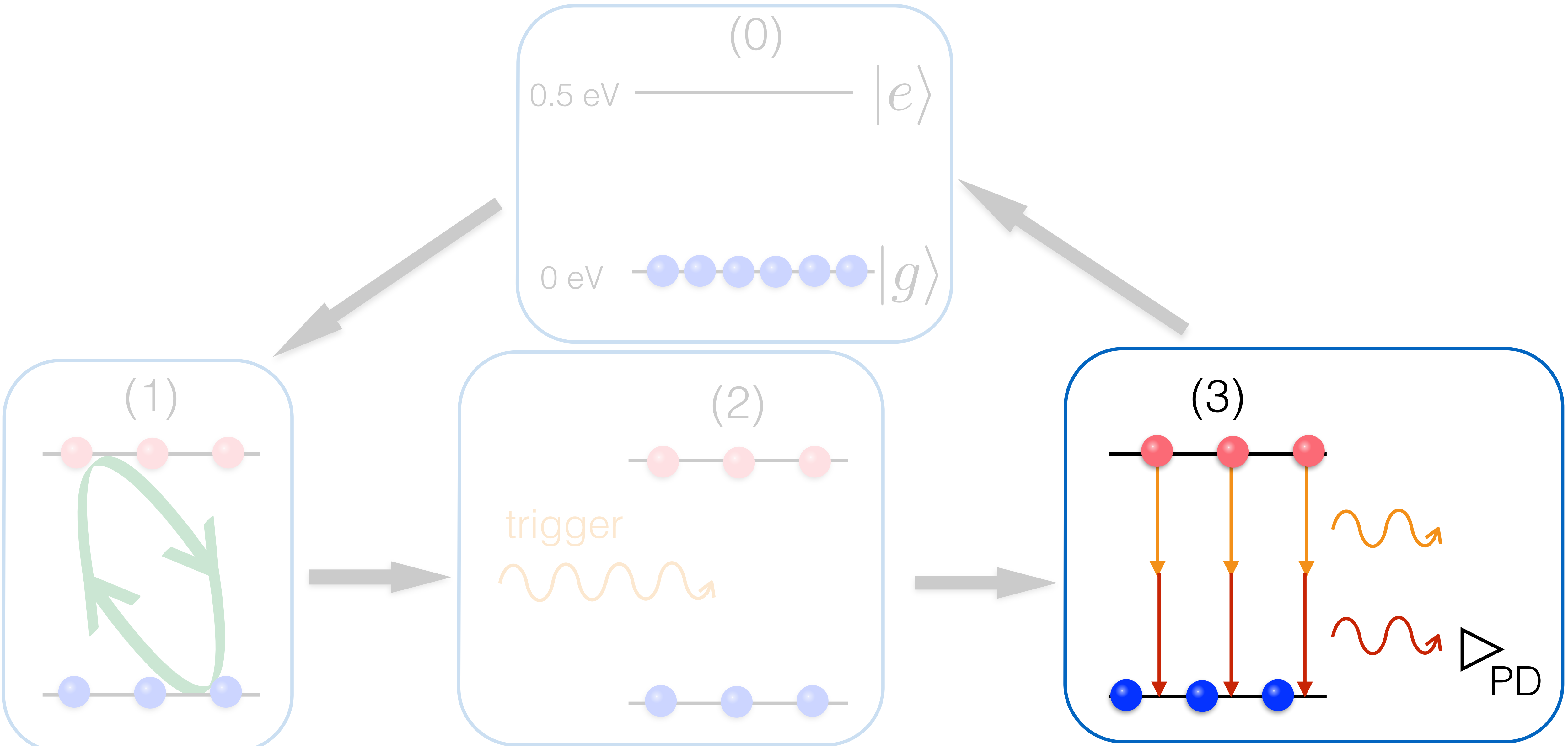
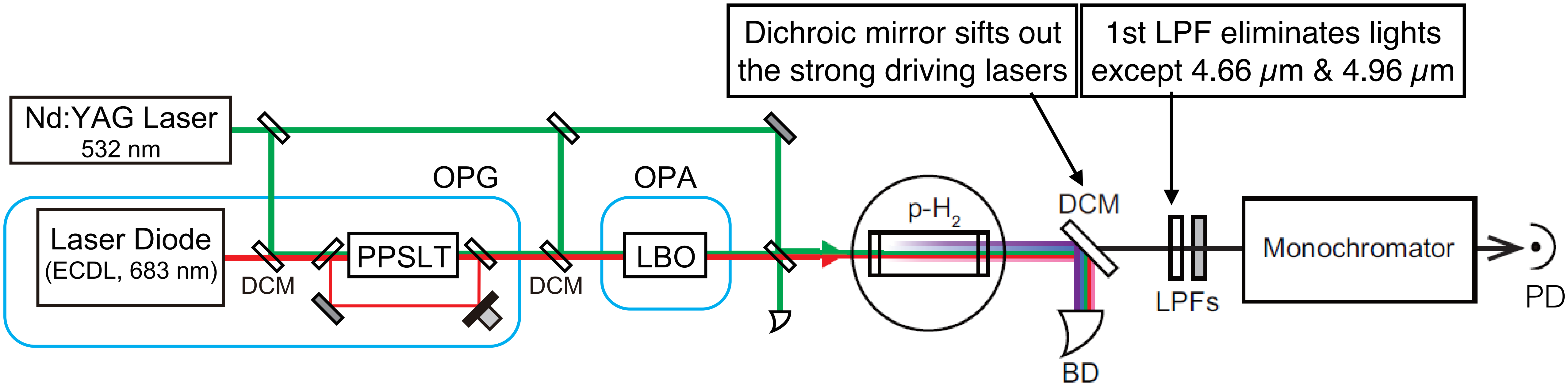
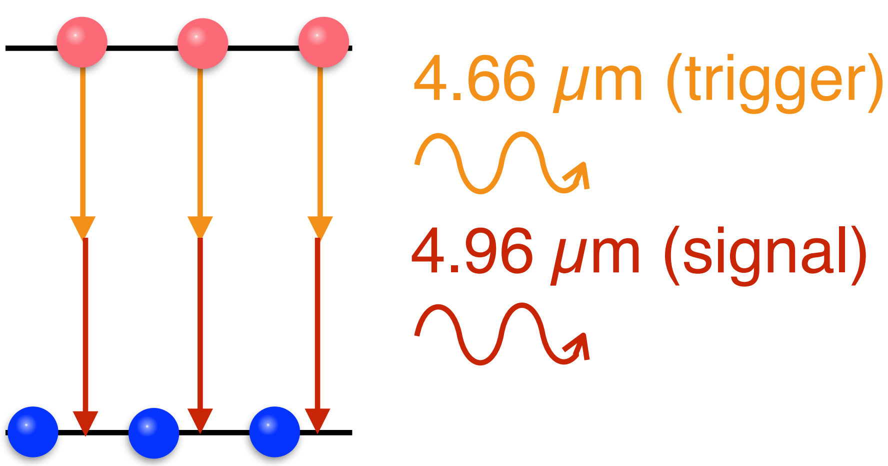


(3) Observation of Emission





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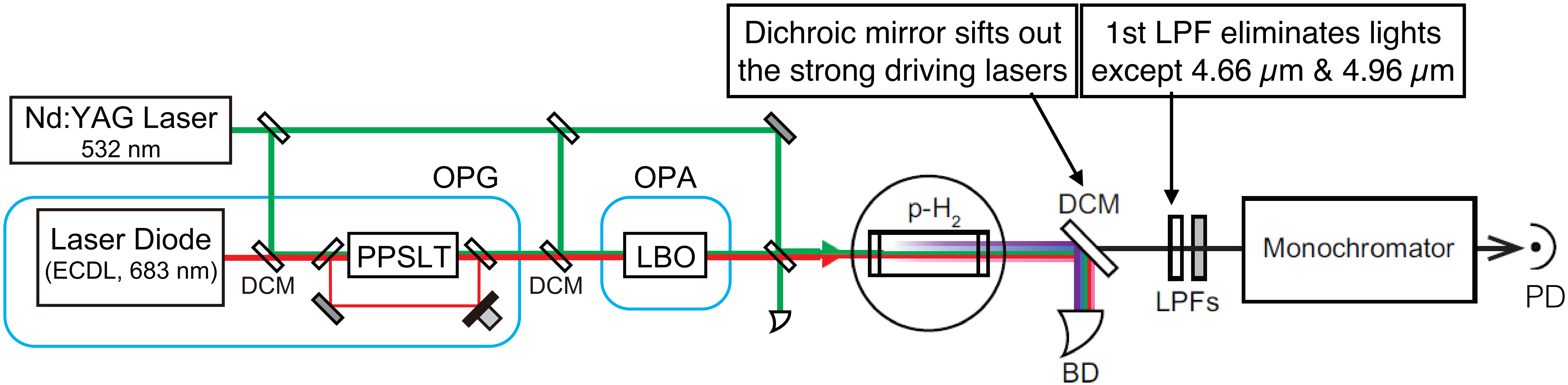

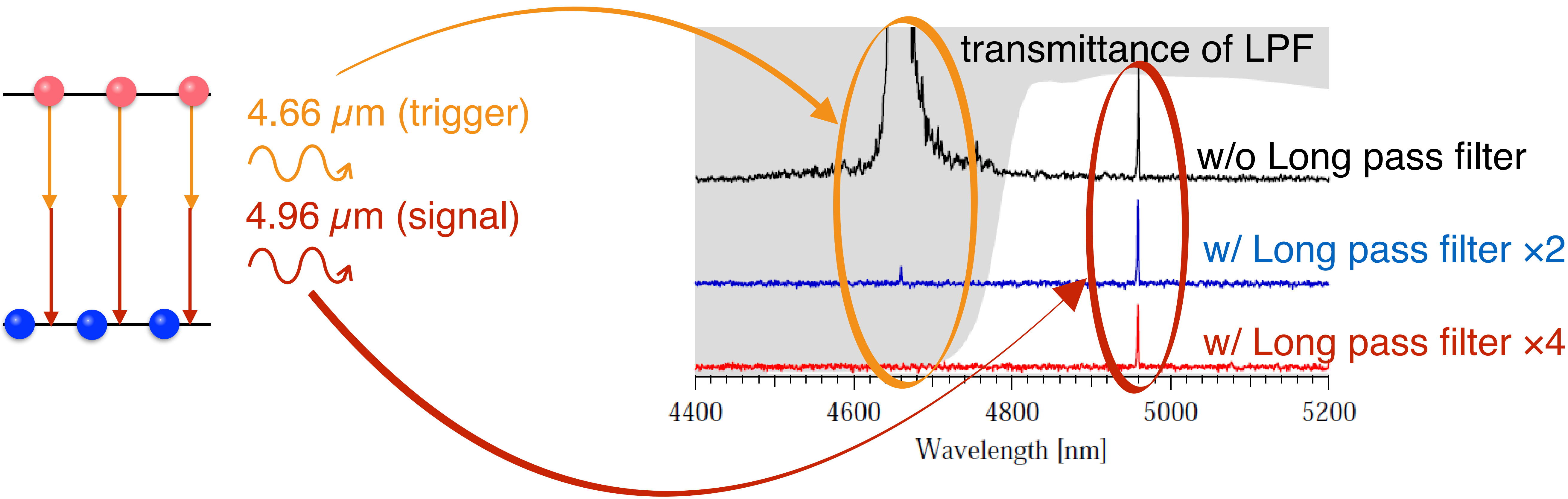

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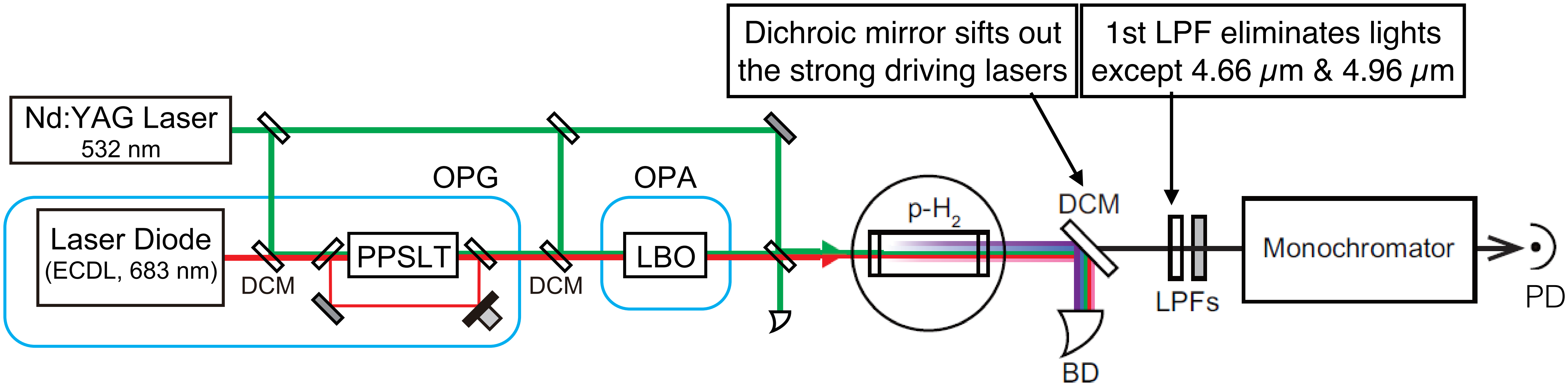
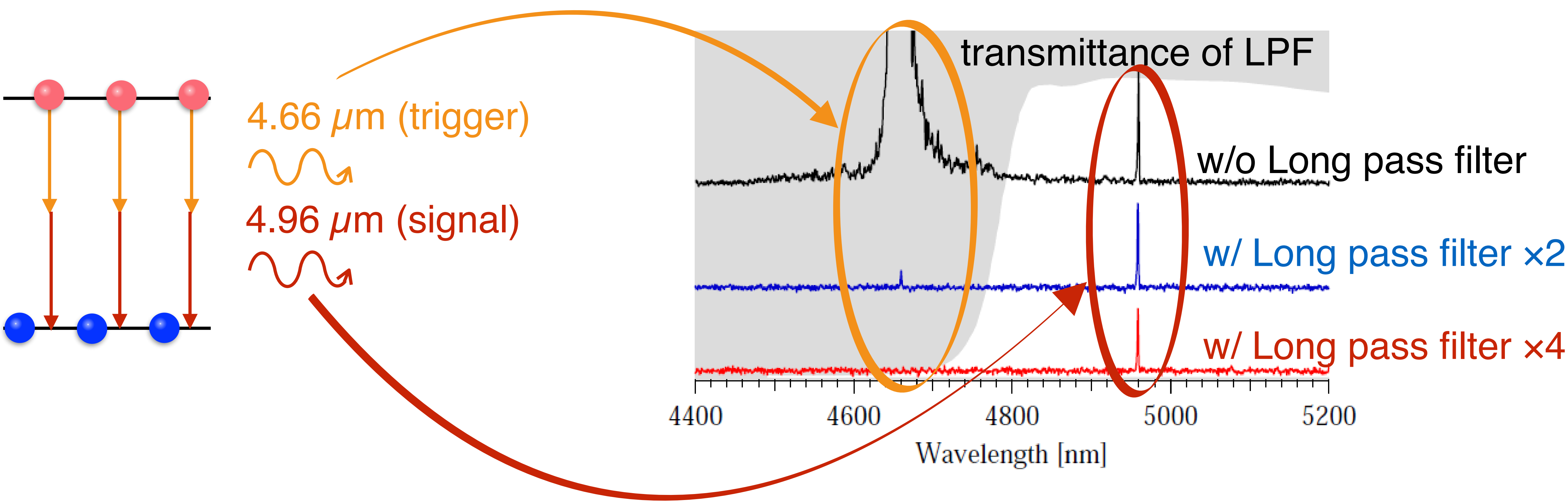
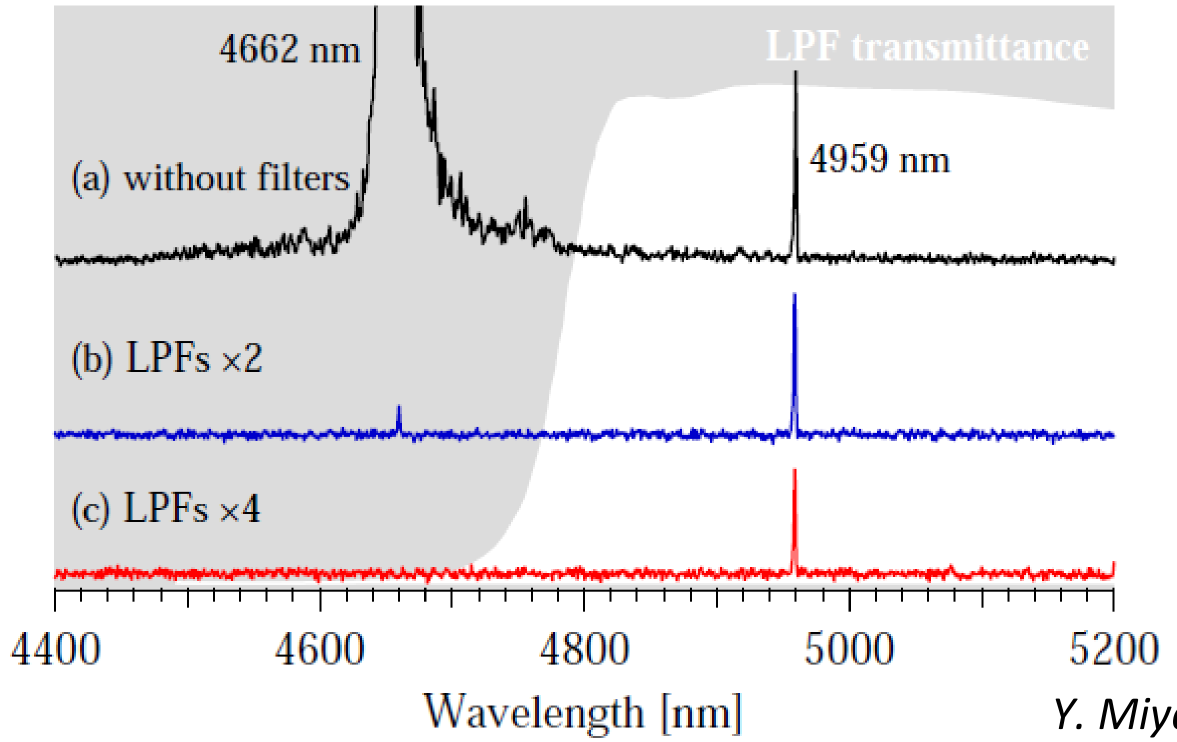




Clear peak exists!!

Enhancement Factor



Y. Miyamoto et. al. , arXiv:1406.2198v2

- Observed number of photons : > 4.4×10^{7} photon/pulse
- Expected number of photons : < 1.6×10^{-8} photon/pulse

Factor	Value
Spontaneous decay rate : dA/dz ($z=\omega/\omega$	3.2×10^{-11} s^{-1} ($z=1/2$)
Energy band width (monochromator) : Δz	4.9×10^{-3}
measurement time : Δt	80 ns
detector solid angle fraction : $\Delta\Omega/(4\pi)$	1.2×10^{-4}
the maximum number of excited molecules	< 1.5×10^{16}
The expected number of photons	< 1.6×10^{-8} photon/pulse

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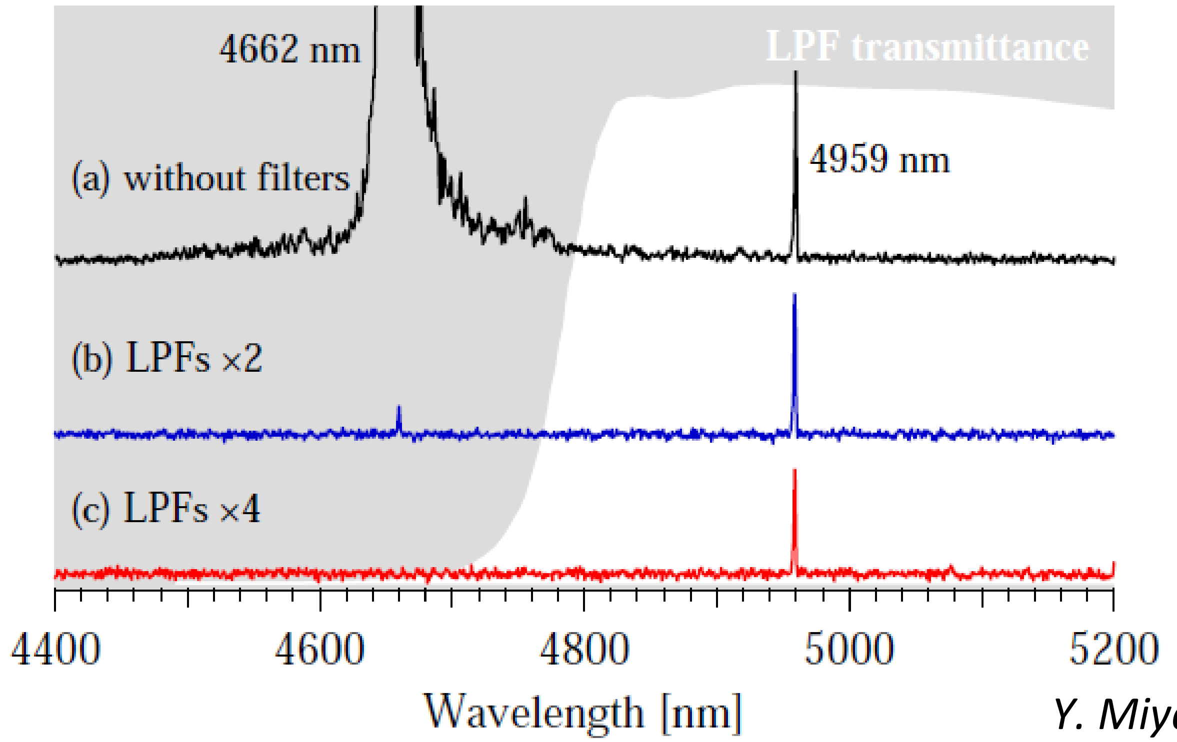

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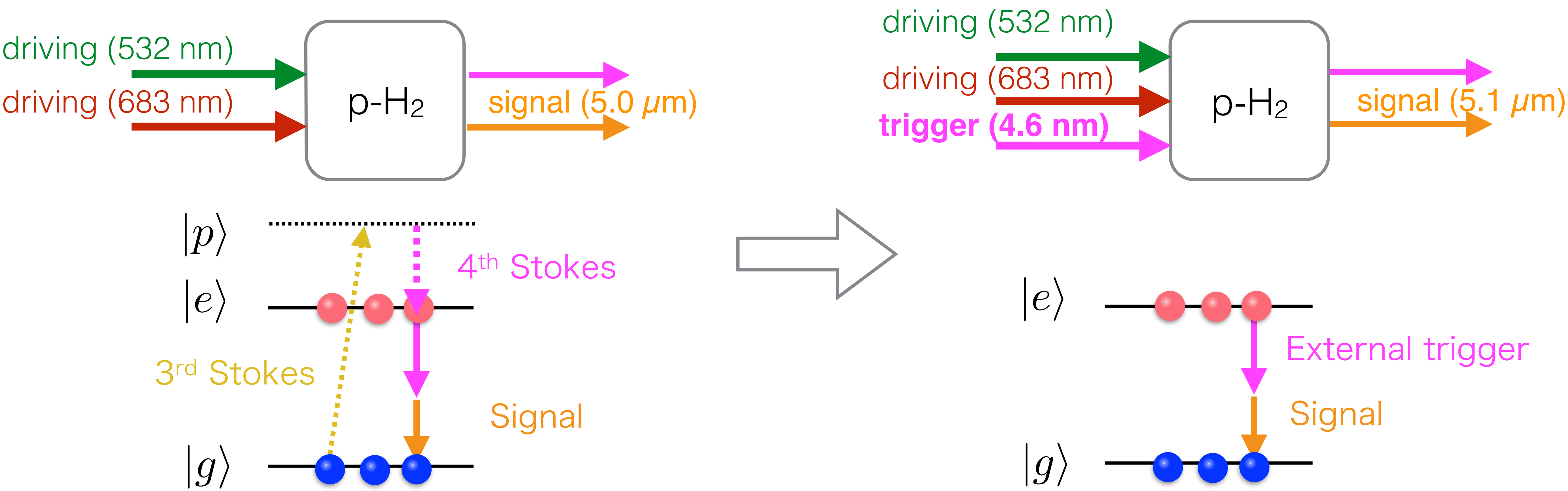
Huge enhancement (>10^{15}) has been obtained!

Next experiments

- PSR with External trigger



Independent control

coherence generation : driving power, p-H_2 pressure, etc.

PSR stimulation : power, timing, etc.

⇒ Quantitative discussion

Summary

- *RENP has potential to determine the neutrino absolute mass.*
  - Macro-coherent Amplification is essential to realize it.

- *Macro-coherent Amplification has been demonstrated* using two photon emission

4.96 μm emission has been observed.
Two photon emission has been enhanced by 10^{15}

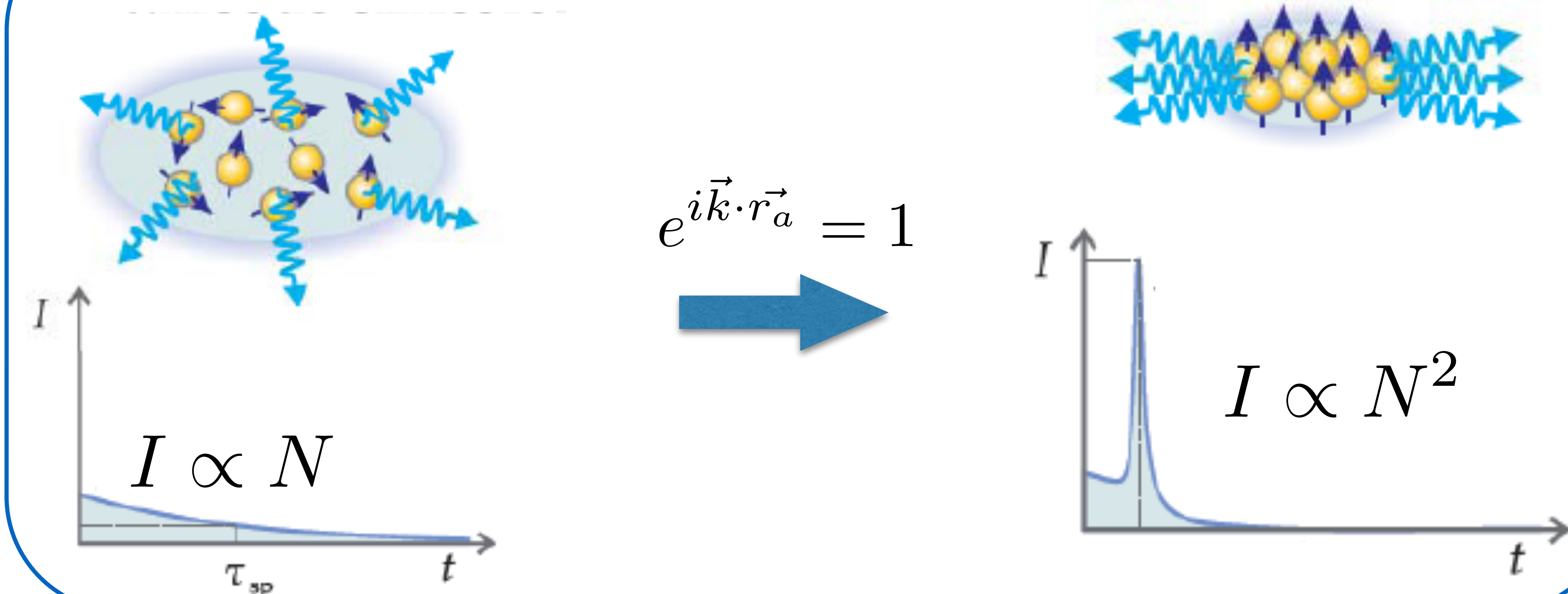
- *The next experiment is on-going*
  - PSR experiment with External trigger
    - Separate the coherence generation and the PSR stimulation.
    - Enable us to discuss more quantitatively.

Back up

Enhancement by Coherence

- Example of the amplification by coherence : **Single particle emission**

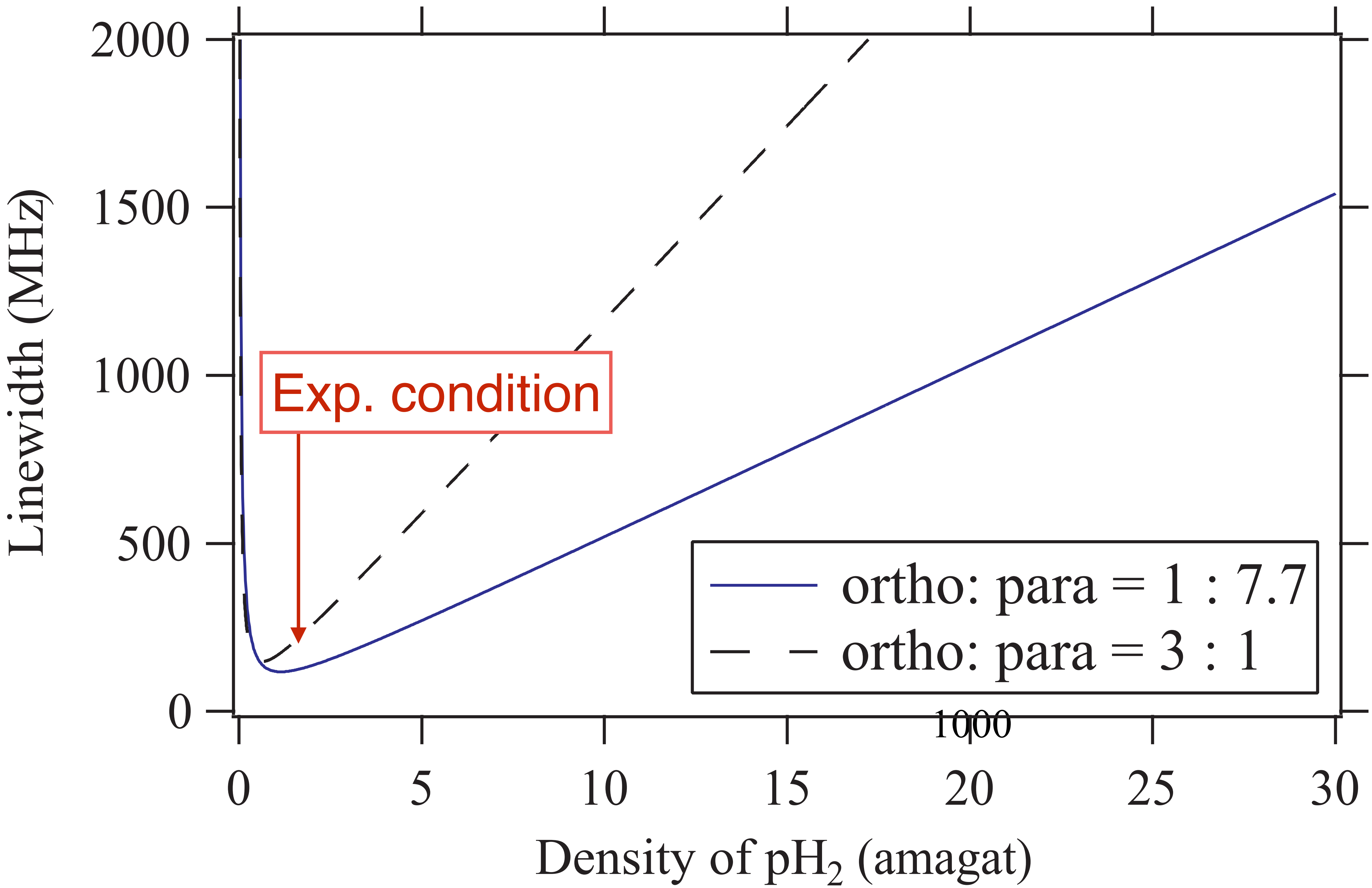
Super-radiance [Dicke, Rhys. Rev. **93** 99 (1954)]



  - The maximal coherent region is *limited by the wavelength* (~1 μm)
    → $N < 10^8$ (for 10^{20} cm^{-3})

- Macro-Coherent Amplification : **Plural particles emission**
  - Thanks to the momentum conservation ($e^{i(k_1+k_2+k_3)r_i} = 1$),
    the wavelength limitation can be removed.
    → *N can reach the Avogadro number.*

pH_2 line width

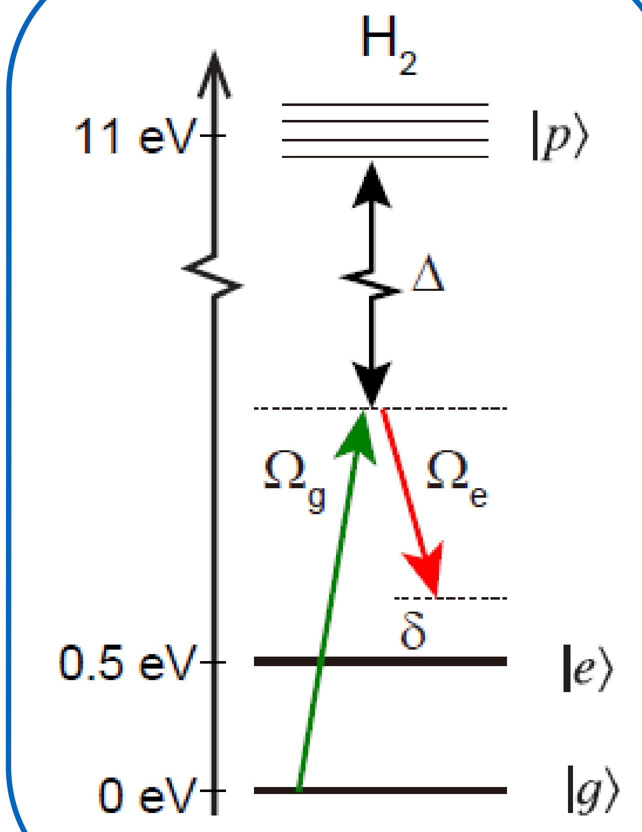


1 amagat ~ 2.7×10^{19} cm^{-3}

Adiabatic Raman Excitation

- State of atoms
  - Wave function $\psi = c_g|g\rangle + c_e|e\rangle$
  - Density matrix : $\rho = \begin{pmatrix} \rho_{gg} & \rho_{ge}e^{-i\phi} \\ \rho_{eg}e^{i\phi} & \rho_{ee} \end{pmatrix} = \begin{pmatrix} |c_g|^2 & c_g c_e^* \\ c_e c_g^* & |c_e|^2 \end{pmatrix}$
- Inject two color lasers(E_g, E_e) simultaneously
  - Effective hamiltonian

$$i\hbar \begin{pmatrix} \frac{\partial c_g}{\partial t} \\ \frac{\partial c_e}{\partial t} \end{pmatrix} = \mathcal{H}_{eff} \begin{pmatrix} c_g \\ c_e \end{pmatrix} = -\hbar \begin{pmatrix} \Omega_{gg} & \Omega_{ge} \\ \Omega_{eg} & \Omega_{ee} - \delta \end{pmatrix} \begin{pmatrix} c_g \\ c_e \end{pmatrix}$$



- Two color lasers change the eigenstates of the system from $|g\rangle$ and $|e\rangle$ to the superposition of them.

Eigenstates : $|\pm\rangle = \cos\frac{\theta}{2}|g\rangle \pm \sin\frac{\theta}{2}e^{-i\phi}|e\rangle$

Mixing angle : $\tan\theta \simeq \frac{2|\Omega_{ge}|}{\delta}$

Coherence : $\rho_{ge} = \frac{1}{2}\sin\theta e^{i\phi}$

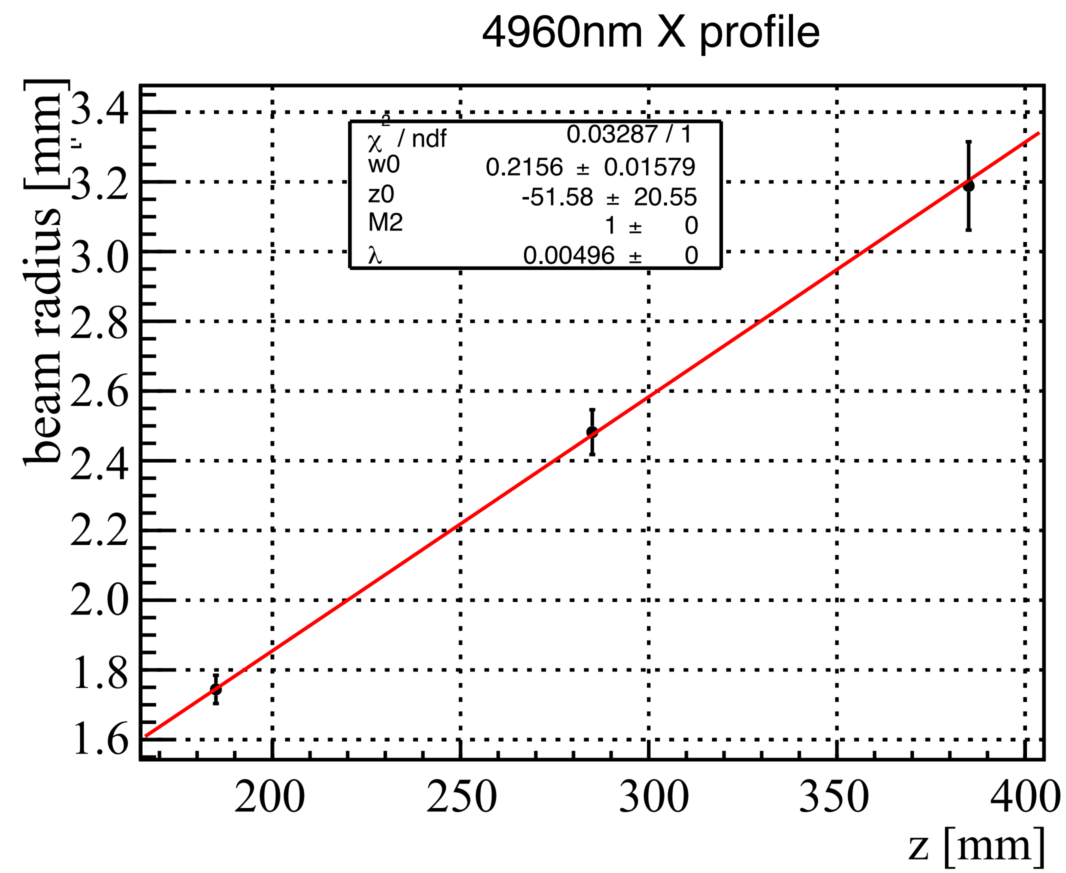
$$\Omega_{ij} \equiv \frac{\Omega_i \Omega_j}{\Delta} = \frac{(d_{ip}E_i)(d_{pj}E_j)}{\Delta}$$

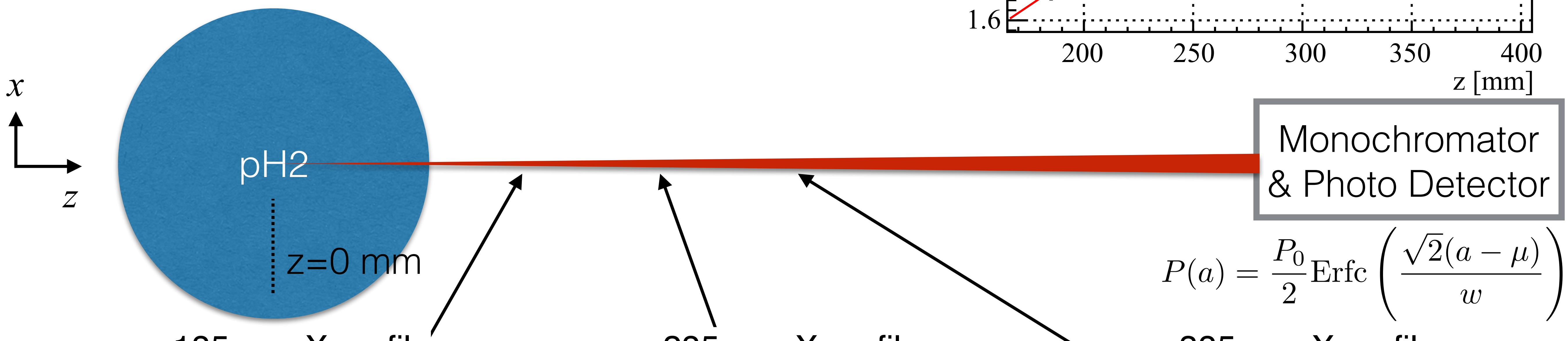
$$\left(e^{i\phi} \equiv \frac{\Omega_{ge}}{|\Omega_{ge}|} \right)$$

4.96 μm spatial profile

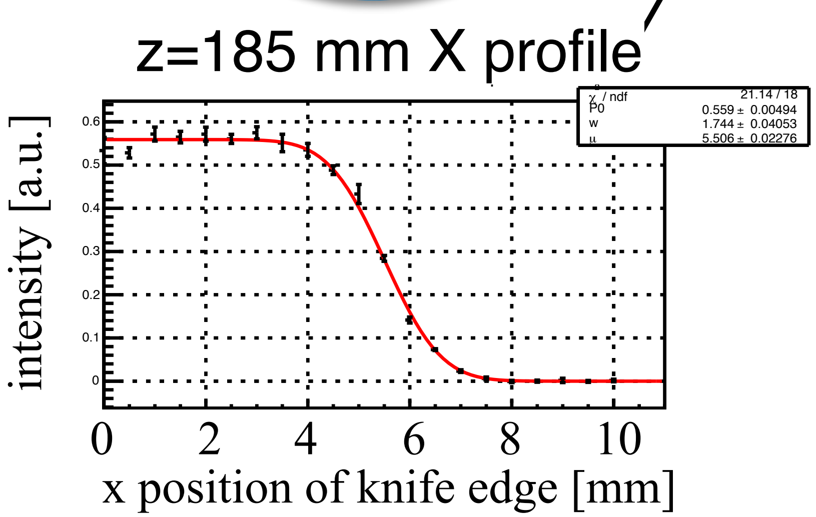
- Knife edge method

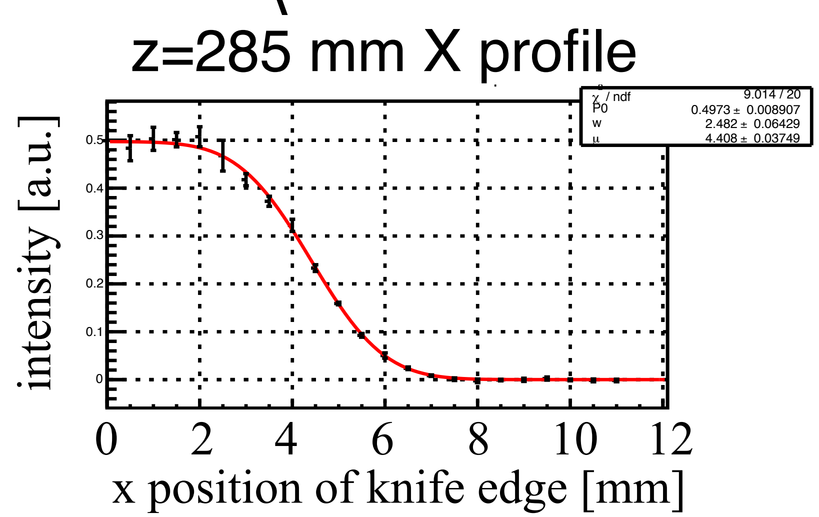
	X [mrad]	Y [mrad]
4.96 um	7.3	9.7
532 nm	1.8	2.0
683 nm	2.0	1.9

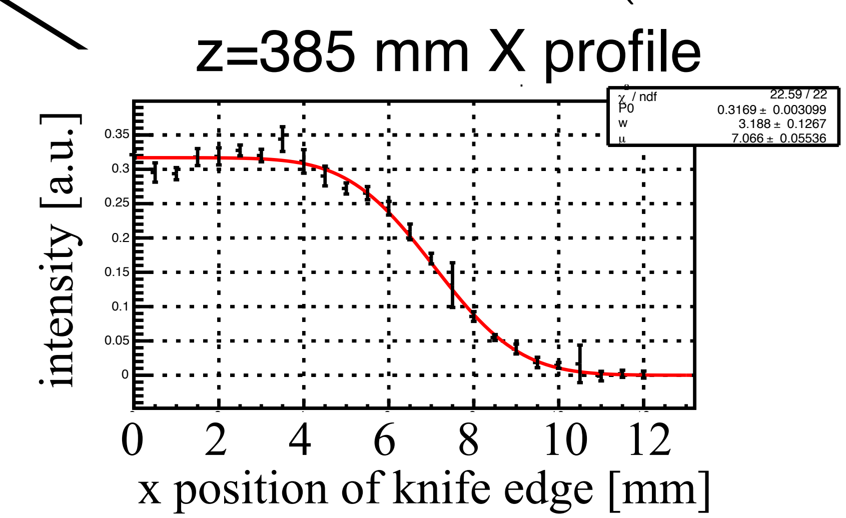




$$P(a) = \frac{P_0}{2}\mathrm{Erfc}\left(\frac{\sqrt{2}(a-\mu)}{w}\right)$$



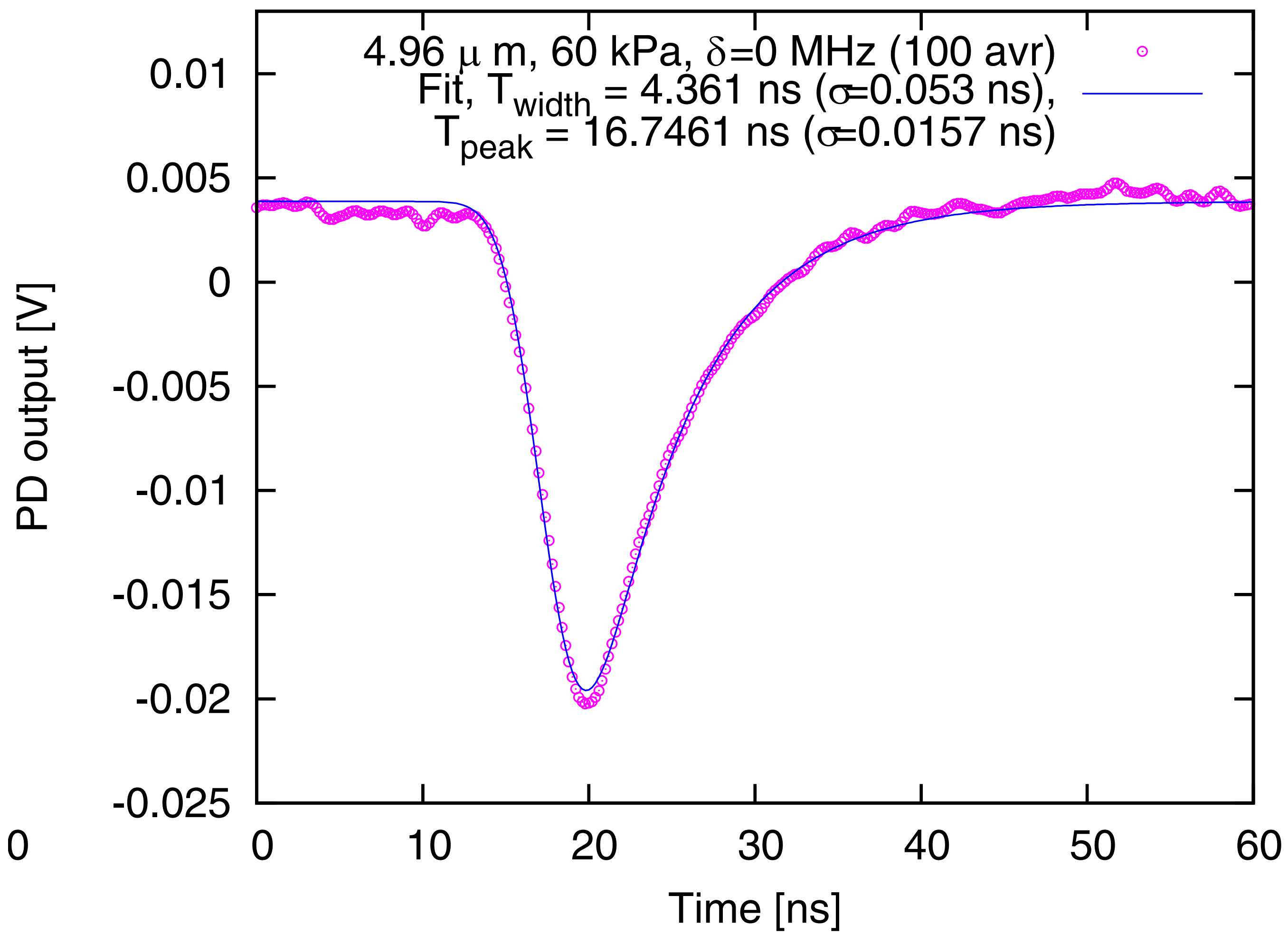




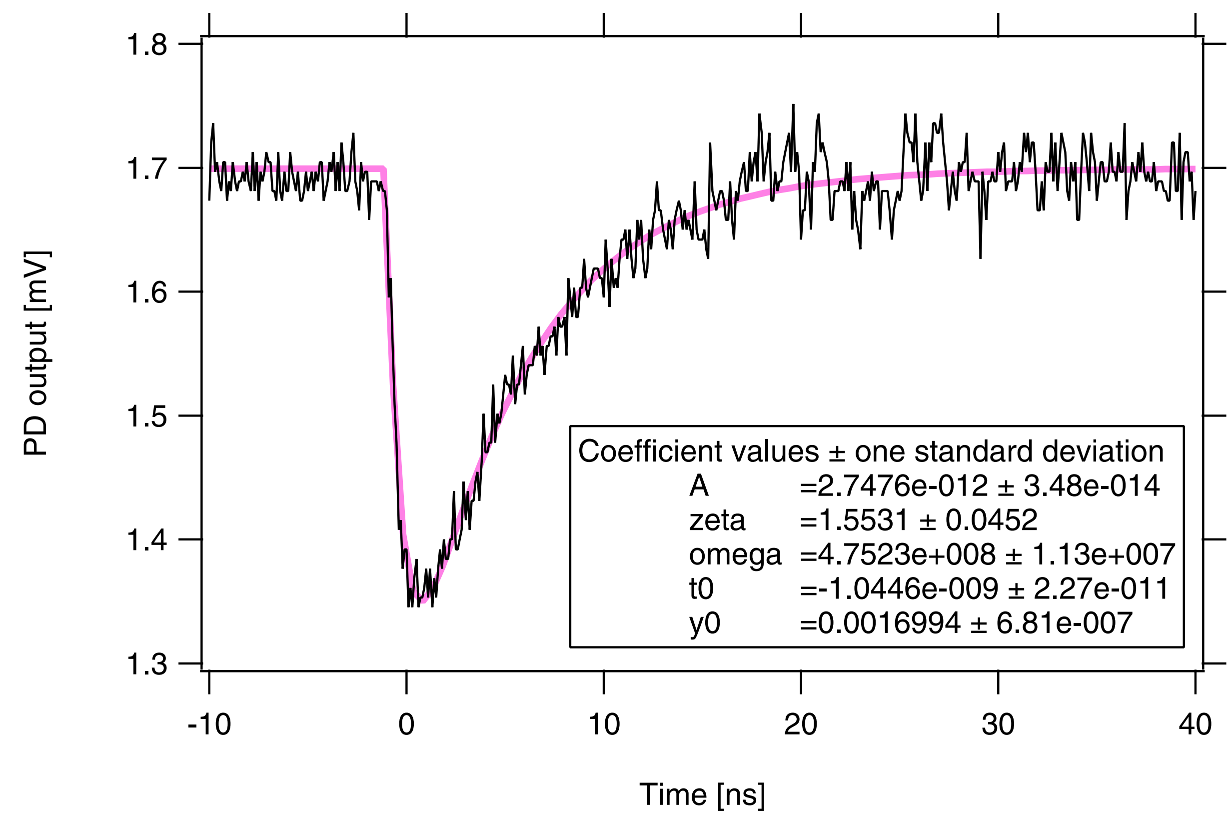
4.96 μm time profile

- Pulse duration of 4.36±0.05 ns is slightly shorter than driving lasers.

4.96 μm pulse output

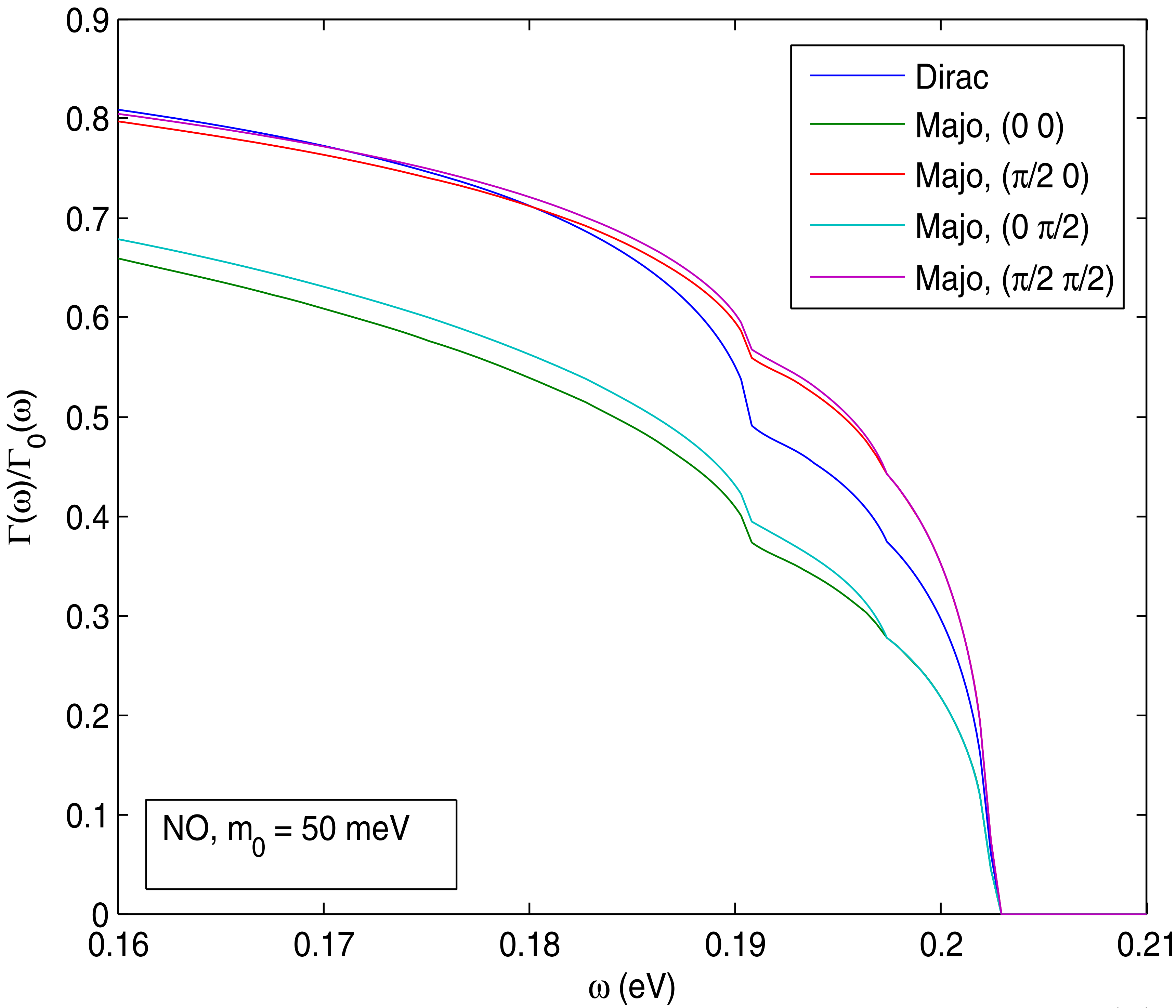


Detector response



$$g(t) = \frac{\omega_n}{\sqrt{\zeta^2 - 1}} e^{-\zeta \omega_n t} \sinh\left(\sqrt{\zeta^2 - 1}\,\omega_n t\right) \ (\zeta > 1)$$

Majorana/Dirac, CPV phases



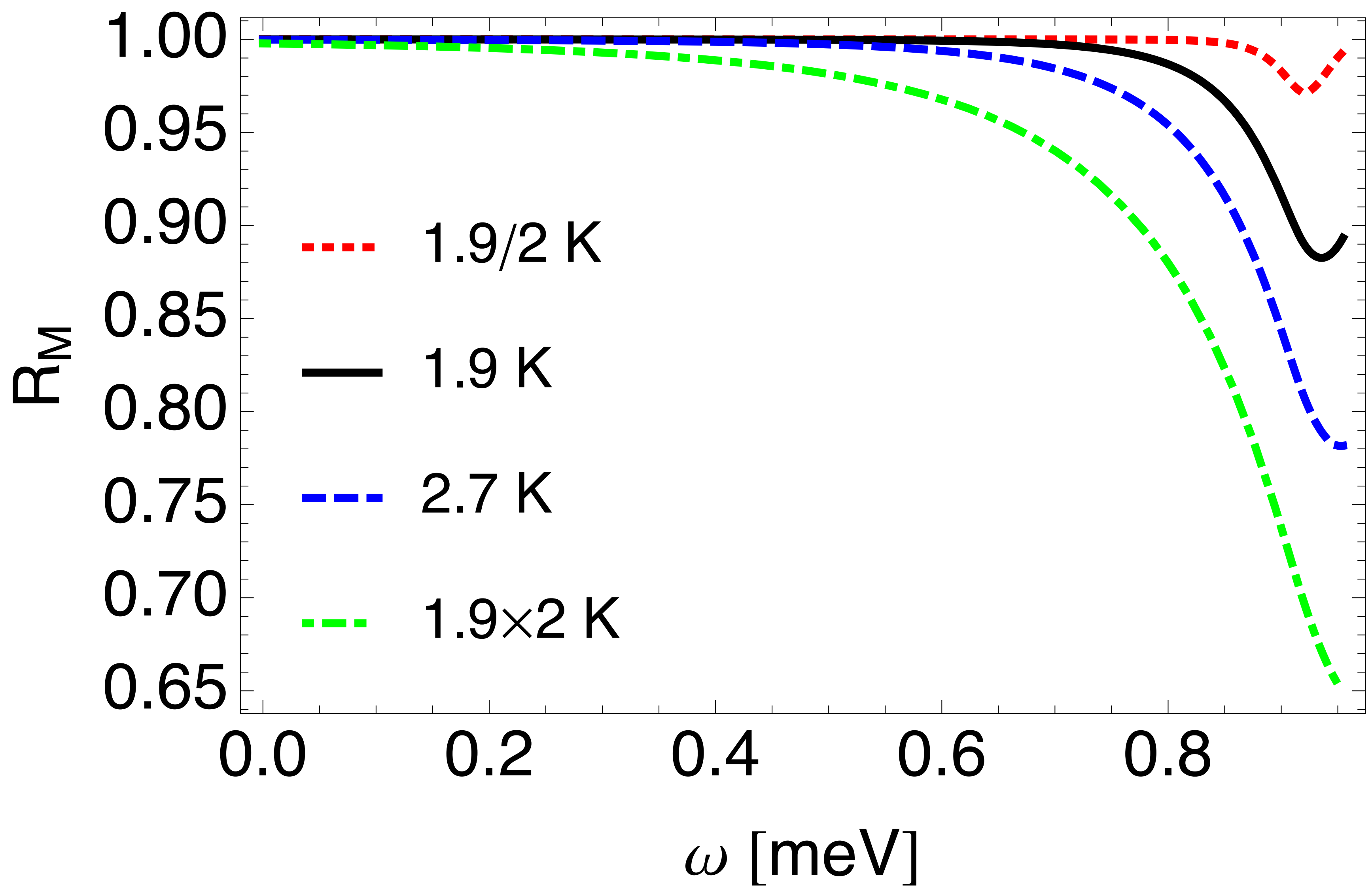
Normal hierarchy

m_1 = 50 meV

ω_{eg} = 0.43 eV

D.N. Dinh et al., Phys. Lett. B**719** (2013)

Cosmic neutrino background



m_{smallest} = 5 meV

ω_{eg} = 11 meV

μ = 0 eV

M. Yoshimura et al., arxiv:1409.3648

Time Development of the System

- Time-development of the system is obtained by numerically solving the Maxwell-Bloch equation
  - Bloch equation

Response of the molecules

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

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

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

  - Maxwell equation

Wave propagation

$$\frac{\partial E_q}{\partial \xi} = \frac{i\omega_q \mathcal{N}}{2c}\left\{(\rho_{gg}\alpha_{gg}^{(q)} + \rho_{ee}\alpha_{ee}^{(q)})E_q + \rho_{eg}\alpha_{eg}^{(q-1)}E_{q-1} + \rho_{ge}\alpha_{ge}^{(q)}E_{q+1}\right\}$$

$$\frac{\partial E_p}{\partial \xi} = \frac{i\omega_q \mathcal{N}}{2c}\left\{(\rho_{gg}\alpha_{gg}^{(p)} + \rho_{ee}\alpha_{ee}^{(p)})E_p + \rho_{eg}\alpha_{ge}^{(p\bar{p})}E_{\bar{p}}^*\right\}$$

Stark Shift

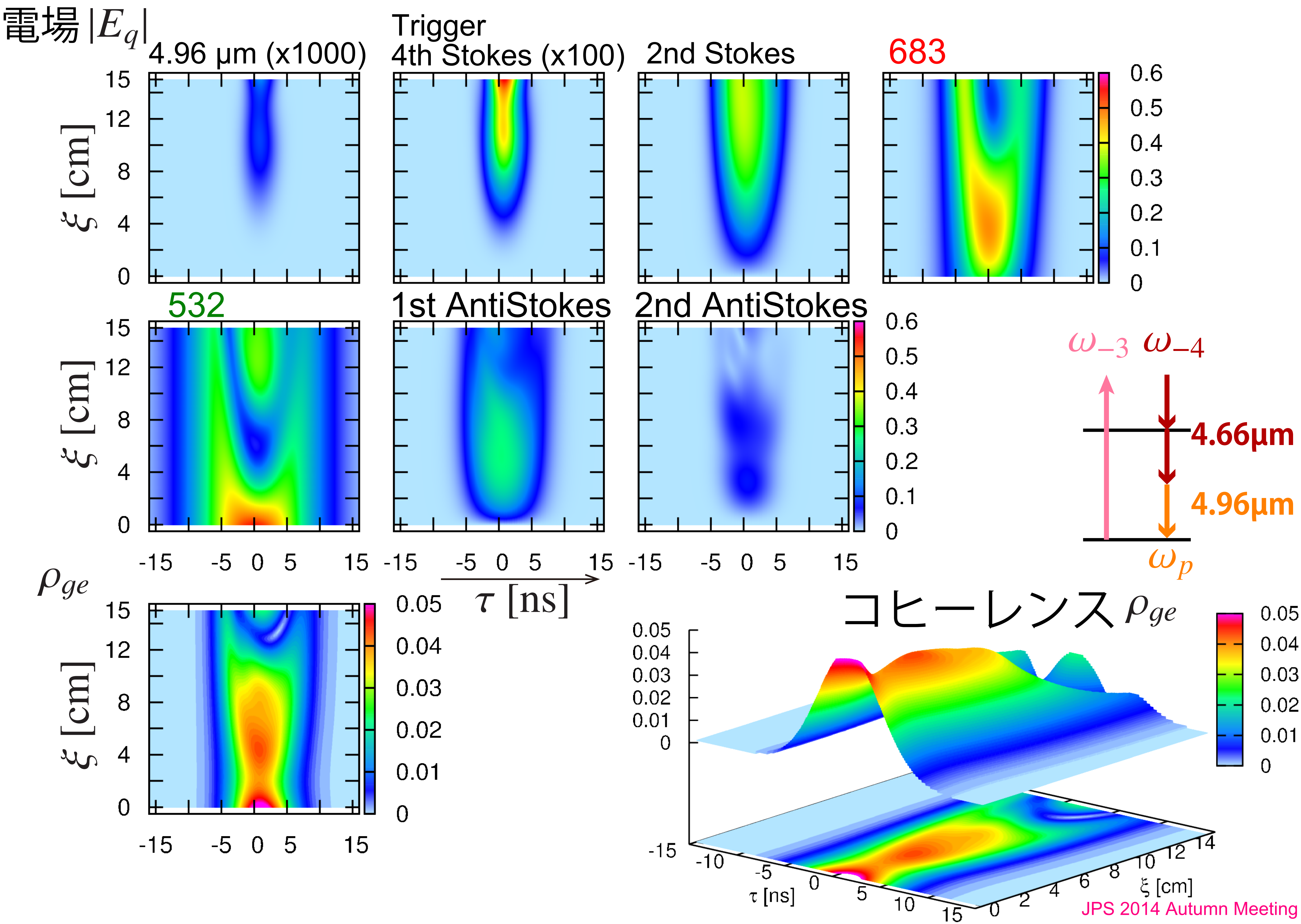
$$\Omega_{aa} = \frac{\varepsilon_0}{4\hbar}\sum_{m=q,p,\bar{p}} \alpha_{aa}^{(m)}|E_m|^2 \quad (a = g, e)$$

Two-photon Rabi frequency

$$\Omega_{ge} = \Omega_{eg}^* = \frac{\varepsilon_0}{4\hbar}\left\{\sum_q \alpha_{ge}^{(q)} E_q E_{q+1}^* + \alpha_{ge}^{(p\bar{p})} E_p^* E_{\bar{p}}^*\right\}$$

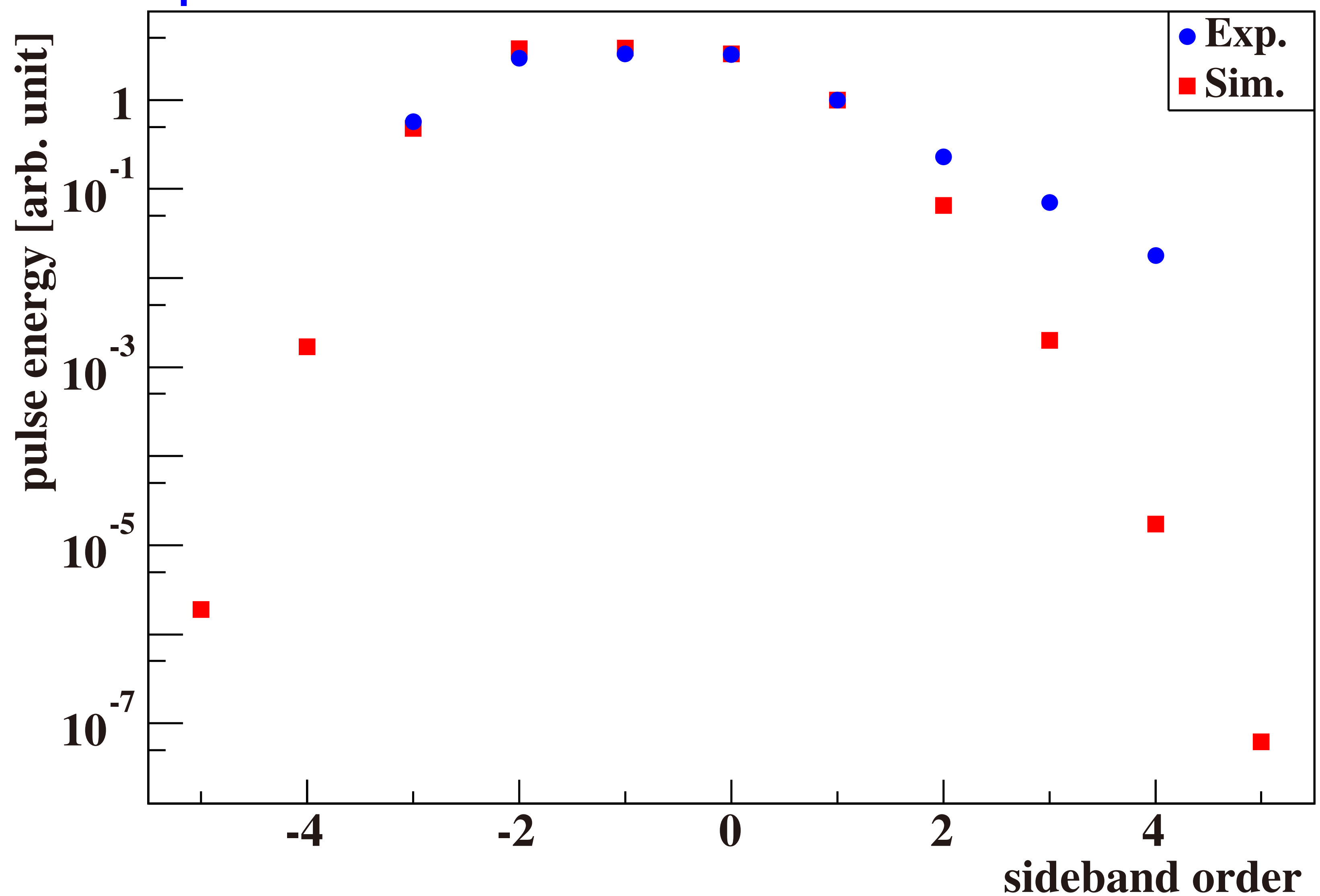
F.L. Kien *et al.*, PRA **60**, 1562 (1999); Y. Miyamoto *et al.*, arXiv:1406.2198v2

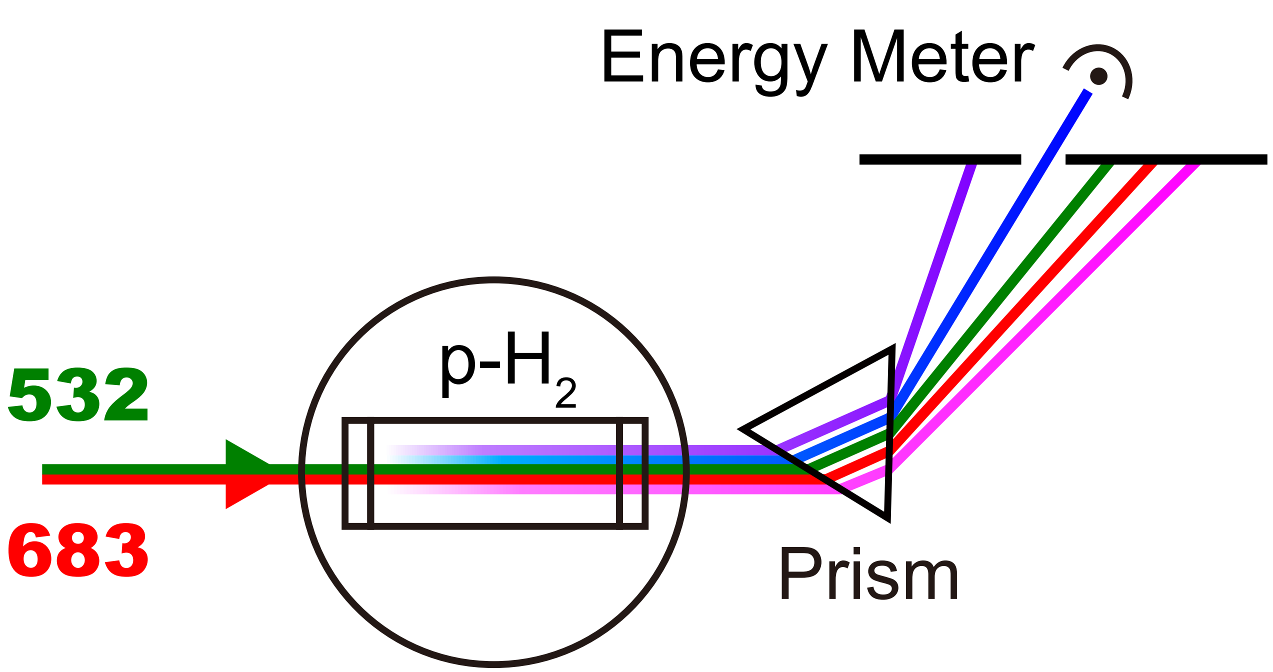
Simulation Results



Raman Coherence Estimation

- Experimental v.s. Simulation result

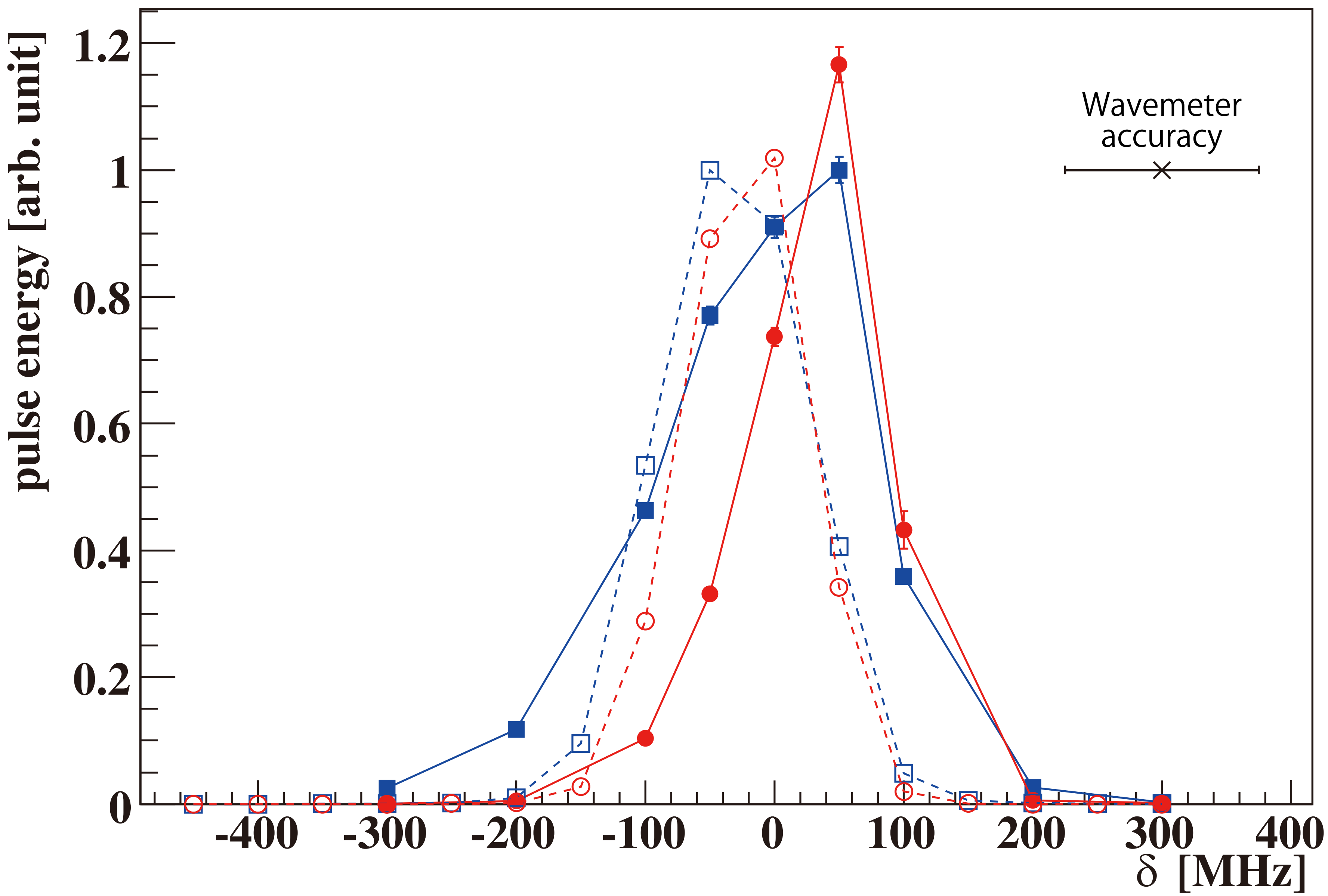


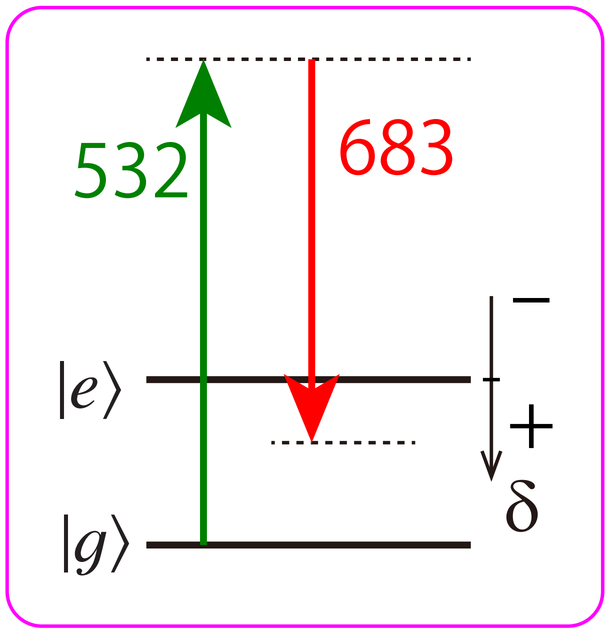


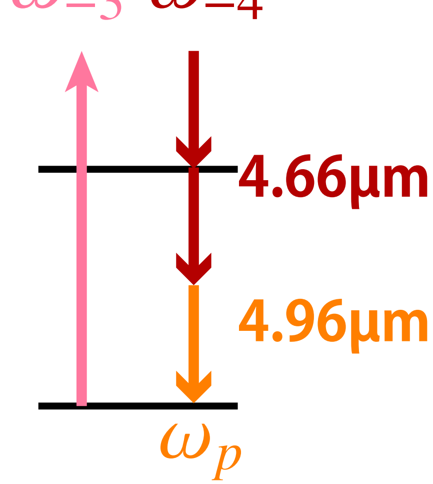
- 全体的な傾向は再現
- q ≧ 3 の再現性は悪い

平均コヒーレンス 0.032

Detuning Curve of Two-Photon Emission

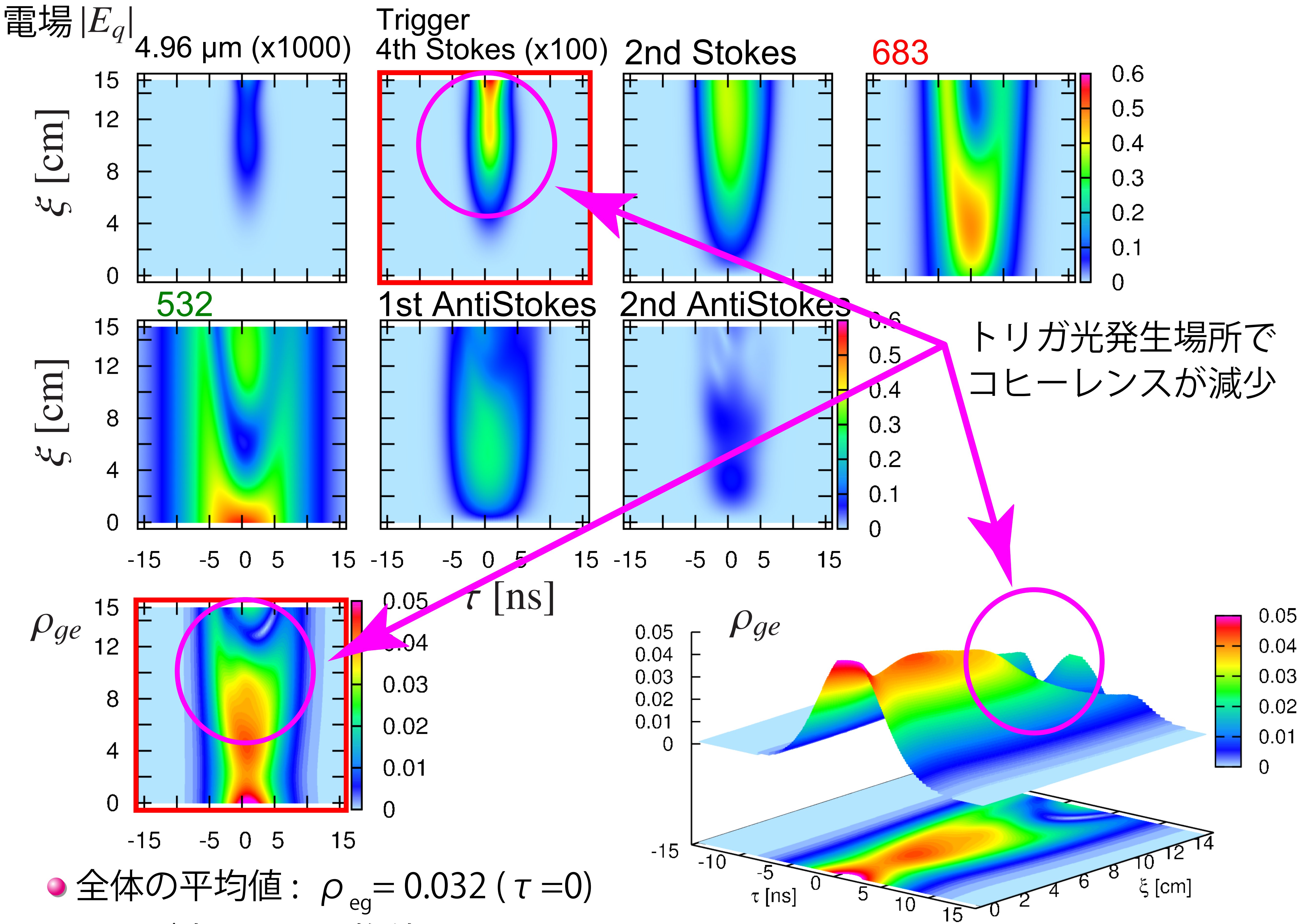






- Detuning curve の形状は一致 (測定誤差範囲内)
- $E_{4.96} / E_{4.66} = 10^{-3}$ two-photon pair の強度比は一致

Simulation モデルの妥当性を確認



- 全体の平均値： $\rho_{eg} = 0.032$ (τ =0)
- トリガ光周辺の平均値： $\rho_{eg} = 0.022$

External trigger exp. setup