Physics
OSAKA UNIVERSITY

Towards Atomic Neutrino Spectroscopy

Minoru TANAKA
Osaka University

HET Seminar@Osaka, Oct. 24, 2017

SPAN project

SPectroscopy with Atomic Neutrino

Okayama U.

H. Hara, T.Hiraki, T. Masuda, Y. Miyamoto, N. Sasao, Y.Takaesu, S. Uetake, A. Yoshimi, K. Yoshimura, M. Yoshimura, …

Other institute

K. Tsumura (Kyoto), M. T. (Osaka),…

INTRODUCTION

What we know about neutrino mass and mixing

Masses:

$$\Delta m^2_{21} \simeq (8.66\ \mathrm{meV})^2,\ \ \Delta m^2_{31(2)} \simeq (50.2(1)\ \mathrm{meV})^2$$

NuFIT 2016

$$\sum m_\nu \lesssim 230\ \mathrm{meV}$$

Planck 2013

Mixing: $U = V_{\mathrm{PMNS}}\, P$

$$V_{\mathrm{PMNS}} =$$

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$P = \mathrm{diag.}(1, e^{i\alpha}, e^{i\beta})$ Majorana phases

Bilenky, Hosek, Petcov; Doi, Kotani, Nishiura, Okuda, Takasugi; Schechter, Valle

$$\sin^2\theta_{12} \simeq 0.31,\ \ \sin^2\theta_{23} \simeq 0.44(59),\ \ \sin^2\theta_{13} \simeq 0.022$$

$$\delta \sim -\pi/2$$

NuFIT 2016

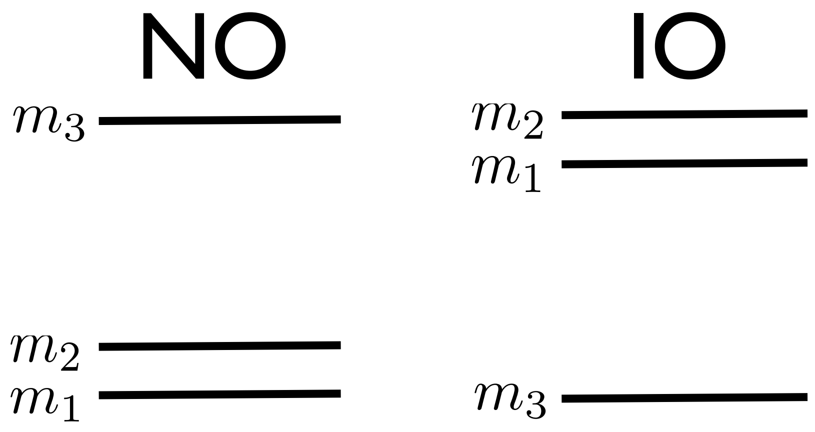
Unknown properties of neutrinos

Absolute mass

$$m_{1(3)} < 71(66)\ \mathrm{meV},\ 50\ \mathrm{meV} < m_{3(2)} < 87(82)\ \mathrm{meV}$$

Ordering pattern

normal or inverted



Mass type

Dirac or Majorana

CP violation

one Dirac phase, two Majorana phases

δ $\alpha,\ \beta$

Neutrino experiments

Conventional approach $E \gtrsim O(10\mathrm{keV})$ big science

Neutrino oscillation: SK, T2K, reactors,...

$\Delta m^2, \ \theta_{ij},$ NO or IO, δ

Neutrinoless double beta decays

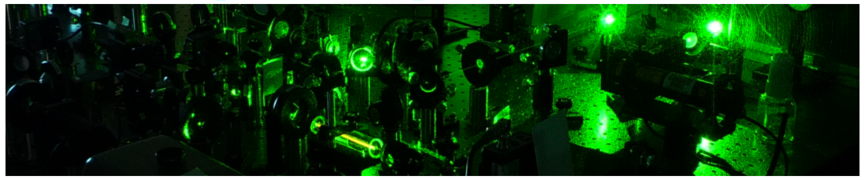
Dirac or Majorana, effective mass $\left|\sum_i m_i U_{ei}^2\right|^2$

Beta decay endpoint: KATRIN

absolute mass

Our approach $E \lesssim O(\mathrm{eV})$ tabletop experiment

Atomic/molecular processes

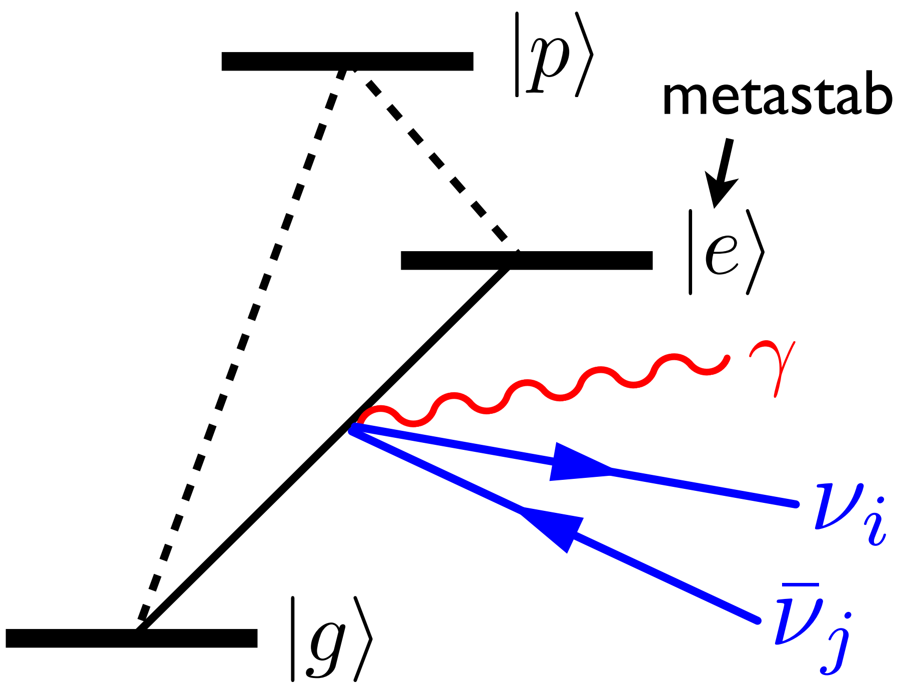


absolute mass, NO or IO, D or M, $\alpha \ (, \beta - \delta)$

RENP

Radiative Emission of Neutrino Pair (RENP)

A.Fukumi et al. PTEP (2012) 04D002, arXiv:1211.4904



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

Λ-type level structure

Ba, Xe, Ca+, Yb,...

H_2, O_2, I_2, ...

Atomic/molecular energy scale ~ eV or less

close to the neutrino mass scale

cf. nuclear processes ~ MeV

Rate $\sim \alpha G_F^2 E^5 \sim 1/(10^{33}\,\mathrm{s})$

Enhancement mechanism?

Rate enhancement by coherence

R.H. Dicke,
Phys. Rev. 93, 99 (1954)

An ensemble of N atoms in a small volume L^3

$$L \ll \text{wave length} \implies e^{-ikx} \sim 1$$

Density matrix $\rho = \rho_{gg}|g\rangle\langle g| + \rho_{ee}|e\rangle\langle e| + \rho_{eg}|e\rangle\langle g| + \rho_{ge}|g\rangle\langle e|$

Fully excited state: $|e\rangle^N = |e\rangle \cdots |e\rangle\,, \;\; \rho_{eg} = 0$

deexcitation: $\left(\sum |g\rangle\langle e|\right) \prod |e\rangle$

$$= |g\rangle|e\rangle \cdots |e\rangle + |e\rangle|g\rangle \cdots |e\rangle + \cdots + |e\rangle|e\rangle \cdots |g\rangle$$

➡ $\Gamma = N\Gamma_0$ **incoherent**

Fully coherent state: $\left[(|g\rangle + |e\rangle)/\sqrt{2}\right]^N \,, \;\; \rho_{eg} = 1/2$

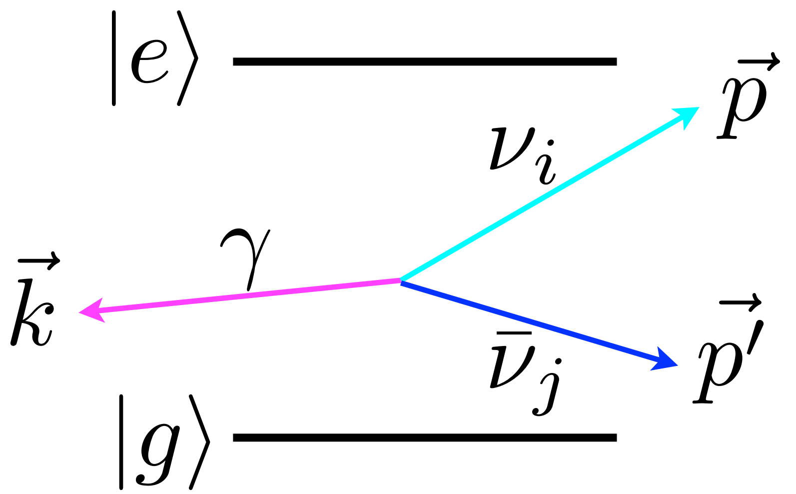
$$\xrightarrow[\text{deexcitation}]{} [|g\rangle(|g\rangle + |e\rangle) \cdots (|g\rangle + |e\rangle)$$

$$+ (|g\rangle + |e\rangle)|g\rangle \cdots (|g\rangle + |e\rangle) + \cdots]/\sqrt{2^N}$$

➡ $\Gamma = N(N+1)\Gamma_0/4 \sim O(N^2)$ coherent

Macrocoherence

Yoshimura et al. (2008)



position of atom

$$\propto e^{-i(\vec{k}+\vec{p}+\vec{p'})\cdot\vec{x}_a}(2\pi)\delta(\epsilon_{eg}-\omega-E_p-E_{p'})$$

$$(\epsilon_{eg}=\epsilon_e-\epsilon_g,\ \omega=|\vec{k}|)$$

Macroscopic target of N atoms, volume V (n=N/V)

total amp. $\propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p'})\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p'})$

$$d\Gamma \propto \boxed{n^2V}(2\pi)^4\delta^4(q-p-p') \qquad (q^\mu)=(\epsilon_{eg}-\omega,-\vec{k})$$

macrocoherent amplification

RENP spectrum

D.N. Dinh, S.T. Petcov, N. Sasao, M.T., M.Yoshimura
PLB719(2013)154, arXiv:1209.4808

Energy-momentum conservation
due to the macrocoherence

→ familiar 3-body decay kinematics
virtual parent particle $(P^\mu) = (\varepsilon_{eg}, \mathbf{0}), \;\; P^2 = \varepsilon_{eg}^2$

Six thresholds of the photon energy

$$\omega_{ij} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}} \qquad i, j = 1, 2, 3$$

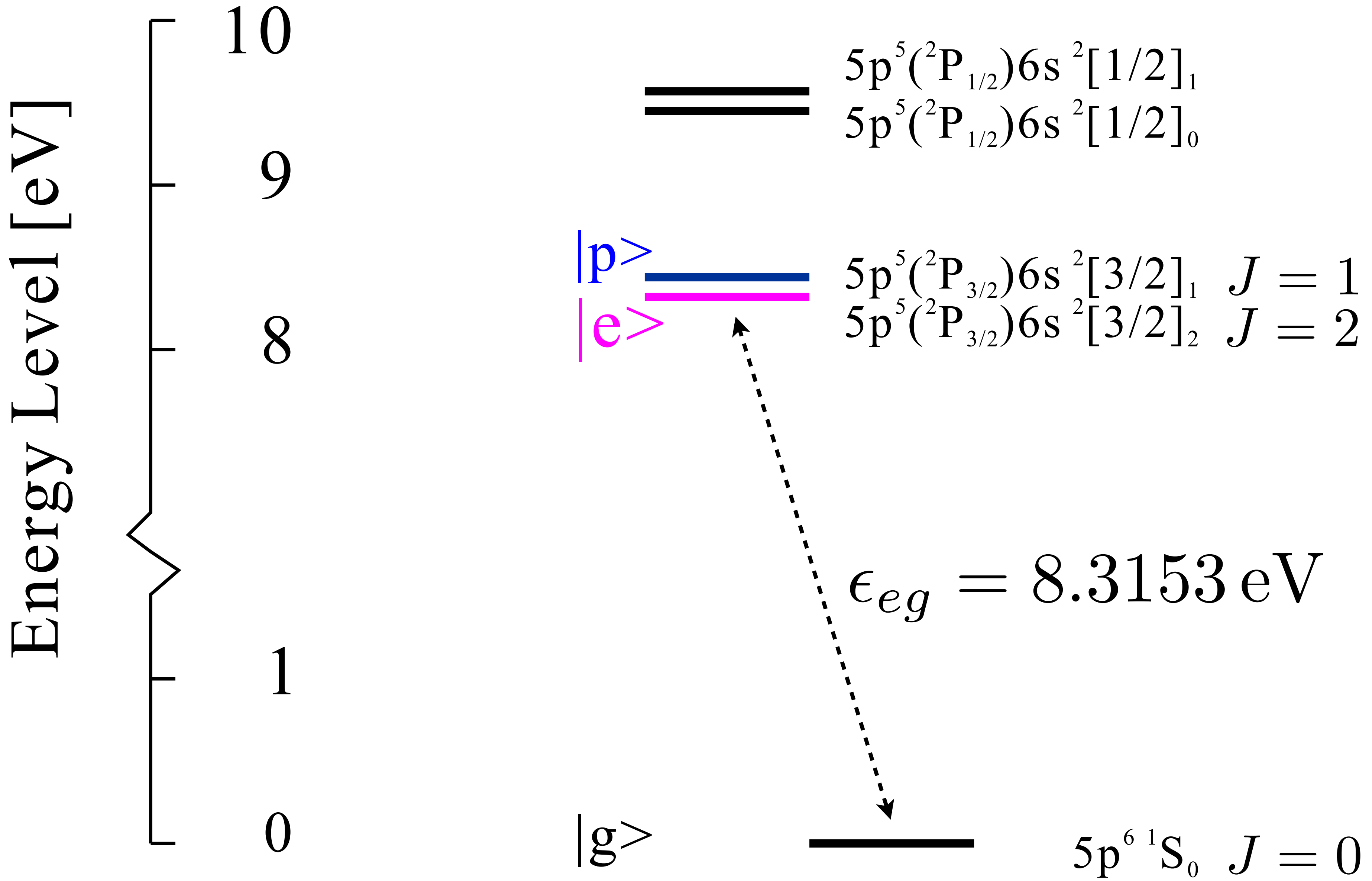
$\epsilon_{eg} = \epsilon_e - \epsilon_g$ atomic energy level splitting

Required energy resolution $\sim O(10^{-6})\,\mathrm{eV}$

typical laser linewidth

$$\Delta\omega_{\mathrm{trig.}} \lesssim 1\,\mathrm{GHz} \sim O(10^{-6})\,\mathrm{eV}$$

Xe



$|e\rangle \leftrightarrow |p\rangle$ M1

$|p\rangle \leftrightarrow |g\rangle$ E1

macro-coherence

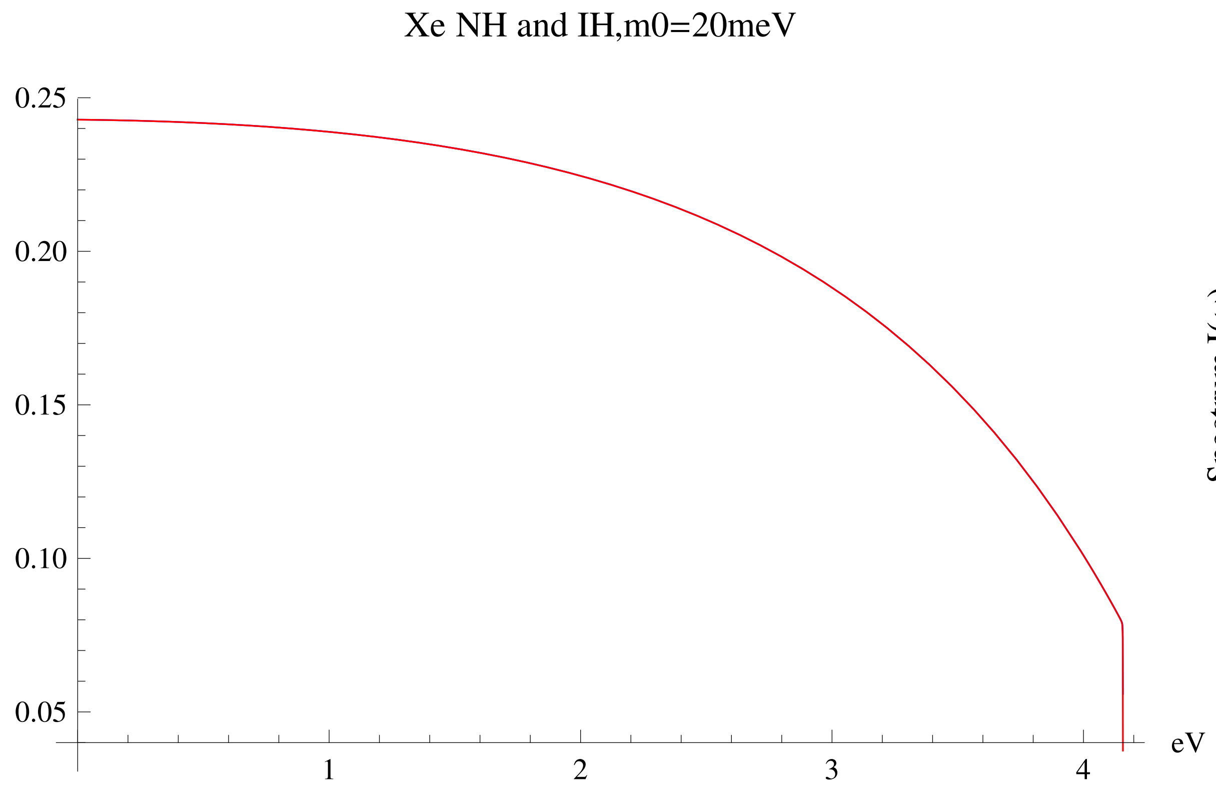
field energy density

$$\Gamma_0^{\mathrm{SC}} \sim \frac{3\boxed{n^2V}G_F^2\gamma_{pg}\boxed{\epsilon_{eg}n}}{2\epsilon_{pg}^3} \sim 1\ \mathrm{mHz}\,(n/10^{21}\mathrm{cm}^{-3})^3(V/10^2\mathrm{cm}^3)$$

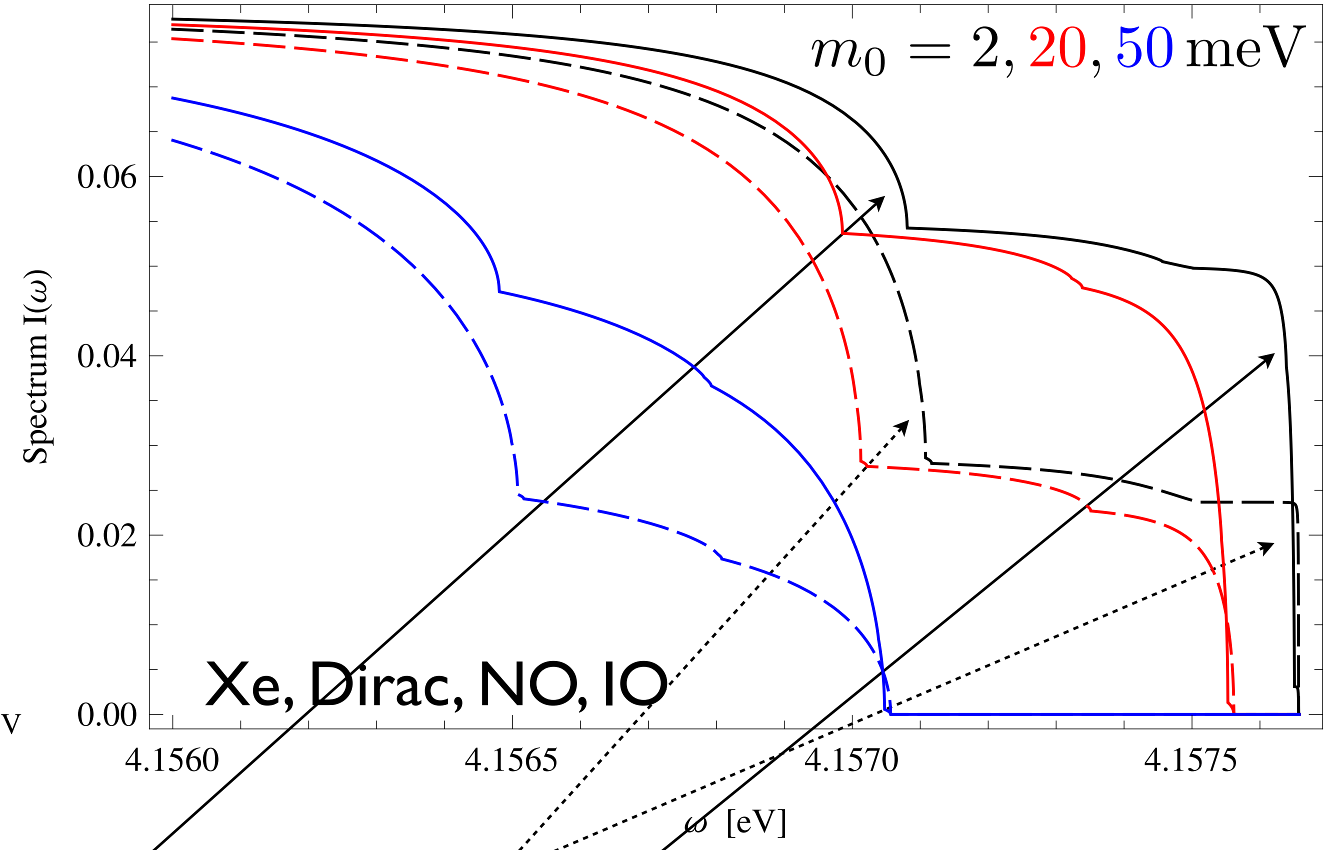
$\gamma_{pg} : |p\rangle \to |g\rangle$ **rate**

Photon spectrum (spin current)

Global shape



Threshold region



The threshold weight factors

B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{13}^2 - 1/2)^2$	$2c_{12}^2 s_{12}^2 c_{13}^4$	$2s_{12}^2 c_{13}^2 s_{13}^2$	$2c_{12}^2 c_{13}^2 s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

Boosted RENP

M.T., K.Tsumura, N.Sasao, S.Uetake, M.Yoshimura, arXiv:1710.07135

Initial spatial phase

Preparation of initial coherent state

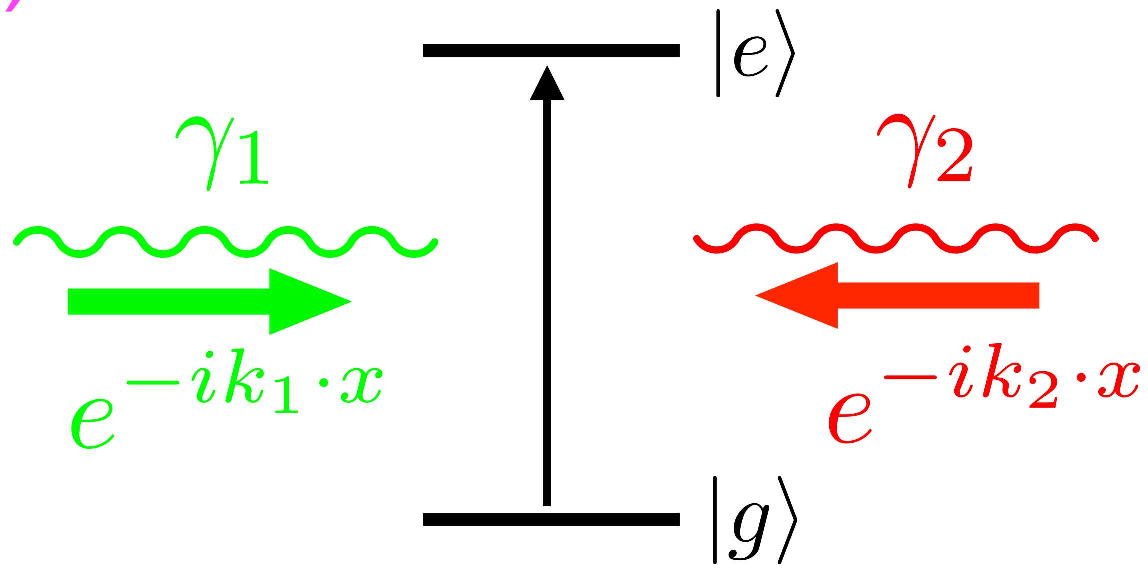
Two-photon absorption: $\gamma_1(k_1) + \gamma_2(k_2) + |g\rangle \to |e\rangle$

Initial spatial phase (ISP)

counter-propagating

$$\langle e|\rho|g\rangle \propto e^{i\boldsymbol{p}_{eg}\cdot\boldsymbol{x}}$$

$$|\boldsymbol{p}_{eg}| = |\boldsymbol{k}_1 + \boldsymbol{k}_2|$$
$$= |\omega_1 - \omega_2|$$



Momentum conservation

$$\gamma_1(k_1) + \gamma_2(k_2) + |g\rangle \to |e\rangle \to |g\rangle + \gamma(k) + \nu_i(p)\bar{\nu}_j(p')$$

$$\sum_a e^{i(\boldsymbol{p}_{eg}-\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{p}')\cdot\boldsymbol{x}_a} \propto \delta^3(\boldsymbol{p}_{eg} - \boldsymbol{k} - \boldsymbol{p} - \boldsymbol{p}')$$

$\boldsymbol{p}_{eg} \sim$ mom. of parent particle → boosted RENP

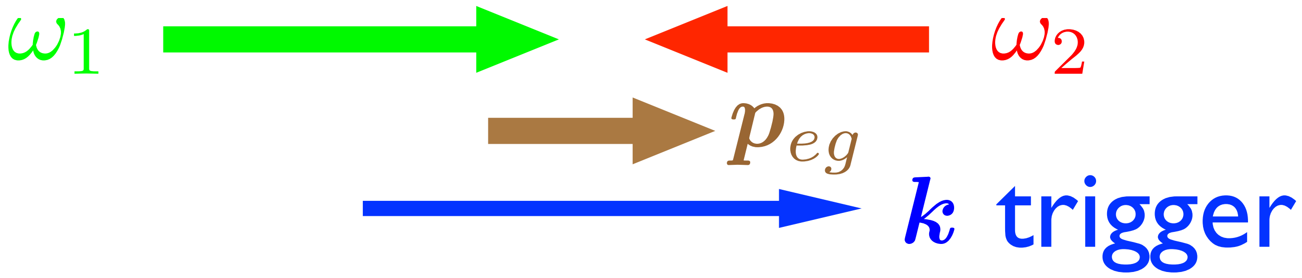
Kinematics of the boosted RENP

4-momentum of parent particle: $(P^\mu) = (\epsilon_{eg}, \boldsymbol{p}_{eg})$

Invariant mass: $P^2 = \epsilon_{eg}^2 - \boldsymbol{p}_{eg}^2 \leq \epsilon_{eg}^2$

smaller mass scale

$\nu_i \bar{\nu}_j$ threshold: $\boldsymbol{p}_{eg} \parallel \boldsymbol{k}, \ \omega_1 \geq \omega_2$



$$\omega_{ij} = \omega_1 - \frac{(m_i + m_j)^2}{4\omega_2}, \ \omega_1 + \omega_2 = \epsilon_{eg}$$

cf. no boost case: $\omega_{ij} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}}$

Dirac-Majorana difference, Majorana phases

Spectral rate

$$\Gamma(E_\gamma) = \text{Dirac part} + \text{Majorana interference}$$

$$\text{M.I.} \propto \mathrm{Re}(U_{ei}^* U_{ej} - \delta_{ij}/2)^2 m_i m_j$$

Majorana phases

$$\mathrm{Re}(U_{e1}^* U_{e2})^2 = c_{12}^2 s_{12}^2 c_{13}^4 \cos 2\alpha \simeq 0.20 \cos 2\alpha$$

$$\mathrm{Re}(U_{e1}^* U_{e3})^2 = c_{12}^2 c_{13}^2 s_{13}^2 \cos 2(\beta - \delta) \simeq 0.015 \cos 2(\beta - \delta)$$

$$\begin{aligned}\mathrm{Re}(U_{e2}^* U_{e3})^2 &= s_{12}^2 c_{13}^2 s_{13}^2 \cos 2(\beta - \delta - \alpha) \\ &\simeq 0.0065 \cos 2(\beta - \delta - \alpha)\end{aligned}$$

sensitive to α

Yb RENP spectra: $E_{eg} = 2.14348\ \mathrm{eV},\ \alpha \in [0, \pi/2],\ \beta = 0$

no boost

boosted: $b := |\boldsymbol{p}_{eg}|/E_{eg} = 0.95$

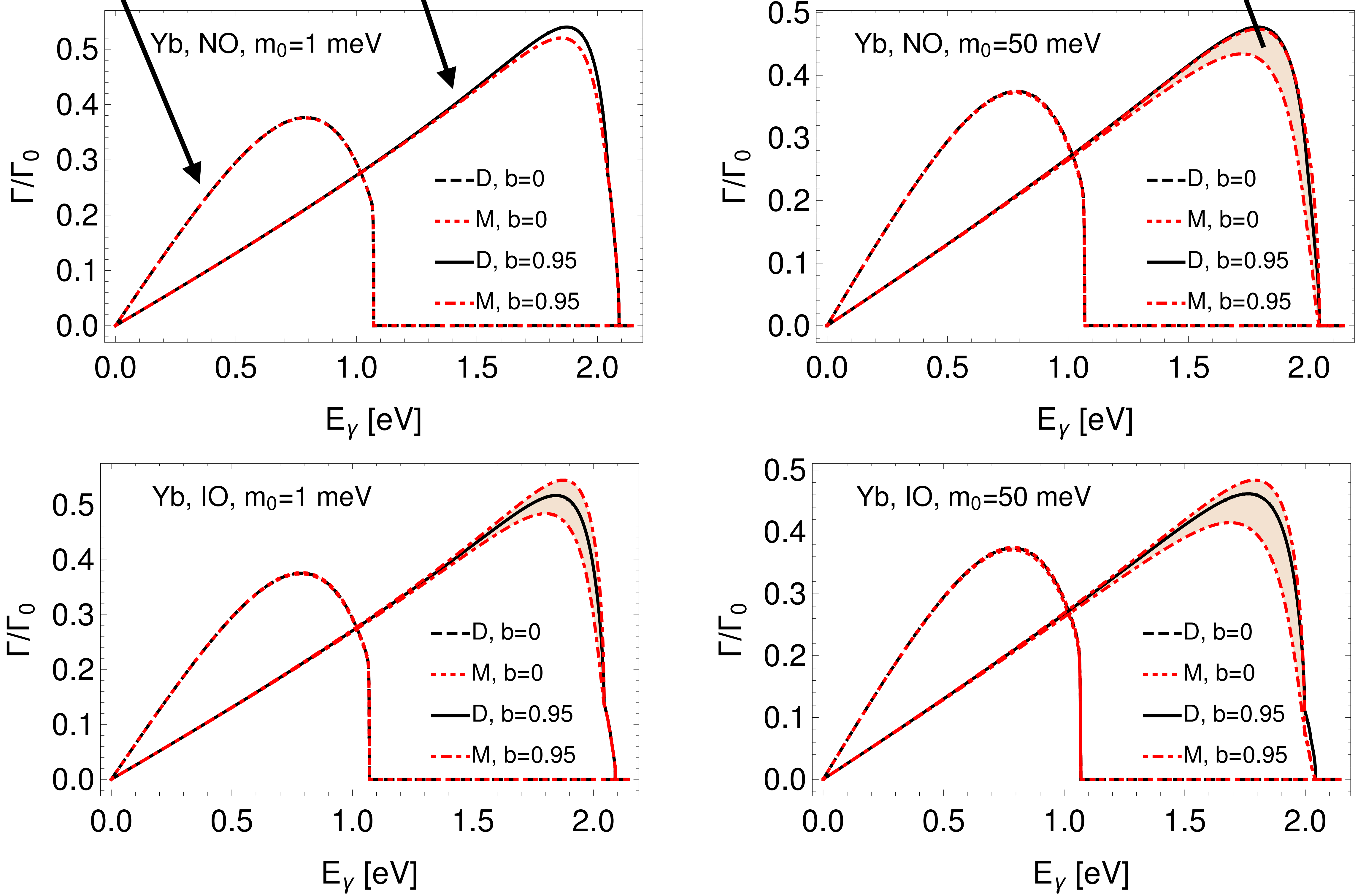
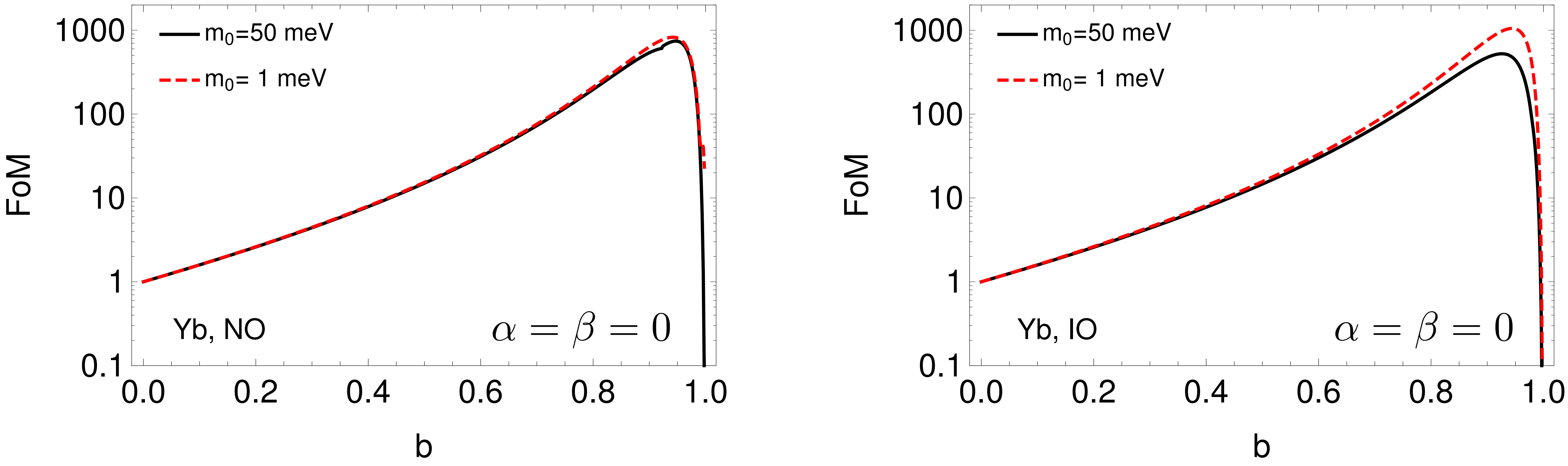


Figure of merit

Power of Dirac-Majorana distinction

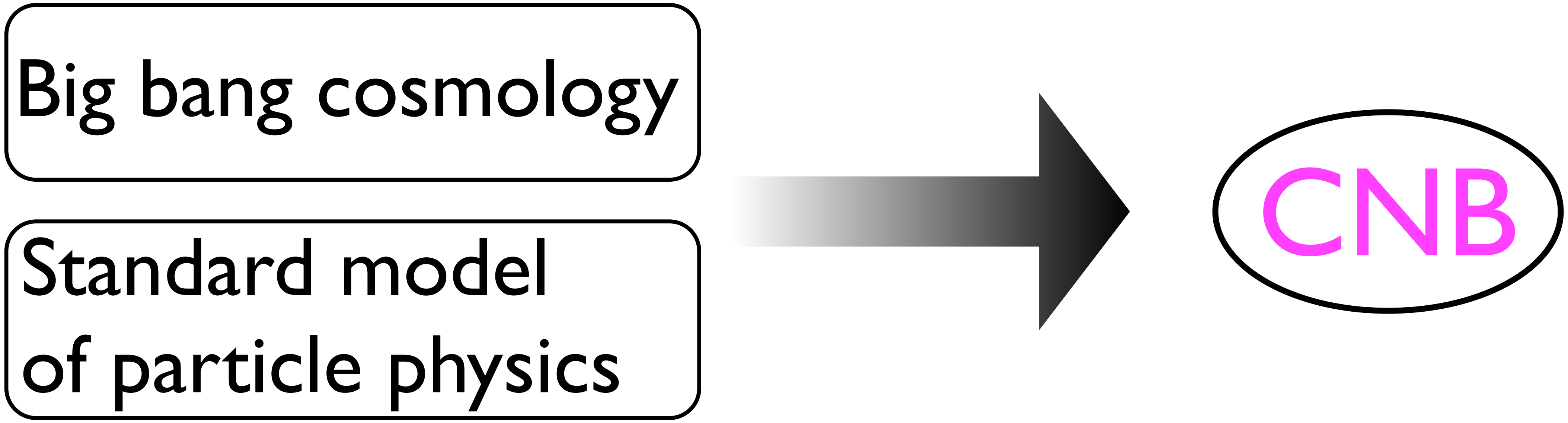
relative enhancement of χ^2



$$\chi^2 = 1 \text{ (no boost)} \Longrightarrow \sim 1000 \text{ (optimal boost)}$$

CNB

Cosmic Neutrino Background (CNB)



Big bang cosmology

Standard model of particle physics

CNB

CNB at present: $f(\boldsymbol{p}) = [\exp(|\boldsymbol{p}|/T_\nu - \xi) + 1]^{-1}$

(not) Fermi-Dirac dist. $|\boldsymbol{p}| = \sqrt{E^2 - m_\nu^2}$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K} \simeq 0.17\ \mathrm{meV}$$

→ $n_\nu \simeq 6 \times 56\ \mathrm{cm}^{-3}$

Detection?

RENP in CNB

M. Yoshimura, N. Sasao, MT,
PRD91, 063516 (2015); arXiv:1409.3648

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

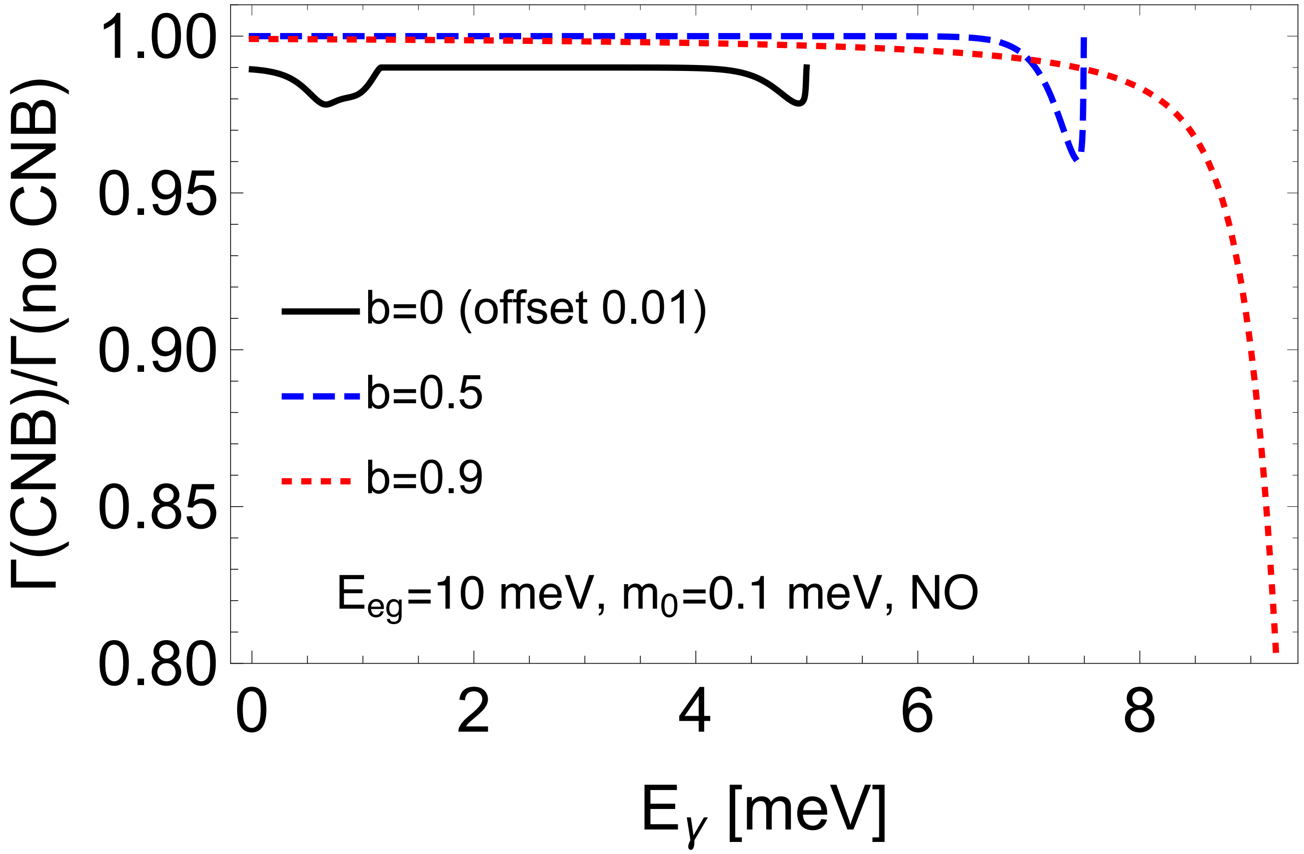
Pauli exclusion

$$d\Gamma \propto |\mathcal{M}|^2 \boxed{[1 - f_i(p)]\,[1 - \bar{f}_j(p')]}$$

→ spectral distortion

Distortion factor

$$\frac{\text{Rate with CNB}}{\text{Rate w/o CNB}} = \frac{\Gamma(E_\gamma, T_\nu)}{\Gamma(E_\gamma, 0)}$$



level splitting

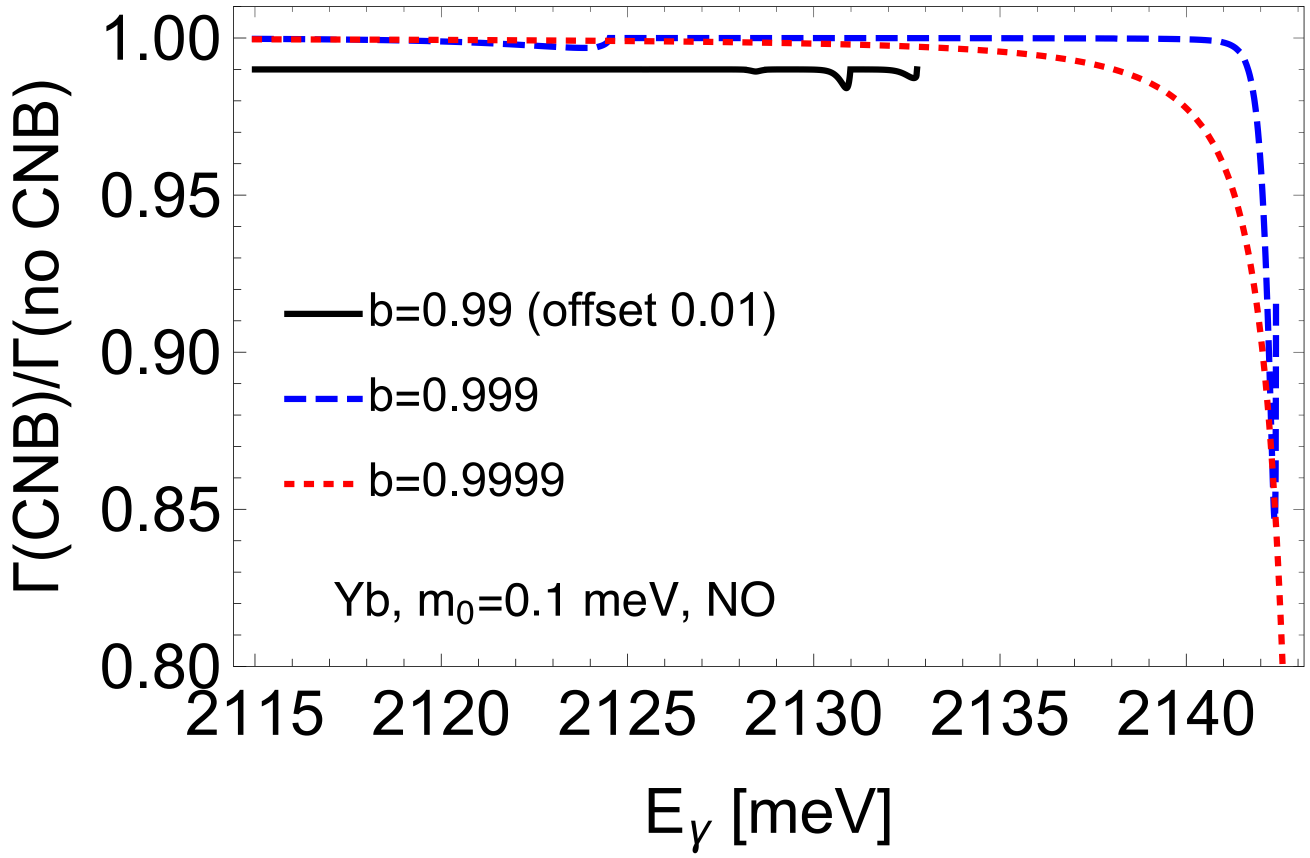
$$\epsilon_{eg} = 10 \text{ meV}$$

smallest neutrino mass

$$m_0 = 0.1 \text{ meV}$$

chemical potential

$$\xi_i \equiv \mu_i / T_\nu = 0$$



Yb

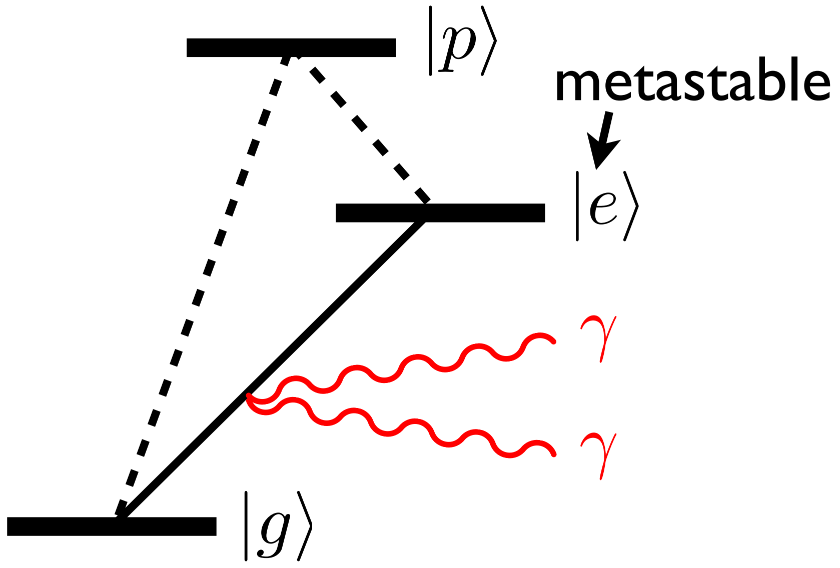
$$m_0 = 0.1 \text{ meV}$$

$$\xi_i = 0$$

PSR

Paired Super-Radiance (PSR)

M. Yoshimura, N. Sasao, MT, PRA86, 013812 (2012)



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

Prototype for RENP

proof-of-concept for the macrocoherence

Preparation of initial state for RENP

coherence generation ρ_{eg}

dynamical factor $\eta_\omega(t)$

Theoretical description to be tested

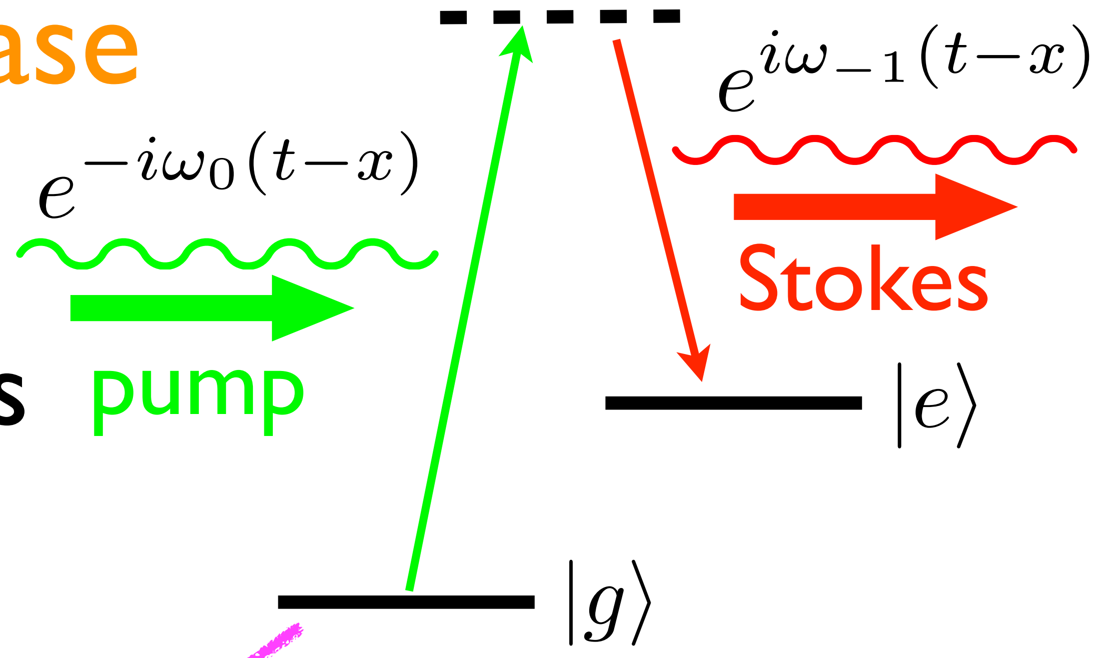
Maxwell-Bloch equation

PSR with initial spatial phase

How to populate $|e\rangle$

Stimulated Raman process

$$\omega_0 - \omega_{-1} = \epsilon_{eg}$$



ISP

Generated coherence

$$\rho_{eg} = \rho_{eg}^{(0)} + \boxed{\rho_{eg}^{(+)} e^{i\epsilon_{eg}x}} + \rho_{eg}^{(-)} e^{-i\epsilon_{eg}x}$$

$$e^{i\omega_p(t-x)} e^{i\omega_{\bar{p}}(t-x)} = e^{i\epsilon_{eg}(t-x)}$$

$$\omega_p + \omega_{\bar{p}} = \epsilon_{eg}$$

momentum conservation in the macrocoherence → Unidirectional PSR

Raman sideband generation

Harris, Sokolov, Phys. Rev. A55,R4019(1997)

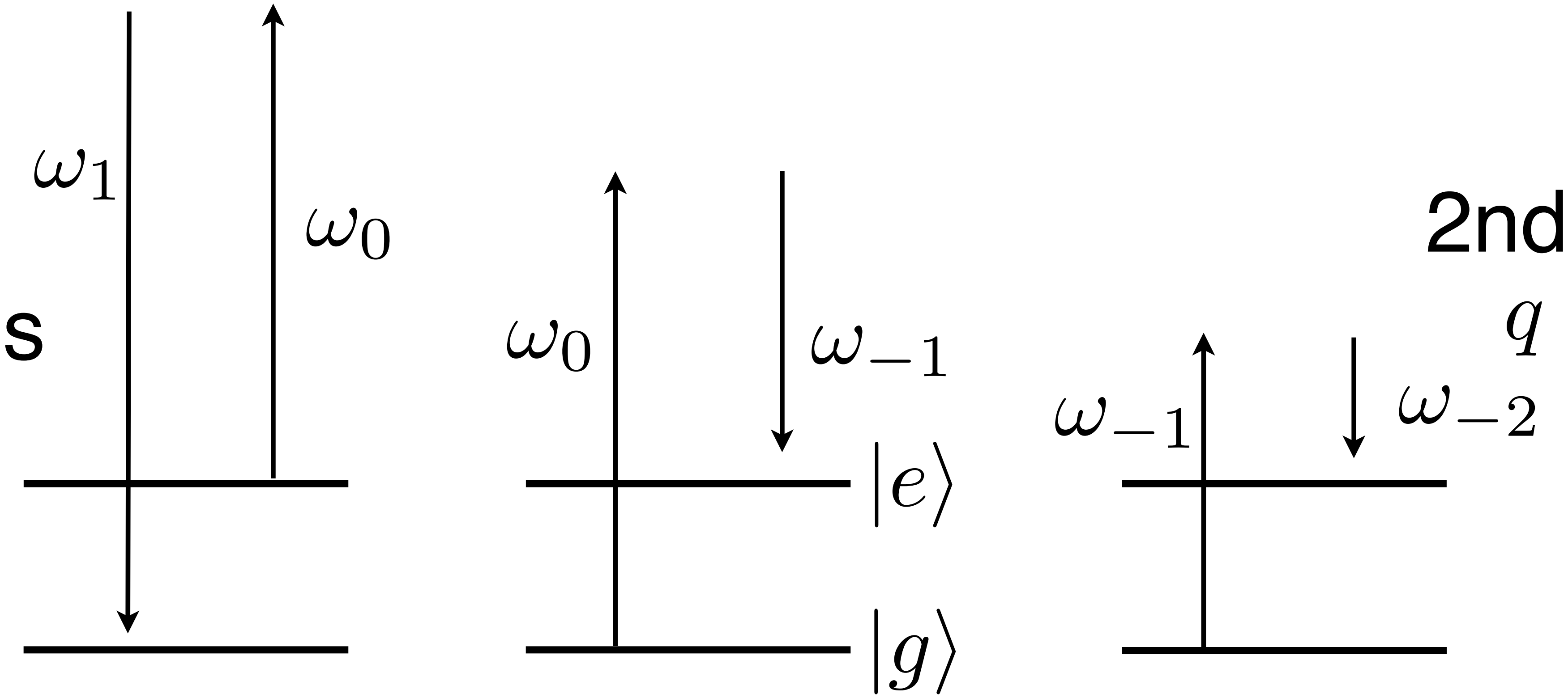
Kien, Liang, Katsuragawa, Ohtsuki, Hakuta, Sokolov, Phys. Rev. A60, 1562(1999)

$q = 1$

1st anti-Stokes

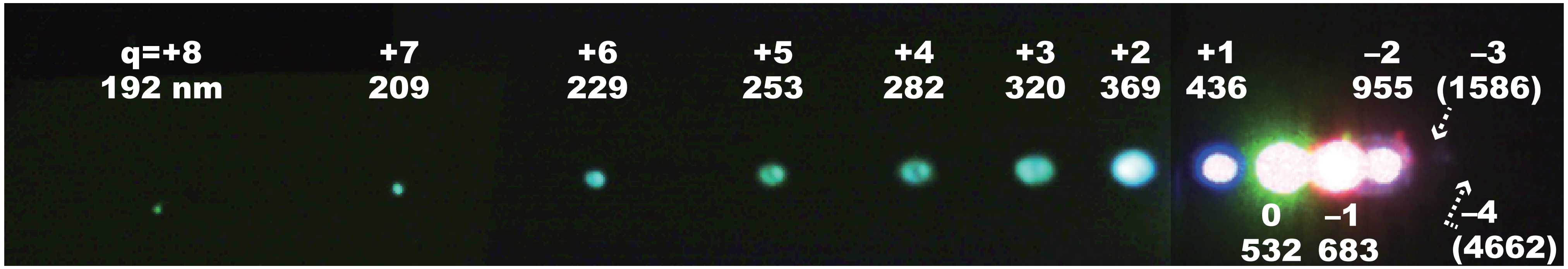
2nd Stokes

$q = -2$



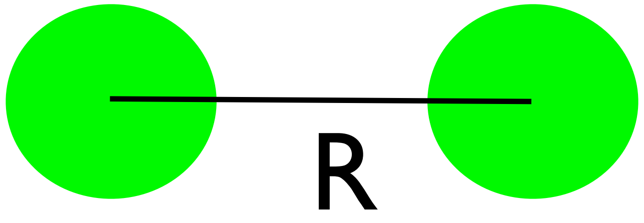
$$\omega_q = \omega_0 + q(\omega_e - \omega_g - \delta) = \omega_0 + q(\omega_0 - \omega_{-1})$$

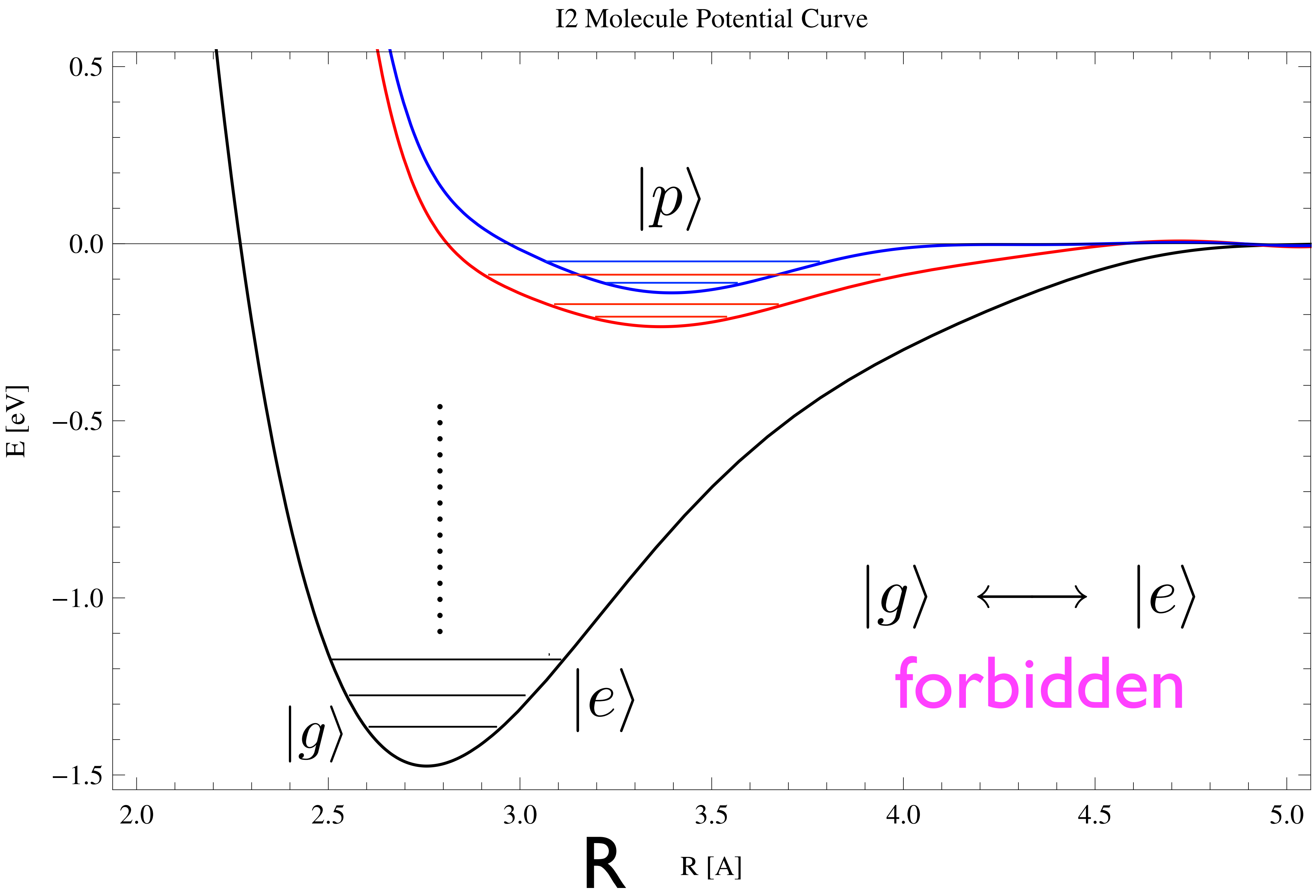
$q \geq q_{\min}$ the lowest Stokes



Homonuclear diatomic molecule

Potential curves





$|g\rangle \longleftrightarrow |e\rangle$

forbidden

Para-hydrogen gas PSR experiment

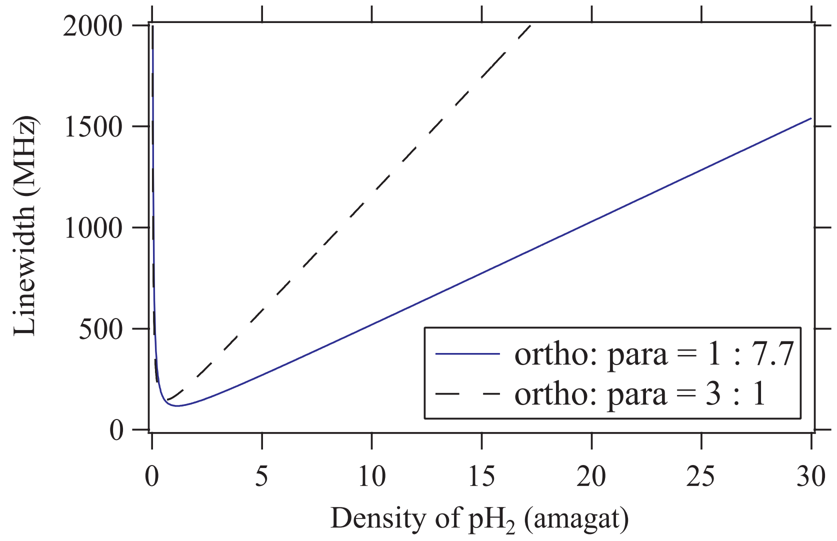
@ Okayama U

Y. Miyamoto et al. PTEP113C01(2014), PTEP081C01(2015)

vibrational transition of p-H2

$$|e\rangle = |Xv=1\rangle \longrightarrow |g\rangle = |Xv=0\rangle$$

two-photon decay: $\tau_{2\gamma} \sim 10^{11}$ s



p-H2: nuclear spin=singlet

smaller decoherence

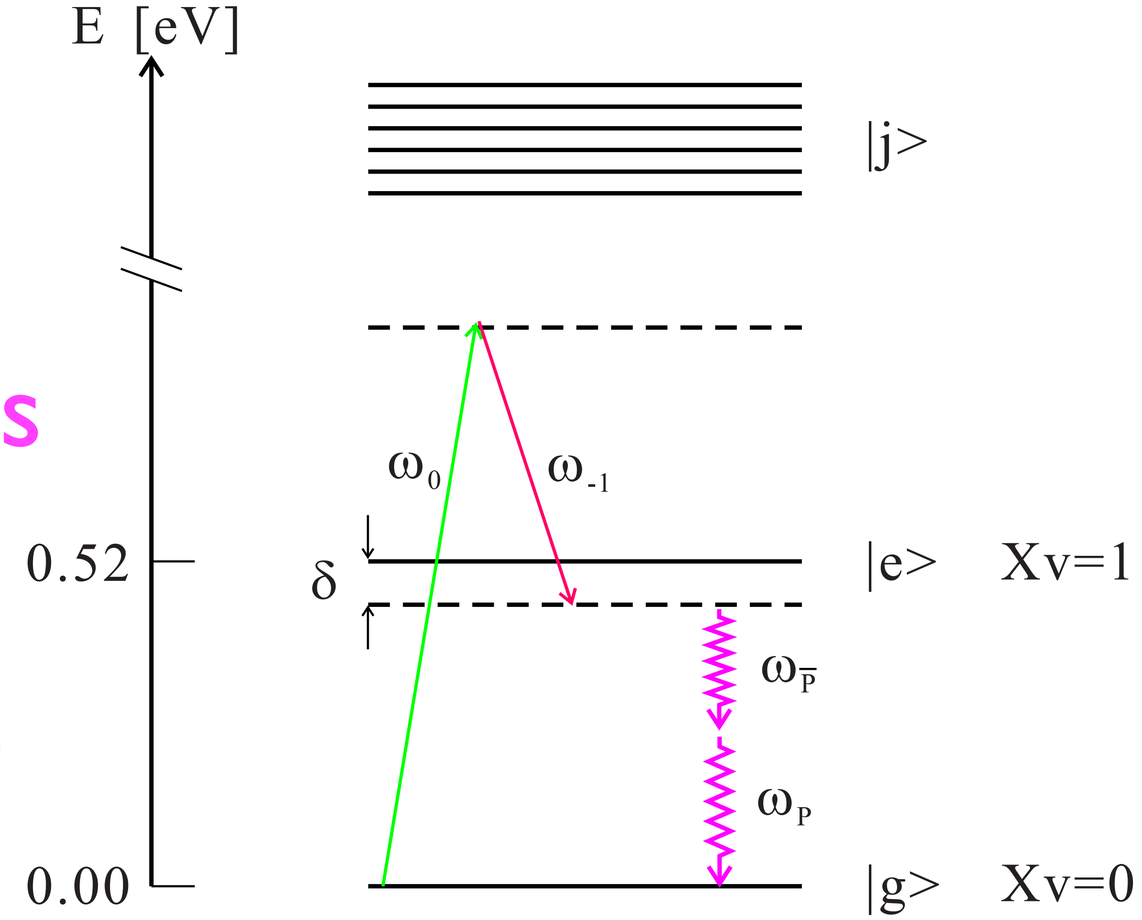
$1/T_2 \sim 130$ MHz

coherence production

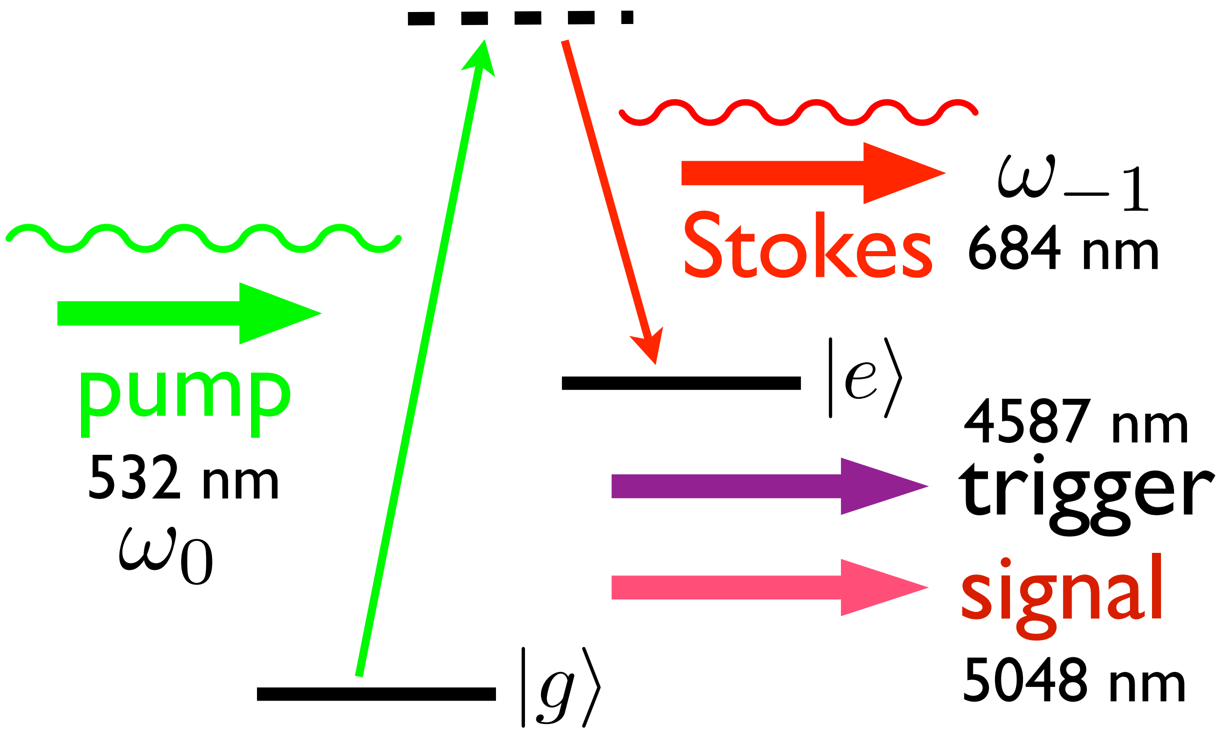
adiabatic Raman process

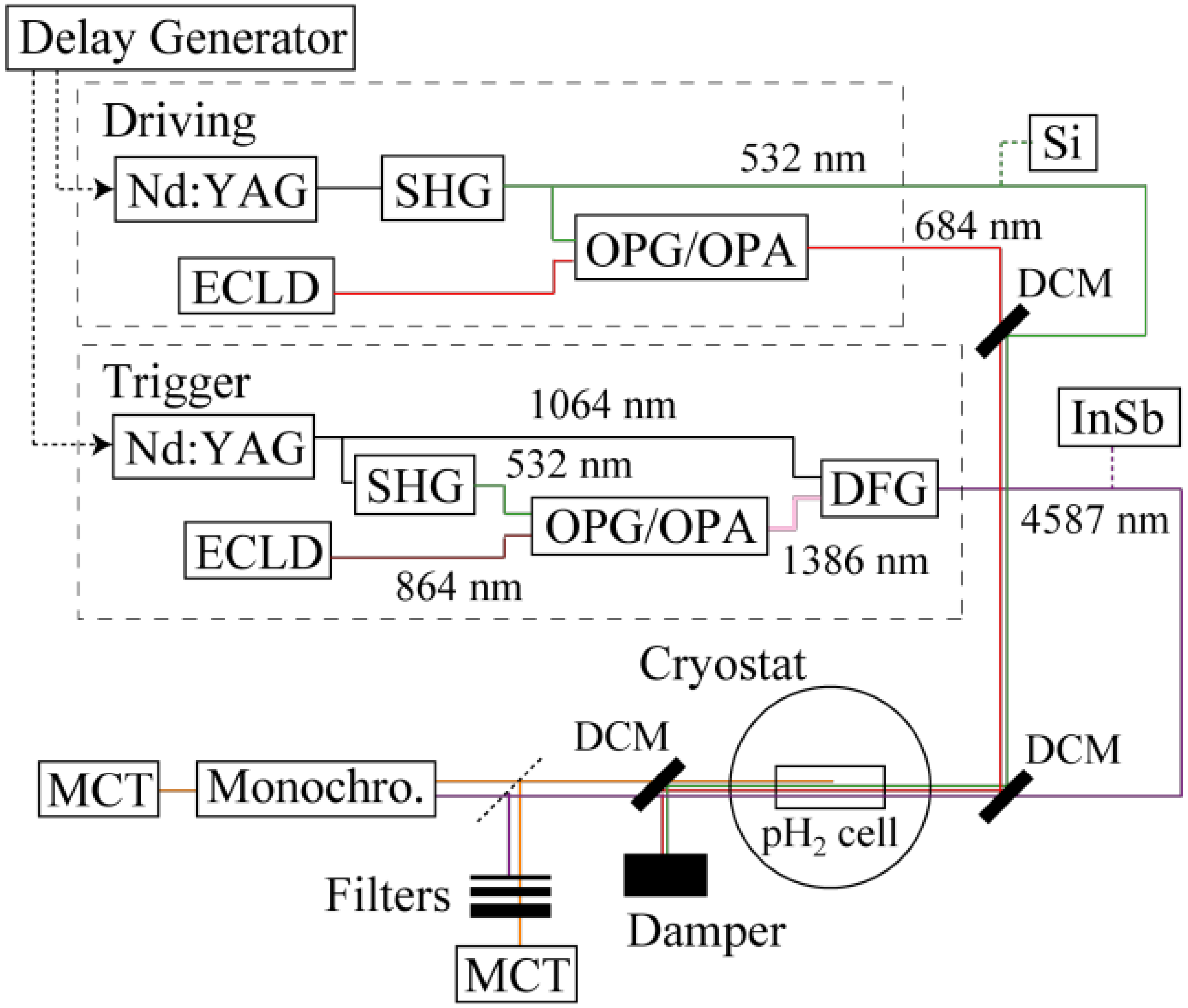
$$\begin{aligned}\Delta\omega &= \omega_0 - \omega_{-1} \\ &= \epsilon_{eg} - \delta \\ &= \omega_p + \omega_{\bar{p}}\end{aligned}$$

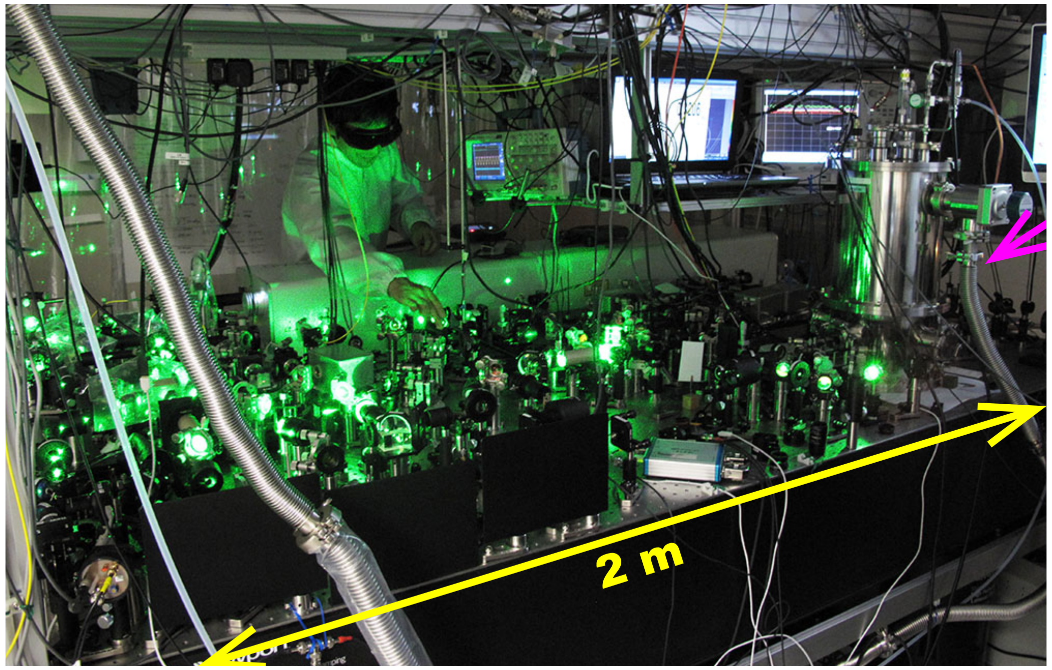
detuning



Experimental setup







Target cell: L=15 cm, Φ=2 cm, 78 K, 60 kPa

$$n = 5.6 \times 10^{19}\ \mathrm{cm}^{-3} \quad 1/T_2 \sim 130\ \mathrm{MHz}$$

Driving lasers: 532, 684 nm

$$5\ \mathrm{mJ},\ \ 9, 6\ \mathrm{ns},\ \ w_0 = 100\ \mu\mathrm{m}\ (5\ \mathrm{GW/cm^2})$$

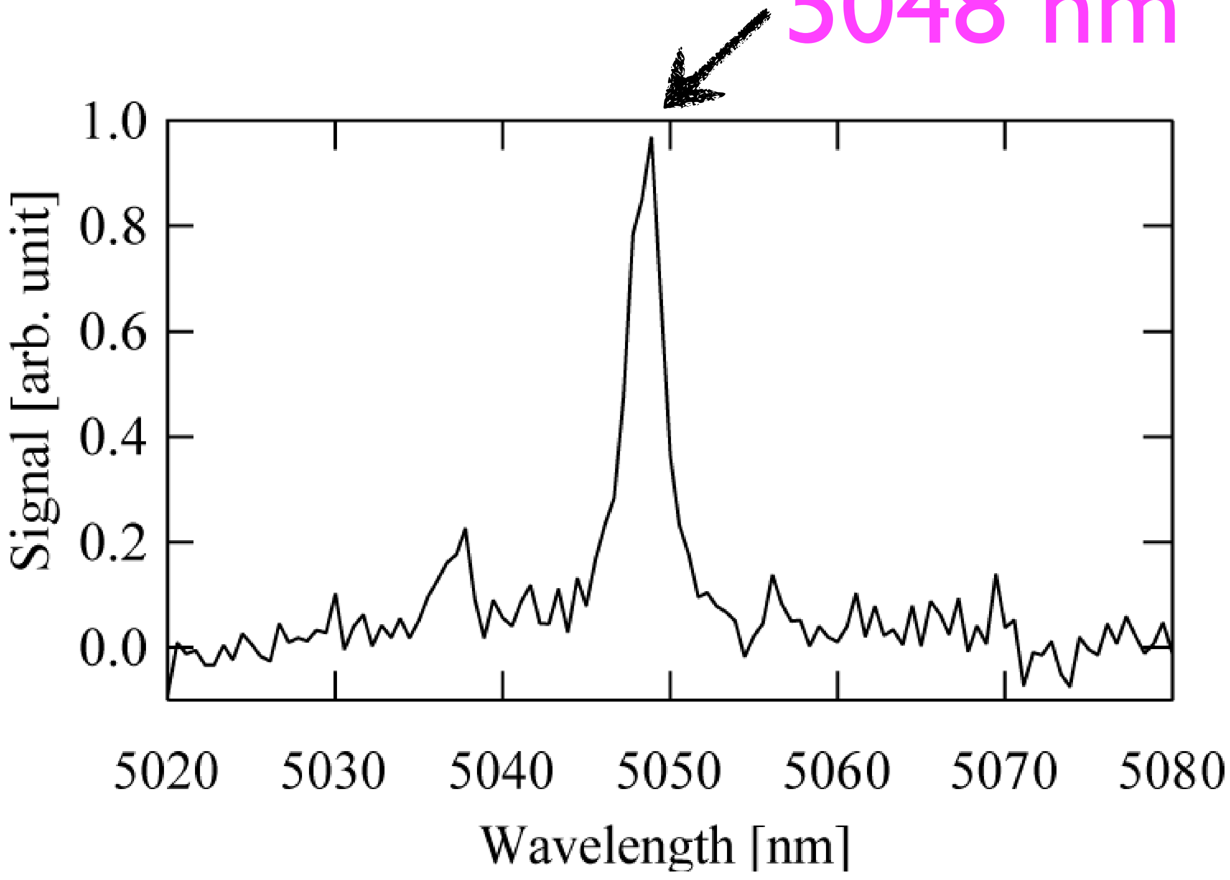
Trigger: 4587 nm

$$150\ \mu\mathrm{J},\ \ 2\ \mathrm{ns}$$

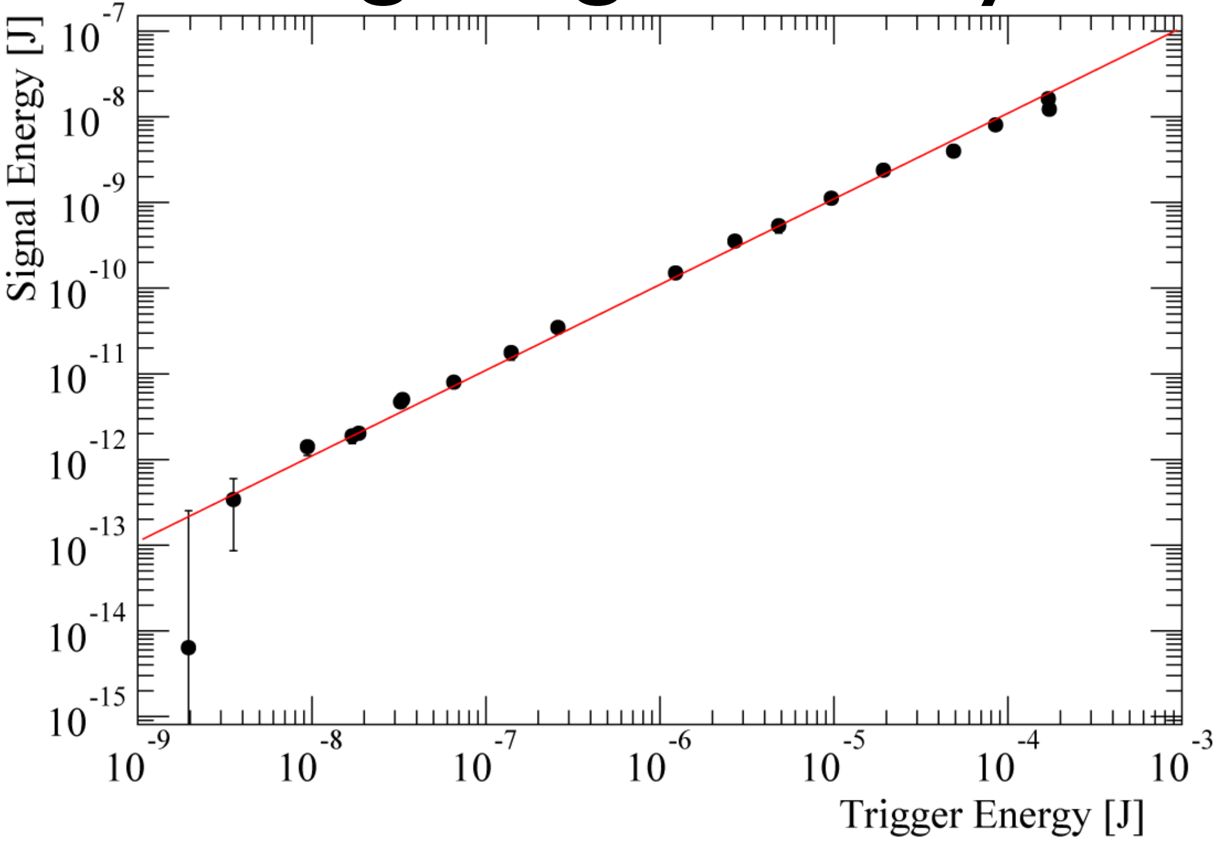
Results

Estimated coherence (from sidebands)

$$|\rho_{eg}| \sim 0.04 \quad (\delta = -160 \text{ MHz})$$


5048 nm

sig.-trig. linearity



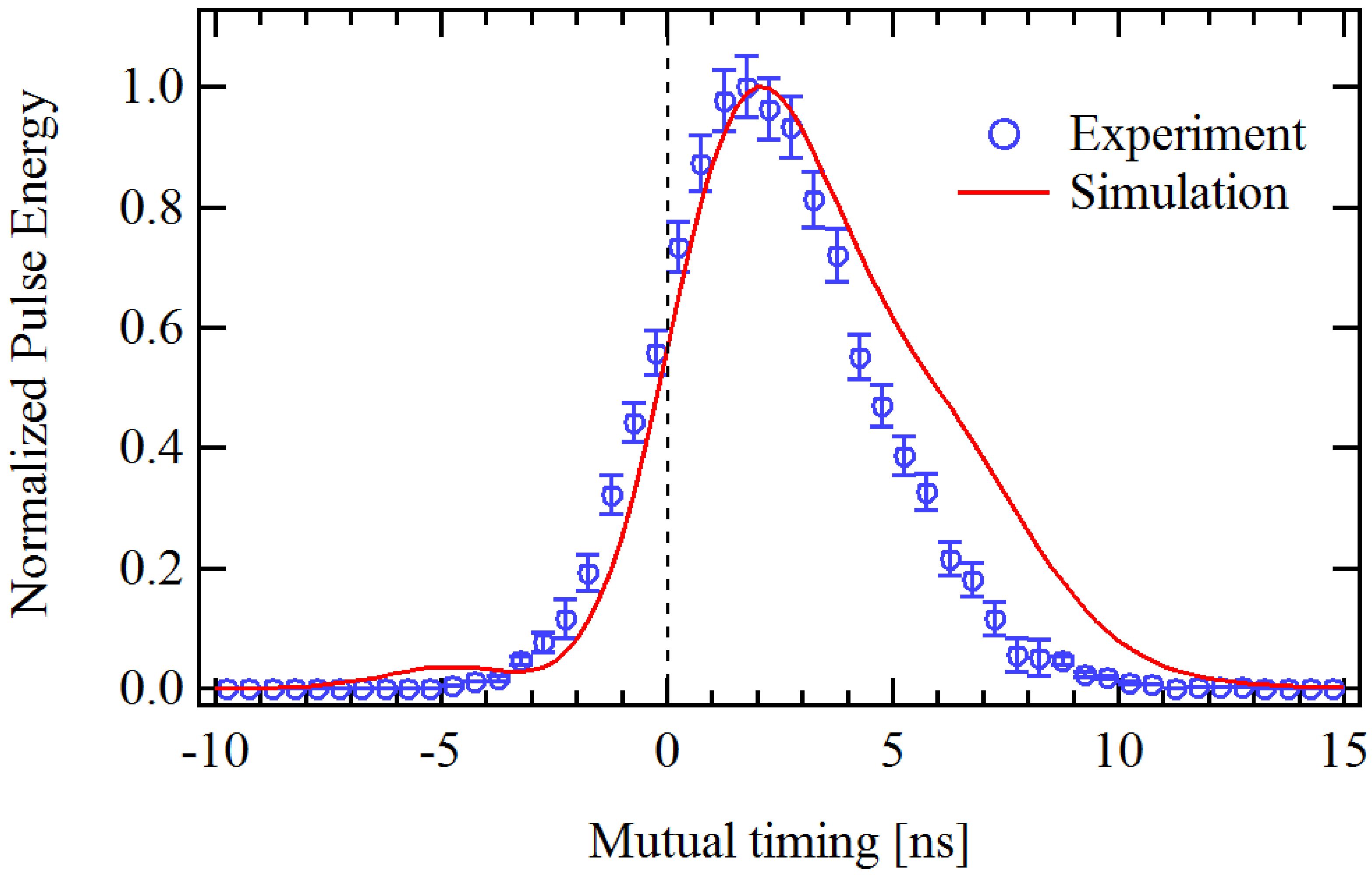
6×10^{11} photons/pulse

→ 10^{18} enhancement

weak field

low coherence

Trigger timing



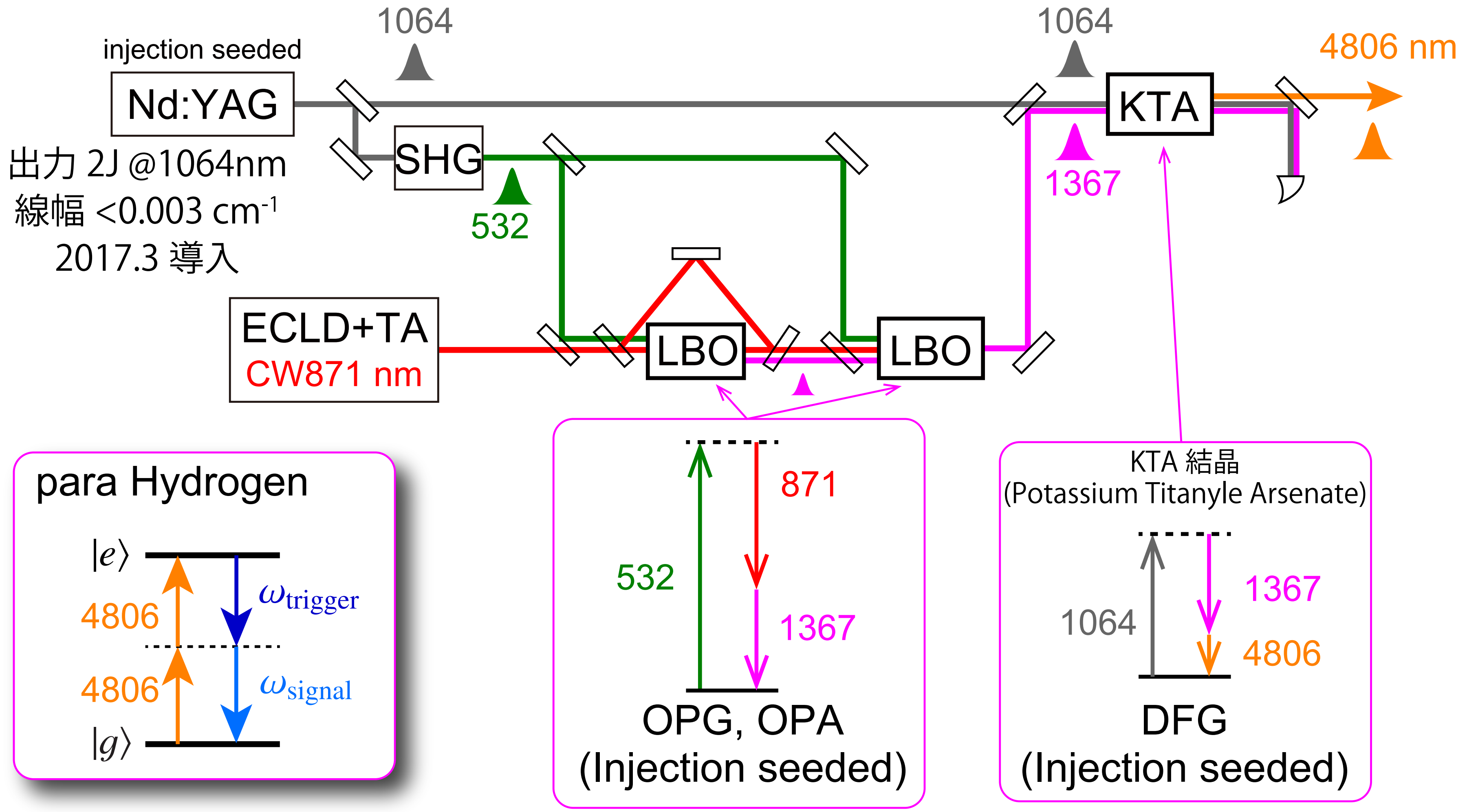
→ trigger delay

Delayed coherence development in the target

less adiabatic, decoherence

Counter-propagating two-photon excitation

Laser Setup



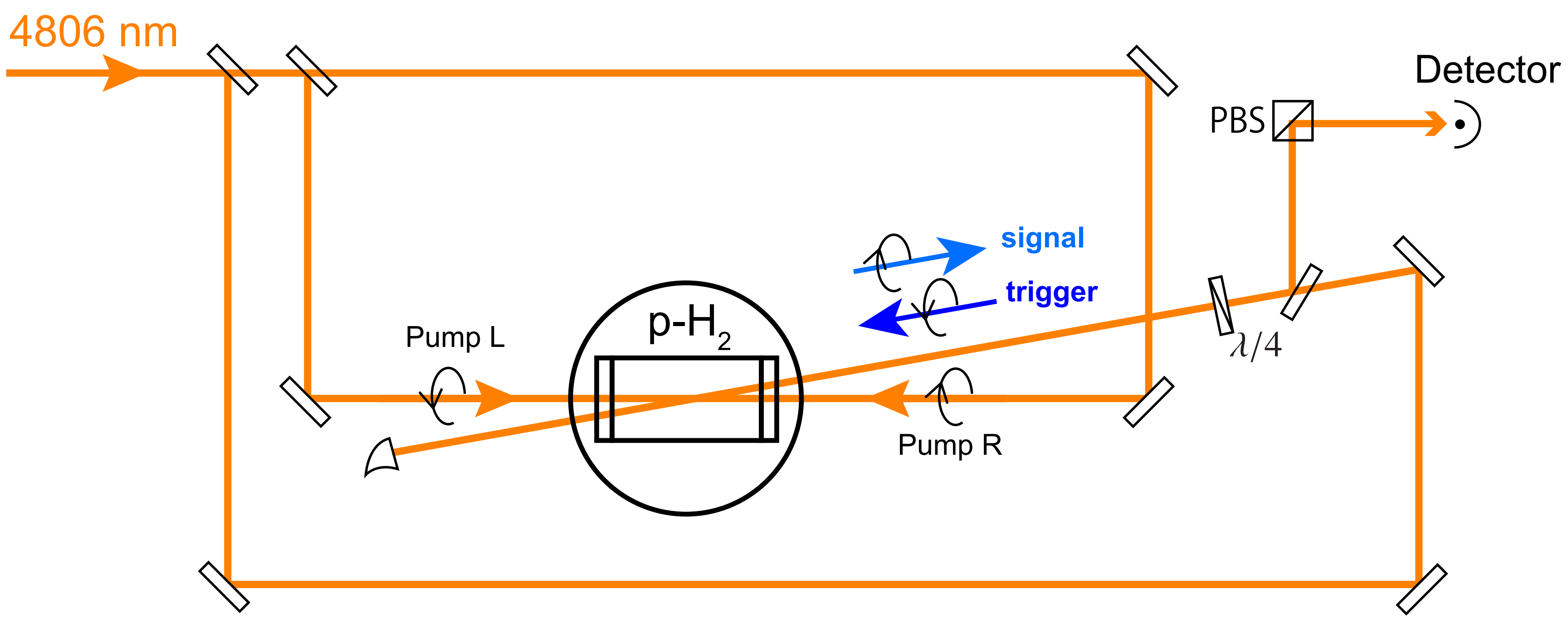
- 非線形光学結晶を用いた波長変換により 4806nm 光を発生
- 4806nm パルスエネルギー：100 μJ (3 月まで)

→ **~5 mJ に増強**

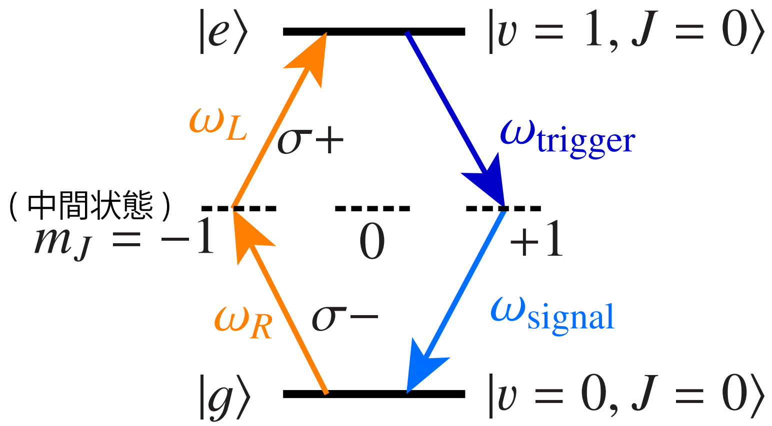
旧バージョン (0.4-1 mJ): Y. Miyamoto et al., Jpn. J. Appl. Phys. **56**, 032101 (2017)
upgrade バージョン : 平木他，物理学会 72 回年会 19pA12-8 (2017) JPS 2017 Autumn Meeting

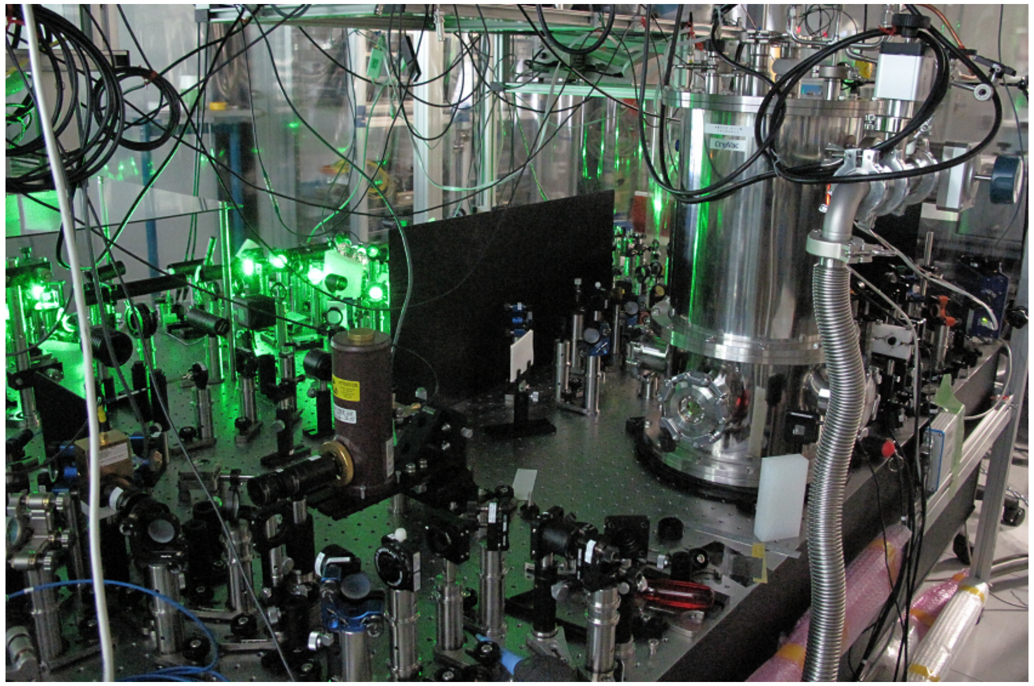
S. Uetake, JPS meeting, Sep. 2017

Counter-Propagate Excitation Experiment



円偏光励起によりシグナルと
バックグラウンドを分離

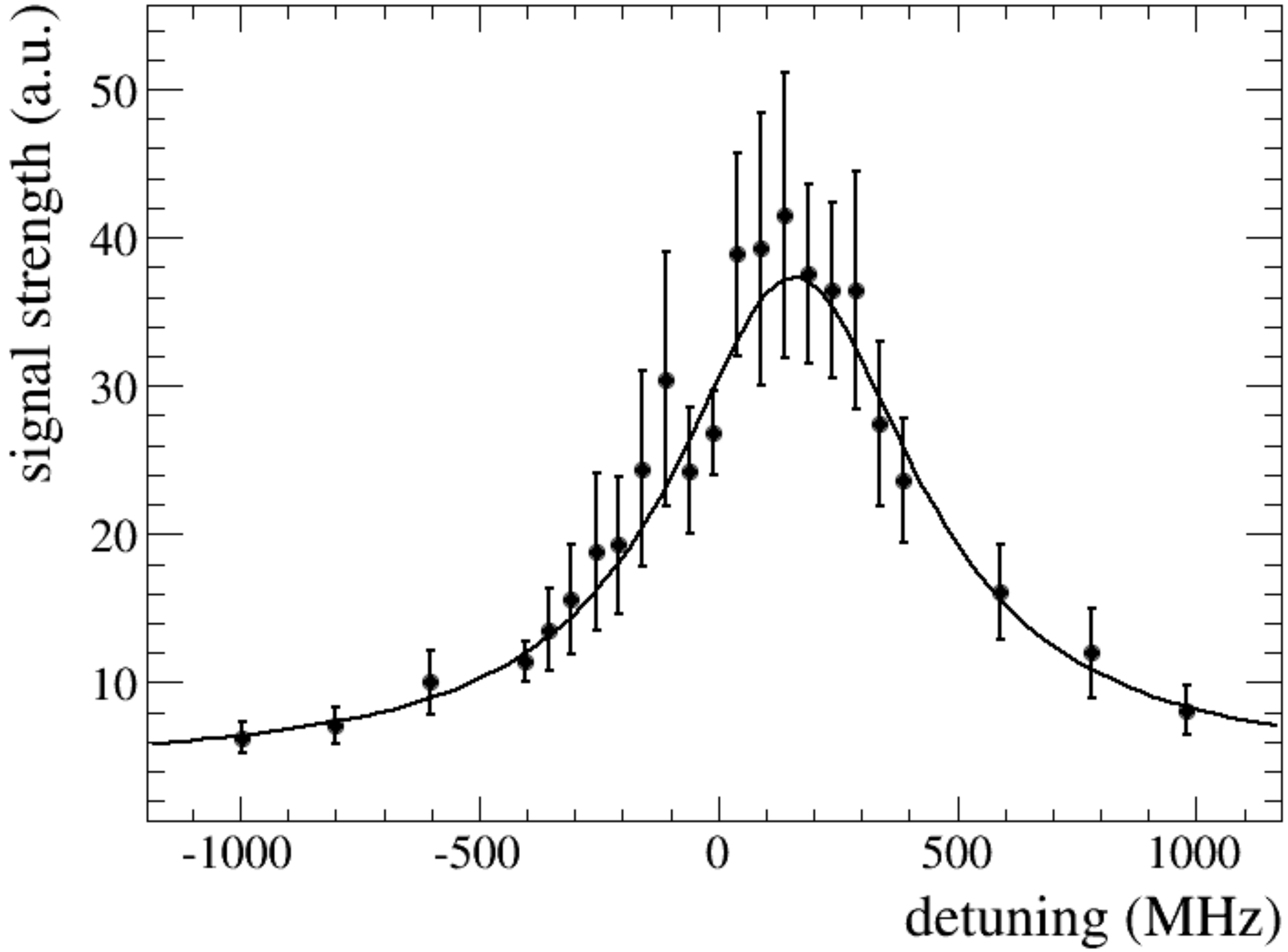




JPS 2017 Autumn Meeting

S. Uetake, JPS meeting, Sep. 2017

Observed signal



S. Uetake, JPS meeting, Sep. 2017

analysis ongoing

SUMMARY

Neutrino Physics with Atoms/Molecules

- RENP spectra are sensitive to unknown neutrino parameters.

  Absolute mass, NO or IO, Dirac or Majorana, CP
- ISP makes RENP more powerful, boosted RENP.
- RENP spectra are sensitive to the CNB.
- Macrocoherent rate amplification is essential.

  Demonstrated by a QED process, PSR.
- Background-free RENP M.Yoshimura, N. Sasao, M.T. PTEP(2015)053B06; arXiv:1501.05713

  Waveguide with photonic crystals

  M.T., K.Tsumura, N. Sasao, M.Yoshimura, PTEP(2017)043B03; arXiv:1612.02423

A new approach to neutrino physics