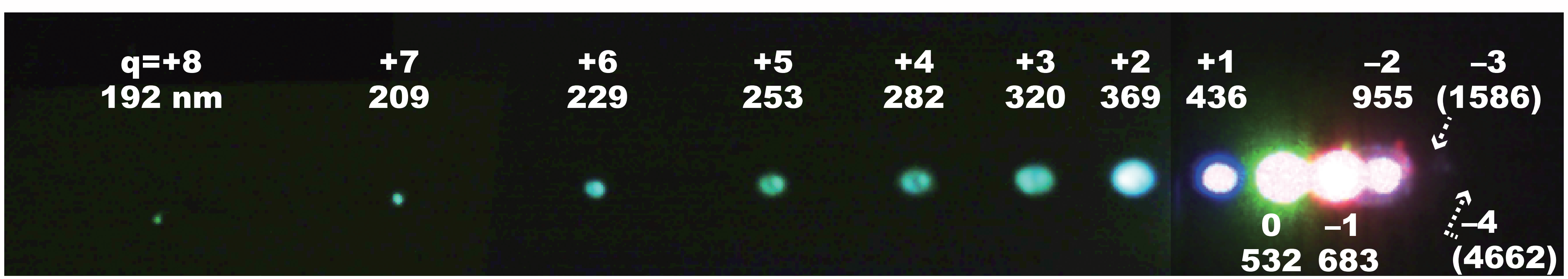
Physics
OSAKA UNIVERSITY

マクロコヒーレンスの理論と実験

田中　実

大阪大学



セミナー@新潟大学, 2015/6/25

SPAN project

SPectroscopy with Atomic Neutrino

Okayama U.

K. Kawaguchi, H. Hara, T. Masuda, Y. Miyamoto,
I. Nakano, N. Sasao, J. Tang, S. Uetake,
A. Yoshimi, K. Yoshimura, M. Yoshimura

Other institute

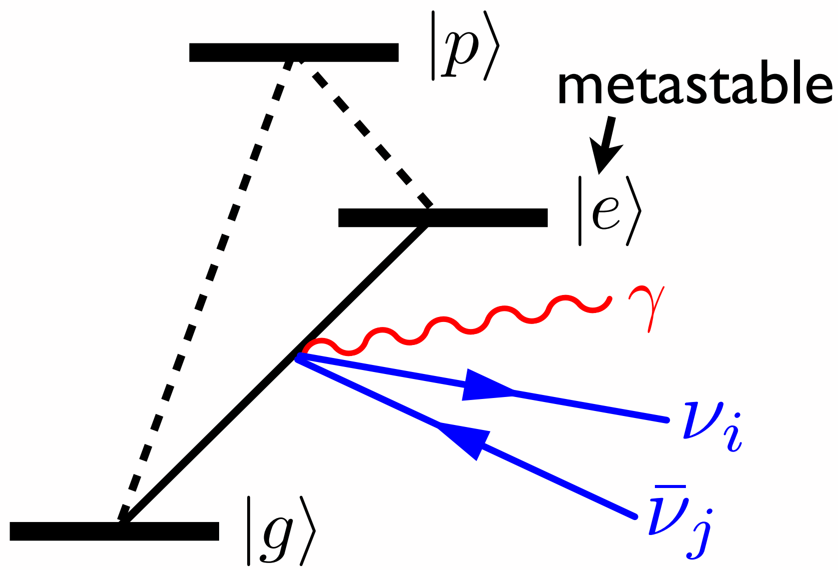
M. T. (Osaka), T. Wakabayashi (Kinki),
A. Fukumi (Kawasaki), S. Kuma (Riken),
C. Ohae (ECU), K. Nakajima (KEK), H. Nanjo (Kyoto)

INTRODUCTION

RENP and PSR

Radiative Emission of Neutrino Pairs (RENP)

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



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

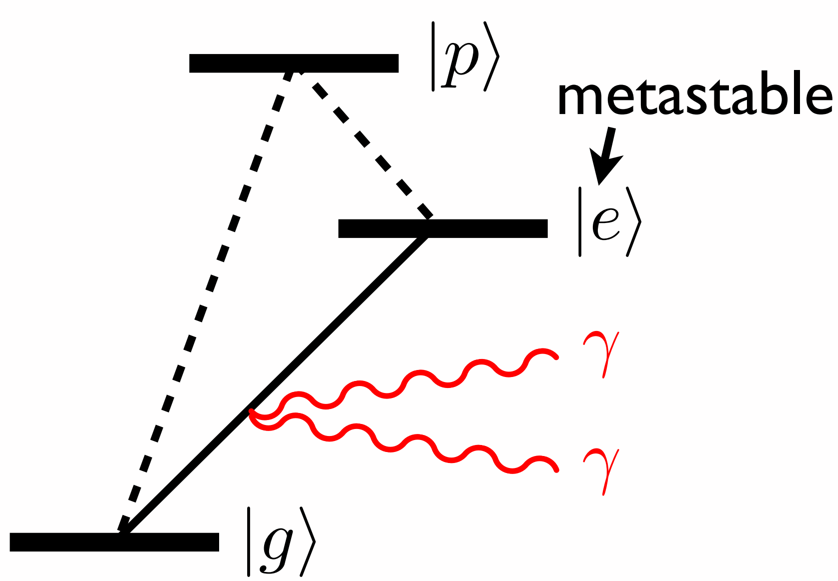
energy scale ~ O(eV)

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

Enhancement by coherence

Paired Super-Radiance (PSR)

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

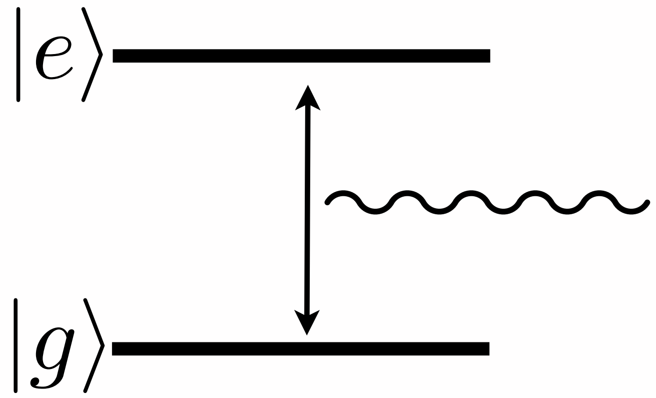


$$|e\rangle \to |g\rangle + \gamma + \gamma$$

Prototype for RENP

proof-of-concept for macrocoherence

Two-level system coupled to a photon



a model of emission from atoms

Hamiltonian

$$\mathcal{H} = \varepsilon_g |g\rangle\langle g| + \varepsilon_e |e\rangle\langle e| - dE|e\rangle\langle g| - d^* E^\dagger |g\rangle\langle e|$$

Density matrix (state)

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

Deexcitation (or emission) rate: $\Gamma = \Gamma_0 \propto |dE|^2$

Coherence (of an atomic state) ρ_{eg}

$$(|g\rangle + e^{i\varphi}|e\rangle)/\sqrt{2} \Longrightarrow \ \rho_{eg} = e^{i\varphi}/2\,, \ |\rho_{eg}| \leq 1/2$$

Rate enhancement by coherence

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

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

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

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

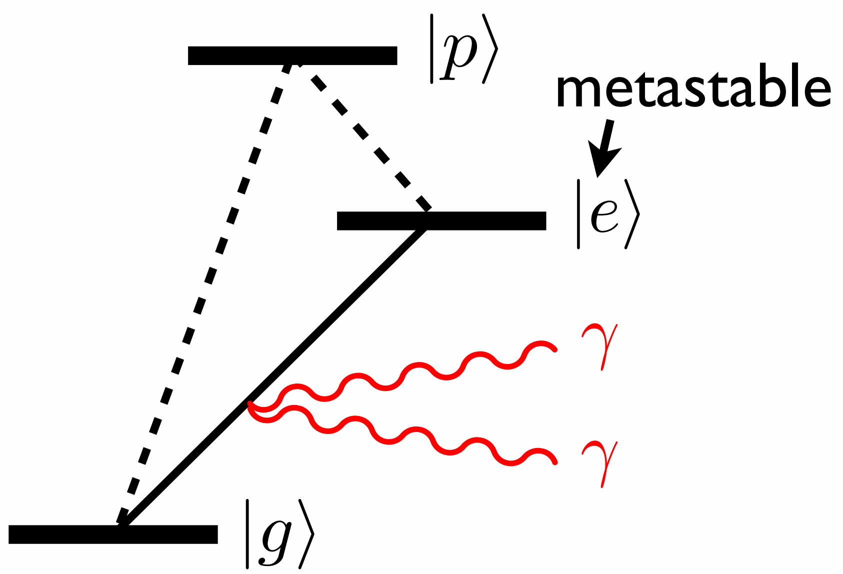
$$\xrightarrow{\text{deexcitation}} [|g\rangle(|g\rangle + |e\rangle) \cdots (|g\rangle + |e\rangle)$$
$$+ (|g\rangle + |e\rangle)|g\rangle \cdots (|g\rangle + |e\rangle) + \cdots]/\sqrt{2^N}$$

→ $\Gamma = N(N+1)\Gamma_0/4 \propto N^2$ coherent

PSR theory

Paired Super-Radiance (PSR)

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



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

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 equation

Effective two-level interaction Hamiltonian

$|g\rangle, |e\rangle,$ ~~$|p\rangle$~~

$$\mathcal{H}_I = \begin{pmatrix} \alpha_{ee} & \alpha_{ge} e^{i\varepsilon_{eg} t} \\ * & \alpha_{gg} \end{pmatrix} E^2$$

$$\alpha_{ge} = \frac{2 d_{pe} d_{pg}}{\epsilon_{pg} + \epsilon_{pe}}\,, \qquad \alpha_{aa} = \frac{2 d_{pa}^2 \epsilon_{pa}}{\epsilon_{pa}^2 - \omega^2}\,, \qquad (a = g\,, e)$$

d_{pa} : dipole matrix element

Field (1+1 dim.)

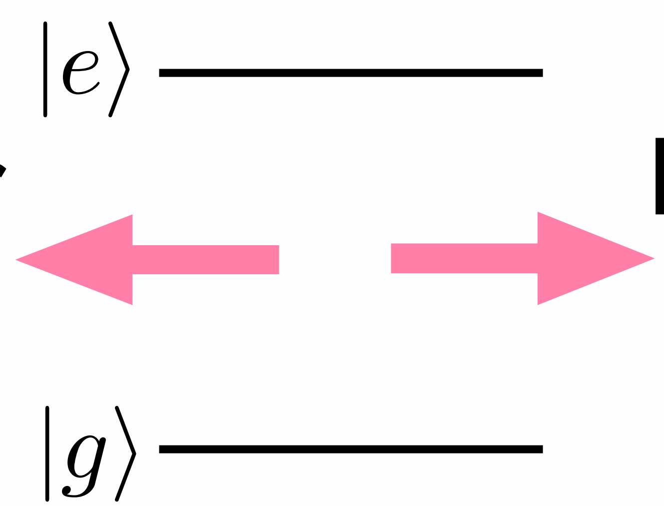
$$\omega = \epsilon_{eg}/2$$

$$E = E_R\, e^{-i(\omega t - kx)} + E_L\, e^{-i(\omega t + kx)} + \text{c.c.}$$

$$k = \omega$$

L-mover

$e^{i\omega(t+x)}$



R-mover

$e^{i\omega(t-x)}$

$$\sim e^{2i\omega t} = e^{i\epsilon_{eg} t}$$

macrocoherence

Bloch equation $\partial_t \rho = i[\rho, \mathcal{H}_I] + \text{relaxation terms}$

T_1, T_2

density matrix

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

coherence (of an atom) $|\rho_{eg}| \leq 1/2$

Maxwell equation $(\partial_t^2 - \partial_x^2)E = -\partial_t^2 P$

macroscopic polarization $P = -\dfrac{\delta}{\delta E}\mathrm{tr}(\rho\mathcal{H}_I)$

Rotating wave approximation (RWA)

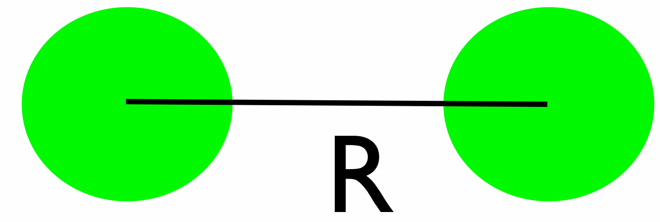
omitting fast oscillation terms

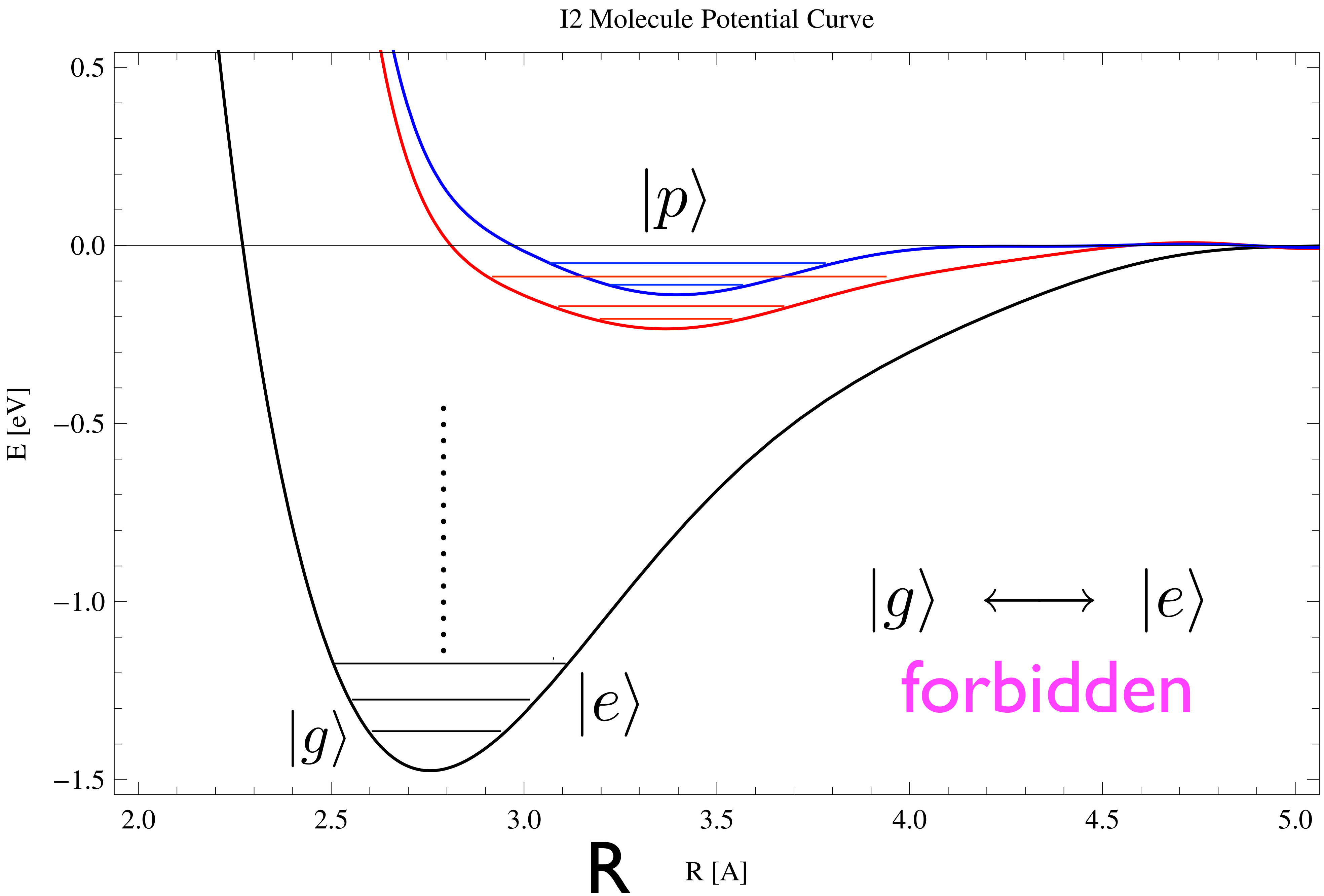
Slowly varying envelope approximation (SVEA)

$$|\partial_{x,t} E_{R,L}| \ll \omega |E_{R,L}|,\quad |\partial_{x,t}\rho| \ll \omega|\rho|$$

Homonuclear diatomic molecule

Potential curves



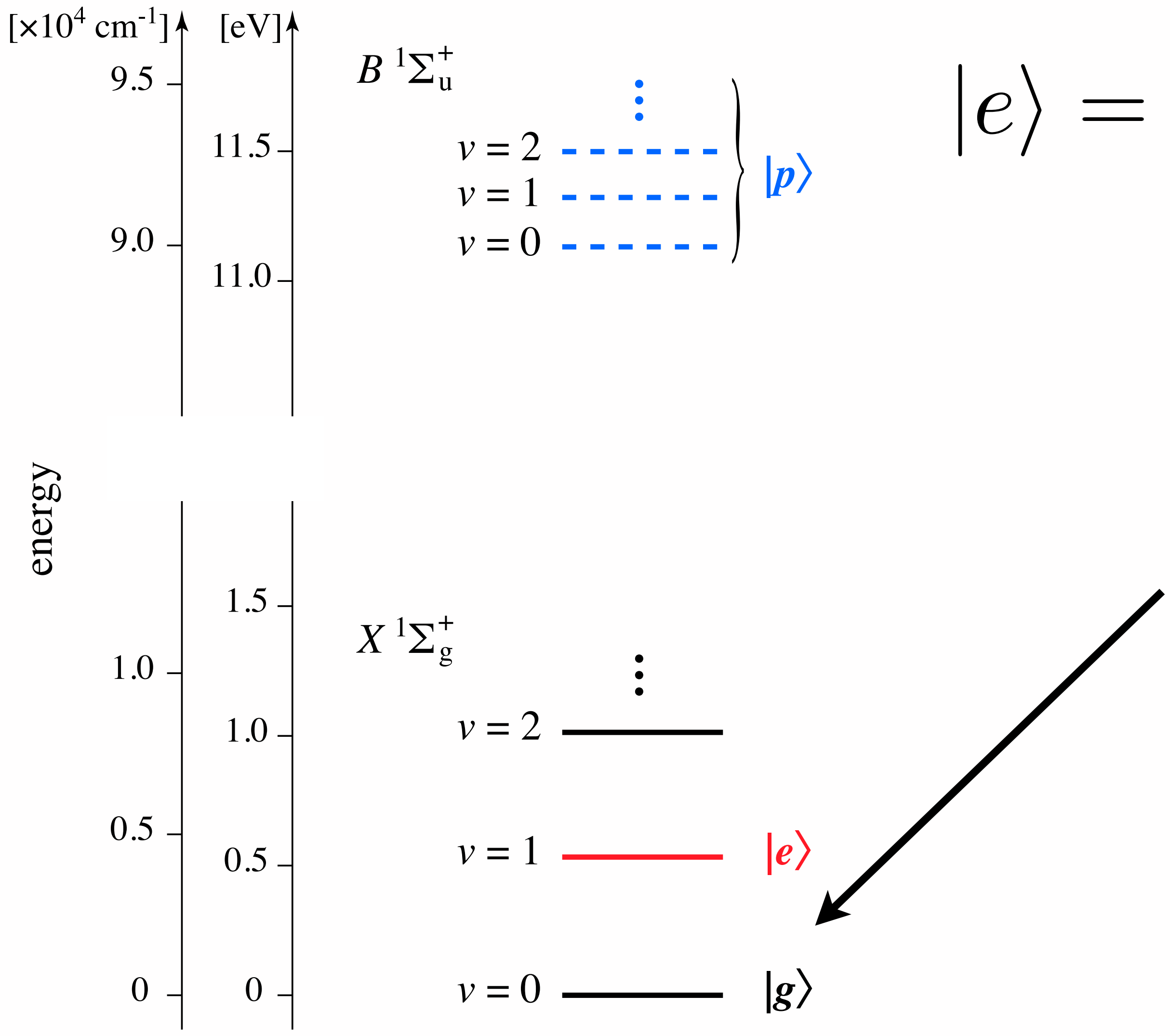


Numerical results

Target system: para-hydrogen molecule

gas or solid

vibrational transition (electronic ground state)



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

no E1 transition

two-photon life ~ 10^{11} sec.

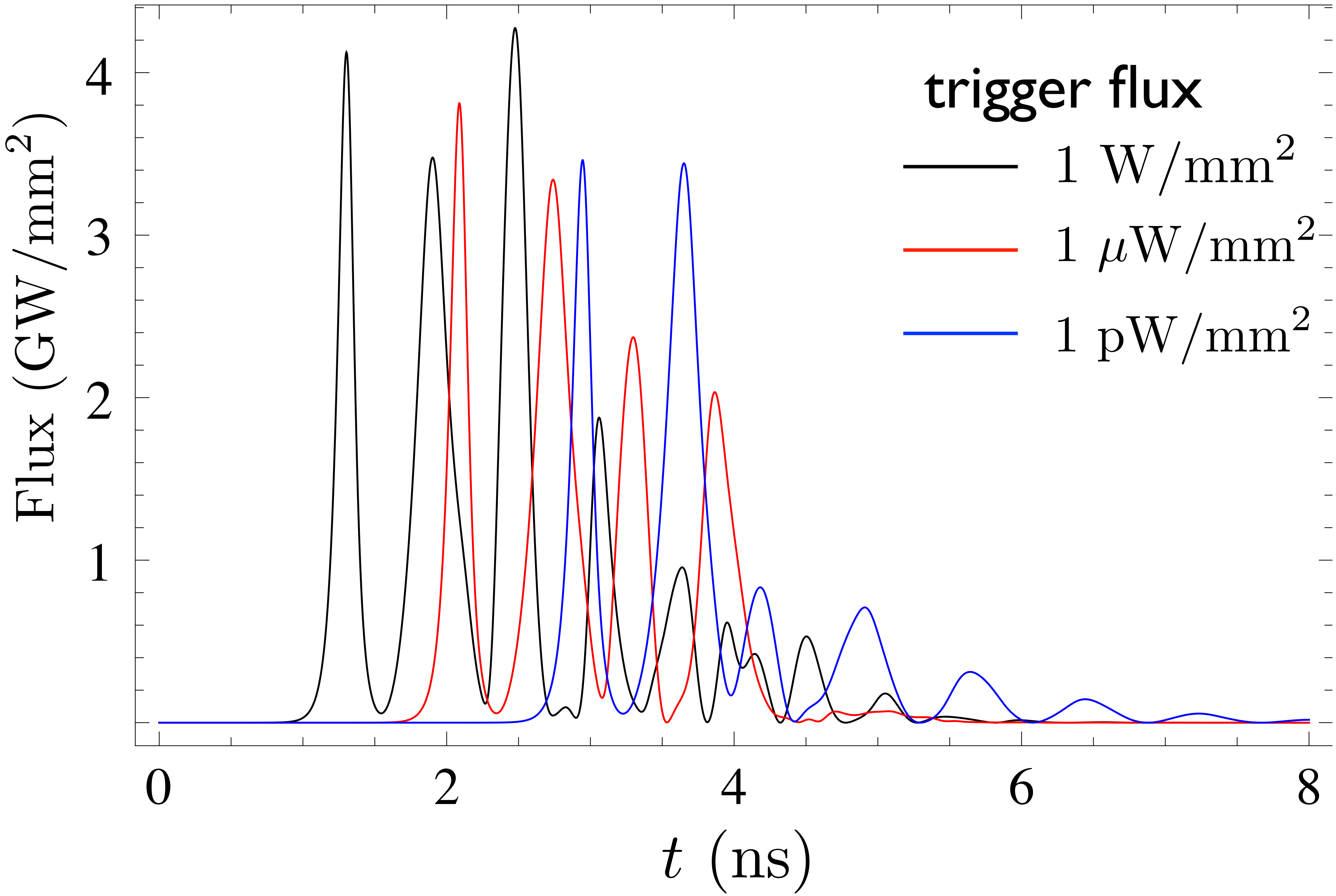
$$\epsilon_{eg} = 0.52\,\text{eV}, \ \gamma_\pm = 15.3, \, 0.64$$

$$t_* \sim 50\,\text{ps}\frac{10^{21}\,\text{cm}^{-3}}{n}$$

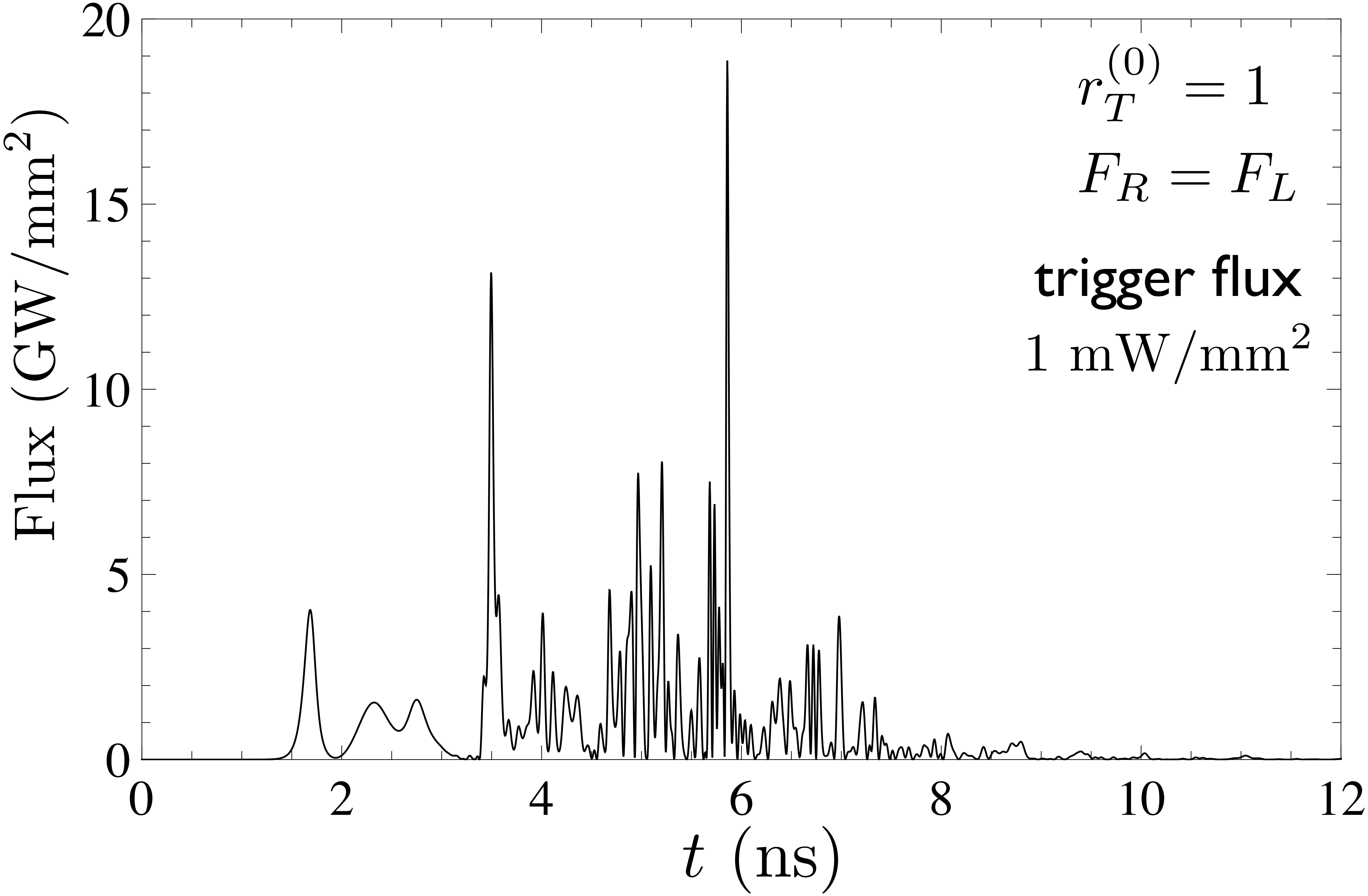
Explosive PSR

$$n = 1 \times 10^{21}/\mathrm{cm}^3 \quad T_1 = 1\,\mu\mathrm{s},\ T_2 = 10\,\mathrm{ns}$$

target length $L = 30\,\mathrm{cm}$ $\qquad r_T^{(0)} = 1 \ \ (\rho_{eg} = 1/2)$



$L = 100\,\mathrm{cm}$



The dynamical factor

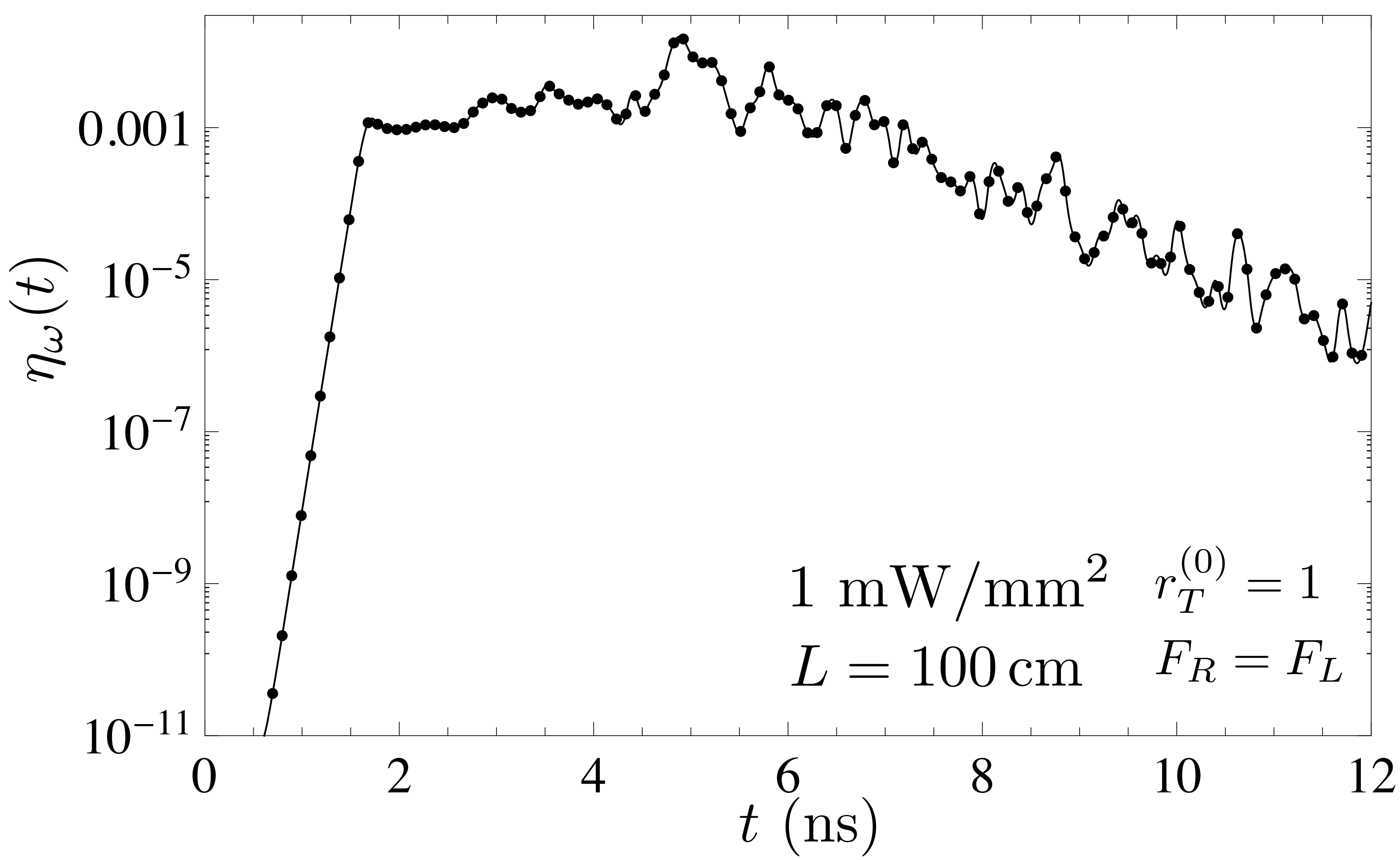
local field-medium activity

$$\eta_\omega(\xi,\tau) = \frac{1}{\epsilon_{eg} n^3}\left|\vec{E}^- \frac{R_1 - iR_2}{2}\right|^2 = \left|\left(e_R^* e^{-i\kappa\xi} + e_L^* e^{i\kappa\xi}\right)\frac{r_1 - ir_2}{2}\right|^2$$

$$= \frac{1}{4}\left[(|e_R|^2+|e_L|^2)(|r_T^{(0)}|^2+|r_T^{(+)}|^2+|r_T^{(-)}|^2) + 2\Re\{e_R^* e_L (r_T^{(0)*} r_T^{(+)} + r_T^{(0)} r_T^{(-)*})\}\right]$$

average over the target length

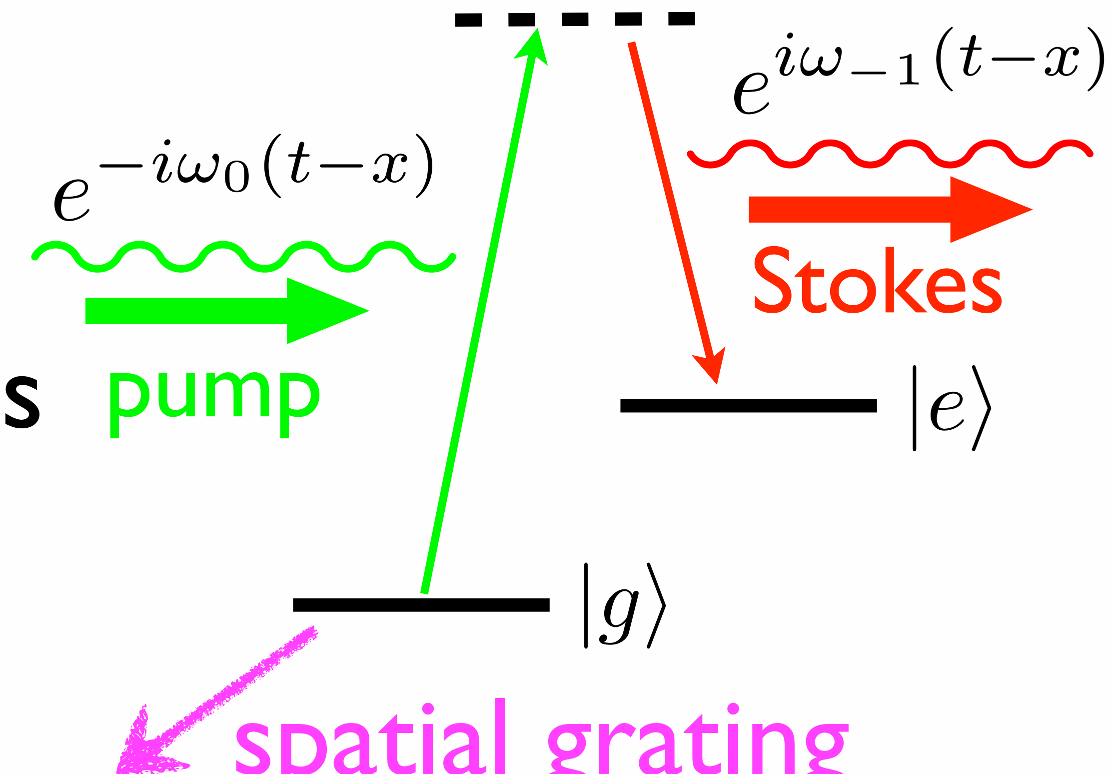
$$\eta_\omega(t) = \langle \eta_\omega(\xi,\tau)\rangle_\xi$$



PSR with spatial gratings

How to populate $|e\rangle$

Stimulated Raman process



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

Generated coherence

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

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

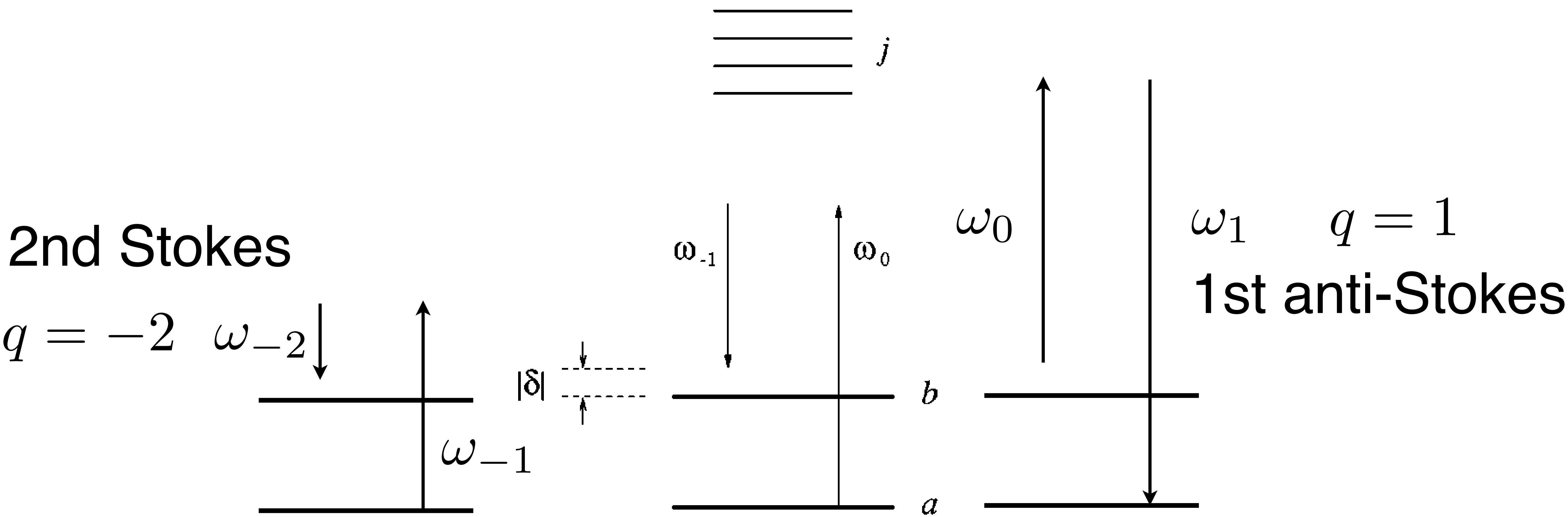
$$\omega_p + \omega_{\bar{p}} = \epsilon_{eg}$$

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)



$$\omega_q = \omega_0 + q(\omega_0 - \omega_{-1}) = \omega_0 + q(\omega_b - \omega_a - \delta)$$

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

detuning

Hamiltonian

$$H_{\rm int} = -\sum_j E(\mu_{ja}\sigma_{ja} + \mu_{aj}\sigma_{aj} + \mu_{jb}\sigma_{jb} + \mu_{bj}\sigma_{bj})$$

$$\mu_{\alpha\beta} = \langle\alpha|d|\beta\rangle \quad \sigma_{\alpha\beta} = |\alpha\rangle\langle\beta|$$

$$E = \frac{1}{2}\sum_q (E_q e^{-i\omega_q\tau} + E_q^* e^{i\omega_q\tau})$$

Effective Hamiltonian

$|j\rangle$ far off-resonance → two-level system

$$H_{\rm eff} = -\hbar\begin{bmatrix}\Omega_{aa} & \Omega_{ab} \\ \Omega_{ba} & \Omega_{bb} - \delta\end{bmatrix}$$

Stark shifts

$$\Omega_{aa}=\frac{1}{2}\sum_q a_q|E_q|^2 \qquad a_q=\frac{1}{2\hbar^2}\sum_j\left(\frac{|\mu_{ja}|^2}{\omega_j-\omega_a-\omega_q}+\frac{|\mu_{ja}|^2}{\omega_j-\omega_a+\omega_q}\right)$$

$$\Omega_{bb}=\frac{1}{2}\sum_q b_q|E_q|^2 \qquad b_q=\frac{1}{2\hbar^2}\sum_j\left(\frac{|\mu_{jb}|^2}{\omega_j-\omega_b-\omega_q}+\frac{|\mu_{jb}|^2}{\omega_j-\omega_b+\omega_q}\right)$$

Two-photon Rabi freq.

$$\Omega_{ab}=\Omega_{ba}^*=\frac{1}{2}\sum_q d_qE_qE_{q+1}^* \qquad d_q=\frac{1}{2\hbar^2}\sum_j\left(\frac{\mu_{aj}\mu_{jb}}{\omega_j-\omega_b-\omega_q}+\frac{\mu_{aj}\mu_{jb}}{\omega_j-\omega_a+\omega_q}\right)$$

Adiabatic eigenstate

$$|+\rangle = \cos\frac{\theta}{2}e^{i\varphi/2}|a\rangle + \sin\frac{\theta}{2}e^{-i\varphi/2}|b\rangle \xrightarrow{E\to 0} |a\rangle$$

$$\tan\theta = \frac{2|\Omega_{ab}|}{\Omega_{aa}-\Omega_{bb}+\delta} \qquad \Omega_{ab}=|\Omega_{ab}|e^{i\varphi}$$

Wave propagation

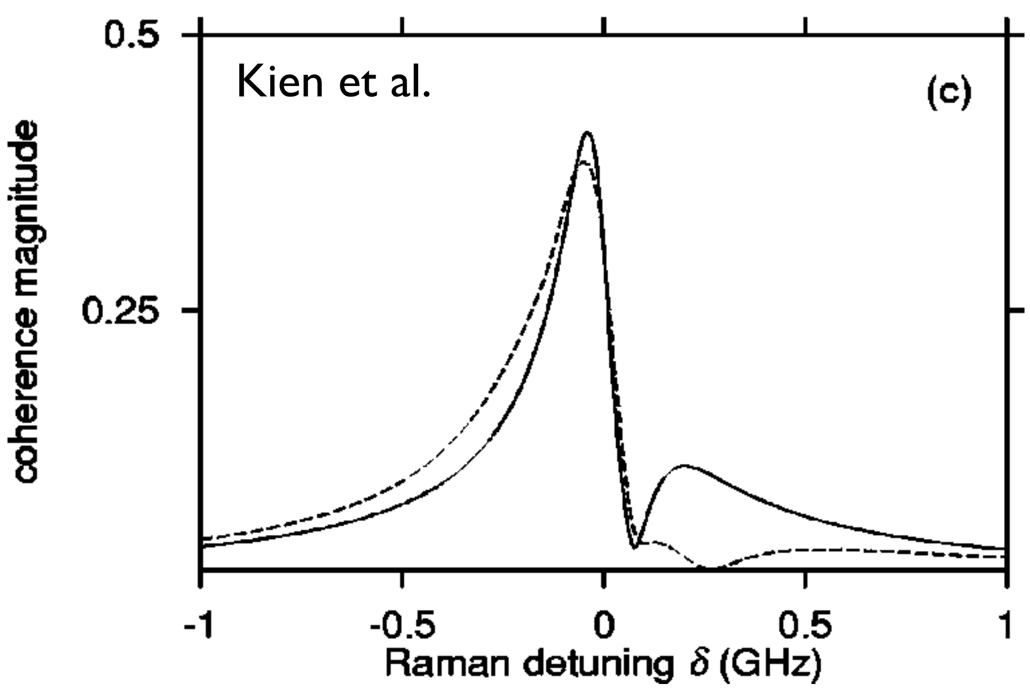
$$(\partial_t + \partial_z)E_q = in\hbar\omega_q \left(a_q\rho_{aa}E_q + b_q\rho_{bb}E_q + d_{q-1}\rho_{ba}E_{q-1} + d_q^*\rho_{ab}E_{q+1}\right)$$

Coherence $\rho_{ab} = \frac{1}{2}\sin\theta e^{i\varphi}$

molecular system of far off-resonance

$\Omega_{aa} \simeq \Omega_{bb}$ $\tan\theta \simeq 2|\Omega_{ab}|/\delta$ → $|\rho_{ab}| \simeq 1/2$

$|\rho_{ab}|$



δ

$\delta > 0\,,\ \sin\theta > 0$

phased state

$\delta < 0\,,\ \sin\theta < 0$

antiphased state

PSR experiments

Para-hydrogen gas PSR experiment

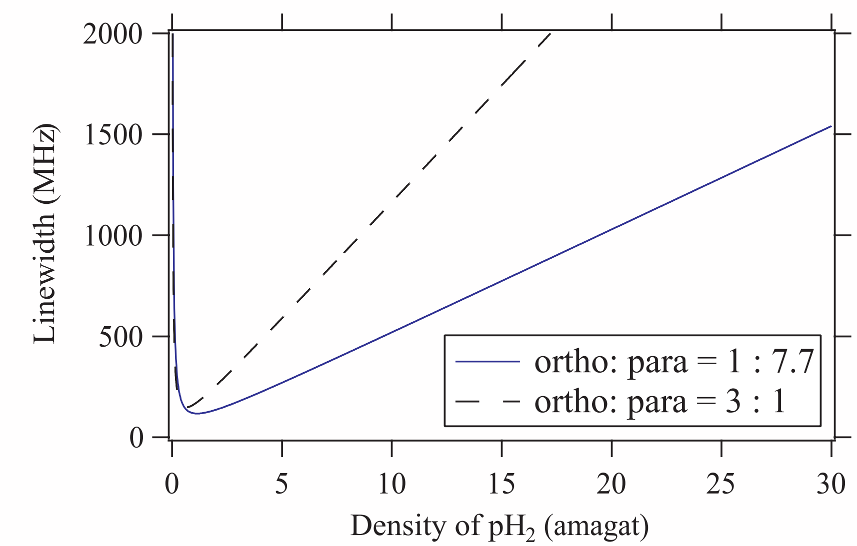
@ Okayama U

Y. Miyamoto et al. PTEP113C01(2014)
arXiv1406.2198

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 テキスト

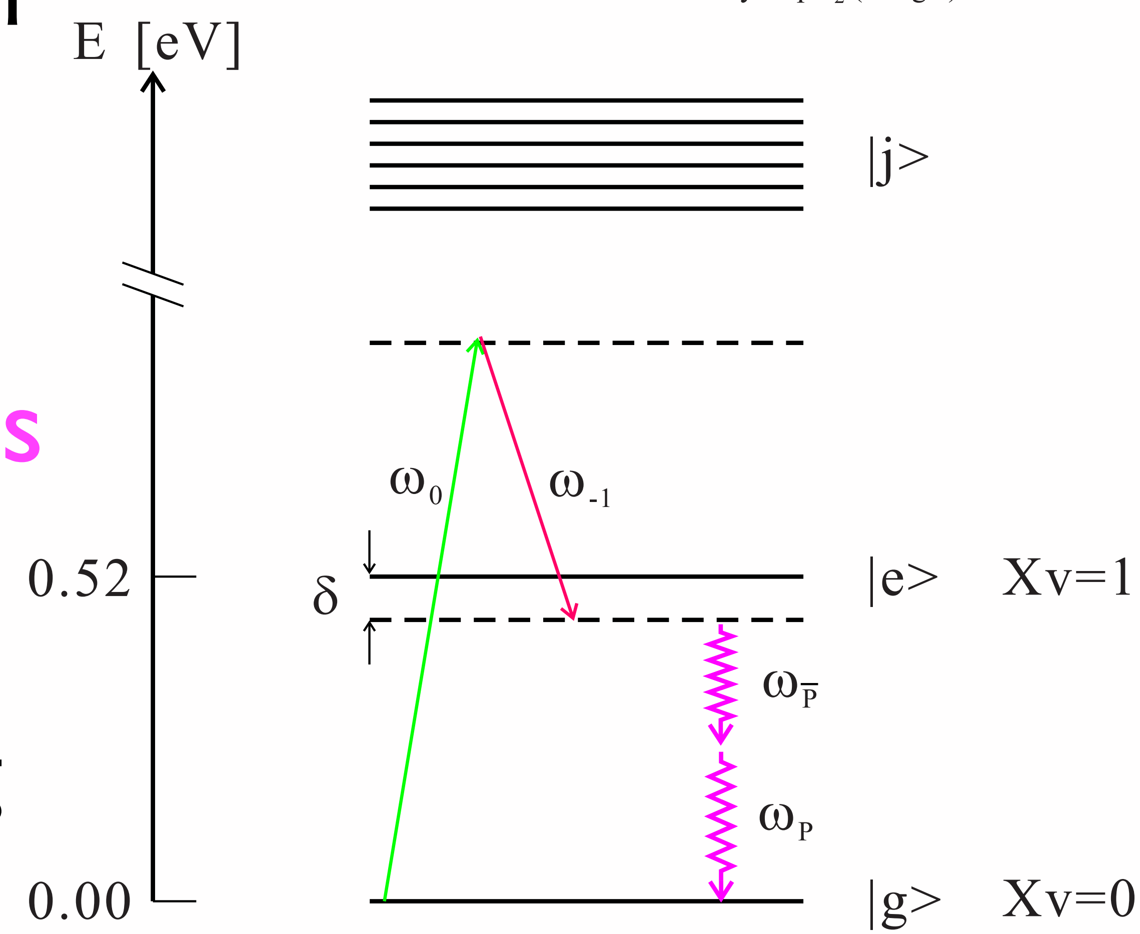
$$1/T_2 \sim 130 \text{ MHz}$$

coherence production

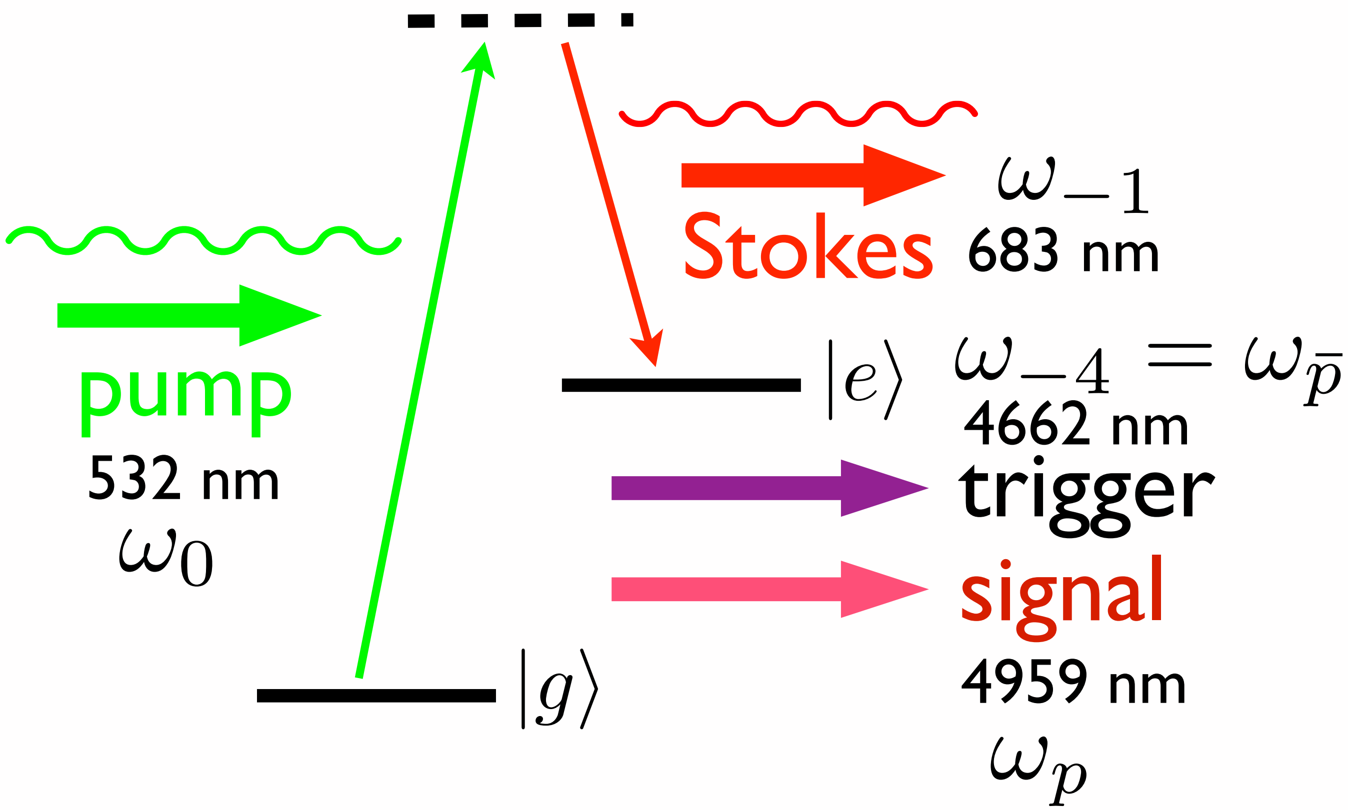
adiabatic Raman process

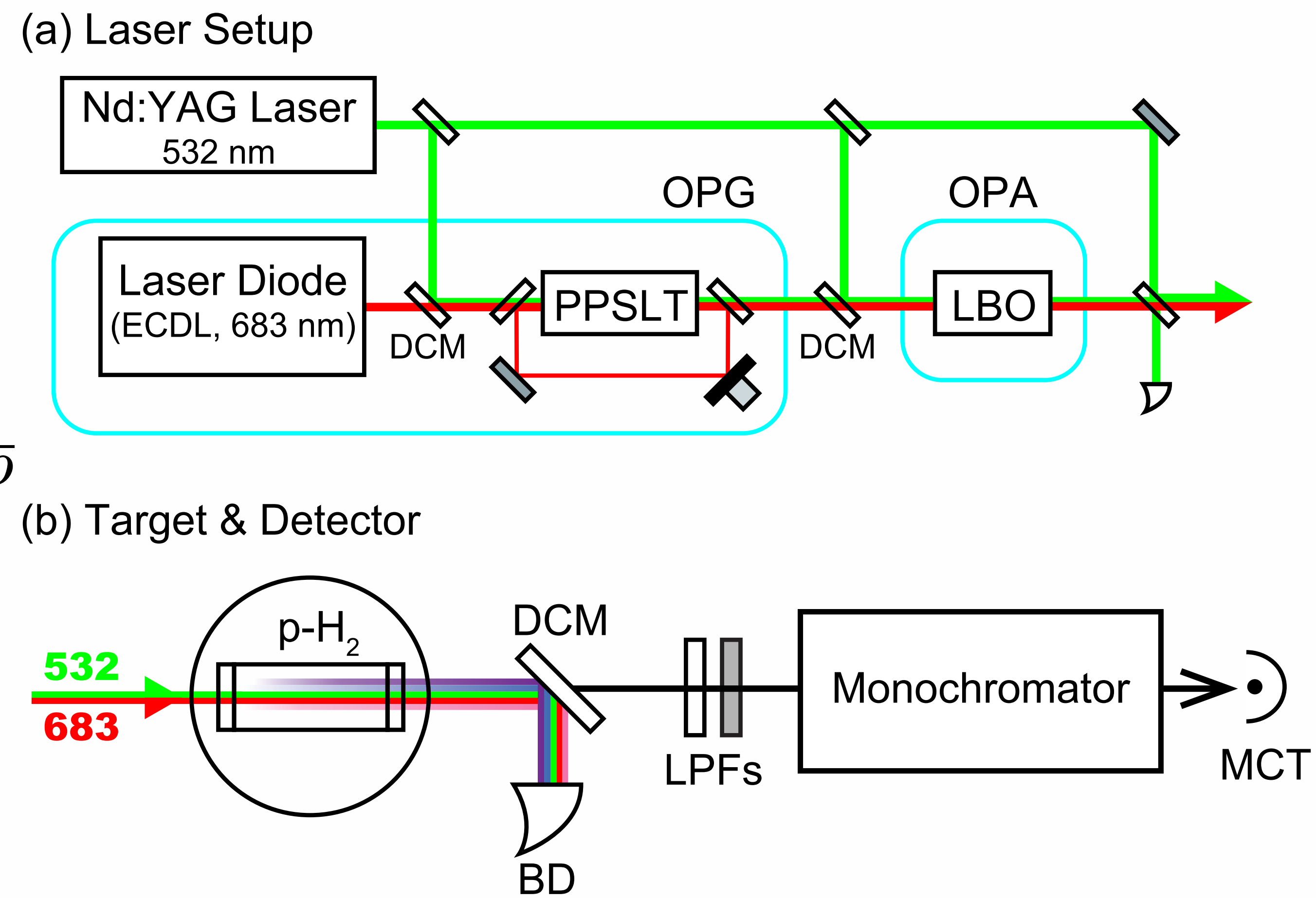
$$\Delta\omega = \omega_0 - \omega_{-1}$$
$$= \epsilon_{eg} - \delta$$
$$= \omega_p + \omega_{\bar{p}}$$

detuning



Experimental setup





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

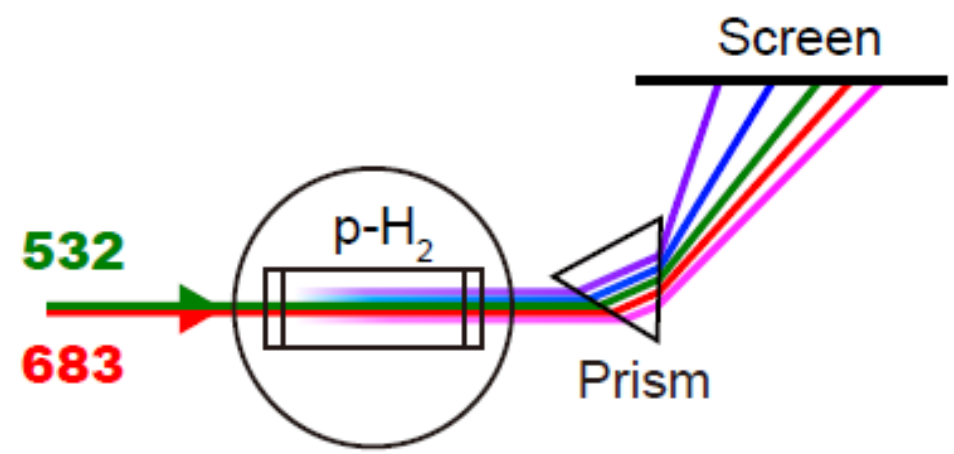
Target cell: length 15 cm, diameter 2 cm, 78 K, 60 kPa

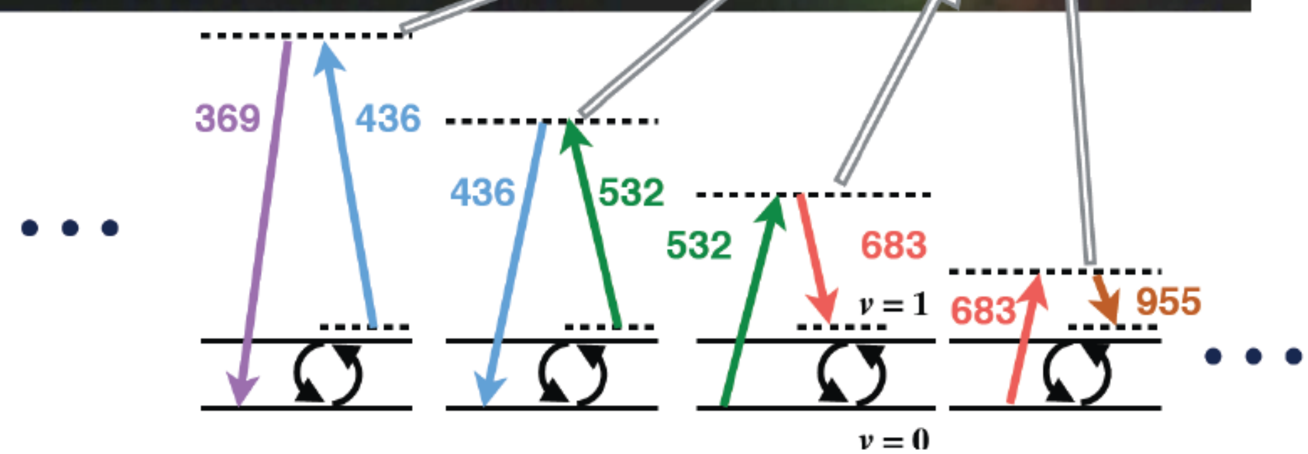
$$n = 5.6 \times 10^{19}\ \mathrm{cm}^{-3} \qquad 1/T_2 \sim 130\ \mathrm{MHz}$$

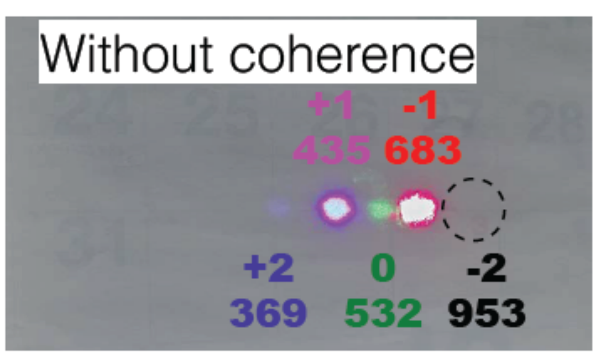
4th Stokes (q=-4) as trigger (internal trigger)

Ultra-broadband Raman sidebands

- Raman sidebands, from 192 to 4662nm, are observed: >24
- Evidence of large coherence







N. Sasao

Generated coherence

Maxwell-Bloch eq.

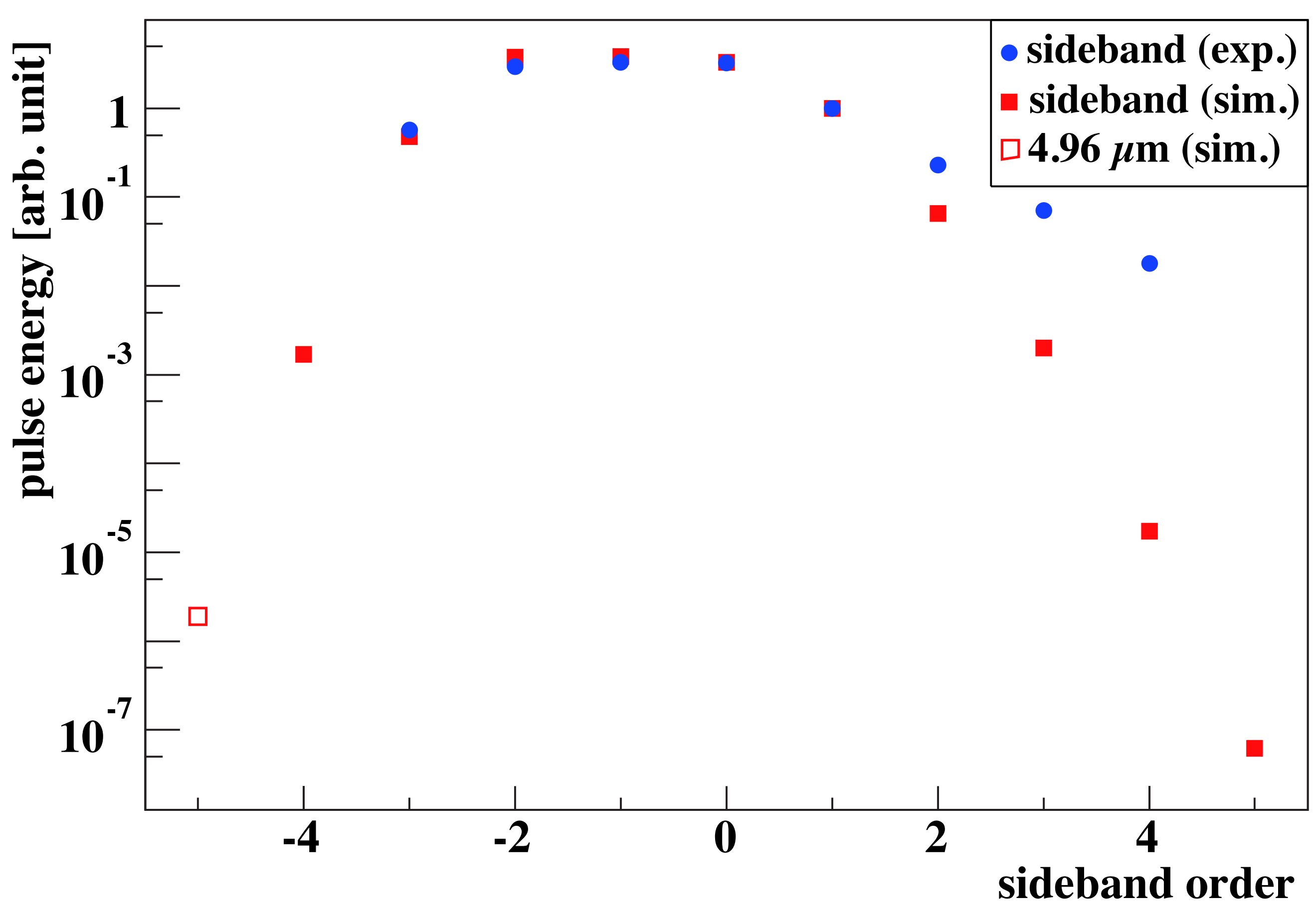
$$\frac{\partial \rho_{gg}}{\partial \tau} = i\Big(\Omega_{ge}\rho_{eg} - \Omega_{eg}\rho_{ge}\Big) + \gamma_1 \rho_{ee},$$

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

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

$$\frac{\partial E_q}{\partial \xi} = \frac{i\omega_q n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(q)} + \rho_{ee}\alpha_{ee}^{(q)}\Big)E_q + \rho_{eg}\alpha_{eg}^{(q-1)}E_{q-1} + \rho_{ge}\alpha_{ge}^{(q)}E_{q+1}\Big\},$$

$$\frac{\partial E_p}{\partial \xi} = \frac{i\omega_p n}{2c}\Big\{\Big(\rho_{gg}\alpha_{gg}^{(p)} + \rho_{ee}\alpha_{ee}^{(p)}\Big)E_p + \rho_{eg}\alpha_{ge}^{(p\bar{p})}E_{\bar{p}}^{*}\Big\}.$$

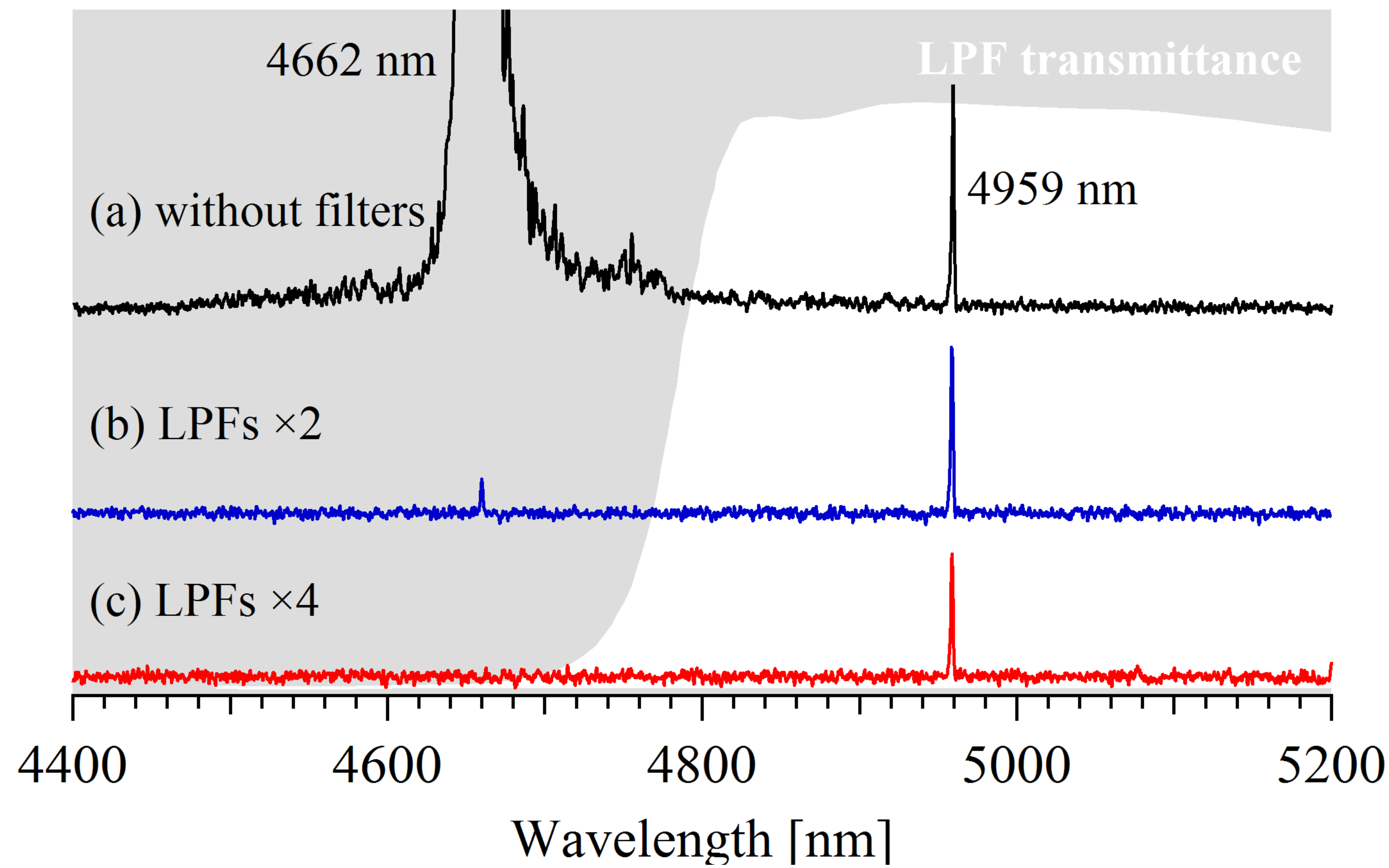


coherence estimation

$$|\rho_{eg}| \simeq 0.032$$

(6% of max.)

Observed two-photon spectrum



$\delta = 0$

# of observed photons

$$4.4 \times 10^7/\text{pulse}$$

Estimated spontaneous rate

$$1.6 \times 10^{-8}$$

$O(10^{15})$ (or more) enhancement!

Experiment with an external trigger

Y. Miyamoto et al. arXiv1505.07663, to appear in PTEP

Internal trigger (4th Stokes)

$$\omega_q = \omega_0 + q(\omega_0 - \omega_{-1})\,,\;\; q = -4$$

frequency, power, timing tied to driving lasers

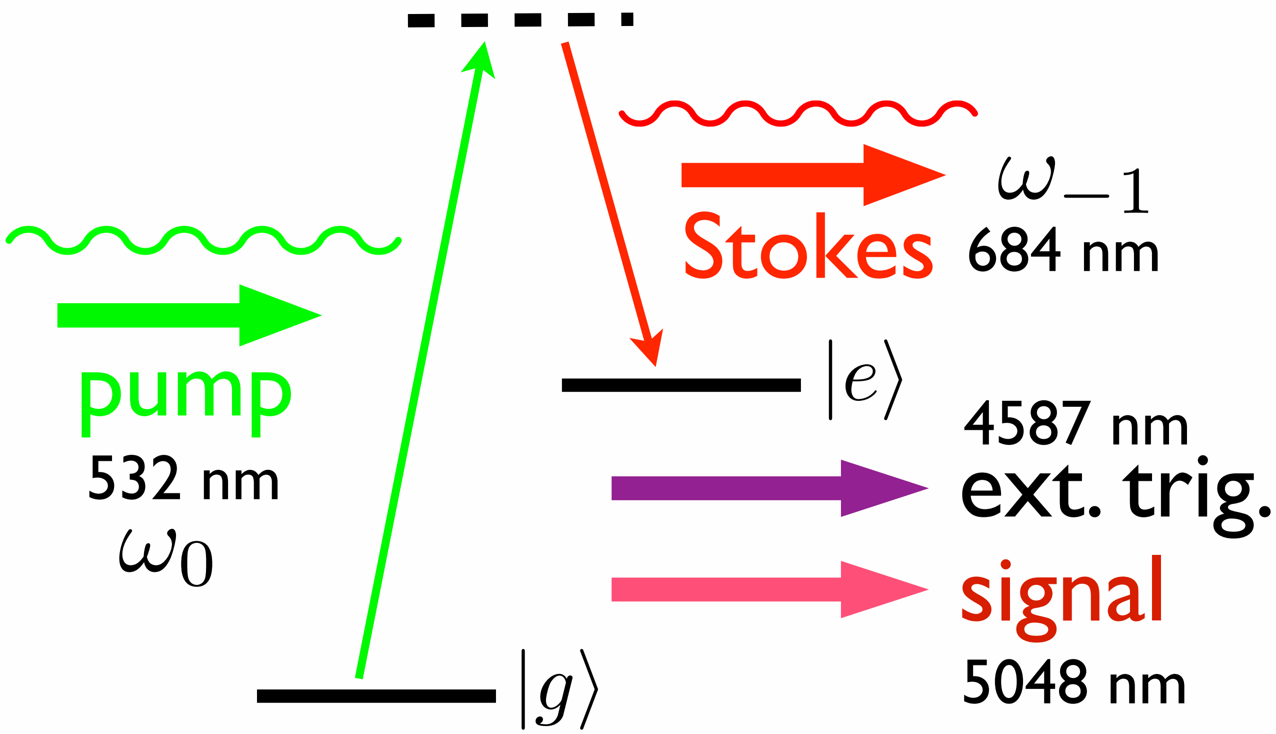
External trigger (additional laser irradiation)

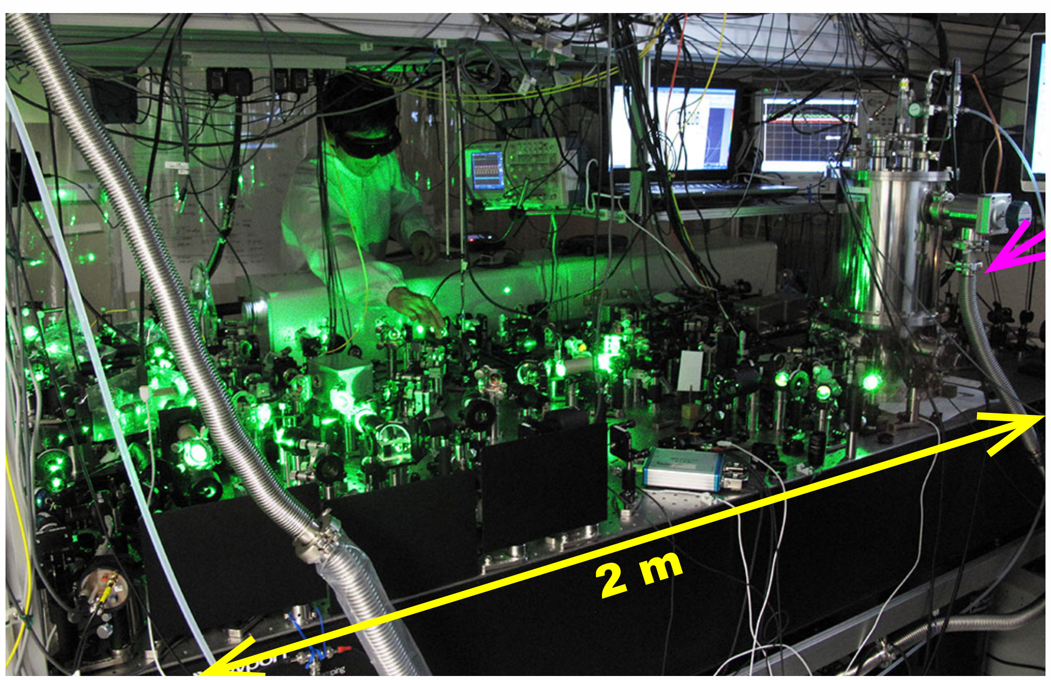
frequency, power, timing indep. of driving lasers

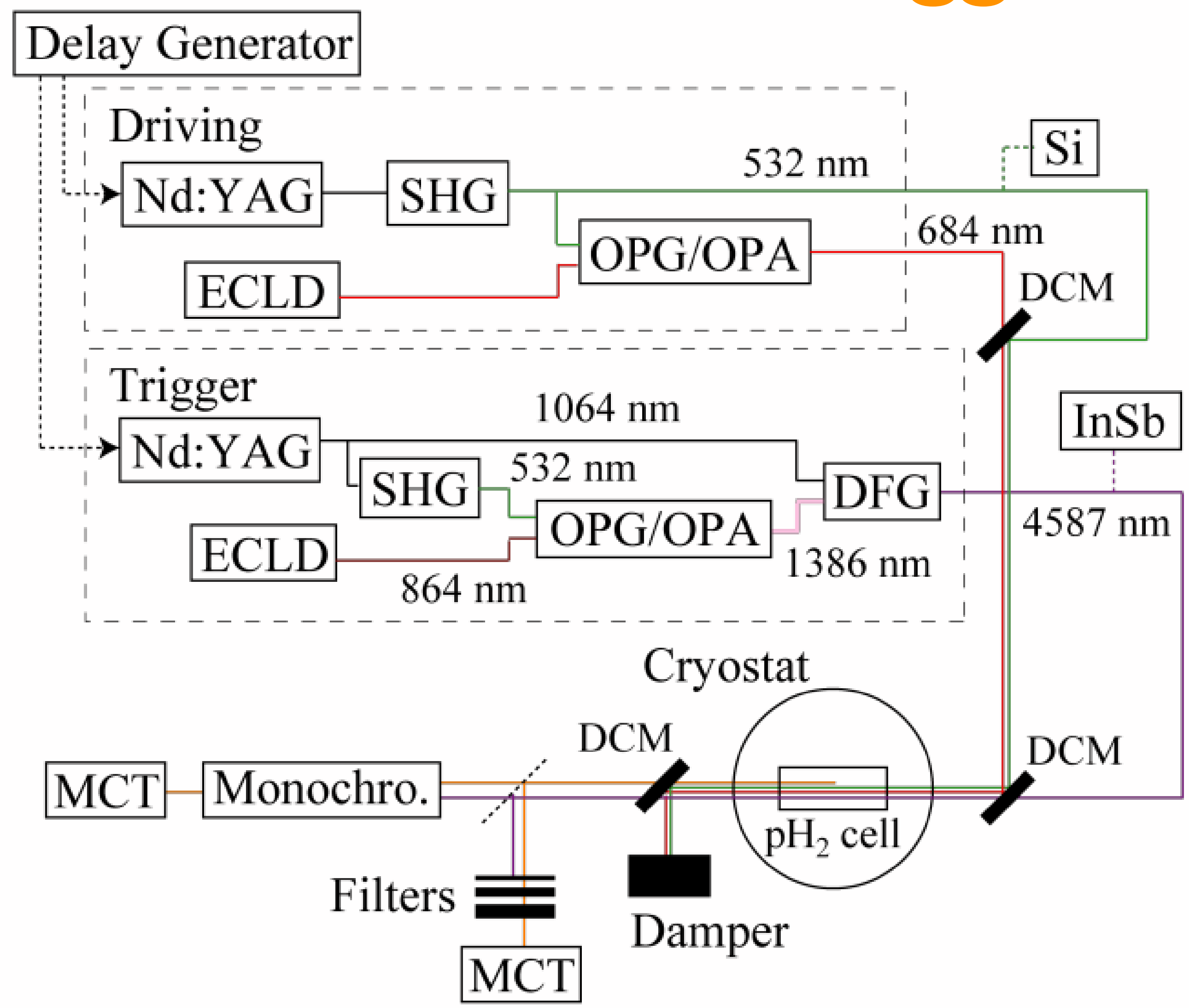
→ More suitable to explore macrocoherence

Mandatory for RENP

Experimental setup with an external trigger







External trigger

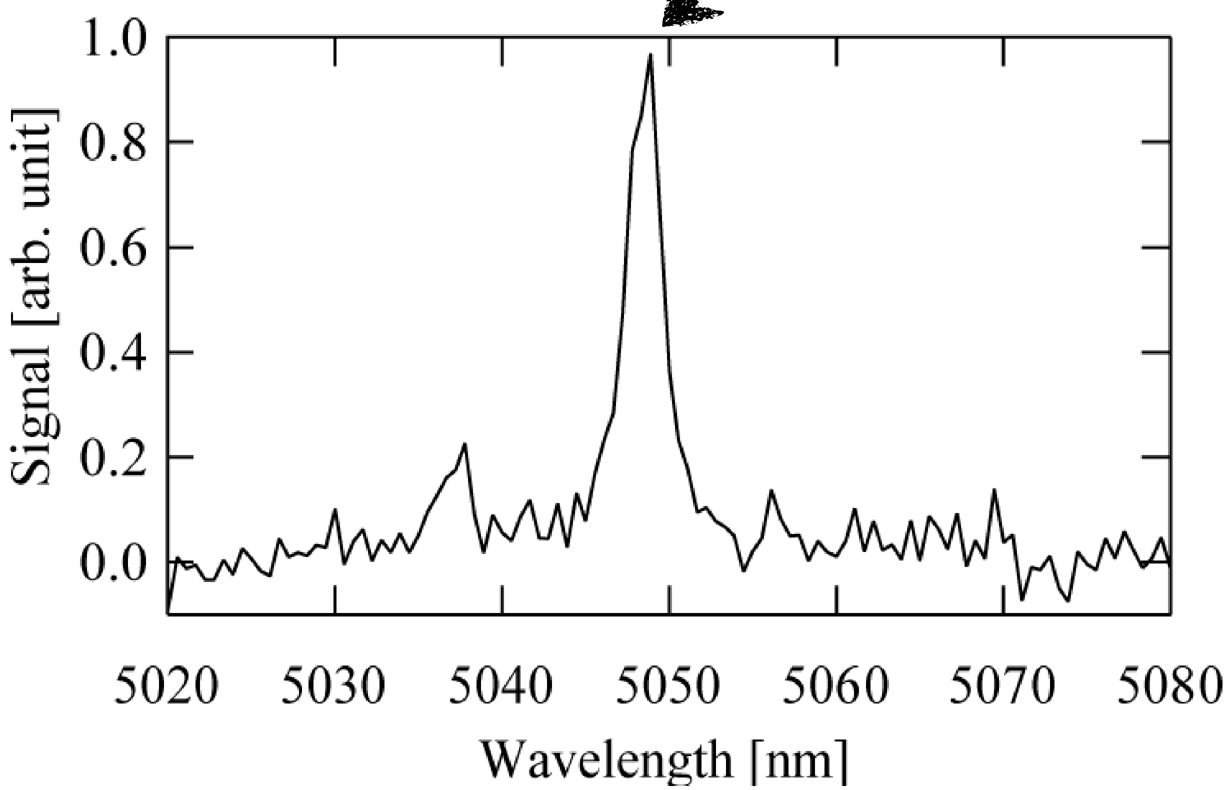
4587 nm, 2 ns, 150 μJ/pulse

Results

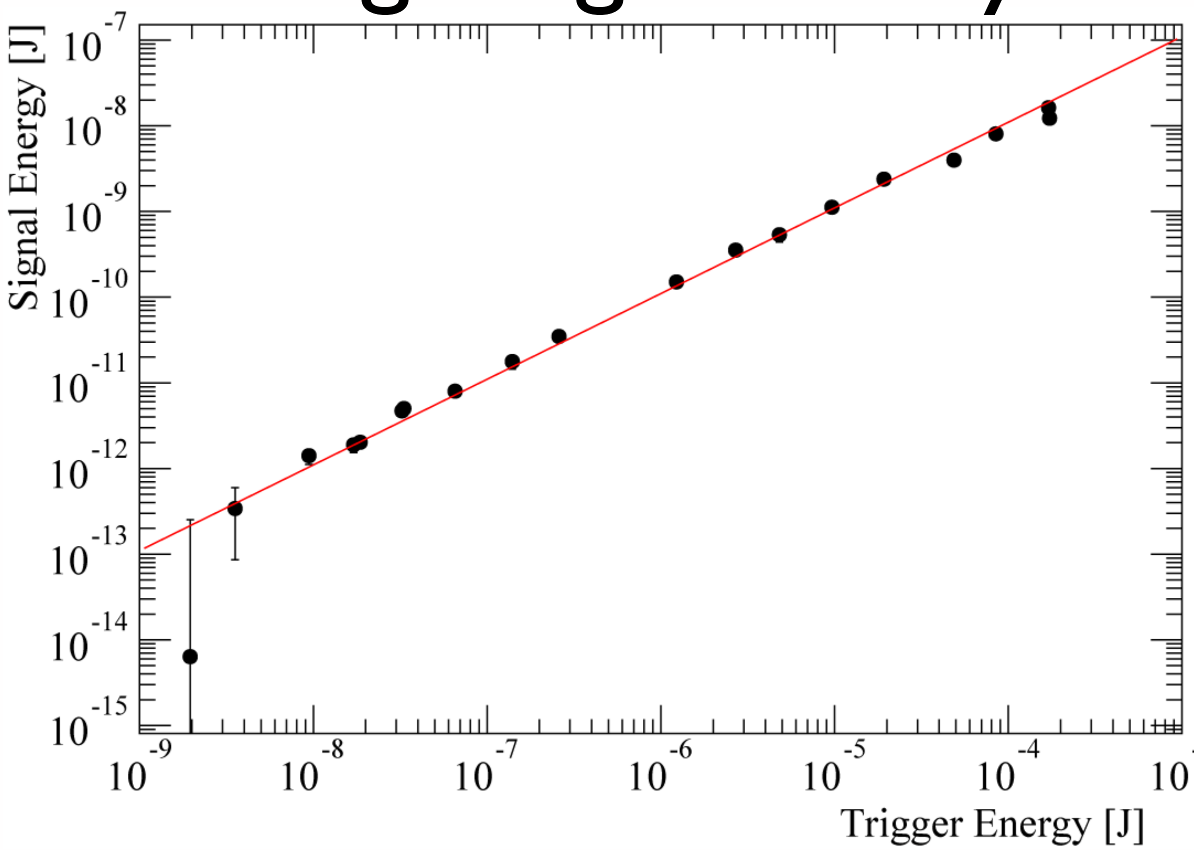
Estimated coherence (from sidebands)

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

5048 nm



sig.-trig. linearity



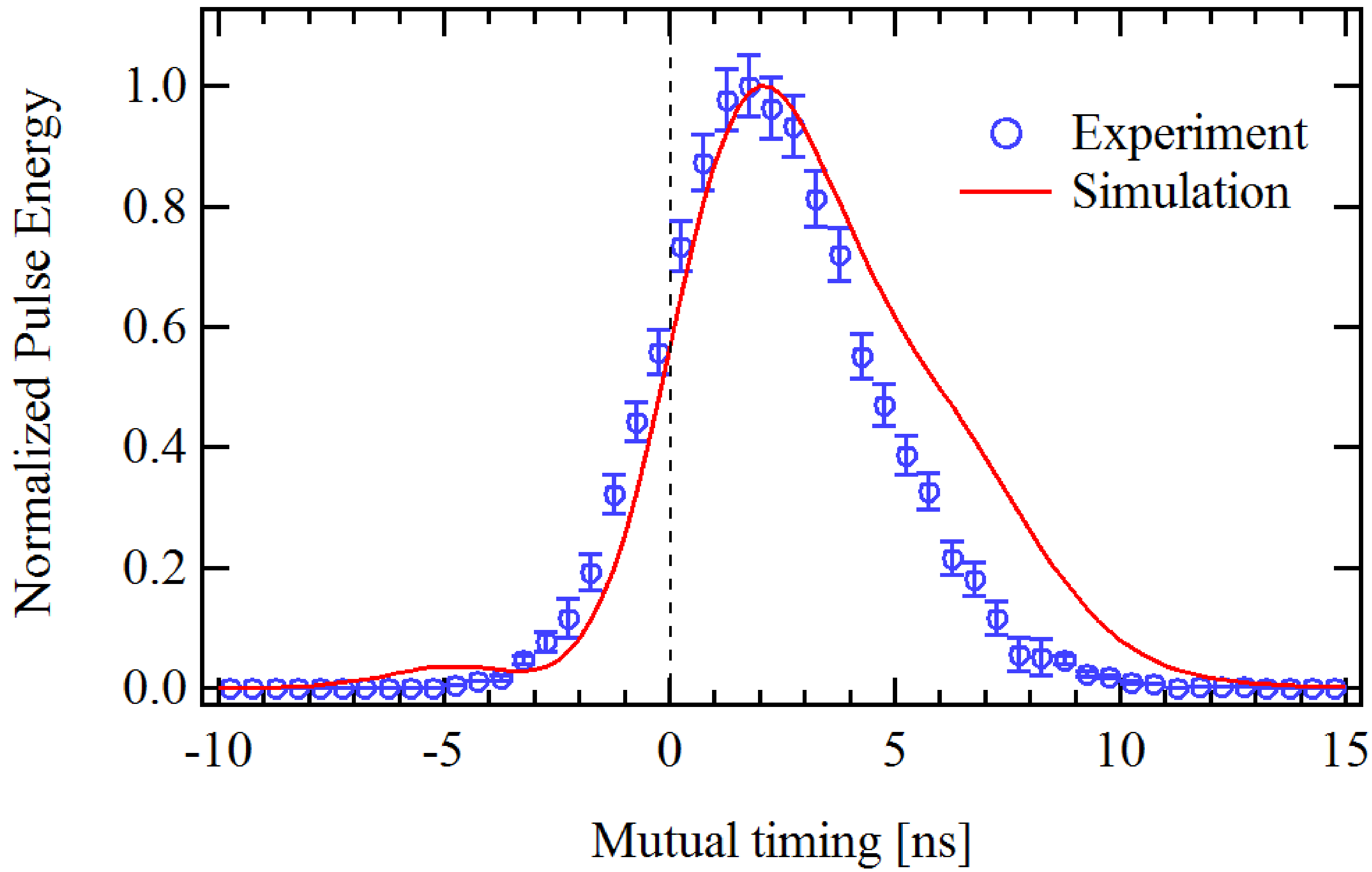
6×10^{11} photons/pulse

→ 10^{18} enhancement

weak field

low coherence

Trigger timing



trigger delay

Delayed coherence development in the target

SUMMARY

Coherences

Atomic coherence ρ_{eg}

Target coherence $\left[(|g\rangle + |e\rangle)/\sqrt{2}\right]^N$

Macrocoherence $e^{i\omega(t-x)}e^{i\omega(t+x)} = e^{2i\omega t}$

Realized in adiabatic Raman process with (internal or external) trigger

→ p-H2 PSR experiments

Huge enhancement confirmed.