原子ニュートリノ分光に向けた対超放射ダイナミクスの研究

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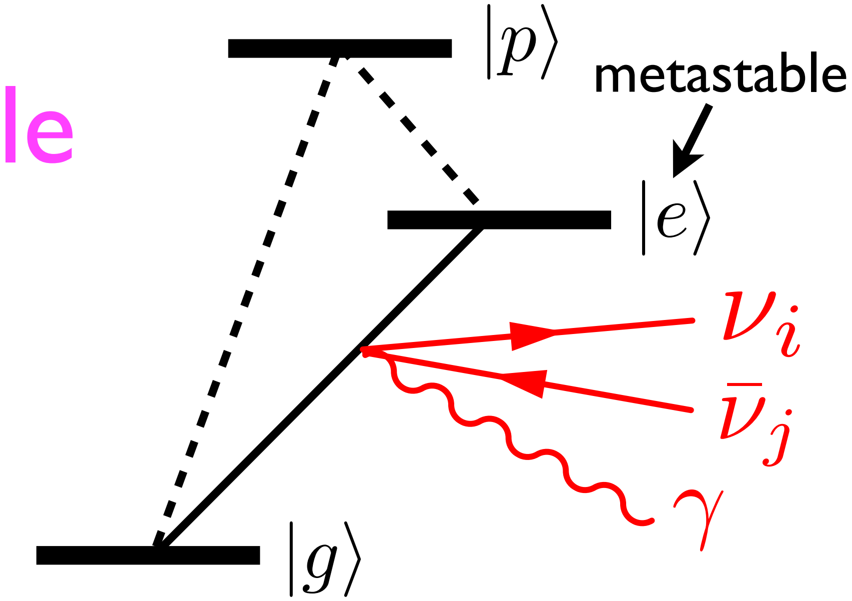
Radiative Emission of Neutrino Pair (RENP)



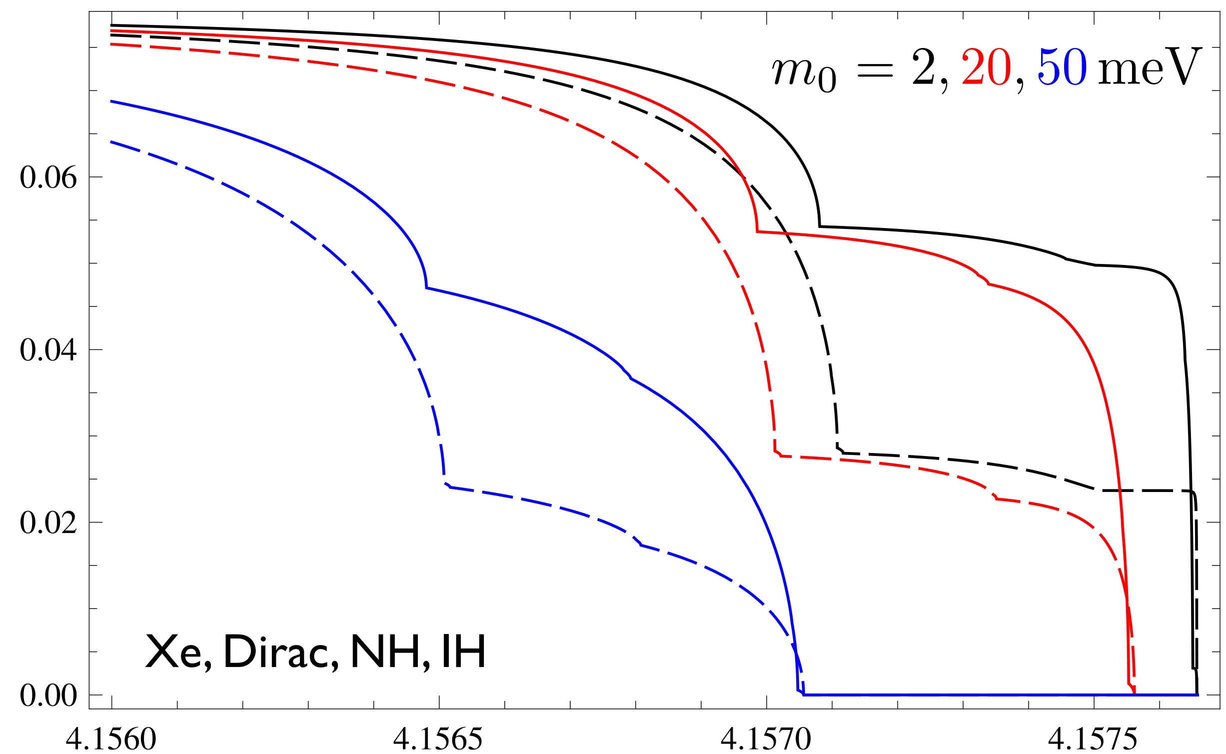
Atomic/molecular energy scale

~ eV or less,

~ the neutrino mass scale.

Photon spectrum

absolute mass,
Dirac/Majorana,
CP phases



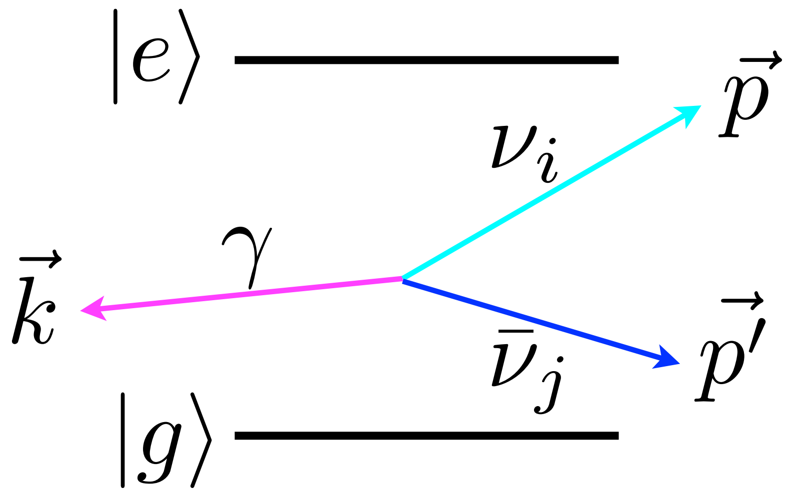
Rate

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

増幅機構が必要 → **macro-coherence**

Macro-coherence

Yoshimura et al. (2008)



position of atom

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

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

N atoms, volume V (n=N/V)

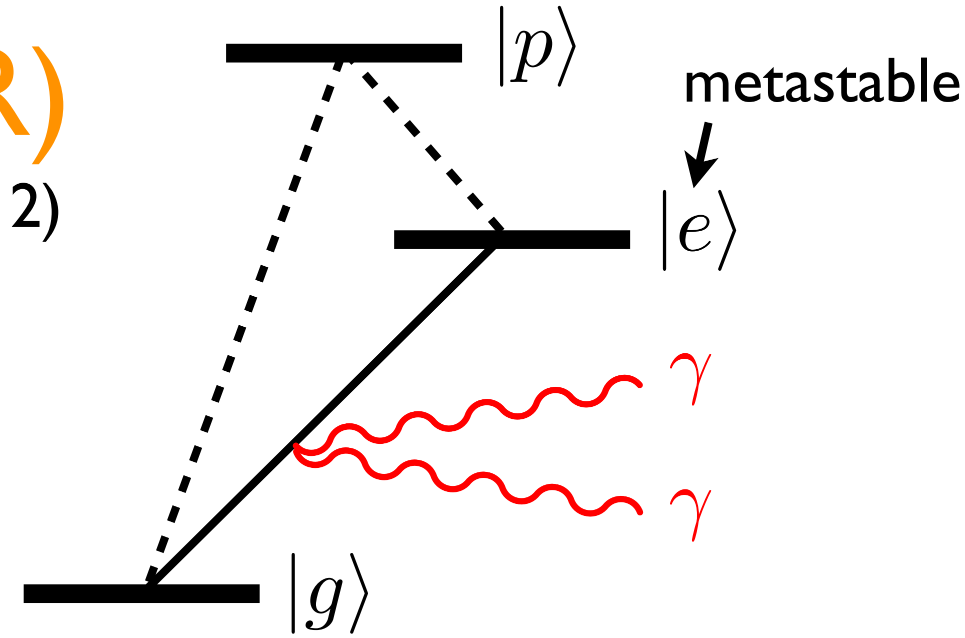
total amp. $\propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p}')$

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

macro-coherent amplification

Paired Super-Radiance (PSR)

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



A prototype of RENP

a proof of concept for the macro-coherence

Theory of PSR

Atomic system: $|\psi\rangle = c_g|g\rangle + c_e|e\rangle$

density matrix $\rho = |\psi\rangle\langle\psi|$

Schrödinger (Bloch) eq.

緩和

$$\partial_t \rho = i[\rho, \mathcal{H}_I] - \frac{1}{T_2}\begin{pmatrix} 0 & \rho_{eg} \\ \rho_{ge} & 0 \end{pmatrix} - \frac{\rho_{ee}}{T_1}\sigma_3$$

Fields: 1+1 dim. Maxwell eq. for two colors

→ Master equation of PSR

coherence

$$E_1,\ E_2,\ \rho_{ee} - \rho_{gg},\ \rho_{eg} = c_e c_g^*$$

PSR in a coherent Raman medium

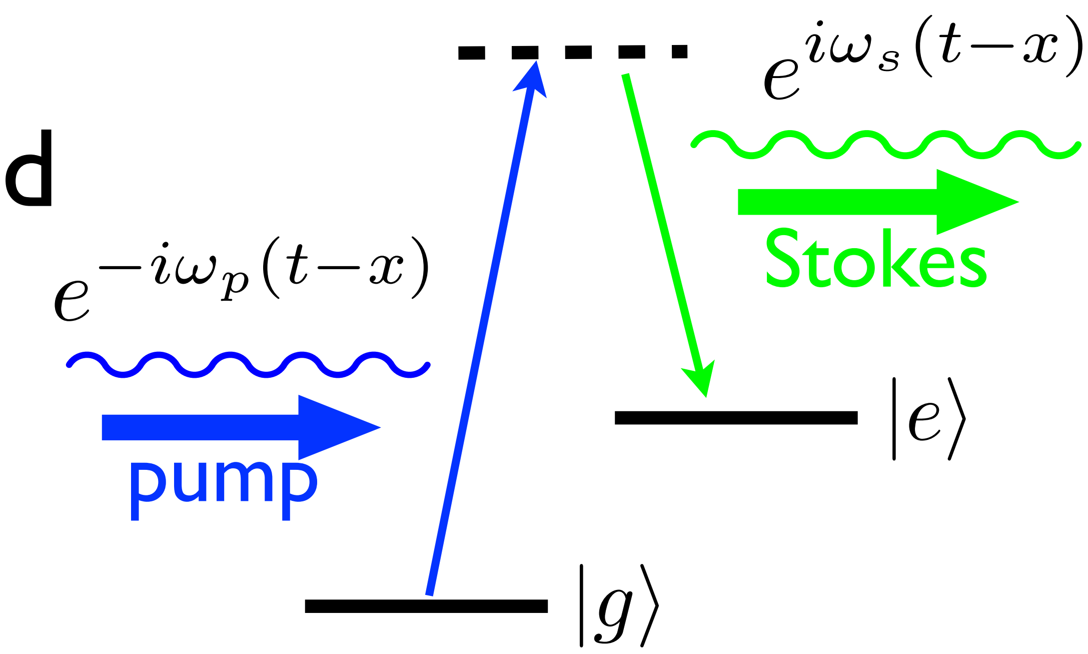
Large initial coherence → large PSR signal

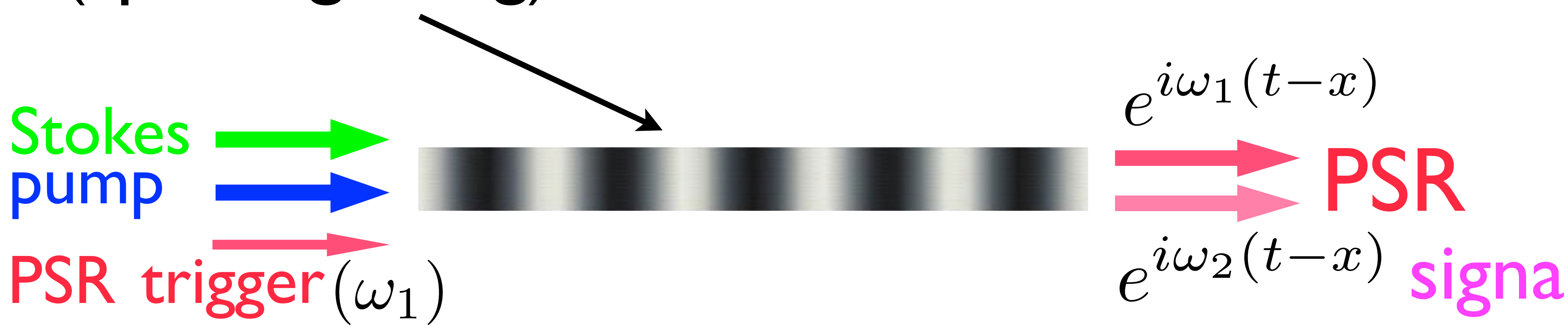
$|\rho_{eg}|$

Initial coherence prepared by Raman process

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

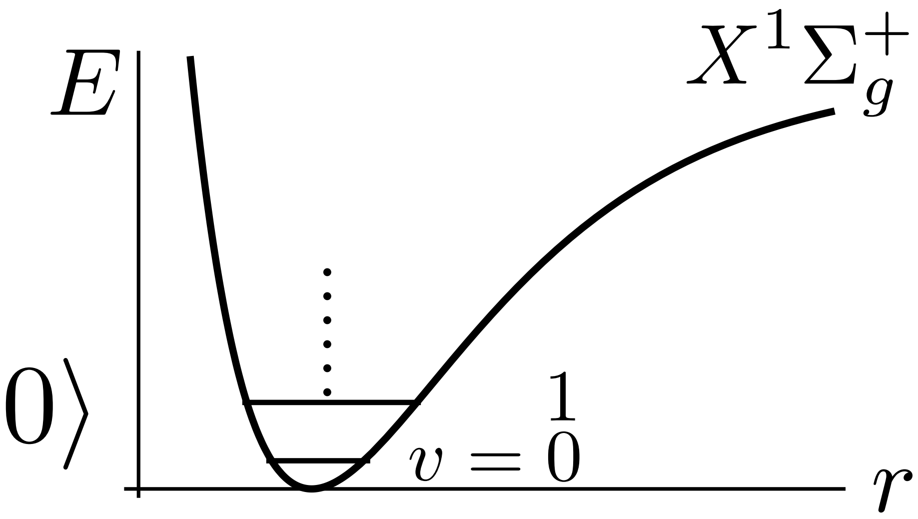
(spatial grating)





Phase matching: $\omega_p - \omega_s = \epsilon_{eg} = \omega_1 + \omega_2$

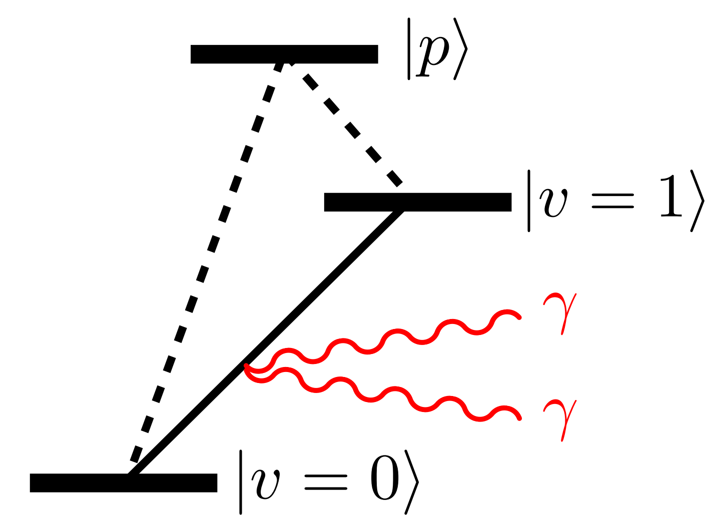
Numerical results



Para-H2 vibrational transition

$$|e\rangle = |v=1\rangle \to |g\rangle = |v=0\rangle$$

$$\epsilon_{eg} = 0.52 \text{ eV}$$



Spontaneous two-photon rate

$$4.6 \times 10^{-16} \text{ s}^{-1}$$

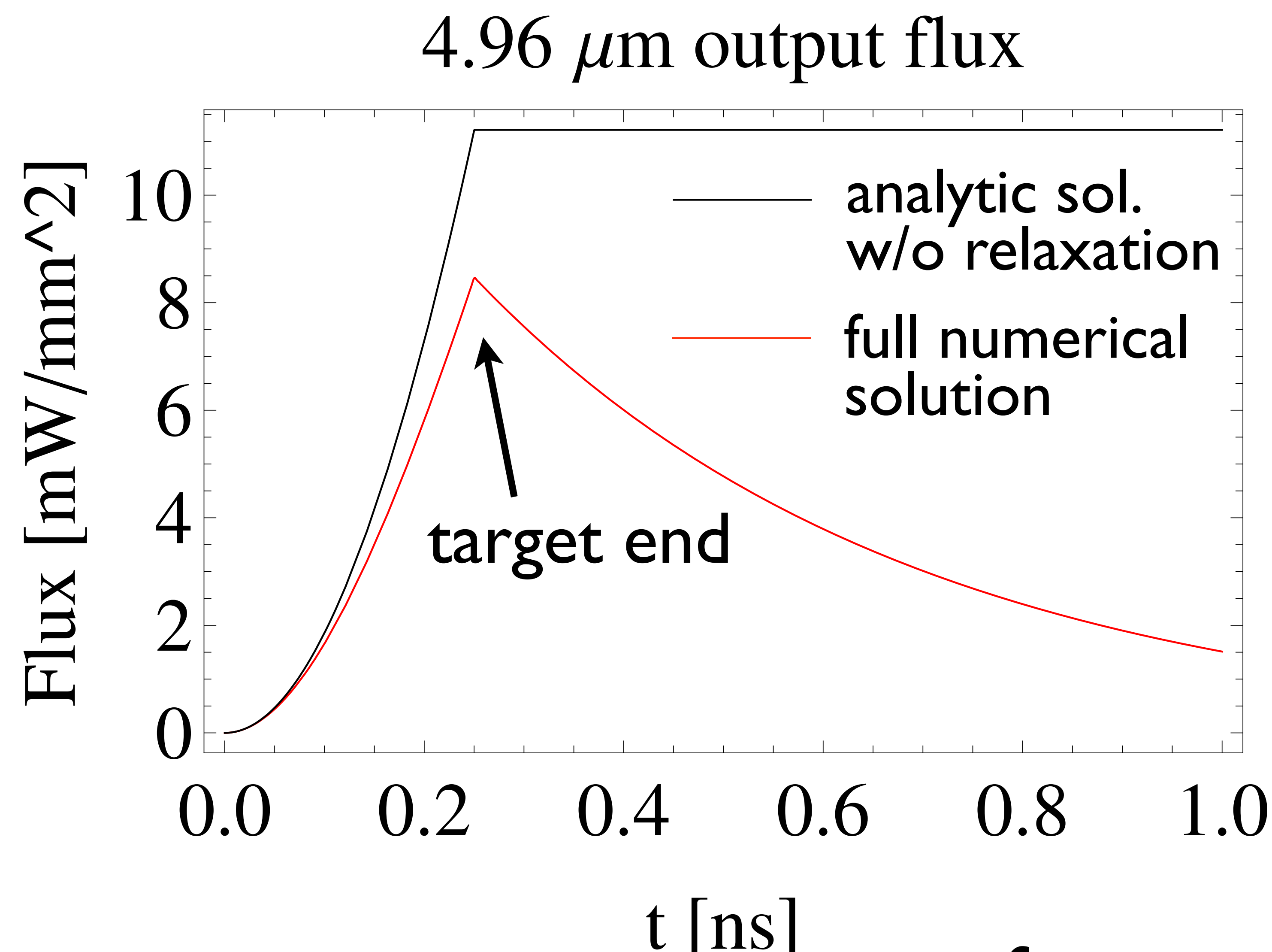
PSR modes: $\omega_1 = 4.66\ \mu\text{m},\ \omega_2 = 4.96\ \mu\text{m}$
trigger signal

4.66 trigger power= $100\ \text{W}/\text{mm}^2$ (5 ns pulse)

Density= $2.11 \times 10^{20}\ \mathrm{cm}^{-3}$ Length= $7.5\ \mathrm{cm}$

Relaxation time: $T_2 = 0.87\ \mathrm{ns}$

Initial coherence: $|\rho_{eq}^{(+)}| = 0.01$



4.96 µm signal≃ $4.5\ \mathrm{pJ/mm^2}$

signal/trigger≃ 8.9×10^{-6}

Coherent rate~ $0.2\ \mathrm{s}^{-1}$

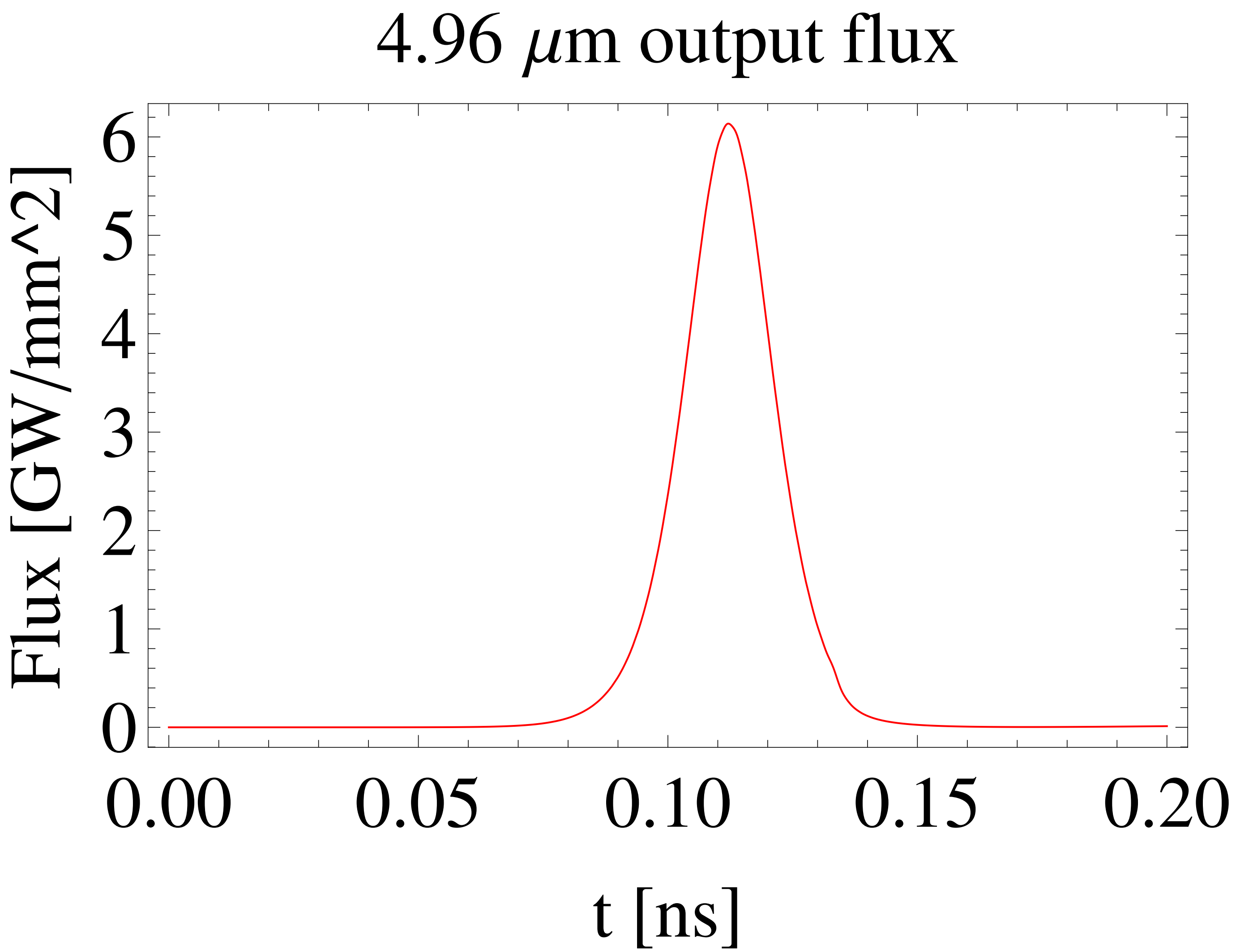
cf. spontaneous rate $\simeq 4.6 \times 10^{-16}\ \mathrm{s}^{-1}$

Explosive PSR in solid pH2

High density: $2.6 \times 10^{22}\ \mathrm{cm}^{-3}$ Length= $4\ \mathrm{cm}$

Long relaxation time: $T_2 \simeq 10\ \mathrm{ns}$

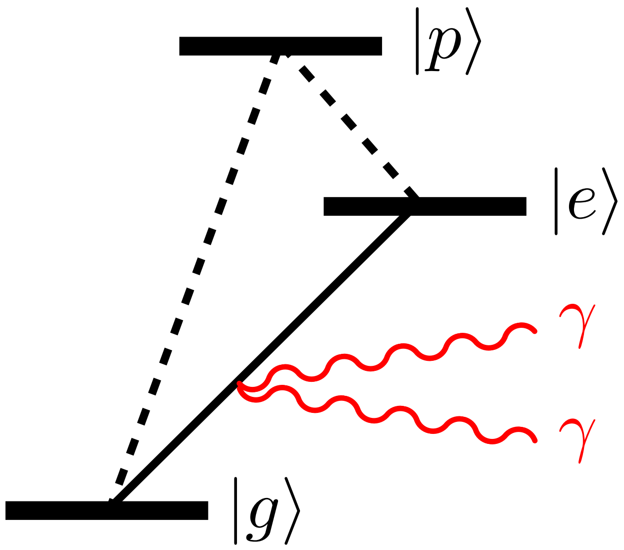
Initial coherence: $|\rho_{eq}^{(+)}| = 0.3$



signal/trigger~ 6×10^7

peak rate enhancement~ 3×10^{24}

Summary



✸ Theoretical study of PSR
master equation

✸ Huge rate enhancement by macro-coherence

✸ Possibility of explosive PSR

✸ Experimental results by Kuma-san

Backup Slides

Coherences in PSR/RENP

Atomic coherence $(|g\rangle + |e\rangle)/\sqrt{2}\,,\ \rho_{eg} = 1/2$

Target coherence $\left[\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)\right]^N$

$$\xrightarrow[J_-]{} \frac{1}{\sqrt{2^N}}[|g\rangle(|g\rangle + |e\rangle)\cdots(|g\rangle + |e\rangle) + (|g\rangle + |e\rangle)|g\rangle\cdots(|g\rangle + |e\rangle) + \cdots\cdots]$$

$$\Gamma \propto N^2$$

Macro-coherence

$$\Gamma \propto N^2/V = n^2 V$$

Instantaneous coherent rate in PSR

instantaneous output flux: $f\ [\mathrm{W/mm^2}]$

energy of each photon: $\epsilon\ [\mathrm{eV}]$

→ deexcitation rate per unit area:

$$R = f/\epsilon\ [\mathrm{cm^{-2}s^{-1}}]$$

target # density: $n\ [\mathrm{cm^{-3}}]$

target length: $L\ [\mathrm{cm}]$

excitation fraction: $\delta = (1 + r_3)/2\ (\sim 0.006)$

→ # of excited molecules per unit area:

$$N = nL\delta\ [\mathrm{cm^{-2}}]$$

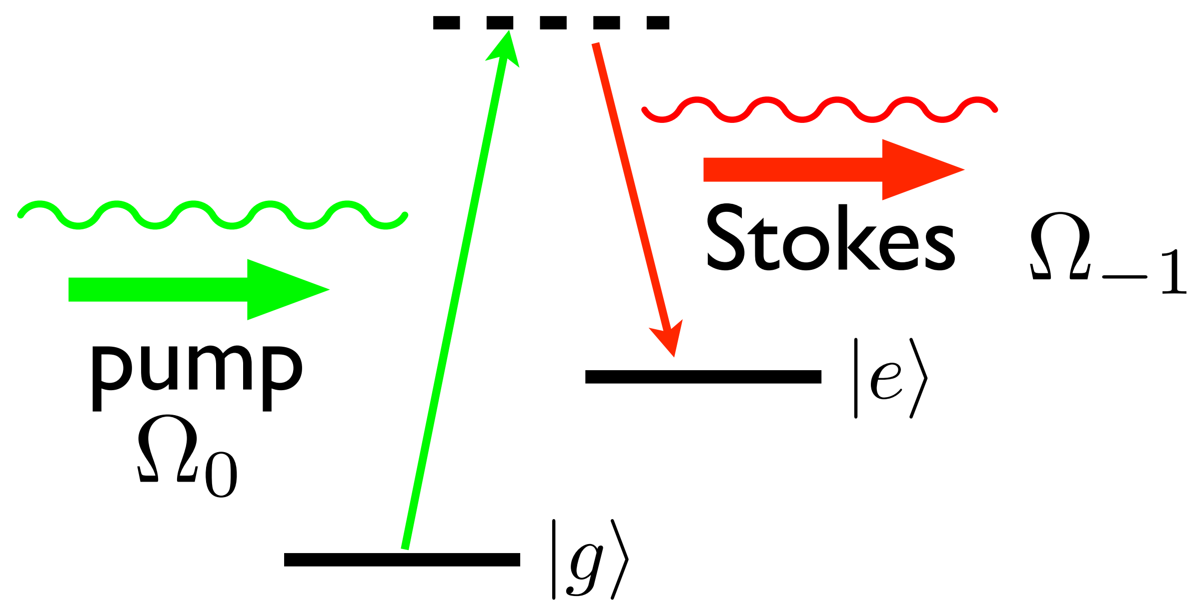
→ coherent deexcitation rate per molecule:

$$\Gamma = R/N\ [\mathrm{s^{-1}}]$$

An Initial Coherent State for PSR/RENP

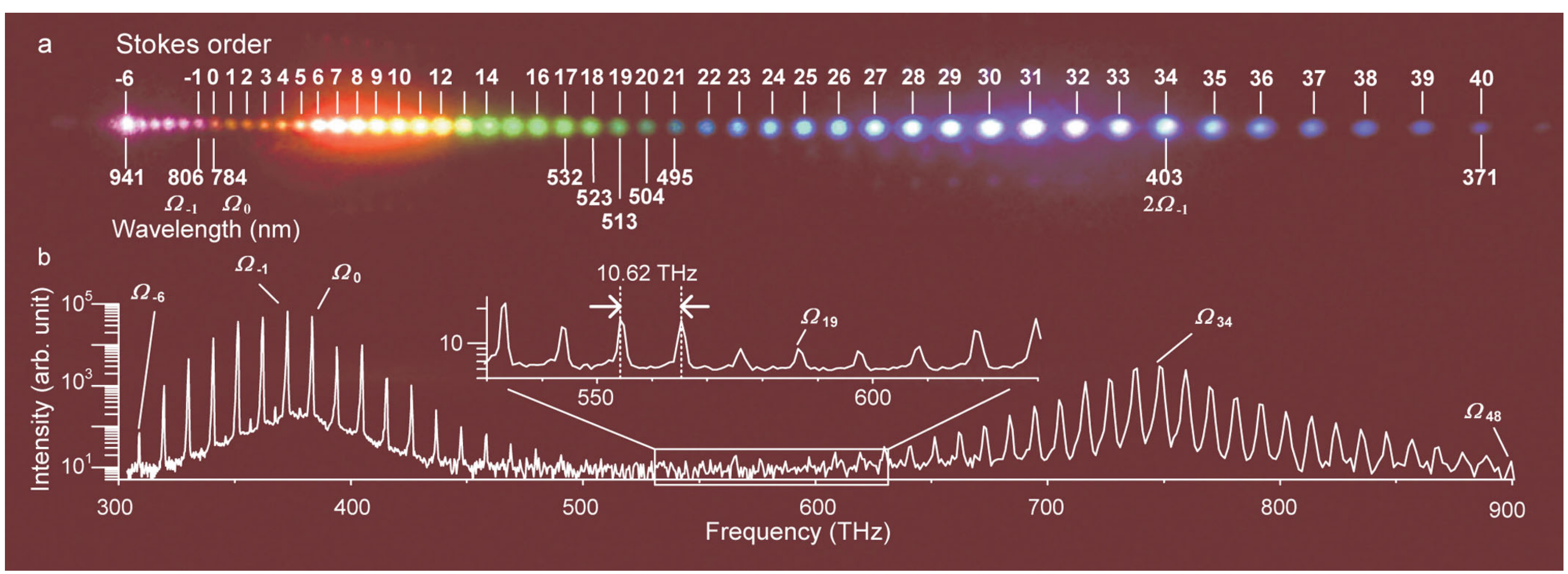
Raman scattering

$$\left[\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)\right]^N$$



Ex. para-H2 Raman comb

T. Suzuki, M. Hirai, M. Katsuragawa, PRL101, 243602(2008)



RENP spectrum

Energy-momentum conservation
due to the macro-coherence
→ familiar 3-body decay kinematics

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 diff.

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

typical laser linewidth

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

RENP rate formula

dynamical factor

$$\Gamma_{\gamma 2\nu}(\omega, t) = \Gamma_0 I(\omega) \eta_\omega(t)$$

spectral function

overall rate

Overall rate

macro-coherence

~ field energy density

$$\Gamma_0 = \frac{3n^2 V G_F^2 \gamma_{pg} \epsilon_{eg} n}{2\epsilon_{pg}^3}(2J_p + 1)C_{ep} \sim 1\,\mathrm{Hz}\,(n/10^{22}\mathrm{cm}^{-3})^3 (V/10^2\,\mathrm{cm}^3)$$

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

$(2J_p + 1)C_{ep}$: atomic spin factor

Spectral function

$$I(\omega) = F(\omega)/(\epsilon_{pg} - \omega)^2$$

$$F(\omega) = \sum_{ij} \Delta_{ij}(B_{ij} I_{ij}(\omega) - \delta_M B^M_{ij} m_i m_j)\theta(\omega_{ij} - \omega)$$

$$\Delta^2_{ij} = 1 - 2\frac{m_i^2 + m_j^2}{q^2} + \frac{(m_i^2 - m_j^2)^2}{q^4} \qquad q^2 = (p_i + p_j)^2$$

$$I_{ij}(\omega) = \frac{q^2}{6}\left[2 - \frac{m_i^2 + m_j^2}{q^2} - \frac{(m_i^2 - m_j^2)^2}{q^4}\right] + \frac{\omega^2}{9}\left[1 + \frac{m_i^2 + m_j^2}{q^2} - 2\frac{(m_i^2 - m_j^2)^2}{q^4}\right]$$

$\delta_M = 0(1)$ for Dirac(Majorana)

$$B_{ij} = |U^*_{ei} U_{ej} - \delta_{ij}/2|^2, B^M_{ij} = \Re[(U^*_{ei} U_{ej} - \delta_{ij}/2)^2]$$

Dynamical factor

$$\sim |\text{coherence} \times \text{field}|^2$$