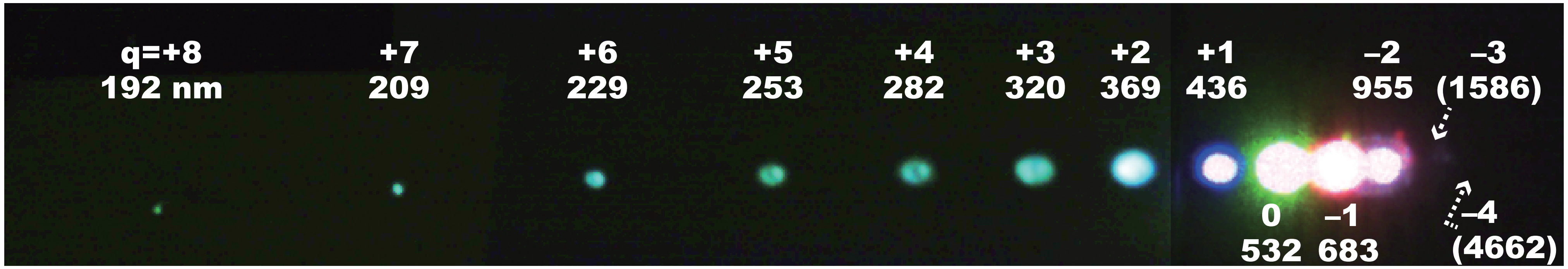
原子・分子過程による

ニュートリノ物理

田中 実

大阪大学



素粒子物理学の進展2015@YITP, 京都, 2015/09/16

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

What we know about neutrino mass and mixing

Masses:

$$\Delta m^2_{21} \simeq (8.66 \text{ meV})^2\,, \ |\Delta m^2_{31(2)}| \simeq (49.6(5) \text{ meV})^2$$

NuFIT (2014)

$$\sum m_\nu \leq 0.23 \text{ eV}$$ PLANCK 2013

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

$$V_{\rm PMNS} =$$

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

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

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

$$\sin^2\theta_{12} \simeq 0.30\,, \ \sin^2\theta_{23} \simeq 0.45(58)\,, \ \sin^2\theta_{13} \simeq 0.022$$

NuFIT (2014)

Unknown properties of neutrinos

Absolute mass

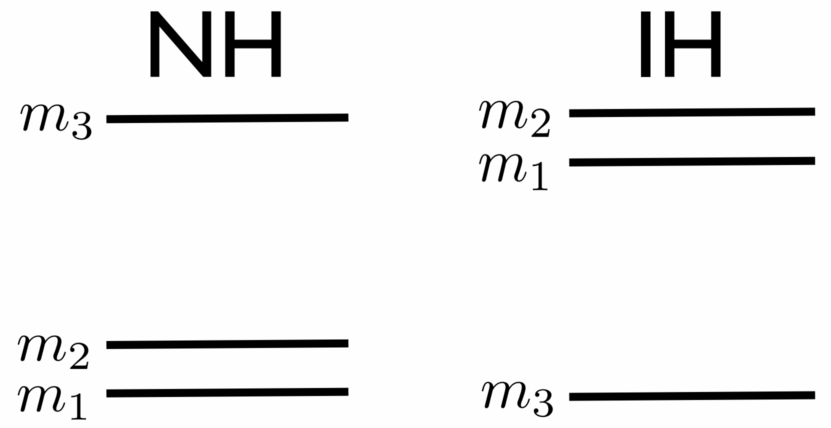
$$m_{1(3)} < 71(66)\ \mathrm{meV},\ \ 50\ \mathrm{meV} < m_{3(2)} < 87(82)\ \mathrm{meV}$$

Mass type

Dirac or Majorana

Hierarchy pattern

normal or inverted



CP violation

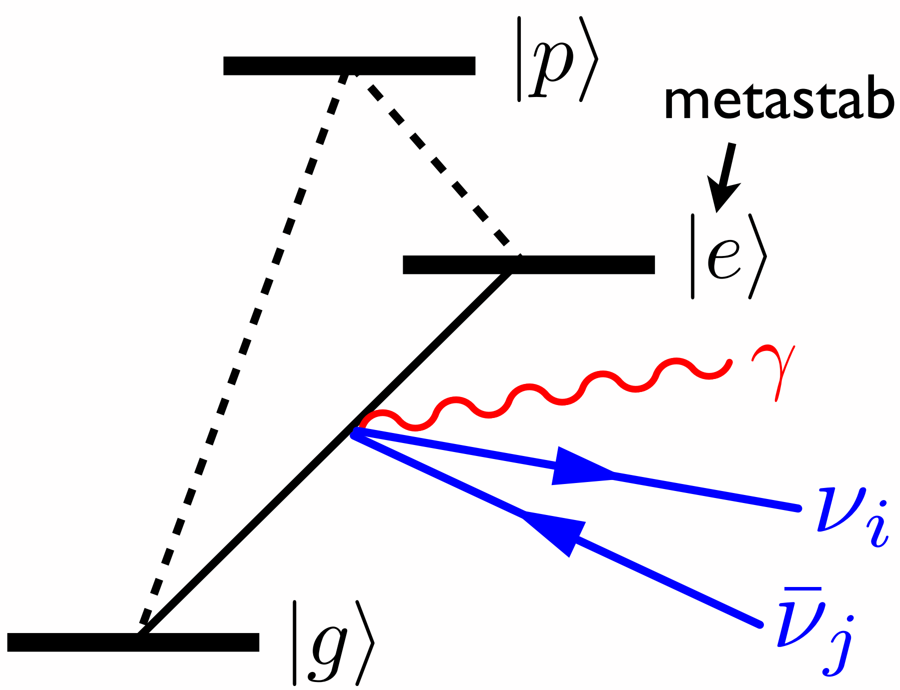
one Dirac phase, two Majorana phases

δ $\alpha,\ \beta$

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

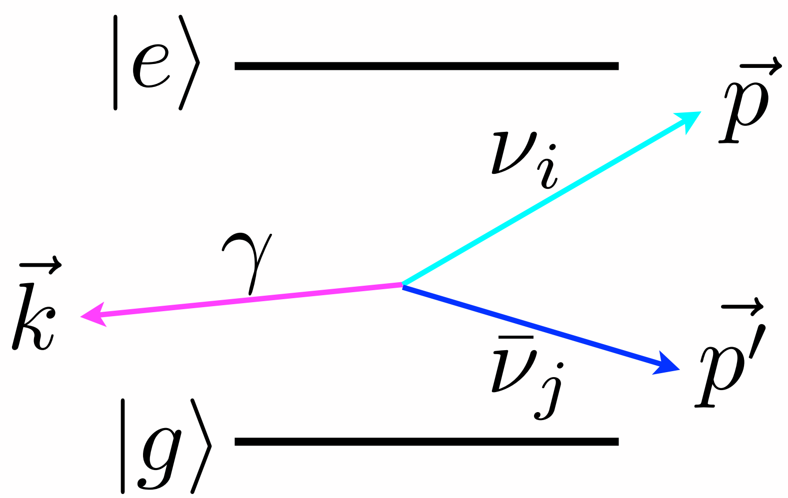
$$\xrightarrow{\text{deexcitation}} [|g\rangle(|g\rangle+|e\rangle)\cdots(|g\rangle+|e\rangle)$$

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

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

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

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

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

Six thresholds of the photon energy

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

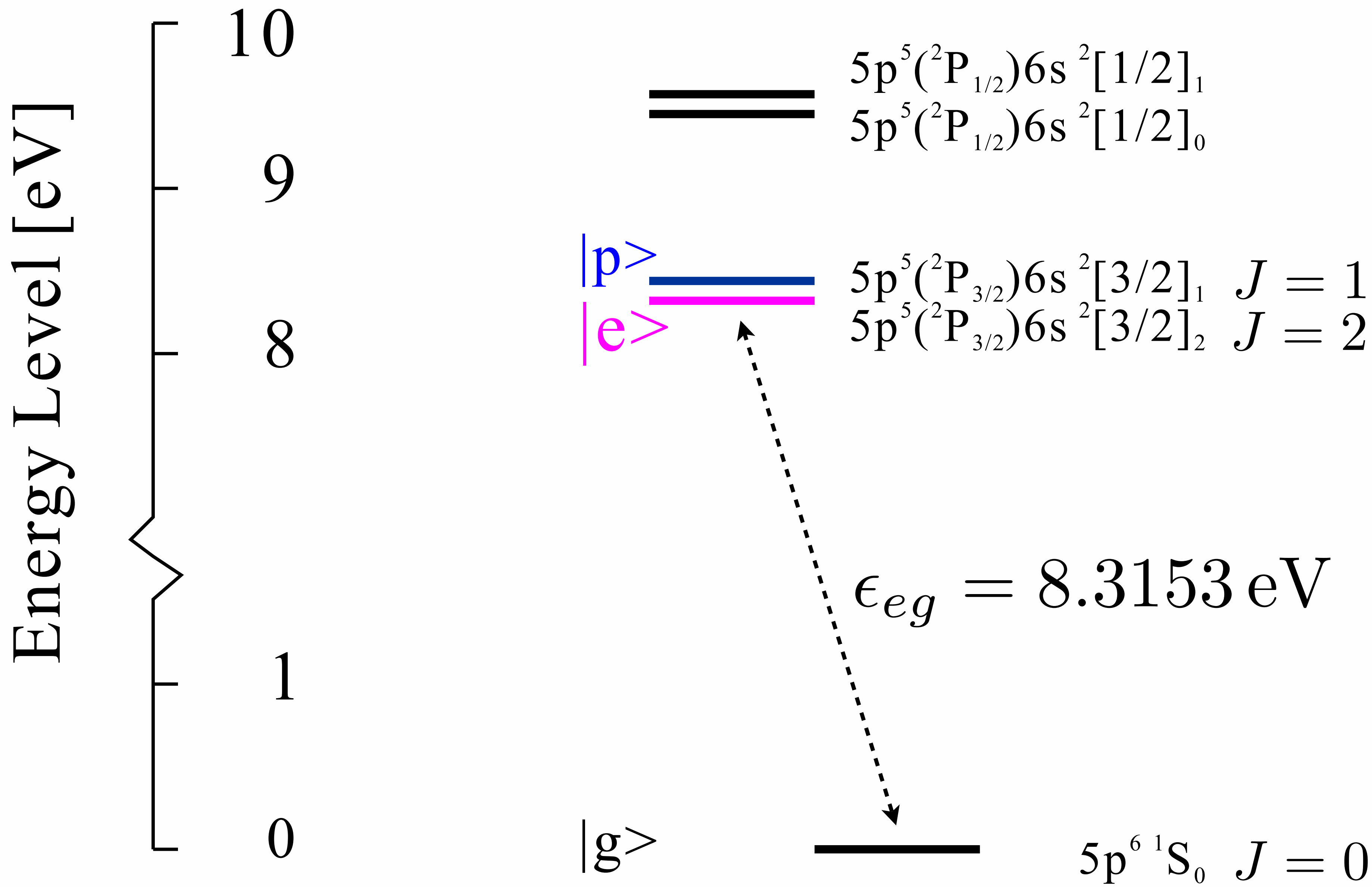
$\epsilon_{eg} = \epsilon_e - \epsilon_g$ atomic energy diff.

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

typical laser linewidth

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

Xe



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

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

macro-coherence

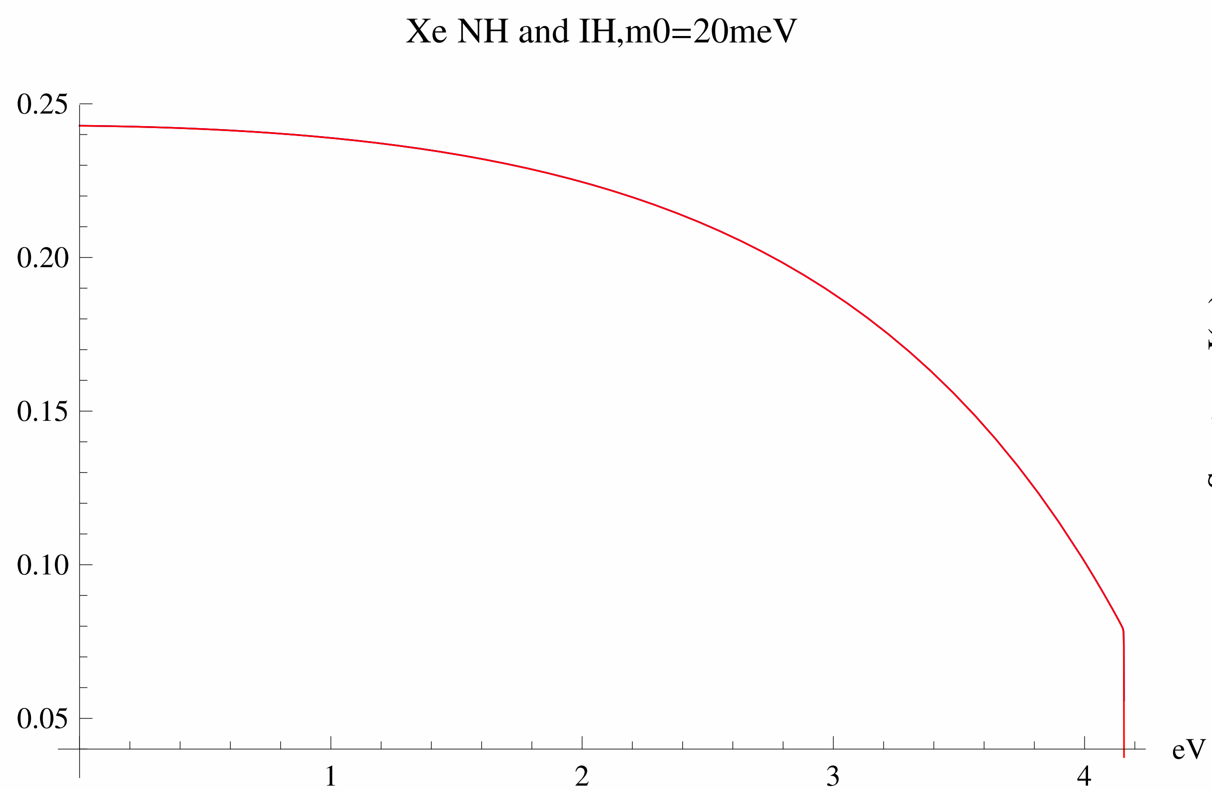
field energy density

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

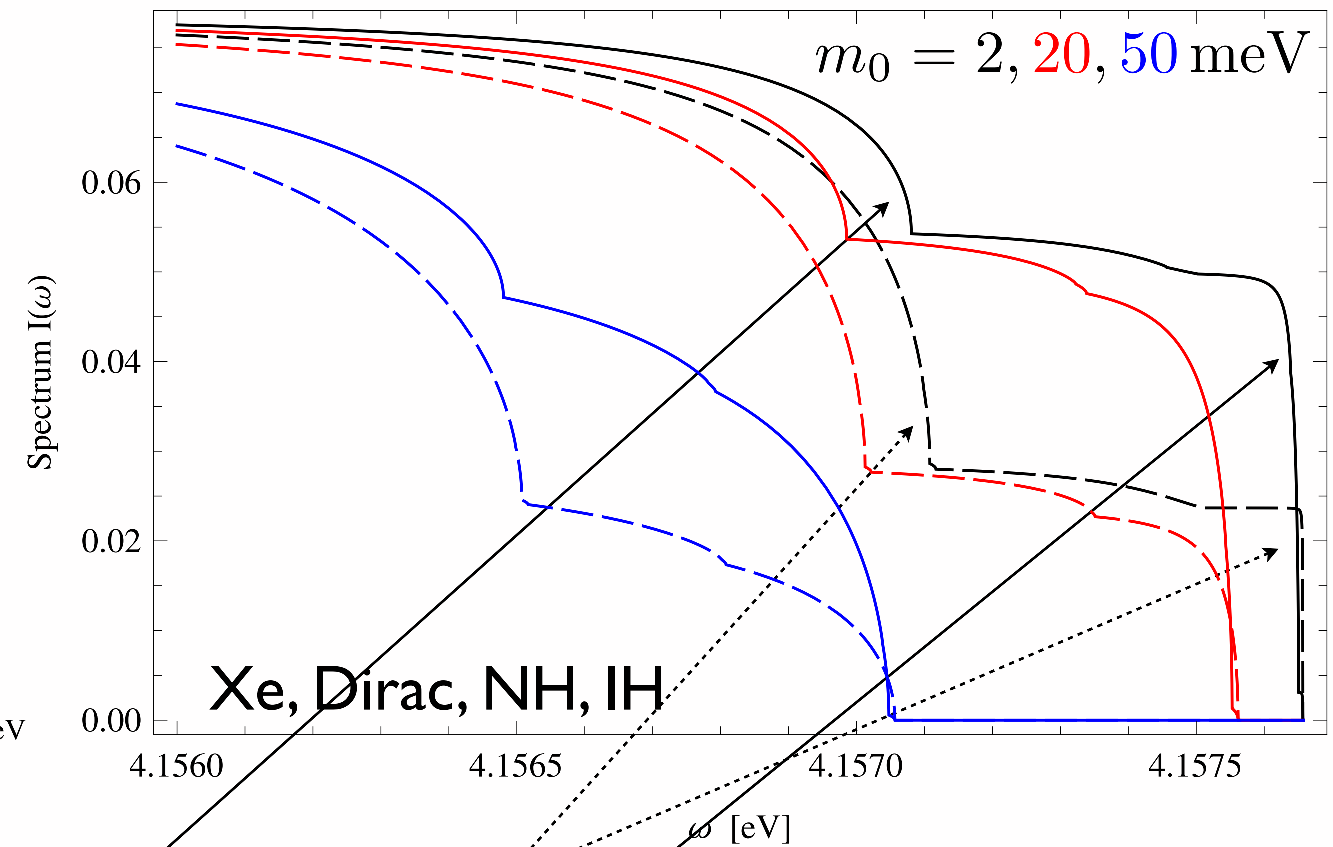
γ_{pg} : $|p\rangle \to |g\rangle$ rate

Photon spectrum (spin current)

Global shape



Threshold region



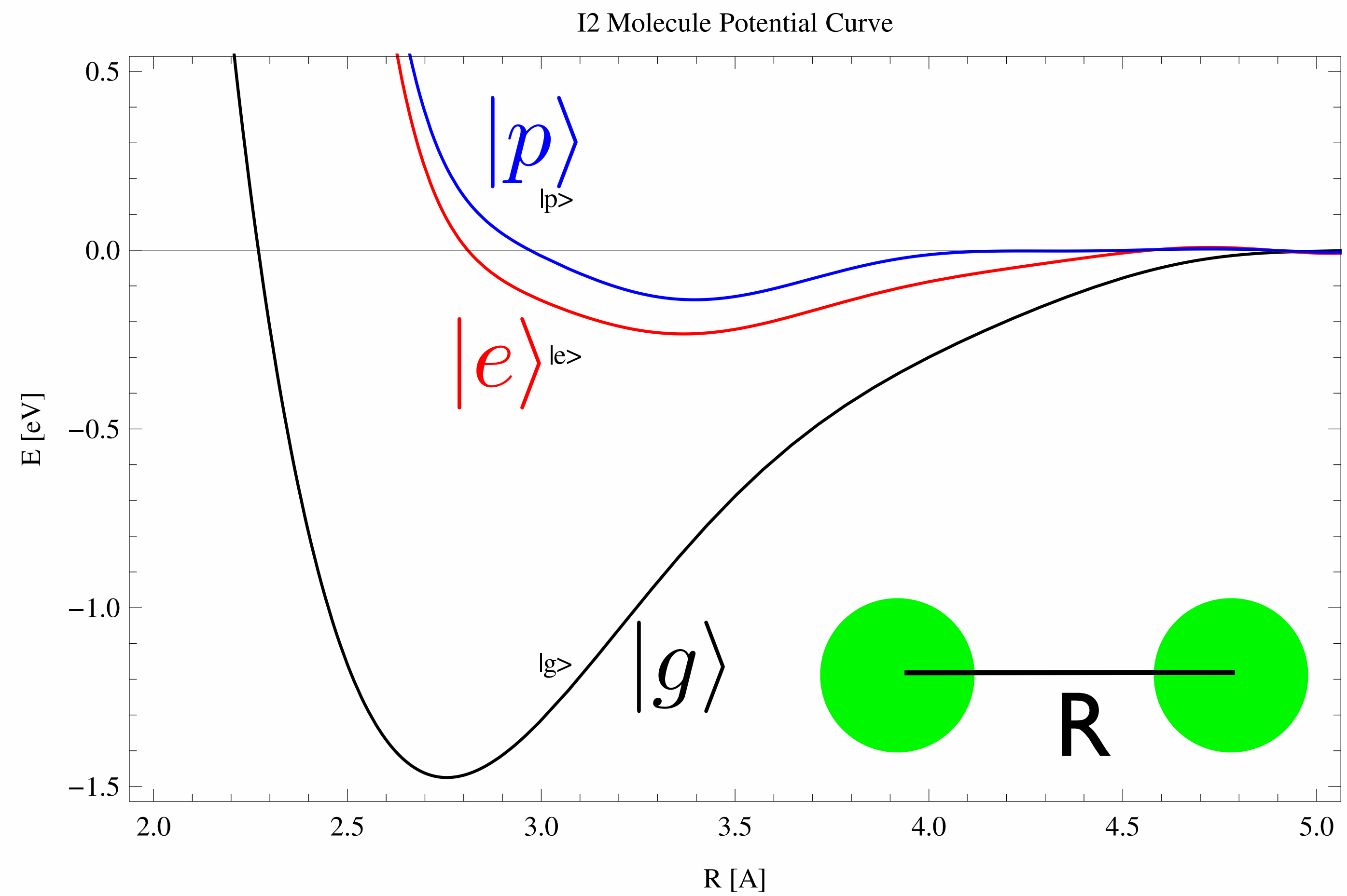
The threshold weight factors

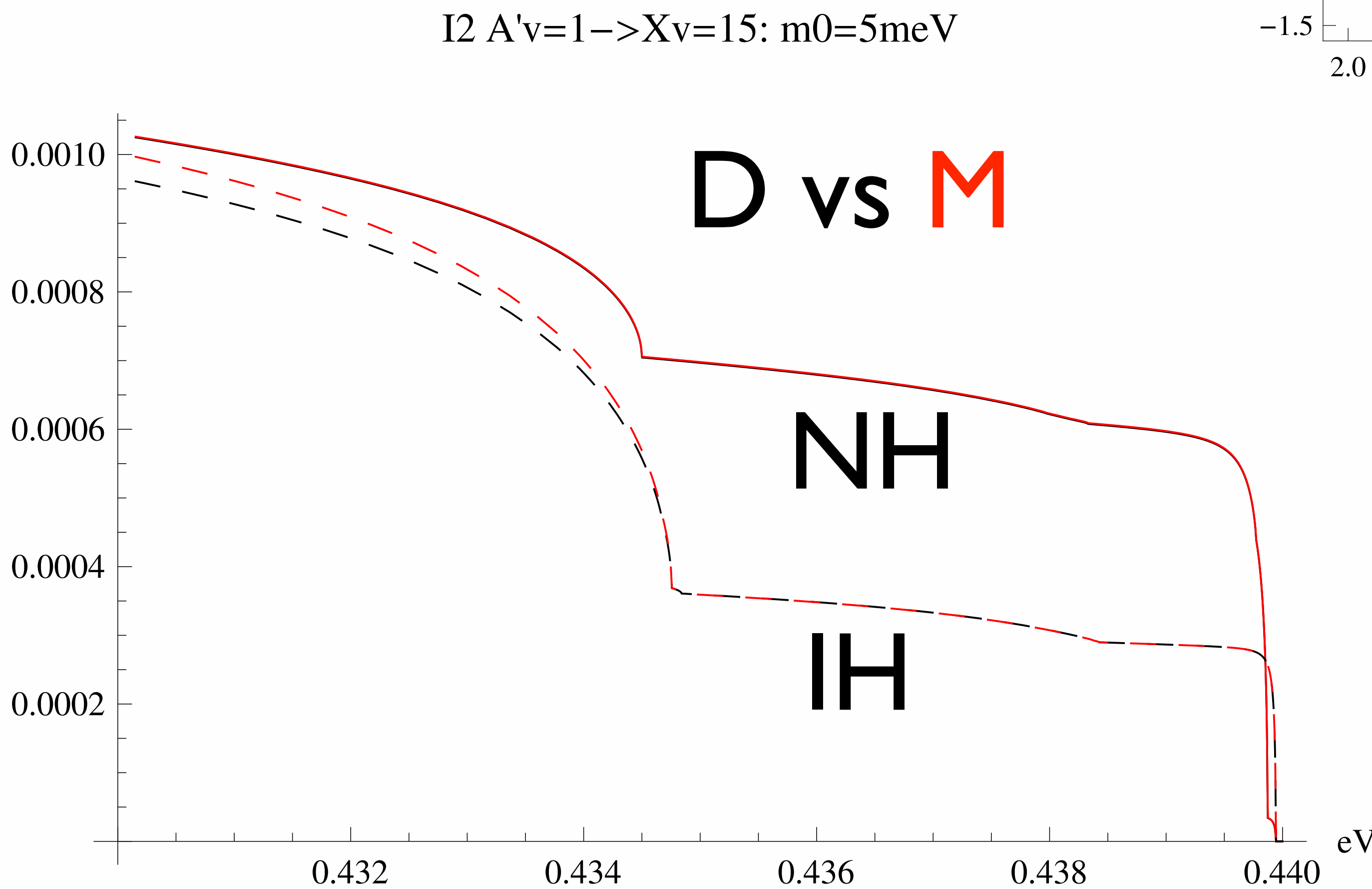
B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{13}^2 - 1/2)^2$	$2c_{12}^2 s_{12}^2 c_{13}^4$	$2s_{12}^2 c_{13}^2 s_{13}^2$	$2c_{12}^2 c_{13}^2 s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

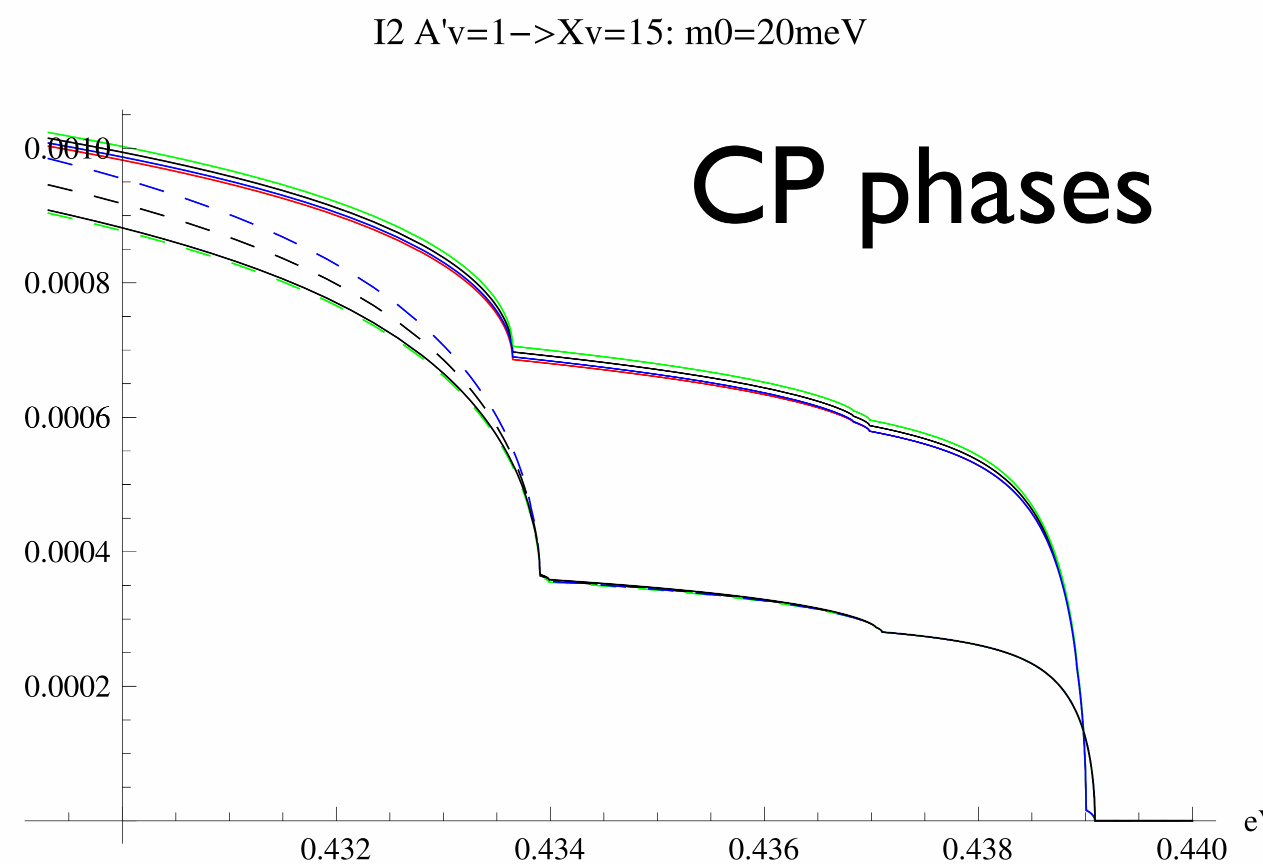
I2 molecule

potential curves

$$\epsilon_{eg} \sim 1\,\mathrm{eV}$$







D-M diff. < 10%

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

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

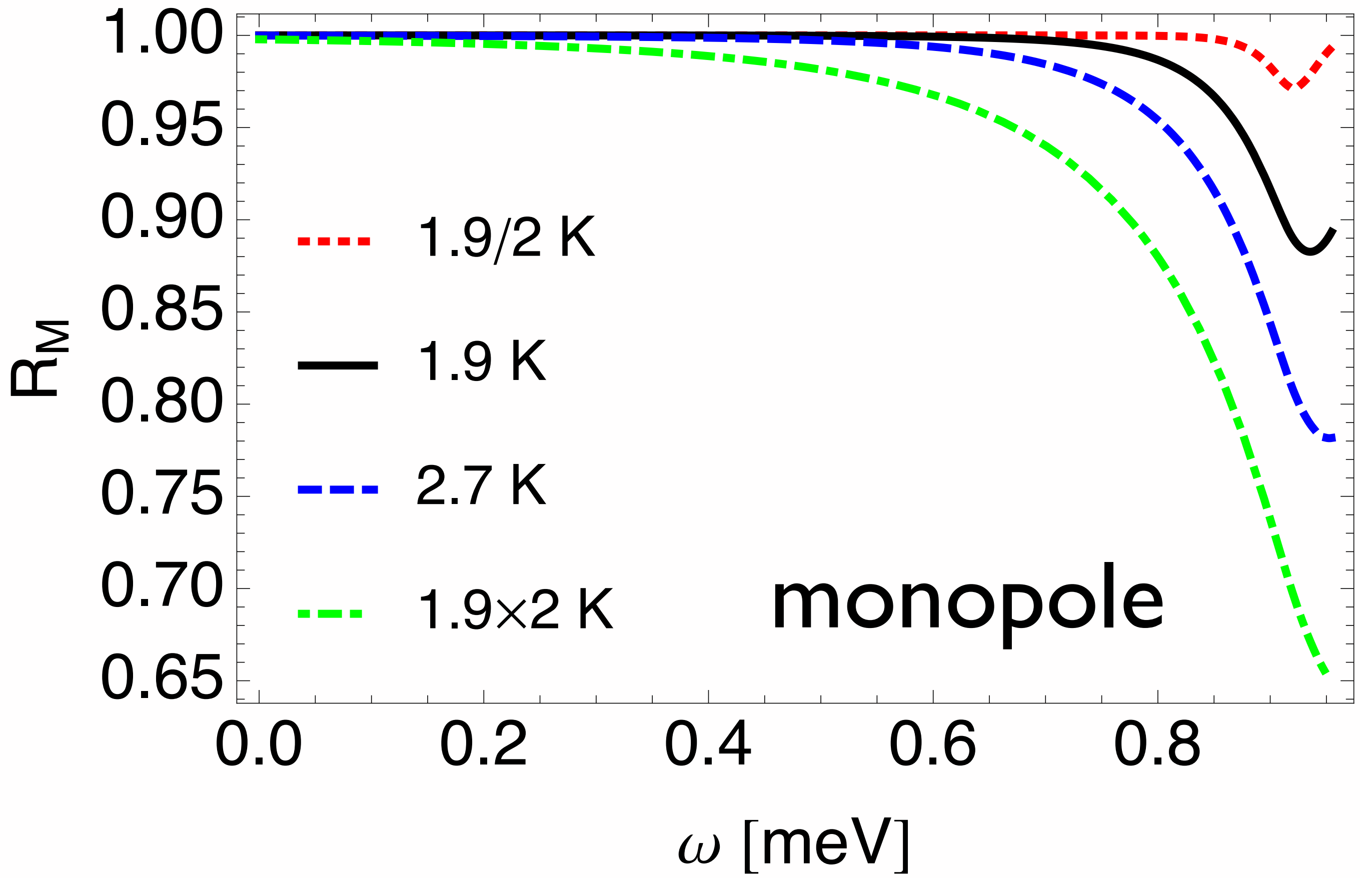
→ spectral distortion

Distortion factor

$$R_X(\omega) \equiv \frac{\Gamma_X(\omega, T_\nu)}{\Gamma_X(\omega, 0)}$$

$$X = \begin{cases} M & \text{nuclear monopole} \\ S & \text{valence } e \text{ spin current} \end{cases}$$

larger rate $i = j$



level splitting

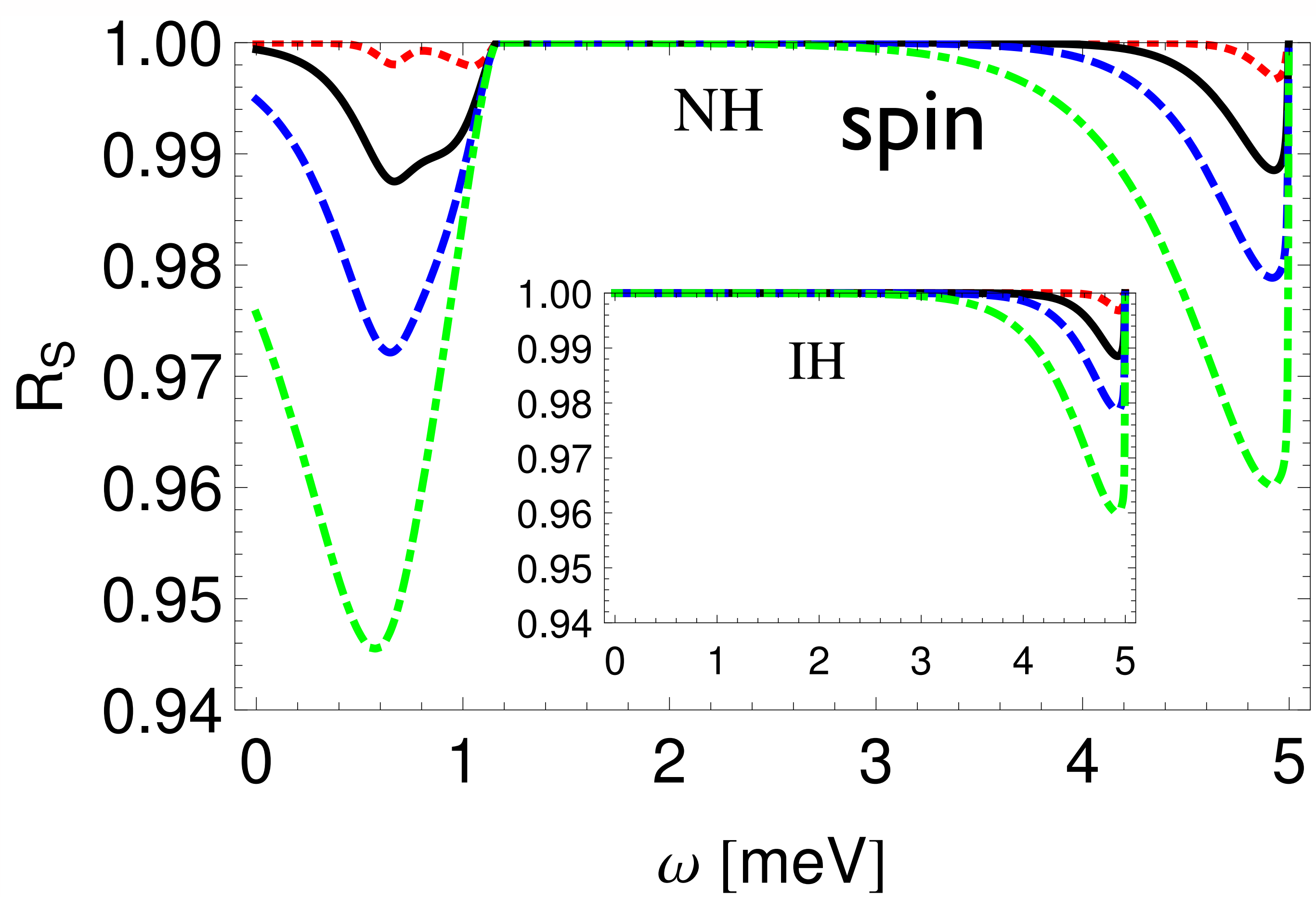
$\epsilon_{eg} = 11$ meV

smallest neutrino mass

$m_0 = 5$ meV

chemical potential

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



$\epsilon_{eg} = 10$ meV

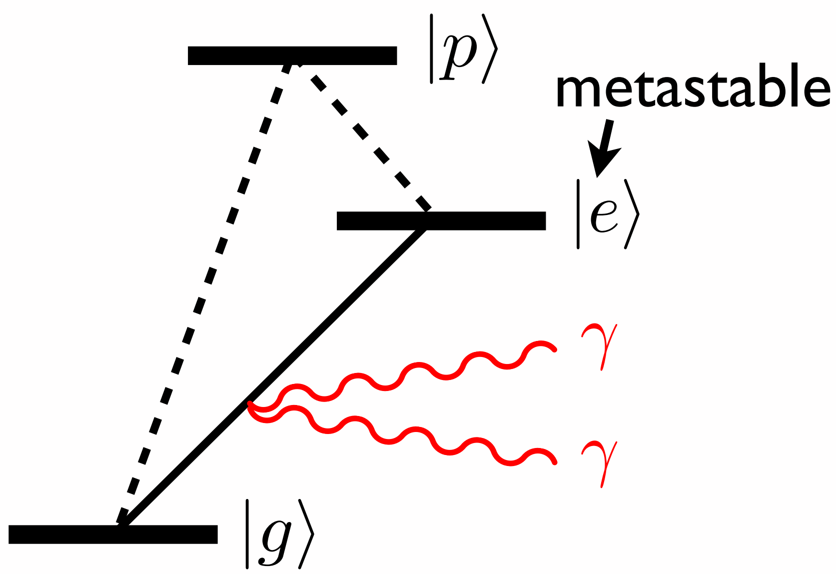
$m_0 = 0.1$ meV

$\xi_i = 0$

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

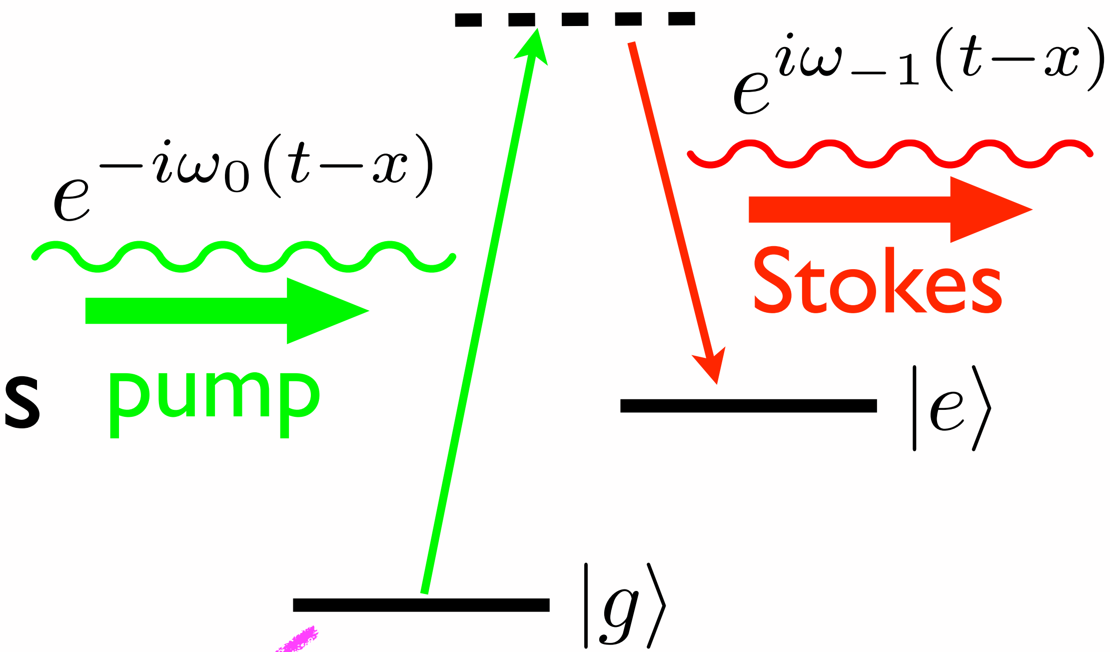
Maxwell-Bloch equation

PSR with spatial gratings

How to populate $|e\rangle$

Stimulated Raman process

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



Generated coherence

spatial grating

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

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

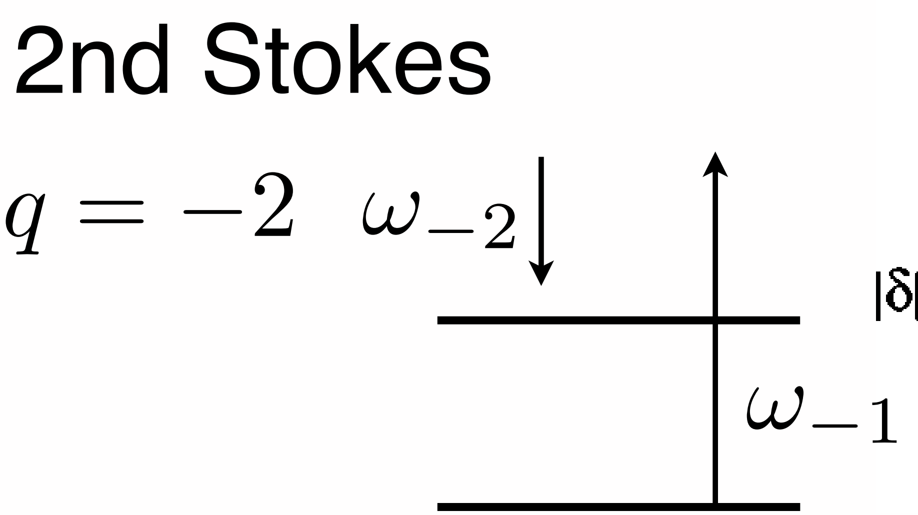
$$\omega_p + \omega_{\bar{p}} = \epsilon_{eg}$$

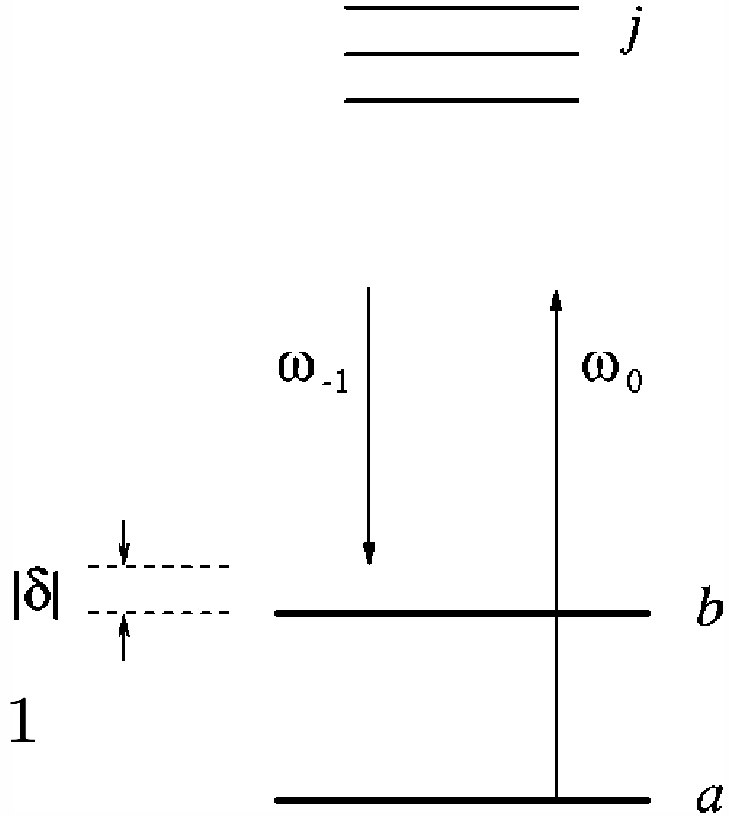
momentum conservation in the macrocoherence → Unidirectional PSR

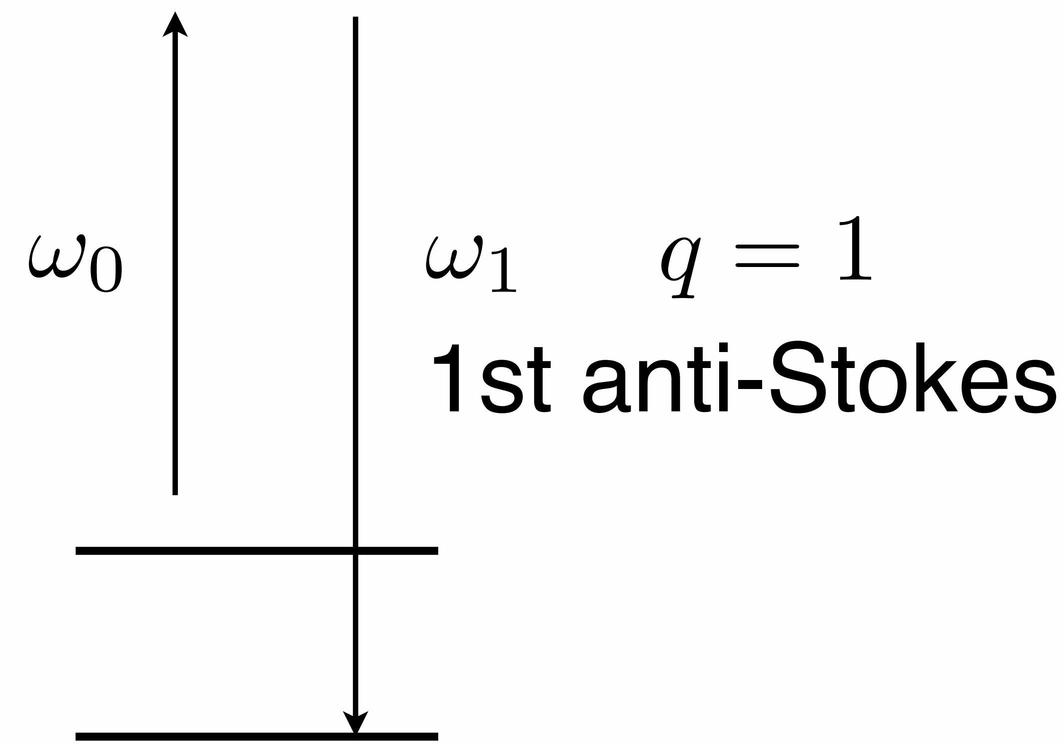
Raman sideband generation

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

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

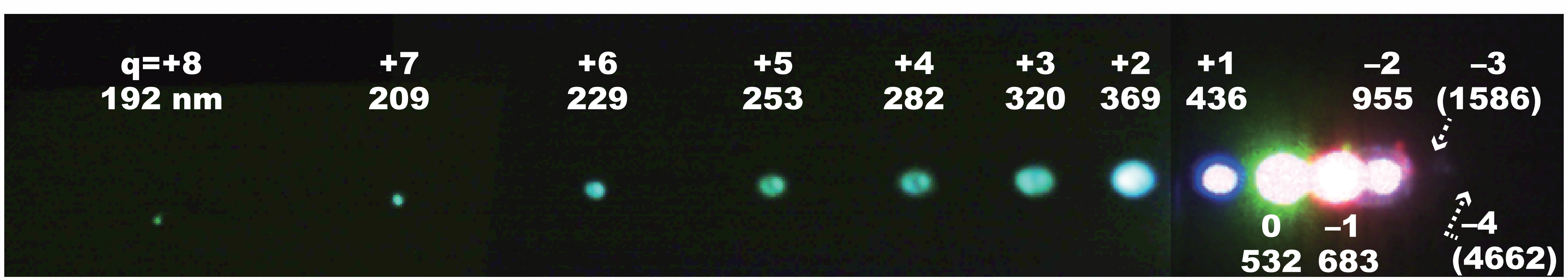






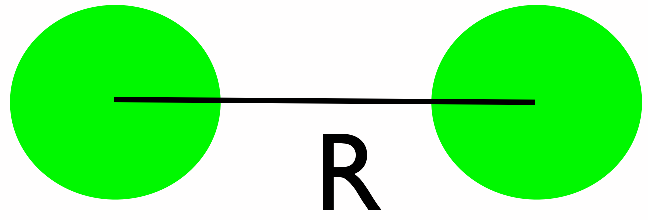
$$\omega_q = \omega_0 + q(\omega_b - \omega_a - \delta) = \omega_0 + q\,\omega_m$$

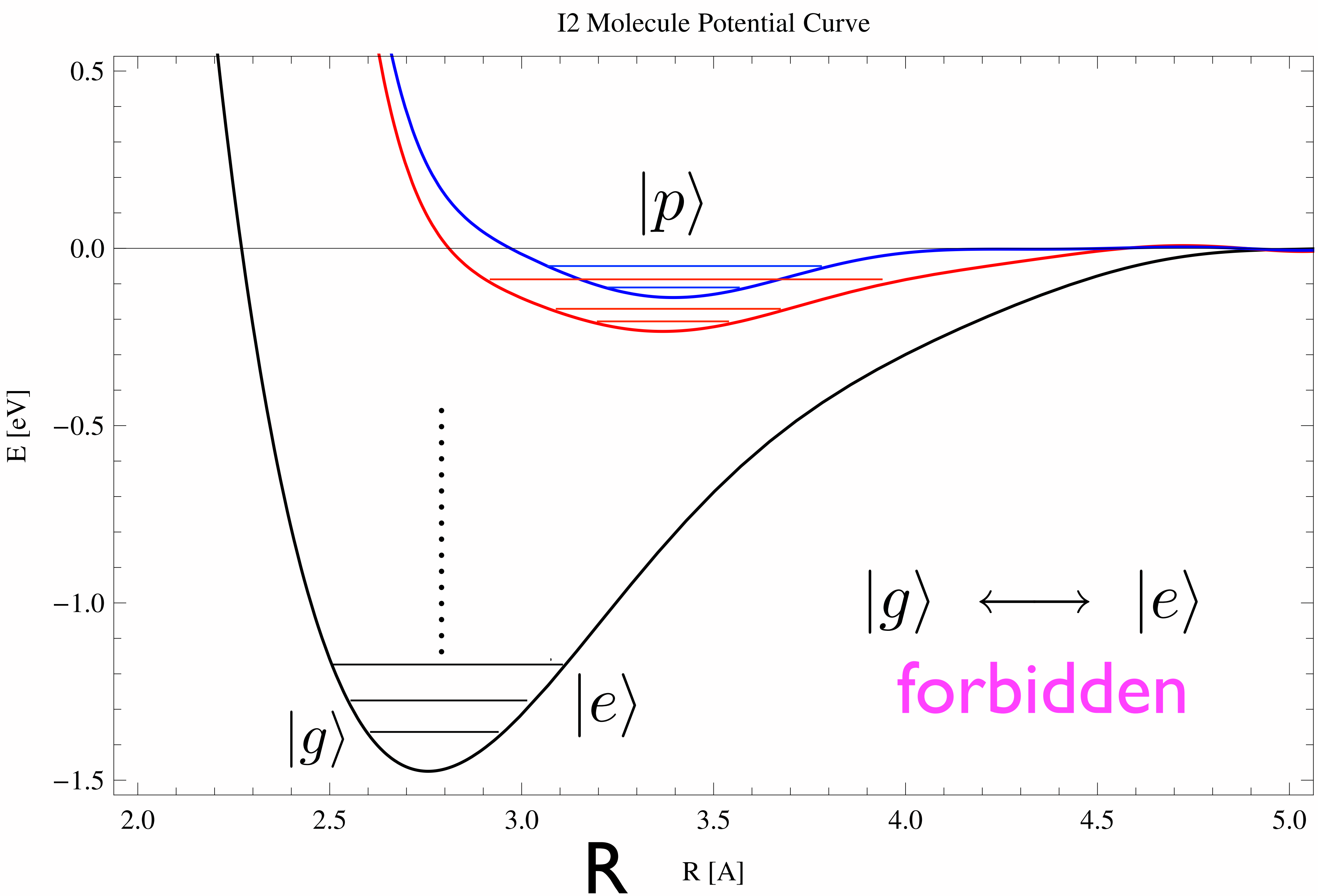
$q \geq q_{\min}$ the lowest Stokes



Homonuclear diatomic molecule

Potential curves





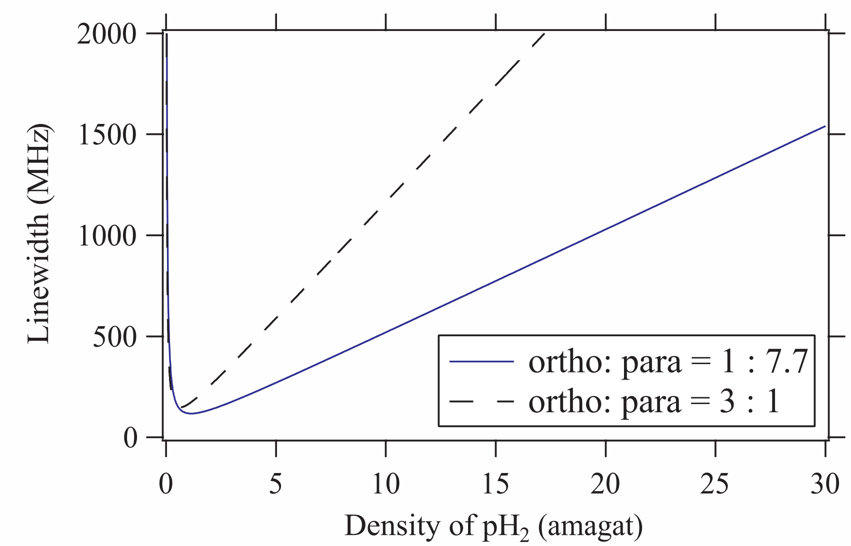
Para-hydrogen gas PSR experiment @ Okayama U

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

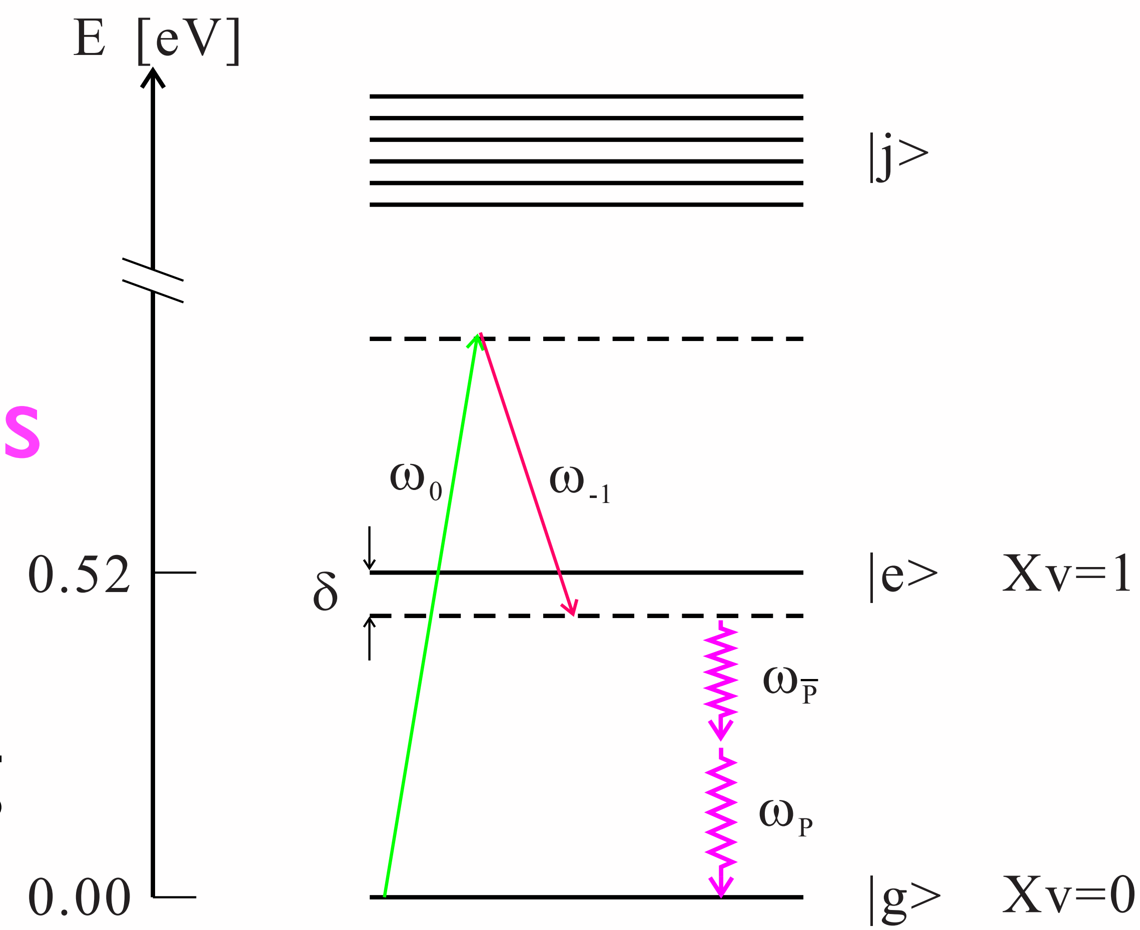
$$1/T_2 \sim 130 \text{ MHz}$$

coherence production

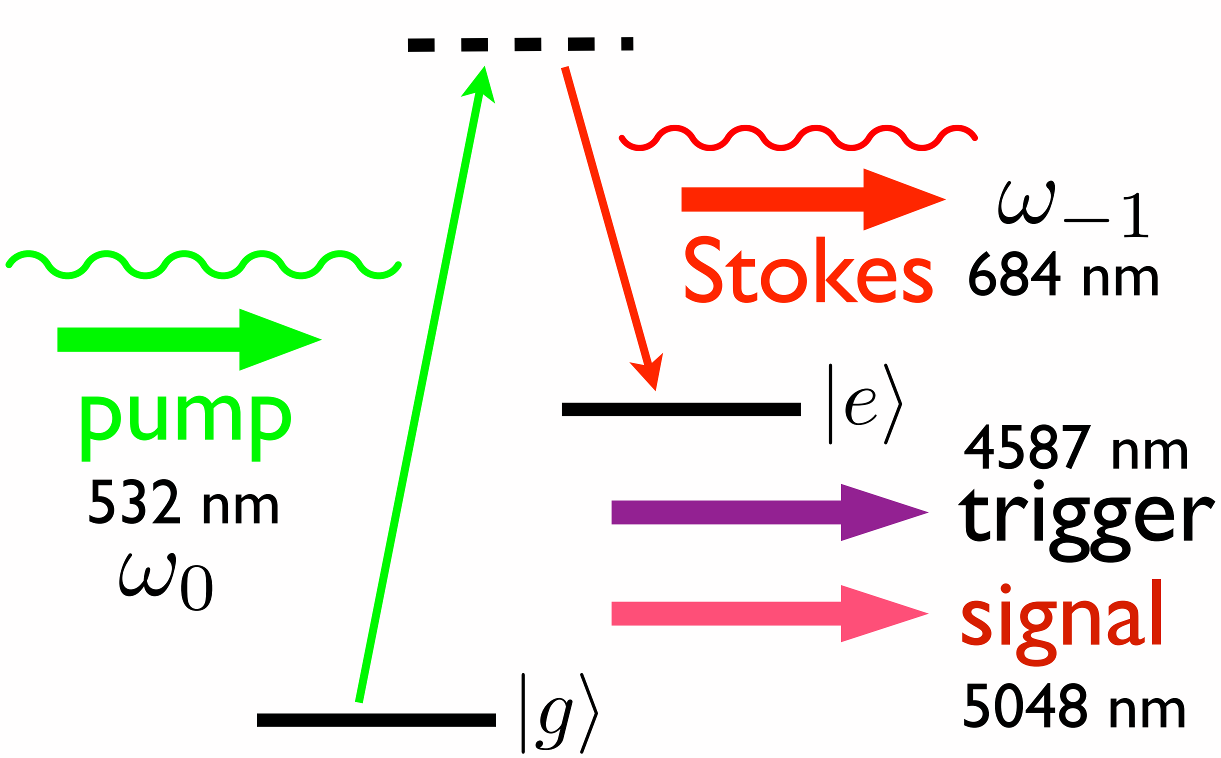
adiabatic Raman process

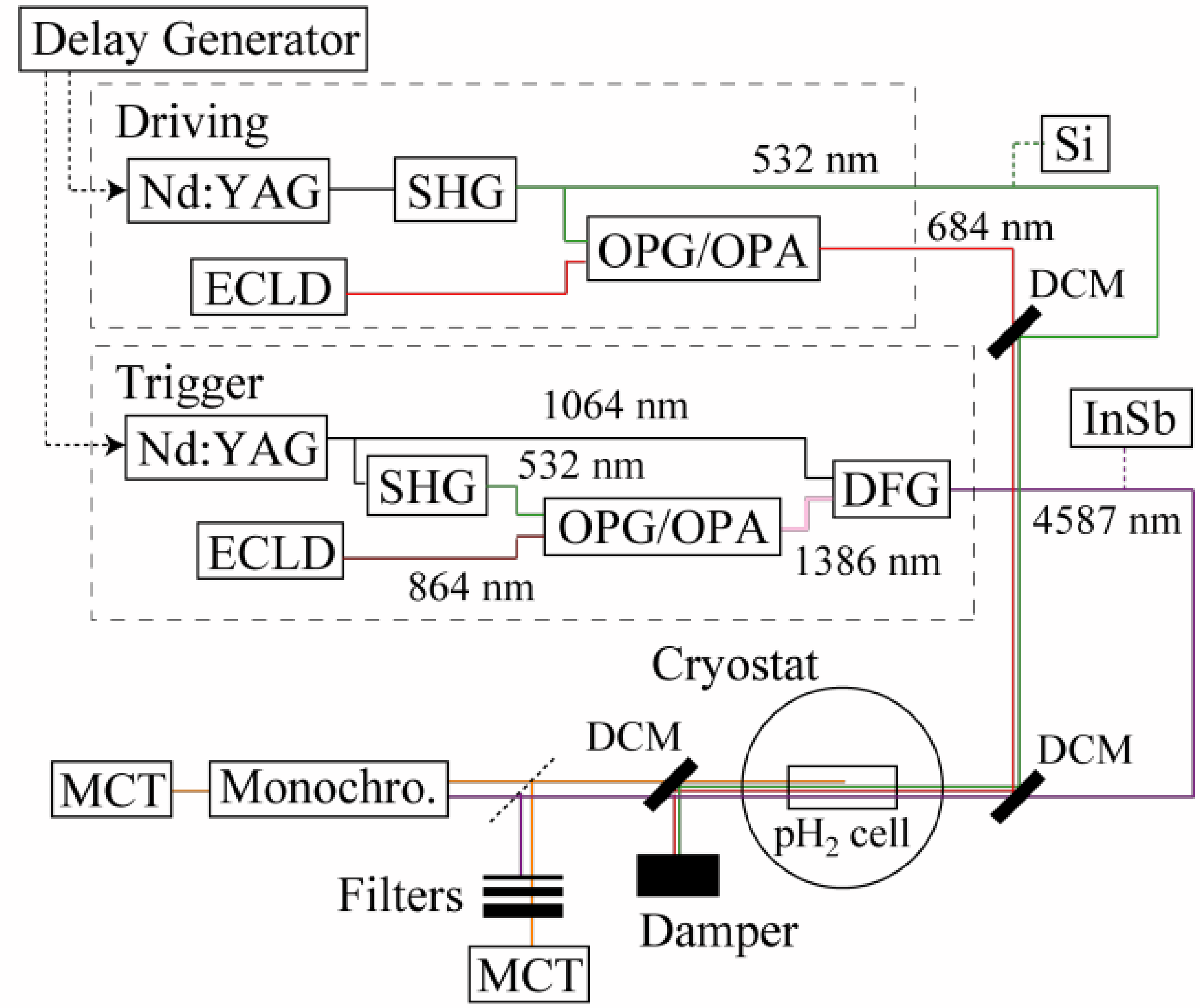
$$\Delta\omega = \omega_0 - \omega_{-1}$$
$$= \epsilon_{eg} - \delta$$
$$= \omega_p + \omega_{\bar{p}}$$

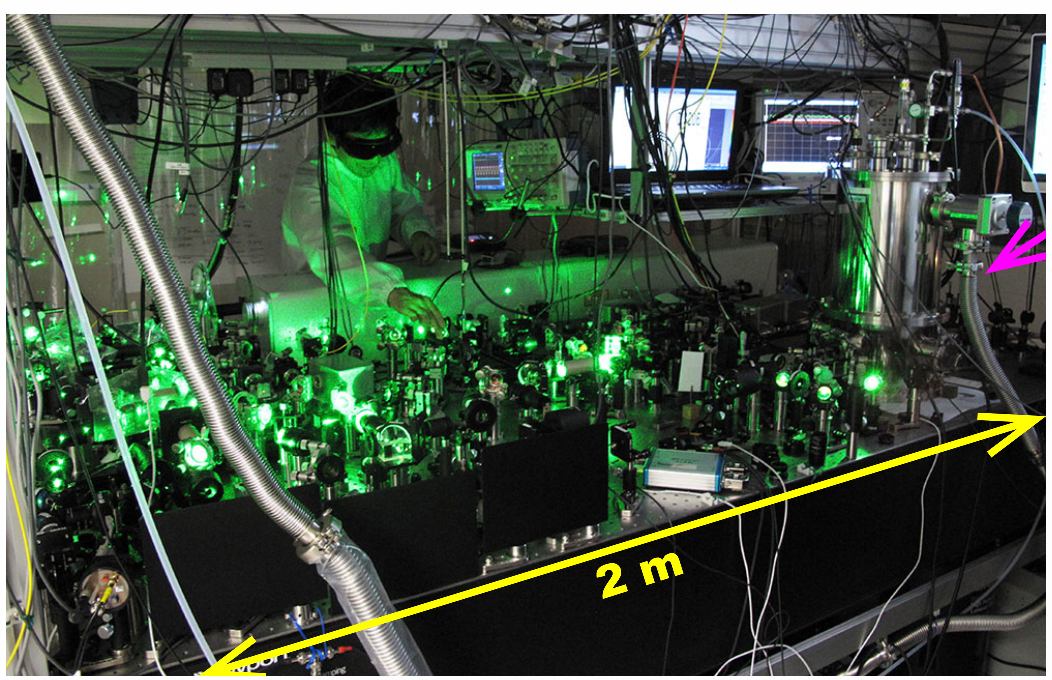
detuning



Experimental setup







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

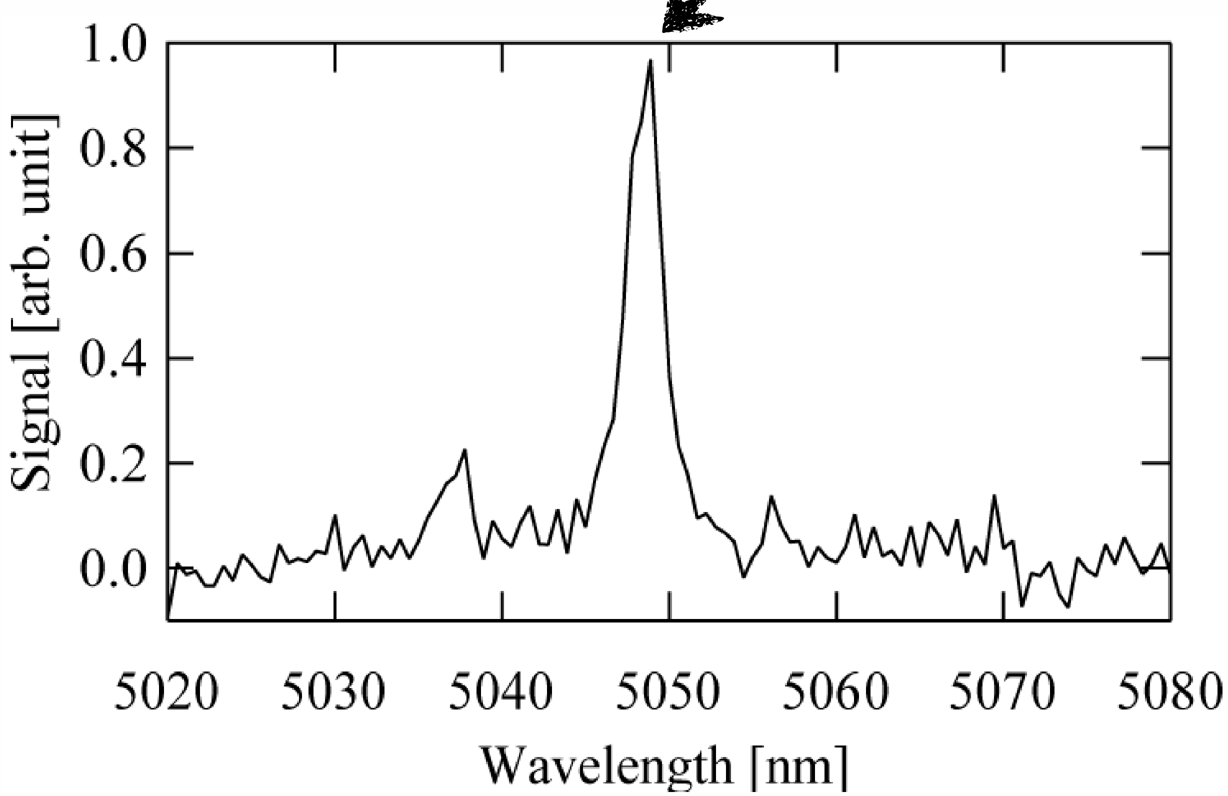
$$150\ \mu\mathrm{J},\ 2\ \mathrm{ns}$$

Results

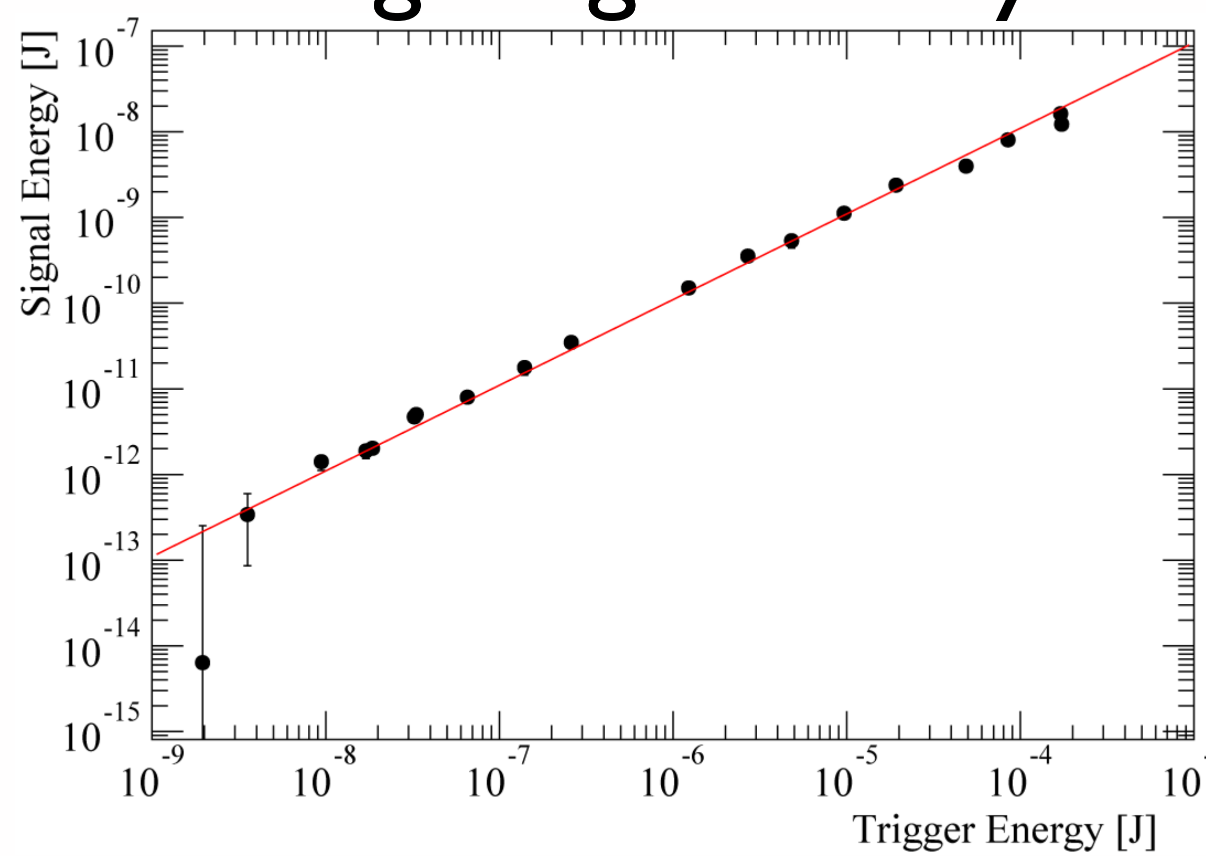
Estimated coherence (from sidebands)

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

5048 nm



sig.-trig. linearity



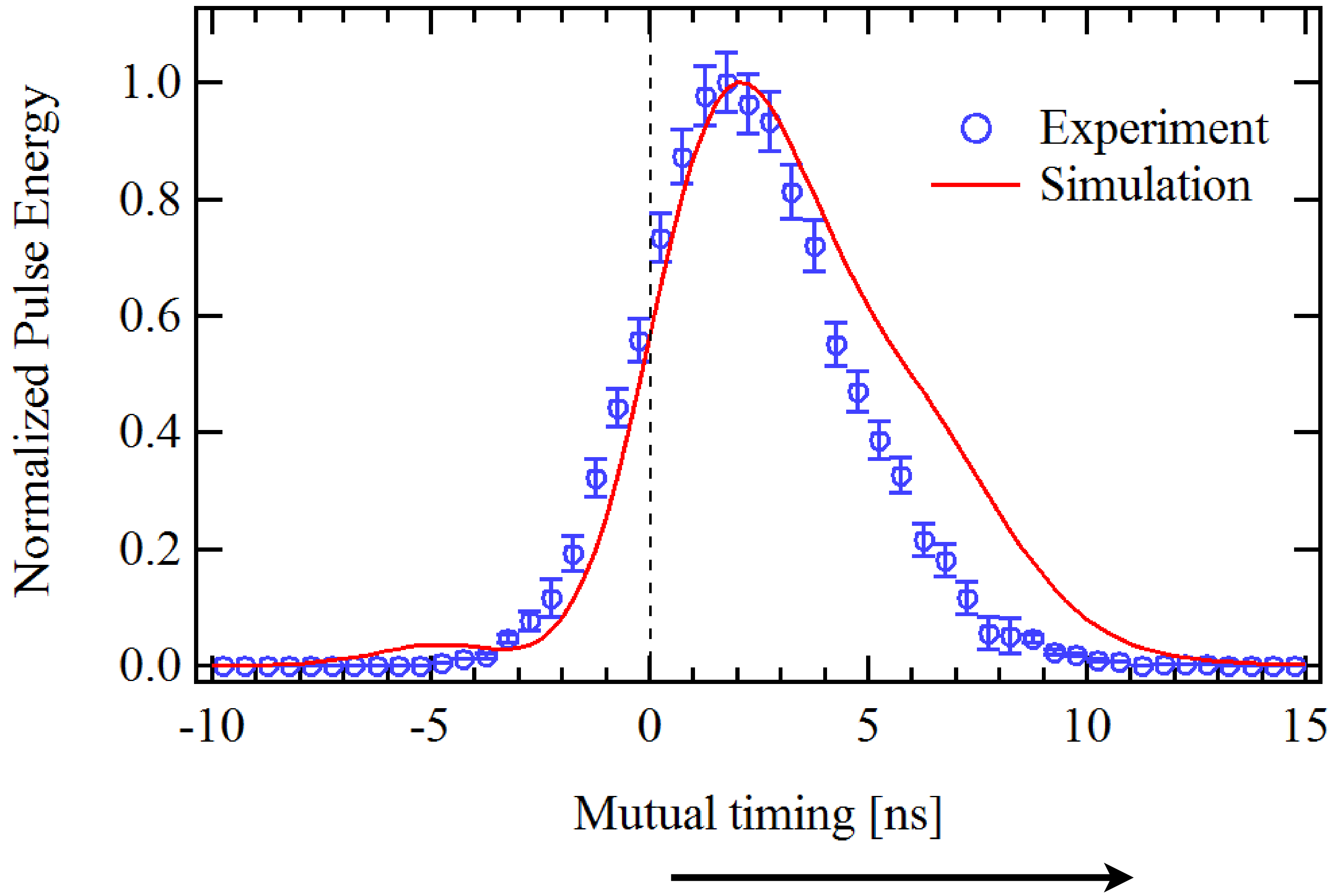
6×10^{11} photons/pulse

→ 10^{18} enhancement

weak field

low coherence

Trigger timing



trigger delay

Delayed coherence development in the target

less adiabatic, decoherence

SUMMARY

Neutrino Physics with Atoms/Molecules

- ✶ RENP spectra are sensitive to unknown neutrino parameters.
  - Absolute mass, Dirac or Majorana, NH or IH, CP
- ✶ RENP spectra are sensitive to the cosmic neutrino background.
- ✶ Macrocoherent rate amplification is essential.
  - Demonstrated by a QED process, PSR.
- ✶ Background-free RENP
  - Waveguide (photonic crystals?)

M. Yoshimura, N. Sasao, M. T.
PTEP (2015) 053B06, arXiv:15010571

A new approach to neutrino physics