Physics
OSAKA UNIVERSITY

# Neutrino Physics with Atomic/Molecular Processes


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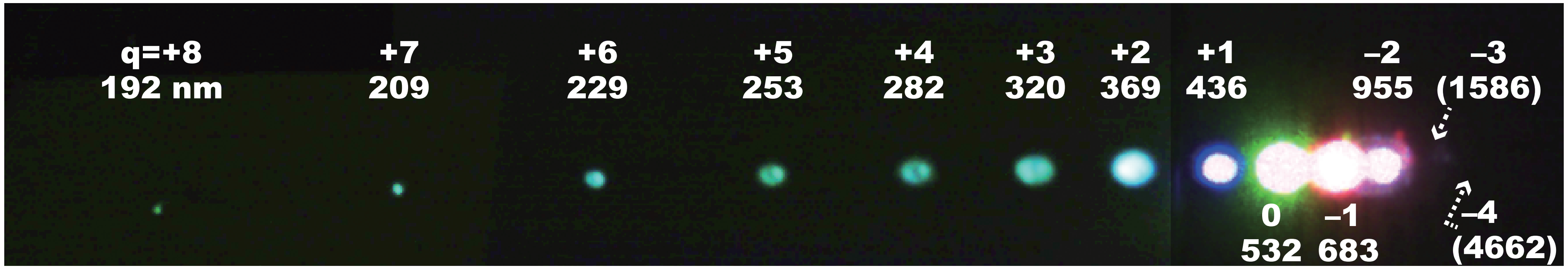


"Beyond the Standard Model in Okinawa"@OIST, Mar. 4, 2016

# 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),
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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

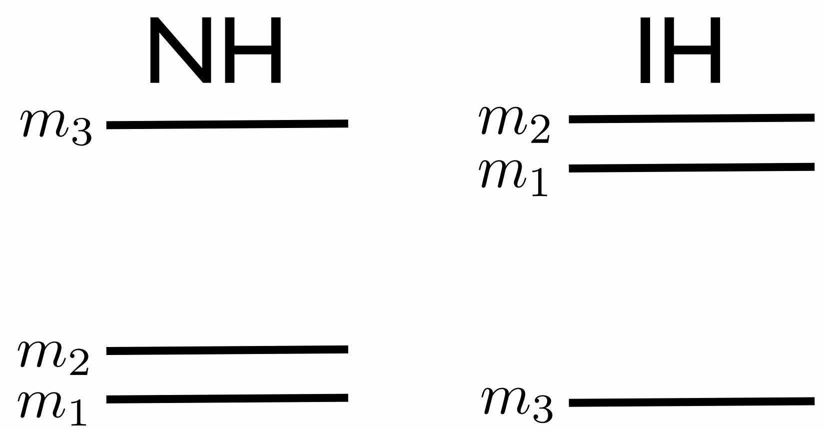
$$m_{1(3)} < 71(66)\ \mathrm{meV},\ \ 50\ \mathrm{meV} < m_{3(2)} < 87(82)\ \mathrm{meV}$$

## Mass type

Dirac or Majorana

## Hierarchy pattern

normal or inverted




## CP violation

one Dirac phase, two Majorana phases

$\delta$ $\alpha,\ \beta$

# Neutrino experiments

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

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

$\Delta m^2, \ \theta_{ij},$ NH or IH, $\delta$

Neutrinoless double beta decays

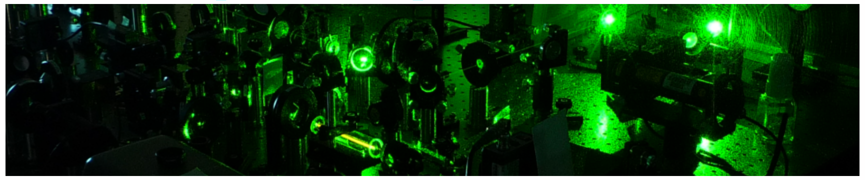
Dirac or Majorana, effective mass $\left|\sum_i m_i U_{ei}^2\right|^2$

Beta decay endpoint: KATRIN

absolute mass

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

Atomic/molecular processes



absolute mass, NH or IH, D or M, $\delta, \ \alpha, \ \beta$

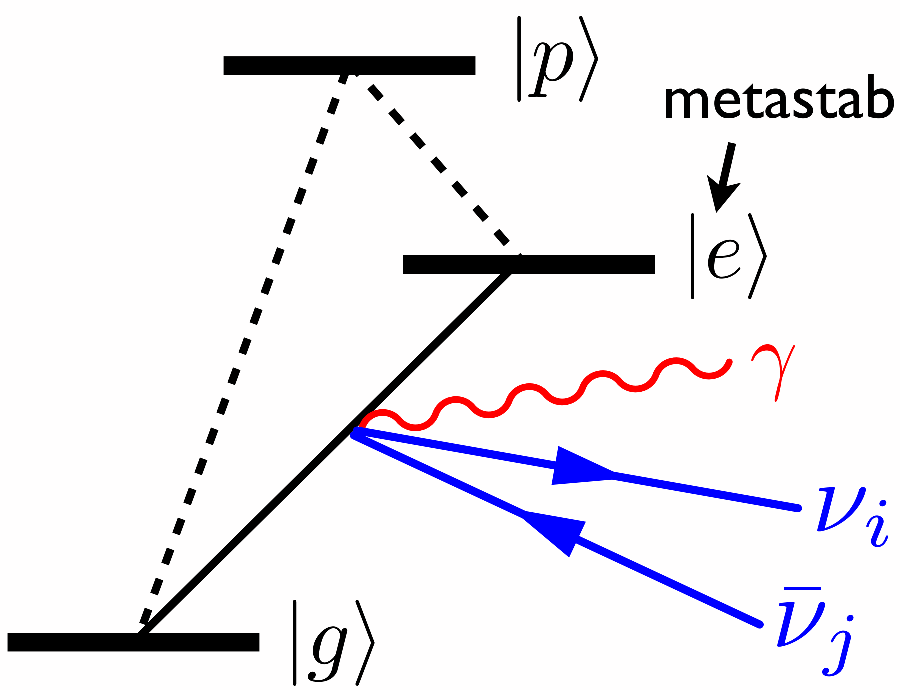
# Plan of talk

- Introduction
- Radiative Emission of Neutrino Pair (RENP)
- Paired Super-Radiance (PSR) Experiment
- Summary

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

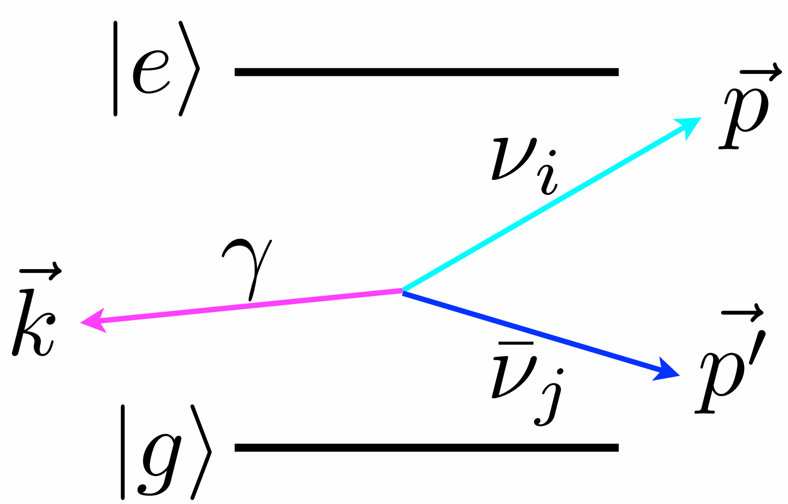
$\xrightarrow{\text{deexcitation}}$ $[|g\rangle(|g\rangle + |e\rangle) \cdots (|g\rangle + |e\rangle)$

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

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

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

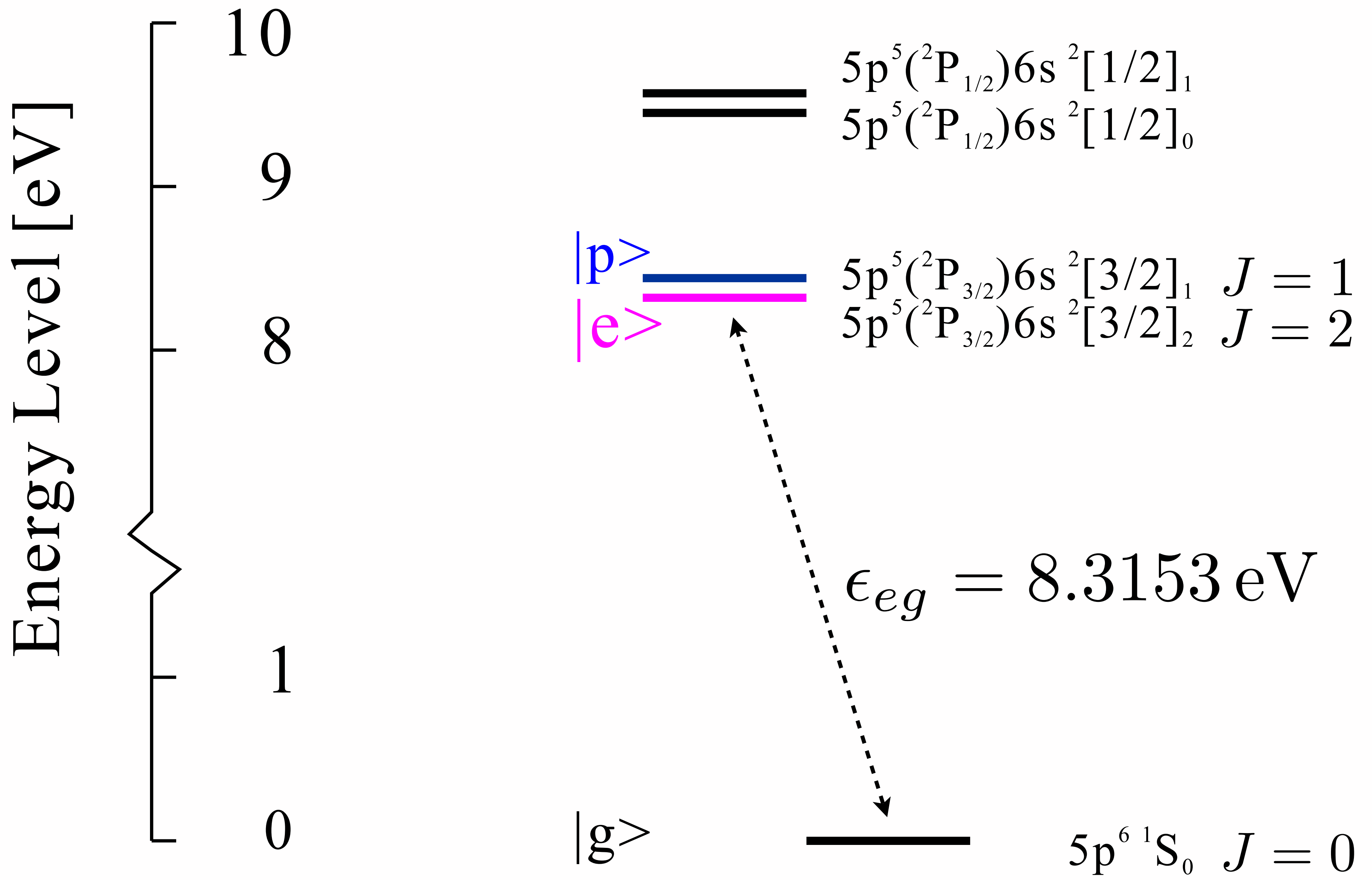
$\epsilon_{eg} = \epsilon_e - \epsilon_g$ atomic energy level splitting

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

macrocoherence

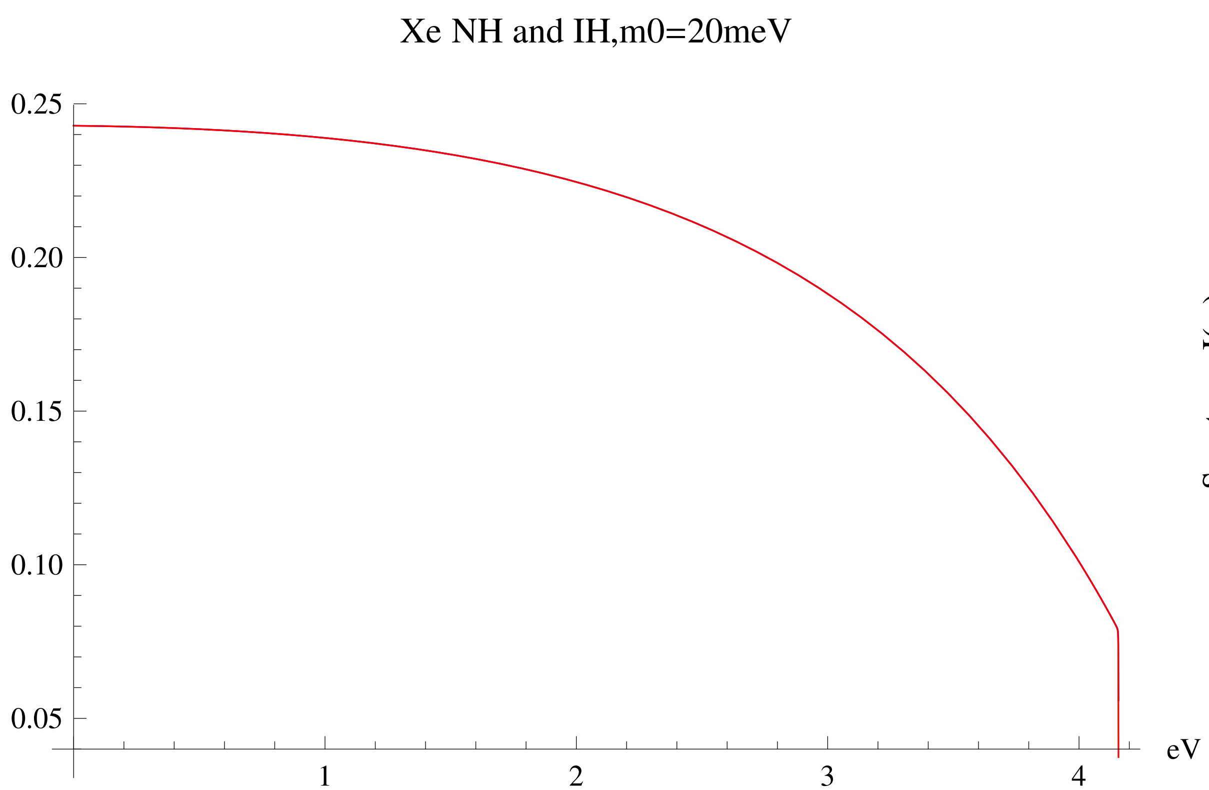
field energy density

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

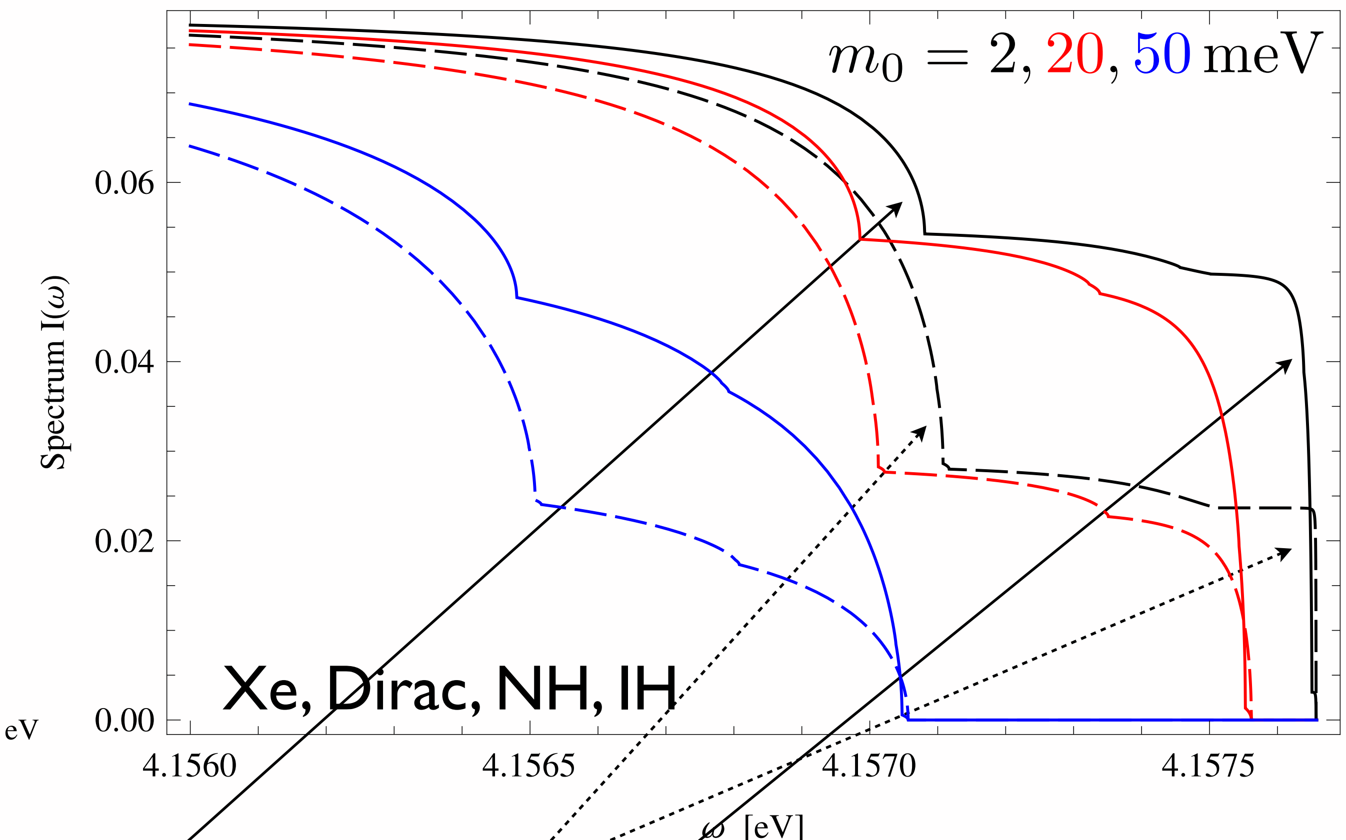
$\gamma_{pg}$ : $|p\rangle \to |g\rangle$ rate

# Photon spectrum (spin current)

## Global shape




## Threshold region



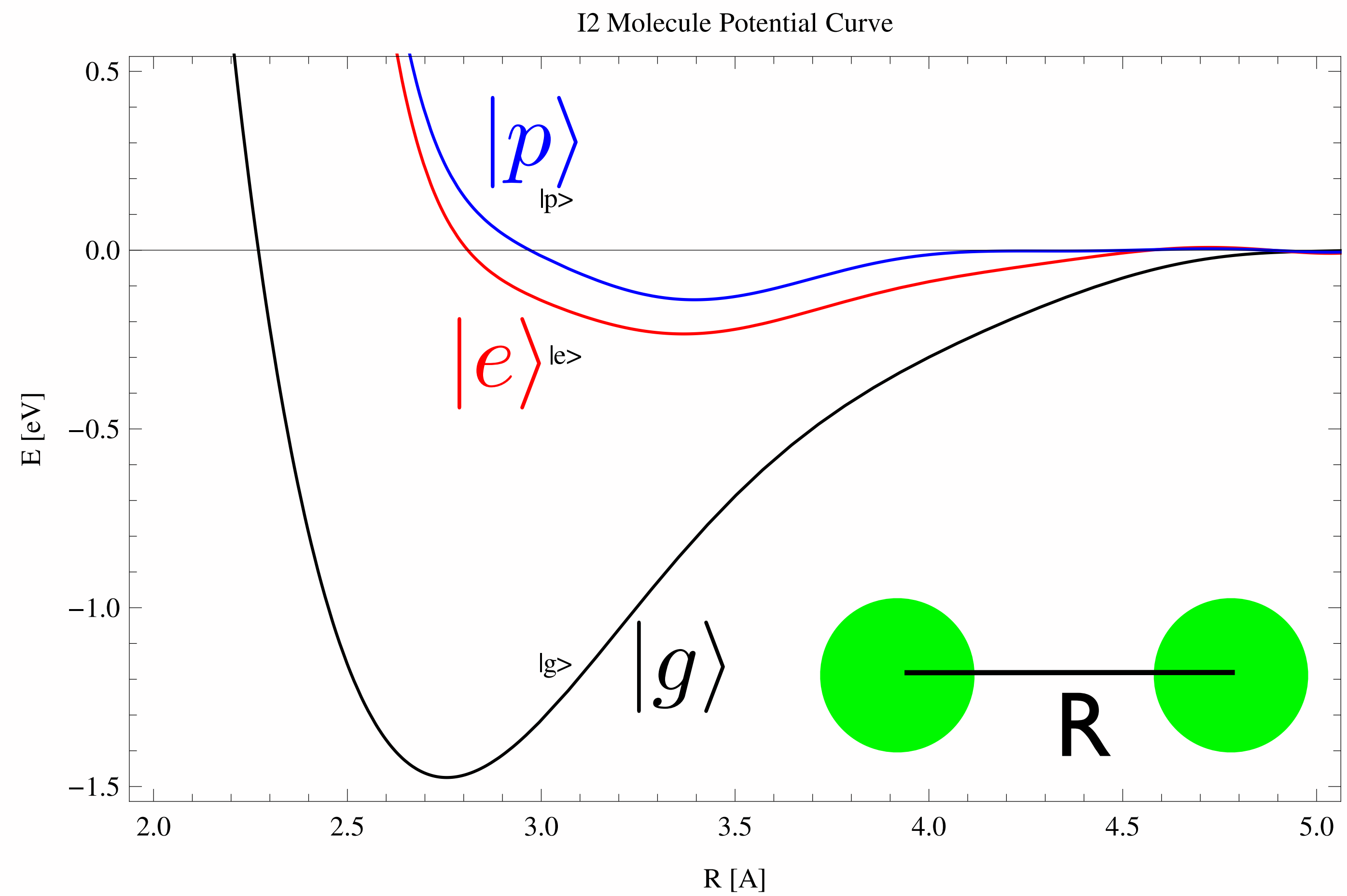

## The threshold weight factors

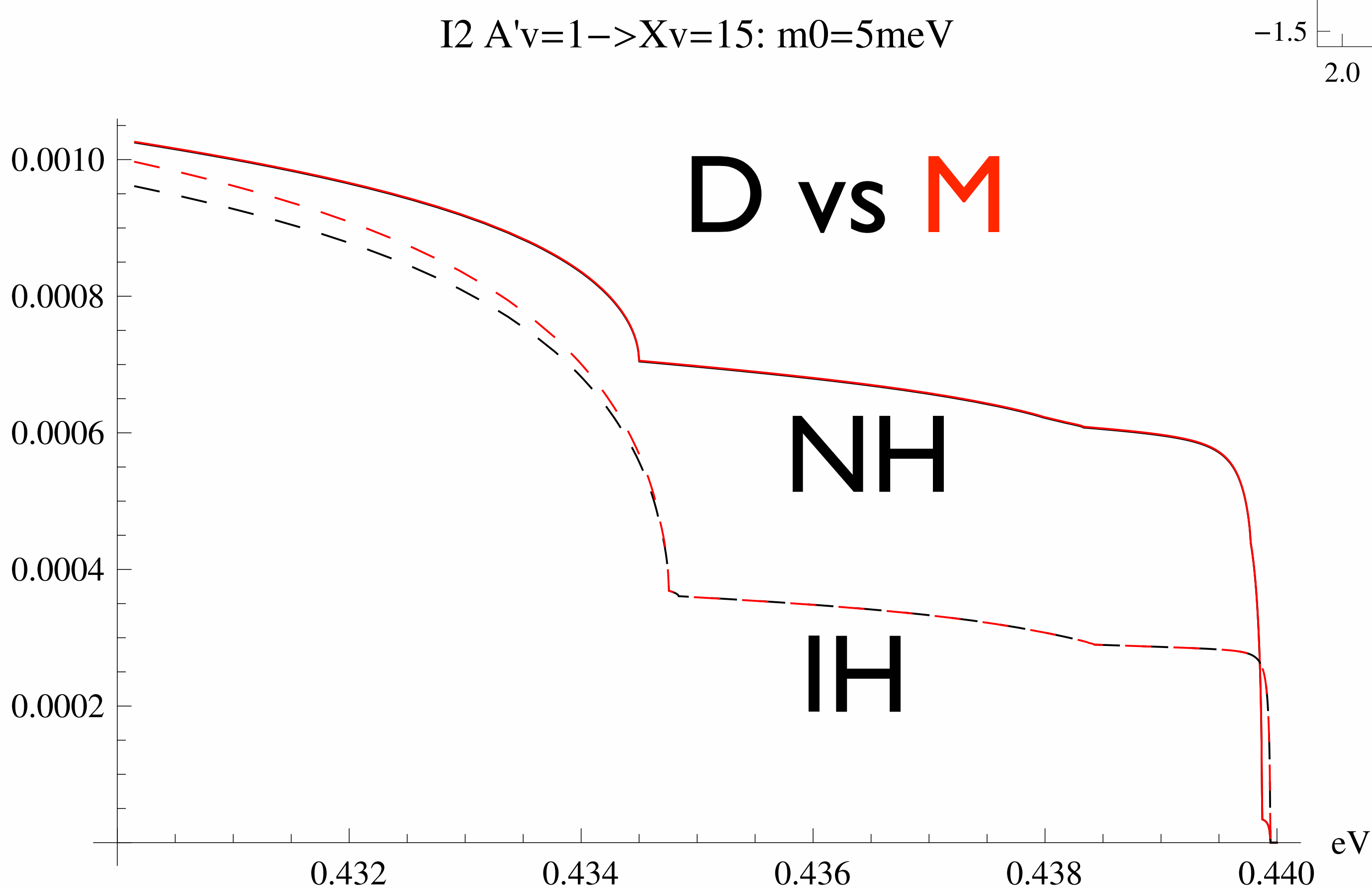
| $B_{11}$ | $B_{22}$ | $B_{33}$ | $B_{12}+B_{21}$ | $B_{23}+B_{32}$ | $B_{31}+B_{13}$ |
|---|---|---|---|---|---|
| $(c_{12}^2 c_{13}^2 - 1/2)^2$ | $(s_{12}^2 c_{13}^2 - 1/2)^2$ | $(s_{13}^2 - 1/2)^2$ | $2c_{12}^2 s_{12}^2 c_{13}^4$ | $2s_{12}^2 c_{13}^2 s_{13}^2$ | $2c_{12}^2 c_{13}^2 s_{13}^2$ |
|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

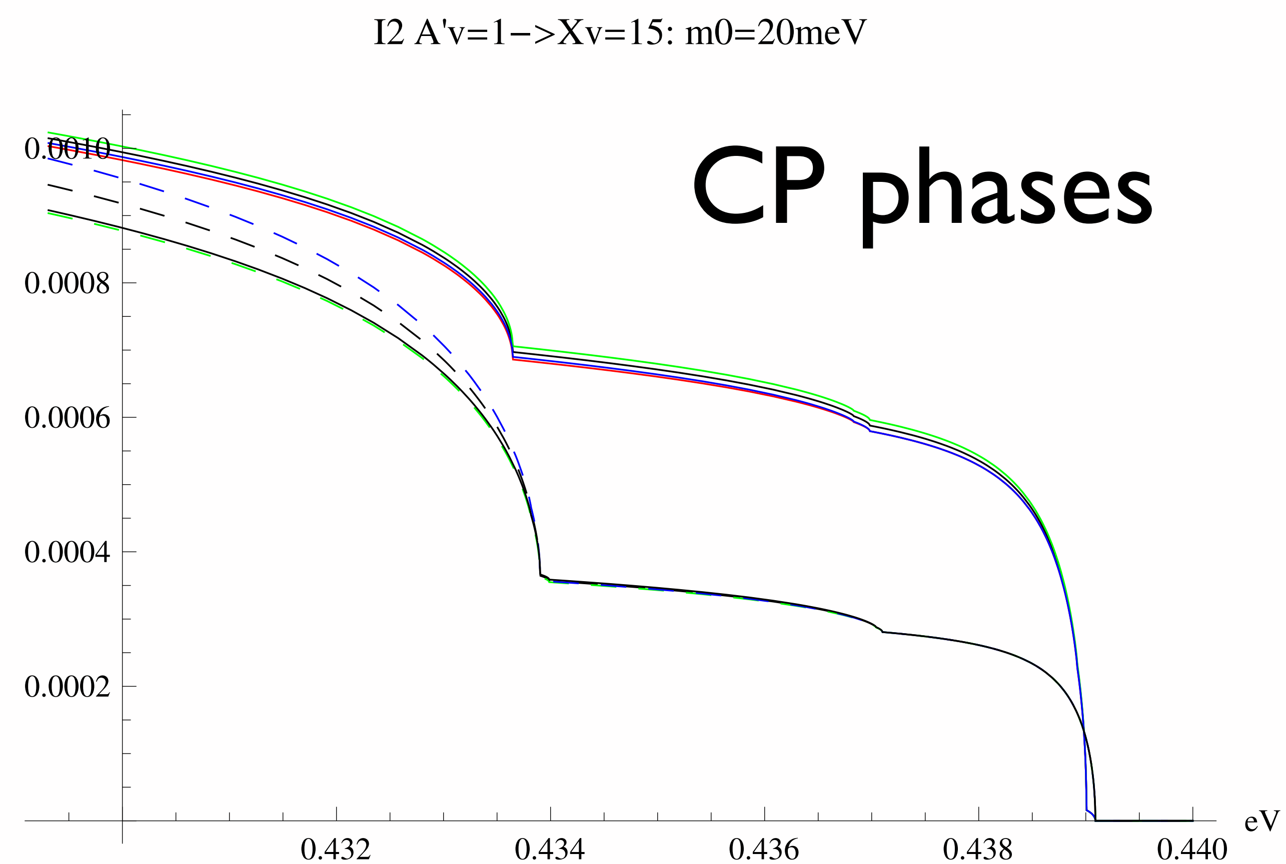
# $I_2$ molecule

## potential curves

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



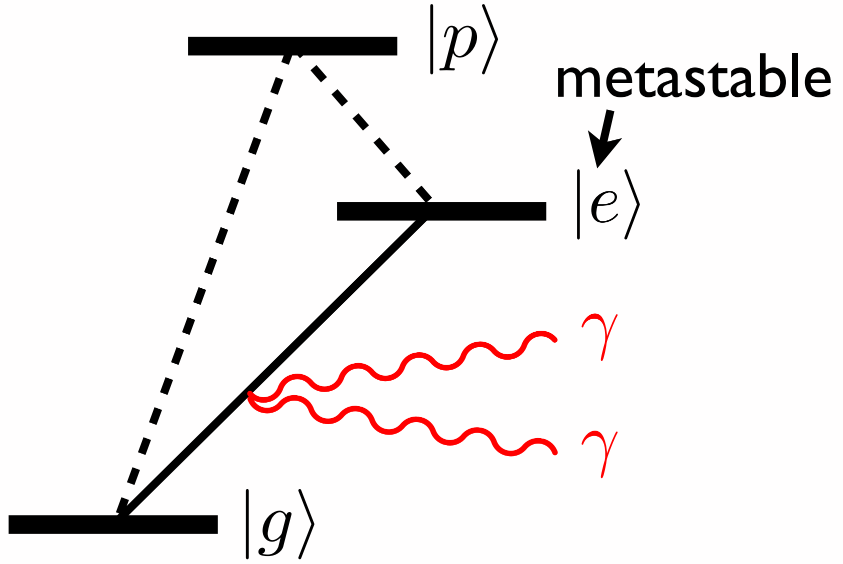

D-M diff. < 10%

# PSR EXPERIMENT

# 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 $\rho_{eg}$

dynamical factor $\eta_\omega(t)$

Theoretical description to be tested

Maxwell-Bloch equation

# Para-hydrogen gas PSR experiment

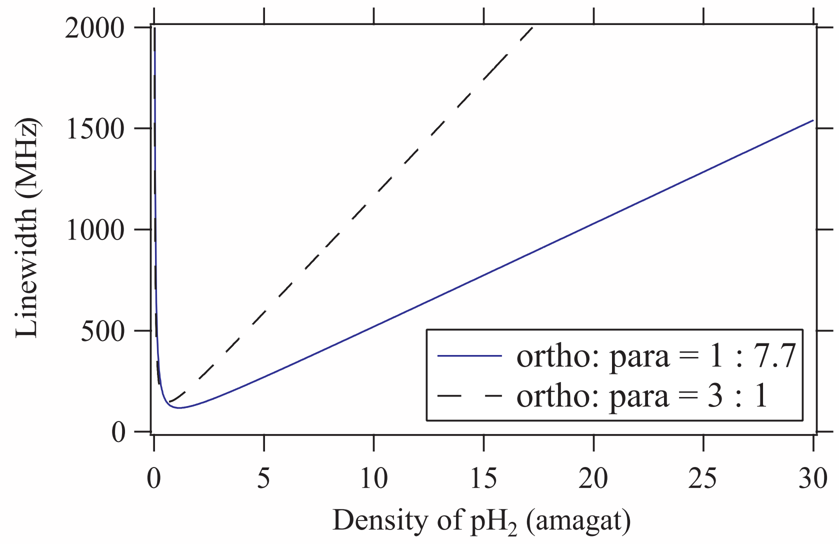
@ Okayama U

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

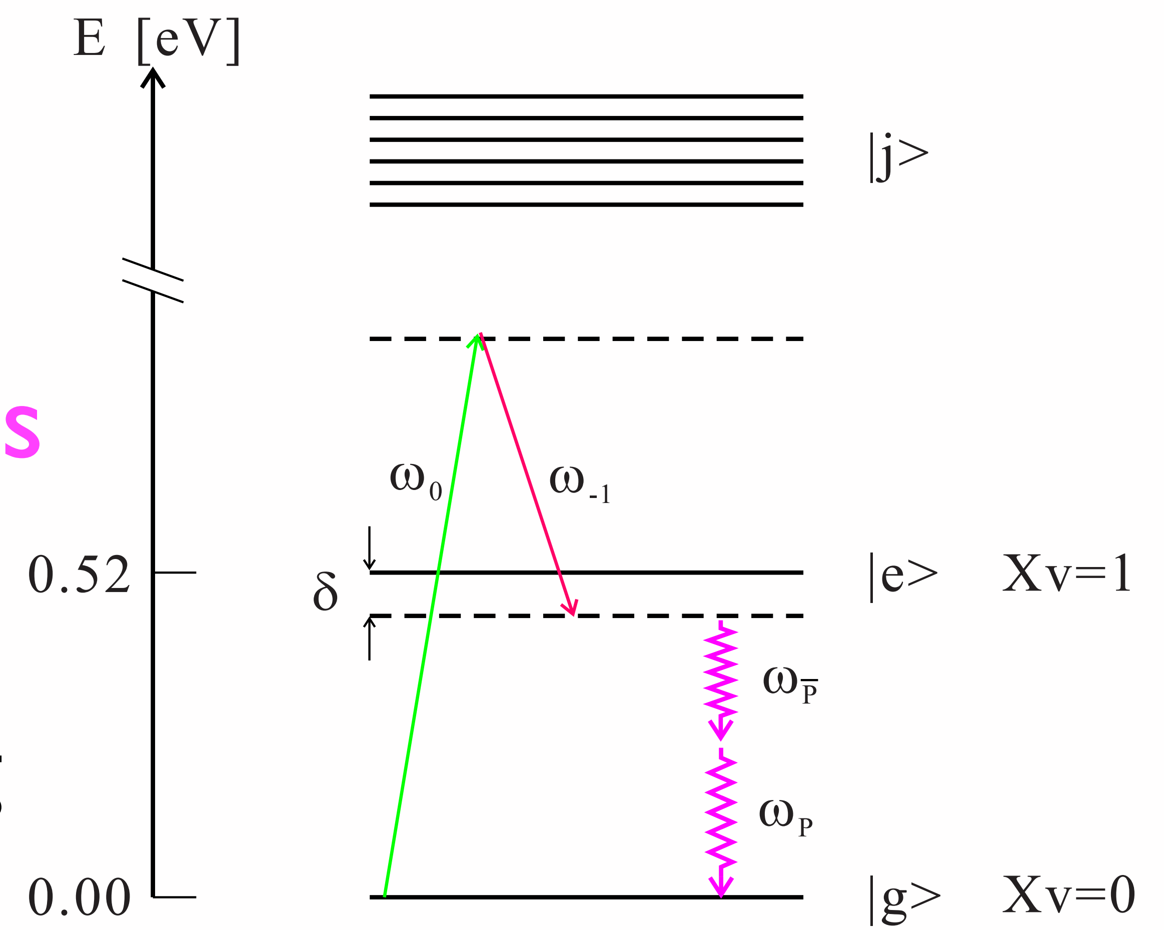
$$1/T_2 \sim 130 \text{ MHz}$$

coherence production

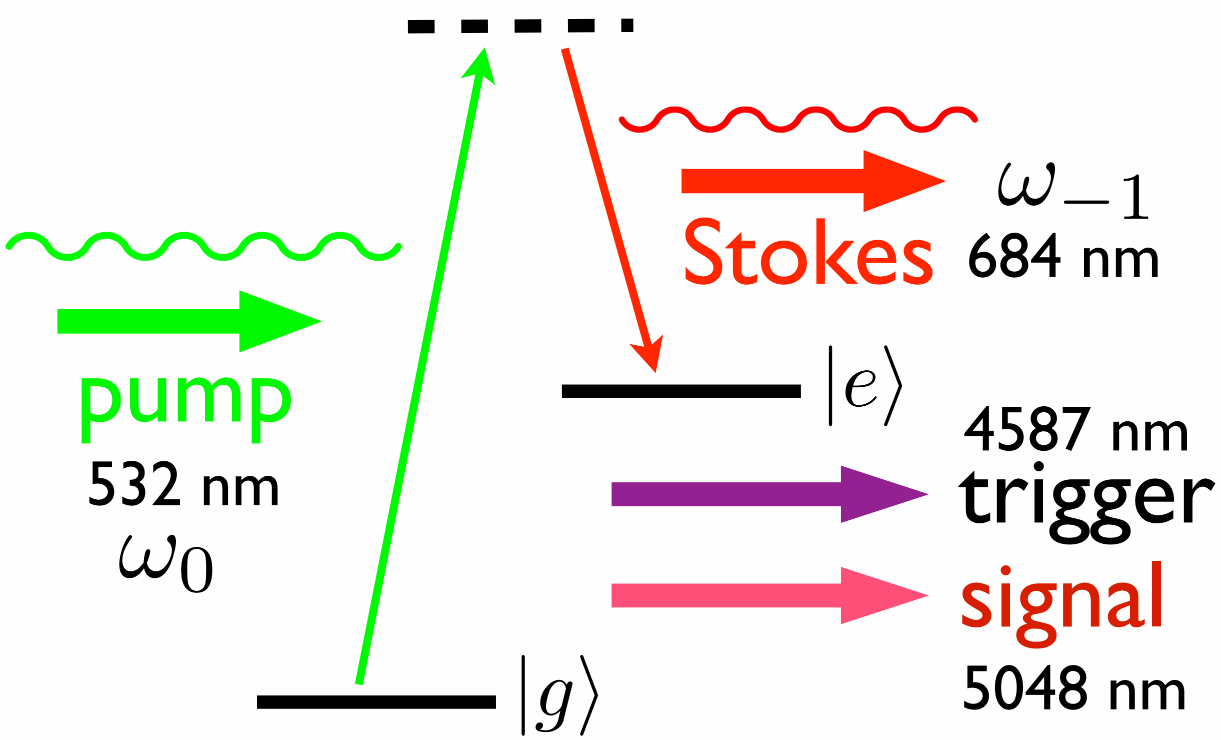
adiabatic Raman process

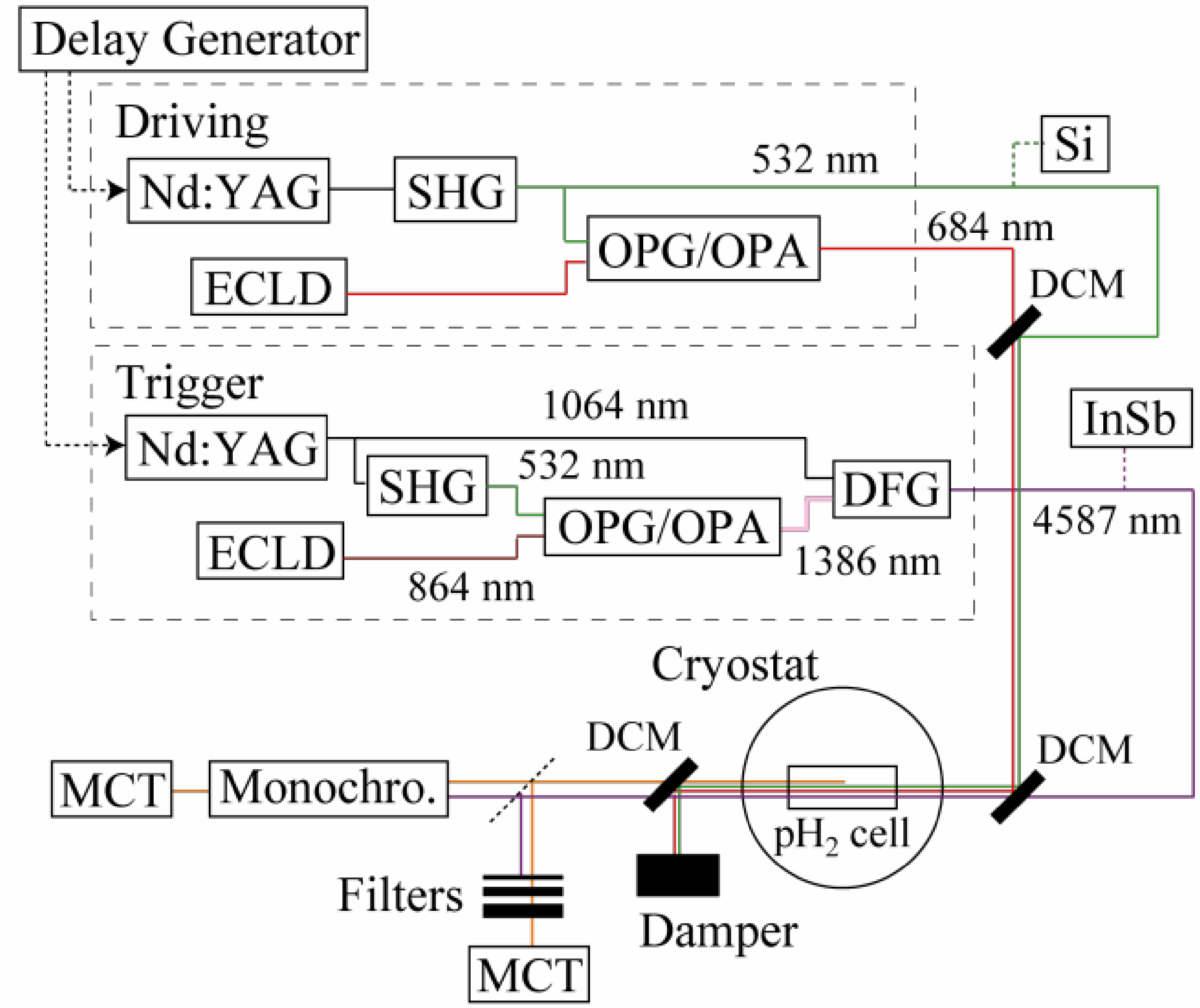
$$\Delta\omega = \omega_0 - \omega_{-1}$$
$$= \epsilon_{eg} - \delta$$
$$= \omega_p + \omega_{\bar{p}}$$

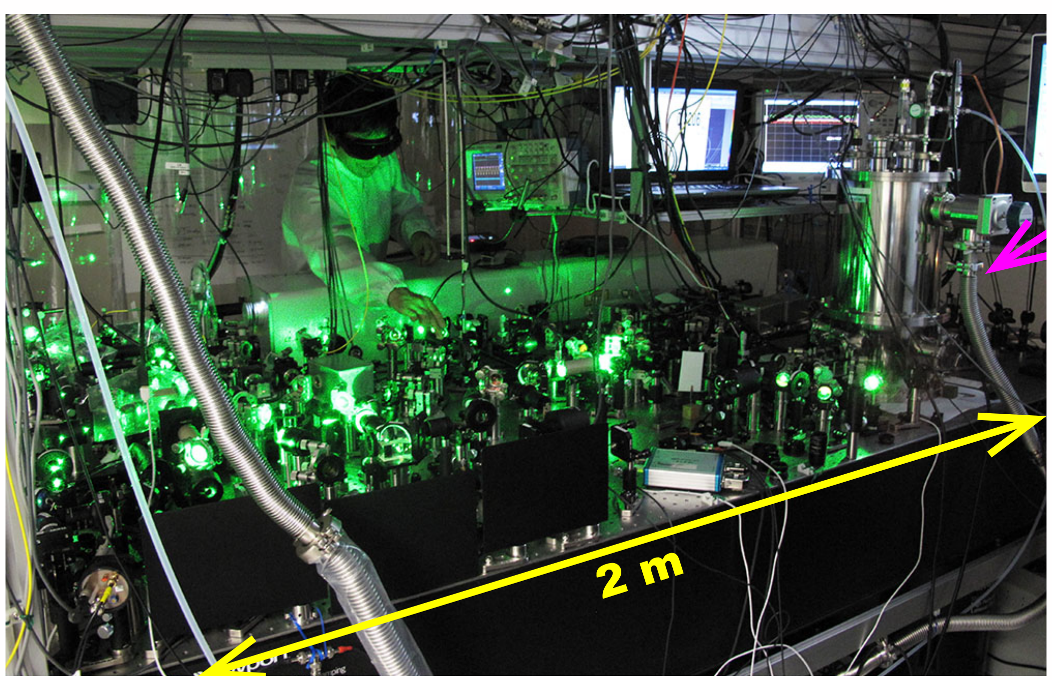
detuning



# 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

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

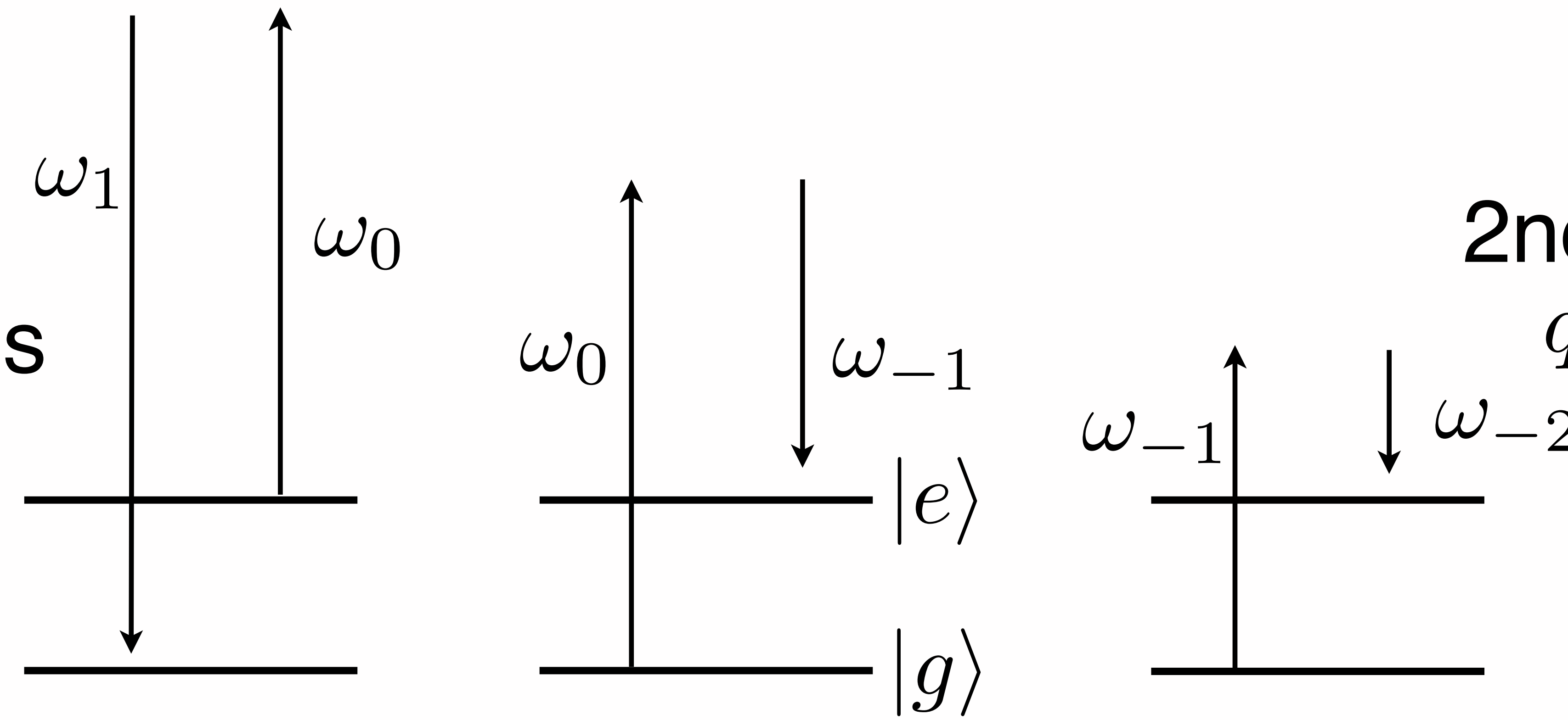
# Raman sideband generation

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

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

$q = 1$

1st anti-Stokes

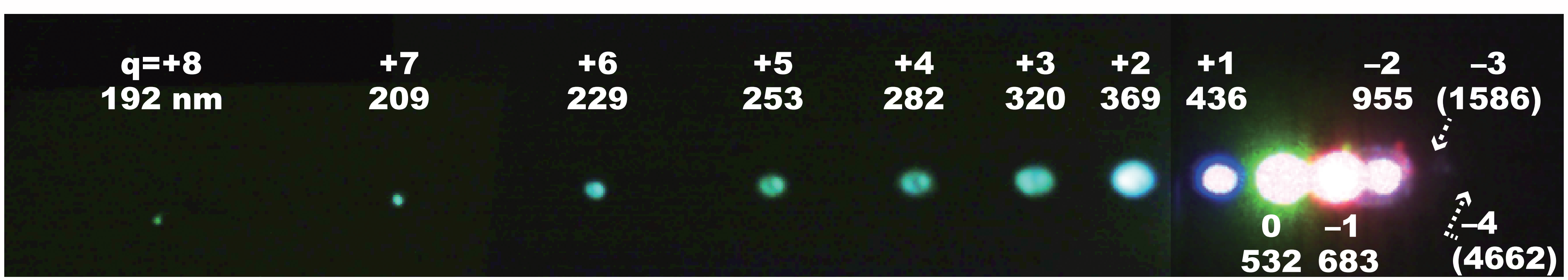



2nd Stokes

$q = -2$

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

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

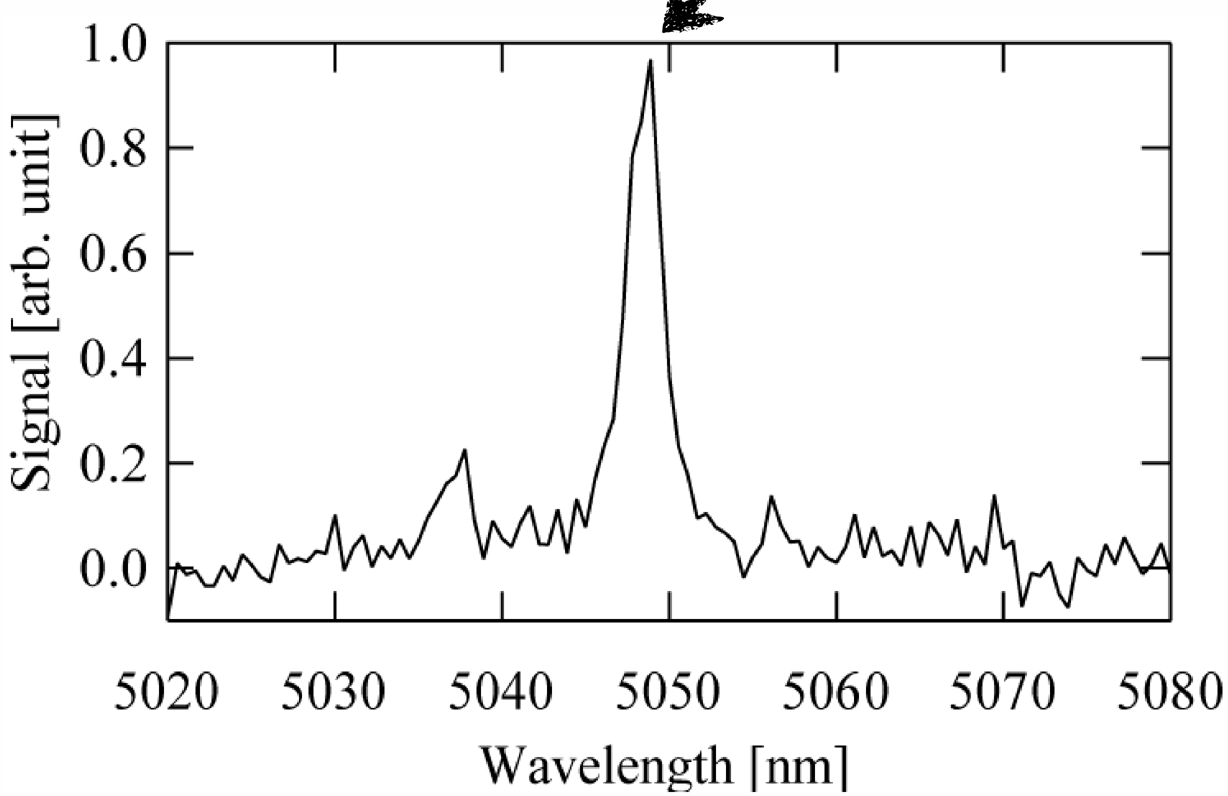


# Results

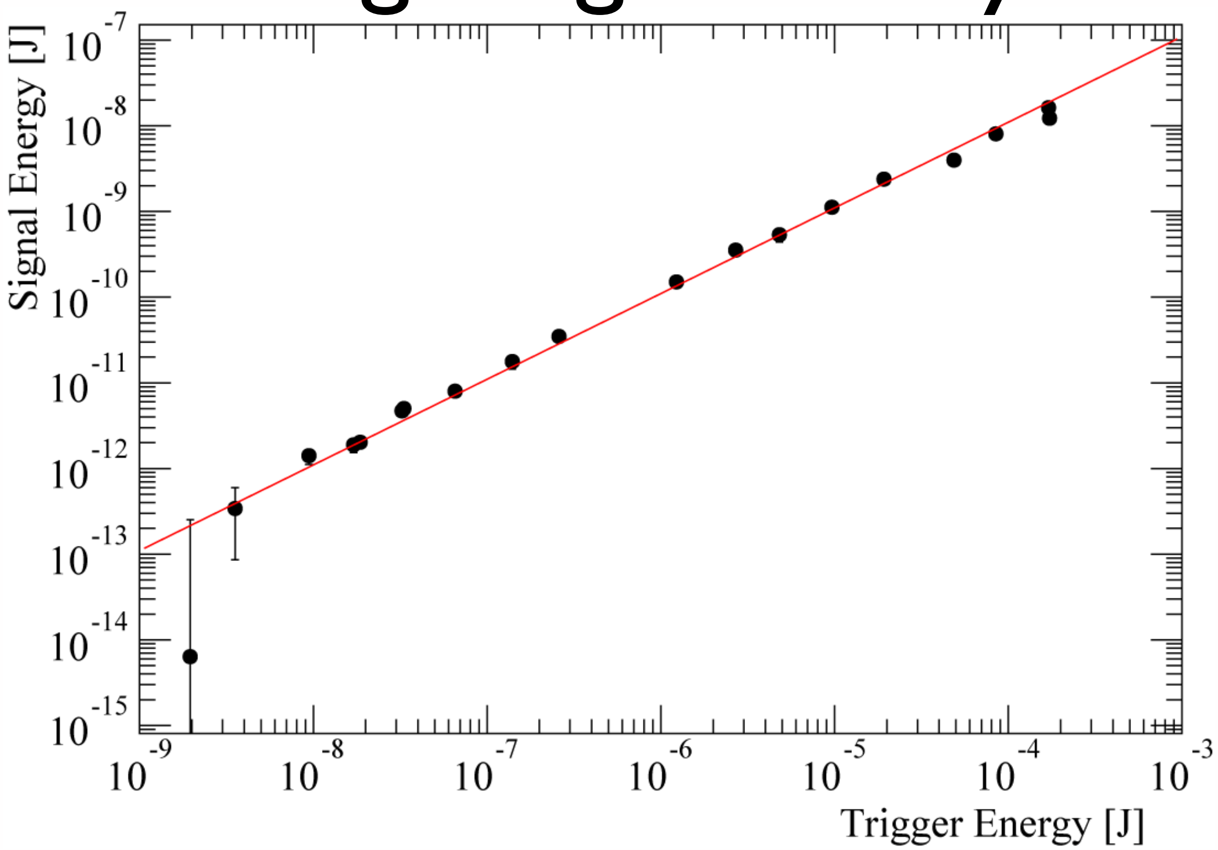
## Estimated coherence (from sidebands)

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

5048 nm




sig.-trig. linearity




$6 \times 10^{11}$ photons/pulse

→ $10^{18}$ enhancement

weak field

low coherence

# SUMMARY

# Neutrino Physics with Atoms/Molecules

- RENP spectra are sensitive to unknown neutrino parameters.

  Absolute mass, Dirac or Majorana,
  NH or IH, CP

- Macrocoherent rate amplification is essential.

  Demonstrated by a QED process, PSR.

- Background-free RENP

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

  Waveguide (photonic crystals)

  M. Yoshimura, N. Sasao, M.T., K. Tsumura, work in progress

**A new approach to neutrino physics**