Physics
OSAKA UNIVERSITY

原子・分子過程による
ニュートリノ物理

田中　実

大阪大学

Refs. : A.Fukumi et al. PTEP (2012) 04D002, arXiv:1211.4904
D.N. Dinh, S.T. Petcov, N. Sasao, M.T., M. Yoshimura
PLB719(2013)154, arXiv:1209.4808

Flavor Physics Workshop 2013, 2013/11/25-28 @ 伊勢志摩

Undetermined Properties of Neutrinos

Absolute mass

$$m_{1(3)} < 0.19\,\mathrm{eV}\,,\ \ 0.050\,\mathrm{eV} < m_{3(2)} < 0.58\,\mathrm{eV}$$

Mass type

Dirac or Majorana

Hierarchy pattern

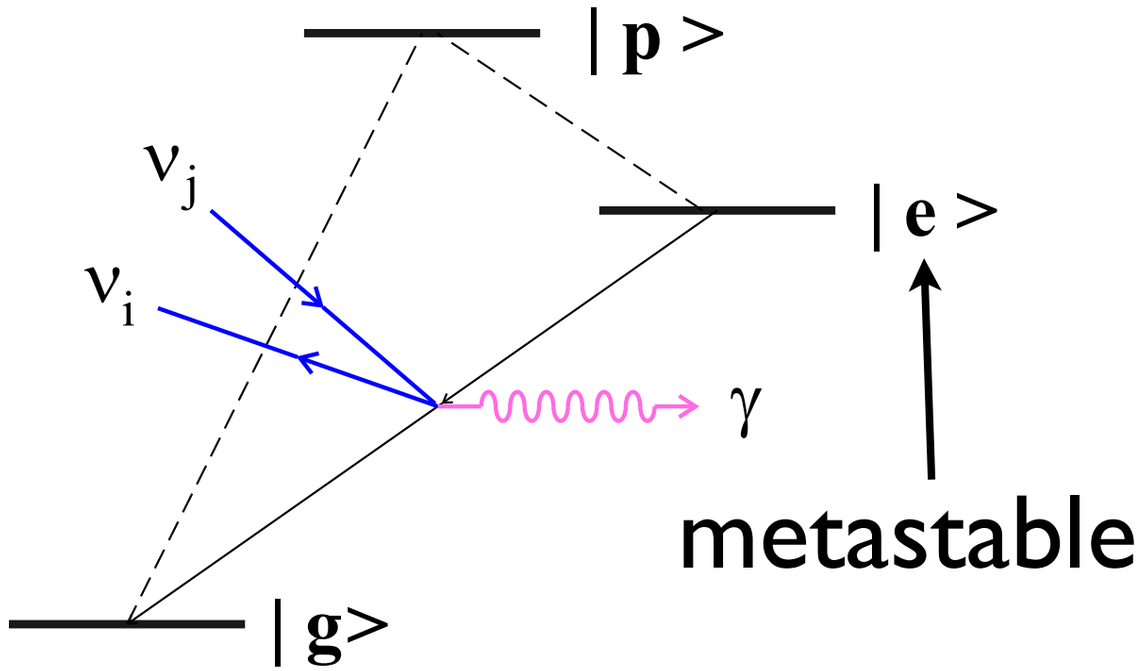
normal or inverted

CP violation

one Dirac phase, two Majorana phases

Atomic/molecular processes may help.

Radiative Emission of Neutrino Pair (RENP)



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

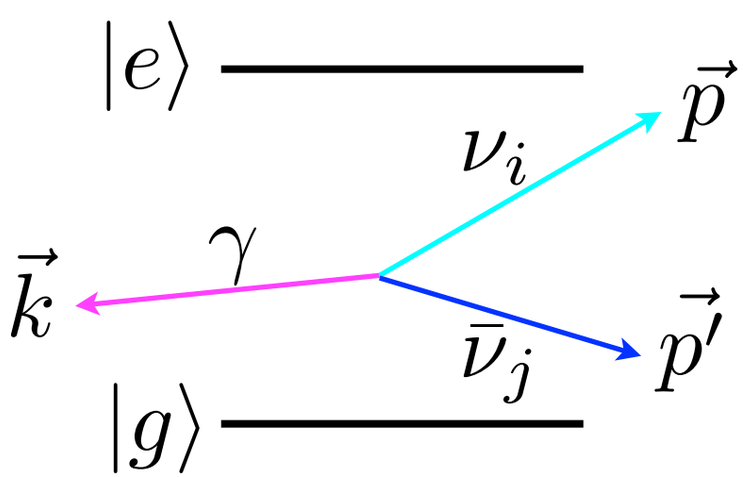
cf. nuclear processes ~ MeV

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

Enhancement mechanism?

Macro-coherence

Yoshimura et al. (2008)



position of atom

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

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

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

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

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

macro-coherent amplification

RENP spectrum

Energy-momentum conservation
due to the macro-coherence

→ familiar 3-body decay kinematics

Six thresholds of the photon energy

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

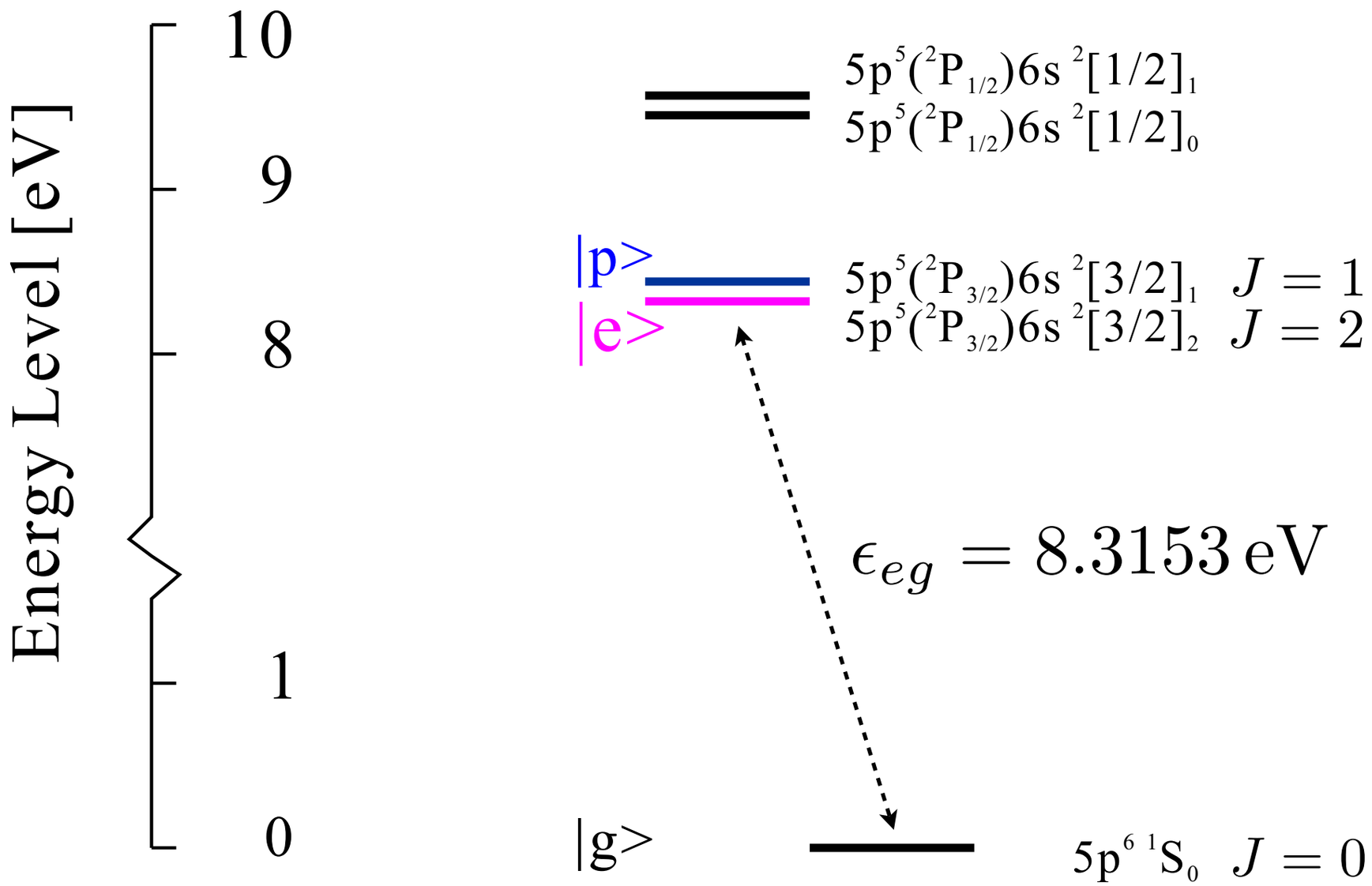
$\epsilon_{eg} = \epsilon_e - \epsilon_g$ atomic energy diff.

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

typical laser linewidth

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

Xe (gas target)



$$|e\rangle \leftrightarrow |p\rangle \quad \mathrm{M1}$$

$$|p\rangle \leftrightarrow |g\rangle \quad \mathrm{E1}$$

RENP rate formula

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

dynamical factor

overall rate

spectral function

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

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

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

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

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

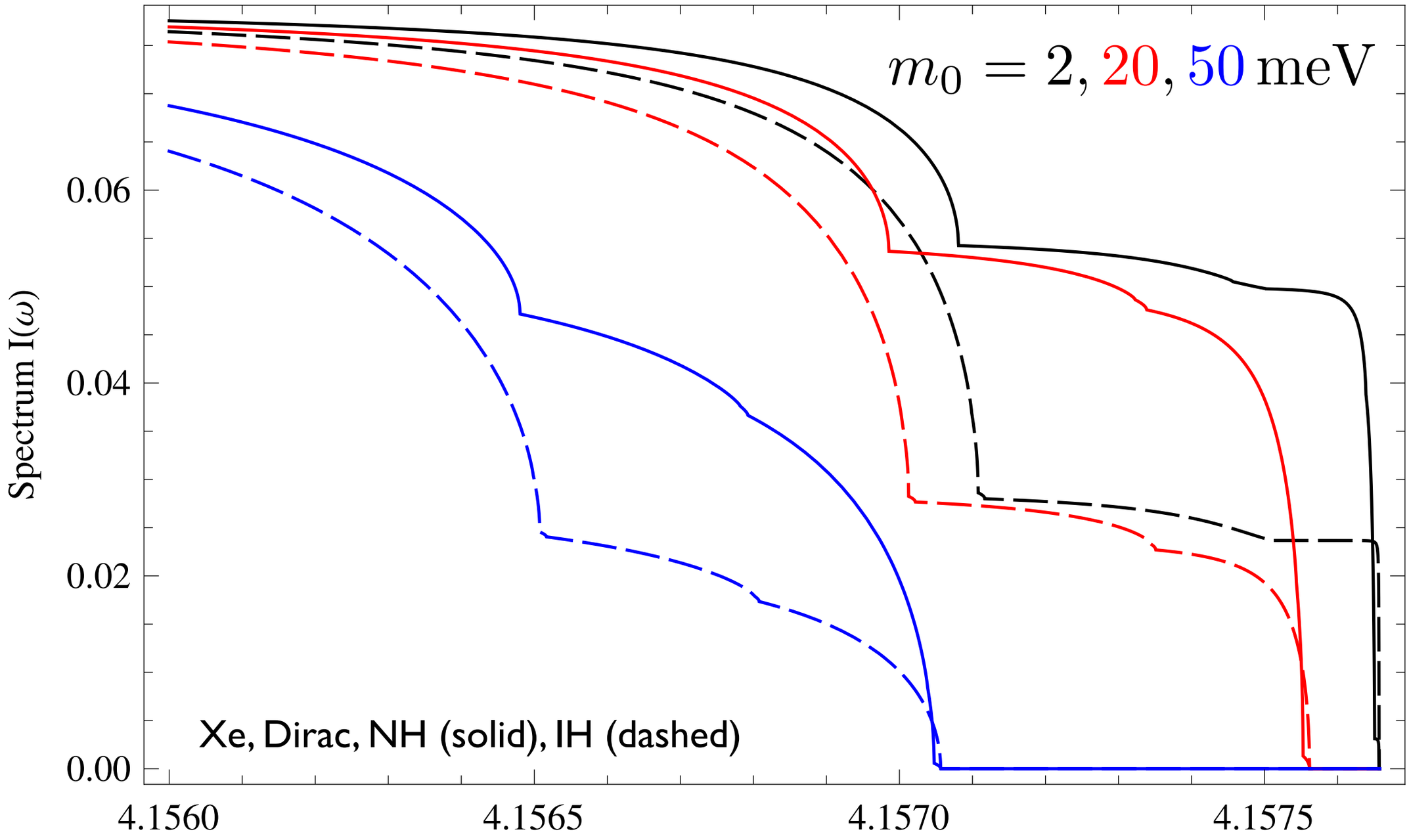
$\delta_M = 0(1)$ for Dirac(Majorana)

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

Dynamical factor

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

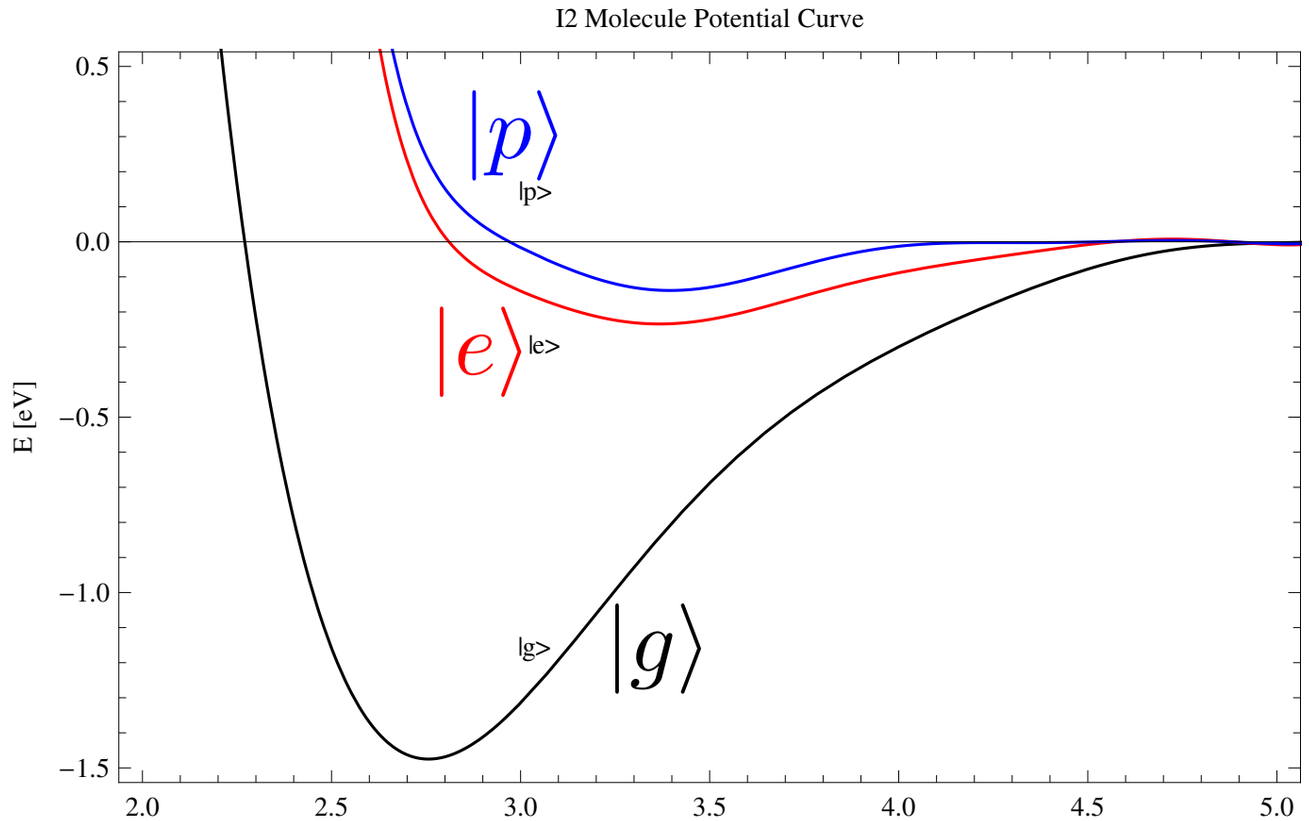
Spectra in the near-threshold region



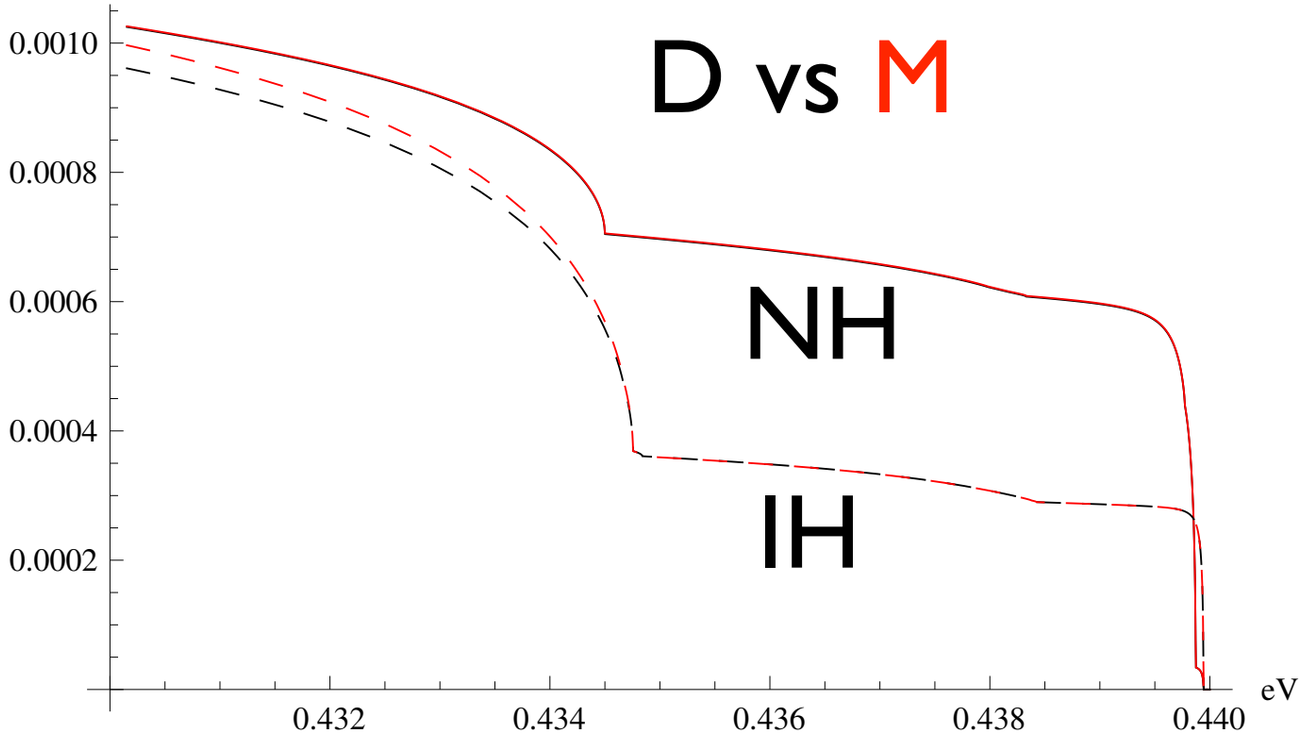
I2 molecule

potential curves

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



I2 A'v=1−>Xv=15: m0=5meV



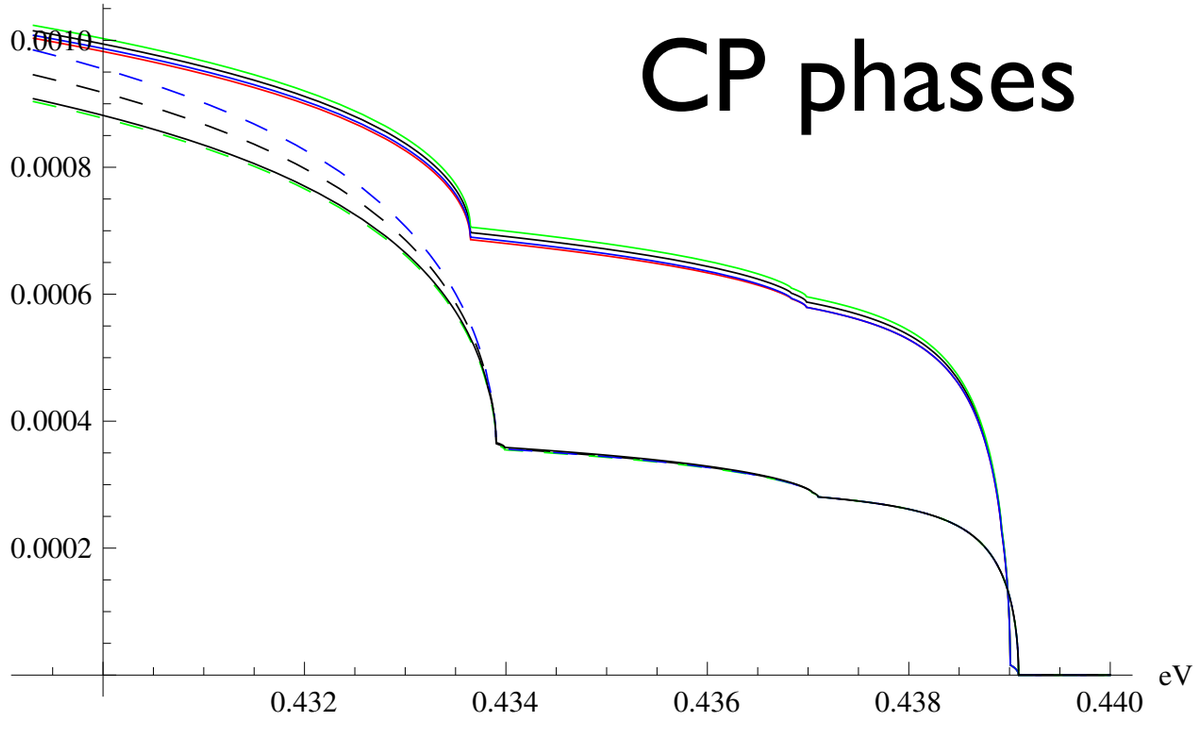
D vs M

NH

IH

D-M diff. < 10%

I2 A'v=1−>Xv=15: m0=20meV

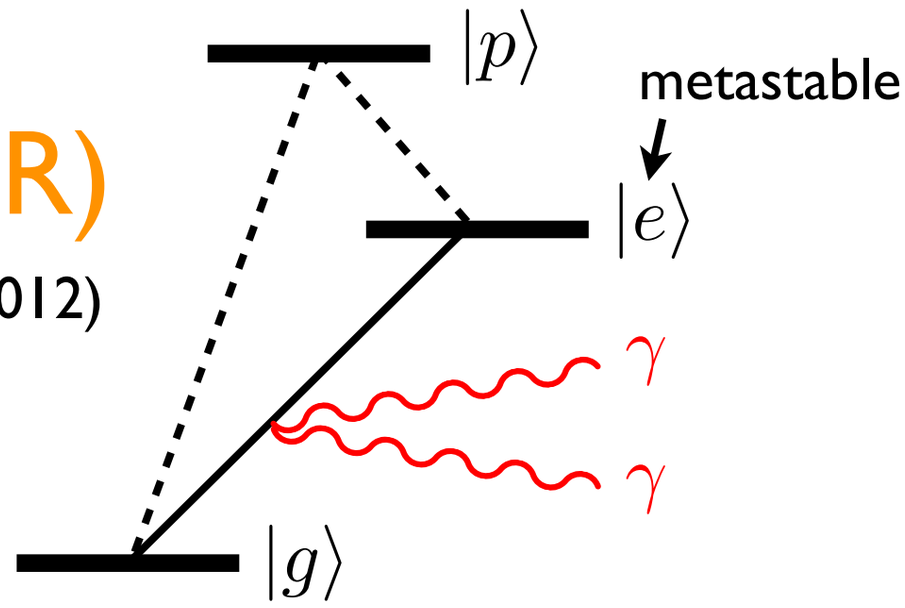


CP phases

Paired Super-Radiance (PSR)

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

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



prototype for RENP

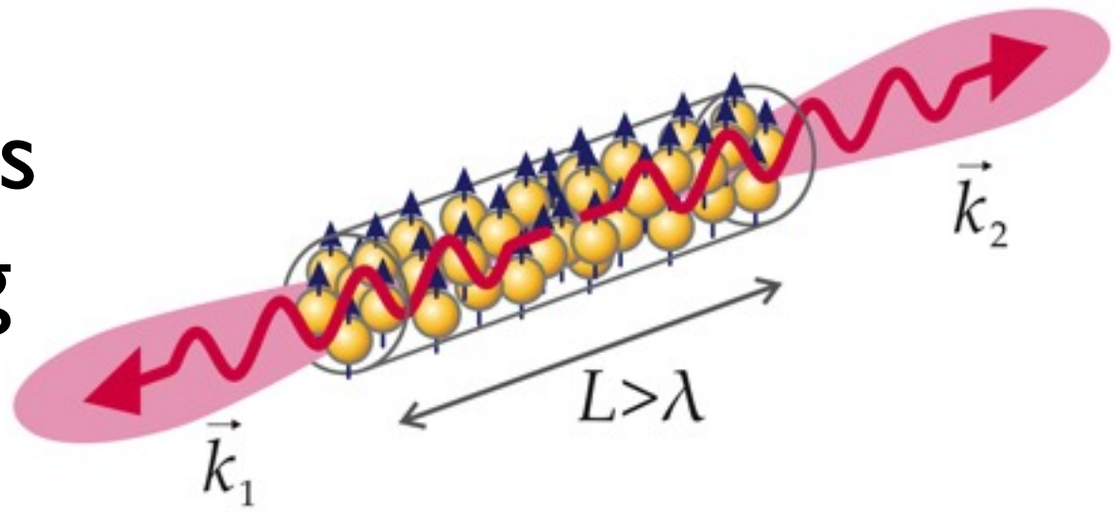
proof-of-concept for the macro-coherence

preparation of initial state for RENP

dynamical factor $\eta_\omega(t)$

background for RENP

A novel coherent process with counter-propagating fields/triggers

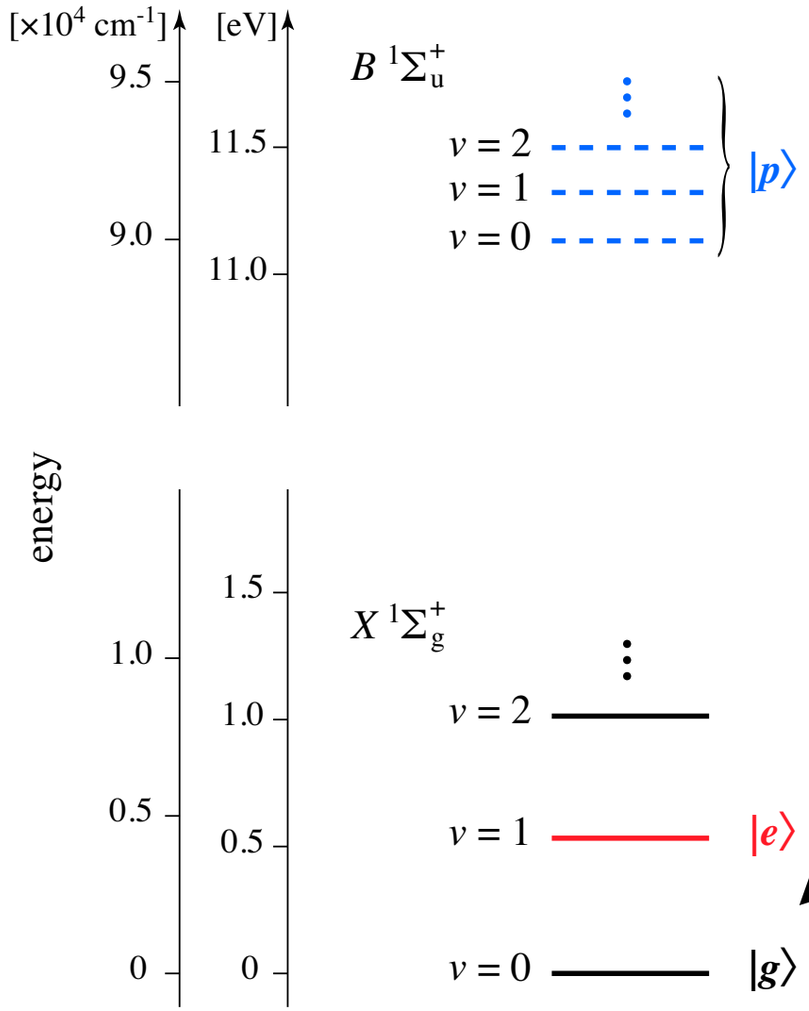


PSR pH2 Numerical Results

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 lifetime ~10^{16} sec.

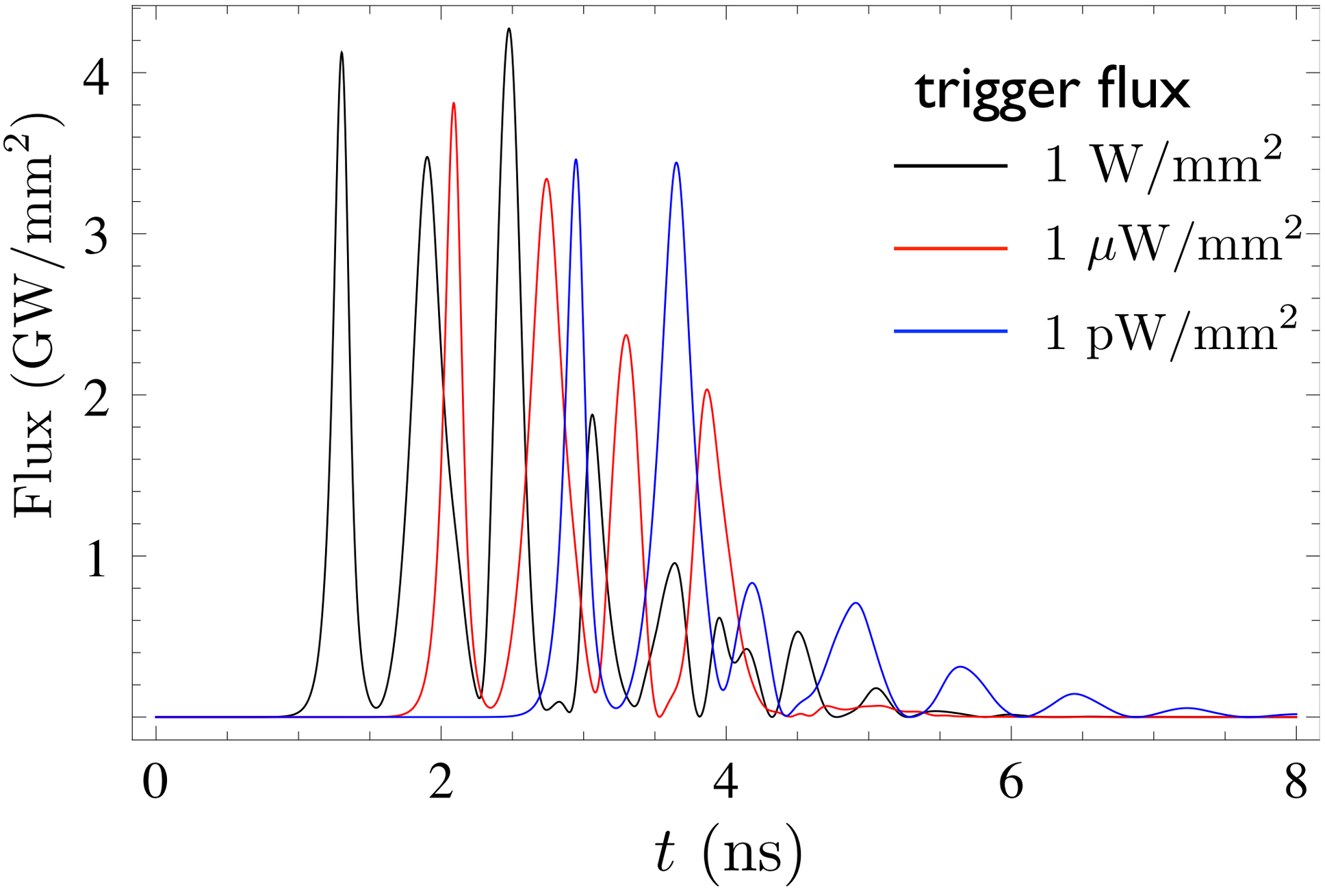
$$\epsilon_{eg} = 0.52\,\mathrm{eV},\ \gamma_{\pm} = 15.3,\ 0.64$$

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

Explosive PSR

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

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



The dynamical factor

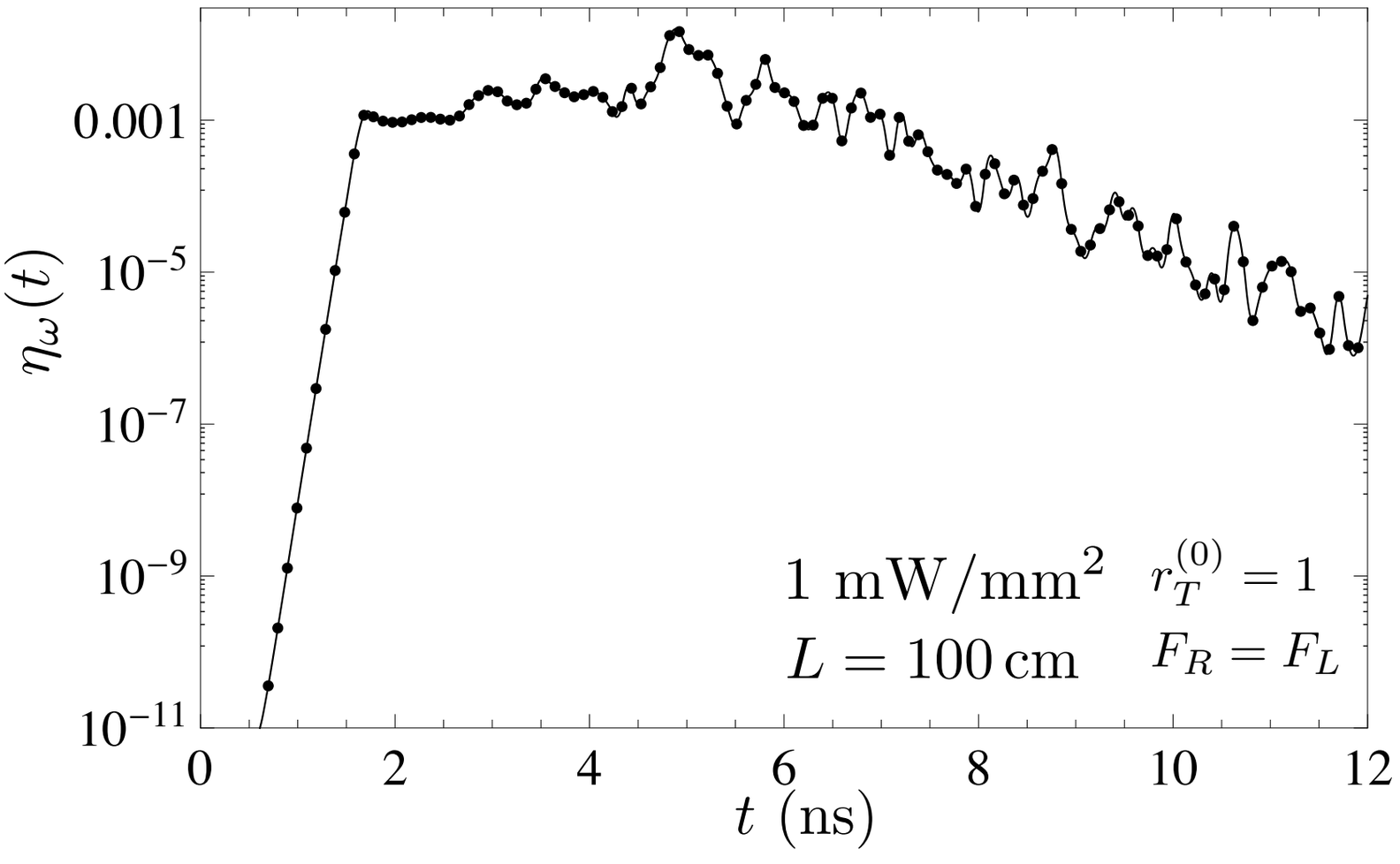
local field-medium activity

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

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

average over
the target length

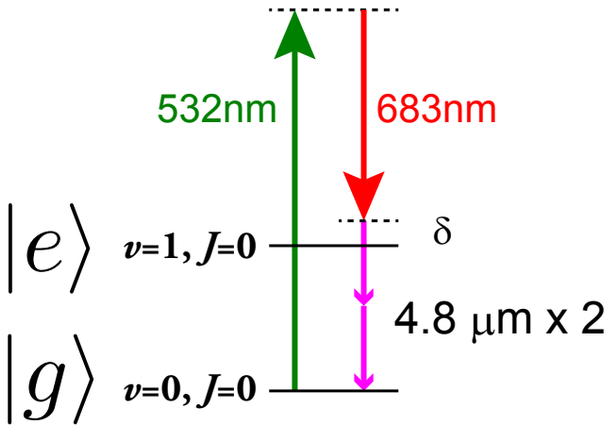
$$\eta_\omega(t) = \langle \eta_\omega(\xi,\tau)\rangle_\xi$$



Experimental Setup Overview

1. Input 532/683 pulses with CW trigger laser

2. Detect MIR pulse with MIR detector (InSb detector)



27 Dec. 2012, X00 meeting

S. Uetake

Neutrino Physics with Atoms/Molecules

★ RENP spectra are sensitive to unknown neutrino parameters.

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

★ The macro-coherence is essential.

Proof by a companion QED process,
paired super-radiance (PSR).

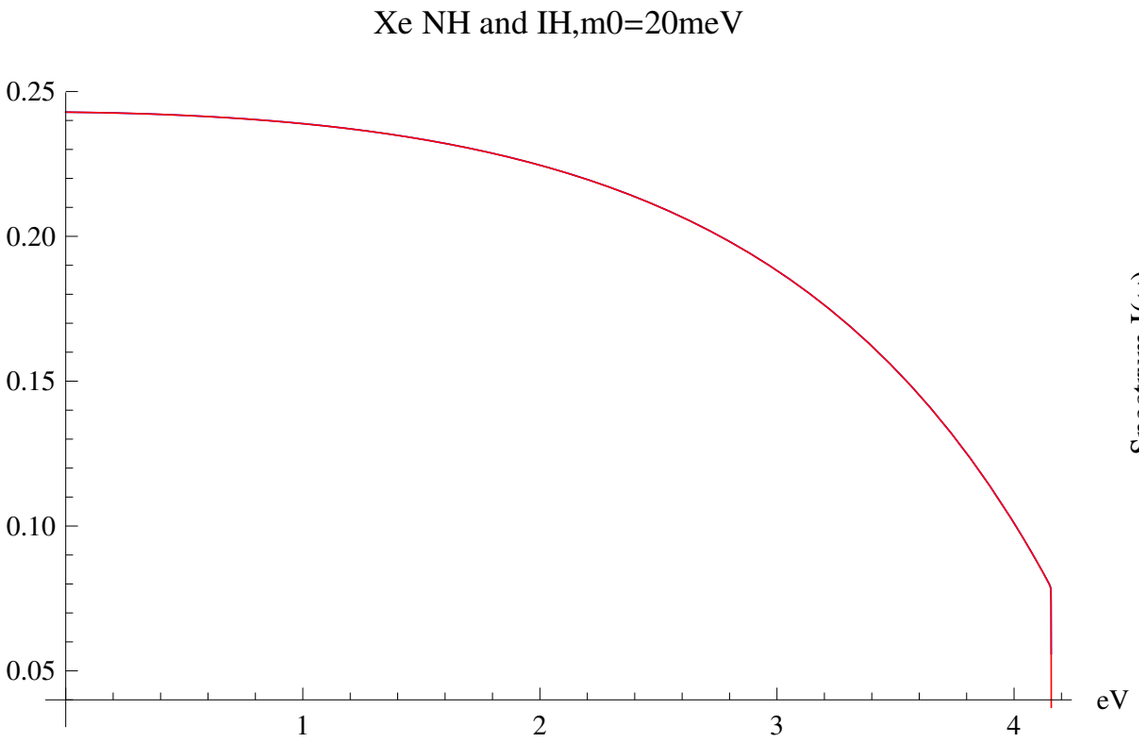
Atomic/molecular processes may help.

Backup Slides

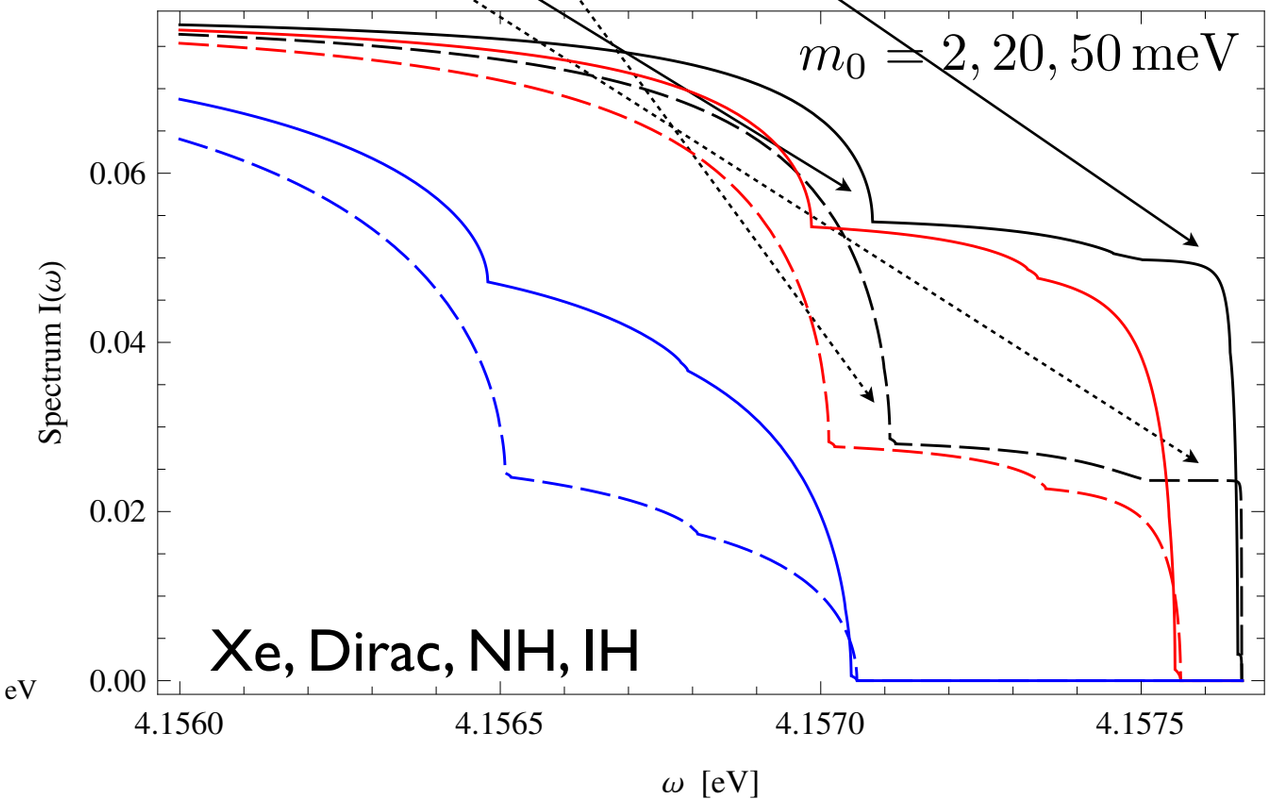
The threshold weight factors

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

Global shape



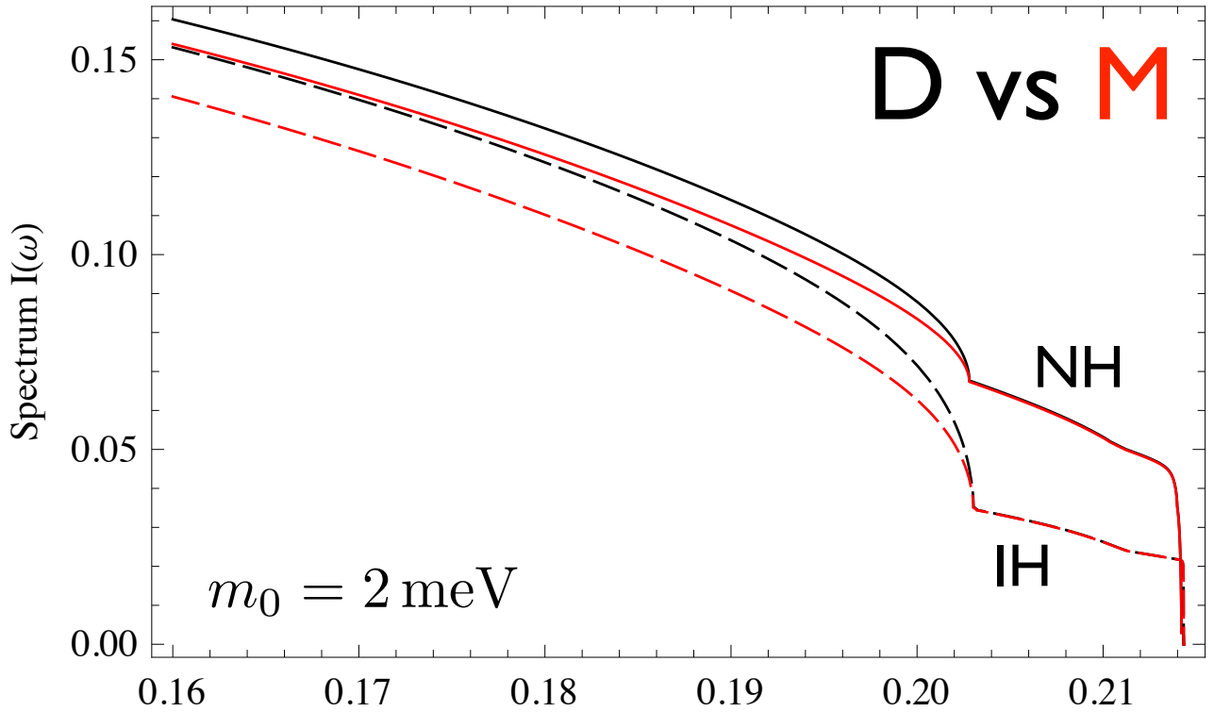
Threshold region

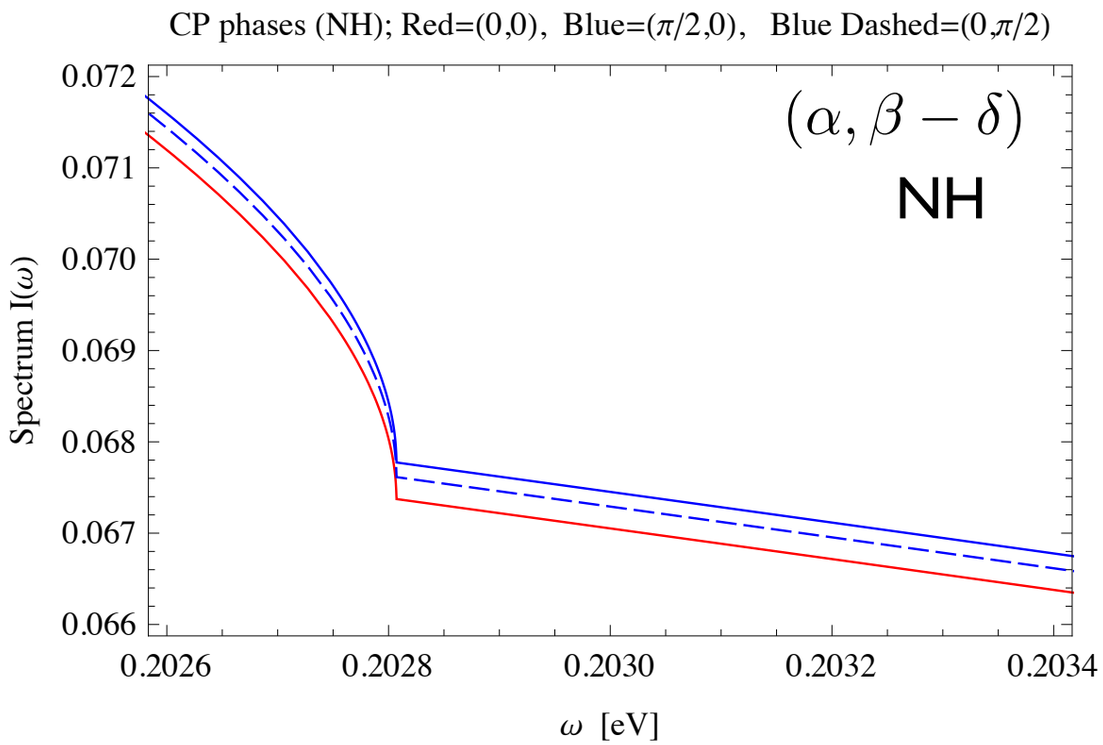


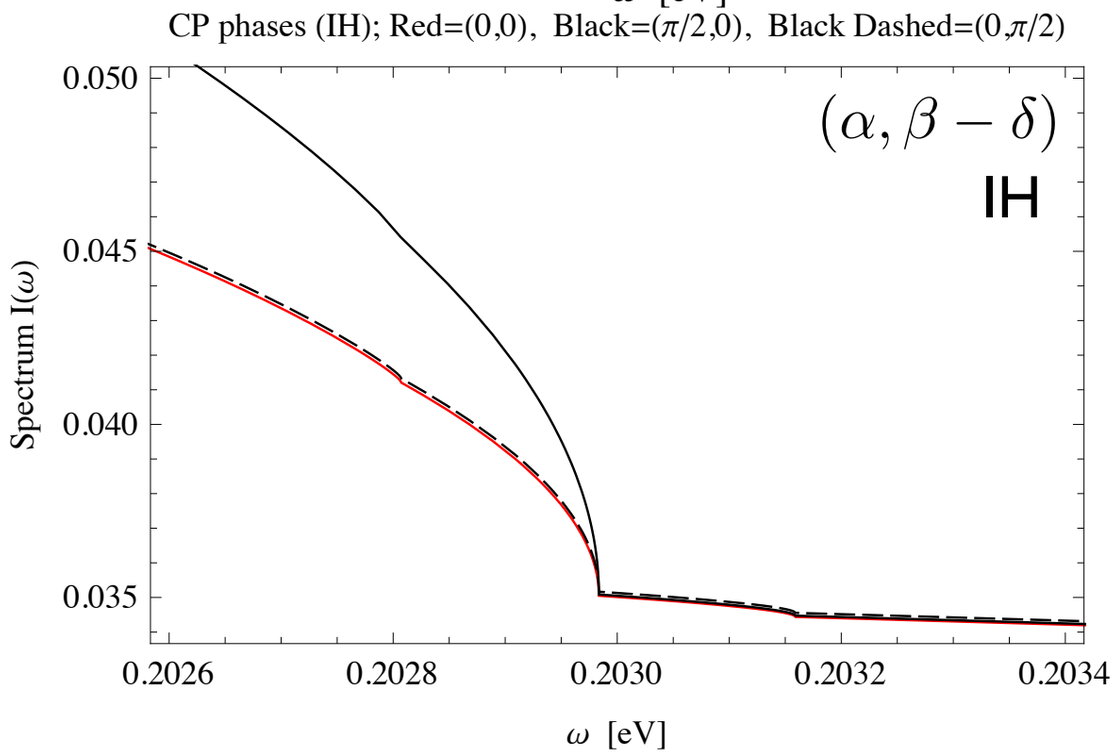
More on Dirac vs Majorana and CP phases

hypothetical atom

$$\epsilon_{eg} = 0.43\,\mathrm{eV}$$







Coherences in 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

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