Physics
OSAKA UNIVERSITY

# Observables in Neutrino Mass Spectroscopy Using Atoms

田中 実（阪大理）

共同研究者
D.N. Dinh, S.T. Petcov (SISSA), 笹尾 登, 吉村太彦 (岡山大)

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# 未知のニュートリノの性質

## 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

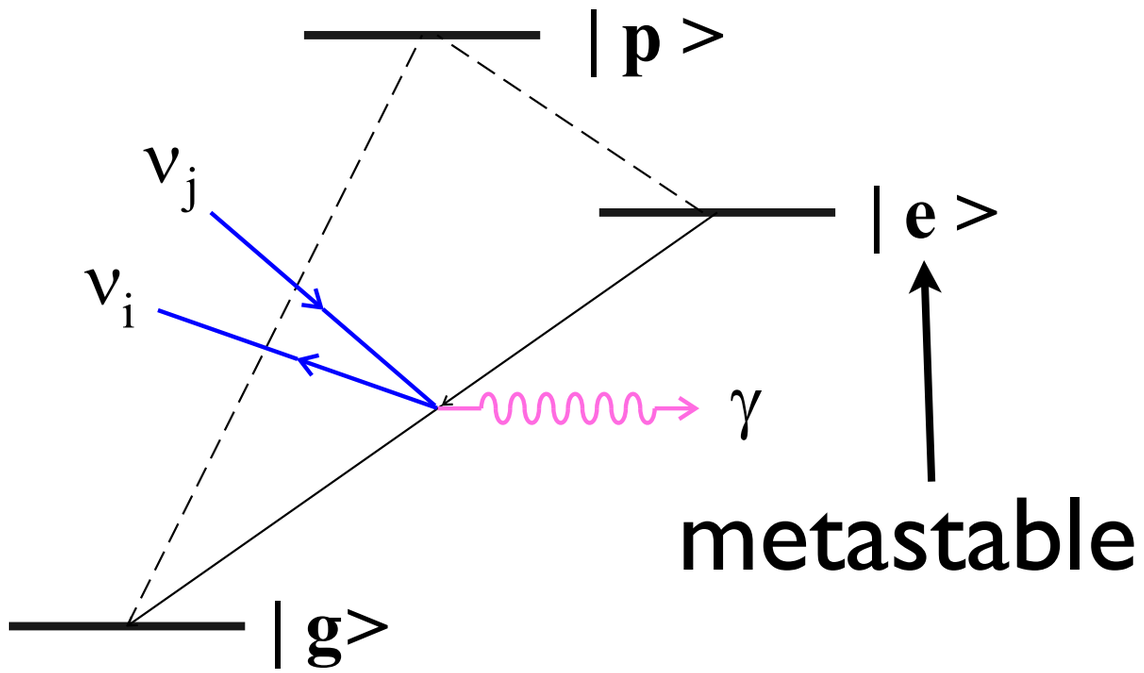
normal or inverted

## CP violation

one Dirac phase, two Majorana phases

原子•分子過程による解明

# 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

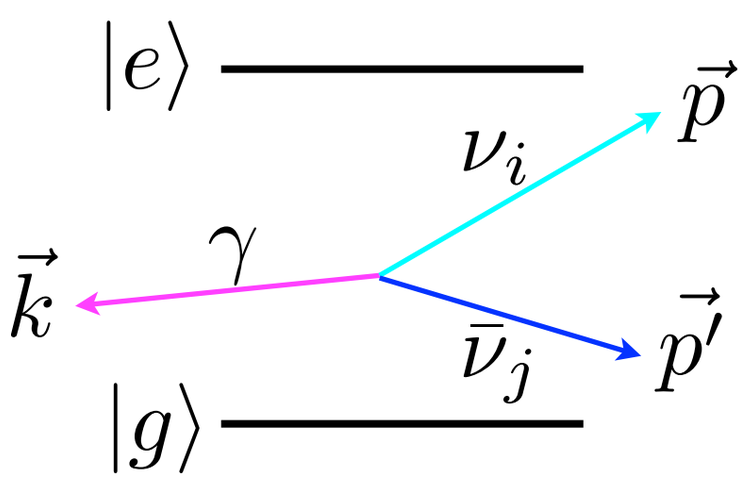
cf. nuclear processes ~ MeV

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

増幅機構が必要

# 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)

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

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

macro-coherent amplification

# RENP spectrum

Energy-momentum conservation
due to the macro-coherence

→ familiar 3-body decay kinematics

Six thresholds of the photon energy

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

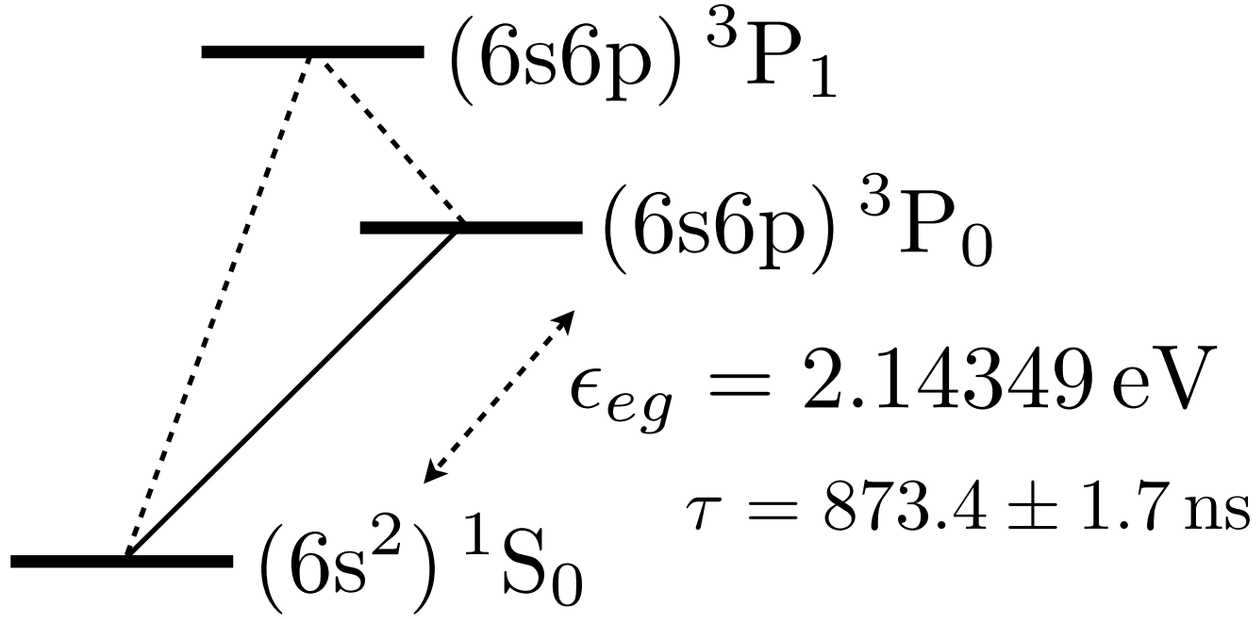
$\epsilon_{eg} = \epsilon_e - \epsilon_g$ atomic energy diff.

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

typical laser linewidth

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

# Yb atom




# Overall rate

macro-coherence

~ field energy density

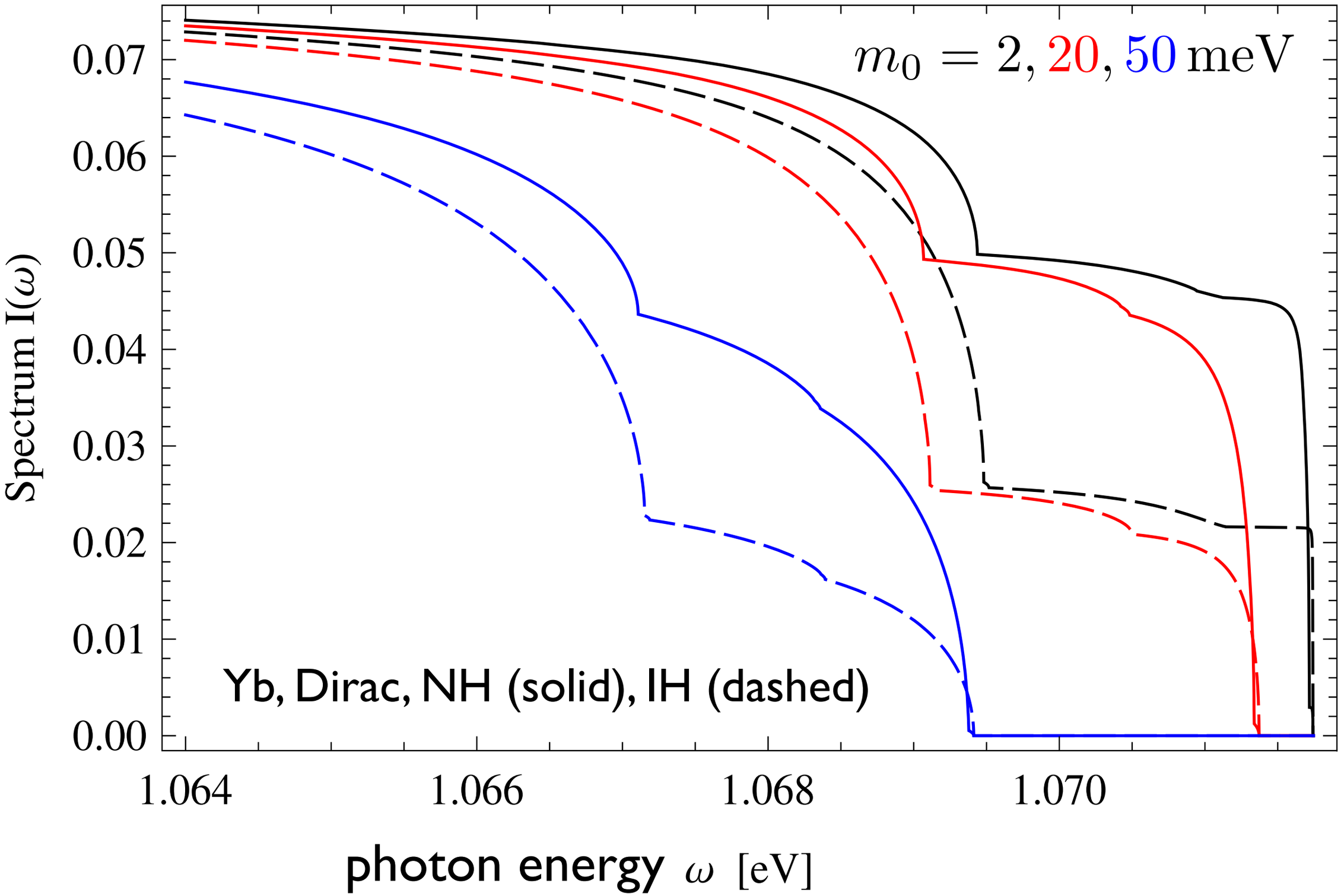
$$\Gamma_0 = \frac{3n^2 V G_F^2 \gamma_{pg} \epsilon_{eg} n}{2\epsilon_{pg}^3}(2J_p+1)C_{ep}$$

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

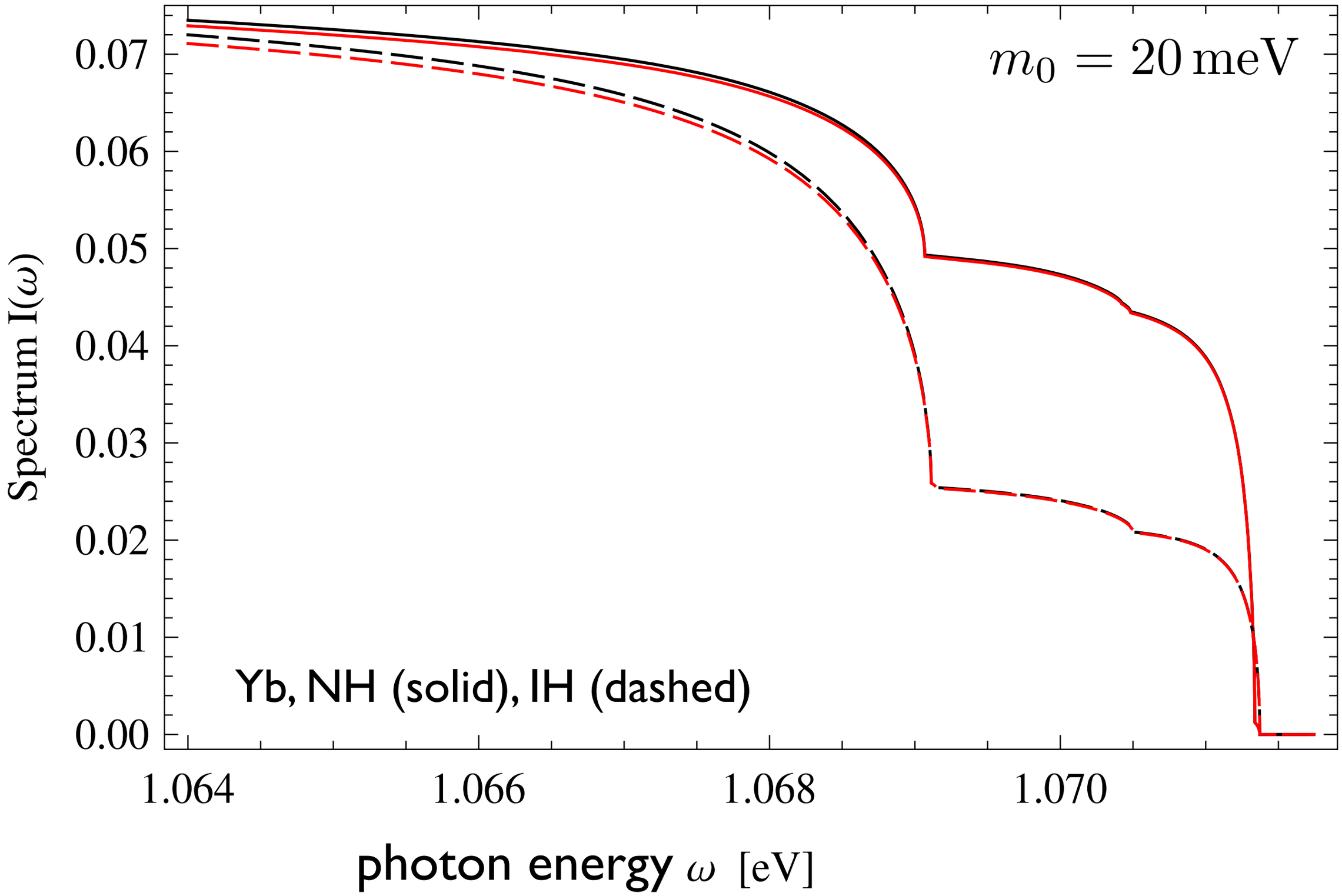
$(2J_p+1)C_{ep}$ : **atomic spin factor**

$$\sim 0.4\,\mathrm{mHz}\,(n/10^{21}\mathrm{cm}^{-3})^3\,(V/10^2\mathrm{cm}^3)$$

# Spectra in the near-threshold region

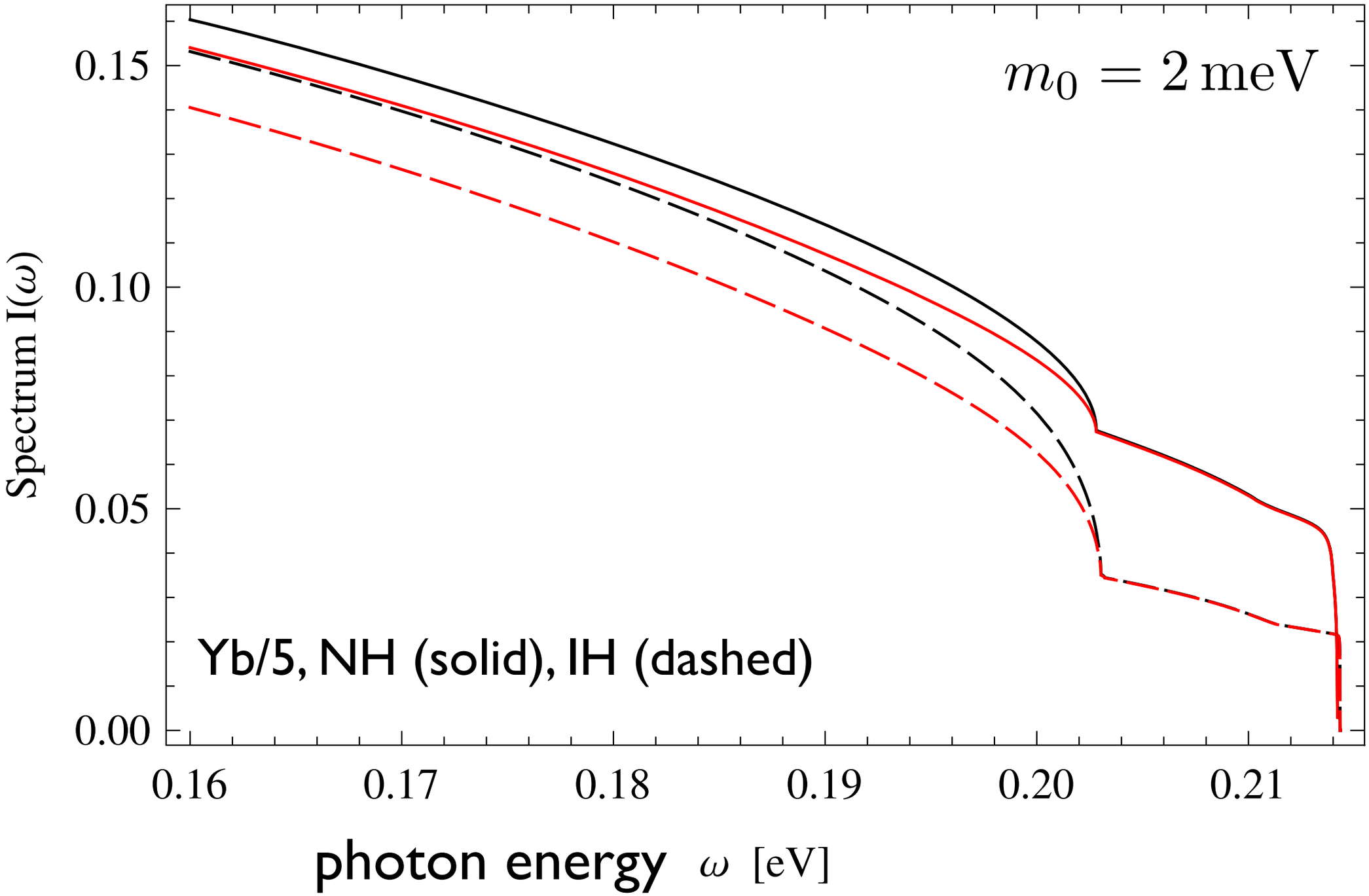


# Dirac vs Majorana ←同種粒子効果



# Dirac vs Majorana for a hypothetical atom

$$\epsilon_{eg} = \epsilon_{eg}(\mathrm{Yb})/5 = 0.428699\,\mathrm{eV}$$



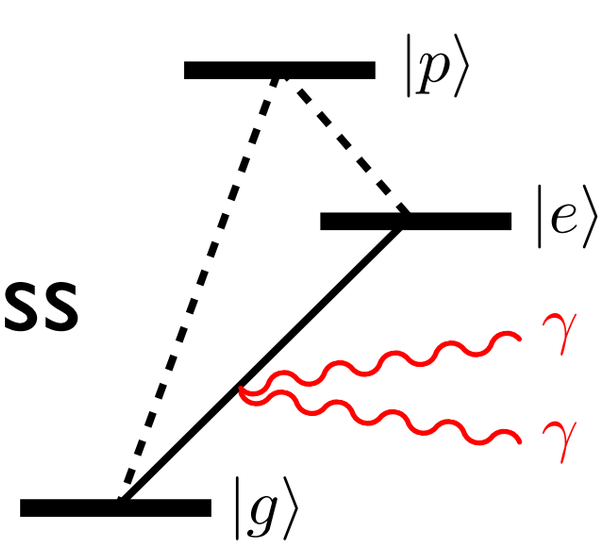
# 原子•分子過程によるニュートリノ物理

★ 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).



# Backup Slides

# RENP rate formula

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

dynamical factor

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

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

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

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

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

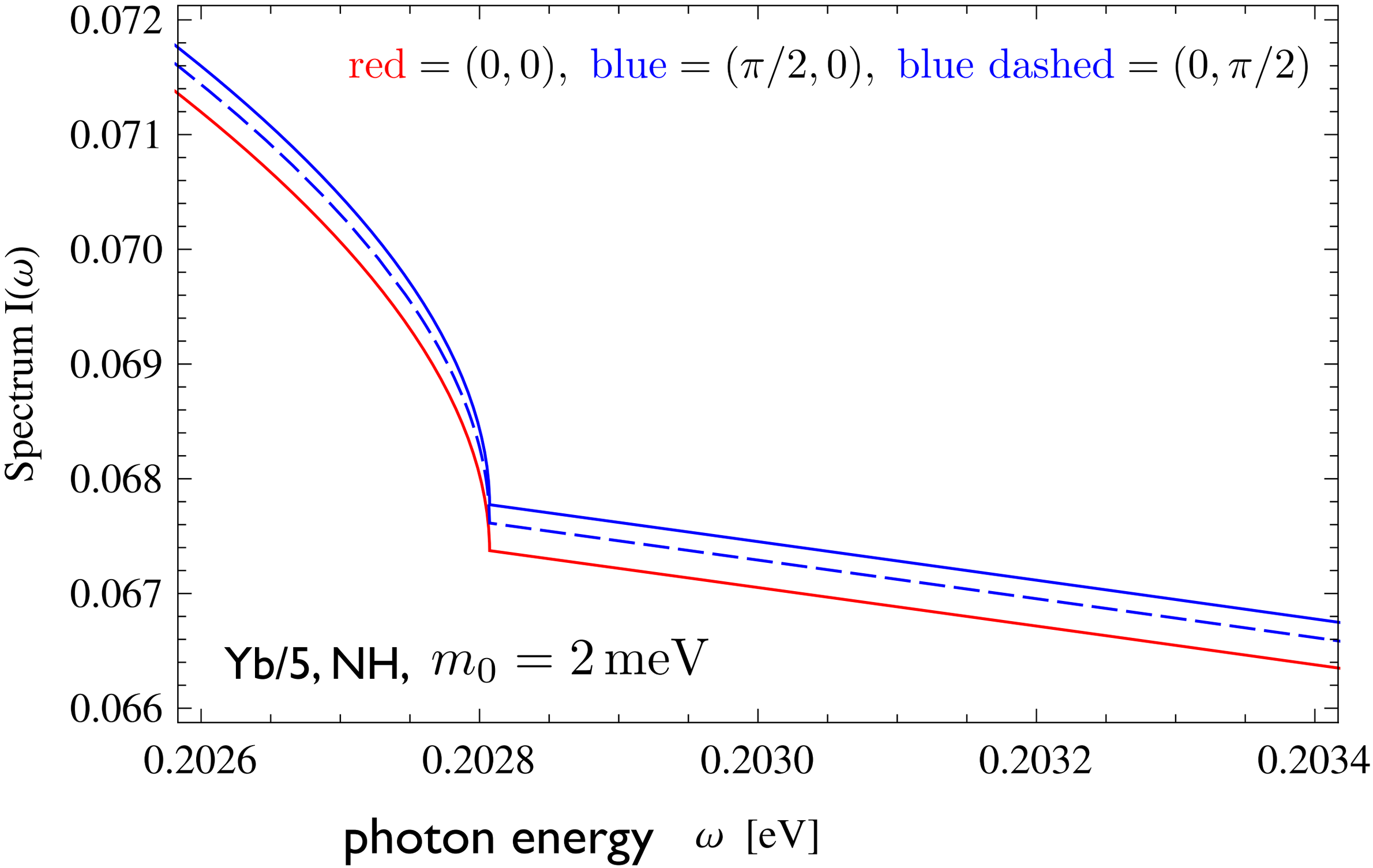
$\delta_M = 0(1)$ for Dirac(Majorana)

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

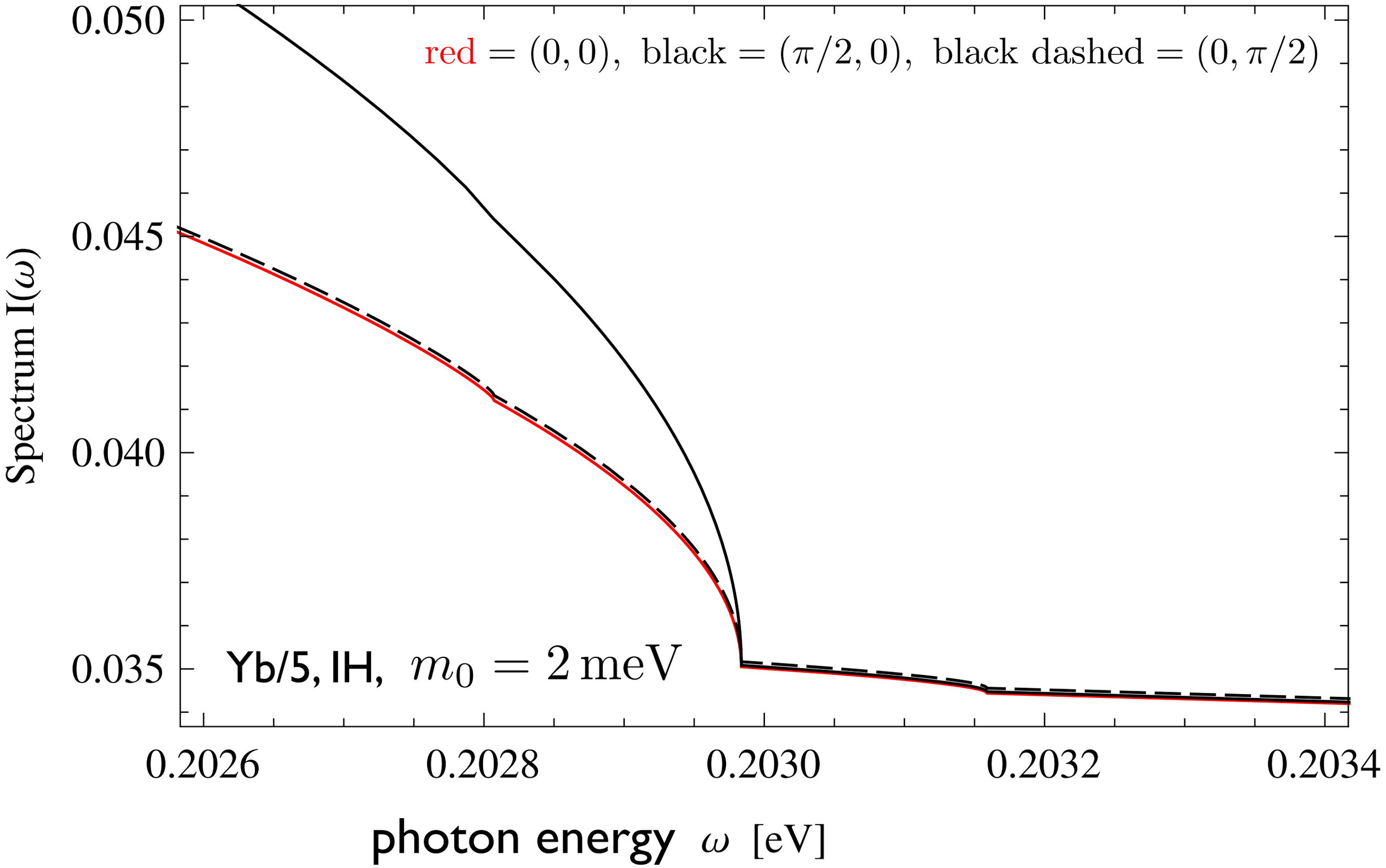
# Dynamical factor

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

# CP phases (NH) $(\alpha, \beta - \delta)$



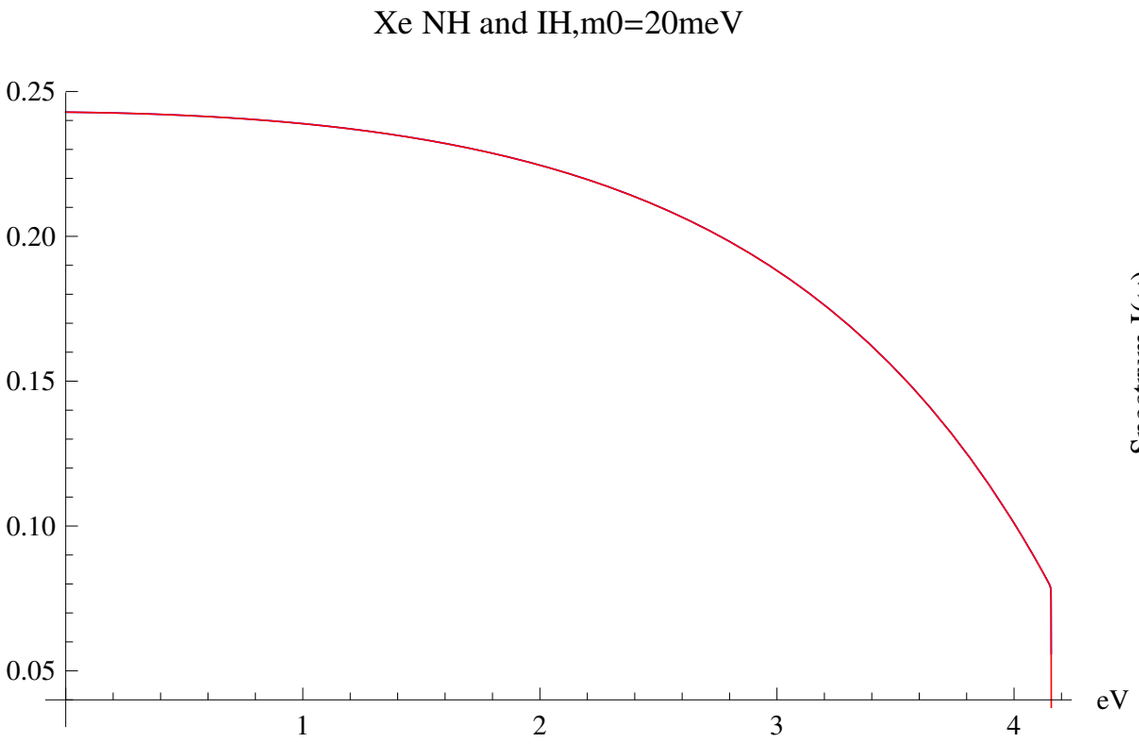
# CP phases (IH) $(\alpha, \beta - \delta)$



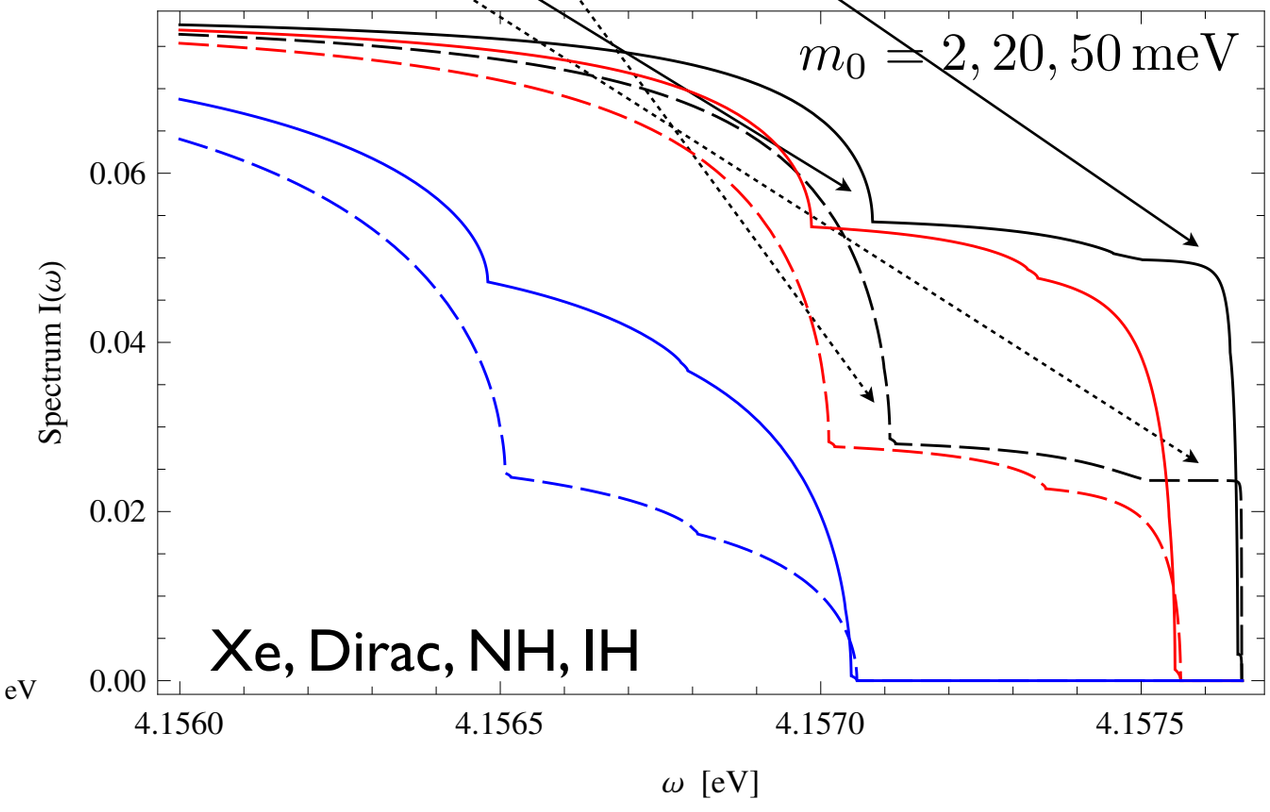
# The threshold weight factors

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

# Global shape




# Threshold region



# Coherences in PSR/RENP

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

Target coherence

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

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

$$\Gamma \propto N^2$$

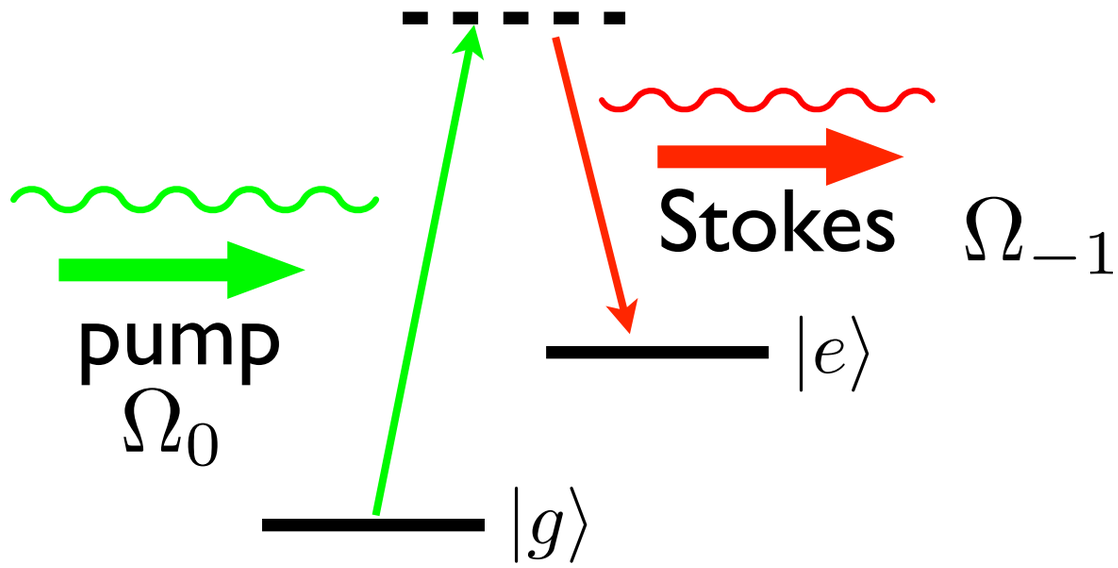
## Macro-coherence

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

# 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)