Physics
OSAKA UNIVERSITY

Implication of initial spatial phase in the coherent radiative neutrino pair emission

Minoru TANAKA
Osaka University

in collaboration with
K. Tsumura (Kyoto U),
N. Sasao, S. Uetake, M. Yoshimura (Okayama U)

10th international workshop on fundamental physics using atoms (FPUA2018)
Jan. 8–9, 2018, Nagoya

INTRODUCTION

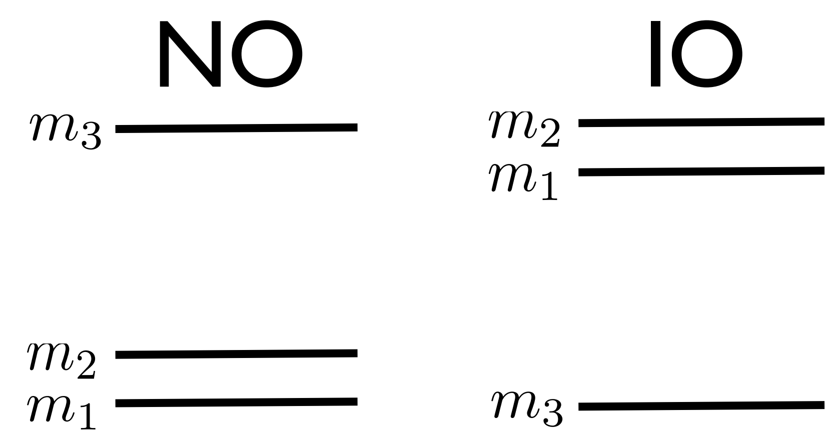
Unknown properties of neutrinos

Absolute mass

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

Ordering pattern

normal or inverted



Mass type

Dirac or Majorana

CP violation

one Dirac phase, two Majorana phases

δ $\qquad$ $\alpha,\ \beta$

Neutrino experiments

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

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

$\Delta m^2,\ \theta_{ij},$ NO or IO, δ

Neutrinoless double beta decays

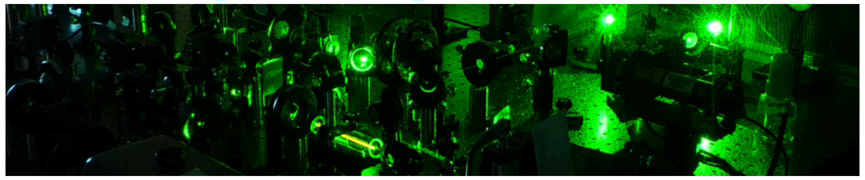
Dirac or Majorana, effective mass $\left|\sum_i m_i U_{ei}^2\right|^2$

Beta decay endpoint: KATRIN

absolute mass

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

Atomic/molecular processes



absolute mass, NO or IO, D or M, $\alpha\ (, \beta - \delta)$

Plan of talk

Introduction (2)

Radiative emission of neutrino pair (RENP) (4)

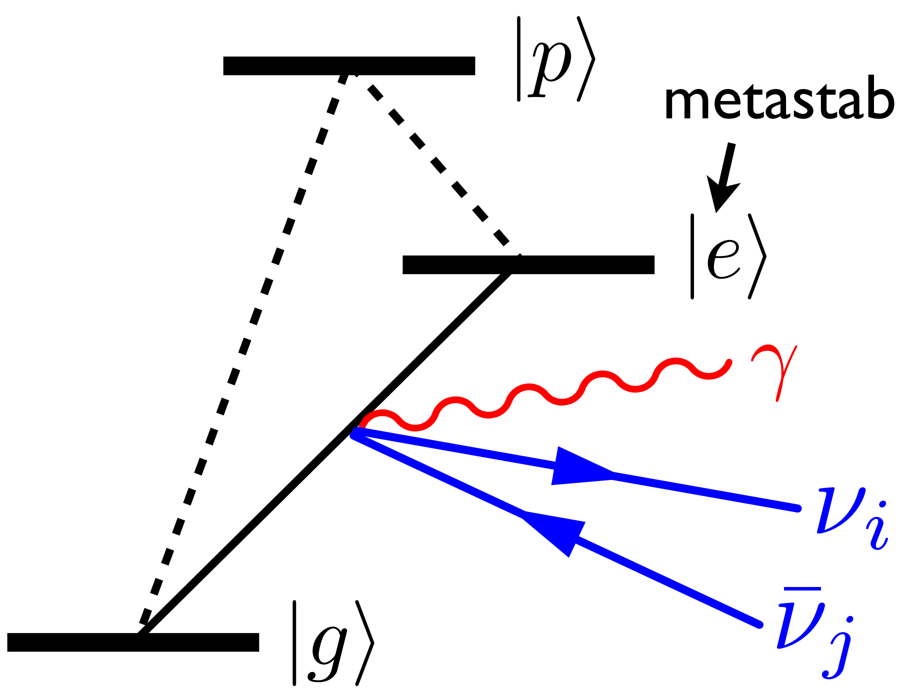
Boosted RENP (4)

Summary (1)

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

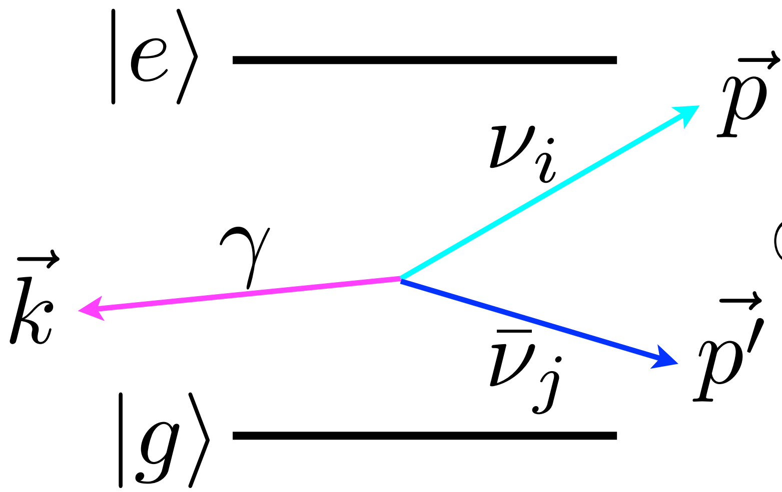
cf. nuclear processes ~ MeV

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

Enhancement mechanism?

Macrocoherence

Yoshimura et al. (2008)



position of atom

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

$$(E_{eg}=E_e-E_g,\ E_\gamma=|\vec{k}|)$$

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

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

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

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
virtual parent particle $(P^\mu) = (E_{eg}, \mathbf{0}), \;\; P^2 = E_{eg}^2$

Six thresholds of the photon energy

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

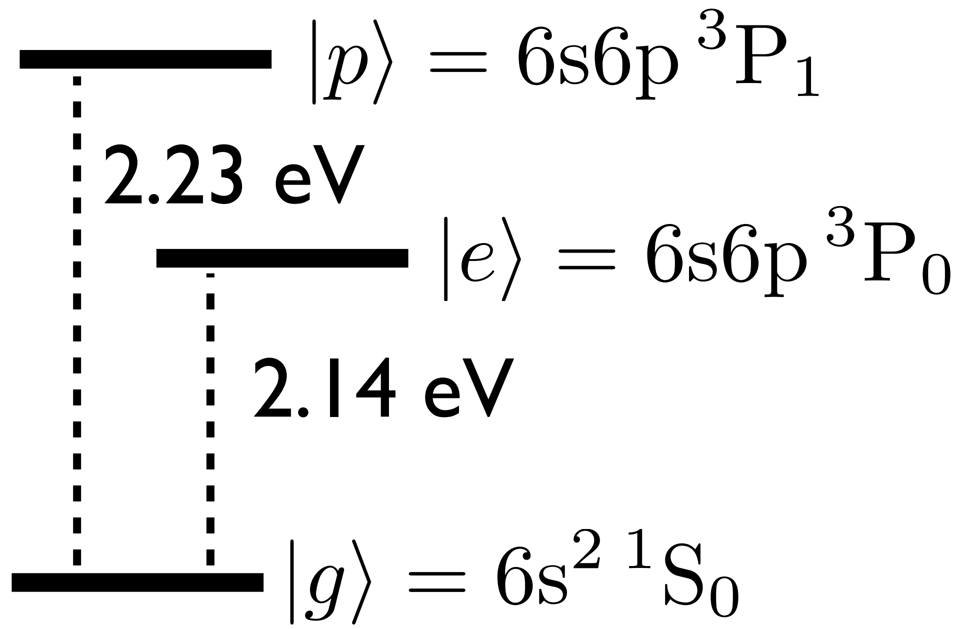
$E_{eg} = E_e - E_g$ atomic energy level splitting

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

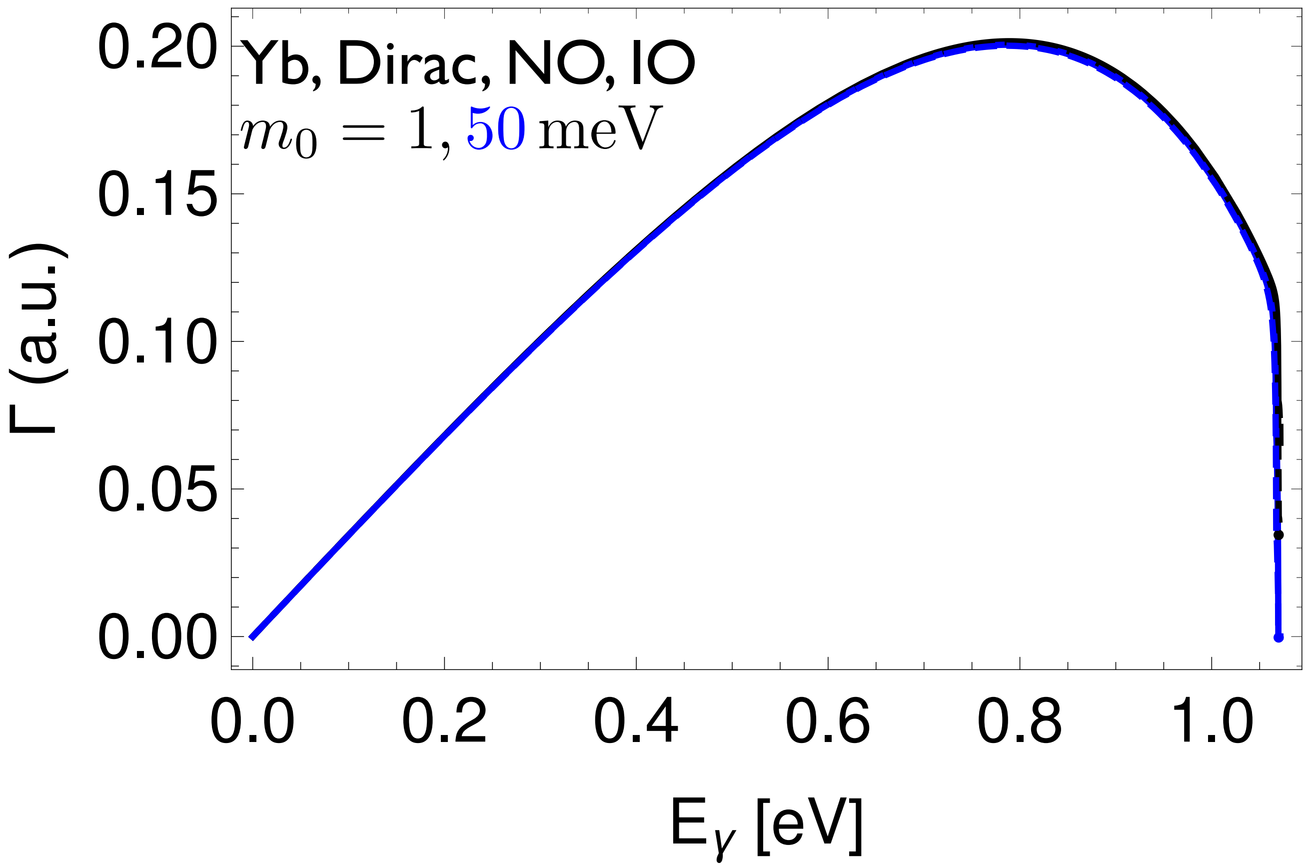
typical laser linewidth

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

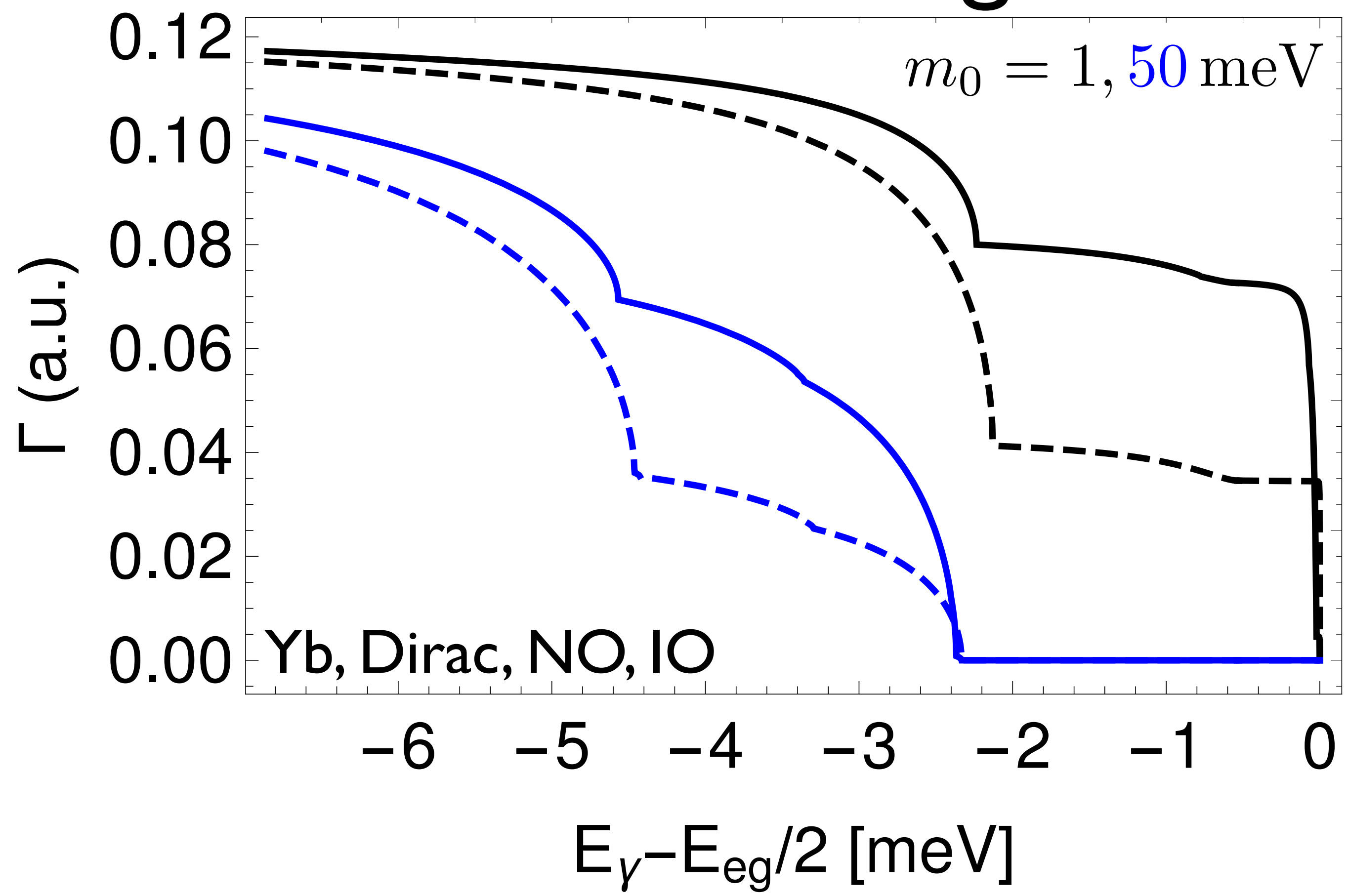
Photon spectrum: Yb



Global shape



Threshold region



Boosted RENP

M.T., K.Tsumura, N.Sasao, S.Uetake, M.Yoshimura, PRD96, 113005 (2017); arXiv:1710.07135

Initial spatial phase

Preparation of initial coherent state

Two-photon absorption: $\gamma_1(k_1) + \gamma_2(k_2) + |g\rangle \to |e\rangle$

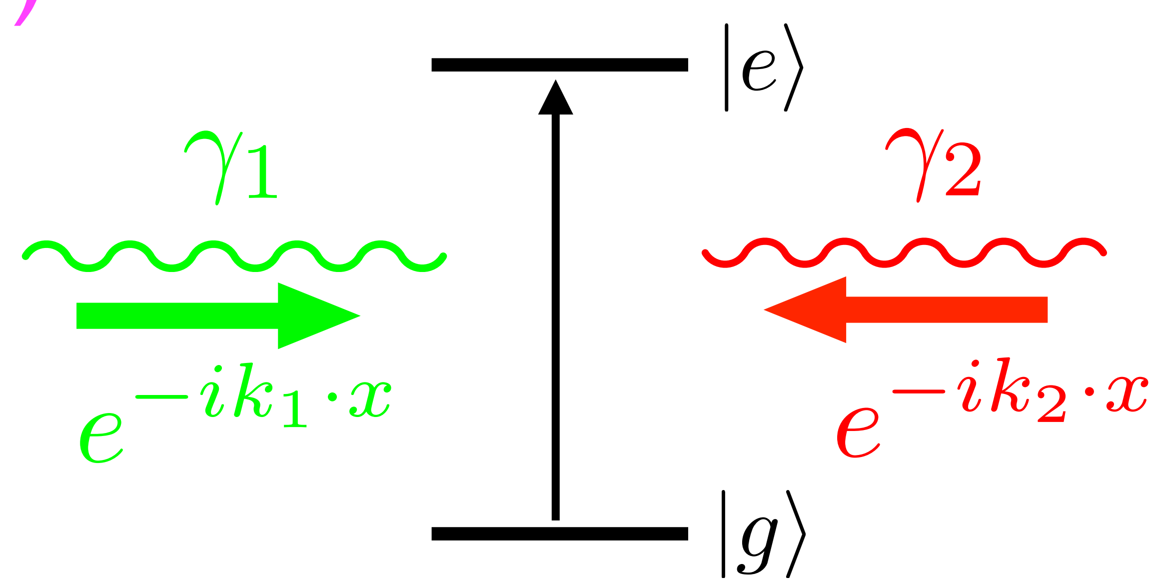
Initial spatial phase (ISP)

counter-propagating

$$\langle e|\rho|g\rangle \propto e^{i\boldsymbol{p}_{eg}\cdot\boldsymbol{x}}$$

$$\boldsymbol{p}_{eg} = \boldsymbol{k}_1 + \boldsymbol{k}_2$$

$$|\boldsymbol{p}_{eg}| = |\omega_1 - \omega_2|$$



Momentum conservation

$$\gamma_1(k_1) + \gamma_2(k_2) + |g\rangle \to |e\rangle \to |g\rangle + \gamma(k) + \nu_i(p)\bar{\nu}_j(p')$$

$$\sum_a e^{i(\boldsymbol{p}_{eg}-\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{p}')\cdot\boldsymbol{x}_a} \propto \delta^3(\boldsymbol{p}_{eg}-\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{p}')$$

$\boldsymbol{p}_{eg} \sim$ mom. of parent particle $\longrightarrow$ boosted RENP

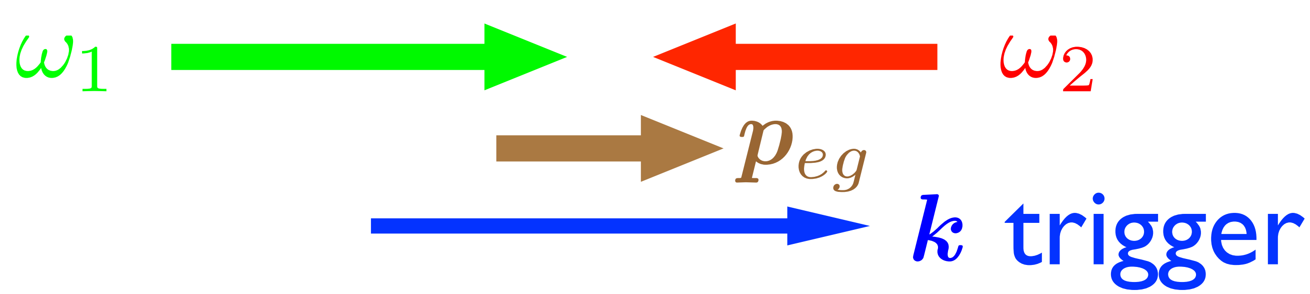
Kinematics of the boosted RENP

4-momentum of parent particle: $(P^\mu) = (E_{eg}, \boldsymbol{p}_{eg})$

Invariant mass: $P^2 = E_{eg}^2 - \boldsymbol{p}_{eg}^2 \leq E_{eg}^2$

smaller energy scale

$\nu_i \bar{\nu}_j$ threshold: $\boldsymbol{p}_{eg} \parallel \boldsymbol{k}, \ \omega_1 \geq \omega_2$



$$\omega_{ij} = \omega_1 - \frac{(m_i + m_j)^2}{4\omega_2}, \ \omega_1 + \omega_2 = E_{eg}$$

cf. no boost case: $\omega_{ij} = \dfrac{E_{eg}}{2} - \dfrac{(m_i + m_j)^2}{2E_{eg}}$

Dirac-Majorana difference, Majorana phases

Spectral rate

$$\Gamma(E_\gamma) = \text{Dirac part} + \text{Majorana interference}$$
$$\propto \mathrm{Re}(U_{ei}^* U_{ej} - \delta_{ij}/2)^2 m_i m_j$$

Majorana phases

$$\mathrm{Re}(U_{e1}^* U_{e2})^2 = c_{12}^2 s_{12}^2 c_{13}^4 \cos 2\alpha \simeq 0.20 \cos 2\alpha$$

$$\mathrm{Re}(U_{e1}^* U_{e3})^2 = c_{12}^2 c_{13}^2 s_{13}^2 \cos 2(\beta - \delta) \simeq 0.015 \cos 2(\beta - \delta)$$

$$\mathrm{Re}(U_{e2}^* U_{e3})^2 = s_{12}^2 c_{13}^2 s_{13}^2 \cos 2(\beta - \delta - \alpha)$$
$$\simeq 0.0065 \cos 2(\beta - \delta - \alpha)$$

sensitive to α

Yb RENP spectra: $E_{eg} = 2.14348\ \mathrm{eV},\ \alpha \in [0, \pi/2],\ \beta = 0$

no boost

boosted: $b := |\boldsymbol{p}_{eg}|/E_{eg} = 0.95$

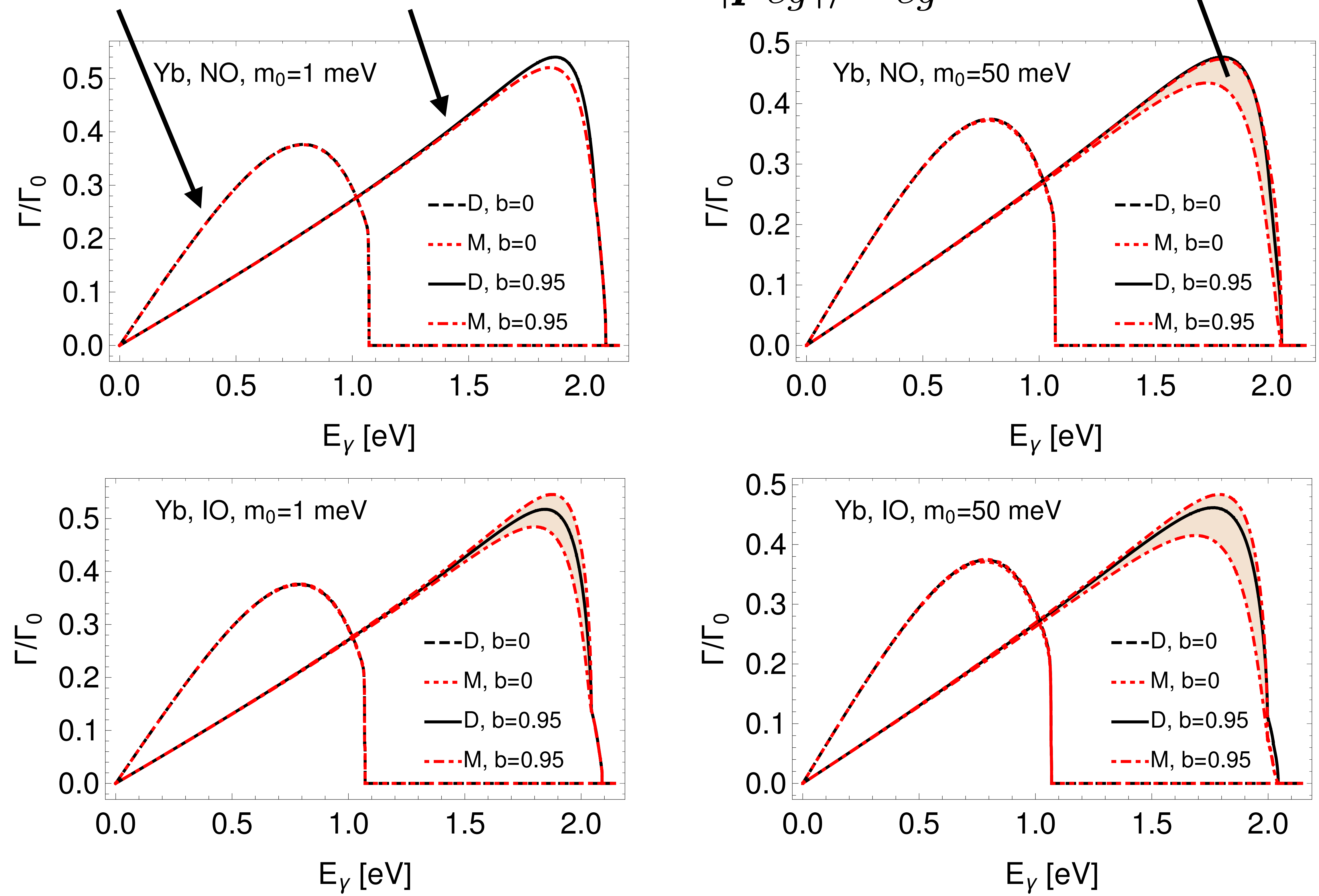
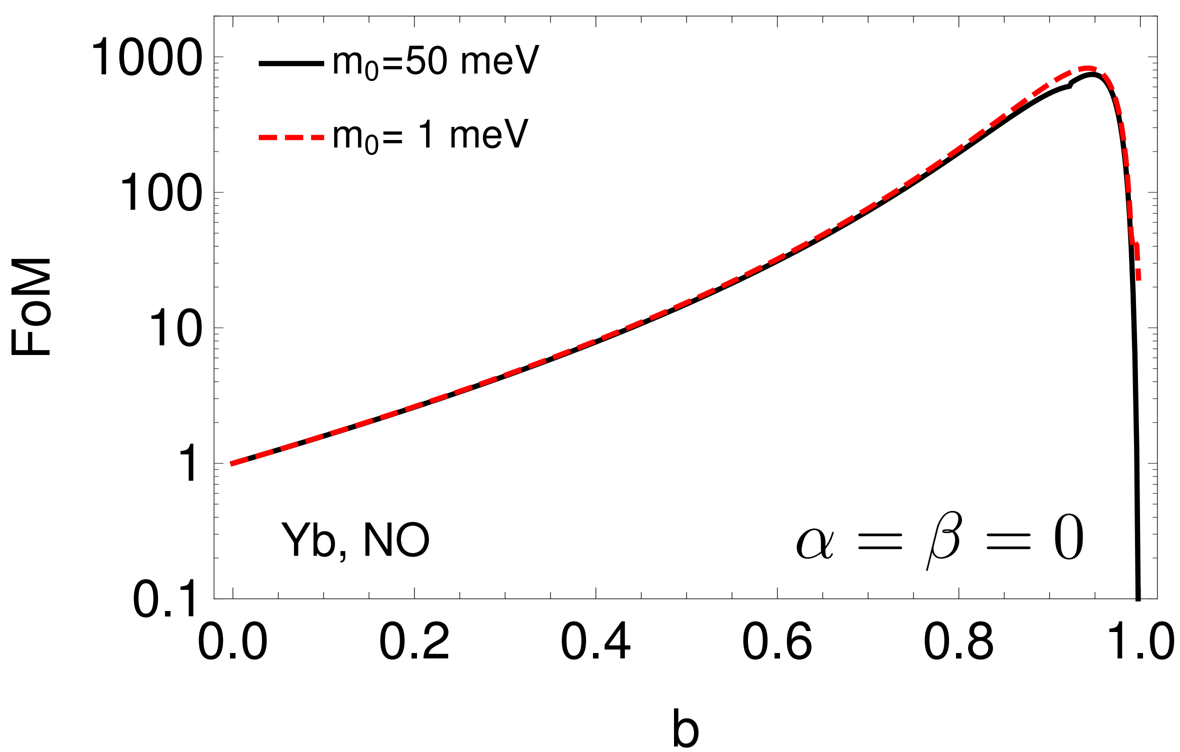
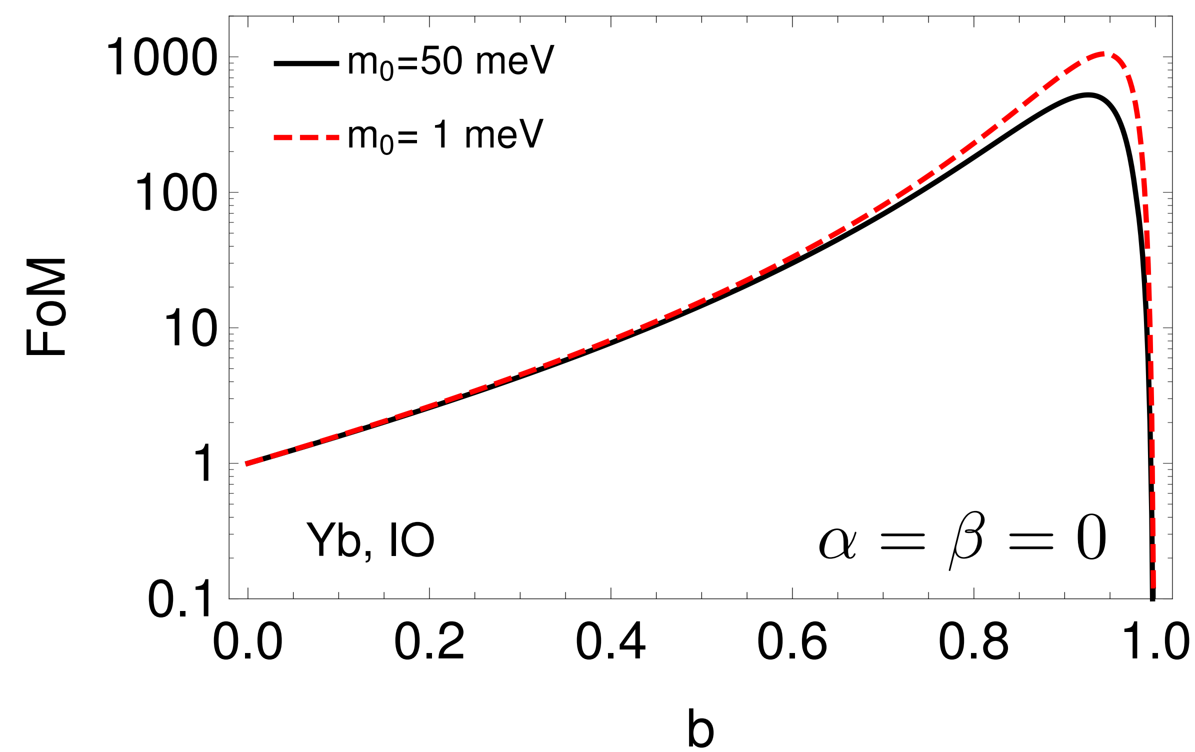


Figure of merit

Power of Dirac-Majorana distinction

relative enhancement of χ^2





$$\chi^2 = 1 \text{ (no boost)} \Longrightarrow \sim 1000 \text{ (optimal boost)}$$

SUMMARY

Neutrino Physics with Atoms/Molecules

- ✶ RENP spectra are sensitive to unknown neutrino parameters.

  Absolute mass, NO or IO, Dirac or Majorana, CP

- ✶ ISP makes RENP more powerful, boosted RENP.
- ✩ RENP spectra are sensitive to the CNB.
- ✩ Background-free RENP M.Yoshimura, N. Sasao, M.T. PTEP(2015)053B06; arXiv:1501.05713

  Waveguide with photonic crystals

  M.T., K.Tsumura, N. Sasao, M.Yoshimura, PTEP(2017)043B03; arXiv:1612.02423

- ✶ Macrocoherent rate amplification is essential.

  Demonstrated by a QED process, PSR.

A new approach to neutrino physics