原子過程を用いた
宇宙背景ニュートリノの測定法

田中 実 (阪大理)
吉村太彦 (岡山大自然), 笹尾 登 (岡山大極限量子)

2015/3/21, 日本物理学会 第70回年次大会 @早稲田

Cosmic Neutrino Background (CNB)

Big bang cosmology

Standard model of particle physics

CNB

holy grail

CNB at present: $f(\boldsymbol{p}) = [\exp(|\boldsymbol{p}|/T_\nu - \xi) + 1]^{-1}$

(not) Fermi-Dirac dist. $|\boldsymbol{p}| = \sqrt{E^2 - m_\nu^2}$

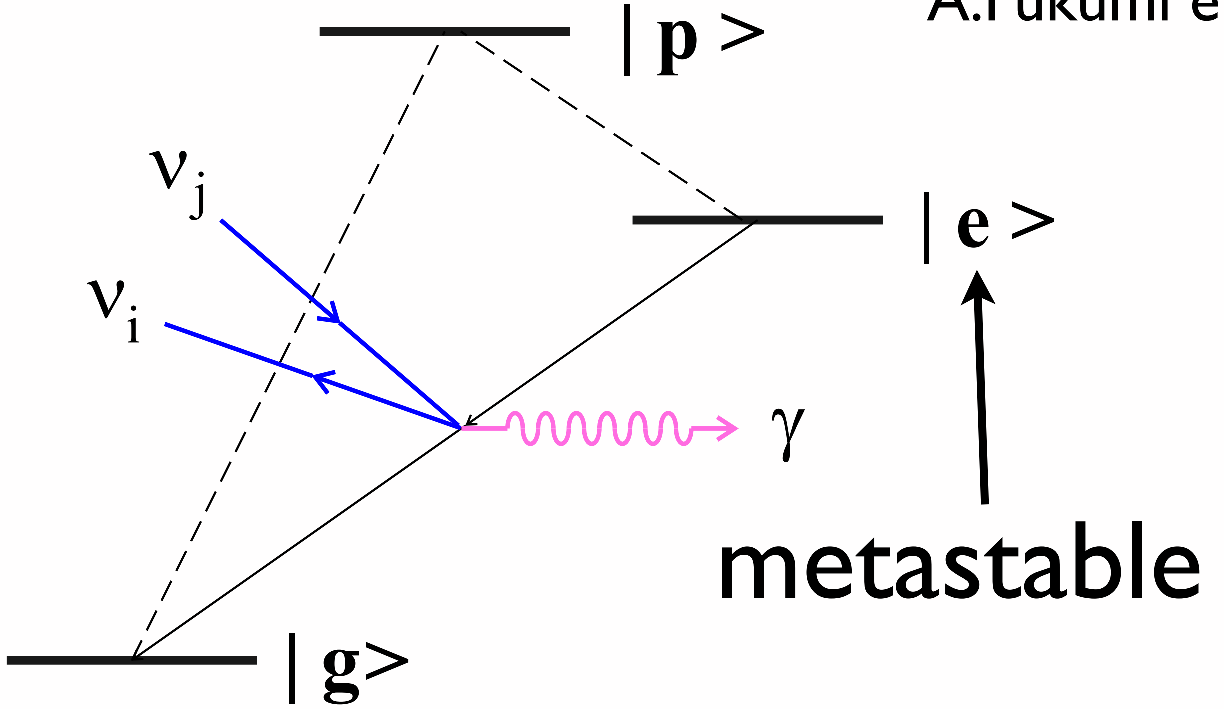
$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K} \simeq 0.17\ \mathrm{meV}$$

$$n_\nu \simeq 6 \times 56\ \mathrm{cm}^{-3}$$

Detection?

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

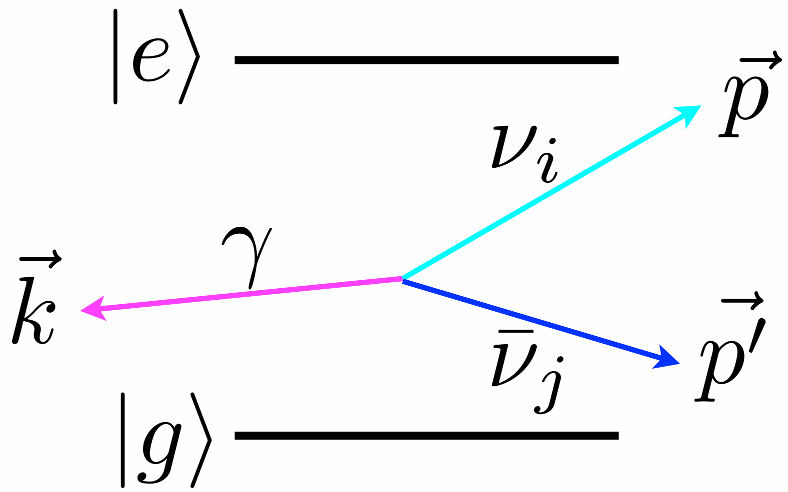
→ measurement of absolute neutrino mass

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

Enhancement mechanism?

Macrocoherence

Yoshimura et al. (2008)



position of atom

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

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

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

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

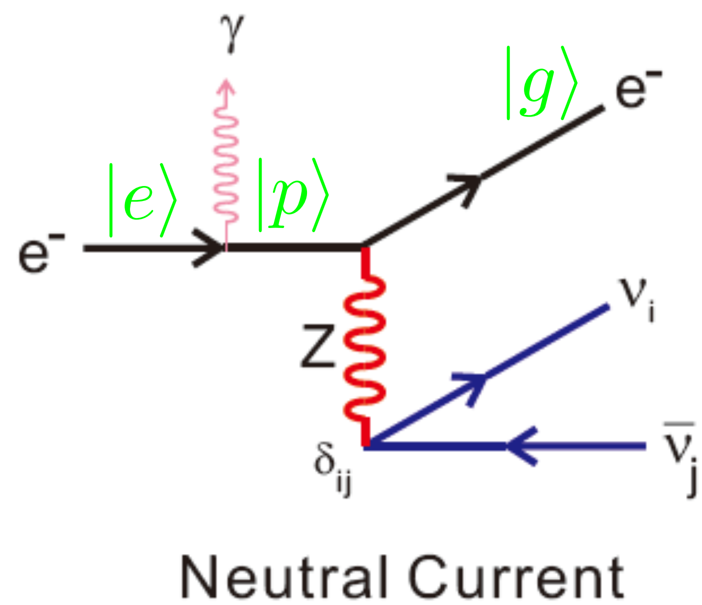
$$d\Gamma \propto \boxed{n^2 V}(2\pi)^4\delta^4(q-p-p') \qquad q^\mu=(\epsilon_{eg}-\omega,-\vec{k})$$

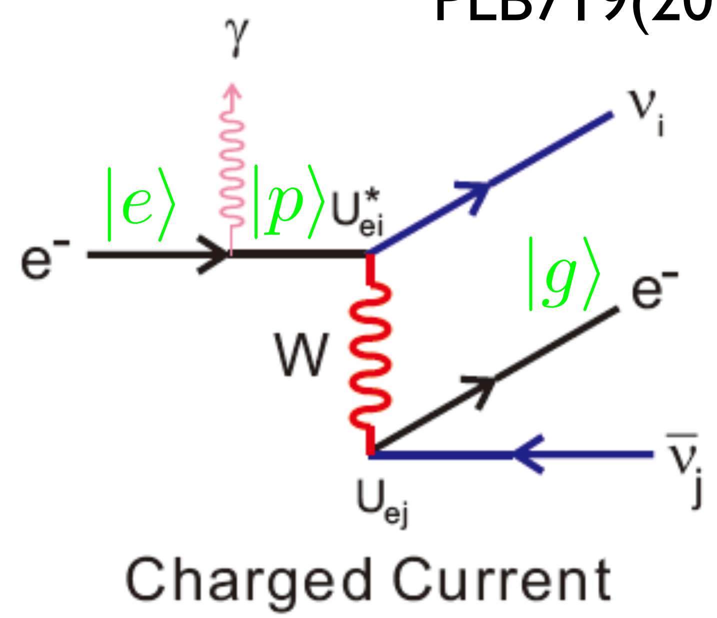
macrocoherent amplification

Neutrino emission mechanisms

Spin current

D.N. Dinh, S.T. Petcov, N. Sasao, M.T., M.Yoshimura
PLB719(2013)154, arXiv:1209.4808

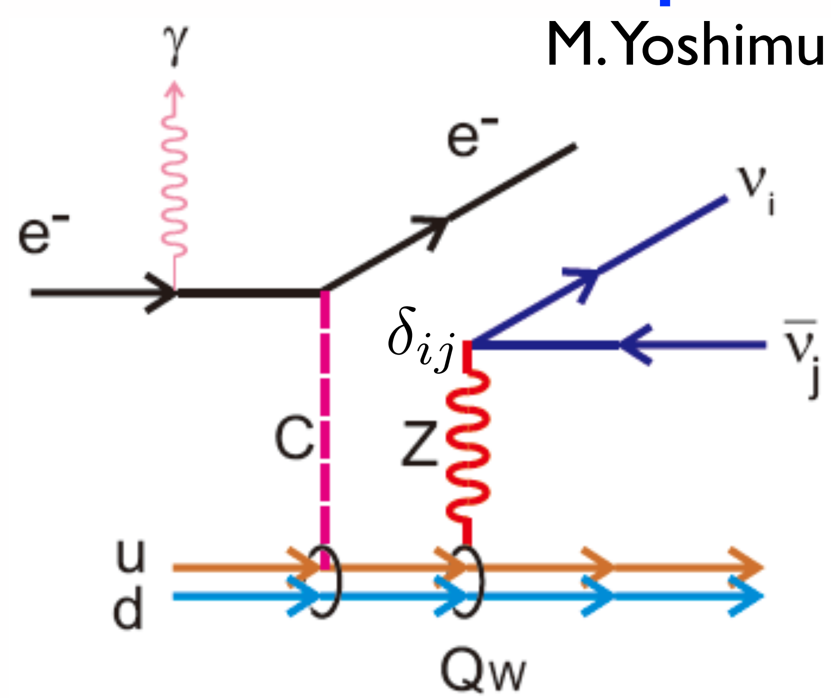




flavor changing
PMNS, phases

Nuclear monopole

M.Yoshimura and N. Sasao, PRD89, 053013(2014), arXiv:1310.6472



flavor diagonal
no PMNS, no phases

$\propto Q_W^2 Z^{8/3}$ enhancement

cf. atomic parity violation

RENP spectrum

Energy-momentum conservation
due to the macrocoherence
→ familiar 3-body decay kinematics

Six (or three) thresholds of the photon energy

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

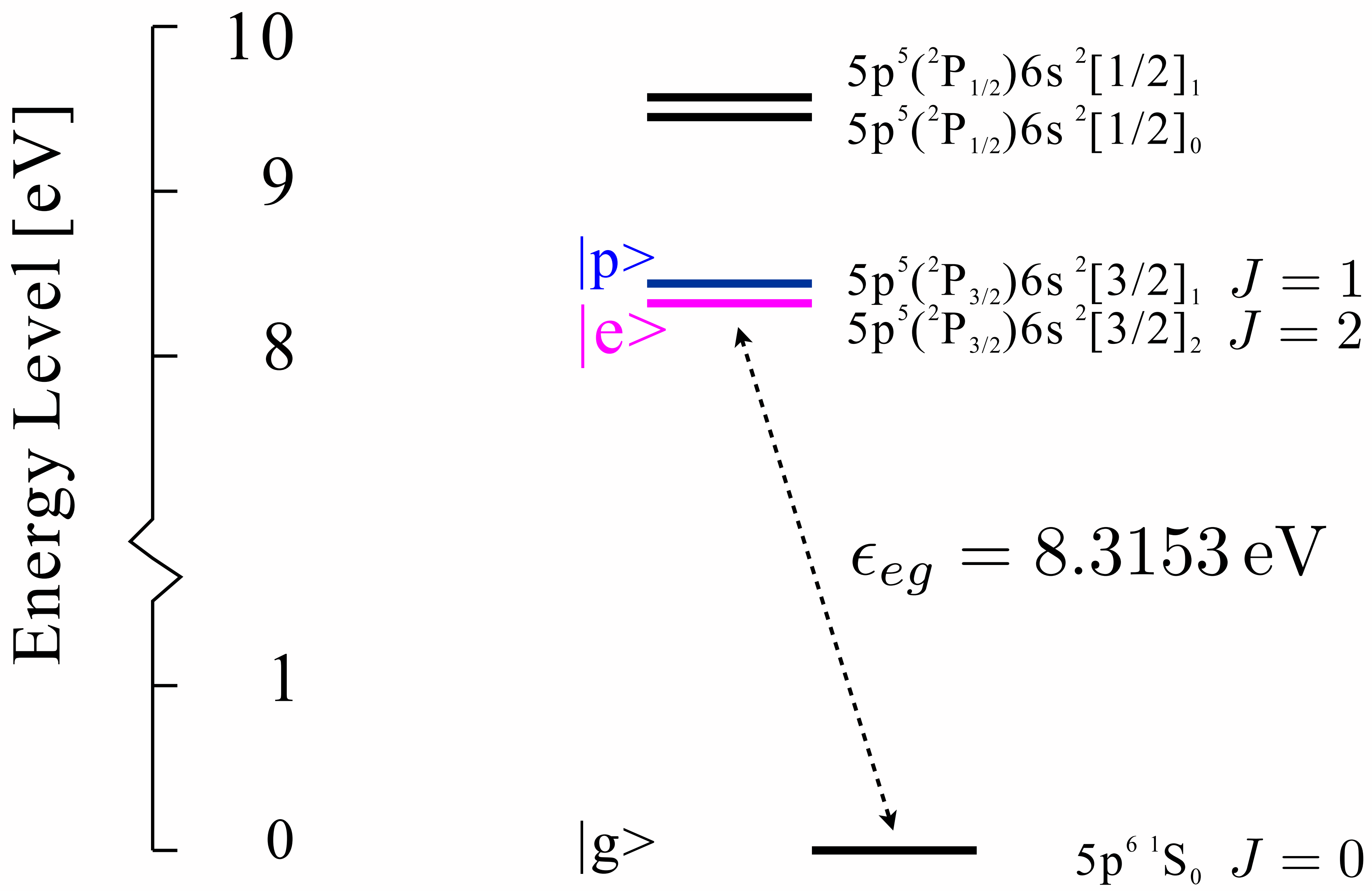
$$\epsilon_{eg} = \epsilon_e - \epsilon_g$$ atomic energy diff.

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)

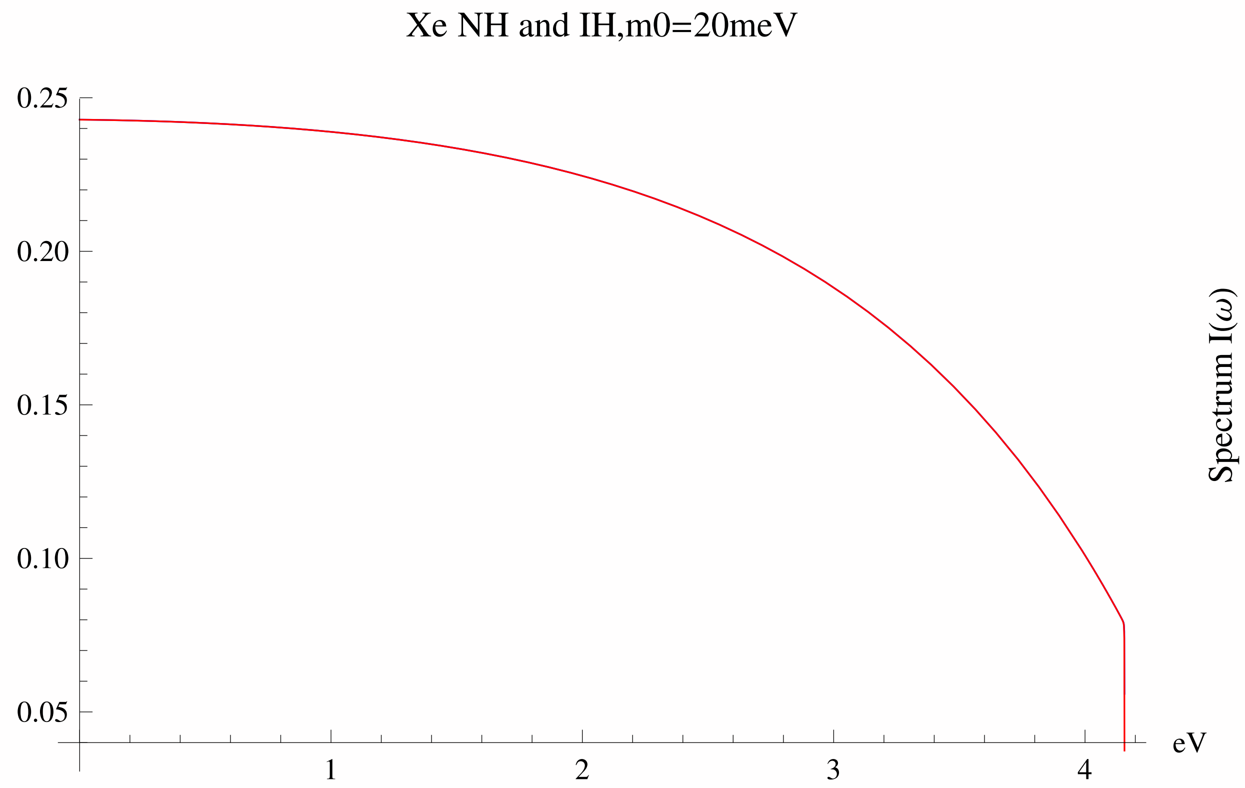


$|e\rangle \leftrightarrow |p\rangle$ M1

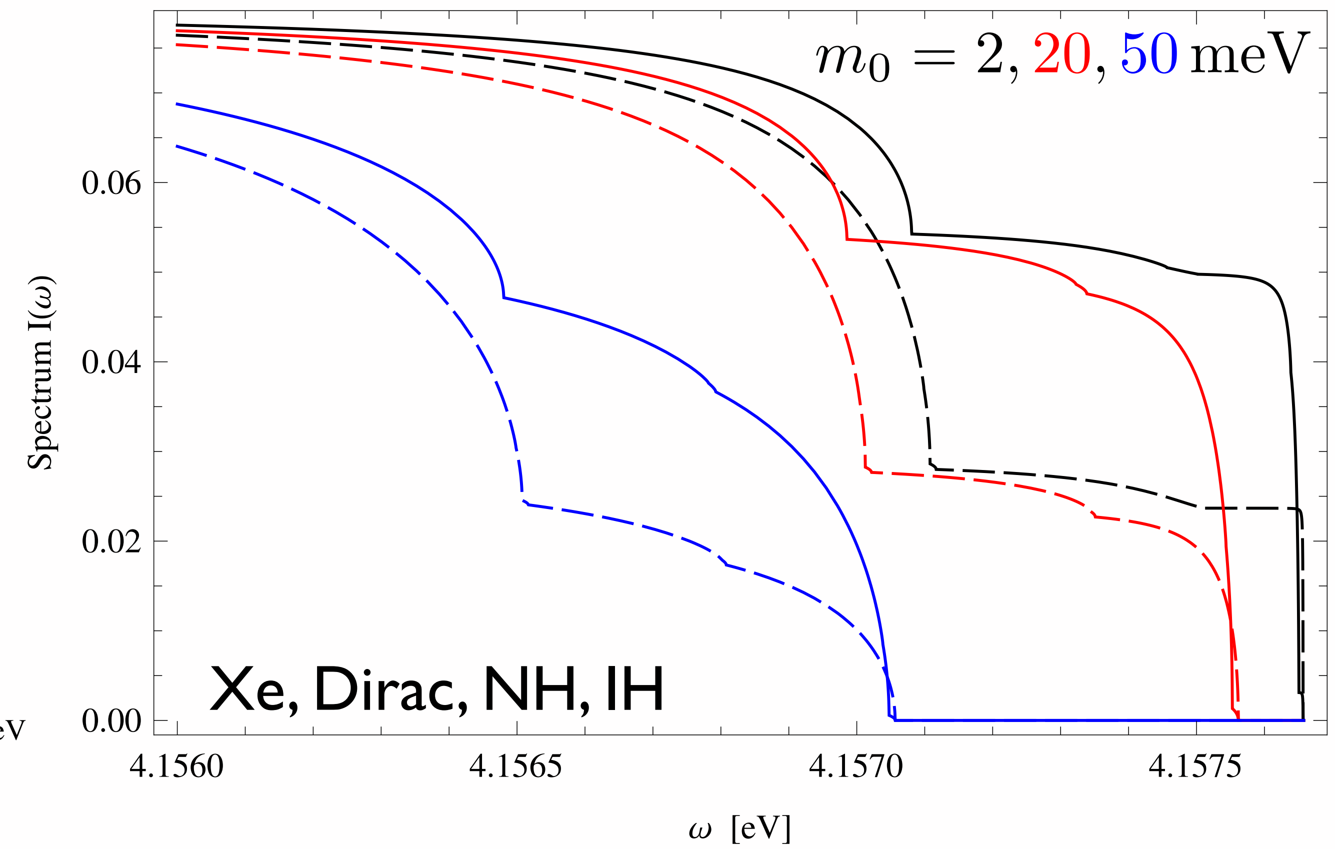
$|p\rangle \leftrightarrow |g\rangle$ E1

Photon spectrum (spin current)

Global shape



Threshold region



The threshold weight factors

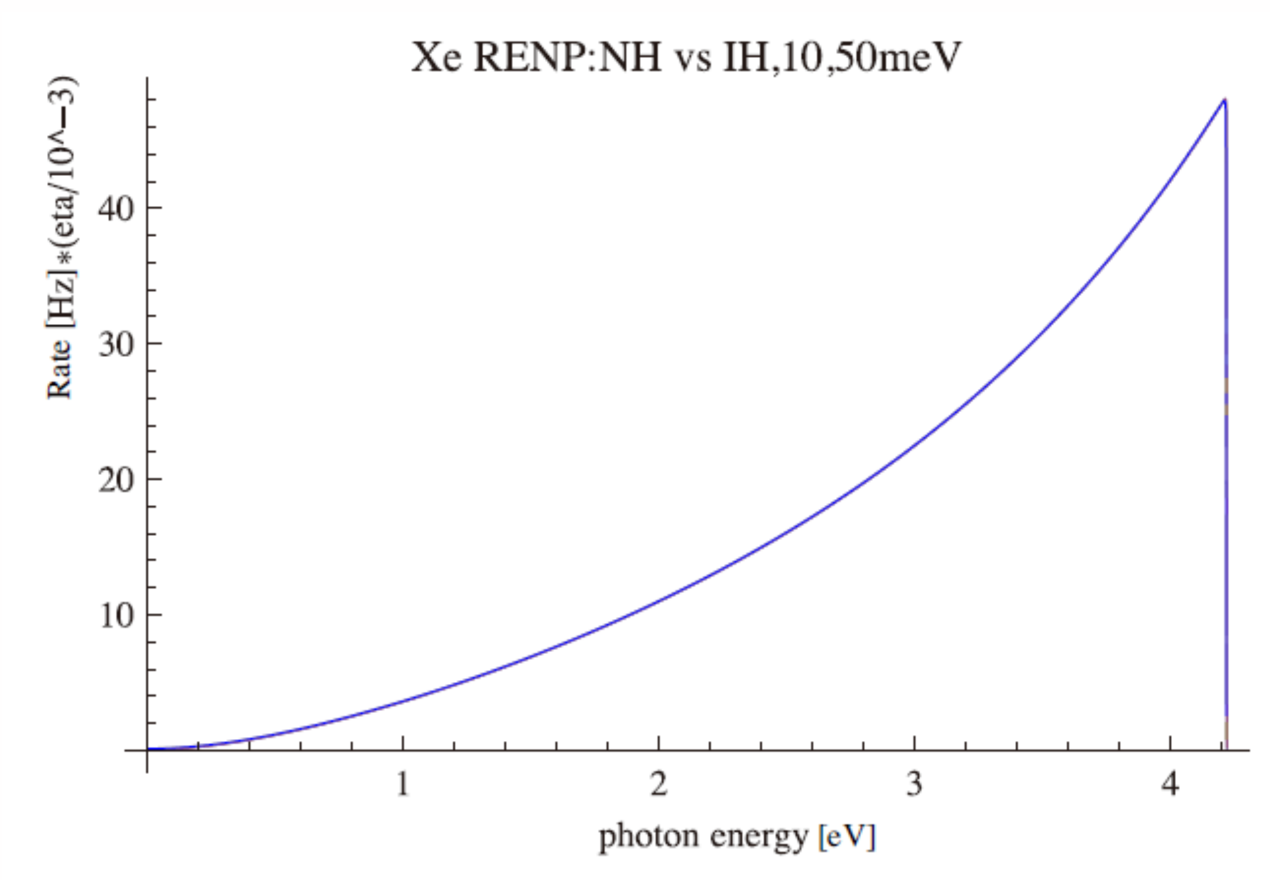
B_{11}	B_{22}	B_{33}	$B_{12}+B_{21}$	$B_{23}+B_{32}$	$B_{31}+B_{13}$
$(c_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{12}^2 c_{13}^2 - 1/2)^2$	$(s_{13}^2 - 1/2)^2$	$2c_{12}^2 s_{12}^2 c_{13}^4$	$2s_{12}^2 c_{13}^2 s_{13}^2$	$2c_{12}^2 c_{13}^2 s_{13}^2$
0.0311	0.0401	0.227	0.405	0.0144	0.0325

Photon spectrum (nuclear monopole)

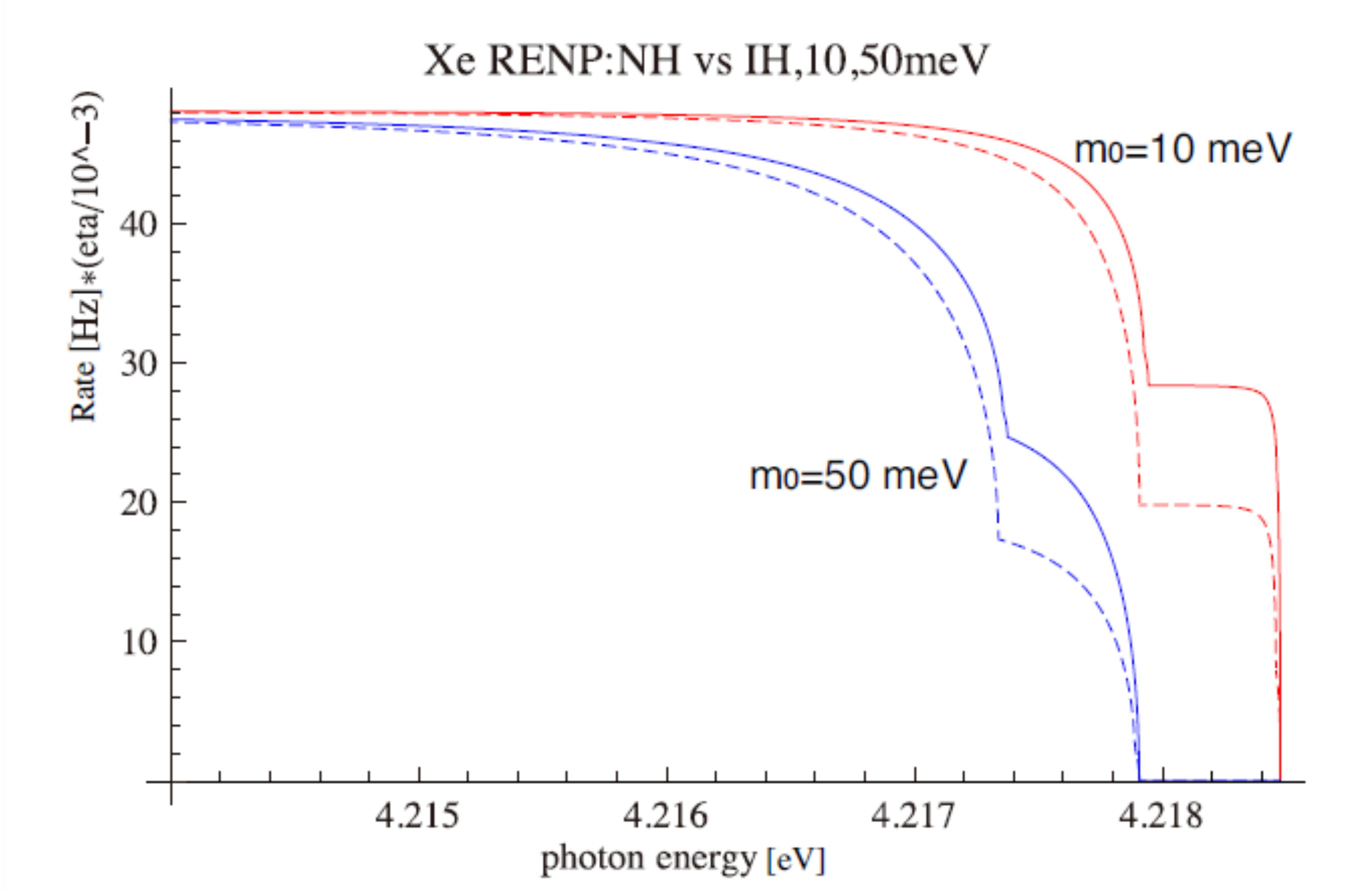
Xe $^3\mathrm{P}_1$ 8.4365 eV

$$n = 7 \times 10^{19}\ \mathrm{cm}^{-3} \quad V = 100\ \mathrm{cm}^3$$

Global shape



Threshold region



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

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

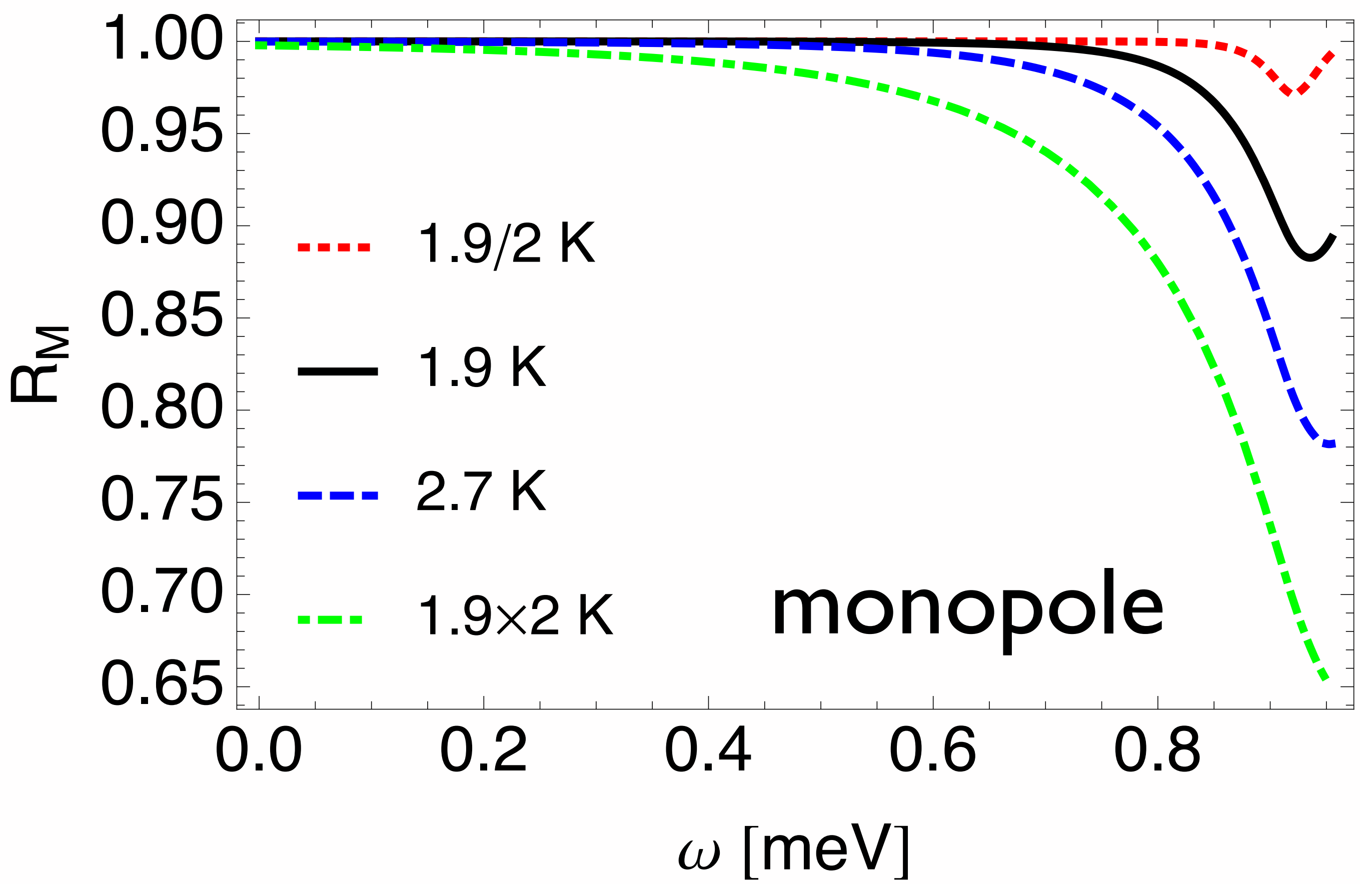
→ spectral distortion

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

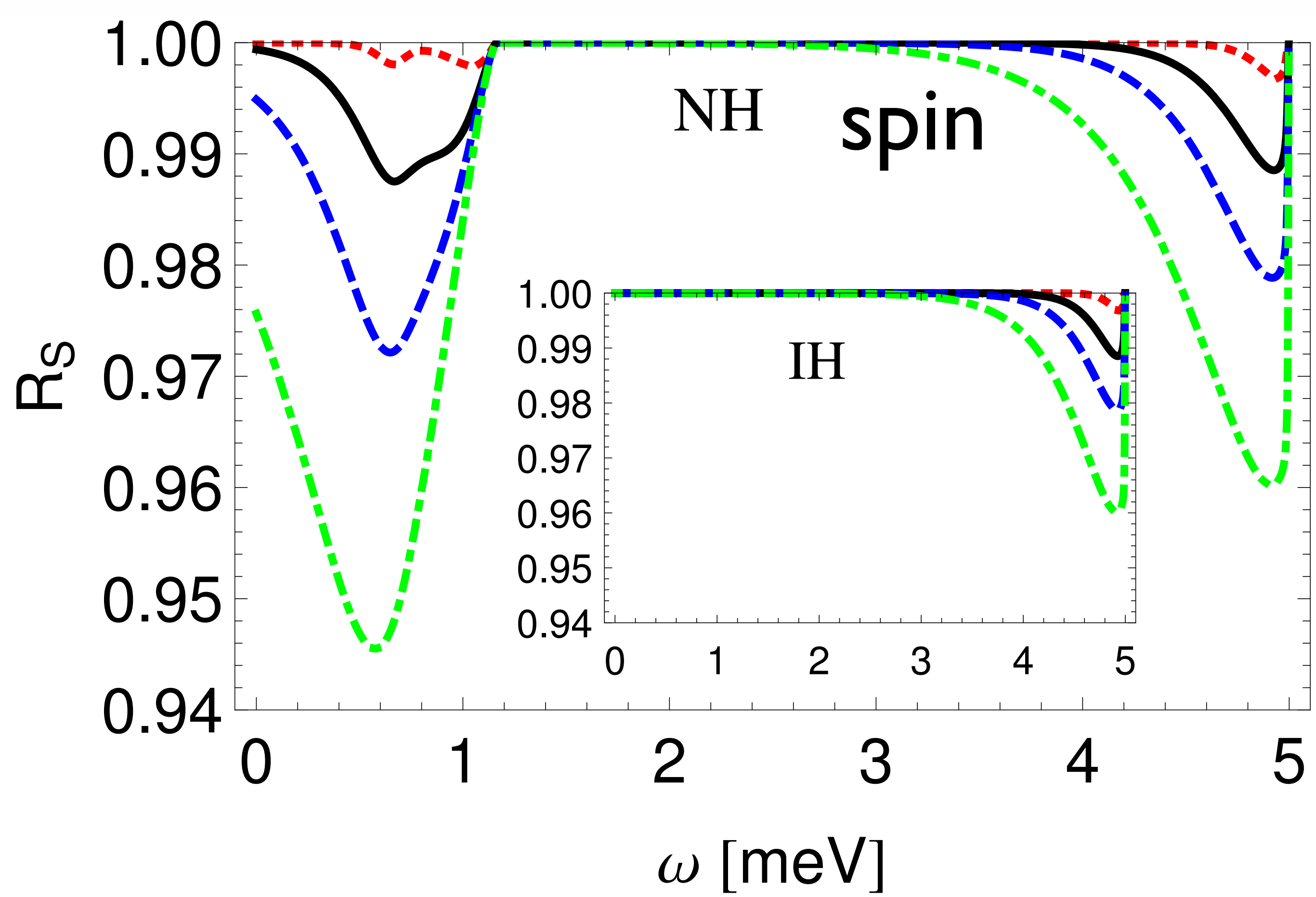
$\epsilon_{eg} = 11 \text{ meV}$

smallest neutrino mass

$m_0 = 5 \text{ meV}$

chemical potential

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

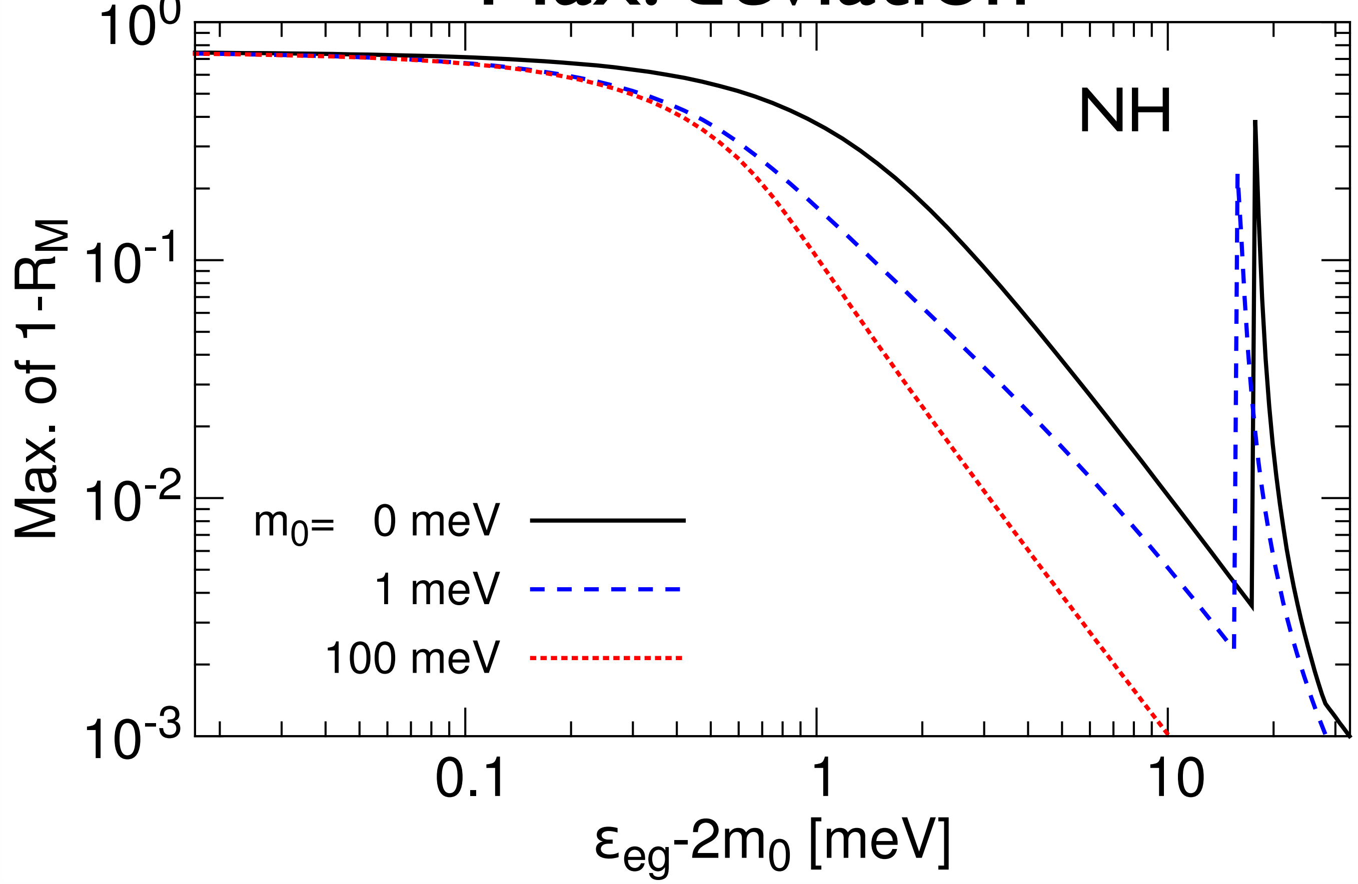


$\epsilon_{eg} = 10 \text{ meV}$

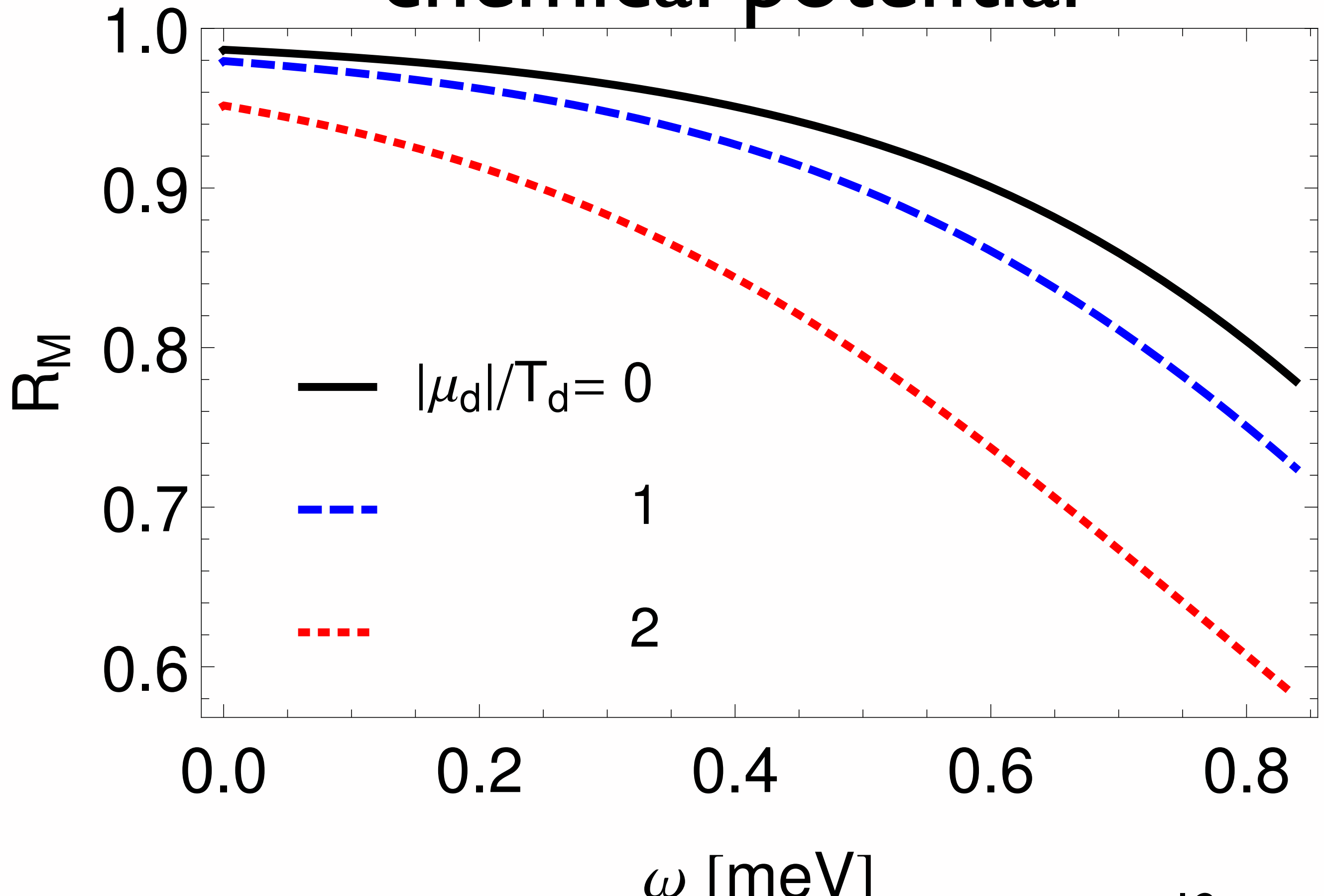
$m_0 = 0.1 \text{ meV}$

$\xi_i = 0$

Max. deviation



chemical potential



$$\epsilon_{eg} = 10T_\nu \simeq 1.7 \text{ meV}$$

$$m_0 = 0$$

Summary

- ✶ RENP spectra are sensitive to unknown neutrino parameters.
  Absolute mass, NH or IH,
  Dirac or Majorana, CP
- ✶ RENP spectra are sensitive to the cosmic neutrino background.
- ✶ Macrocoherent rate amplification is essential.
  Demonstrated by a QED process, Paired Super-Radiance (PSR).
  $O(10^{15})$ enhancement achieved.

Y. Miyamoto et al.
PTEP113C01(2014),
arXiv1406.2198

A new approach to CNB detection

SPAN@春の学会

SPectroscopy with Atomic Neutrino

3/21 午後: DJ 田中 (CNB)
3/22 午前: DF 増田, 原 (PSR)
午後: DB 笹尾 (シンポ), AG 植竹 (PSR)
3/24 午前: BG 中島, 大饗 (FEL SR), CE 吉見 (Th)

Backup

Past Proposals

Coherent scattering on macroscopic targets

Mechanical force by neutrino wind, $\lambda \sim 2 \text{ mm}$

High-energy beam scattering

$p + \bar{\nu}_{\text{CNB}} \to n + e^{+}$ ULHC

High-energy cosmic ray scattering

$\nu_{\text{CR}} + \bar{\nu}_{\text{CNB}} \to Z$ Z burst

Neutrino capture on beta nuclei

$(Z, A) + \nu_{\text{CNB}} \to (Z + 1, A) + e^{-}$ tritium, Re

Thermal history of cosmic neutrinos

$T \gtrsim 3.2\ \mathrm{MeV}$ $\nu_{e,\mu,\tau}$ in equilibrium

$T \simeq 3.2\ \mathrm{MeV}$ $\nu_{\mu,\tau}$ decoupling

$T \simeq 1.9\ \mathrm{MeV}$ ν_e decoupling

$$f_D(\boldsymbol{p}) = \left[\exp\left(\frac{\sqrt{\boldsymbol{p}^2 + m^2}}{T_D} - \xi\right) + 1\right]^{-1}$$

$T \lesssim 1.9\ \mathrm{MeV}$ free propagation

Present $a = 1$ $f(\boldsymbol{p}) = f_D(\boldsymbol{p}/a_D)$

$$f(\boldsymbol{p}) = \left[\exp\left(\frac{\sqrt{\boldsymbol{p}^2 + (ma_D)^2}}{T_D a_D} - \xi\right) + 1\right]^{-1}$$

$T_\nu = T_D a_D$ $ma_D \ll m$