Modulated Neutrino Signals in a Wave Dark Matter Background

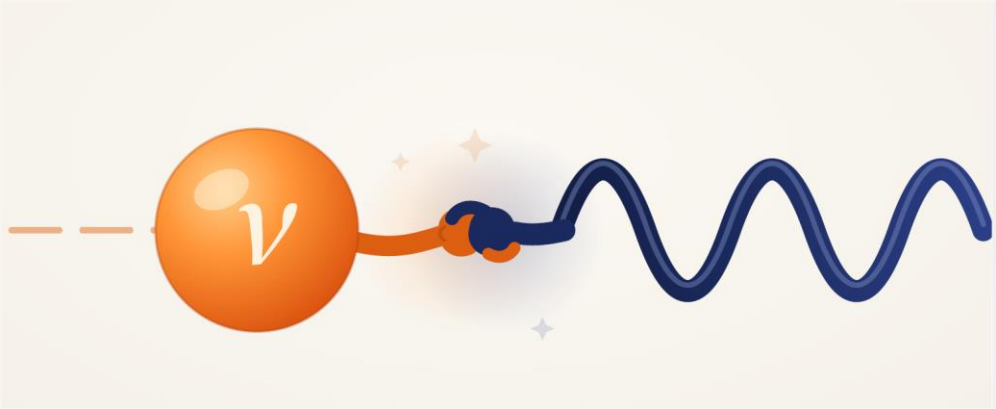
Yechan Kim

KAIST

arXiv: 2305.16900. PRD 108, 095028 (2023)

arXiv: 2503.04949. JHEP 07 (2025) 269

arXiv: 2604.14480. PRD 114, 055045 (2026)



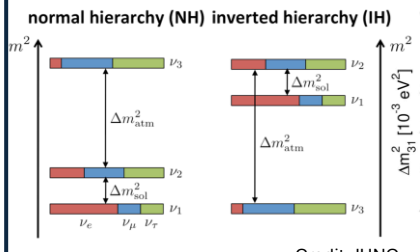
25th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN26)

Unknown & BSM of Neutrino Physics

Neutrino oscillation parameters

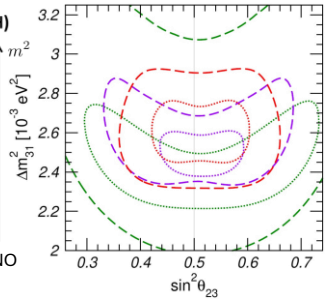
Undetermined

Mass ordering

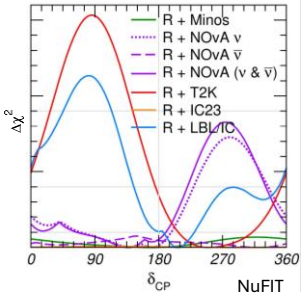


Credit: JUNO

Octant problem



CPV phase

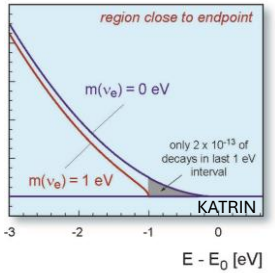


NuFIT

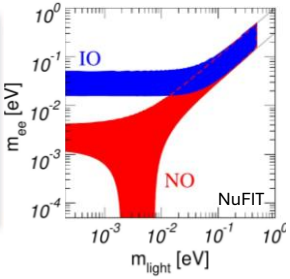
Neutrino absolute mass

Unknown

Beta decay spectrum

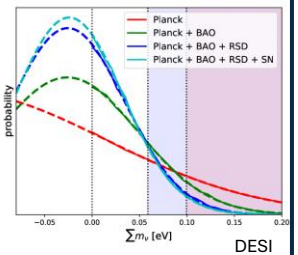


0νββ decay



NuFIT

CMB bound

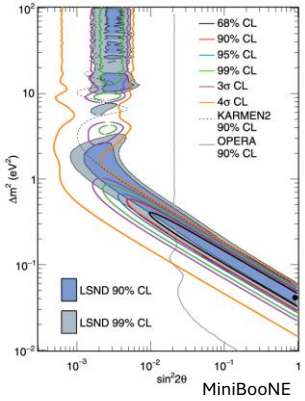


DESI

Sterile neutrino

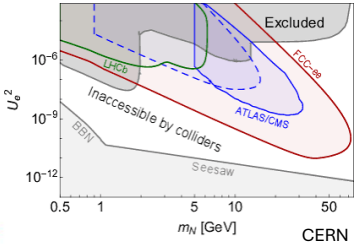
Hypothetical

3+1 regime



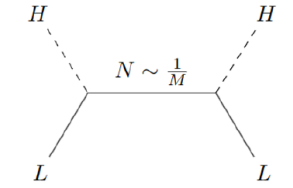
MiniBooNE

HNL search



CERN

Seesaw mechanism

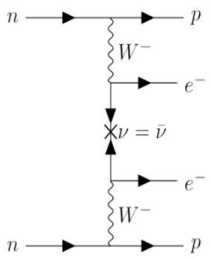


$$-\frac{y}{M}LLHH \rightarrow m_\nu = \frac{yv^2}{M}$$

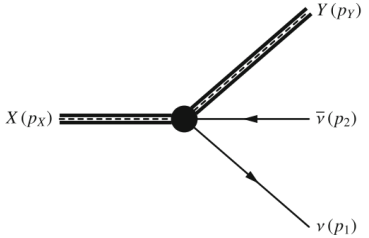
Dirac/Majorana types

Undetermined

LNV process



Neutrino pair emission

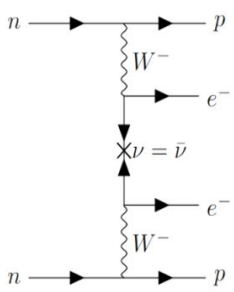


CS Kim et al. (2023)

Rare event searches probing Neutrino natures

0νββ decay

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



Majorana nature

$$\langle 0 \,|\, \nu_i(x)\nu_i(y)^T \,|\, 0 \rangle \neq 0$$

Effective Majorana mass

$$m_{ee} = \left| \sum_i m_i U_{ei}^2 \right|$$

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \left(\frac{m_{ee}}{m_e} \right)^2$$

$T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ yr KamLAND-Zen

$m_{ee} < 28 - 122$ meV

Process requires helicity-flip (Majorana)

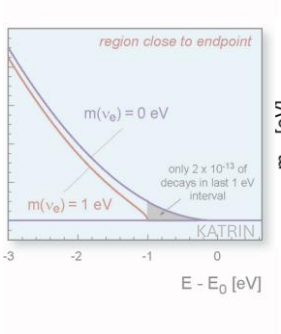
→ Amplitude ∝ m/E

→ **Hard to detect** for E>>m **(Relativistic)**

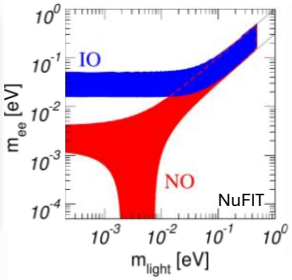
Undetected

Neutrino absolute mass

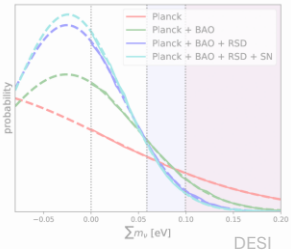
Beta decay spectrum



0νββ decay

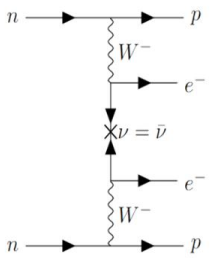


CMB bound

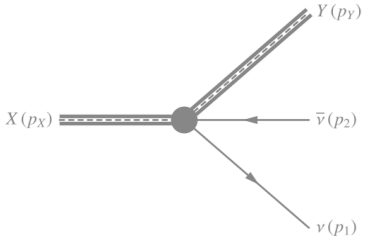


Dirac/Majorana types

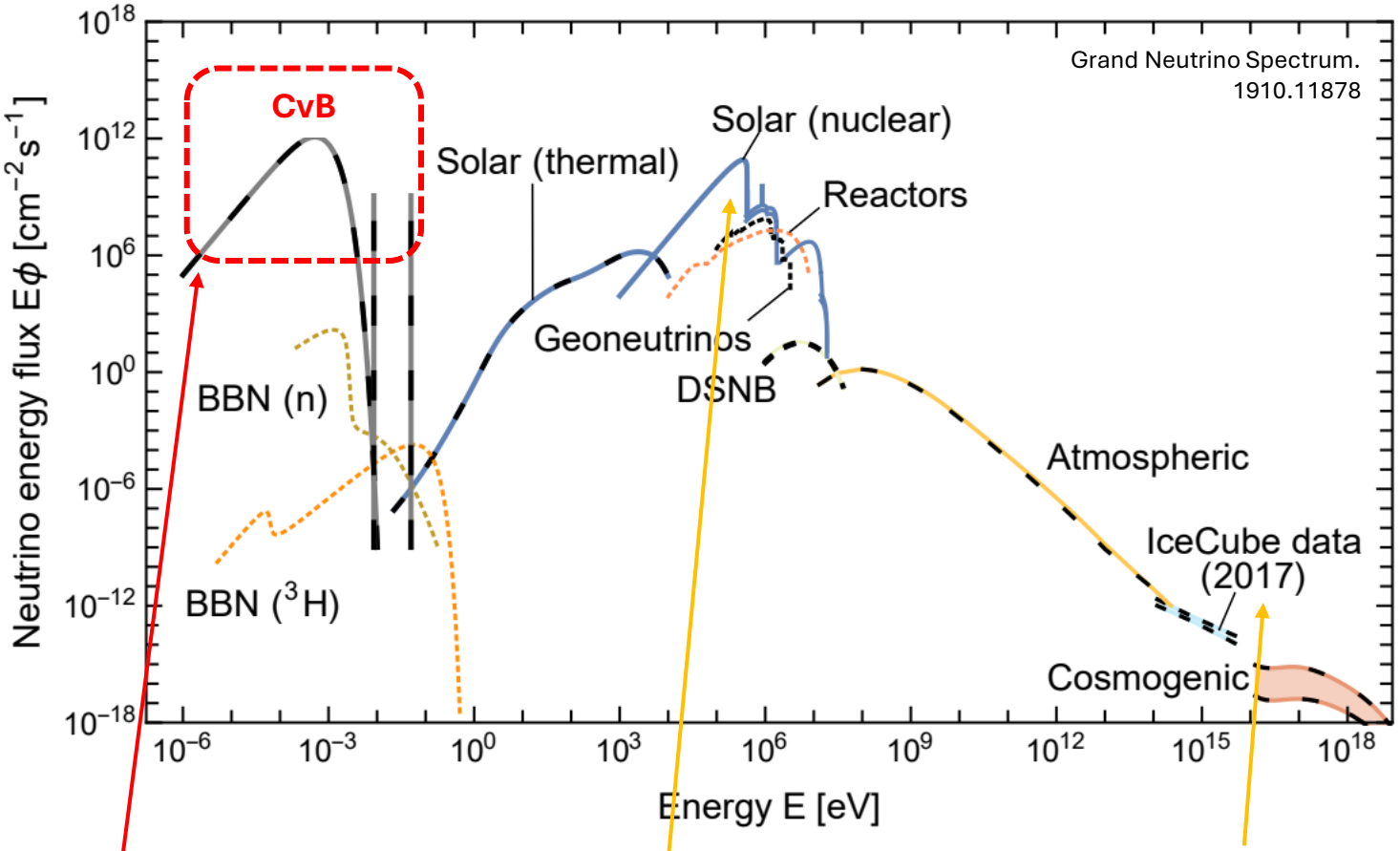
LNV process



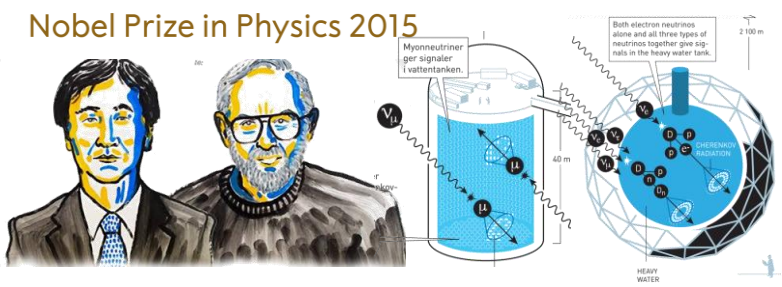
Neutrino pair emission

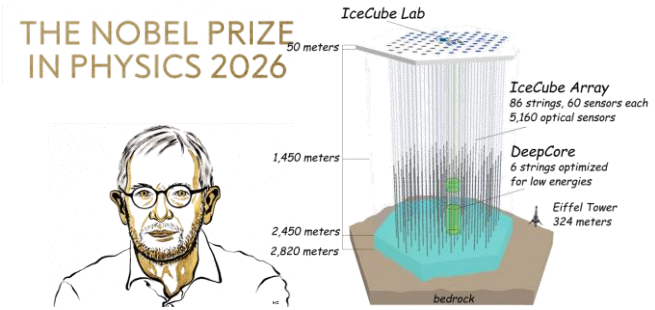


CS Kim et al. (2023)



Low-E neutrino
as probe nature!!

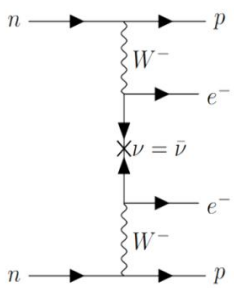




Rare event searches probing Neutrino natures

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Process requires helicity-flip (Majorana)

→ Amplitude ∝ m/E

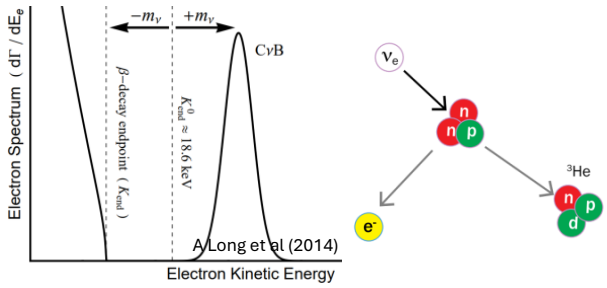
→ **Hard to detect** for E>>m **(Relativistic)**

Undetected

CνB

$$\nu + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$

Shift as m_ν



$T_\nu = 0.168$ meV **(Non-relativistic)**

$\Gamma_{C\nu B}^{D} \approx 4.06\ \mathrm{yr}^{-1}$

$\Gamma_{C\nu B}^{M} \approx 8.12\ \mathrm{yr}^{-1}$

PTOLEMY (target 100g)

Twice for **Majorana type** with contributions form both helicities

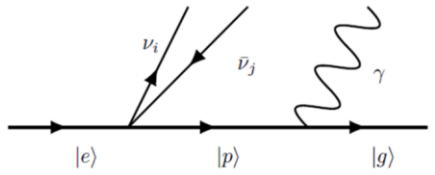
Rare event & large background

$\bar{\sigma} \simeq 10^{-45}\ \mathrm{cm}^2$

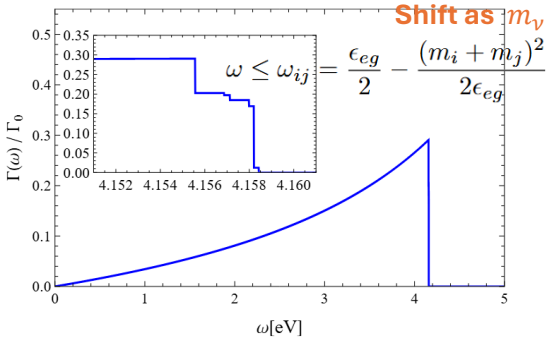
Undetected

Neutrino emission in atom

$$|e\rangle \to |g\rangle + \gamma(\omega) + \nu_i \bar{\nu}_j$$



Shift as m_ν



E~m (Near **non-relativistic** around thresold)

→ **Dirac/Majorana distinction**

Rare event & large background

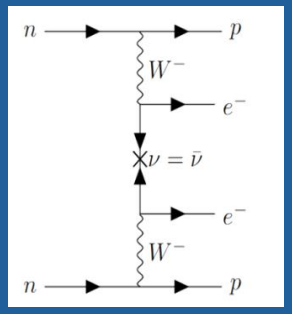
$\Gamma_0 \simeq 1\mathrm{Hz}\ (n/10^{22}\mathrm{cm}^{-3})^3 (V/10^2\mathrm{cm}^3)$

Undetected

Rare event searches probing Neutrino natures

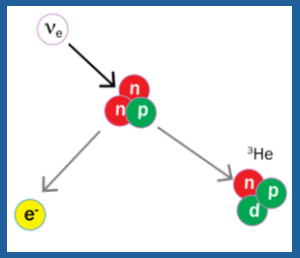
0νββ decay

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



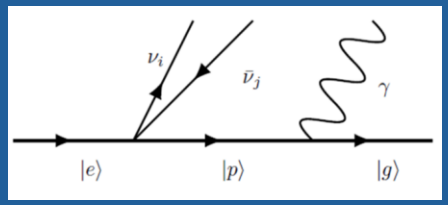
CνB

$$\nu + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$



Neutrino emission in atom

$$|e\rangle \to |g\rangle + \gamma(\omega) + \nu_i \bar{\nu}_j$$



Dark sector

(WIMP, Dark portal, Wave DM, Dark energy …)

Neutrino with Dark sector

Neutrino NSI

(Non-Standard Interaction)

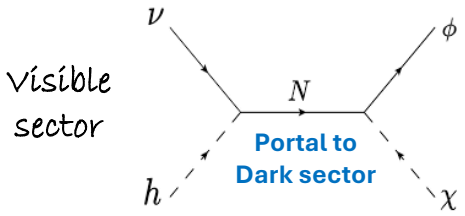
$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'C}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f'\right)$$

$$\varepsilon \propto \frac{m_W^2}{m_X^2}$$ **Small correction**

Constraint by neutrino oscillation

Neutrino portal

$$\mathcal{L} \supset -y\bar{L}HN - \mathcal{L}_{\mathrm{int}}(N,\chi)$$



Neutrino with wave DM

Today's Focus!

$$\phi(t) = \phi_0\cos(m_\phi t) \rightarrow \mathcal{L} \supset -g\phi\bar{\nu}\nu$$

Modulation signals

- Neutrino oscillation
- Neutrino mass
- Dirac/Majorana type
- CvB

MaVaNs

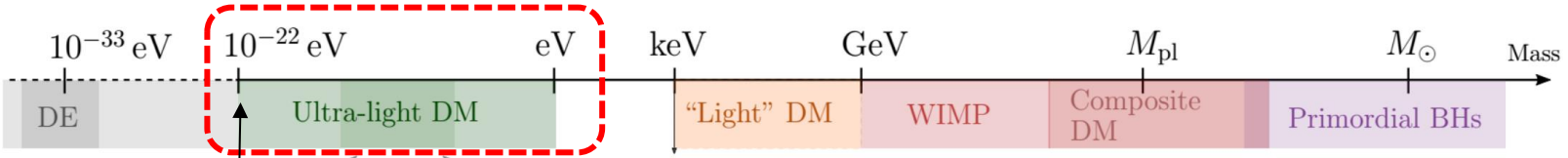
(Mass Varying Neutrinos)

Coupled with Dark energy

$$\dot{\rho}_\nu + 3H(\rho_\nu + p_\nu) = -C_{\mathrm{int}}(\nu, Q)$$
$$\dot{\rho}_Q + 3H(\rho_Q + p_Q) = C_{\mathrm{int}}(\nu, Q)$$

→ Neutrino mass variation $m_\nu(Q)$
& varying equation of state $\omega_Q(z)$

Ultralight wave dark matter



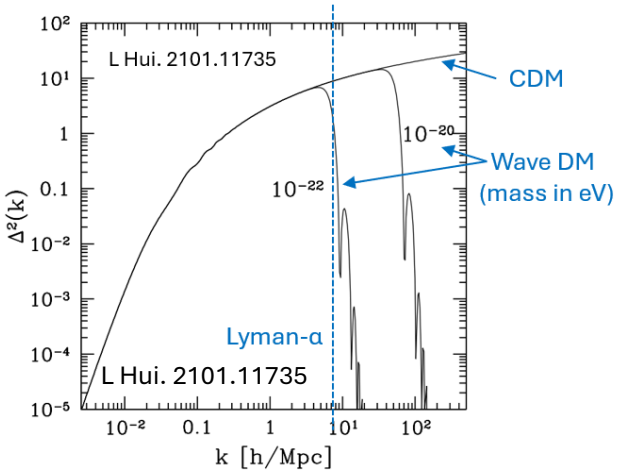
E Ferreria. 2005.03254

$$\mathcal{O}(r_s) \sim \lambda_{\rm dB} \sim 1\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m_\phi}\right)\left(\frac{10^{-4}c}{v}\right)$$

Core size of Dwarf galaxy

$$m_a \sim \frac{\Lambda^2}{f_a} \sim \frac{m_\pi f_\pi}{f_a}$$

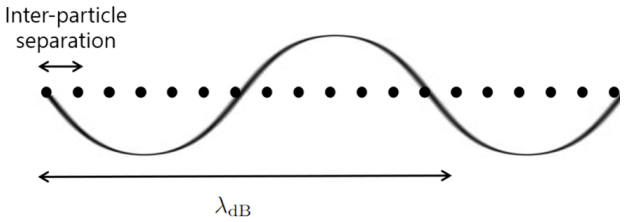
QCD axion or ALP



Matter power spectrum

$$k_{1/2} \simeq 6\left(\frac{m_\phi}{10^{-22}\,{\rm eV}}\right)^{4/9} {\rm h/Mpc}$$

➔ **Lower bound** $10^{-22}\,{\rm eV} \lesssim m_\phi$



Wave-like behavior

$$\lambda_{\rm dB} = \frac{2\pi}{m_\phi v} \gg \ell_{\rm sep} = \left(\frac{m_\phi}{\rho_{\rm DM}}\right)^{1/3}$$

$$\mathcal{N} = n\,\lambda_{\rm dB}^3 = \left(\frac{30\,{\rm eV}}{m_\phi}\right)^4 \left(\frac{10^{-4}}{v}\right)^3 \gg 1$$

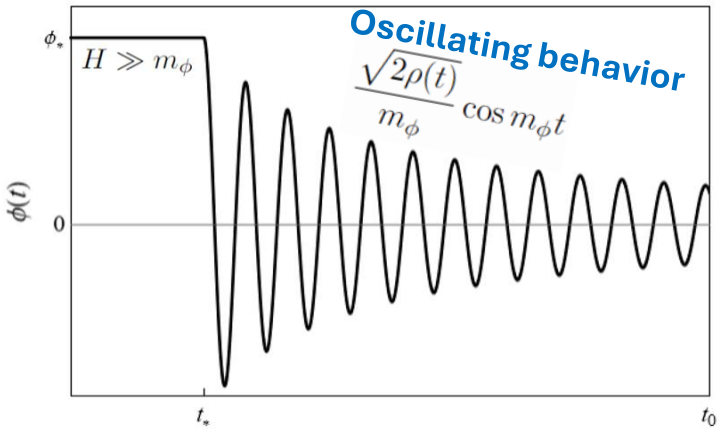
➔ **Upper bound** $m_\phi \ll 30\,{\rm eV}$

Ultralight wave dark matter

$$S = \int d^4x \sqrt{-g}\left[-\frac{1}{2} g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - \frac{1}{2} m_\phi^2 \phi^2\right]$$

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

$$\phi(t) = \begin{cases} \phi_* & H > m_\phi \\ \dfrac{\sqrt{2\rho(t)}}{m_\phi}\cos m_\phi t & H < m_\phi \end{cases}$$



Coupled to gauge boson

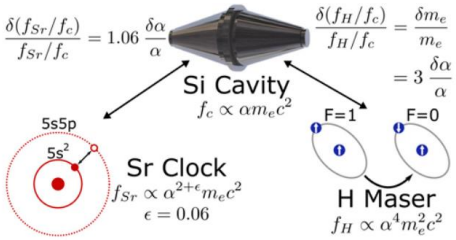
$$\mathcal{L} \supset -\frac{1}{4} d_e\,\kappa\,\phi\,F_{\mu\nu}F^{\mu\nu}$$

$$\alpha(t) = \alpha\left[1 + d_e\,\kappa\,\phi_0\cos(m_\phi t)\right]$$

$$\mathcal{L} \supset -\frac{1}{4} d_g\,\kappa\,\phi\,G^a_{\mu\nu}G^{a\,\mu\nu}$$

$$\Lambda_{\rm QCD}(t) = \Lambda_{\rm QCD}\left[1 + d_g\,\kappa\,\phi_0\cos(m_\phi t)\right]$$

A Arvanitaki et al. 1405.2925
K Van Tilburg et al. 1503.06886
CJ Kennedy et al. 2008.08773
J Guo et al. 2206.14221



Coupled to SM fermion

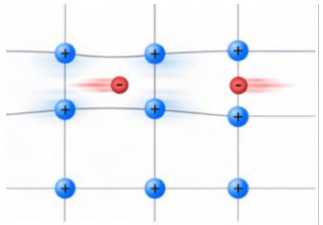
$$\mathcal{L} \supset -d_{m_e}\,\kappa\,\phi\,m_e\,\bar{e}e$$

$$m_e(t) = m_e\left[1 + d_{m_e}\,\kappa\,\phi_0\cos(m_\phi t)\right]$$

$$\mathcal{L} \supset -d_{m_q}\,\kappa\,\phi\,m_q\,\bar{q}q$$

$$m_q(t) = m_q\left[1 + d_{m_q}\,\kappa\,\phi_0\cos(m_\phi t)\right]$$

A Arvanitaki et al. 1405.2925
CJ Kennedy et al. 2008.08773
M Filzinger et al. 2312.13723
YL ChoeJo, YK, HS Lee, J Lee, J Yi. 2509.22892



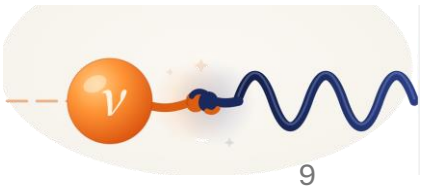
Coupled to neutrino

$$\mathcal{L} \supset -g\,\phi\,\overline{N}N$$

$$M_N(t) = M_N + g\,\phi_0\cos(m_\phi t)$$

Dirac or **Majorana** mass?

A Berlin. 1608.01307
G Krnjaic et al. 1705.06740
A Dev et al. 2205.06821
YL ChoeJo, YK, HS Lee. 2305.16900



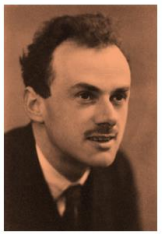
Dirac vs. Majorana types

Dirac mass Majorana mass

$$\mathcal{L} = -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \bar{\nu}_M \nu_M$$

$$\nu_D = \nu_L + \nu_R$$
$$\nu_M = \nu_R + \nu_R^c$$

Dirac



vs

Majorana



Quasi-Dirac type $(m_D \gg m_R)$



$$\mathcal{L} = -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \bar{\nu}_M \nu_M$$

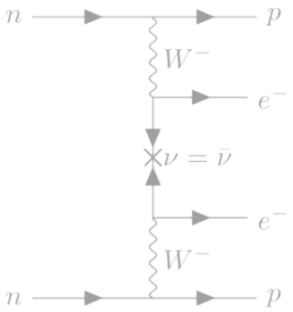
Seesaw mechanism

Seesaw is broken

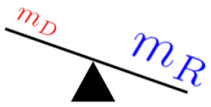
$$m_\nu = -\frac{m_D^2}{m_R}$$

Neutrinoless double beta decay

LNV is suppressed



Majorana type $(m_D \ll m_R)$



$$\mathcal{L} = -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \bar{\nu}_M \nu_M$$

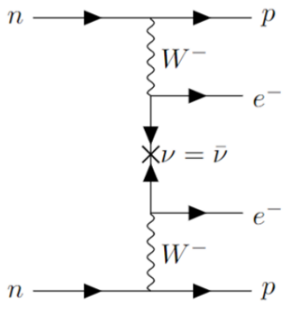
Seesaw mechanism

(for small m_ν)

$$m_\nu = -\frac{m_D^2}{m_R}$$

Neutrinoless double beta decay

(as LNV process)



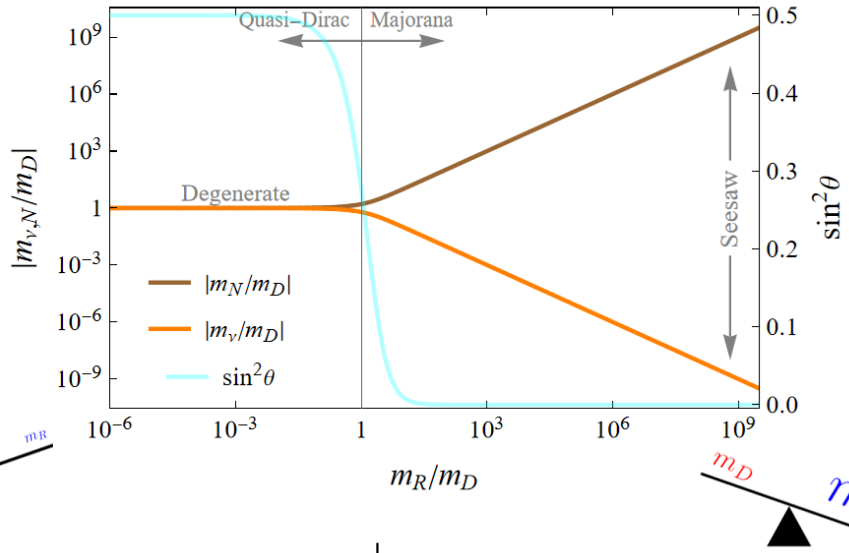
Dirac vs. Majorana types

Dirac mass Majorana mass

$$\mathcal{L} = -m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \bar{\nu}_M \nu_M$$

$$\nu_D = \nu_L + \nu_R$$
$$\nu_M = \nu_R + \nu_R^c$$

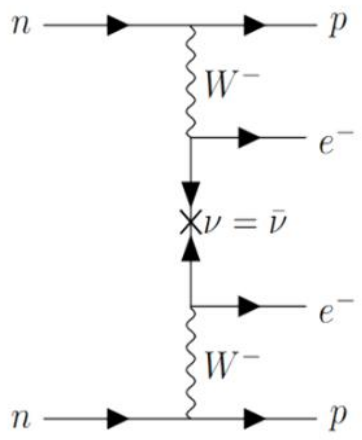
YL ChoeJo, YK, HS Lee. 2305.16900





	Pure Dirac case $(m_R = 0)$	Quasi-Dirac limit $(m_D \gg m_R)$	Majorana limit $(m_D \ll m_R)$
Mass eigenvalues	$\lvert m_{l,h}\rvert = m_D$	Nearly degenerate: $\lvert m_{l,h}\rvert \simeq m_D(1 \mp 2\delta)$ where $\delta = m_R/4m_D$	$m_l \simeq -\frac{m_D^2}{m_R}$, $m_h \simeq m_R$ Seesaw mechanism
Mixing angle	$\sin^2\theta_{LR} = \frac{1}{2}$	& maximal mixing: $\sin^2\theta_{LR} \simeq \left(\frac{1-\delta}{\sqrt{2}}\right)^2$	$\sin^2\theta_{LR} \simeq \left(\frac{m_D}{m_R}\right)$
Mass eigenstates	$\nu_{l,h} = \frac{1}{\sqrt{2}}\left((\nu_L + \nu_L^c) \pm (\nu_R + \nu_R^c)\right)$	$\nu_{l,h} \simeq \pm\frac{1 \pm \delta}{\sqrt{2}}(\nu_L + \nu_L^c) + \frac{1 \mp \delta}{\sqrt{2}}(\nu_R + \nu_R^c)$	$\nu_l \simeq \nu_L + \nu_L^c$, $\nu_h \simeq \nu_R + \nu_R^c$
Mass term	$\frac{1}{2}(m_l \bar{\nu}_l \nu_l + m_h \bar{\nu}_h \nu_h) = m_D \bar{\nu}_D \nu_D$	$\frac{1}{2}(m_l \bar{\nu}_l \nu_l + m_h \bar{\nu}_h \nu_h) \simeq m_D \bar{\nu}_D \nu_D + \mathcal{O}(\delta)$ Dominant Dirac mass	$\frac{1}{2}(m_l \bar{\nu}_l \nu_l + m_h \bar{\nu}_h \nu_h)$

0νββ decay in Dirac/Majorana types



$$\Gamma_{0\nu\beta\beta} \propto \mathcal{A}^2$$

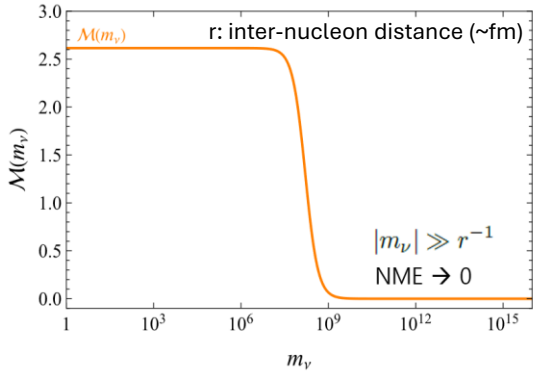
$$\mathcal{A} = \left| \sum_i U_{ei}^2 m_i \mathcal{M}(m_i) \right|$$

Extended PMNS matrix

Nuclear matrix element (NME)

$$\mathcal{M}(m_\nu) = m_p m_e \frac{|\mathcal{M}_N^{0\nu}|}{\langle p \rangle^2 + m_\nu^2}$$

$$\text{where } \langle p \rangle^2 = m_p m_e \left| \frac{\mathcal{M}_N^{0\nu}}{\mathcal{M}_\nu^{0\nu}} \right|$$



Single-flavor pair:

$$\mathcal{A} = \left| m_l \cos^2\theta_{LR} \mathcal{M}(m_l) + m_h \sin^2\theta_{LR} \mathcal{M}(m_h) \right|$$

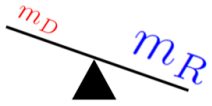
$|m_\nu| \simeq |m_N|$, $\cos^2\theta \simeq \sin^2\theta$ in **quasi-Dirac limit**

→ $\mathcal{A}$ is strongly suppressed



$\sin^2\theta_{LR} \simeq 0$, $\mathcal{M}(m_h) \simeq 0$ in **Majorana limit**

→ 0νββ decay is activated

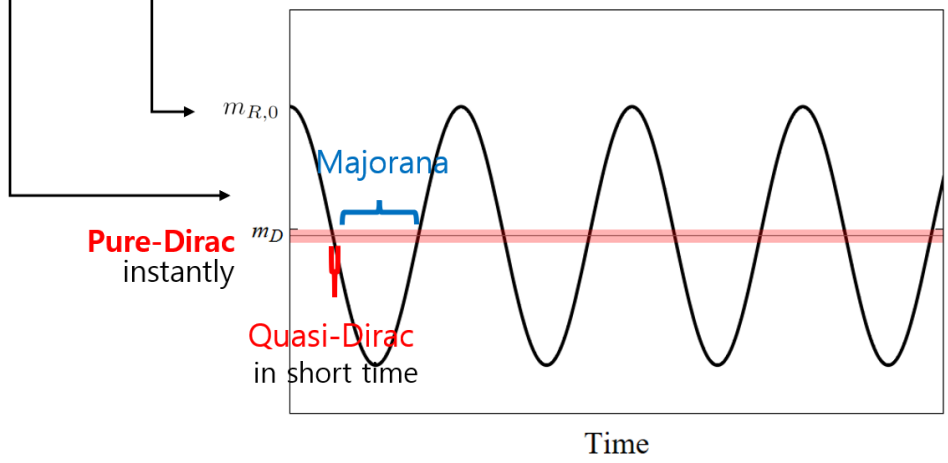


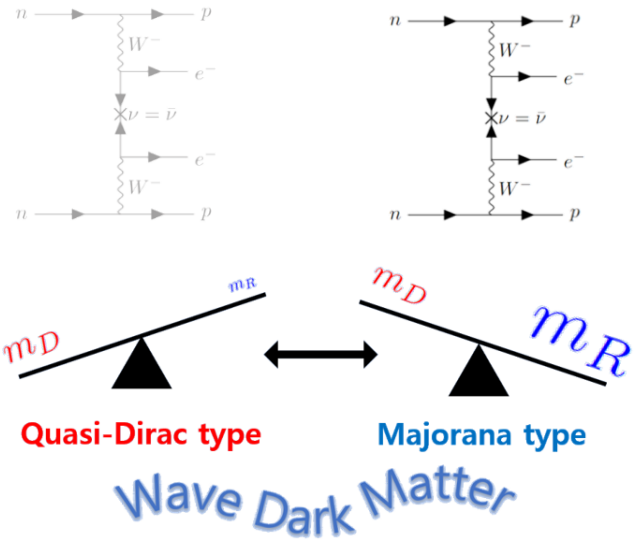
0νββ decay in Dirac/Majorana types

$$\mathcal{L} = -yHLN - g\,\phi NN + h.c.$$

$$m_D = \frac{yv}{\sqrt{2}} \qquad m_R(t) = m_{R,0}\cos m_\phi t$$

(fixed) where $m_{R,0} = g\frac{\sqrt{2\rho_\phi}}{m_\phi}$

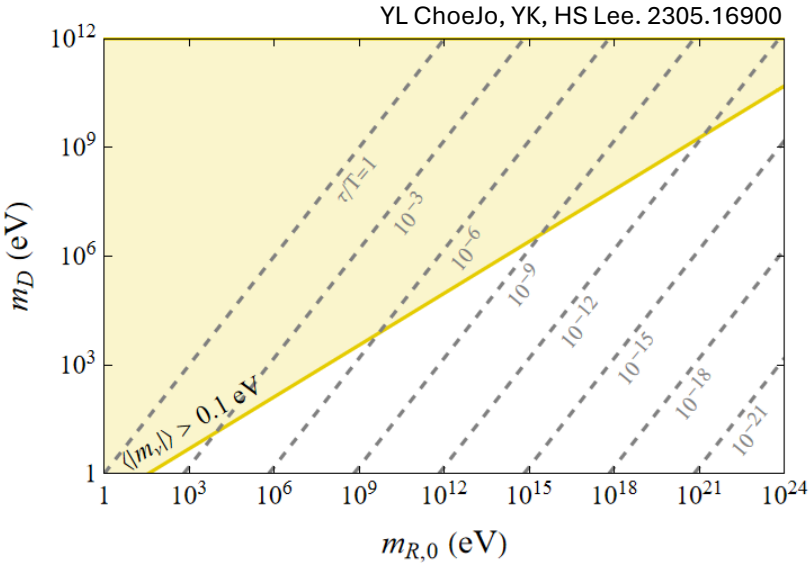


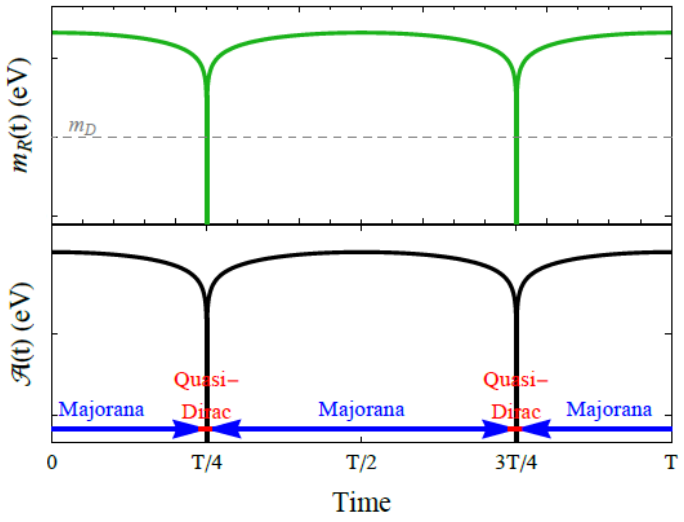


"Dirac-Majorana neutrino type oscillation"

0νββ decay in Dirac/Majorana types

YL ChoeJo, YK, HS Lee. 2305.16900





Time average

$$\langle|m_\nu|\rangle = \frac{1}{T}\int_0^T |m_\nu(t)|dt < 0.1 \text{ eV}$$

Remark: If bare Majorana mass term exists, there is no instant pure-Dirac moment, but both relatively effective Quasi-Dirac time ratio and natural scale of mass terms can be simultaneously guaranteed

Quasi-Dirac time ratio τ/T

$$\frac{\tau}{T} = 1 \qquad \text{for } m_D > m_{R,0}$$

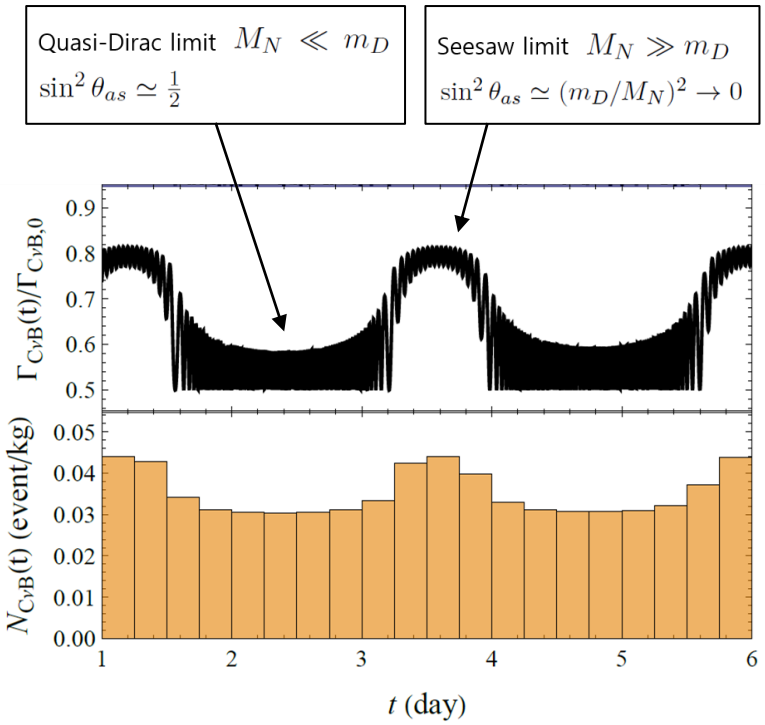
$$\frac{m_D}{m_{R,0}} = \sin\left(\frac{\pi}{2}\frac{\tau}{T}\right) \qquad \text{for } m_D < m_{R,0}$$

Implications in CvB / Atomic neutrinos

CvB

Detection rate w/ active-sterile neutrino mixing

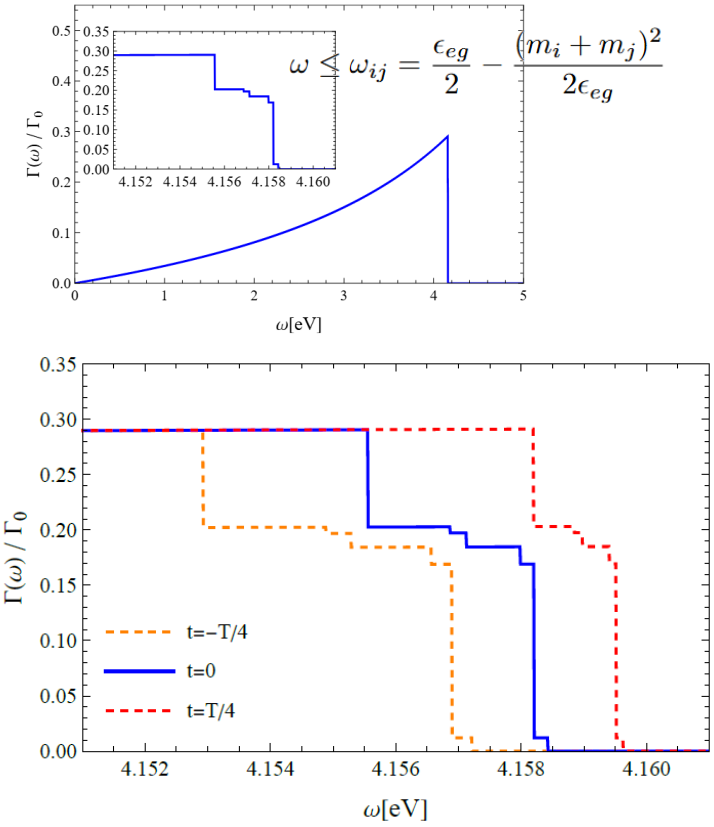
$$\Gamma_{C\nu B} \propto (1 - P(\nu_a \to \nu_s))$$
$$\sim (1 - \tfrac{1}{2}\sin^2 2\theta_{as})$$



YK, HS Lee. 2503.04949

Neutrino emission in atom

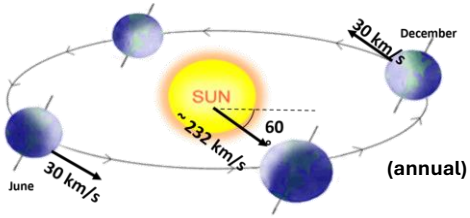
Endpoint modulation by mass variation



Remark: Dirac/Majorana distinction is also possible

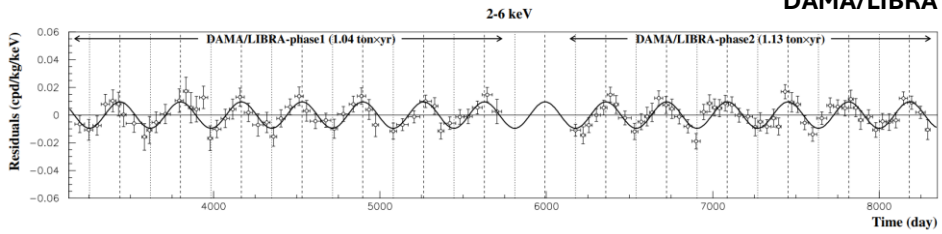
Modulation signatures from DM

Modulation from the Earth's motion in DM halo

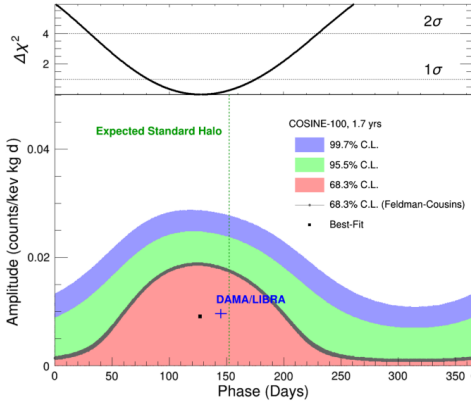


(annual)

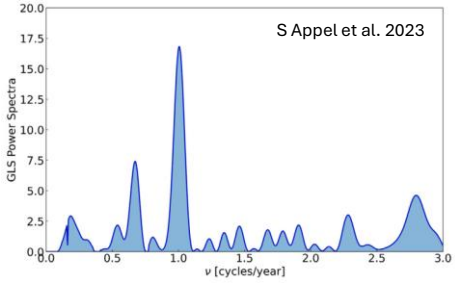
DAMA/LIBRA



COSINE 100

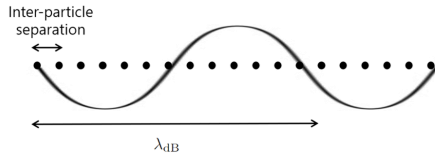


Power spectrum

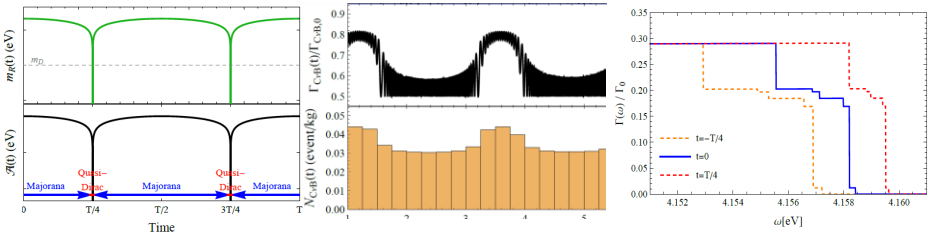


$$\text{Rate} = C + p_0 \exp\left(-\frac{\ln 2t}{p_1}\right) + A\cos\frac{2\pi(t-t_0)}{T}$$

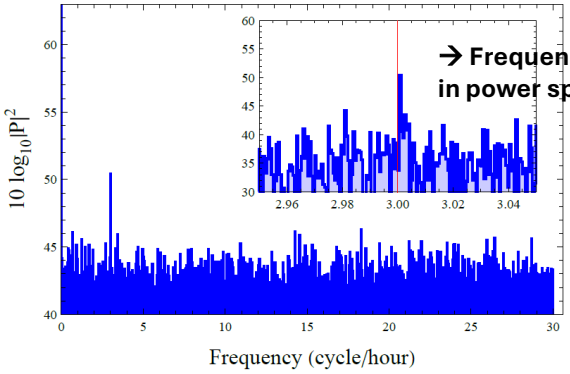
Modulation from oscillating wave DM



0νββ decay **CνB** **Atomic neutrino**

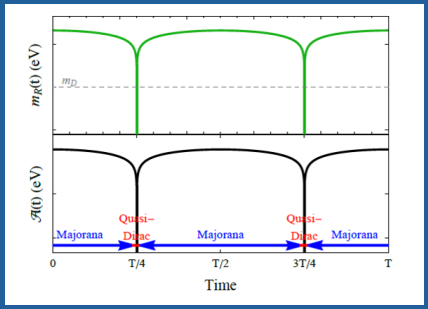


$$P(f_j) = \frac{1}{\mathcal{N}}\left|\sum_{k=1}^{\mathcal{N}} \Delta N_k e^{-2\pi i f_j t_k}\right|^2$$

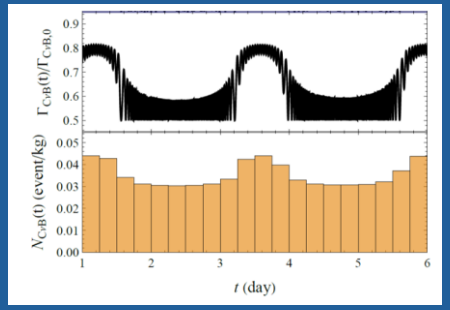


Wave Dark Matter

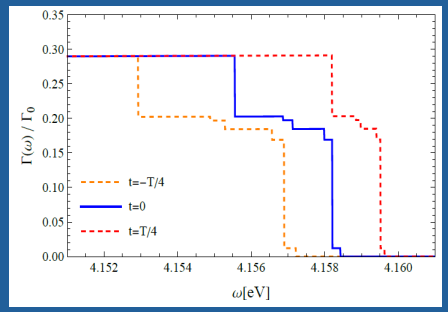
0νββ decay

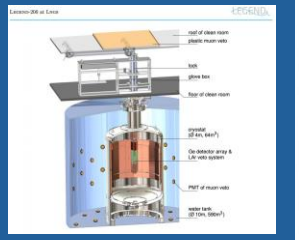


CvB

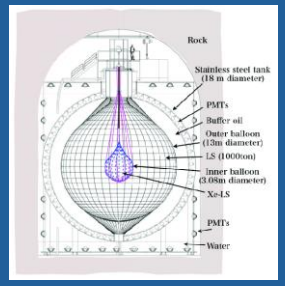


Atomic neutrino

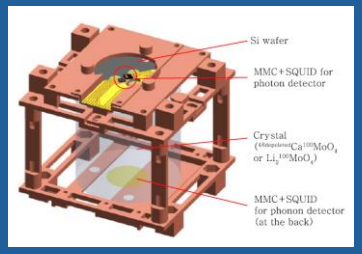




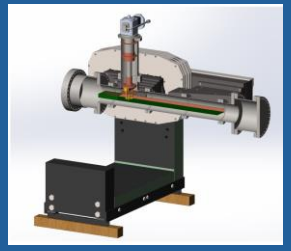
LEGEND



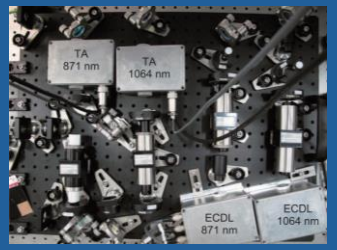
KamLAND-Zen



AMoRE



PTOLEMY



RENP

Neutrino detectors can search for rare signals through modulation signature!

Single vs. Mixed wave dark matter

Single wave dark matter

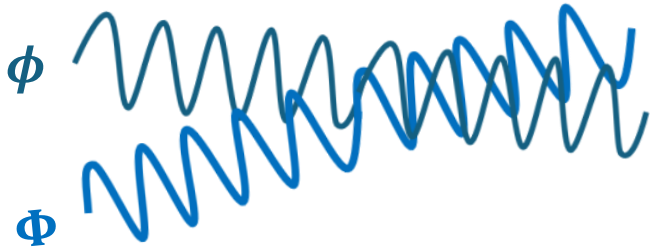


Harmonic oscillation

$$\phi(t) = \phi_a \cos m_\phi t$$

single frequency
(monochromatic)

Mixed wave dark matter
(motivated by multi-axion model or axiverse)



Non-trivial time-dependent structure
(symmetry-broken, non-monochromatic, ...)

$$\phi(t) = \phi_0(t) + \phi_a(t) f(m_\phi, M_\Phi, t)$$

$$\Phi(t) = \Phi_0(t) + \Phi_a(t) g(m_\phi, M_\Phi, t)$$

Multiple frequencies
(Non-monochromatic)

Mixed wave DM and parametric structure

$$V(\phi,\Phi)=\frac{1}{2}m^2\phi^2+\frac{1}{2}M^2\Phi^2+\frac{1}{2}\kappa\phi^2\Phi^2$$

Wave DM mixing (subdominant)

For $M^2 \gg \kappa\phi^2$

$$\Phi(t) \simeq \Phi_0 \sin(Mt)$$

EoM of ϕ

$$\ddot{\phi}+3H\dot{\phi}+(m^2+\kappa\Phi^2)\phi=0$$

$$\phi''(z)+\left[A-2q\cos(2z)\right]\phi(z)=0$$

Mathieu-type equation

where $z \equiv Mt \quad ' = d/dz$

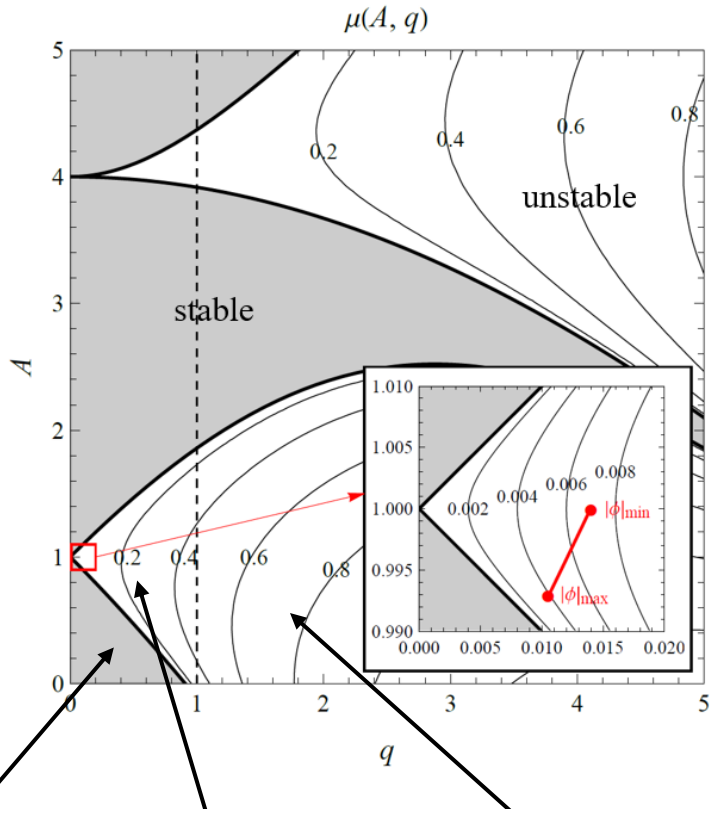
$$q\equiv\frac{\kappa\Phi_0^2}{4M^2}, \quad A\equiv\frac{m^2}{M^2}+2q$$

Solution

$$\phi(z)=e^{\tilde{\mu}(A,q)\,z}\,P(z)$$

$\tilde{\mu}=\mu+i\nu$: Mathieu characteristic

$P(z)$: Periodic function



Stable region

$\mu = 0,\ \nu = n + \delta$

Narrow resonance $q \ll 1$

Insufficient amplification

Broad resonance $q \gg 1$

i.e., Parametric resonance

(Preheating after inflation)

Mixed wave DM and parametric structure

Solution

$$\phi(z) = e^{\tilde{\mu}(A,q)\, z}\, P(z)$$

$\tilde{\mu} = \mu + i\nu$: Mathieu characteristic

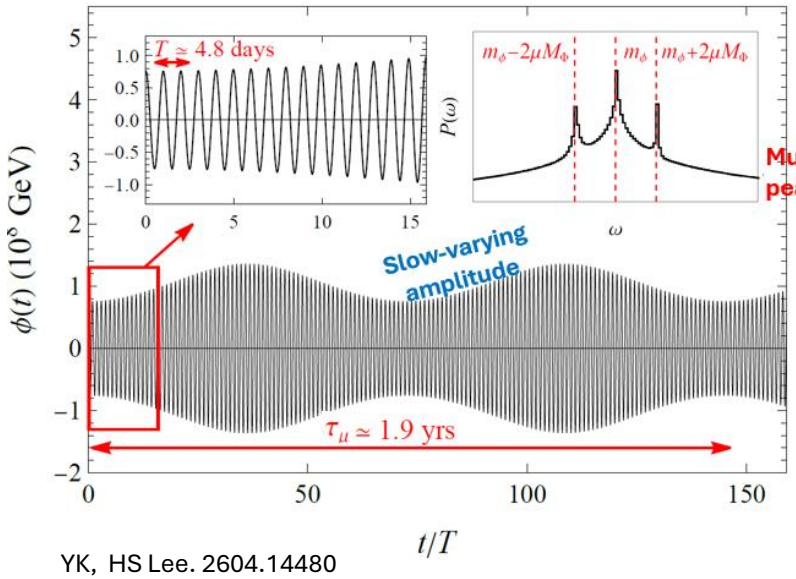
$e^{\mu z}$ with $z = Mt$

New time scale $\tau_\mu \simeq \dfrac{2\pi}{\mu M} \gg T \simeq \dfrac{2\pi}{M}$ for $\mu \ll 1$ (Narrow resonance)

Slow oscillation from mixing — Wave DM oscillation

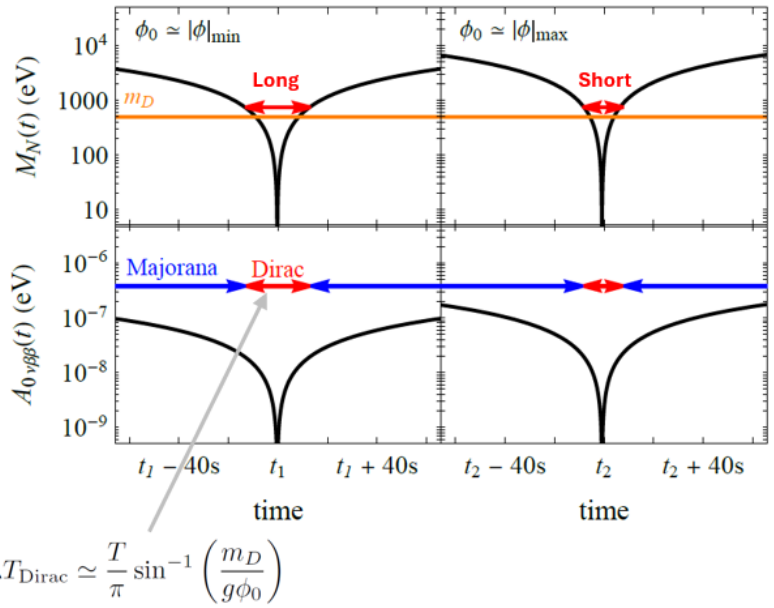
Insufficient amplification & Non-linear Back-reaction

"Wave-envelope DM"



YK, HS Lee. 2604.14480

Modulation of turn-off time of 0νββ decay



$$\Delta T_{\rm Dirac} \simeq \frac{T}{\pi} \sin^{-1}\left(\frac{m_D}{g\phi_0}\right)$$

Summary

- Many unknown natures of neutrino (i.e., mass scale, Dirac/Majorana type) can be probed by the rare event searches (i.e., 0νββ decay, CvB, atomic neutrinos), but they are hard to detect.
- If oscillating ultralight wave DM couples to neutrino sector, these processes may show the modulation signatures along type oscillation or mass variation.
- Therefore, neutrino detectors can observe rare signals of neutrino through modulation search with finding frequency peak in power spectrum.
- In addition, mixed wave DM leads to beyond simple harmonic oscillation regime (i.e., wave-envelope with multiple peaks).



Thank you!