Neutrino Oscillations in Dark Matter

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Based on arXiv: 1909.10478, Ki-Young Choi, Eung Jin Chun, **JKK**

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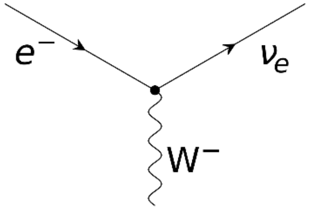
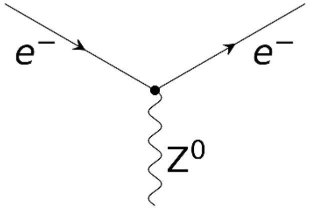
Neutrino oscillation in vacuum

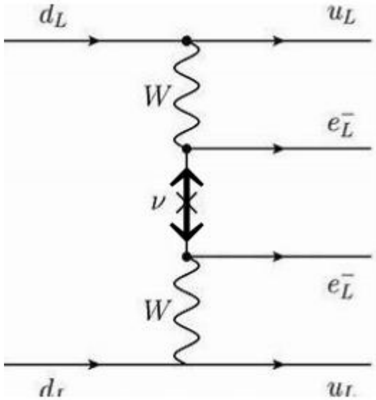
- Flavored neutrinos: Weak interaction eigenstates
  - Production & Detection

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$





- Massive neutrinos: Majorana VS Dirac
  - Majorana: $\nu = \nu^c \;\; (\nu_R \sim \nu_L^*)$
  - neutrinoless-double beta decay



  - Dirac: $\nu \neq \nu^c \;\; (\nu^c \sim N)$

Neutrino oscillation in vacuum

- Flavor eigenstates ≠ Mass eigenstates
  - $\nu_\alpha = U_{\alpha i}\nu_i$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot P_M$$

$$P_M = \mathrm{Diag}[1, e^{i\varphi_2}, e^{i\varphi_2}]$$

- Two-flavor neutrino propagation in vacuum

$$\nu_e \rightarrow \nu_\mu$$

$$U = \begin{bmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{bmatrix}$$

- Conversion probability

$$P_{e\mu} = \left|\langle\nu_\mu|\nu_e(t)\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino oscillation in matter

- **Majorana**
  - Only a LH component
- Adding the matter term the equation of motion for neutrino wave function

$$(i\partial\!\!\!/ - A\gamma_0)\nu_L = m\bar{\nu}_L$$

- Squaring: $(E-A)^2 - p^2 \simeq mm^\dagger$
  - Mass matrix is symmetric
- Dispersion relation: $p \simeq E - (\frac{mm^\dagger}{2E} + A)$

Neutrino oscillation in matter

- **Dirac**
  - Have both a LH and RH component
- Equation of Motion

$$\begin{cases} i\partial\!\!\!/\nu_L & = m\bar{\nu}_R + A\gamma_0\nu_L \\ i\partial\!\!\!/\bar{\nu}_R & = m^\dagger\nu_L \end{cases}$$

- Eliminating the RH neutrino

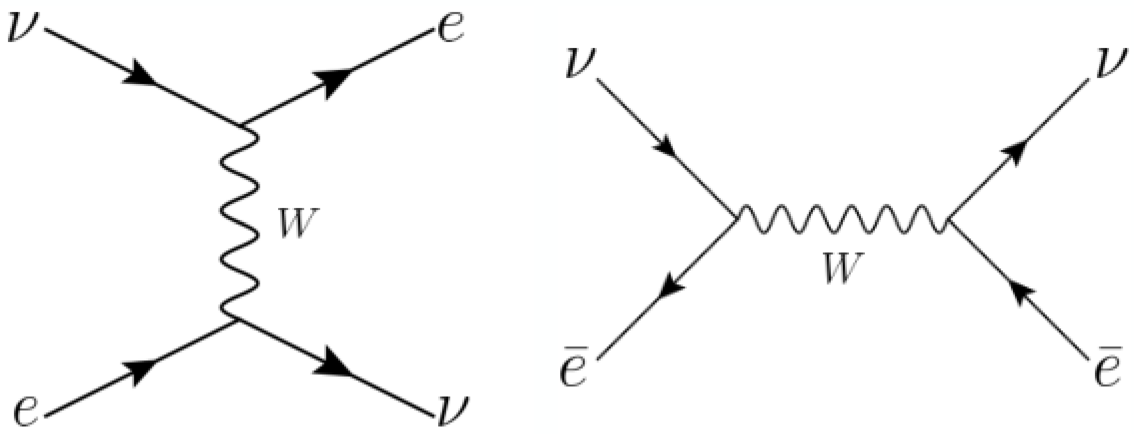
$$[\partial^2 + mm^\dagger + A\ i\partial\!\!\!/\gamma_0]\nu_L = 0.$$

- Dispersion relation: $p \simeq E - (\frac{mm^\dagger}{2E} + A)$

Neutrino oscillation in matter

- Consider neutrino/anti-neutrino propagation in a general background
  - electron, positron

- **Coherent forward scattering**



- $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 x}{4E}\right)$

Standard MSW effect

- Generalized matter potential

$$V_{\nu,\bar{\nu}}^{SM} = \sqrt{2} G_F (N_e + N_{\bar{e}}) \frac{\pm\epsilon\, m_W^4 - 2 m_W^2 m_e E_\nu}{m_W^4 - 4 m_e^2 E_\nu^2}$$

- Standard matter potential
  - $\epsilon = 1 \; (N_{\bar{e}} = 0)$
  - $m_W^2 \gg 2 m_e E_\nu$

$\Rightarrow \quad \pm\sqrt{2} G_F N_e$

- Matter potential @ high energy
  - $V_{\nu,\bar{\nu}}^{SM} \approx \frac{\sqrt{2} G_F m_W^2 (N_e + N_{\bar{e}})}{2 m_e E_\nu}$

DM models

- A lot of models of DM and mediator

$$\mathcal{L}' = g_{\alpha i}\,\overline{f_{iL}}\gamma^{\mu}\nu_{\alpha L}\,X_{\mu} + h.c.$$

$$g_{\alpha i}\,\bar{f}_R\nu_{\alpha L}\,\phi_i + h.c.$$

$$g_{\alpha i}\,\overline{f_{iR}}\nu_{\alpha L}\,\phi + h.c.$$

$$g_{\alpha\beta}\,\overline{\nu^c_{\beta R}}\nu_{\alpha L}\,\phi + h.c.$$

$$g_{\alpha\beta}\,\overline{\nu^c_{\beta R}}\nu_{\alpha L}\,\phi + y\,\phi\,\bar{f}_R f_L + h.c.$$

General formulation

- Equation of motion in the momentum space

$$(\not{p} - \not{\Sigma})u_L = (M^\dagger + \bar{\Sigma}_0)u_R,$$
$$(\not{p} - \bar{\not{\Sigma}})u_R = (M + \Sigma_0)u_L,$$

  - $\not{\Sigma} \equiv \Sigma_\mu \gamma^\mu,\ \bar{\not{\Sigma}} \equiv \bar{\Sigma}_\mu \gamma^\mu,\ \Sigma_0$: corrections

R. F. Sawyer, 1999
P. Q. Hung, 2000
A. Berlin, 2016
S. F. Ge, S. Parke, 2019
H. Davoudiasl, G. Mohlabeng, M. Sulliovan, 2019
G. D'Amico, T. Hamill, N. Kaloper, 2018
F. Capozzi, I. Shoemaker, L. Vecchi 2018

- In a Lorenz invariant medium:

  - $\not{\Sigma} = \not{p}\,\Sigma_1 + \not{k}\,\Sigma_2;\ \bar{\not{\Sigma}} = \not{p}\,\bar{\Sigma}_1 + \not{k}\,\bar{\Sigma}_2,$

- Canonical basis of the kinetic term:

$$u_L \simeq \left(1 + \frac{\Sigma_1}{2}\right)\tilde{u}_L,$$
$$u_R \simeq \left(1 + \frac{\bar{\Sigma}_1}{2}\right)\tilde{u}_R,$$

General formulation

- **The Equation of Motion**

$$(\not{p} - \not{k}\Sigma_2)\tilde{u}_L = \tilde{M}^\dagger \tilde{u}_R,$$
$$(\not{p} - \not{k}\bar{\Sigma}_2)\tilde{u}_R = \tilde{M}\tilde{u}_L.$$

- Correction to the neutrino mass matrix

$$\tilde{M} \simeq \left(1 + \frac{\bar{\Sigma}_1}{2}\right) M \left(1 + \frac{\Sigma_1}{2}\right)$$

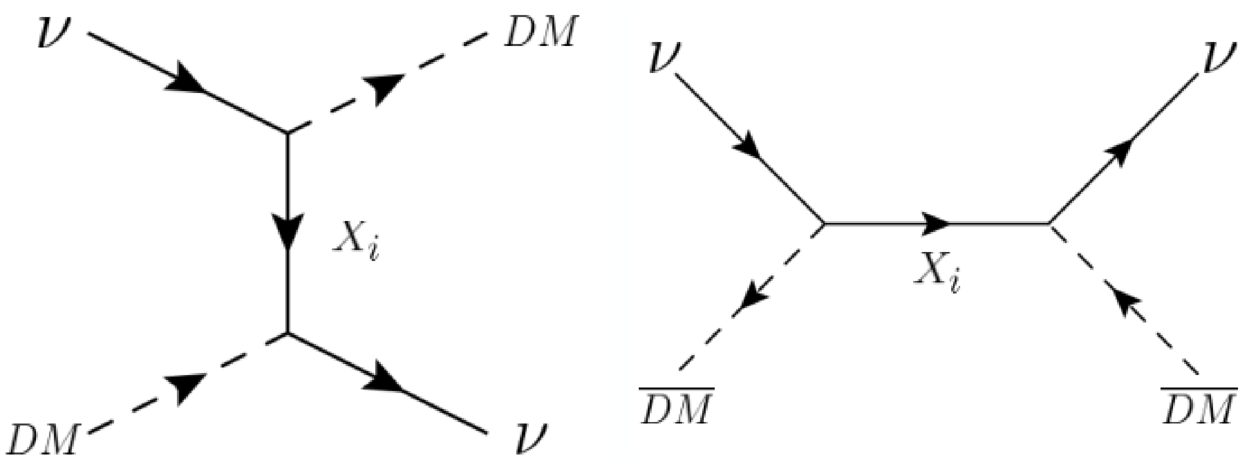
  - Original mass term is modified
  - For large parameter space, the mass correction is subdominant

DM model

- Bosonic DM (ϕ) and fermionic messenger (X_i)
- Lagrangian

$$\mathcal{L}_{int} = g_{\alpha i}\bar{f}_i P_L \nu_\alpha \phi^* + h.c.$$

- **Coherent forward scattering**



General formulation

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- Corrections

$$\Sigma_1\,(\text{or}\;\bar{\Sigma}_1) \;\simeq\; \frac{\lambda^{(T)}}{2}\frac{\rho_{DM}}{m_{DM}^2}\frac{\pm\epsilon\,2m_{DM}E_\nu - m_X^2}{m_X^4 - 4m_{DM}^2E_\nu^2},$$

$$\Sigma_2\,(\text{or}\;\bar{\Sigma}_2) \;\simeq\; \frac{\lambda^{(T)}}{2}\frac{\rho_{DM}}{m_{DM}^2}\frac{\pm\epsilon\,m_X^2 - 2m_{DM}E_\nu}{m_X^4 - 4m_{DM}^2E_\nu^2},$$

- $\lambda_{\alpha\beta} \equiv g_{\alpha i}^{*}\, g_{\beta i}\;\; (\lambda^T = \lambda^*)$

- $\epsilon \equiv (\rho_{DM} - \rho_{\overline{DM}})/(\rho_{DM} + \rho_{\overline{DM}})$

- $\varepsilon = 0, m_X \to 0$: **S-F Ge, Murayama 1904.02518**

Dark NSI potential

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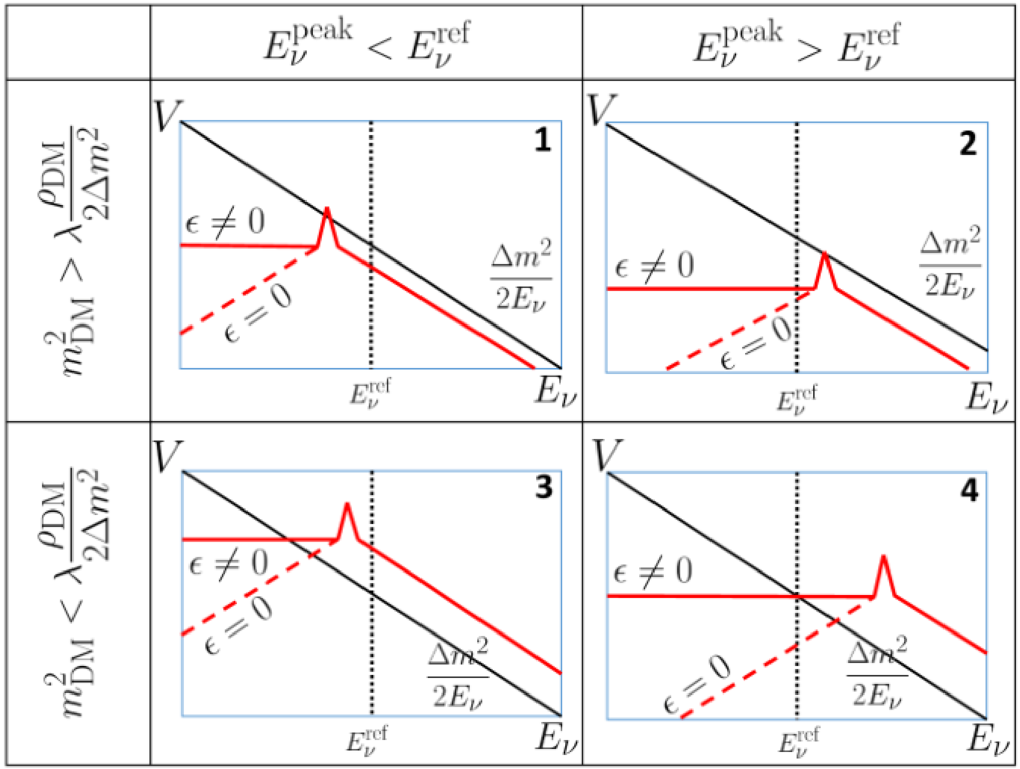

$$E_\nu^{\rm ref} = 1\text{MeV} \sim 100\text{GeV}$$

- Change of shape:

$$E_\nu^{peak} = \frac{m_X^2}{2m_{DM}}$$

- **Low Energy Limit:**

$$V_{\nu,\bar{\nu}}^{DM} \simeq \pm\epsilon \frac{\lambda^{(T)}}{4} \frac{\rho_{DM}}{m_{DM}^2 E_\nu^{peak}}$$

- **High Energy limit:**

$$V_{\nu,\bar{\nu}}^{DM} \simeq \frac{\lambda^{(T)}}{2} \frac{\rho_{DM}/m_{DM}^2}{2E_\nu}$$

Dark NSI potential

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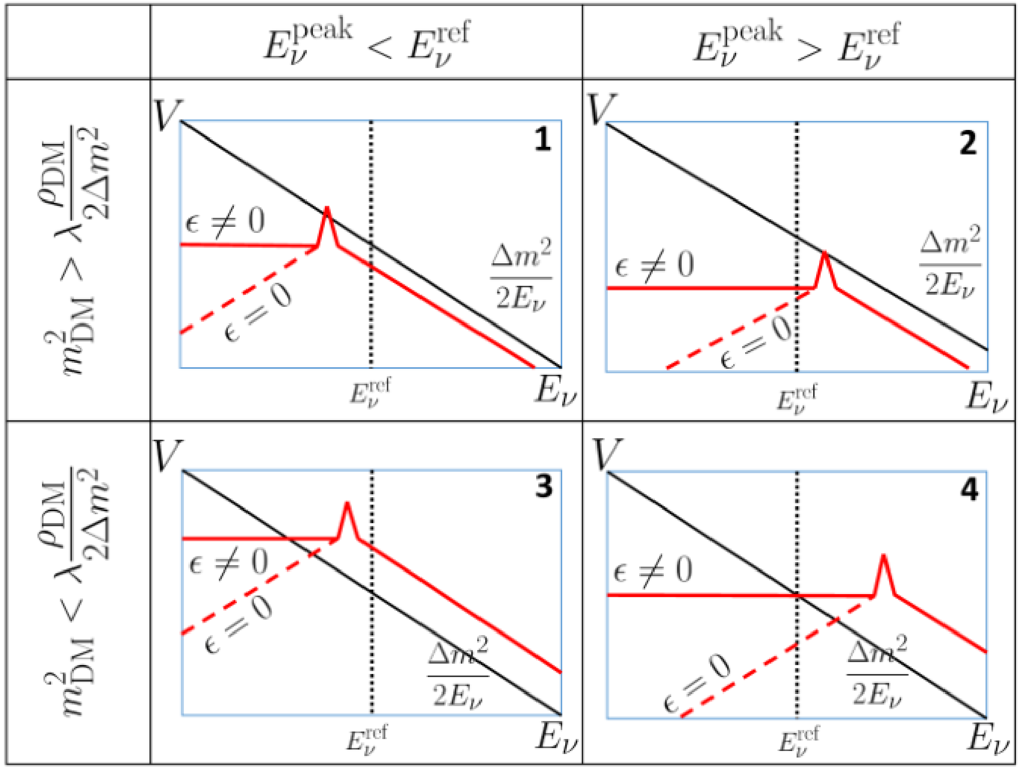

$E_\nu^{\rm ref} = 1{\rm MeV} \sim 100{\rm GeV}$

1. Constrained DM potential:
   - **1 ~ 10%** of $\Delta m^2/2E$
2. **NSI Probes:**
   - $\varepsilon_{\alpha\beta} \equiv V_{\alpha\beta}^{DM}/V_W^{SM}$
3. **Ruled out** DM potential:
   - Massless oscillation
4. **Future probe** of DM potential
   - Governing oscillations of ultra-relativistic neutrinos

Two-flavor oscillation

- The effective Hamiltonian

$$\mathcal{H}_M = \frac{\Delta m^2}{4E} \begin{pmatrix} -(\cos 2\theta - x) & \sin 2\theta + y \\ \sin 2\theta + y & \cos 2\theta - x \end{pmatrix}$$

- $x \equiv \dfrac{(V_{\mu\mu} - V_{\tau\tau})/2}{\Delta m^2/4E}$, and $y \equiv \dfrac{V_{\mu\tau}}{\Delta m^2/4E}$

- The mixing angle & mass squared difference in the medium

$$\sin^2 2\theta_M = \frac{(\sin 2\theta + y)^2}{(\cos 2\theta - x)^2 + (\sin 2\theta + y)^2},$$

$$\Delta m_M^2 = \Delta m^2 \sqrt{(\cos 2\theta - x)^2 + (\sin 2\theta + y)^2}.$$

Mass difference between ν&ν̄

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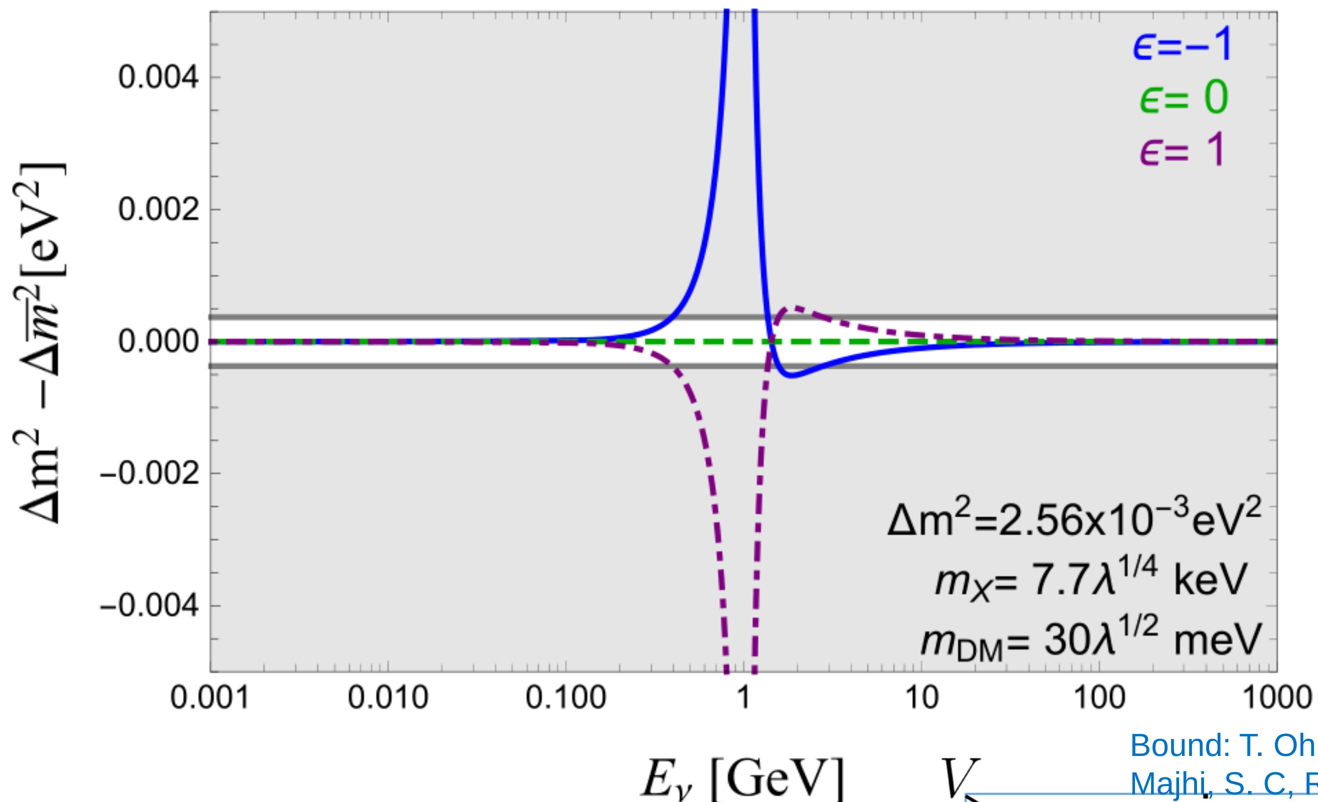
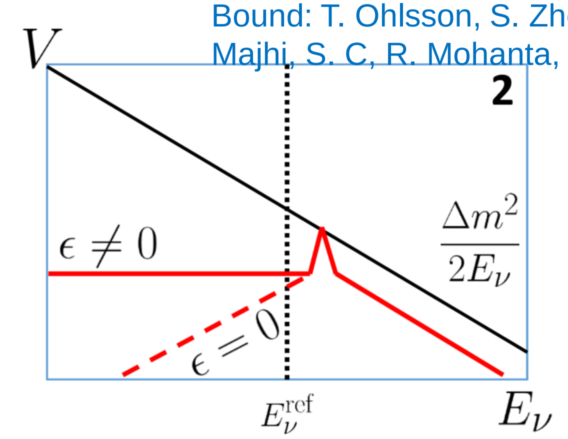


Bound: T. Ohlsson, S. Zhou, 2015, R. Majhi, S. C, R. Mohanta, 2019



- $E_\nu^{Peak} = 1$GeV
- $x \to 0.75$ @ High Energy limit

Modified mixing angle

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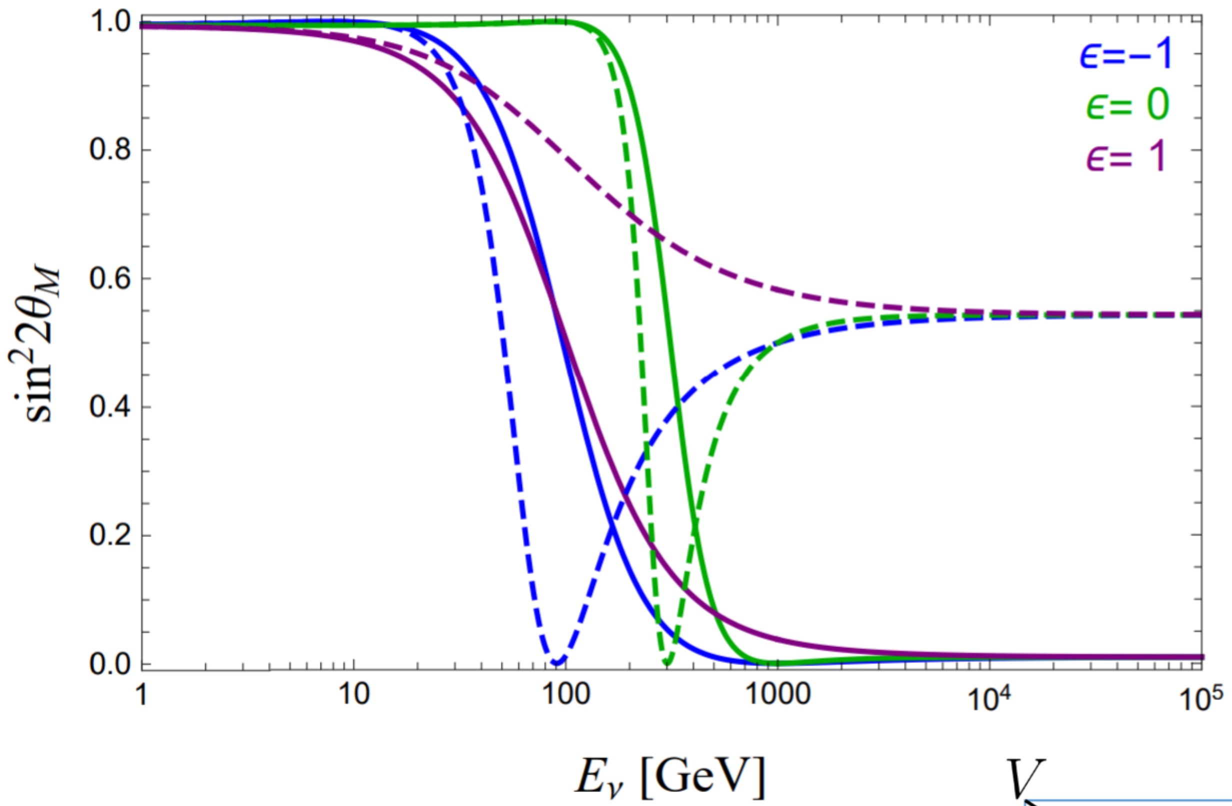
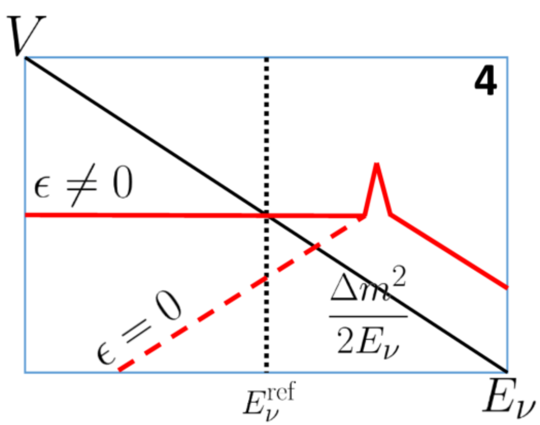


- $E_\nu^{Peak} = 1\text{TeV}$
- Solid line: $x \to 10, y \to 0$
- Dashed line: $x \to 10, y \to 10$



DM assisted neutrino oscillation

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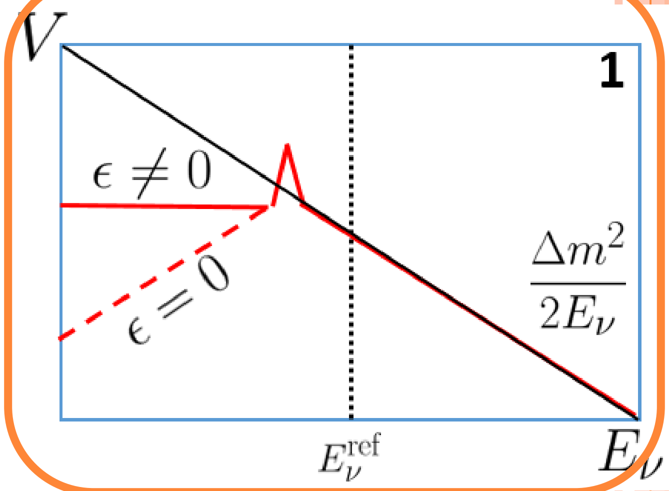
- In the case of $m_X^2 \ll 2m_{DM}E_\nu$ **(Peak energy << 1MeV)**

$$V_{\nu,\bar\nu}^{DM} \simeq \frac{\lambda^{(T)}}{2}\frac{\rho_{DM}/m_{DM}^2}{2E_\nu}$$

$$\approx \frac{3\times 10^{-3}\mathrm{eV}^2}{2E_\nu}\lambda^{(T)}\left(\frac{20\mathrm{meV}}{m_{DM}}\right)^2$$



- $$\lambda = \frac{2m_{DM}^2}{\rho_{DM}}U^*\mathrm{diag}(\Delta m^2)U^T,$$

$$\simeq \begin{pmatrix} 0.026 & 0.091 & 0.085 \\ 0.091 & 0.381 & 0.408 \\ 0.085 & 0.408 & 0.477 \end{pmatrix} \left(\frac{20\mathrm{meV}}{m_{DM}}\right)^2 \left(\frac{0.3\,\mathrm{GeV\,cm}^{-3}}{\rho_{DM}}\right)$$

- Standard neutrino oscillation can occur from the symmetric DM effect even for **massless neutrino**.

DM assisted neutrino oscillation

- **Predictions**

Work in progress

Ki-Young Choi, Eung Jin Chun, JKK, A. Smirnov

- No observation in the absolute neutrino mass
  - \- neutrinoless double beta decay
  - \- cosmological observation of the sum over neutrino mass

- Asymmetric oscillation in the neutrino and anti-neutrino
  - \- Thanks to anisotropic velocity of DM on the Earth, the matter potential has asymmetry
  - \- Annual modulation of neutrino oscillation

- Directional dependence of neutrino oscillation
  - \- Matter potential oscillates depending on time

DM assisted neutrino oscillation

Work in progress

Ki-Young Choi, Eung Jin Chun, JKK, A. Smirnov

- **Predictions**
- No observation in the absolute neutrino mass
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➔ Too small corrections

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  - \- M

➔ Too small corrections

DM-neutrino interactions

- **Constraints**

Work in progress

Ki-Young Choi, Eung Jin Chun, JKK, A. Smirnov

	Early Universe	**Present Universe**
$\langle \sigma_{\mathrm{DMDM} \to \nu\nu} v \rangle$	-DM relic density -Neutrino reheating : Neff, BBN	Neutrino flux
$\sigma_{\mathrm{DM}\nu \to \mathrm{DM}\nu} v$	-CMB anisotropy -Large Scale Structure	Supernovae-1987A **IceCube-170922A** Ki-Young Choi, JKK, Carsten Rott - Neutrino flux suppression - Neutrino flux anisotropy

Questions?

- UV-completion?
  - Dark sector coupling only to neutrinos
- Observable DM effect if $m_{X,DM} \ll$ meV & $|\lambda| \ll 1$
  - BBN ➔ N_{eff}
  - Neutrino-DM scattering
  - Star cooling
  - Supernovae cooling / trapping
- Origin of DM
  - Ultra-light particle
  - Cold

Conclusions

- A systematic study of neutrino oscillations in a medium of DM
- **Asymmetric medium induces CPT violation** in neutrino oscillations which may be tested near future
- **DM assisted neutrino oscillation**
  - DM interaction with neutrino can explain neutrino oscillation
- Further studies on phenomenological implications and viability are needed

Conclusions

- A systematic study of neutrino oscillations in a medium of DM

Thank you.

  - DM interaction with neutrino can explain neutrino oscillation

- Further studies on phenomenological implications and viability are needed