Neutrino Oscillations in Dark Matter

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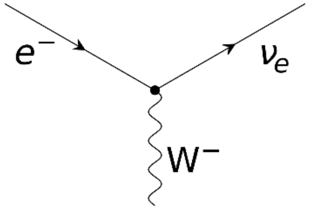
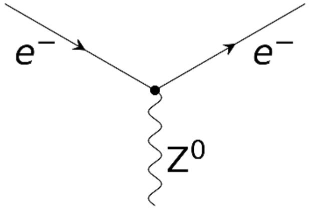
- Conclusions

Neutrino oscillation in vacuum

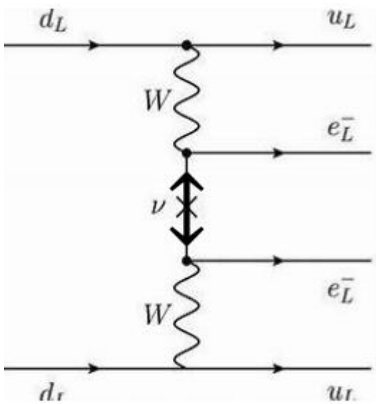
- Flavored neutrinos: Weak interaction eigenstates
  - Production & Detection

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





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



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

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

$$|\nu_e(0)\rangle = c_\theta|\nu_1\rangle + s_\theta|\nu_2\rangle$$

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

$$|\nu_e(t)\rangle = c_\theta\, e^{i\phi_1}|\nu_1\rangle + s_\theta e^{i\phi_2}|\nu_2\rangle$$

$$\phi_i = E_i t - \boldsymbol{p}_i L$$

Neutrino oscillation in vacuum

- Ultra-relativistic limit ($t \cong L$)

$$E_i \approx \boldsymbol{p} + \frac{m_i^2}{2\boldsymbol{p}} \approx E + \frac{m_i^2}{2E}$$

$$\Delta\phi = \phi_2 - \phi_1 \approx \frac{\Delta m^2 L}{2E}$$

- 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

- Wolfenstein Potential

  L. Wolfenstein, 1978

  - Coherent forward scattering of neutrinos leaving the medium unchanged must be taken into account

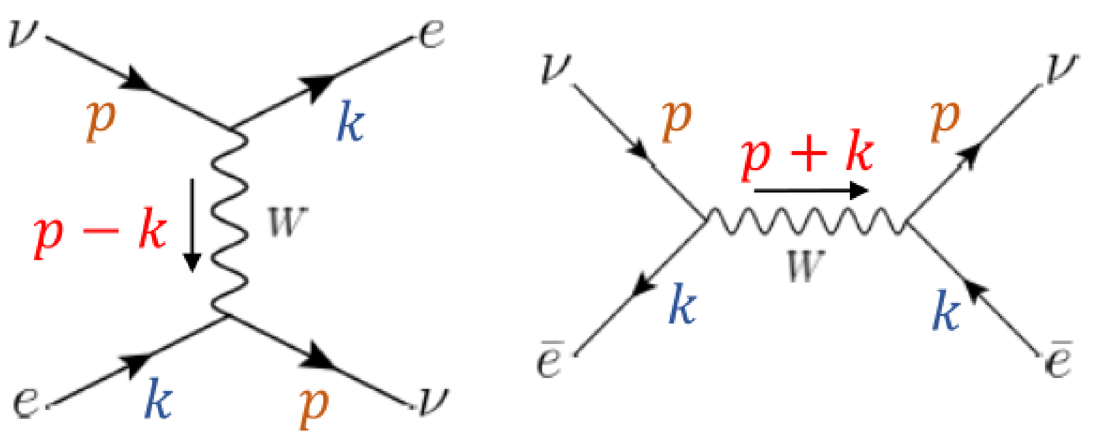
- Consider neutrino/anti-neutrino propagation in a general background
  - electron, positron

- Effective Hamiltonian

$$\mathcal{H}_{eff} = 2\sqrt{2}\, G_F m_W^2 \frac{\overline{\nu_{eL}}\gamma^\mu e_L\, \overline{e_L}\,\gamma_\mu \nu_{eL}}{m_W^2 - q^2}$$

Neutrino oscillation in matter

- **Coherent forward scattering**

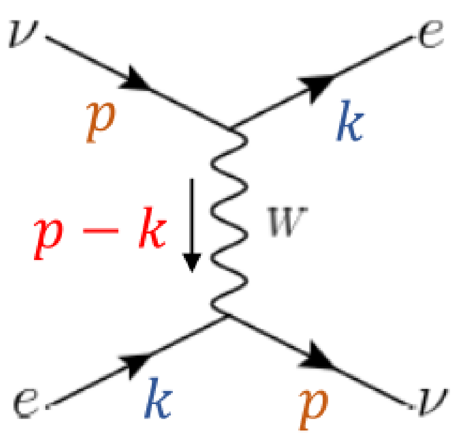


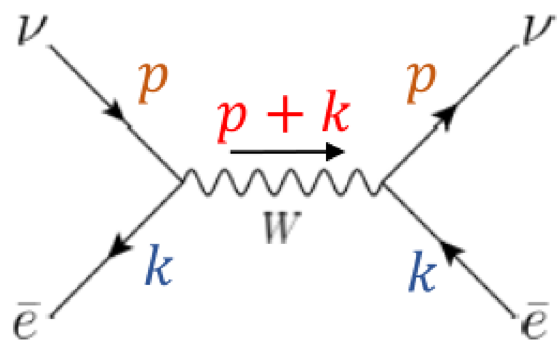
- $$\langle \mathcal{H}_\nu \rangle = \not{k}\,\sqrt{2} G_F m_W^2 \left[\frac{N_e/m_e}{m_W^2 - (p-k)^2} - \frac{N_{\bar{e}}/m_e}{m_W^2 - (p+k)^2} \right]$$

$$\langle \mathcal{H}_{\bar{\nu}} \rangle = \not{k}\,\sqrt{2} G_F m_W^2 \left[\frac{N_{\bar{e}}/m_e}{m_W^2 - (p-k)^2} - \frac{N_e/m_e}{m_W^2 - (p+k)^2} \right]$$

Neutrino oscillation in matter

- **Coherent forward scattering**





- Generalized matter potential

$$\epsilon \equiv \frac{N_e - N_{\bar{e}}}{N_e + N_{\bar{e}}}$$

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

Standard MSW effect

- Standard matter potential

L. Wolfenstein, 1978

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

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

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

Neutrino Oscillations without mass?

- Probability

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

General formulation

- Equation of motion in the momentum space

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

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

General formulation

- **The Equation of Motion**

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

- Neutrino/ anti-neutrino Hamiltonian

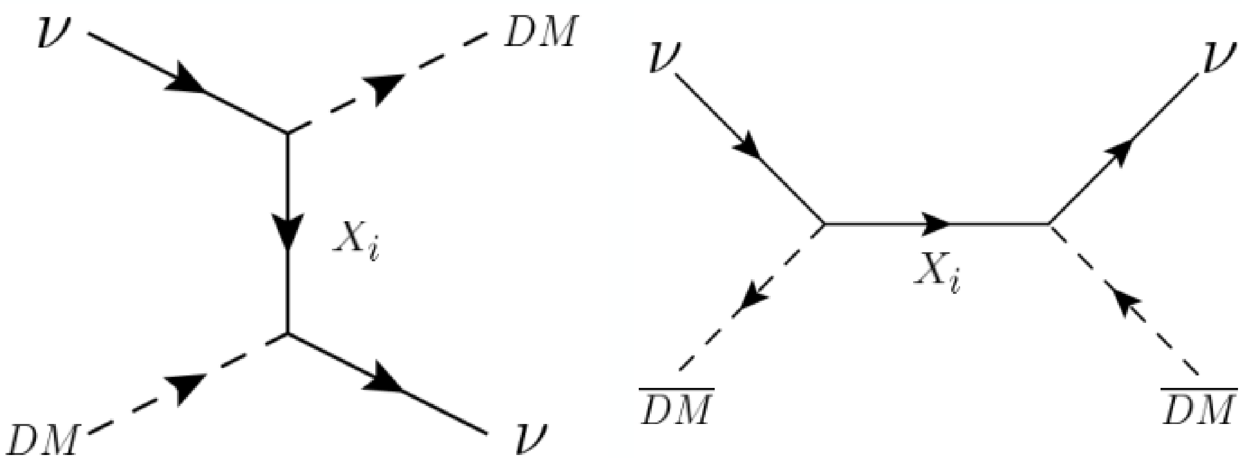
$$H_\nu = E_\nu + \frac{\tilde{M}^\dagger \tilde{M}}{2E_\nu} + k^0\Sigma_2,$$
$$H_{\bar{\nu}} = E_\nu + \frac{\tilde{M}\tilde{M}^\dagger}{2E_\nu} + k^0\bar{\Sigma}_2,$$

DM model

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

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

- **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**
  But, sign for anti-neutrino is wrong

Neutrino potential

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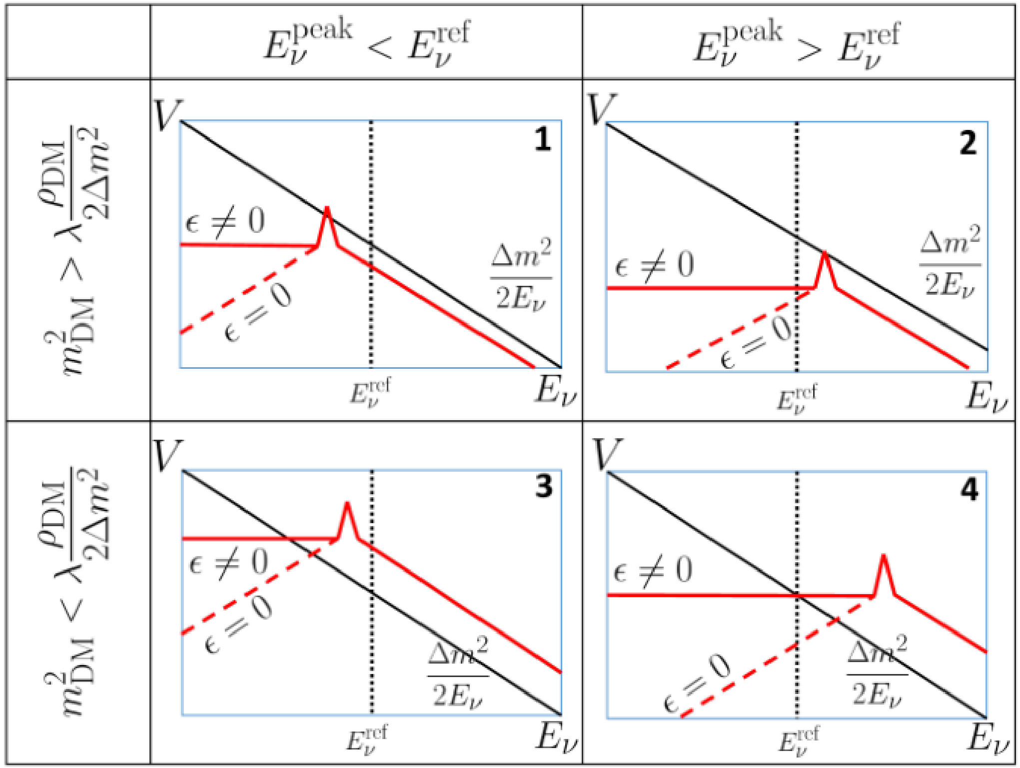

- Change of shape:

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

- **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:**

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

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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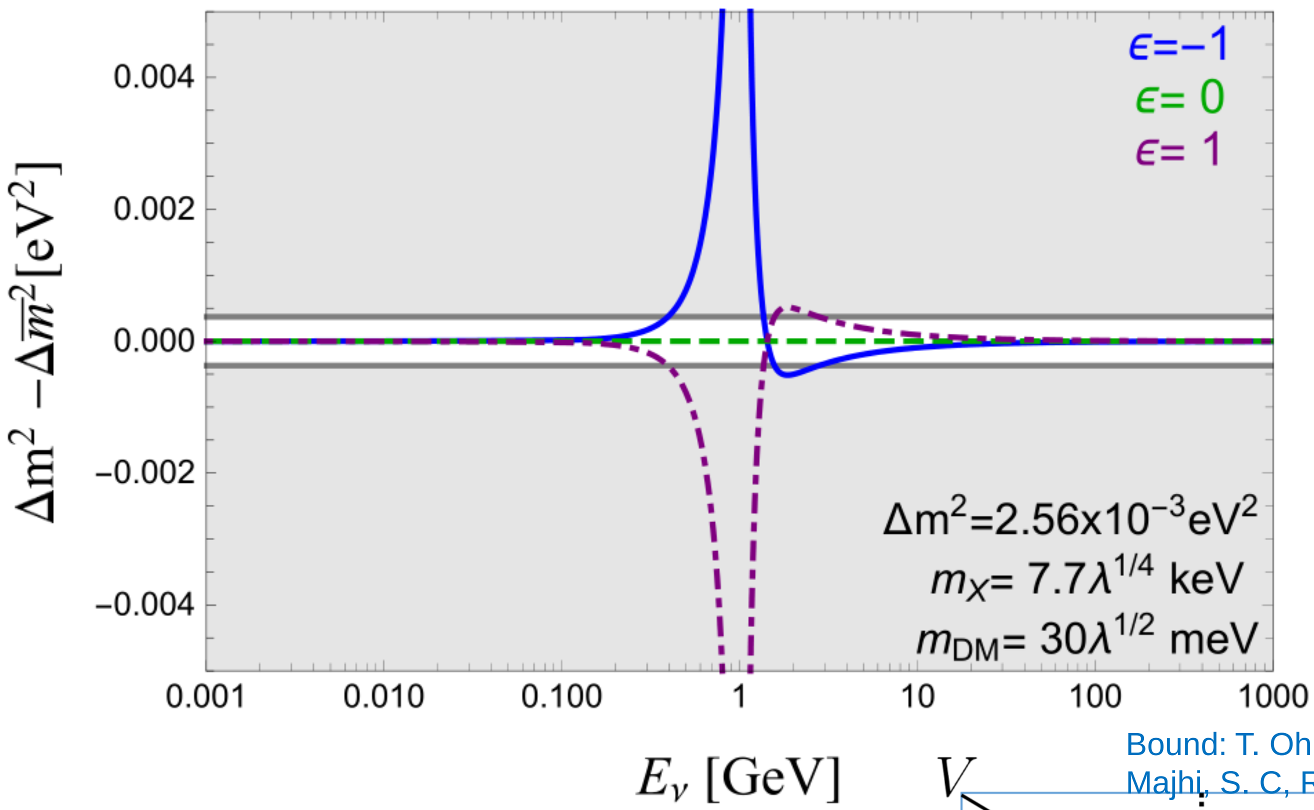
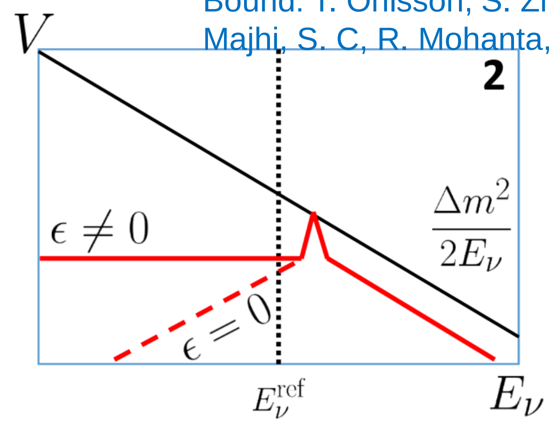
- 

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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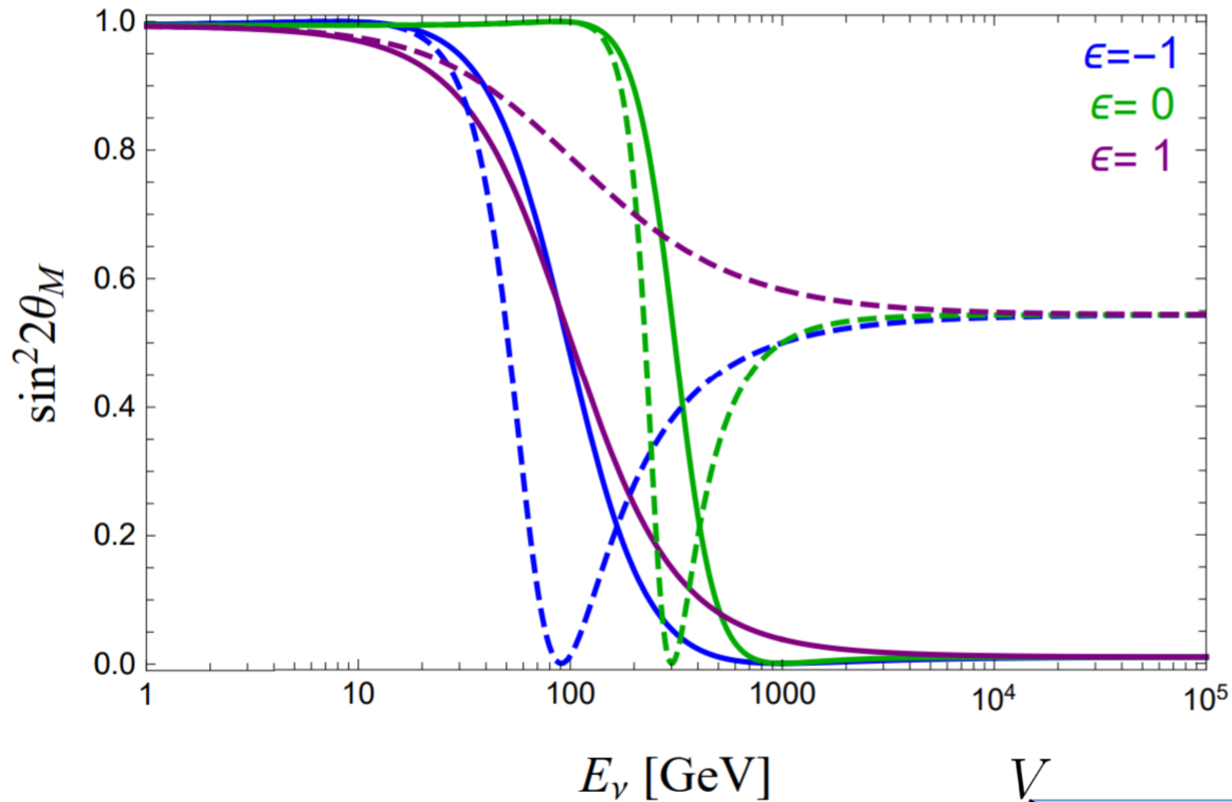
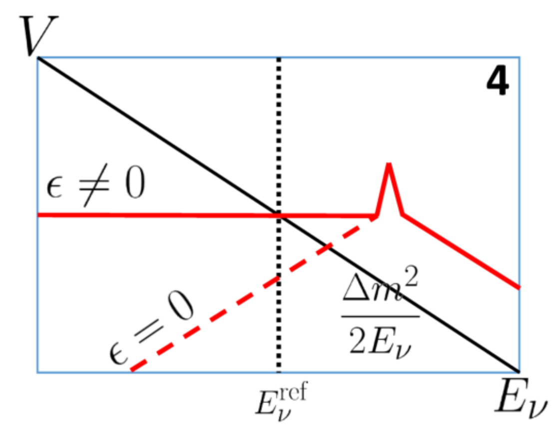


- $E_\nu^{Peak} = 1$TeV
- Solid line: $x \to 10, y \to 0$
- Dashed line: $x \to 10, y \to 10$



DM assisted neutrino oscillation

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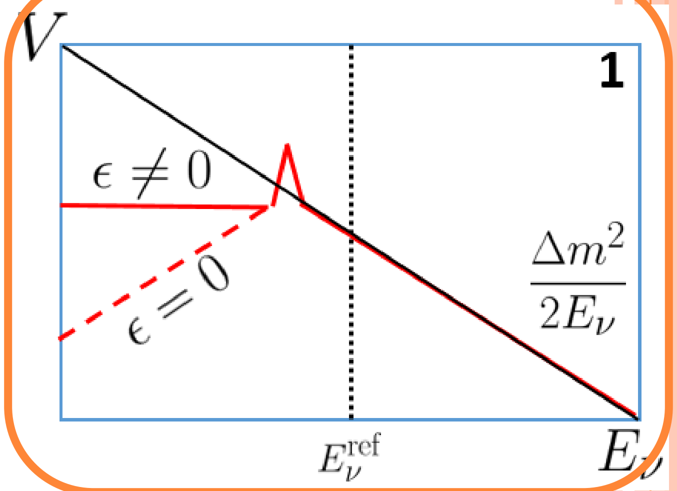
- In the case of $m_X^2 \ll 2 m_{DM} E_\nu$ **(Peak energy << 1MeV)**

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

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



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

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

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

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