Neutrino Oscillations in Dark Matter

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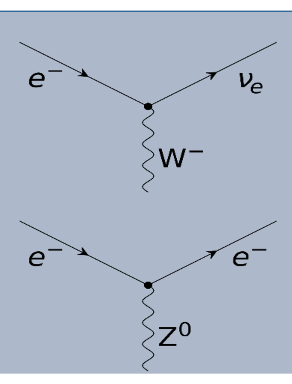
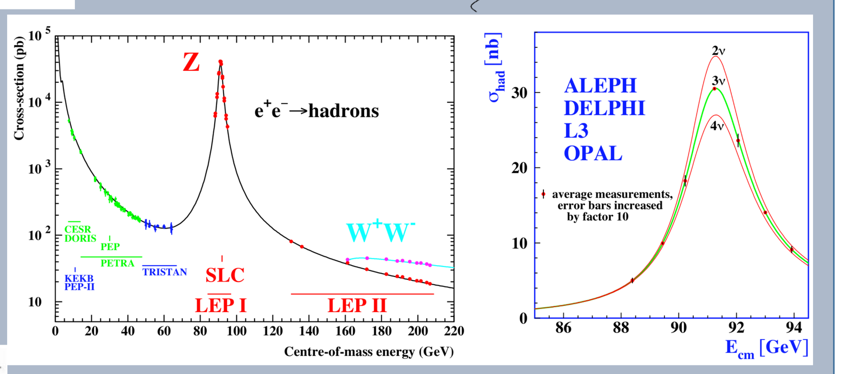
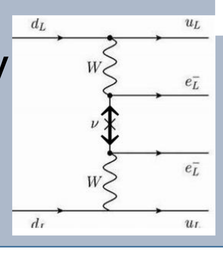
Introduction



- Flavored neutrinos: Weak interaction eigenstates
- Production & Detection $\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$

- The number of neutrinos = 3
- From LEP, Z boson invisible decay
- Massive neutrinos:
- Dirac: $\nu \neq \nu^c$ $(\nu^c \sim N)$
- Majorana: $\nu = \nu^c$ $(\nu_R \sim \nu_L^*)$
- Neutrinoless-double beta decay





General formulation

- Equation of motion in the momentum space: $(\not p - \not\Sigma)u_L = (M^\dagger + \bar\Sigma_0)u_R,$ $(\not p - \not{\bar\Sigma})u_R = (M + \Sigma_0)u_L,$
- In a Lorenz invariant medium: $\not\Sigma \equiv \Sigma_\mu\gamma^\mu,\ \not{\bar\Sigma} \equiv \bar\Sigma_\mu\gamma^\mu,\ \Sigma_0$
- Canonical basis of the kinetic term: $\not\Sigma = \not p\Sigma_1 + \not k\Sigma_2;\ \not{\bar\Sigma} = \not p\bar\Sigma_1 + \not k\bar\Sigma_2,$
- The Equation of Motion becomes $\boxed{(\not p - \not k\Sigma_2)\tilde u_L = \tilde M^\dagger \tilde u_R,\quad (\not p - \not k\bar\Sigma_2)\tilde u_R = \tilde M \tilde u_L.}$
- 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

Neutrino oscillations in vacuum

- Flavor eigenstates ≠ Mass eigenstates
- $\nu_\alpha = U_{\alpha i}\nu_i$
- Two-flavor neutrino propagation in vacuum

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

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

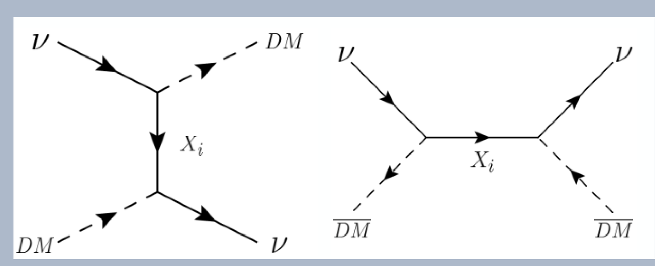
$\nu_e \to \nu_\mu$ $\quad U = \begin{bmatrix}c_\theta & s_\theta\\ -s_\theta & c_\theta\end{bmatrix}$

$$|\nu_e(0)\rangle = c_\theta|\nu_1\rangle + s_\theta|\nu_2\rangle$$
$$|\nu_e(t)\rangle = c_\theta\, e^{i\phi_1}|\nu_1\rangle + s_\theta e^{i\phi_2}|\nu_2\rangle$$

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

Dark Matter model

- Neutrino-DM Interaction: $\mathcal{L}_{int} = g_{\alpha i}\bar X_i P_L \nu_\alpha \phi^* + h.c.$
- Coherent forward scattering



- 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, H. Murayama, arXiv:1904.02518

Neutrino oscillation in matter

L. Wolfenstein, 1978

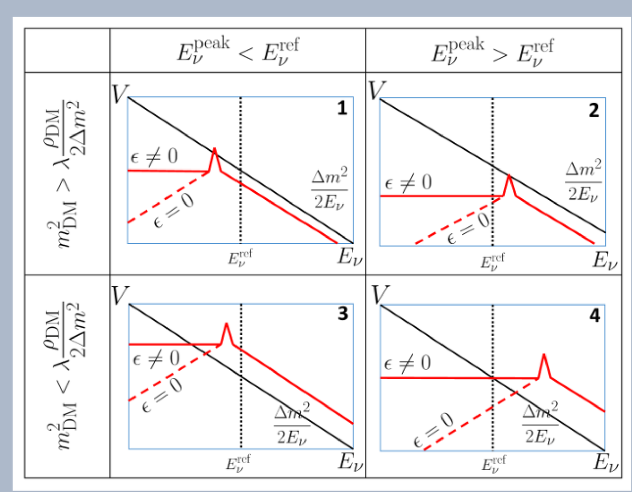
- Wolfenstein Potential
- Coherent forward scattering of neutrinos leaving the medium unchanged must be taken into account

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

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

Neutrino potential

- Neutrino energy VS matter potential



- Change of shape: $E_\nu^{peak} = \dfrac{m_X^2}{2m_{DM}}$
- Low energy limit $V_{\nu,\bar\nu}^{DM} \simeq \pm\epsilon\dfrac{\lambda^{(T)}}{4}\dfrac{\rho_{DM}}{m_{DM}^2E_\nu^{peak}}$
- High energy limit $V_{\nu,\bar\nu}^{DM} \simeq \dfrac{\lambda^{(T)}}{2}\dfrac{\rho_{DM}/m_{DM}^2}{2E_\nu}$

- The effective Hamiltonian

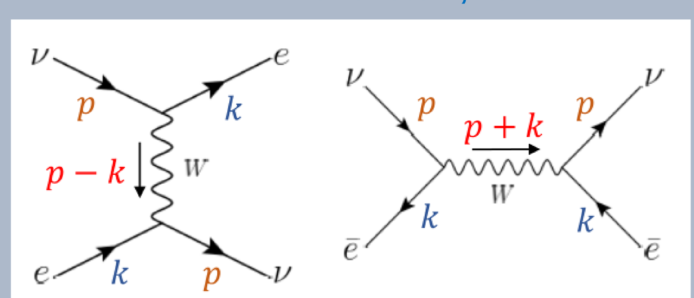
$$\mathcal{H}_M = \frac{\Delta m^2}{4E}\begin{pmatrix}-(\cos 2\theta - x) & \sin 2\theta + y\\ \sin 2\theta + y & \cos 2\theta - x\end{pmatrix}$$

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

Neutrino oscillation in matter

L. Wolfenstein, 1978

- Coherent forward scattering



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

- Generalized matter potential

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

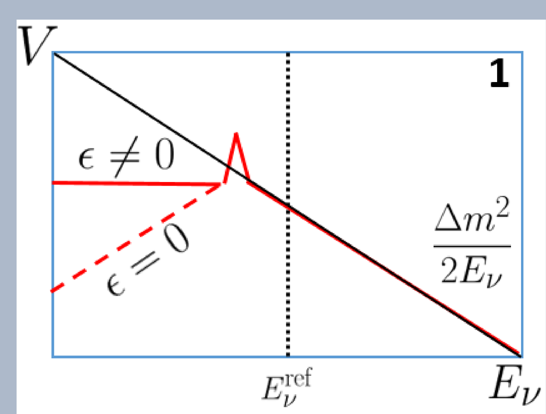
$$\epsilon \equiv \frac{N_e - N_{\bar e}}{N_e + N_{\bar e}}$$

DM assisted neutrino oscillation

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

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

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



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

Standard MSW effect

L. Wolfenstein, 1978

- Standard matter potential
- $\epsilon = 1\ (N_{\bar e} = 0)$
- $m_W^2 \gg 2m_eE_\nu$ $\quad\Rightarrow\quad \boxed{\pm\sqrt{2}G_F N_e}$

- Matter potential at ultra-high energy

$$V_{\nu,\bar\nu}^{SM} \approx \frac{\sqrt{2}G_F m_W^2(N_e + N_{\bar e})}{2m_eE_\nu}$$

- Conversion probability

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

Conclusion and discussion

- We provided a systematic study of neutrino oscillations in a medium of dark matter.
- A formula is derived to describe the medium effect.
- Apparent CP violations arises from the asymmetric distribution of dark matter.
- Precise determination of the neutrino oscillation parameters may be able to reveal the presence of the dark matter asymmetry.
- The medium potential has a resonance peak at $E_\nu = m_f^2/2m_{DM}$.
- In the case of E_ν< 1MeV, the medium potential mimics the standard oscillation parameters and thus solar and atmospheric neutrino data might be accounted for even with massless neutrinos.