2022 International Workshop on
Baryon and Lepton Number Violation
September 5-8 2022, Université Libre de Bruxelles

Neutrino transition in dark matter

2112.05057
1909.10478, 2012.09474

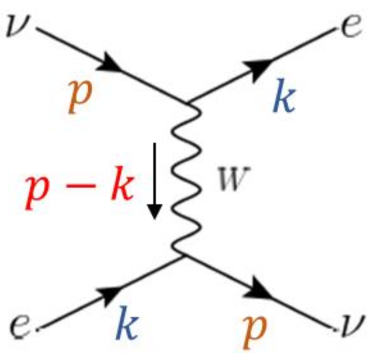
Eung Jin Chun

KOREA INSTITUTE FOR ADVANCED STUDY

Neutrino oscillations in matter

Wolfenstein 1978

- "The effect of coherent forward scattering (leaving the medium unchanged) must be taken into account when considering the oscillations of neutrinos traveling through matter."



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

$$\Rightarrow \sqrt{2} G_F N_e\, \overline{\nu_{eL}}\gamma^0 \nu_{eL}$$

$$\rightarrow E \approx \mathrm{p} + \frac{m_\nu^2}{2\mathrm{p}} + \sqrt{2} G_F N_e$$

"Wolfenstein potential"

Neutrino oscillations in Dark Matter

- Consider neutrinos propagating in a classical DM background

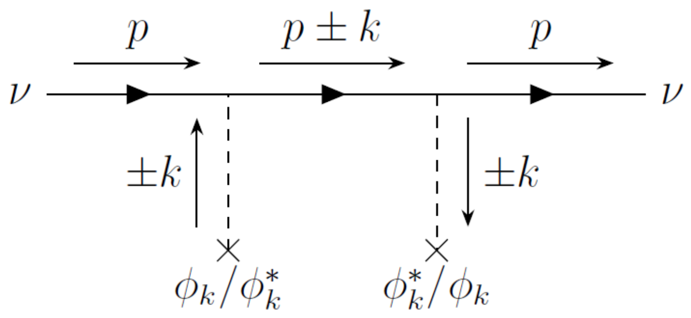
$$\mathcal{L}' = \frac{1}{2} g \hat{\phi} \nu\nu + \frac{1}{2} g^* \hat{\phi}^+ \bar{\nu}\bar{\nu}$$

$$\mathcal{L}' = \frac{1}{2} g \hat{\phi} \nu f + \frac{1}{2} g^* \hat{\phi}^+ \bar{\nu}\bar{f}$$

$$\hat{\phi}(x) \to \phi_c(x) = \phi_k e^{-ik\cdot x} + \bar{\phi}_k e^{ik\cdot x}$$

LNV: $\bar{\phi}_k = \phi_k^*$

- Coherent forward scattering → medium contribution to the propagator
  → modified dispersion relation



In the relativistic limit:

$$E \approx \mathrm{p} + \frac{m_\nu^2 + |g\phi_k|^2 + |g\bar{\phi}_k|^2}{2\mathrm{p}}$$

Choi, EJC, Kim, 1909.10478
2012.09474

"Neutrino oscillations even with $m_\nu = 0$"
(Wolfenstein)

Neutrino Propagation in Dark Matter

- Medium effect in neutrino propagation in a classical DM background

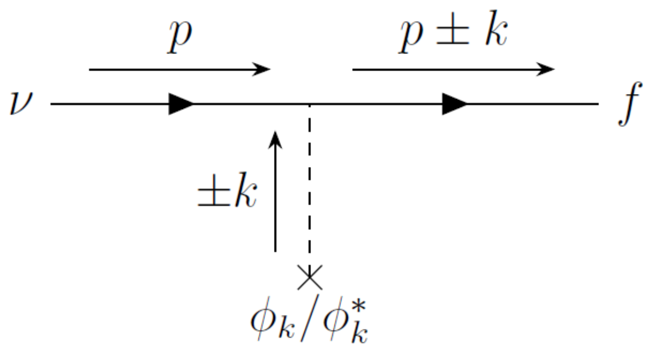
$$\mathcal{L}' = \frac{1}{2} g\hat{\phi}\nu\nu + \frac{1}{2} g^*\hat{\phi}^+\bar{\nu}\bar{\nu}$$

$$\mathcal{L}' = \frac{1}{2} g\hat{\phi}\nu f + \frac{1}{2} g^*\hat{\phi}^+\bar{\nu}\bar{f}$$

$$\hat{\phi}(x) \to \phi_c(x) = \phi_k e^{-ik\cdot x} + \bar{\phi}_k e^{ik\cdot x}$$

LNV: $\bar{\phi}_k = \phi_k^*$

- Yet unexplored coherent process of transition



$$A_{\nu\to f} \propto g\phi_k \bar{u}_{p+k} P_L u_p$$
$$g\bar{\phi}_k \bar{u}_{p-k} P_L u_p$$

EJC, 2112.05057

Coherent state=classical field

Glauber, Sudarshan, 1963

- Eigenstate of annihilation operator:

$$|\phi_c\rangle \propto e^{\int_{\mathrm{k}} \phi_{\mathrm{k}} a_{\mathrm{k}}^{+}}|0\rangle$$

$$\langle\phi_c|a_k|\phi_c\rangle = \phi_k;\ \langle\phi_c|a_k^{+}|\phi_c\rangle = \phi_k^*$$

$$\hat{\phi}(x) = \int \frac{d^3\mathrm{k}}{(2\pi)^3 2E_{\mathrm{k}}}\left[a_{\mathrm{k}} e^{-ik\cdot x} + a_{\mathrm{k}}^{\dagger} e^{ik\cdot x}\right]$$

$$\phi_c(x) \equiv \langle\phi_c|\hat{\phi}(x)|\phi_c\rangle = \int \frac{d^3\mathrm{k}}{(2\pi)^3 2E_{\mathrm{k}}}\left[\phi_{\mathrm{k}} e^{-ik\cdot x} + \phi_{\mathrm{k}}^* e^{ik\cdot x}\right]$$

Monochromatic + non-relativistic

$$\phi_k = (2\pi)^3 2E_0 \delta^3(\mathrm{k}-\mathrm{k}_0)\phi_0,\ k_0 \approx (m_\phi, m_\phi \vec{v})$$

- Energy density:

$$\rho_\phi V = \langle\phi_c| \int_{\mathrm{k}} E_{\mathrm{k}} a_{\mathrm{k}}^{+} a_{\mathrm{k}} |\phi_c\rangle = \int_{\mathrm{k}} E_{\mathrm{k}} |\phi_{\mathrm{k}}|^2$$

$$\rho_\phi \approx 2E_0^2|\phi_0|^2 \approx 2m_\phi^2|\phi_0|^2$$

$$|\phi_0| \approx 10^8\mathrm{GeV}\left(\frac{10^{-20}\mathrm{eV}}{m_\phi}\right)$$

Analysis setup

- Work in the mass basis of neutrinos coupling to a classical background:

$$\mathcal{L}' = \frac{1}{2} g_{ij} \hat{\phi}(x) \overline{\nu_i^c} P_L \nu_j + \frac{1}{2} g_{ij}^* \hat{\phi}^\dagger(x) \overline{\nu_j} P_R \nu_i^c$$

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{\nu_i} \overline{\nu_i^c} P_L \nu_i + \frac{1}{2} m_{\nu_i}^* \bar{\nu}_i P_R \nu_i^c$$

$$|g\phi_0| \sim 0.01\text{eV}$$

$$\Rightarrow g \sim 10^{-19} \left(\frac{m_\phi}{10^{-20}\text{eV}}\right)$$

"Flavour structure of the coupling"

$$g_{ij} = g_{\alpha\beta} U_{\alpha i} U_{\beta j}$$

Two-flavour case

- Consider two-flavor neutrinos:

$$\nu_e = c_\theta \nu_1 - s_\theta \nu_2$$
$$\nu_\mu = s_\theta \nu_1 + c_\theta \nu_2$$

- The $\nu_e \to \nu_\mu$ transition amplitude:

$$A_{\mu e} = c_\theta s_\theta (A_{11} - A_{22}) + c_\theta^2 A_{21} - s_\theta^2 A_{12}$$

Standard oscillation + Medium effect in transition with $g_{11,22} \neq 0$

Medium effect with $g_{12} \neq 0$

Transition amplitudes in medium

- $\nu_i \to \nu_j$ transition amplitude:

$$A_{ji} = \langle \phi_c; \nu_j, \mathrm{p}_2 | e^{-iH_0 t_2} U(t_2, t_1) e^{iH_0 t_1} | \nu_i, \mathrm{p}_1; \phi_c \rangle$$

$$U(t_2, t_1) = T e^{i \int_{t_1}^{t_2} dt\, \mathcal{L}'(t)} = I + i \int_{t_1}^{t_2} dt \int d^3\mathrm{x}\, \mathcal{L}'(x) + \cdots$$

- $U = I$: Standard neutrino oscillation

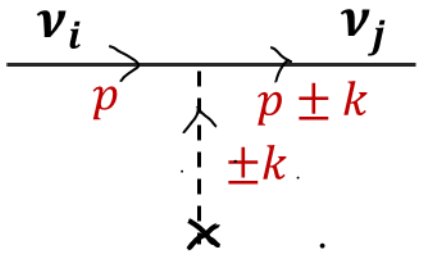
$$A_{ji}^0 = \langle \phi_c; \nu_j, \mathrm{p}_2 | e^{-iH_0(t_2 - t_1)} | \nu_i, \mathrm{p}_1\, ; \phi_c \rangle \propto e^{-i\, E_i L}\, \delta_{ji} \text{ with } L = t_2 - t_1$$

Transition amplitudes in medium

- $U = i\int_{t_1}^{t_2} dt\ \int d^3\mathrm{x}\ \mathcal{L}'(x)$: Medium-induce transition $\nu_i(\mathrm{p}) \to \nu_j(\mathrm{p} \pm \mathrm{k})$

$$A_{ji}^{1} = \langle \phi_c; \nu_j, \mathrm{p}_2 | e^{-iH_0 t_2} i \int_{t_1}^{t_2} dt \int d^3\mathrm{x}\ \mathcal{L}'(x)\, e^{iH_0 t_1} | \nu_i, \mathrm{p}_1; \phi_c \rangle$$

$$\mathcal{L}' = \frac{1}{2} g_{ji} \overline{\nu_j^c} P_L \nu_i \hat{\phi}(x`) + \frac{1}{2} g_{ji}^* \bar{\nu}_i P_R \nu_j^c \hat{\phi}^\dagger(x)$$



$$\phi_c(x) = \phi_0 e^{-ik_0\cdot x} + \phi_0^*\, e^{ik_0\cdot x} \qquad \nu(x) = \int_\mathrm{p} a_\mathrm{p}^s u_\mathrm{p}^s e^{-ip\cdot x} + a_\mathrm{p}^{s+} v_\mathrm{p}^s e^{ip\cdot x}$$

$$A_{ji}^{1\pm} \propto g_{ji}^{(*)} \int_{t_1}^{t_2} dt\ e^{i(E_{\mathrm{p}\pm\mathrm{k}_0} - E_\mathrm{p} \mp E_{\mathrm{k}_0})t}\ \phi_0^{(*)} \frac{\left[\overline{u_{\mathrm{p}\pm\mathrm{k}_0}^s} P_L u_\mathrm{p}^s - \overline{v_\mathrm{p}^s} P_R v_{\mathrm{p}\pm\mathrm{k}_0}^s\right]}{2E_{\mathrm{p}\pm\mathrm{k}_0}\ 2E_\mathrm{p}}$$

Transition probability

- Three independent contributions: $P_{\mu e} \propto \left|A^0_{\mu e}\right|^2 + \left|A^{1+}_{\mu e}\right|^2 + \left|A^{1-}_{\mu e}\right|^2$

- Assuming $|g\phi_0| \ll m_\nu$, consider two couplings independently g_{12}, g_{22}:

$$E_{\rm p} \approx E_\nu + \frac{m_\nu^2}{2E_\nu}, \qquad E_{\rm k_0} \approx m_\phi$$

- Additional contribution to be smaller:

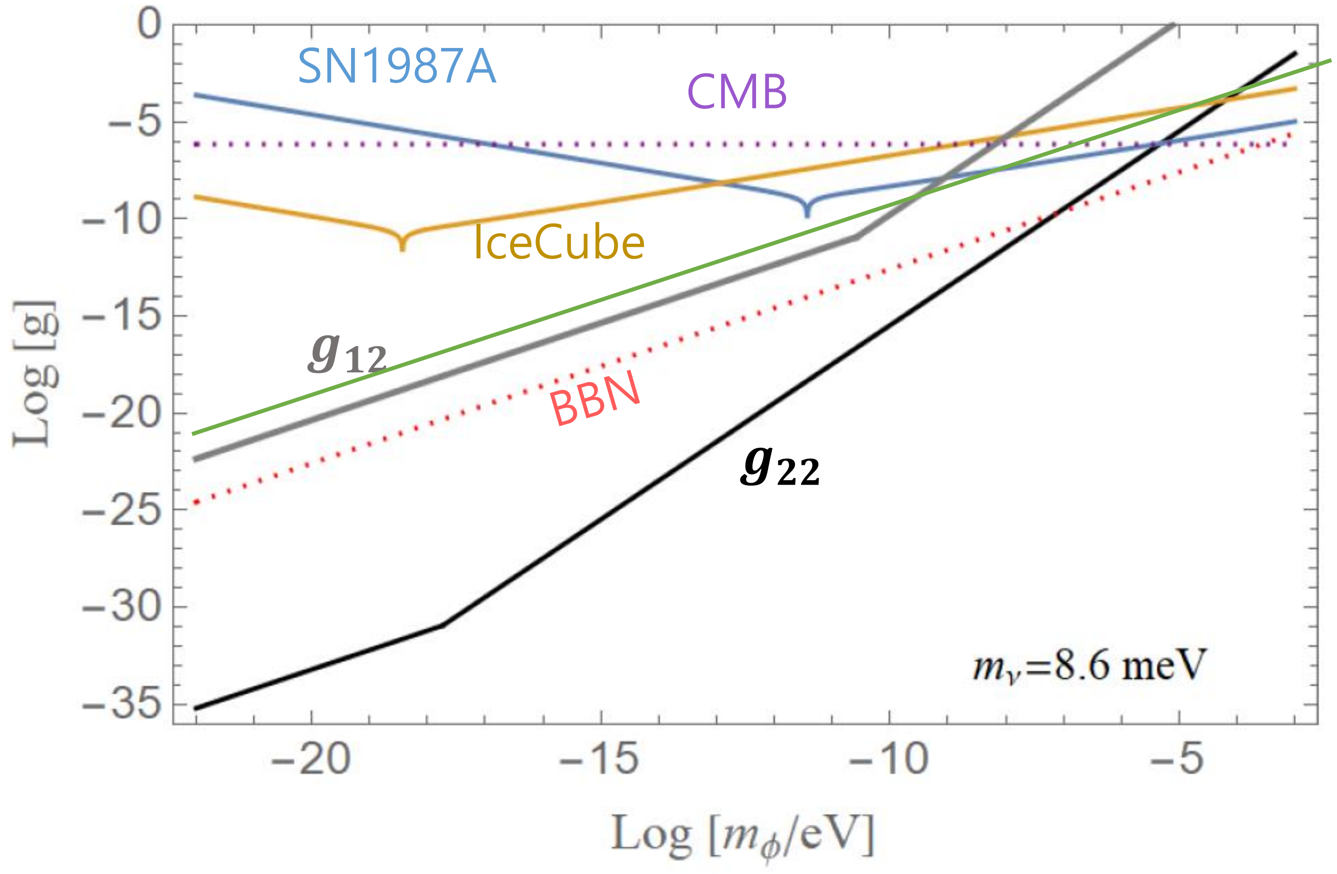
$$\delta P_{\mu e} \lesssim 0.1\, P_{\mu e}^{\rm obs.}$$

$$P_{\mu e} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) \qquad \Delta_{21}^{\pm} \equiv \frac{\Delta m_{21}^2}{2E_\nu} \pm m_\phi$$

$$+\cos^2(2\theta)\frac{|g_{12}\phi_0|^2 m_{\nu_2}^2}{\left(\Delta_{21}^{\pm}E_\nu\right)^2}\sin^2\left(\frac{\Delta_{21}^{\pm}L}{2}\right)$$

$$+\sin^2(2\theta)\frac{|g_{22}\phi_0|^2 m_{\nu_2}^2}{m_\phi^2 E_\nu^2}\sin^2\left(\frac{m_\phi L}{2}\right)$$

Constraints from neutrino oscillation data



$|g\phi_0| \sim 0.01\text{eV}$

CMB: 1904.07810
BBN: 2009.08104

Summary

- Interesting medium effects in neutrino propagation – medium potential, induced mass-squared, CPV, etc..

- Discussed yet another transition process $\nu_i(\mathrm{p}) \to \nu_j(\mathrm{p} \pm \mathrm{k})$ that occurs in the classical background of ϕ_k/ϕ_k^*, and is highly constrained by the neu trino oscillation data.

- This process is suppressed in the limit of $m_\nu \to 0$, where neutrino oscillat ions can be solely due to the medium effect.