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Neutrino transition in dark matter

arXiv: 2112.05057

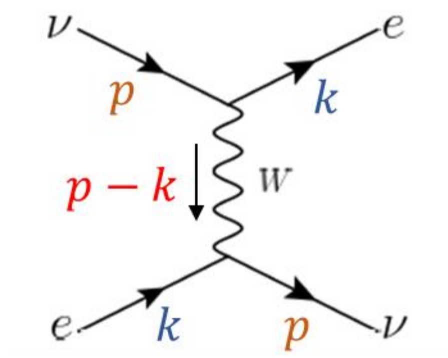
Eung Jin Chun

KIAS
KOREA INSTITUTE FOR ADVANCED STUDY

Introduction

Studies of medium effect in neutrino propagation

- Neutrinos traveling through matter (Wolfenstein '78):
  "Coherent forward scattering leaving the medium unchanged
  must be taken into account in neutrino oscillations."



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

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

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

Introduction

- Neutrinos traveling through an ultralight DM:

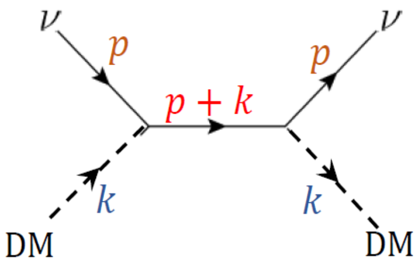
$$\mathcal{L}' = \frac{1}{2} g \hat{\phi} \nu \nu + h.c.$$

$$\hat{\phi}(x) \to \phi_c(x) = \phi_0 e^{-ik\cdot x} + h.c.$$

i) Time-oscillating mass: $m_\nu^{\rm eff} = m_\nu^0 + 2g|\phi_0|\cos(m_\phi t)$

Berlin, 1608.01307
Krnjaic, et.al., 1705.06740
Brdar, et.al., 1705.09455
Pablo's talk

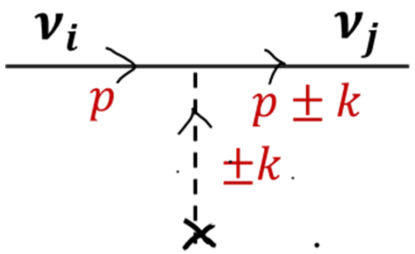
ii) Modified dispersion:



$\to E \approx \mathrm{p} + \frac{m_\nu^2 + |g\phi_0|^2}{2\mathrm{p}}$

Ge, Murayama, 1904.02518
Choi, EJC, Kim, 1909.10478
2012.09474

iii) Medium-induced $\nu_i \to \nu_j$ transition



EJC, 2112.05057

Dark medium of an ultra-light boson

- Huge number density → classical field

Hui, 2101.11735
Myriam's talk

$$n_\phi = \frac{\rho_\phi}{m_\phi} \approx 3 \times 10^{14} \left(\frac{10^{-6}\mathrm{eV}}{m_\phi}\right) \mathrm{cm}^{-3}$$

$$\rho_\phi = \rho_\odot \approx 0.3\ \mathrm{GeV/cm^3}$$

$$\lambda_{\mathrm{dB}} = \frac{2\pi}{m_\phi v} \approx 1.5\mathrm{km} \left(\frac{10^{-6}\mathrm{eV}}{m_\phi}\right) \left(\frac{250\mathrm{km/s}}{v}\right)$$

$$n_{\mathrm{dB}} = n_\phi \lambda_{\mathrm{dB}}^3 \approx 10^{30} \left(\frac{10^{-6}\mathrm{eV}}{m_\phi}\right)^4 \left(\frac{250\mathrm{km/s}}{v}\right)^3$$

Glauber, Sudarshan, '63

Classical field=Coherent state:
Indefinite number of particles in phase

Coherent state

- Eigenstate of annihilation operator:

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

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

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

- Energy density:

Monochromatic: $\phi_k = (2\pi)^3 2E_0 \delta^3(\mathrm{k}-\mathrm{k}_0)\phi_0$

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

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

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

Analysis setup

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

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

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

(*) $|g\phi_0| \sim 0.01\text{eV}$
$\Rightarrow g{\sim}10^{-19} \left(\frac{m_\phi}{10^{-20}\text{eV}}\right)$

"Flavour structure in the coupling?"

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

For a simple picture

- 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 in medium is describe by :

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

Standard oscillation & Medium effect 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

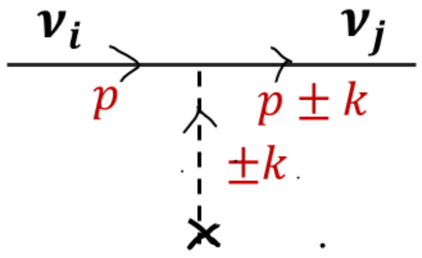
$$A_{ji}^0 = \langle \phi_c; \nu_j, \mathrm{p}' | e^{-iH_0(t_2 - t_1)} | \nu_i, \mathrm{p}\,; \phi_c \rangle \propto e^{-i\,E_i L}\, \delta_{ji} \text{ with } L = t_2 - t_1$$

Transition amplitudes in medium

- Medium-induce transition: $\nu_i(\mathrm{p}) \rightarrow \nu_j(\mathrm{p} \pm \mathrm{k})$

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

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



$$\phi_c(x) = \phi_0 e^{-ik_0 \cdot x} + \phi_0^*\, e^{ik_0 \cdot x} \qquad \nu(x) = \int_{\mathrm{p}} a^s_{\mathrm{p}} u^s_{\mathrm{p}} e^{-ip\cdot x} + a^{s+}_{\mathrm{p}} v^s_{\mathrm{p}} e^{ip\cdot x}$$

$$A^{1\pm}_{ji} \propto g^{(*)}_{ji} \int_{t_1}^{t_2} dt\, e^{i\left(E_{\mathrm{p}\pm\mathrm{k}_0} - E_{\mathrm{p}} \mp E_{\mathrm{k}_0}\right)t}\, \phi_0^{(*)} \frac{\left[\overline{u^s_{\mathrm{p}\pm\mathrm{k}_0}} P_L u^s_{\mathrm{p}} - \overline{v^s_{\mathrm{p}}} P_R v^s_{\mathrm{p}\pm\mathrm{k}_0}\right]}{2E_{\mathrm{p}\pm\mathrm{k}_0}\, 2E_{\mathrm{p}}}$$

The transition probability

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

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

$$P_{\mu e} \propto \left|A_{\mu e}^{0}\right|^2 + \left|A_{\mu e}^{1+}\right|^2 + \left|A_{\mu e}^{1-}\right|^2$$

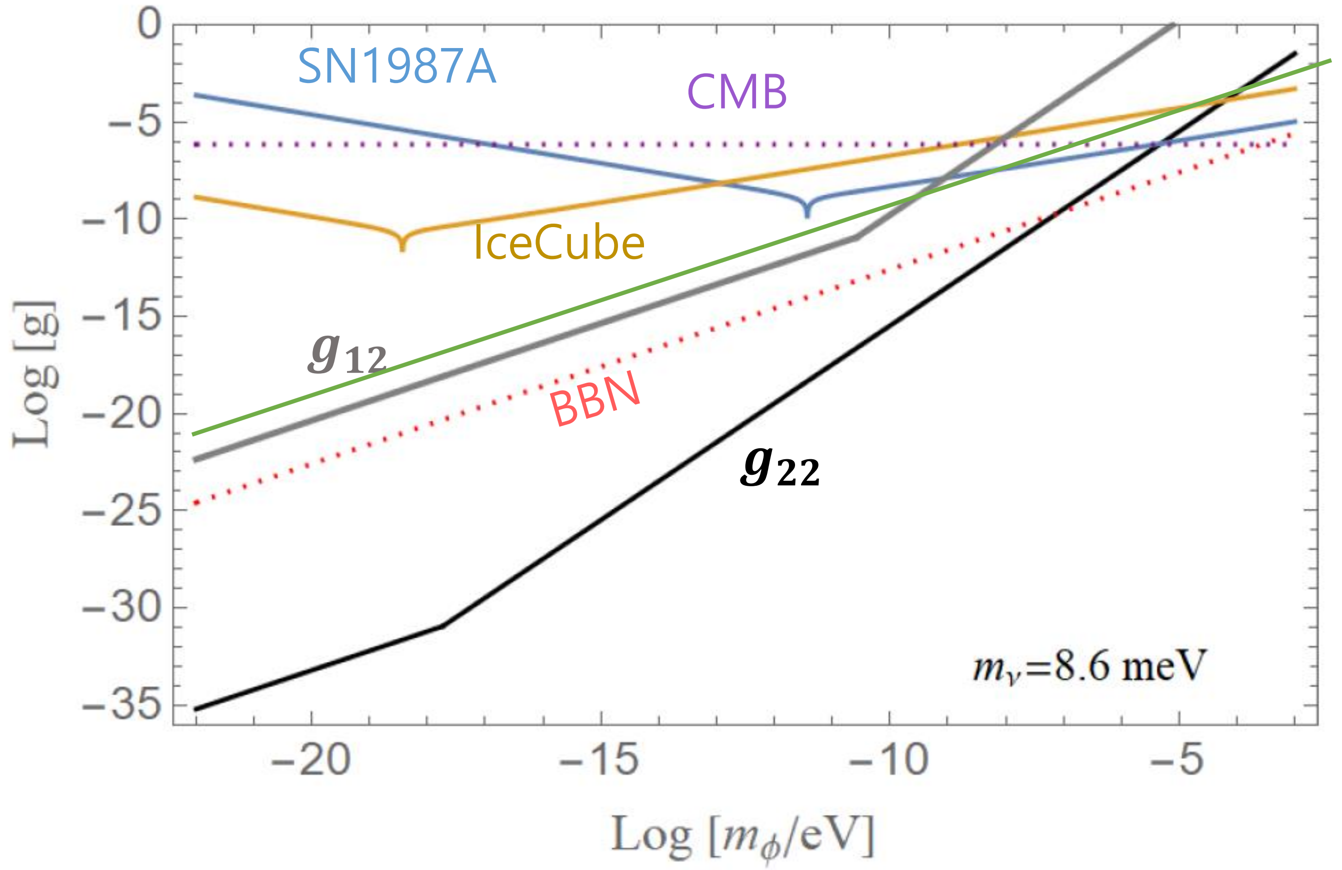
$$P_{\mu e} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

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

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

$$\Delta_{21}^{\pm} \equiv \frac{\Delta m_{21}^2 L}{2E_\nu} \pm m_\phi$$

Constraints from neutrino oscillation data



CMB: 1904.07810
BBN: 2009.08104

Conclusion

- Ultralight boson can form a coherent state providing a classical backgro und of DM.
- It has interesting impacts on neutrino oscillations, cosmology & astroph ysics when coupled to neutrinos.
- A yet unexplored process $\nu_i(\mathrm{p}) \to \nu_j(\mathrm{p} \pm \mathrm{k})$ in neutrino propagation is di scussed.
- Depending on flavour structure, strong constraints can be obtained.
- This process is suppressed in the opposite limit of $m_\nu \to 0$, where neutri no oscillations may be solely due to the medium effect.