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Neutrino oscillations in a medium

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Outline

- Neutrinos interacting with a hot/dense medium

  Coherent forward scattering modifies/drives neutrino oscillations Wolfenstein 78

  Adiabatic conversion of solar neutrinos Mikheyev-Smirnov 85

- Study of dispersion relation at a finite temperature

  Thermal mass of fermions Weldon 82

  Re-derivation of Wolfenstein potential Mannheim 88; Notzold-Raffeld 88; Pal-Pham 89; Nieves 89; …

- Dispersion of neutrinos in non-standard media

  An approximate solution in high-momentum limit Ge-Murayama 19; Choi-EJC-Kim 19

  General solutions in various limits Choi-EJC-Kim 20

- Implications:

  Medium-induced masses and oscillations; cosmological/astrophysical limits

Neutrino oscillations in matter

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(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

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general dispersion relations

by medium-induced mass-squared

dark matter

ν-DM interaction

Neutrino oscillations in vacuum

- Propagation Hamiltonian:

$$i\frac{d}{dt}\psi = H\,\psi$$

$$\psi = (\nu_1, \nu_2, \nu_3)^T \qquad \psi = (\nu_e, \nu_\mu, \nu_\tau)^T \qquad \nu_\alpha = U_{\alpha i}\,\nu_i$$

$$H \approx \mathrm{p} + \frac{m_i^2}{2\mathrm{p}} \qquad H \Rightarrow \frac{Um^2U^+}{2\mathrm{p}} = \frac{MM^+}{2\mathrm{p}}$$

- Two-flavor evolution:

$$H \approx \frac{\Delta m^2}{4\mathrm{p}}\begin{bmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{bmatrix} \rightarrow P_{e\mu} = \left|\langle\nu_\mu|e^{iHt}|\nu_e\rangle\right|^2 = \sin^2 2\theta\,\sin^2\left(\frac{\Delta m^2 L}{4\mathrm{p}}\right)$$

Wolfenstein potential

- "Oscillations for massless neutrinos can occur as a result of coherent forward scattering provided that this scattering is off-diagonal in ne utrino flavor":

$$\mathcal{H}_{eff} = G_{\alpha\beta}\, \bar{\nu}_\alpha \gamma^\mu P_L\, \bar{\nu}_\beta\, \bar{f} \gamma_\mu f \;\Rightarrow H \sim G_{\alpha\beta}\, N_f$$

(momentum-independent)

- "In the standard model, vacuum oscillations are modified by the cha rged current scattering":

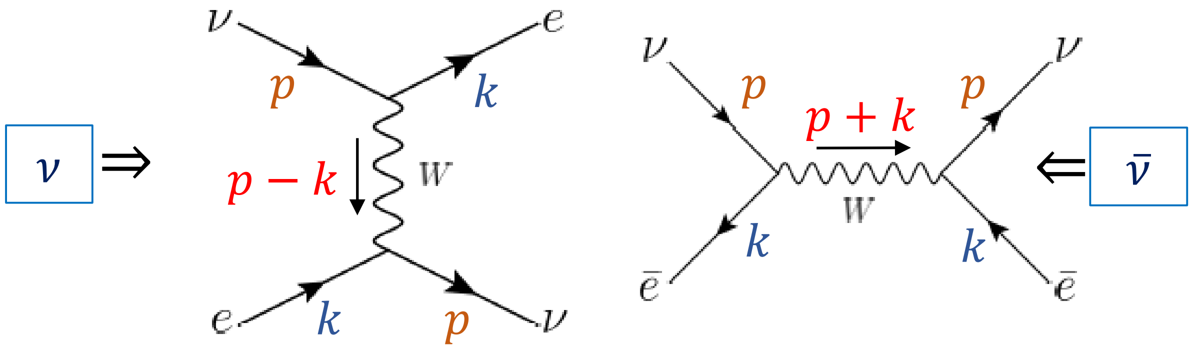
$$H_{\nu/\bar{\nu}} \approx \frac{\Delta m^2}{4p} \begin{bmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{bmatrix} \pm \begin{bmatrix} V_W & 0 \\ 0 & 0 \end{bmatrix}$$

$$V_W = \sqrt{2}\, G_F N_e(t)$$

MSW effect

Generalizing the Wolfenstein effect

- In a medium with arbitrary N_e and $N_{\bar{e}}$



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

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

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

$$\langle N_e, N_{\bar{e}} | e\bar{e} | N_e, N_{\bar{e}} \rangle = -\frac{1}{2} \sum_s u_s(k) \bar{u}_s(k) \frac{N_e}{2k^0} + \frac{1}{2} \sum_s v_s(k) \bar{v}_s(k) \frac{N_{\bar{e}}}{2k^0}$$

"Free" neutrinos in a medium

- Self-energy correction by the coherent forward scattering:

$$\mathcal{L}_{kin} \Rightarrow \overline{\nu_L}(p^\mu - k^\mu \Sigma_W)\gamma_\mu \nu_L$$

$$\Sigma_W = g_\nu^2 \frac{N_{e+\bar{e}}}{m_e} \frac{-2m_e E + \epsilon(m_W^2 - p^2 - m_e^2)}{(m_W^2 - p^2 - m_e^2)^2 - 4m_e^2 E^2}$$

$$g_\nu^2 \equiv \sqrt{2} G_F m_W^2$$

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

$$p^\mu = (E, \vec{\mathrm{p}}) \quad p^2 = E^2 - \mathrm{p}^2$$

$$k^\mu = (m_e, \vec{0})$$

- Dispersion of Weyl neutrino in the high-momentum limit ($E \approx \mathrm{p}$):

$$(p - k\Sigma_W)^2 = (E - m_e \Sigma_W)^2 - \mathrm{p}^2 = 0 \xrightarrow[2m_e\mathrm{p} \gg m_W^2]{m_W^2 \gg 2m_e\mathrm{p}} \begin{cases} E_{\nu/\bar{\nu}} \approx \mathrm{p} \pm \epsilon\, g_\nu^2 \dfrac{N_{e+\bar{e}}}{m_W^2} + \cdots & \text{Potential} \\ E_{\nu/\bar{\nu}} \approx \mathrm{p} + g_\nu^2 \dfrac{N_{e+\bar{e}}/m_e}{2\mathrm{p}} + \cdots & \text{Oscillation} \end{cases}$$

(For Majorana neutrino, p.11)

Dispersion of neutrinos in a medium

General formulation

- Eqs. of motion in a Lorenz invariant medium:

$$(\not{p} - \not{p}\Sigma^u_{1L} - \not{k}\Sigma^u_{2L})u_L(p) = (M^+ + \Sigma^+_0)u_R(p)$$

$$(\not{p} - \not{p}\Sigma^u_{1R} - \not{k}\Sigma^u_{2R})u_R(p) = (M + \Sigma_0)u_L(p)$$

(3,4) (1,2,3,4) (5)

$$\Sigma^+_{1,2} = \Sigma_{1,2}$$

- For v-spinors: $\Sigma^v_1(p) = \Sigma^u_1(-p)$

$$\Sigma^v_2(p) = -\Sigma^u_2(-p)$$

- Neutrinos interacting with dark matter and mediator

$$\mathcal{L}' = g_{\alpha i}\,\overline{f_{iL}}\gamma^\mu \nu_{\alpha L}\,X_\mu + h.c. \quad (1)$$

$$g_{\alpha i}\,\bar{f}_R \nu_{\alpha L}\,\phi_i + h.c. \quad (2)$$

$$g_{\alpha i}\,\overline{f_{iR}}\nu_{\alpha L}\,\phi + h.c. \quad (3)$$

$$g_{\alpha\beta}\,\overline{\nu^c_{\beta R}}\nu_{\alpha L}\,\phi + h.c. \quad (4)$$

$$g_{\alpha\beta}\,\overline{\nu^c_{\beta R}}\nu_{\alpha L}\,\phi + y\,\phi\,\bar{f}_R f_L + h.c. \quad (5)$$

General eqs. for dispersion

- For $k = (m_\phi, \vec{0})$ & $p = (E, \hat{z}\mathrm{p})$, EoM (for ν_L/ν_R) is solved by

$$L \cdot R - m_\nu^2 \pm H = 0$$

$$L \equiv p - \Sigma_L \equiv (L_0, \hat{z}L_z)$$
$$R \equiv p - \Sigma_R \equiv (R_0, \hat{z}R_z)$$

$$H \equiv L_z R_0 - R_z L_0$$

$$0 = (E^2 - \mathrm{p}^2)(1-\Sigma_{1L})(1-\Sigma_{1R}) - m_\nu^2 + m_\phi^2 \Sigma_{2L}\Sigma_{2R}$$
$$-m_\phi(E \pm \mathrm{p})\Sigma_{2L}(1-\Sigma_{1R}) - m_\phi(E \mp \mathrm{p})\Sigma_{2R}(1-\Sigma_{1L})$$

$$\xrightarrow{E \to \mathrm{p}} 2\mathrm{p}\, m_\phi \begin{cases} \Sigma_{2L}(1-\Sigma_{1R}) \\ \Sigma_{2R}(1-\Sigma_{1L}) \end{cases}$$

- Approximate solutions for $|\Sigma_1| \ll 1$ & $m_\phi |\Sigma_2| \ll m_\nu, \mathrm{p}$

$$E^2 \approx \mathrm{p}^2 + m_\nu^2\left(1 + \Sigma_{1L}^{(0)} + \Sigma_{1R}^{(0)}\right)$$
$$-m_\phi\left(E_0[\Sigma_{2L}^{(0)} + \Sigma_{2R}^{(0)}] \pm \mathrm{p}[\Sigma_{2L}^{(0)} - \Sigma_{2R}^{(0)}]\right)$$

$$\Sigma^{(0)} = \Sigma(E_0, \mathrm{p});$$
$$E_0 = \sqrt{p^2 + m_\nu^2}$$

Wolfenstein:
$(\Sigma_{1L,R} = 0;\ m_\phi \Sigma_{2L,R} = \pm V_W)$
$E_{\nu,\bar{\nu}}^2 = \mathrm{p}^2 + m_\nu^2 + V_W^2 \pm 2\mathrm{p}\, V_W$

(Sun: $m_\nu^2 \sim 2\mathrm{p}V_W$)

Application to different types of neutrinos

- Weyl ($m_\nu = 0$): $u_L(u_R)$ for ν ($\bar{\nu}$)

$$\left(E_{\nu,\bar{\nu}} - \mathrm{p}\right)\left(1 - \Sigma_{1L,R}\right) - m_\phi \Sigma_{2L,R} = 0 \;\Rightarrow\; E_{\nu,\bar{\nu}} \approx \mathrm{p} + m_\phi \Sigma_{2L,R}^{(0)}$$

- Majorana ($\nu = \nu^c$): $u_L(u_R)$ for ν ($\bar{\nu}$) for $E \to \mathrm{p}$

$$(u_R = v_L^c, v_R = u_L^c)$$

$$\Sigma_R^u(p) = [\Sigma_L^v(p)]^* = -[\Sigma_L^u(-p)]^* = [\Sigma_L^u(p)]^*_{\epsilon\to-\epsilon}$$

$$E_{\nu,\bar{\nu}} \approx E_0 + \frac{m_\nu^2}{2E_0}\left(\Sigma_{1L}^{(0)} + \Sigma_{1R}^{(0)}\right) + \frac{m_\phi}{2}\left(\left(\Sigma_{2L}^{(0)} + \Sigma_{2R}^{(0)}\right) \pm \frac{\mathrm{p}}{E_0}\left(\Sigma_{2L}^{(0)} - \Sigma_{2R}^{(0)}\right)\right)$$

asymmetric

- Dirac ($\nu \neq \nu^c, m_\nu \neq 0$) with $\Sigma_R = 0$:

$$(E^2 - \mathrm{p}^2)(1 - \Sigma_{1L}) - m_\nu^2 - m_\phi \Sigma_{2L}(E \pm \mathrm{p}) = 0$$

$$E_{\nu_L,\nu_R} \approx E_0 + \frac{m_\nu^2}{2E_0}\Sigma_{1L}^{(0)} + \frac{m_\phi}{2}\Sigma_{2L}^{(0)}\left(1 \pm \frac{\mathrm{p}}{E_0}\right) \xrightarrow{\epsilon\to-\epsilon} E_{\bar{\nu}_L,\bar{\nu}_R}$$

Neutrinos in a medium of complex scalar

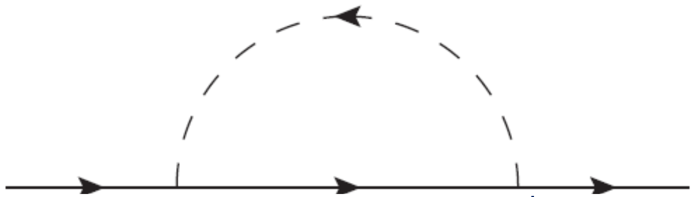
$$\mathcal{L}' = g\overline{f_R}\nu_L\phi + g^*\,\bar{\nu}_L f_R \phi^*$$

Modified neutrino propagator

- Finite temperature/density calculation

$$S_\nu^{-1}(p) = (\not{p} - \not{\Sigma}) = (\not{p} - \not{p}\Sigma_1 - \not{k}\Sigma_2)$$

$$\not{\Sigma} = i\, g g^\dagger \int \frac{d^4k}{(2\pi)^4} \Delta_\phi(k)\, S_f(p+k)$$



$$\Delta_\phi(k) = \frac{1}{k^2} - 2\pi i\, \delta(k^2 - m_\phi^2)\, f_\phi(k)$$

$$S_f(q) = (\not{q} + m_f)\left(\frac{1}{q^2 - m_f^2} + 2\pi i\, \delta(q^2 - m_f^2)\, f_f(q)\right)$$

Medium 4-momentum: $k = (k^0, \vec{k}) \simeq (m_\phi, 0)$

Distribution functions:

$$f_f(q) = 0$$

$$f_\phi(k) = \left(\theta(k_0) n_\phi + \theta(-k^0)\, n_{\bar{\phi}}\right)(2\pi)^3 \delta^3(\vec{k})$$

Self-energy corrections

$$\Sigma_{1L}^{u,v}(p), \Sigma_{1L,R} = S(p) \pm \epsilon A(p)$$
$$\Sigma_{2L}^{u,v}(p), \Sigma_{2L,R} = A(p) \pm \epsilon S(p)$$

$$\epsilon \equiv \frac{N_\phi - N_{\bar{\phi}}}{N_\phi + N_{\bar{\phi}}} \qquad \delta m^2 \equiv |g|^2 \frac{N_\phi + N_{\bar{\phi}}}{2\, m_\phi}$$

$$S(p) = \delta m^2 \frac{p^2 + m_\phi^2 - m_f^2}{\left(p^2 + m_\phi^2 - m_f^2\right)^2 - 4 m_\phi^2 E^2}$$

$$A(p) = \delta m^2 \frac{-2 m_\phi E}{\left(p^2 + m_\phi^2 - m_f^2\right)^2 - 4 m_\phi^2 E^2}$$

$$E^2 = p^2 - \mathrm{p}^2$$

nb) Consistent with the diagrammatic calculation.

$$\mathrm{S}_\nu^{-1}(p) = (\not{p} - \not{p}\Sigma_1 - \not{k}\Sigma_2)$$

Modified dispersion relations

$$E = E(\mathrm{p};\, m_\nu^2, \delta m^2, m_f^2, m_\phi^2)$$

depending on the parameter hierarchies:

1. Decoupling limit: $m_f^2 \gg \delta m^2, m_\nu^2, 2 m_\phi \mathrm{p} \gg m_\phi^2$
2. Heavy neutrino limit: $m_\nu^2 \gg \delta m^2, m_f^2, 2 m_\phi \mathrm{p}$
3. High momentum limit: $2 m_\phi \mathrm{p} \gg m_f^2, \delta m^2, m_\nu^2$
4. High density limit: $\delta m^2 \gg m_f^2, m_\nu^2, 2 m_\phi \mathrm{p}$

Dispersion of Weyl/Majroana neutrinos

$*)$ Weyl: $m_\nu = 0$

1. Decoupling limit

i) $p \to \infty$: $E_{\nu,\bar{\nu}} \approx p + \frac{m_\nu^2}{2p}\left(1 - 2\frac{\delta m^2}{m_f^2}\right) \mp \epsilon m_\phi \frac{\delta m^2}{m_f^2}$

ii) $p \to 0$: $E_{\nu,\bar{\nu}} \approx m_\nu \left(1 - \frac{\delta m^2}{m_f^2}\right)$

2. Heavy neutrino limit

i) $p \to \infty$: $E_{\nu,\bar{\nu}} \approx p + \frac{m_\nu^2}{2p}\left(1 + 2\frac{\delta m^2}{m_\nu^2}\right) \pm \epsilon m_\phi \frac{\delta m^2}{m_\nu^2}$

ii) $p \to 0$: $E_{\nu,\bar{\nu}} \approx m_\nu \left(1 + \frac{\delta m^2}{m_\nu^2}\right)$

3. High momentum limit

$$E_{\nu,\bar{\nu}} \approx p + \frac{m_\nu^2 + \delta m^2}{2p} \mp \epsilon \frac{\delta m^2 (m_\nu^2 - m_f^2)}{4 m_\phi p^2}$$

4. High density limit

$m_\nu^2 \gg \delta m^2$ (→ 2. Heavy neutrino limit)

i) $p \to \infty$: $E_{\nu,\bar{\nu}} \approx p + \frac{m_M^2}{2p} \pm \epsilon m_\phi \frac{\delta m^2}{m_M^2 + \delta m^2}$

ii) $p \to 0$: $E_{\nu,\bar{\nu}} \approx m_M$

$$m_M \equiv \frac{1}{2}\left(m_\nu + \sqrt{m_\nu^2 + 4\delta m^2}\right)$$

Rest mass correction!

Dispersion of Dirac neutrinos

1. Decoupling limit

i) $p \to \infty$:

$$E_{\nu_L,\overline{\nu_L}}\ (E_{\nu_R,\overline{\nu_R}}) \approx p + \frac{m_\nu^2}{2p}\left(1 - \frac{\delta m^2}{m_f^2}\right) \mp (0)\ \epsilon m_\phi \frac{\delta m^2}{m_f^2}$$

ii) $p \to 0$: $E_{\nu,\bar{\nu}} \approx m_\nu \left(1 - \frac{\delta m^2}{2m_f^2}\right) \mp \epsilon m_\phi \frac{\delta m^2}{2m_f^2}$

$m_\nu^2 \gg \delta m^2$

2. Heavy neutrino limit

i) $p \to \infty$:

$$E_{\nu_L,\overline{\nu_L}}\ (E_{\nu_R,\overline{\nu_R}}) \approx p + \frac{m_\nu^2 + \delta m^2}{2p} + \frac{\delta m^2}{2p}\frac{m_f^2}{m_\nu^2} \left(\mp \epsilon m_\phi \frac{\delta m^2}{m_\nu^2}\right)$$

ii) $p \to 0$: $E_{\nu,\bar{\nu}} \approx m_\nu \left(1 + \frac{\delta m^2}{2m_\nu^2}\right)$

3. High momentum limit

$$E_{\nu_L,\bar{\nu}_L} \approx p + \frac{m_\nu^2 + \delta m^2}{2p} \pm \epsilon \frac{\delta m^2 m_f^2}{4 m_\phi p^2}$$

$$E_{\nu_R,\bar{\nu}_R} \approx p + \frac{m_\nu^2}{2p} \pm \epsilon \frac{\delta m^2 m_\nu^2}{4 m_\phi p^2}$$

4. High density limit

i) $p \to \infty$: $E_{\nu_L,\overline{\nu_L}} \approx p + \frac{m_D^2}{2p} + \frac{\delta m^2}{2p}\frac{m_f^2}{m_D^2}$

$$E_{\nu_R,\overline{\nu_R}} \approx p + \frac{m_D^2}{2p} + \frac{\delta m^2}{2p}\frac{m_f^2}{m_D^2} \mp \epsilon m_\phi \frac{\delta m^2}{m_D^2}$$

ii) $p \to 0$: $E_{\nu,\bar{\nu}} \approx m_D$

$m_D \equiv \sqrt{m_\nu^2 + \delta m^2}$ $\neq m_M$!!

Implications

Effective mass in a medium

- L-conserving mass-squared without chirality-flip:

$$\delta m^2 = \frac{g g^+}{2} \frac{\rho_{\phi+\bar{\phi}}}{2m_\phi}$$

$$m_M = \frac{1}{2}\left(m_\nu + \sqrt{m_\nu^2 + 4\delta m^2}\right)$$

$$E \xrightarrow{\mathrm{p}\to 0} m_{M,D}$$

$$m_D = \sqrt{m_\nu^2 + \delta m^2}$$

- Affecting neutrino oscillations:

$$\mathrm{p}^2 \gg 2m_\phi \mathrm{p} \gg \delta m^2, m_\nu^2 \;\Longrightarrow E \sim \frac{m_\nu^2 + \delta m^2}{2\mathrm{p}}$$

$$\mathrm{p}^2 \gg \delta m^2, m_\nu^2 \gg 2m_\phi \mathrm{p} \;\Longrightarrow E \sim \frac{m_{M,D}^2}{2\mathrm{p}}$$

Oscillation as a dark medium effect

- Solar and Atmospheric neutrino oscillations: $E_\nu \approx \mathrm{p}$

$$\mathrm{p_{sol}} = (0.1 - 10)\mathrm{MeV}\,, \qquad \mathrm{p_{atm}} = (0.1 - 100)\ \mathrm{GeV}$$

$$\Delta m^2_{\mathrm{sol}} = 7.5 \times 10^{-5}\ \mathrm{eV}^2\,, \quad \Delta m^2_{\mathrm{atm}} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

$$\frac{\Delta m^2}{2\mathrm{p}} = \left\{ \begin{matrix} 3.8 \times 10^{-10:-12}\ \mathrm{eV} \\ 1.2 \times 10^{-11:-14}\ \mathrm{eV} \end{matrix} \right\}$$

- Weyl neutrinos can oscillates due to $\rho^{loc}_{\mathrm{DM}} \approx 0.3\ \mathrm{GeV/cm^3} \approx 2.3 \times 10^{-6}\ \mathrm{eV}^4$

$$\delta m^2_{loc} = g^2 \frac{\rho^{loc}_{DM}}{2m^2_{DM}} \sim \Delta m^2_{\mathrm{sol,\ atm}} \quad \Longrightarrow m_\phi \approx 0.03g\ \mathrm{eV} \left(\frac{2.5 \times 10^{-3}\ \mathrm{eV}^2}{\delta m^2_{loc}} \right)^{\frac{1}{2}}$$

- CPV may also appear: $E_\nu \ni \pm\epsilon \dfrac{m_f^2}{2m_{\mathrm{DM}}\mathrm{p}} \dfrac{\delta m^2}{2\mathrm{p}}$; $\pm\epsilon m_{\mathrm{DM}}$

Cosmological limitation

- Neutrinos were heavier at earlier time.

$$\delta m^2(z) = \delta m^2_{loc} \frac{\rho^0_{DM}}{\rho^{loc}_{DM}} (1+z)^3 \approx 6650 \left(\frac{z}{1100}\right)^3 \delta m^2_{loc}$$

- Around the CMB decoupling, neutrinos cannot be too heavy:

$$\delta m^2(z) \lesssim (0.1\mathrm{eV})^2 \Rightarrow \delta m^2_{loc} < 10^{-6}\mathrm{eV}^2$$

- To explain the neutrino oscillations as an local DM effect, the current DM component needs to be generated well after the decoupling.

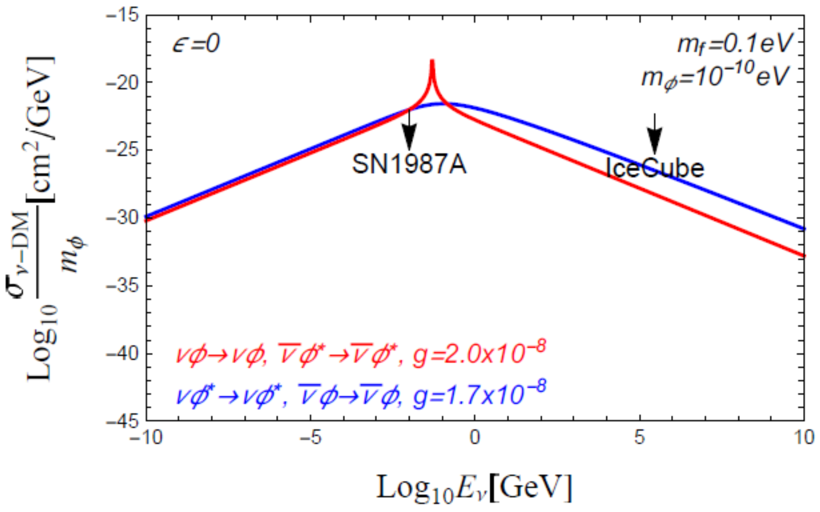
Astrophysical bounds

- The present neutrino-DM scattering cross-section is constrained by SN1987A ($E_\nu \sim 10$ MeV) and IceCube-170922A ($E_\nu \sim 300$TeV) neutrino observations: $\frac{\sigma_{\nu-\phi}}{m_\phi} \approx \frac{g^4}{32\pi\, m_\phi^2 E_\nu} \lesssim 10^{-22}\ \mathrm{cm^2/GeV} \Longrightarrow m_\phi \gtrsim 2\times 10^6 g^2\ \mathrm{eV}$

- Combined with the condition for the "massless" oscillation

$$g \lesssim 1.5\times 10^{-8}\left(\frac{2.5\times 10^{-3}\ \mathrm{eV}^2}{\delta m^2_{loc}}\right)^{\frac{1}{2}}$$

$$m_\phi \lesssim 4.5\times 10^{-10}\ \mathrm{eV}\left(\frac{2.5\times 10^{-3}\ \mathrm{eV}^2}{\delta m^2_{loc}}\right)^{\frac{1}{2}}$$



Conclusion

- General dispersion relations of neutrinos propagating in a medium are found up to first order in perturbation considering the four limiting situations.
- Effective mass is generated and the neutrino oscillations may be due to the medium effect (partly or totally even for Weyl neutrinos).
- The scenario is limited by the cosmological mass generation and the neutrino-DM interaction is constrained by the astrophysical neutrino observations.
- Sensible UV-completion for the origin of scalar DM?

  Dark sector coupling only to neutrinos; late generation of ultra-light cold DM