Flavour-Selective Neutrino Scattering in Dark Matter Background

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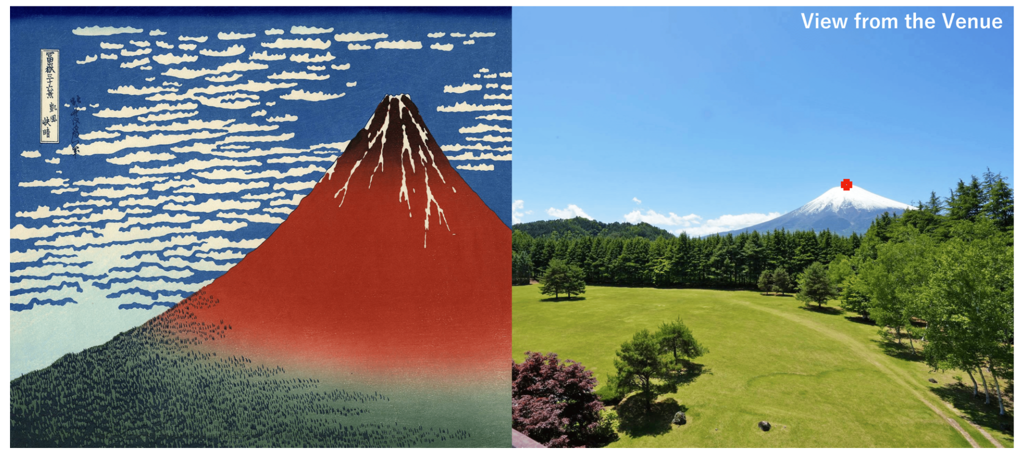

30th International Summer Institute on the Phenomenology of Elementary Particle Physics and Cosmology (SI2026)

11/August/2026

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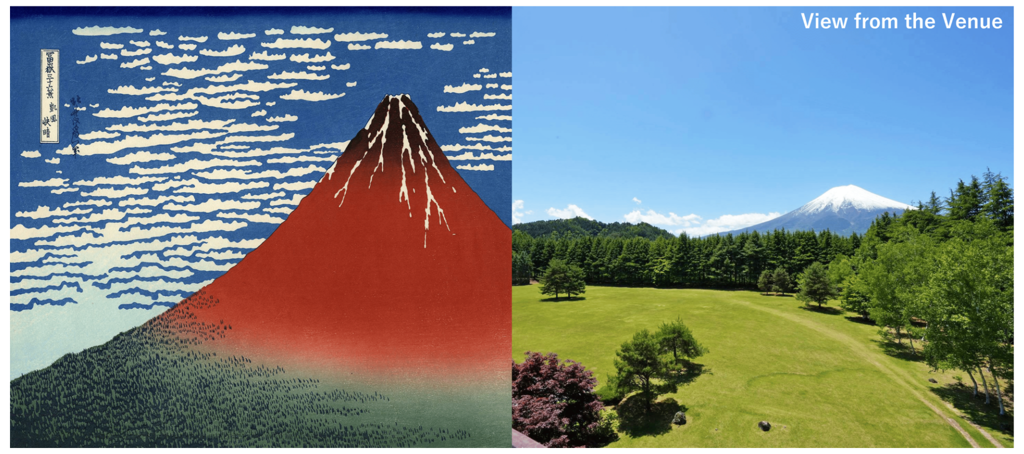

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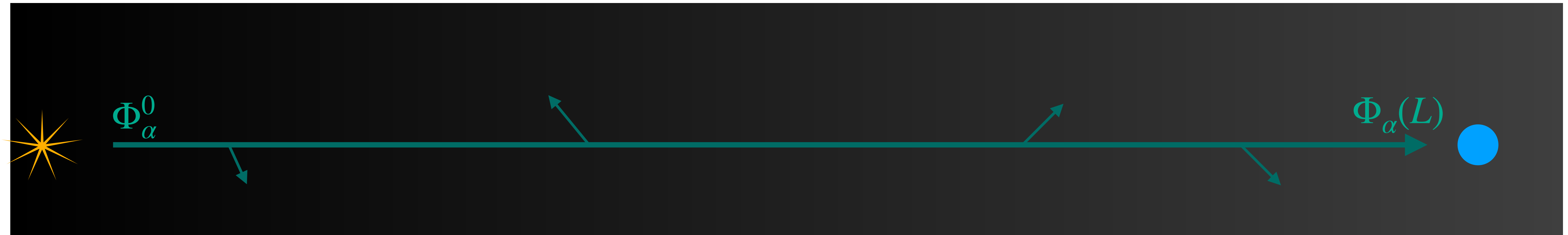

Review

[1] M. Sen and A. Y. Smirnov, "Refractive neutrino masses, ultralight dark matter and cosmology," JCAP 01, 040 (2024), arXiv:2306.15718 [hep-ph].

[2] S.-F. Ge, C.-F. Kong, and A. Y. Smirnov, "Testing the Origins of Neutrino Mass with Supernova-Neutrino Time Delay," Phys. Rev. Lett. 133, 121802 (2024), arXiv:2404.17352 [hep-ph].

[3] K.-Y. Choi, J. Kim, and C. Rott, *Phys. Rev. D* 99, no. 8, 083018 (2019) [arXiv:1903.03302 [astro-ph.HE]].

Astrophysical neutrinos travel long distances from their sources to the Earth traversing dark matter halos of clusters of galaxies and that of our own Milky Way. The interaction of neutrinos with dark matter may affect the flux of neutrinos. The recent multimessenger observation of a high energy neutrino, IceCube-170922A, can give a robust upper bound $\sigma/M_{\rm dm} \lesssim 5.1 \times 10^{-23}\ {\rm cm}^2/\,{\rm GeV}$ on the interaction between neutrino and dark matter at a neutrino energy of 290 TeV allowing 90% suppression. Combining the constraints from CMB and LSS at different neutrino energies, we can constrain models of dark matter-neutrino interactions.

Introduction of Neutrino (ν)

Neutrino Oscillation and non-zero mass

$$\left|\nu_\alpha\right\rangle = \sum_{i=1}^{3} U^*_{\alpha i} \left|\nu_i\right\rangle$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left|A_{\alpha\rightarrow\beta}\right|^2 = \sum_{i,j} U^*_{\beta i} U_{\alpha i} U_{\beta j} U^*_{\alpha j} e^{-i\left(\frac{\Delta m^2_{ij}}{2E}\right)L}$$

- For distinct flavours ($\alpha \neq \beta$), the transition probability $P(\nu_\alpha \rightarrow \nu_\beta)$ is non-zero only if the mass squared differences satisfy $\Delta m^2_{ij} \neq 0$.

- The experiment demonstrates total flux conservation :solar neutrino deficits stem strictly from quantum oscillation, not attenuation.

[4] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.* **89**, no. 1, 011301 (2002) [arXiv:nucl-ex/0204008].

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix} = \begin{bmatrix} 0.801 \sim 0.842 & 0.519 \sim 0.580 & 0.142 \sim 0.155 \\ 0.252 \sim 0.501 & 0.496 \sim 0.680 & 0.652 \sim 0.756 \\ 0.276 \sim 0.518 & 0.485 \sim 0.673 & 0.637 \sim 0.743 \end{bmatrix}$$

$$|U|_{mid} \approx \begin{bmatrix} 0.822 & 0.550 & 0.149 \\ 0.377 & 0.588 & 0.704 \\ 0.397 & 0.579 & 0.690 \end{bmatrix}$$

$$,0.822^2 + 0.550^2 + 0.149^2 = 1.000385$$

The unitary PMNS matrix $U_{\alpha i}$ which relates the neutrino flavour eigenstates $(\alpha \in \{e, \mu, \tau\})$ to the mass eigenstates $(i \in \{1,2,3\})$ by $|\nu_\alpha\rangle = \Sigma_i U^*_{\alpha i} |\nu_i\rangle$.

[5] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro, and T. Schwetz, *JHEP* **12**, 216 (2024) [arXiv:2410.05380 [hep-ph]].

Neutrino attenuation in Dark Matter background

Neutrino attenuation in Dark Matter background

Assumption: Dark Matter can distinguish Lepton flavours

Consequences:

- As neutrino flux propagates from a specific sources propagate, DM interacting flavours scatter.
- The flavour ratios observed at Earth from a specific point like source may then be differ from maximal mixing.
- What would be the ratio of ν observed at earth?

Observed flavour ratio equation

$$\Phi_i(\tau) = \Phi_i^0 \exp\left(- \sum_{\beta \in I} |U_{\beta i}|^2 \tau \right)$$

$$\phi_\alpha(\tau) = \sum_{i=1}^{3} |U_{\alpha i}|^2 \phi_i(\tau)$$

$$f_\alpha(\tau) = \frac{\phi_\alpha(\tau)}{\sum_\beta \phi_\beta(\tau)} = \frac{\sum_i |U_{\alpha i}|^2 \phi_i(\tau)}{\sum_j \phi_j(\tau)}$$

$$\tau \equiv \int n_{DM} \sigma \, dx = \frac{\sigma}{m_{DM}} \int \rho_{DM}(x) = dx$$

- The decoherence of an astrophysical neutrino occurs because its constituent mass eigenstates travel at different velocities.
- Flavour Eigen states are then projected onto flavour Eigen states
- τ is optical depth. Its value depends on σ/m_{DM} and path integral

Constraining ν flavour ratio due to DM-ν with IceCube-170922A

IceCube-170922A

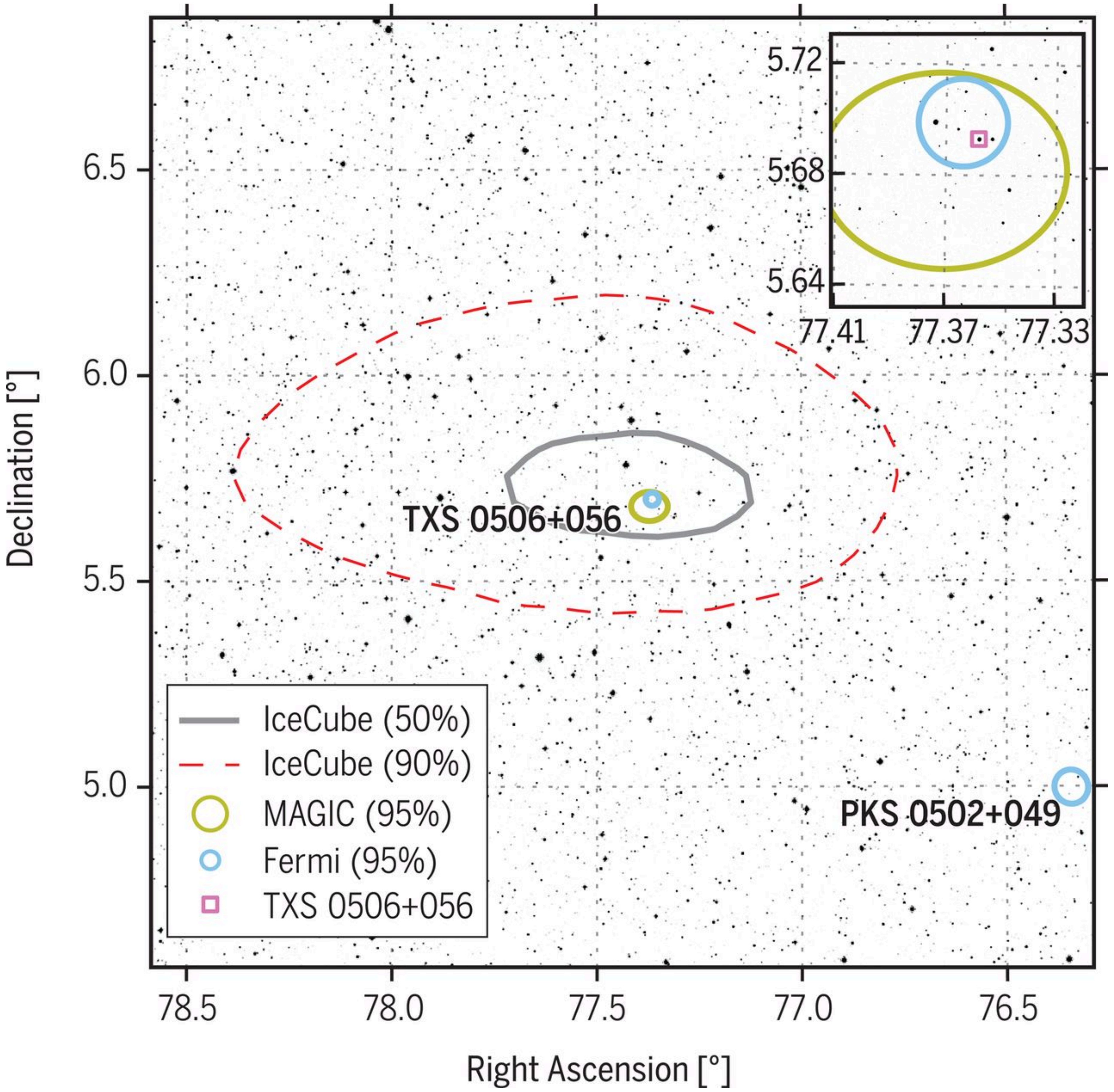

FIG 2: Multimessenger observations of blazar TXS 0506+056. Taken from [6]

Energy

A **290 TeV** muon neutrino observed on September 22, 2017 and publicized via alert, IceCube- 170922A, is the first high energy neutrino whose origin can be identified with high confidence. Its source, the γ-ray blazar TXS 0506+056, was located at redshift $z = 0.3365 \pm 0.0010$, corresponding to a **distance = 1421 ±4 Mpc.**

[6] M. G. Aartsen *et al.* (IceCube Collaboration), *Science* **361**, no. 6398, eaat1378 (2018) [arXiv:1807.08816 [astro-ph.HE]]

Constraining cross section between DM-ν with IceCube-170922A

Neutrino energy	$\sigma/M_{\mathrm{dm}}[\mathrm{cm}^2/\mathrm{GeV}]$	Exp. [Ref.]
~ 100 eV	6×10^{-31}	CMB [13–15]
~ 100 eV	10^{-33}	Lyman-α [11]
10 MeV	10^{-22}	SN1987A [9]
290 TeV	5.1×10^{-23}	IceCube-170922A [1]

TABLE I: Upper bound on the neutrino-DM scattering cross section. Taken from [5].

$$\tau \equiv \int n_{DM}\sigma\, dx = \frac{\sigma}{M_{DM}} \int \rho_{DM}(x) dx$$

$$\approx \frac{\sigma}{M_{DM}} \left(7.2 \times 10^{21} GeV/cm^2 \;+\; 3.8 \times 10^{22} GeV/cm^2\right) < 3.6$$

Taken from [5].

They didn't consider the flavour ratio.

[2] K.-Y. Choi, J. Kim, and C. Rott, *Phys. Rev. D* **99**, no. 8, 083018 (2019) [arXiv:1903.03302 [astro-ph.HE]].

High energy (>TeV) neutrino origin

High energy (>TeV) neutrino origin

According to [7]

$$P + \gamma_{bg} \to p + \pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

Consequently initial fluxes of each ν and $\bar{\nu}$:

$$(F_e^0 + F_{\bar{e}}^0) : (F_\mu^0 + F_{\bar{\mu}}^0) : (F_\tau^0 + F_{\bar{\tau}}^0) = 1 : 2 : 0$$

composition arriving at the detector [7]

$$(F_e + F_{\bar{e}}) : (F_\mu + F_{\bar{\mu}}) : (F_\tau + F_{\bar{\tau}}) = 1 : 1 : 1$$

[7] M. Ahlers and F. Halzen, *Prog. Part. Nucl. Phys.* **102**, 73–88 (2018) [arXiv:1805.11112 [astro-ph.HE]].

[8] Y. Farzan and A. Y. Smirnov, *Nucl. Phys. B* **805**, no. 1-2, 356–376 (2008) [arXiv:0803.0495 [hep-ph]].

Astrophysical Neutrino Attenuation in a Single-Flavour Interaction with Dark Matter Background Framework

Only ν_e Interacting with DM

$$(F_e^0 + F_{\bar{e}}^0) : (F_\mu^0 + F_{\bar{\mu}}^0) : (F_\tau^0 + F_{\bar{\tau}}^0) = 1 : 2 : 0$$

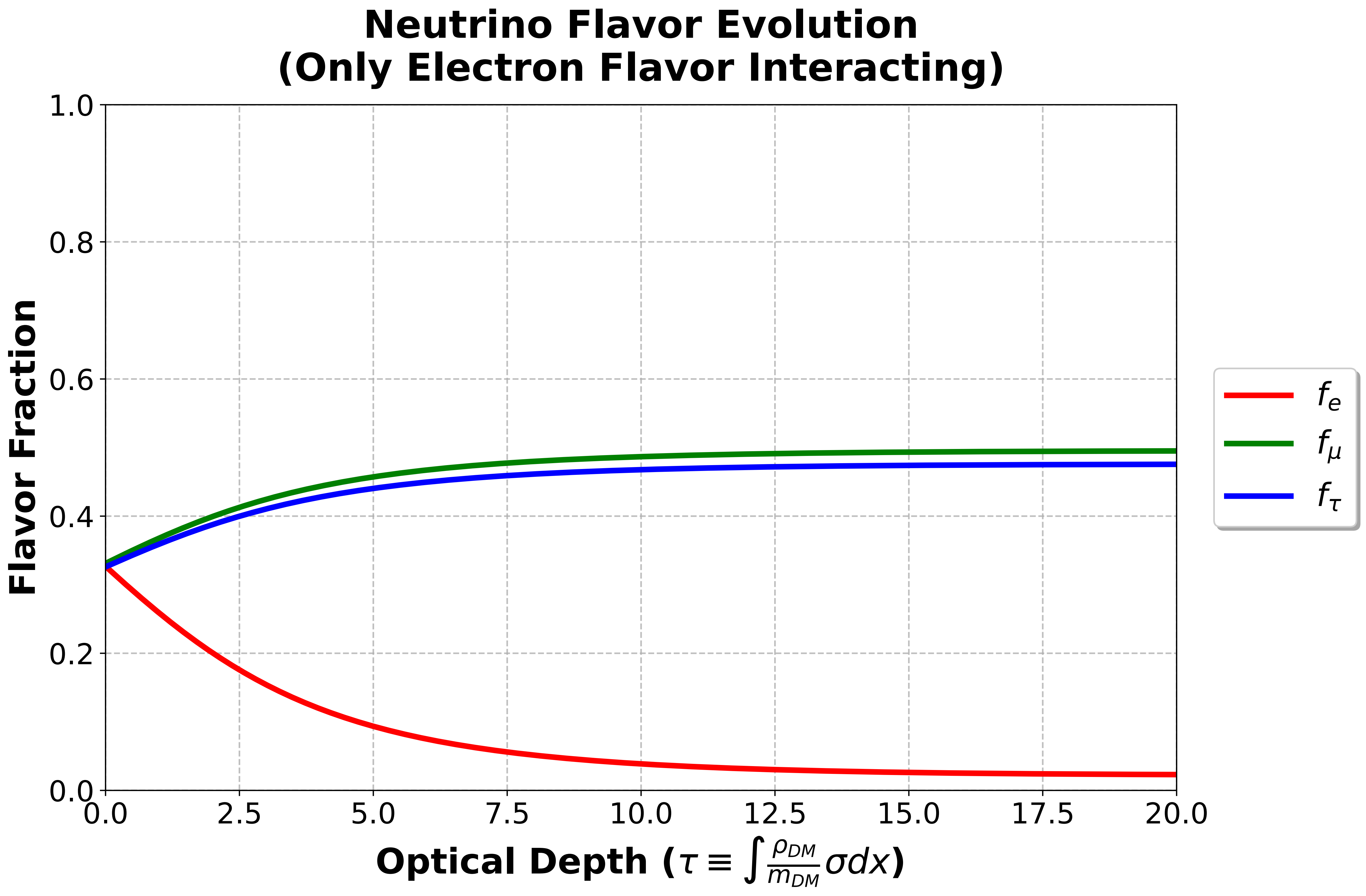

FIG 3: flavour ratio due to ν_e interacting with dark matter case.

- $\tau = 0$: at a fraction of roughly 1/3. This is the standard expectation for astrophysical neutrinos.
- $\tau > 0$: As neutrino propagates, electron flavour fraction scatters and flavour ratio changes.

Comparison between only ν_e interacting with DM and ν_μ interacting with DM

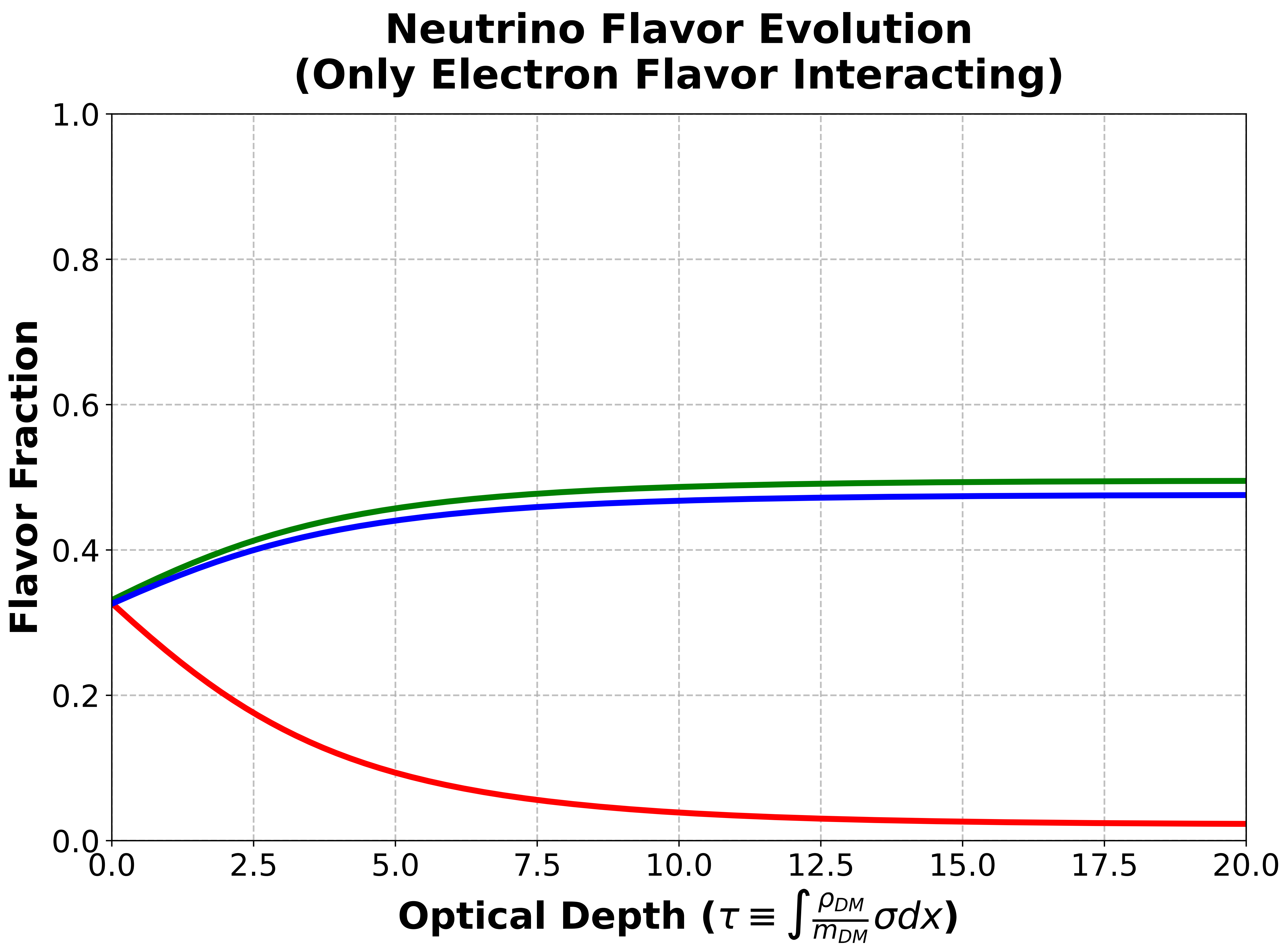

FIG 3: flavour ratio due to ν_e interacting with dark matter case.

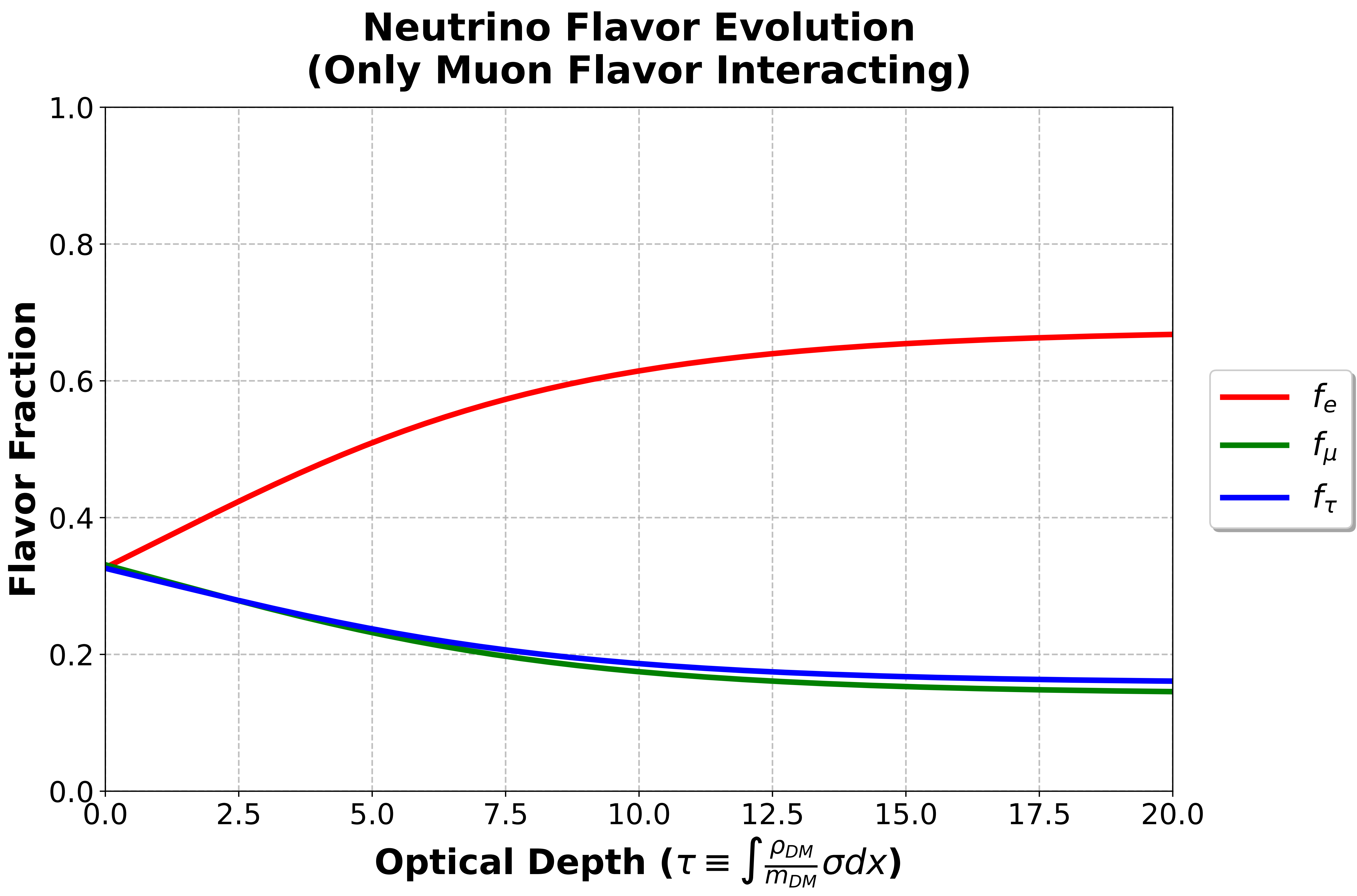

FIG 4: flavour ratio due to ν_μ interacting with dark matter case.

Only ν_τ Interacting with DM

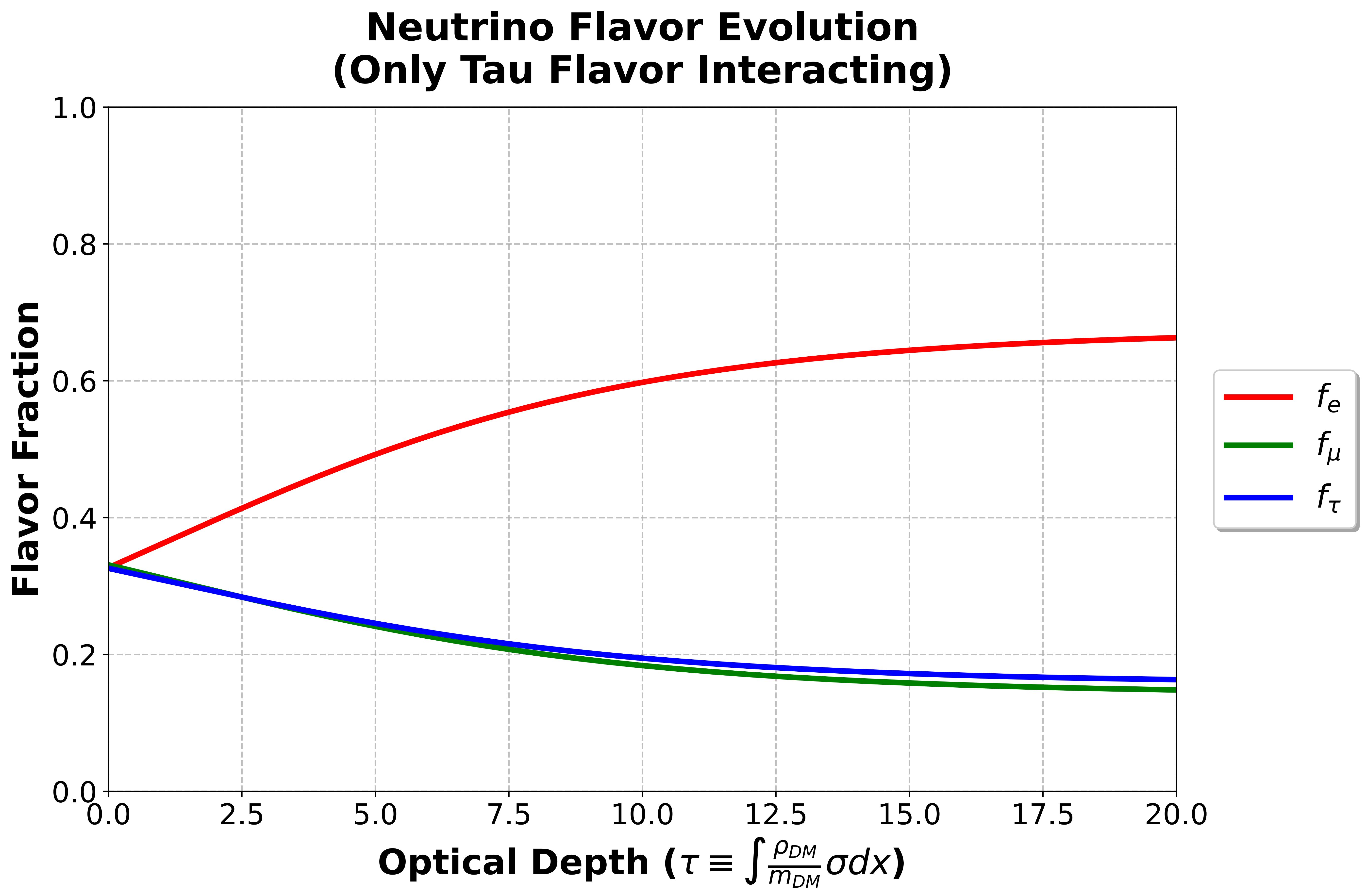

FIG 5: flavour ratio due to ν_τ interacting with dark matter case.

Astrophysical Neutrino Attenuation in a Two-Flavour Interaction with Dark Matter Framework

ν_e and ν_μ interacting with DM

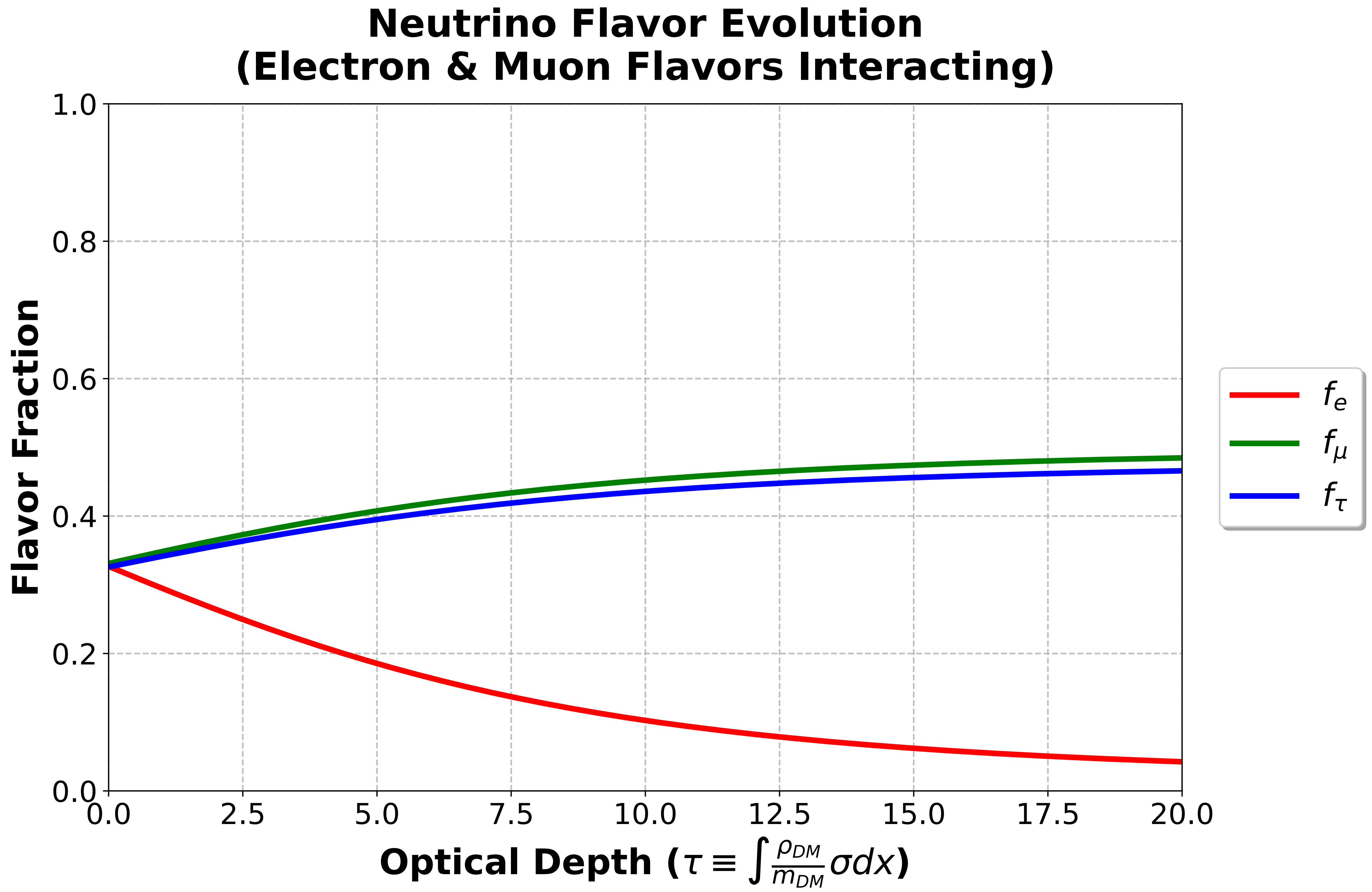

FIG 6: flavour ratio due to ν_e and ν_μ interacting with dark matter case.

- $\tau = 0$: at a fraction of roughly 1/3. This is the standard expectation for astrophysical neutrinos.

- $\tau > 0$: mass Eigen states 1 and 2 scatter the most and the result reflects mainly the composition of mass Eigen state 3.

Comparison between ν_e, ν_μ - Dark matter and ν_μ, ν_τ - Dark matter interactions

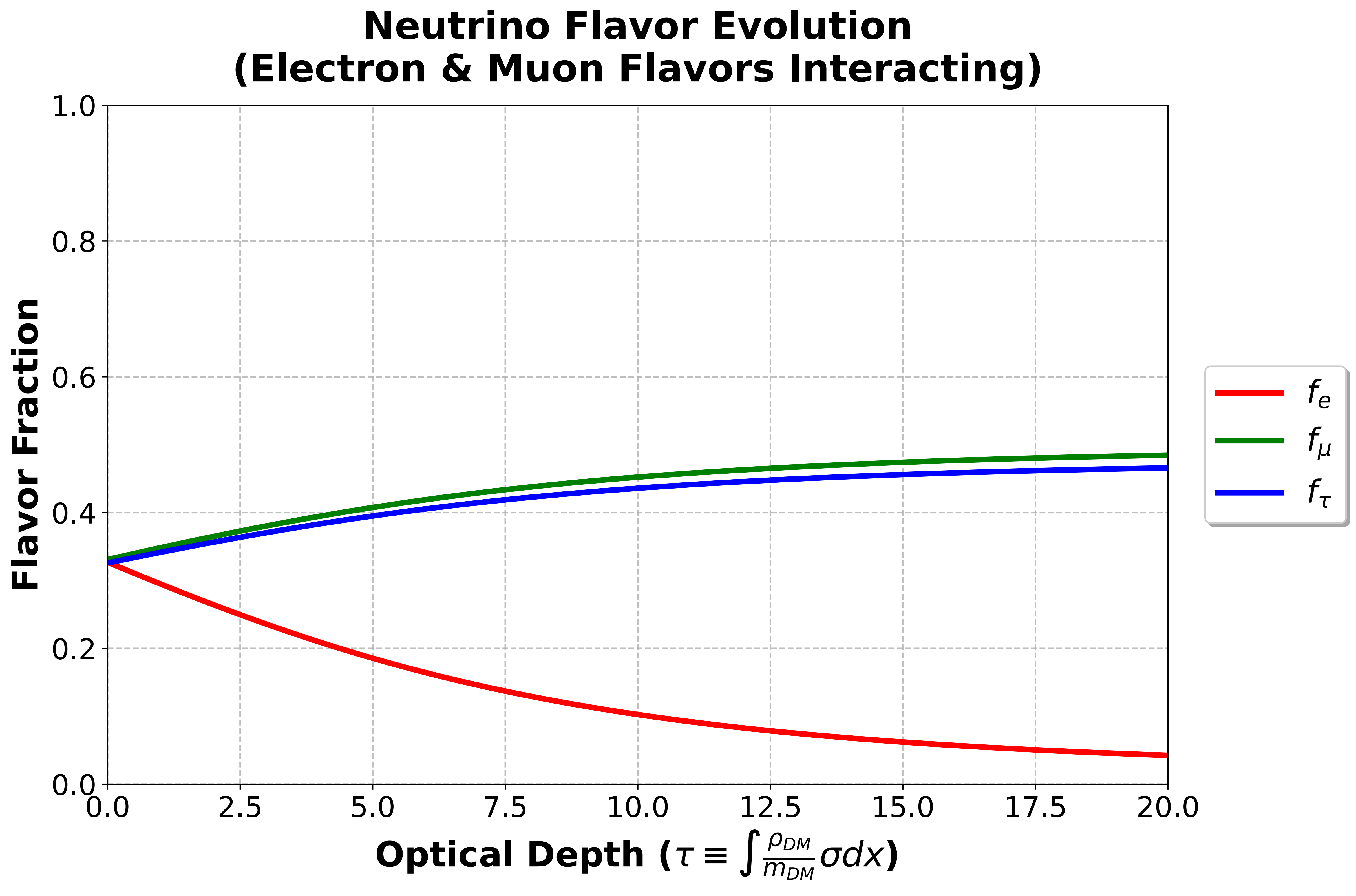

FIG 6: flavour ratio due to ν_e and ν_μ interacting with dark matter case.

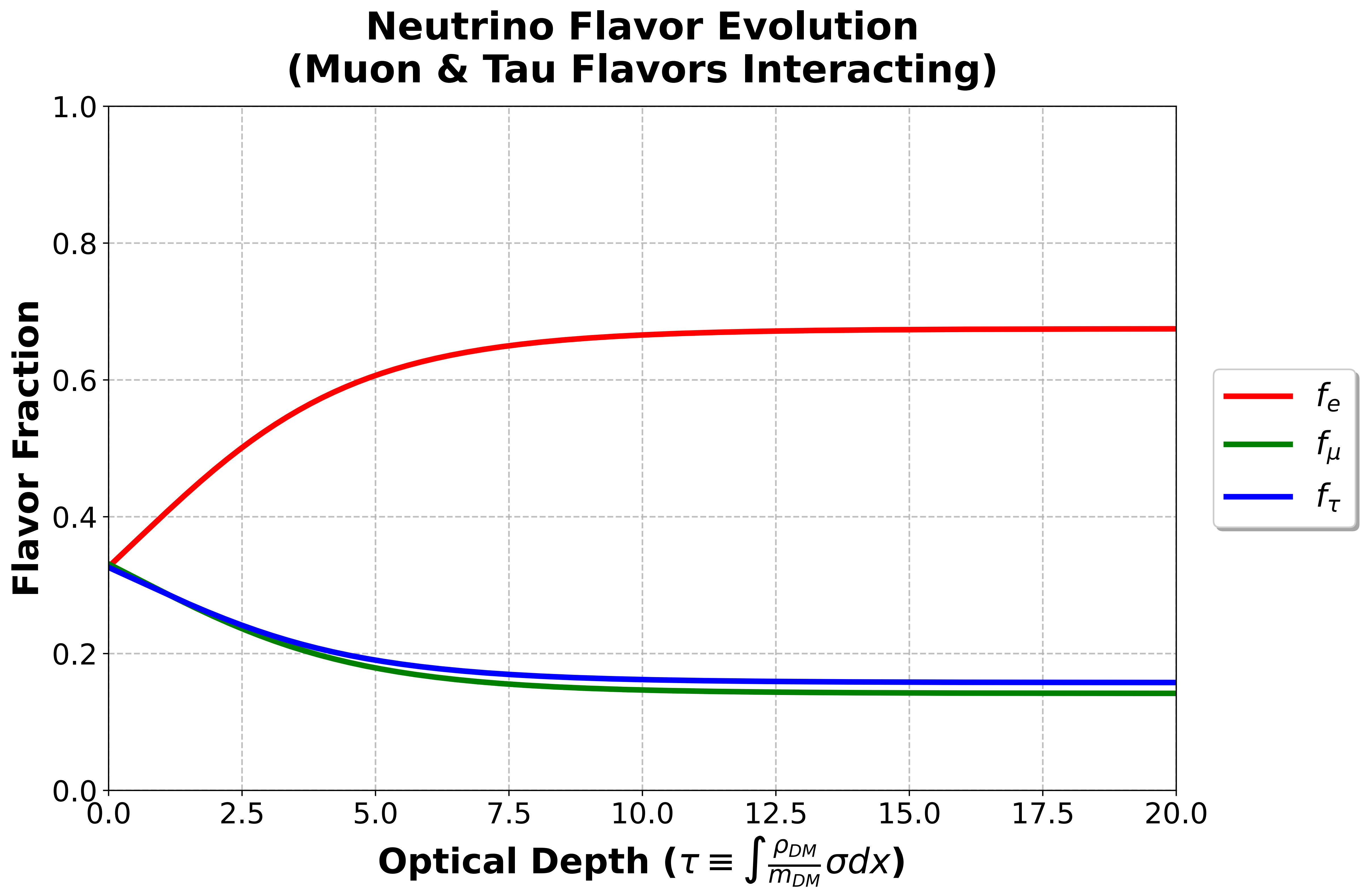

FIG 7: flavour ratio due to ν_μ and ν_τ interacting with dark matter case.

Dual-Flavor Interactions

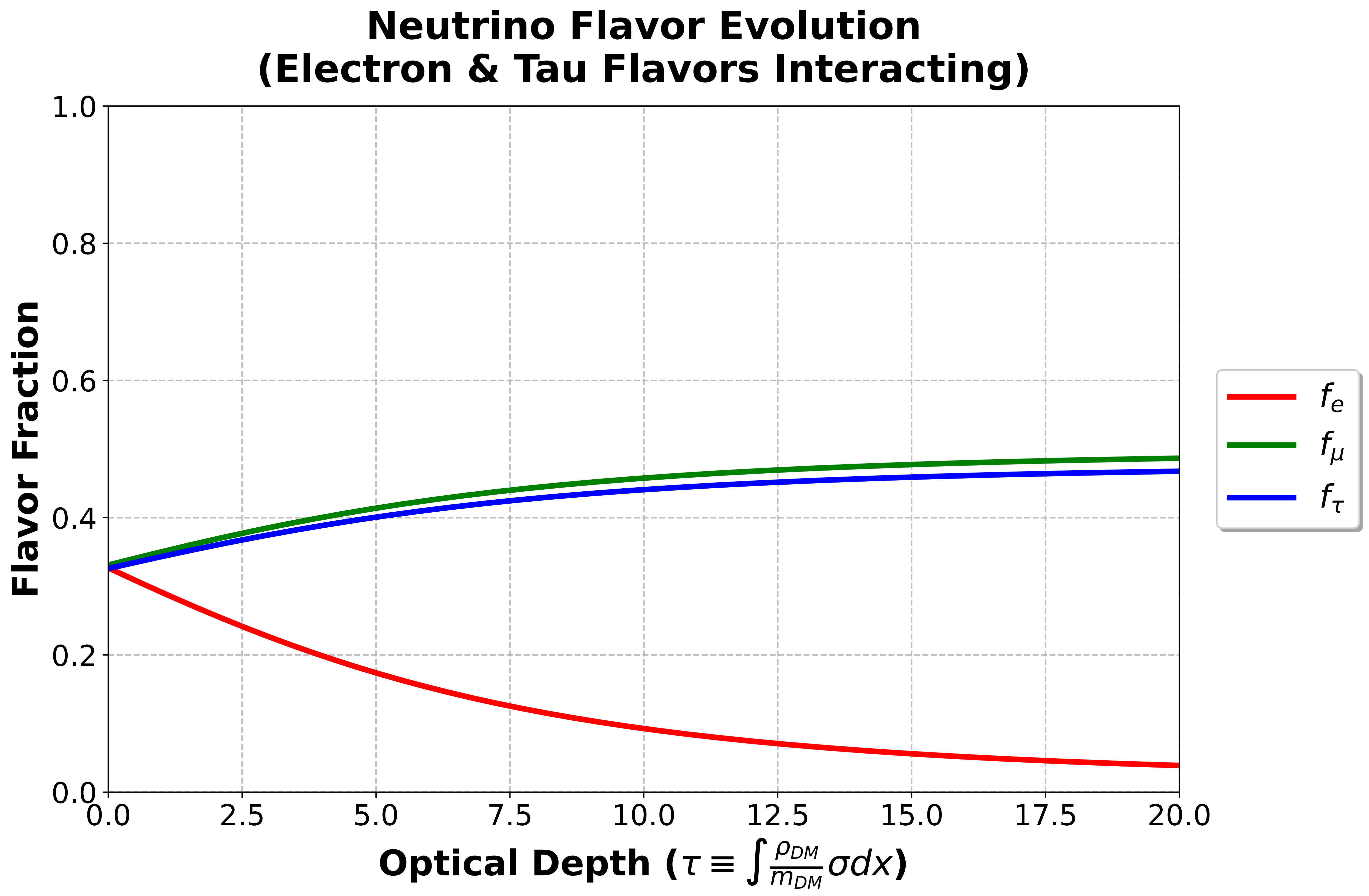

FIG 6: flavour ratio due to ν_e and ν_τ interacting with dark matter case.

Conclusion

- **Constraining Interactions between neutrino and dark matter via Multimessenger Events:** High-energy astrophysical phenomena, notably the IceCube-170922A event, can be used to constrain the cross-sections of neutrino-dark matter interactions.

- **Asymmetric Attenuation of Mass Eigenstates:** If neutrinos couple to dark matter via specific weak flavour eigenstates, the resulting flux attenuation will disproportionately affect certain mass eigenstates due to their varying flavour compositions.

- **Deviation in flavour ratio from a Point-Source Observations:** Consequently, over galactic propagation baselines, the observed flavour ratio from a specific, resolved point source can deviate from standard astrophysical expectations which is 1:1:1 ratio [9].

Backup Slides

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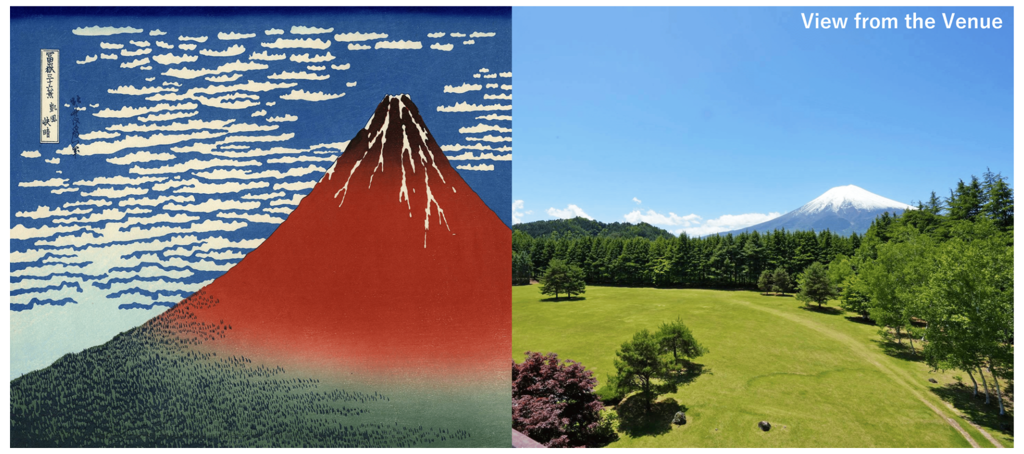

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ν-DM interaction model

The model has complex bosonic dark matter ϕ with mass m_ϕ and fermionic mediator f_i with Dirac mass m_f:

$$\mathscr{L}_{\text{int}} = g_{\alpha i}\,\bar{f}_i\,P_L\,\nu_\alpha\,\phi^* + \text{h.c.}$$

MSW effect due to dark matter

MSW effect due to dark matter

$$H_{\text{matter}} = \begin{pmatrix} -\frac{\Delta m^2 \cos(2\theta)}{4E} + \frac{1}{2}V_{CC} & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2 \cos(2\theta)}{4E} - \frac{1}{2}V_{CC} \end{pmatrix}$$

$$H_{\text{matter}} \equiv \frac{\Delta m_M^2}{4E}\begin{pmatrix} -cos\left(2\theta_m\right) & sin\left(2\theta_m\right) \\ sin\left(2\theta_m\right) & cos\left(2\theta_m\right) \end{pmatrix}$$

$$\frac{sin(2\theta_m)}{cos(2\theta_m)} = tan(2\theta_m) = \frac{\Delta m^2 sin(2\theta)}{\Delta m^2 cos(2\theta) - 2EV_{CC}}$$

$2EV_{CC} \gg \Delta m^2 cos(2\theta) \Rightarrow tan(2\theta_m) \to 0 \Rightarrow \theta_m \to \frac{\pi}{2}$, meaning in a very dense medium, mixing is highly suppressed.

Maximal mixing happens at $tan(2\theta_m) \to \infty \Rightarrow \Delta m^2 cos(2\theta) = 2EV_{CC}$

ν comparison with other messengers

ν and GRB may share a common source.

Problem

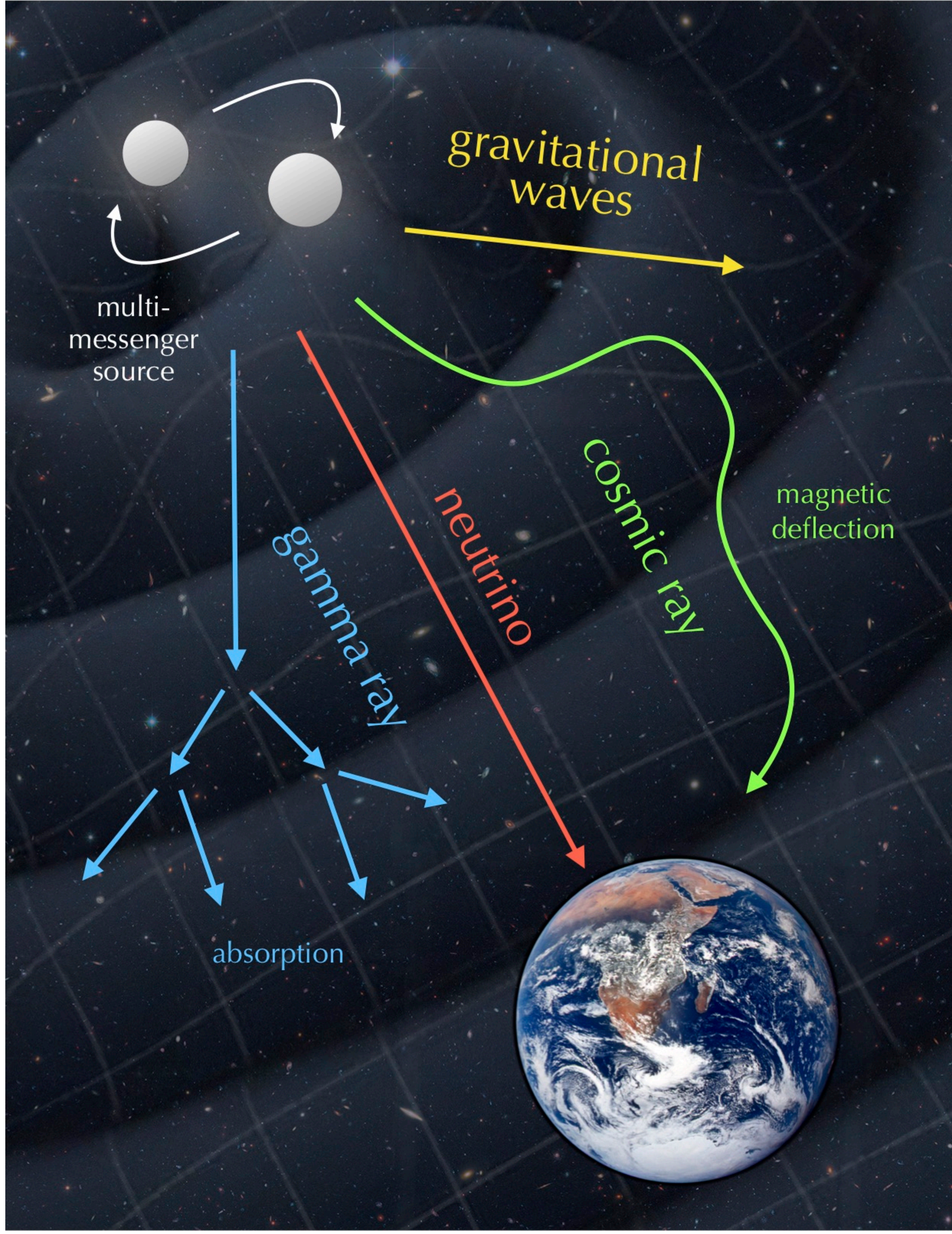
No correlation was found between Ultra High Energy neutrinos and Gamma Ray Burst despite sensitive searches.

IceCube Collaboration, M. G. Aartsen et al., An All-Sky Search for Three Flavors of Neutrinos from Gamma-Ray Bursts with the IceCube Neutrino Observatory, Astrophys. J. 824 (2016), no. 2 115, [arXiv:1601.06484].

Albert et al., Search for high-energy neutrinos from bright GRBs with ANTARES, arXiv:1612.08589. [Mon. Not. Roy. Astron. Soc.469,906(2017)].

A. Achterberg, M. Ackermann, J. Adams, J. Ahrens, K. Andeen, J. Auffenberg, J. N. Bahcall, X. Bai, B. Baret, S. W. Barwick, and et al., The Search for Muon Neutrinos from Northern Hemisphere Gamma-Ray Bursts with AMANDA, Astrophys. J. 674 (Feb., 2008) 357–370, [arXiv:0705.1186].

References should be original and relevant work.



Over the last few decades, our view of the Universe has expanded to incorporate four astrophysical messengers, at high energies. These messengers are photons (in the form of gamma rays), neutrinos (observed by IceCube), gravitational waves (observed by LIGO-VIRGO) and cosmic rays.*

* University of Copenhagen, https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

Mass hierarchies of neutrino

Some notes to be remarked.

- FIG.1: each mass Eigen states are composed of different ratio of flavour Eigen states.
- Matter Potential (MSW Effect): flavour-dependent potential alters the effective mixing parameters.

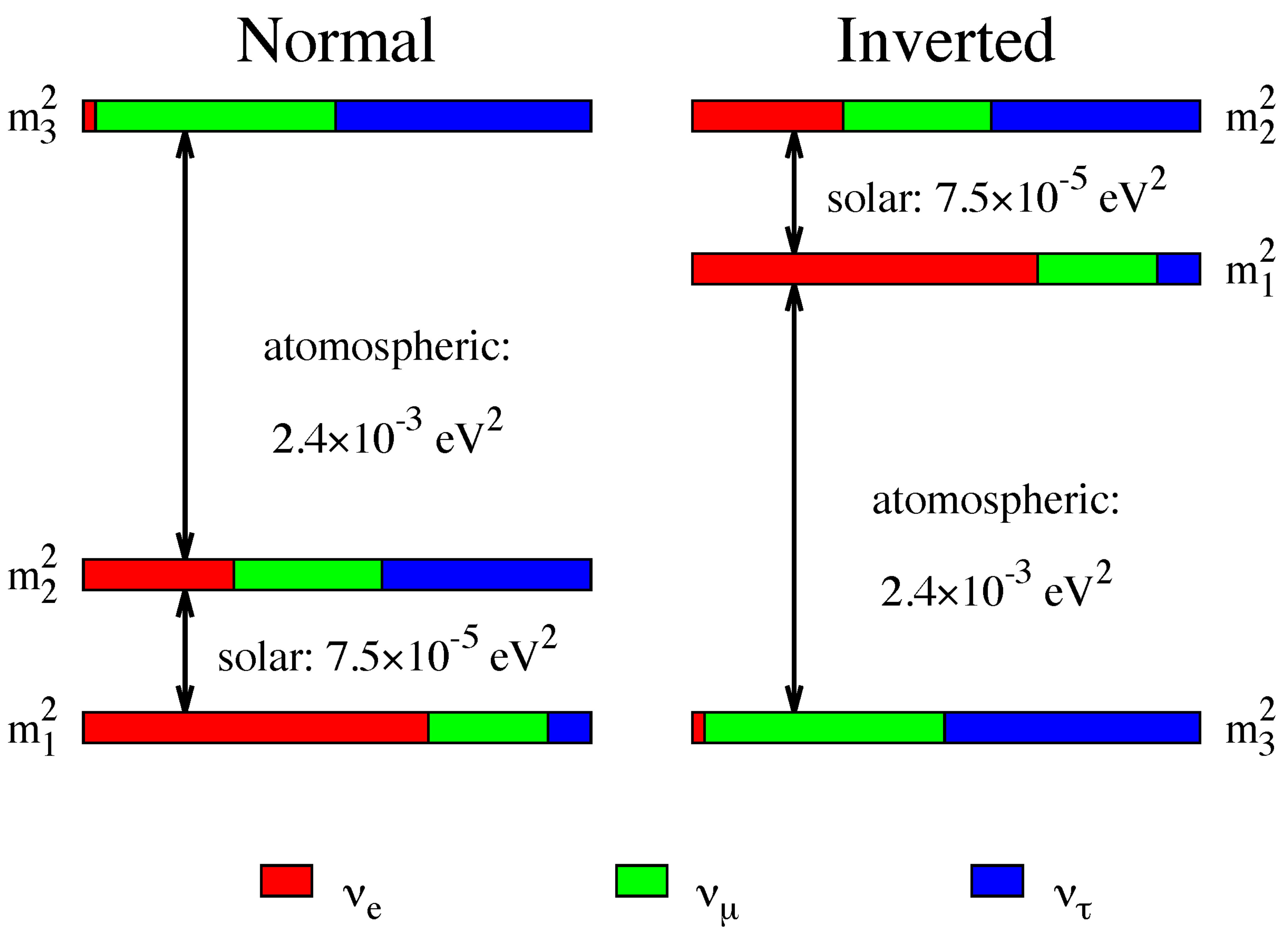
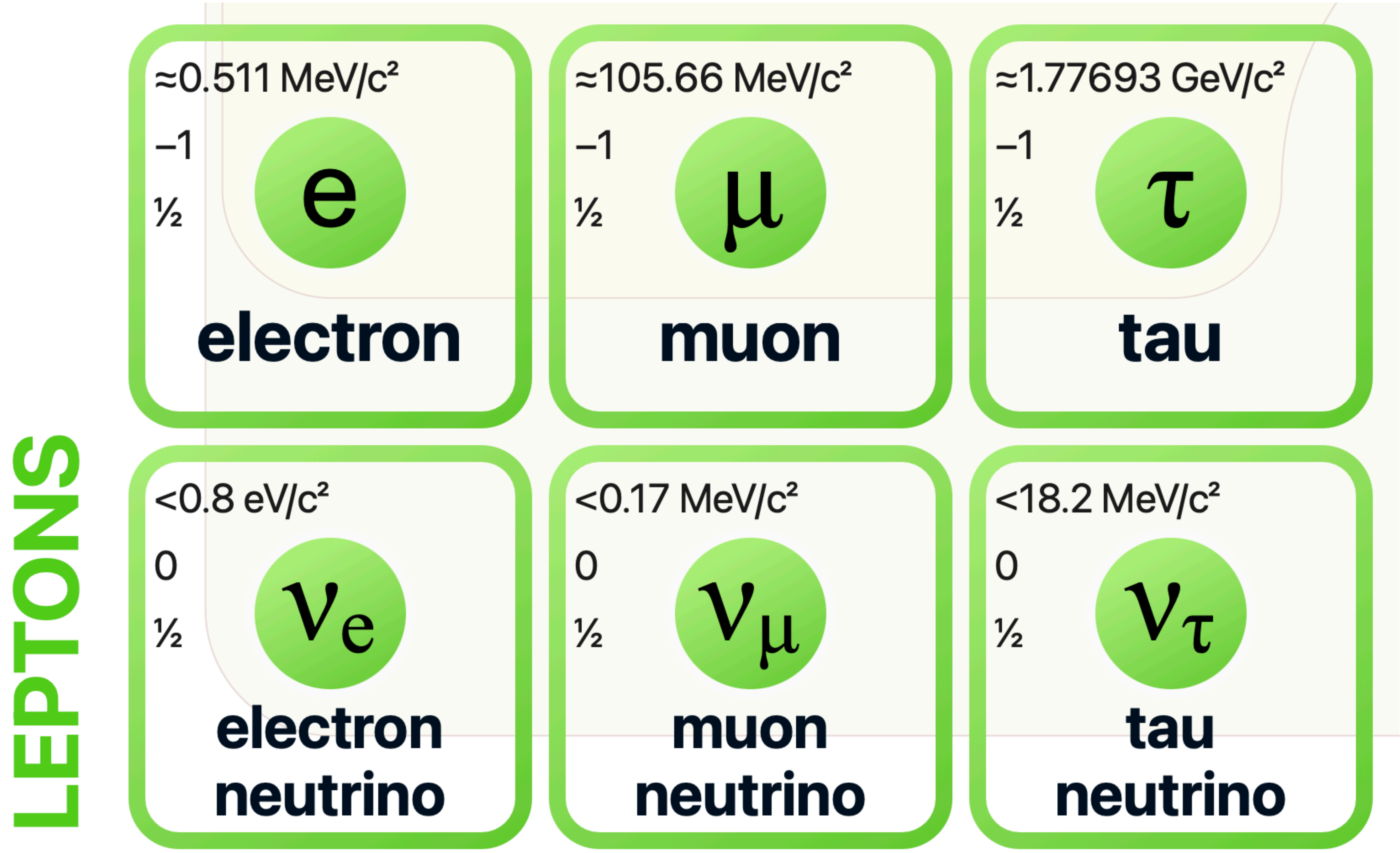


FIG.1 : Neutrino mass eigenstate flavour composition and mass pattern in the two cases of normal (left) and inverted (right) hierarchies. Taken from [3]

[3] F. An *et al.* (JUNO Collaboration), *J. Phys. G* **43**, no. 3, 030401 (2016) [arXiv:1507.05613 [physics.ins-det]].

Neutrino weak flavour



$$n \rightarrow e^- + p^+ + \bar{\nu}_e$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Lepton number is conserved