Present and future constraints on flavor-dependent long-range interactions of high-energy astrophysical neutrinos

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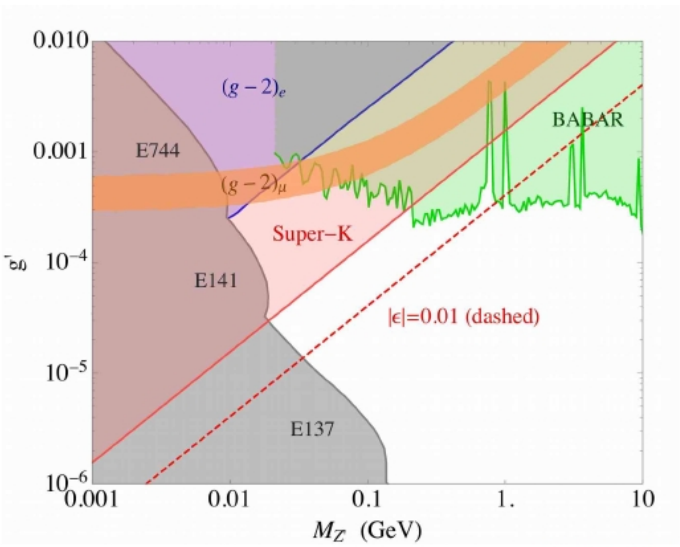
U(1) Extension of SM

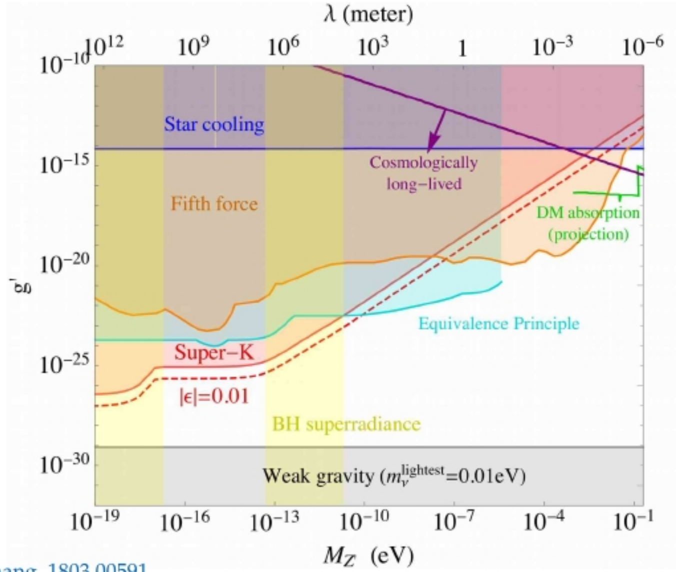
$$\mathcal{L}_{Z'}^{\text{matter}} = -g'\big(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e + b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\big)Z'_\alpha$$

Model	a_u	a_d	a_e	b_e	b_μ	b_τ
$L_e - L_\mu$	0	0	1	1	−1	0
$L_e - L_\tau$	0	0	1	1	0	−1
$L_\mu - L_\tau$	0	0	0	0	1	−1
$B - 3L_e$	$\frac{1}{3}$	$\frac{1}{3}$	−3	−3	0	0
$B - 3L_\mu$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	−3	0
$B - 3L_\tau$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	−3
$B - \frac{3}{2}(L_\mu + L_\tau)$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	$-\frac{3}{2}$	$-\frac{3}{2}$
$L_e - \frac{1}{2}(L_\mu + L_\tau)$	0	0	1	1	$-\frac{1}{2}$	$-\frac{1}{2}$
$B_y + L_\mu + L_\tau$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	1	1
$L_e + 2L_\mu + 2L_\tau$	0	0	1	1	2	2

MeV–GeV masses



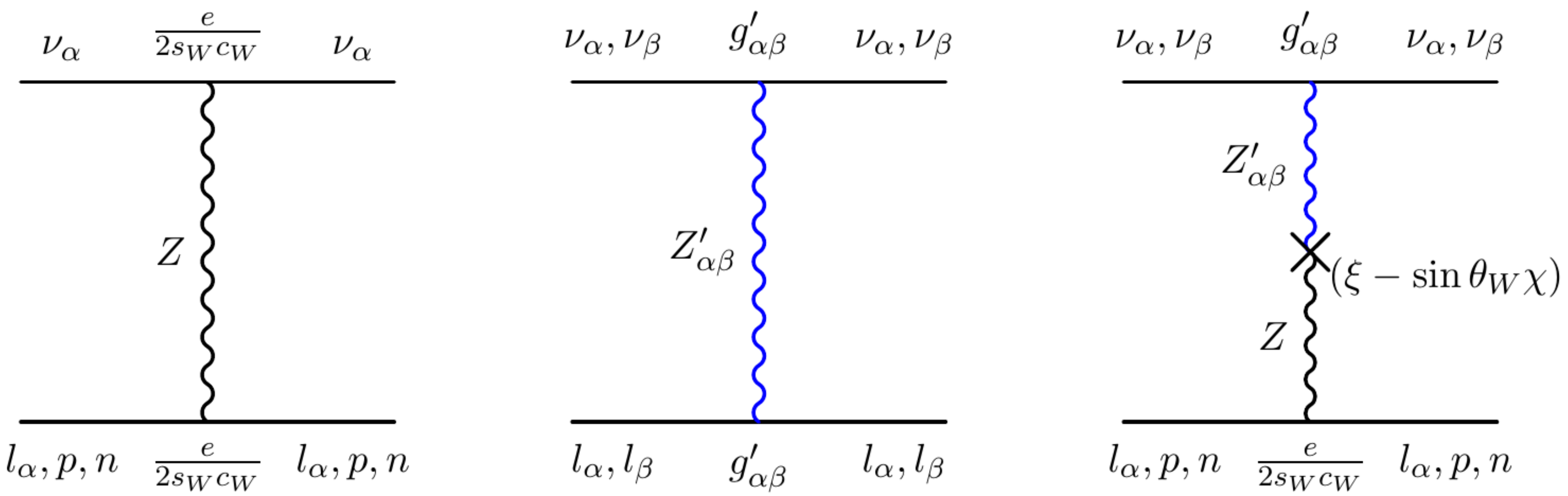
Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Effective neutrino-matter interaction

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{\rm mix}$$



(a) $\mathcal{L}_{\rm SM}$ (b) $\mathcal{L}_{Z'}$ (c) $\mathcal{L}_{\rm mix}$

$$\mathcal{L}_{\rm SM} = \frac{e}{\sin\theta_W \cos\theta_W} Z_\mu \left[-\frac{1}{2}\bar{l}_\alpha \gamma^\mu P_L l_\alpha + \frac{1}{2}\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha + \frac{1}{2}\bar{u}\gamma^\mu P_L u - \frac{1}{2}\bar{d}\gamma^\mu P_L d \right]$$

$$\mathcal{L}_{Z'} = g'_{\alpha\beta} Z'_\sigma (\bar{l}_\alpha \gamma^\sigma l_\alpha - \bar{l}_\beta \gamma^\sigma l_\beta + \bar{\nu}_\alpha \gamma^\sigma P_L \nu_\alpha - \bar{\nu}_\beta \gamma^\sigma P_L \nu_\beta)$$

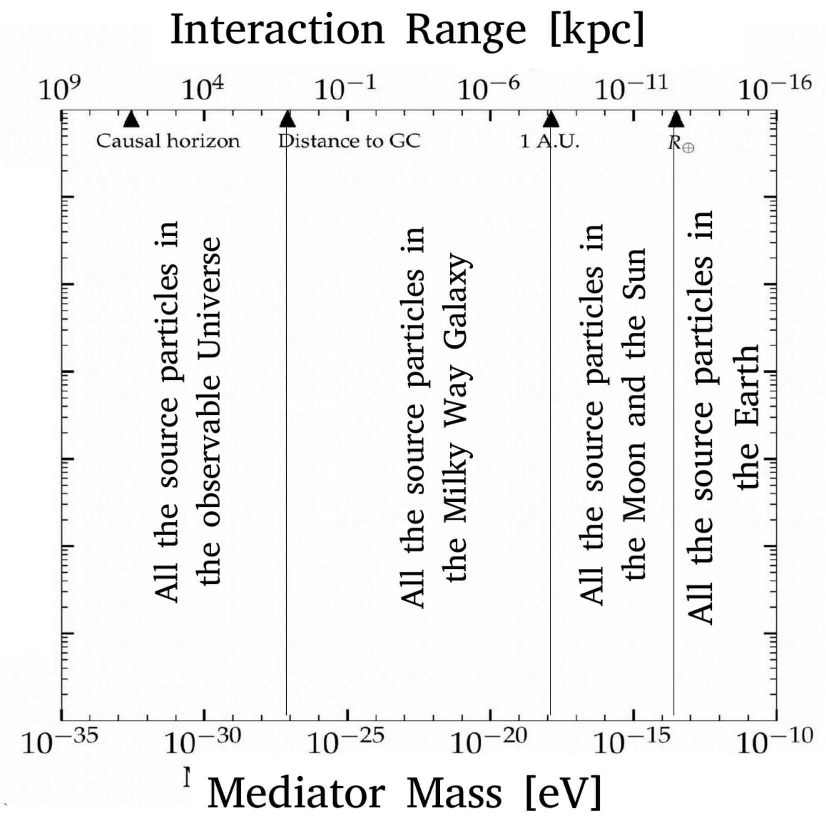
$$\mathcal{L}_{\rm mix} = (\xi - \sin\theta_W \chi) Z'_\mu Z^\mu$$

Long-range interaction potential in $U(1)'_{L_\alpha - L_\beta}$

$$V_{\alpha\beta} = \mathcal{G}_{\alpha\beta}\frac{e^{-m'_{\alpha\beta}d}}{4\pi d} \times \begin{cases} N_e \ , \text{ for } \alpha,\beta = e,\mu \text{ or } e,\tau \\ N_n \ , \text{ for } \alpha,\beta = \mu,\tau \end{cases}$$

$$\mathcal{G}_{\alpha\beta} = \begin{cases} g'^2_{e\mu} & , \text{ for } \alpha,\beta = e,\mu \\ g'^2_{e\tau} & , \text{ for } \alpha,\beta = e,\tau \\ g'_{\mu\tau}(\xi - \sin\theta_W \chi)\frac{e}{4\sin\theta_W\cos\theta_W} & , \text{ for } \alpha,\beta = \mu,\tau \end{cases}$$

Interaction Range: $1/m'_{\alpha\beta}$

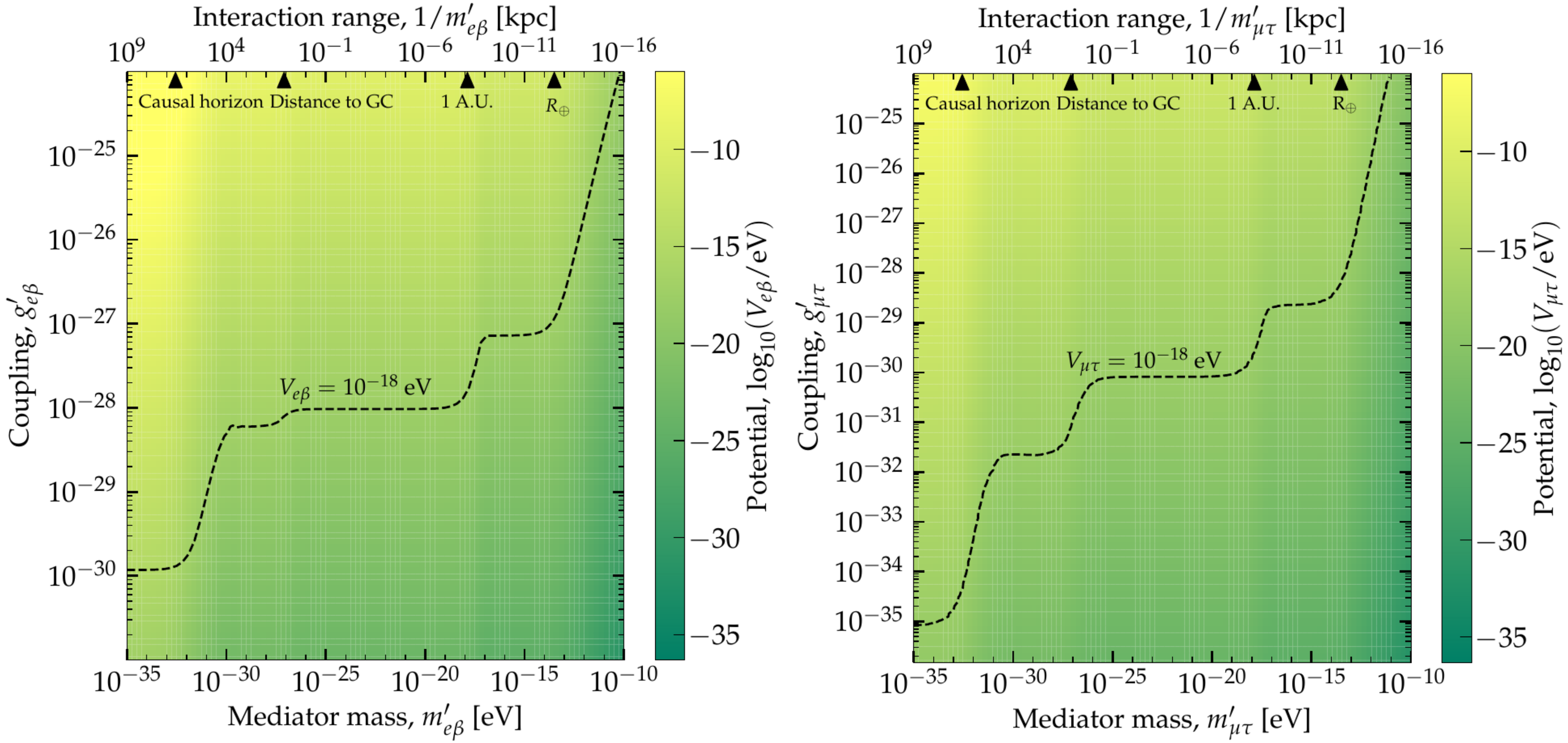


$$V_{\alpha\beta} = V^{\oplus}_{\alpha\beta} + V^{☾}_{\alpha\beta} + V^{\odot}_{\alpha\beta} + V^{\mathrm{MW}}_{\alpha\beta} + \langle V^{\cos}_{\alpha\beta}\rangle$$

Total potential

$$(\xi - \sin\theta_W \chi) = 5 \times 10^{-24}$$

Heeck et. al. (2011)



Effect of Long-range potential

The neutrino propagation Hamiltonian

$$\mathbf{H} = \mathbf{H}_{\text{vac}} + \mathbf{V}_{\text{mat}} + \mathbf{V}_{\alpha\beta}$$

$$\mathbf{H}_{\text{vac}} = \frac{1}{2E}\mathbf{U}\ \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})\ \mathbf{U}^\dagger$$

$$\mathbf{V}_{\text{mat}} = \text{diag}(V_{\text{CC}}, 0, 0)$$

$$\mathbf{V}_{\alpha\beta} = \begin{cases} \text{diag}(V_{e\mu}, -V_{e\mu}, 0), & \text{for } \alpha,\beta = e,\mu \\ \text{diag}(V_{e\tau}, 0, -V_{e\tau}), & \text{for } \alpha,\beta = e,\tau \\ \text{diag}(0, V_{\mu\tau}, -V_{\mu\tau}), & \text{for } \alpha,\beta = \mu,\tau \end{cases}$$

Flavor Oscillation Probability

$$P_{\alpha\beta} = \left| \sum_{i=1}^{3} U'_{\alpha i} \exp\left[\frac{-\Delta\tilde{m}^2_{i1} L}{4E} \right] U'^{*}_{\beta i} \right|^2$$

For very large distances: $\frac{\Delta\tilde{m}^2_{i1} L}{4E} >> 1$

$$\bar{P}_{\alpha\beta} = \sum_{i=1}^{3} |U'_{\alpha i}|^2 |U'_{\beta i}|^2$$

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} \bar{P}_{\beta\alpha} f_{\beta,\text{S}}$$

Where flavor ratio at source:

$$f_{\text{S}} = (f_{e,\text{S}} : f_{\mu,\text{S}} : f_{\tau,\text{S}})$$

Flavor transitions with $V_{\alpha\beta}=0$

$p + \gamma \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e$

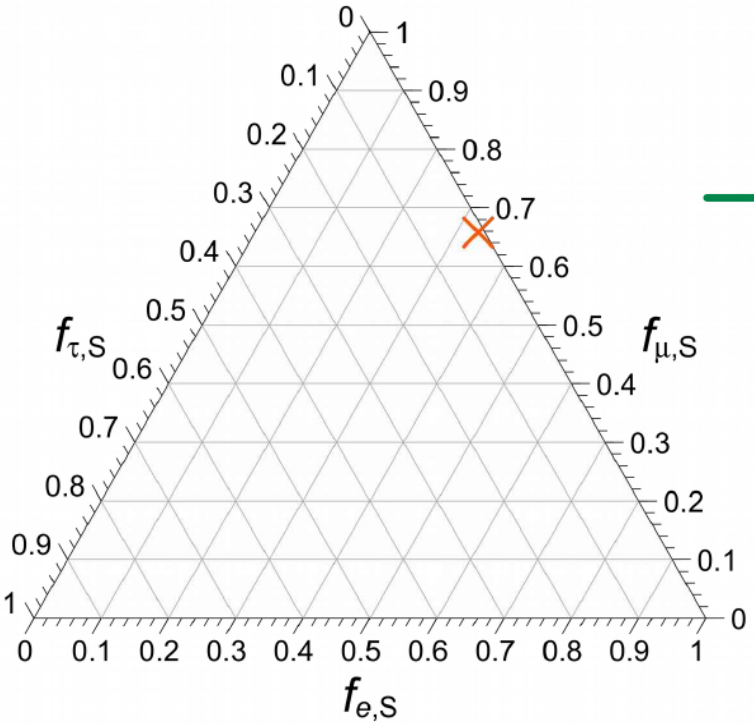
At the sources

$(f_e : f_\mu : f_\tau)_S = (1/3 : 2/3 : 0)_S$

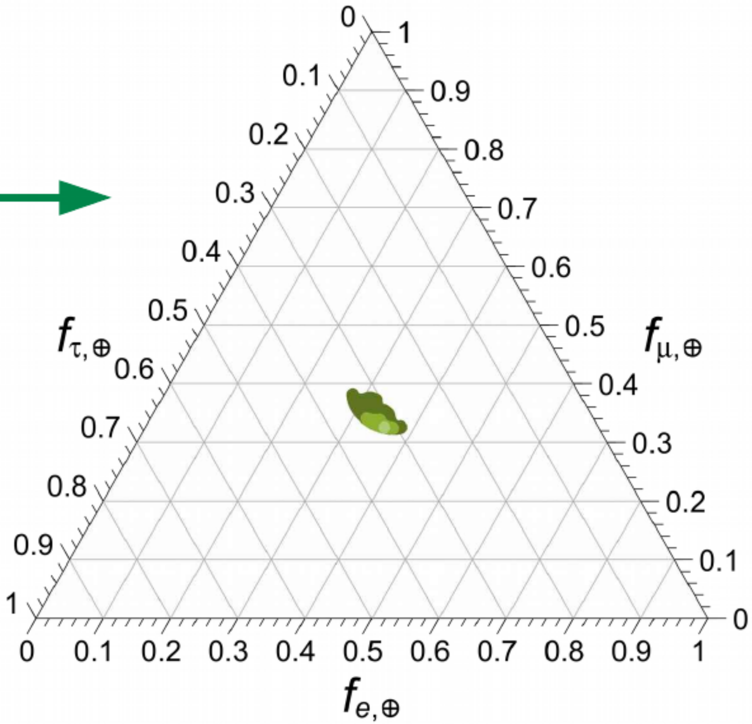
Neutrino oscillations →

At Earth

$(0.36 : 0.32 : 0.32)_\oplus$



Uncertainties in values of mixing parameter (1σ, 3σ) →



Flavor transitions with LRI

- The neutrino flavor transition Hamiltonian

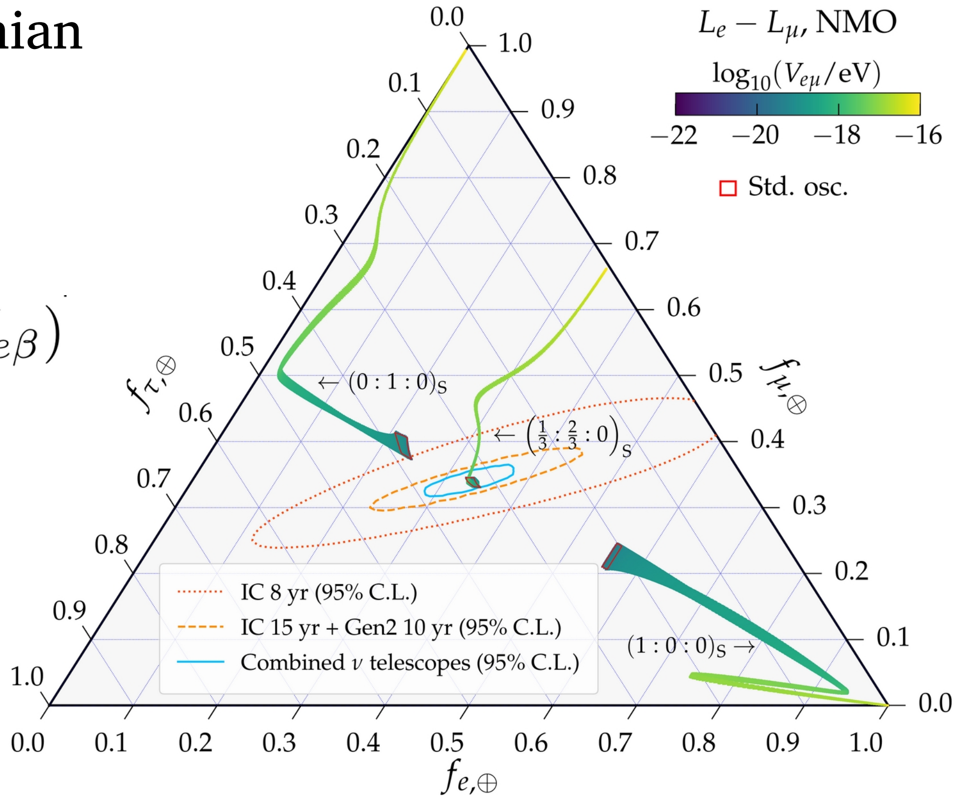
$$\mathbf{H} = \mathbf{H}_{\rm vac} + \mathbf{V}_{\rm mat} + \mathbf{V}_{\alpha\beta}$$

where

$$\mathbf{V}_{e\beta} = \mathrm{diag}\left(V_{e\beta}, -\delta_{\mu\beta}V_{e\beta}, -\delta_{\tau\beta}V_{e\beta}\right)$$
$$\mathbf{V}_{\mu\tau} = \mathrm{diag}(0, V_{\mu\tau}, -V_{\mu\tau})$$

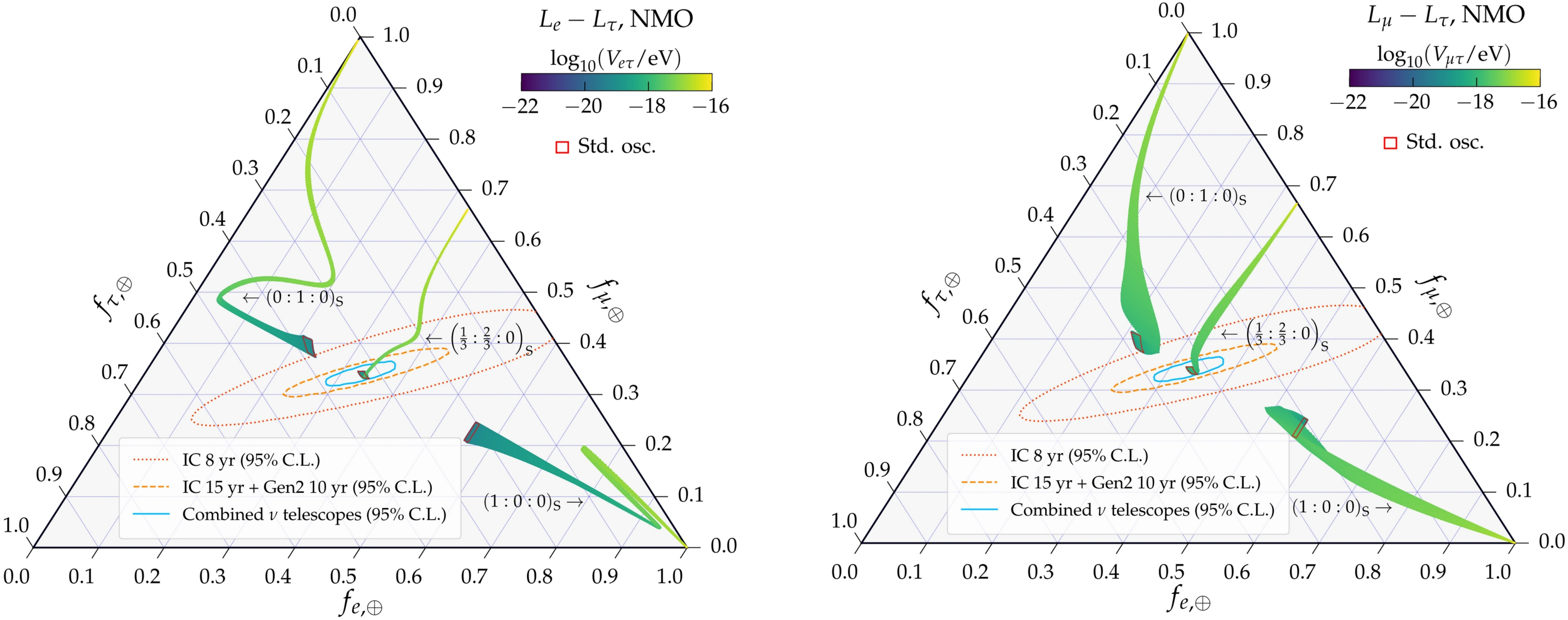
- In this case, probability

$$\bar{P}_{\alpha\beta} = \sum_{i=1}^{3} |U'_{\alpha i}|^2 |U'_{\beta i}|^2$$
$$f_{\beta,\oplus} = \sum_{\alpha} P_{\alpha\beta} f_{\alpha,S}$$



Flavor evolution with LRI potential

Flavor transitions with LRI



Analysis and Results

Bayesian statistics

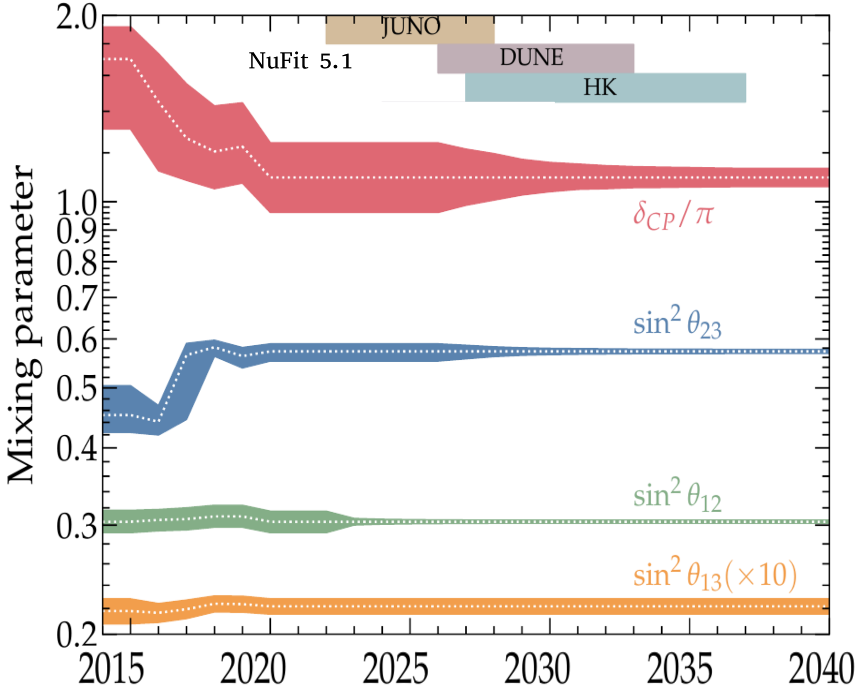
$$\mathcal{P}\left(V_{\alpha\beta}\right) = \int d\boldsymbol{\vartheta}\, \mathcal{L}\left(\left\langle \boldsymbol{f}_{\oplus}\left(V_{\alpha\beta}, \boldsymbol{\vartheta}\right)\right\rangle\right) \pi(\boldsymbol{\vartheta}) \pi\left(V_{\alpha\beta}\right)$$

uniform prior

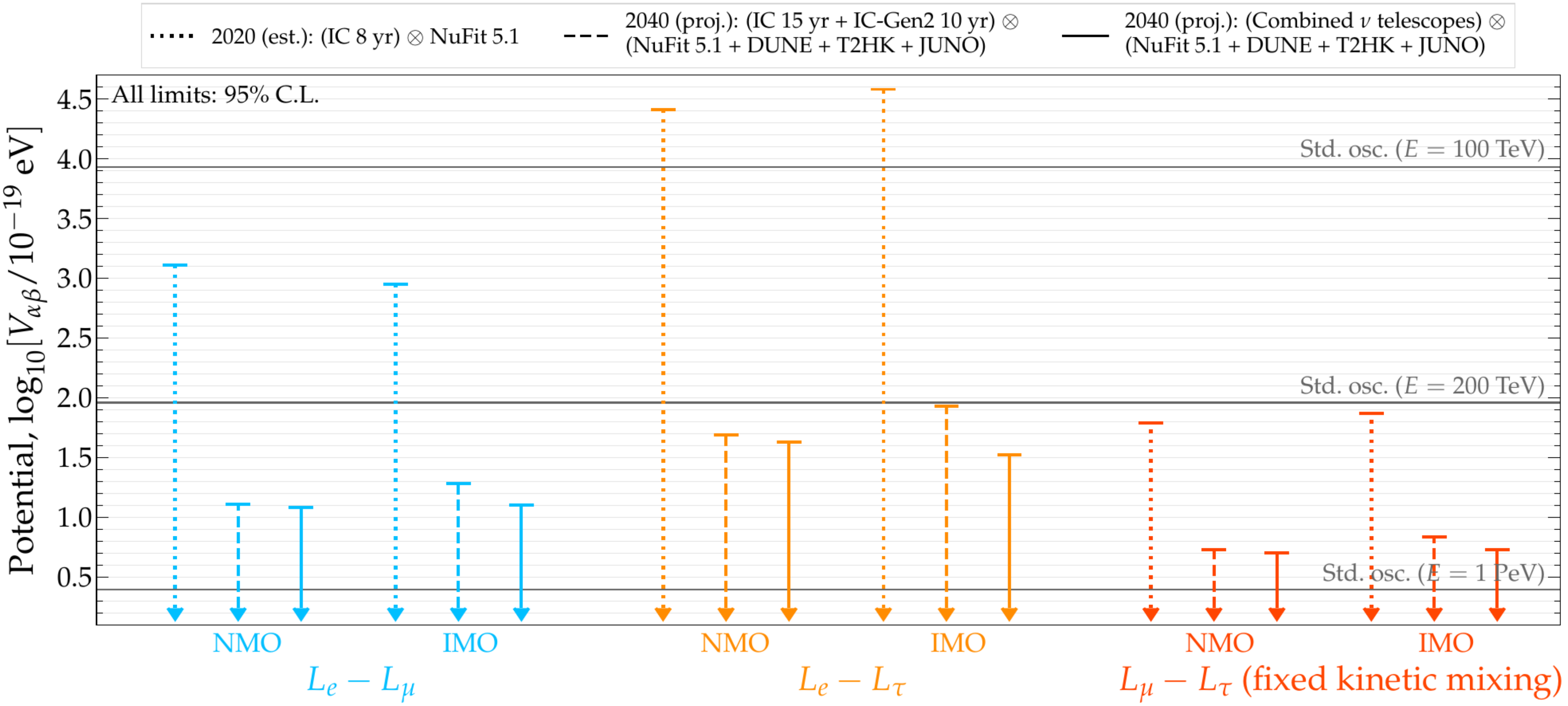
Year	Neutrino telescopes	Flavor ratios at Earth $f_{e,\oplus}$	$f_{\mu,\oplus}$	$f_{\tau,\oplus}$
2020	IC 8 yr	$0.30^{+0.13}_{-0.11}$	$0.36^{+0.059}_{-0.053}$	$0.34^{+0.16}_{-0.18}$
2040	IC 15 yr+Gen2 10 yr	$0.30^{+0.039}_{-0.037}$	$0.36^{+0.017}_{-0.016}$	$0.34^{+0.049}_{-0.050}$
2040	IC+Gen2+KM3NeT +GVD+P-ONE+TAMBO	$0.30^{+0.030}_{-0.027}$	$0.36^{+0.011}_{-0.011}$	$0.34^{+0.037}_{-0.039}$

IceCube-Gen2 Collaboration (2021)
Song et. al. (2021)

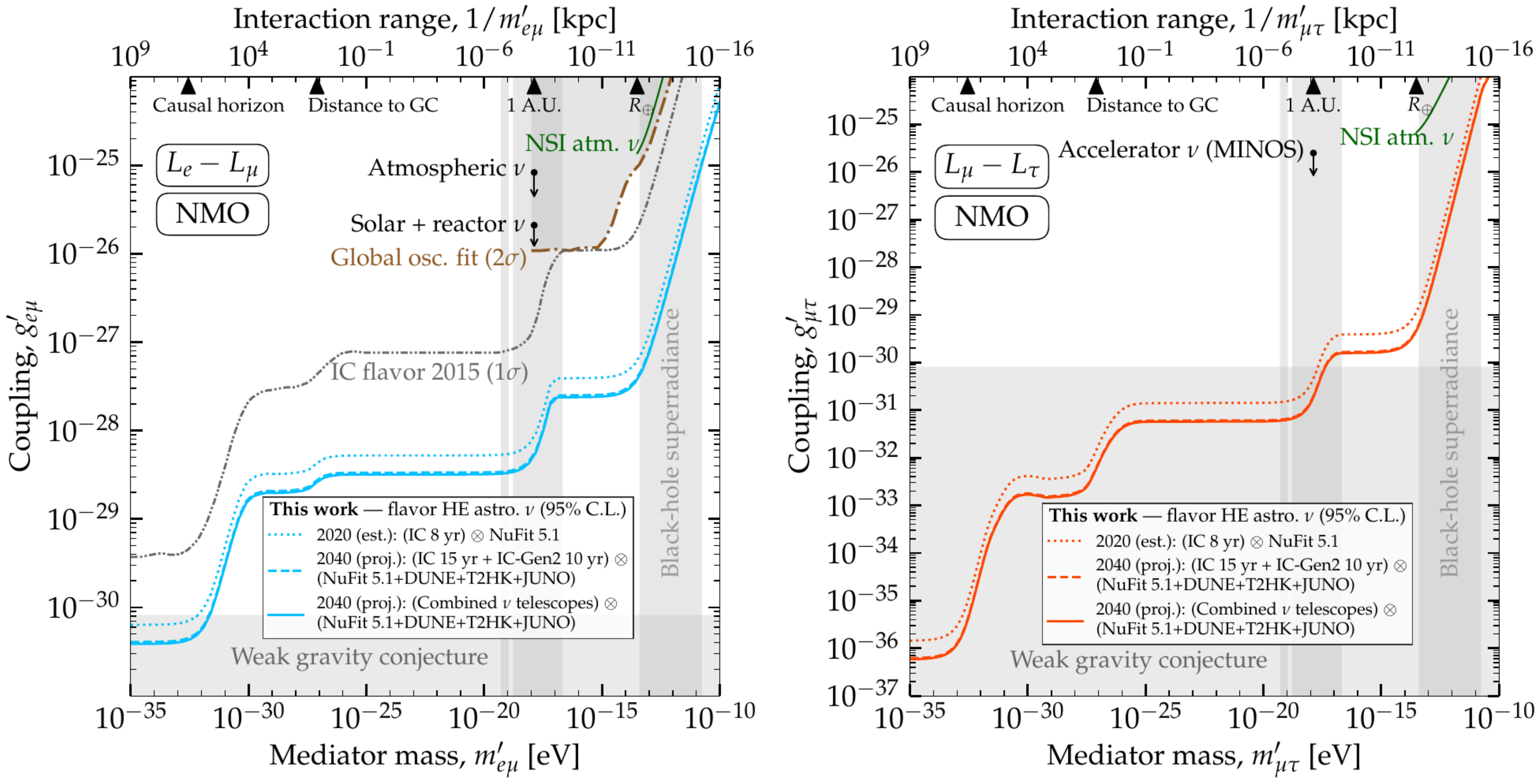
Song et. al. (2021)



Limits on the LRI potential



Limits projected on g-m plane



Summary and Outlook

- We examined the sensitivity to new flavor-dependent interactions between neutrinos and electrons and neutrons, both now and in the future.
- The flavor composition of the diffuse astrophysical neutrino flux (ν_e, ν_μ, and ν_τ) holds the potential to detect flavor-dependent long-range interactions.
- By analyzing the flavor composition of the diffuse astrophysical neutrino flux, we placed constraints on long-range interactions.
- Surprisingly, with the current flavor sensitivity of IceCube and existing mixing parameter uncertainties, high-energy astrophysical neutrinos can tightly constrain long-range interactions, surpassing existing limits.
- In the next two decades, modest improvements are expected with the same analysis, while substantial gains may be achieved by upgrading to utilize higher event rates and potential advancements in flavor composition measurement.

Thank You

Back up

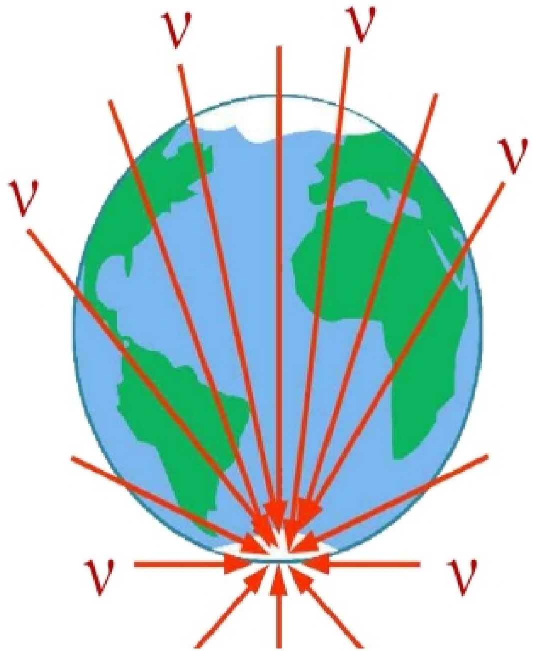
The potential due to the Earth

$$V^{\oplus}_{\alpha\beta} = \frac{\mathcal{G}_{\alpha\beta}}{2} \int_0^{\pi} d\theta_z \int_0^{r_{\max}(\theta_z)} dr\; r \sin\theta \; e^{-m'_{\alpha\beta} r} \times \begin{cases} \langle n_{e,\oplus} \rangle_{\theta_z} & \text{, for } \alpha, \beta = e, \mu \text{ or } e, \tau \\ \langle n_{n,\oplus} \rangle_{\theta_z} & \text{, for } \alpha, \beta = \mu, \tau \end{cases}$$

$$r_{\max}(\theta) = (R_{\oplus} - d_{\rm IC}) \cos\theta + \left[(R_{\oplus} - d_{\rm IC})^2 \cos^2\theta + (2R_{\oplus} - d_{\rm IC}) d_{\rm IC} \right]^{1/2}$$

We assume matter in the Earth is isoscalar and charge-neutral

$$\langle n_{e,\oplus} \rangle_{\theta_z} = \langle n_{n,\oplus} \rangle_{\theta_z}$$



The potential due to the Moon and the Sun

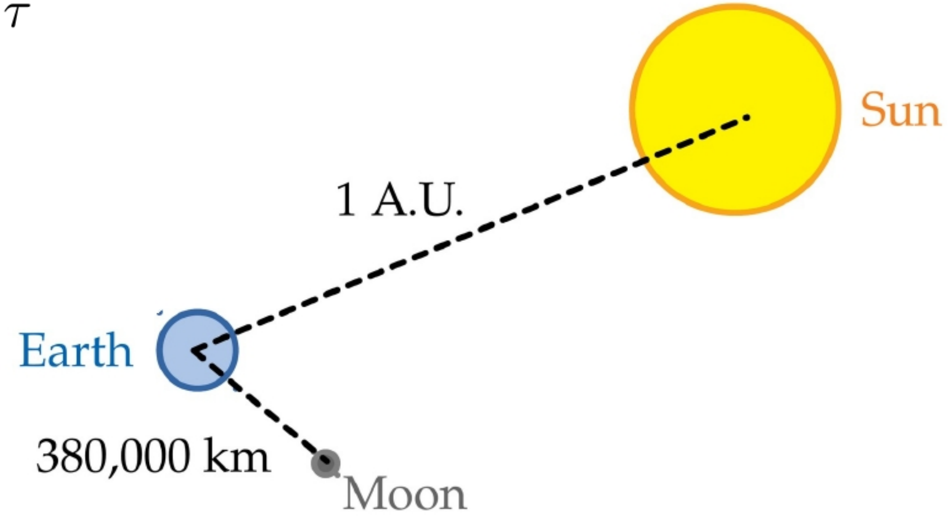
$$V_{\alpha\beta}^{☾} = -\mathcal{G}_{\alpha\beta}\frac{e^{-m'_{\alpha\beta}d_{☾}}}{4\pi d_{☾}} \times \begin{cases} N_{e,☾} & \text{, for } \alpha,\beta = e,\mu \text{ or } e,\tau \\ N_{n,☾} & \text{, for } \alpha,\beta = \mu,\tau \end{cases}$$

$$V_{\alpha\beta}^{\odot} = -\mathcal{G}_{\alpha\beta}\frac{e^{-m'_{\alpha\beta}d_{\odot}}}{4\pi d_{\odot}} \times \begin{cases} N_{e,\odot} & \text{, for } \alpha,\beta = e,\mu \text{ or } e,\tau \\ N_{n,\odot} & \text{, for } \alpha,\beta = \mu,\tau \end{cases}$$

$$N_{e,☾} = N_{n,☾} \sim 5 \cdot 10^{49}$$

$$N_{e,\odot} \sim 10^{57}$$

$$N_{n,\odot} = N_{e,\odot}/4$$



The potential due to the Milky-way galaxy

$$V_{\alpha\beta}^{\rm MW} = \frac{\mathcal{G}_{\alpha\beta}}{4\pi}\int_0^\infty dr\int_0^\pi d\theta\int_0^{2\pi} d\phi\, r\sin\theta\, e^{-m'_{\alpha\beta}r}\times\begin{cases} n_{e,\rm MW}(r,\theta,\phi) & \text{, for } \alpha,\beta = e,\mu \text{ or } e,\tau \\ n_{n,\rm MW}(r,\theta,\phi) & \text{, for } \alpha,\beta = \mu,\tau \end{cases}$$

Density of baryonic matter:

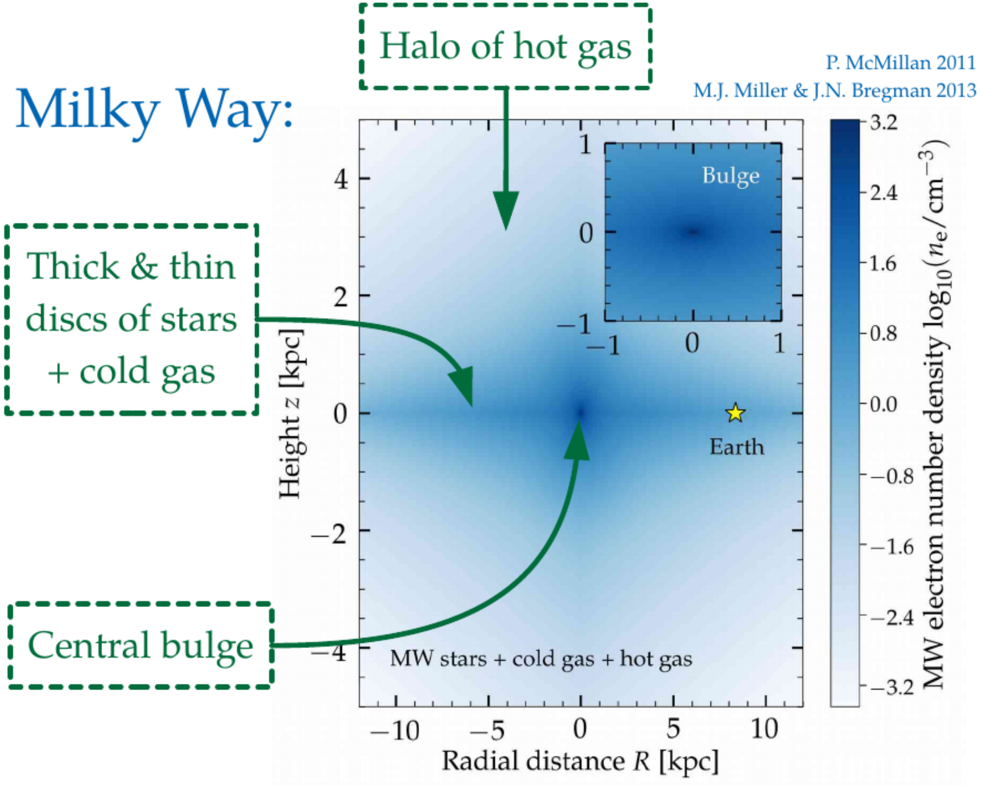
$$\rho_{Thick} = \frac{\Sigma_{d,0}}{2z_d}Exp\left(-\frac{|z|}{z_d}-\frac{R}{R_d}\right)$$

$$\rho_{Thin} = \frac{\Sigma'_{d,0}}{2z'_d}Exp\left(-\frac{|z|}{z'_d}-\frac{R}{R'_d}\right)$$

$$\rho_{Bulge} = \frac{\rho_{b,0}}{(1+\frac{r'}{r_0})^\alpha}Exp\left[-\left(\frac{r'}{r_{cut}}\right)\right]$$

Isoscalar and charge-neutral matter:

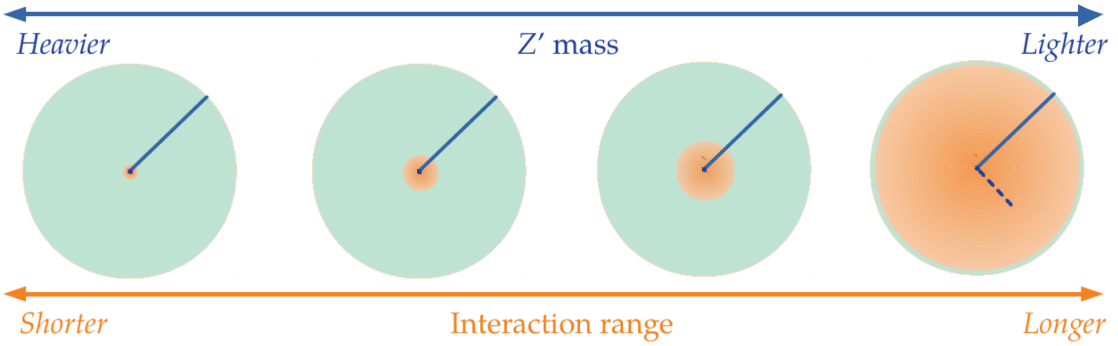
$$n_{e,\rm MW} = n_{n,\rm MW}$$



The potential due to the large-scale Universe

- Consider a neutrino at the center of a sphere of radius R

$$V_{\alpha\beta} = \int_0^R dr\, V_{\alpha\beta}(g_{\alpha\beta}, m_{\alpha\beta}, r) \times n(r)$$



- For a constant density of source particles

$$V_{\alpha\beta} \propto n \left[\frac{1 - e^{-m_{\alpha\beta}R}(1 + m_{\alpha\beta}R)}{m_{\alpha\beta}^2} \right]$$

- To account for the expanding Universe

$$R(z) = H_0^{-1} \int_0^z \frac{dz'}{(1+z')h(z')}$$

$$h(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$$

$$\Omega_M = 0.315$$

$$\Omega_\Lambda = 1 - \Omega_M \quad H_0 = 67.4 km sec^{-1} Mpc^{-1}$$

$$M(z) = \frac{H_0^2}{16 G_N} R^3(z) \Omega_b^0$$

$$\mathcal{V}(z) = \frac{4}{3}\pi R^3(z)$$

$$n = \frac{\mathcal{N}(z)}{\mathcal{V}(z)}$$

$$N_{n,\cos}(z) = N_{e,\cos}(z)/7$$

$$N_{e,\cos}(z) \simeq 7 M_{\rm H}(z)/(8 m_p + 7 m_e)$$