Constraints on flavor-dependent long-range interactions of high-energy astrophysical neutrinos

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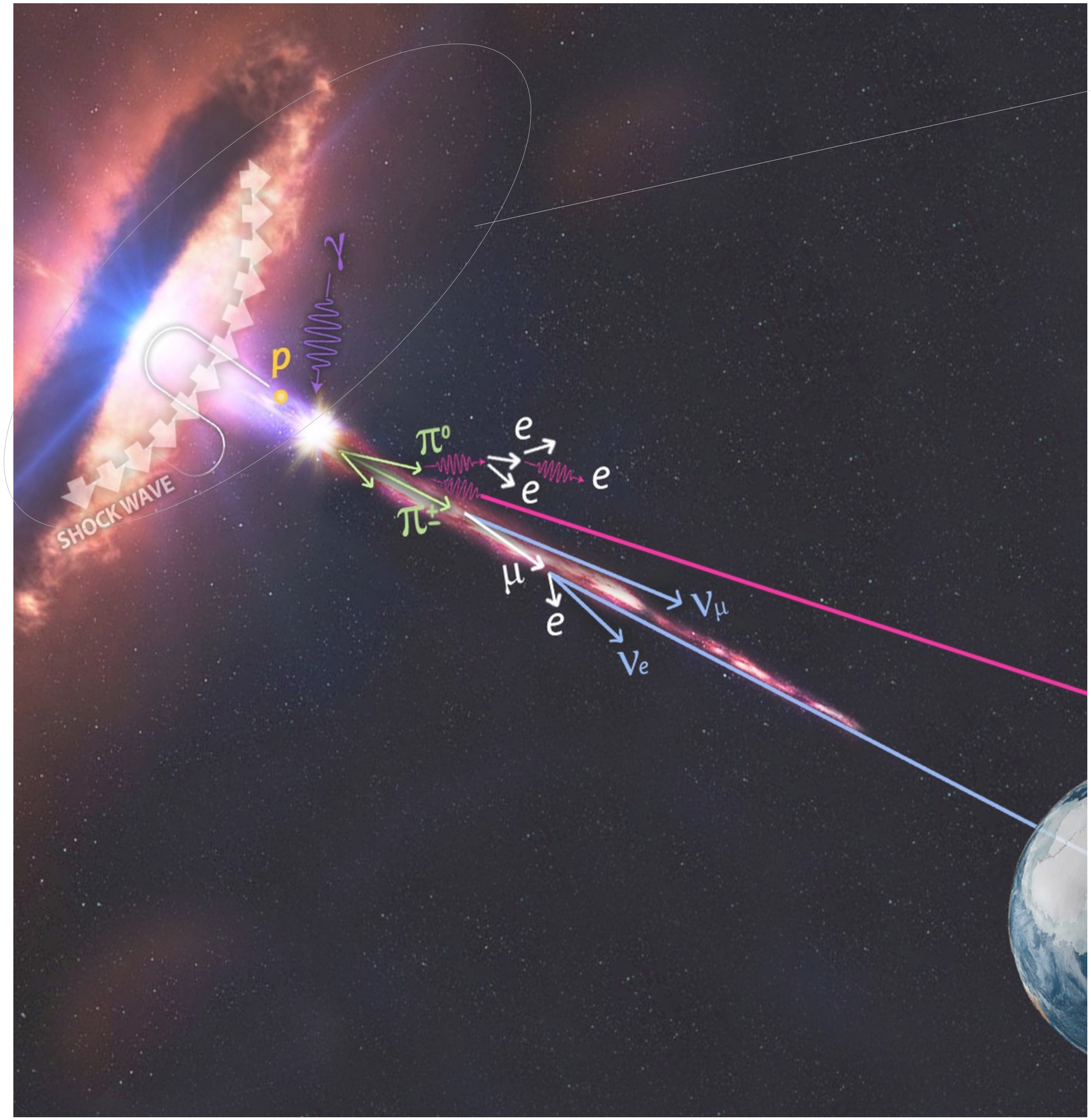
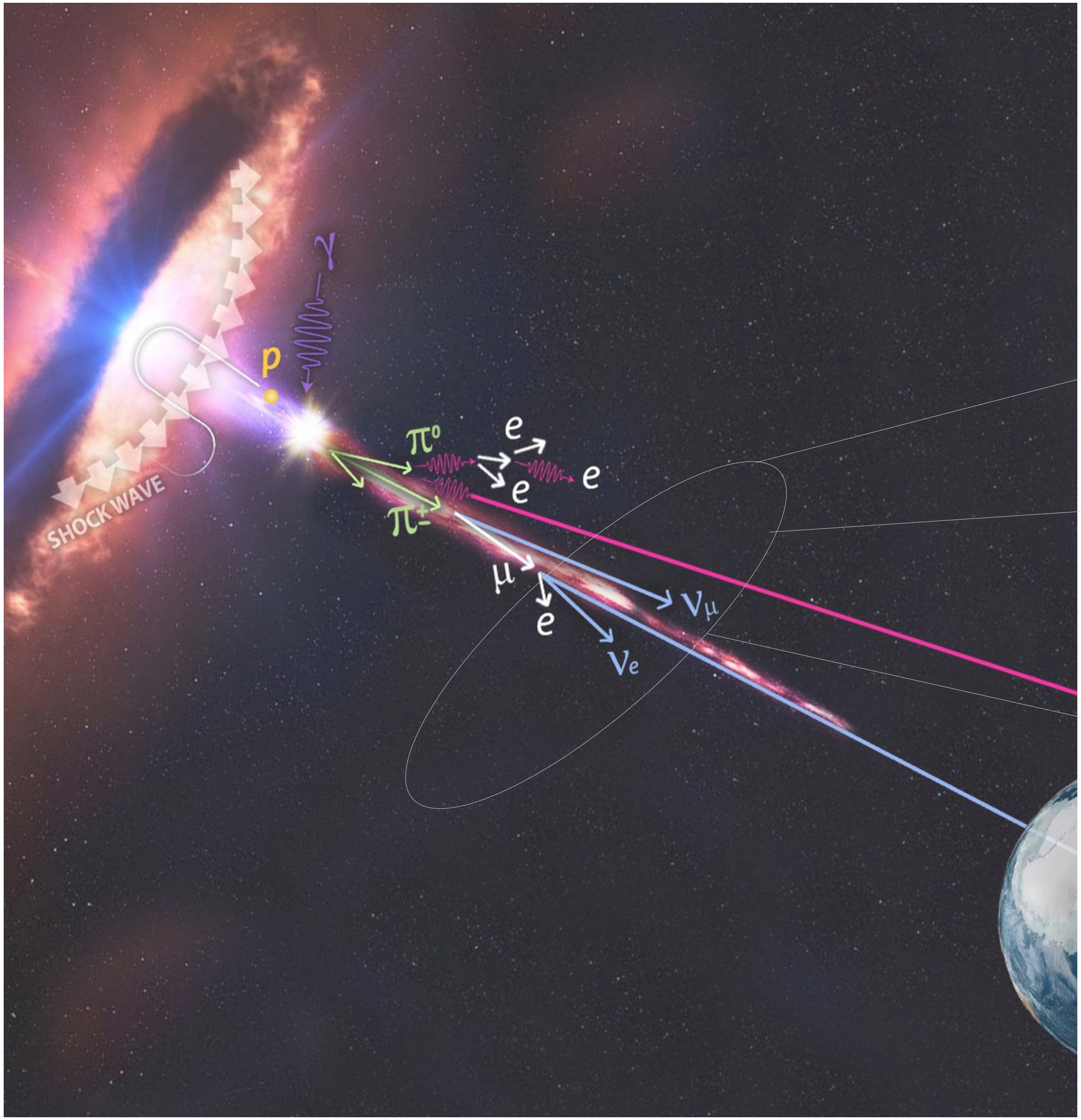
Introduction



AGN, Gamma ray bursts, Supernovae, Galaxy clusters...

www.forbes.com

Introduction



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AGN, Gamma ray bursts, Supernovae, Galaxy clusters...

TeV - EeV energy scale

Highest energy among all sources

MPC to GPC distances

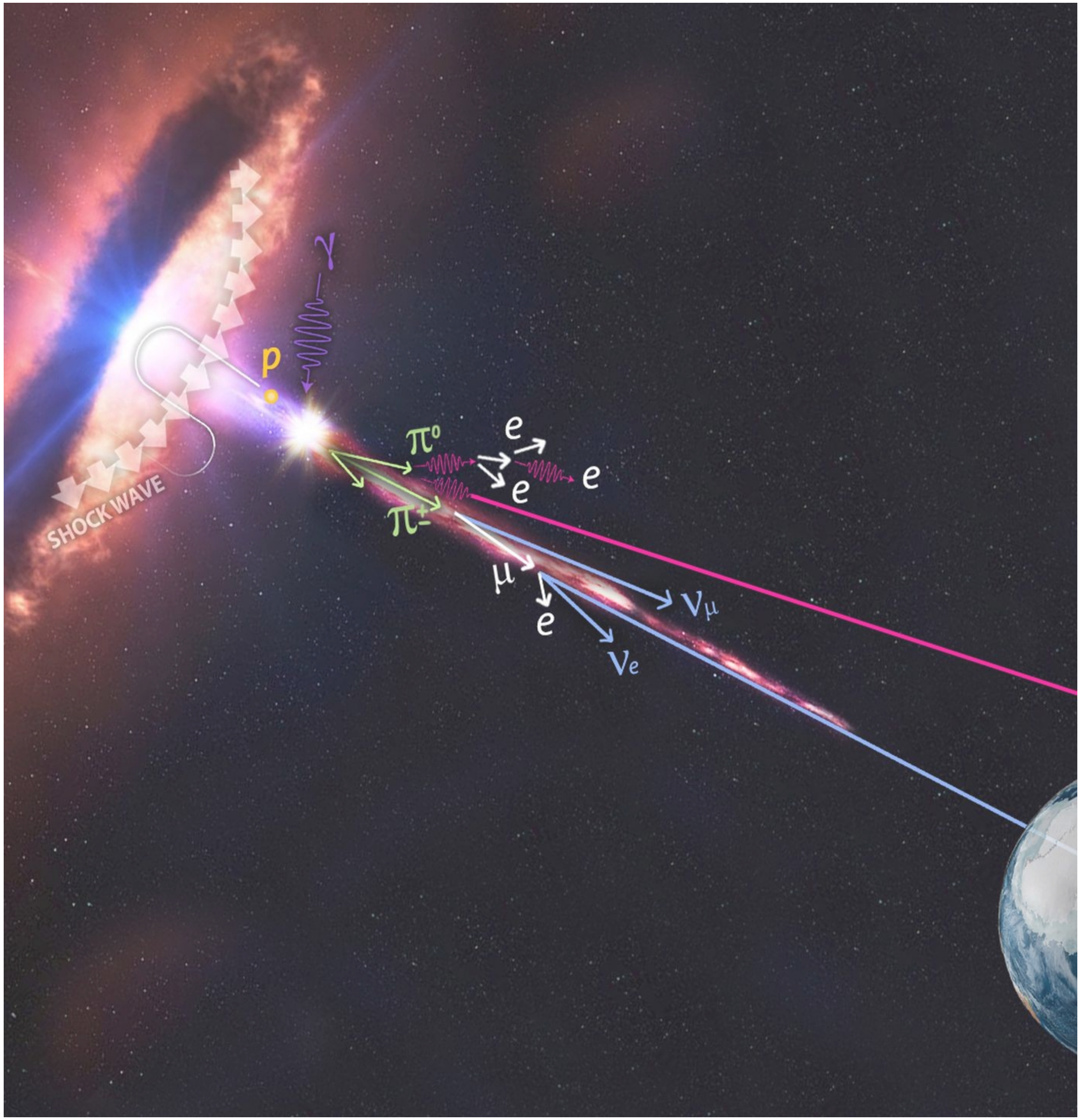
Travel longest distances

Weakly interacting

Travel almost straight from the source.

Excellent Massenger for various Astrophysical activities.

Introduction



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- Neutrino flavor oscillation

$$P_{\alpha\beta} = \left| \sum_{i=1}^{3} U_{\alpha i} \exp\left[-i \frac{\Delta m_{i1}^2 L}{2E}\right] U_{\beta i}^* \right|^2$$

$\Delta m_{ij}^2 L/(2E) \gg 1$

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

- Neutrino flavor compostions

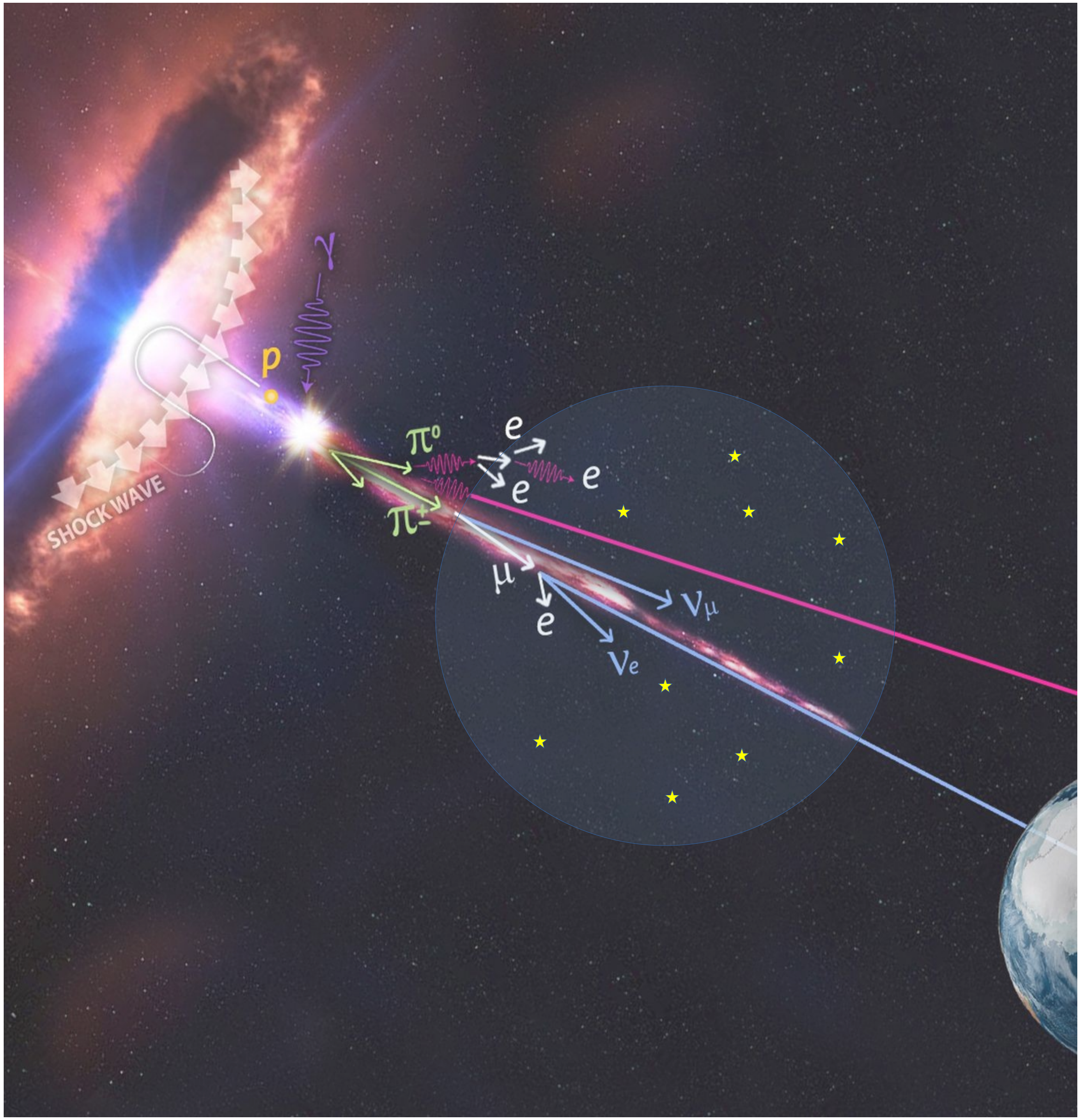
$$(f_e : f_\mu : f_\tau)_{\mathrm{S}} = (1:2:0)$$

$\bar{P}_{\beta\alpha} f_{\beta,\mathrm{S}}$

$$(f_e : f_\mu : f_\tau)_{\oplus} \approx (1:1:1)$$

Assumption:
Neutrino propagating in vacuum

Introduction



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Neutrino interaction with the surrounding matter

- Neutrino flavor oscillation

$$\bar{P}_{\alpha\beta}(U_{\alpha i}) \Longrightarrow \bar{P}'_{\alpha\beta}(U_{\alpha i}, V, E_\nu)$$

- Neutrino flavor compostions

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

$$\Big\Downarrow \ \bar{P}_{\beta\alpha} f_{\beta,S}$$

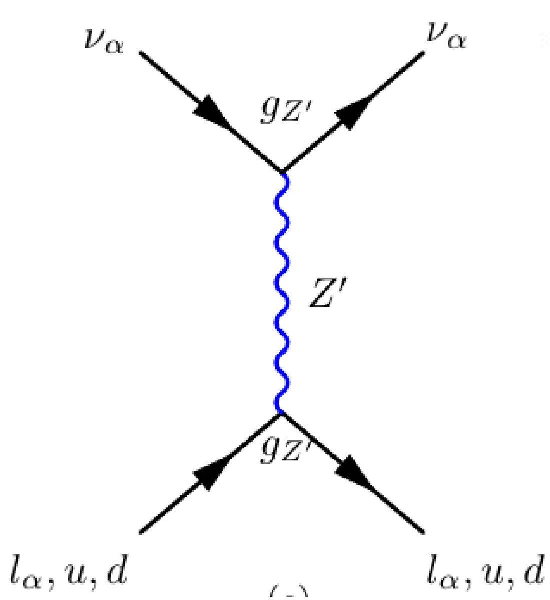
$$(f_e : f_\mu : f_\tau)_\oplus = x : y : z$$

- Deviation from the **1:1:1** may hint toward a new interaction

Neutrino-matter interaction in Z′ models

$$\mathrm{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'_X}$$

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



$$V^f_{\alpha\beta} = \delta_{\alpha\beta} a_f b_\alpha V^f_0$$

Ultra-light Z′

⇩

Long-range interaction

Range $\propto \frac{1}{m_{Z'}}$

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

Classifications of the Models

Flavor-dependent Interaction potential: $V^{f}_{\alpha\alpha} \propto \frac{1}{2}\, a_f\, b_\alpha\, V^{f}_{0}$

Class - I

$$\begin{pmatrix} \bullet & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

$B - 3L_e$
$L - 3L_e$
$B - \frac{3}{2}(L_\mu + L_\tau)$
$L_e - \frac{3}{2}(L_\mu + L_\tau)$
$L_e + 2(L_\mu + L_\tau)$
$B_y + L_\mu + L_\tau$

Class - II

$$\begin{pmatrix} 0 & & \\ & \bullet & \\ & & 0 \end{pmatrix}$$

$B - 3L_\mu$
$L - 3L_\mu$

Class - III

$$\begin{pmatrix} 0 & & \\ & 0 & \\ & & \bullet \end{pmatrix}$$

$B - 3L_\tau$
$L - 3L_\tau$

Class - IV

$$\begin{pmatrix} \bullet & & \\ & \bullet & \\ & & 0 \end{pmatrix}$$

$L_e - L_\mu$

Class - IV

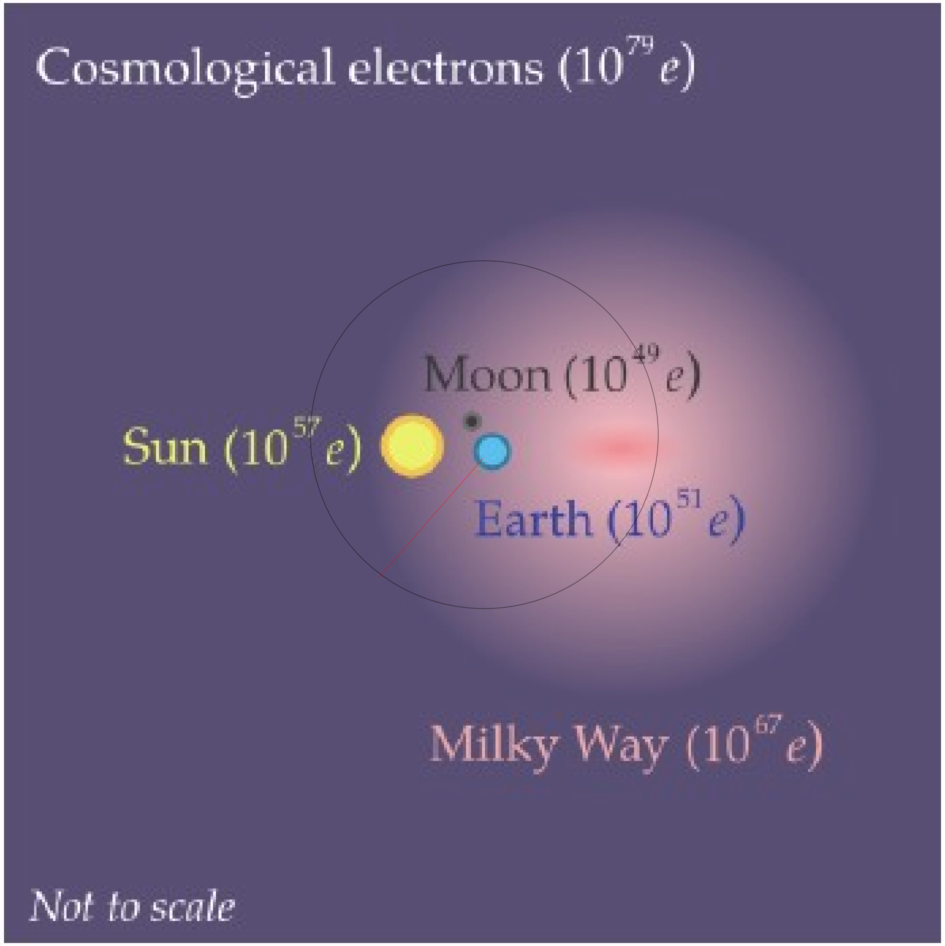
$$\begin{pmatrix} \bullet & & \\ & 0 & \\ & & \bullet \end{pmatrix} \Bigg\} \; L_e - L_\tau$$

Class - VI

$$\begin{pmatrix} 0 & & \\ & \bullet & \\ & & \bullet \end{pmatrix} \Bigg\} \; B - L_e - 2L_\tau$$

Long-range neutrino matter interaction with U(1)' models

Matter particles inside the interaction range will contribute to the potential.



Bustamante, Agarwalla, PRL, 2019

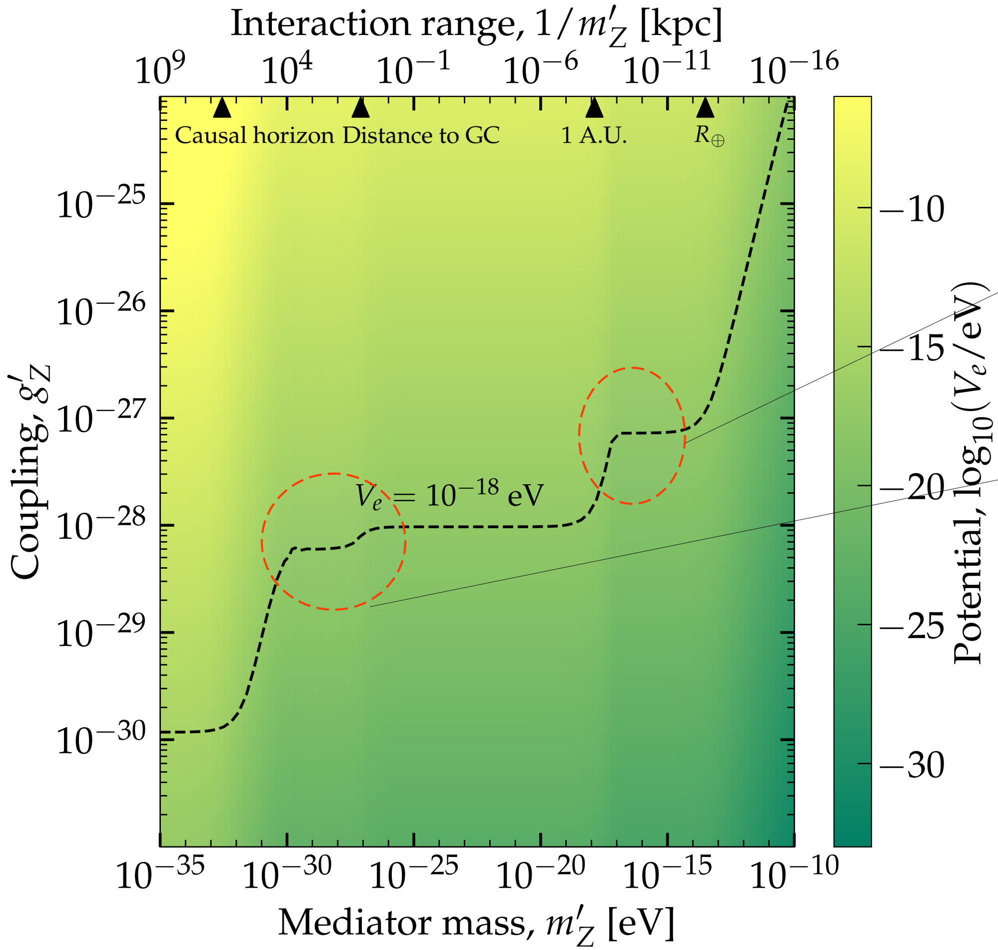
Interaction range $\propto \frac{1}{m_{Z'}}$

$$V_0^f = g_{Z'}^2 \frac{n_f}{4\pi d} e^{-m_{Z'} d}$$

$$V_f(m_{Z'}, G') = \left(V_f^{\oplus} + V_f^{☾} + V_f^{\odot} + V_f^{\mathrm{MW}} + V_f^{\cos}\right)$$

$$V_{\mathrm{LRI},\alpha} = b_\alpha \sum_{f=e,p,n} a_f V_f(m_{Z'}, G')$$

Long-range neutrino matter interaction with U(1)' models



Inclusion of electrons in Sun

Electrons from Galactic Centre

Neutrino flavor composition in the presnece of long-range potential

- Neutrino propagation Hamiltonian

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

New potential

$$\mathbf{H}_{\rm vac} = \frac{1}{2E}\mathbf{U}\ {\rm diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)\ \mathbf{U}^\dagger\ , \qquad \mathbf{V}_{\rm mat} = {\rm diag}(V_{\rm CC}, 0, 0)\ ,$$

- Neutrino flavor transition probability

$$\Delta\tilde{m}_{ij}^2 L/(2E) \gg 1$$

$$\bar{P}_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}^m|^2 |U_{\beta i}^m|^2\ .$$

$$U^m \to U^m(\theta_{23}^m, \theta_{13}^m, \theta_{12}^m, \delta^m)$$ ⇨ Modified Mass-mixing parameters

- Neutrino flavor compostion at Earth

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

$$f_{\alpha,\oplus} \to (f_e : f_\mu : f_\tau)_\oplus$$

$$f_{\alpha,S} \to (f_e : f_\mu : f_\tau)_S$$

Assumed flavor composition At source

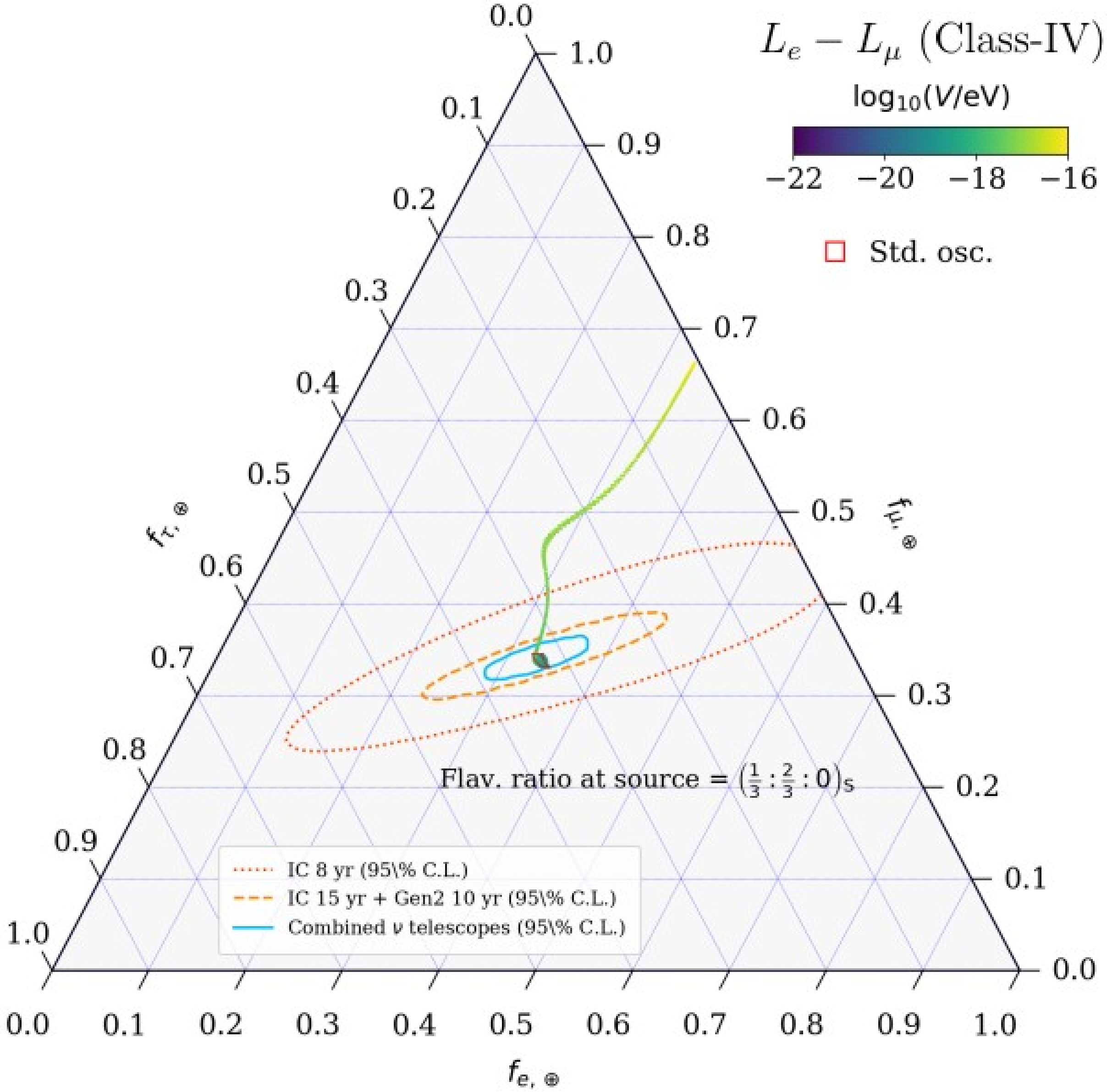
$$(f_e : f_\mu : f_\tau)_{\rm S} = (1 : 2 : 0)$$

From pp or $p\gamma$ collision

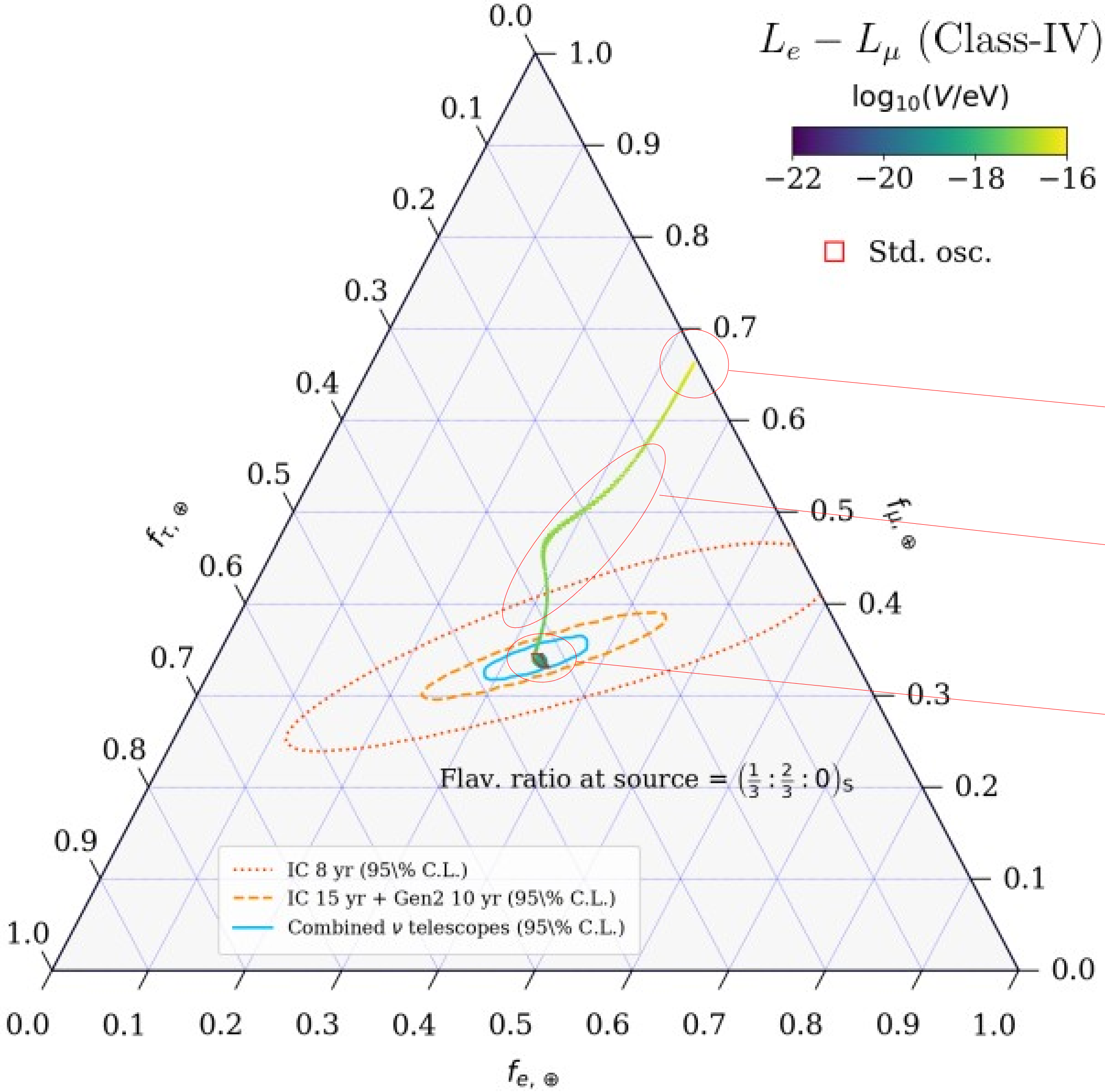
$$\pi^+ \to \mu^+ + \nu_\mu$$

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

Neutrino Flavor compostion



Neutrino Flavor compostion

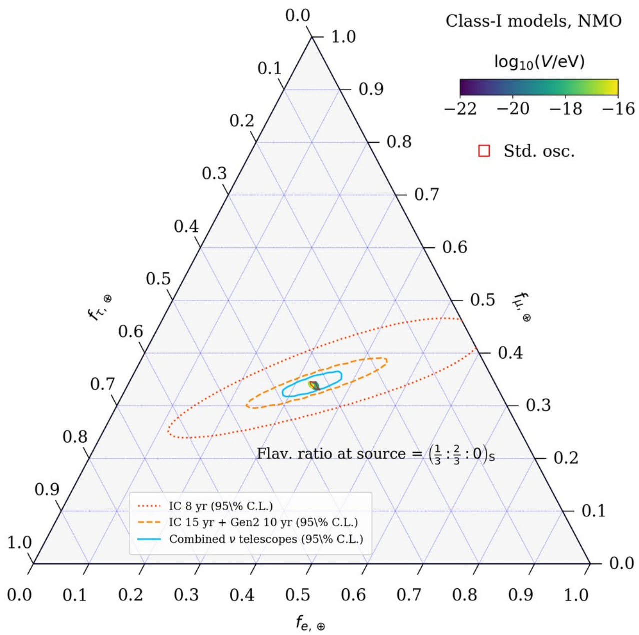


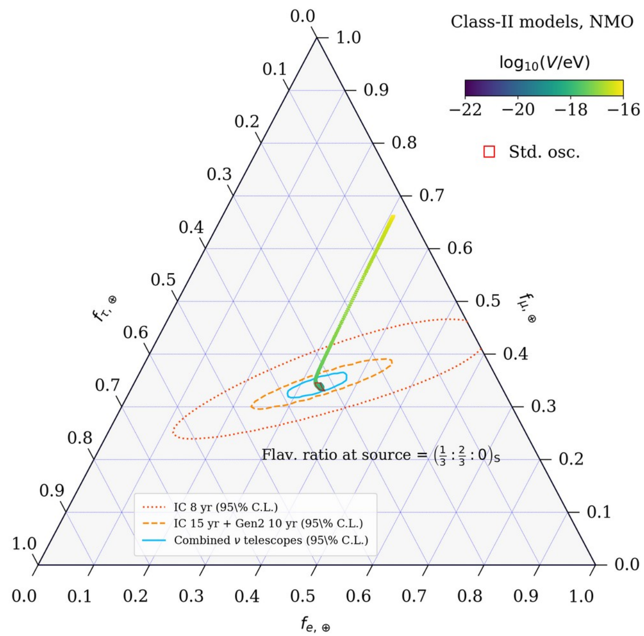
$V_{\alpha\beta} \gg \Delta m^2_{ij}/(2E)$

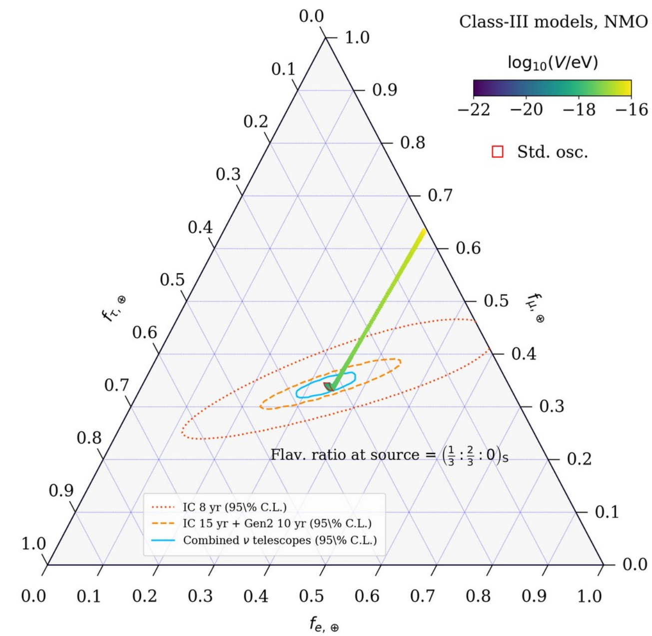
$V_{\alpha\beta} \sim \Delta m^2_{ij}/(2E)$

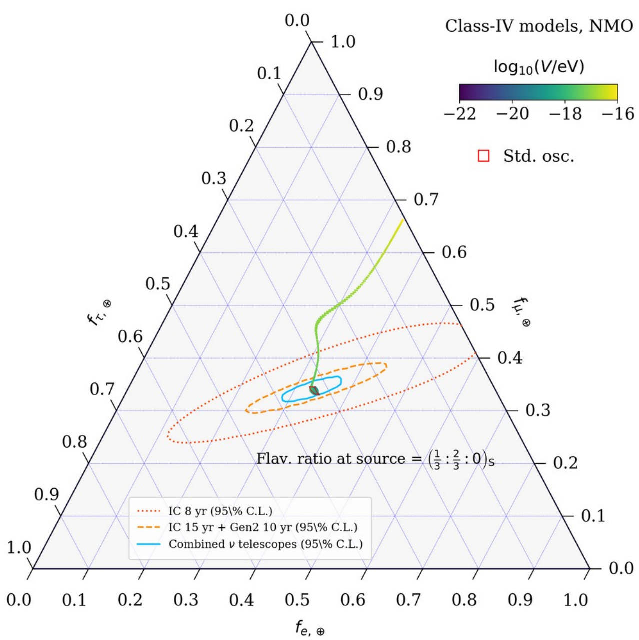
$V_{\alpha\beta} \ll \Delta m^2_{ij}/(2E)$

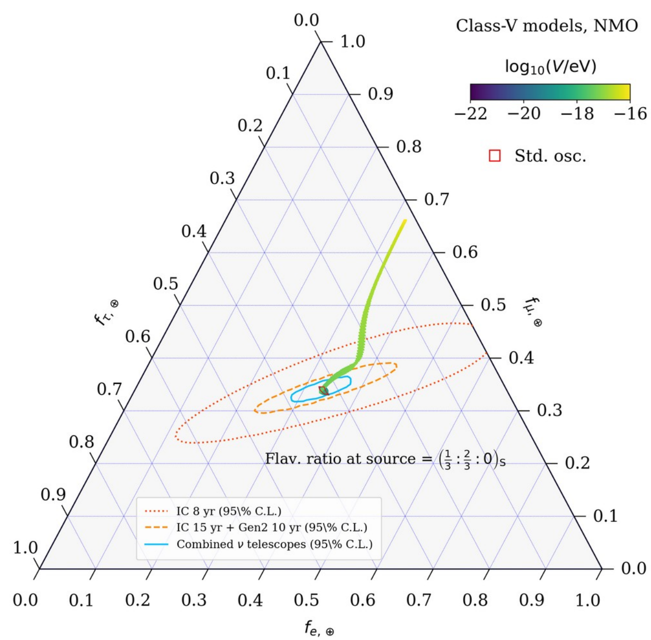
Neutrino Flavor compostion

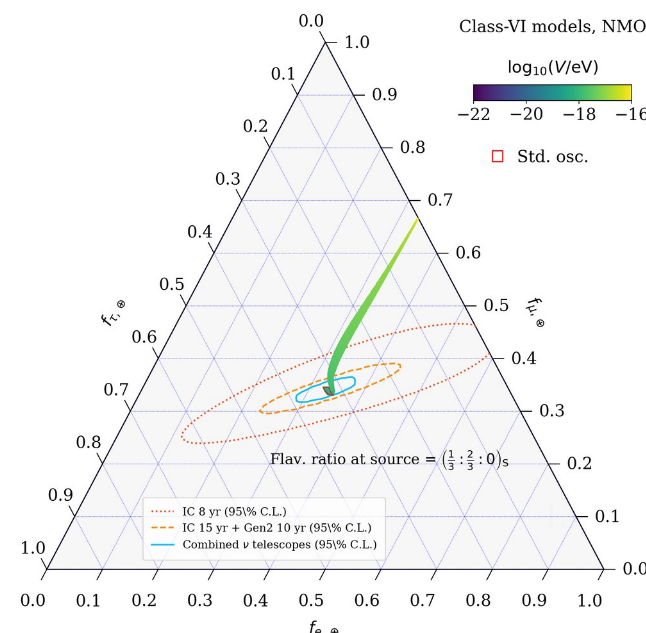












Statistical Analysis

- Posterior probability density of the long-range potential :

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

$$\boldsymbol{\vartheta} \equiv \left(\sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{\rm CP}\right) \quad , \qquad \langle \boldsymbol{f}_{\oplus}\rangle \equiv \left(\langle f_{e,\oplus}\rangle, \langle f_{\mu,\oplus}\rangle, \langle f_{\tau,\oplus}\rangle\right)$$

- Estimated and projected neutrino flavor composition from neutrino telescopes

Observation epoch	Neutrino telescopes	Neutrino mixing parameters
2020 (estimated)	IC 8 yr	NuFit 5.1 (2021)
2040 (projected)	IC 15 yr + IC-Gen2 10 yr	NuFit 5.1 + JUNO + DUNE + HK
2040 (projected)	Combined ν telescopes	NuFit 5.1 + JUNO + DUNE + HK

Song, Li, Arguelles, Bustamante, Vincent, 2020

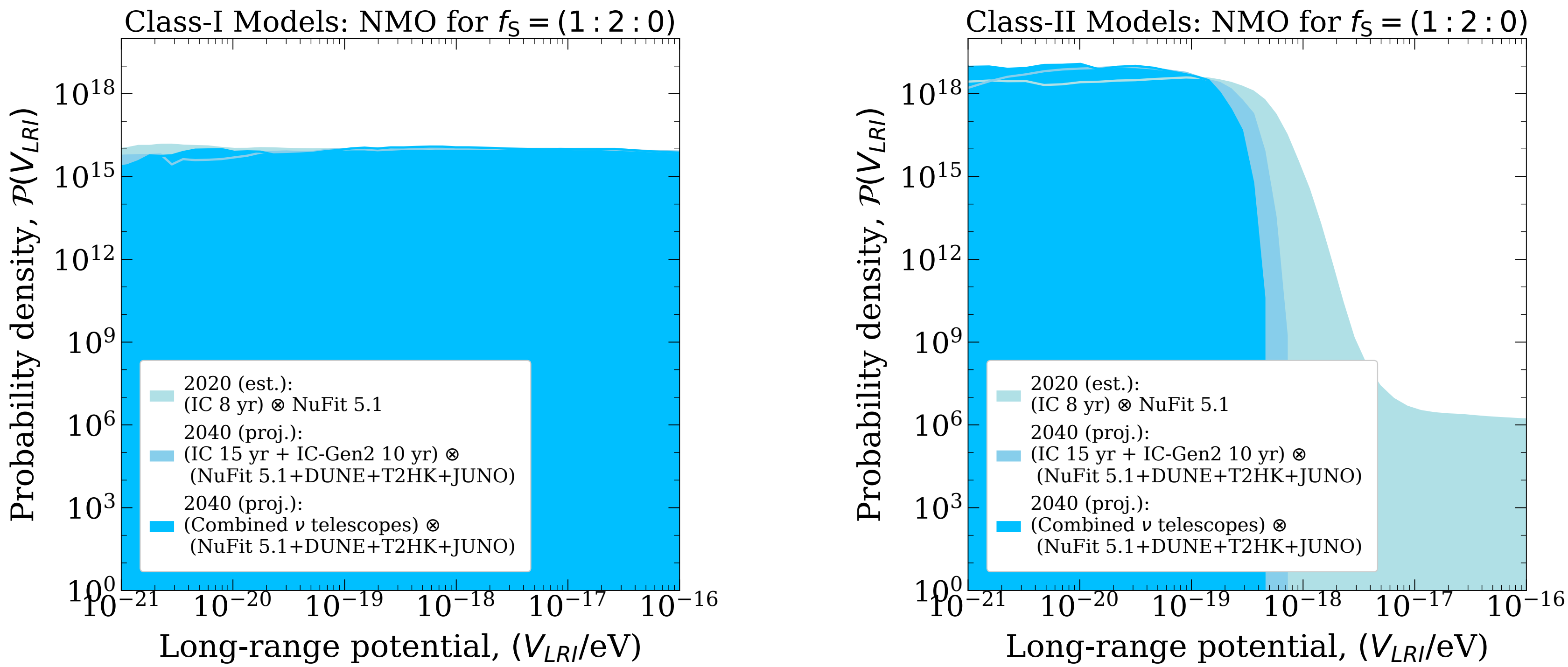
IC 8 yr : estimated through-going + HESE events at IceCube

IC + IC-Gen2 : projected 15 yr IceCube + 10 yr IceCube-Gen2 10 yr

Combined telescopes : projected data from IceCube+Gen2+KM3NeT +GVD+P-ONE+TAMBO

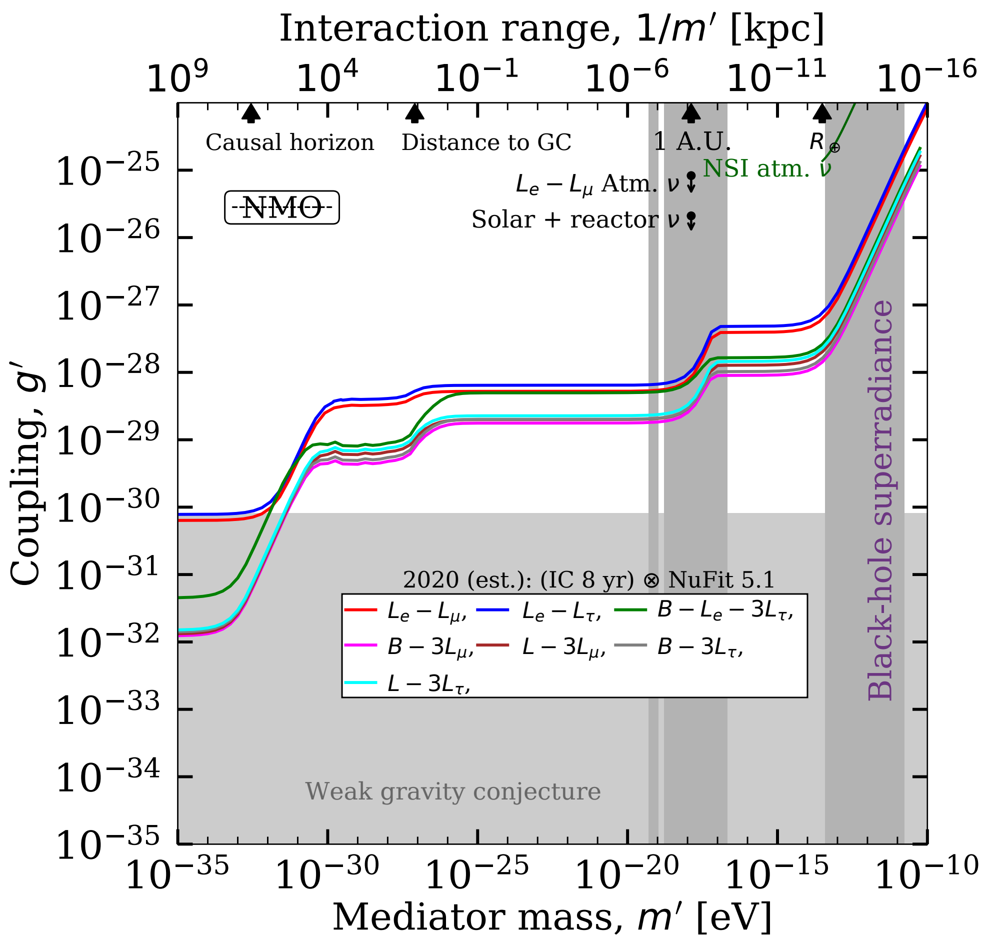
Improvements in $\theta_{12}, \theta_{23}, \delta_{CP}$

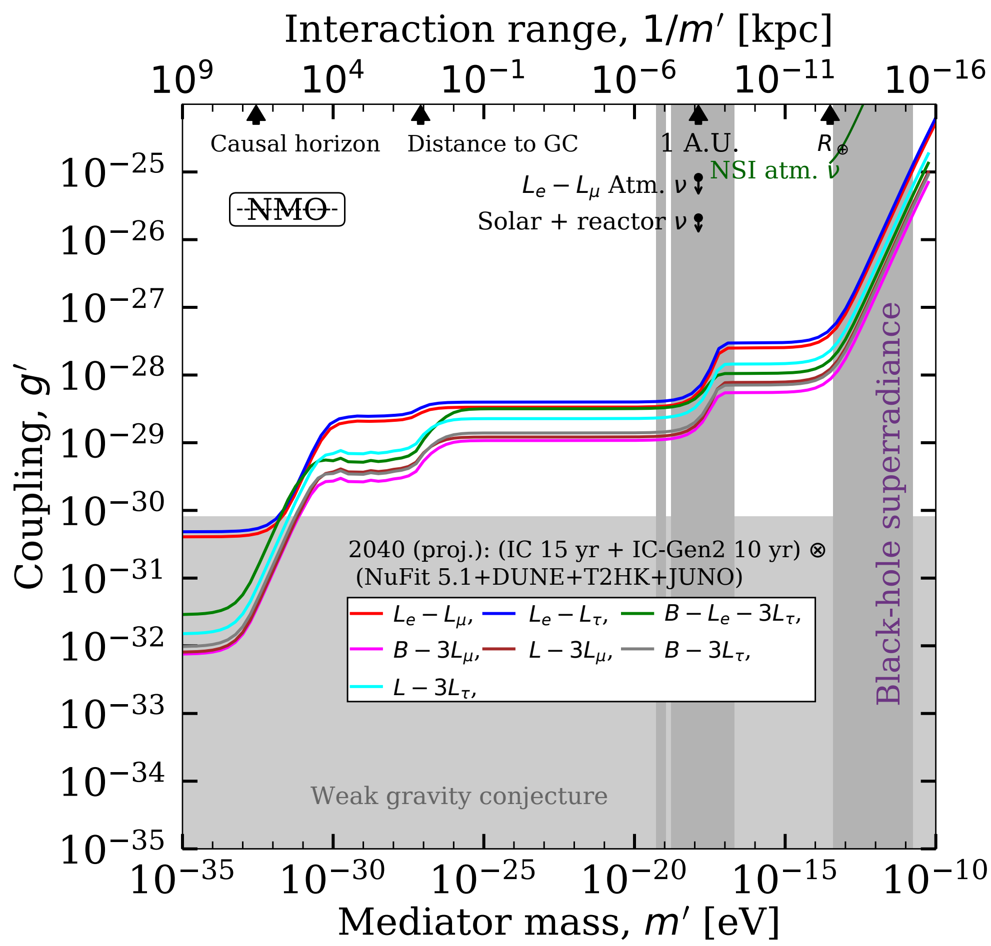
Constraints on long-range potential



Models	Upper limit (95% C.L.) on potential $[10^{-19}$ eV]		
	IC 8 yr	IC 15 yr + Gen2 10 yr	Combined ν telescopes
Class - I	–	–	–
Class-II	3.20	1.19	1.04
Class-III	4.16	1.99	1.76
Class-IV	3.11	1.11	1.08
Class-V	4.41	1.69	1.63
Class-VI	1.79	0.731	0.702

Constraints in coupling-mass plane





Work under progress...
Sanjib Kumar Agarwalla, SD, Ashish Narang

Summary

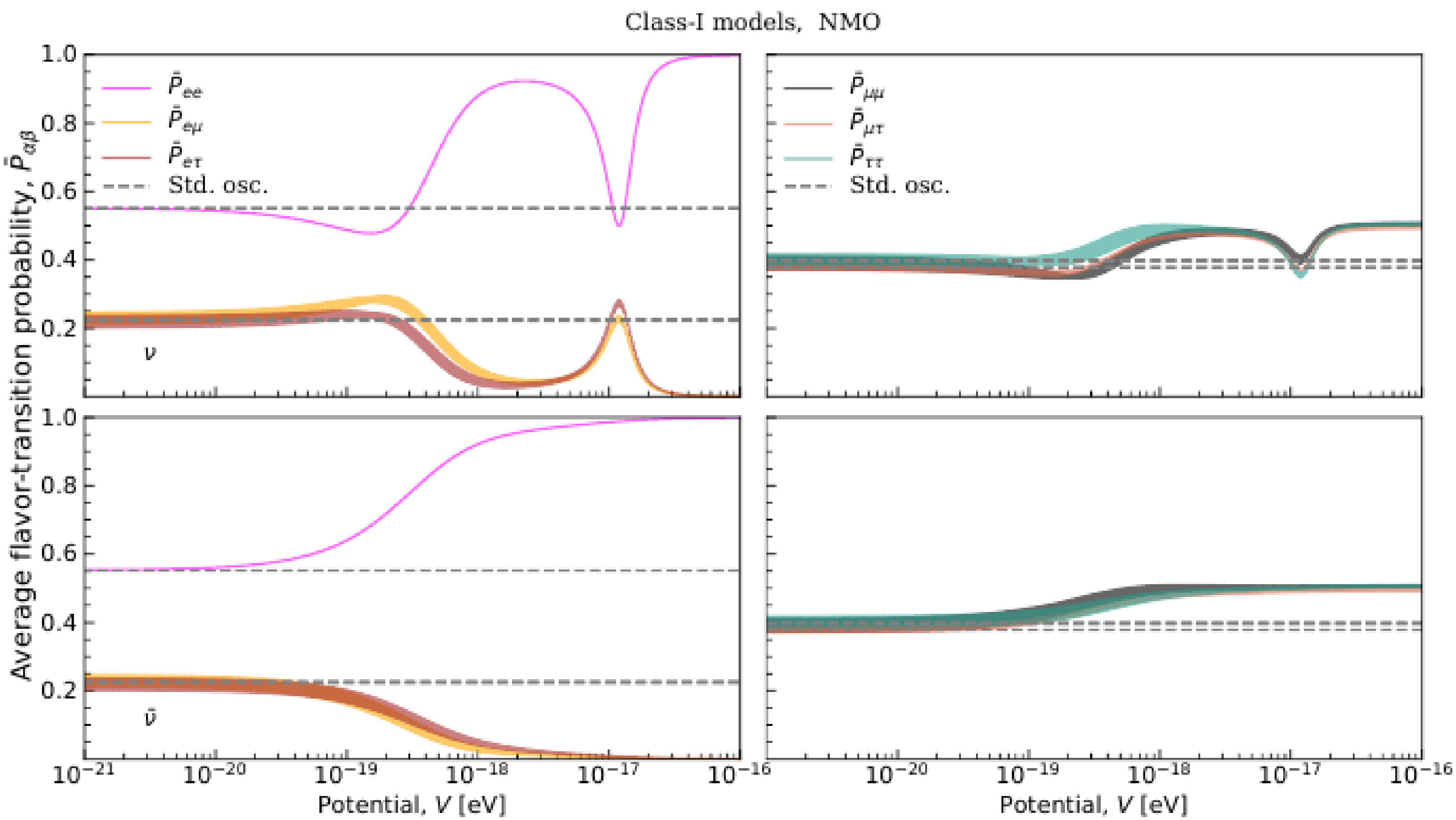
- We probe the possible new neutrino-matter long-range interactions (LRI) induced by anomaly-free $U(1)'$ models.

- Neutrino flavor composition estimates from IceCube and other neutrino telescopes can constrain certain models.

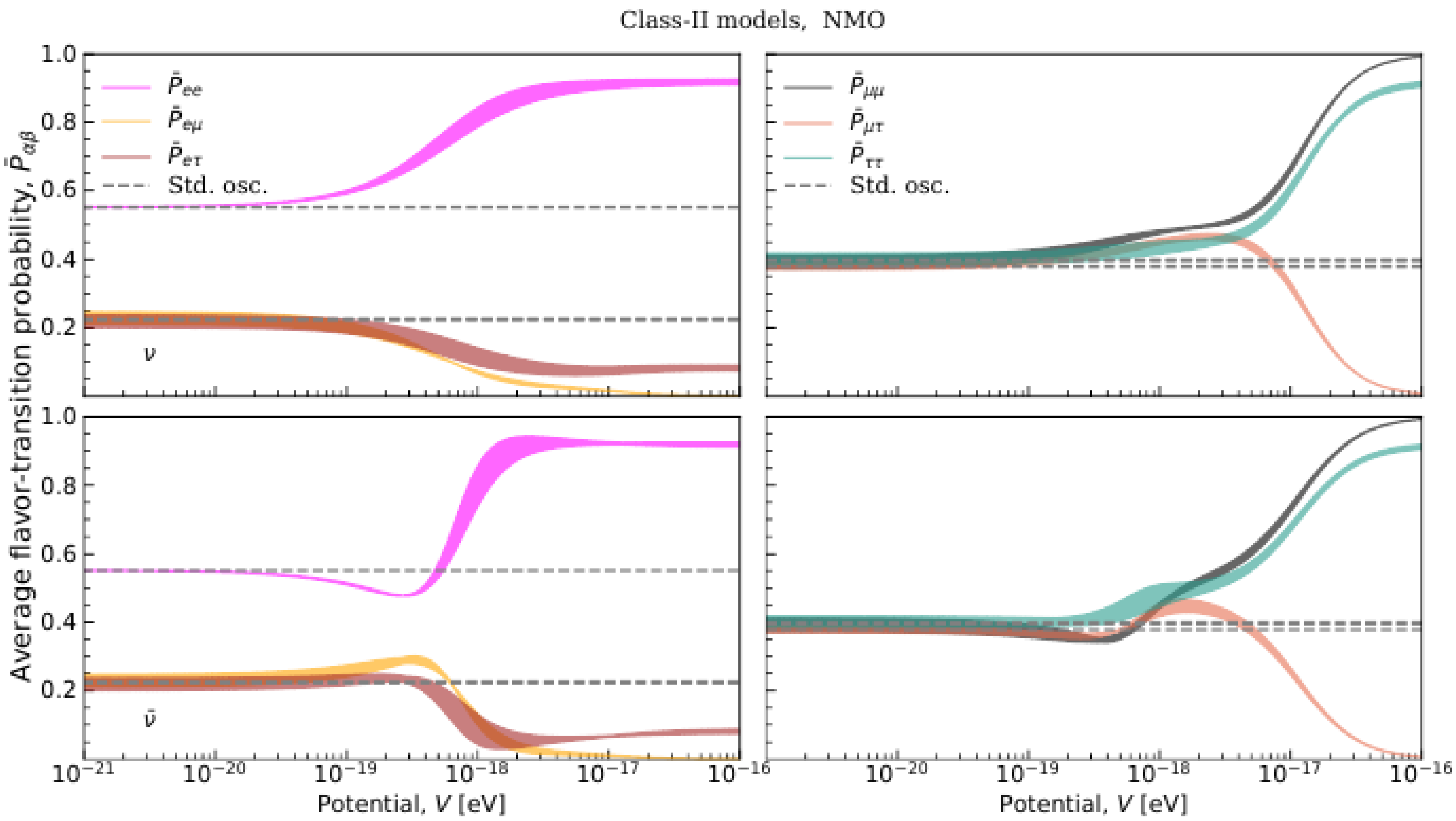
- **We find that using the estimated current flavor sensitivity of IceCube and current mixing parameter uncertainties, high-energy astrophysical neutrinos could tightly constrain long-range interactions, surpassing existing limits.**

Thank You

Back-up slides



Back-up slides



Back-up slides

IceCube 8 yrs estimates (year 2020) : Estimated sensitivity to flavor composition using HESE+through going events in IceCube.

IceCube 15yrs + Gen2 10 yrs projections (year 2040) : 15 years projeted sensitivity of IceCube and 10 years projected sensitiity of IceCube-Gen2 using HESE and through going events.

Projected data from the combined telescopes (year 2040) : Apart from IceCube-Gen2, the next generation neutrino telescopes used for the our analysis are KM3NeT, GVD, P-ONE, and TAMBO.

- 2040 projections for the other neutrino telescopes based on the projections for IceCube-Gen2.

$$\ln \mathcal{L}_{\rm comb.} = \Xi_{\rm S} \ln \mathcal{L}_{\rm Gen2-10yr} + \ln \mathcal{L}_{\rm IC-15\,yr} + \ln \mathcal{L}_{\rm TAMBO}$$

$$\Xi_S = \frac{\Xi_{\rm Gen2-10yr} + \Xi_{\rm KM3NeT} + \Xi_{\rm GVD} + \Xi_{\rm P-ONE}}{\Xi_{\rm Gen2-10yr}}$$

$$-2 \ln \mathcal{L}_{\rm TAMBO} = \frac{(N_{\nu_\tau} - \bar{N}_{\nu_\tau})^2}{\bar{N}_{\nu_\tau}}$$

$$\Xi_{\rm Gen2-10yr} = 81.6~{\rm km}^3\,{\rm yr}$$

$$\Xi_{\rm KM3NeT} = 42.1~{\rm km}^3\,{\rm yr}$$

$$\Xi_{\rm GVD} = 24.3~{\rm km}^3\,{\rm yr}$$

$$\Xi_{\rm P-ONE} = 31.6~{\rm km}^3\,{\rm yr}$$

Back-up slides

- **Alternative flavor composition choices** : We use only one canonical choice of the flavor ratio at source, $(1:2:0)_{\mathrm{S}}$. our methods are general and applicable also for other choices of flavor ratio at the source.

- **Energy dependence of the flavor composition :** Our analysis based on the estimated flavor composition at Earth, assuming it is energy independent. In principle, it can be energy dependent.

- **Computing neutrino propagation :** We compute the long-range matter potent-ial at the location where the neutrinos are detected, at IceCube. Potential can be calculated for each point of the propagating neutrinos along the trajectory.

- **Flavor-measurement capabilities of upcoming detectors :** Our forecasts for the upcoming neutrino telescopes assume the capabilities to measure the flavor composition will be similar to those of IceCube. This is a necessary assumpt-ion, given the absence of their realistic capabilities.