Probing Scalar Non-Standard Neutrino Interactions using High-Energy Astrophysical Neutrinos

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arXiv : 2606.25050

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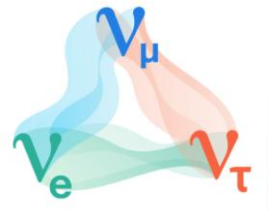
CETUP 2026

SM is not complete

- Oscillations require nonzero neutrino masses and mixing, absent in the minimal SM.
- The mechanism of neutrino mass generation remains unknown.



Neutrino Oscillations → Nonzero Neutrino mass → BSM Physics

https://neutrino.physics.iastate.edu/project/dune

- New physics in neutrino sector can give rise to non-standard interactions(NSI) of neutrinos.
- may be mediated by light vector/scalar particles
- Such interactions can leave observable imprints in neutrino production, propagation, and detection.

Massive Neutrinos

- **Dirac mass:** Can introduce right handed neutrino fields & generate Dirac masses via tiny yukawa couplings $y^D \bar{L}_L \tilde{\Phi} N_R$ $\tilde{\Phi} = i\tau_2 \Phi^*$

- **Majorana mass:** Add a scalar triplet which features a neutral scalar with small vev

$$y^L \overline{L_L^c} i\sigma^2 \Delta L_L$$

- **Dirac–Majorana neutrino mass term:** $y^L \overline{L_L^c} i\sigma^2 \Delta L_L + y^D \bar{L}_L \tilde{\Phi} N_R + y^R \overline{N_R^c} \Phi_s N_R$

$$M^{\mathrm{D+M}} \equiv \begin{pmatrix} M^L & M^{\mathrm{D}^T} \\ M^{\mathrm{D}} & M^R \end{pmatrix}$$

- Many of these mass-generation mechanisms, particularly those involving Higgs sector extensions, may also naturally give rise to novel neutrino scalar interactions.

Light Scalar NSI Models

- Can be realized in variety of models:

— Higgs Extended model with additional SU(2) doublet, singlet and a triplet

Yukawa term $\bar{l}'^{c}_{L_i}(y')_{ij} i\sigma_2 \Delta l'_{L_j}$ can give NSI of neutrinos .

generates a Majorana type interaction term $-\bar{\nu}'^{c}_{L_i} i\left(y'\right)_{ij} \nu'_{L_j} \rho_t$ ⇒ in mass basis $\bar{\nu}^{c} \nu \phi$

B.Dutta, S.Ghosh, T.Li, A.Thompson and A.Verma (JHEP 03 (2023) 163)

— Majoron model *(Babu–Rothstein–Seckel '93)*

— Effective-operator Approach *(Babu–Chauhan–Bhupal Dev '20)*:
Add a light real scalar singlet ϕ , Z_2 symmetry

$(i)\ \bar{\psi}_L \widetilde{H} \nu_R \frac{\phi}{\Lambda_\nu}$ $\quad (ii)\ \bar{\psi}_L H e_R \frac{\phi^2}{\Lambda_e^2}$ can be generated by adding new vector-like fermions to the SM

Scalar NSI

- Consider interactions between neutrinos and fermions present inside matter mediated by a light scalar

Dirac $\nu - \phi$ coupling | Dirac Mass

$$\mathcal{L} \supset \begin{matrix} -y_{\alpha\beta}\bar{\nu}_\alpha \phi \nu_\beta \\ \text{OR} \\ -\frac{y_{\alpha\beta}}{2}\overline{\nu^c_\alpha}\phi\nu_\beta \end{matrix} \quad \begin{matrix} -m_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \\ \text{OR} \\ -\frac{m_{\alpha\beta}}{2}\overline{\nu^c_\alpha}\nu_\beta \end{matrix} \quad -y_f \bar{f}\phi f - \frac{m_\phi^2}{2}\phi^2$$

Majorana $\nu - \phi$ coupling | Majorana Mass

— Can be probed at:

- **Scattering experiments** *JHEP 05 (2018) 066, JHEP 03 (2023) 163*
- **Long-baseline oscillations** *JHEP 07 (2024) 213, JHEP 06 (2024) 128*
- **Solar neutrinos** *JHEP 01 (2025) 097, Phys. Rev. D 101, 095029 (2020)*
- **Astrophysical Probes** *PRD 104 (2021) 123014, PLB 867 (2025) 139615, PRD 112 (2025) L101301*
- **Cosmology: BBN and CMB** *PRD 101 (2020) 095029, Eur.Phys.J.C 83 (2023) 8, 709*

Scalar NSI-Matter effects on the neutrino propagation

- Consider interactions between neutrinos and fermions present inside matter mediated by a light scalar.

$$\mathcal{L}_S = \bar{\nu}(i\gamma^\mu \partial_\mu - m_\nu)\nu - (y_\nu)_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi - y_f \bar{f} f \phi - \frac{1}{2}(\partial_\mu \phi)^2 - \frac{m_\phi^2}{2}\phi^2$$

- Scalar equation of motion:

$$(\partial^2 + m_\phi^2)\phi = (y_\nu)_{\alpha\beta}\overline{\nu_\alpha}\nu_\beta + y_f \bar{f} f$$

$$(\partial^2 + m_\phi^2)\langle\phi\rangle_{\text{med}} = (y_\nu)_{\alpha\beta}\langle\overline{\nu_\alpha}\nu_\beta\rangle + y_f \langle\bar{f} f\rangle$$

- Oscillation: forward, coherent scattering in-medium with zero momentum transfer

$$q^2 \simeq 0 \qquad \Rightarrow \langle\phi\rangle_{\text{med}} \simeq \frac{1}{m_\phi^2}\left[(y_\nu)_{\alpha\beta}\langle\overline{\nu_\alpha}\nu_\beta\rangle + y_f \langle\bar{f} f\rangle\right]$$

$$\langle\bar{f} f\rangle_{\text{med}} = \int \frac{d^3p}{(2\pi)^3}\frac{m_f}{E_p}\left[f_f(E_p) + f_{\bar{f}}(E_p)\right]$$

$$\langle\bar{f} f\rangle_{\text{med}} \simeq n_f + n_{\bar{f}} \quad \text{for nonrelativistic matter, } E_p \simeq m.$$

Scalar NSI-Matter effects on the neutrino propagation

Inserting the ϕ background value into the neutrino equation of motion

$$\left[i\gamma^{\mu}\partial_{\mu} - M_{\alpha\beta} - (y_{\nu})_{\alpha\beta}\langle\phi\rangle_{\text{med}}\right]\nu_{\beta} = 0$$

Smirnov, A.Y. and Xu, X.-J. (2019) , JHEP 12 (2019) 046

Ge, S.-F. and Parke, S.J. (2019) PRL, 122(21), p. 211801

Babu, K.S., Chauhan, G. and Dev, P.S.B. (2020) PRD, 101(9), p. 095029

$$M_{\alpha\beta} \rightarrow M_{\alpha\beta}^{\text{med}} = M_{\alpha\beta} + \delta M_{\alpha\beta} \qquad\qquad \delta M_{\alpha\beta} = (y_{\nu})_{\alpha\beta}\langle\phi\rangle_{\text{med}}$$

- The effect of SNSI on neutrino propagation is equivalent to changing the neutrino mass.
- Propagation Hamiltonian: $H_{\alpha\beta} = \frac{1}{2E_{\nu}}(\mathbb{M} + \delta\mathbb{M})^{\dagger}_{\alpha\beta}(\mathbb{M} + \delta\mathbb{M})_{\alpha\beta} + V_{\text{CC}}$

- In the presence of scalar NSI, the oscillation probabilities are sensitive to absolute mass scale of neutrinos $\mathbb{M}^{\dagger} \cdot \delta\mathbb{M}$

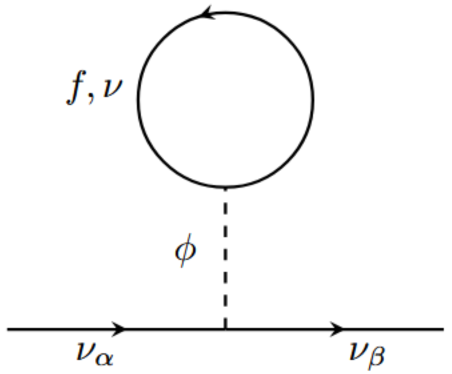
SNSI as an In-Medium Mass Insertion

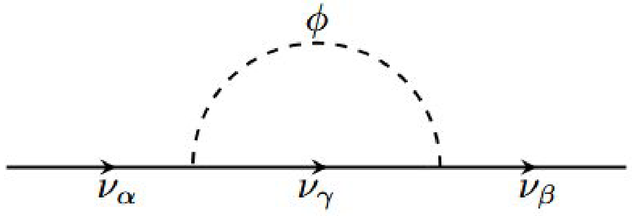
Diagrammatically, the background value of φ comes from the scalar one-point function

$$\Delta m_{\nu,\alpha\beta} = \frac{y_{\alpha\beta} y_f m_f}{\pi^2 m_\phi^2} \int_{m_f}^{\infty} dk_0 \sqrt{k_0^2 - m_f^2} \left[n_f(k_0) + n_{\bar{f}}(k_0) \right]$$

$$\Delta m_{\nu,\alpha\beta} = \begin{cases} \dfrac{y_f y_{\alpha\beta}}{m_\phi^2} \left(N_f + N_{\bar{f}}\right) & (\mu, T \ll m_f) \\ \dfrac{y_f y_{\alpha\beta}}{m_\phi^2} \dfrac{m_f}{2} \left(\dfrac{3}{\pi}\right)^{\frac{2}{3}} \left(N_f^{2/3} + N_{\bar{f}}^{2/3}\right) & (\mu > m_f \gg T) \\ \dfrac{y_f y_{\alpha\beta} m_f}{3\, m_\phi^2} \left(\dfrac{\pi^2}{12\,\zeta(3)}\right)^{\frac{2}{3}} \left(N_f^{2/3} + N_{\bar{f}}^{2/3}\right) & (\mu < m_f \ll T) \end{cases}$$

Neutrino self-energy diagrams





Babu, K.S., Chauhan, G. and Dev, P.S.B. (2020) Physical Review D, 101(9), p. 095029

Pseudo-Dirac framework from scalar NSI

$$\mathcal{L} \supset -M^D_{\alpha\beta}\bar{\nu}_{R\alpha}\nu_{L\beta} + y^D_{\alpha\beta}\phi\bar{\nu}_{R\alpha}\nu_{L\beta} + \frac{1}{2}y^M_{\alpha\beta}\phi\nu^T_{L\alpha}C\nu_{L\beta} - \frac{m^2_\phi}{2}\phi^2 + \text{H.c.}$$

$$(\Box + m^2_\phi)\phi = -\left[y^D_{\alpha\beta}\bar{\nu}_{R\alpha}\nu_{L\beta} + \frac{1}{2}y^M_{\alpha\beta}\nu^T_{L\alpha}C\nu_{L\beta} + \text{ H.c.}\right]$$

$$\langle\phi\rangle_{\text{bg}} \simeq -\frac{y^D_{\text{eff}}}{m^2_\phi}\langle\bar{\nu}_R\nu_L\rangle_{\text{C}\nu\text{B}} - \frac{y^M}{m^2_\phi}\cancelto{0}{\langle\nu^T_L C\nu_L\rangle_{\text{C}\nu\text{B}}} \qquad \langle\phi\rangle_{\text{bg}} \simeq -\frac{y^D_{\text{eff}}}{m^2_\phi}(n_\nu + n_{\bar{\nu}})$$

- The Dirac scalar interaction sources a scalar tadpole from the CvB through the Dirac bilinear, and the Majorana-type scalar interaction converts the resulting scalar expectation value into a small effective Majorana mass.

$$\delta M^L_{\alpha\beta} = y^M_{\alpha\beta}\langle\phi\rangle_{\text{bg}} \simeq -\frac{y^M_{\alpha\beta}y^D_{\text{eff}}}{m^2_\phi}(n_\nu + n_{\bar{\nu}}) \qquad \delta M^D_{\alpha\beta} = y^D_{\alpha\beta}\langle\phi\rangle_{\text{bg}} \simeq -\frac{y^D_{\alpha\beta}y^D_{\text{eff}}}{m^2_\phi}(n_\nu + n_{\bar{\nu}})$$

Pseudo-Dirac framework from scalar NSI

$$\mathcal{M}_{\text{eff}} = \begin{pmatrix} \delta M^L & M^D + \delta M^D \\ (M^D + \delta M^D)^T & 0 \end{pmatrix}$$

$$|\delta M^L|, |\delta M^D| \ll |M^D|$$

$$\delta M^L_{\alpha\beta} = y^M_{\alpha\beta} \langle \phi \rangle_{\text{bg}} \simeq -\frac{y^M_{\alpha\beta} y^D_{\text{eff}}}{m^2_\phi} (n_\nu + n_{\bar{\nu}})$$

$$\delta M^D_{\alpha\beta} = y^D_{\alpha\beta} \langle \phi \rangle_{\text{bg}} \simeq -\frac{y^D_{\alpha\beta} y^D_{\text{eff}}}{m^2_\phi} (n_\nu + n_{\bar{\nu}})$$

$$n_\nu(z) = n_{\nu,0}(1+z)^3 \text{ with } n_{\nu,0} \simeq 56 \text{ cm}^{-3}$$

- SNSI can induce a small active-sterile mass splitting via a Majorana-type interaction due to the matter effect from relic neutrinos. This framework leads to pseudo-Dirac behavior of neutrinos during propagation, introducing rich phenomenology in neutrino oscillations, particularly for high-energy astrophysical neutrinos.

$$m_{i+} \simeq m_i + \frac{\delta m_i}{2}, \quad m_{i-} \simeq m_i - \frac{\delta m_i}{2}$$

pseudo-Dirac splitting of the i-th pair

$$\delta m_i \equiv \left(U_L^T \delta M^L U_L\right)_{ii}$$

$$m^2_{i+} = m^2_i + \delta\left(m^2_i\right)/2 = m^2_i + m_i\,|\delta m_i|$$
$$m^2_{i-} = m^2_i - \delta\left(m^2_i\right)/2 = m^2_i - m_i\,|\delta m_i|$$

Pseudo-Dirac oscillations in the presence of SNSI matter effects

- In the scalar-NSI framework, the matter potential generated by the relic neutrino background induces a tiny active–sterile mass splitting that modifies the standard oscillation pattern of astro-physical neutrinos.

$$P_{\alpha\beta}^{\rm SNSI} = \frac{1}{2}\sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \left[1 + \cos\left(\frac{2m_j\,|\delta m_j| L_{\rm eff}}{4E_\nu}\right)\right]$$

$$L_{\rm eff} = \int \frac{dz}{H(z)(1+z)^2}$$

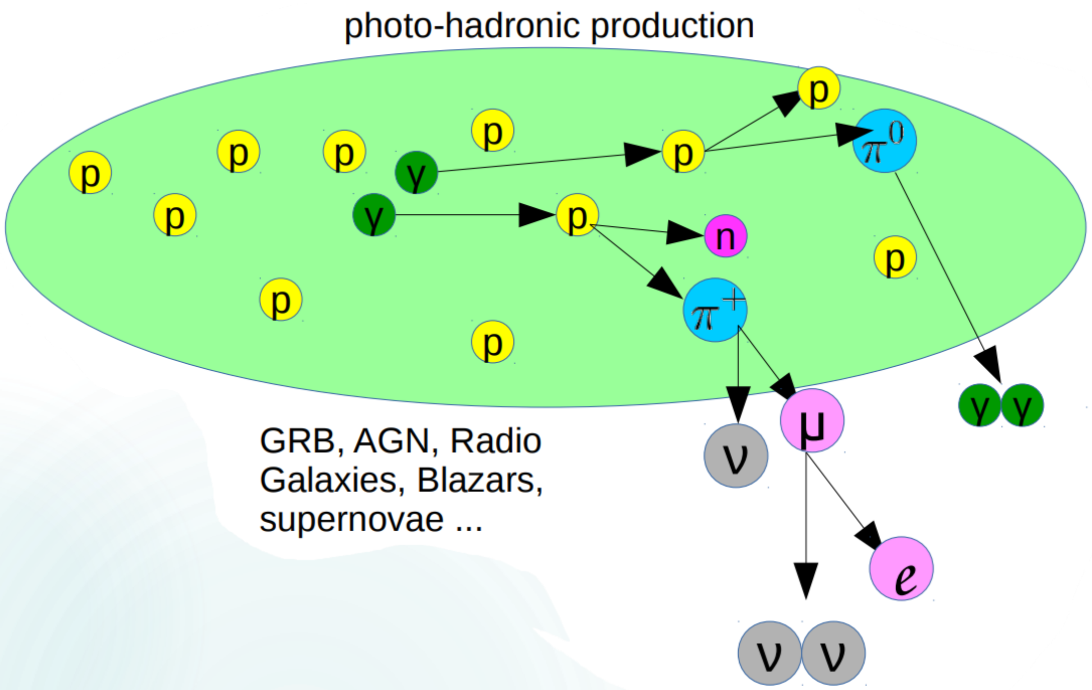
(Dev, Machado and Martinez-Soler, 2024)
(Carloni et al., 2024)
See also C. S. Fong talk on Cosmological Constraints on Pseudo-Dirac ν

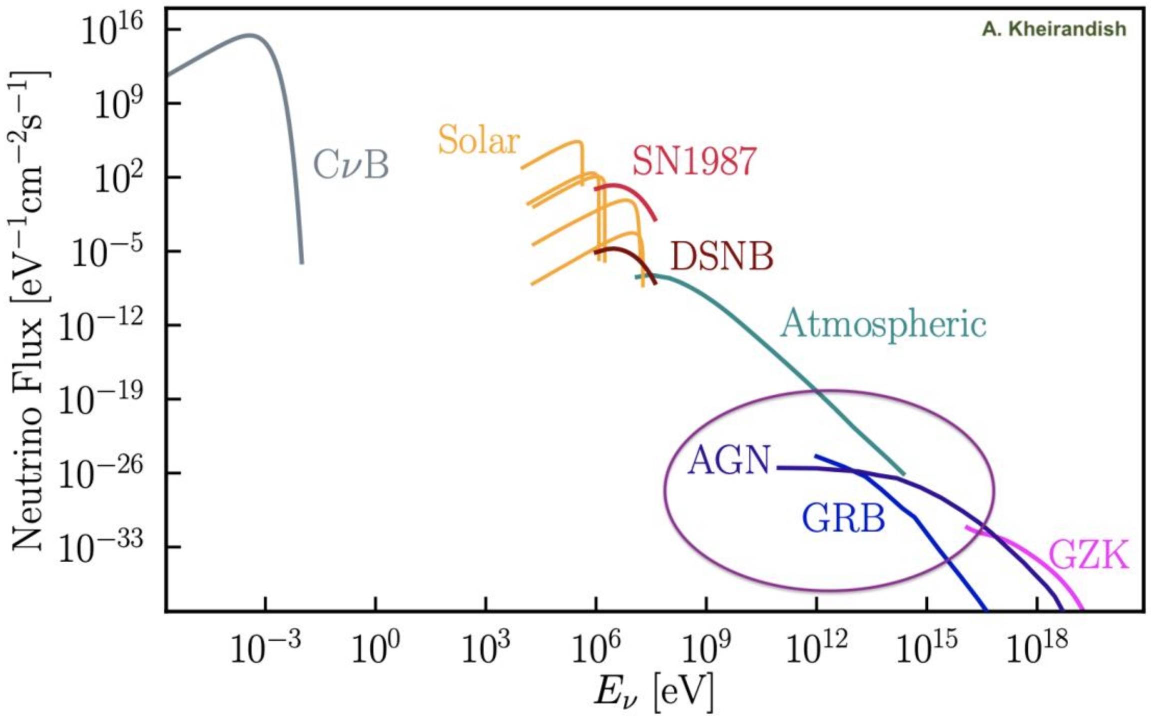
- The effective active-sterile oscillation length scale in the presence of matter is

$$L_{\rm osc}^{(j)} \simeq \frac{2\pi E_\nu}{m_j |U_{\alpha j}|^2\,|\delta M_{\alpha\alpha}|} \approx 80{\rm Mpc}\left(\frac{E_\nu}{1{\rm TeV}}\right)\left(\frac{0.01{\rm eV}}{m_j}\right)\left(\frac{10^{-16}{\rm eV}}{|\delta M_{\alpha\alpha}|}\right)\left(\frac{0.5}{|U_{\alpha j}|^2}\right)$$

$$L_{\rm coh}^{(j)} = \frac{2\sqrt{2}E_\nu^2}{m_j\left|\left(U_L^T \delta M^L U_L\right)_{jj}\right|}\sigma_x \approx 10^7{\rm Gpc}\left(\frac{E_\nu}{1{\rm TeV}}\right)^2\left(\frac{0.01{\rm eV}}{m_j}\right)\left(\frac{10^{-16}{\rm eV}}{|\delta M_{\alpha\alpha}|}\right)\left(\frac{0.5}{|U_{\alpha j}|^2}\right)\left(\frac{\sigma_x}{10^{-10}\ {\rm m}}\right).$$

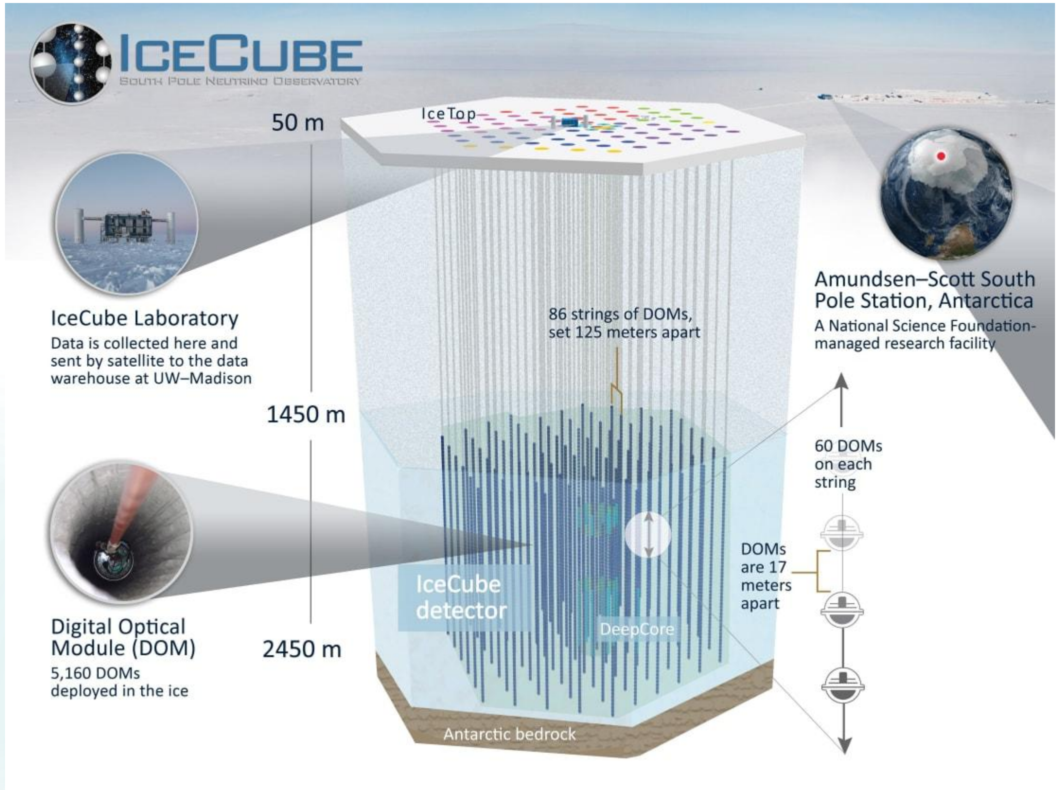
Neutrinos from Astrophysical sources





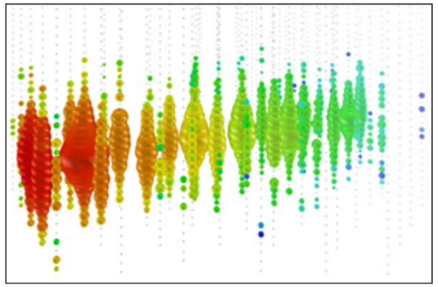
- typical distance ($\gtrsim$ Mpc) to the extragalactic astrophysical sources.
- origins of these astrophysical neutrinos remain largely unknown
- High energy in the range TeV–PeV
- Power law $[\phi_\nu(E) = \phi_0 E^{-\gamma}]$

High Energy neutrino signals at Icecube

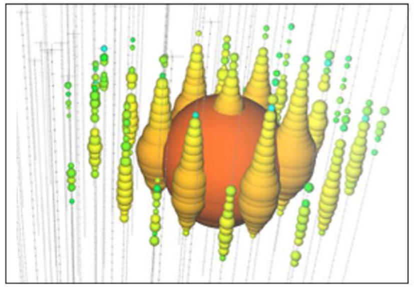


IceCube-Gen2 Collaboration • M.G. Aartsenet al. J.Phys.G 48 (2021) 6, 060501

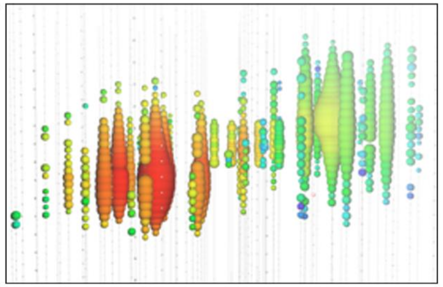
IceCube detects three types of neutrino-induced events:



Tracks: CC ν_μ



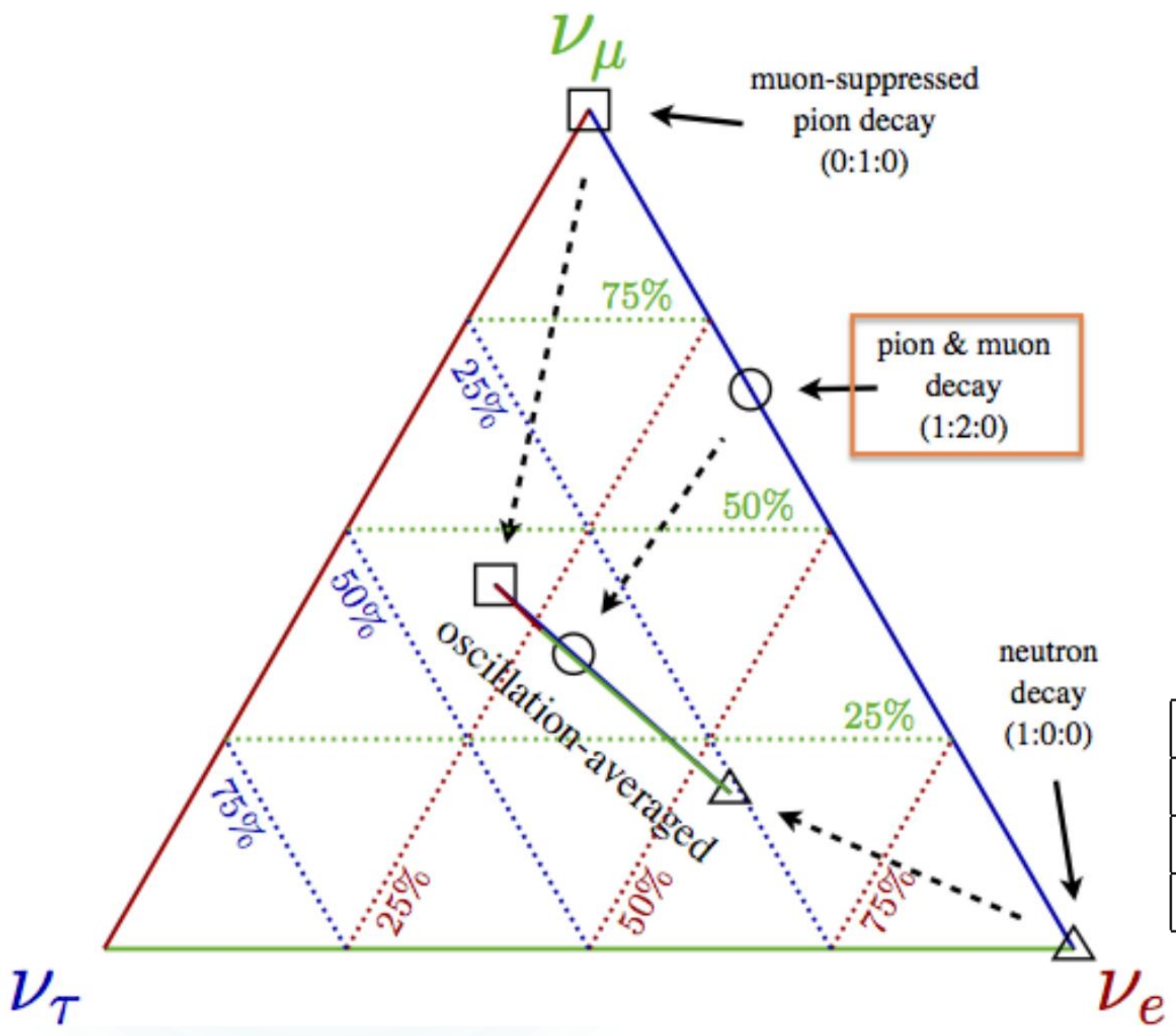
Cascades:
CC ν_e, ν_τ
NC: all



Double Cascades:
CC ν_τ

Showers: Good energy resolution, but poor angular resolution
Tracks: Excellent angular resolution, but modest energy resolution
Track events are ideal for astrophysical source identification but insensitive to the full neutrino flavor information.

Standard flavor ratios



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

$$(f_e^S, f_\mu^S, f_\tau^S) \longrightarrow f_\beta^\oplus = \sum_{\alpha=e,\mu,\tau} P^{\rm VO}_{\alpha\beta} f_\alpha^S$$

(At the source S) (At Earth)

Vacuum Oscillations (NO)	
π-decay	$(1/3, 2/3, 0)_S \to (0.30, 0.37, 0.33)_\oplus$
μ-damped	$(0, 1, 0)_S \to (0.17, 0.47, 0.36)_\oplus$
n-decay	$(1, 0, 0)_S \to (0.55, 0.17, 0.28)_\oplus$

Strategy

- determine whether light-scalar non-standard interactions (SNSI) can imprint the TeV-PeV neutrino sky with the characteristic hallmarks of pseudo-Dirac oscillations, namely, energy-dependent spectral modulations and coherent shifts in the flavor composition at Earth.
  - Diffuse Flux- Flavor analysis
  - Diffuse Flux- Spectral analysis (from CASCADE and ESTES (tracks) dataset)
  - Point Source- Spectral analysis (for the most significant sources identified by IceCube)

- For our analysis we assume that the neutrino flux is generated solely through the canonical charged-pion decay chain with the source flavor ratio $(1{:}\,2{:}\,0)_S$
- Standard oscillation best-fit values from NufiT 6.0. and lightest neutrino mass = 0.01eV

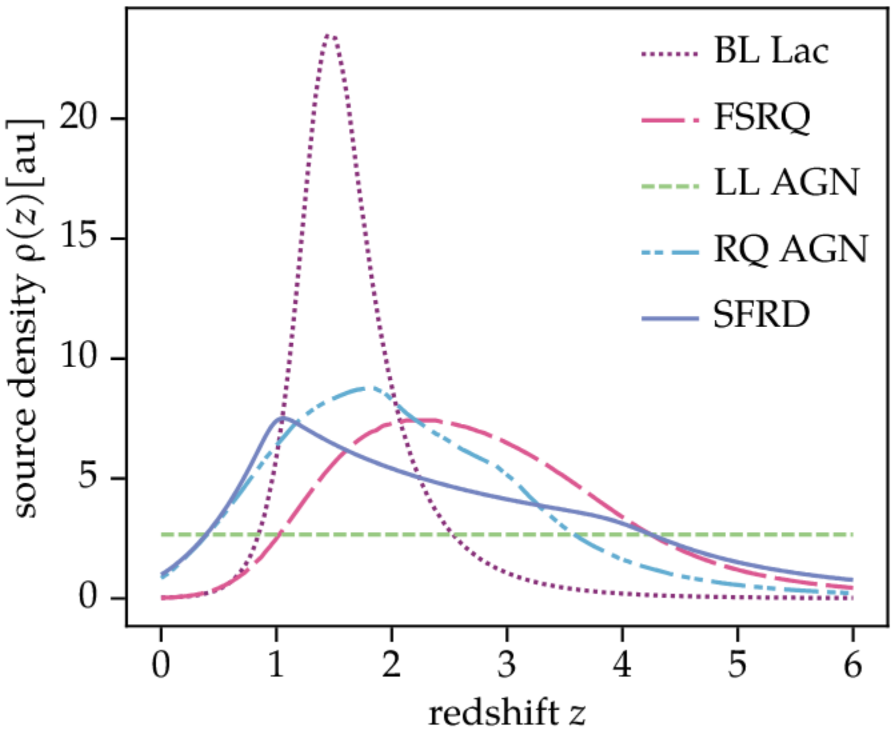
Diffuse neutrino Flux

- The diffuse flux of neutrinos observed on Earth is the sum of contributions from sources located at different cosmological distances and time scales.

$$\frac{dN(z)}{dz} = \frac{dN(z)}{dV}\frac{dV}{dz} \propto \rho_s(z) \times 4\pi r(z)^2 \frac{dr(z)}{dz}$$

$$r(z) = \int_0^z \frac{dz'}{H(z')} \text{ is the comoving distance}$$

Carloni, K. et al. (2025), arXiv:2503.19960



- account the distribution of the sources for several physically motivated source evolution templates, corresponding to BL Lacs, flat-spectrum radio quasars (FSRQ), star-formation rate density (SFRD), low-luminosity AGN (LLAGN), and radio-quiet AGN (RQAGN)

i) Diffuse Flux - Flavor analysis

- We can use the flavor modifications of astrophysical neutrinos as a probe of scalar NSI, comparing with the existing flavor ratio constraints from IceCube and with projections for next-generation neutrino telescopes like IceCube-Gen2.

- The expected neutrino flux of flavor β from the diffused source is

$$\left\langle \phi_\beta^\oplus \right\rangle \propto \sum_{\alpha=e,\mu,\tau} \int_{E_{\min}}^{E_{\max}} dE \int_{z_{\min}}^{z_{\max}} dz P_{\alpha\beta}^{\mathrm{SNSI}}(E,z) f_\alpha^s \frac{\rho_s(z)}{H(z)} \frac{d\phi_\nu}{dE}(E(1+z))$$

where, Hubble parameter $H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}$ $\quad H_0 = 67.4 \text{ km s}^{-1}\text{Mpc}^{-1}$

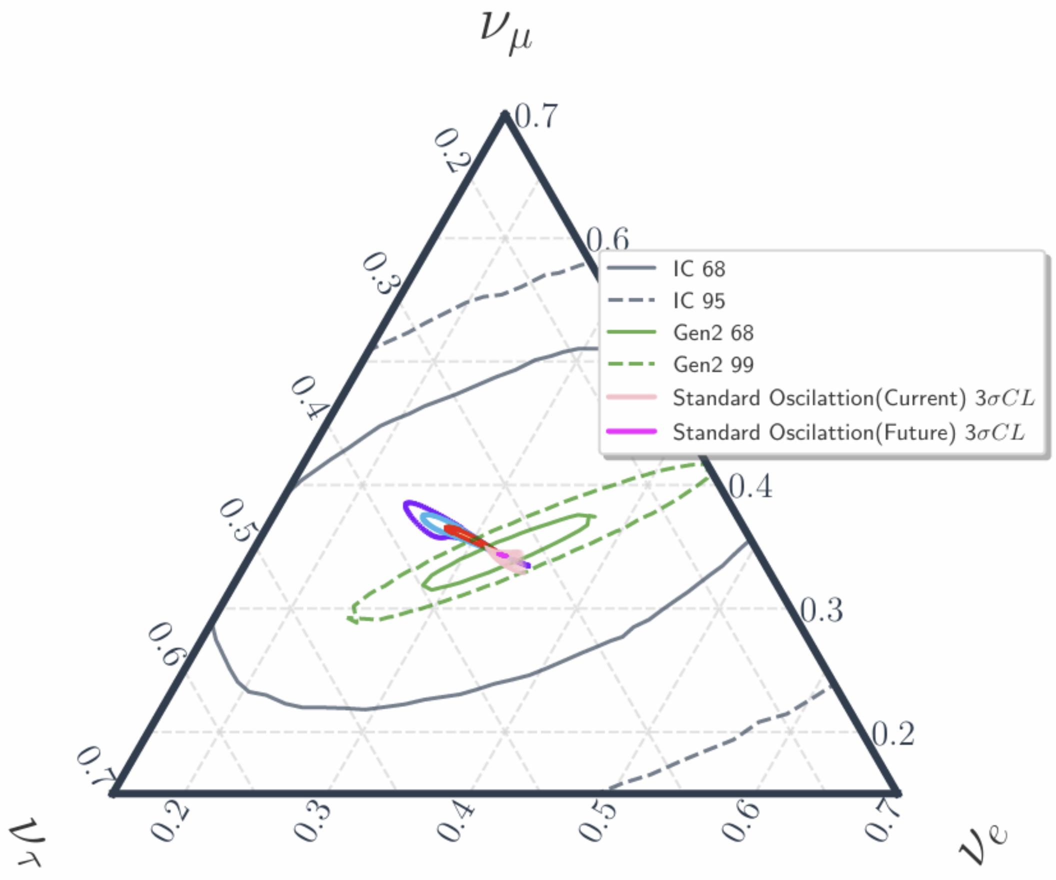
➢ Flavor ratios at earth : $\langle f_\alpha^\oplus \rangle \approx \dfrac{\langle \phi_\alpha^\oplus \rangle}{\sum_{\beta=e,\mu,\tau} \langle \phi_\beta^\oplus \rangle}$

$\left[\phi_\nu(E) = \phi_0 E^{-\gamma}\right]$

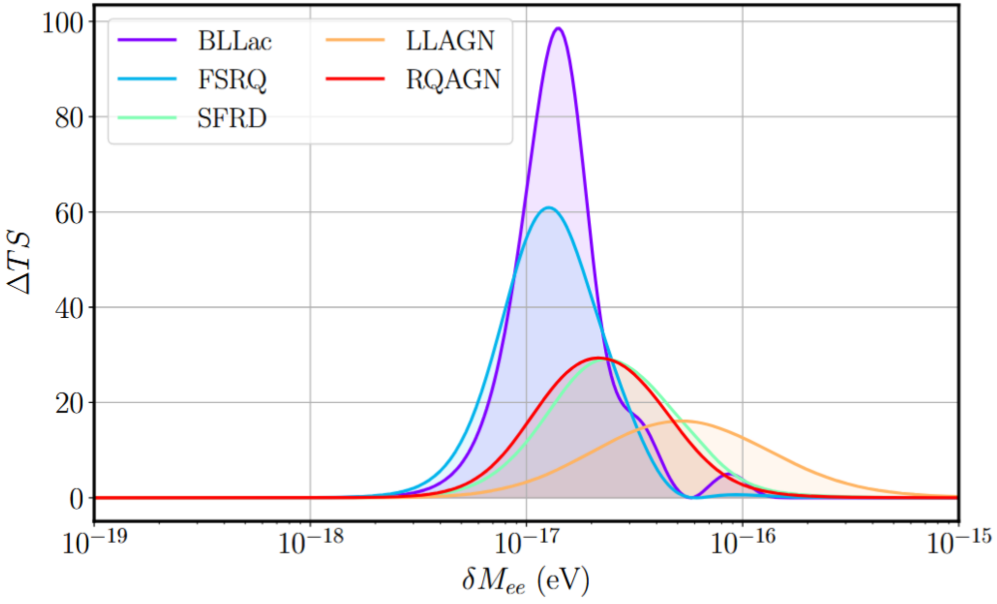
spectral index $\gamma = 2.5$

i) Diffuse Flux - Flavor analysis

δM_{ee}, Energy averaged, Diffused flux



IC-Gen2



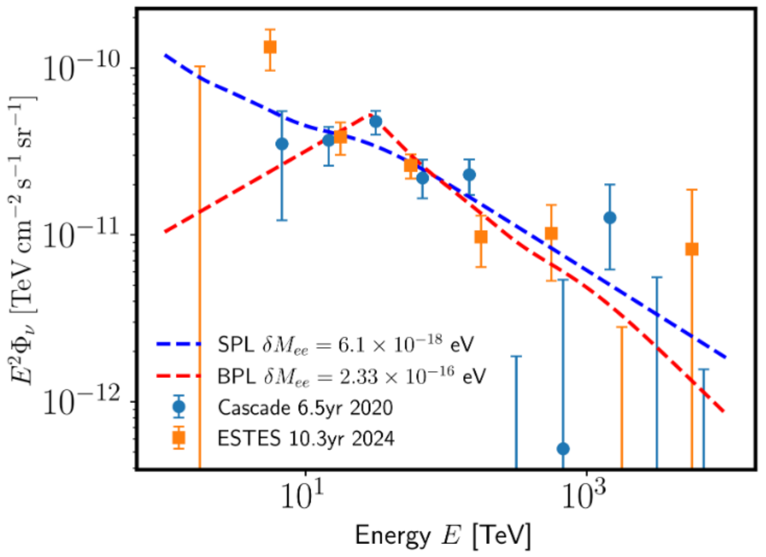
ii) Diffuse Flux - Shape analysis

- Two statistically independent IceCube datasets that probe distinct event topologies
  - **CASCADE** — electromagnetic and hadronic showers accumulated over 6.5 yr 10.1103/PhysRevLett.125.121104
  - **ESTES** - "starting" muon tracks (ν_μ CC interactions with vertices inside the instrumented volume) collected over 10.3 yr (Abbasi et al. 2024)
- Flavour-dependent neutrino flux that reaches Earth at an observed energy E :

$$\phi_\beta^\oplus(E) = \sum_{\alpha=e,\mu,\tau} \int_{z_{\min}}^{z_{\max}} dz P_{\alpha\beta}^{SNSI}(E,z) f_\alpha^S \frac{\rho_{src}(z)}{H(z)} \phi_\nu(E(1+z))$$

Model prediction: $$\mu_i^S(\tilde{\boldsymbol{\theta}}) = \Delta T^S \int_{E_i}^{E_{i+1}} dE \sum_\alpha \phi_\alpha^\oplus(E \mid \tilde{\boldsymbol{\theta}}) A_\alpha^S(E)$$

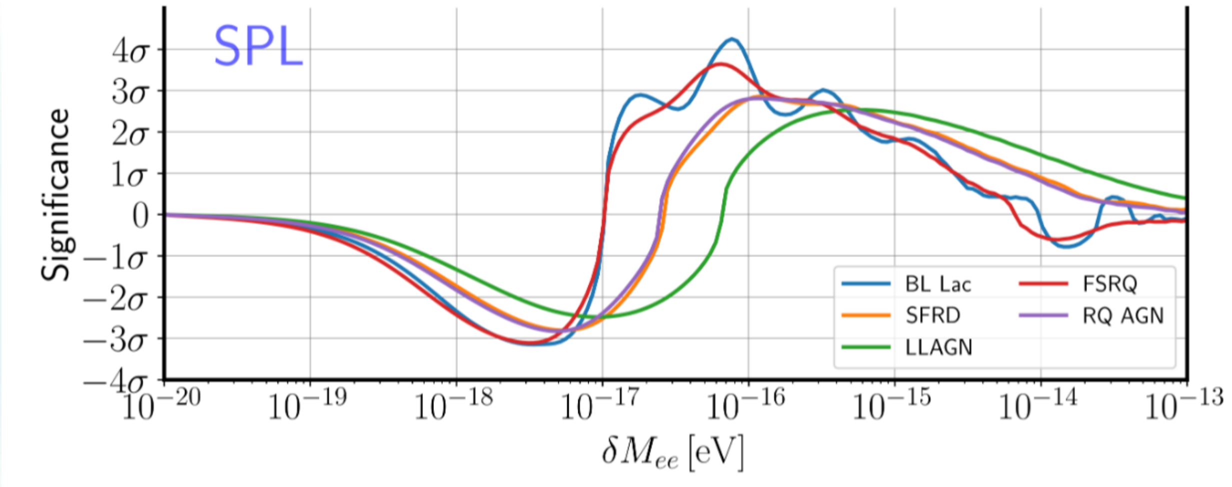
flux nuisance parameters $\tilde{\boldsymbol{\theta}}$

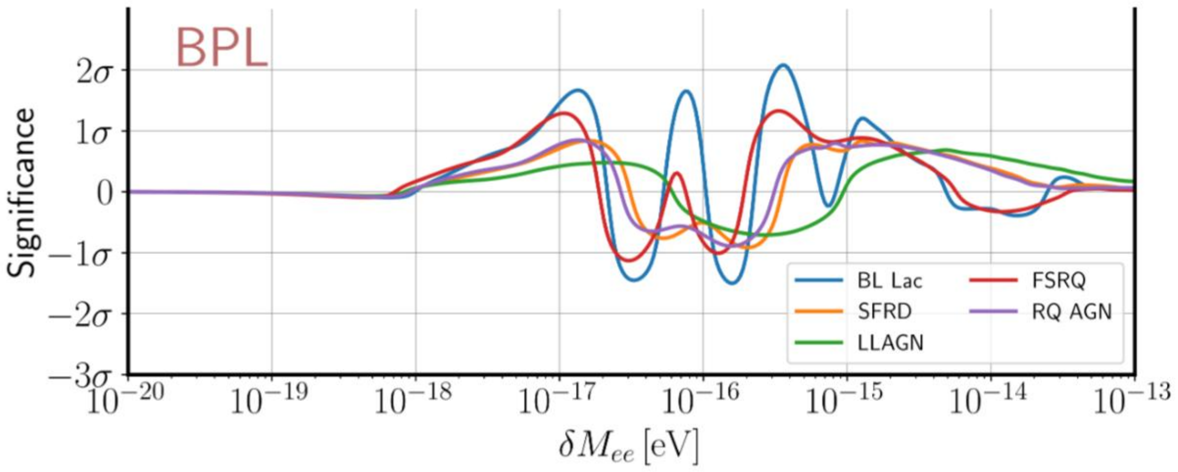


ii) Diffuse Flux - Shape analysis

$$\mathrm{TS}(\delta M) = \min_{\tilde{\boldsymbol{\theta}}} \sum_i \left[-2 \log \mathcal{L}_i \left(N_i^S \mid \mu_i^S(\delta M; \tilde{\boldsymbol{\theta}}) \right) \right]$$

$$\Delta\,\mathrm{TS}(\delta M) \equiv \mathrm{TS}(\delta M) - \mathrm{TS}(0)$$





iii) Point Source - Shape analysis

- Most significant sources from IceCube's combined 14-year track and 10-year cascade sample

	Source Name	Class	Redshift z	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{\text{local, combined}})$
1	NGC 1068	SBG	0.003793	-0.01	92.32	3.14	5.902
2	PKS 1424+240	BLL	0.6010	23.8	75.79	3.50	3.534
3	PMN J1650-5044	BLL	(unknown)	-50.75	88.46	2.93	2.856
4	GB6 J1542+6129	BLL	0.507	61.5	50.79	3.34	2.709
5	TXS 0506+056	BLL	0.3365	5.7	9.67	0.87	2.663
6	G343.1-2.3	PWN	Galactic	-44.3	77.60	2.92	2.085
7	PMN J1603-4904	BLL	0.2321	-49.06	84.59	3.10	2.046
8	MGRO J2019+37	GAL	Galactic	36.8	43.35	2.99	2.000

Galactic and extragalactic point sources probe a broad range of baselines from few kpc to Gpc and are therefore sensitive to complementary ranges of δm_i^2

iii) Point Source - Shape analysis

- Expected number of events in reconstructed-energy bin i from a source s:

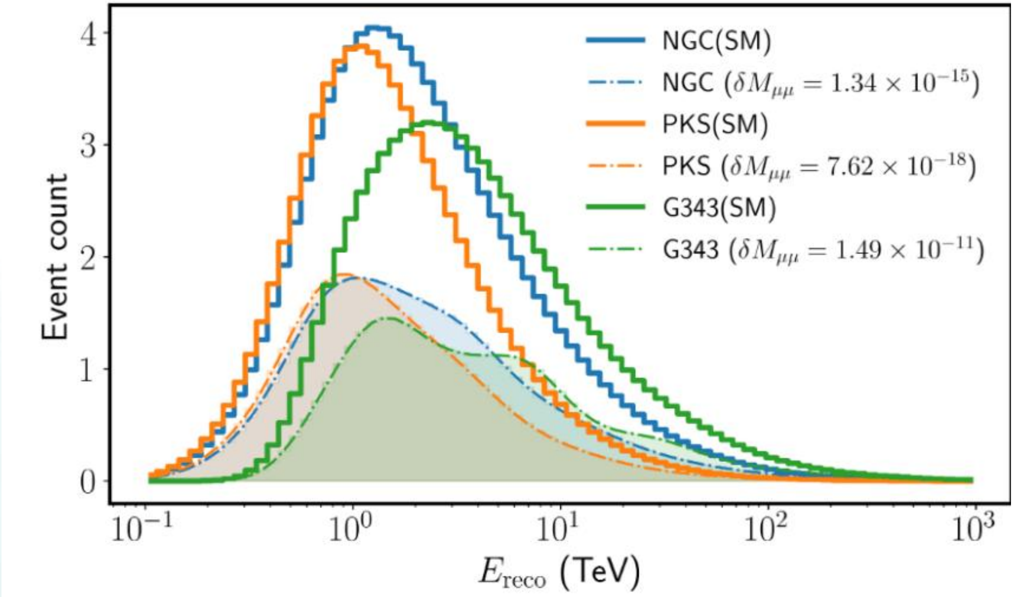
$$\mu_{i,s}^{t}(\delta M) = \Delta T_t \sum_{\alpha,\beta=e,\mu,\tau} \int dE_{\rm true}\, \Phi_\alpha^s\,(E_{\rm true}\,) P_{\alpha\beta}^{\rm SNSI}\,(E_{\rm true}\,, z_s) A^t\,(E_{\rm true}\,) \mathcal{M}_i^t\,(E_{\rm true}\,)$$

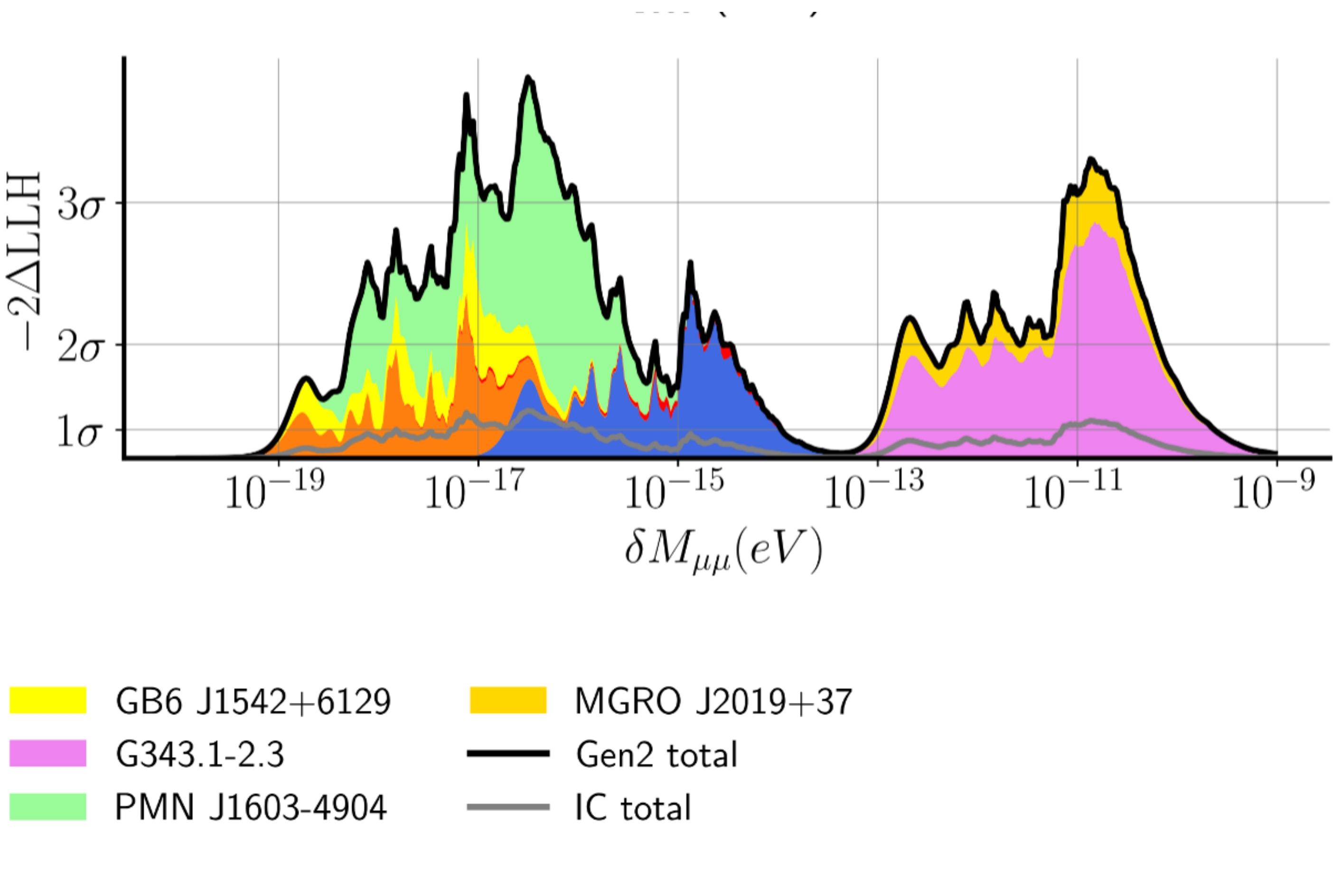
$t \in \{\ \text{track}\ ,\ \ \text{cascade}\ \}$ $\quad \Delta T_t = \text{live-time} \quad A^t(E) = \text{Effective Area}$

$$-2\ln\mathcal{L}_s(\delta M) = \min_{\Phi_0,\gamma} \sum_{t\in\{\ \text{track,cascade}\ \}} \sum_i 2\left[\mu_{i,s}^t(\delta M) - N_{i,s}^t + N_{i,s}^t \ln\left(\frac{N_{i,s}^t}{\mu_{i,s}^t(\delta M)}\right)\right]$$

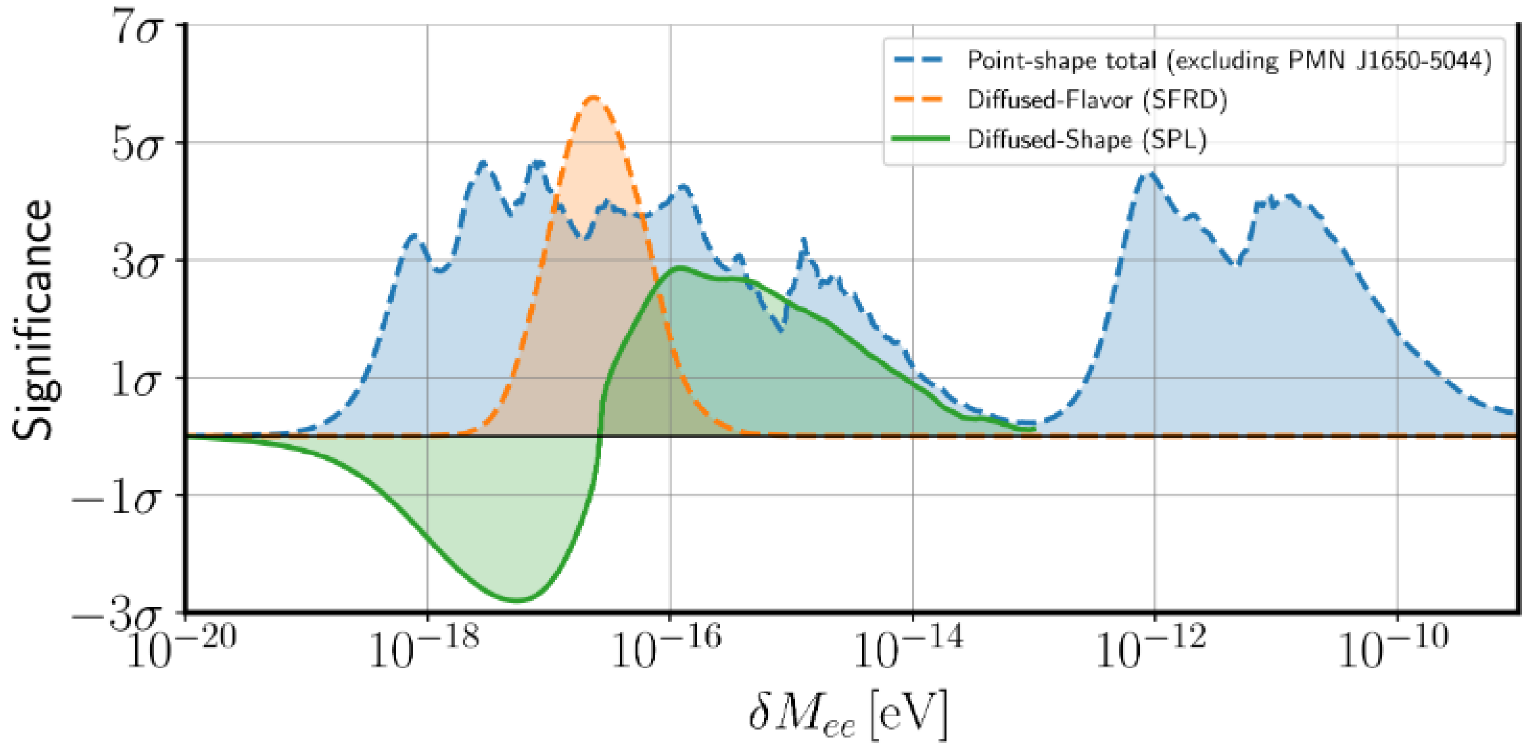
(we again treat the flux normalization and spectral index as nuisance parameters)

iii) Point Source - Shape analysis

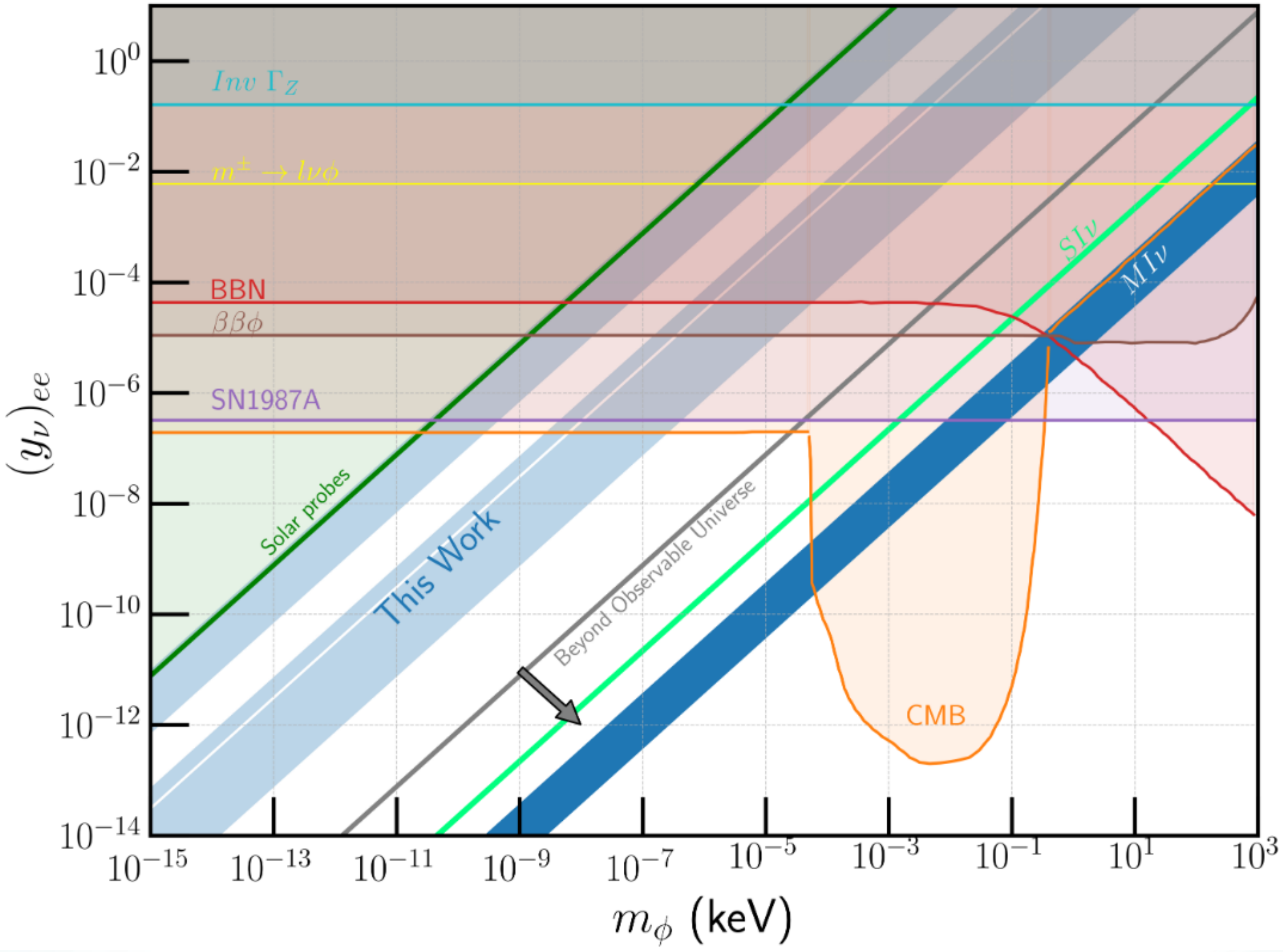




Combined Sensitivities



Sensitivity plots



Revisiting BBN/SN in-medium mass bounds

- In the relativistic limit, $T \gg m_\nu$,

$$\Delta m_{\nu,\alpha\beta} = \frac{y_f y_{\alpha\beta} m_\nu}{3m_\phi^2} \left(\frac{\pi^2}{12\zeta(3)}\right)^{\frac{2}{3}} \left(n_\nu^{2/3} + n_{\bar{\nu}}^{2/3}\right)$$

(uses vacuum scalar propagator)

- in a finite density or finite-temperature medium, the scalar propagator must also be dressed

$$\frac{1}{q^2 - m_\phi^2} \to \frac{1}{q^2 - m_\phi^2 - \Pi_\phi\left(q_0, \mathbf{q}; T, \mu\right)}$$

$$m_\phi^2 \to m_{\phi,\mathrm{eff}}^2 \simeq m_\phi^2 + \Delta m_\phi^2, \quad \Delta m_\phi^2 \equiv \Pi_\phi(0, \mathbf{q} \to 0; T, \mu)$$

$$\Delta m_\phi^2\left(T, N_\nu\right) = \frac{y_\nu^2}{3} \left(\frac{\pi^2}{12\zeta(3)}\right)^{\frac{2}{3}} \left(n_\nu^{2/3} + n_{\bar{\nu}}^{2/3}\right)$$

Revisiting BBN/SN in-medium mass bounds

- in-medium neutrino mass correction including the dressed scalar propagator

$$\Delta m_\nu = \frac{y_\nu^2 m_\nu}{3\left(m_\phi^2 + \Delta m_\phi^2\right)} \mathcal{N}_\nu = m_\nu \frac{\frac{y_\nu^2}{3}\mathcal{N}_\nu}{\left(m_\phi^2 + \frac{y_\nu^2}{3}\mathcal{N}_\nu\right)} \qquad \mathcal{N}_\nu \equiv \left(\frac{\pi^2}{12\zeta(3)}\right)^{2/3} \left(n_\nu^{2/3} + n_{\bar{\nu}}^{2/3}\right)$$

$$\Delta m_\nu \leq m_\nu$$

- the induced correction saturates at a value of order the vacuum neutrino mass in a high density environment such as Supernova or at the time of BBN.

  Consequently, the MeV-scale medium-induced mass corrections required for the BBN and supernova bounds are not obtained in the neutrino-only coupling scenario once the scalar propagator is consistently dressed.

Conclusion

- Scalar NSI can generate **environment-dependent neutrino mass corrections**, modifying the effective propagation Hamiltonian.
- As high-energy astrophysical neutrinos propagate through the **CvB background**, scalar NSI can induce tiny pseudo-Dirac-like splittings modifying the predicted **flavor ratios** and **energy spectra** at Earth
- Using **IceCube flavor, diffuse-spectrum, and point-source data**, astrophysical neutrinos can provide complementary probe of the **ultra-light scalar NSI parameter space.** Future neutrino telescopes can improve sensitivity to CvB-induced hidden scalar interactions.