# Hidden Forces in Neutrino Oscillations:

## Probing New Long- and Short-Range Interactions

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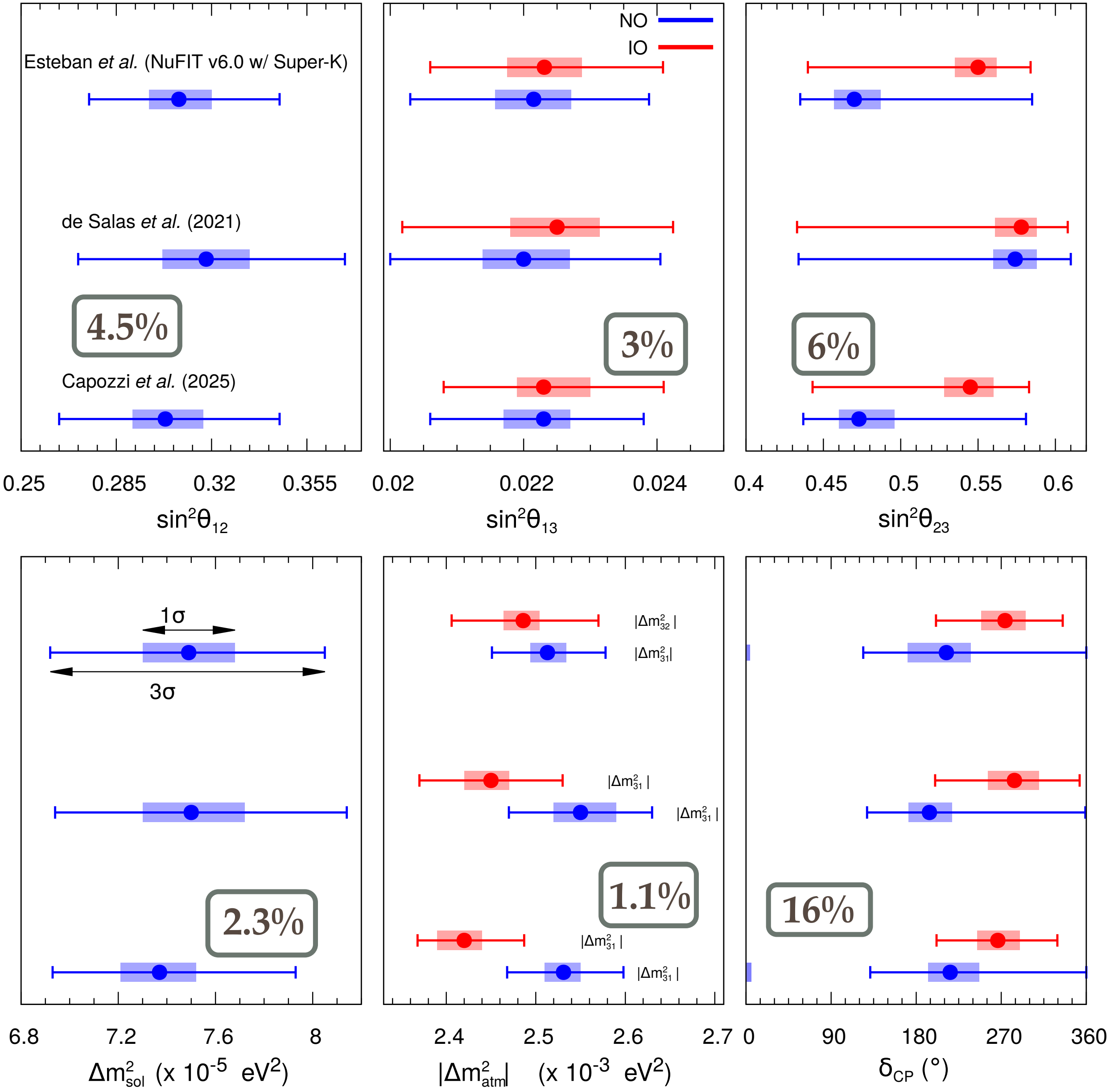
# *Remarkable Precision on Neutrino Oscillation Parameters*

**Robust three-flavor neutrino oscillation paradigm**



**Huge boost to search for BSM physics at ν expts**

**Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206**

# Probing BSM Scenarios Across 18 orders in E and 25 orders in L

## Non-zero neutrino mass: first experimental proof (gateway) for BSM physics

**Several BSM possibilities can be introduced in the framework of Effective Field Theory (EFT)**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \cdots$$

**d=5 Weinberg Operator: LLHH, Λ: New Physics Scale**
**S. Weinberg, PRL 43 (1979) 1566**

**BSM Scenarios naturally arise due to different mechanisms for generating ν masses (e.g., seesaw)**

Many models of BSM physics suggest new fundamental particles and interactions, new sources of CP violation, lepton number and lepton flavor violations, possibilities of Lorentz and CPT violation

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**Probe BSM Physics at High Energies (TeV-PeV)**

High-Energy (TeV-PeV) Astrophysical Neutrinos coming from cosmic distances (Mpc-Gpc)

Giant Neutrino Telescopes: IceCube@South Pole, KM3NeT@Mediterranean Sea, future IceCube-Gen2

Novel Approach --
New Physics beyond the reach of modern Colliders

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### Probe BSM Physics at Low Energies (MeV-GeV)

Low-Energy (MeV-GeV) Accelerator & Atmospheric **ν**s travelling terrestrial distances (few m - 1000s of km)

Accelerator: NOvA, DUNE@USA, T2K, HK@Japan
Atmospheric: Super-K, DeepCore, DUNE, Hyper-K

Expected to measure oscillation parameters with a precision around a few % -- sensitive to sub-leading BSM physics at low energies

Complement BSM search @ High-Energy Colliders

# Landscape of BSM Scenarios affecting Neutrino Experiments

DM-ν interaction

DE-ν interaction

Lorentz+CPT violation

Neutrino decay

Heavy relics

Long-range interactions

DM annihilation

Secret νν interactions

Supersymmetry

DM decay

Sterile ν

Effective operators

Leptoquarks

Boosted DM

NSI

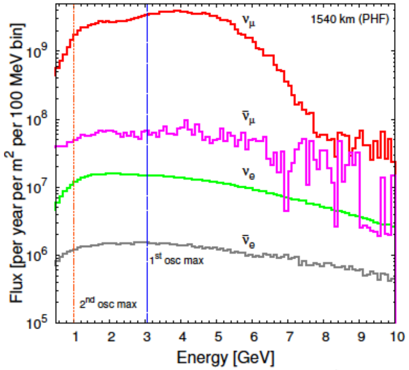
Extra dimensions

Superluminal ν

Monopoles

# Landscape of BSM Scenarios affecting Neutrino Experiments

Alters neutrino flux



Agarwalla et al., JHEP 05 (2012) 154

Acts at production

- Heavy relics
- DM annihilation
- DM decay
- Sterile ν
- Boosted DM
- NSI

- DM-ν interaction
- DE-ν interaction
- Lorentz+CPT violation
- Neutrino decay
- Long-range interactions
- Secret νν interactions
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- Leptoquarks
- Extra dimensions
- Superluminal ν
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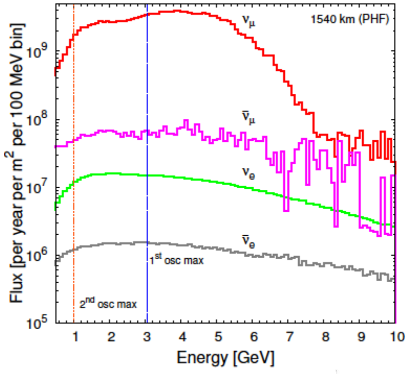
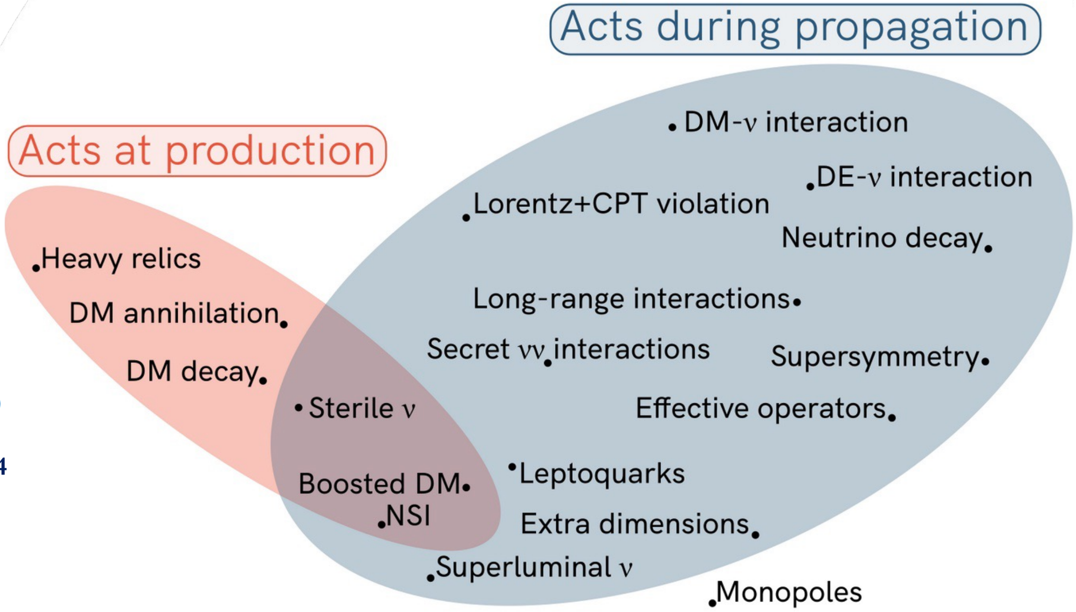
# *Landscape of BSM Scenarios affecting Neutrino Experiments*

Alters neutrino flux, oscillation, mixing

Alters neutrino flux



**Agarwalla et al., JHEP 05 (2012) 154**



Acts at production

Acts during propagation

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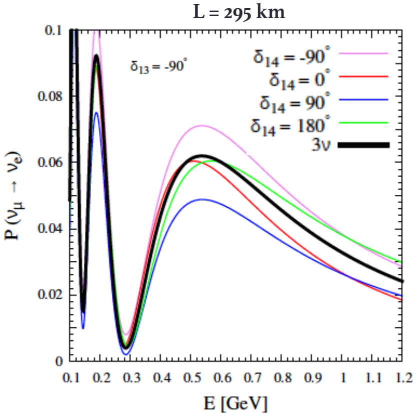
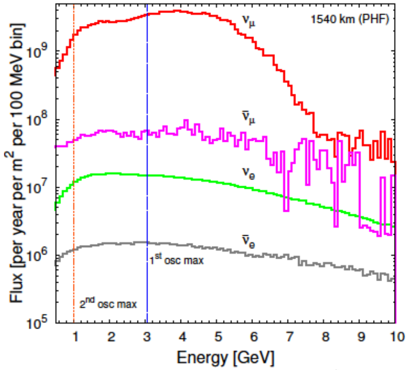


**Agarwalla et al., JHEP 02 (2016) 111**

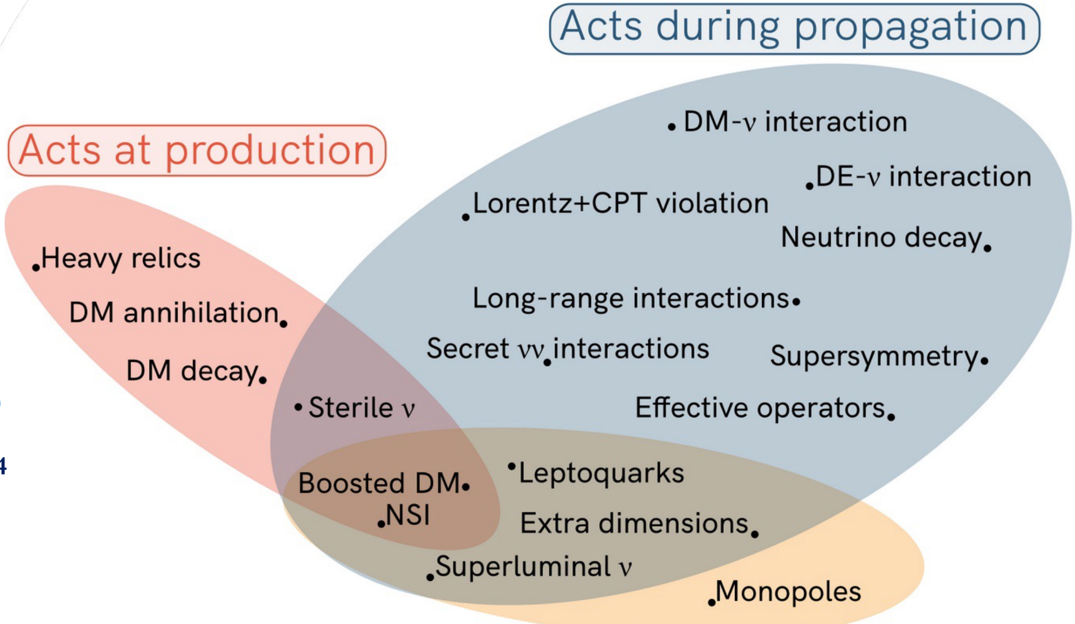
# *Landscape of BSM Scenarios affecting Neutrino Experiments*

Alters neutrino flux, oscillation, mixing

Alters neutrino flux



**Agarwalla et al., JHEP 05 (2012) 154**



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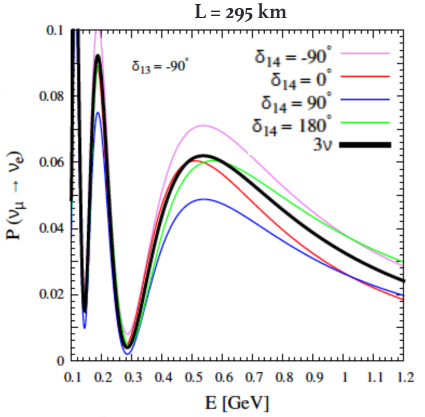

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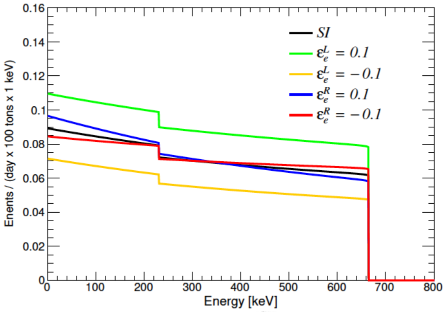


**Agarwalla et al., JHEP 02 (2020) 038**

Acts at detection

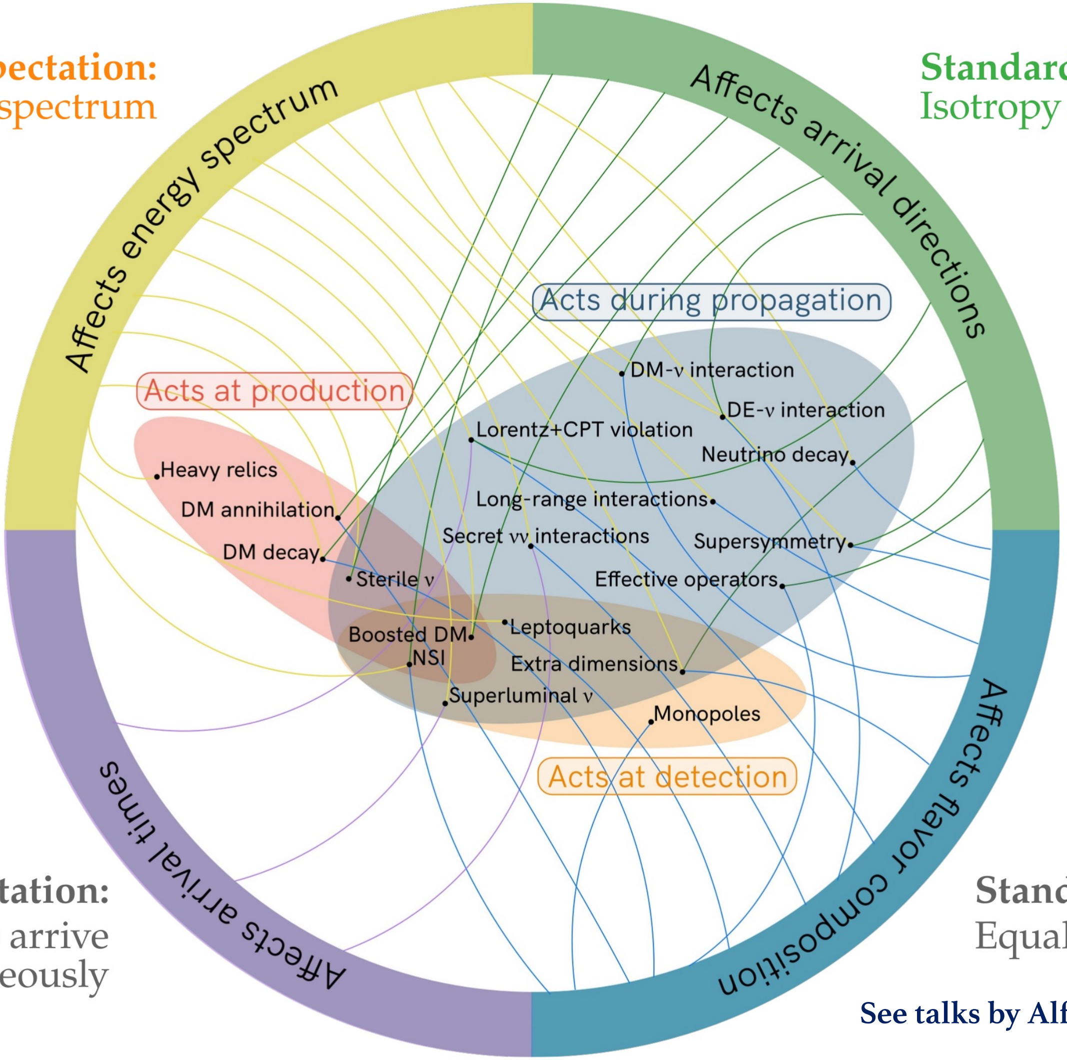
Alters neutrino detection cross sections

# Novel Connections between Observables and BSM Scenarios in IceCube

**A new multi-dimensional approach → four key observables of astrophysical neutrinos**

**Standard expectation:**
Power-law energy spectrum

**Standard expectation:**
Isotropy (for diffuse flux)



**Arguelles,**
**Bustamante,**
**Kheirandish,**
**Palomares-Ruiz,**
**Salvado, Vincent,**
***PoS* ICRC2019 (2020) 849**

**For applications, see:**
**Song, Li, Arguelles,**
**Bustamante, Vincent,**
**arXiv: 2012.12893 [hep-ph]**

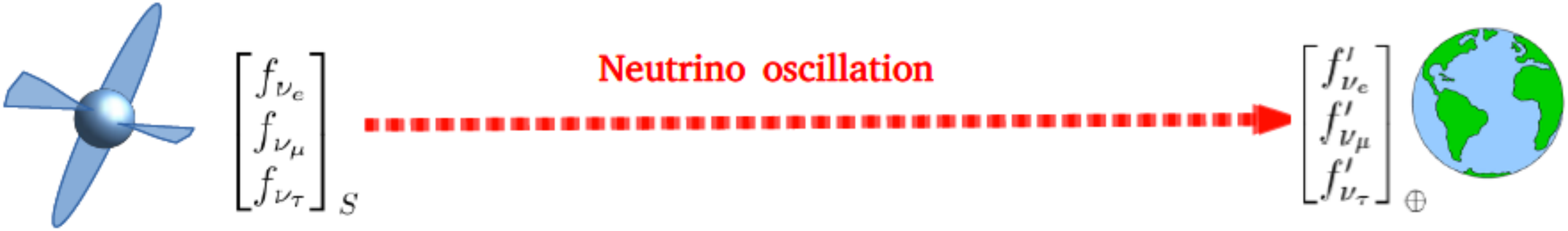
**Standard expectation:**
ν and γ from transients arrive simultaneously

**Standard expectation:**
Equal number of $\nu_e$, $\nu_\mu$, $\nu_\tau$

**See talks by Alfonso Garcia & Teppei Katori**

**energy spectrum, arrival directions, flavor composition, and arrival times to explore BSM Physics**

# Flavor Ratio of Astrophysical Neutrinos



$$\begin{bmatrix} f_{\nu_e} \\ f_{\nu_\mu} \\ f_{\nu_\tau} \end{bmatrix}_S \qquad \begin{bmatrix} f'_{\nu_e} \\ f'_{\nu_\mu} \\ f'_{\nu_\tau} \end{bmatrix}_\oplus$$

Oscillation probability

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

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

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

Neutrino flavor ratio at Earth

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

$$\bar{P}_{\alpha\beta} = P_{\alpha\beta}(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\mathrm{CP}})$$

<u>Assumption:</u>

Neutrino propagating in vacuum

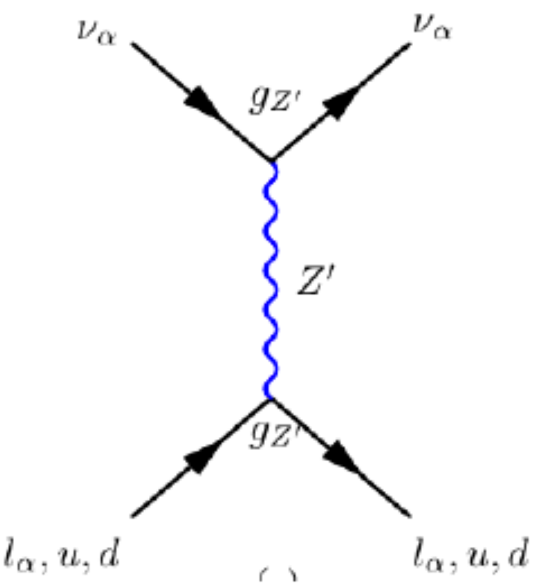
# Neutrino Matter Interactions in Z′ Models

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

New interaction induces
flavor-dependent Yukawa potentials

$$V_{e\beta} = -g'^2_{e\beta}\frac{N_e}{4\pi d}e^{-m'_{e\beta}d}$$

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



**Ultra-light Z′**

⇩

**Long-range interaction**

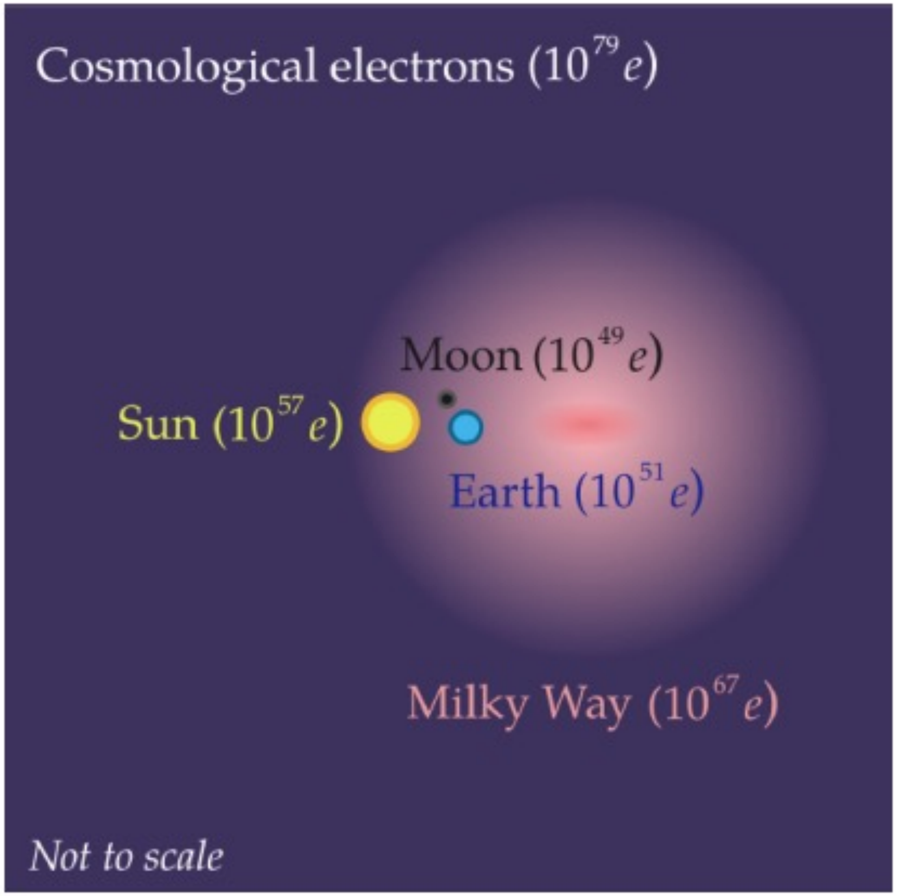
**Range ∝ $\frac{1}{m_{Z'}}$**

| Model (X) | $a_u$ | $a_d$ | $a_e$ | $b_e$ | $b_\mu$ | $b_\tau$ |
|---|---|---|---|---|---|---|
| $B-3L_e$ | $\frac{1}{3}$ | $\frac{1}{3}$ | $-3$ | $-3$ | 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 | $-\frac{3}{2}$ | $-\frac{3}{2}$ |
| $L_e-L_\mu$ | 0 | 0 | 1 | 1 | $-1$ | 0 |
| $L_e-L_\tau$ | 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 | $-1$ |

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

*S. K. Agarwalla, Vietnam Neutrino Conference 2025, ICISE, Quy Nhon, Vietnam, 23rd July 2025*

# *Long-Range Neutrino Matter Interactions in U(1)$'$ Models*



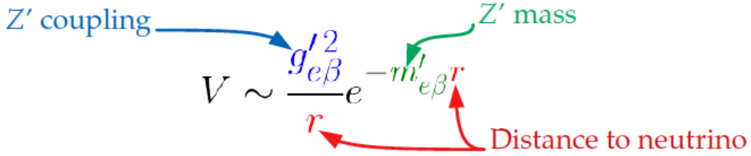
**Huge Electron repositories in the local and distant Universe**

**Oscillations sensitive to long-ranged flavor interactions between neutrinos and electrons. Use flavor composition of TeV-PeV astrophysical neutrinos at IceCube**

**Bustamante, Agarwalla PRL 122, 061103 (2019)**

Matter particles inside the interaction range will contribute to the potential

Under the $L_e$-$L_\mu$ or $L_e$-$L_\tau$ symmetry, an electron sources a Yukawa potential —



$$V \sim \frac{g'^{2}_{e\beta}}{r} e^{-m'_{e\beta} r}$$

A neutrino “feels” all the electrons within the interaction range $\sim(1/m')$

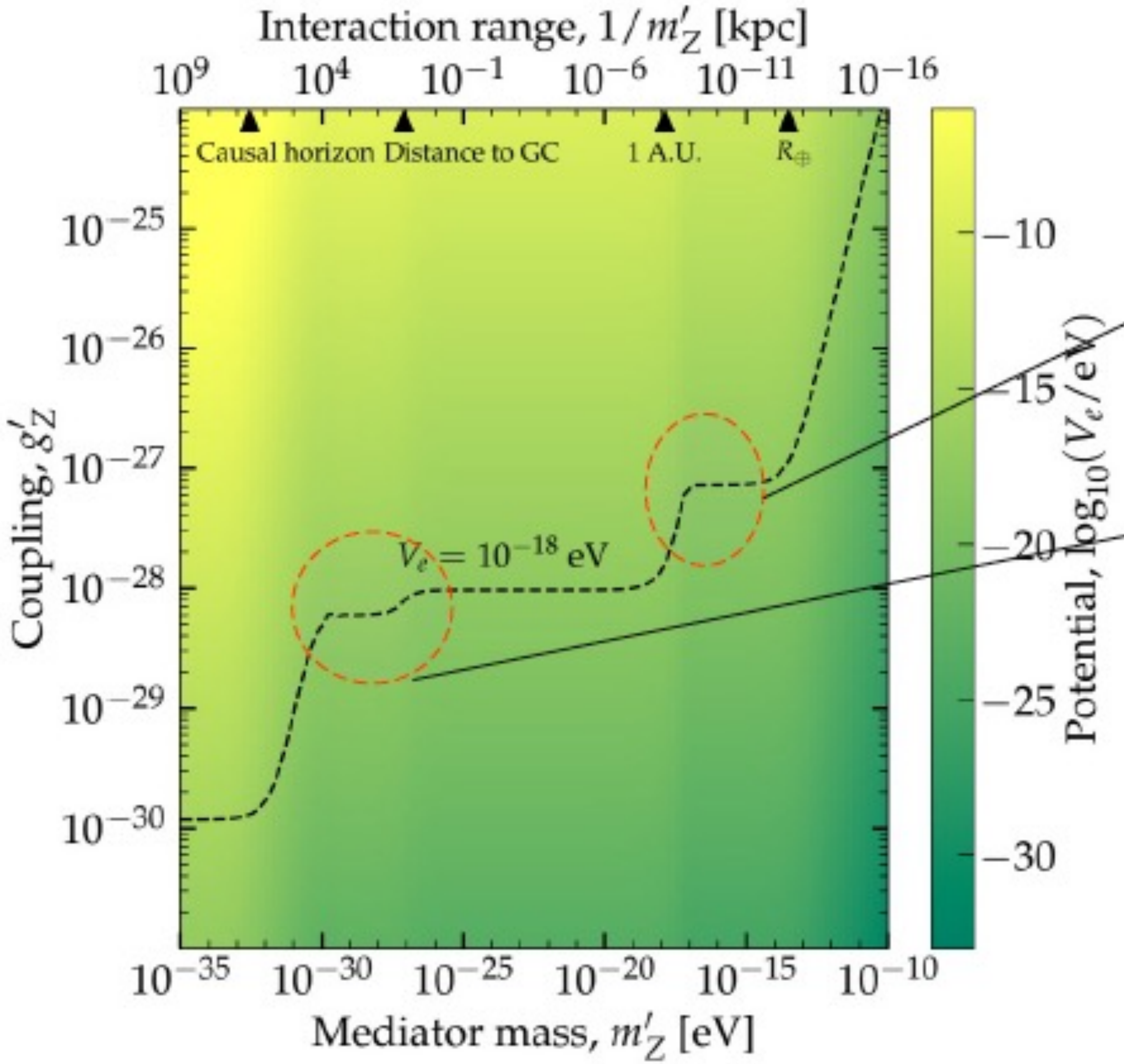
$$\text{Interaction range} \propto \frac{1}{m_{Z'}}$$

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

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

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

# *Long-Range Neutrino Matter Interactions in $U(1)'$ Models*



Inclusion of electrons from the Sun

Inclusion of electrons from the Galactic Centre

**Bustamante, Agarwalla PRL 122, 061103 (2019)**

# *Neutrino Flavor Composition in the presence of Long-Range Potential*

- Neutrino propagation Hamiltonian

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

New potential

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

$$\mathbf{V}_{\rm LRI} = \mathrm{diag}(V_e, -V_e, 0)$$

- Neutrino flavor transition probability

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

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

$$U^m \to U^m(\theta^m_{23}, \theta^m_{13}, \theta^m_{12}, \delta^m) \Longrightarrow$$

Modified Mass-mixing parameters

- Neutrino flavor compostion at Earth

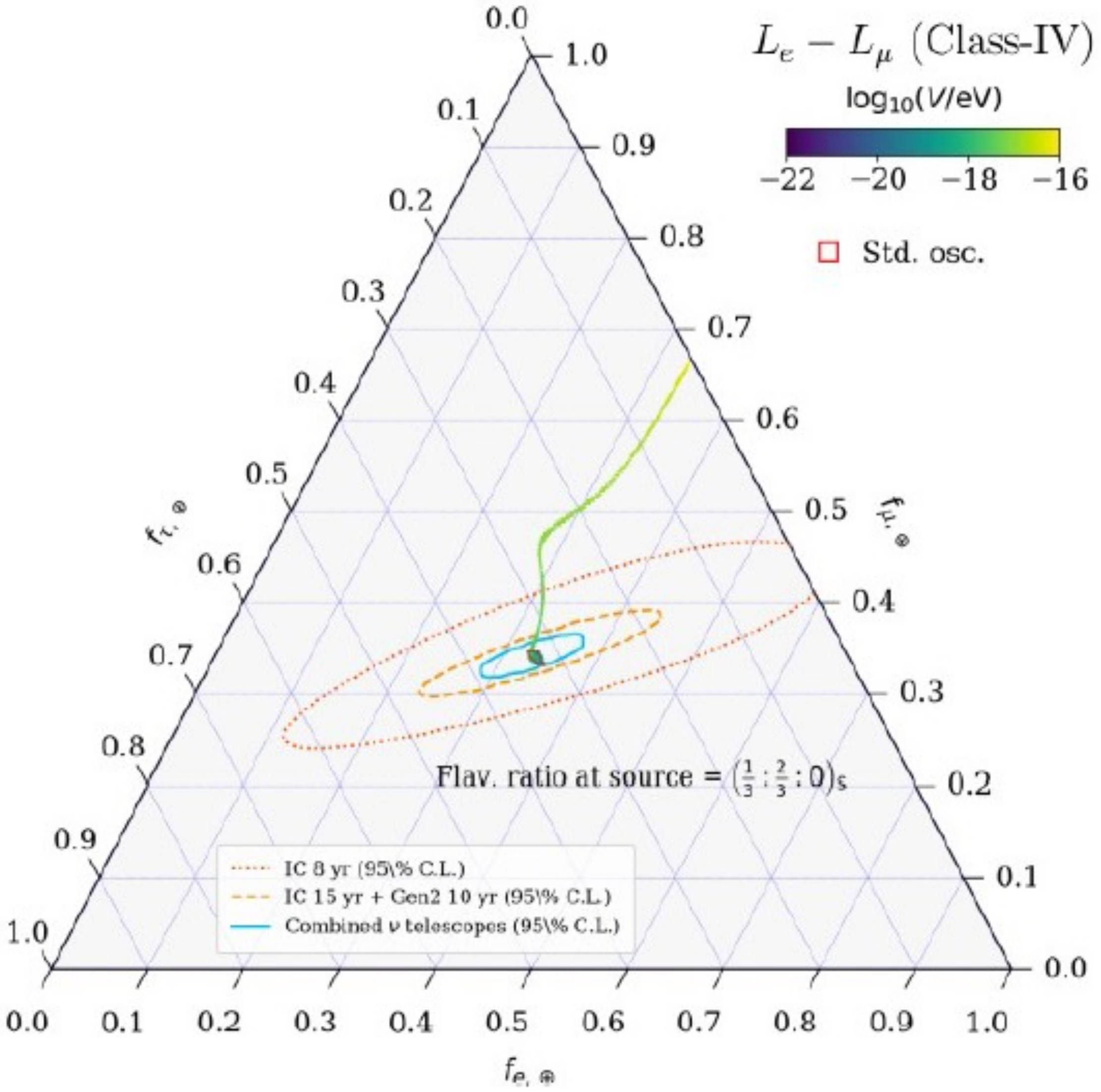
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} \bar{P}_{\beta\alpha} f_{\beta,\rm S}\ ,$$

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

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

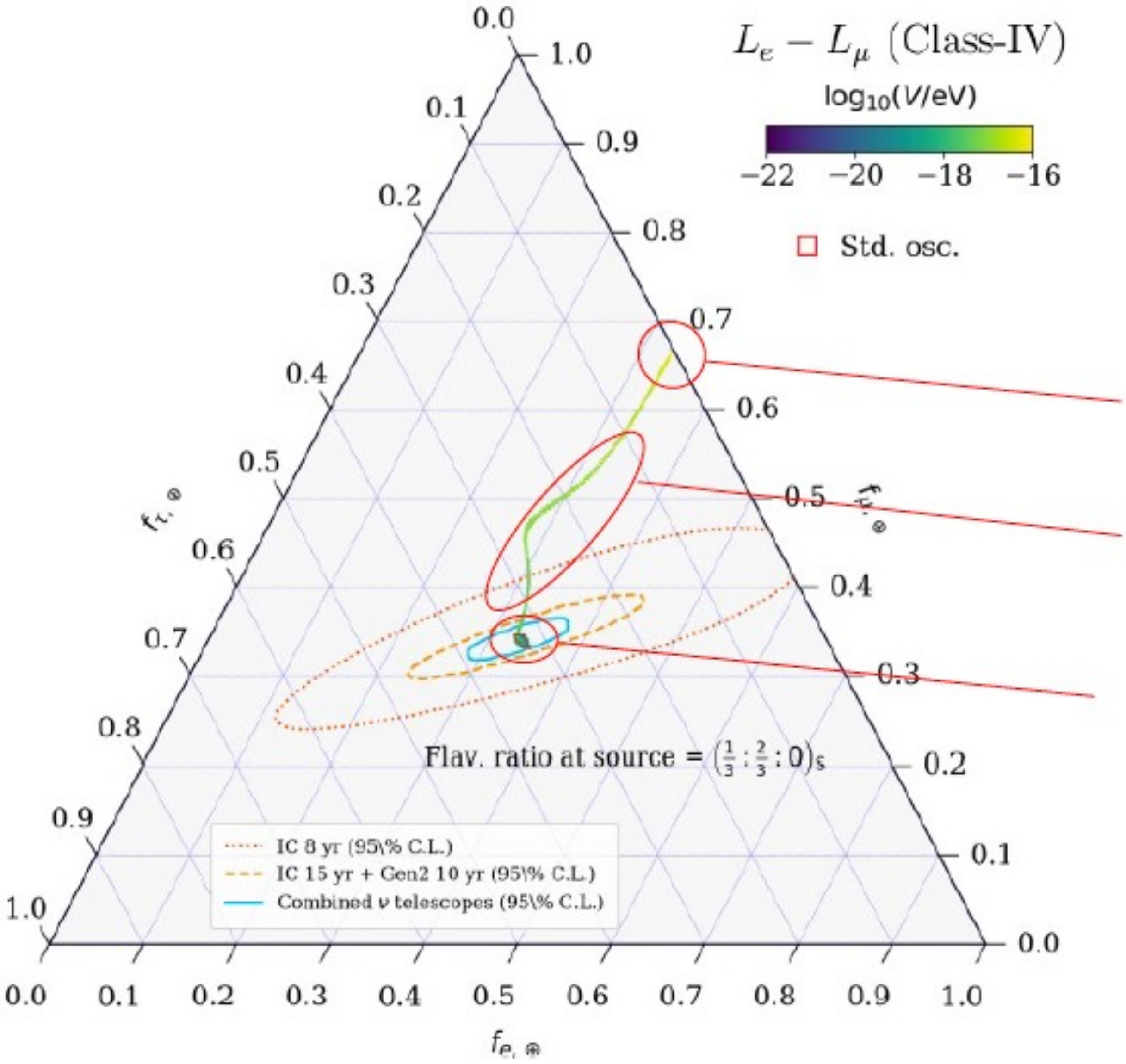
$$(f_e : f_\mu : f_\tau)_{\rm S} = (1 : 2 : 0)$$

# Neutrino Flavor Composition



**Agarwalla, Bustamante, Das, Narang, JHEP 08 (2023) 113**

# Neutrino Flavor Composition



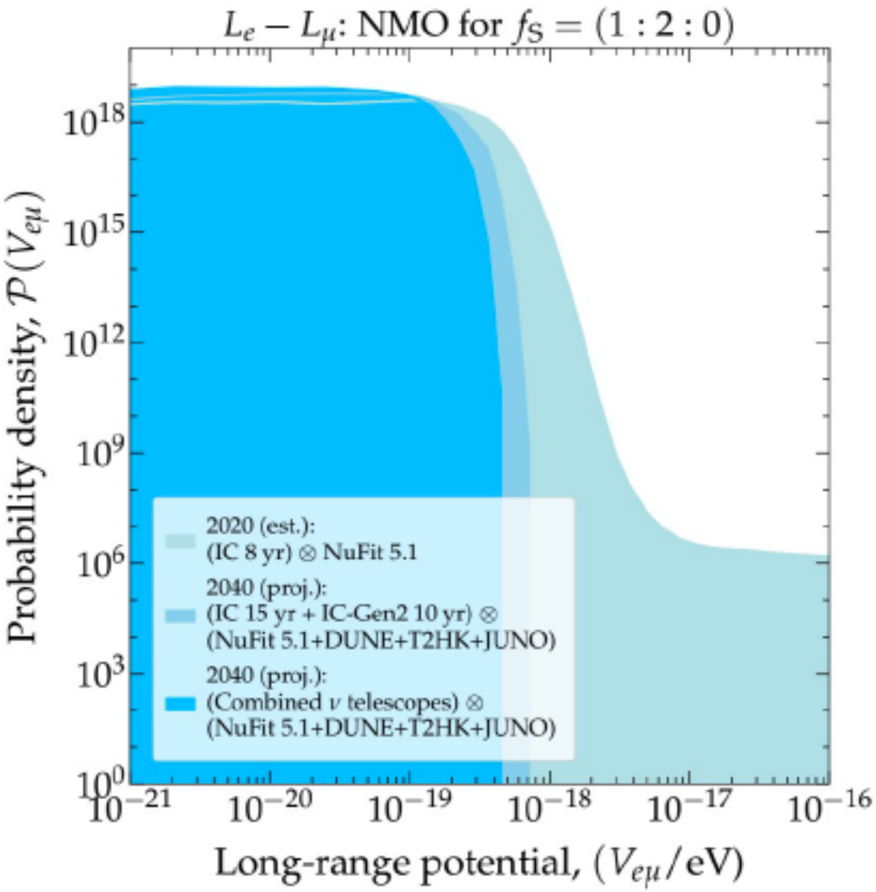
$$V_{\alpha\beta} \gg \Delta m^2_{ij}/(2E)$$

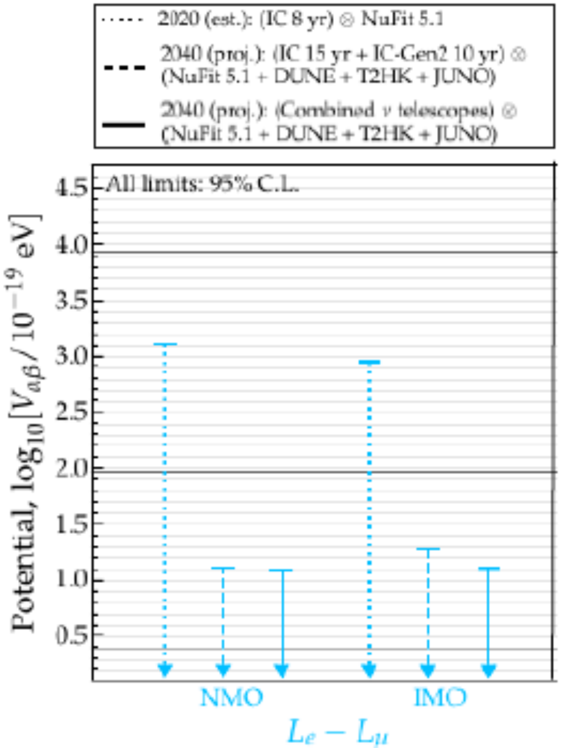
$$V_{\alpha\beta} \sim \Delta m^2_{ij}/(2E)$$

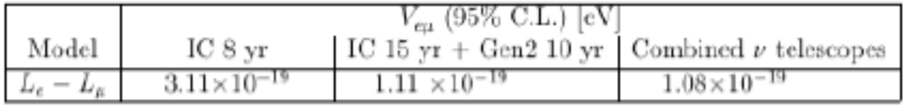
$$V_{\alpha\beta} \ll \Delta m^2_{ij}/(2E)$$

**Agarwalla, Bustamante, Das, Narang, JHEP 08 (2023) 113**

# Sensitivity towards Long-Range Potential







| Model | $V_{e\mu}$ (95% C.L.) [eV] | | |
|---|---|---|---|
| | IC 8 yr | IC 15 yr + Gen2 10 yr | Combined ν telescopes |
| $L_e - L_\mu$ | $3.11\times10^{-19}$ | $1.11\ \times10^{-19}$ | $1.08\times10^{-19}$ |

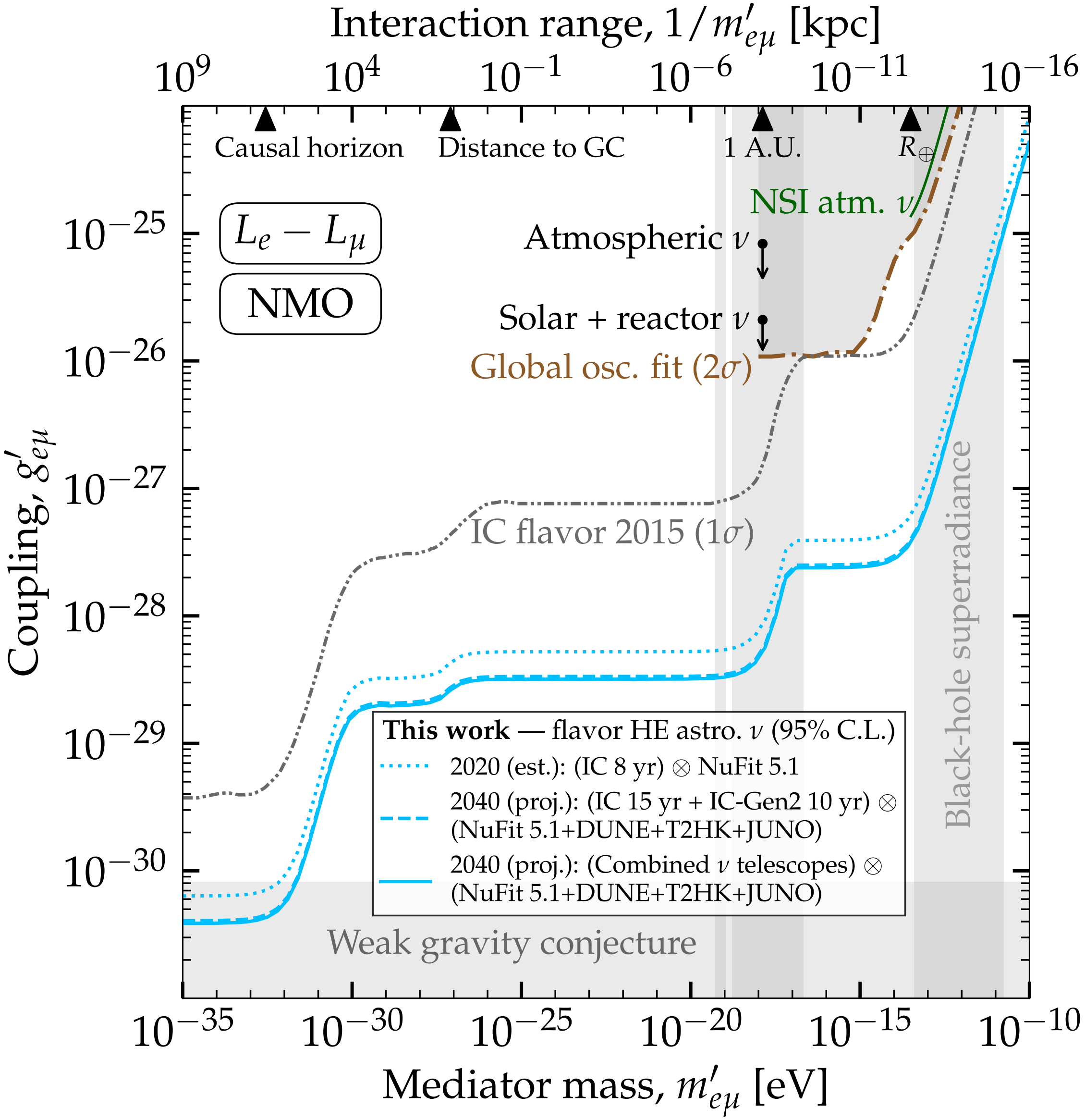
IC 8 yr : estimated through-going + HESE events at IceCube

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

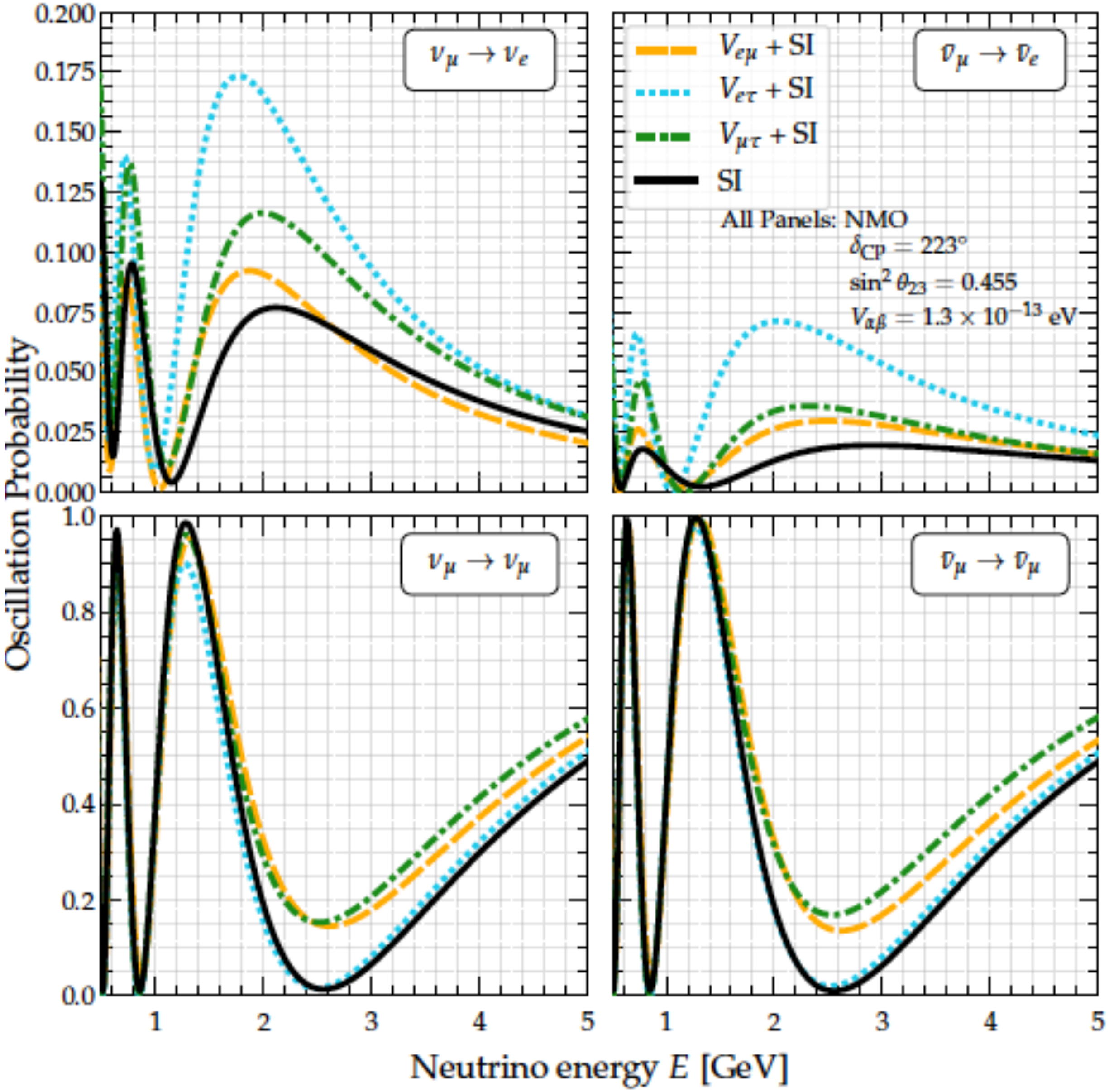
Agarwalla, Bustamante, Das, Narang, JHEP 08 (2023) 113

# *Limits on Long-Range Interactions in the Mass vs. Coupling Plane*



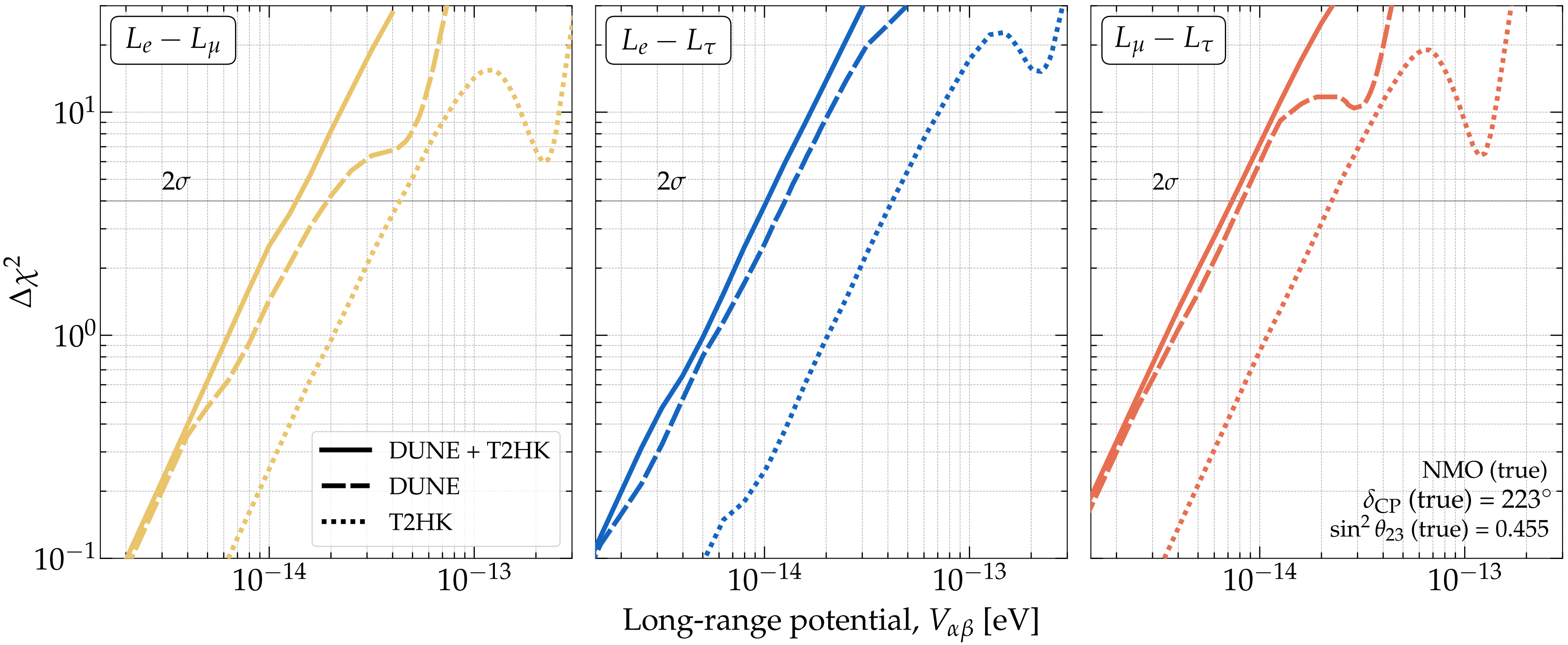
**Agarwalla, Bustamante, Das, Narang, JHEP 08 (2023) 113**

# *Three-Flavor Oscillation Probability in DUNE in the Presence of LRI*



**Singh, Bustamante, Agarwalla, JHEP 08 (2023) 101**

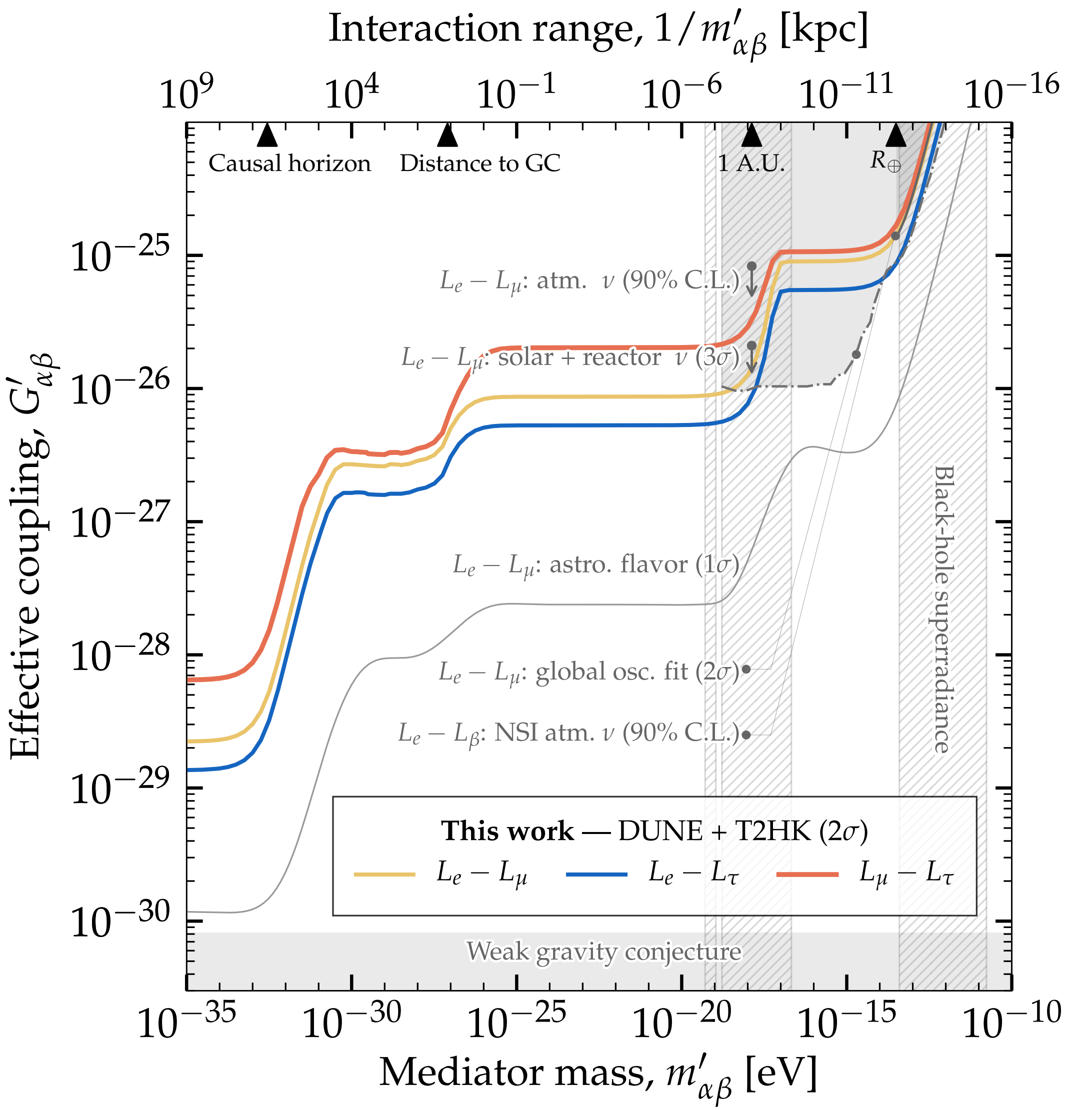
# Constraints on Long-Range Interactions from DUNE + T2HK



$$\Delta\chi^2 = \min_{\sin^2\theta_{23}\,,\,\delta_{\rm CP}\,,\,\pm\Delta m^2_{31}} \{\chi^2({\rm SI}+{\rm LRI}) - \chi^2({\rm SI})\}$$

**Singh, Bustamante, Agarwalla, JHEP 08 (2023) 101**

# *Constraints on Long-Range Interactions from DUNE + T2HK*



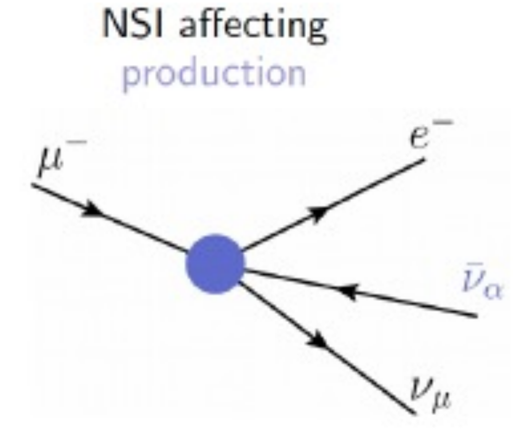
$$G'_{\alpha\beta} = \begin{cases} g'_{e\mu} & , \quad \text{for } \alpha,\beta = e,\mu \\ g'_{e\tau} & , \quad \text{for } \alpha,\beta = e,\tau \\ \sqrt{g'_{\mu\tau}(\xi - \sin\theta_W \chi)} & , \quad \text{for } \alpha,\beta = \mu,\tau \end{cases}$$

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

DUNE + Hyper-K may place strong constraints on LRI, especially for mediators lighter than $10^{-18}$ eV

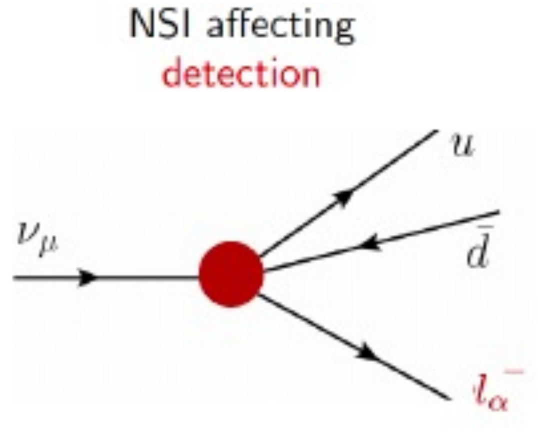
**Singh, Bustamante, Agarwalla, JHEP 08 (2023) 101**

# Neutrino Non-Standard Interactions (NSIs)



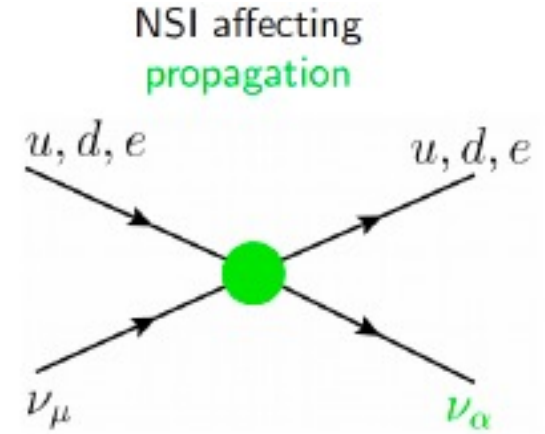
$\varepsilon^{e\mu,P}_{\mu\alpha} \, (\bar{e}\gamma^\rho P \mu)\,(\bar{\nu}_\mu \gamma_\rho P_L \nu_\alpha)$

CC



$\varepsilon^{ud,P}_{\mu\alpha} \, (\bar{d}\gamma^\rho P u)\,(\bar{\nu}_\mu \gamma_\rho P_L l_\alpha)$

CC



$\varepsilon^{f,P}_{\mu\alpha} \, (\bar{f}\gamma^\rho P f)\,(\bar{\nu}_\mu \gamma_\rho P_L \nu_\alpha)$

NC

NC-NSIs may address the tension between T2K and NOvA

Denton, Gehrlein, Pestes
PRL 126 (2021) 5, 051801

Chatterjee and Palazzo
PRL 126 (2021) 5, 051802

SciPost SciPost Phys. Proc. 2, 001 (2019)

Neutrino non-standard interactions: A status report

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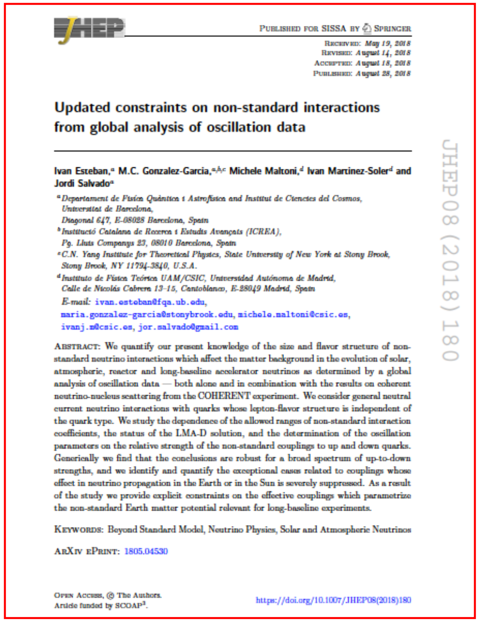

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**Updated constraints on non-standard interactions from global analysis of oscillation data**

JHEP08(2018)180

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Abstract: We quantify our present knowledge of the size and flavor structure of non-standard neutrino interactions which affect the matter background in the evolution of solar, atmospheric, reactor and long-baseline accelerator neutrinos as determined by a global analysis of oscillation data — both alone and in combination with the results on coherent neutrino-nucleus scattering from the COHERENT experiment. We consider general neutral current neutrino interactions with quarks whose lepton-flavor structure is independent of the quark type. We study the dependence of the allowed ranges of non-standard interaction coefficients, the status of the LMA-D solution, and the determination of the oscillation parameters on the relative strength of the non-standard couplings to up and down quarks. Generically we find that the conclusions are robust for a broad spectrum of up-to-down strengths, and we identify and quantify the exceptional cases related to couplings whose effect in neutrino propagation in the Earth or in the Sun is severely suppressed. As a result of the study we provide explicit constraints on the effective couplings which parametrize the non-standard Earth matter potential relevant for long-baseline experiments.

Keywords: Beyond Standard Model, Neutrino Physics, Solar and Atmospheric Neutrinos

ArXiv ePrint: 1805.04530

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Exciting BSM prospects @ DUNE

See the publication:
**EPJC 81 (2021) 322**

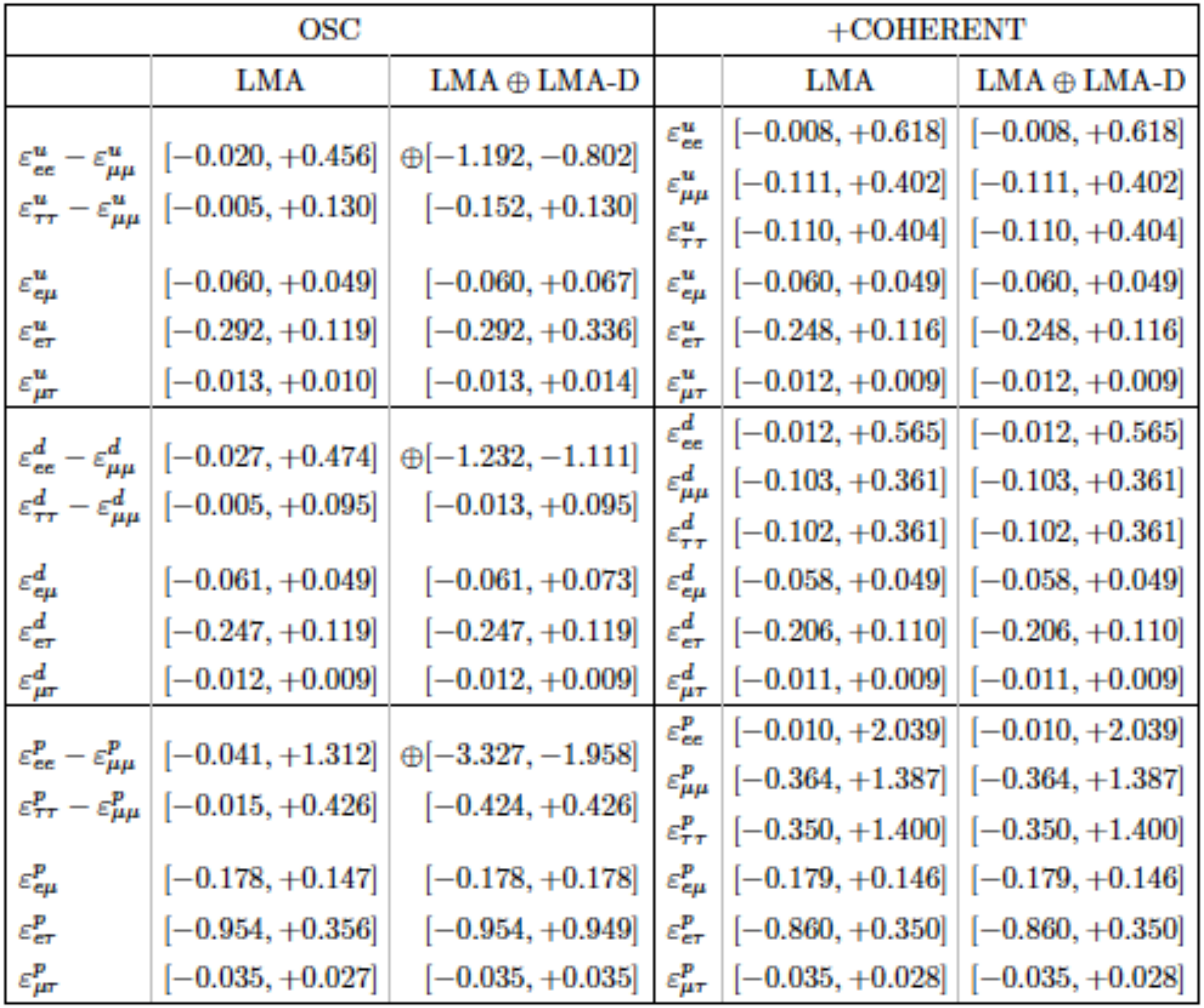
# Neutrino NC-NSIs in Propagation

dimension-6
4-fermion
operators

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$f, f' \in \{e,u,d\}$ and $P \in \{P_L, P_R\}$

2$\sigma$ allowed ranges for the NSI couplings $\varepsilon^u_{\alpha\beta}$, $\varepsilon^d_{\alpha\beta}$ and $\varepsilon^p_{\alpha\beta}$



| OSC | | | +COHERENT | | |
|---|---|---|---|---|---|
| | LMA | LMA $\oplus$ LMA-D | | LMA | LMA $\oplus$ LMA-D |
| $\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$ | $[-0.020, +0.456]$ | $\oplus[-1.192, -0.802]$ | $\varepsilon^u_{ee}$ | $[-0.008, +0.618]$ | $[-0.008, +0.618]$ |
| $\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$ | $[-0.005, +0.130]$ | $[-0.152, +0.130]$ | $\varepsilon^u_{\mu\mu}$ | $[-0.111, +0.402]$ | $[-0.111, +0.402]$ |
| | | | $\varepsilon^u_{\tau\tau}$ | $[-0.110, +0.404]$ | $[-0.110, +0.404]$ |
| $\varepsilon^u_{e\mu}$ | $[-0.060, +0.049]$ | $[-0.060, +0.067]$ | $\varepsilon^u_{e\mu}$ | $[-0.060, +0.049]$ | $[-0.060, +0.049]$ |
| $\varepsilon^u_{e\tau}$ | $[-0.292, +0.119]$ | $[-0.292, +0.336]$ | $\varepsilon^u_{e\tau}$ | $[-0.248, +0.116]$ | $[-0.248, +0.116]$ |
| $\varepsilon^u_{\mu\tau}$ | $[-0.013, +0.010]$ | $[-0.013, +0.014]$ | $\varepsilon^u_{\mu\tau}$ | $[-0.012, +0.009]$ | $[-0.012, +0.009]$ |
| $\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$ | $[-0.027, +0.474]$ | $\oplus[-1.232, -1.111]$ | $\varepsilon^d_{ee}$ | $[-0.012, +0.565]$ | $[-0.012, +0.565]$ |
| $\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$ | $[-0.005, +0.095]$ | $[-0.013, +0.095]$ | $\varepsilon^d_{\mu\mu}$ | $[-0.103, +0.361]$ | $[-0.103, +0.361]$ |
| | | | $\varepsilon^d_{\tau\tau}$ | $[-0.102, +0.361]$ | $[-0.102, +0.361]$ |
| $\varepsilon^d_{e\mu}$ | $[-0.061, +0.049]$ | $[-0.061, +0.073]$ | $\varepsilon^d_{e\mu}$ | $[-0.058, +0.049]$ | $[-0.058, +0.049]$ |
| $\varepsilon^d_{e\tau}$ | $[-0.247, +0.119]$ | $[-0.247, +0.119]$ | $\varepsilon^d_{e\tau}$ | $[-0.206, +0.110]$ | $[-0.206, +0.110]$ |
| $\varepsilon^d_{\mu\tau}$ | $[-0.012, +0.009]$ | $[-0.012, +0.009]$ | $\varepsilon^d_{\mu\tau}$ | $[-0.011, +0.009]$ | $[-0.011, +0.009]$ |
| $\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$ | $[-0.041, +1.312]$ | $\oplus[-3.327, -1.958]$ | $\varepsilon^p_{ee}$ | $[-0.010, +2.039]$ | $[-0.010, +2.039]$ |
| $\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$ | $[-0.015, +0.426]$ | $[-0.424, +0.426]$ | $\varepsilon^p_{\mu\mu}$ | $[-0.364, +1.387]$ | $[-0.364, +1.387]$ |
| | | | $\varepsilon^p_{\tau\tau}$ | $[-0.350, +1.400]$ | $[-0.350, +1.400]$ |
| $\varepsilon^p_{e\mu}$ | $[-0.178, +0.147]$ | $[-0.178, +0.178]$ | $\varepsilon^p_{e\mu}$ | $[-0.179, +0.146]$ | $[-0.179, +0.146]$ |
| $\varepsilon^p_{e\tau}$ | $[-0.954, +0.356]$ | $[-0.954, +0.949]$ | $\varepsilon^p_{e\tau}$ | $[-0.860, +0.350]$ | $[-0.860, +0.350]$ |
| $\varepsilon^p_{\mu\tau}$ | $[-0.035, +0.027]$ | $[-0.035, +0.035]$ | $\varepsilon^p_{\mu\tau}$ | $[-0.035, +0.028]$ | $[-0.035, +0.028]$ |

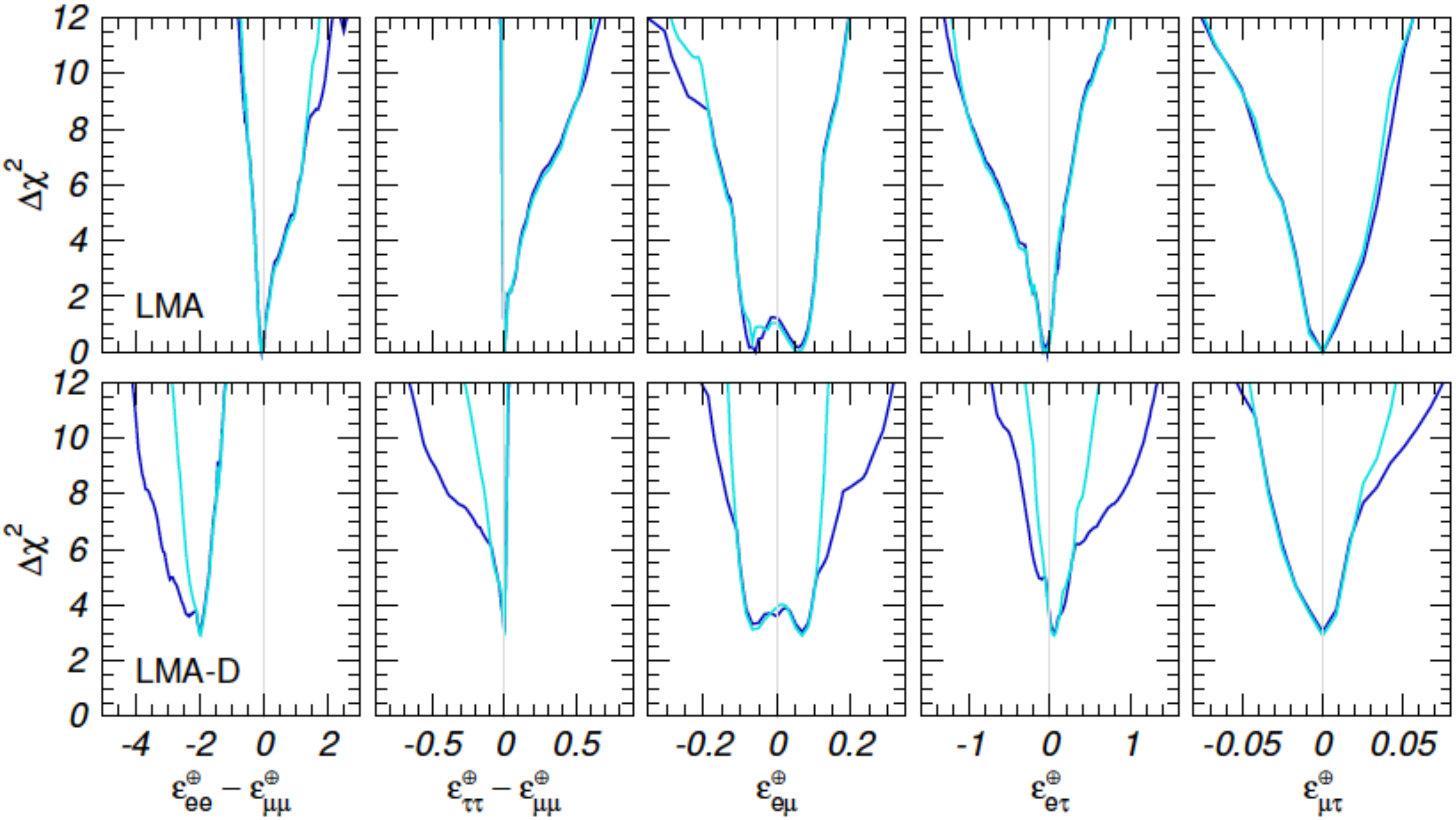
$$a \equiv 2\sqrt{2}G_F N_e E$$

$$H = \frac{1}{2E}\left[U_{\rm PMNS}\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\rm PMNS} + a\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

**Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP 08 (2018) 180**

# Neutrino NC-NSIs in Propagation

Dependence of the $\Delta\chi^2$ function on the effective NSI parameters



**Blue lines: All Oscillation data** **Cyan lines: All Oscillation data + COHERENT data**

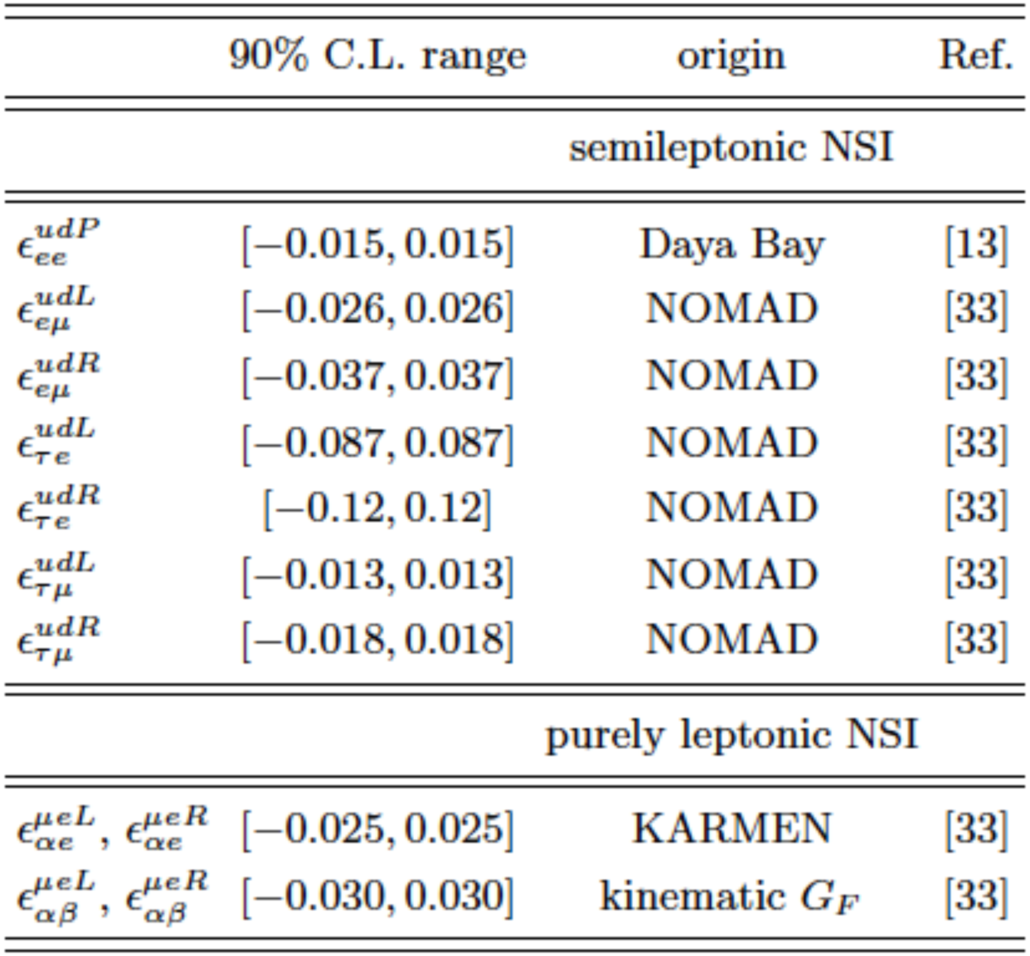
Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP 08 (2018) 180

# Neutrino CC-NSIs at Production and Detection

dimension-6
4-fermion
operators

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

$f, f' \in \{e, u, d\}$ and $P \in \{P_L, P_R\}$

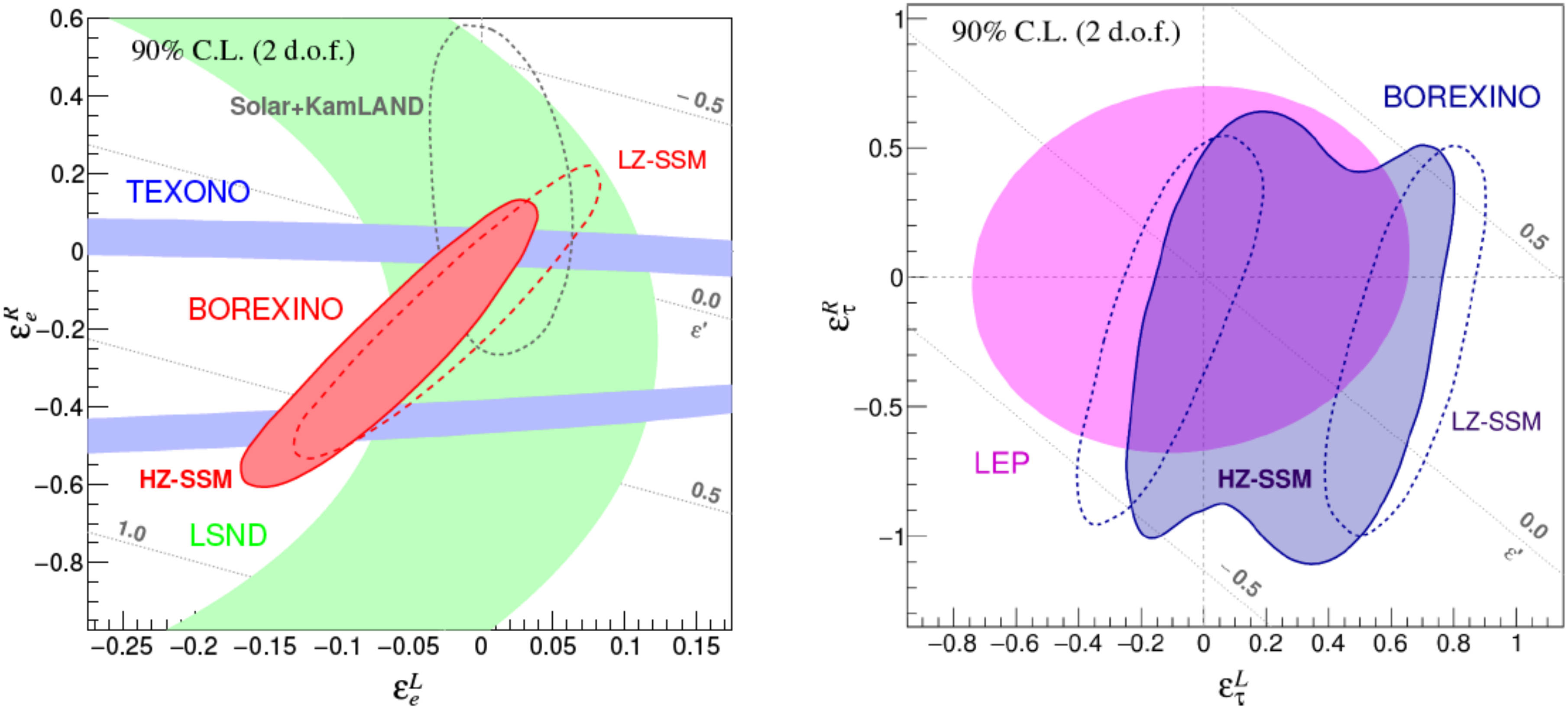


| | 90% C.L. range | origin | Ref. |
|---|---|---|---|
| | | semileptonic NSI | |
| $\epsilon^{udP}_{ee}$ | $[-0.015, 0.015]$ | Daya Bay | [13] |
| $\epsilon^{udL}_{e\mu}$ | $[-0.026, 0.026]$ | NOMAD | [33] |
| $\epsilon^{udR}_{e\mu}$ | $[-0.037, 0.037]$ | NOMAD | [33] |
| $\epsilon^{udL}_{\tau e}$ | $[-0.087, 0.087]$ | NOMAD | [33] |
| $\epsilon^{udR}_{\tau e}$ | $[-0.12, 0.12]$ | NOMAD | [33] |
| $\epsilon^{udL}_{\tau\mu}$ | $[-0.013, 0.013]$ | NOMAD | [33] |
| $\epsilon^{udR}_{\tau\mu}$ | $[-0.018, 0.018]$ | NOMAD | [33] |
| | | purely leptonic NSI | |
| $\epsilon^{\mu eL}_{\alpha e}$, $\epsilon^{\mu eR}_{\alpha e}$ | $[-0.025, 0.025]$ | KARMEN | [33] |
| $\epsilon^{\mu eL}_{\alpha\beta}$, $\epsilon^{\mu eR}_{\alpha\beta}$ | $[-0.030, 0.030]$ | kinematic $G_F$ | [33] |

Farzan, Tortola, Front.in Phys. 6 (2018) 10

**Ref. [13]: Agarwalla, Bagchi, Forero, Tortola, JHEP 07 (2015) 060**
**Ref. [33]: Biggio, Blennow, Fernandez-Martinez, JHEP 08 (2009) 090**

# *New Constraints on Flavor-Diagonal NSIs from Borexino Phase-II*



| | HZ-SSM | LZ-SSM |
|---|---|---|
| $\varepsilon_e^R$ | $[-0.15, +0.11]$ | $[-0.20, +0.03]$ |
| $\varepsilon_e^L$ | $[-0.035, +0.032]$ | $[-0.013, +0.052]$ |
| $\varepsilon_\tau^R$ | $[-0.83, +0.36]$ | $[-0.42, +0.43]$ |
| $\varepsilon_\tau^L$ | $[-0.11, +0.67]$ | $[-0.19, +0.79]$ |

**one parameter at-a-time limit at 90% C.L. (1 d.o.f.)**

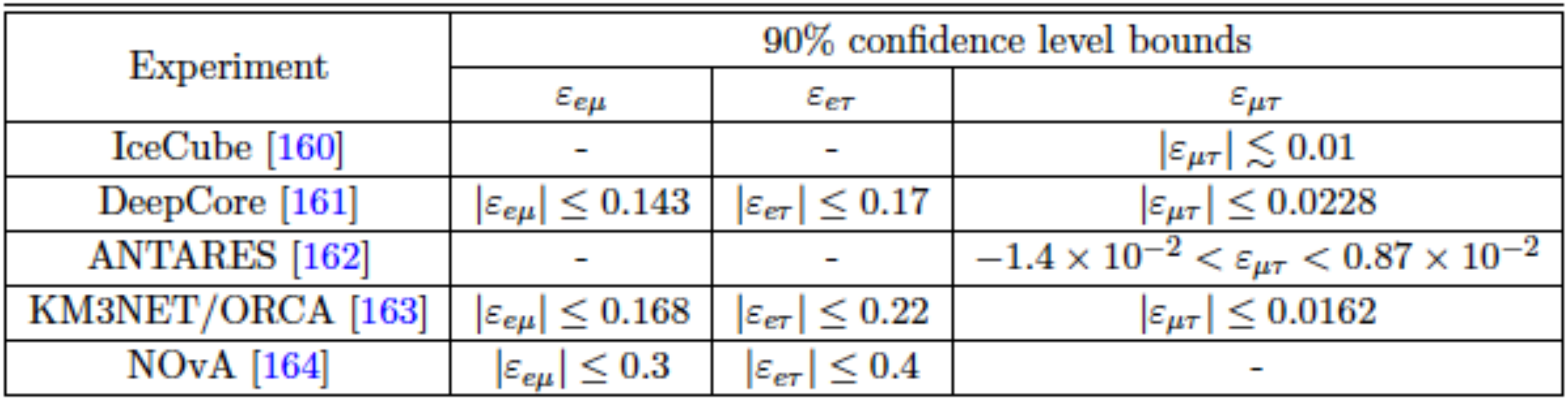
$$g_{\alpha R} \quad \rightarrow \quad \tilde{g}_{\alpha R} = g_{\alpha R} + \varepsilon_\alpha^R$$
$$g_{\alpha L} \quad \rightarrow \quad \tilde{g}_{\alpha L} = g_{\alpha L} + \varepsilon_\alpha^L$$

$$\boxed{\frac{d\tilde{\sigma}_{\nu_\alpha}(E_{\nu_\alpha}, T)}{dT} = \frac{2G_F^2 m_e}{\pi}\left[\tilde{g}_{\alpha L}^2 + \tilde{g}_{\alpha R}^2\left(1 - \frac{T}{E_{\nu_\alpha}}\right)^2 - \tilde{g}_{\alpha L}\tilde{g}_{\alpha R}\frac{m_e T}{E_{\nu_\alpha}^2}\right]}$$

**Nice complementarity between Borexino and Texono**

**S. K. Agarwalla et al., JHEP 02 (2020) 038**
**(On behalf of the Borexino Collaboration)**

# Constraints on the NC-NSI Parameters



| Experiment | 90% confidence level bounds | | |
|---|---|---|---|
| | $\varepsilon_{e\mu}$ | $\varepsilon_{e\tau}$ | $\varepsilon_{\mu\tau}$ |
| IceCube [160] | - | - | $\lvert\varepsilon_{\mu\tau}\rvert \lesssim 0.01$ |
| DeepCore [161] | $\lvert\varepsilon_{e\mu}\rvert \leq 0.143$ | $\lvert\varepsilon_{e\tau}\rvert \leq 0.17$ | $\lvert\varepsilon_{\mu\tau}\rvert \leq 0.0228$ |
| ANTARES [162] | - | - | $-1.4 \times 10^{-2} < \varepsilon_{\mu\tau} < 0.87 \times 10^{-2}$ |
| KM3NET/ORCA [163] | $\lvert\varepsilon_{e\mu}\rvert \leq 0.168$ | $\lvert\varepsilon_{e\tau}\rvert \leq 0.22$ | $\lvert\varepsilon_{\mu\tau}\rvert \leq 0.0162$ |
| NOvA [164] | $\lvert\varepsilon_{e\mu}\rvert \leq 0.3$ | $\lvert\varepsilon_{e\tau}\rvert \leq 0.4$ | - |

**Krishnamoorthi J. et al., arXiv:2507.02167 [hep-ph]**

**Ref. [160]: IceCube Collaboration, PRL 129 (2022) 1, 011804**

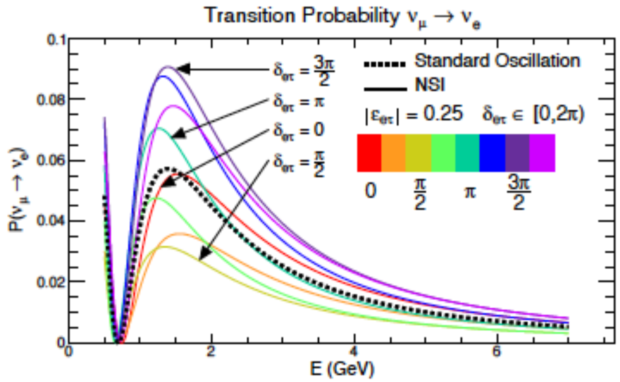
**Ref. [161]: IceCube Collaboration, PRD 104 (2021) 7, 072006**

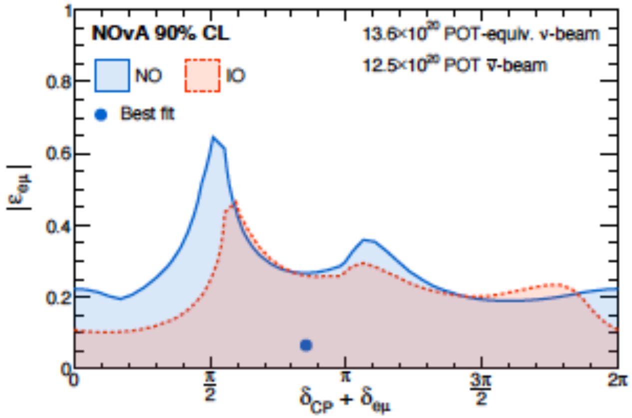
**Ref. [162]: ANTARES Collaboration, JHEP 07 (2022) 048**

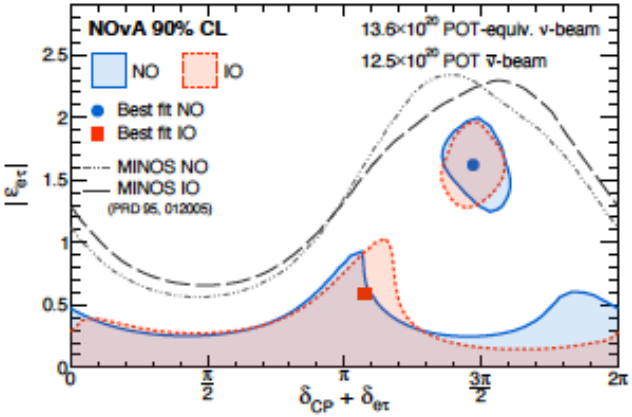
**Ref. [163]: KM3NeT Collaboration, JCAP 02 (2025) 073**

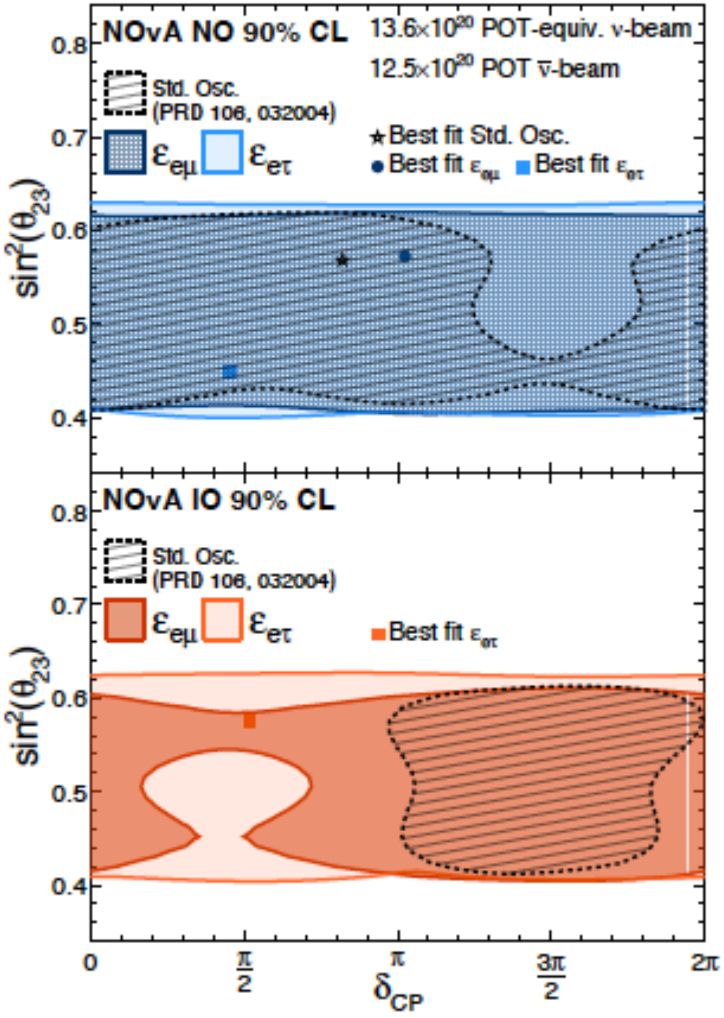
**Ref. [164]: NOvA Collaboration, PRL 133 (2024) 20, 201802**

# CP-violating Neutrino NSIs at NOνA









**NOvA Collaboration, PRL 133 (2024) 20, 201802**

# *Concluding Remarks*

**High-energy astrophysical neutrinos detected by big neutrino telescopes may reveal the presence of new fundamental particles and interactions, probing energy and distance scales far exceeding those accessible in the laboratory**

**Various BSM scenarios may affect the outcome of next-generation high-precision neutrino oscillation experiments as the precision on the neutrino oscillation parameters and CP violation measurements continues to improve**

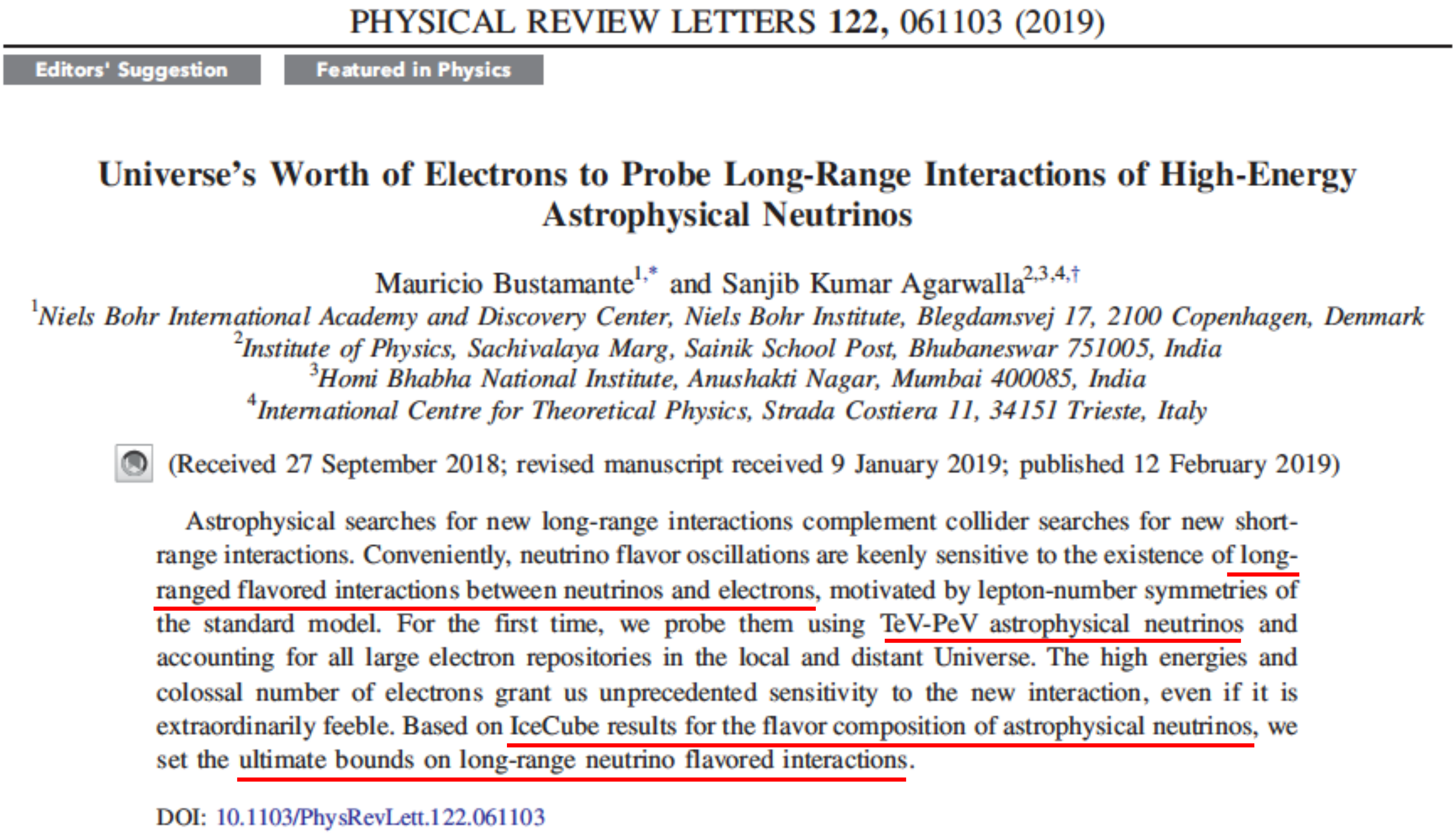
**BSM physics may become the dominant physics topic of next-generation neutrino experiments!**

**Stay tuned!**

**Apologies for missing your important work. Time is too short to cover everything**

**Thank you!**

# Ultimate Bounds on Long-Range Interactions



PHYSICAL REVIEW LETTERS **122,** 061103 (2019)

## Universe's Worth of Electrons to Probe Long-Range Interactions of High-Energy Astrophysical Neutrinos

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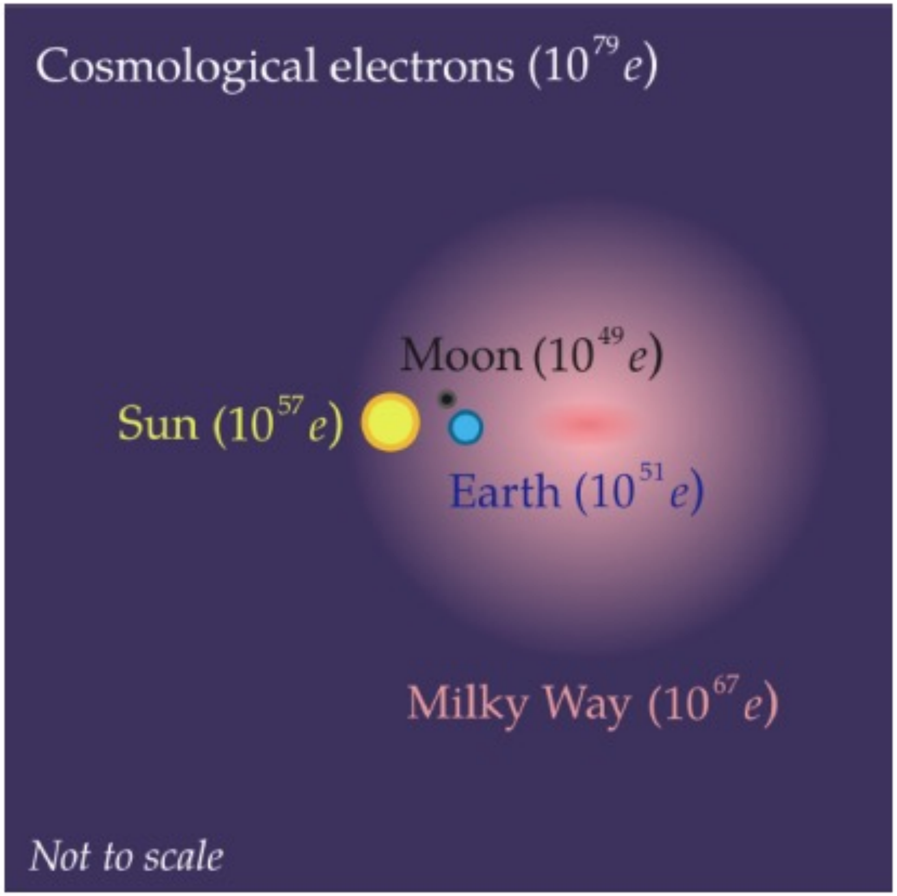
Astrophysical searches for new long-range interactions complement collider searches for new short-range interactions. Conveniently, neutrino flavor oscillations are keenly sensitive to the existence of long-ranged flavored interactions between neutrinos and electrons, motivated by lepton-number symmetries of the standard model. For the first time, we probe them using TeV-PeV astrophysical neutrinos and accounting for all large electron repositories in the local and distant Universe. The high energies and colossal number of electrons grant us unprecedented sensitivity to the new interaction, even if it is extraordinarily feeble. Based on IceCube results for the flavor composition of astrophysical neutrinos, we set the ultimate bounds on long-range neutrino flavored interactions.

DOI: 10.1103/PhysRevLett.122.061103

# *Ultimate Bounds on Long-Range Interactions*



**Huge Electron repositories in the local and distant Universe**

**Oscillations sensitive to long-ranged flavored interactions between neutrino and electron. Use flavor composition of TeV-PeV astrophysical neutrinos at IceCube**

**Bustamante, Agarwalla PRL 122, 061103 (2019)**

Under the $L_e$-$L_\mu$ or $L_e$-$L_\tau$ symmetry, an electron sources a Yukawa potential —

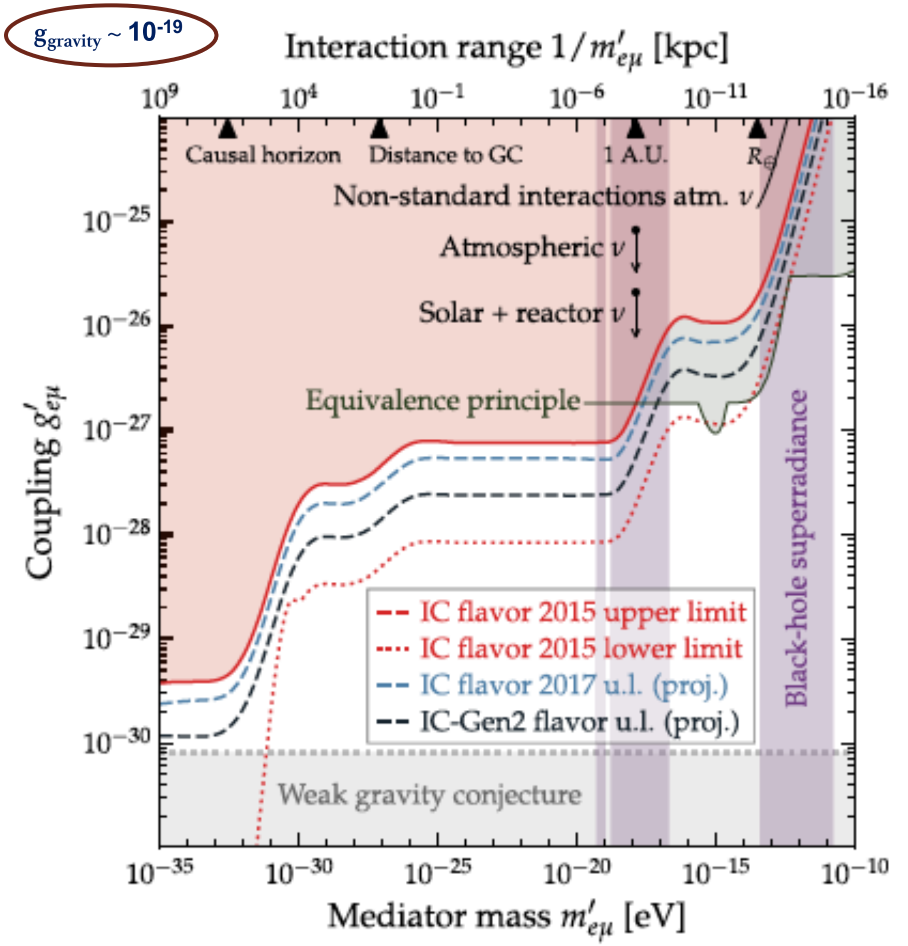
$Z'$ coupling

$Z'$ mass

$$V \sim \frac{g'^2_{e\beta}}{r} e^{-m'_{e\beta} r}$$

Distance to neutrino

A neutrino "feels" all the electrons within the interaction range ~$(1/m')$


$g_{gravity}$ ~ $10^{-19}$