Neutrino Oscillations and Beyond the Standard Model Physics

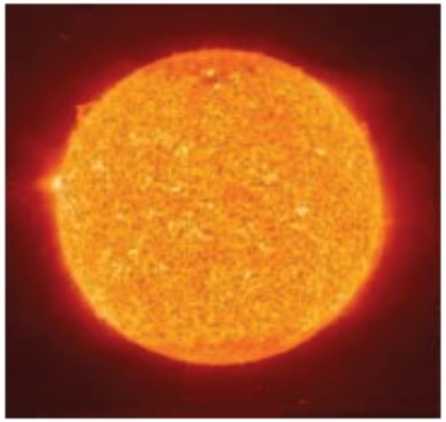
Sanjib Kumar Agarwalla

sanjib@iopb.res.in and sagarwalla@icecube.wisc.edu

Institute of Physics (IOP), Bhubaneswar, India
Department of Physics and WIPAC, UW Madison, USA

Golden Age of Neutrino Physics (1998 – 2022 & Beyond)

sun

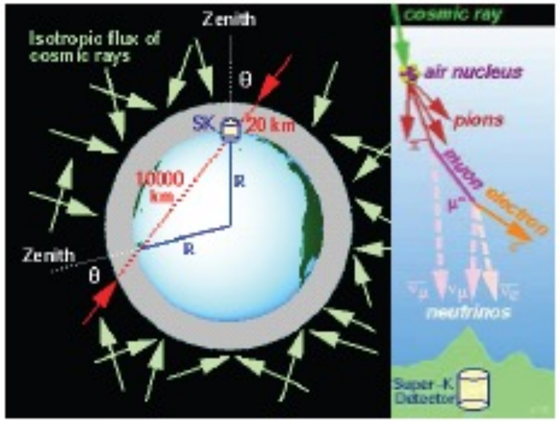


Homestake,SAGE,GALLEX
SuperK, SNO, Borexino

reactors

KamLAND, CHOOZ
Double Chooz, Daya Bay, RENO

atmosphere



SuperKamiokande
IceCube, DeepCore

accelerators

K2K, MINOS, T2K
NOvA

Over the last two decades or so, marvelous data from world-class experiments

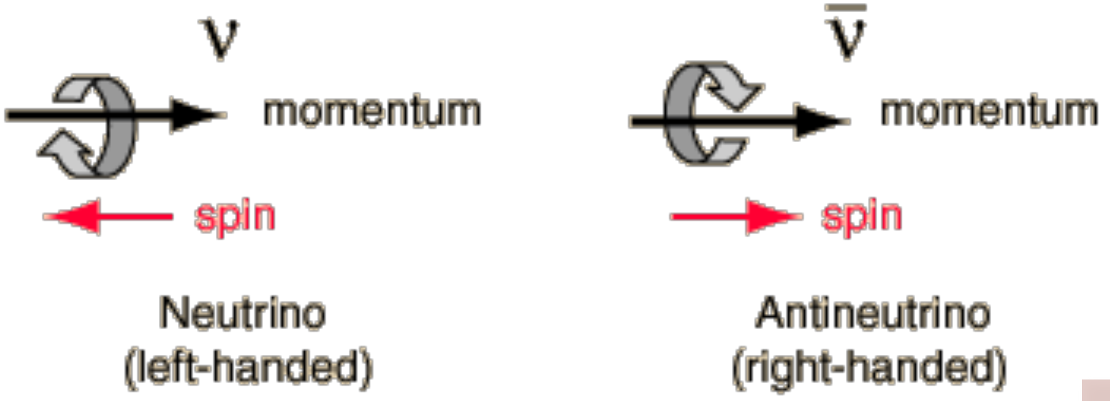
- Solar neutrinos (ν_e)
- Atmospheric neutrinos $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$
- Reactor anti-neutrinos $(\bar{\nu}_e)$
- Accelerator neutrinos $(\nu_\mu, \bar{\nu}_\mu)$

Data from various neutrino sources and vastly different energy and distance scales

Neutrinos change their flavor as they move in space and time

We have just started our journey in the mysterious world of neutrinos

The Standard Model: Massless Neutrinos



Helicity is the projection of the spin onto the direction of momentum

- **Only left-handed neutrinos**
- **No right-handed neutrinos**
- **No Dirac mass term:**

$$m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

Neutrinos are massless in the Basic SM

☐ Over the past decades, excellent data from pioneering neutrino experiments firmly established that they change flavor after propagating a finite distance

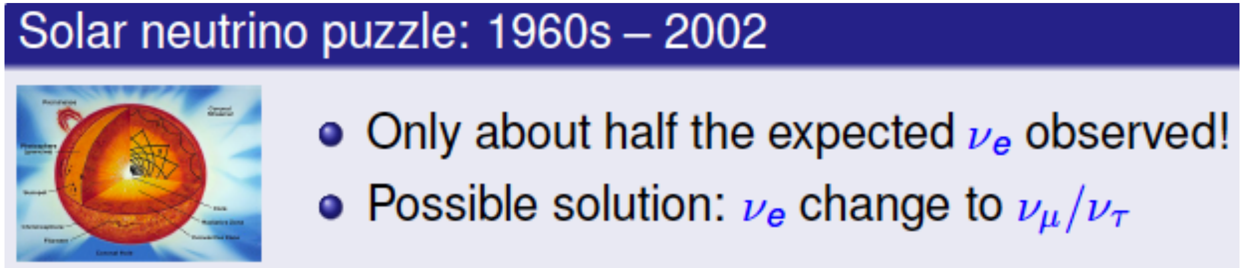
☐ Neutrino flavor change (oscillation) demands non-zero mass and mixing

Non-zero ν mass: first experimental proof for physics beyond the Standard Model

!! An extension of the Standard Model is necessary !!

Discovery of Neutrino Oscillations: Neutrinos have mass

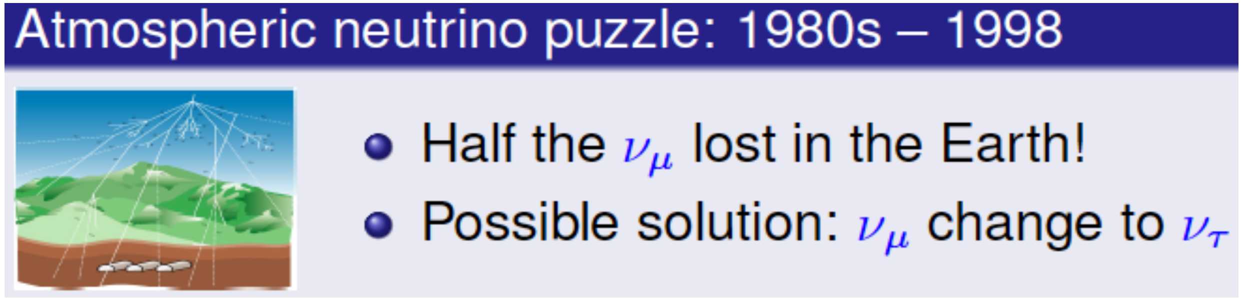
The Nobel Prize in Physics 2015



Solar neutrino puzzle: 1960s – 2002

- Only about half the expected ν_e observed!
- Possible solution: ν_e change to ν_μ/ν_τ

Arthur B. McDonald solved this puzzle at SNO



Atmospheric neutrino puzzle: 1980s – 1998

- Half the ν_μ lost in the Earth!
- Possible solution: ν_μ change to ν_τ

Takaaki Kajita solved this puzzle at Super-Kamiokande

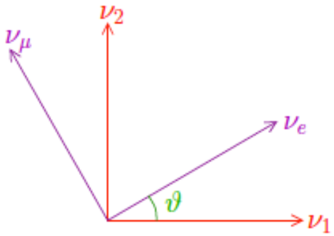
Neutrinos change their flavor ➔ Neutrinos have mass

Neutrino Flavor Oscillations

- **Flavor States :** ν_e and ν_μ (produced in weak interactions)
- **Mass Eigenstates :** ν_1 and ν_2 (propagate from source to detector)

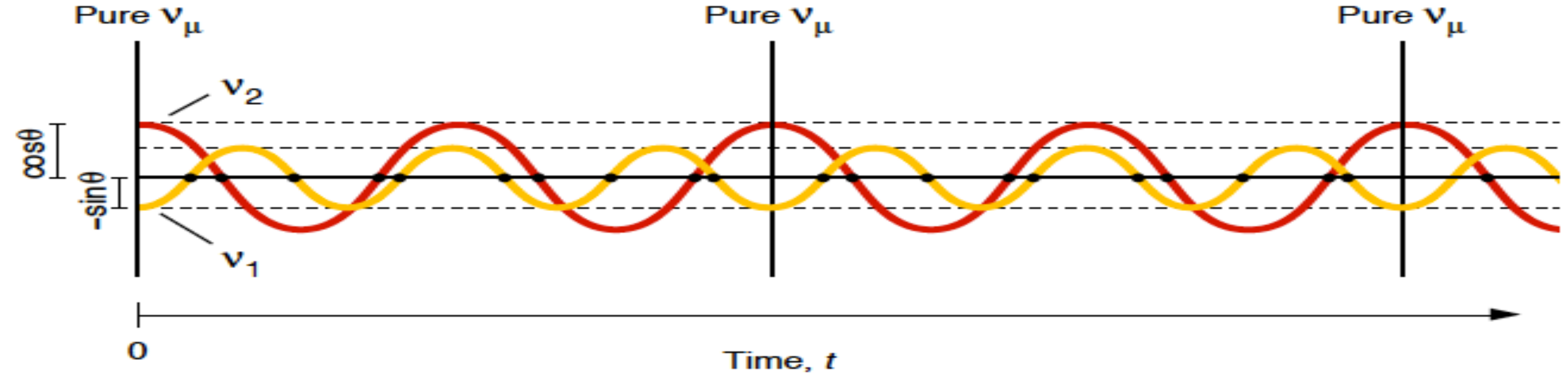
A Flavor State is a linear superposition of Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu)$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$\boxed{\begin{aligned} |\nu_e\rangle &= \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle \end{aligned}}$$



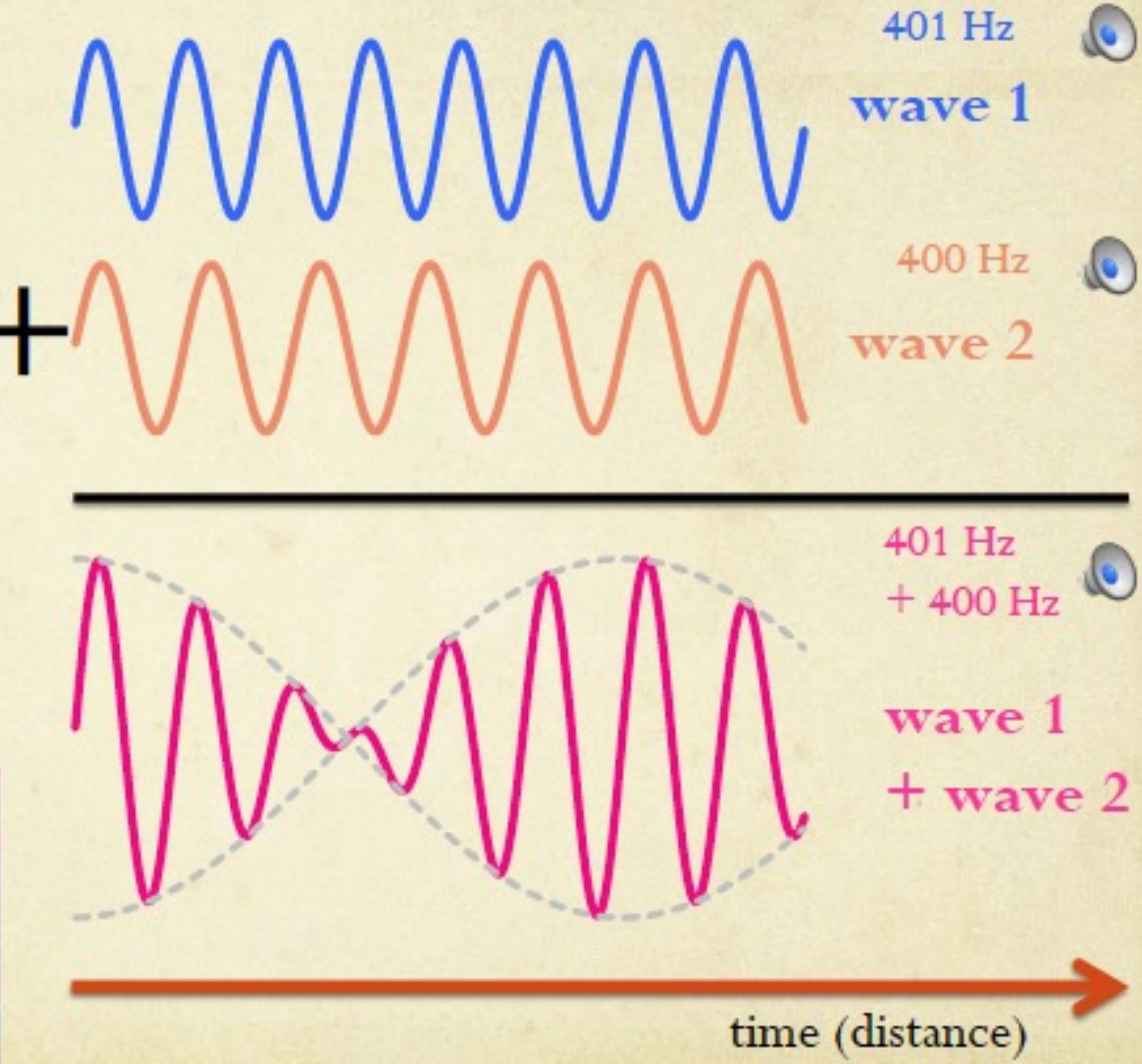
If the masses of these two states are different, then they will take different times to reach the same point and there will be a phase difference and hence interference

Neutrino Flavor Oscillations

Quantum mechanics
particle ←→ wave
mass determines frequency

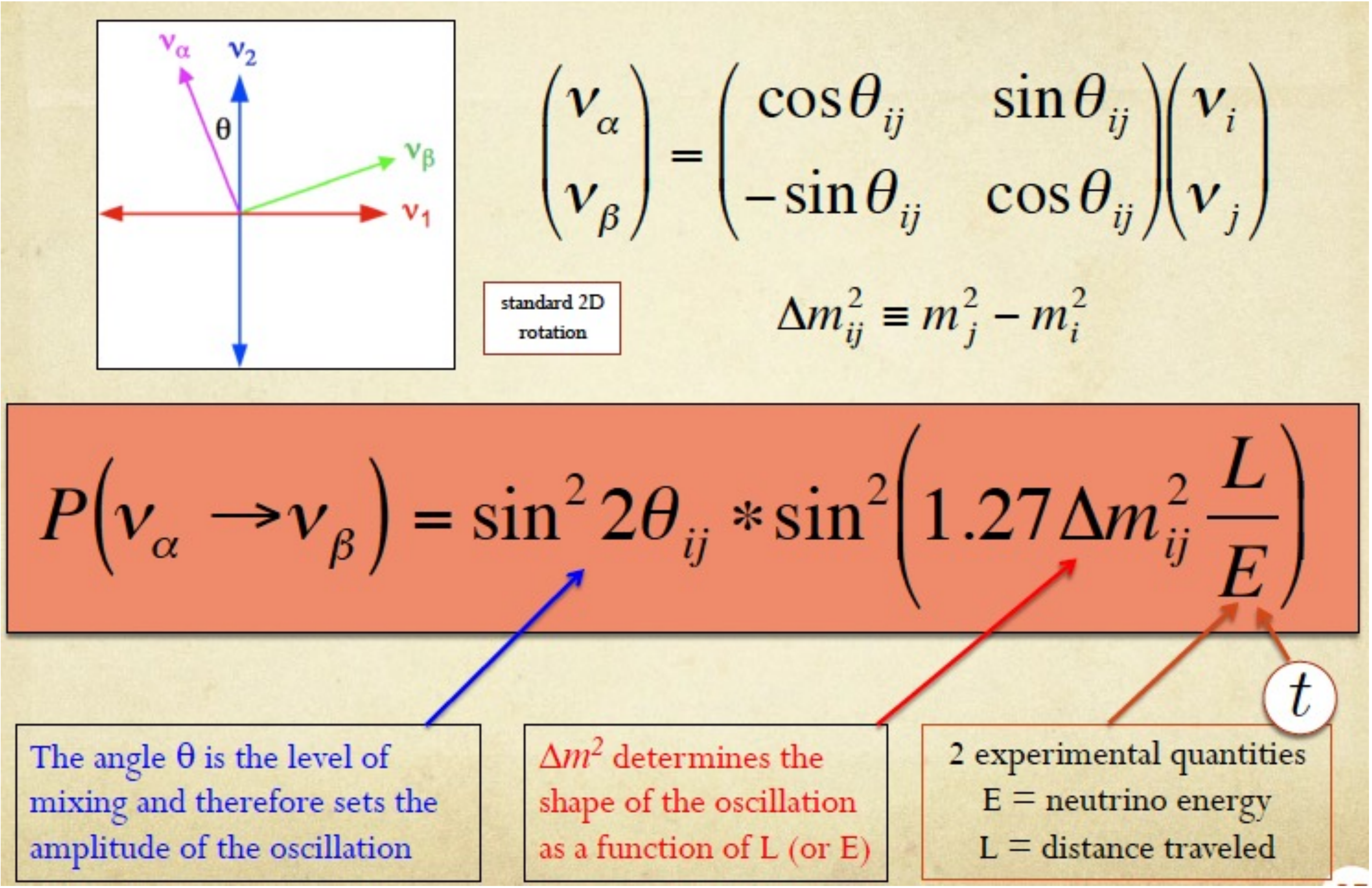
neutrinos (ν_e,ν_μ,ν_τ) are *actually* mixtures of multiple waves with *different* frequencies different masses)…

These wave functions can *interfere* and change the neutrino's flavor composition




www.scienceclarified.com

Two Neutrino Mixing



$$\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}=\begin{pmatrix}\cos\theta_{ij} & \sin\theta_{ij}\\ -\sin\theta_{ij} & \cos\theta_{ij}\end{pmatrix}\begin{pmatrix}\nu_i\\ \nu_j\end{pmatrix}$$

standard 2D rotation

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

t

The angle θ is the level of mixing and therefore sets the amplitude of the oscillation

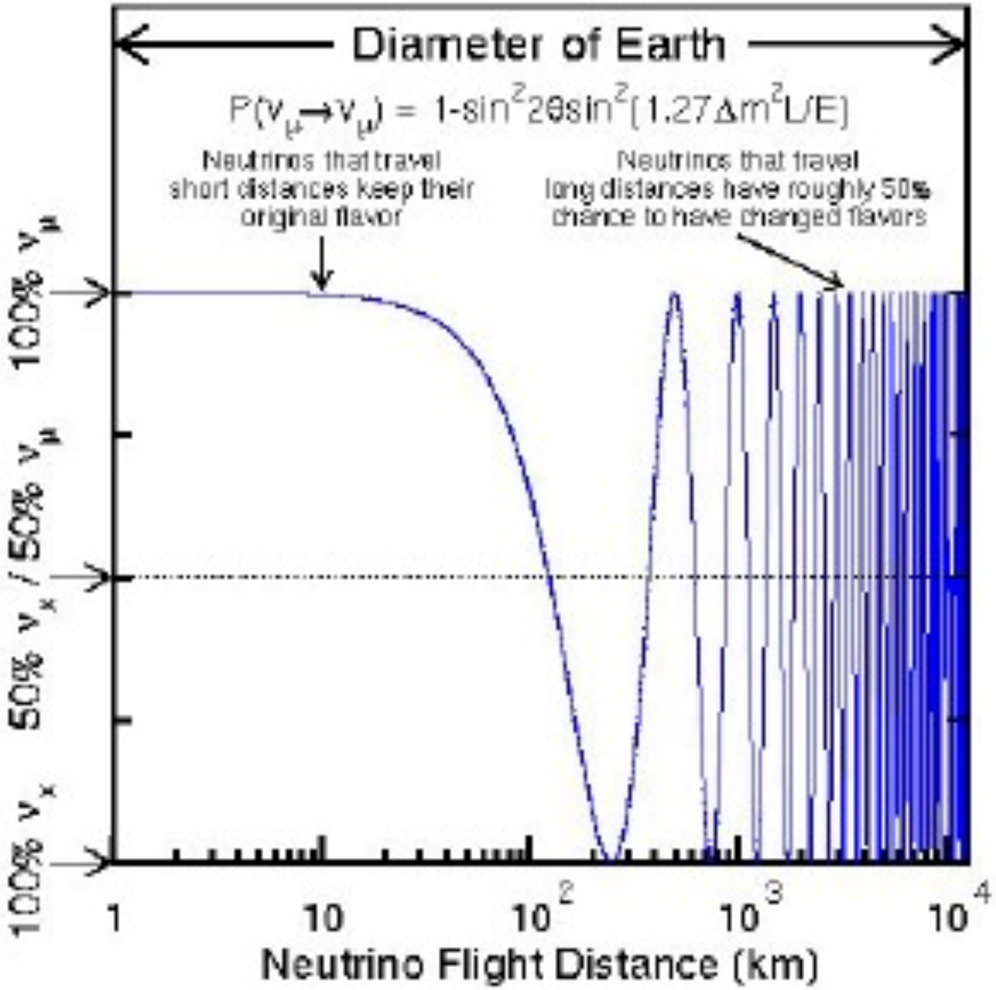
Δm^2 determines the shape of the oscillation as a function of L (or E)

2 experimental quantities

E = neutrino energy

L = distance traveled

Neutrino oscillation as a function of distance travelled



- More neutrinos 'lost' when $\cos(\Theta) < 0$

(Θ : angle made with the zenith)

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2\,(\mathrm{eV}^2)\, L\,(\mathrm{km})}{E\,(\mathrm{GeV})} \right)$$

Three Neutrino Mixing

Three neutrino mixing firmly established…

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

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

neutrino mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric & Long-baseline accelerator neutrinos

Quasi 2-neutrino mixing

Solar & Long-baseline reactor neutrinos

$$L/E = 500 \text{ km/GeV}$$

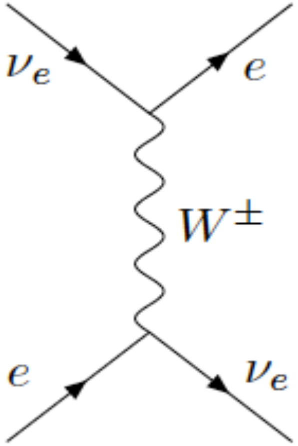
$$\Delta m^2_{31} \sim 2.5 \times 10^{-3} \text{ eV}^2$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m^2_{ij} \frac{L}{E}\right)$$

$$L/E = 15,000 \text{ km/GeV}$$

$$\Delta m^2_{21} \sim 7.6 \times 10^{-5} \text{ eV}^2$$

Neutrino Oscillations in Matter: MSW Effect



Neutrino propagation through matter modify the oscillations significantly

Coherent forward scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e

MSW matter term: $\boxed{A = \pm 2\sqrt{2} G_F N_e E}$ or $\boxed{A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})}$

N_e = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to antineutrino mode

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

→ *even if $\delta_{CP} = 0$, causes fake CP asymmetry*

Matter term modifies oscillation probability differently depending on the sign of Δm^2

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$$

→ *Resonant conversion – Matter effect*

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ *Resonance occurs for neutrinos (anti-neutrinos)*
if Δm^2 is positive (negative)

Some Things We Know and Don't Know

Three neutrino mixing firmly established…

$\theta_{12} \approx 34^\circ$

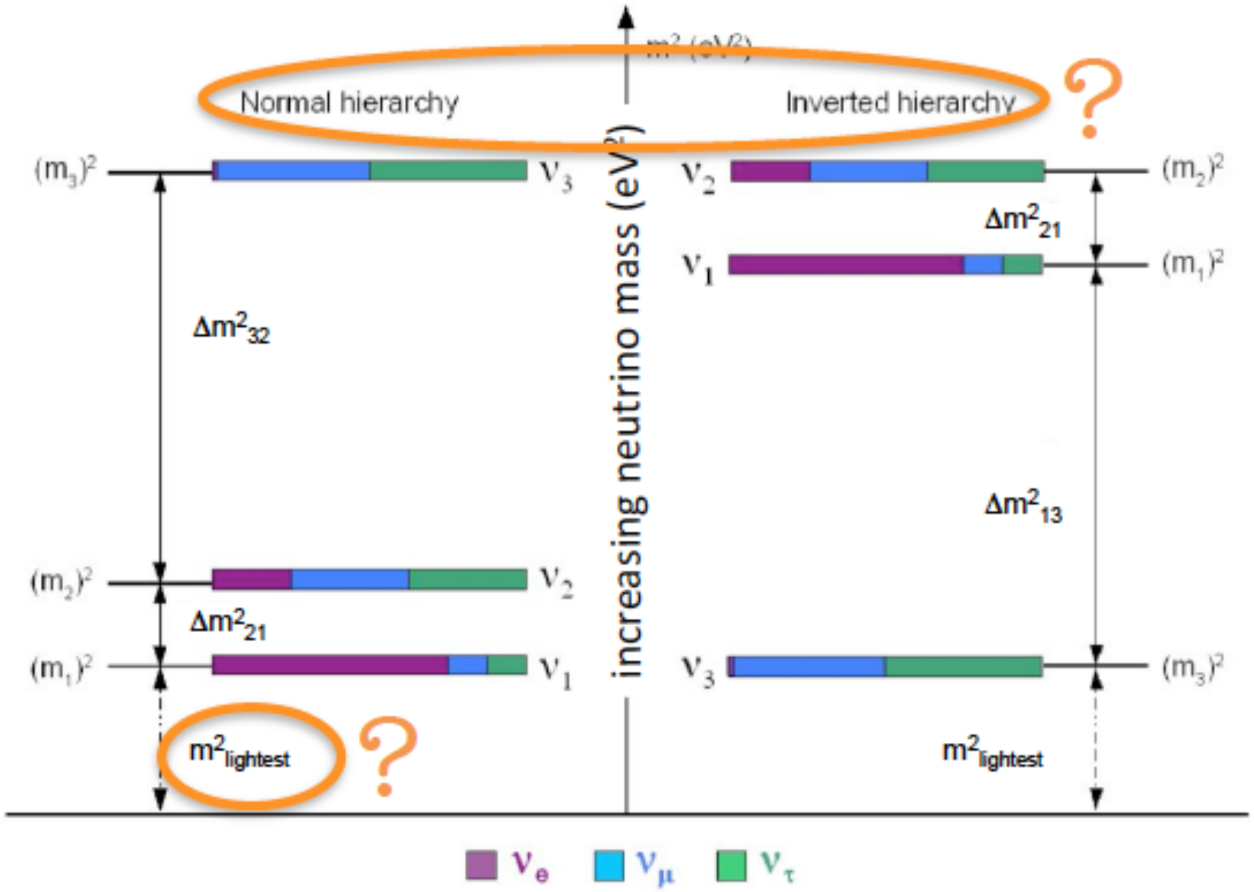
$\theta_{23} \approx 45^\circ$

$\theta_{13} \approx 9^\circ$

$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$

$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$

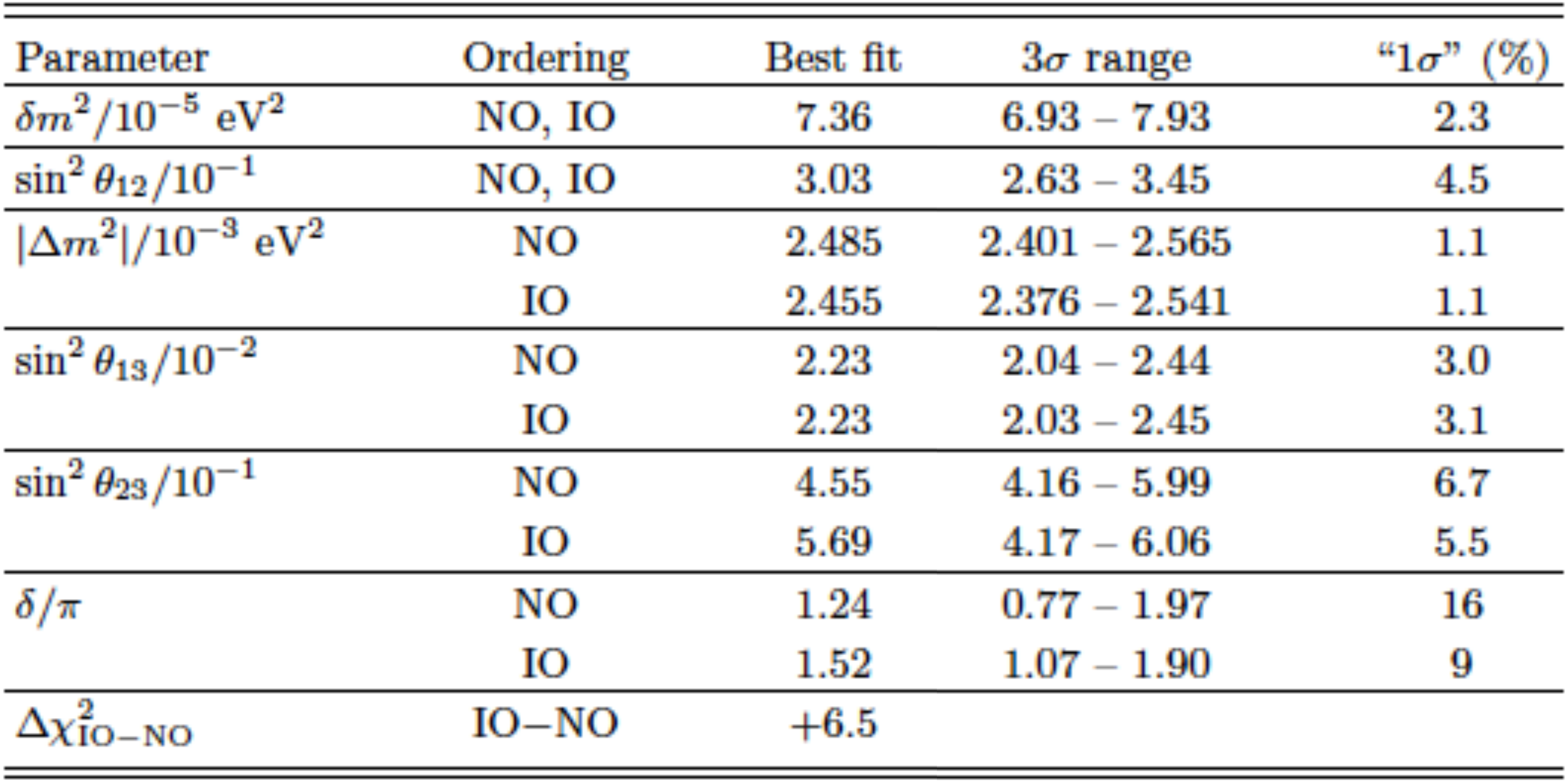
$\delta_{CP} = \ ?$?



flavor content of the mass eigenstates determined by mixing matrix elements (mixing angles) that are measured experimentally

Present Status of Neutrino Oscillation Parameters Circa 2021

Preference for Normal Mass Ordering (~ 2.5σ), $\theta_{23} < 45$ degree and sin$\boldsymbol{\delta} < 0$ (both at 90% C.L.)



Parameter	Ordering	Best fit	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.401 – 2.565	1.1
	IO	2.455	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.04 – 2.44	3.0
	IO	2.23	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.16 – 5.99	6.7
	IO	5.69	4.17 – 6.06	5.5
δ/π	NO	1.24	0.77 – 1.97	16
	IO	1.52	1.07 – 1.90	9
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+6.5		

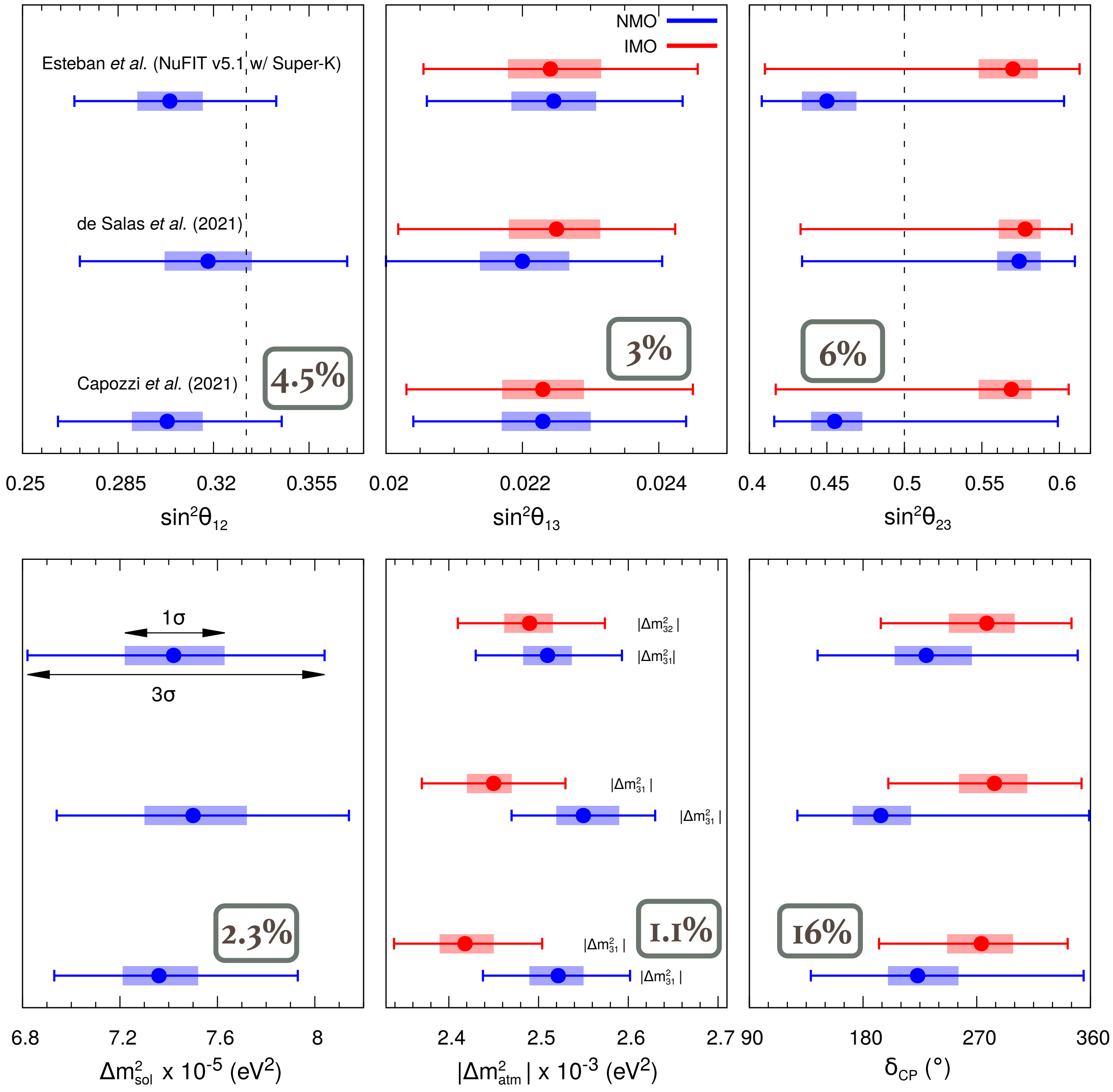
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

See also, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792v1 [hep-ph], NuFIT v5.1 w/SK

See also, de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortolla, Valle, arXiv:2006.11237v2 [hep-ph]

Remarkable Precision on Neutrino Oscillation Parameters

Robust three-flavor neutrino oscillation paradigm



Tremendous boost to search for BSM physics in 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-invariance violation, lepton number and lepton flavor violations

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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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New Physics beyond the reach of modern Colliders

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: DUNE@USA, T2HK@Japan
Atmospheric: DeepCore, DUNE, Hyper-K, INO

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

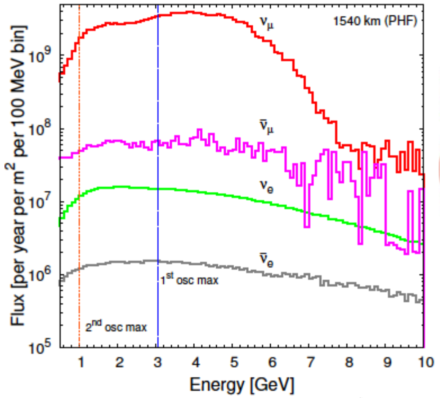
Landscape of BSM Scenarios affecting Neutrino Experiments

- 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

Courtesy M. Bustamante

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
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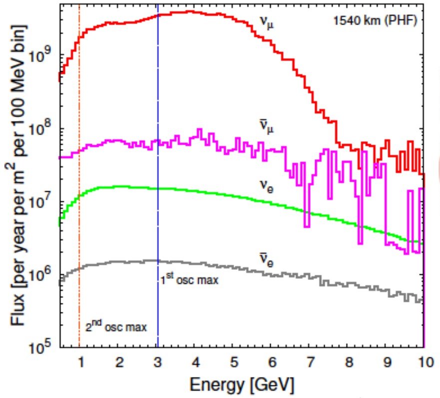
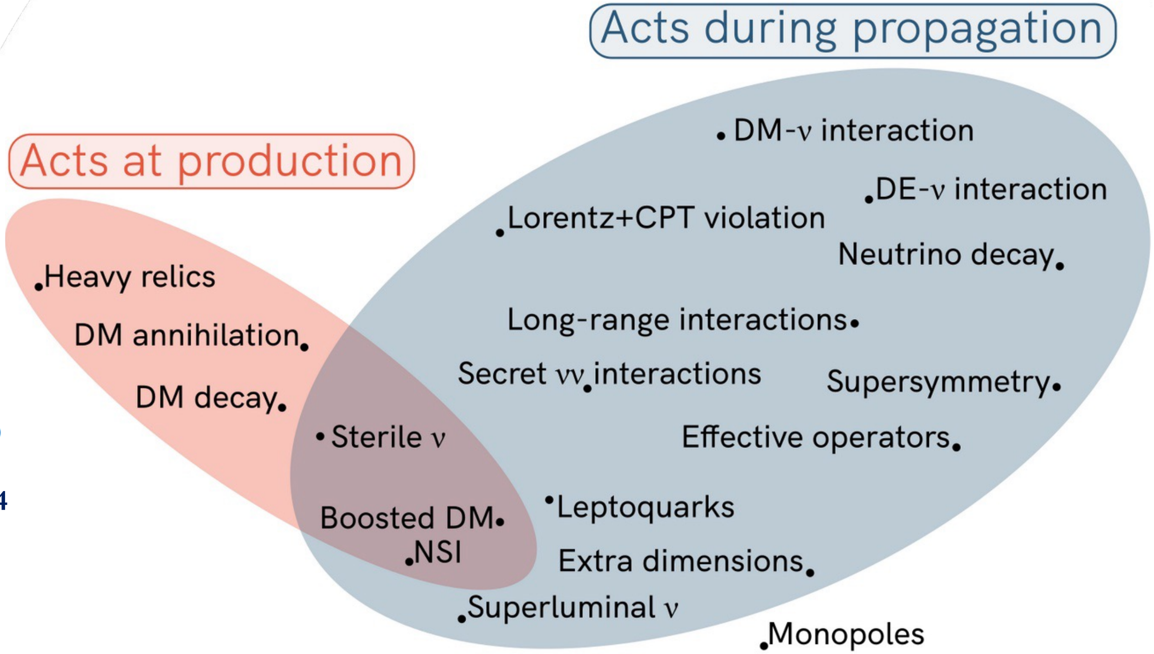


Agarwalla et al., JHEP 05 (2012) 154



Acts at production

- Heavy relics
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Acts during propagation

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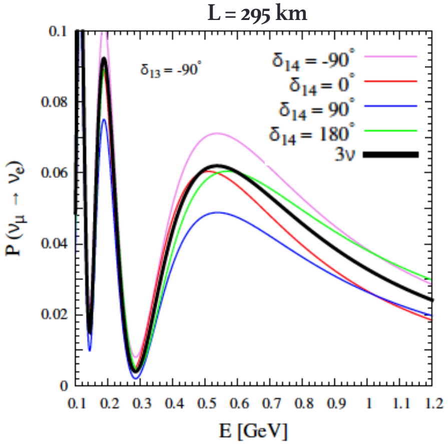
- Sterile ν
- Boosted DM
- NSI

- Monopoles

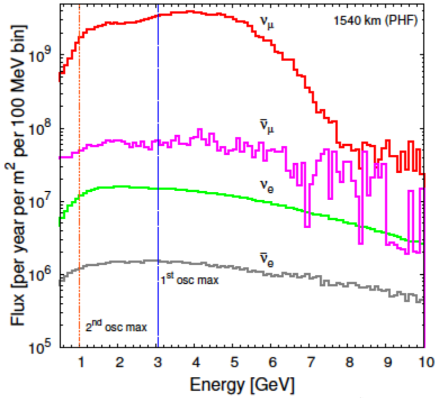
Alters neutrino flux, oscillation, mixing



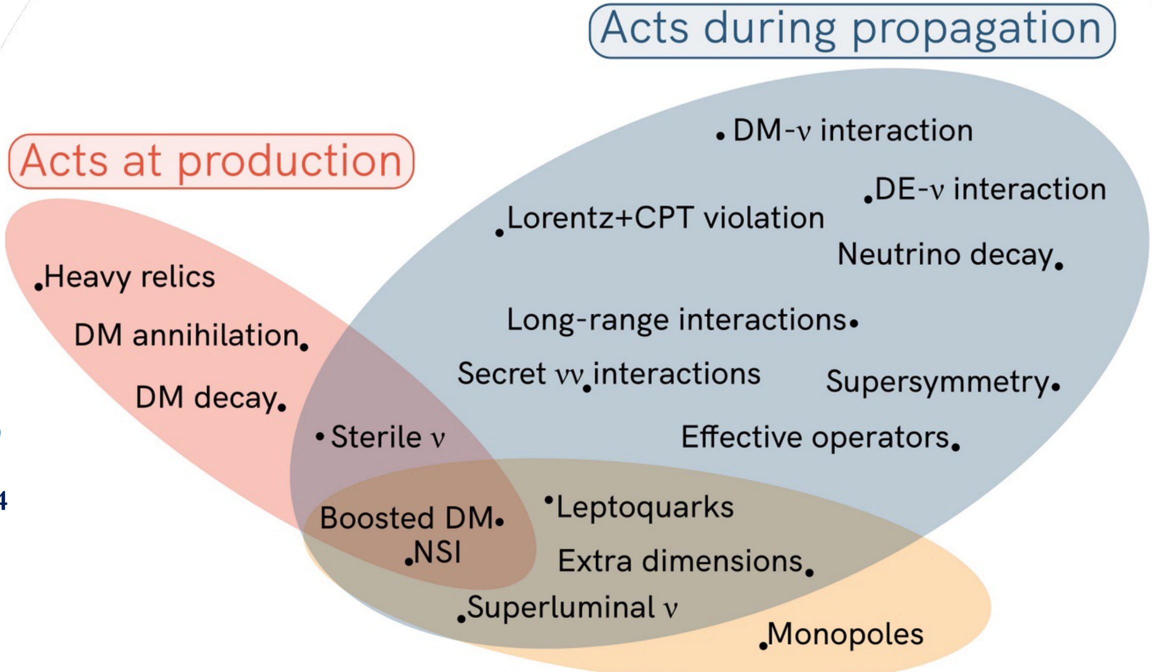
Agarwalla et al., JHEP 02 (2016) 111

Landscape of BSM Scenarios affecting Neutrino Experiments

Alters neutrino flux



Agarwalla et al., JHEP 05 (2012) 154



Acts at production

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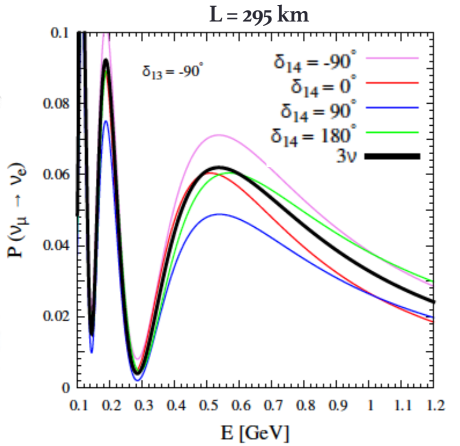
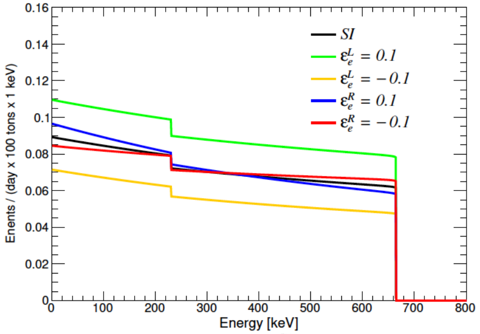


Agarwalla et al., JHEP 02 (2016) 111



Agarwalla et al., JHEP 02 (2020) 038

Acts at detection

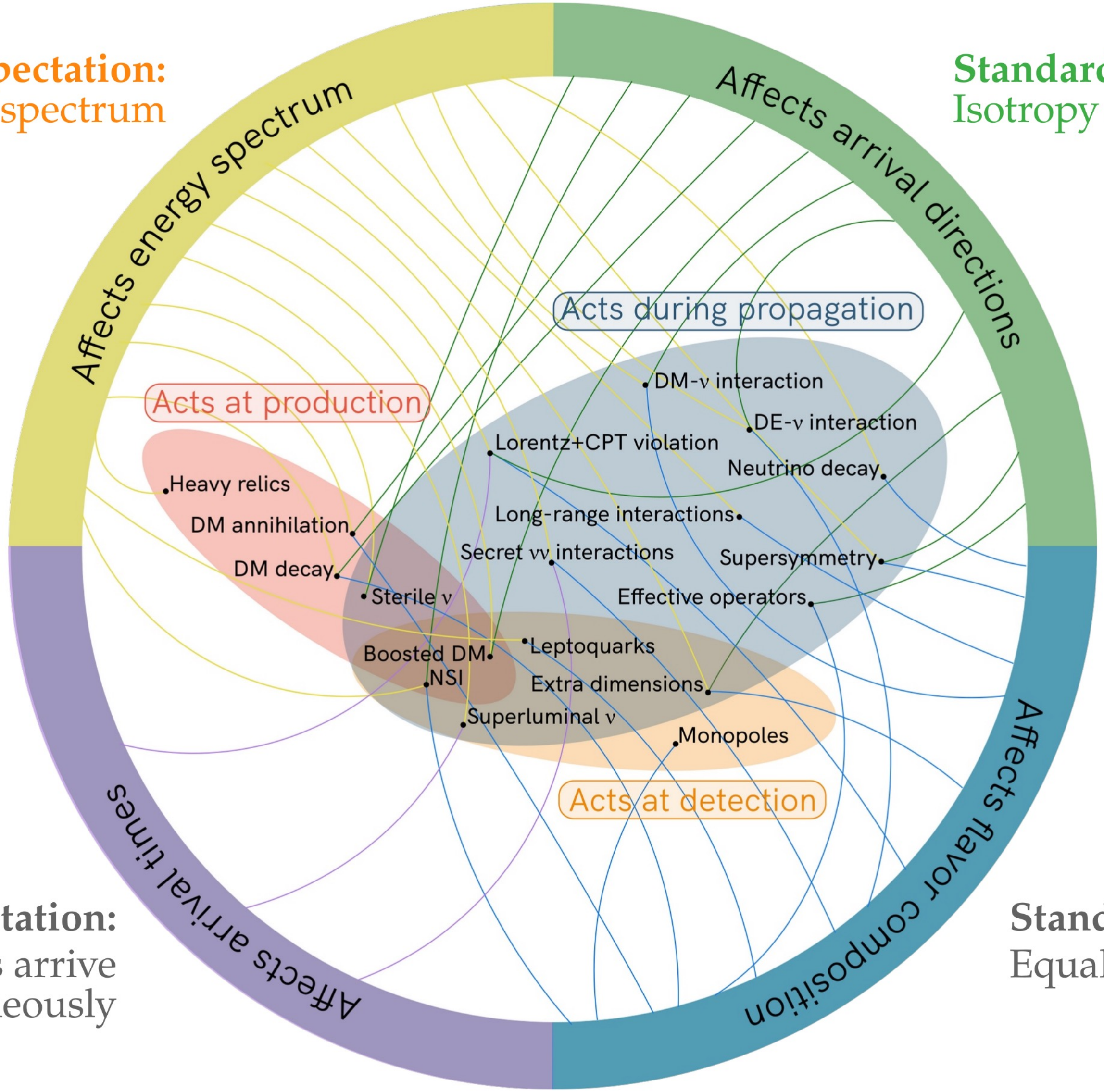
Alters neutrino detection cross sections

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**

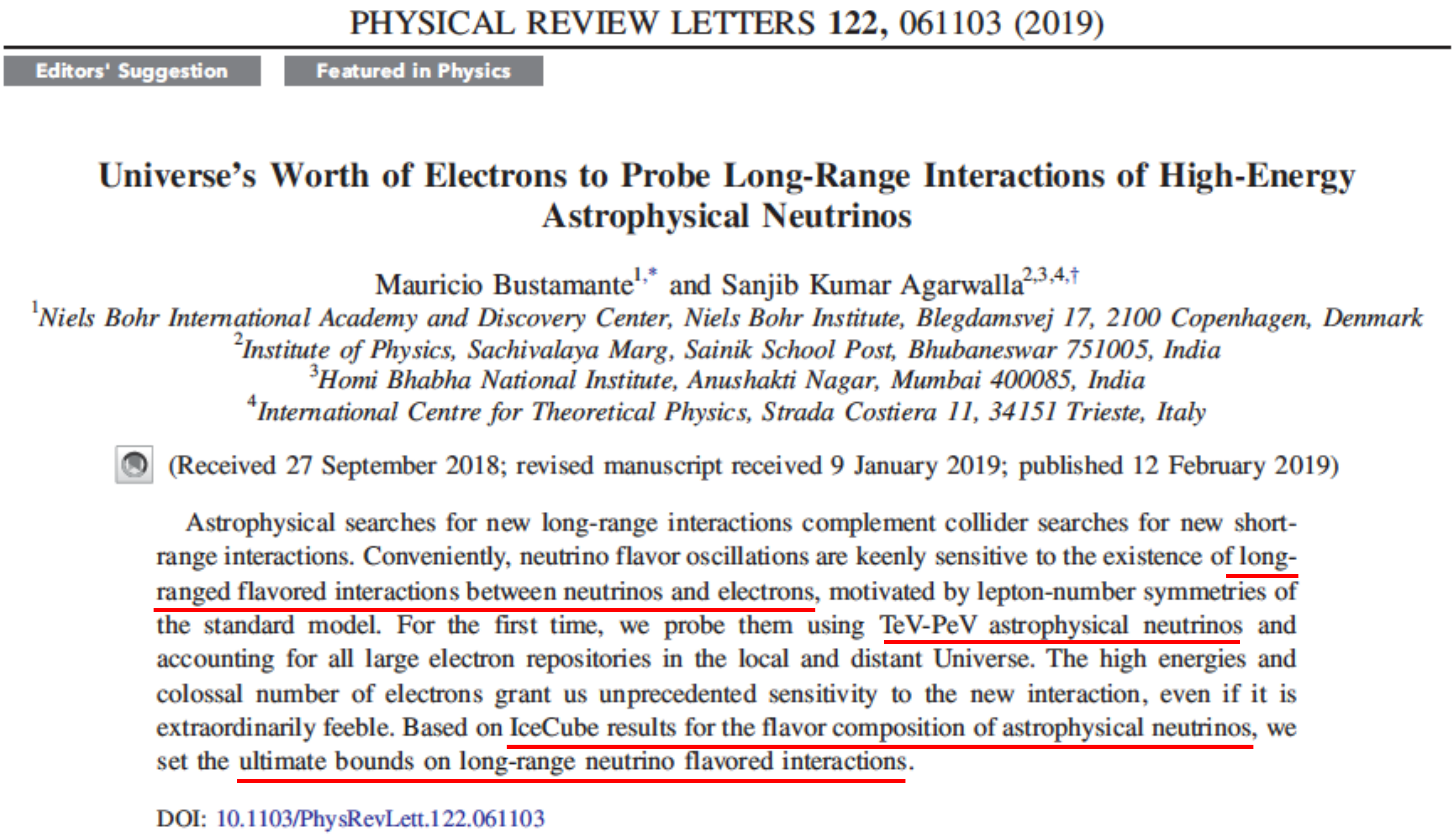
**For applications, see:
Song, Li, Arguelles,
Bustamante, Vincent,
arXiv: 2012.12893 [hep-ph]**

Standard expectation:
ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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

Ultimate Bounds on Long-Range Interactions



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

Editors' Suggestion Featured in Physics

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

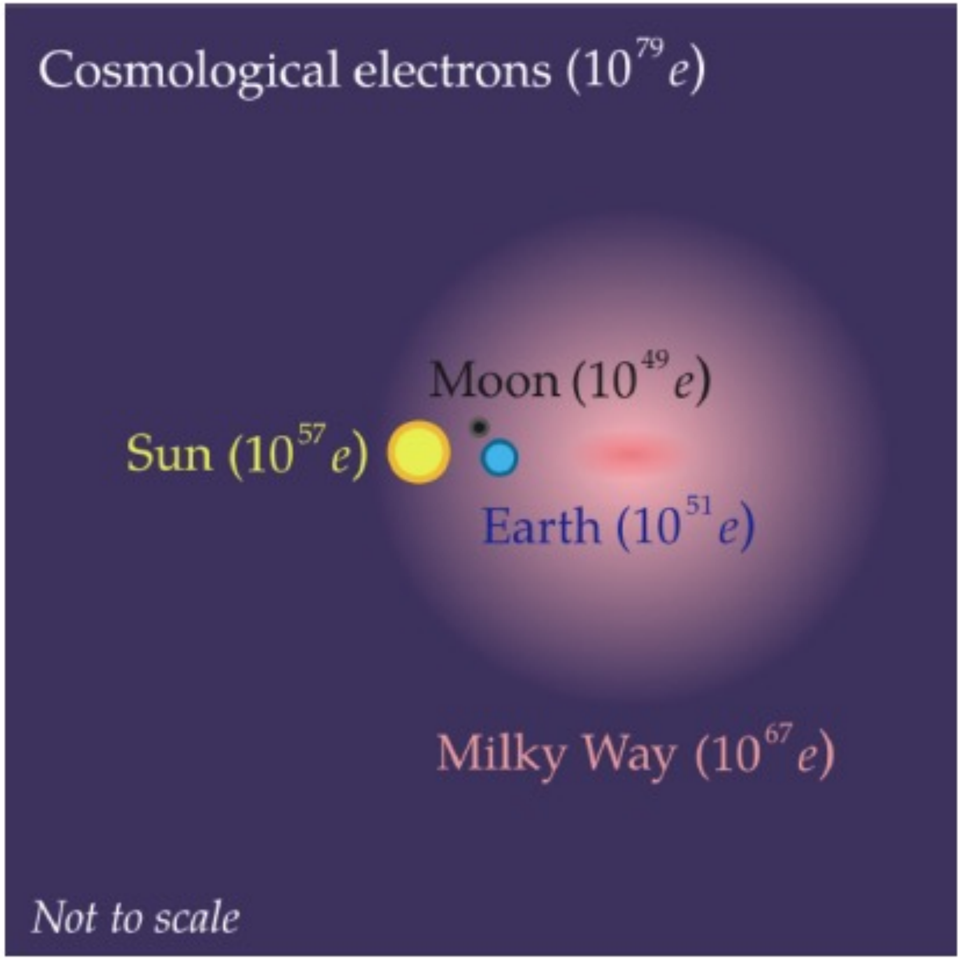
Mauricio Bustamante[1,*] and Sanjib Kumar Agarwalla[2,3,4,†]
[1]*Niels Bohr International Academy and Discovery Center, Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[2]*Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*
[3]*Homi Bhabha National Institute, Anushakti Nagar, Mumbai 400085, India*
[4]*International Centre for Theoretical Physics, Strada Costiera 11, 34151 Trieste, Italy*

(Received 27 September 2018; revised manuscript received 9 January 2019; published 12 February 2019)

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_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

Z′ coupling

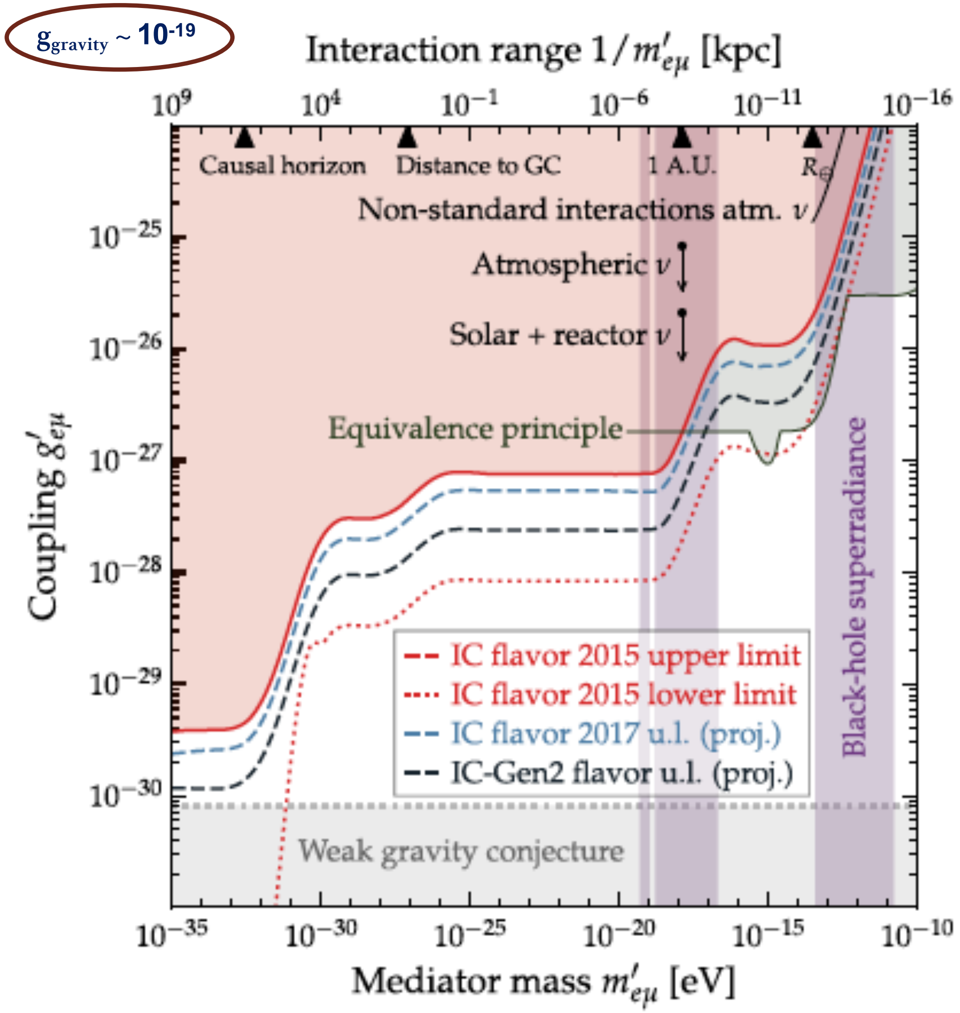
Z′ mass

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

Distance to neutrino

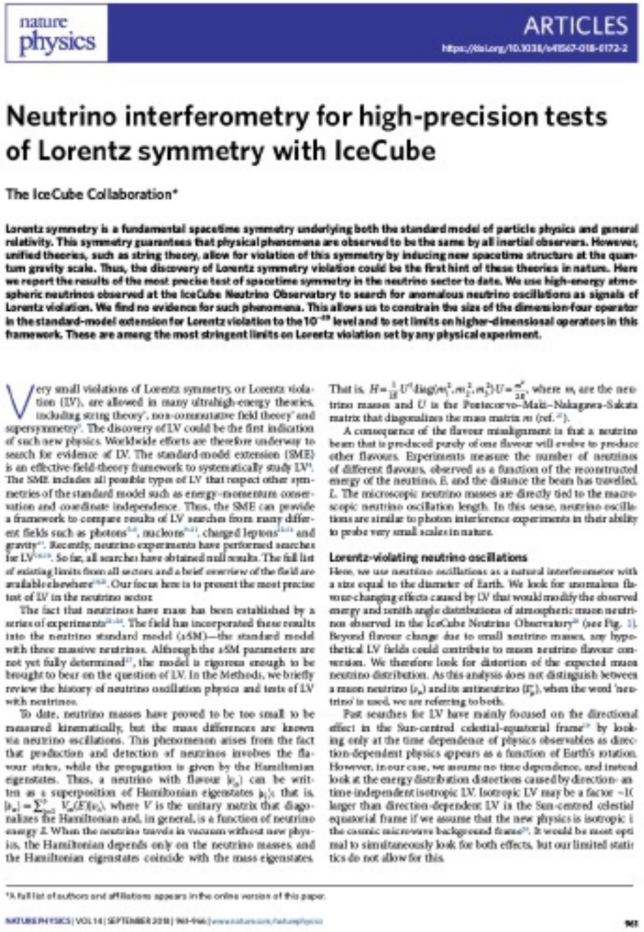
A neutrino "feels" all the electrons within the interaction range ~$(1/m')$

$g_{\text{gravity}} \sim 10^{-19}$



Test of Lorentz Violation with Atmospheric Neutrinos @ IceCube

Nature Physics vol. 14, p 961-966 (2018)



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Neutrino interferometry for high-precision tests of Lorentz symmetry with IceCube

The IceCube Collaboration*

Lorentz symmetry is a fundamental spacetime symmetry underlying both the standard model of particle physics and general relativity. This symmetry guarantees that physical phenomena are observed to be the same by all inertial observers. However, unified theories, such as string theory, allow for violation of this symmetry by inducing new spacetime structure at the quantum gravity scale. Thus, the discovery of Lorentz symmetry violation could be the first hint of these theories in nature. Here we report the results of the most precise test of spacetime symmetry in the neutrino sector to date. We use high-energy atmospheric neutrinos observed at the IceCube Neutrino Observatory to search for anomalous neutrino oscillations as signals of Lorentz violation. We find no evidence for such phenomena. This allows us to constrain the size of the dimension-four operator in the standard-model extension for Lorentz violation to the 10^{-28} level and to set limits on higher-dimensional operators in this framework. These are among the most stringent limits on Lorentz violation set by any physical experiment.

Very small violations of Lorentz symmetry, or Lorentz violation (LV), are allowed in many ultrahigh-energy theories, including string theory, non-commutative field theory and supersymmetry. The discovery of LV could be the first indication of such new physics. Worldwide efforts are therefore underway to search for evidence of LV. The standard-model extension (SME) is an effective-field-theory framework to systematically study LV. The SME includes all possible types of LV that respect other symmetries of the standard model such as energy–momentum conservation and coordinate independence. Thus, the SME can provide a framework to compare results of LV searches from many different fields such as photons, nucleons, charged leptons and gravity. Recently, neutrino experiments have performed searches for LV. So far, all searches have obtained null results. The full list of existing limits from all sectors and a brief overview of the field are available elsewhere. Our focus here is to present the most precise test of LV in the neutrino sector.

The fact that neutrinos have mass has been established by a series of experiments. The field has incorporated these results into the neutrino standard model (νSM)—the standard model with three massive neutrinos. Although the νSM parameters are not yet fully determined, the model is rigorous enough to be brought to bear on the question of LV. In the Methods, we briefly review the history of neutrino oscillation physics and tests of LV with neutrinos.

To date, neutrino masses have proved to be too small to be measured kinematically, but the mass differences are known via neutrino oscillations. This phenomenon arises from the fact that production and detection of neutrinos involves the flavour states, while the propagation is given by the Hamiltonian eigenstates. Thus, a neutrino with flavour $|\nu_\alpha\rangle$ can be written as a superposition of Hamiltonian eigenstates $|\nu_i\rangle$; that is, $|\nu_\alpha\rangle = \sum_{i=1}^{3} V_{\alpha i}(E)|\nu_i\rangle$, where V is the unitary matrix that diagonalizes the Hamiltonian and, in general, is a function of neutrino energy E. When the neutrino travels in vacuum without new physics, the Hamiltonian depends only on the neutrino masses, and the Hamiltonian eigenstates coincide with the mass eigenstates. That is, $H = \frac{1}{2E} U^{\dagger}\mathrm{diag}(m_1^2, m_2^2, m_3^2)U = \frac{m^2}{2E}$, where m_i are the neutrino masses and U is the Pontecorvo–Maki–Nakagawa–Sakata matrix that diagonalizes the mass matrix m (ref.).

A consequence of the flavour misalignment is that a neutrino beam that is produced purely of one flavour will evolve to produce other flavours. Experiments measure the number of neutrinos of different flavours, observed as a function of the reconstructed energy of the neutrino, E, and the distance the beam has travelled, L. The microscopic neutrino masses are directly tied to the macroscopic neutrino oscillation length. In this sense, neutrino oscillations are similar to photon interference experiments in their ability to probe very small scales in nature.

Lorentz-violating neutrino oscillations

Here, we use neutrino oscillations as a natural interferometer with a size equal to the diameter of Earth. We look for anomalous flavour-changing effects caused by LV that would modify the observed energy and zenith angle distributions of atmospheric muon neutrinos observed in the IceCube Neutrino Observatory (see Fig. 1). Beyond flavour change due to small neutrino masses, any hypothetical LV fields could contribute to muon neutrino flavour conversion. We therefore look for distortion of the expected muon neutrino distribution. As this analysis does not distinguish between a muon neutrino (ν_μ) and its antineutrino ($\bar{\nu}_\mu$), when the word 'neutrino' is used, we are referring to both.

Past searches for LV have mainly focused on the directional effect in the Sun-centred celestial-equatorial frame by looking only at the time dependence of physics observables as direction-dependent physics appears as a function of Earth's rotation. However, in our case, we assume no time dependence, and instead look at the energy distribution distortions caused by direction- an time-independent isotropic LV. Isotropic LV may be a factor ~1(larger than direction-dependent LV in the Sun-centred celestial equatorial frame if we assume that the new physics is isotropic i the cosmic microwave background frame. It would be most opti mal to simultaneously look for both effects, but our limited statis tics do not allow for this.

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*A full list of authors and affiliations appears in the online version of this paper.

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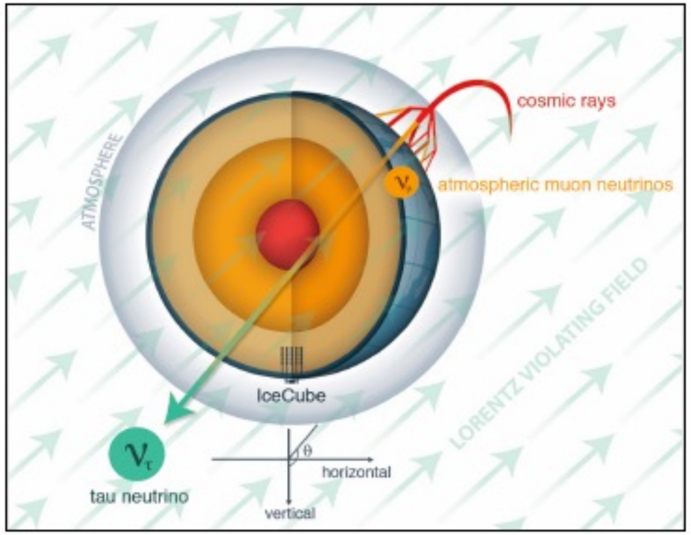

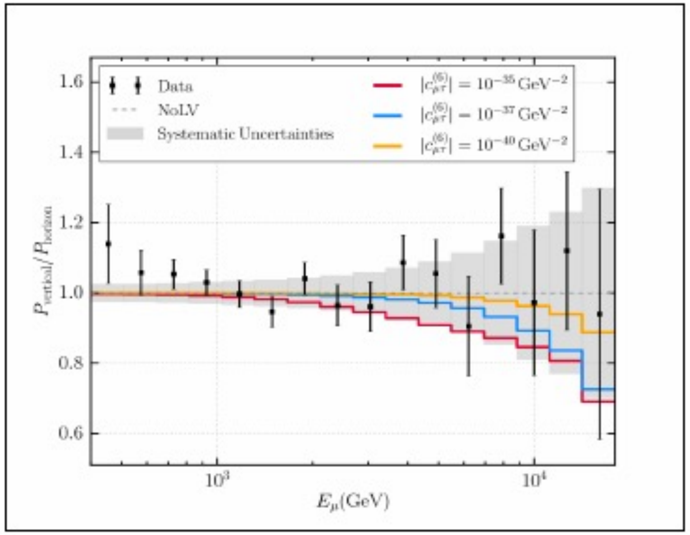

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \ldots$$

$$|\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})|, |\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})| \begin{array}{l} < 2.9 \times 10^{-24}\ \mathrm{GeV}\ (99\%\ \mathrm{C.L.}) \\ < 2.0 \times 10^{-24}\ \mathrm{GeV}\ (90\%\ \mathrm{C.L.}) \end{array}$$

2 years of IceCube data ~ 35,000 atmospheric muon neutrino events with E < 20 TeV and $-1 < \cos\theta < 0.2$

Concluding Remarks

High-energy astrophysical neutrinos detected by IceCube 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 current or upcoming high-precision neutrino oscillation experiments as the precision on the neutrino oscillation parameters and CP violation measurements continue to improve in the near future. IceCube/DeepCore and its upgrade are going to play a crucial role along this direction

BSM physics may become the dominant physics topics of next generation neutrino experiments

So, let us explore the vast landscape of neutrino oscillations and BSM physics with IceCube at South Pole

Thank you!

Motivation for BSM Searches in Neutrino Experiments

- Physics beyond the Standard Model (BSM) has manifested itself in one clear way – neutrino masses are non-zero

- Rich experimental program in neutrino physics for the coming decade or two to validate the three-neutrino paradigm and to have extensive search for BSM physics

- The upcoming high-precision neutrino oscillation experiments are expected to determine the neutrino mass ordering, mixing angles, and CP violation at high C.L. and to provide a rigorous test of the three-flavor neutrino oscillation framework at various baselines (L) and energies (E) in the presence of Earth's matter effect

- These facilities are supposed to measure the mixing angles and mass-squared differences with a precision around *few %* and therefore, these next generation neutrino experiments may be sensitive to various BSM scenarios at low-energies

- BSM searches in low-energy neutrino experiments complement the quest for new physics at the ongoing LHC and future collider facilities at high-energies

Few Interesting Issues in Neutrino BSM Physics

- **To what extent does the three-flavor neutrino oscillation framework describe Nature?**

- Can future high-precision neutrino oscillation experiments reveal the presence of new fundamental particles or interactions?

- How do the oscillation parameters get modified in the presence of flavor conserving and flavor violating non-standard interactions (NSIs) of the neutrino inside the Earth matter?

- Can we Improve the constraints on NSIs using upcoming scattering and oscillation data?

- How many neutrino species are there? Do sterile neutrinos exist? How can they affect the measurements of various oscillation parameters in neutrino experiments?

- Possibility of new sources of CP violation due to the new phases with a light sterile neutrino?

- How can we discriminate between various new physics models in neutrino experiments?

- Importance of second oscillation maximum, spectral information, near detector, highly precise tracking and energy measurements, low energy thresholds, excellent timing resolution, charge identification capabilities, hadron energy information (inelasticity)

- **Machine learning techniques in data analysis to develop improved selection criteria**