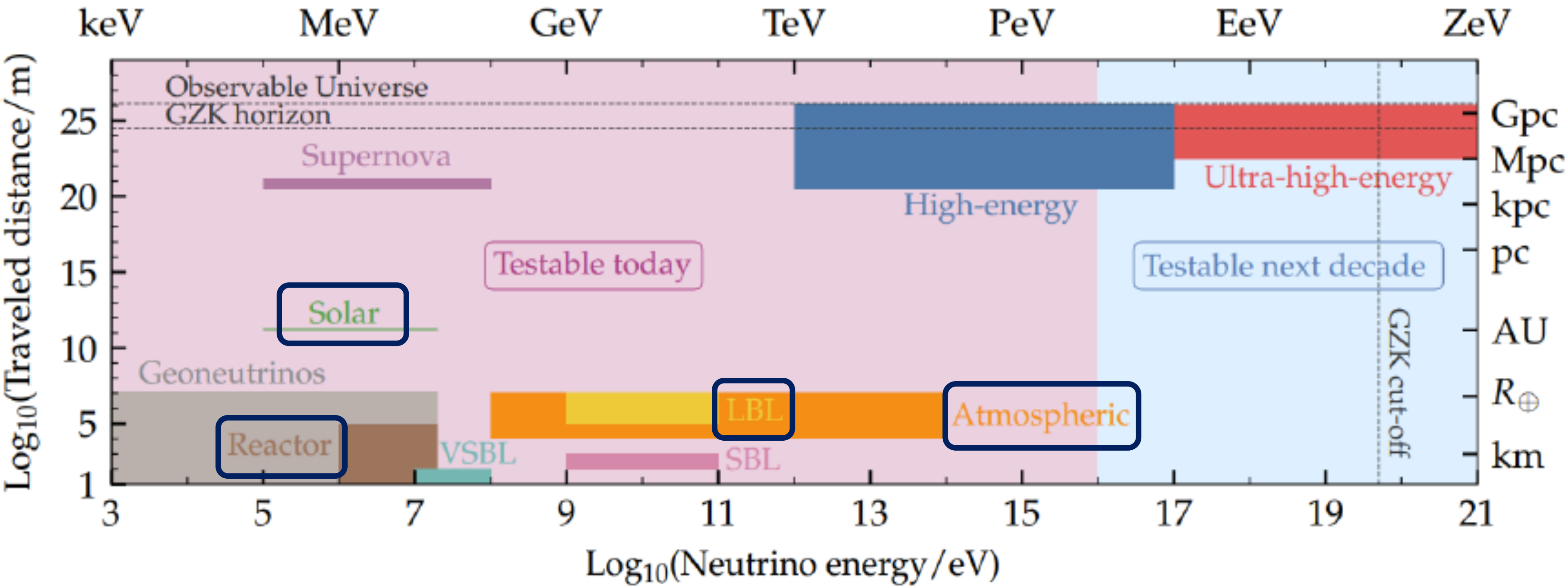
Beyond the Standard Model Searches in Neutrino Experiments

Sanjib Kumar Agarwalla
sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India

Neutrino Oscillation – A Signature for BSM Physics



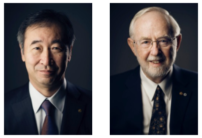
Neutrinos change their flavor as they move in space and time → Neutrinos Oscillate

Solar, Atmospheric, Reactor, and Accelerator (LBL) experiments firmly established Neutrino Flavor Oscillation → implies Neutrinos are Massive and Mix with each other

Neutrinos are Massless in the basic Standard Model (SM) of particle physics

Physics beyond the Standard Model (BSM) necessary to explain non-zero ν mass & mixing

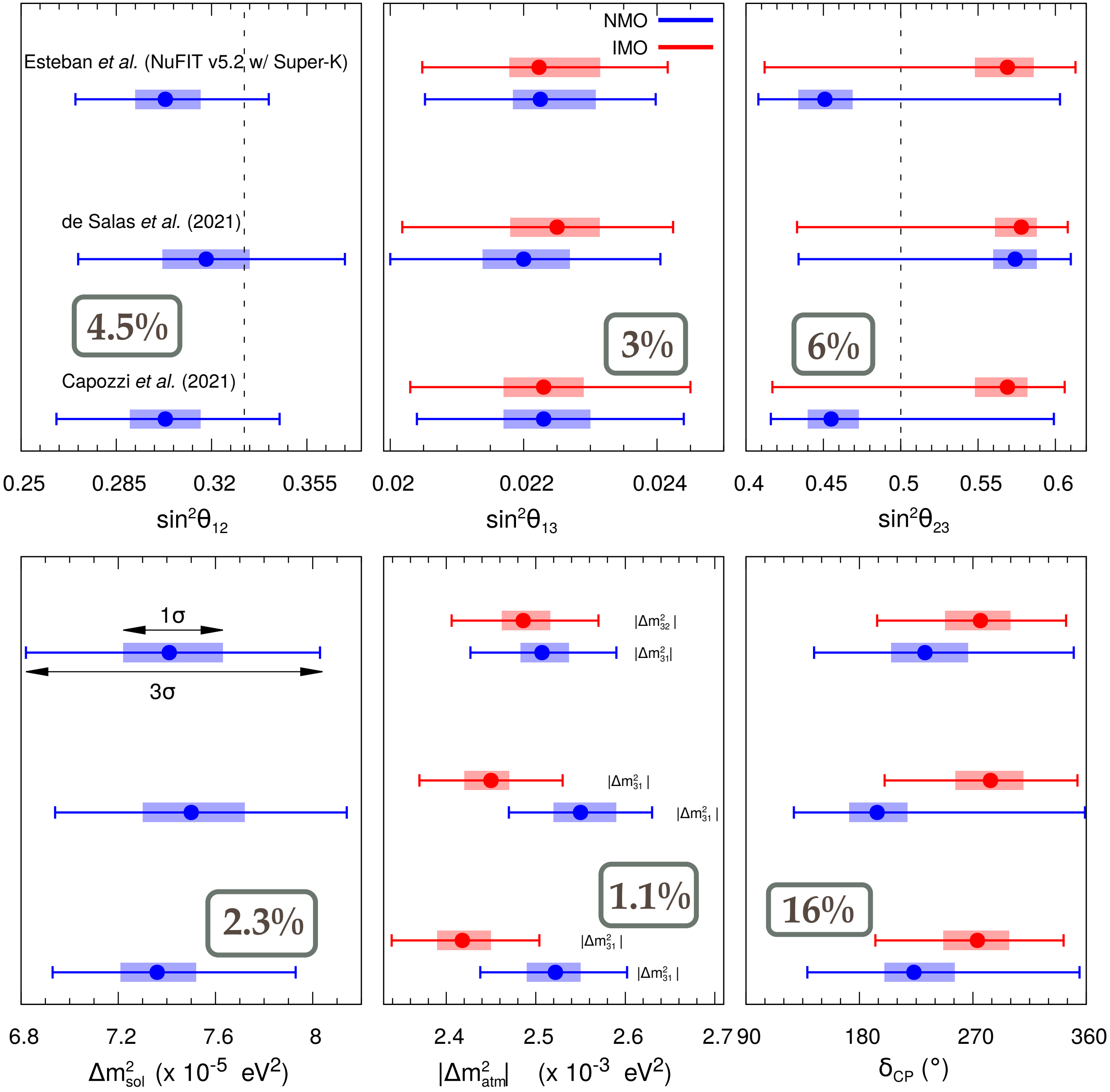
2015 Nobel Prize to Takaaki Kajita (Super-K) & Arthur B. McDonald (SNO)



S. K. Agarwalla, PASCOS 2024, ICISE, Quy Nhon, Vietnam, 10th July 2024

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)

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

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: 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

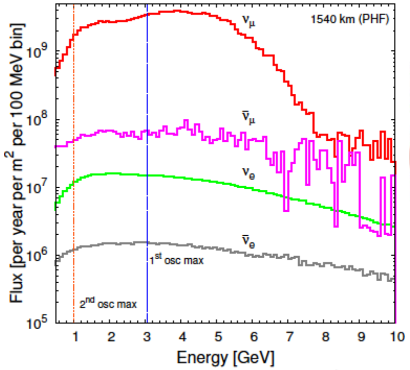
Superluminal ν

Monopoles

Courtesy Mauricio 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
- Sterile ν
- Boosted DM
- NSI

- DM-ν interaction
- Lorentz+CPT violation
- DE-ν interaction
- Neutrino decay
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- Secret νν interactions
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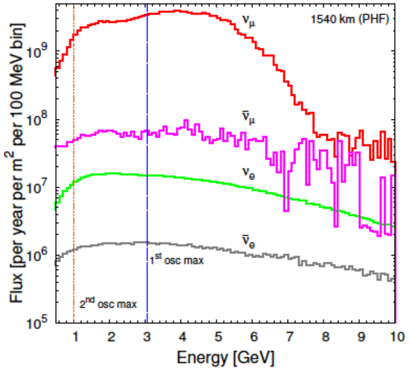
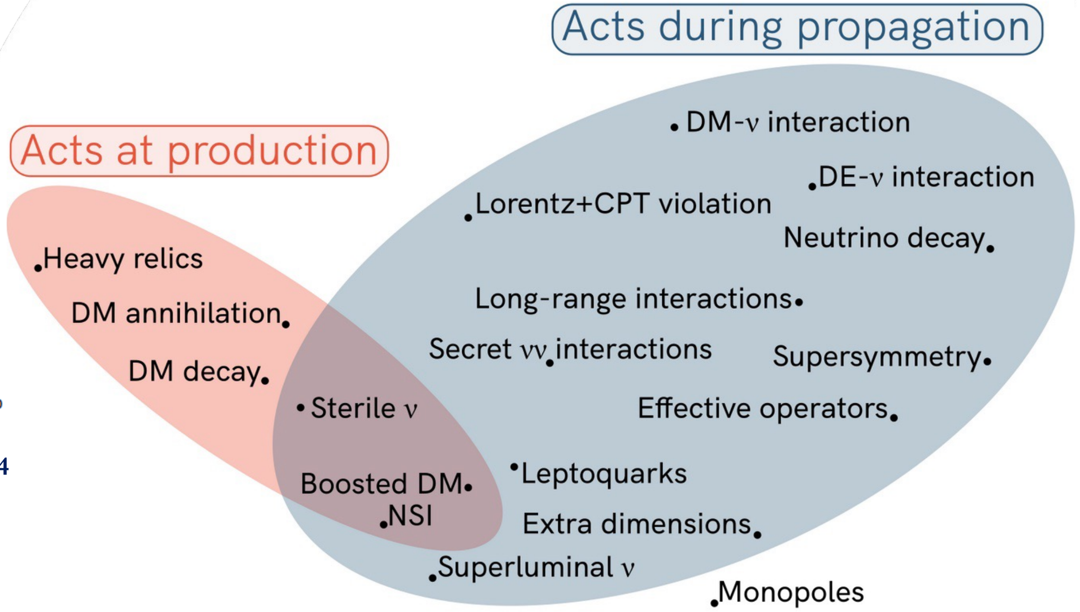


Agarwalla et al., JHEP 05 (2012) 154



Acts at production

Acts during propagation

- Heavy relics
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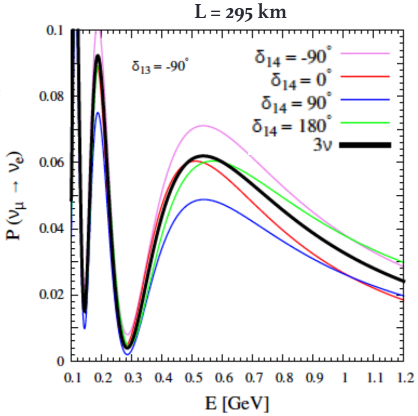
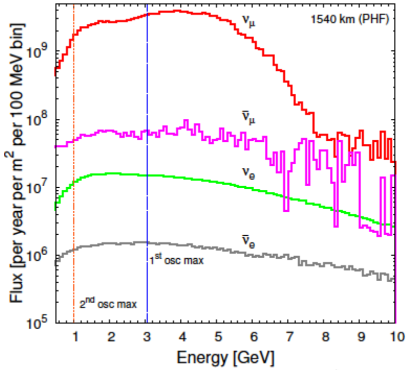
Alters neutrino flux, oscillation, mixing



Agarwalla et al., JHEP 02 (2016) 111

Landscape of BSM Scenarios affecting Neutrino Experiments

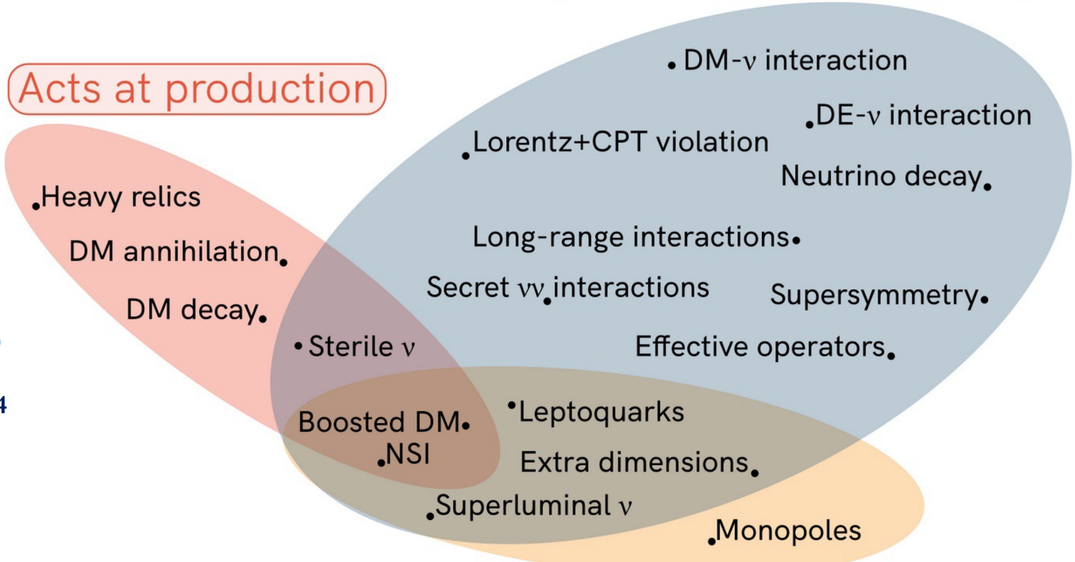
Alters neutrino flux



Agarwalla et al., JHEP 05 (2012) 154

Acts at production

Acts during propagation



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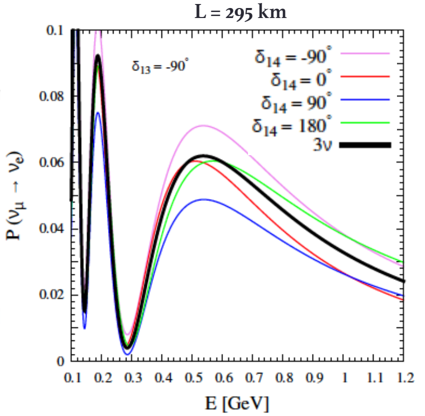
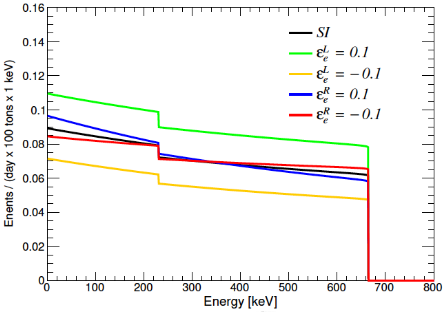


Agarwalla et al., JHEP 02 (2016) 111



Agarwalla et al., JHEP 02 (2020) 038

Acts at detection

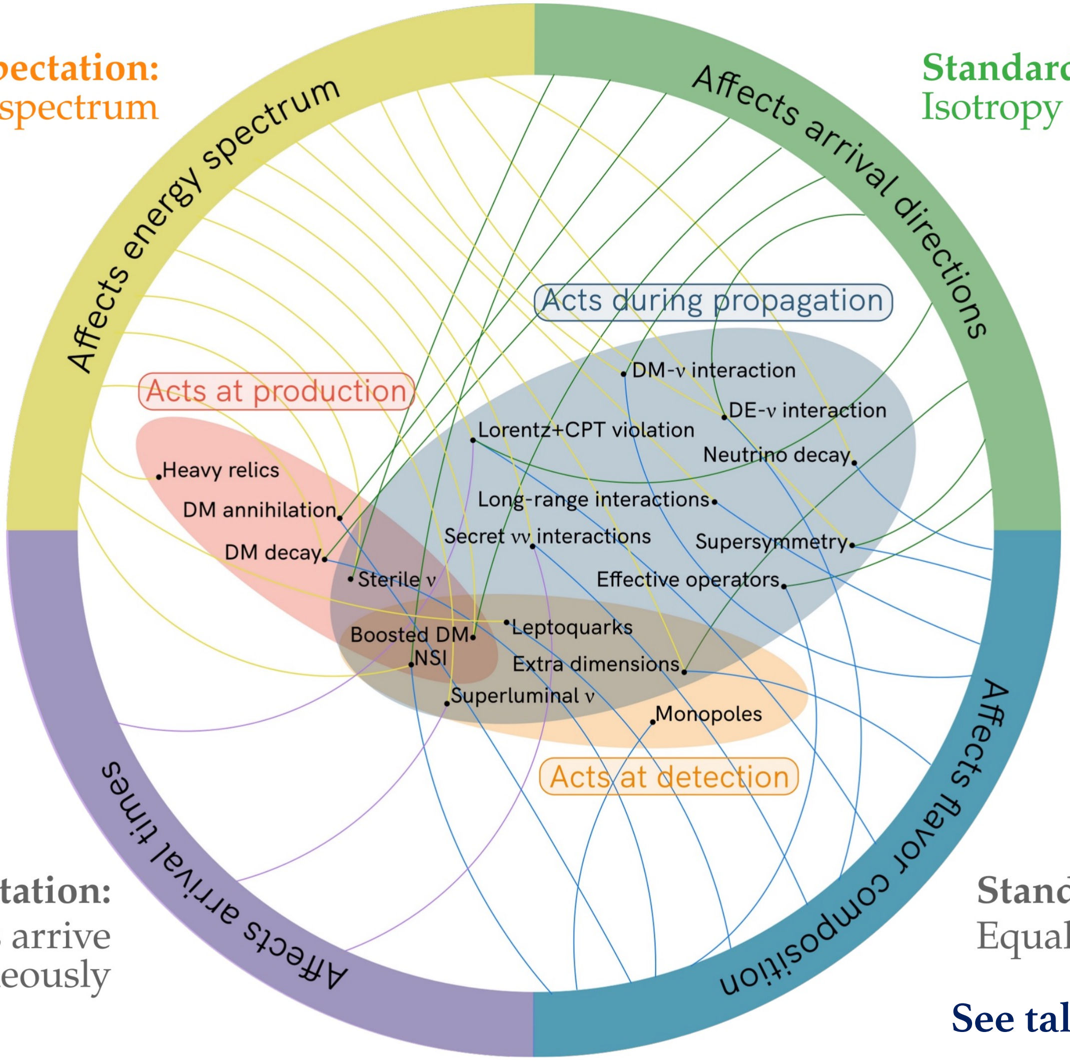
Alters neutrino detection cross sections

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]**

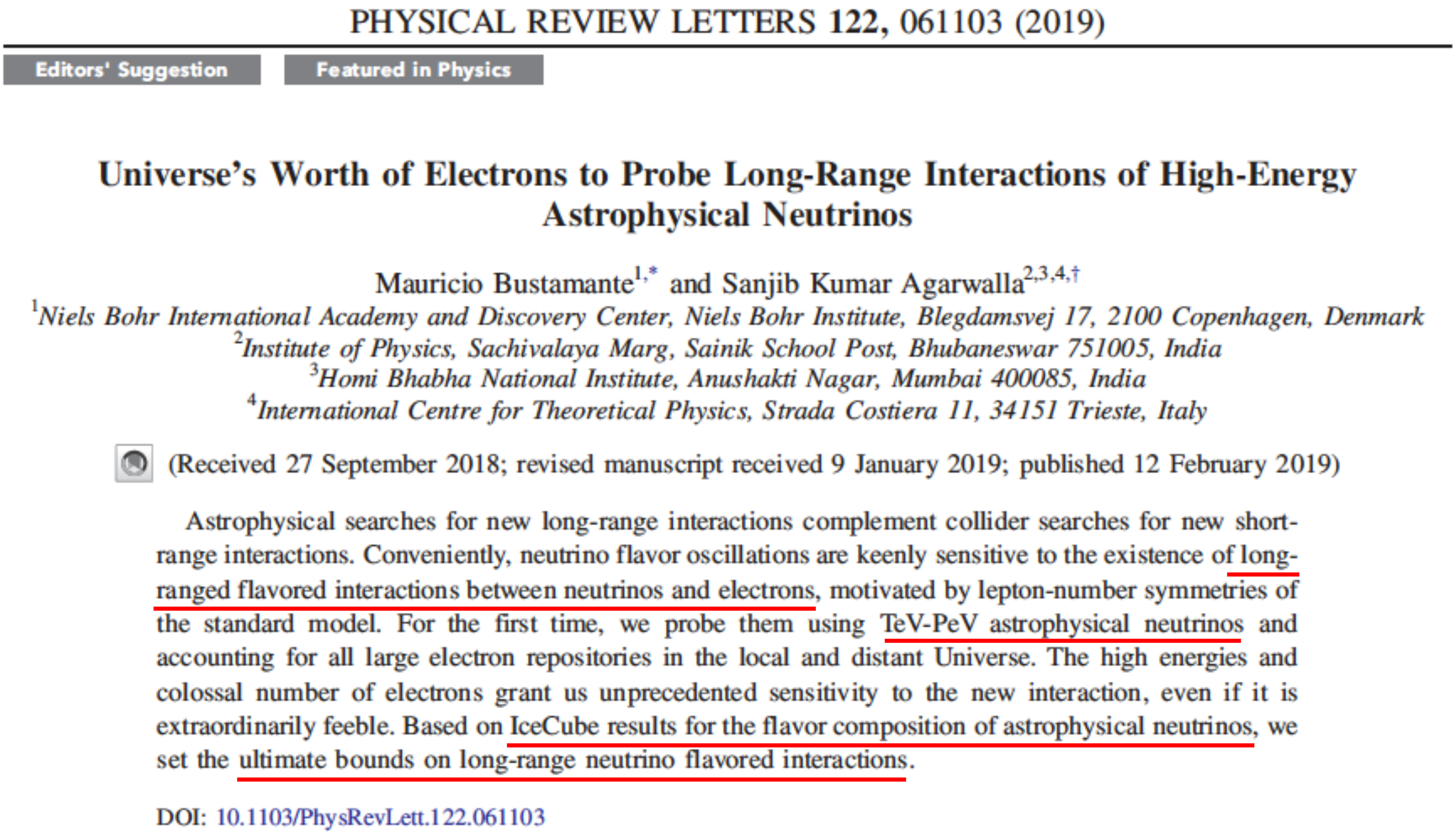
Standard expectation:
ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

See talk by Kareem Farrag

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

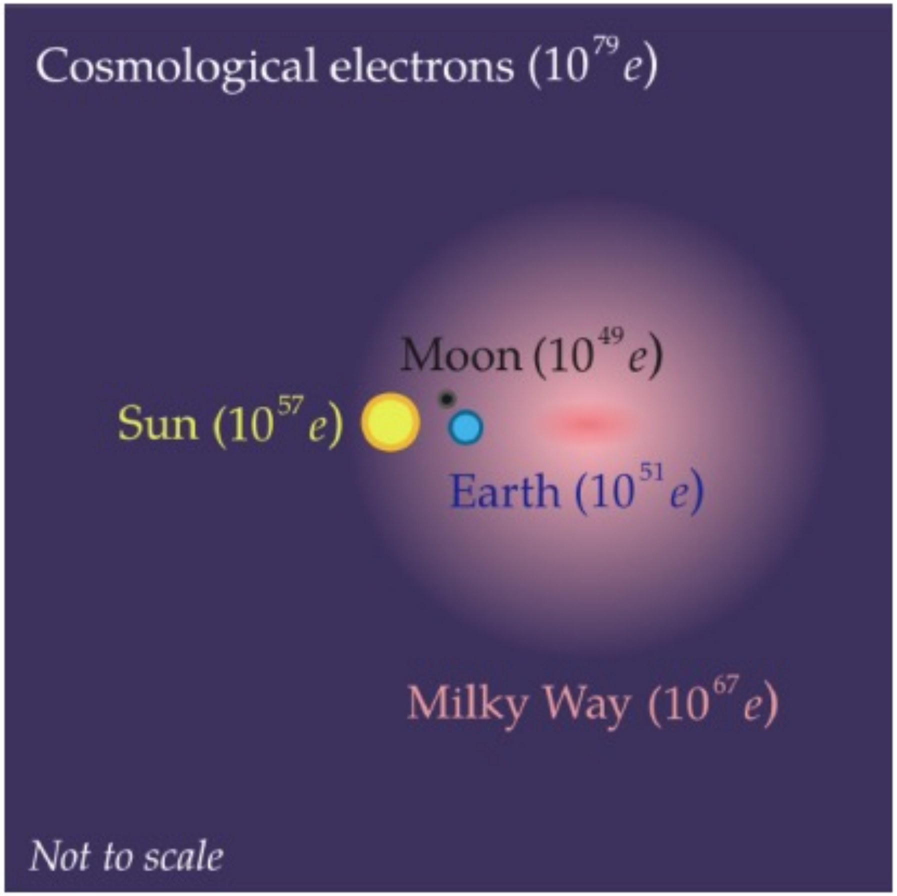
Mauricio Bustamante[1,*] and Sanjib Kumar Agarwalla[2,3,4,†]
[1]*Niels Bohr International Academy and Discovery Center, Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[2]*Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*
[3]*Homi Bhabha National Institute, 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

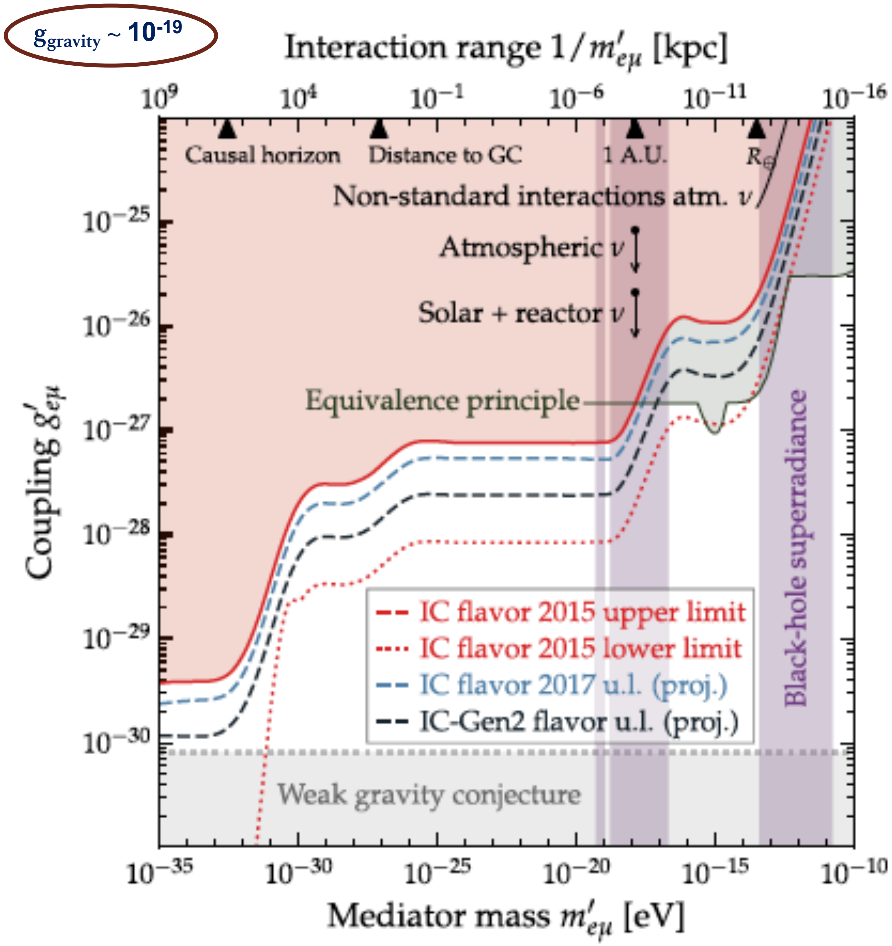
Z′ mass

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

Distance to neutrino

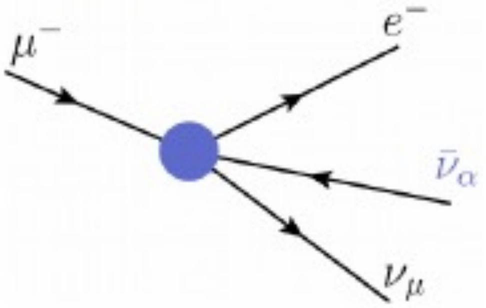
A neutrino "feels" all the electrons within the interaction range ~$(1/m')$

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



Neutrino Non-Standard Interactions (NSIs)

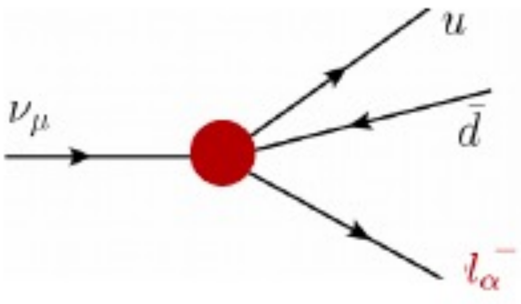
NSI affecting production



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

CC

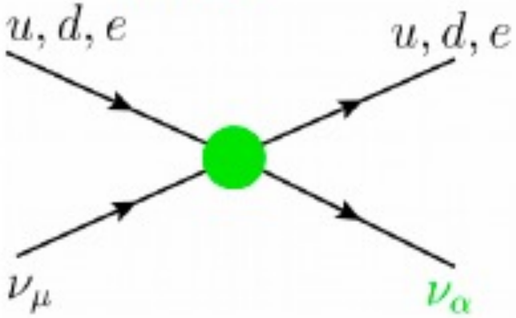
NSI affecting detection



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

CC

NSI affecting propagation



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

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

See talk by
Wilf Shorrock

SciPost Phys. Proc. 2, 001 (2019)

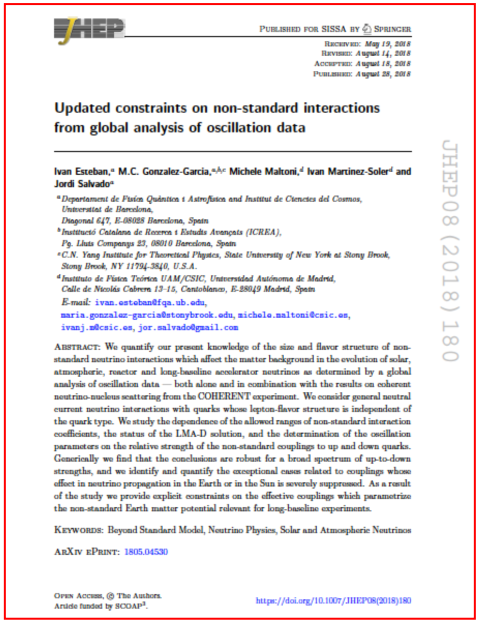
Neutrino non-standard interactions: A status report

P. S. Bhupal Dev[1,2*], K. S. Babu[2,3], Peter B. Denton[4], Pedro A. N. Machado[2], Carlos A. Argüelles[5], Joshua L. Barrow[6,7], Sabya Sachi Chatterjee[8], Mu-Chun Chen[9], André de Gouvêa[10], Bhaskar Dutta[11], Dorival Gonçalves[12], Tao Han[12], Matheus Hostert[8], Sudip Jana[1,2], Kevin J. Kelly[2], Shirley Weishi Li[13], Ivan Martinez-Soler[2,10,14], Poonam Mehta[15], Irina Mocioiu[16], Yuber F. Perez-Gonzalez[2,10,14], Jordi Salvado[17], Ian M. Shoemaker[18], Michele Tammaro[19], Anil Thapa[1,2], Jessica Turner[2] ans Xun-Jie Xu[20]

1 Department of Physics and McDonnell Center for the Space Sciences,
Washington University, St. Louis, MO 63130, USA
2 Theoretical Physics Department, Fermi National Accelerator Laboratory,
P.O. Box 500, Batavia, IL 60510, USA
3 Department of Physics, Oklahoma State University, Stillwater, OK, 74078, USA
4 Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA
5 Massachusetts Institute of Technology, Cambridge, MA 02139, USA
6 Fermi National Accelerator Laboratory, MS220, PO Box 500, Batavia, IL 60510, USA
7 Department of Physics & Astronomy, The University of Tennessee,
Knoxville, TN 37996, USA
8 Institute for Particle Physics Phenomenology, Department of Physics,
Durham University, South Road, Durham DH1 3LE, United Kingdom
9 Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
10 Department of Physics & Astronomy, Northwestern University,
2145 Sheridan Road, Evanston, IL 60208, USA
11 Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and
Astronomy, Texas A&M University, College Station, TX 77843, USA
12 Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT PACC),
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
13 SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
14 Colegio de Física Fundamental e Interdisciplinaria de las Américas (COFI),
254 Norzagaray street, San Juan, Puerto Rico 00901
15 School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110067, India
16 Department of Physics, The Pennsylvania State University, University Park, PA 16802
17 Departament de Fiśica Quántica i Astrofísica and Institut de Ciències del Cosmos,
Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain
18 Center for Neutrino Physics, Department of Physics,
Virginia Tech, Blacksburg, VA 24061, USA
19 Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA
20 Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

⋆ bdev@wustl.edu

Neutrino Non-Standard Interactions,
FERMILAB-CONF-19-299-T
doi:10.21468/SciPostPhysProc.2



Published for SISSA by Springer

Received: *May 19, 2018*
Revised: *August 14, 2018*
Accepted: *August 18, 2018*
Published: *August 28, 2018*

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

Ivan Esteban,[a] M.C. Gonzalez-Garcia,[a,b,c] Michele Maltoni,[d] Ivan Martinez-Soler[d] and Jordi Salvado[a]

[a] *Departament de Física Quàntica i Astrofísica and Institut de Ciencies del Cosmos, Universitat de Barcelona,*
Diagonal 647, E-08028 Barcelona, Spain
[b] *Institució Catalana de Recerca i Estudis Avançats (ICREA),*
Pg. Lluis Companys 23, 08010 Barcelona, Spain
[c] *C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook,*
Stony Brook, NY 11794-3840, U.S.A.
[d] *Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid,*
Calle de Nicolás Cabrera 13–15, Cantoblanco, E-28049 Madrid, Spain
E-mail: ivan.esteban@fqa.ub.edu, maria.gonzalez-garcia@stonybrook.edu, michele.maltoni@csic.es, ivanj.m@csic.es, jor.salvado@gmail.com

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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Article funded by SCOAP^3.

https://doi.org/10.1007/JHEP08(2018)180

JHEP08(2018)180

Exciting BSM prospects @ DUNE

See the publication:
EPJC 81 (2021) 322

See talk by
Jae Yu

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 $P \in \{P_L, P_R\}$

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

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

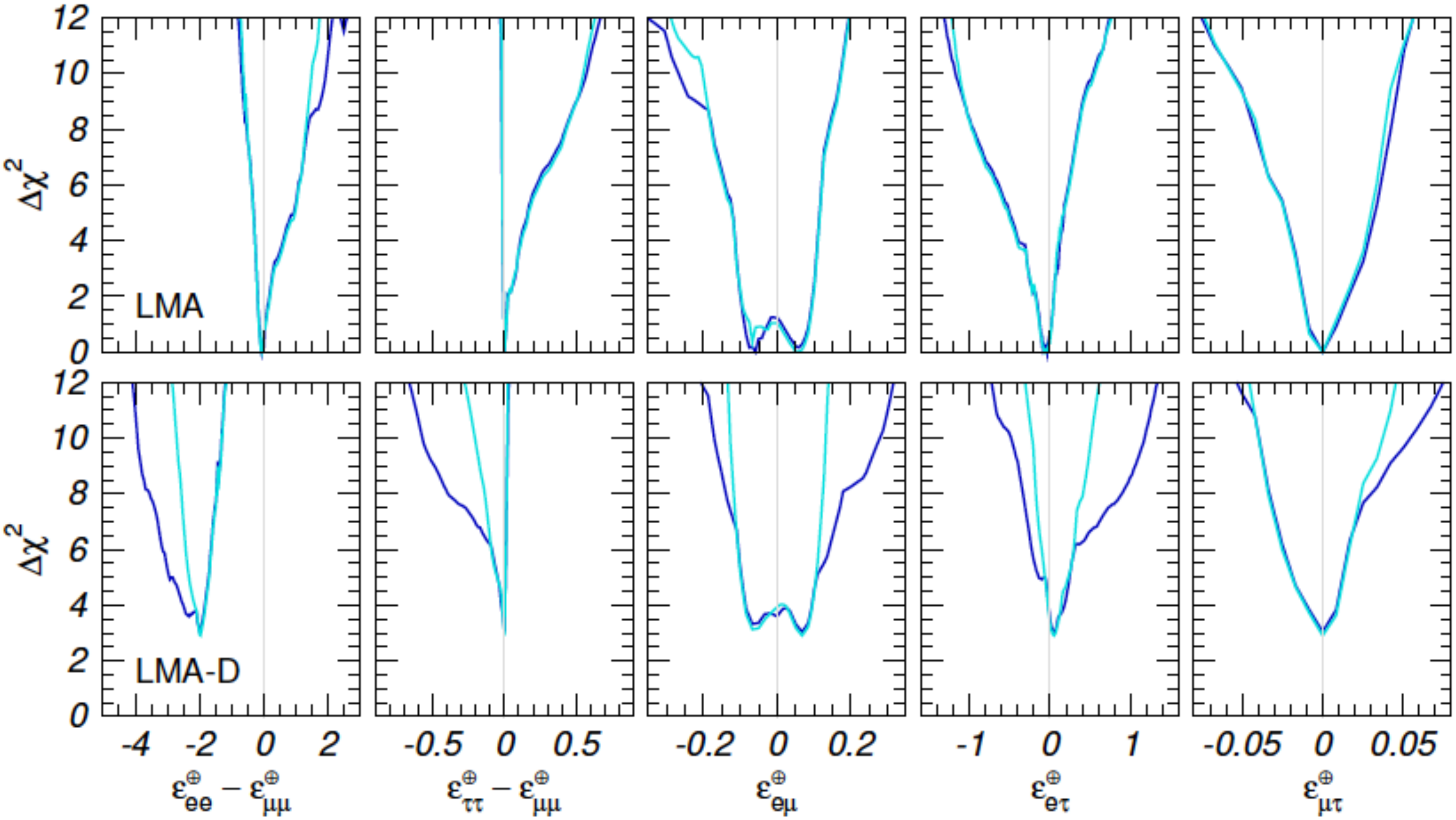
$$a \equiv 2\sqrt{2}G_F N_e E$$

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

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**

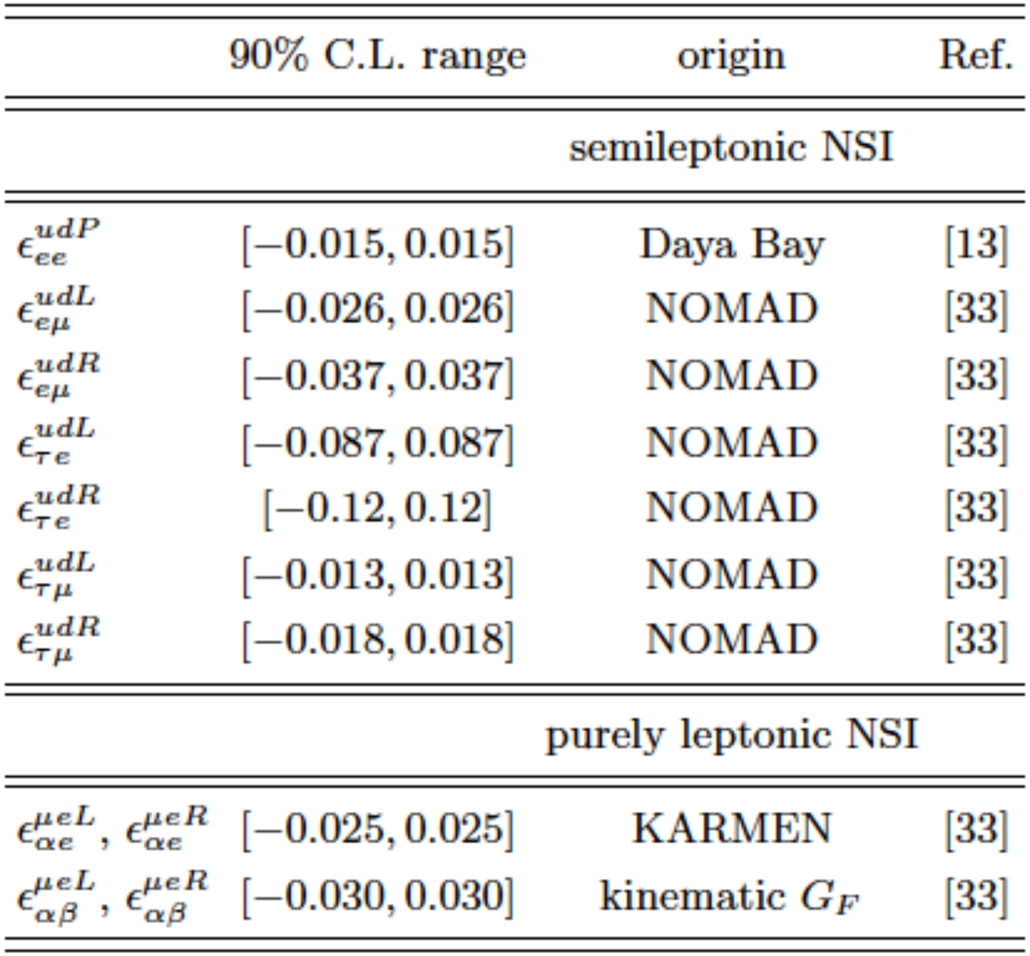
Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP 08 (2018) 180

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 $P \in \{P_L, P_R\}$

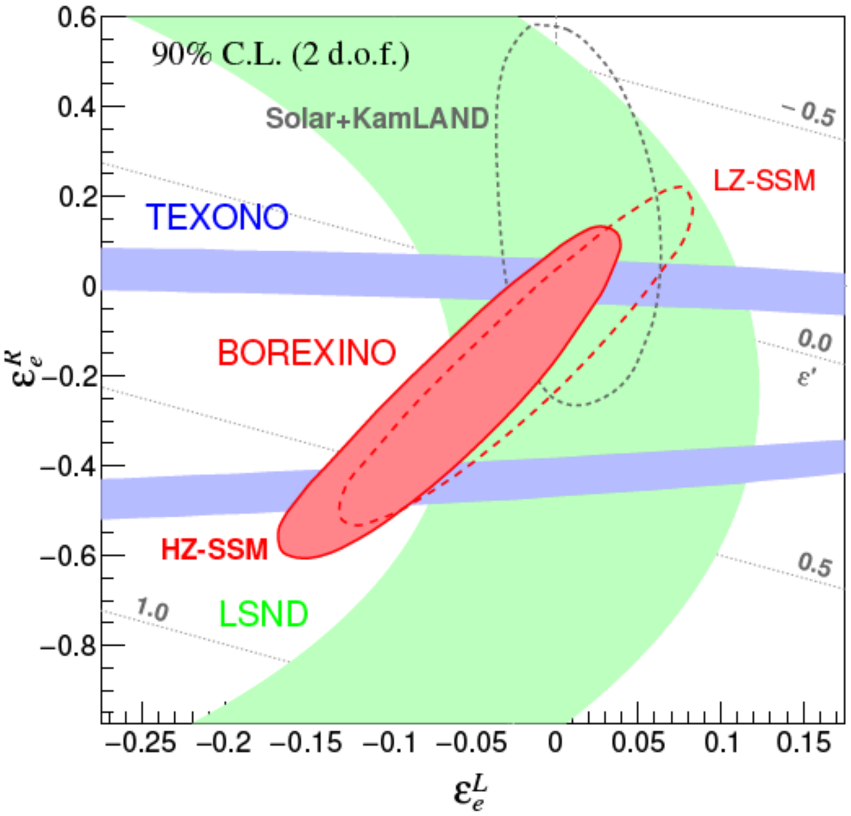


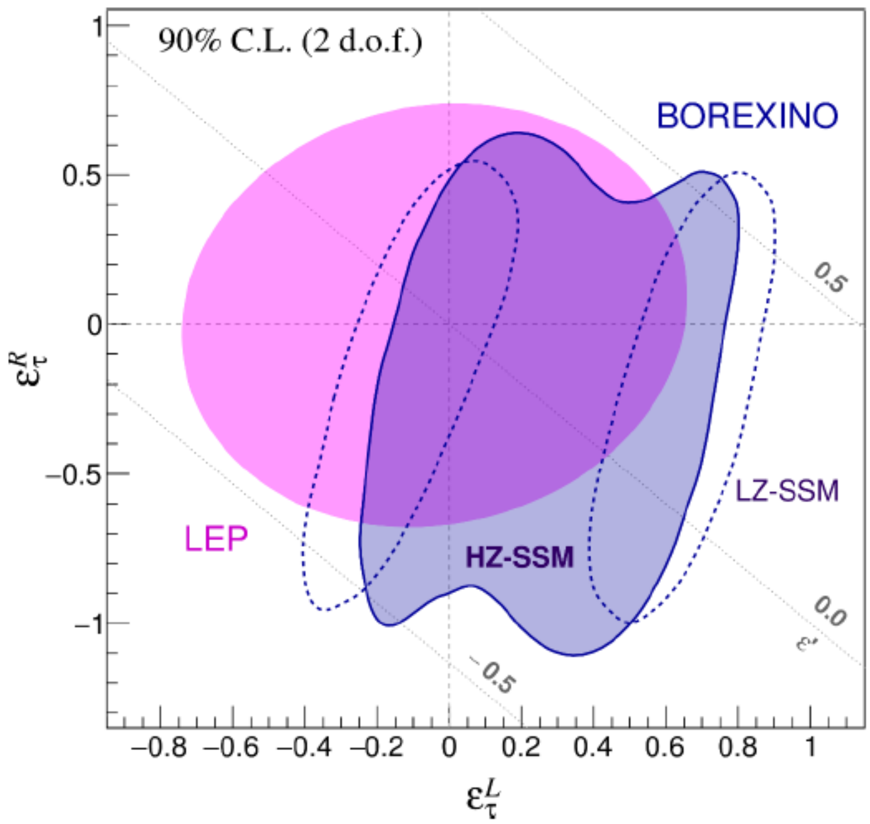
	90% C.L. range	origin	Ref.
		semileptonic NSI	
ϵ^{udP}_{ee}	$[-0.015, 0.015]$	Daya Bay	[13]
$\epsilon^{udL}_{e\mu}$	$[-0.026, 0.026]$	NOMAD	[33]
$\epsilon^{udR}_{e\mu}$	$[-0.037, 0.037]$	NOMAD	[33]
$\epsilon^{udL}_{\tau e}$	$[-0.087, 0.087]$	NOMAD	[33]
$\epsilon^{udR}_{\tau e}$	$[-0.12, 0.12]$	NOMAD	[33]
$\epsilon^{udL}_{\tau\mu}$	$[-0.013, 0.013]$	NOMAD	[33]
$\epsilon^{udR}_{\tau\mu}$	$[-0.018, 0.018]$	NOMAD	[33]
		purely leptonic NSI	
$\epsilon^{\mu e L}_{\alpha e}$, $\epsilon^{\mu e R}_{\alpha e}$	$[-0.025, 0.025]$	KARMEN	[33]
$\epsilon^{\mu e L}_{\alpha\beta}$, $\epsilon^{\mu e R}_{\alpha\beta}$	$[-0.030, 0.030]$	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
ε_e^R	$[-0.15, +0.11]$	$[-0.20, +0.03]$
ε_e^L	$[-0.035, +0.032]$	$[-0.013, +0.052]$
ε_τ^R	$[-0.83, +0.36]$	$[-0.42, +0.43]$
ε_τ^L	$[-0.11, +0.67]$	$[-0.19, +0.79]$

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

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

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

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

Nice complementarity between Borexino and Texono

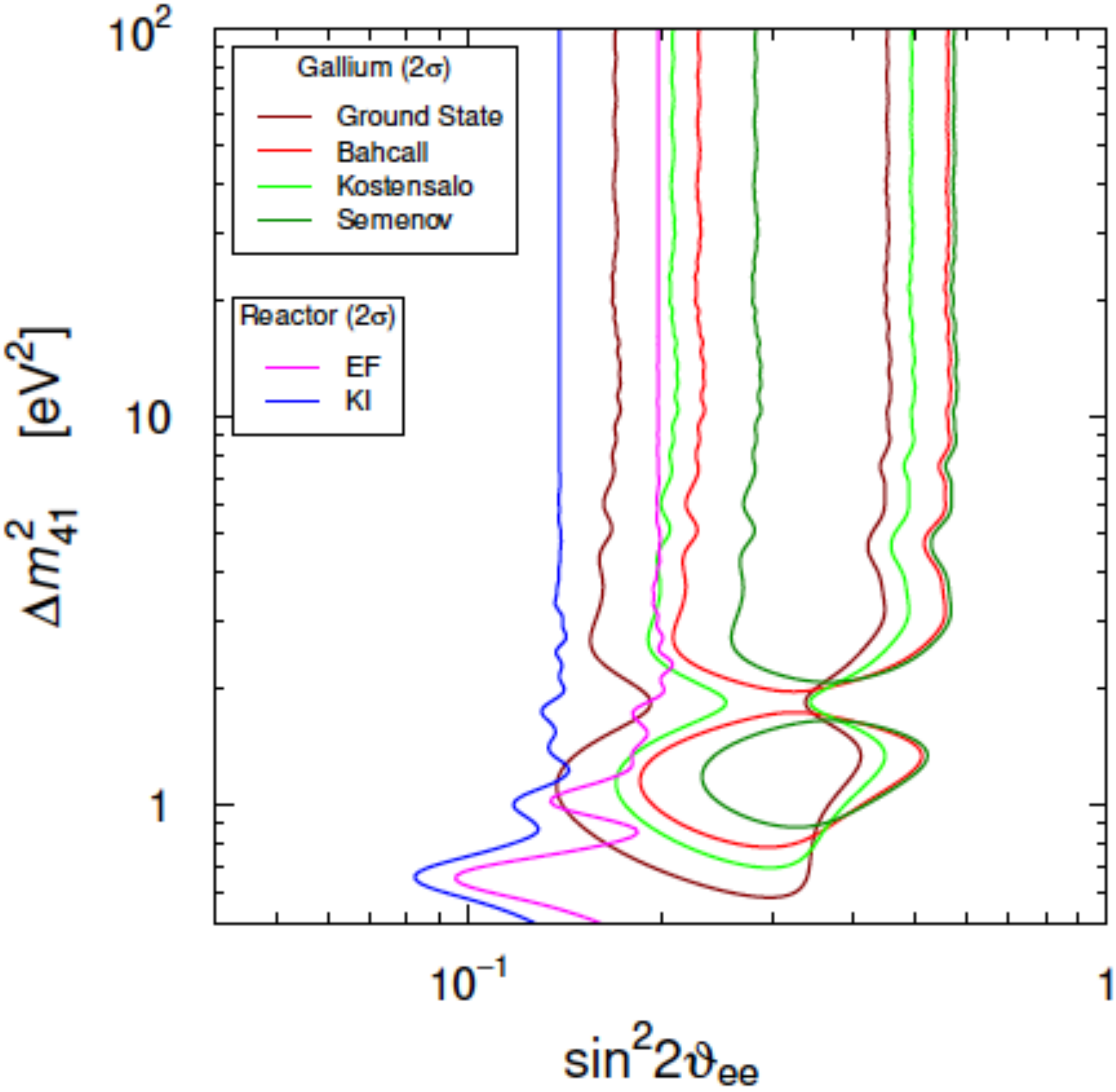
S. K. Agarwalla et al., JHEP 02 (2020) 038

Several Anomalies at Short-Baseline Experiments

Long-standing saga of eV-scale anomalies!

- **1995 LSND Anomaly: $\sim 3.8\sigma$** **[PRD 64 (2001) 22, 112007]**
- **2008 MiniBooNE Anomaly (combined ν & antineutrino): $\sim 4.8\sigma$** **[PRL 121 (2018) 22, 221801]**
- **2011 Reactor Antineutrino Anomaly: $\sim 3\sigma$** **[PRD 83 (2011) 073006, PRC 84 (2011) 024617]**
- **2005 Gallium Neutrino Anomaly: $\sim 2.9\sigma$** **[PRC 83 (2011) 065504, PLB 795 (2019) 542]**
- **NEOS: $\sim 3\sigma$** **[PRL 118, 121802 (2017)]**
- **DANSS: $\sim 2.8\sigma$** **[PLB 787 (2018) 56]**
- **Neutrino-4: $\sim 2.8\sigma$** **[JETP Lett. 109 (2019) 4, 213]**

Reactor Anomaly vs. Gallium Anomaly



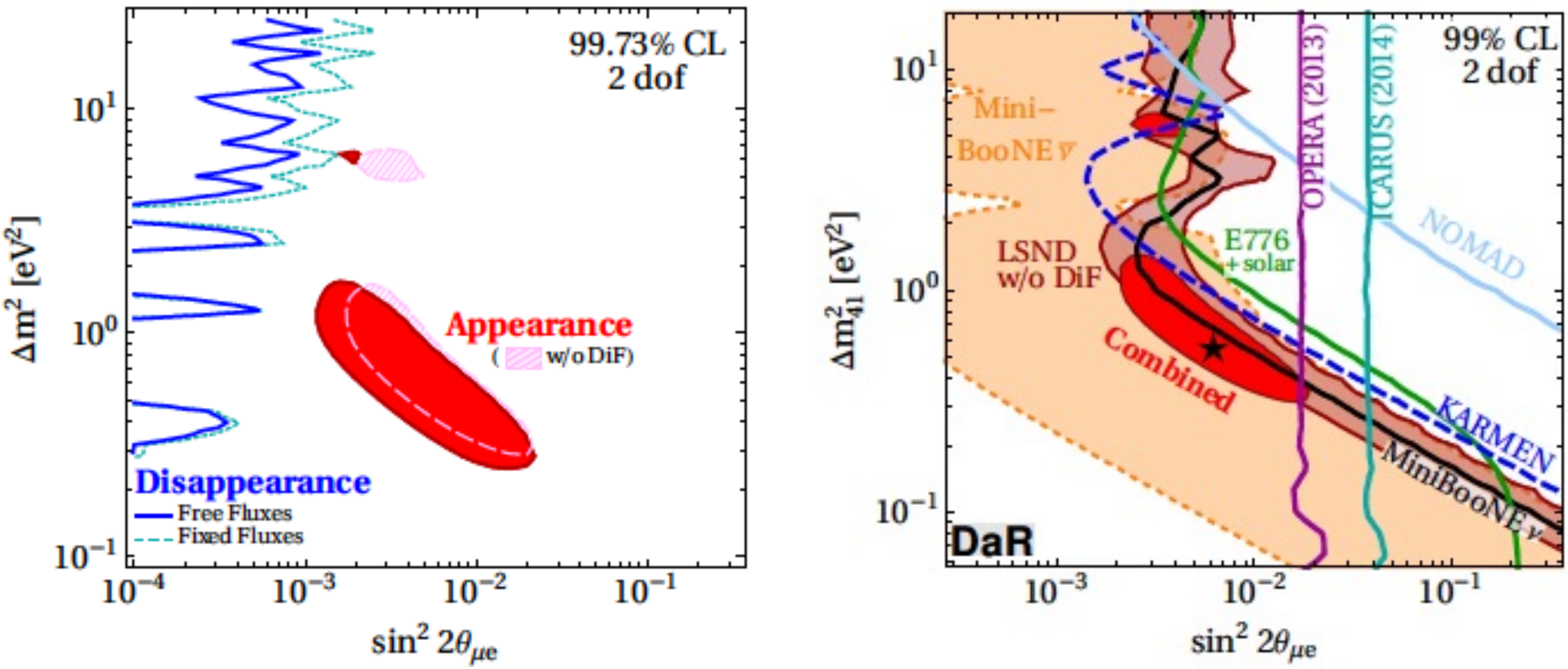
Gallium neutrino anomaly has been reinforced after the new measurements from Baksan Experiment on Sterile Transitions (BEST), suggesting more than 5σ deficit of $\boldsymbol{\nu}_e$

The reactor rates and the fuel evolution data are consistent with the recent reactor flux models, leading to a plausible robust demise of the reactor antineutrino anomaly

Remember that reactor anomaly deals with electron antineutrinos, but Gallium anomaly deals with electron neutrinos

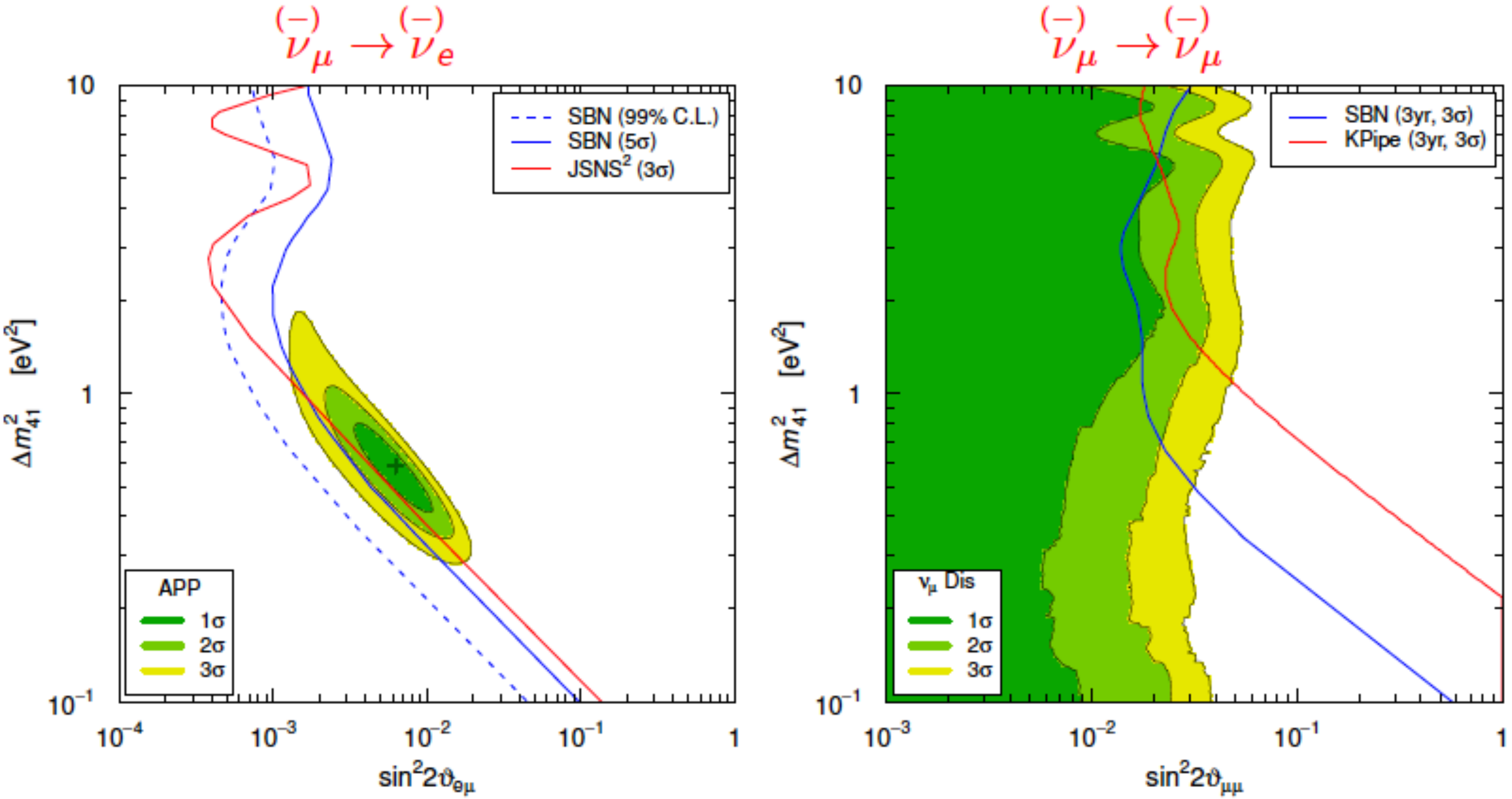
Giunti, Li, Ternes, Tyagi, Xin, arXiv:2209.00916

Significant tension between appearance and disappearance results



Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, JHEP 08 (2018) 010

New Dedicated Experiments



Fermilab SBN Program, JSNS² and JSNS² – II

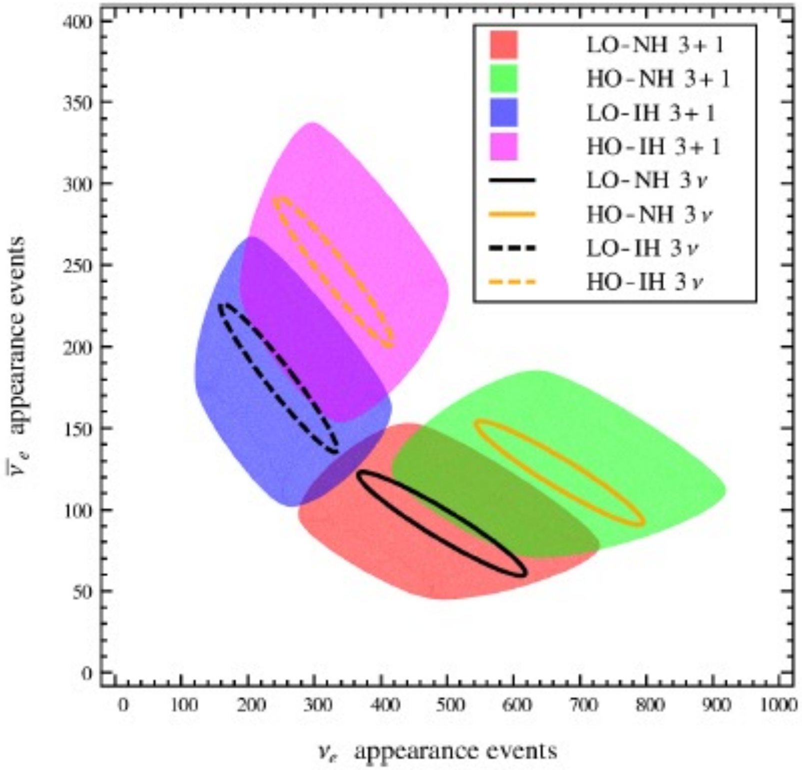
First Study on θ_{23} Octant with Light Sterile Neutrino

PRL **118,** 031804 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Octant of θ_{23} in Danger with a Light Sterile Neutrino

Sanjib Kumar Agarwalla,[1,2,*] Sabya Sachi Chatterjee,[1,2,†] and Antonio Palazzo[3,4,‡]
[1]*Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*
[2]*Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400085, India*
[3]*Dipartimento Interateneo di Fisica "Michelangelo Merlin", Via Amendola 173, 70126 Bari, Italy*
[4]*Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Via Orabona 4, 70126 Bari, Italy*

(Received 23 May 2016; revised manuscript received 5 December 2016; published 20 January 2017)



$\sin^2\theta_{23}$ = 0.42 (LO) and 0.58 (HO)

- Three-flavor ellipses due to variation in δ_{13} in [$-\pi$ to π]
- Four-flavor blobs due to variation in δ_{13} and δ_{14} in [$-\pi$ to π]
- Due to new CP phases, sensitivity towards octant lost in DUNE

CPT and Lorentz Symmetry Violation

- **Unified theories, such as string theory, allow for violation of Lorentz symmetry by inducing new spacetime structure at the quantum gravity scale**

- **The direct observation of Lorentz Invariance Violation (LIV) at low-energy would provide access to the Planck-scale (M_p) physics**

☞ **Introduce LIV or CPT violation in the framework**

If one extends the SM to include LIV terms using the SME framework:

$$H = H_{std} + \frac{p_\lambda}{E}\begin{pmatrix} a^\lambda_{ee} & a^\lambda_{e\mu} & a^\lambda_{e\tau} \\ a^{\lambda *}_{e\mu} & a^\lambda_{\mu\mu} & a^\lambda_{\mu\tau} \\ a^{\lambda *}_{e\tau} & a^{\lambda *}_{\mu\tau} & a^\lambda_{\tau\tau} \end{pmatrix} + \frac{p_\lambda p_\sigma}{E}\begin{pmatrix} c^{\lambda\sigma}_{ee} & c^{\lambda\sigma}_{e\mu} & c^{\lambda\sigma}_{e\tau} \\ c^{\lambda\sigma *}_{e\mu} & c^{\lambda\sigma}_{\mu\mu} & c^{\lambda\sigma}_{\mu\tau} \\ c^{\lambda\sigma *}_{e\tau} & c^{\lambda\sigma *}_{\mu\tau} & c^{\lambda\sigma}_{\tau\tau} \end{pmatrix}$$

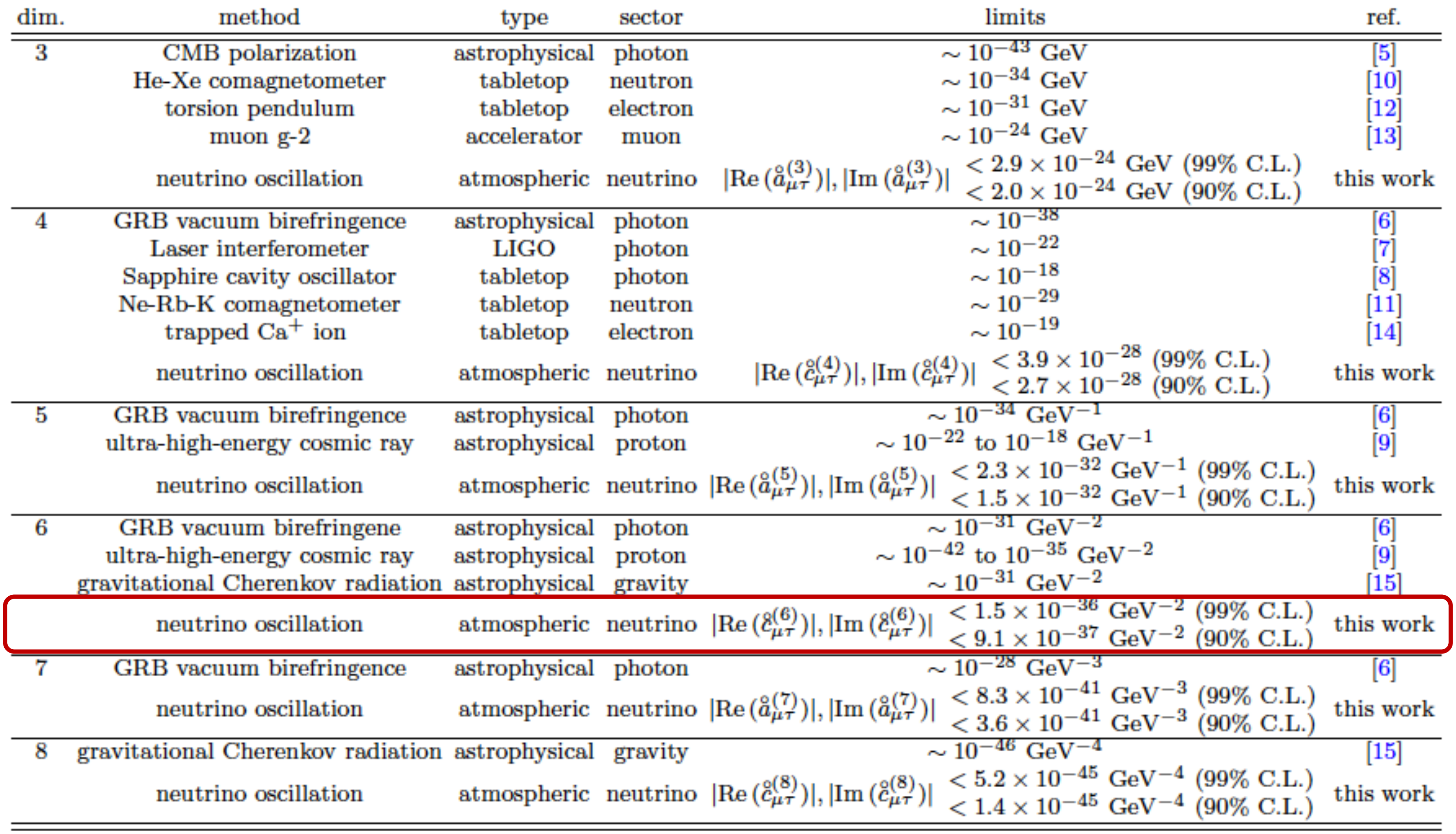
here $p_\lambda = (E, \vec{p})$

We assume that "a" and "c" only have a time component: $H = H_{std} + \tilde{a}^{T} + E\tilde{c}^{TT}$

Kostelecky, Mewes, PRD 69 (2004) 016005

For a comprehensive list of the constraints on all the relevant LIV/CPT-violating parameters, see
Kostelecky, Russel, RMP 83 (2011) 11, arXiv:0801.0287v13 [hep-ph]

Current Bounds on LIV using IceCube Atmospheric Neutrino Data



dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[5]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[6]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[7]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[8]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[6]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

Nature Phys 14, 961–966 (2018)

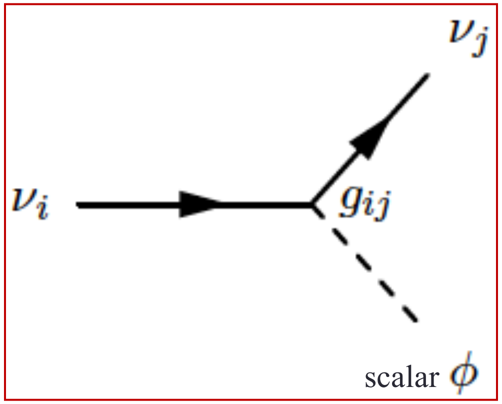
Very strong limits on LIV induced by dimension-six operators!

Neutrino Decays (Visible and Invisible)

- **Various new physics models predict neutrino decay**

$$\boxed{\mathcal{L} \supset g_{ij}\bar{\nu}_j\nu_i\phi + h_{ij}\bar{\nu}_j i\gamma_5\nu_i\phi + \text{h.c.}}$$

Chikashige, Mohapatra, Peccei, PLB 98 (1981) 265
Gelmini, Roncadelli, PLB 99 (1981) 411; Gelmini, Valle, PLB 142 (1984) 181



- **Invisible decay:** either the decay products are sterile neutrinos, or have sufficiently low energy avoiding detection
- **Visible decay:** involves regeneration of lower energy neutrinos and provides additional detection signatures

- Invisible decay: $\nu_3 \rightarrow$ sterile neutrino + Majoron ($m_\phi \lesssim m_\nu$)

$$\boxed{P^{2G}_{\mu\mu} = \left[\cos^2\theta_{23} + \sin^2\theta_{23}\exp(-m_3L/\tau_3E)\right]^2 - \sin^2 2\theta_{23}\exp(-m_3L/\tau_3E)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)}$$

☞ **Existing bounds:**

- Super-Kamiokande + K2K + MINOS:
  $\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV at 90% C.L.
  Gonzalez-Garcia, Maltoni, PLB 663 (2008) 405

- T2K + MINOS:
  $\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV at 90% C.L.
  Gomes, Gomes, Peres, PLB 740 (2015) 345

Neutrino Decays (Visible and Invisible)

☞ Expected bounds:

- T2K + NOvA:
  $\tau_3/m_3 > 1.5 \times 10^{-12}$ s/eV at 3σ C.L.
  Choubey, Dutta, Pramanik, JHEP 08 (2018) 141
- DUNE (40 kt, 5 yr ν + 5 yr anti- ν):
  $\tau_3/m_3 > 4.5 \times 10^{-11}$ s/eV at 90% C.L. for NO
  Choubey, Goswami, Pramanik, JHEP 02 (2018) 055
- JUNO:
  $\tau_3/m_3 > 7.5 \times 10^{-11}$ s/eV at 95% C.L.
  Abrahao, Minakata, Nunokawa, Quiroga JHEP 11 (2015) 001
- ICAL@INO (500 kt·yr exposure):
  $\tau_3/m_3 > 1.51 \times 10^{-10}$ s/eV at 90% C.L.
  Choubey, Goswami, Gupta, Lakshmi, Thakore
  PRD 97 (2018) 3, 033005
- KM3NeT-ORCA (after 10 years of run):
  $\tau_3/m_3 > 2.5 \times 10^{-10}$ s/eV at 90% C.L.
  de Salas, Pastor, Ternes, Thakore, Tortola
  PLB 789 (2019) 472

☞ Limits from CMB:

Hannestad, Raffelt, PRD 72 (2005) 103514; Escudero, Fairbairn, PRD 100 (2019) 10, 103531

☞ Limits from Solar Neutrinos:

Berryman, de Gouvea, Hernandez, PRD 92 (2015) 7, 073003

☞ Invisible ν decay ($\tau/m = 10^2$ s/eV) resolves IceCube's track & cascade ($> 3\sigma$) tension:

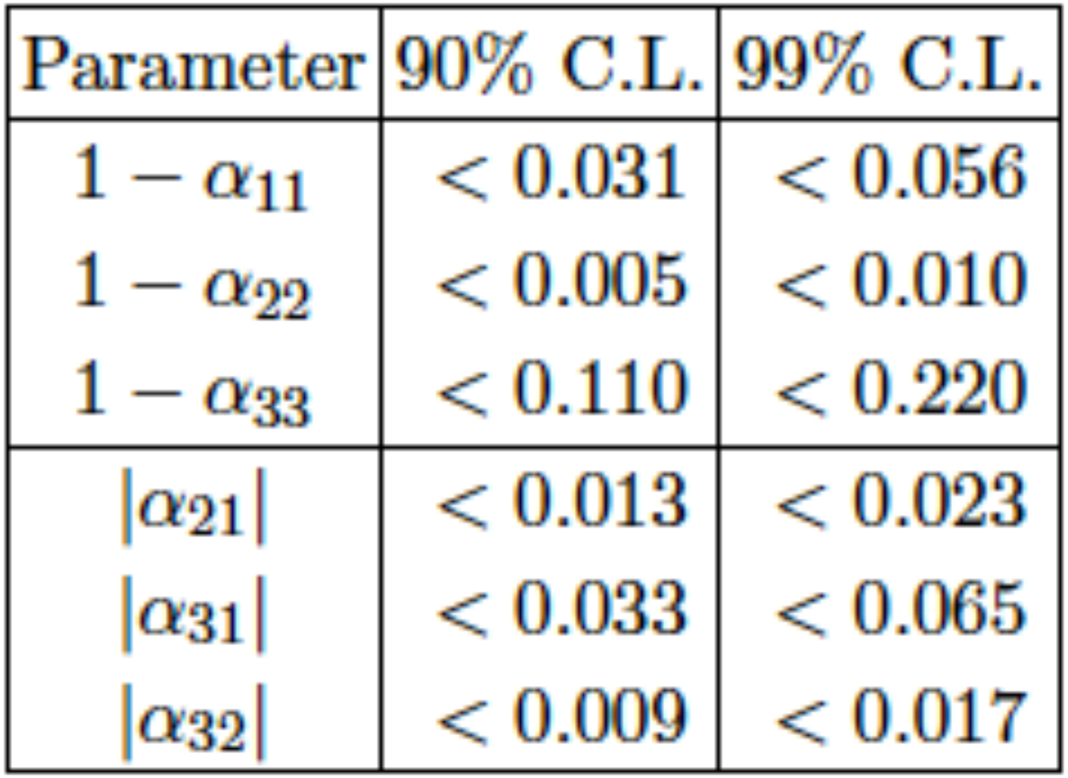
Denton, Tamborra, PRL 121, 121802 (2018)

☞ Visible decay:

MINOS + T2K: Gago, Gomes, Gomes, Jones-Perez, Peres, JHEP 11 (2017) 022
DUNE: Coloma, Peres, e-Print: 1705.03599 [hep-ph]

Unitarity Constraints

$$N = N^{NP}U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$



Parameter	90% C.L.	99% C.L.
$1-\alpha_{11}$	< 0.031	< 0.056
$1-\alpha_{22}$	< 0.005	< 0.010
$1-\alpha_{33}$	< 0.110	< 0.220
$\lvert\alpha_{21}\rvert$	< 0.013	< 0.023
$\lvert\alpha_{31}\rvert$	< 0.033	< 0.065
$\lvert\alpha_{32}\rvert$	< 0.009	< 0.017

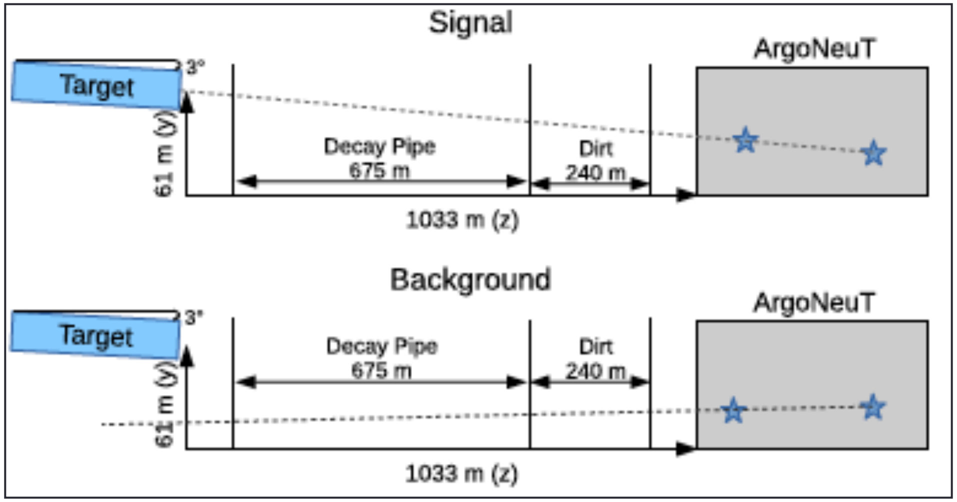
Combine data from SBL and LBL

SBL: NOMAD, NuTeV

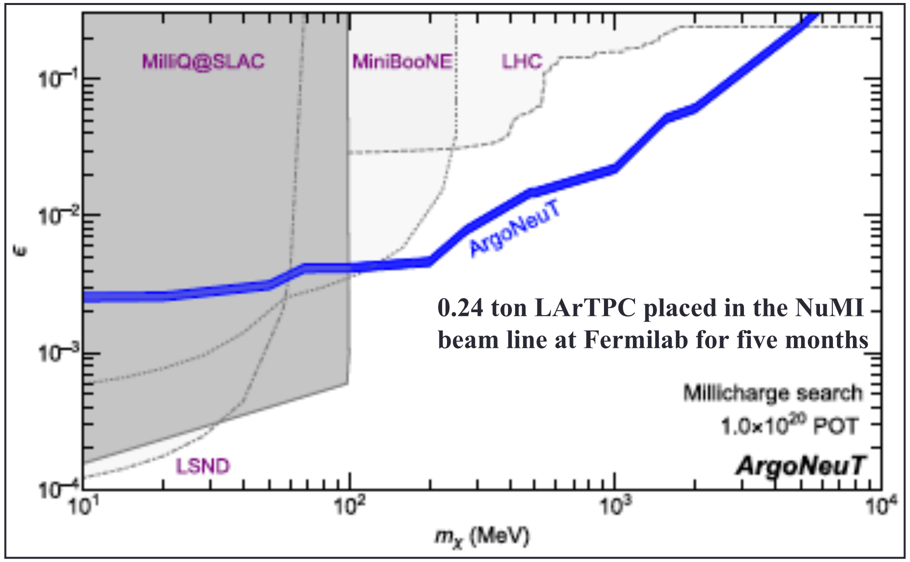
LBL: MINOS/MINOS+, T2K, NOvA

Forero, Giunti, Ternes, Tortola, arXiv:2103.01998v3 [hep-ph]

Search for Millicharged Particles (MCPs)

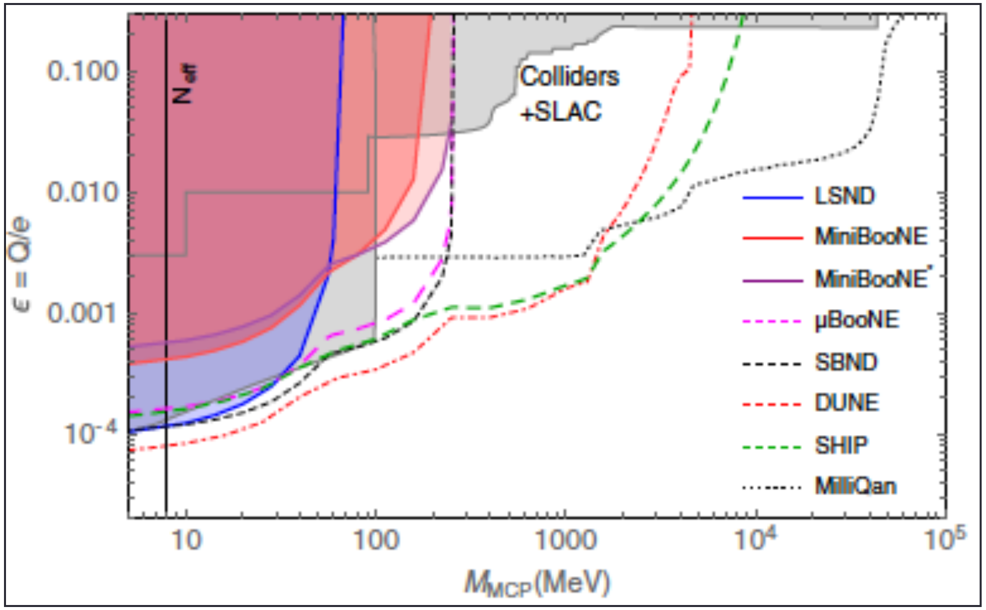


Harnik, Liu, Palamara, JHEP 07 (2019) 170



0.24 ton LArTPC placed in the NuMI beam line at Fermilab for five months

ArgoNeuT Collaboration, PRL 124, 131801 (2020)



Magill, Plestid, Pospelov, Tsai, PRL 122, 071801 (2019)

MCPs (electric charge $Q_\chi = \epsilon e$ where $\epsilon \ll 1$) mostly violate the quantization of charge seen in the SM and could make up part of the DM in the Universe

MCPs mainly produced at any intense fixed-target produced beam via the decays of neutral meson and detected via elastic scattering with electrons

ArgoNeut search for an event signature with two soft hits (MeV-scale energy depositions) aligned with the upstream target and sensitive to MCPs with charges between $10^{-3}e$ and $10^{-1}e$ with masses in the range from 0.1 to 3 GeV

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 topics of next generation neutrino experiments!

Stay tuned!

I apologize for missing your important work, time is too short to cover everything

Thank you!