

White paper: BSM effects on neutrino flavor

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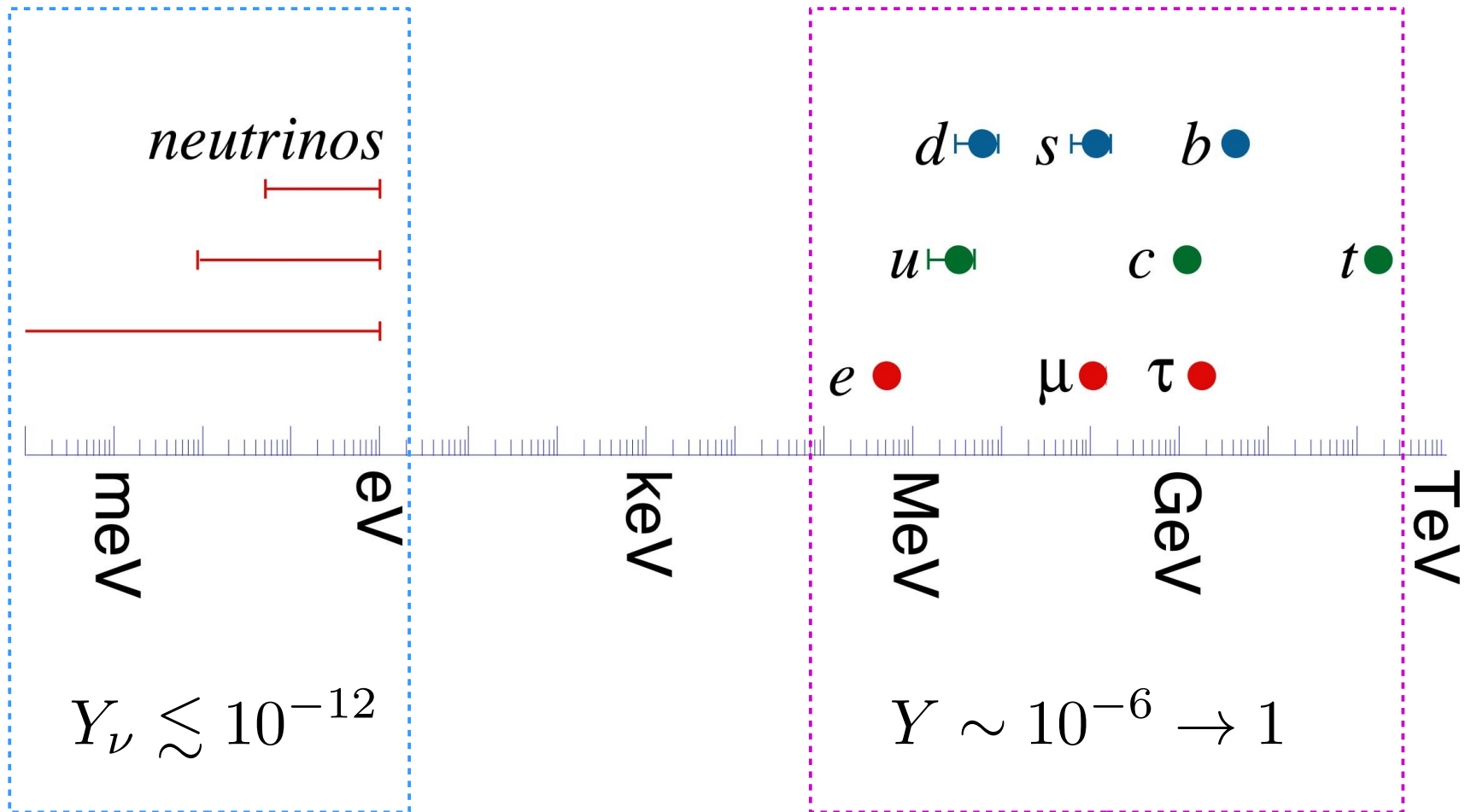
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Thank you all for your hard
work!!!

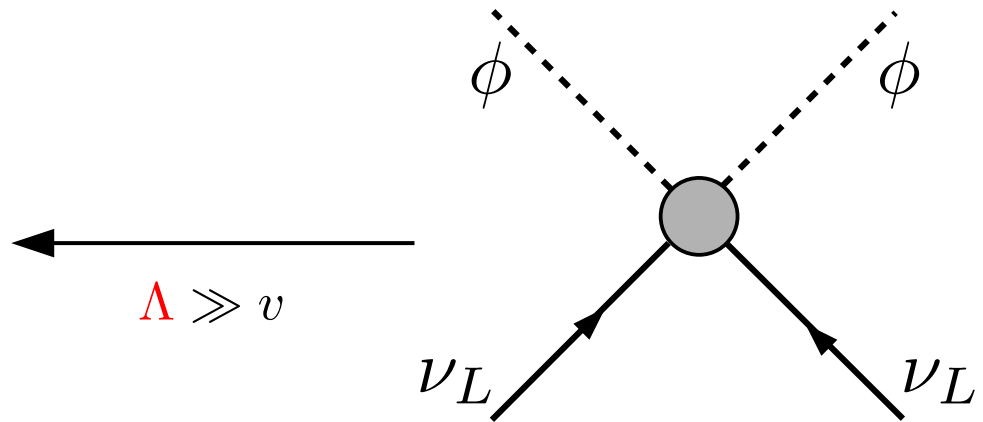
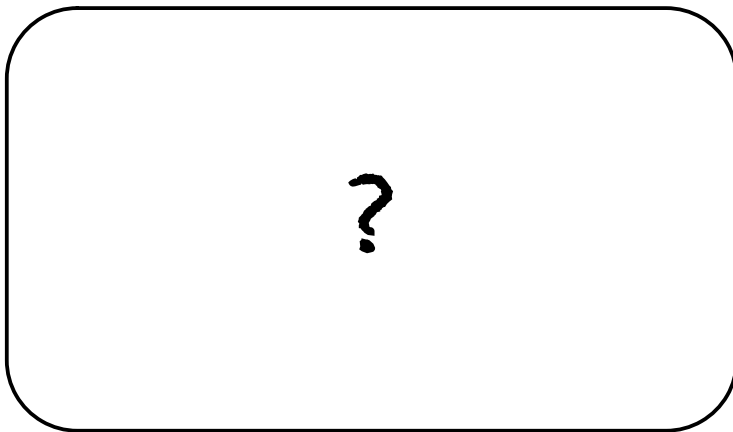
→ **Disclaimer:** very few references in this talk
(you can find lots of them in the white paper)

Why BSM?



Neutrino masses

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2} \delta\mathcal{L}^{d=6} + \dots$$

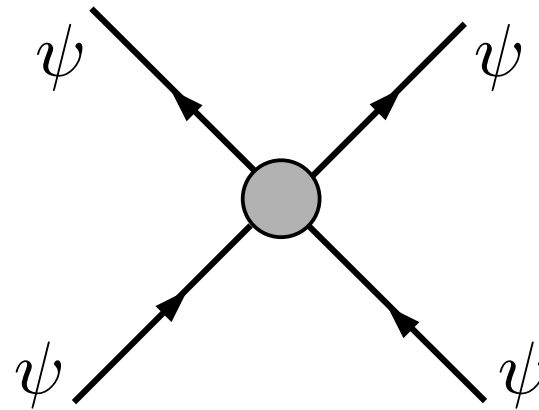


$$\propto \frac{1}{\Lambda} (\bar{L}_L \tilde{\phi}) (\tilde{\phi}^t L_L^c)$$

Weinberg, 1979

Additional BSM signals?

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \delta\mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2} \delta\mathcal{L}^{d=6}} + \dots$$



$$G_x \sim \frac{g^2}{\Lambda^2}$$

Scope of this white paper

- What this paper is about:

any BSM scenario that can lead to new effects on: oscillation probabilities, flavor ratios and spectral distortions for ultra-high energy neutrinos, or new patterns in flavor conversion in supernovae.

- What this paper is NOT about:

using neutrino experiments as fixed targets (searches for HNLs, dark matter, ALPs, double-bangs, etc), neutrino electromagnetic properties, sterile neutrino oscillations, or phenomenology using CEvNS experiments.

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- 2.2 New interactions in the neutrino sector
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 - 2.2.6 Neutrino interactions with dark matter
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 - 2.4.1 CPT violation
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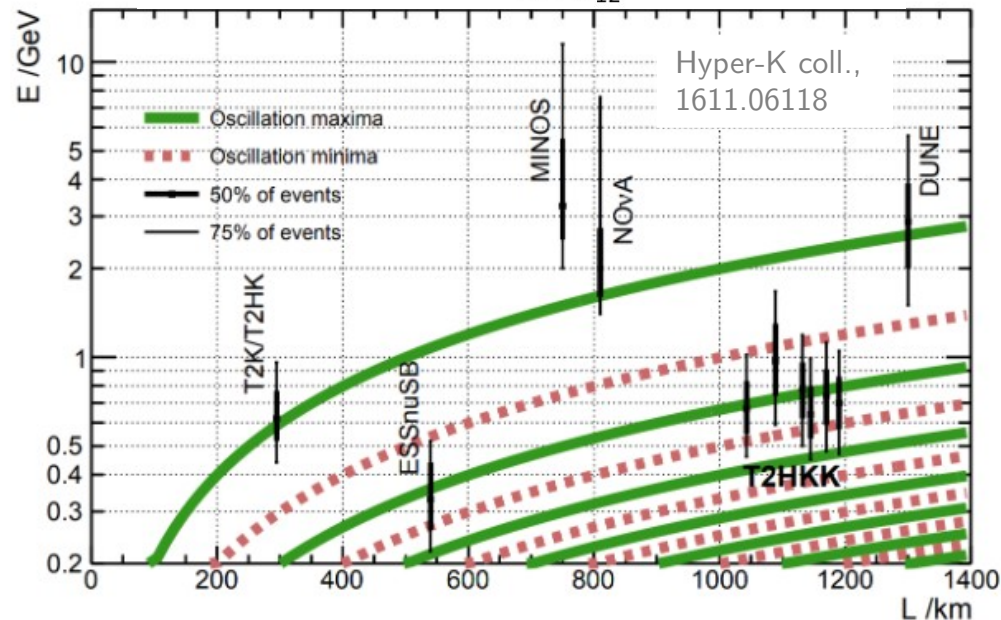
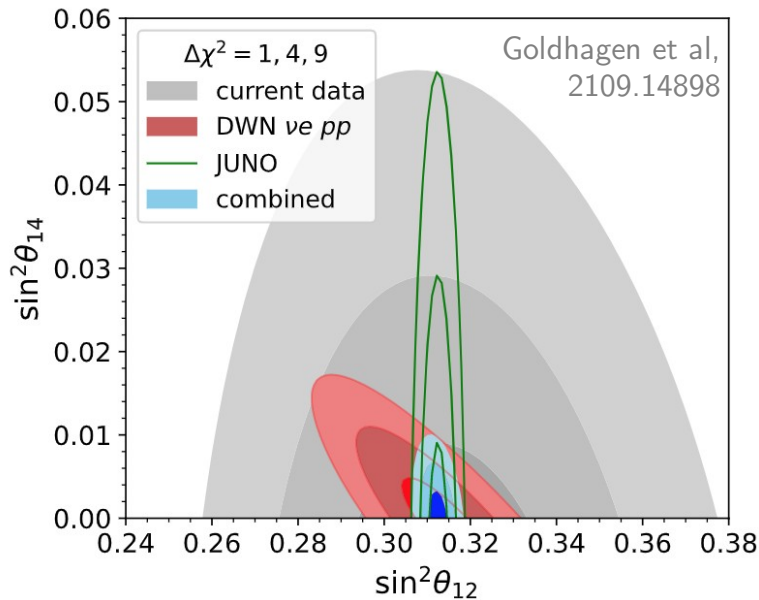
Theory/pheno

3 Experimental overview and prospects

- 3.1 Low energies: neutrino experiments below the GeV
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 - 3.2.2.2 DUNE
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Experiment

Overview of experiments covered



Energy Range	Experiment
$< 10^3$ GeV	JUNO
$< 10^3$ GeV	DUNE
$< 10^3$ GeV	THEIA
$< 10^3$ GeV	WATCHMAN
$< 10^3$ GeV	Super-Kamiokande
$< 10^4$ GeV	Hyper-Kamiokande
$< 10^5$ GeV	ANTARES
$< 10^6$ GeV	IceCube/IceCube-Gen2
$< 10^6$ GeV	KM3NeT
$< 10^6$ GeV	Baikal-GVD
$< 10^6$ GeV	P-ONE
1 – 100 PeV	TAMBO
> 1 PeV	Trinity
> 10 PeV	RET-N
> 10 PeV	IceCube-Gen2
> 10 PeV	ARIANNA-200
> 20 PeV	POEMMA
> 100 PeV	RNO-G
> 100 PeV	Auger/GCOS
> 100 PeV	ANITA/PUEO
> 100 PeV	Beacon
> 100 PeV	GRAND

Table adapted from Argüelles et al, 1912.09486

Additional states

$$\nu_\alpha = \sum_{i=1, \dots, n} \mathcal{U}_{\alpha i} \nu_i \quad \mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

$$N = \begin{pmatrix} 1 - \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1 - \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1 - \alpha_{\tau\tau} \end{pmatrix} U$$

	“Flavour+electroweak” ($m > \text{EW}$)	“Averaged out oscillations” $\Delta m^2 \gtrsim 0.1 \text{ eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$ [32]	$8.4 \cdot 10^{-3}$ [51]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [32]	$5.0 \cdot 10^{-3}$ [52]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [32]	$6.5 \cdot 10^{-2}$ [53]
$ \alpha_{\mu e} $	$6.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$) [32]	$9.2 \cdot 10^{-3}$
$ \alpha_{\tau e} $	$2.7 \cdot 10^{-3}$ [32]	$1.4 \cdot 10^{-2}$
$ \alpha_{\tau\mu} $	$1.2 \cdot 10^{-3}$ [32]	$1.1 \cdot 10^{-2}$

Updated compilation of present bounds on non-unitarity for the two regimes

Additional states

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \left| \sum_{j=1}^3 \sum_{n=0}^{\infty} U_{\alpha j}^* U_{\beta j} (L_j^{0n})^2 \exp \left(-i \frac{(\lambda_j^{(n)})^2}{2ER^2} L \right) \right|^2$$

The mixing between the SM neutrinos and the KK tower is parametrized by:

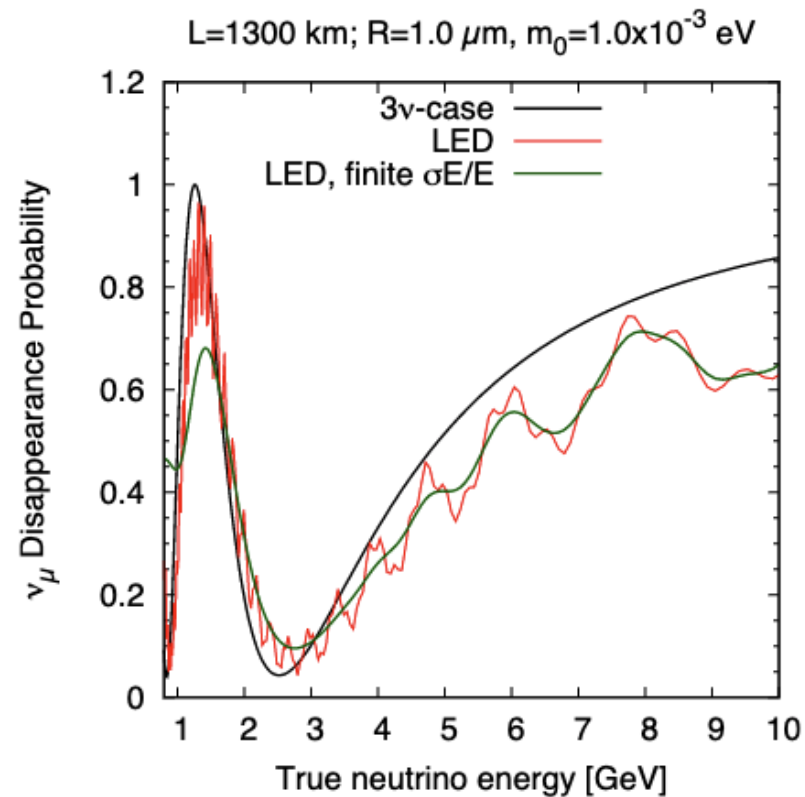
$$(L_j^{0n})^2 = \frac{2}{1 + \pi^2 (m_j^D R)^2 + \left[\lambda_j^{(n)} / (m_j^D R) \right]^2}$$

The masses of the tower of states are given by

$$m_i^{(n)} = \frac{\lambda_i^{(n)}}{R} \simeq \frac{n}{R} \quad (n = 0, 1, \dots)$$

Additional states

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \left| \sum_{j=1}^3 \sum_{n=0}^{\infty} U_{\alpha j}^* U_{\beta j} (L_j^{0n})^2 \exp \left(-i \frac{(\lambda_j^{(n)})^2}{2ER^2} L \right) \right|^2$$



Additional interactions

Charged-current NSI:

We include an overview of current and future bounds

$$-2\sqrt{2}G_F V_{jk} \left\{ [1 + \epsilon_L^{jk}]_{\alpha\beta} (\bar{u}^j \gamma^\mu P_L d^k) (\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \right. \\ \left. + [\epsilon_R^{jk}]_{\alpha\beta} (\bar{u}^j \gamma^\mu P_R d^k) (\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) + \dots \right\}$$

Neutral-current NSI:

Vector operators:

$$-2\sqrt{2}G_F \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

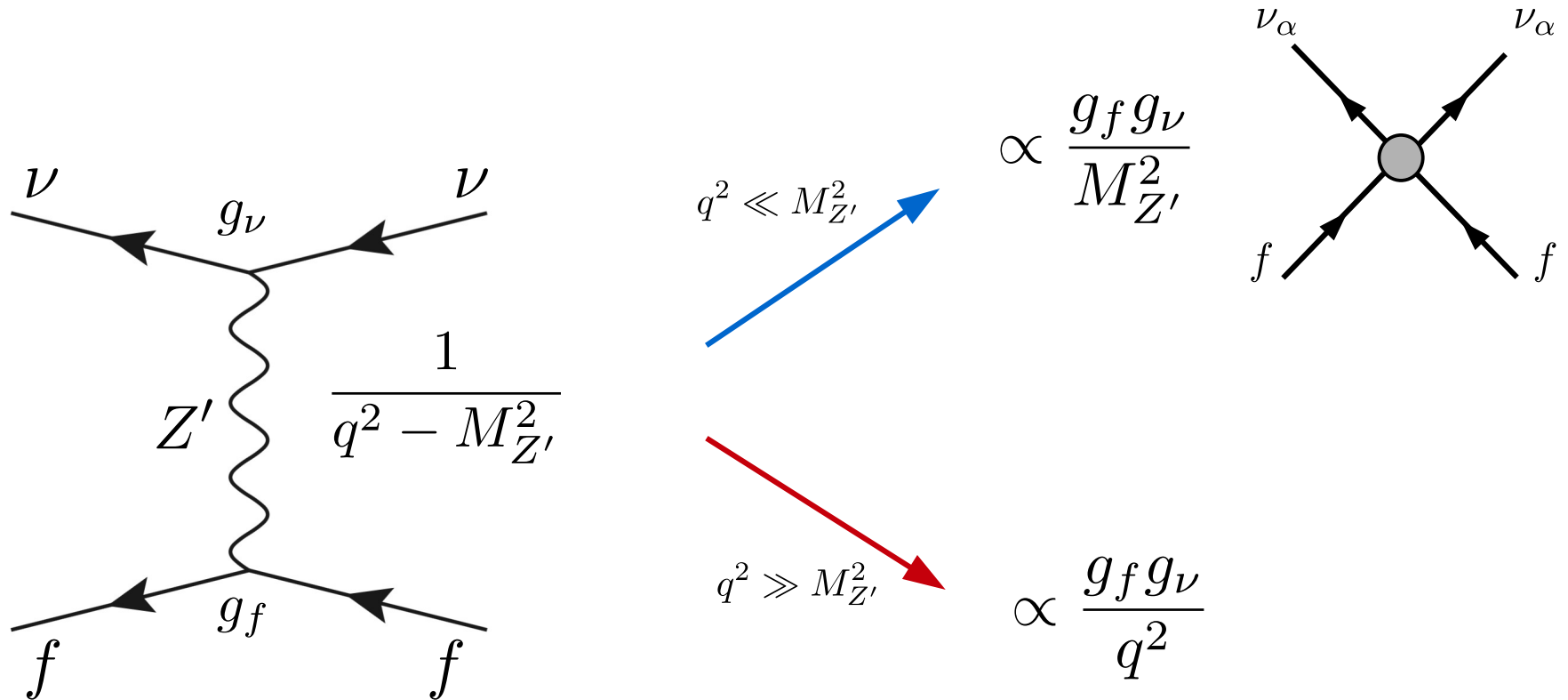
$$V(x) = \sqrt{2}G_F n_e(x) \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

Scalar operators:

$$\sqrt{2}G_F \eta_{\alpha\beta} (\bar{\nu}_\alpha \nu_\beta) (\bar{f} f)$$

$$\delta m_{\alpha\beta} = \sqrt{2}G_F \eta_{\alpha\beta} (n_f + n_{\bar{f}})$$

Model building challenges



→ Given the renewed interest in this topic, we include a detailed compilation of bounds on light Z' mediators, not only from oscillations but also other experiments (scattering, colliders, etc)

Additional interactions

1) Operators involving additional neutrino states, e.g.: $(\bar{N}\gamma^\mu N)(\bar{f}\gamma_\mu P f)$

$$V(x) = \begin{pmatrix} V_{CC} & & & \\ & 0 & & \\ & & 0 & \\ & & & V_b - V_{NC} \end{pmatrix}$$

2) Dark matter – neutrino connections: e.g., the interactions of neutrinos with ultra-light (bosonic) dark matter (as light as 10^{-20} eV)

$$\phi(x) = \frac{\sqrt{2\rho_{DM}(x)}}{m_\phi} \cos[m_\phi(t - \vec{v} \cdot \vec{x})]$$

leads to several effects, including a time modulation of the parameters measured in neutrino experiments:

$$\sin \theta_{12}(t) \simeq \sin \theta_{12} + \frac{\cos \theta_{12}}{\Delta m_{12}} \frac{g_\phi \sqrt{2\rho_{DM}}}{m_\phi} \cos m_\phi t$$

Neutrino decay

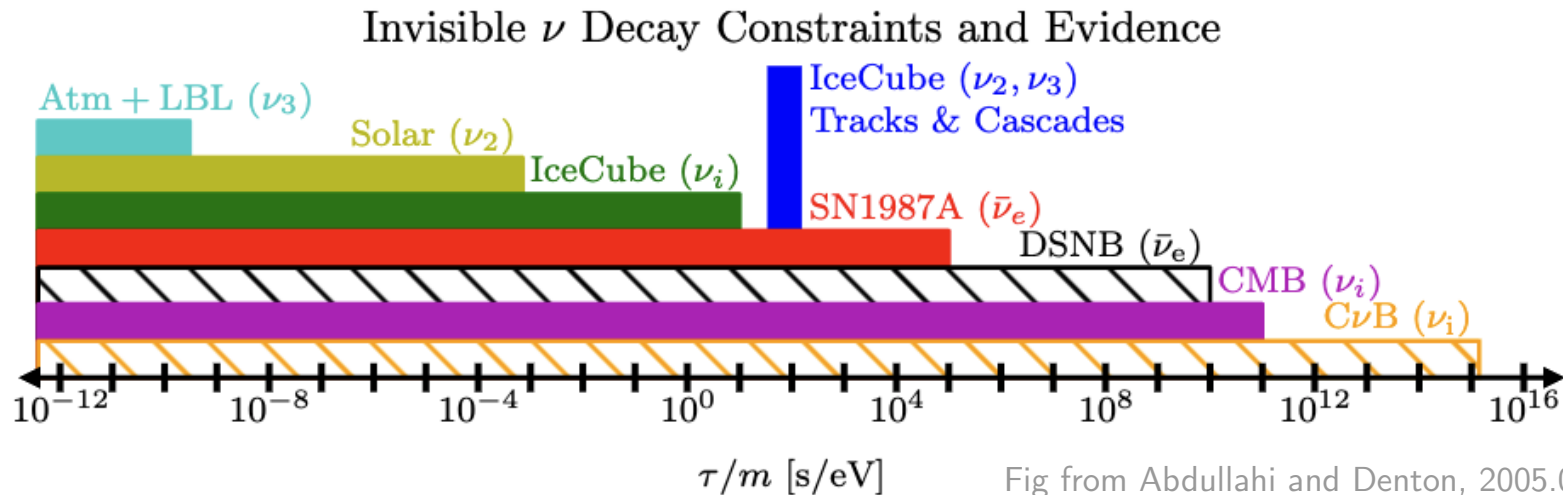
Neutrino decay typically arises in Majoron models. For example, for Majorana neutrinos

$$\mathcal{L} \supset \frac{f_{ij}}{2\Lambda^2} (L_i H)(L_j H)\phi + \text{h.c.} \longrightarrow \frac{f_{ij}v^2}{2\Lambda^2} \nu_i \nu_j \phi + \text{h.c.}$$

The phenomenology depends on whether neutrinos are Majorana/Dirac, and on whether the field is a scalar or a pseudoscalar.

We typically distinguish between invisible or visible decay, according to the expected signatures in neutrino experiments.

Neutrino decay

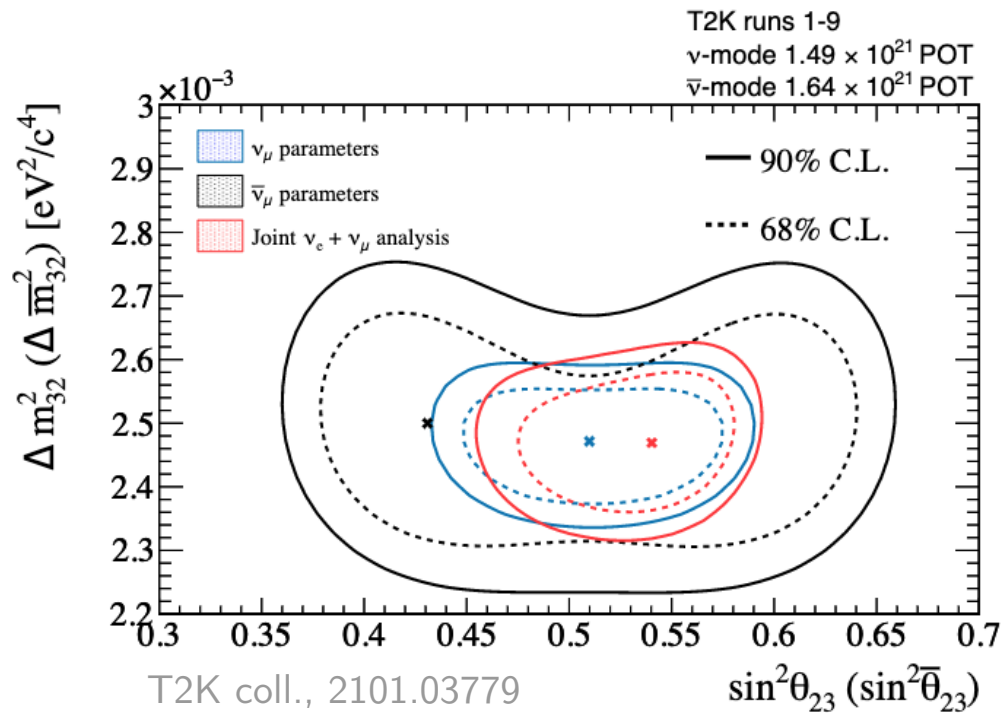


Decay mode	Experiments	τ_3/m_3 (s/eV)	Reference
Invisible	SK I + SK II+ K2K+ MINOS	2.9×10^{-10}	[323]
	MINOS+ T2K	2.8×10^{-12}	[324]
	OPERA	1.3×10^{-13}	[325]
	NOVA+T2K	2.3×10^{-12}	[326]
Visible	MINOS+T2K	1.0×10^{-11}	[327]
	Borexino+KamLAND	$1.0(7.0) \times 10^{-5\dagger}$	[328]

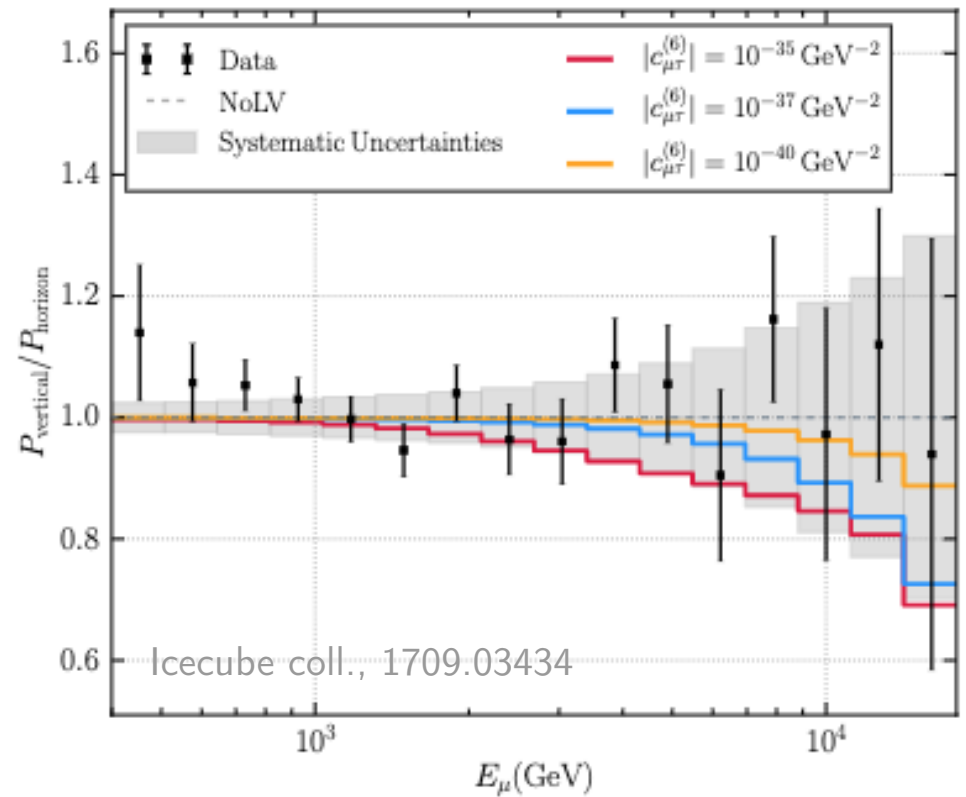
[†] These two bounds corresponds to $\nu_3 \rightarrow \bar{\nu}_2 + X$ and $\nu_3 \rightarrow \bar{\nu}_1 + X$

Tests of fundamental symmetries

CPT violation



Lorentz violation



Tests of fundamental symmetries

Quantum decoherence:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 2 \sum_{i < j} \text{Re} \left[\tilde{U}_{\alpha i}^* \tilde{U}_{\beta i} \tilde{U}_{\alpha j} \tilde{U}_{\beta j}^* \right] \left(1 - e^{-\gamma_{ij} L} \cos \tilde{\Delta}_{ij} \right) \\ - 2 \sum_{i < j} \text{Im} \left[\tilde{U}_{\alpha i}^* \tilde{U}_{\beta i} \tilde{U}_{\alpha j} \tilde{U}_{\beta j}^* \right] e^{-\gamma_{ij} L} \sin \tilde{\Delta}_{ij}$$

$$\gamma_{ij} = \gamma_{ij}^0 \left(\frac{E}{\text{GeV}} \right)^n$$

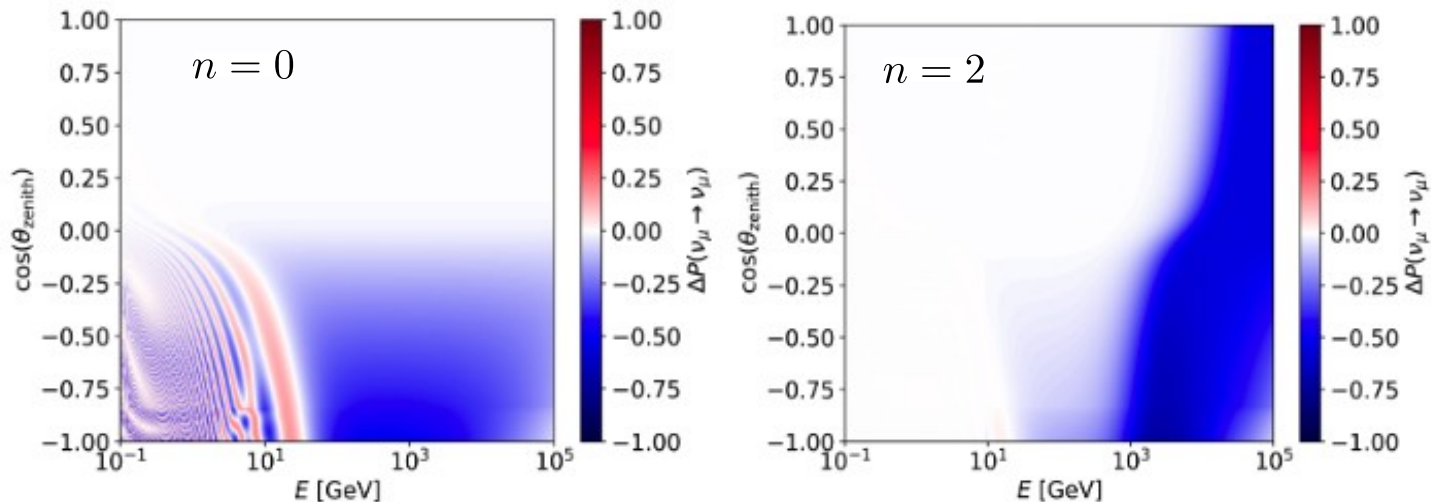


Figure from Stuttard and Jensen, 2007.00068

$$\gamma^0 = 1.3 \times 10^{-23} \text{GeV}$$

Summary

- This white paper aims to cover the main players for BSM effects on neutrino flavor
- The topic is very broad, and we have tried to capture the main interests from the community on this topic
- With respect to last Snowmass, there have been some changes:
 - there has been a renewed interest in NSI and light mediators, as well as on non-unitarity of the PMNS
 - we have new data from long-baseline neutrino oscillation experiments, and from DeepCore and ANTARES
 - the field of neutrino telescopes is blooming with new proposals, data, and exciting prospects

We want your feedback!

- Two feedback/writing sessions organized here, please join us this afternoon!
- For further comments and suggestions, please reach out:
 - teppei.katori at kcl.ac.uk
 - pilar.coloma at ift.csic.es
 - dvanegas at udemedellin.edu.co
- We will distribute the paper and a google form very soon through slack and mailing lists, stay tuned

Thank you!

Scope of this white paper

We identified a total of
38 Lols which are
relevant to this white
paper

	A	B	C
1	Link to Lol	title of Lol	Comments
2	https://www.snowmass21.org/	NSI from a flavorful Z' model	NSI
3	https://www.snowmass21.org/	Constraints on Non-Standard Neutrino Interactions Utilizing Copulas	NSI
4	https://www.snowmass21.org/	Neutrino Non-Standard Interactions	NSI
5	https://www.snowmass21.org/	A comprehensive EFT global fit in the neutrino oscillation experiments	NSI
6	https://www.snowmass21.org/	Coherent Elastic Neutrino-Nucleus Scattering: Theoretical and experimental	NSI
7	https://www.snowmass21.org/	Neutrino self-interactions	NSI
8	https://www.snowmass21.org/	Large Extra-Dimension Searches	steriles
9	https://www.snowmass21.org/	Global Light Sterile Neutrino Fits	steriles
10	https://www.snowmass21.org/	Long-Baseline Accelerator Probes for Light Sterile Neutrinos	steriles
11	https://www.snowmass21.org/	Testing quasi-Dirac leptogenesis through neutrino oscillations	steriles
12	https://www.snowmass21.org/	Follow up of anomalies measured in short baseline neutrino experiments	steriles
13	https://www.snowmass21.org/	Non-Unitarity of the neutrino mixing matrix	non-unitarity
14	https://www.snowmass21.org/	Atmospheric $\nu\tau$ Appearance in DUNE	non-unitarity/NSI
15	https://www.snowmass21.org/	Tau Neutrino Physics	non-unitarity/NSI
16	https://www.snowmass21.org/	Cosmological Neutrinos	steriles/NSI/exotic
17	https://www.snowmass21.org/	Neutrino Decay as a Solution to the Short-Baseline Anomalies	decay
18	https://www.snowmass21.org/	Ultralight dark matter and neutrinos	exotic
19	https://www.snowmass21.org/	Neutrinos as Probes for Lorentz and CPT Symmetry	exotic
20	https://www.snowmass21.org/	Exploration of a new model for neutrino oscillations using a kiloton-scale	exotic
21	https://www.snowmass21.org/	Ultra-High-Energy Neutrinos	exotic?
22	https://www.snowmass21.org/	Cosmic Neutrino Probes of Fundamental Physics	exotic/decay
23	https://www.snowmass21.org/	Astrophysical neutrinos and dark matter experiments	solar/astro
24	https://www.snowmass21.org/	Low Background kTon-Scale Liquid Argon Time Projection Chambers	solar/astro
25			

Link to Lol	title of Lol	Comments
https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF7-NF5_NF3_PandaX-073.pdf	The PandaX Experiment	solar/astro
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_Gavin_Davies-117.pdf	The NOvA Experiment and Exotic Neutrino	steriles/NSI
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF2_Ben_Jones-046.pdf	BSM Neutrino Oscillation Searches	steriles/NSI/exotic
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF6_NF10-RF6_RF0_Rupak_Mahapatra-147.pdf	Miner experiment	NSI, CEvNS
https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF7_CF6-NF4_NF10_Nepomuk_Otte-202.pdf	Trinity: A large Field-of-View Air-Shower	exotic
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF0_NF0-RF4_RF0-CF1_CF0_HyperK-187.pdf	The Hyper-Kamiokande Experiment	
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF4_NF1-RF4_RF0-CF7_CF1_SUPERK-050.pdf	Ongoing Science Program of Super-Kamiokande	
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF4_NF10-IF6_IF0_Orebi_Gann-089.pdf	Astrophysical neutrinos at THEIA	solar/astro
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF2-TF11_TF0_DUNE-051.pdf	BSM in DUNE	steriles/NSI/non-unitarity
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF5_NF4_Baudis-085.pdf	Neutrino physics with the DARWIN	solar/astro
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF6_NF2-EF0_EF0-AF2_AF4_Kenneth_Lorant-073.pdf	Neutrinos from stored muons; $\nu\mu$	steriles
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF4-CF7_CF0-TF11_TF0_Segev_Benzion-073.pdf	Supernova detection in IceCube	solar/astro
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF4-CF7_CF1-TF11_TF0_Darren_Griffiths-073.pdf	The IceCube Neutrino Observatory	
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF2-CF7_CF1-TF9_TF8_Katori-073.pdf	New physics with astrophysical neutrinos	exotic
https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF0_Tom_Stuttard-058.pdf	Neutrino oscillations with IceCube	steriles/non-unitarity/NSI/exotic