New Physics in Astrophysical Neutrino Flavor

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based on arXiv:1506.02043

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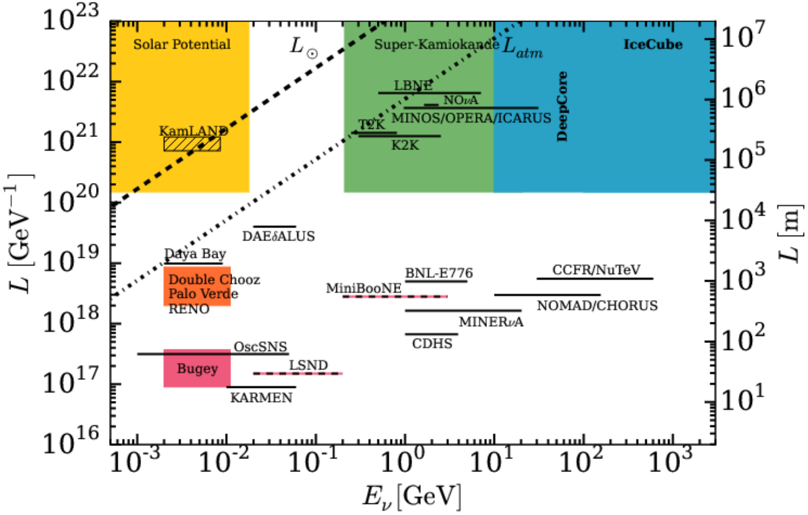
Neutrino experiments overview

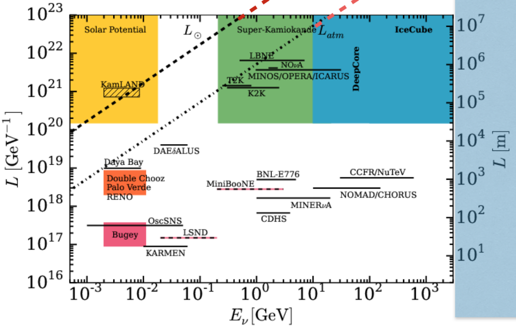


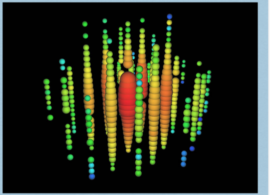
[modified from J.S. Diaz and V.A. Kostelecky, Phys.Lett. B700, 25 (2011)] slide concept by T. Katori

Extra Galactic

?

1 Mpc (~Andromeda)





> 10 TeV

Flavor content 101

The flavor content at Earth depends on the initial flavor content $(\phi_e, \phi_\mu, \phi_\tau)$:

- $(1:2:0) \rightarrow$ pion beam
- $(1:0:0) \rightarrow$ neutron decay
- $(0:1:0) \rightarrow$ damped muon
- $(1:1:0) \rightarrow$ charmed meson decay

General astrophysical scenarios produce $(x, 1-x, 0)$ by combination of the above processes.

Flavor content 101

The propagation Hamiltonian

$$H(E) = V(E)^\dagger \begin{pmatrix} \Delta_1(E) & 0 & 0 \\ 0 & \Delta_2(E) & 0 \\ 0 & 0 & \Delta_3(E) \end{pmatrix} V(E)$$

Under in the full decoherence regime we have

$$\bar{P}_{\nu_\alpha \to \nu_\beta}(E) = \sum_i |V_{\alpha i}|^2 \, |V_{\beta i}|^2 \ ,$$

The Earth flavor content

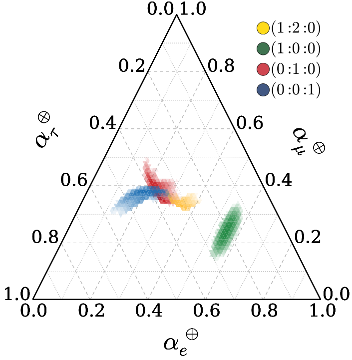
$$\phi_\beta^\oplus(E) = \sum_\alpha \bar{P}_{\nu_\alpha \to \nu_\beta}(E) \phi_\alpha^p(E) \ .$$

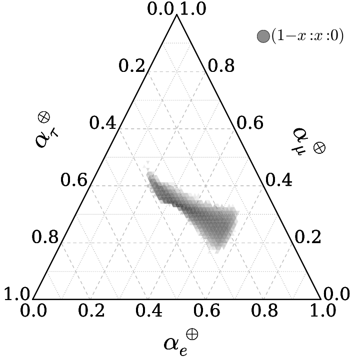
Standard three flavor expectation

For std-vacuum oscillations

$$H = \frac{1}{2E} U^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U$$

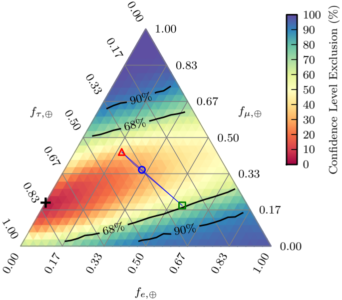
so V(E) = U (PMNS matrix).



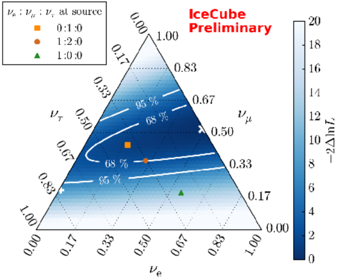


IceCube flavor content results

- IceCube has recently measured the astrophysical flavor ratio.
- Both analysis are compatible with (1:1:1) at a 1σ level.
- Minor tension between best fit points from different analysis.



Phys. Rev. Lett. 114, 171102 (2015)



https://indico.in2p3.fr/event/10819/

It's complicated

- The flavor ratio best fit strongly depends on the analysis energy range, spectral index, spectral cut off, background estimation.
- The *track-cascade* mis-ID is very important.

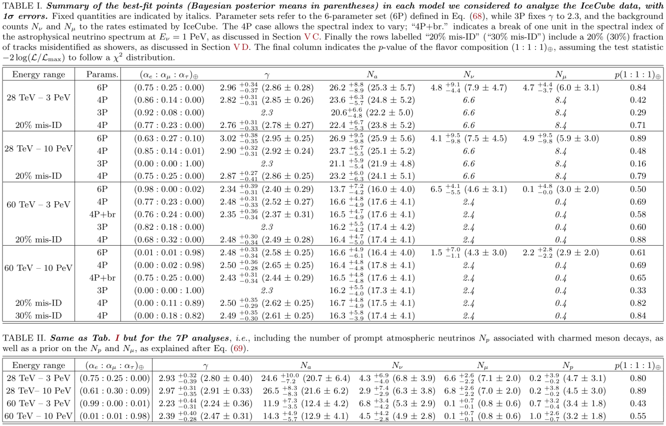


TABLE I. ***Summary of the best-fit points (Bayesian posterior means in parentheses) in each model we considered to analyze the IceCube data, with 1σ errors.*** Fixed quantities are indicated by italics. Parameter sets refer to the 6-parameter set (6P) defined in Eq. (68), while 3P fixes γ to 2.3, and the background counts N_ν and N_μ to the rates estimated by IceCube. The 4P case allows the spectral index to vary; "4P+br." indicates a break of one unit in the spectral index of the astrophysical neutrino spectrum at $E_\nu = 1$ PeV, as discussed in Section V C. Finally the rows labelled "20% mis-ID" ("30% mis-ID") include a 20% (30%) fraction of tracks misidentified as showers, as discussed in Section V D. The final column indicates the p-value of the flavor composition $(1:1:1)_\oplus$, assuming the test statistic $-2\log(\mathcal{L}/\mathcal{L}_{\max})$ to follow a χ^2 distribution.

Energy range	Params.	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	$p(1:1:1)_\oplus$
28 TeV – 3 PeV	6P	(0.75 : 0.25 : 0.00)	$2.96\,^{+0.34}_{-0.37}$ (2.86 ± 0.28)	$26.2\,^{+8.8}_{-8.9}$ (25.3 ± 5.7)	$4.8\,^{+9.1}_{-4.4}$ (7.9 ± 4.7)	$4.7\,^{+4.4}_{-3.7}$ (6.0 ± 3.1)	0.84
	4P	(0.86 : 0.14 : 0.00)	$2.82\,^{+0.31}_{-0.31}$ (2.85 ± 0.26)	$23.6\,^{+6.3}_{-5.7}$ (24.8 ± 5.2)	*6.6*	*8.4*	0.42
	3P	(0.92 : 0.08 : 0.00)	*2.3*	$20.6^{+6.6}_{-4.8}$ (22.2 ± 5.0)	*6.6*	*8.4*	0.29
20% mis-ID	4P	(0.77 : 0.23 : 0.00)	$2.76\,^{+0.31}_{-0.33}$ (2.78 ± 0.27)	$22.4\,^{+6.7}_{-5.3}$ (23.8 ± 5.2)	*6.6*	*8.4*	0.71
28 TeV – 10 PeV	6P	(0.63 : 0.27 : 0.10)	$3.02\,^{+0.38}_{-0.35}$ (2.95 ± 0.25)	$26.9\,^{+9.5}_{-9.8}$ (25.9 ± 5.6)	$4.1\,^{+9.5}_{-9.8}$ (7.5 ± 4.5)	$4.9\,^{+9.5}_{-9.8}$ (5.9 ± 3.0)	0.89
	4P	(0.85 : 0.14 : 0.01)	$2.90\,^{+0.32}_{-0.31}$ (2.92 ± 0.24)	$23.7\,^{+6.7}_{-5.5}$ (25.1 ± 5.2)	*6.6*	*8.4*	0.48
	3P	(0.00 : 0.00 : 1.00)	*2.3*	$21.1\,^{+5.9}_{-5.4}$ (21.9 ± 4.8)	*6.6*	*8.4*	0.16
20% mis-ID	4P	(0.75 : 0.25 : 0.00)	$2.87\,^{+0.27}_{-0.41}$ (2.86 ± 0.25)	$23.2\,^{+6.0}_{-6.3}$ (24.1 ± 5.1)	*6.6*	*8.4*	0.79
60 TeV – 3 PeV	6P	(0.98 : 0.00 : 0.02)	$2.34\,^{+0.39}_{-0.31}$ (2.40 ± 0.29)	$13.7\,^{+7.2}_{-4.2}$ (16.0 ± 4.0)	$6.5\,^{+4.1}_{-5.5}$ (4.6 ± 3.1)	$0.1\,^{+4.8}_{-0.0}$ (3.0 ± 2.0)	0.50
	4P	(0.77 : 0.23 : 0.00)	$2.48\,^{+0.31}_{-0.33}$ (2.52 ± 0.27)	$16.6\,^{+4.8}_{-4.9}$ (17.6 ± 4.1)	*2.4*	*0.4*	0.69
	4P+br	(0.76 : 0.24 : 0.00)	$2.35\,^{+0.36}_{-0.34}$ (2.37 ± 0.31)	$16.5\,^{+4.7}_{-4.9}$ (17.6 ± 4.1)	*2.4*	*0.4*	0.58
	3P	(0.82 : 0.18 : 0.00)	*2.3*	$16.2\,^{+5.5}_{-4.2}$ (17.4 ± 4.2)	*2.4*	*0.4*	0.60
20% mis-ID	4P	(0.68 : 0.32 : 0.00)	$2.48\,^{+0.30}_{-0.34}$ (2.49 ± 0.28)	$16.4\,^{+4.7}_{-5.0}$ (17.4 ± 4.1)	*2.4*	*0.4*	0.88
60 TeV – 10 PeV	6P	(0.01 : 0.01 : 0.98)	$2.48\,^{+0.33}_{-0.34}$ (2.58 ± 0.25)	$16.6\,^{+4.9}_{-6.1}$ (16.4 ± 4.0)	$1.5\,^{+7.0}_{-1.1}$ (4.3 ± 3.0)	$2.2\,^{+2.8}_{-2.2}$ (2.9 ± 2.0)	0.61
	4P	(0.00 : 0.02 : 0.98)	$2.50\,^{+0.36}_{-0.28}$ (2.65 ± 0.25)	$16.4\,^{+4.8}_{-4.8}$ (17.8 ± 4.1)	*2.4*	*0.4*	0.69
	4P+br	(0.75 : 0.25 : 0.00)	$2.43\,^{+0.31}_{-0.34}$ (2.44 ± 0.29)	$16.5\,^{+4.8}_{-4.8}$ (17.6 ± 4.1)	*2.4*	*0.4*	0.65
	3P	(0.00 : 0.00 : 1.00)	*2.3*	$16.2\,^{+5.5}_{-4.0}$ (17.3 ± 4.1)	*2.4*	*0.4*	0.33
20% mis-ID	4P	(0.00 : 0.11 : 0.89)	$2.50\,^{+0.35}_{-0.29}$ (2.62 ± 0.25)	$16.7\,^{+4.8}_{-4.9}$ (17.5 ± 4.1)	*2.4*	*0.4*	0.82
30% mis-ID	4P	(0.00 : 0.18 : 0.82)	$2.49\,^{+0.35}_{-0.30}$ (2.61 ± 0.25)	$16.3\,^{+5.8}_{-3.9}$ (17.4 ± 4.1)	*2.4*	*0.4*	0.84

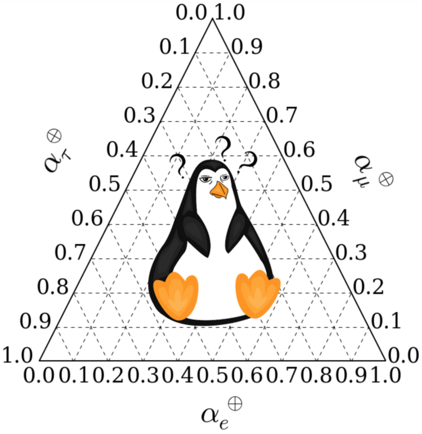
TABLE II. ***Same as Tab. I but for the 7P analyses***, *i.e.*, including the number of prompt atmospheric neutrinos N_p associated with charmed meson decays, as well as a prior on the N_p and N_μ, as explained after Eq. (69).

Energy range	$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$	γ	N_a	N_ν	N_μ	N_p	$p(1:1:1)_\oplus$
28 TeV – 3 PeV	(0.75 : 0.25 : 0.00)	$2.93\,^{+0.32}_{-0.39}$ (2.80 ± 0.40)	$24.6\,^{+10.0}_{-7.2}$ (20.7 ± 6.4)	$4.3\,^{+6.9}_{-4.0}$ (6.8 ± 3.9)	$6.6\,^{+2.6}_{-2.2}$ (7.1 ± 2.0)	$0.2\,^{+3.9}_{-0.2}$ (4.7 ± 3.1)	0.80
28 TeV– 10 PeV	(0.61 : 0.30 : 0.09)	$2.97\,^{+0.31}_{-0.35}$ (2.91 ± 0.33)	$26.5\,^{+8.3}_{-8.3}$ (21.6 ± 6.2)	$2.9\,^{+7.4}_{-2.9}$ (6.3 ± 3.8)	$6.8\,^{+2.6}_{-2.2}$ (7.0 ± 2.0)	$0.2\,^{+3.8}_{-0.2}$ (4.5 ± 3.0)	0.89
60 TeV – 3 PeV	(0.99 : 0.00 : 0.01)	$2.23\,^{+0.44}_{-0.31}$ (2.24 ± 0.36)	$11.9\,^{+7.3}_{-3.5}$ (12.4 ± 4.2)	$6.8\,^{+3.4}_{-4.2}$ (5.3 ± 2.9)	$0.1\,^{+0.7}_{-0.1}$ (0.8 ± 0.6)	$0.7\,^{+3.2}_{-0.4}$ (3.4 ± 1.8)	0.43
60 TeV – 10 PeV	(0.01 : 0.01 : 0.98)	$2.39\,^{+0.40}_{-0.28}$ (2.47 ± 0.31)	$14.3\,^{+4.9}_{-5.7}$ (12.9 ± 4.1)	$4.5\,^{+4.2}_{-2.8}$ (4.9 ± 2.8)	$0.1\,^{+0.7}_{-0.1}$ (0.8 ± 0.6)	$1.0\,^{+2.6}_{-0.7}$ (3.2 ± 1.8)	0.55

Palomarez-Ruiz et al. arXiv:1502.02649

?

- More statistics is needed to precisely measure the astrophysical flavor ratio (Gen-2?).
- What are the allowed regions on the flavor triangle in the presence of **new physics**?



Introducing new physics

We introduce new operators that represent new physics

$$\hat{H}_n = \left(\frac{E}{\Lambda_n}\right)^n \hat{O}_n$$

the new total propagation Hamiltonian

$$H = \frac{1}{2E} U^\dagger M^2 U + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n^\dagger O_n \tilde{U}_n = V^\dagger \Delta V$$

we assume that total decoherence still holds in the presence of the new operators.

Setting the scale of O_n

We study $n = 0$ and $n = 1$. We can reinterpret the LV/CPT neutrino limits to our operators:

- Best limits from : SK, Phys.Rev. D91 (5) (2015) 052003., IceCube, Phys.Rev. D82 (2010) 112003.
- On O_0: $O(10^{-23}\mathrm{GeV})$. [a-term]
- On O_1/Λ_1: $O(10^{-27})$. [c-term]

Kostelecky et al. Rev. Mod. Phys. 83 (2011) 11-31 [arXiv:0801.0287]

Choosing $\tilde{U}_n$

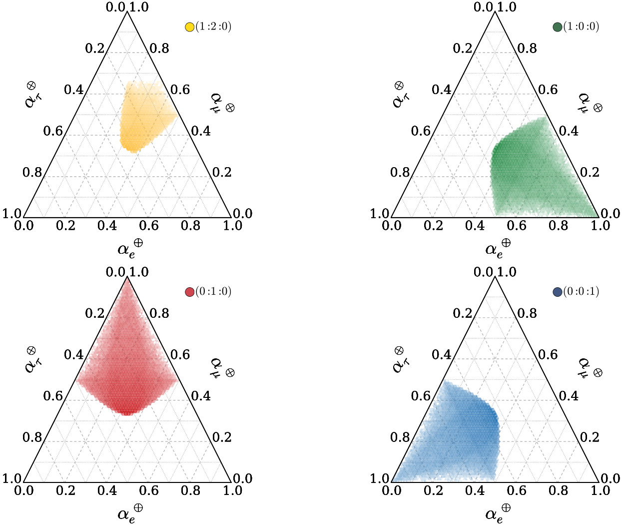
For the flavor structure of the new operators we assume they follow *anarchic sampling*:

$$d\tilde{U}_n = d\tilde{s}_{12}^2 \wedge d\tilde{c}_{13}^4 \wedge d\tilde{s}_{23}^2 \wedge d\tilde{\delta} \ ,$$

where $\tilde{s}_{ij}$, $\tilde{c}_{ij}$ and $\tilde{\delta}$ are the corresponding sines and cosines and phase respectively for the new physics *n*-operator mixing angles.

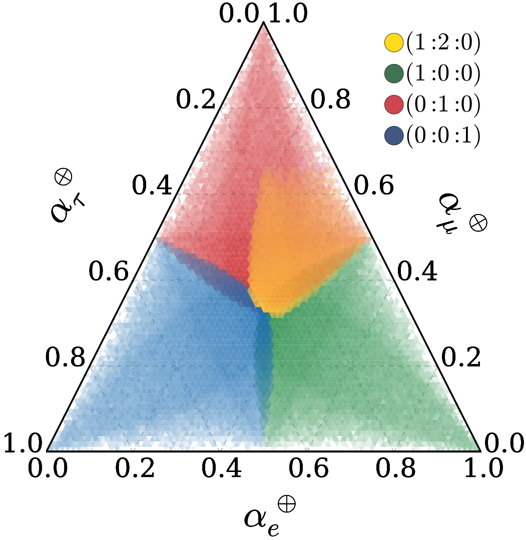
Say $H = \tilde{H}_n$

If we set the propagation Hamiltonian to just one of the new operators then ...



Now consider the Hamiltonian with mass term

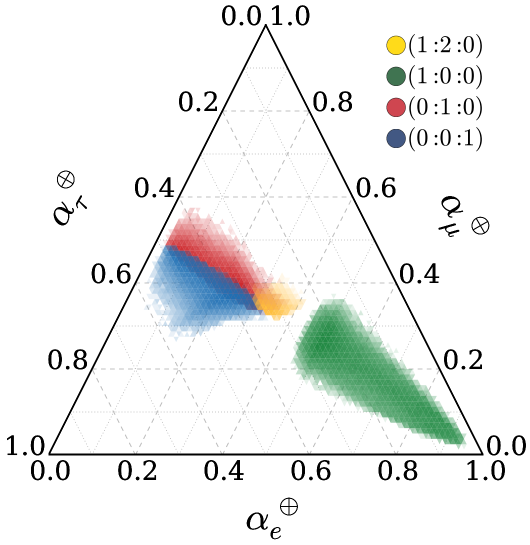
If we only add O_0 at a $10^{-23}\mathrm{GeV}$ scale



same result with O_1 for $O_1/\Lambda_1 \sim O(10^{-27})$

Set $O_0 \sim O(10^{-26}\mathrm{GeV})$

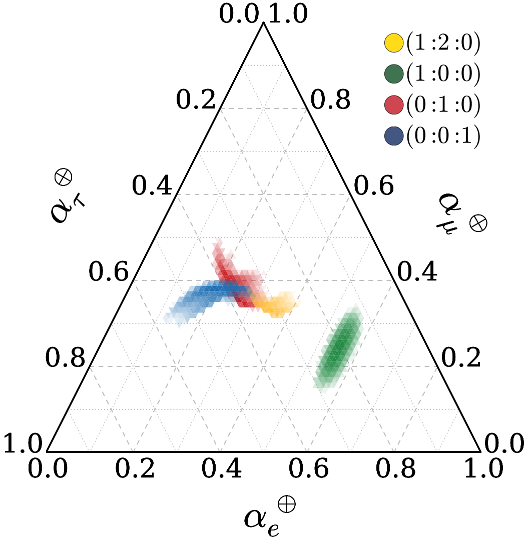
If the new operators are dominant only for $E_\nu > 35$ TeV



very similar result with O_1 for $O_1/\Lambda_1 \sim O(10^{-30})$

Set $O_0 \sim O(10^{-29}\mathrm{GeV})$

If the new operators are dominant only for $E_\nu > 2$ PeV



very similar result with O_1 for $O_1/\Lambda_1 \sim O(10^{-34})$

Closing remarks

- We have presented the reach of new physics scenarios in the astrophysical flavor ratio under the presence of LV/CPT-like scenarios.
- Precise measurement of the flavor ration can put strong constrains on O_i; in particular LV/CPT operators.
- Special thanks to Walter Winter and Mauricio Bustamante for useful and entertaining discussions (please read also arXiv:1506.02645).
- More data is needed! Meanwhile, we hope for non standard flavor ratio.
- Also stay tune for the new ν_μ IceCube disappearance result!!!

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Thanks!