Massachusetts Institute of Technology

TeVPA 2017

New physics searches with the PeV scale neutrinos

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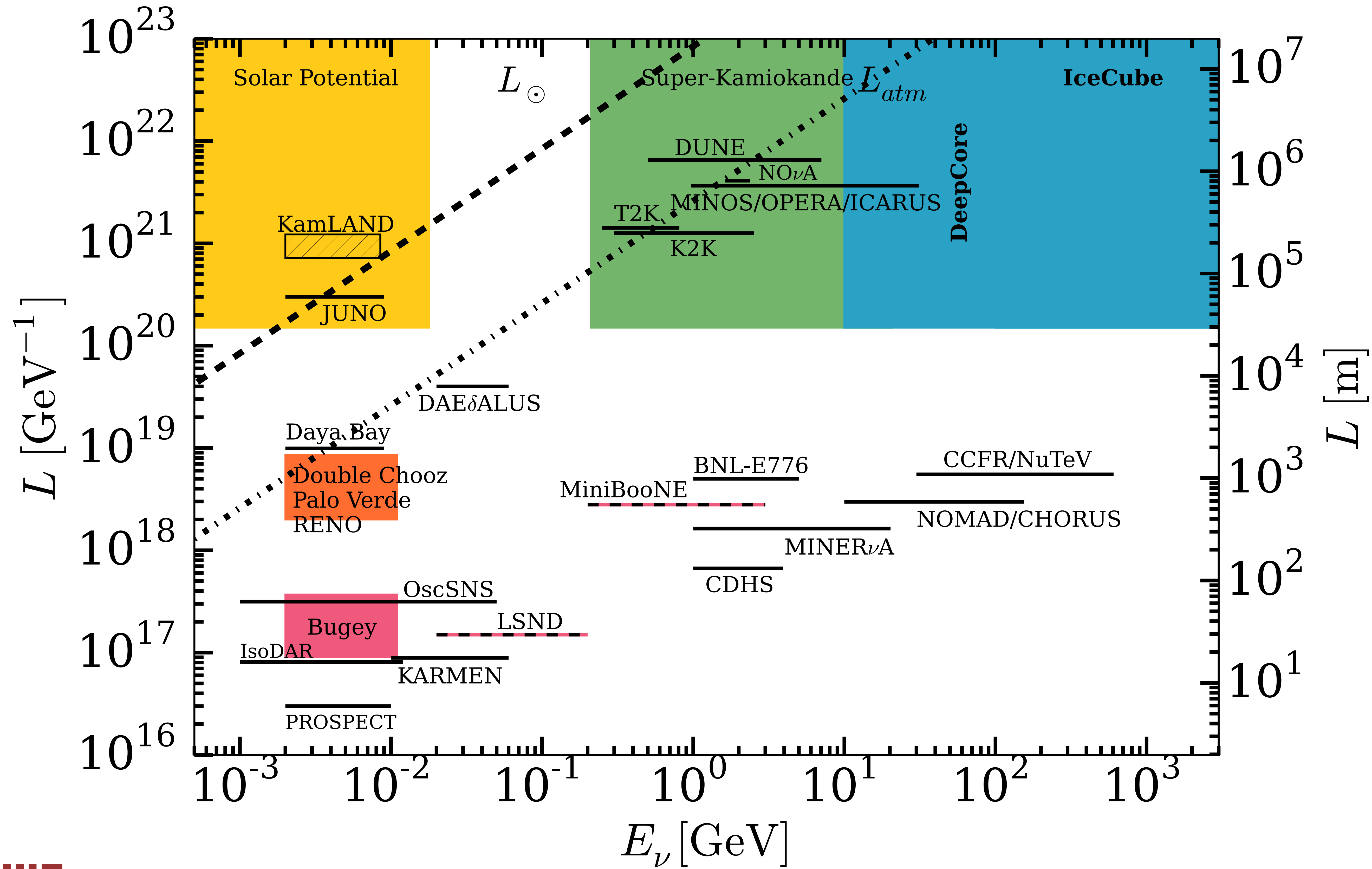
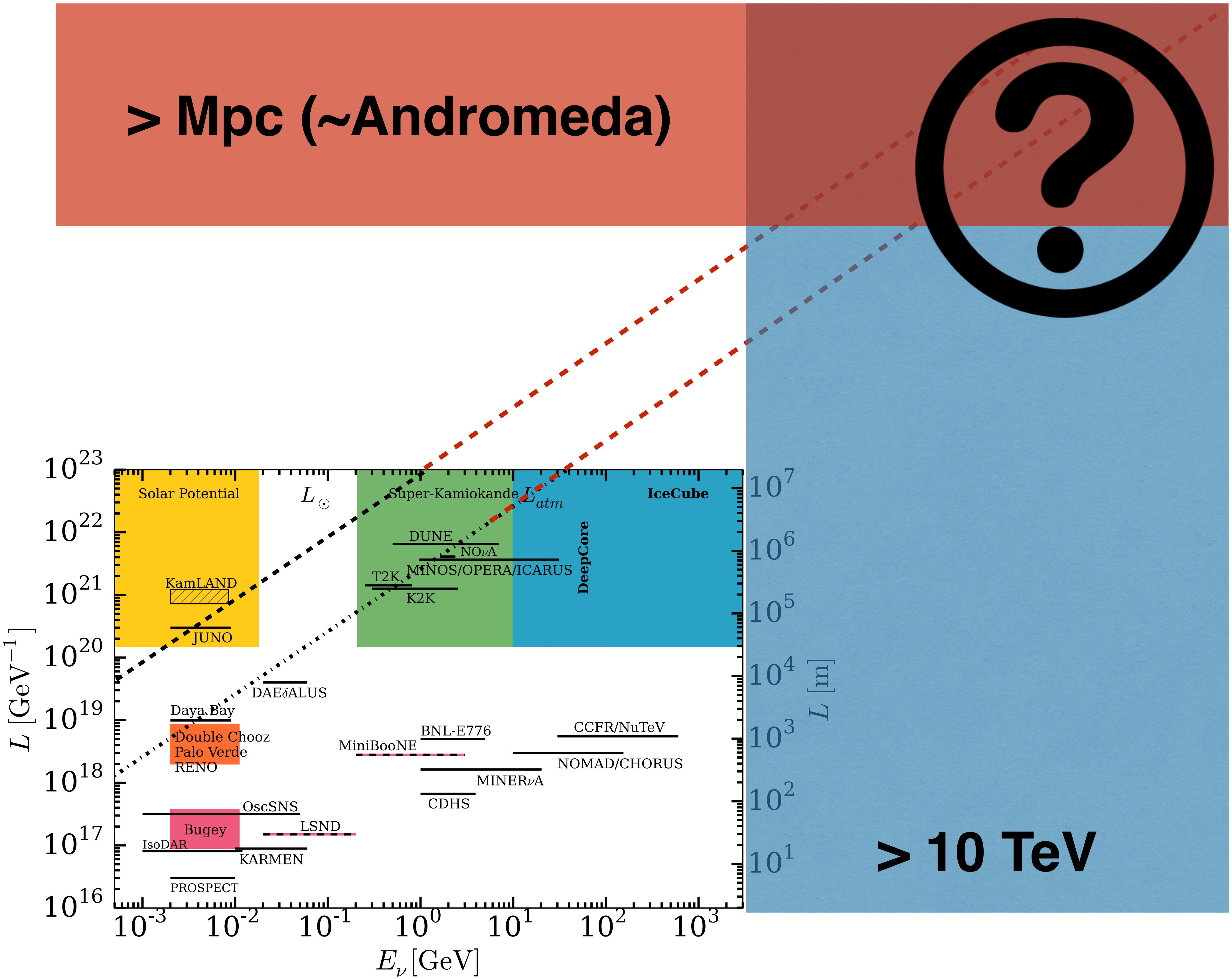
in collaboration with Teppei Katori and Jordi Salvado

Based on PRL 115, 161303 (2015)
(arXiv:1506.02043)

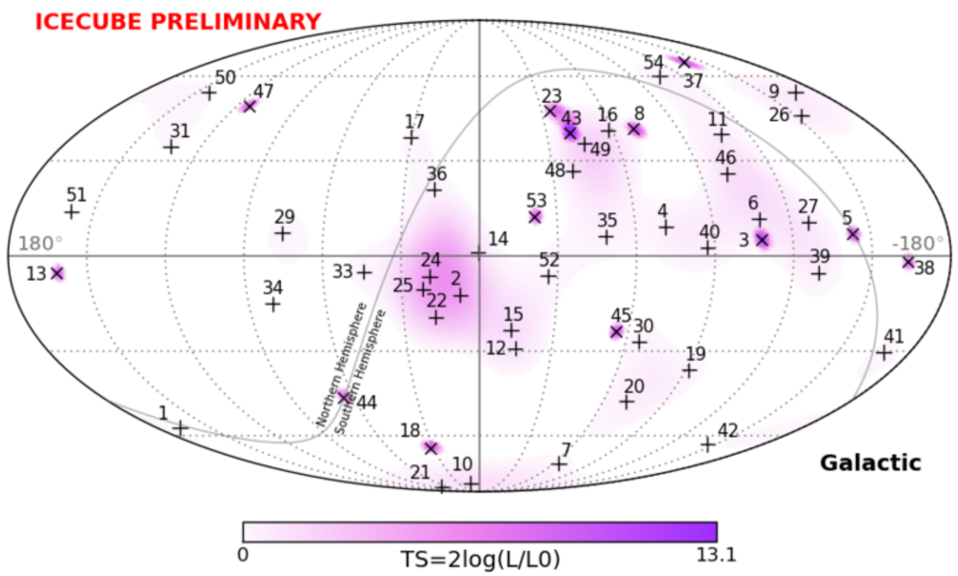
What we have explored so far…

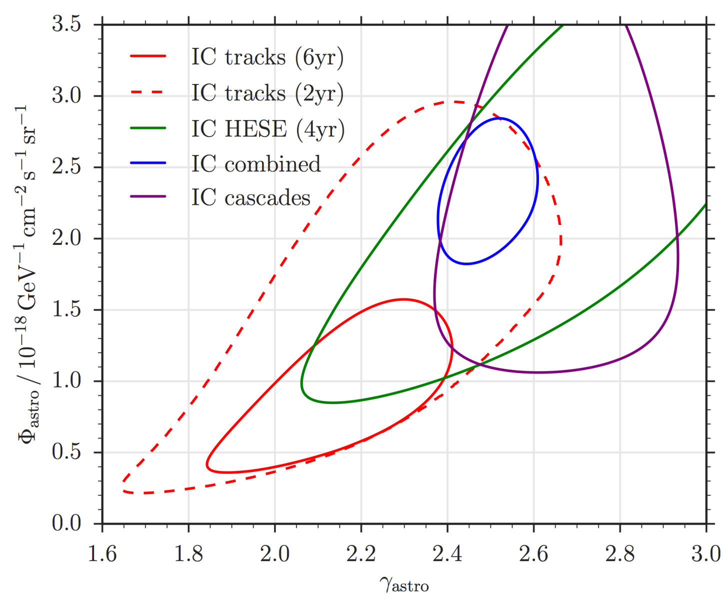


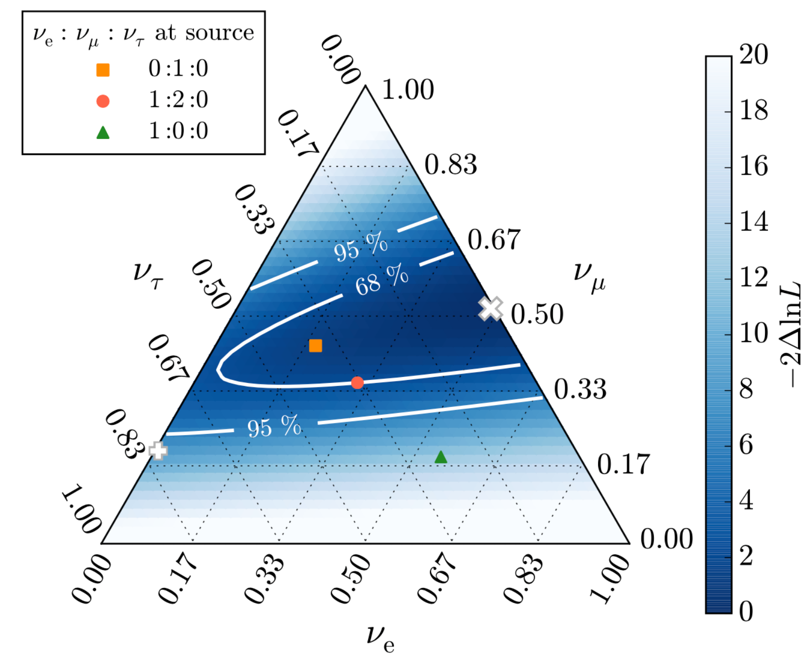
Cosmic neutrinos frontier



What do we know about astrophysical neutrinos?







- ~80 Events in 6 years.
- Events spatial distribution compatible with **isotropic** hypothesis.
- **No statistically significant correlation** with Galactic plane.
- Event distribution suggests extragalactic origin for the majority of the events.
- **Flavor ratio** is consistent with 1:1:1 ratio.

see Astrophys.J. 809 (2015) no.1, 98; Astrophys.J. 833 (2016) no.1, 3

New physics searches

	At the Source	At Propagation
Energy	Matter effects	New interactions, sterile neutrinos
Direction	DM decay/annihilation	New interactions with Galaxy/Earth
Flavor	Matter effects	Decay, sterile, new operators

(C.A., M. Bustamante, J. Conrad, A. Kheirandish, and A. Vincent *in preparation*)

New physics searches

	At the Source	At Propagation
Energy	Matter effects	New interactions, sterile neutrinos
Direction	DM decay/annihilation	**Next talk by Ali!** New interactions with Galaxy/Earth
Flavor	Matter effects	Decay, sterile, new operators **This talk!**

(C.A., M. Bustamante, J. Conrad, A. Kheirandish, and A. Vincent *in preparation*)

Initial flavor

Flavor mixing

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

Standard Expectation

New Physics!

Flavor composition @ source

(GRBs, AGNs, blazars, pulsars…)		$(\alpha_e : \alpha_\mu : \alpha_\tau)$
Pion	$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\downarrow$ $\mu^+ \rightarrow e^+ + \nu_\mu + \bar{\nu}_e$	(1:2:0)
Muon-damped	$\pi^+ \rightarrow \cancel{\mu^+} + \nu_\mu$	(0:1:0)
Neutron	$n \rightarrow p + e^- + \bar{\nu}_e$	(1:0:0)

Calculating $\bar{P}_{\nu_\alpha \to \nu_\beta}(E)$

The oscillation probability depends on the neutrino propagation hamiltonian

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

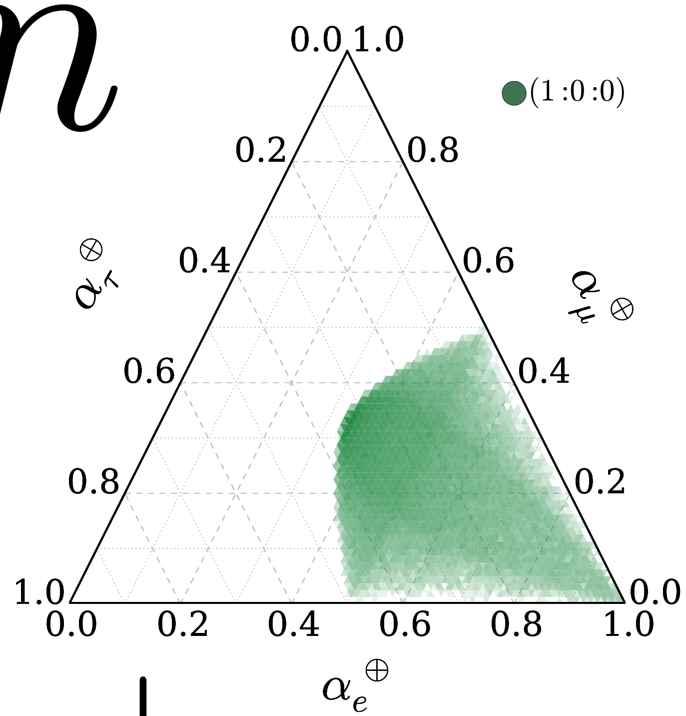
Since the oscillation length is much smaller than the distance of the sources

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

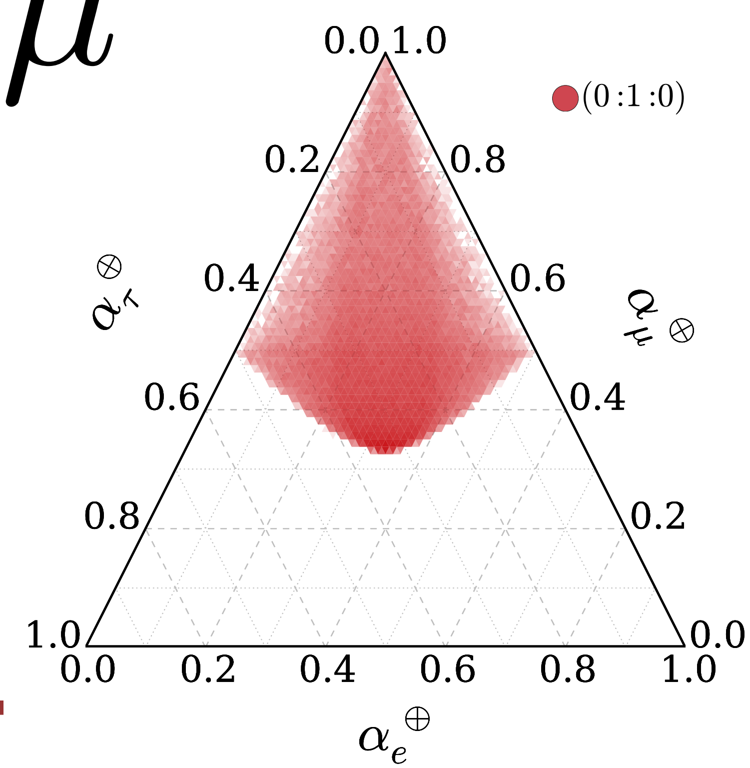
Oscillation probabilities depend only on the mixing elements!

Possible flavor triangles

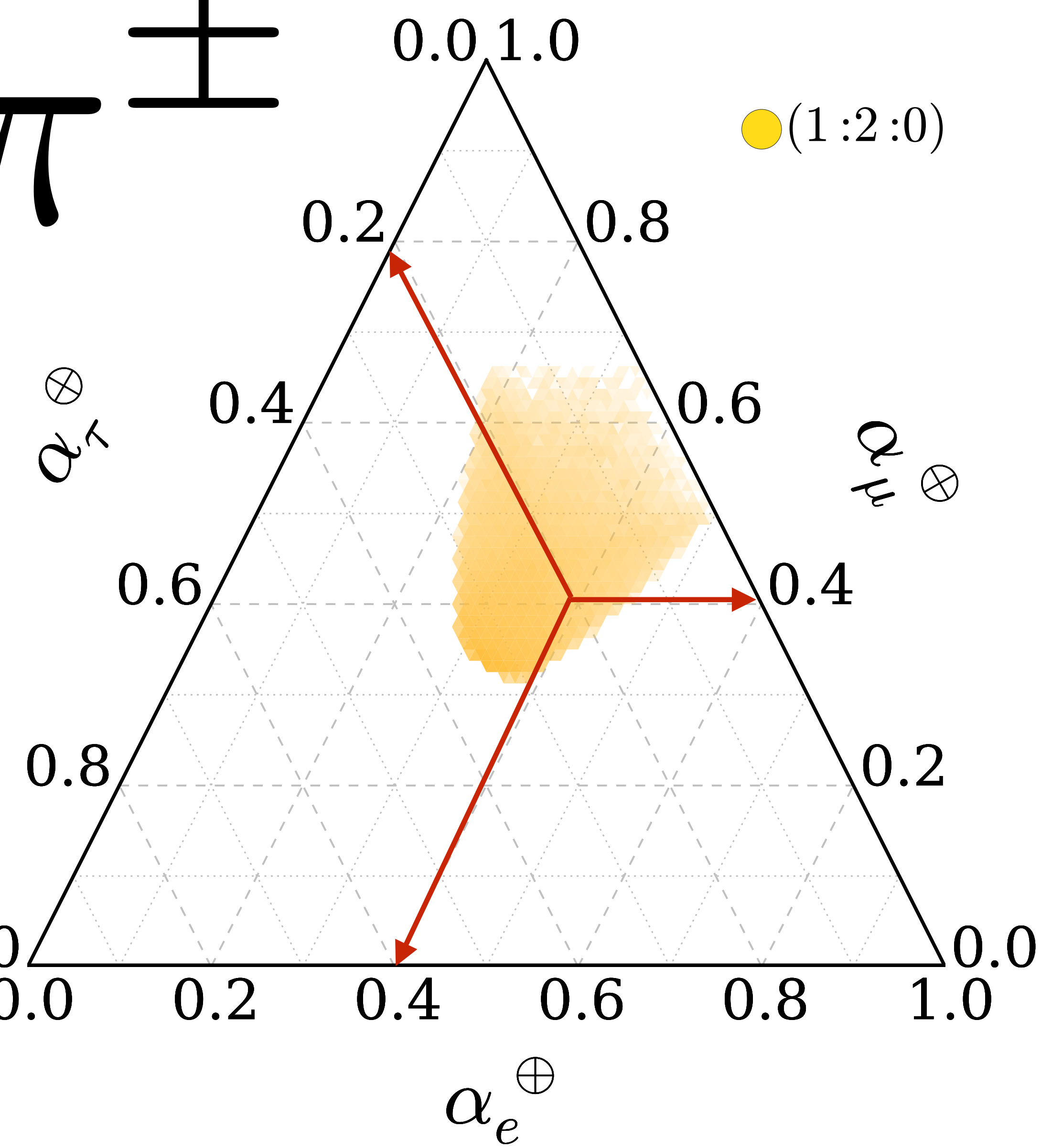
n



$\mu^\pm$



$\pi^\pm$



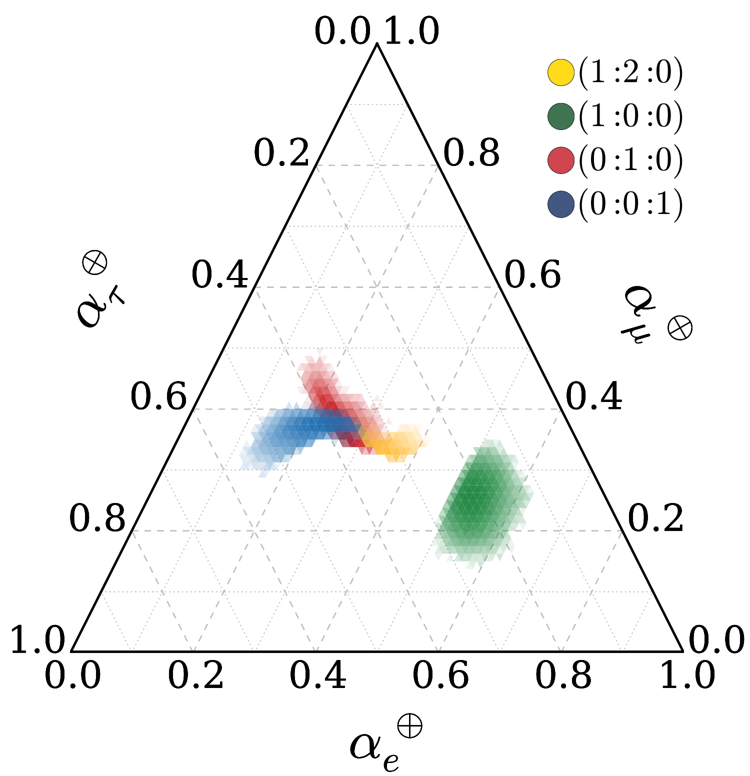
Due to unitarity the possible Earth flavor ratios for a given initial flavor composition is confined.

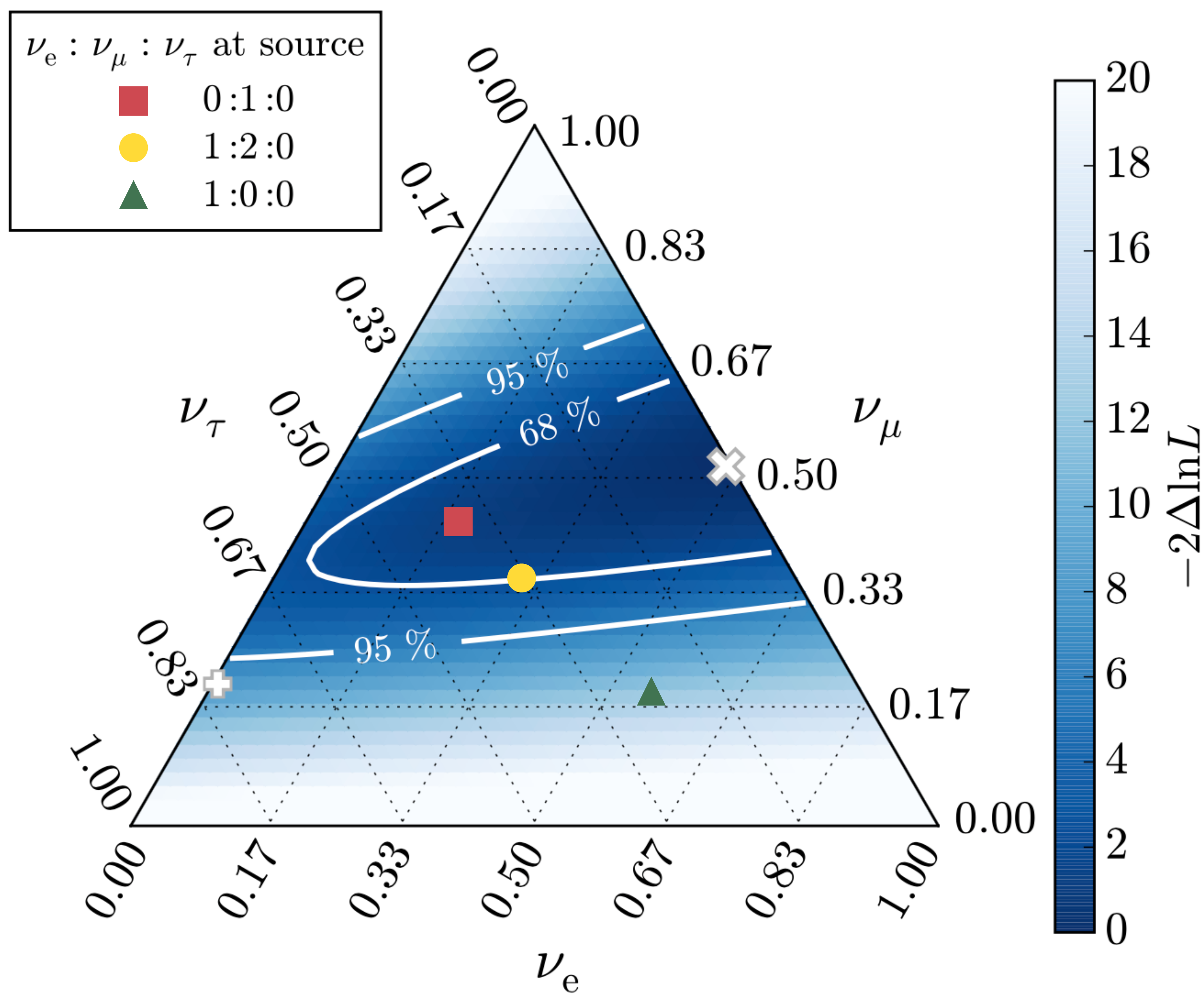
Astrophysical neutrino flavor

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

IceCube 1507.03991

standard oscillation prediction





C.A., T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

M. Bustamante, J. Beacom, W. Winter (Phys. Rev. Lett. **115**, 161302)

+ New physics

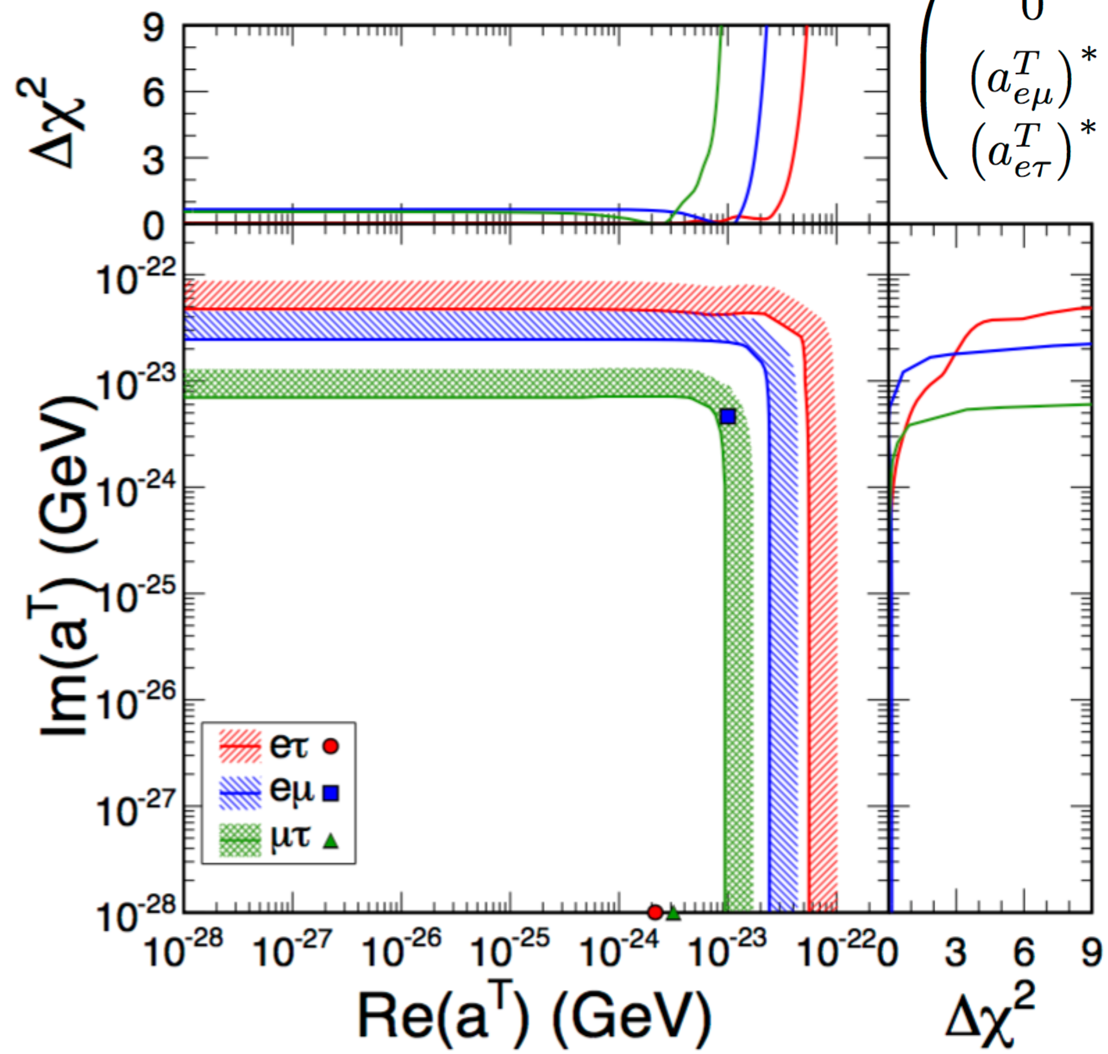
$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

$$\sim 10^{-24}\text{GeV}\left(\frac{TeV}{E}\right)$$

$$O_0 < \mathrm{O}(10^{-23})\ \text{GeV}$$
$$O_1/\Lambda_1 < \mathrm{O}(10^{-27})$$

Current best terrestrial limits on the new terms from IceCube+SK.

$$\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix}$$

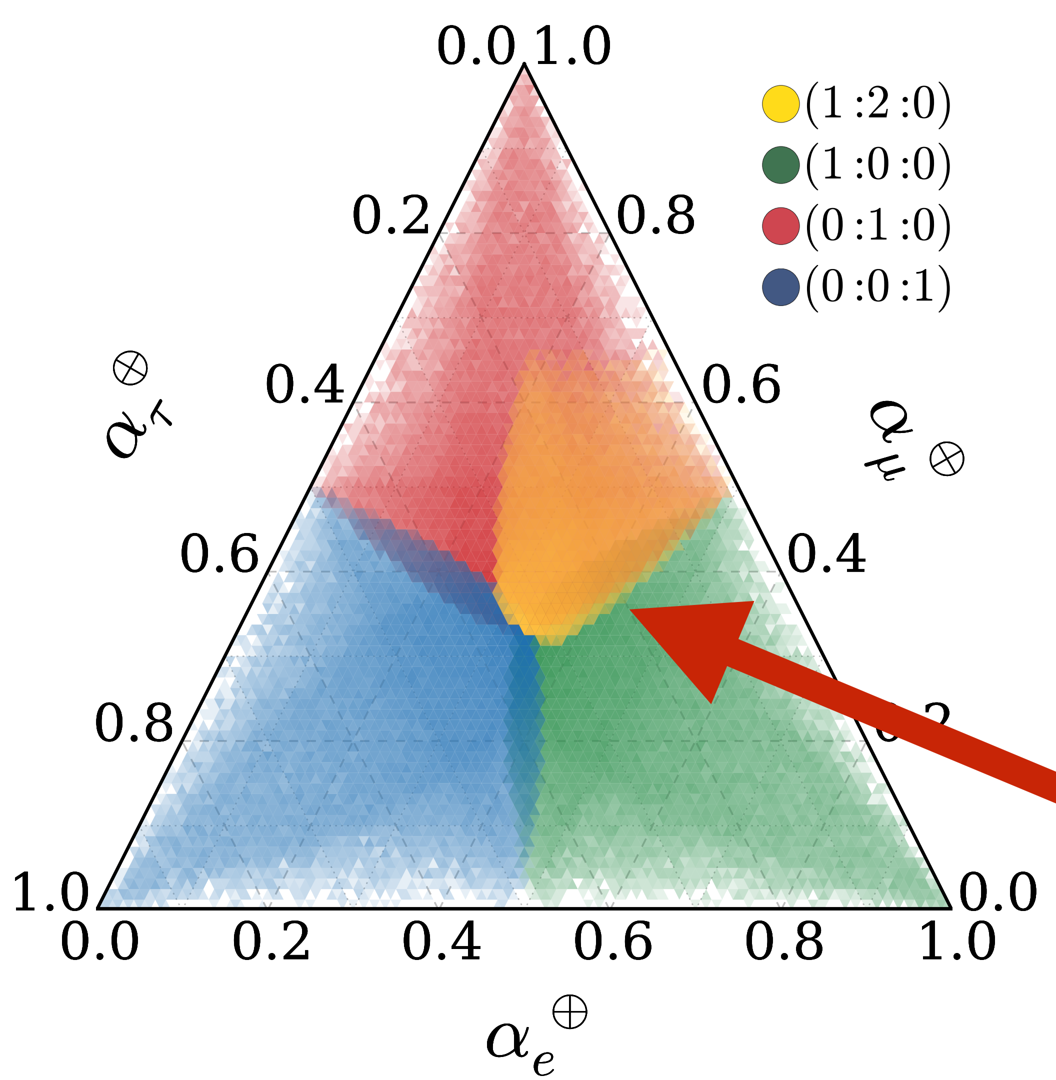


Phys.Rev. D91 (5) (2015) 052003,
Phys.Rev. D82 (2010) 112003.

+ New physics

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

(setting operators scales to current SK bounds)



Since the new physics flavor structure is unknown we sample randomly:

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

New physics term dominates (given current bounds). But more confined in pion case

C.A., T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)
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$$H = \frac{1}{2E} U M^2 U^\dagger + \boxed{\sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger}$$

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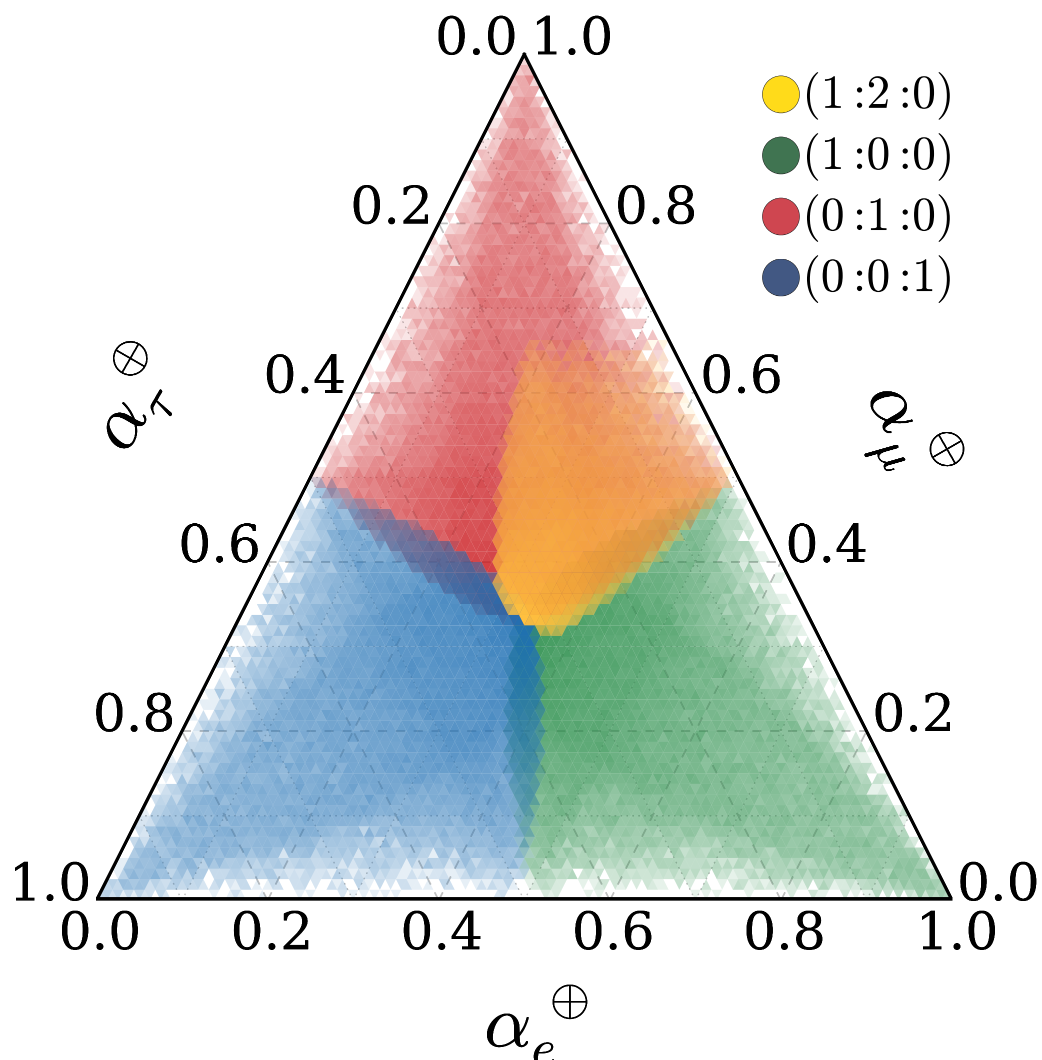
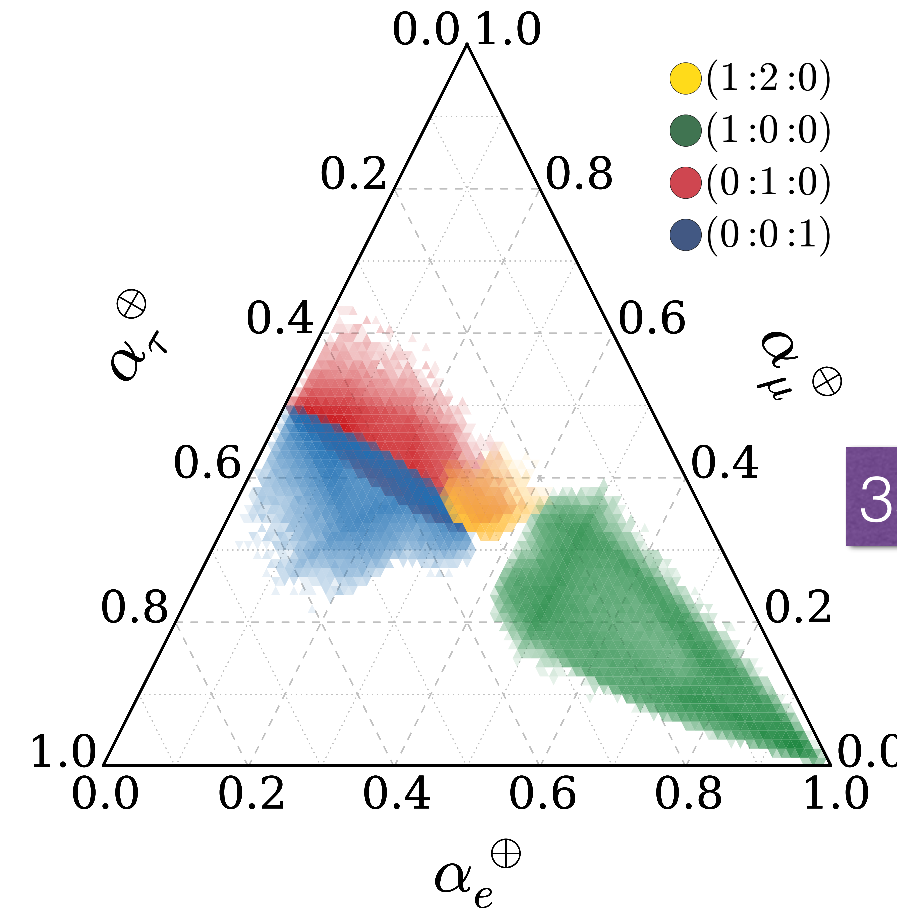
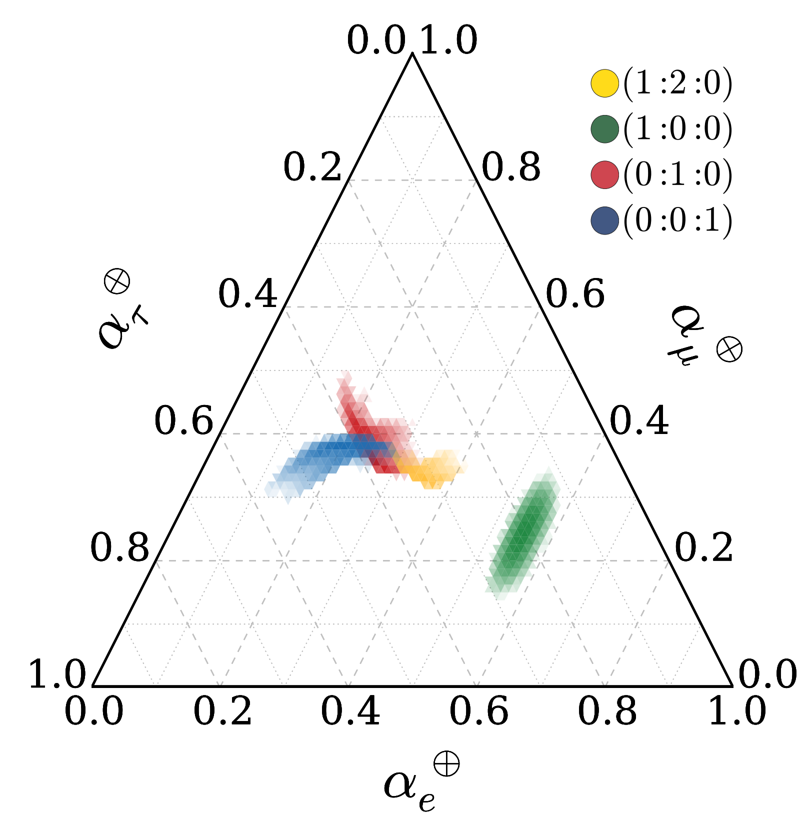


$O_0 \sim \mathrm{O}(10^{-23})$ GeV

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



35 TeV



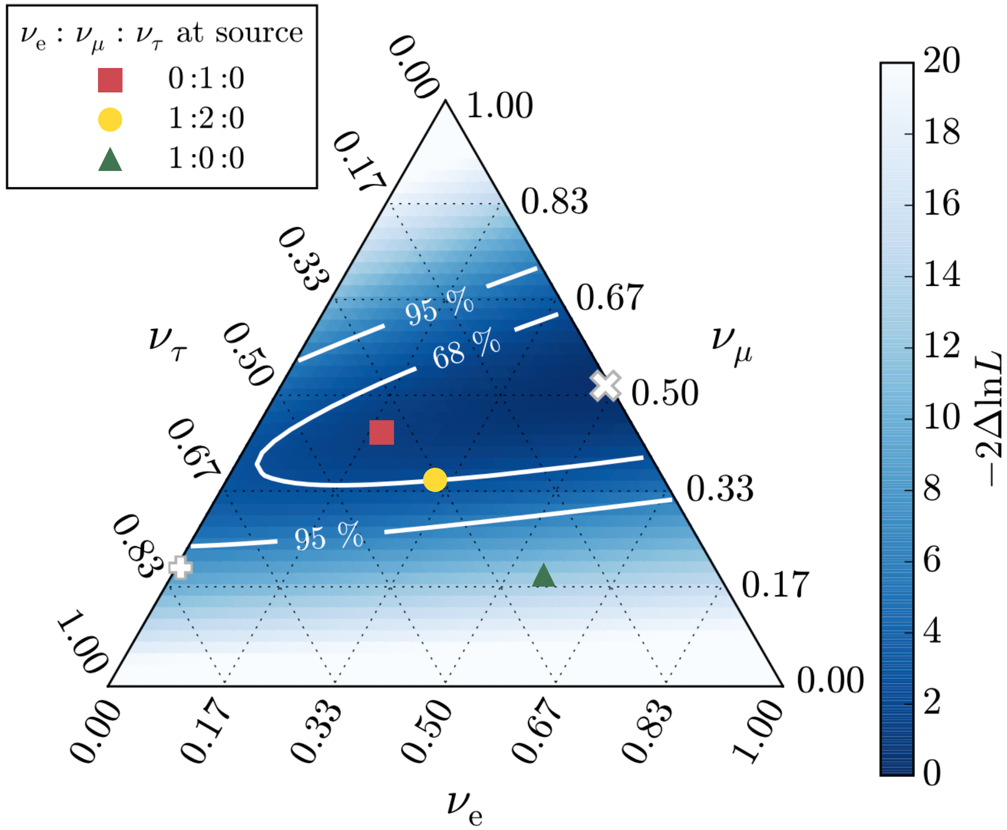
1 PeV

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

IceCube -> IceCube-Gen2!

IceCube keeps collecting more data: triangle will improve!

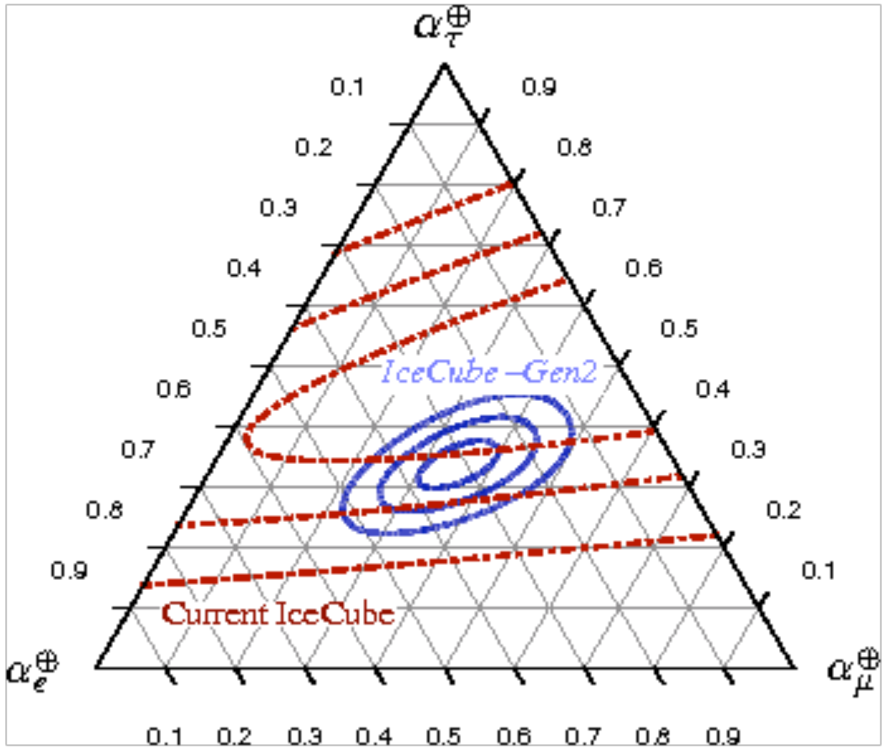
(current limits)



IceCube 1507.03991

Current limits is **statistically limited!**

An IceCube extension can help further constrain new physics!



Shoemaker et al. Phys.Rev. D93 (2016) no.8, 085004

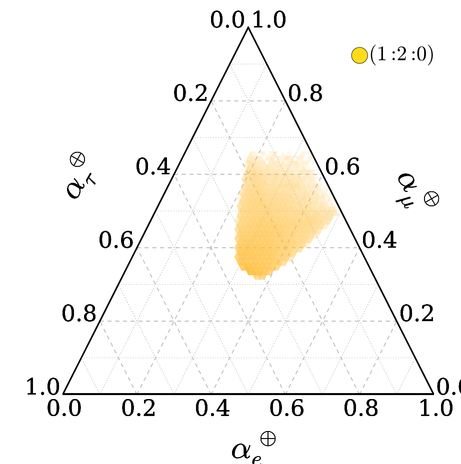
Take home message

✤ 

(3 neutrinos — unitarity)

+ $\pi^{\pm}$

(pion production is dominant)

= 

*

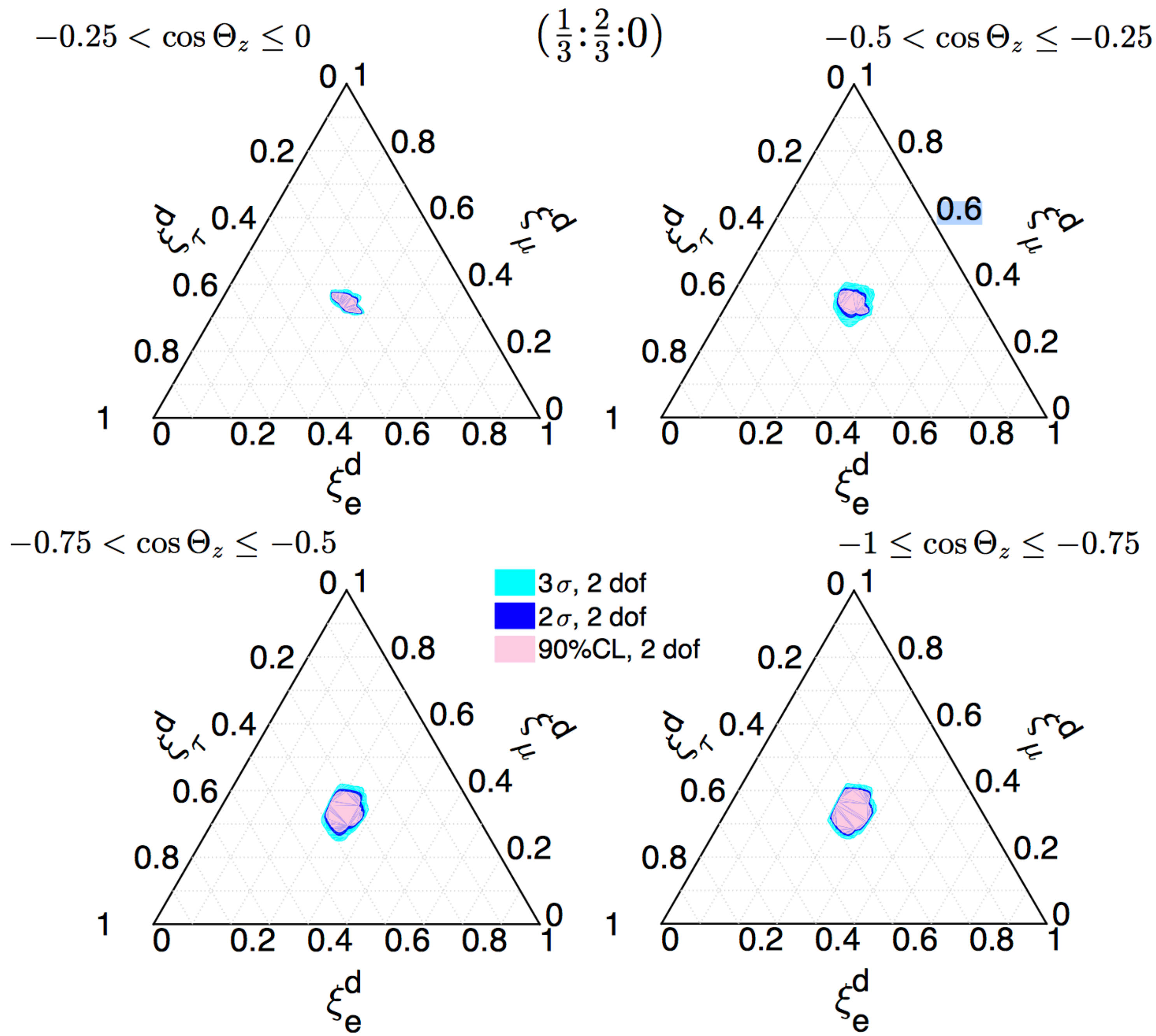
- ✤Current observations of the flavor triangle are already more restrictive than terrestrial measurements.
- ✤Expect improvement on flavor measurements from IceCube-Gen2: **better systematics and more statistics**!

THANKS!

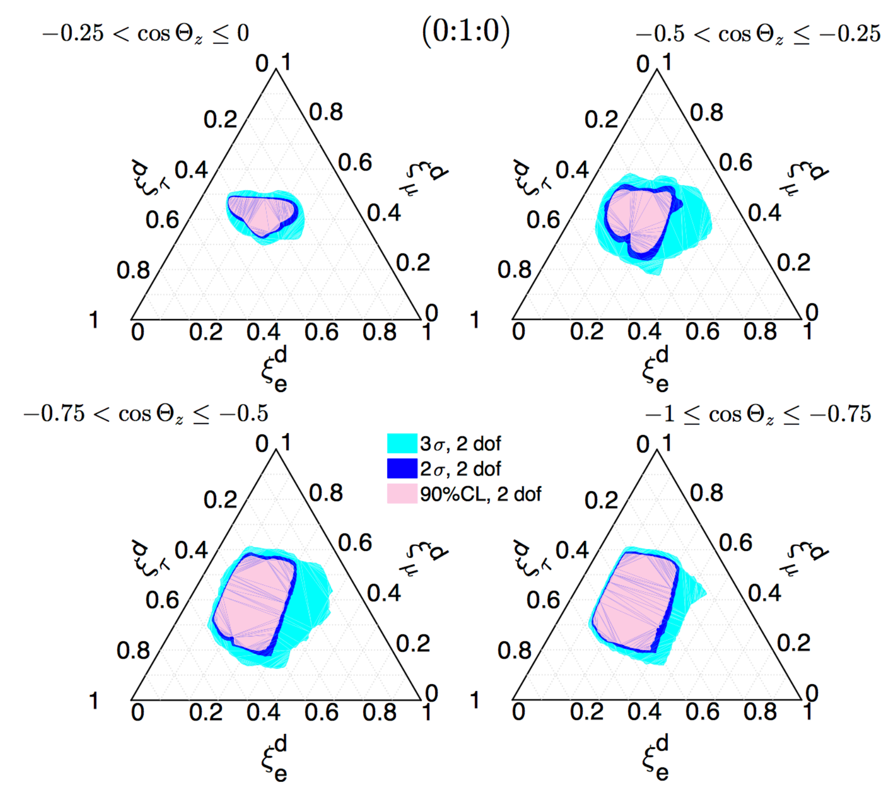
*conclusion robust under NSI and steriles (see bonus slides)

BONUS SLIDES!

+ NSI@Earth

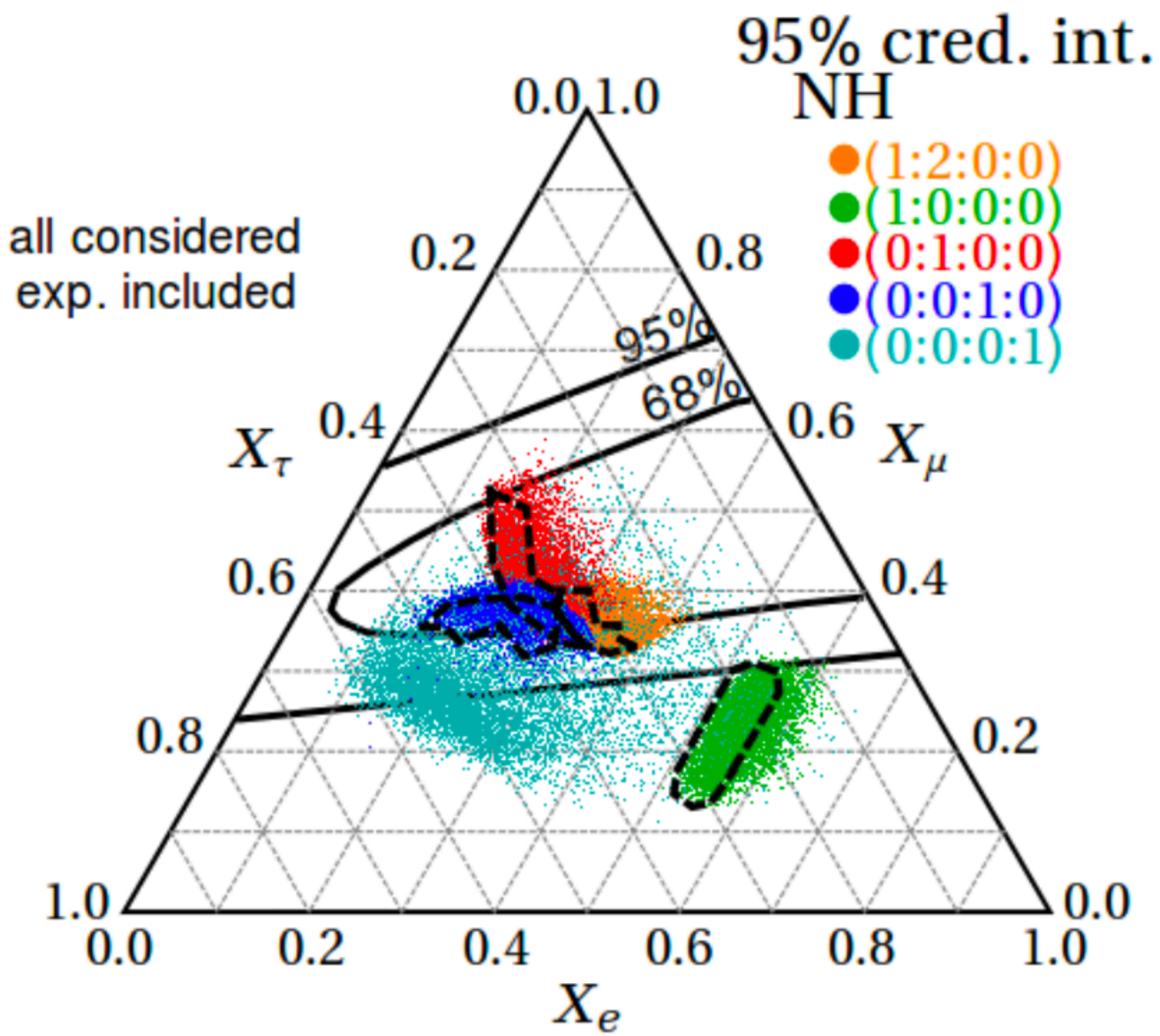


In the pion scenario NSI effects are small. This is not the case for other initial flavor ratios.



Gonzalez-Garcia et al. Astroparticle Physics 84 (2016) 15-22

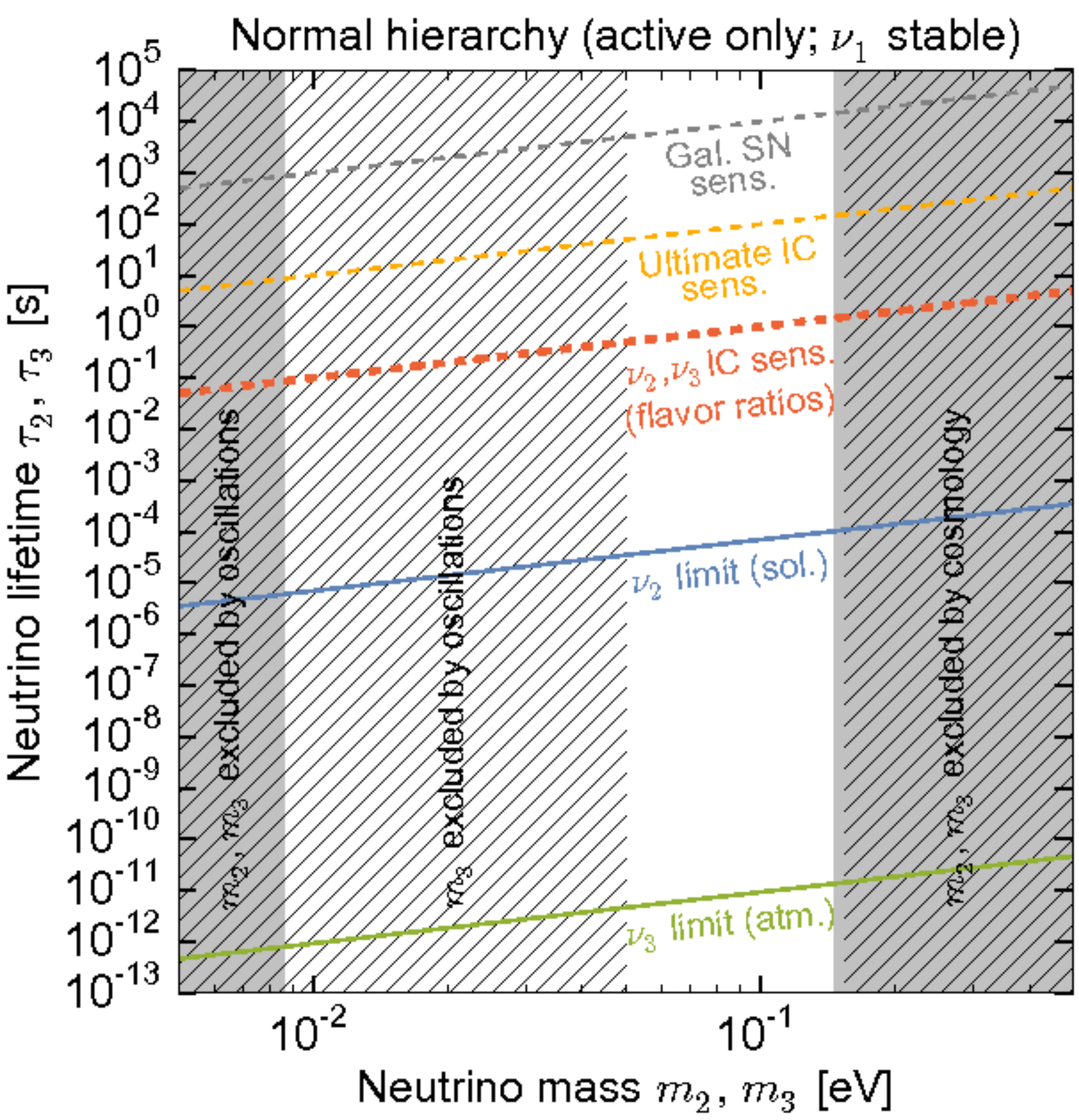
+ (eV) sterile neutrino

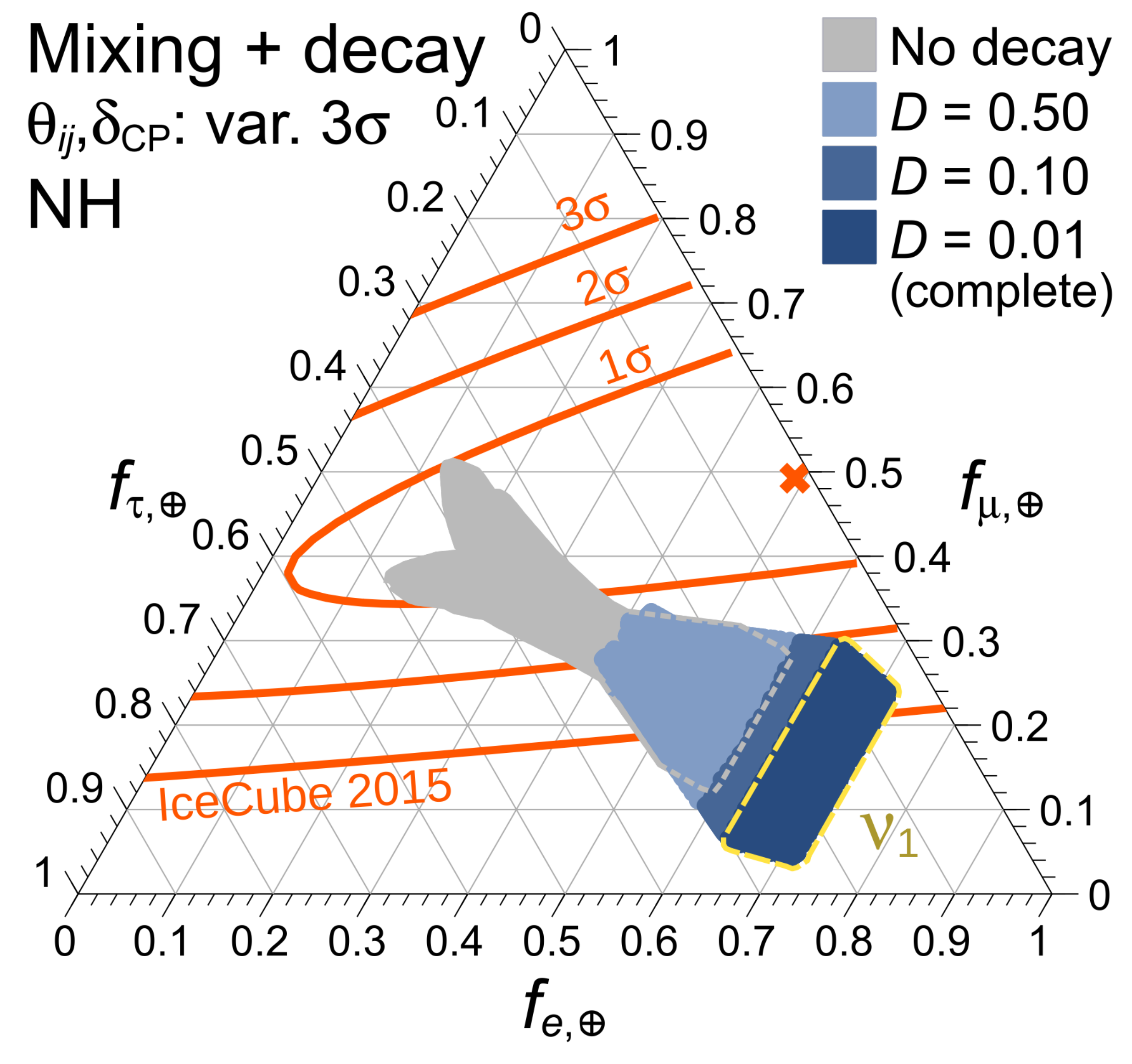


- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

Brdar et al. JCAP 1701 (2017) no.01, 026

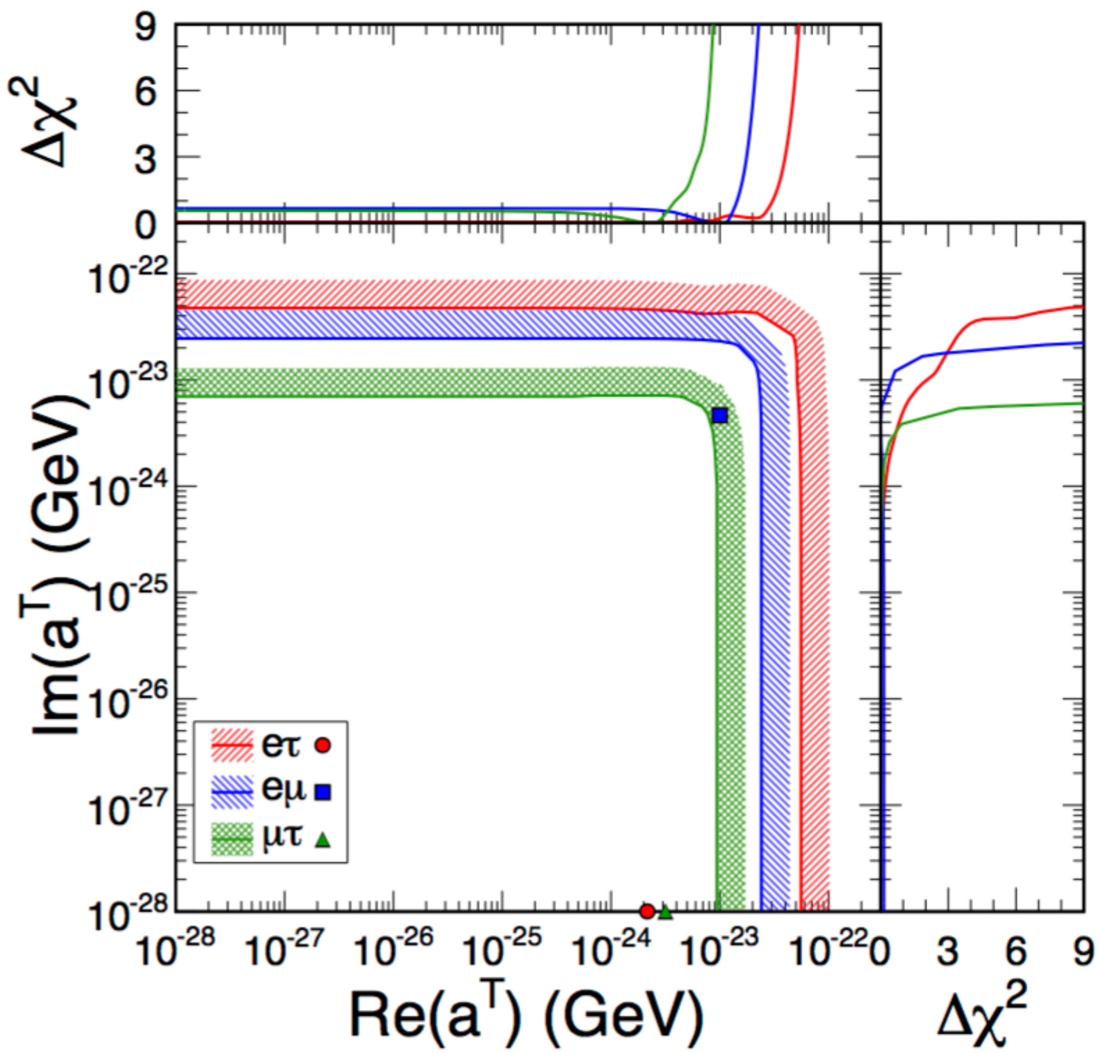
+Neutrino decay



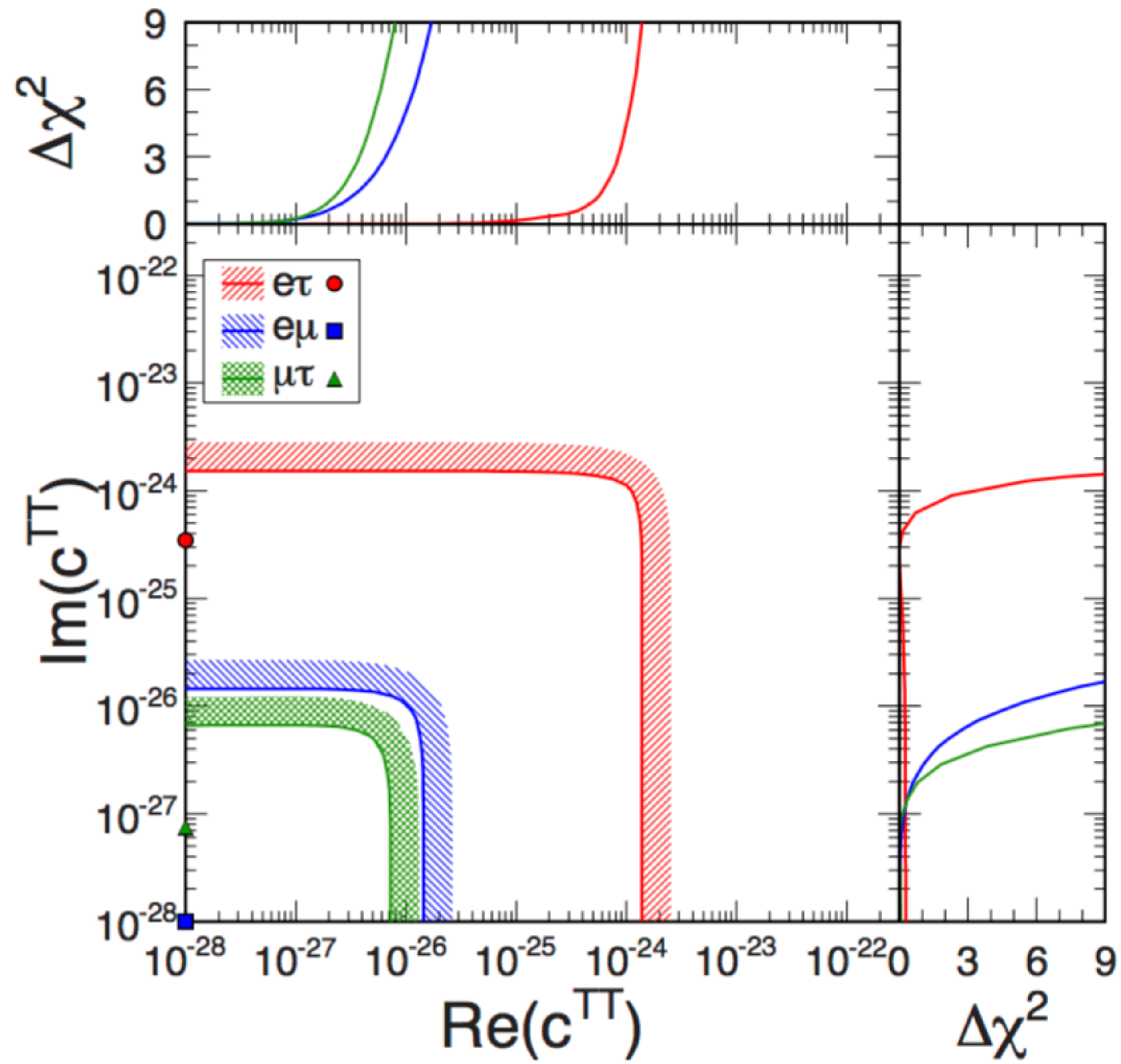


M. Bustamante, J. Beacom, K. Murase (1610.02096) arXiv:1410.4267

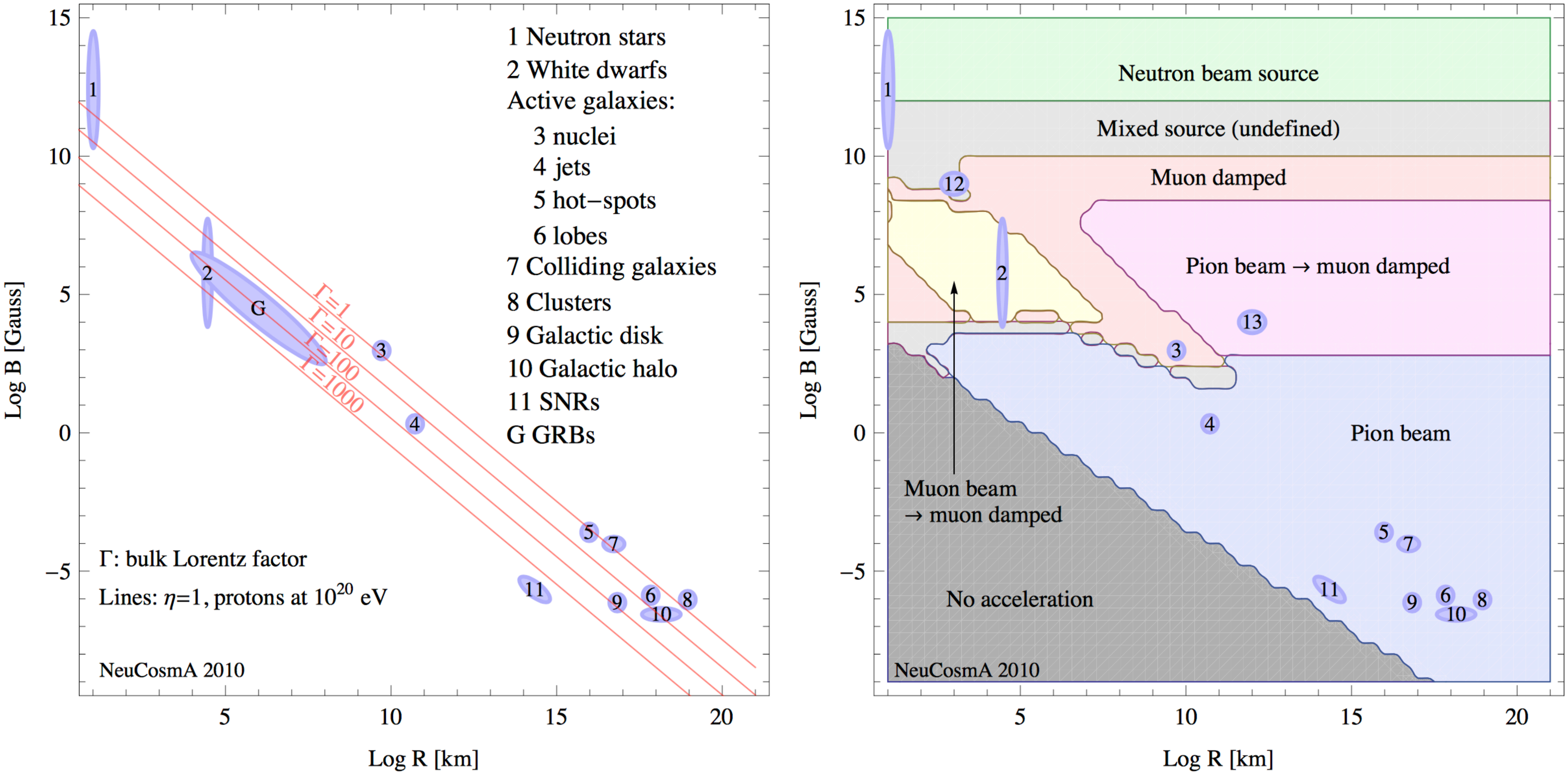
Current bounds from SK



$$\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$



LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit	
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV	[58]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV			
	Re (c^{TT})	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20}	[58]
	Im (c^{TT})	8.0×10^{-27}	1.0×10^{-28}			
$e\tau$	Re (a^T)	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV	[59]
	Im (a^T)	2.8×10^{-23} GeV	1.0×10^{-28} GeV			
	Re (c^{TT})	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17}	[59]
	Im (c^{TT})	1.0×10^{-24}	3.5×10^{-25}			
$\mu\tau$	Re (a^T)	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–	
	Im (a^T)	5.1×10^{-24} GeV	1.0×10^{-28} GeV			
	Re (c^{TT})	4.4×10^{-27}	1.0×10^{-28}	0.1	–	
	Im (c^{TT})	4.2×10^{-27}	7.5×10^{-28}			



(arXiv:1007:0006)