IceCube
South Pole Neutrino Observatory

CPT and Lorentz Symmetry Violation in Atmospheric Neutrino Experiments

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PANE
Triest, Italy 2018

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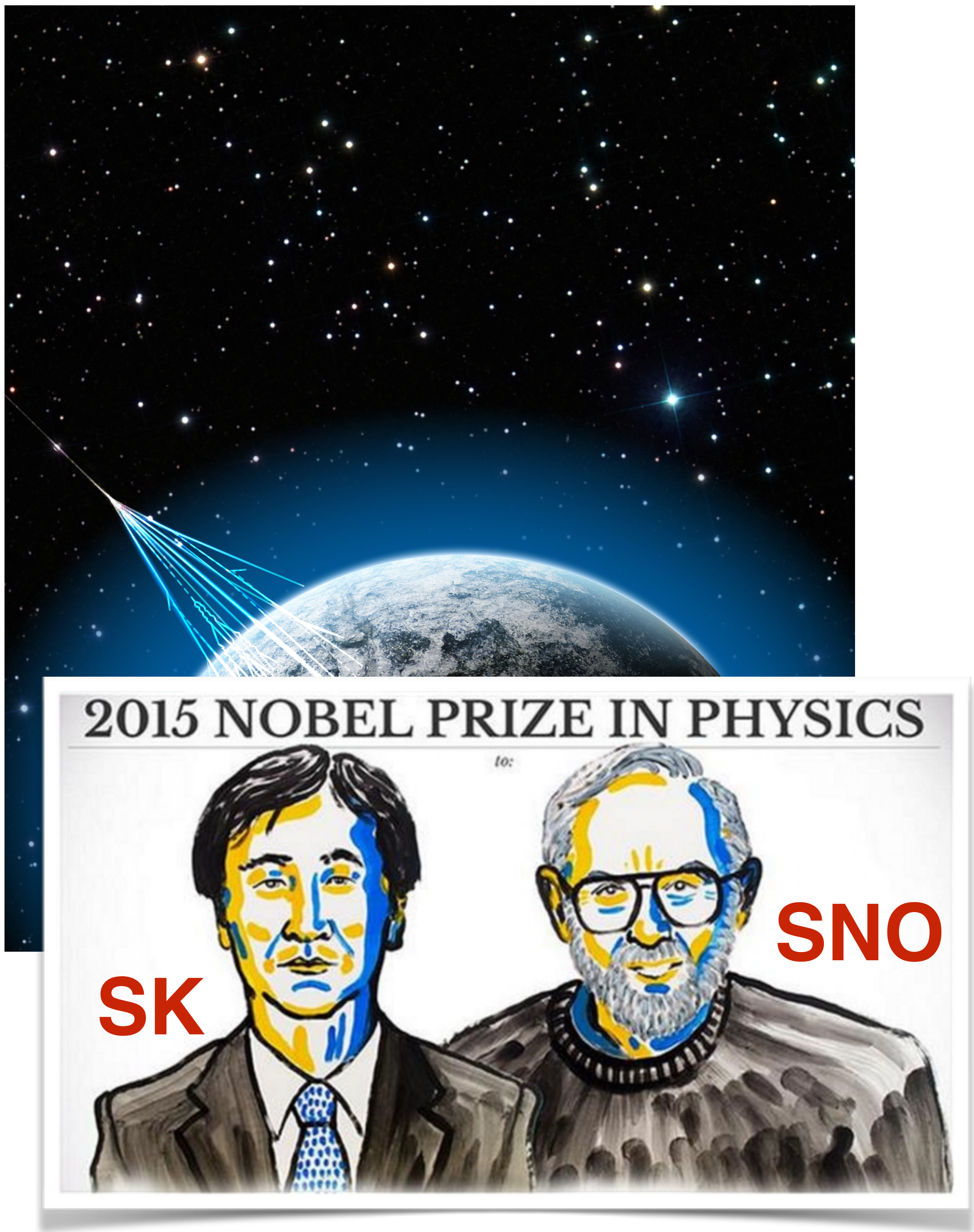
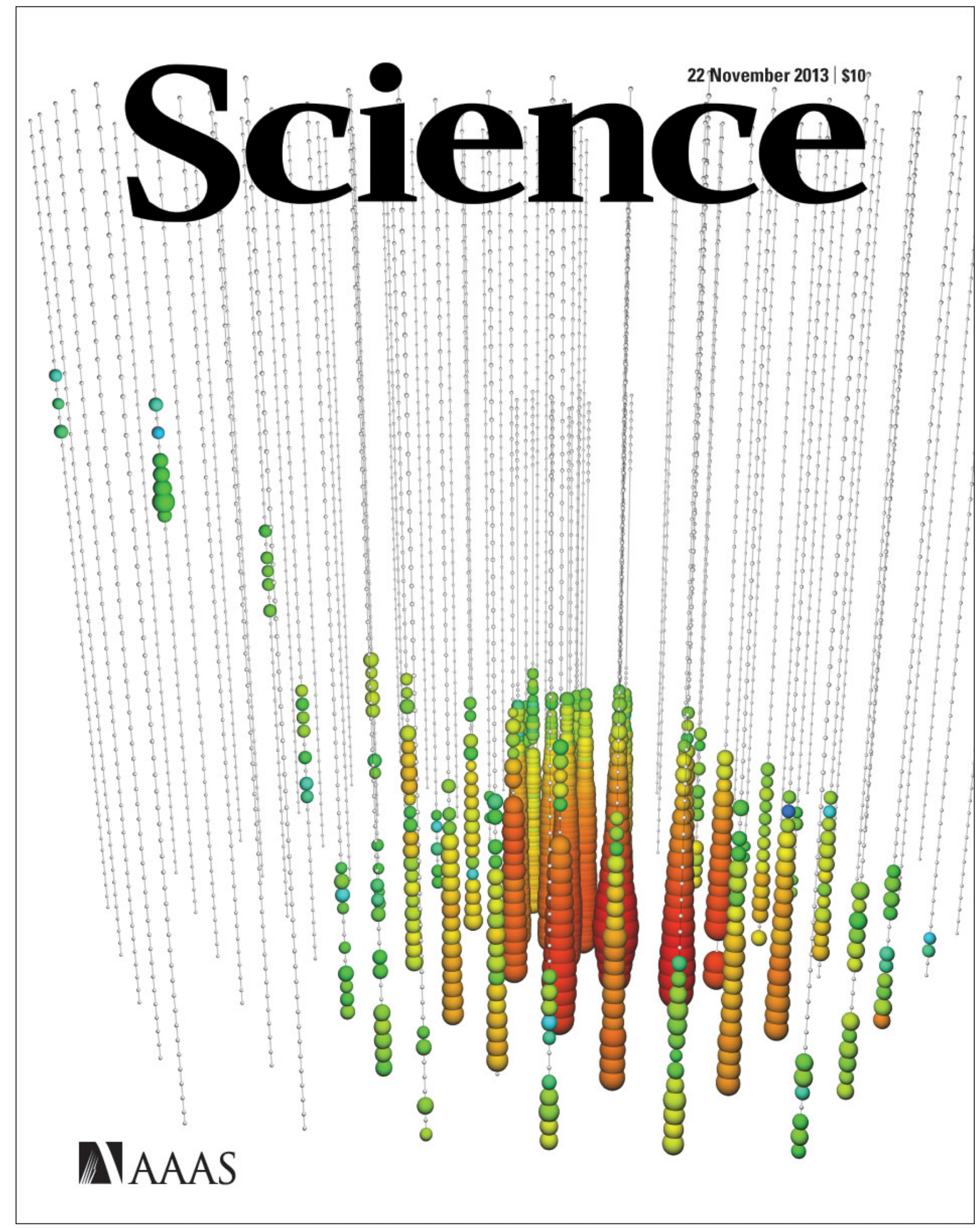
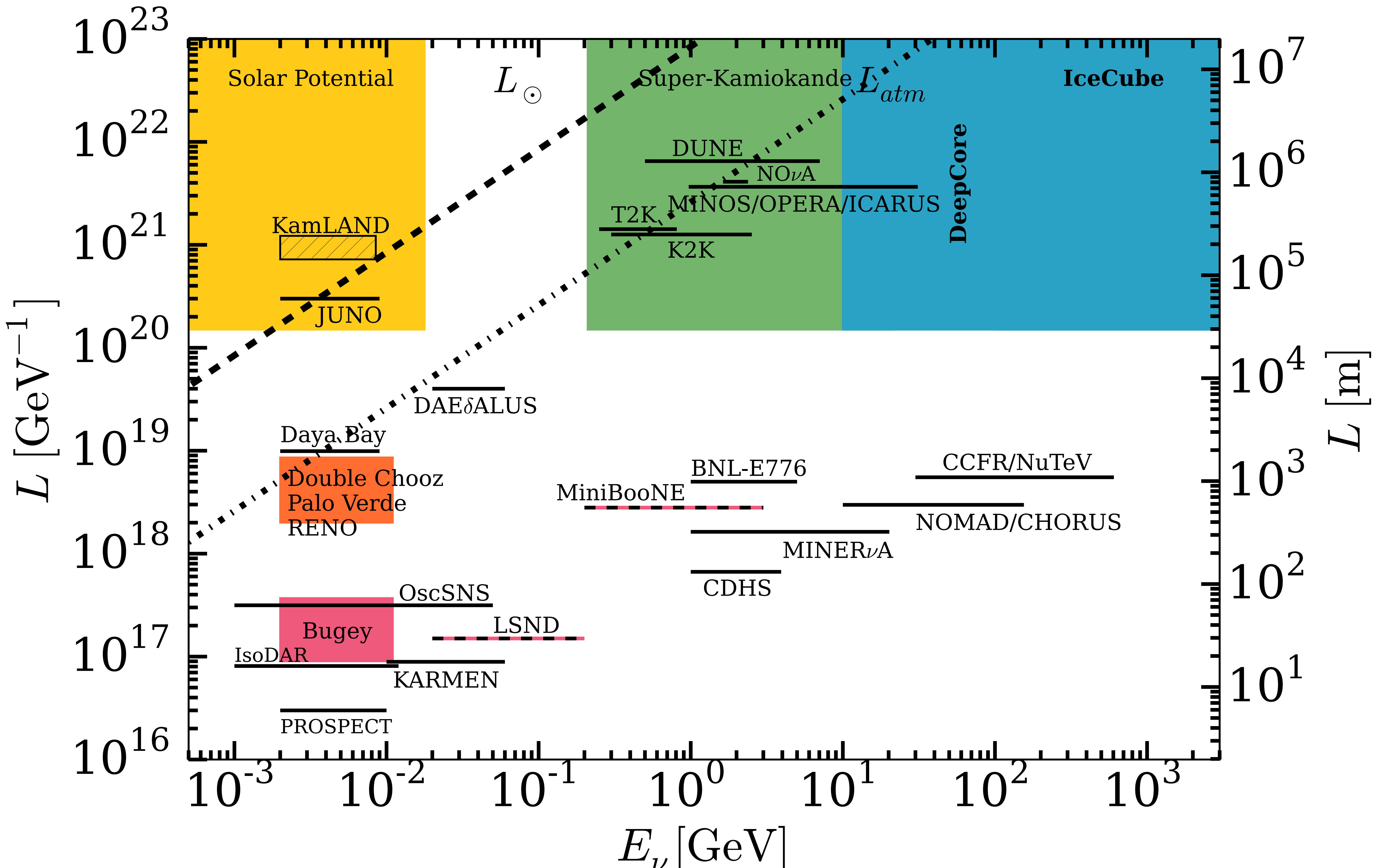
Thanks to the organizers for inviting me!

Old and *new* windows to search for new neutrino physics





What we have explored so far…



Adding LV/CPT violation

If one **extends the standard model to include LV/CPT violating terms** using the SME:

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

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

Simplifying assumption: lets assume that “a” and “c” only have a time component.

$$H = H_{std} + \tilde{a}^{T} + E\tilde{c}^{TT}$$

Kostelecky Phys.Rev. D69 (2004) 016005

Hamiltonian dominance

$$H = H_{vac} + H_{matter} + \tilde{a}^{\mathsf{T}} + E\tilde{c}^{\mathsf{TT}}$$

$\sim 10^{-24}\mathrm{GeV}\left(\frac{TeV}{E}\right)$ $\quad (\sim 10^{-23}\mathrm{GeV})$ $\quad$? $\quad$ E*?

note that the matter potential only affects the *ee* component

back of the envelope sensitivity

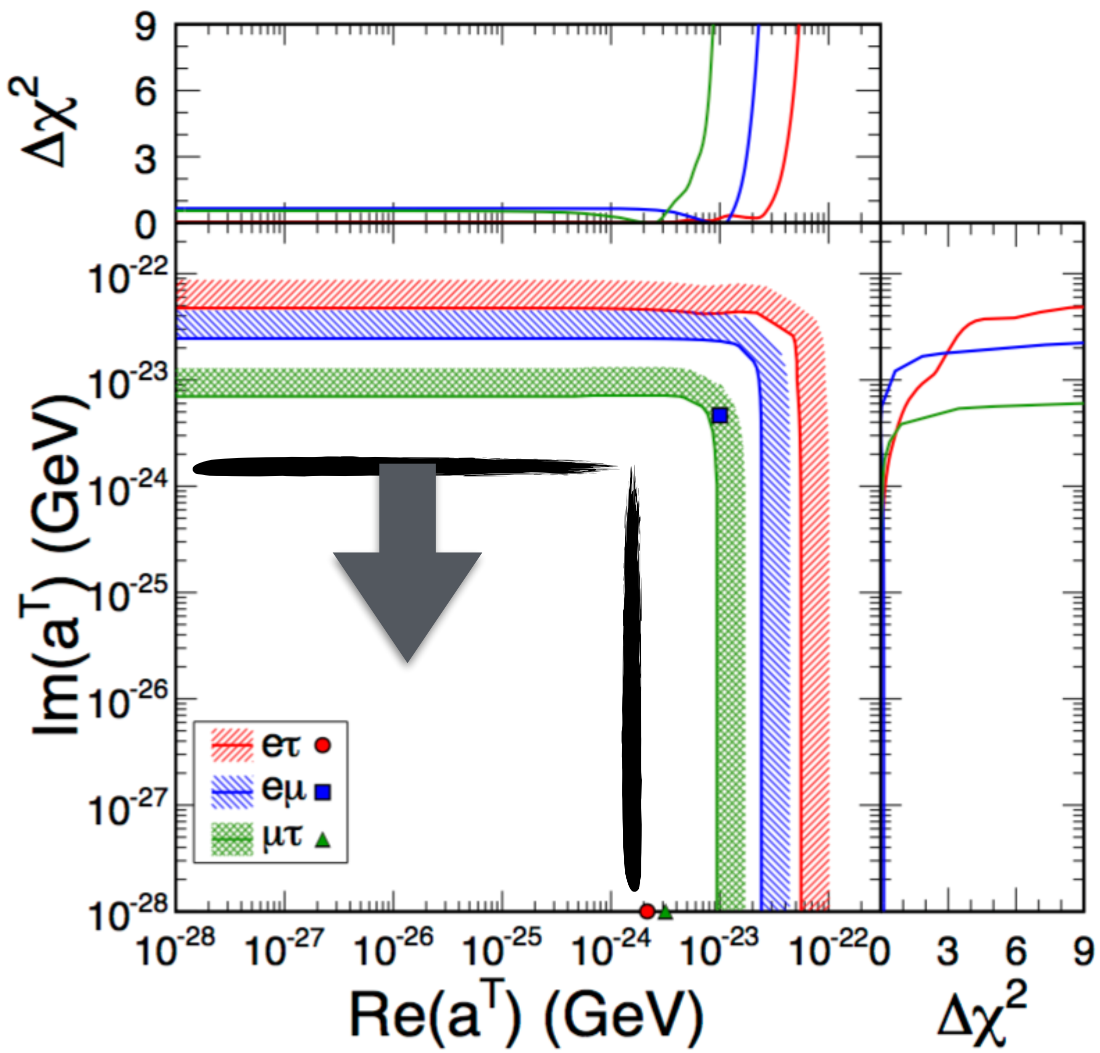
$$\tilde{a}^{\mathsf{T}} \sim 10^{-24}\mathrm{GeV} \rightarrow 10^{-27}\mathrm{GeV}$$

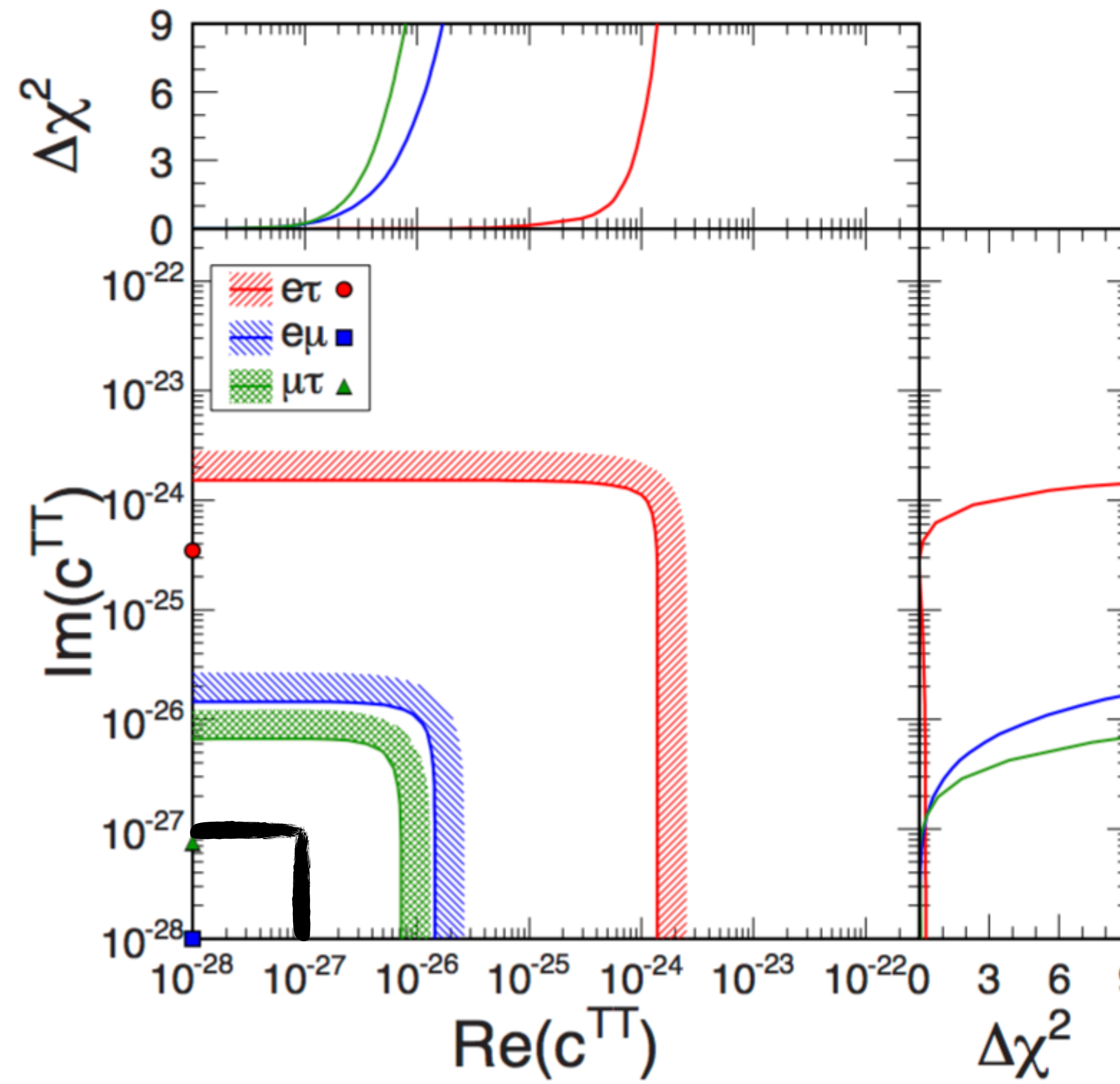
$$\tilde{c}^{\mathsf{TT}} \sim 10^{-27} \rightarrow 10^{-32}$$

arXiv:1410.4267

Current bounds from SK

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

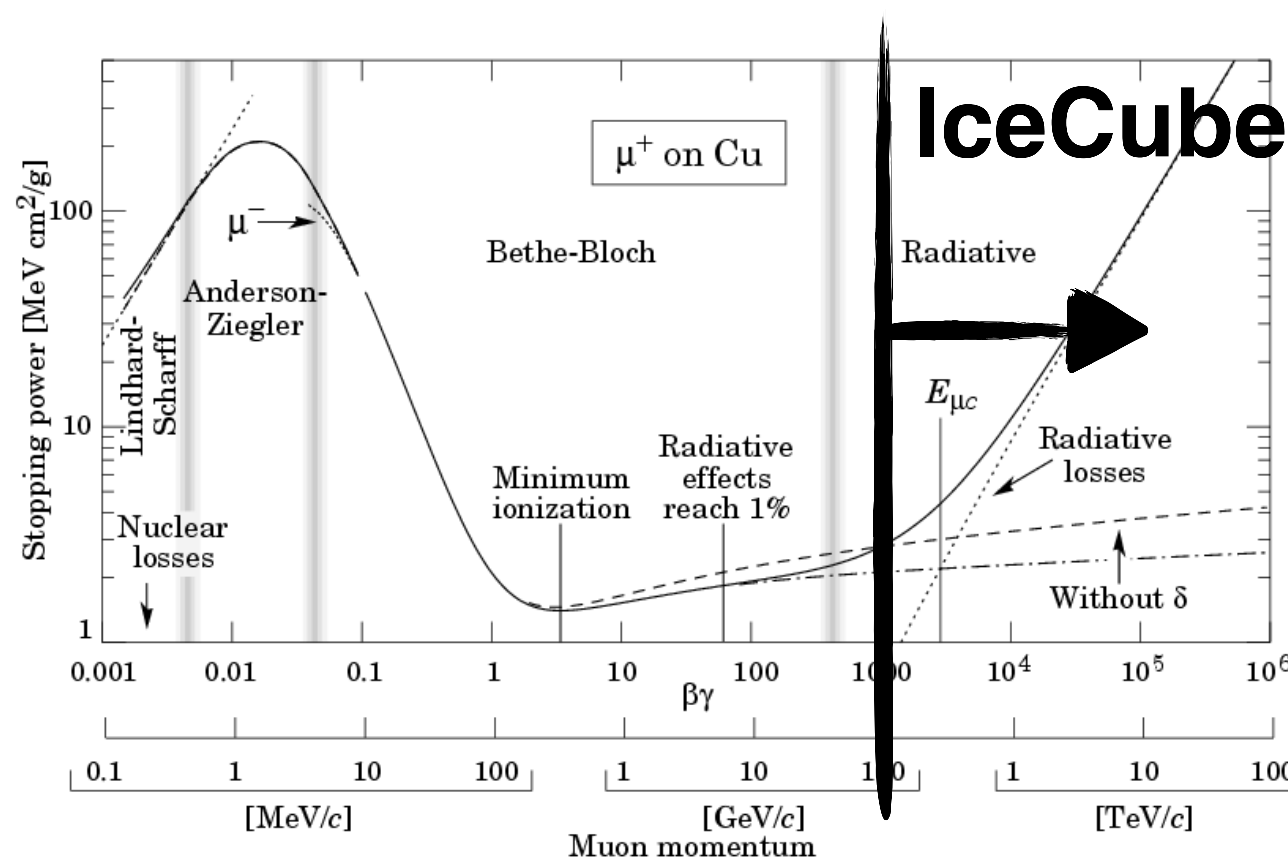




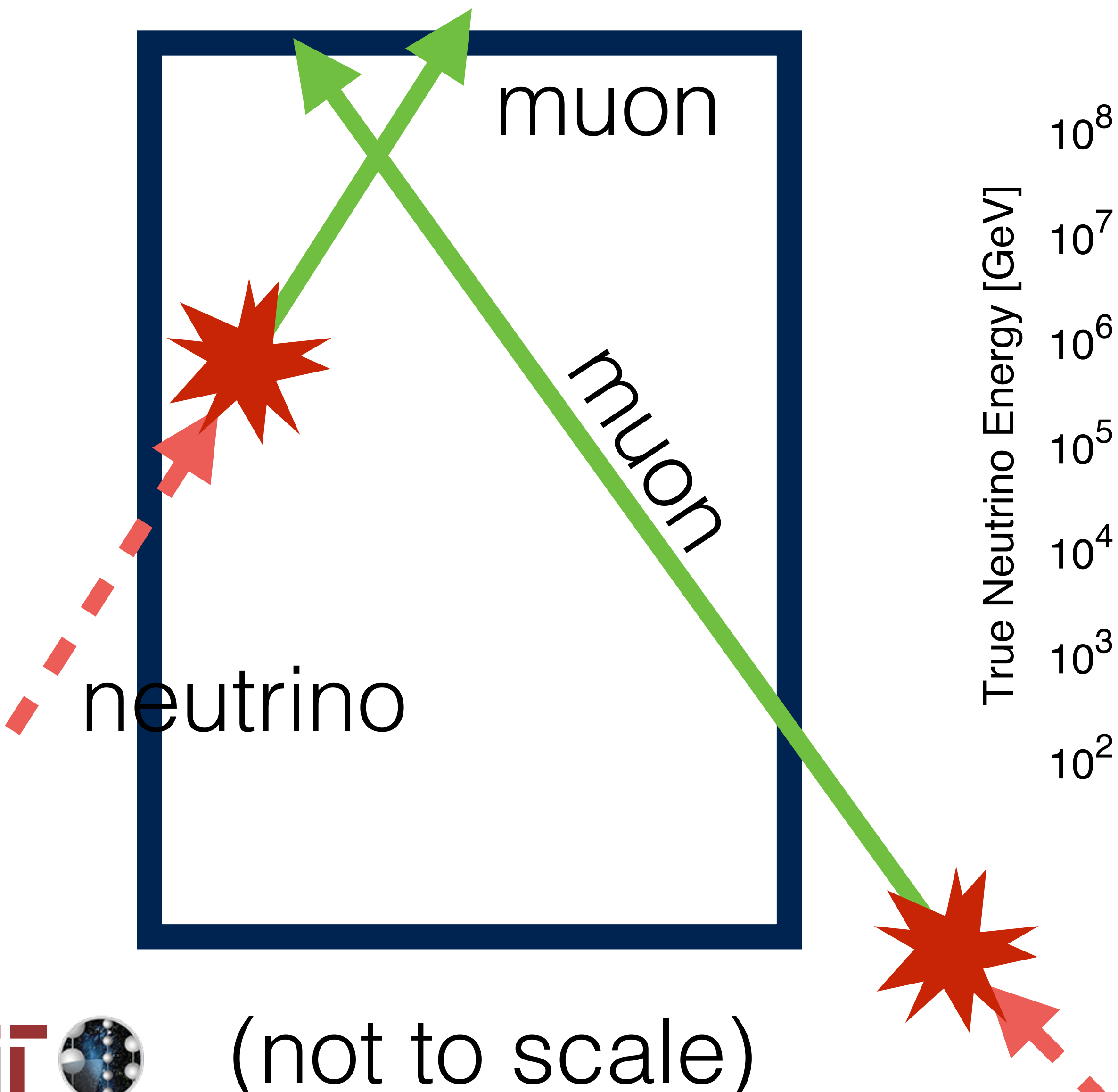
LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit	
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV	[58]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV			
	Re (c^{TT})	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20}	[58]
	Im (c^{TT})	8.0×10^{-27}	1.0×10^{-28}			
$e\tau$	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}			

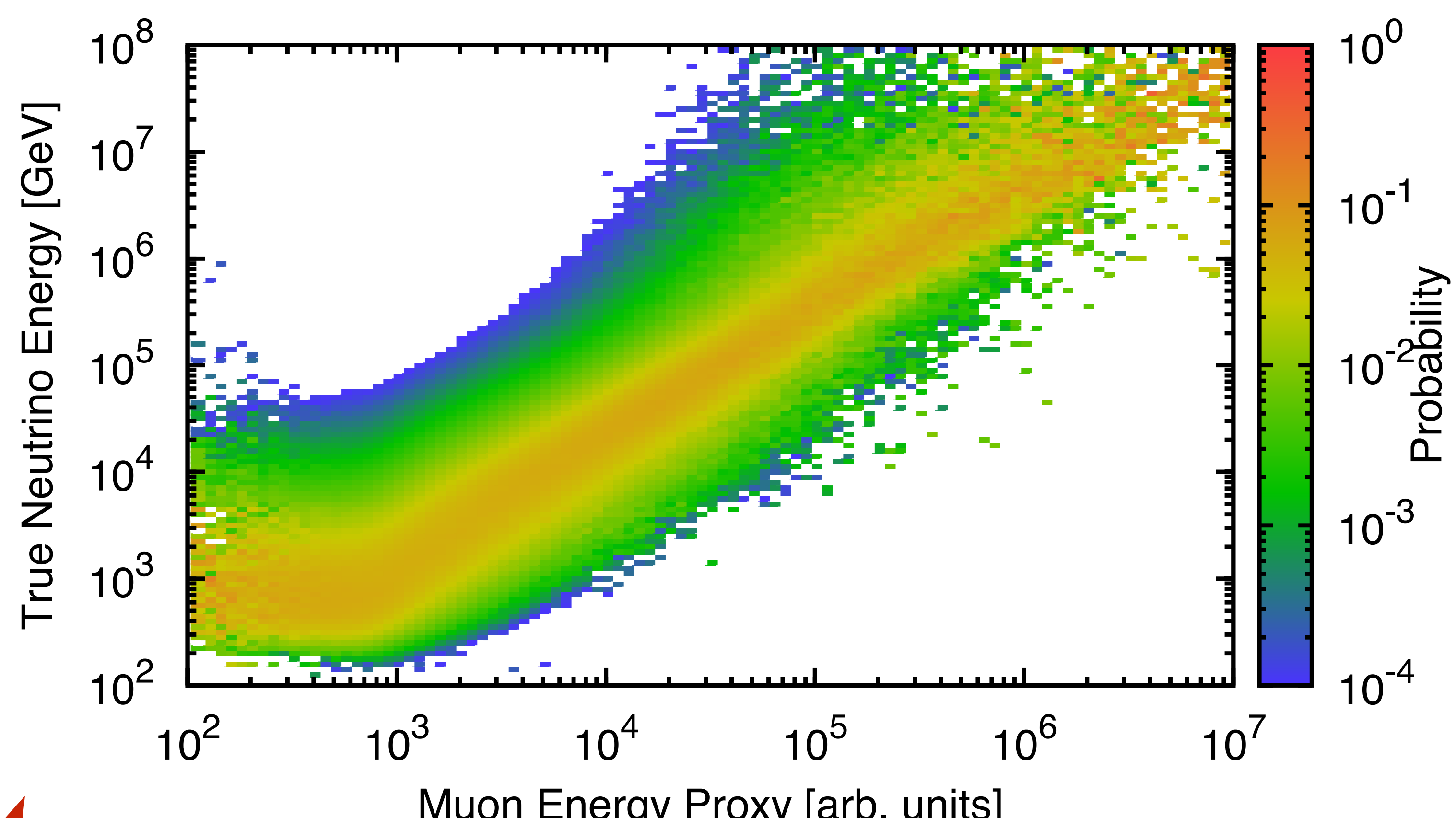
IC wins a lot in c due to the E factor

Through-going muons in IceCube



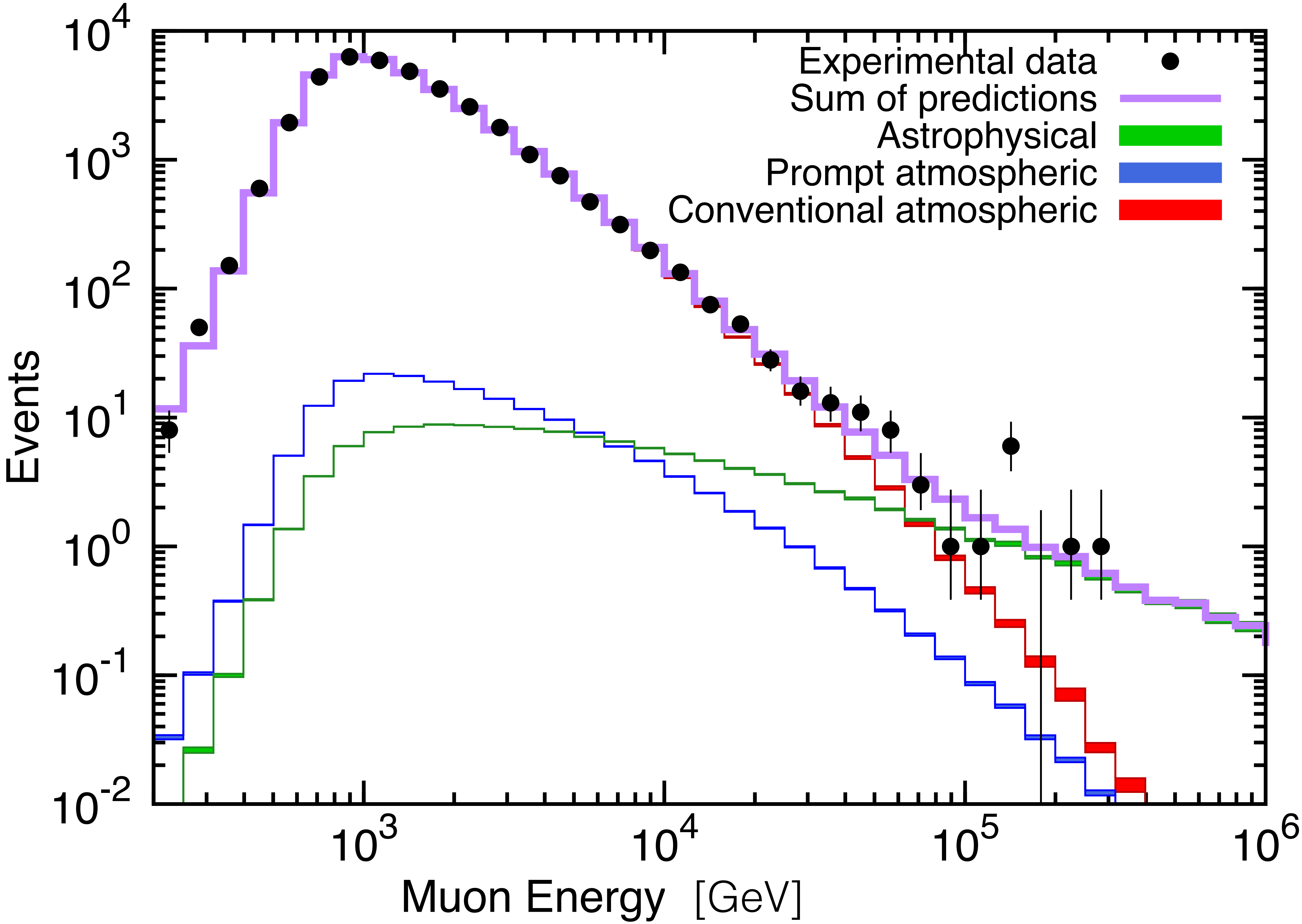
$$\Delta\theta \sim 1^o$$





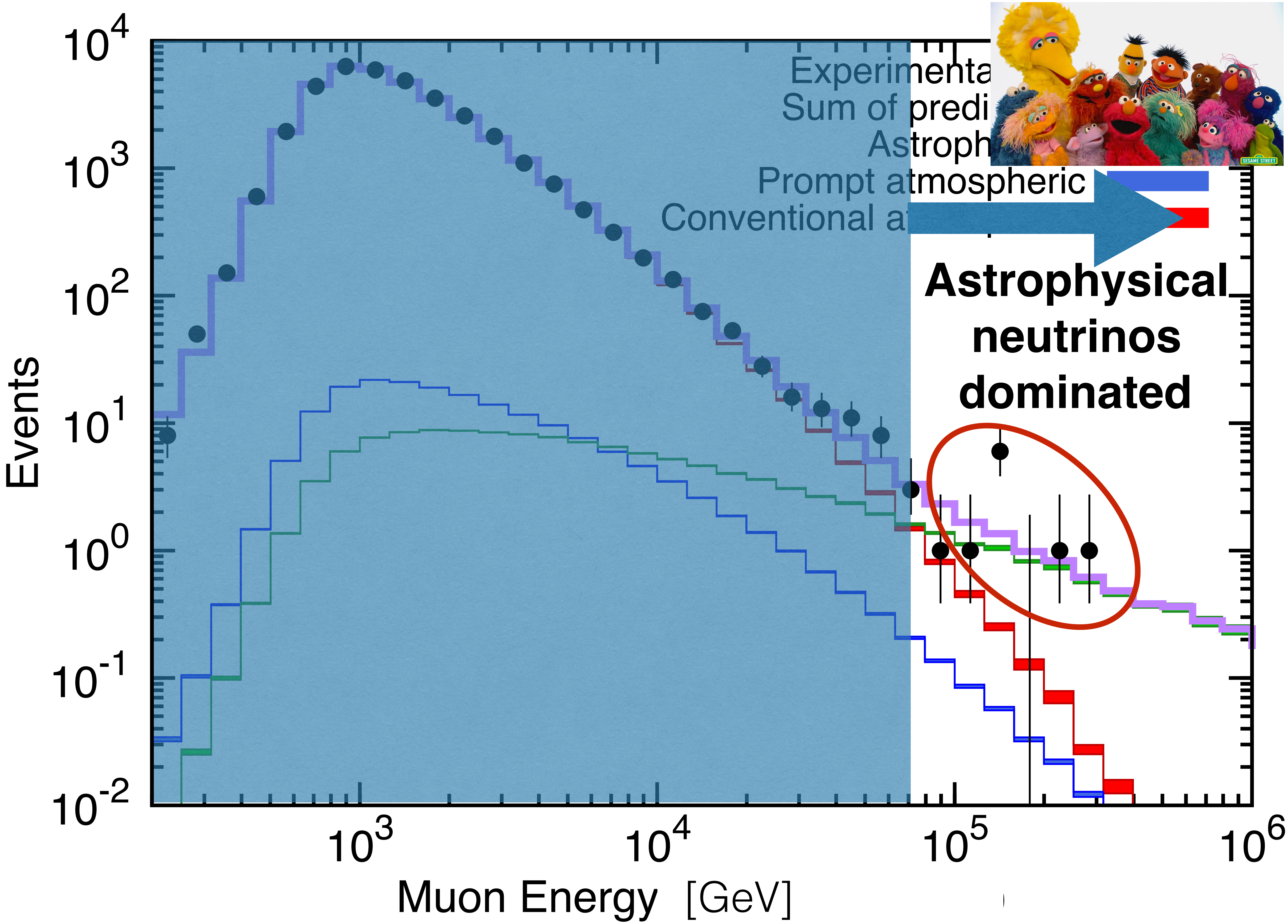
(not to scale)

Through-going nu-mu energy distribution



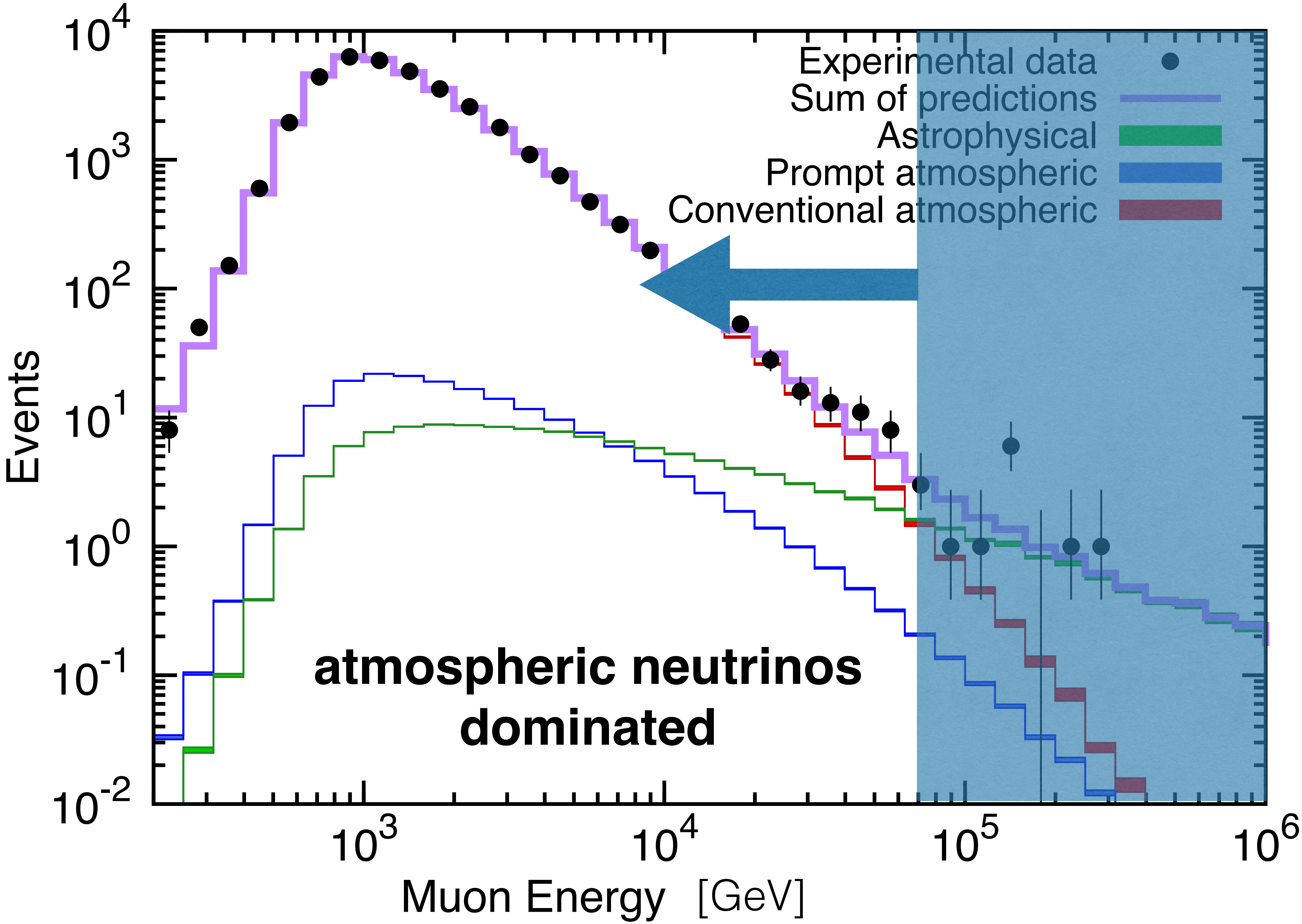
Phys. Rev. Lett. 115, 081102 (2015)

Astrophysical neutrino dominate at highest energies!



Phys. Rev. Lett. 115, 081102 (2015)

IceCube observes a lot of atmospheric neutrinos!



Phys. Rev. Lett. 115, 081102 (2015)

More information about the sample and systematics!

- ✤Use two years of IceCube data ~ 35 000 atmospheric muon neutrino events.
- ✤Restrict ourselves from -1<\cos\theta<0.2 and E < 20 TeV
- ✤Non-\nu_\mu CC contamination (NC, \nue, atm. mu) < 0.1%.

Systematic uncertainties considered in the analysis:

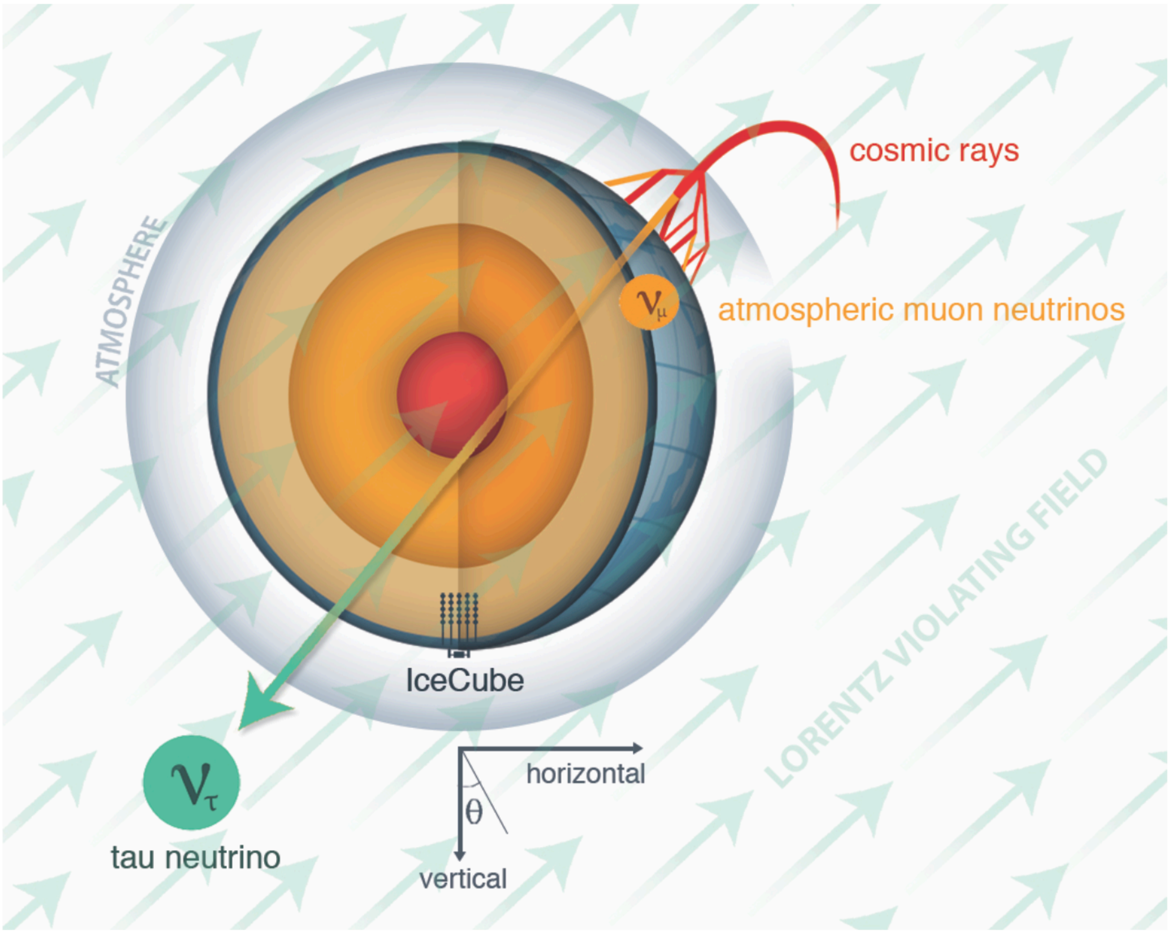
- ✤Overall conventional normalization (40%),
- ✤Uncertainty in CR accounted model by a change in tilt (2%),
- ✤Relative contribution of pion to kaon neutrino components (10%),
- ✤Overall prompt contribution (unconstrained),
- ✤Astrophysical component: normalization (unconstrained) spectral index (-1.5,-2.5).

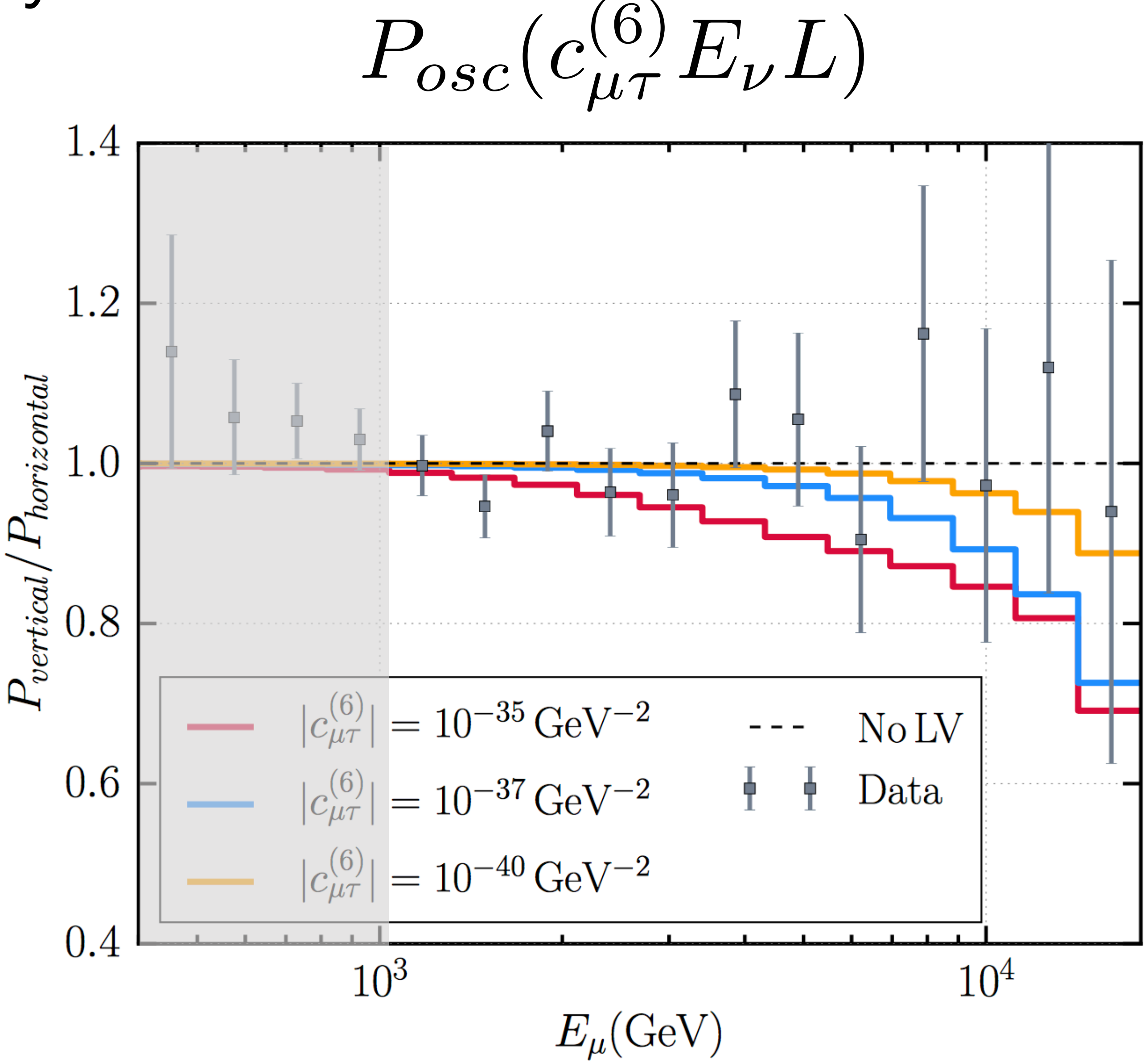
Sub-leading systematics we checked:

- ✤Uncertainties in the detector efficiency is controlled by the energy distribution peak,
- ✤impact of light propagation model uncertainties on the horizontal to vertical ratio is less than 5% at few TeV

Signal kicks in at high energies

- ✤The analysis sensitivity, specially for high-dimension operators, is dominated by the highest energy events.
- ✤We are **very much** statistically limited.





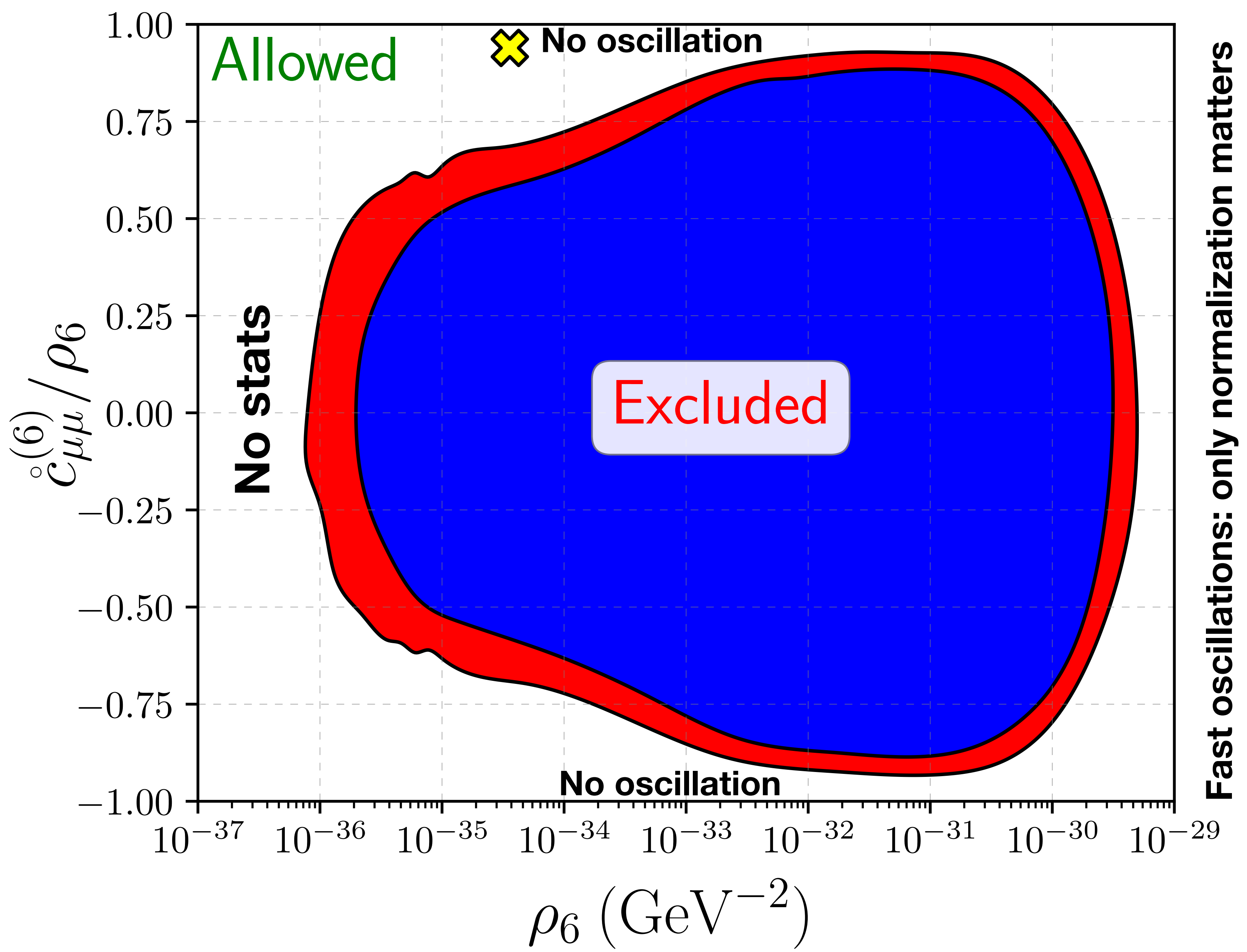
Gray region is irrelevant for the analysis. Removing it changes it marginally.

Anatomy of the dim-6 operator constraint

- X marks the best-fit point: no significance evidence for LV.
- We use Wilk's theorem with 3 dof.

$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

$$P(\nu_\mu \to \nu_\tau) \sim \left(\frac{\mathring{a}^{(d)}_{\mu\tau} - \mathring{c}^{(d)}_{\mu\tau}}{\rho_d} \right)^2 \sin^2(L\rho_d \cdot E^{d-}$$

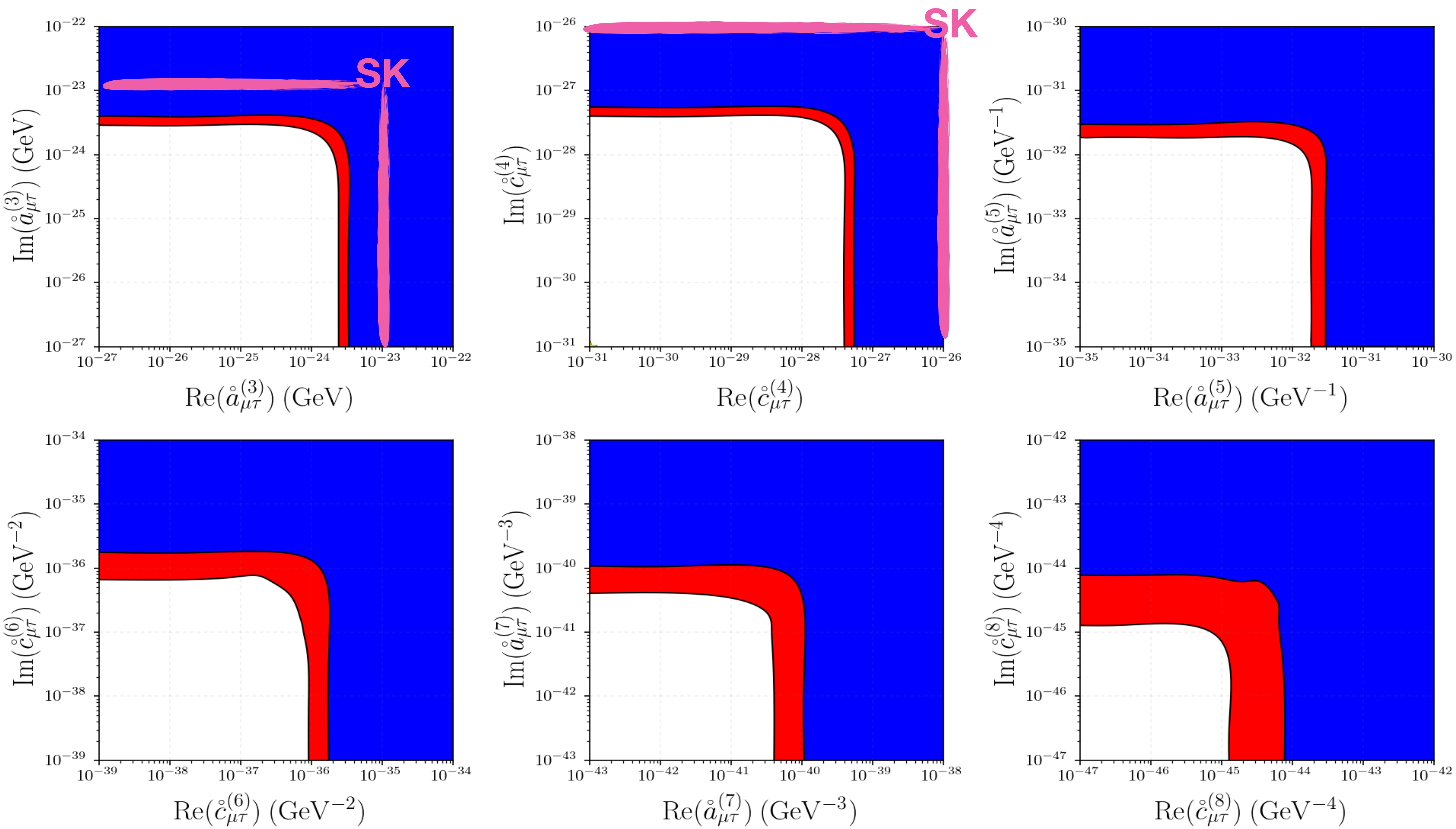


$$\rho_d \equiv \sqrt{(\mathring{c}^{(d)}_{\mu\mu})^2 + \mathrm{Re}\,(\mathring{c}^{(d)}_{\mu\tau})^2 + \mathrm{Im}\,(\mathring{c}^{(d)}_{\mu\tau})^2}$$

IceCube Collaboration, arXiv:1709.03434

Our results in the maximum-flavor violating assumption

Maximum flavor violation = set diagonal terms to zero.
(same assumption as SK)



White: allowed, red: 90% CL, blue: 99% CL.

IceCube Collaboration, arXiv:1709.03434

Comparison with other sectors

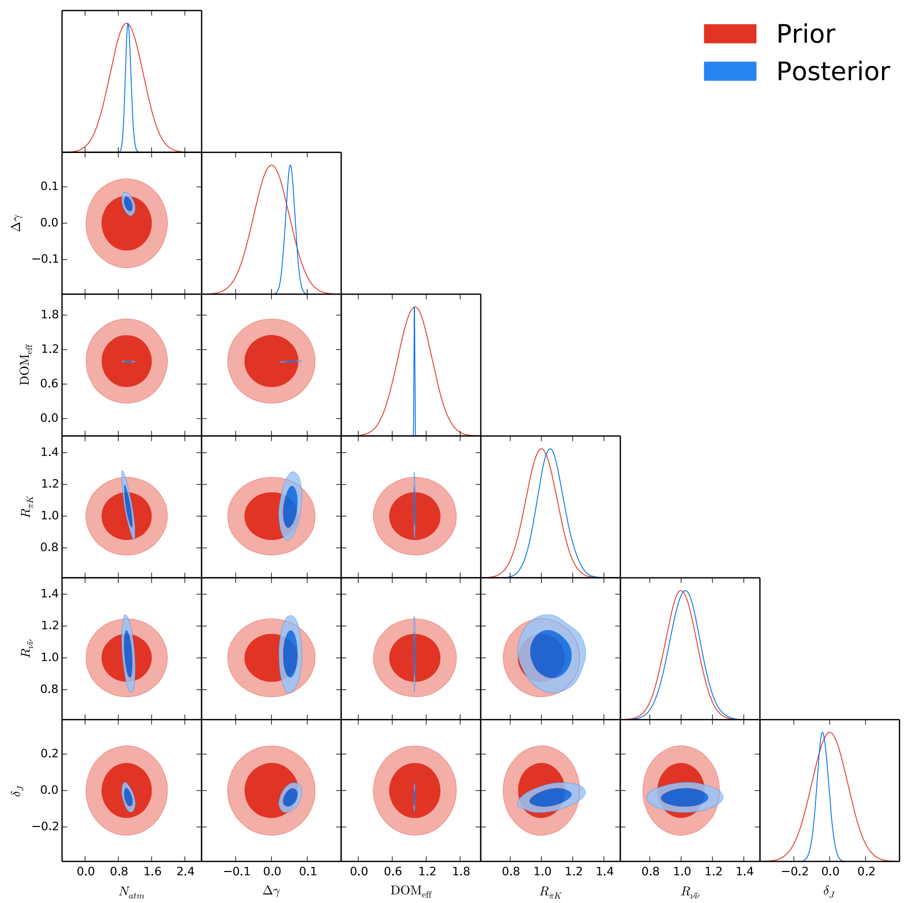
dim.	method	type	sector	limits		ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	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		$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	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}	[7]
	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}	[7]
	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}	[7]
	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

Very strong limits on Lorentz Violation induced by dimension-6 operators!

See talk by Francesco Capozzi for non-LV interpretations of our results!

Aside: note on upcoming 7-year high-energy sterile analysis

1 year analysis systematic treatment



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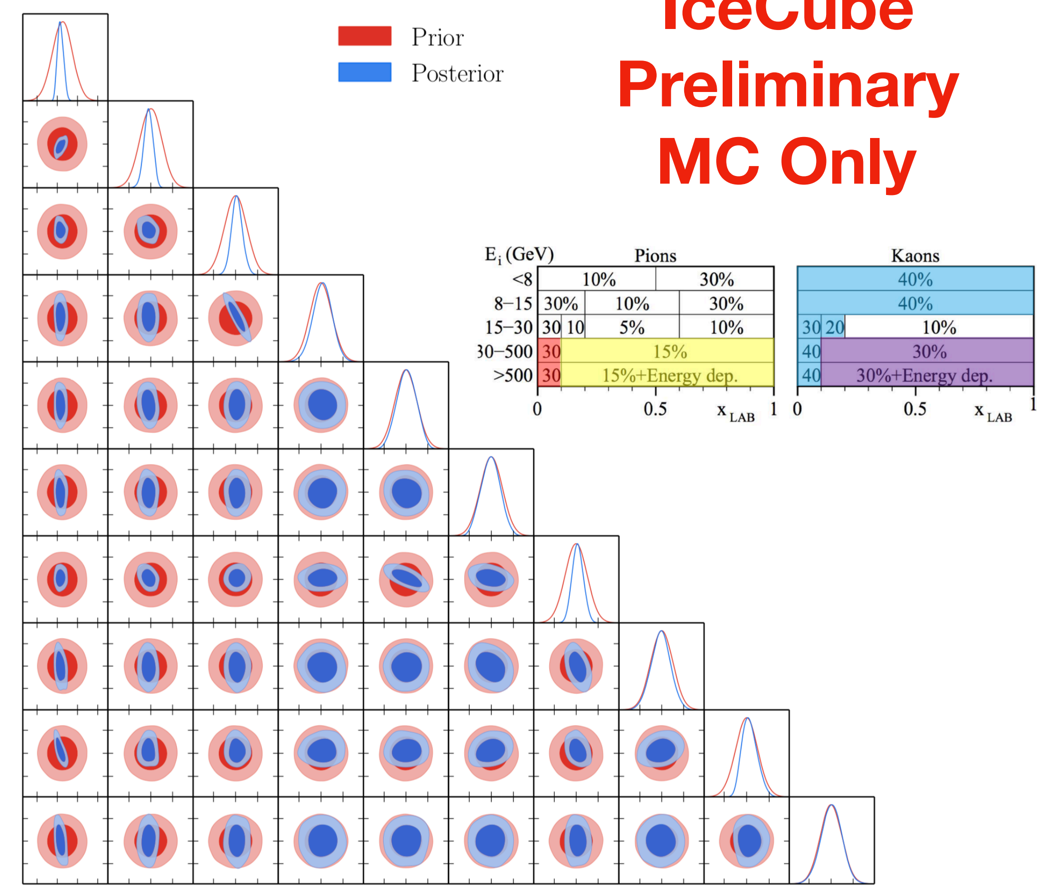
Atmospheric flux		
ν flux template	discrete (7)	
ν / $\bar{\nu}$ ratio	continuous	0.025
π / K ratio	continuous	0.1
Normalization	continuous	none[1]
Cosmic ray spectral index	continuous	0.05
Atmospheric temperature	continuous	model tuned
Detector and ice model		
DOM efficiency	continuous	
Ice properties	discrete (4)	
Hole ice effect on angular response	discrete (2)	
Neutrino propagation and interaction		
DIS cross section	discrete (6)	
Earth density	discrete (9)	

7 year analysis systematic treatment



IceCube Preliminary MC Only

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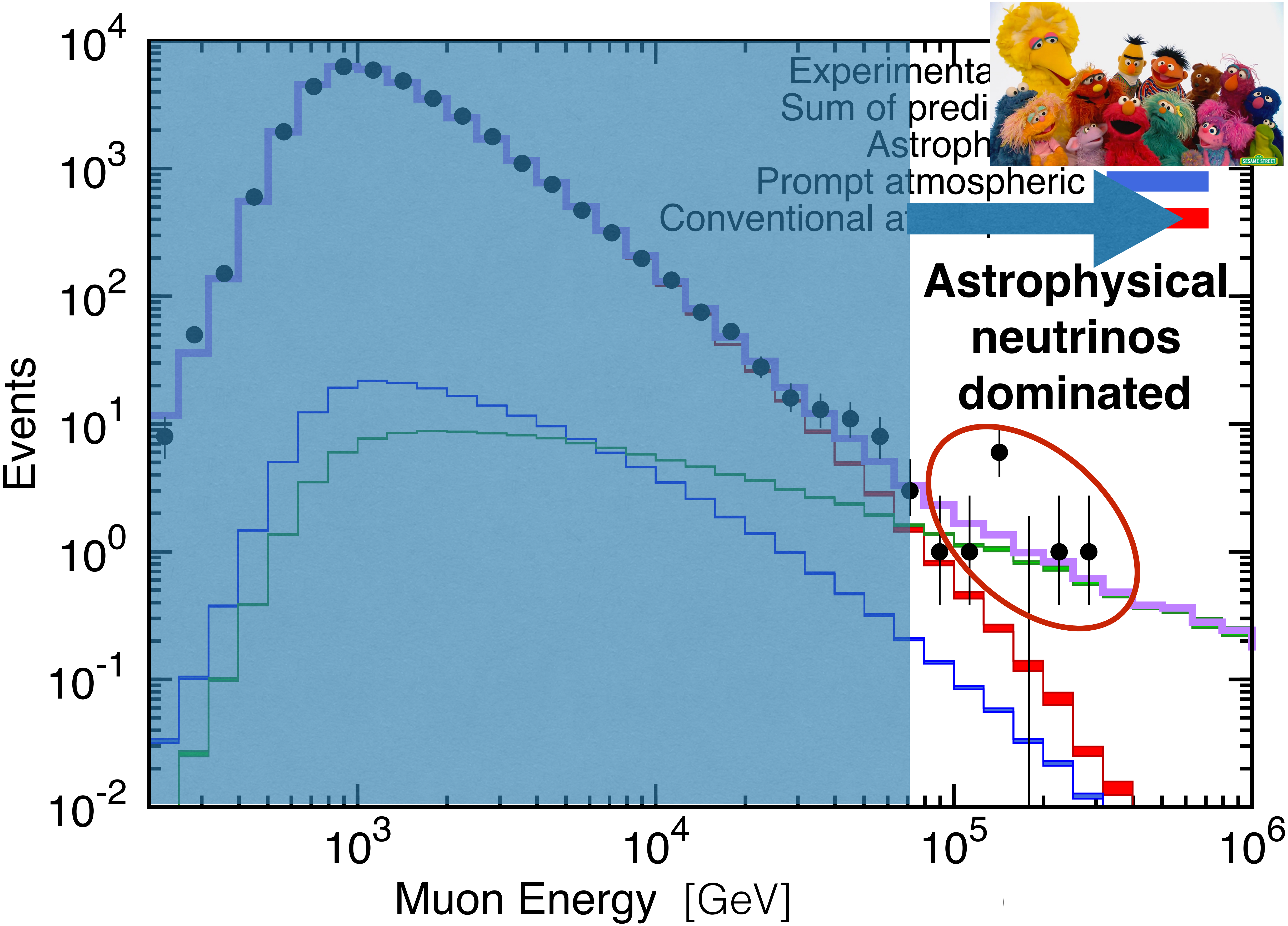
New continuous and more precise detector systematic treatment!

People working in flux and detector systematics are the superheroes of our times!

“With great <u>statistical</u> power comes great <u>systematic</u> responsibility”

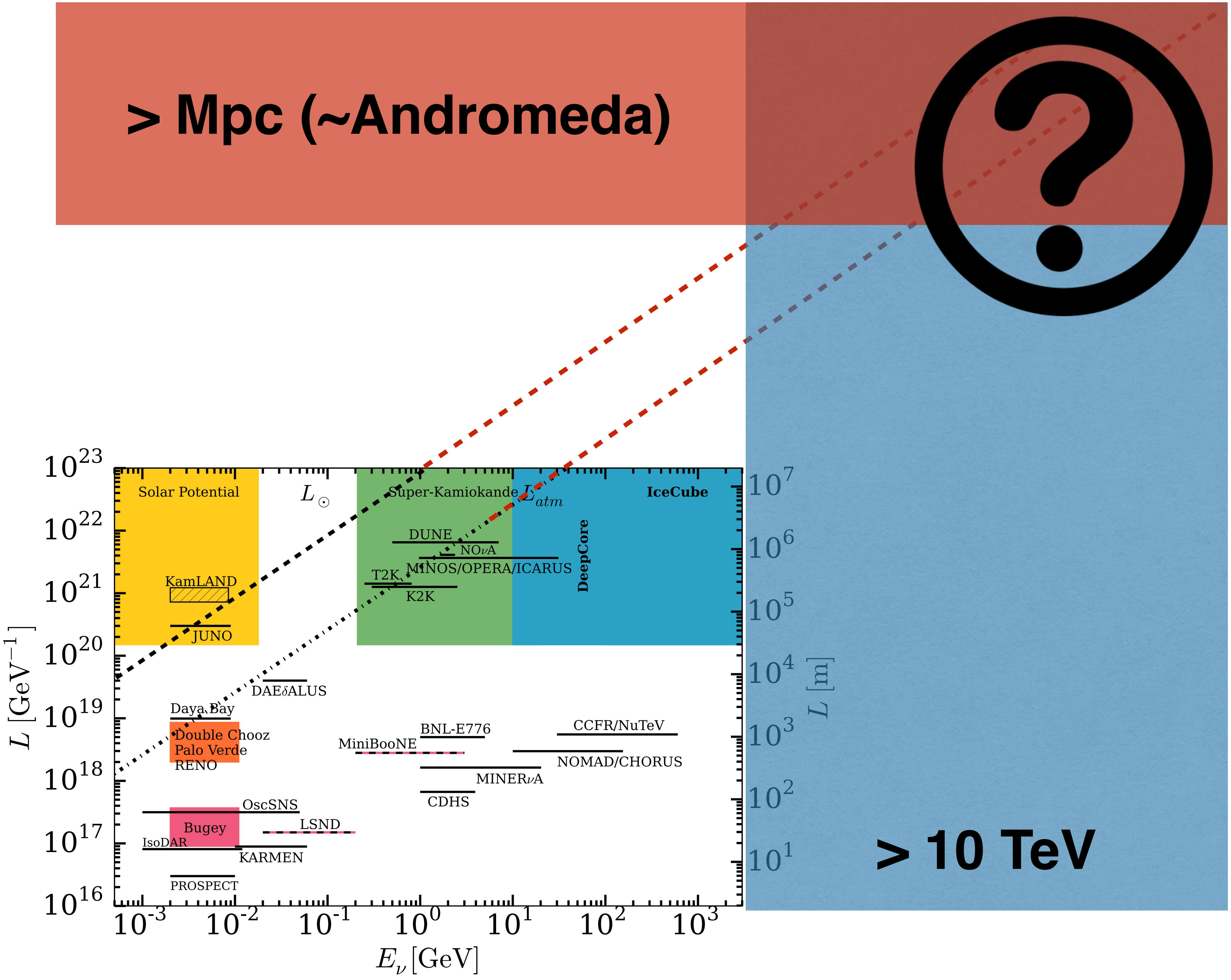
Many, many talks this week on this! Awesome talks/work by Fedynitch, Honda, Gaisser, Garzelli, and many others! Thank you guys!

Astrophysical neutrino dominate at highest energies!



Phys. Rev. Lett. 115, 081102 (2015)

Cosmic neutrinos frontier



Initial flavor



Flavor mixing

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

Standard Expectation

New Physics!



Flavor composition @ source

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

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

The oscillation probability depends on the neutrino propagation hamiltonian

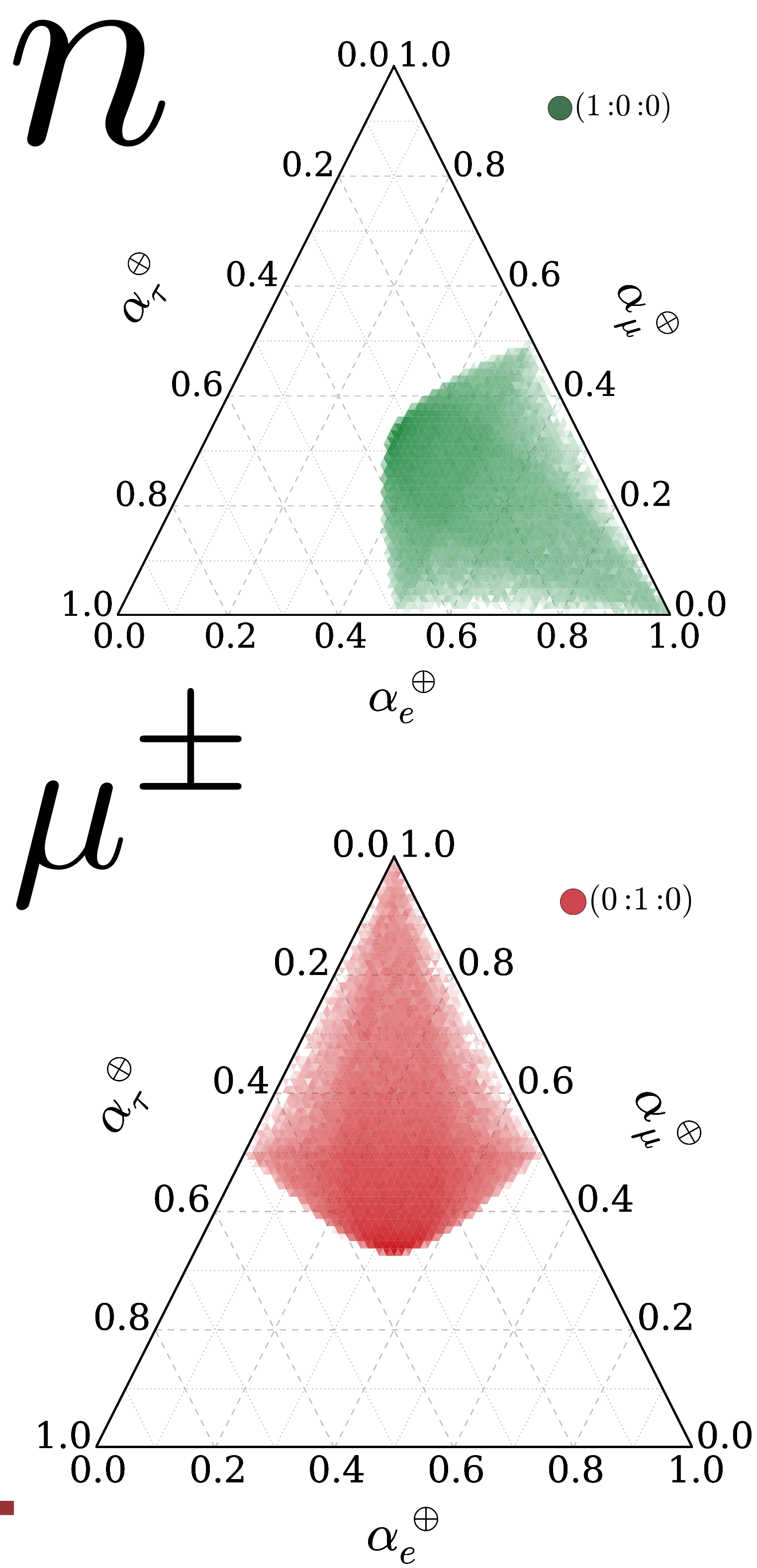
$$H(E) = V(E)^\dagger \begin{pmatrix} \Delta_1(E) & 0 & 0 \\ 0 & \Delta_2(E) & 0 \\ 0 & 0 & \Delta_3(E) \end{pmatrix} V(E)$$

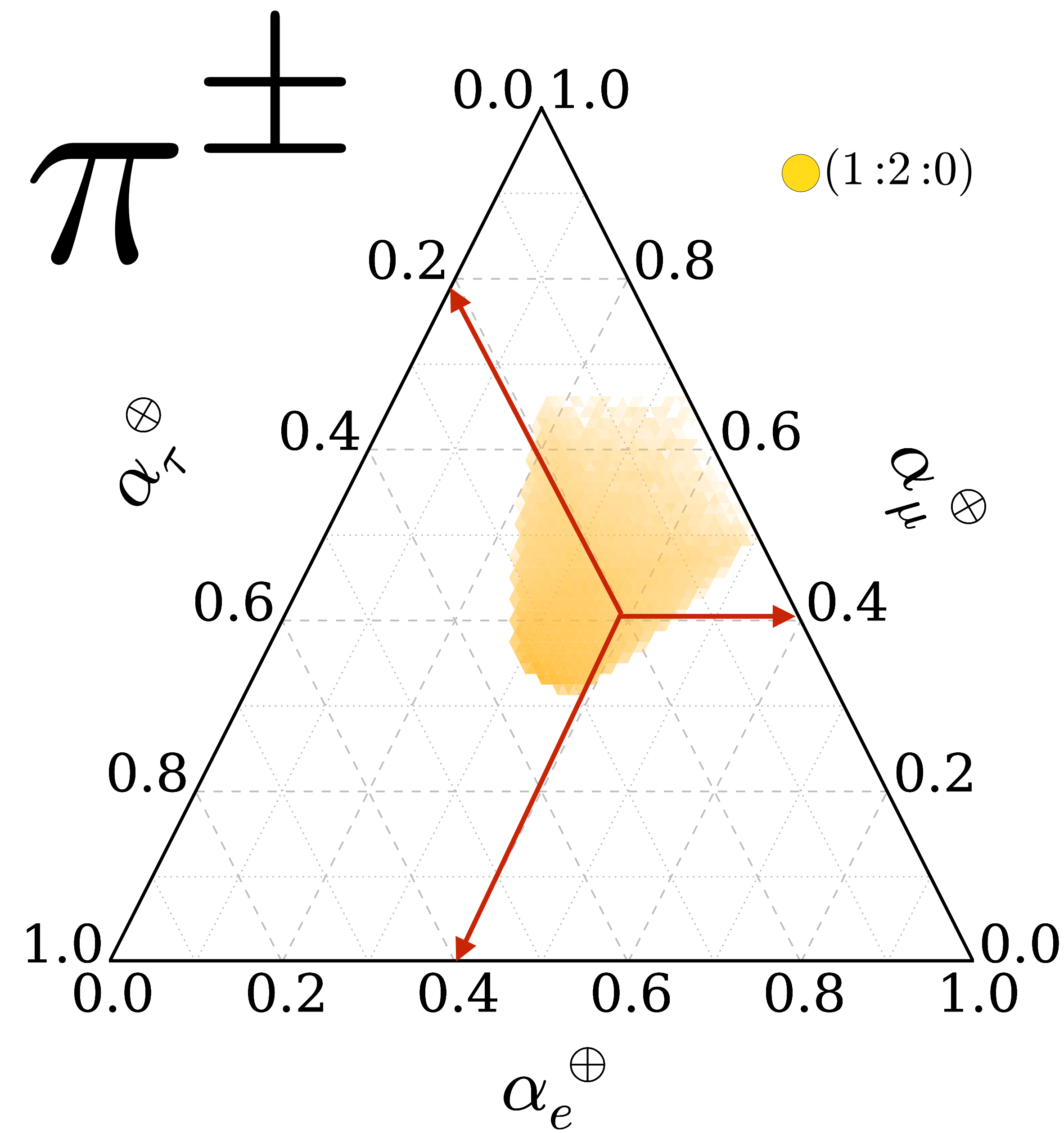
Since the oscillation length is much smaller than the distance of the sources

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

Oscillation probabilities depend only on the mixing elements!

Possible flavor triangles





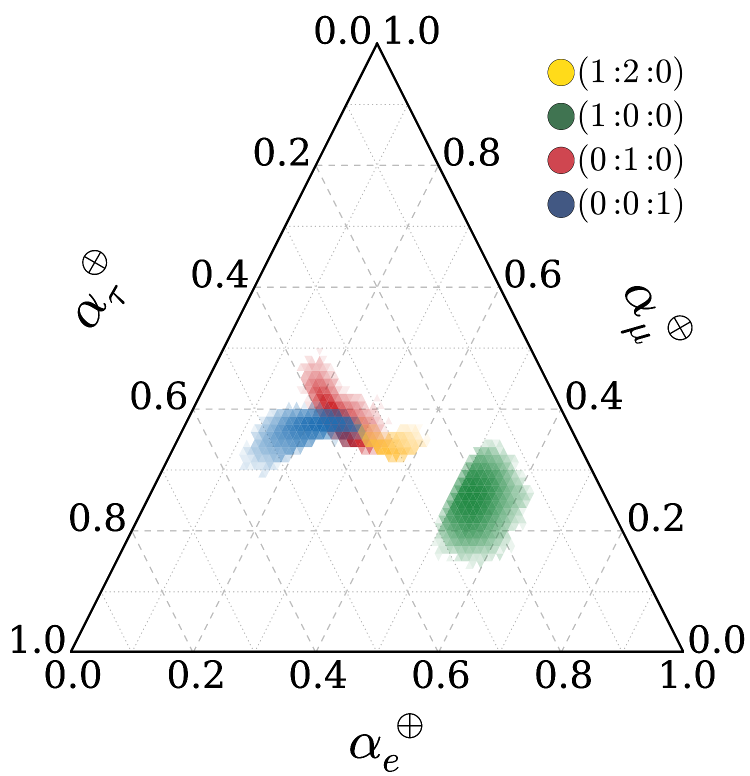
Due to unitarity the possible Earth flavor ratios for a given initial flavor composition is confined.

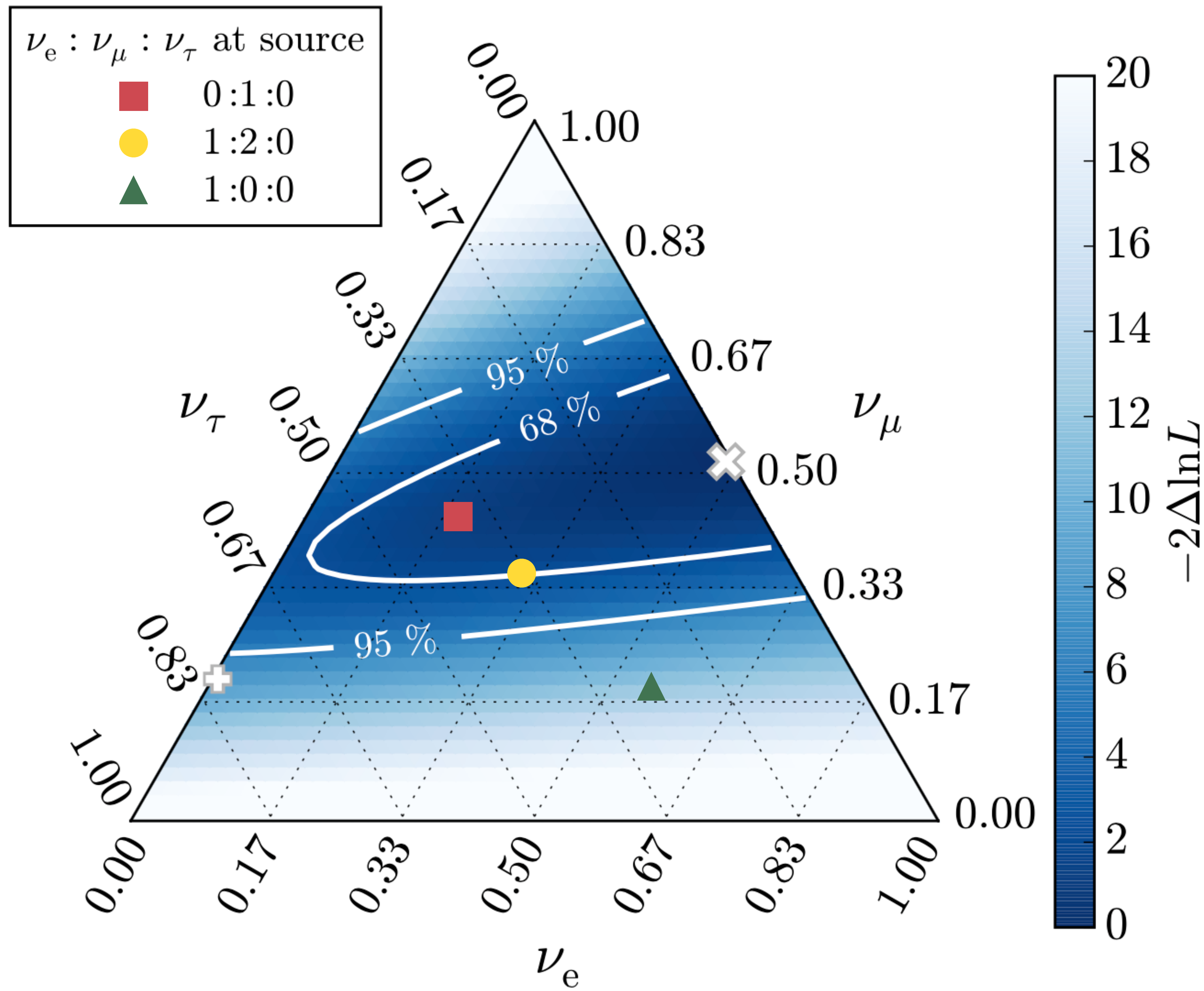
Astrophysical neutrino flavor

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

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: effective operators

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

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

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

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

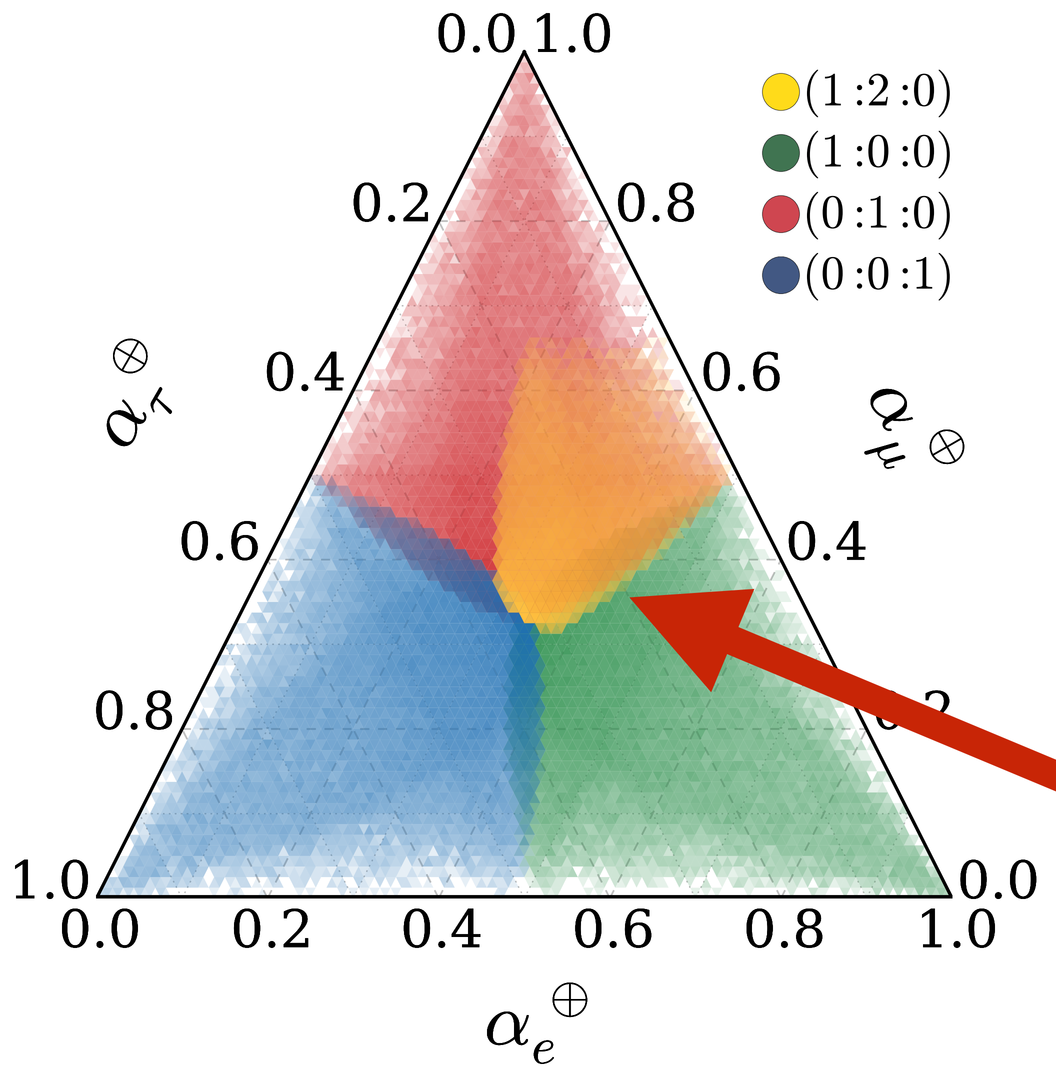
Phys.Rev. D91 (5) (2015) 052003,
Phys.Rev. D82 (2010) 112003.

IceCube Collaboration arXiv:1709.03434

+ New physics: effective operators

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

(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

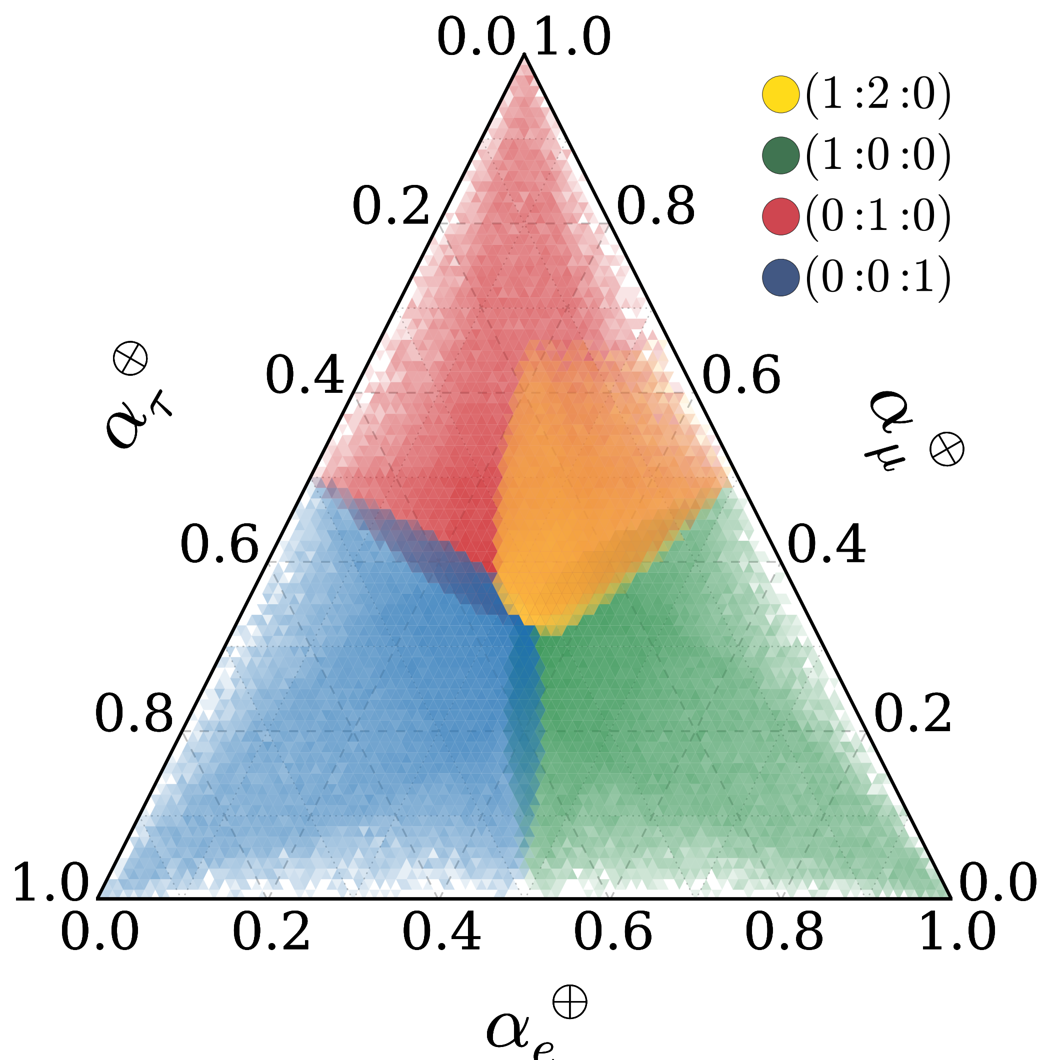
C.A., T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

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

+ New physics: effective operators

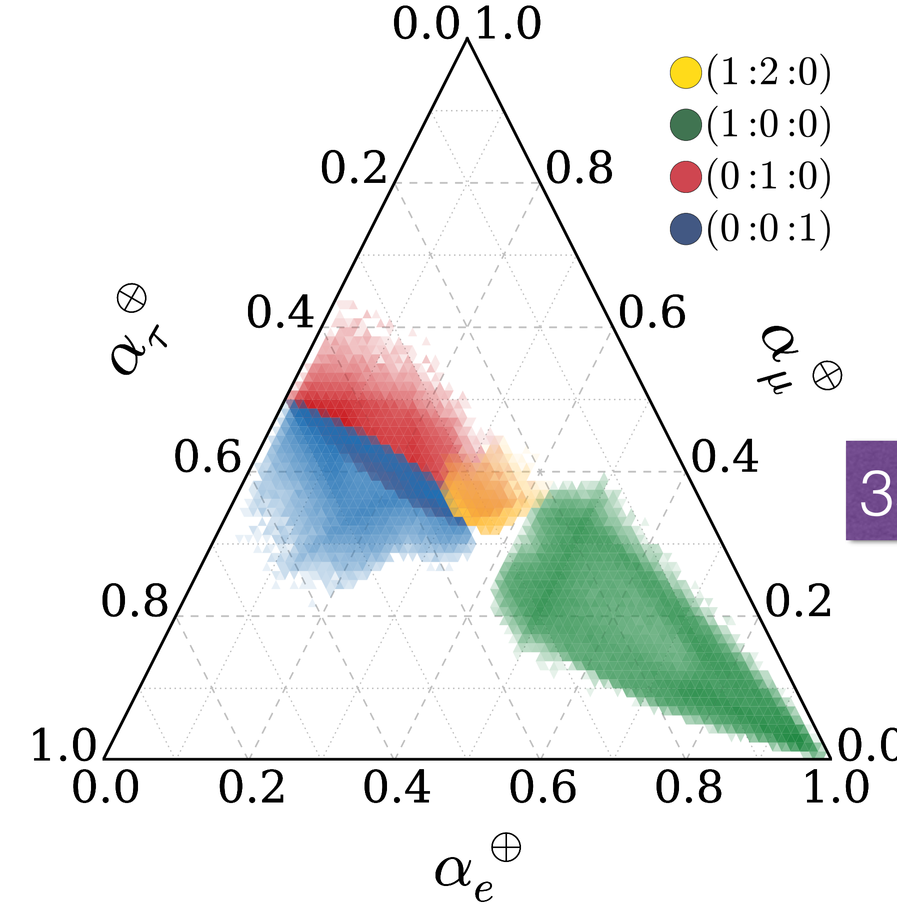
$$H = \frac{1}{2E} U M^2 U^\dagger + \boxed{\sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger}$$

(setting operators scales to current SK bounds)

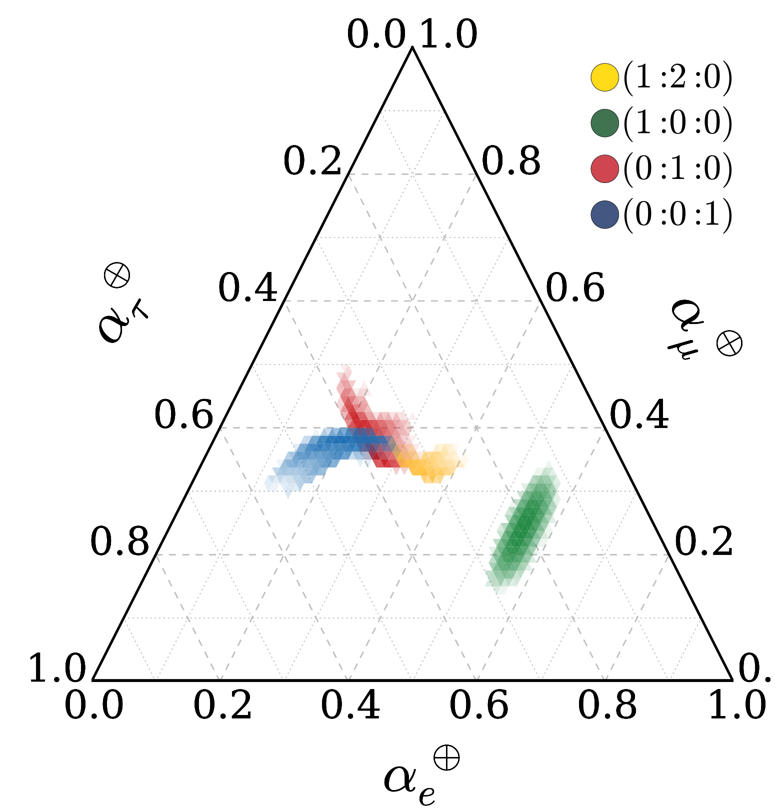


$O_0 \sim \mathrm{O}(10^{-23})$ GeV

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



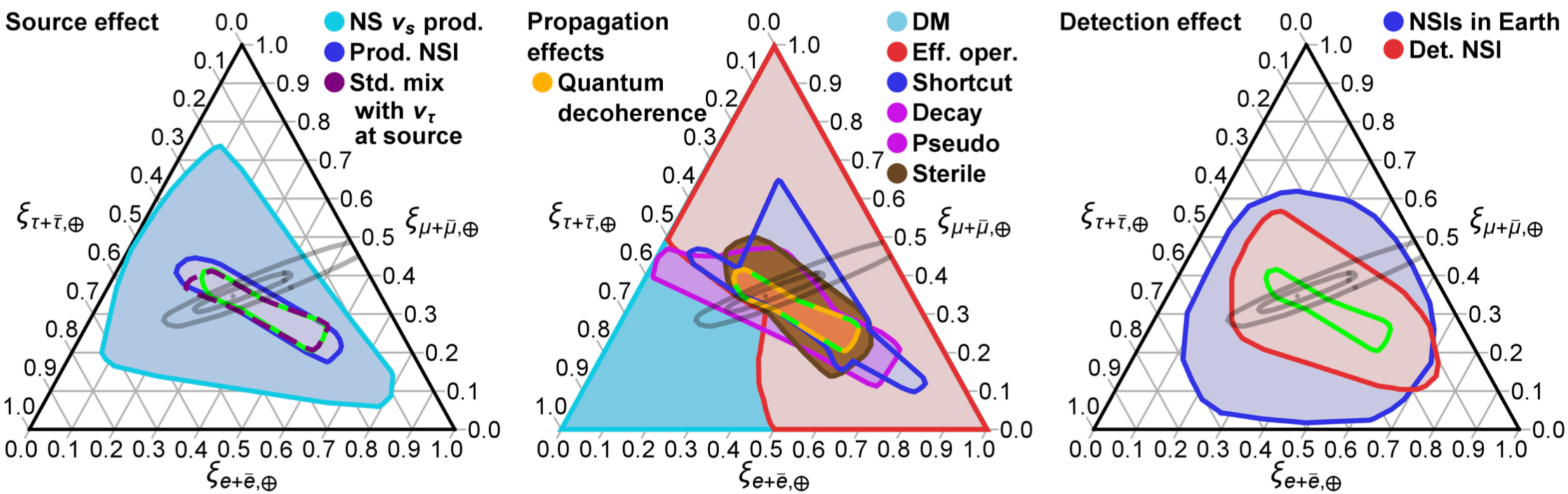
35 TeV



1 PeV

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

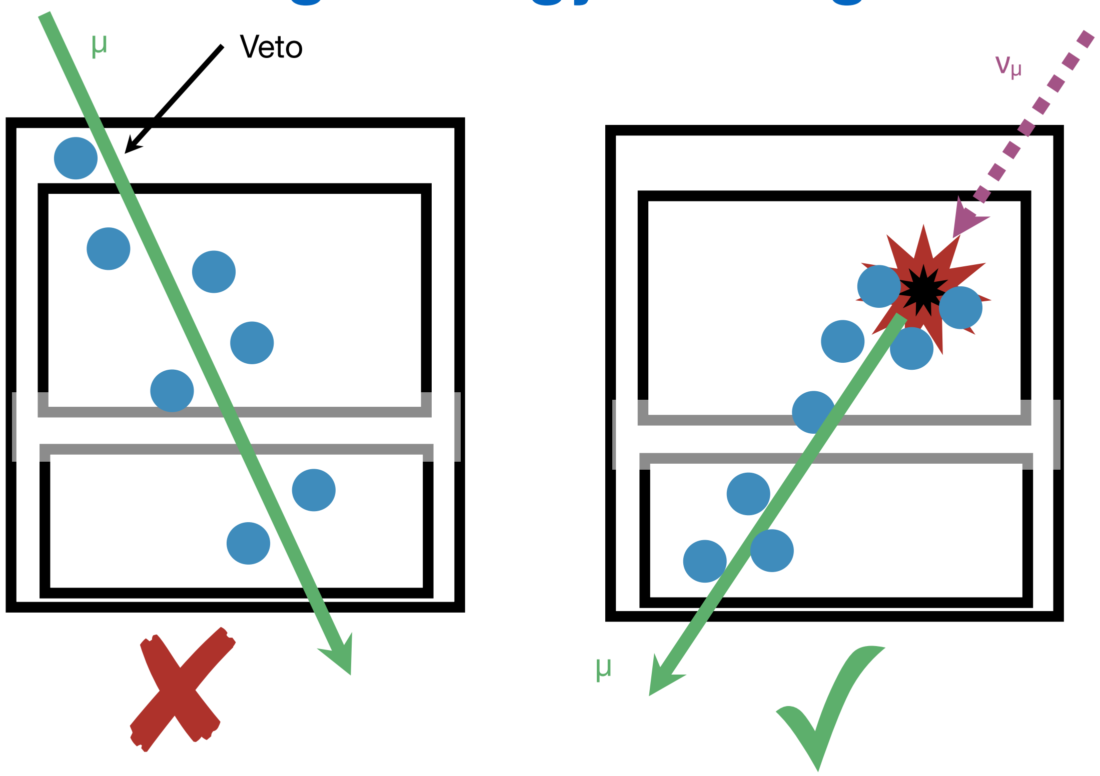
Note recent compilation on effects of BSM astrophysical neutrino flavor triangle



Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684

Analysis@HESE-7 years

HESE: high energy starting events



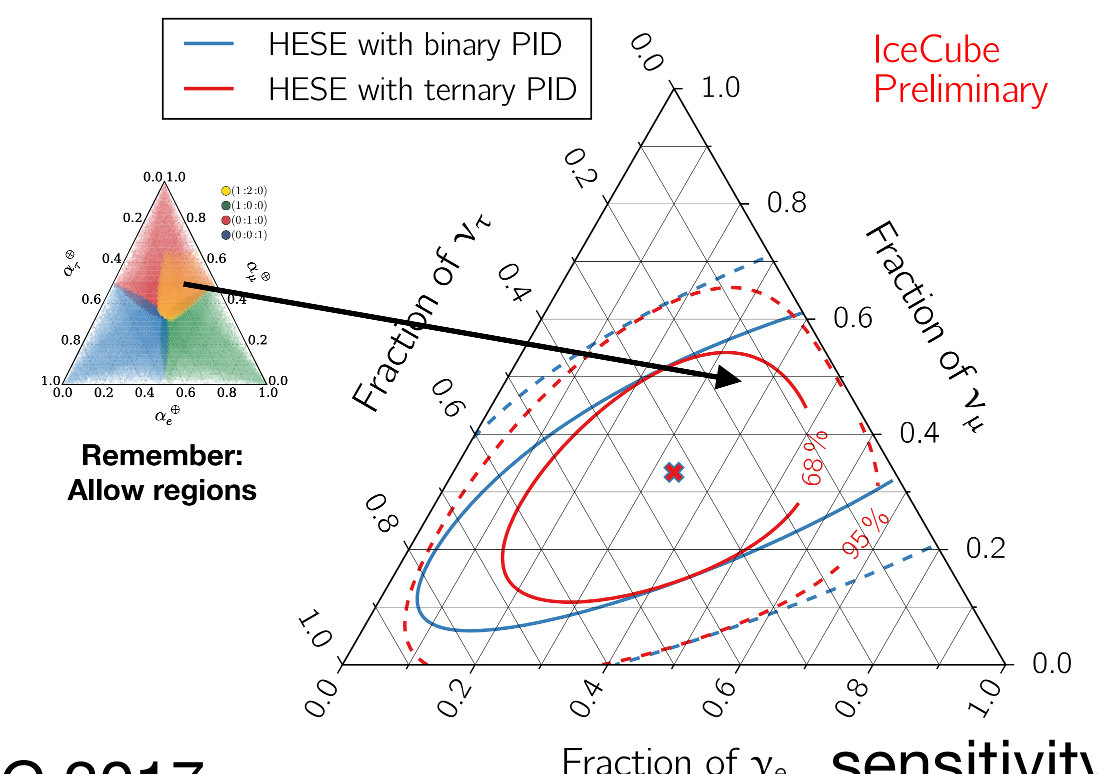
Latest iteration of the original HESE analysis. To be presented at Neutrino2018!

Updates:

- More statistics,
- Improved systematic treatment,
- New self-veto! (see talk by T. Yuan),
- Updated ice model and reconstructions,
- Now includes not only astrophysical characterization, but also BSM! Among them LV.

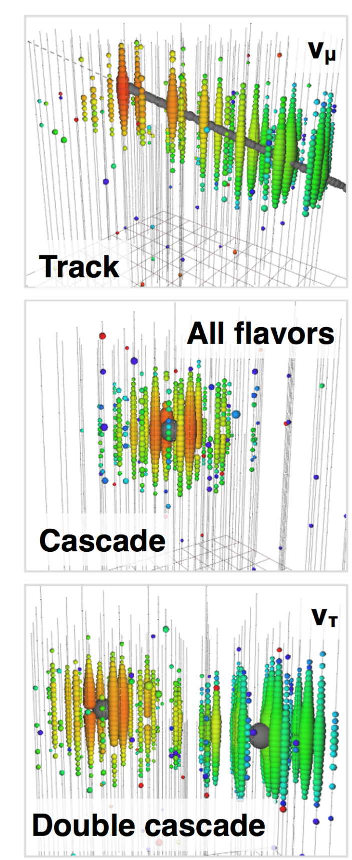
Expected sensitivity to flavor:

(6 year HESE)



Remember: Allow regions

sensitivity



Technical detail: finite Monte Carlo (MC) statistics

- **Monte Carlo generation in IceCube typically is done by generating according to an E^-\gamma distribution:**
  - Larger MC statistical errors at the high-energy region,
  - Often different MC statistics for different flavors,
  - Atmospheric muon background, generated with CORSIKA, has large MC stat. errors.
- Small signal statistics: not in the gaussian regime! $\chi^2_{\mathrm{mod}} \equiv \sum \frac{(n_i - \mu_i)^2}{\mu_i + \sum_j \sigma^2_{ij}}$

How can we account for this in our analyses?

$$L_{\mathbf{P}}(\theta) = \prod_{\text{bins } i} \frac{e^{-\sum_j w_{j,i}(\theta)} \left(\sum_j w_{j,i}(\theta)\right)^{k_i}}{k_i!}$$

$$= \prod_{\text{bins } i} \int_0^\infty \frac{e^{-\lambda_i} {\lambda_i}^{k_i}}{k_i!} \cdot \delta\left(\lambda_i - \sum_j^{k_{mc,i}} w_{j,i}(\theta)\right) d\lambda_i$$

Probabilistic approach (Glüsenkamp 2017)

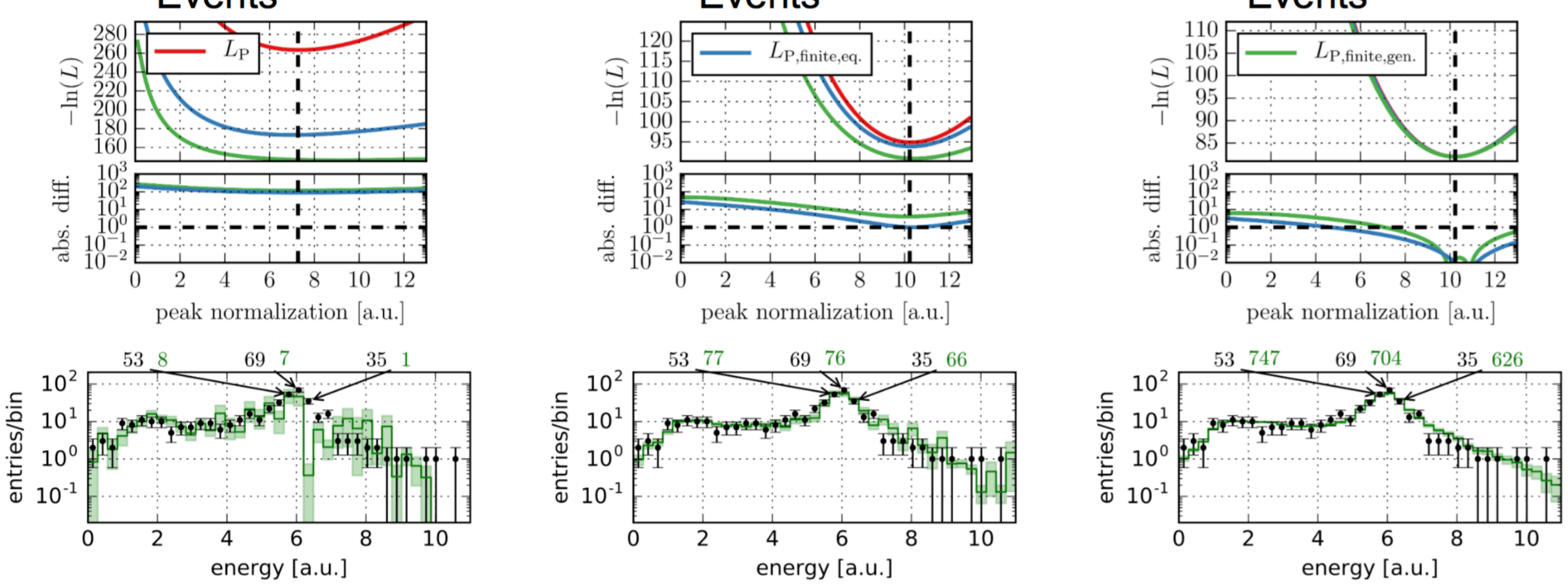
Various ideas in the literature:

- Barlow et al. (1993),
- Bohm et al. (2012),
- Chirkin (2013),
- Glüsenkamp (2017).

Use with care: can introduce significant bias.

Works well, though slow to compute.

268 MC Events | 2682 MC Events | 26821 MC Events



Glüsenkamp (2017)

Austin Schneider, CA, Tianlu Yuan, *in preparation*

What do we expect to do with HESE?

Simple back of the envelope "sensitivity reach" calculation:

$$H_d = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{\frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger} = V_d(E) \Delta V_d^\dagger(E)$$

DIM 3

$$\boxed{\frac{1}{E} \cdot 10^{-21}\text{GeV}} \sim \boxed{\frac{1}{\Lambda}}$$

60 TeV ~ 1E4 GeV

$$\Lambda_3^{-1} \sim 10^{-25}\text{GeV}$$

10 PeV = 1E7 GeV

$$\Lambda_3^{-1} \sim 10^{-28}\text{GeV}$$

$$\boxed{10^{-25}\text{GeV} < \Lambda_3^{-1} < 10^{-28}\text{GeV}}$$

DIM 6

$$\boxed{\frac{1}{E} \cdot 10^{-21}\text{GeV}} \sim \boxed{\frac{E^3}{\Lambda}}$$

60 TeV ~ 1E4 GeV

$$\Lambda_6^{-1} \sim 10^{-37}\text{GeV}^{-2}$$

10 PeV = 1E7 GeV

$$\Lambda_6^{-1} \sim 10^{-49}\text{GeV}^{-2}$$

$$\boxed{10^{-37}\text{GeV}^{-2} < \Lambda_6^{-1} < 10^{-49}\text{GeV}^{-2}}$$

Additional assumptions

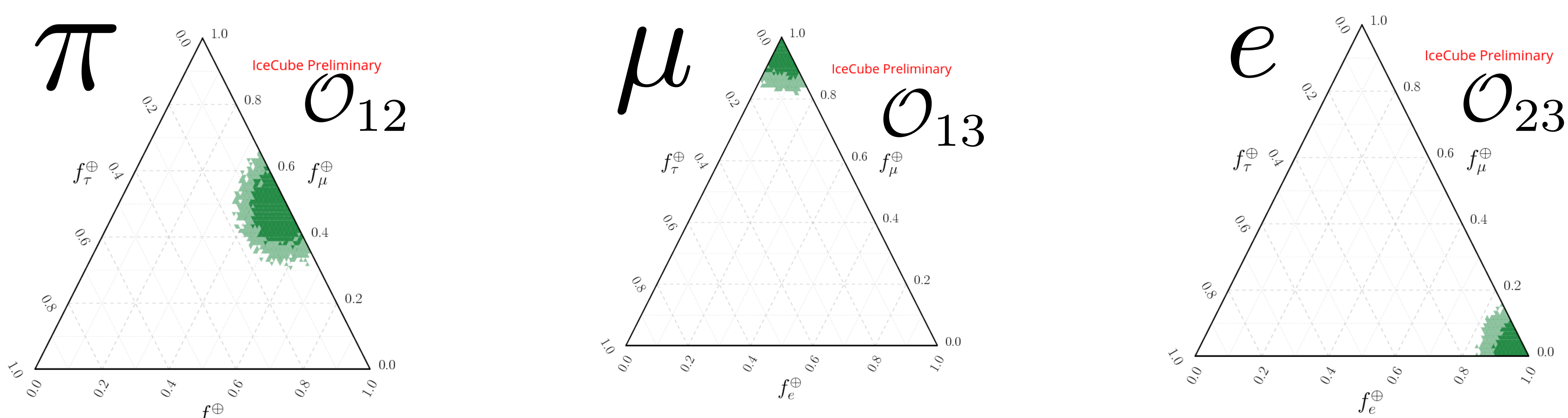
- **We will fix the initial flavor ratio to one of the usual scenarios.**
- **We will also study maximum flavor violating operators, a la SK.**

New Physics Mixing Matrix

$$\tilde{U}_d = \quad \mathcal{O}_{12} = \frac{\pi}{4} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \mathcal{O}_{13} = \frac{\pi}{4} \begin{pmatrix} \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{pmatrix} \quad \mathcal{O}_{23} = \frac{\pi}{4} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

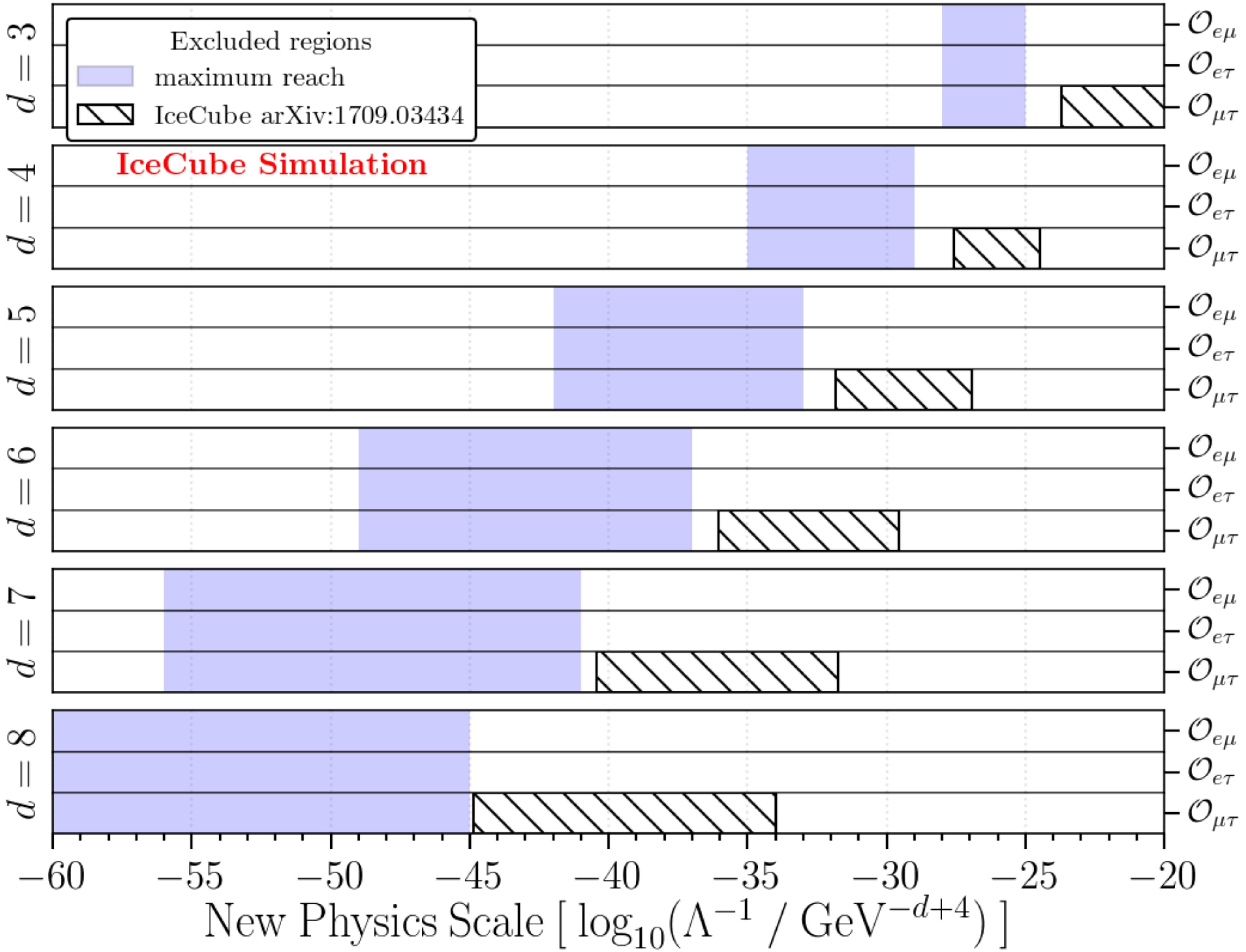
$\mathcal{O}_{13} = 0 \quad \mathcal{O}_{23} = 0$ | $\mathcal{O}_{12} = 0 \quad \mathcal{O}_{23} = 0$ | $\mathcal{O}_{12} = 0 \quad \mathcal{O}_{13} = 0$

How do some these look in the triangle?



(in these triangles a “fake”/gaussian detector smearing have been added)

Summary of IceCube sensitive + limits



dashed: atmospheric neutrinos, solid cosmic neutrinos

Summary and outlook

- ✤Atmospheric neutrinos in IceCube provide robust and strongest bounds on LV operators. And other things we have discussed in this workshop: sterile (jordi salvado), NSI (thomas ehrhardt), decoherence (tom studdard), …
- ✤Astrophysical neutrinos have great potential, but results are conditional on the astrophysical source initial composition. If its pion dominated and we observe 1:1:1 things don't look good for LV limits/discovery.

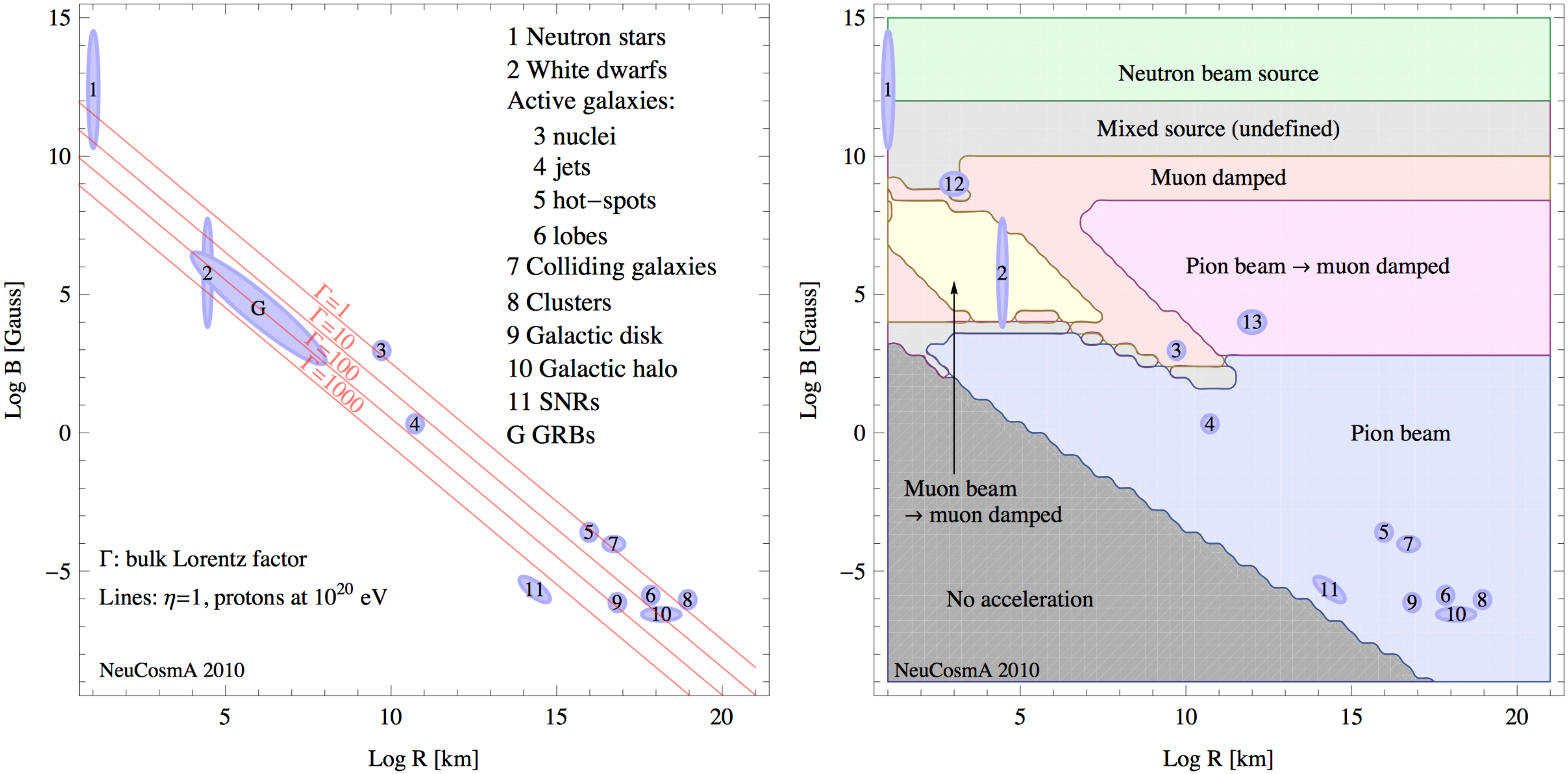
- ✤Only two years of high-energy muon neutrino data studied! Expect update with ~ 7 years soon. **Of course, with greater statistics, comes greater systematic responsibility**!
- ✤We also have the high-energy atmospheric cascades (MESE)! We will be looking onto that too!
- ✤Expect exciting results on LV@Neutrino2018! Keep tuned!

Check out our public data releases:
https://icecube.wisc.edu/science/data

For questions on our public data don't hesitate to ask: analysis@icecube.wisc.edu
If you have ideas and/or want to discuss shoot me an email too: caad@mit.edu

We are friendly and curious penguins :)

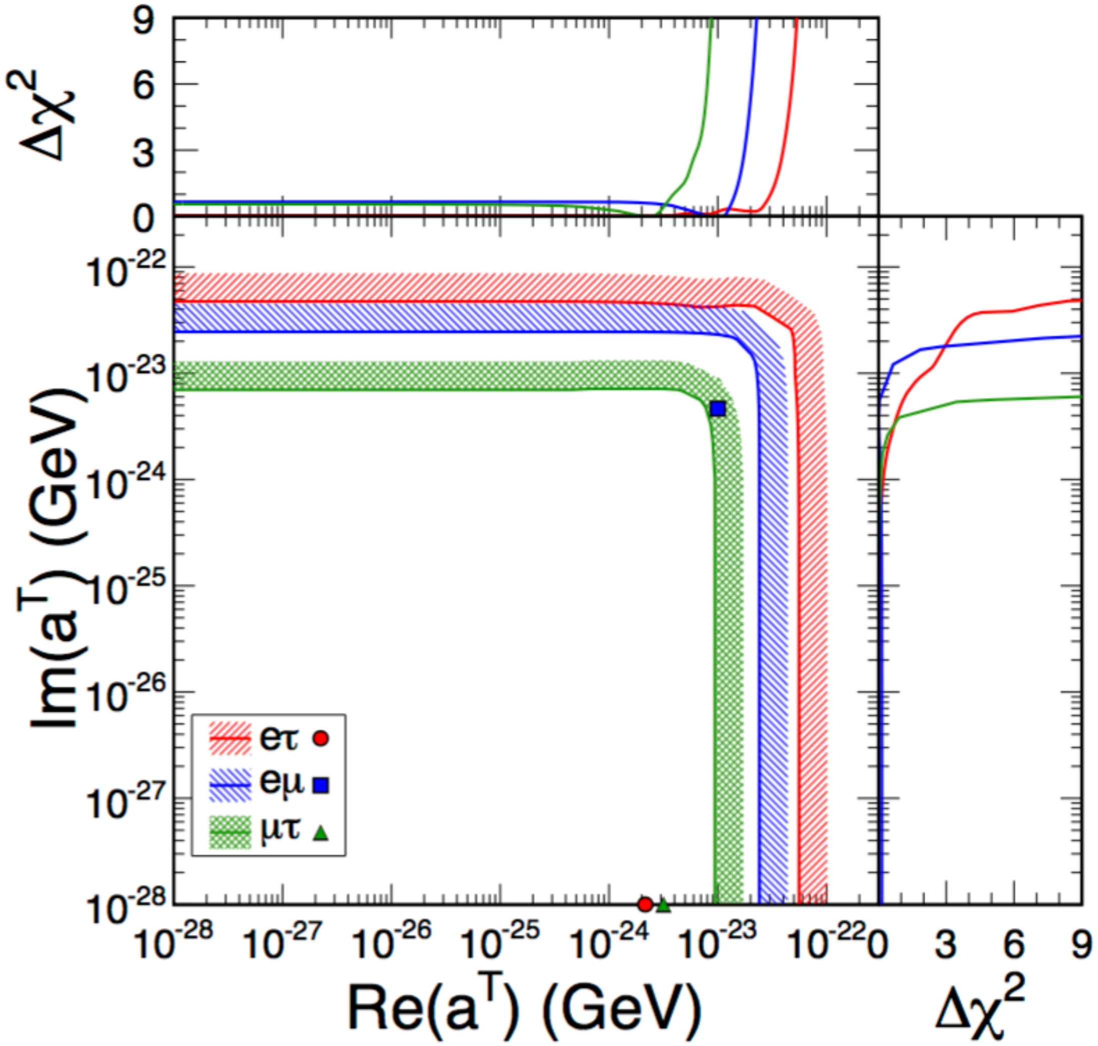
BONUS SLIDES!



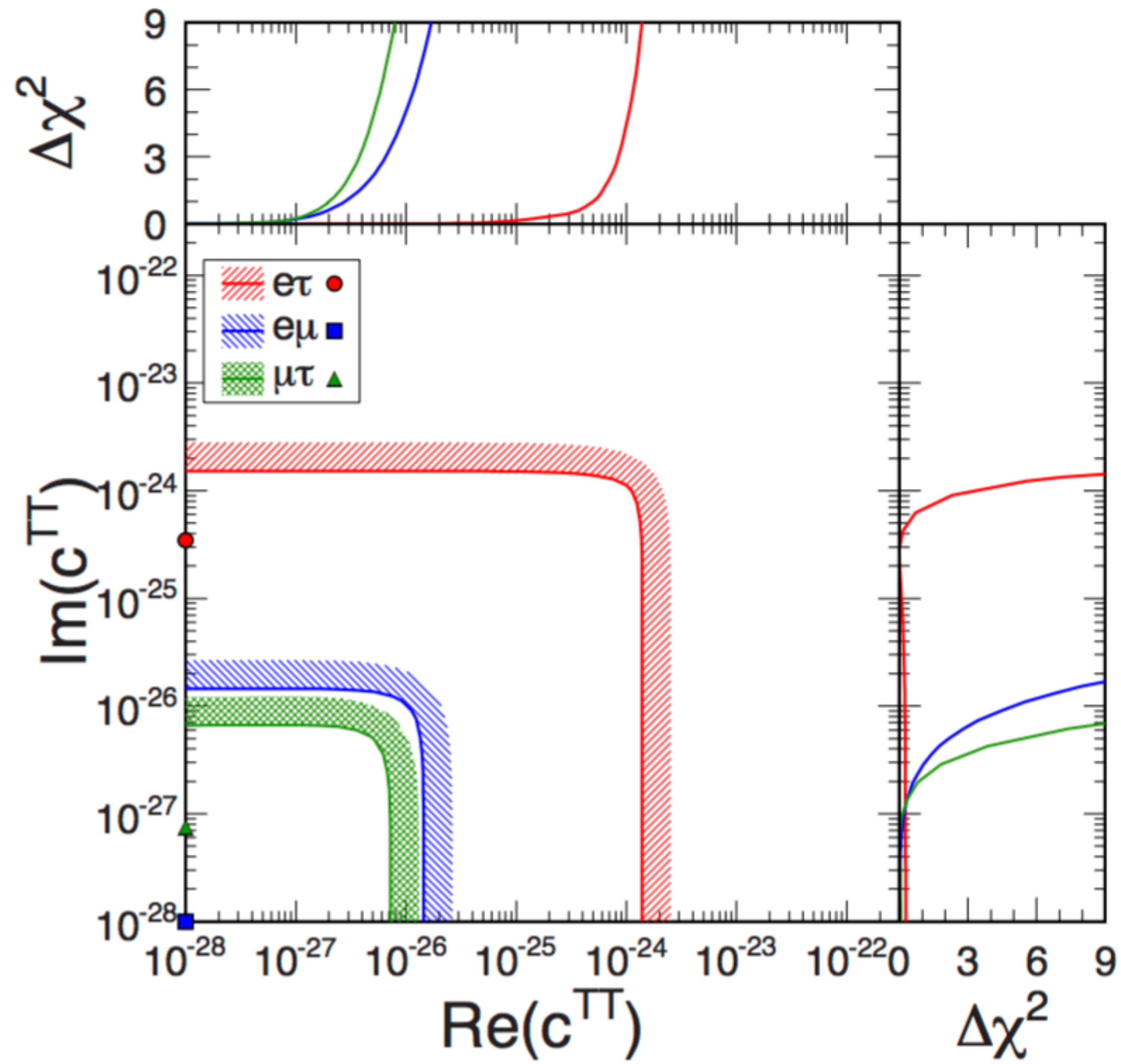
(arXiv:1007:0006)

arXiv:1410.4267

Current bounds from SK

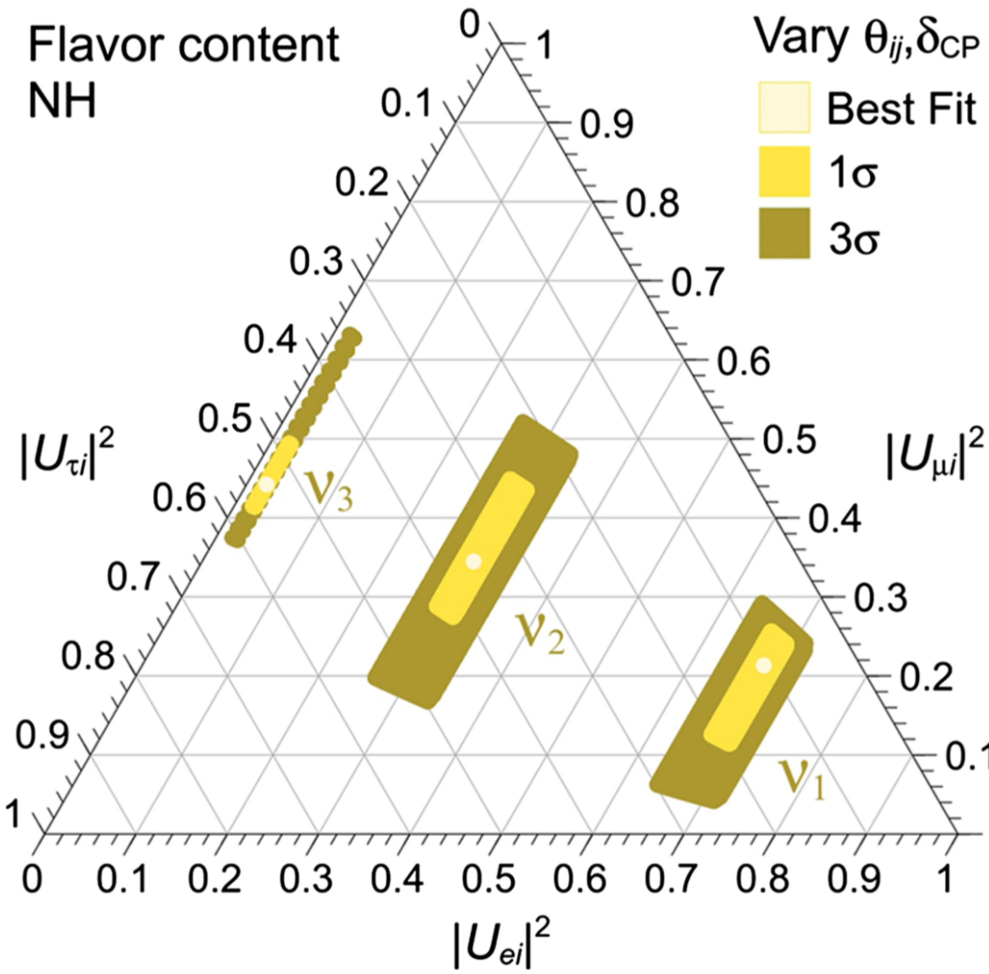


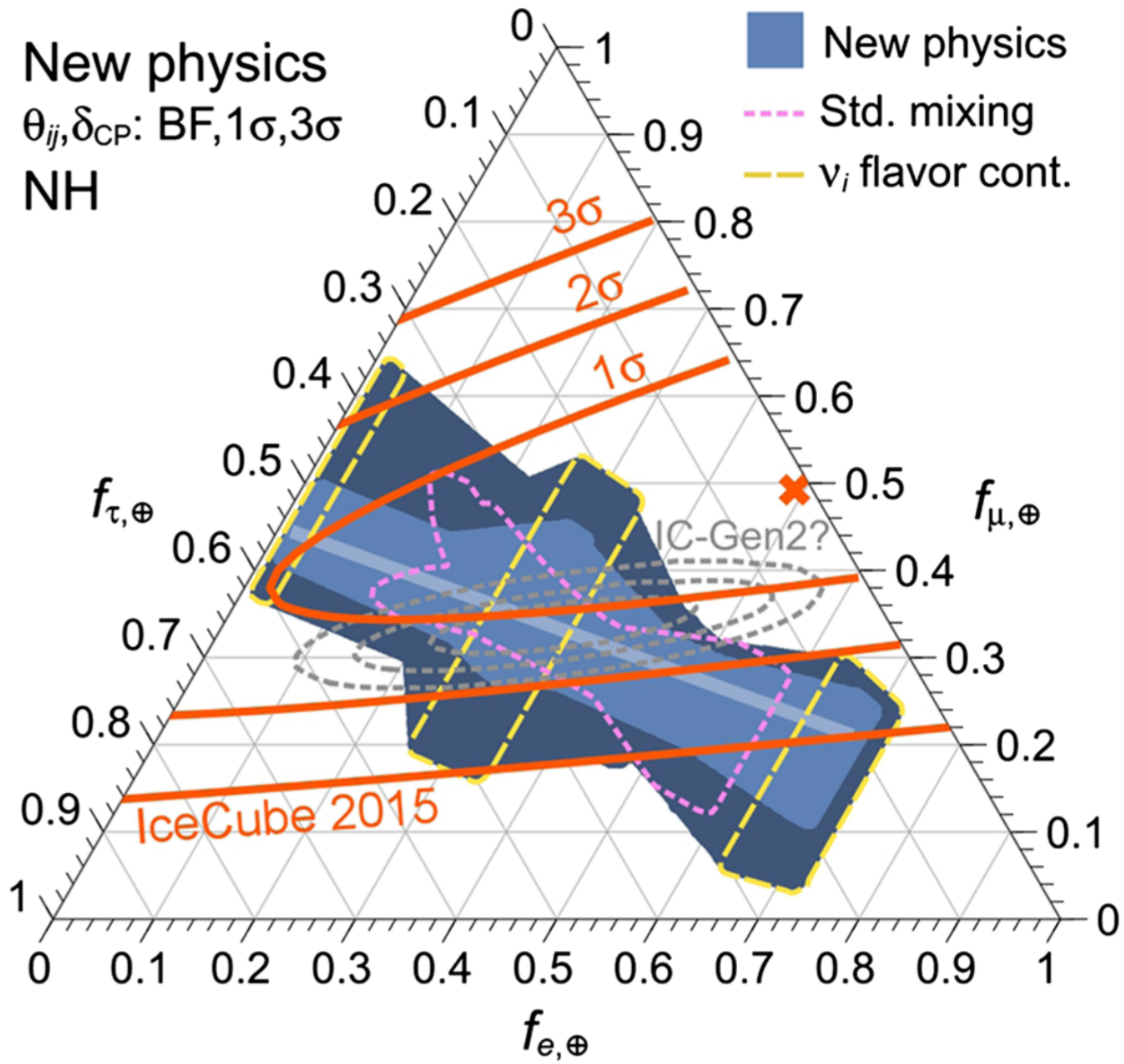
$$\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$



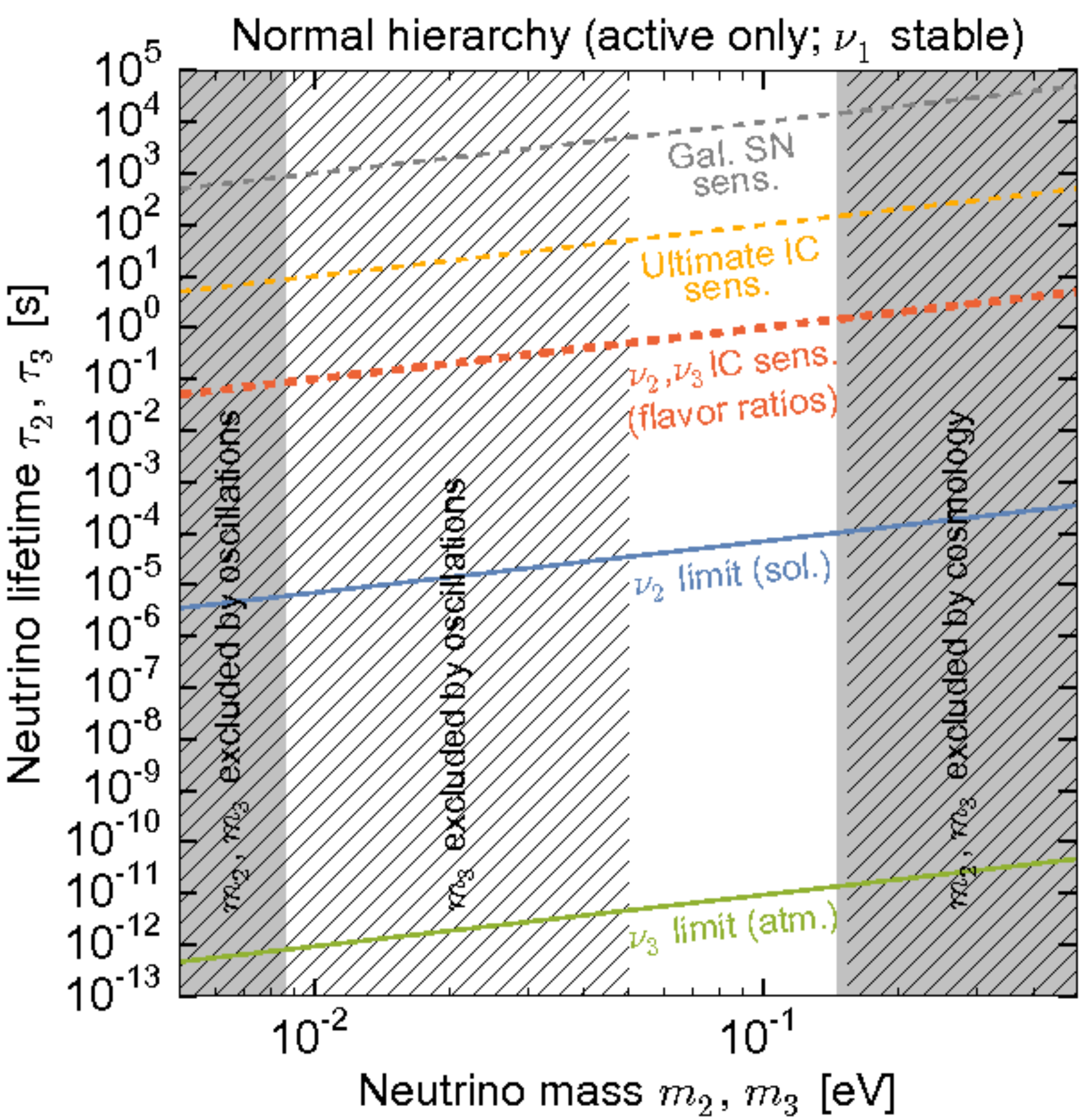
LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [58]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	Re (c^{TT})	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [58]
	Im (c^{TT})	8.0×10^{-27}	1.0×10^{-28}		
$e\tau$	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}		

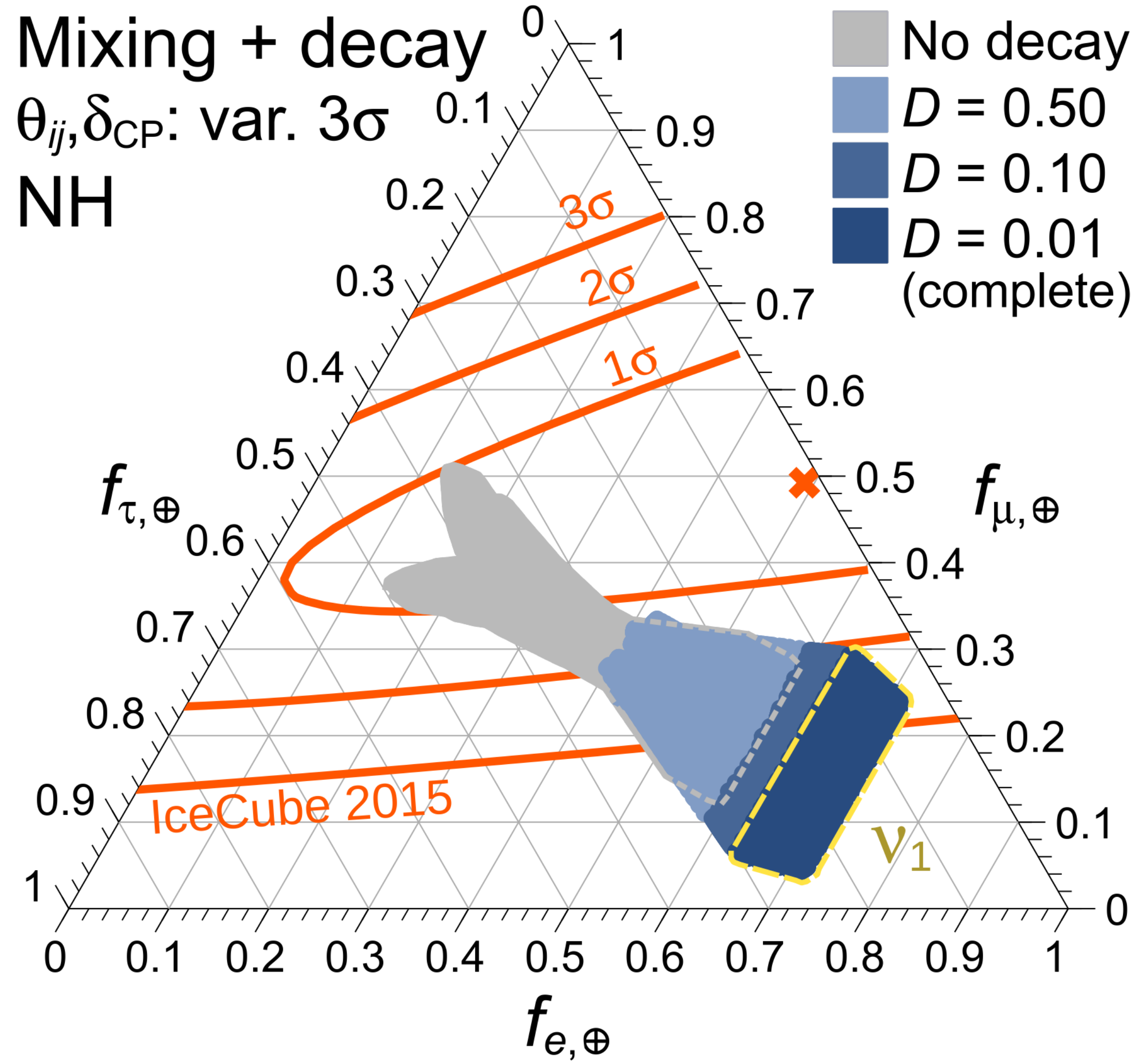
+ New physics mixing





+Neutrino decay

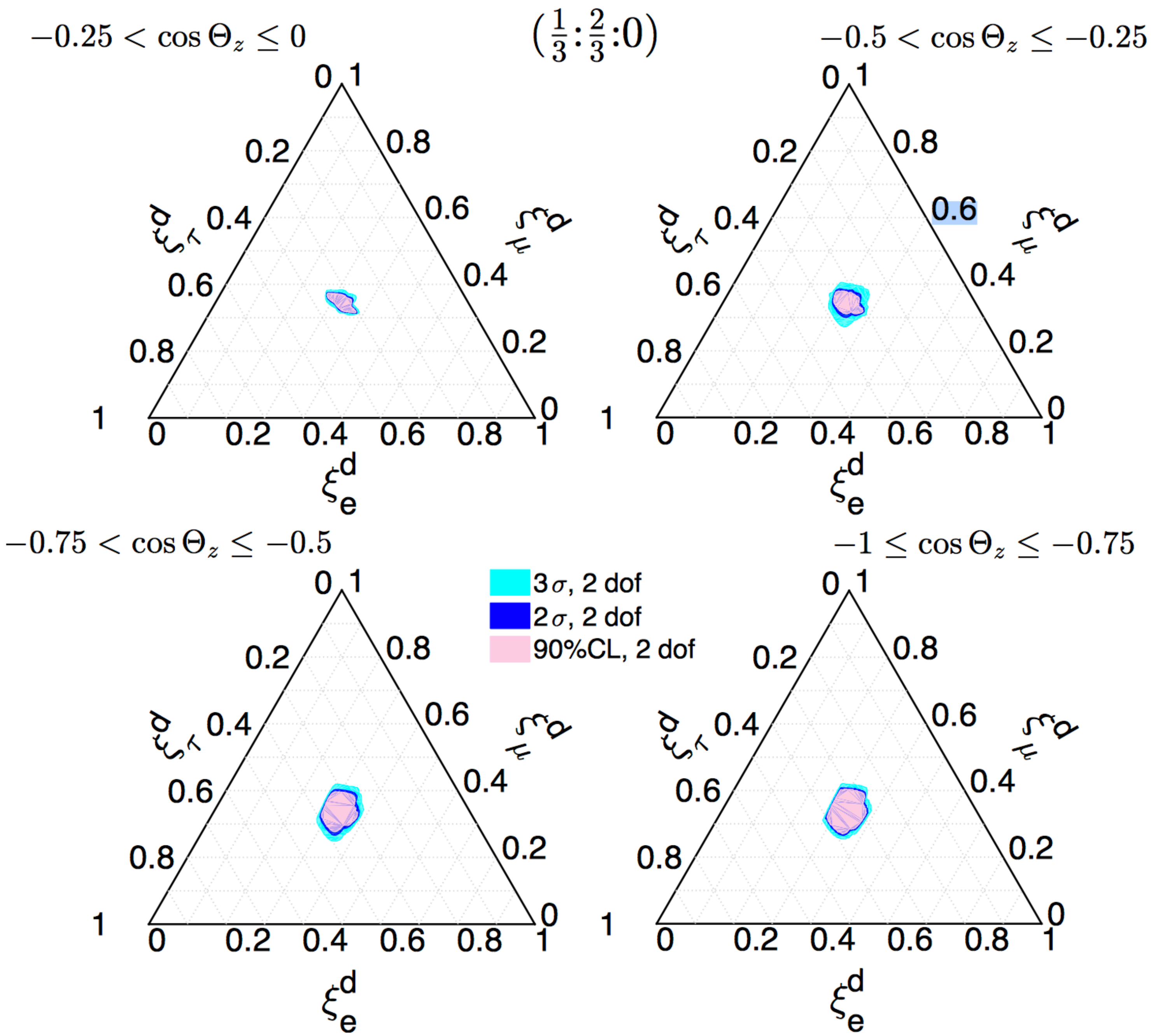


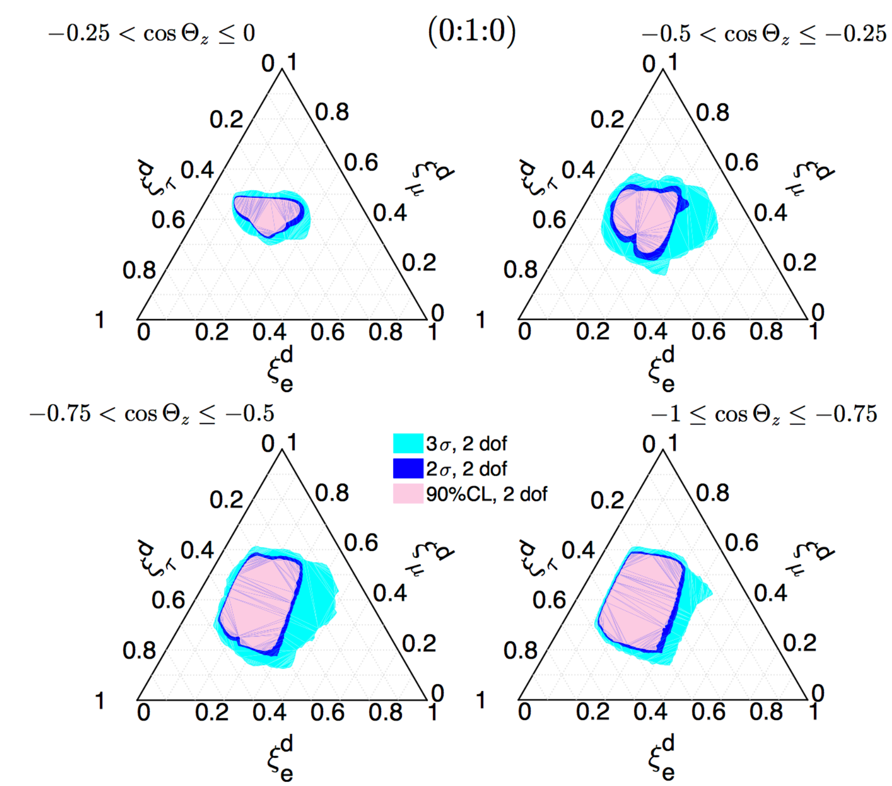


M. Bustamante, J. Beacom, K. Murase (1610.02096)

+ NSI@Earth

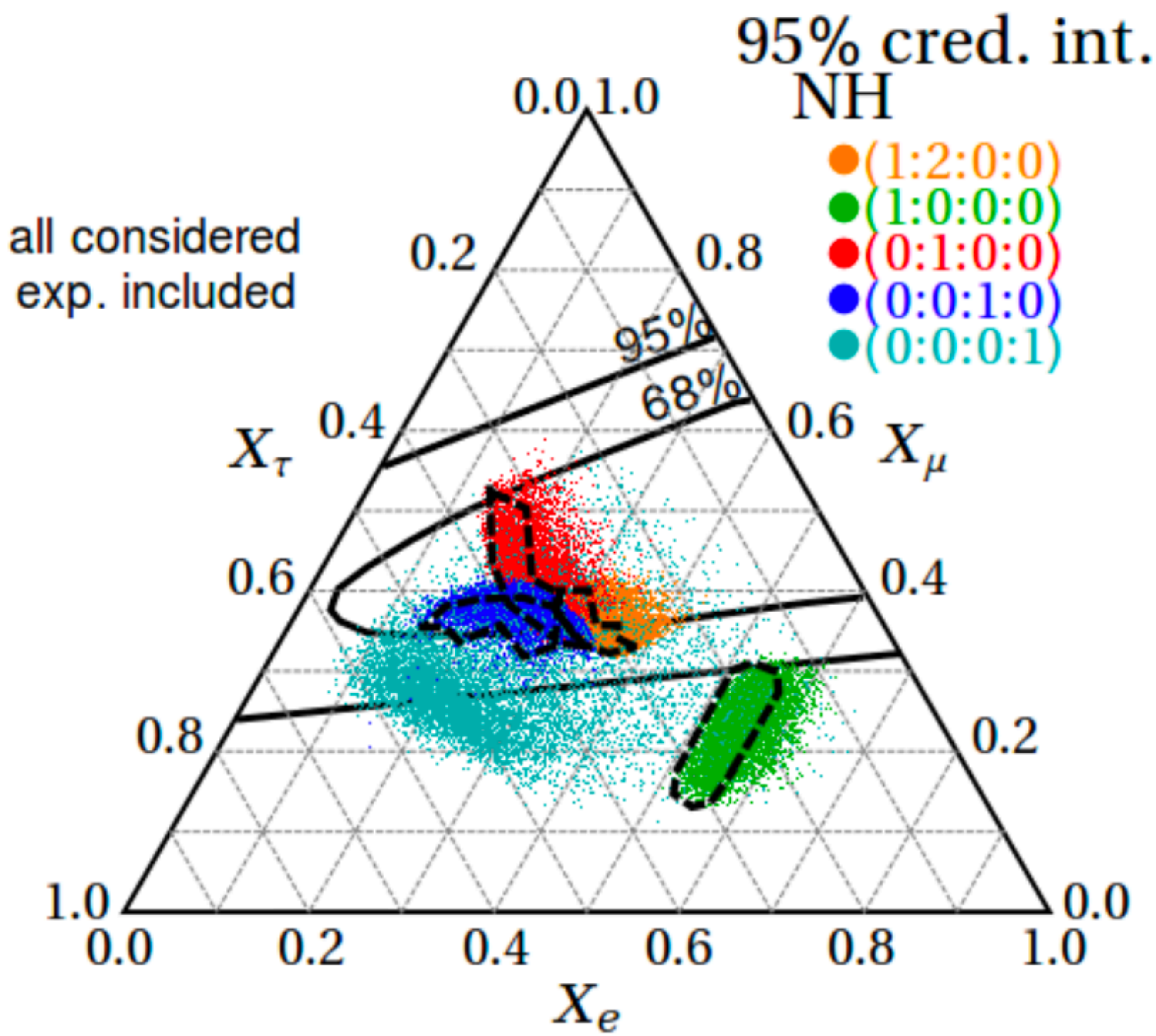
In the pion scenario NSI effects are small.
This is not the case for other initial flavor ratios.





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

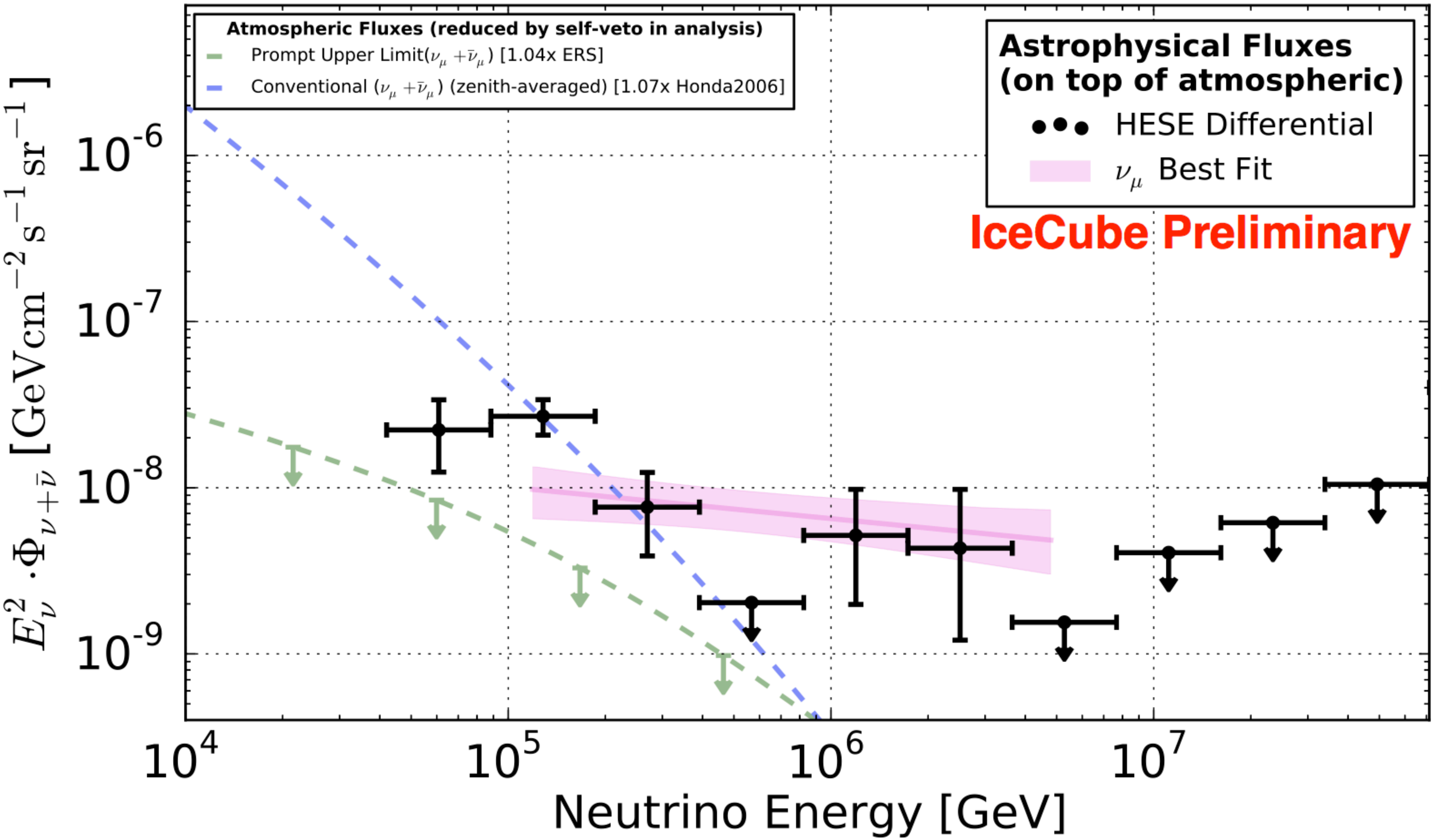
+ (eV) sterile neutrino

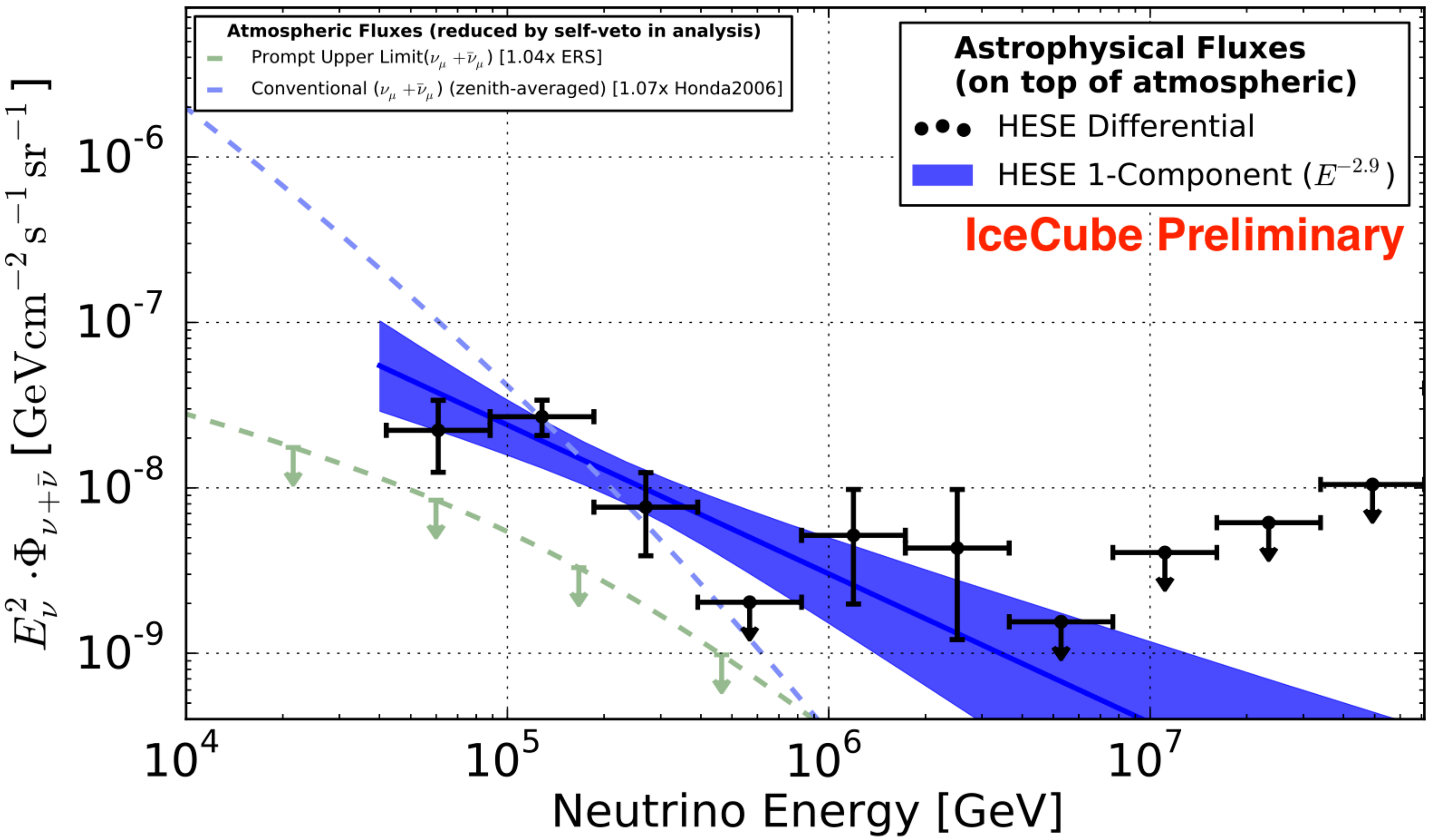


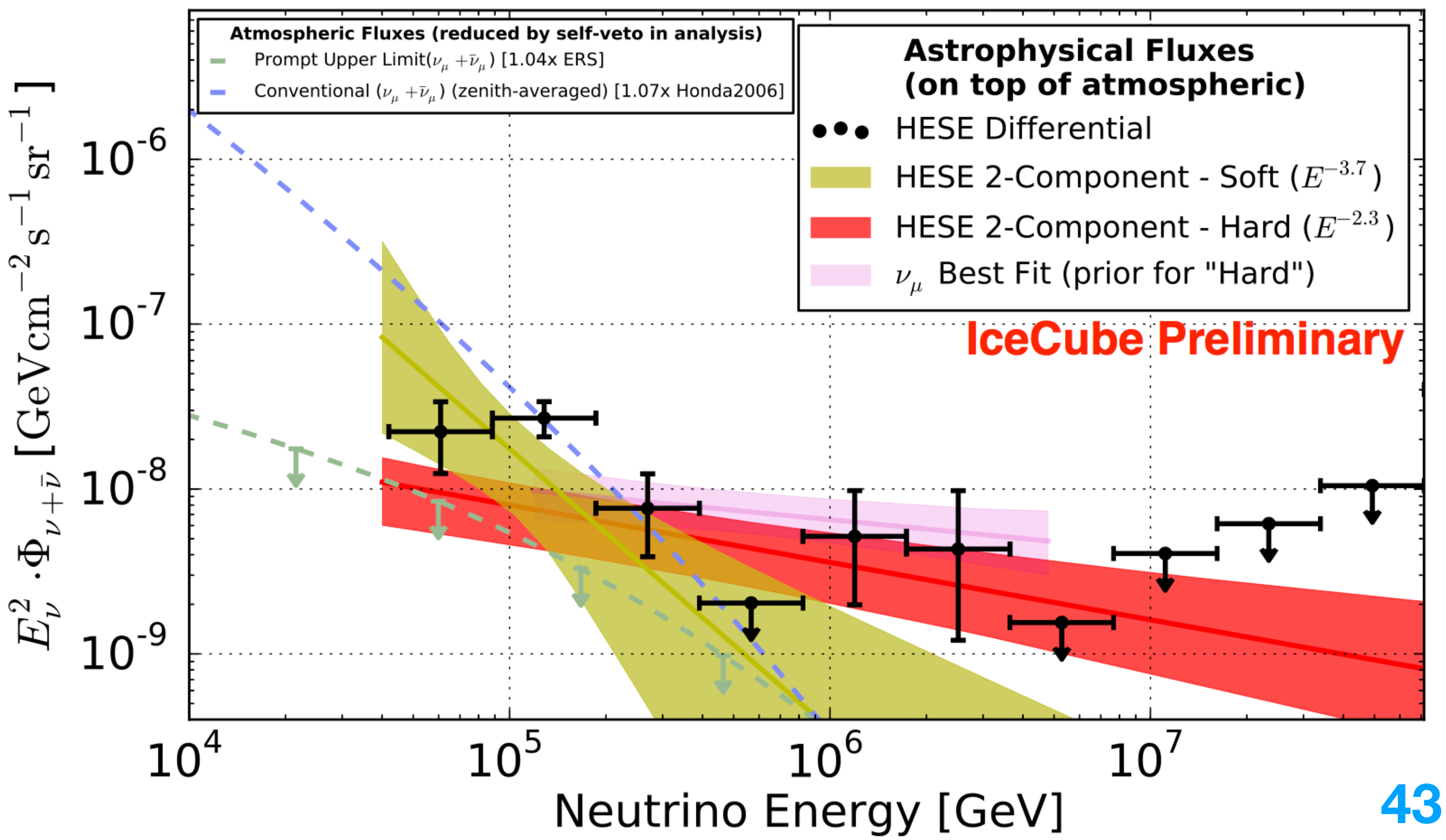
- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

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

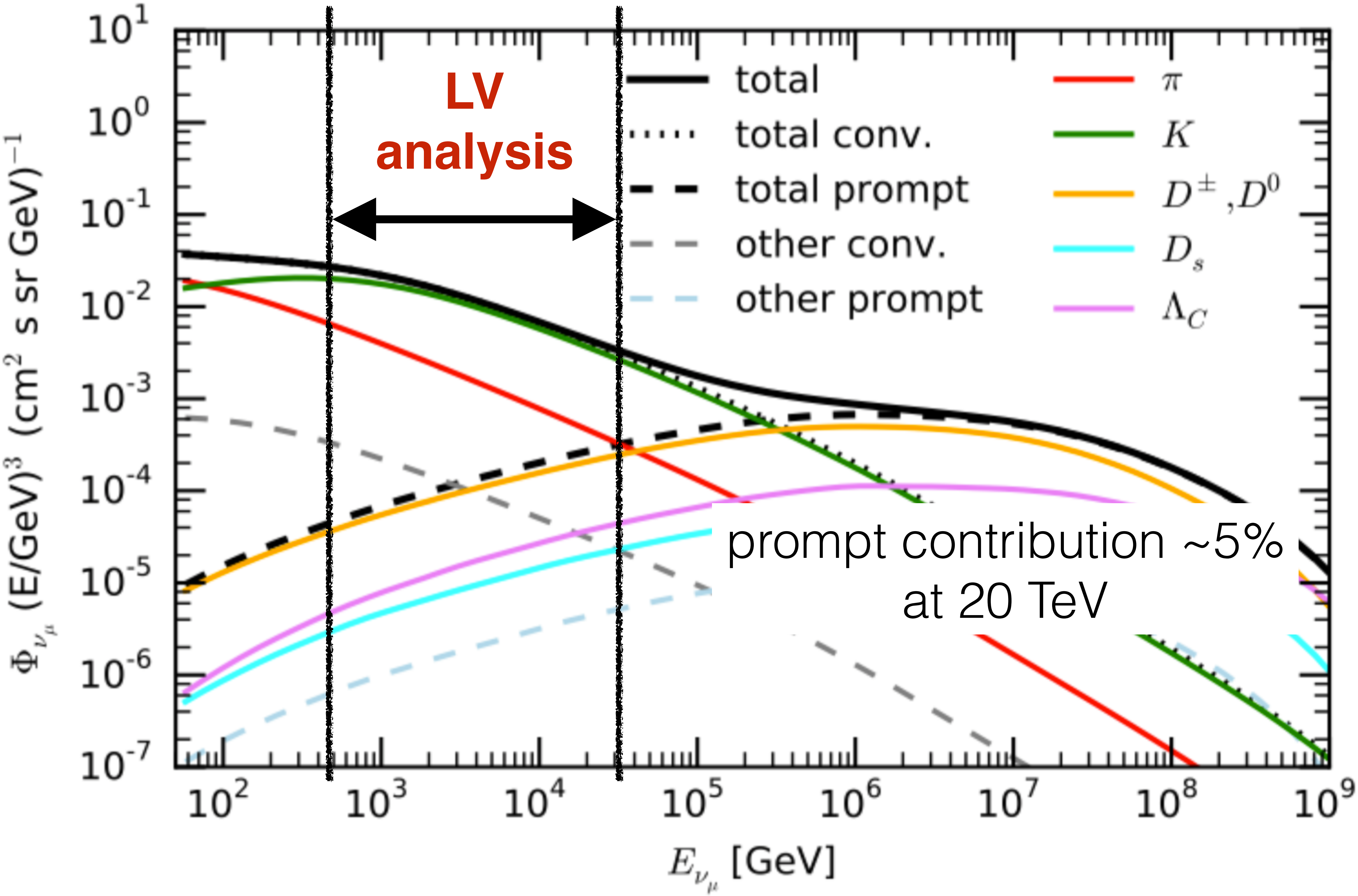
HESE 6 year unfolded




Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes
(on top of atmospheric)
HESE Differential
HESE 1-Component ($E^{-2.9}$)
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
Neutrino Energy [GeV]

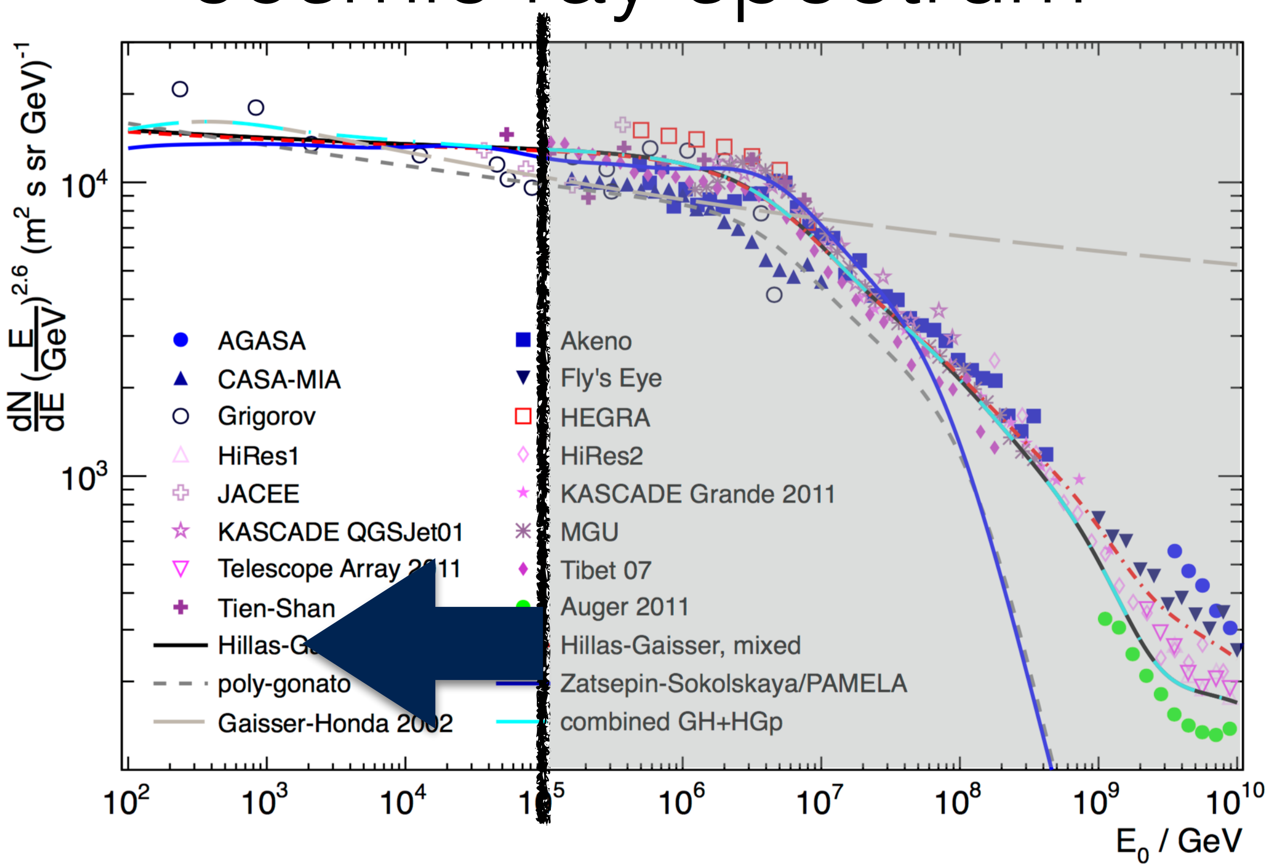

Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes
(on top of atmospheric)
HESE Differential
HESE 2-Component - Soft ($E^{-3.7}$)
HESE 2-Component - Hard ($E^{-2.3}$)
ν_μ Best Fit (prior for "Hard")
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^4
10^5
10^6
10^7
Neutrino Energy [GeV]

Atmospheric flux decomposed



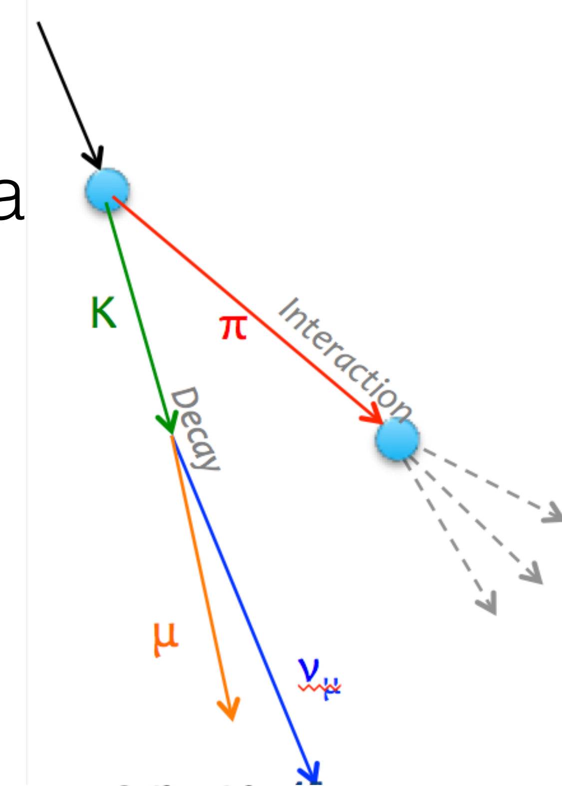
Atmospheric neutrino flux uncertainties

cosmic ray spectrum



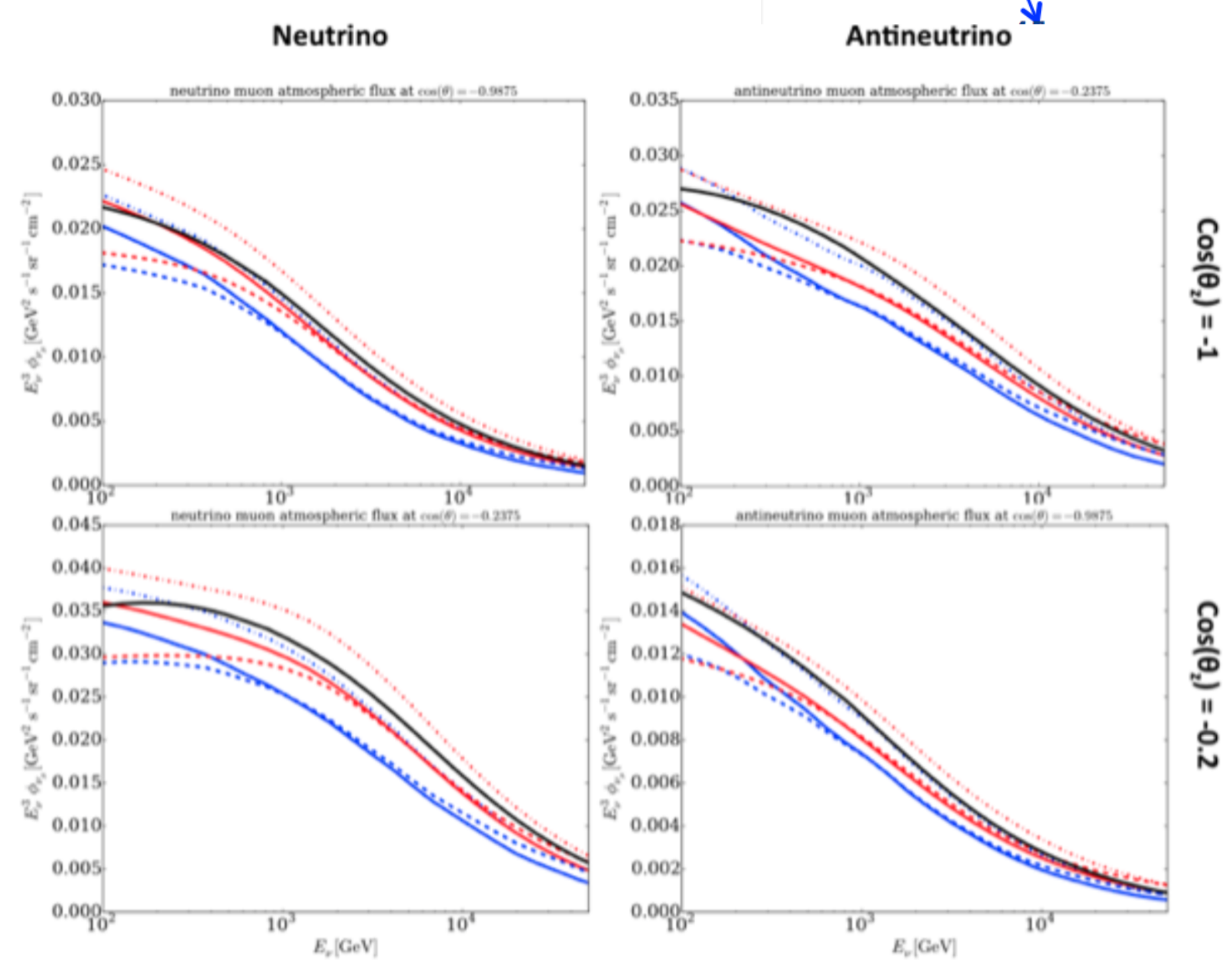
Cosmic ray models:

- Zatsepin-Sokolskaya
- Polygonato
- Gaisser+Honda



Hadronic models:

- Sibyll 2.3
- QGSJET II

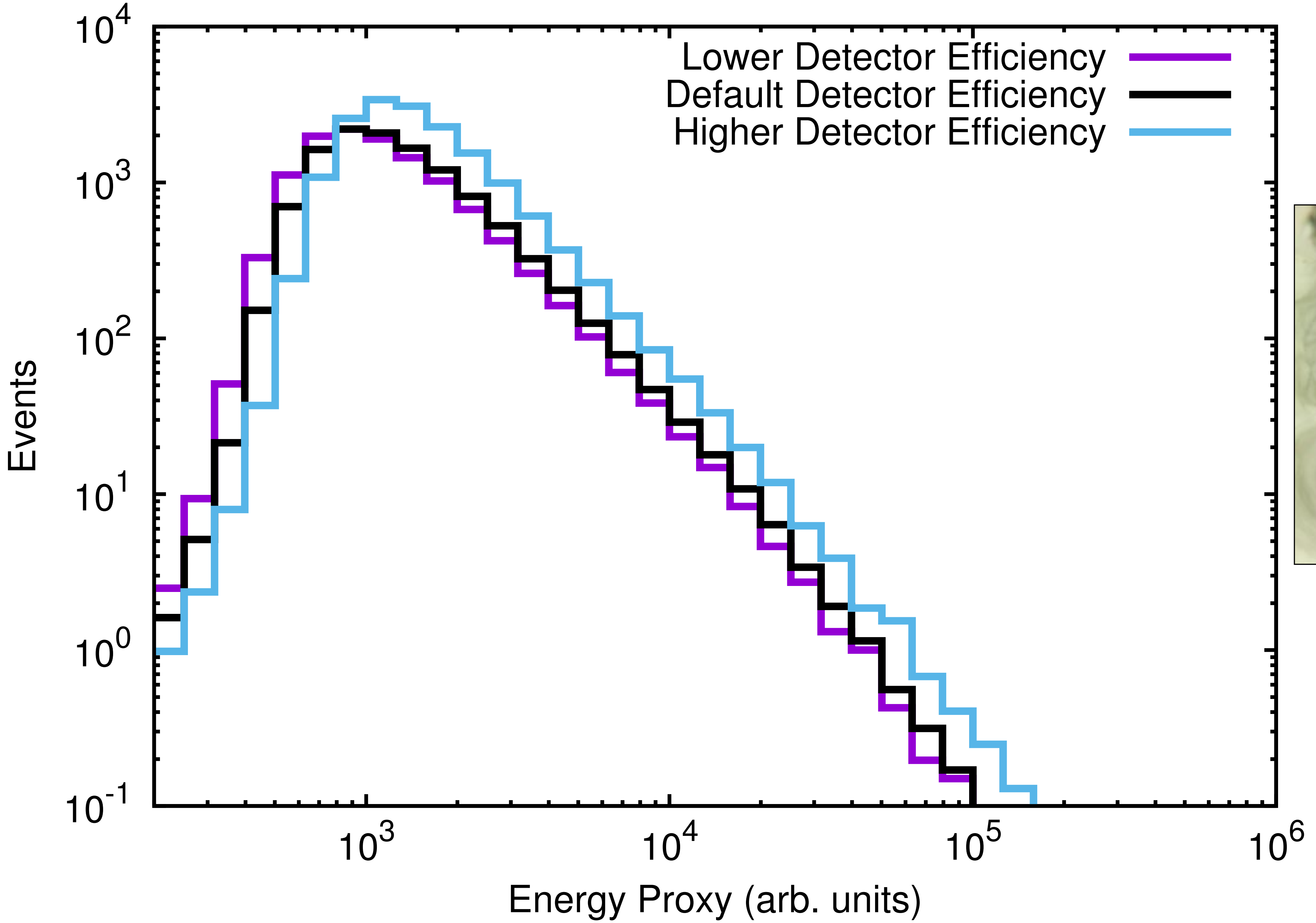


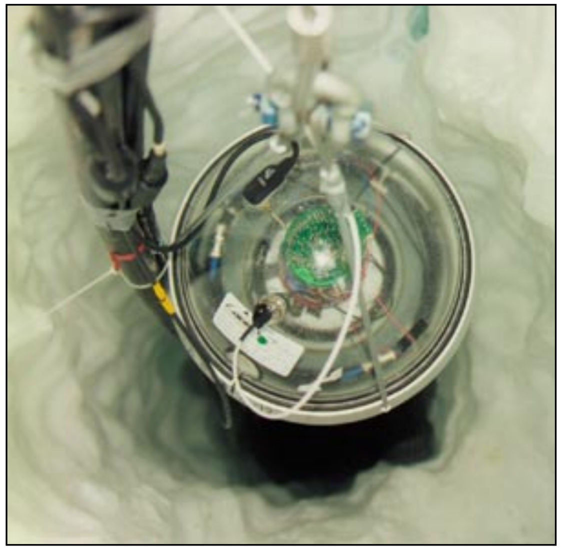
$$\phi_{atm} = N_0 \left(\phi_K + R_{\pi/K} \phi_\pi \right) \times E_\nu^{-\Delta\gamma}$$

[Fedynitch et al. arXiv:1504.06639]
[Collins et al. URL: http://dspace.mit.edu/handle/1721.1/98078]

Detector Systematics: DOM efficiency!

Effect of changing the DOM efficiency in the parameter space:

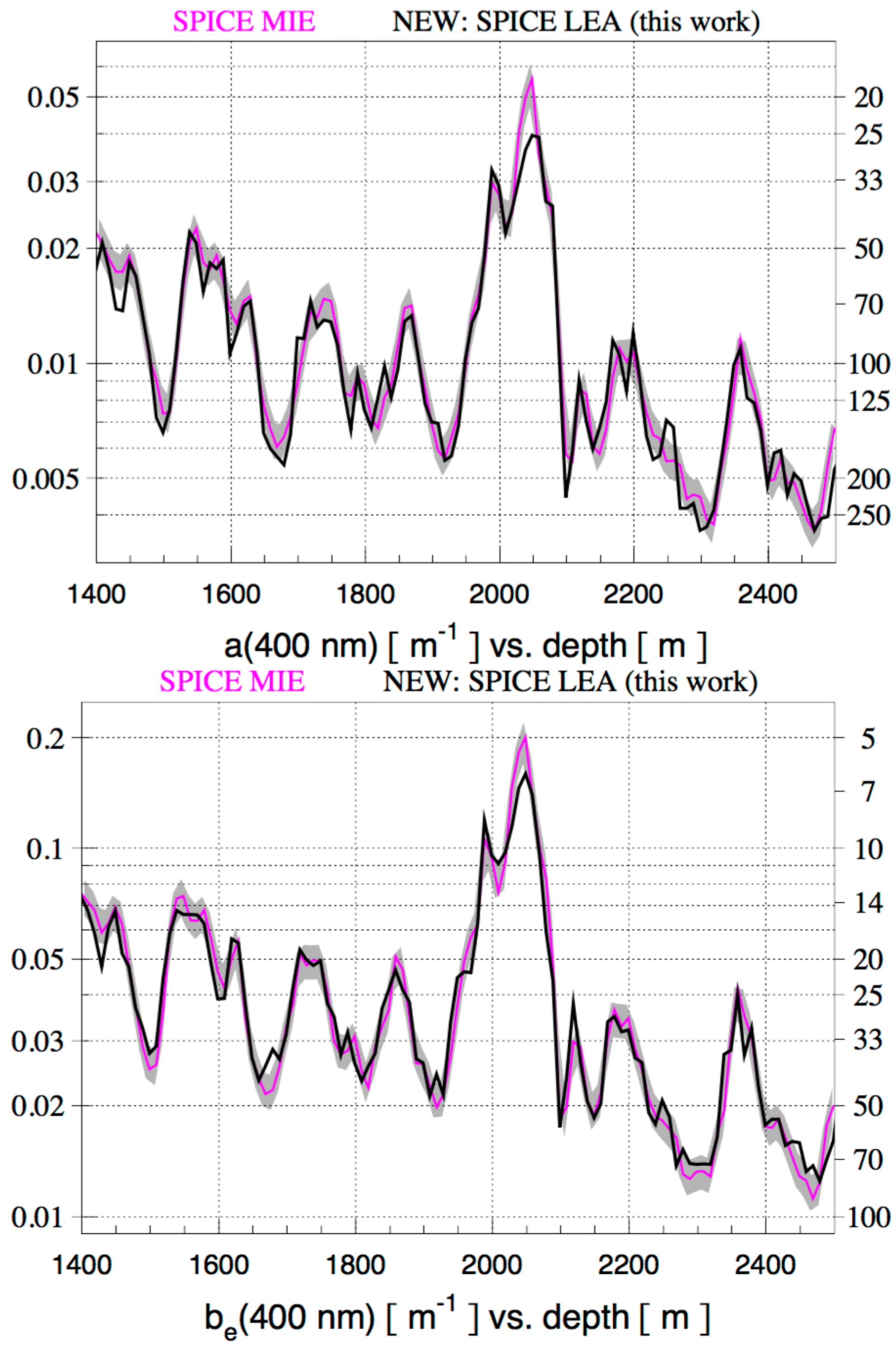


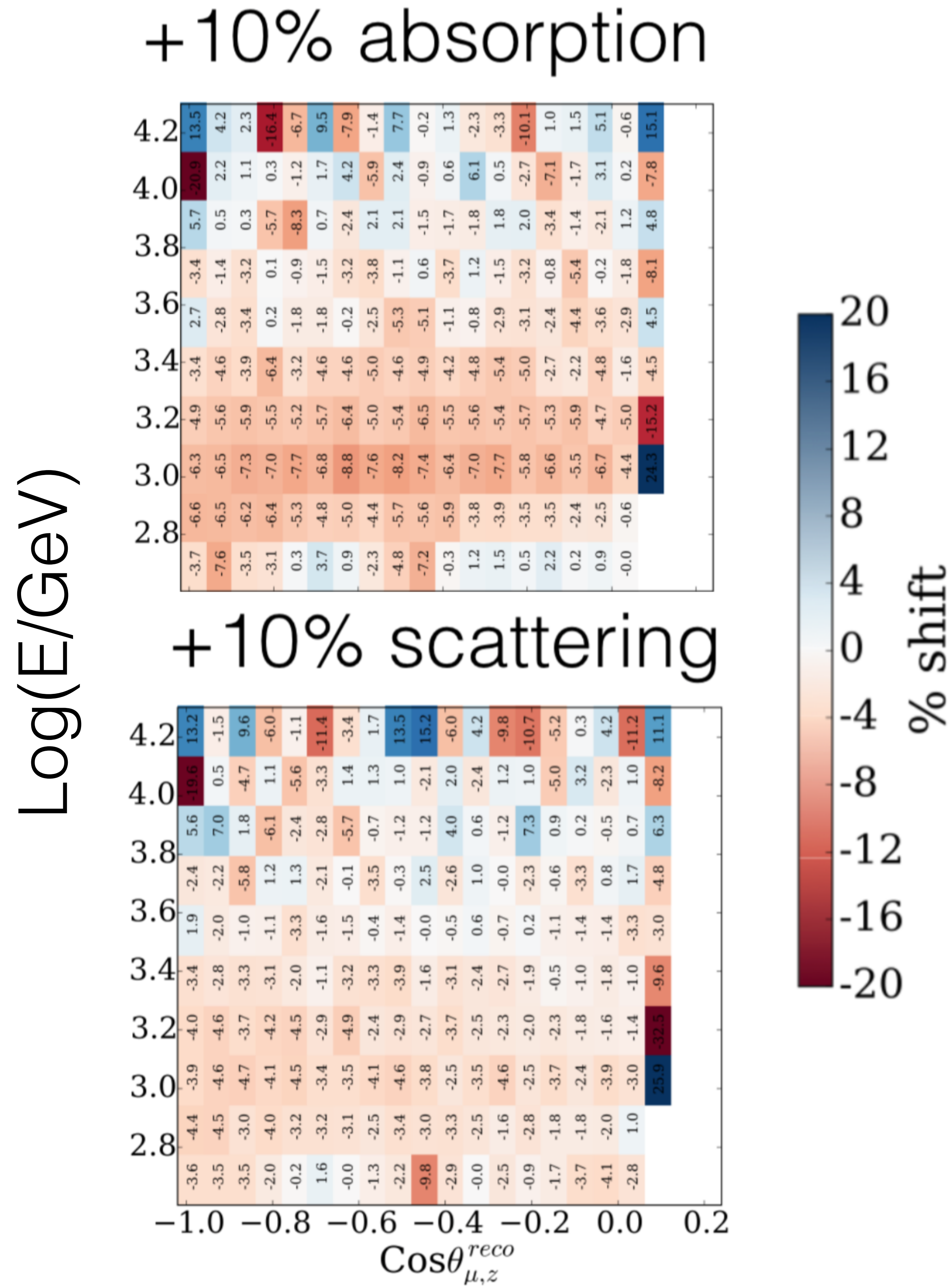


Efficiency of the DOM is imprecisely know. We apply corrections due to ice and cable shadow.

Ice uncertainties

Fit for ice properties as a function of depth.





Hole Ice

Refrozen ice in the hole have **air bubbles** that produce **extra scattering**.