ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

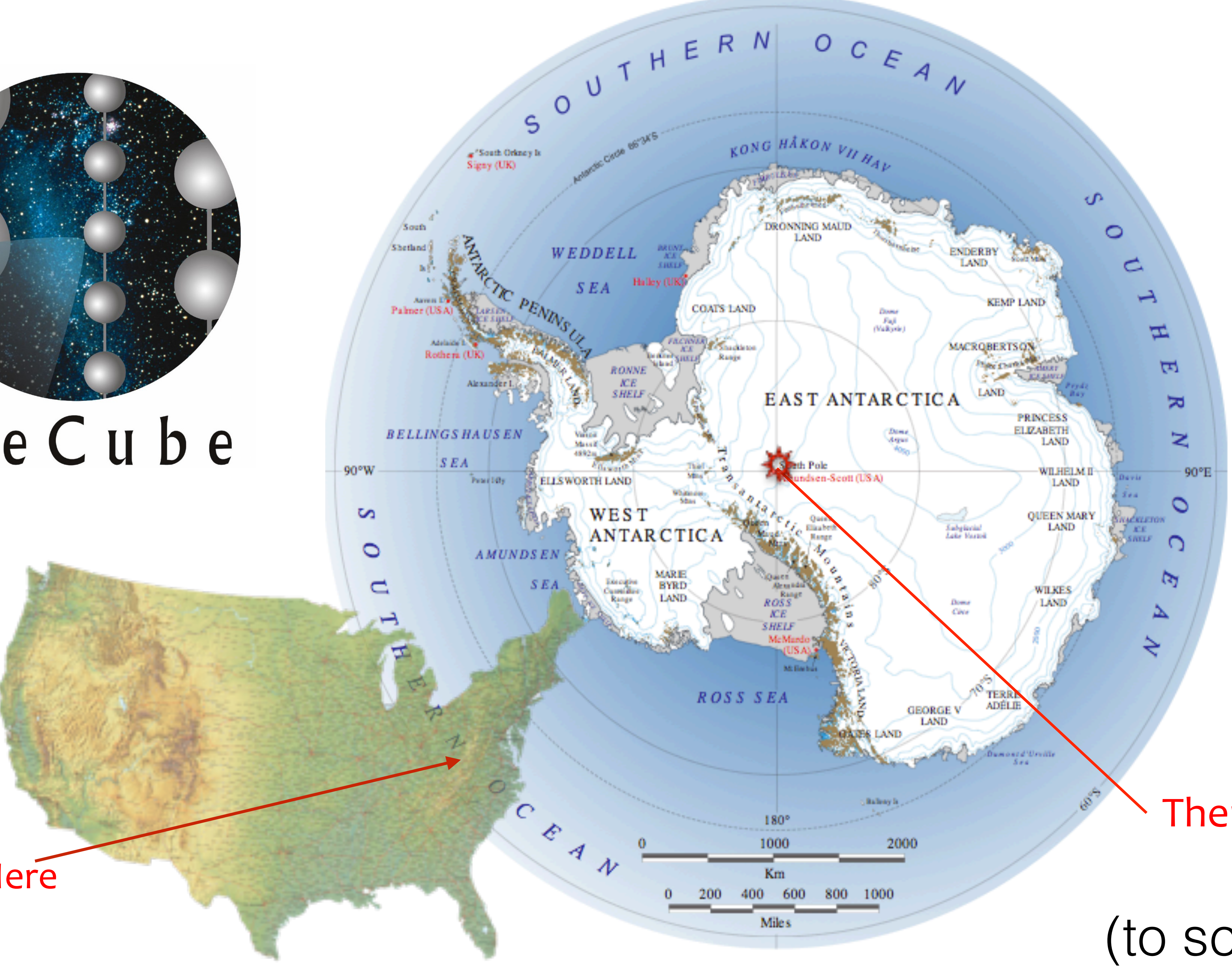
Recent particle physics results from IceCube

Carlos Argüelles

nuFACT
Virginia Tech, 2018

Massachusetts
Institute of
Technology

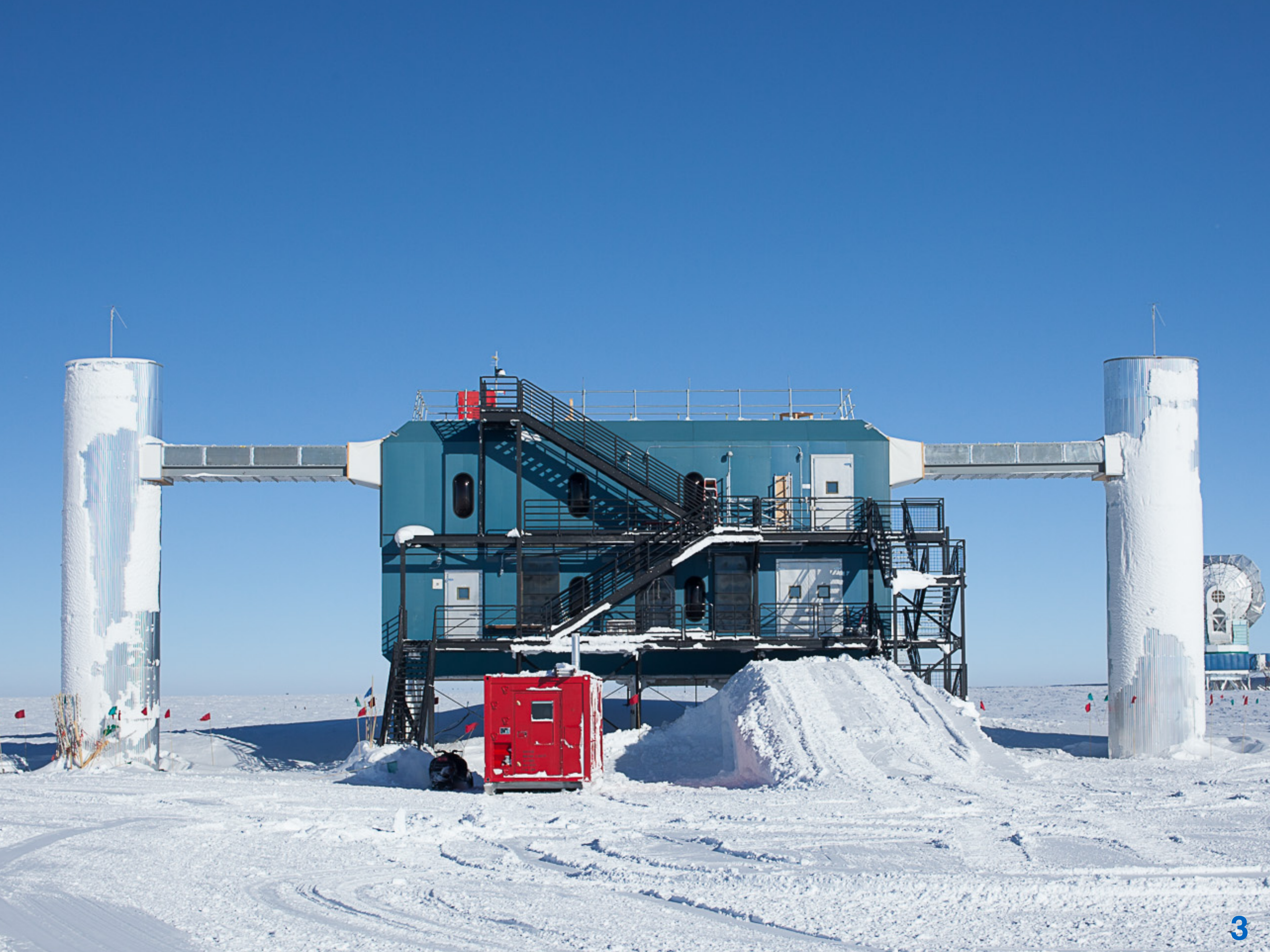
The IceCube experiment



There

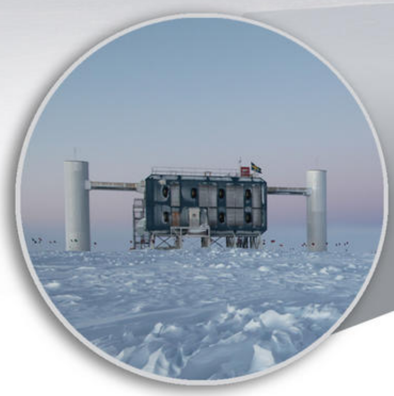
Here

(to scale)



ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

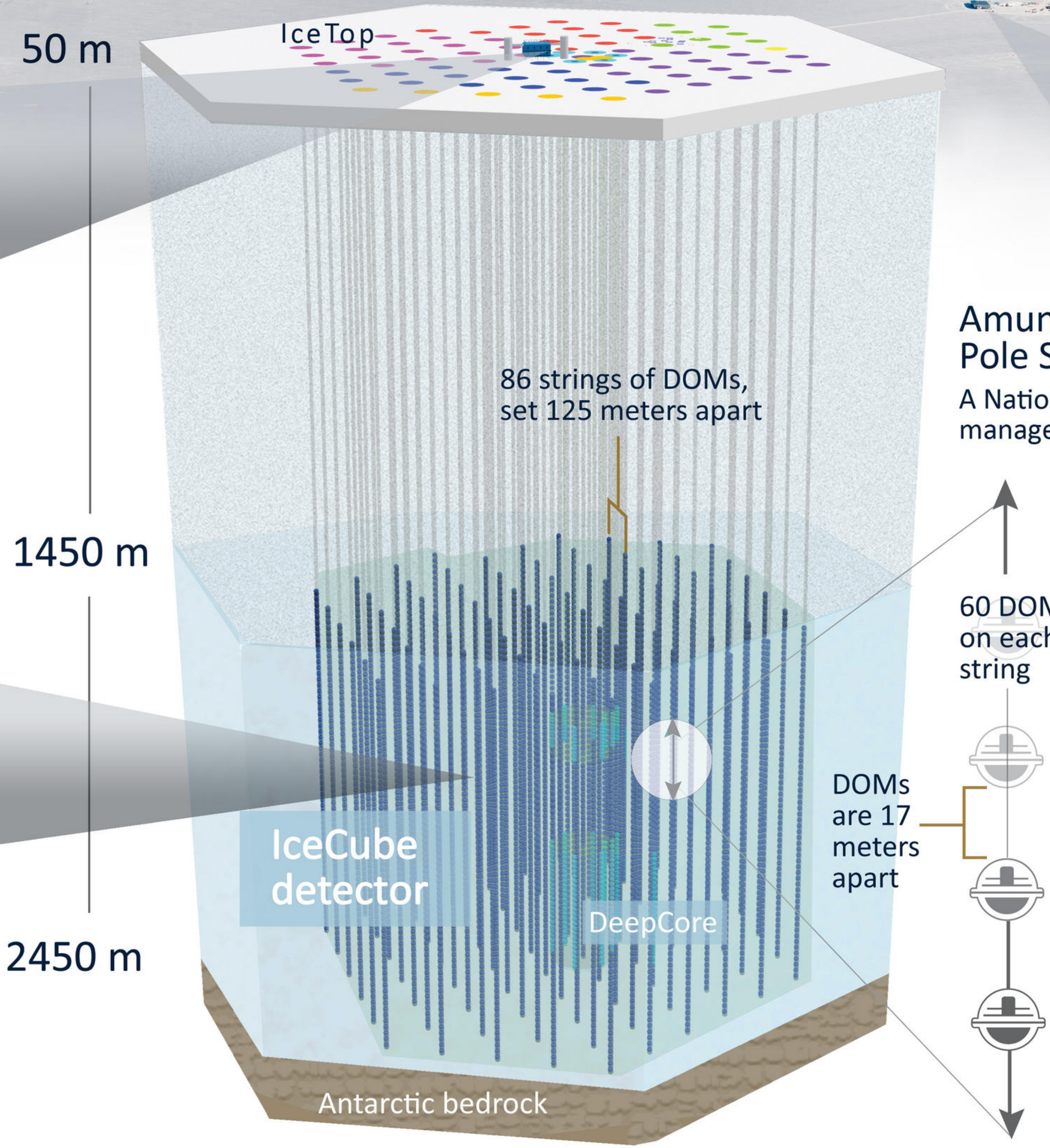


IceCube Laboratory

Data is collected here and
sent by satellite to the data
warehouse at UW–Madison

Digital Optical Module (DOM)

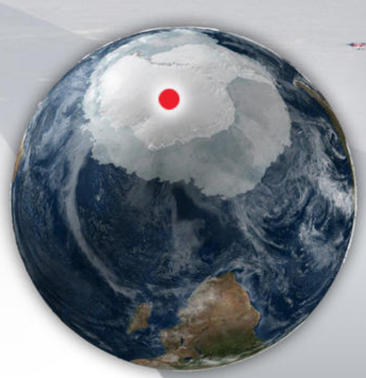
5,160 DOMs
deployed in the ice



86 strings of DOMs,
set 125 meters apart

60 DOMs
on each
string

DOMs
are 17
meters
apart

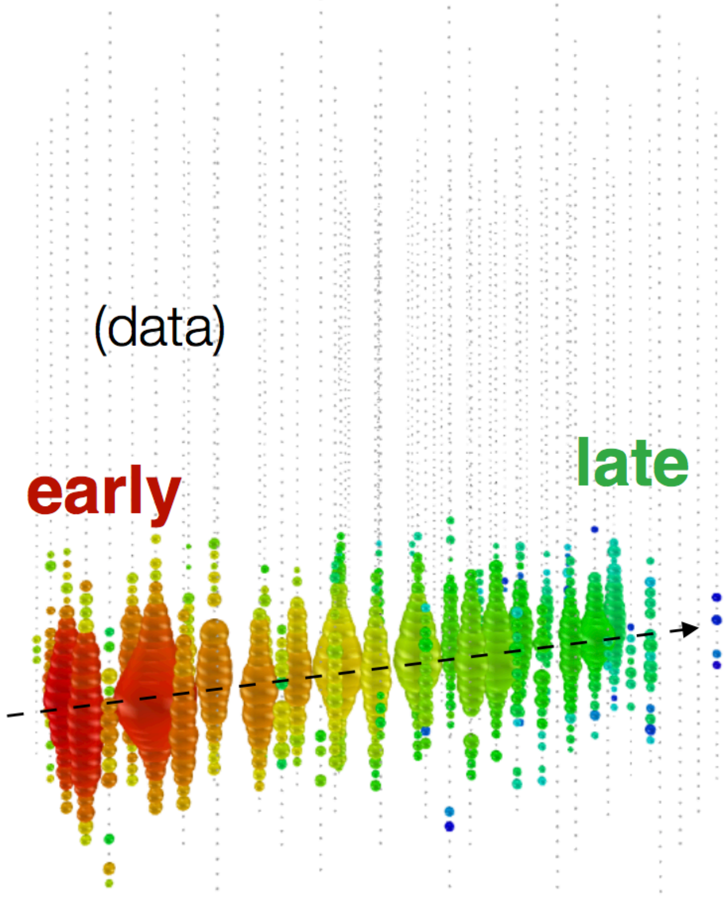


Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-
managed research facility

Event topologies

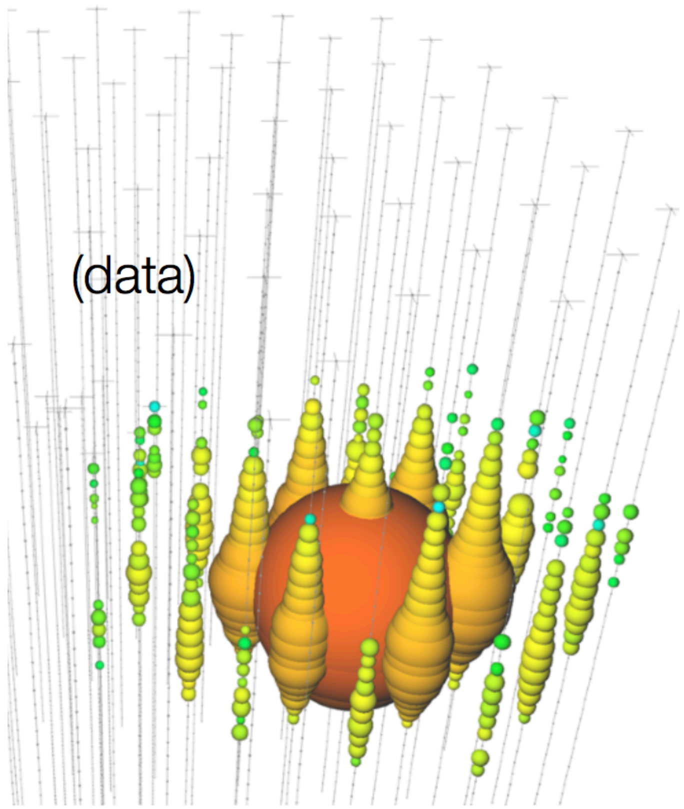
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

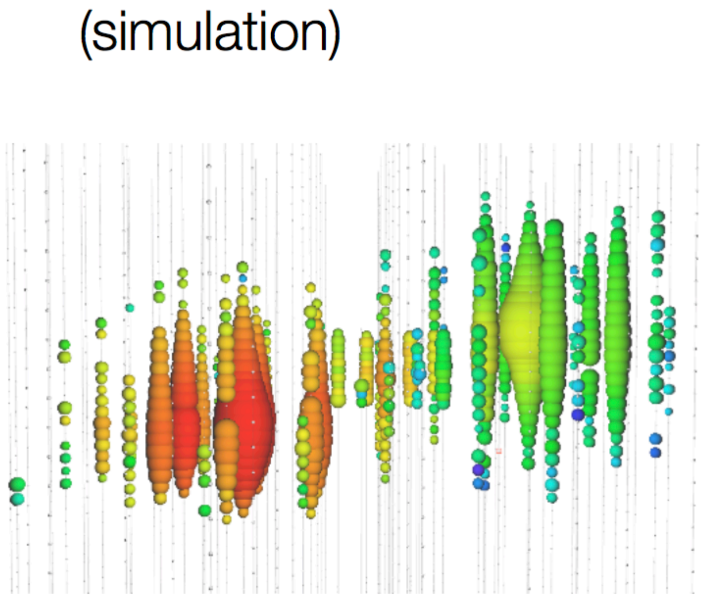
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

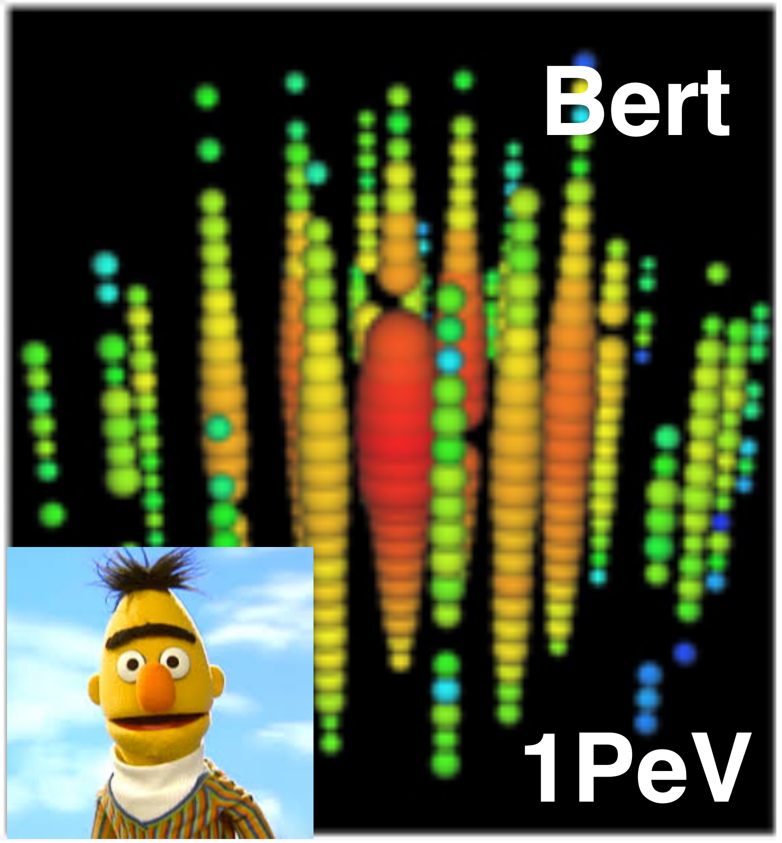


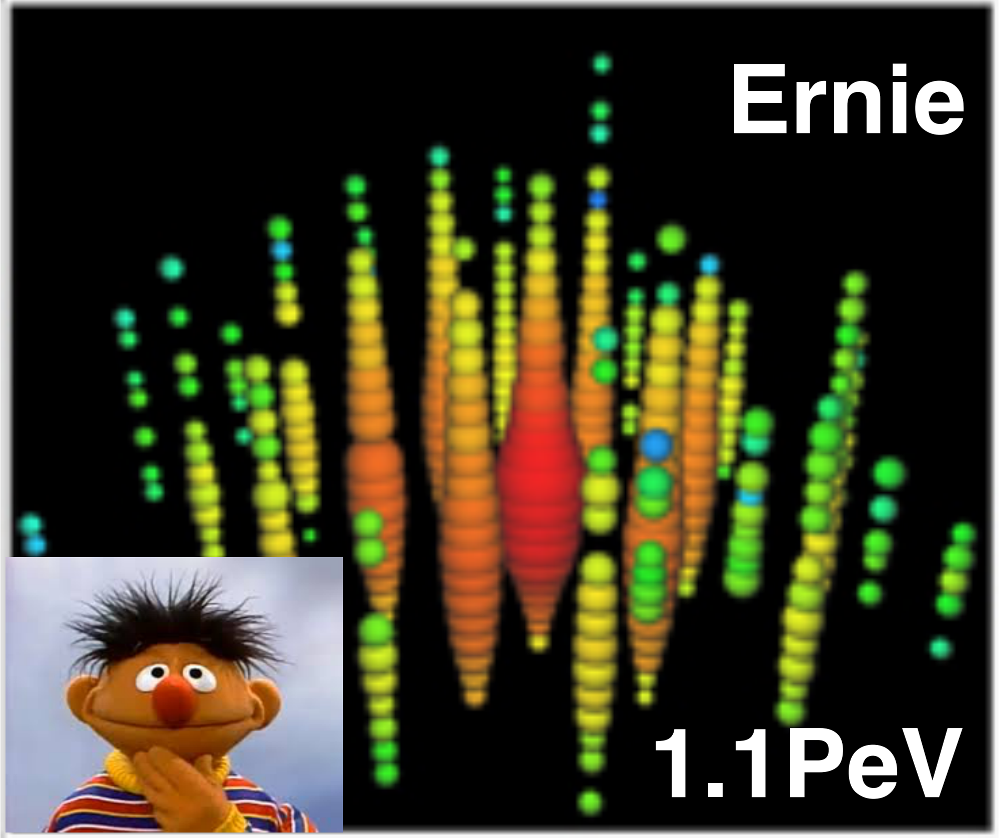
Double cascade

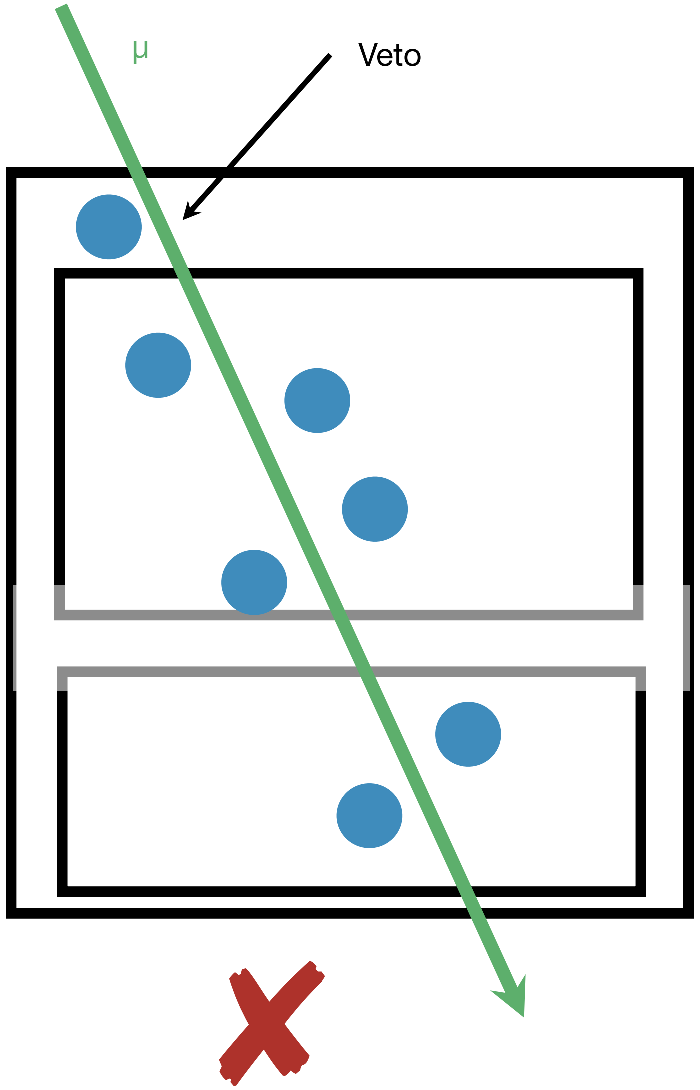
(resolvable above ~100 TeV deposited energy)

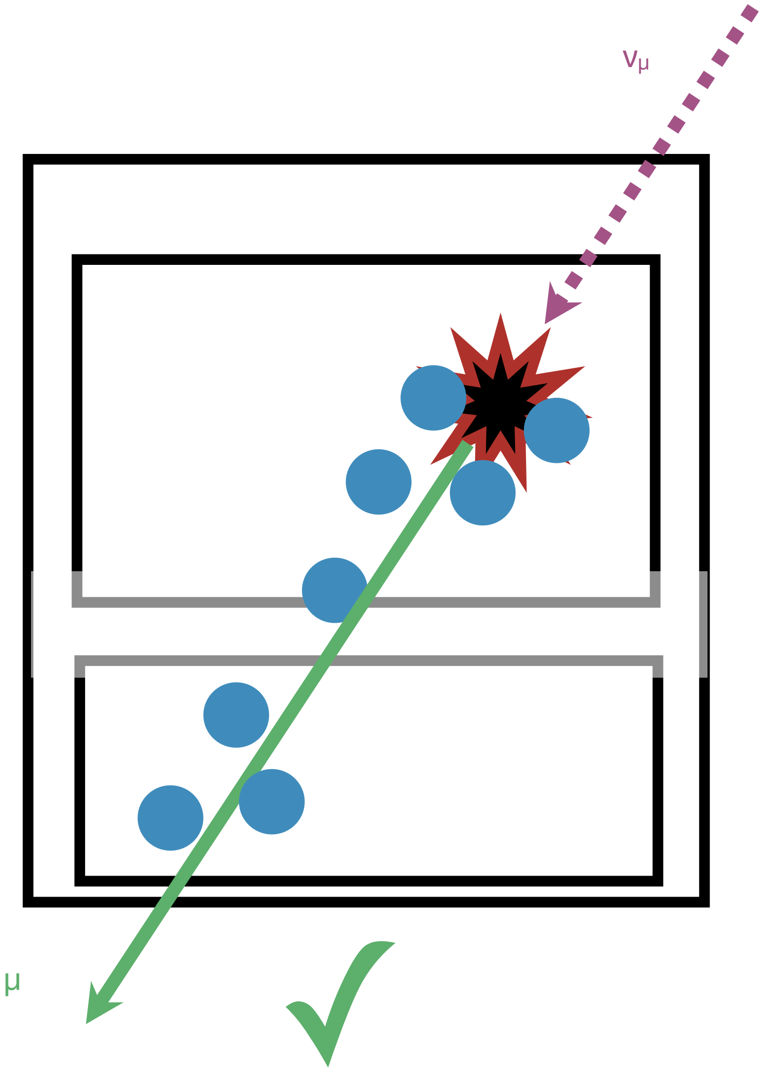
Astrophysical neutrinos

High-Energy Starting Events





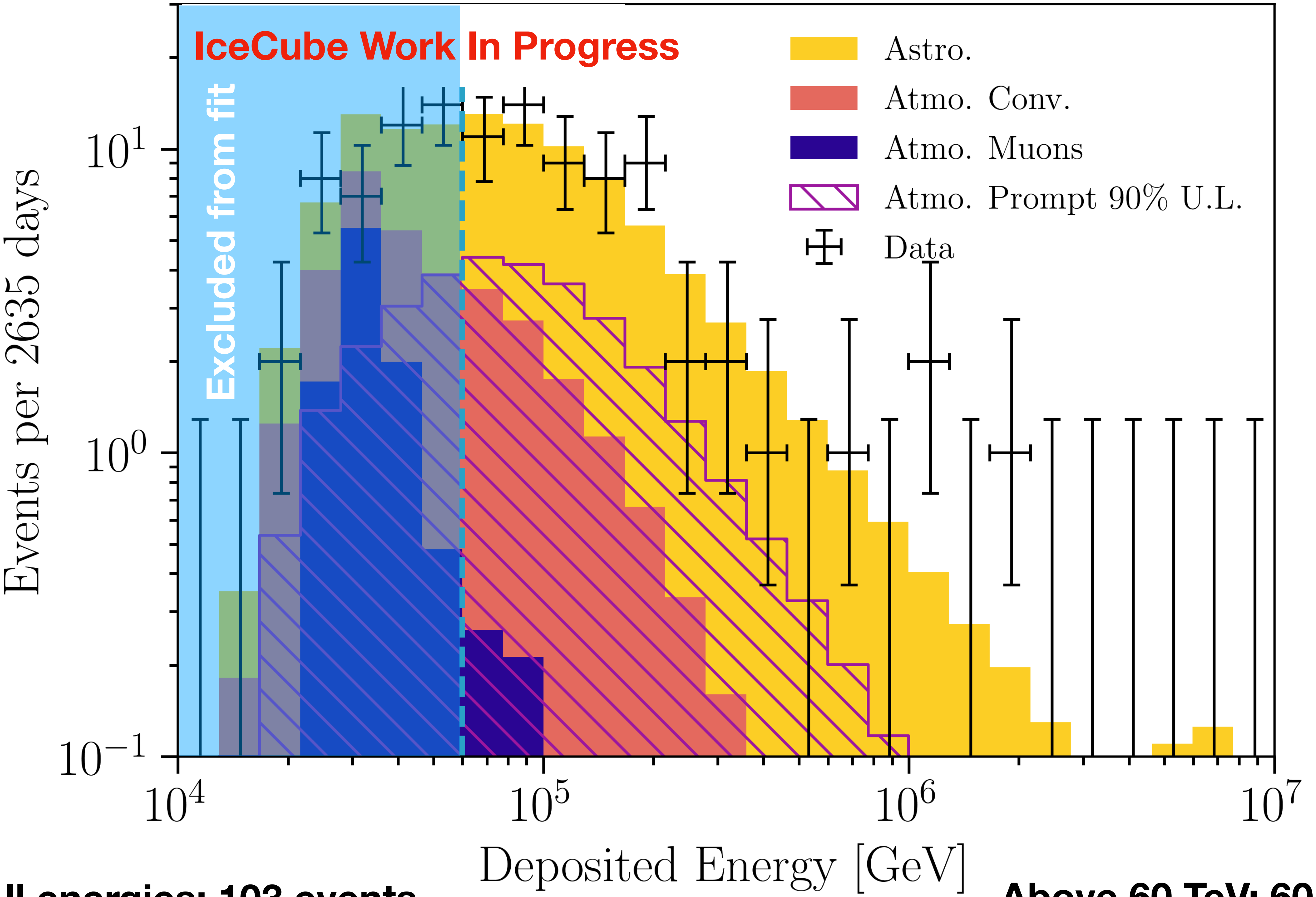




IceCube first PeV astrophysical neutrinos

New **7.5 years high-energy starting events data!**

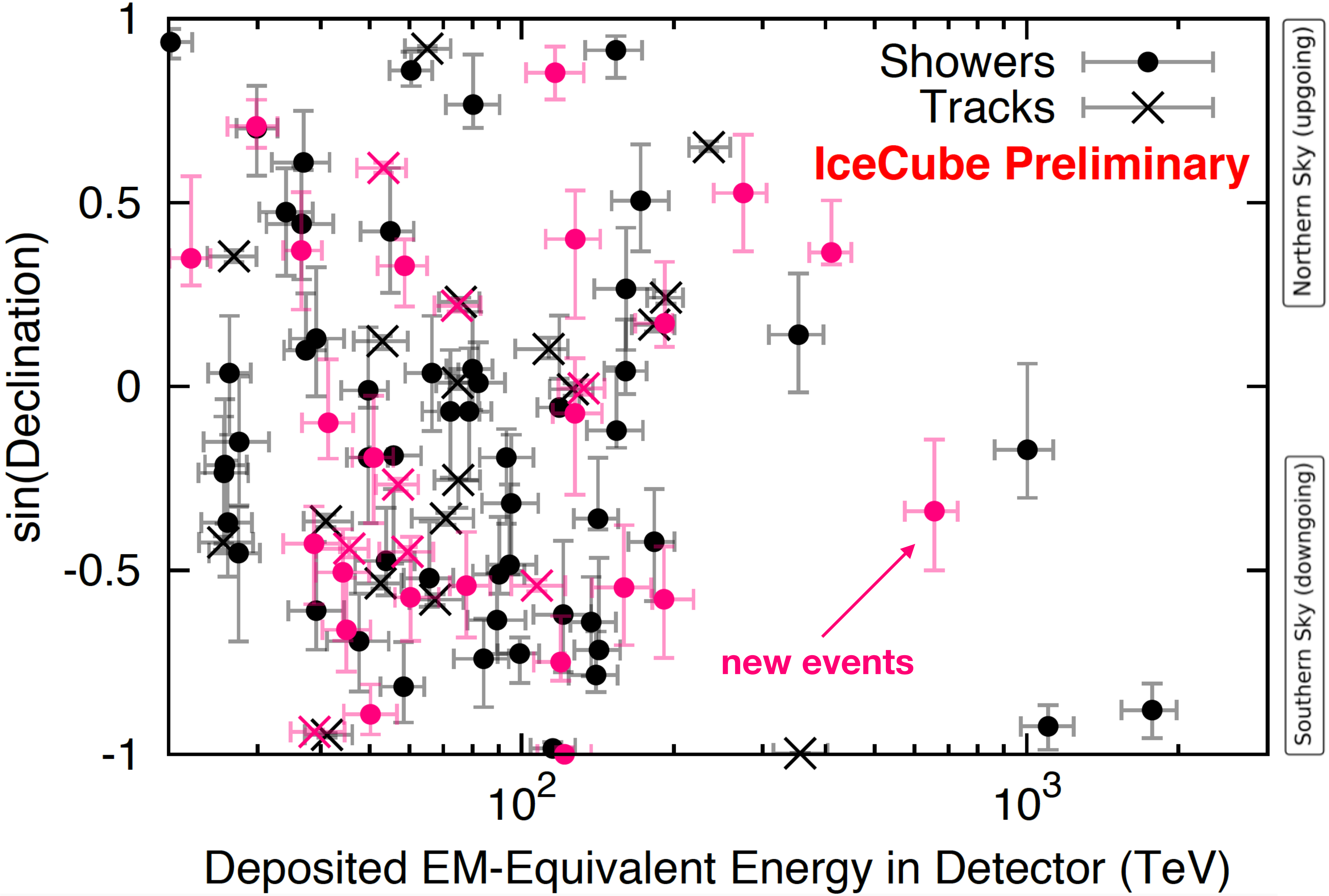
***HESE = high-energy starting events**



All energies: 103 events
22 new events in 2016
9 new events in 2017

Above 60 TeV: 60 events
12 new events in 2016
4 new events in 2017

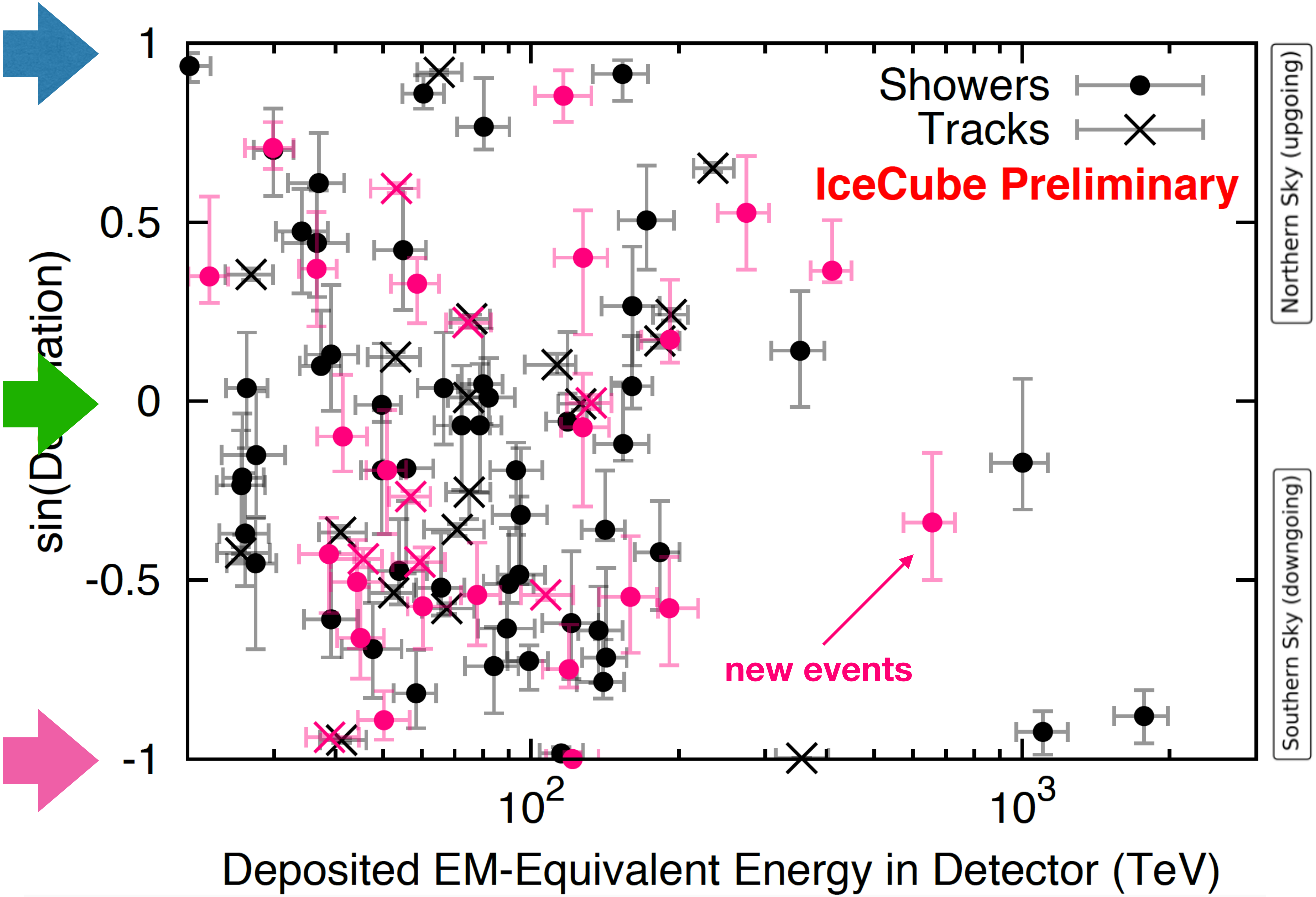
New **HESE-7.5 years distribution**



***HESE = high-energy starting events**

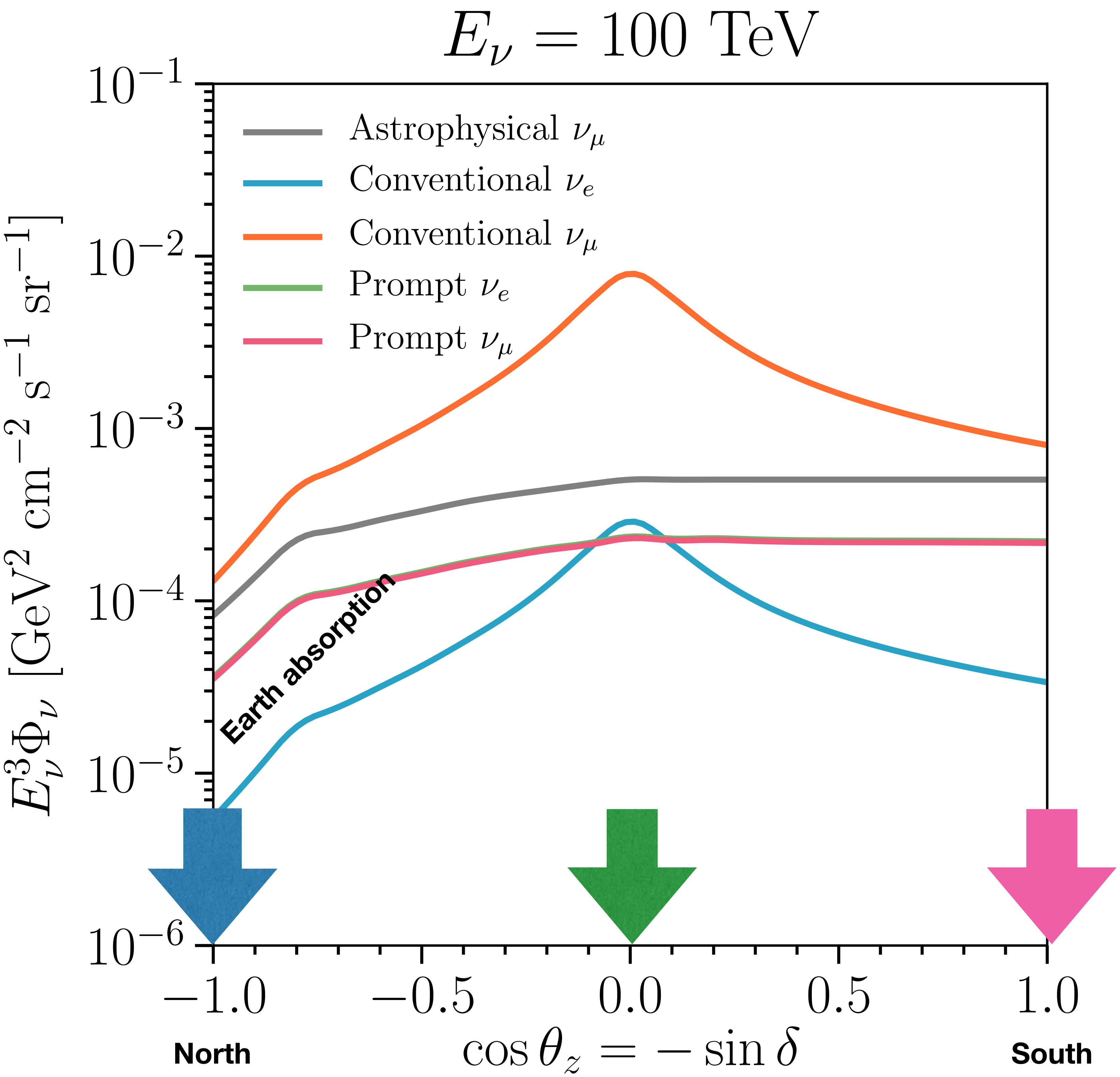
New **HESE-7.5 years distribution**

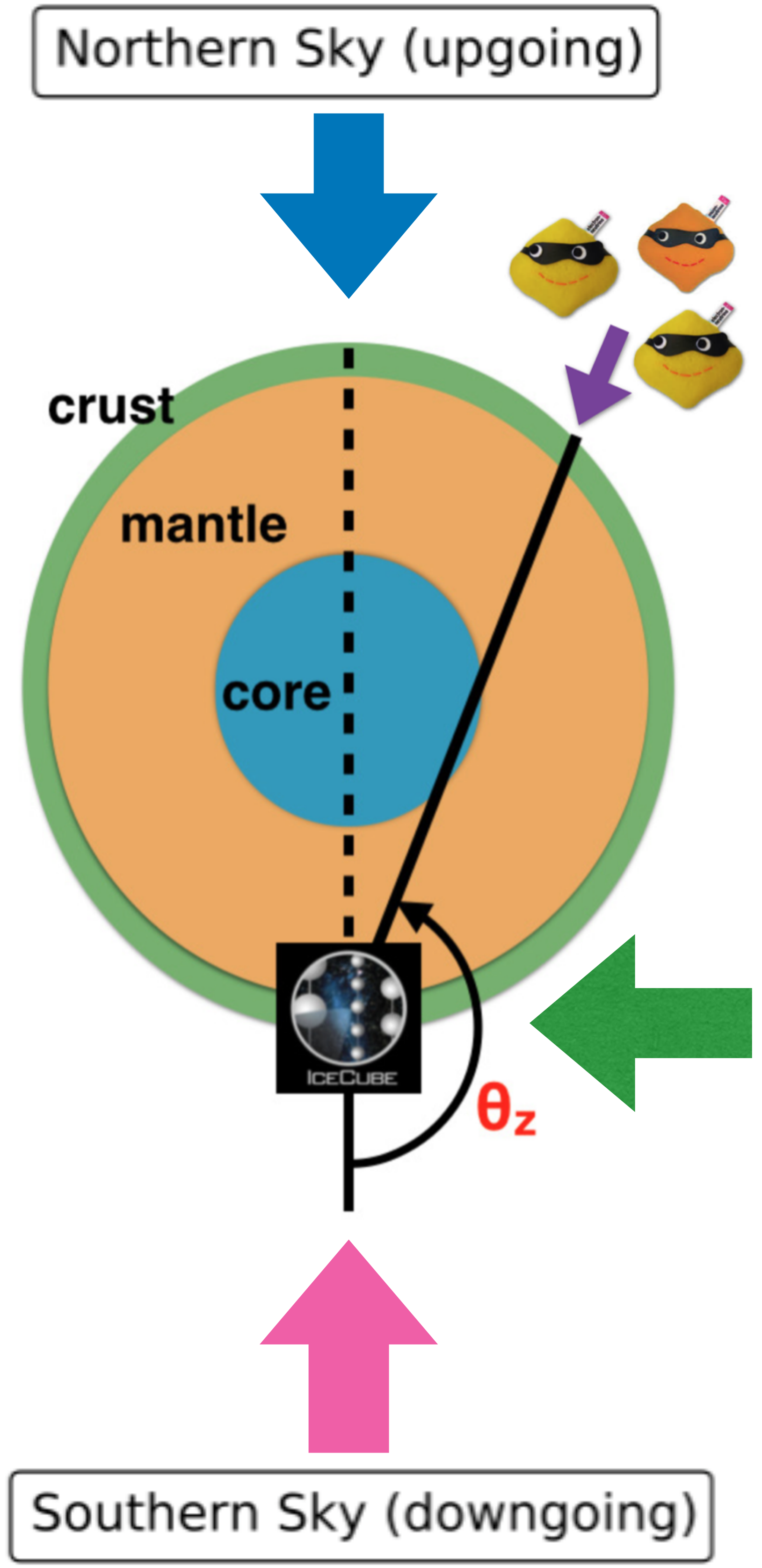
Let's examine the angular distribution



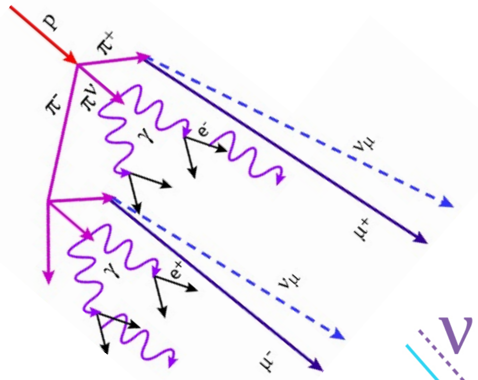
***HESE = high-energy starting events**

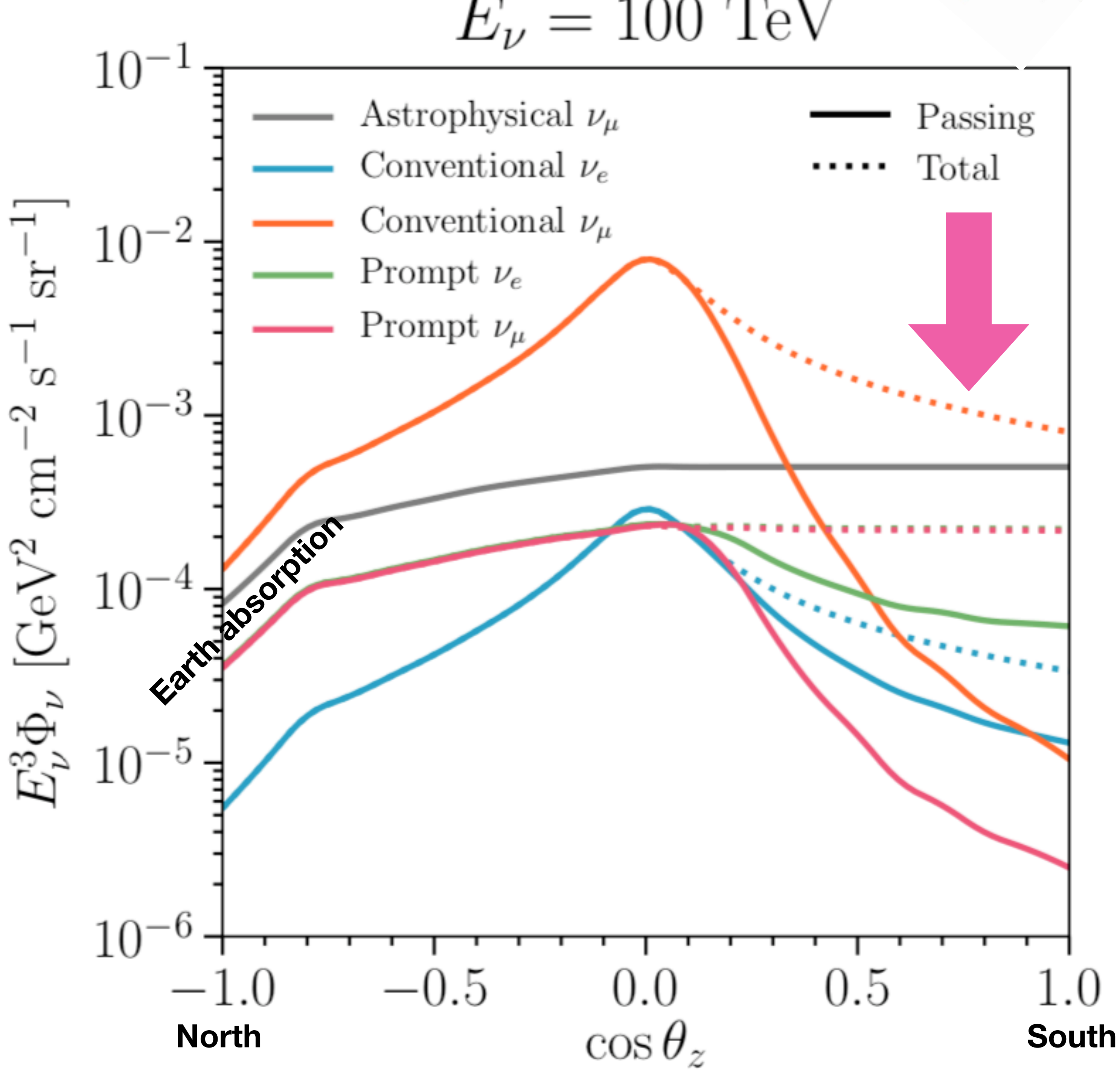
Expected angular distributions

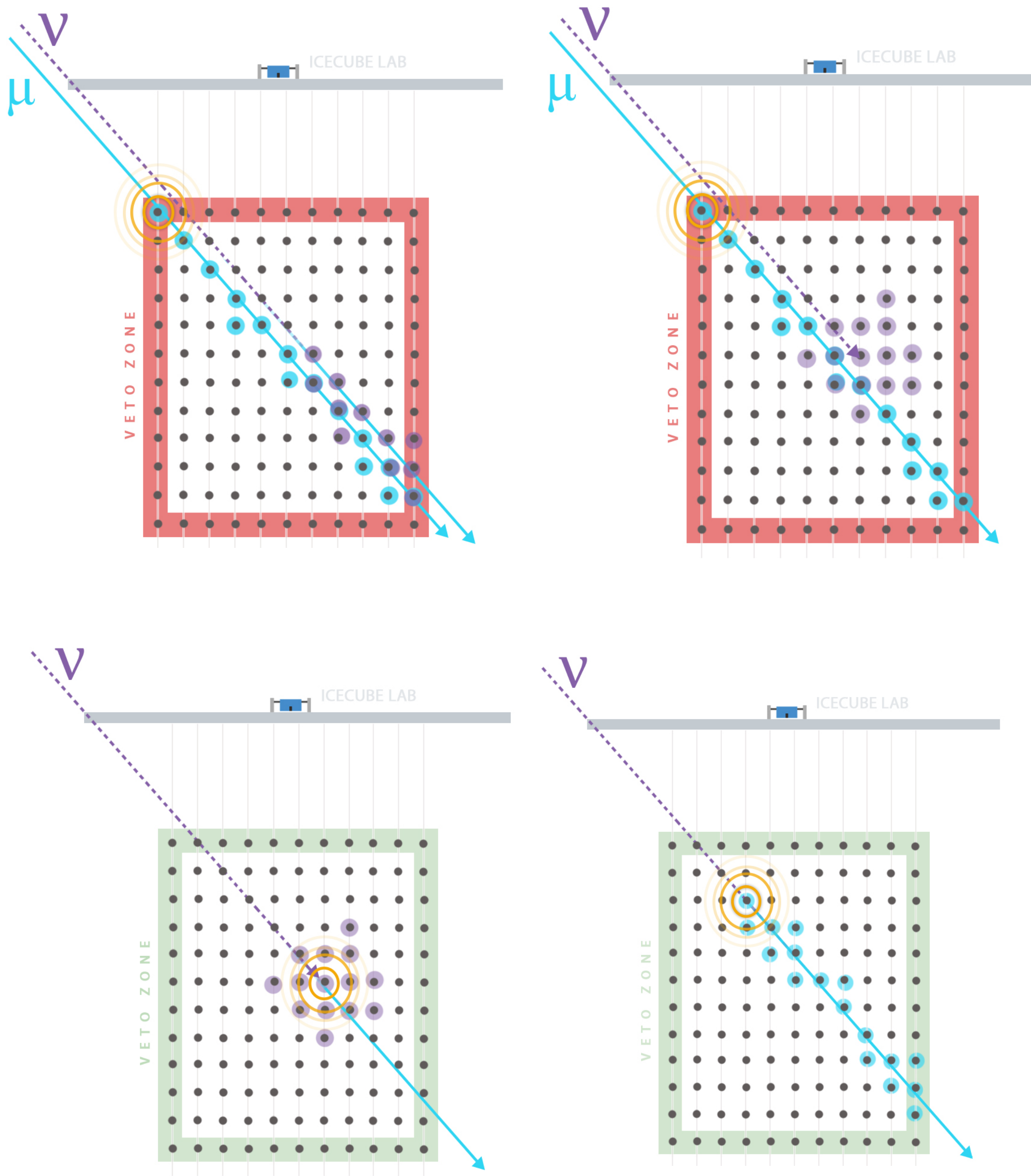




Atmospheric neutrinos with accompanying muons are suppressed

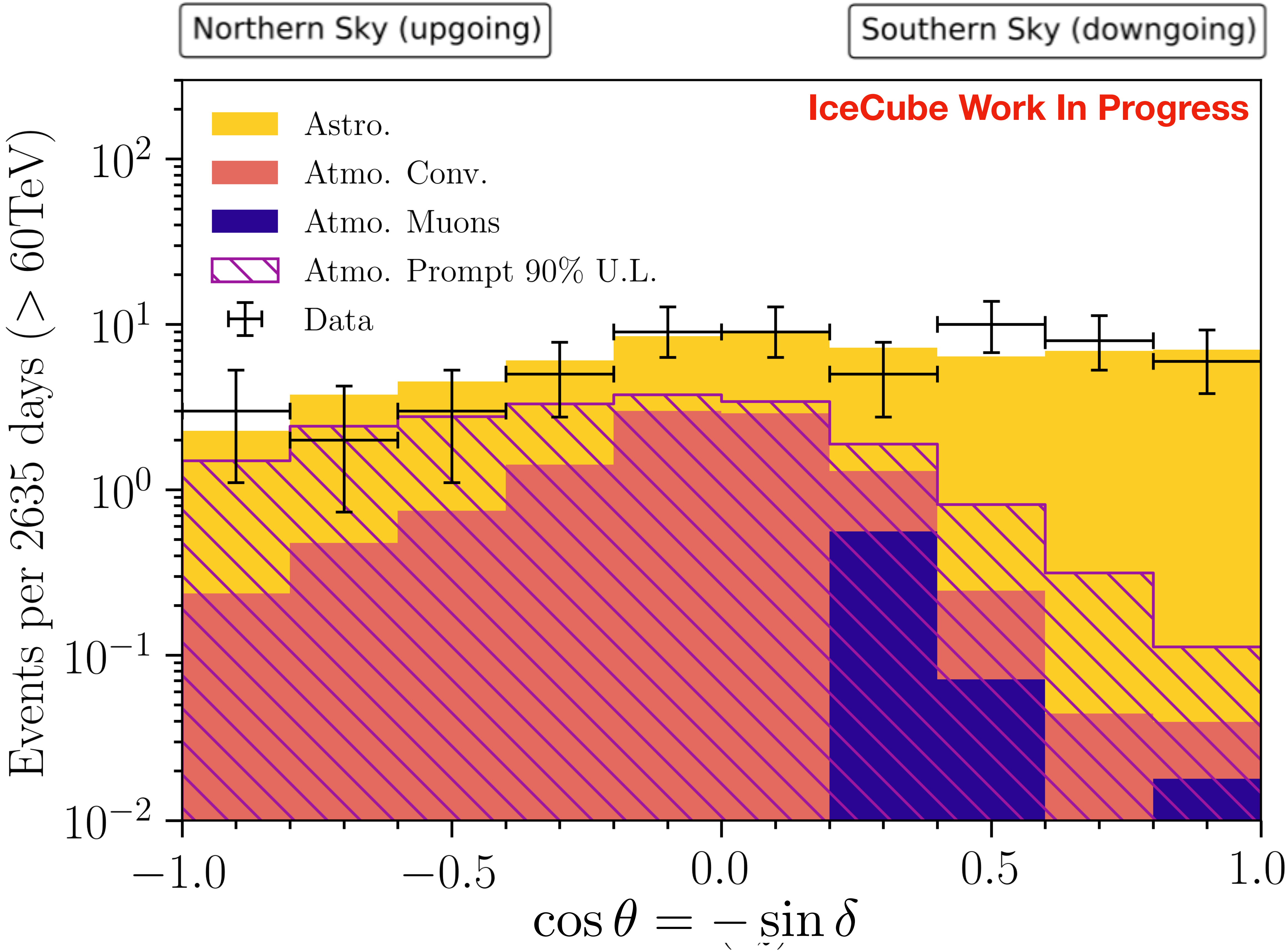






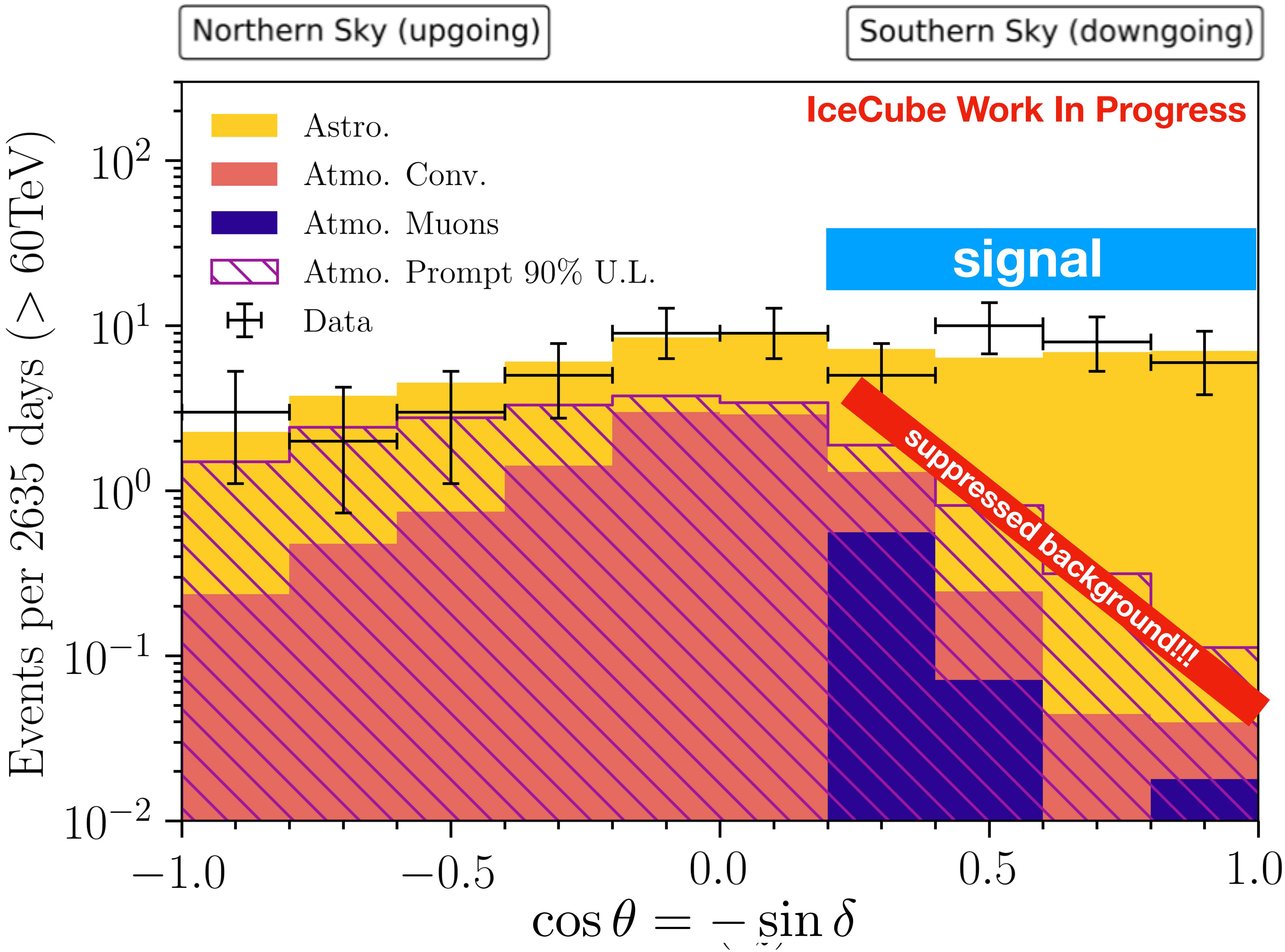
Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
CA., Palomares-Ruiz, Schneider, Wille, Yuan
JCAP 1807 (2018) no.07, 047

New **7.5 years high-energy starting events data!**



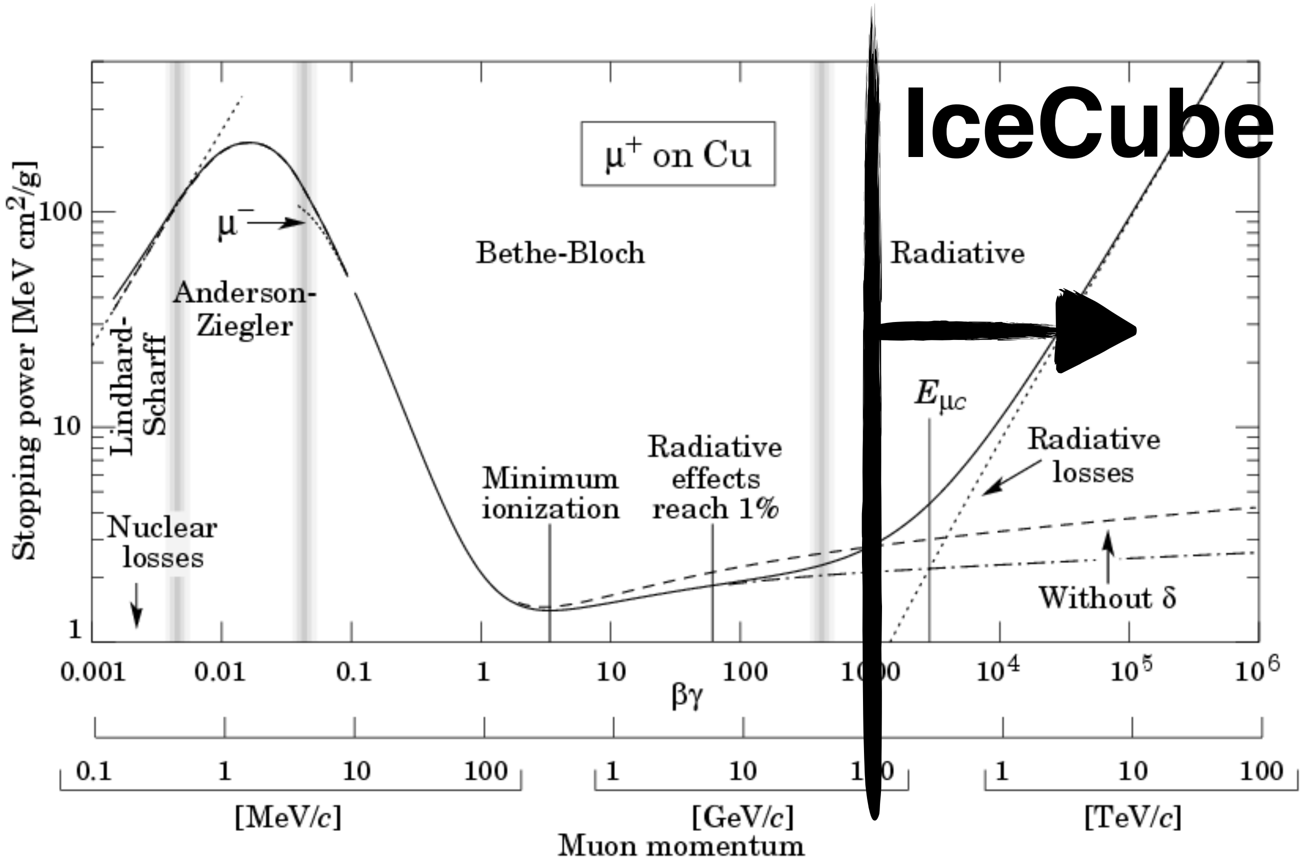
***HESE = high-energy starting events**

New **7.5 years high-energy starting events data!**

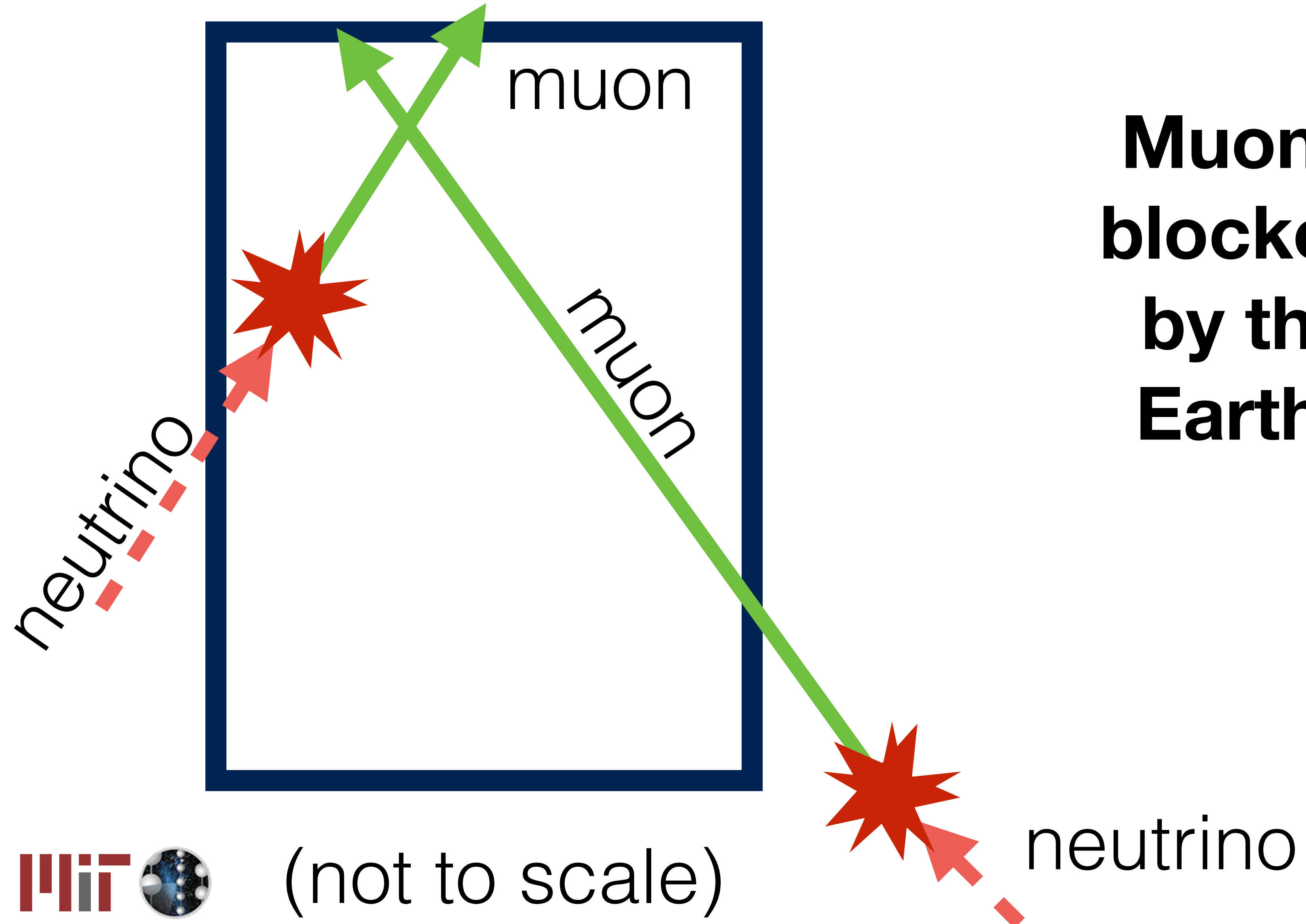


***HESE = high-energy starting events**

Through-going muons in IceCube

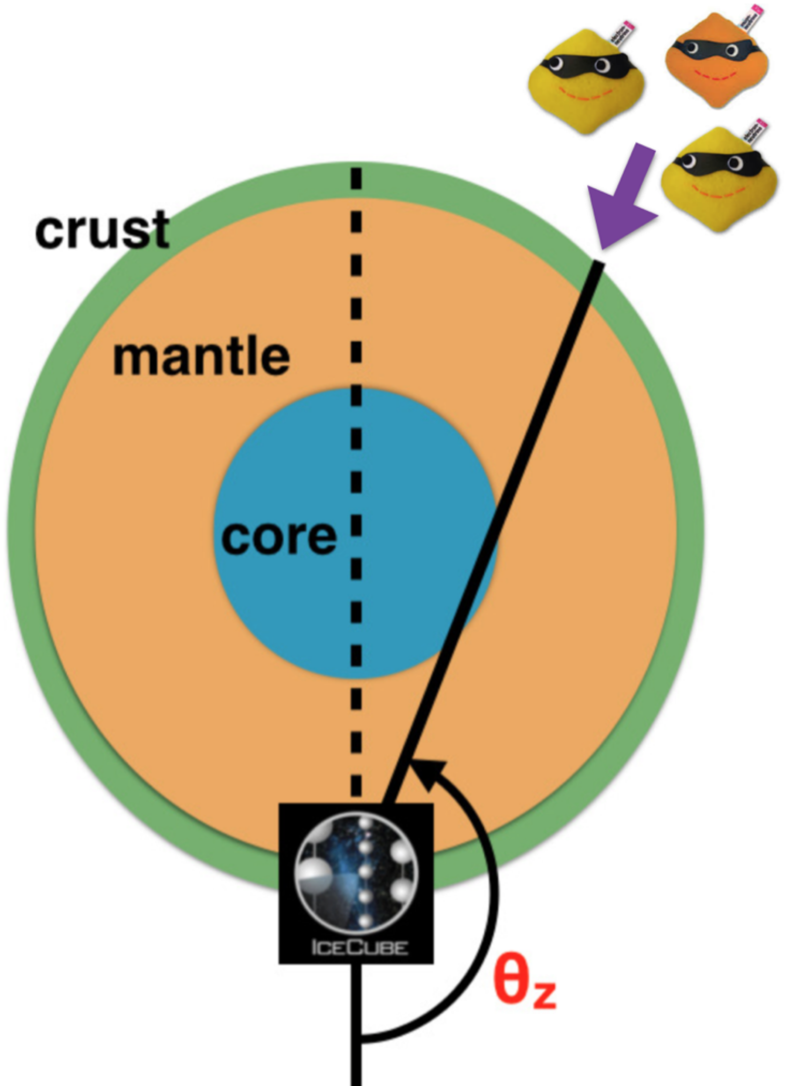


$$\Delta\theta \sim 1^o$$



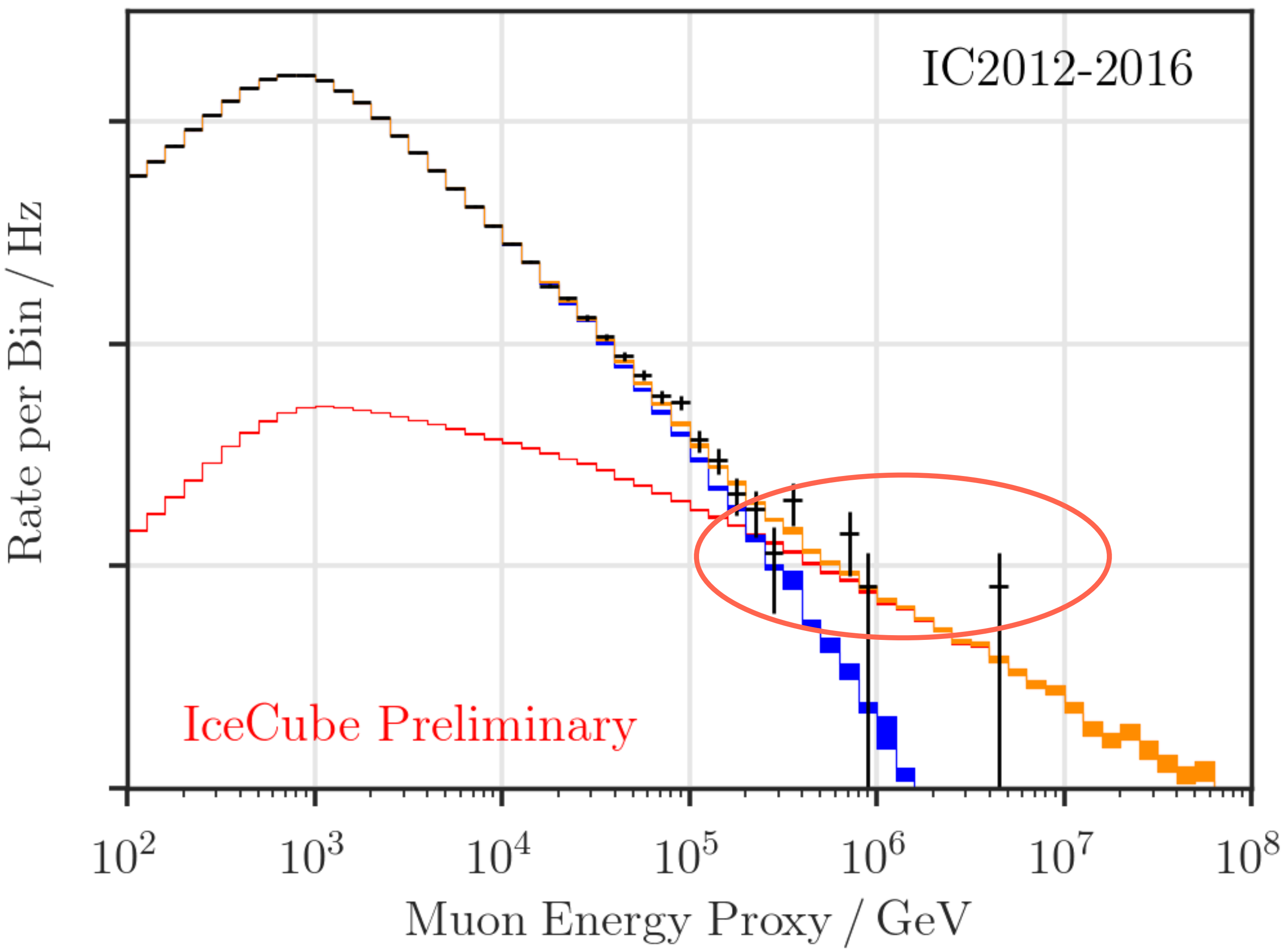
(not to scale)

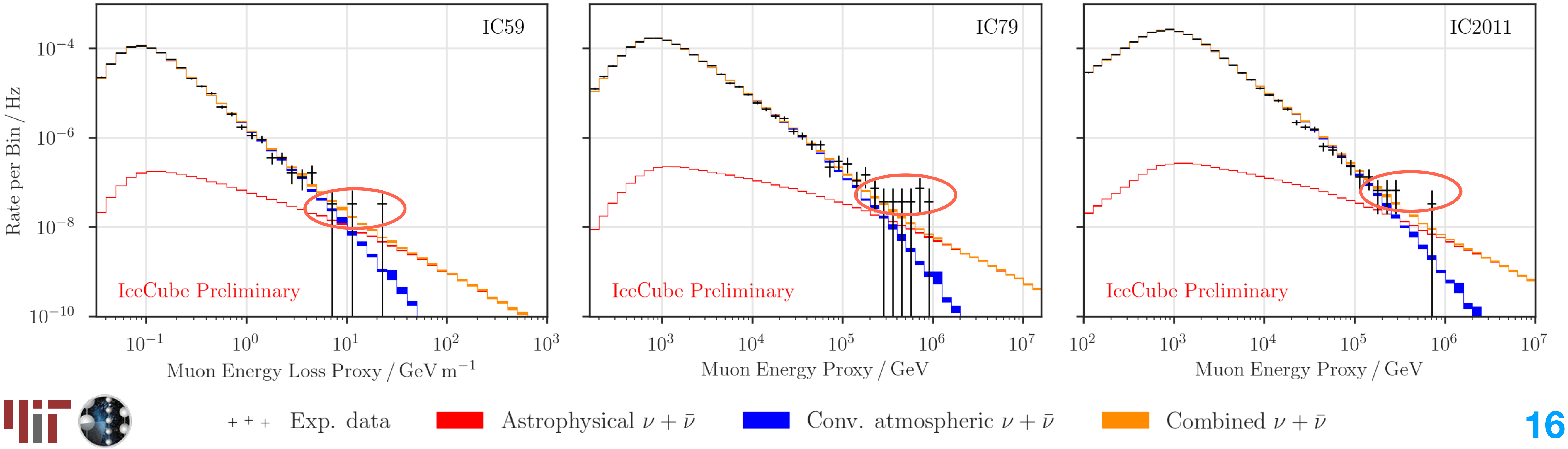
Muons blocked by the Earth!



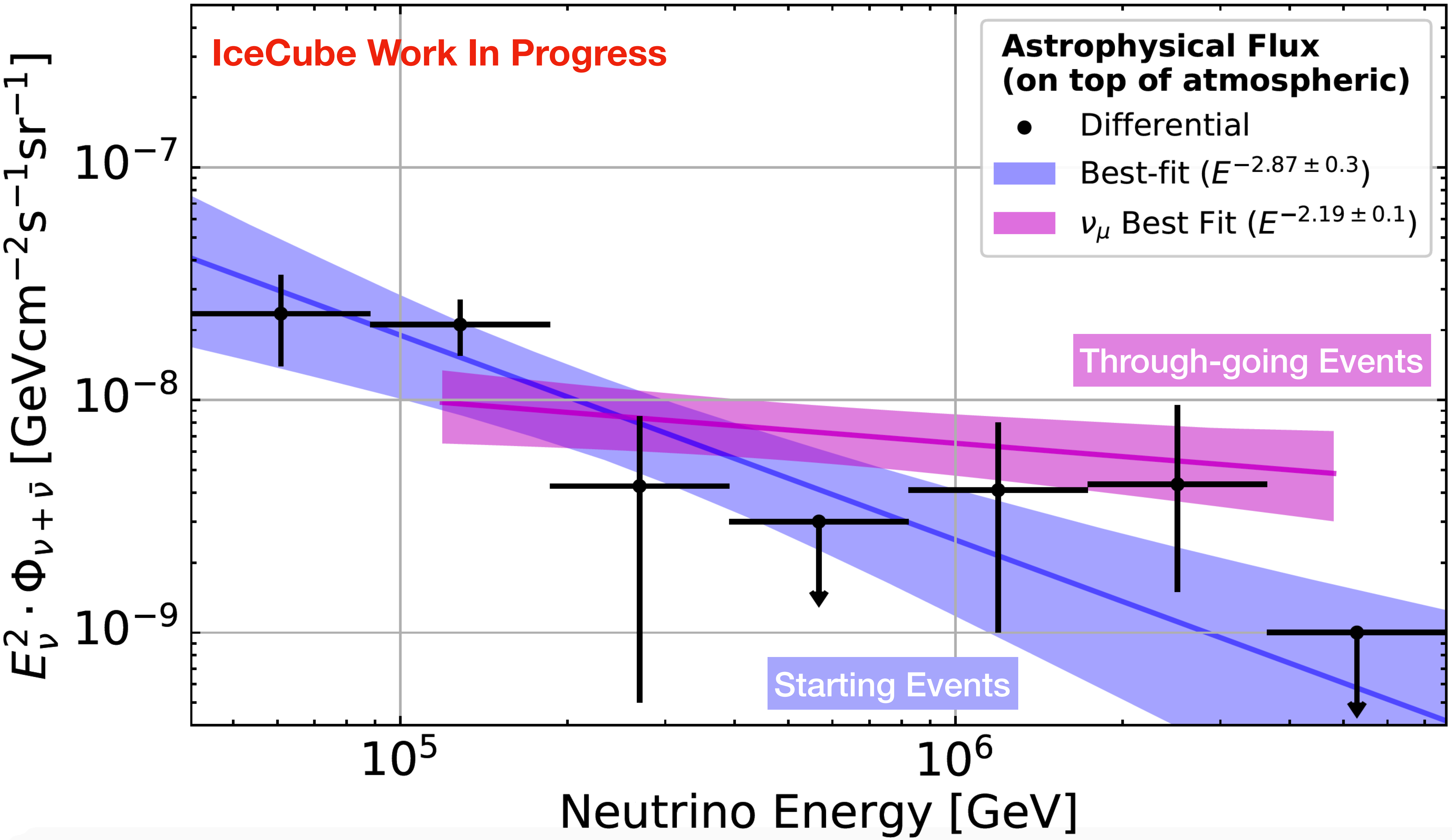
8 years through-going muon neutrinos!

- Eight years of through-going ν_μ data analyzed.
- Astrophysical component sticks out over the conventional background every year.
- Consistent hard astrophysical spectrum observed.





High-energy starting events unfolded



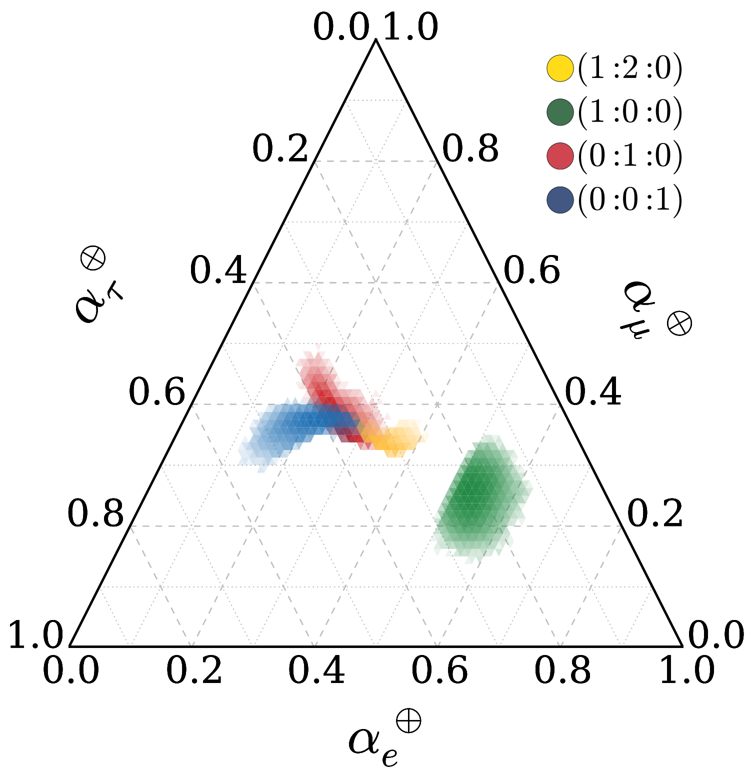
Good agreement between through-going ν_μ and starting events above ~ 200 TeV. Low energy in tension, but not significant. Under investigation.

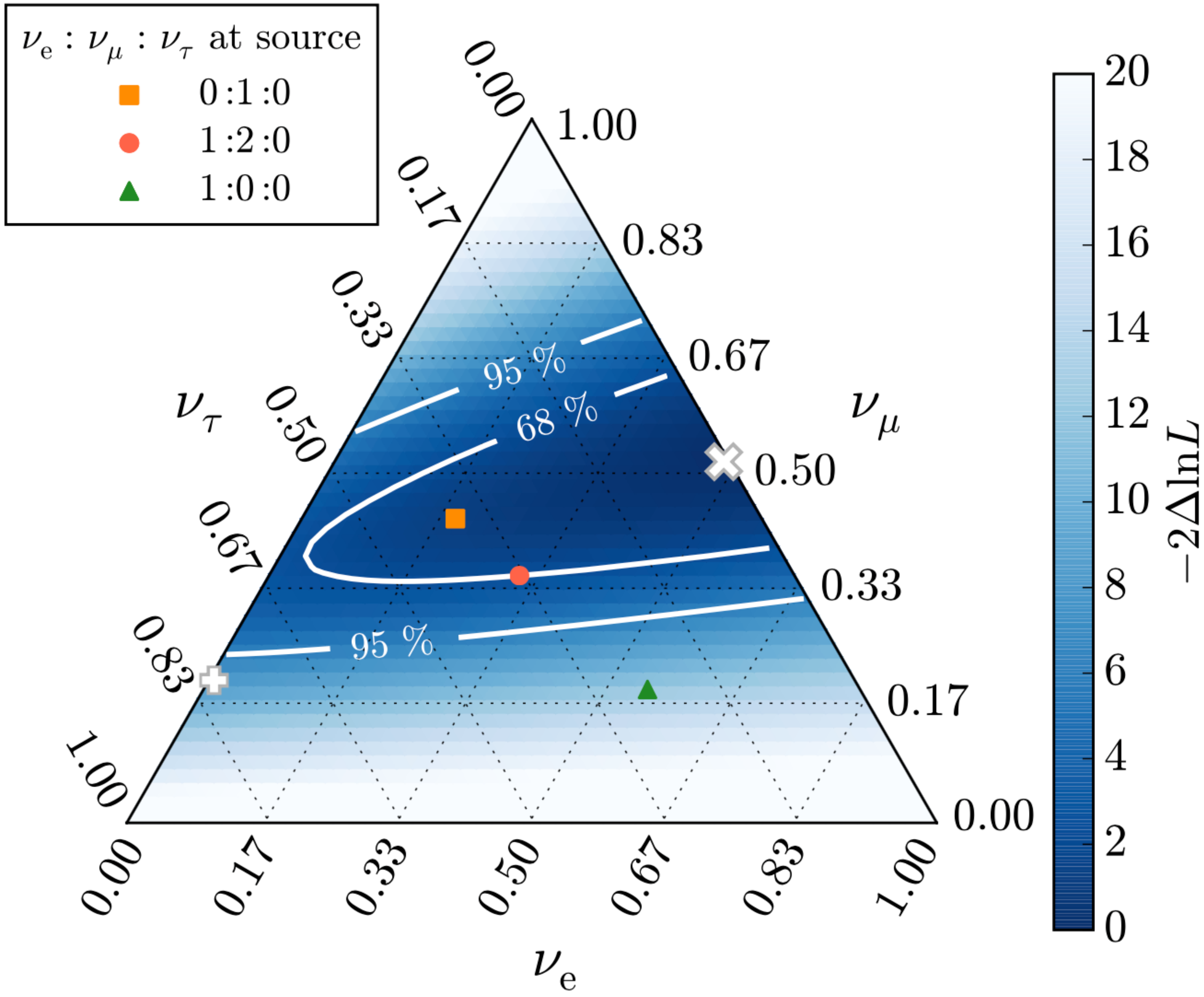
Astrophysical neutrino flavor

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

IceCube 1507.03991
Astrophysical Journal 809, 98 (2015)

standard oscillation prediction



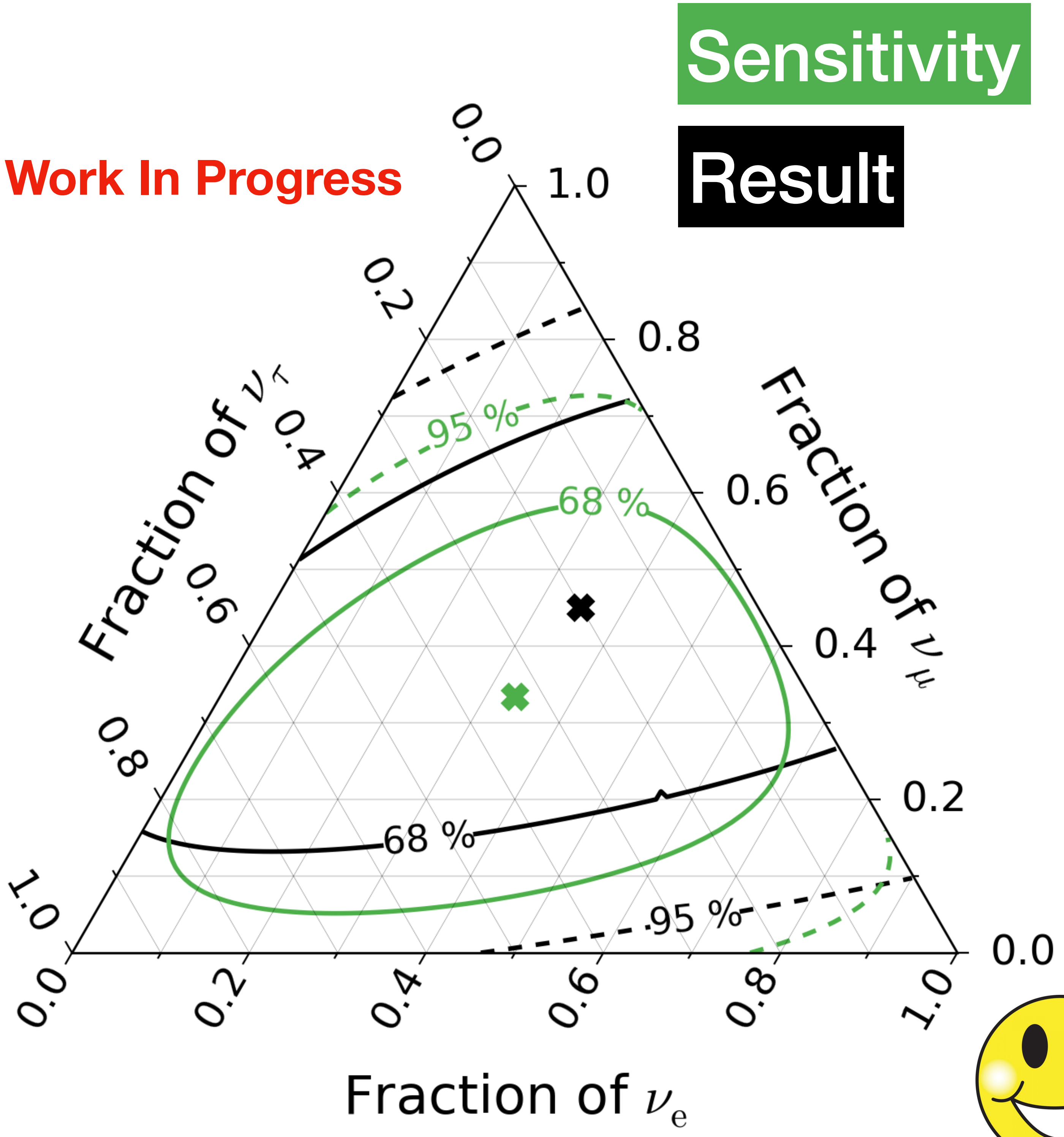


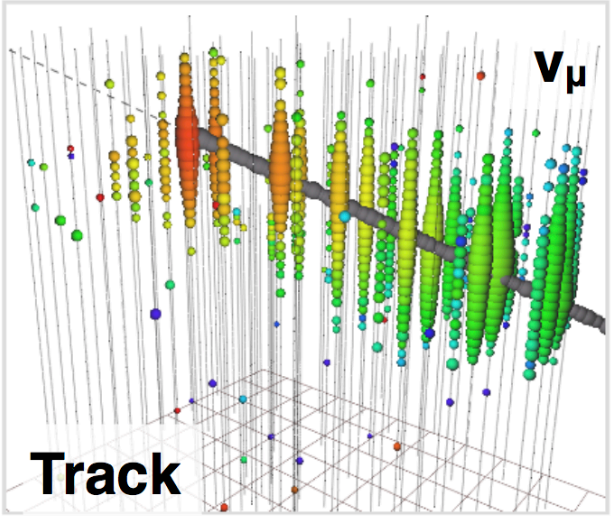
C.A., T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

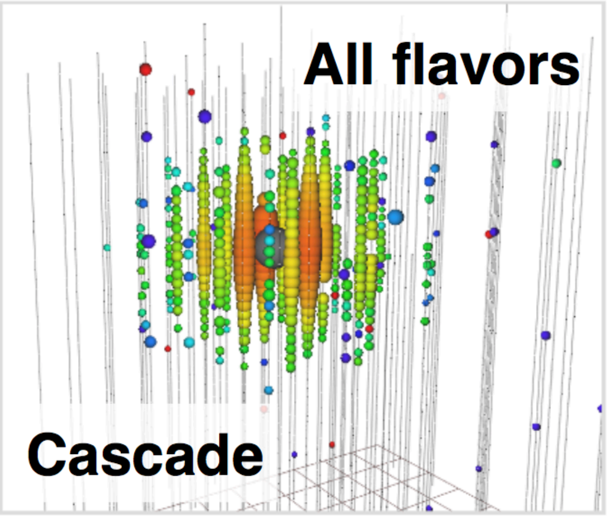
M. Bustamante, J. Beacom, W. Winter (Phys. Rev. Lett. **115**, 161302)

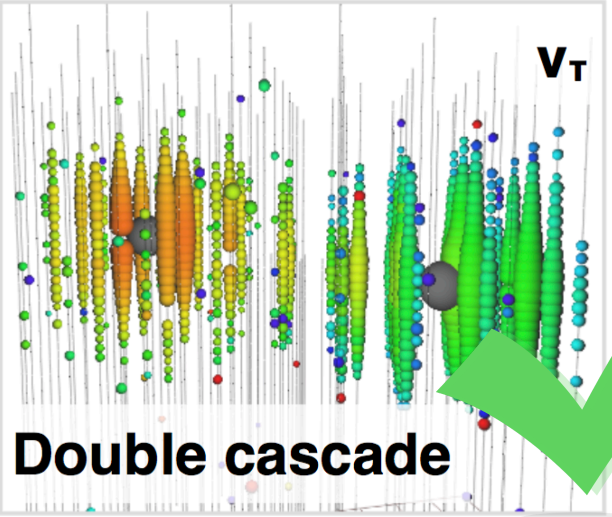
Updated **search for astrophysical tau neutrinos with starting events with double cascades!**

IceCube Work In Progress

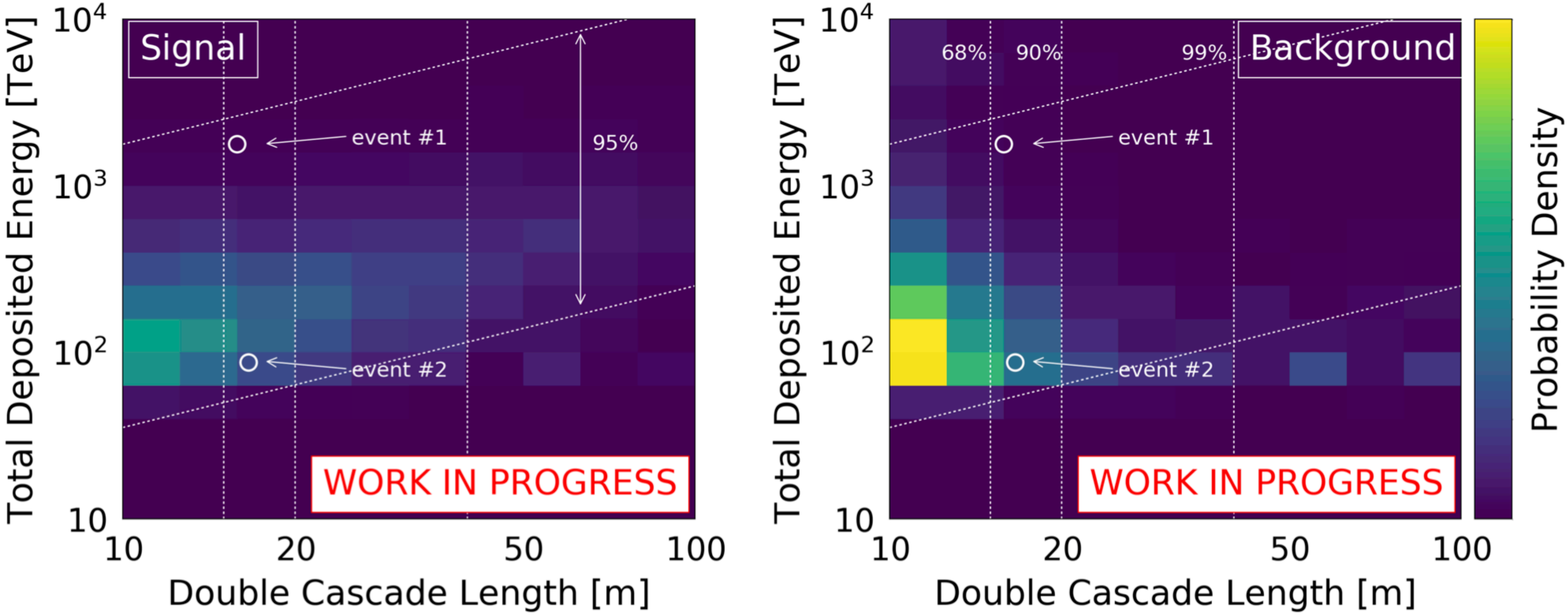








Two **candidate events**

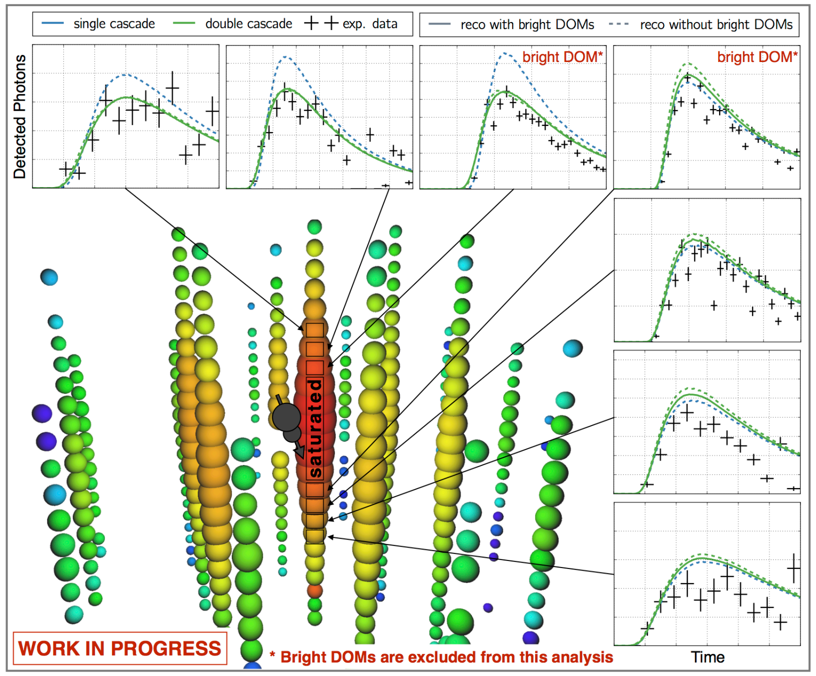


- **Two double cascades have been identified!**
- **Double cascades can arise from \nu_\tau or backgrounds (astro. or atm).**
- **Dedicated studies of “tauness” of the double cascade events is on-going.**

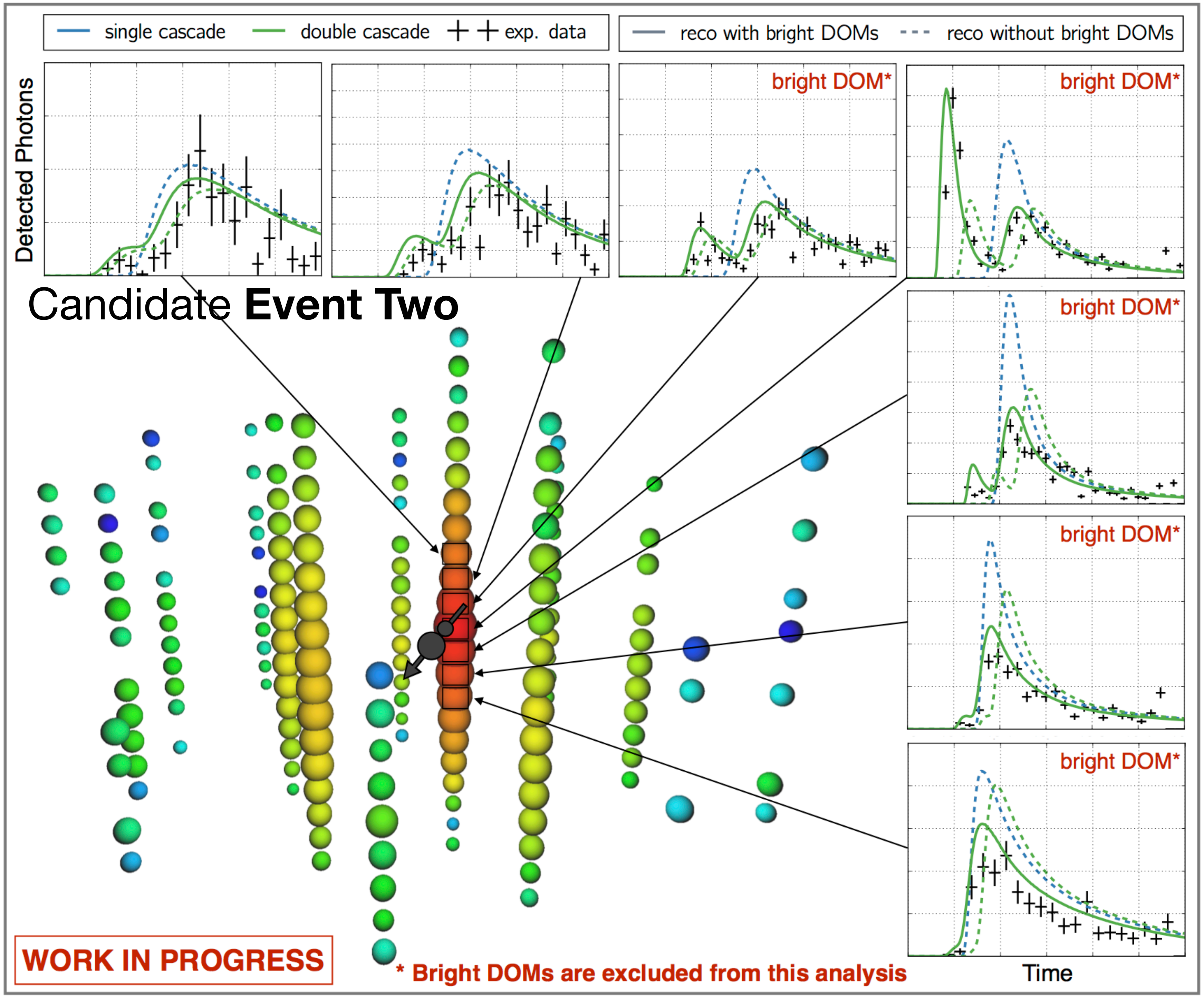
Tauness: “How likely is this event to be from a \nu_\tau CC interaction?”

Zooming in on the candidate events

Candidate **Event One**



Candidate **Event Two**



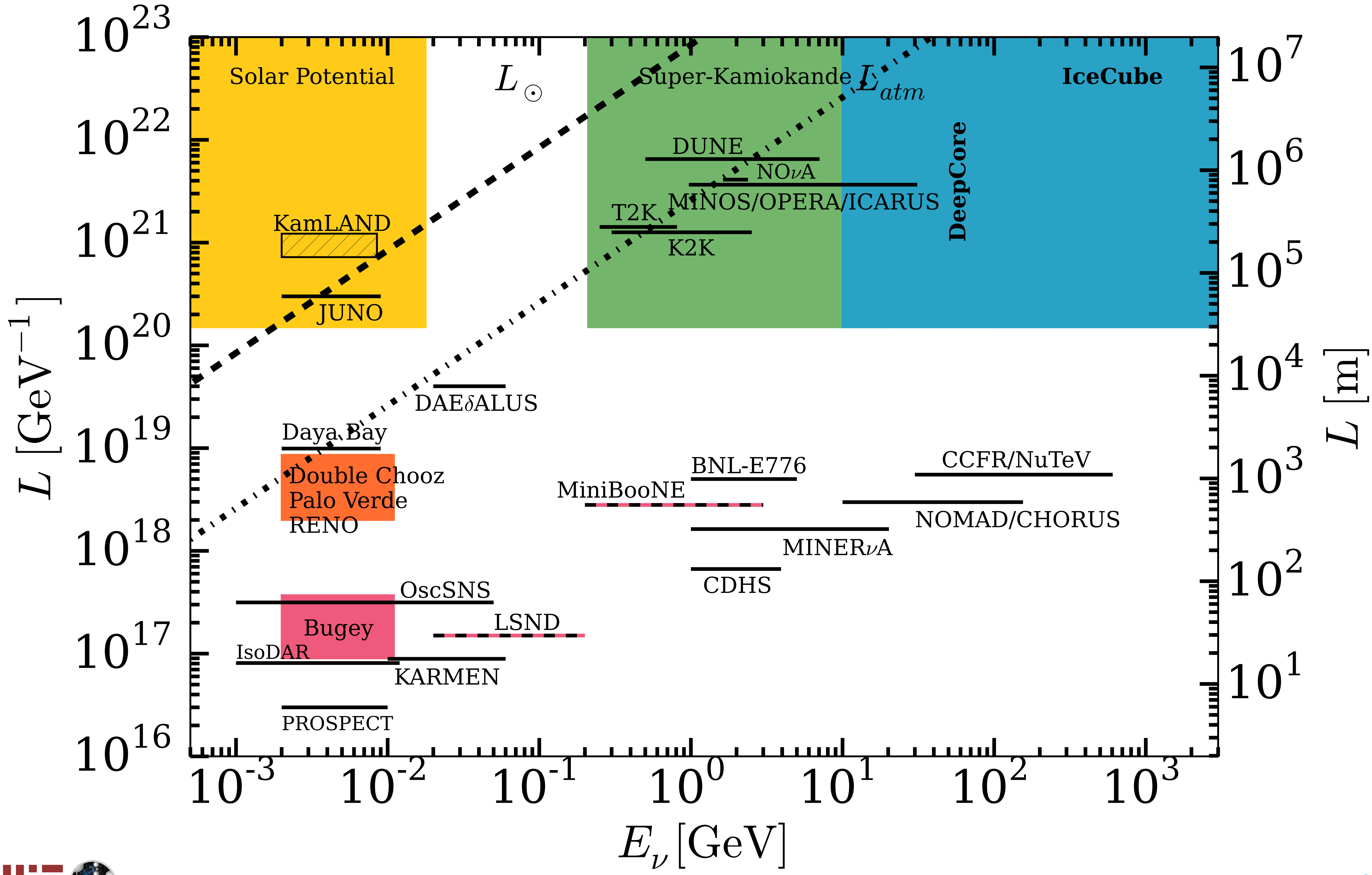
✤**“Bright” DOMs not used in the reconstruction.**

✤**Direction and two reconstructed cascades shown in dark gray.**

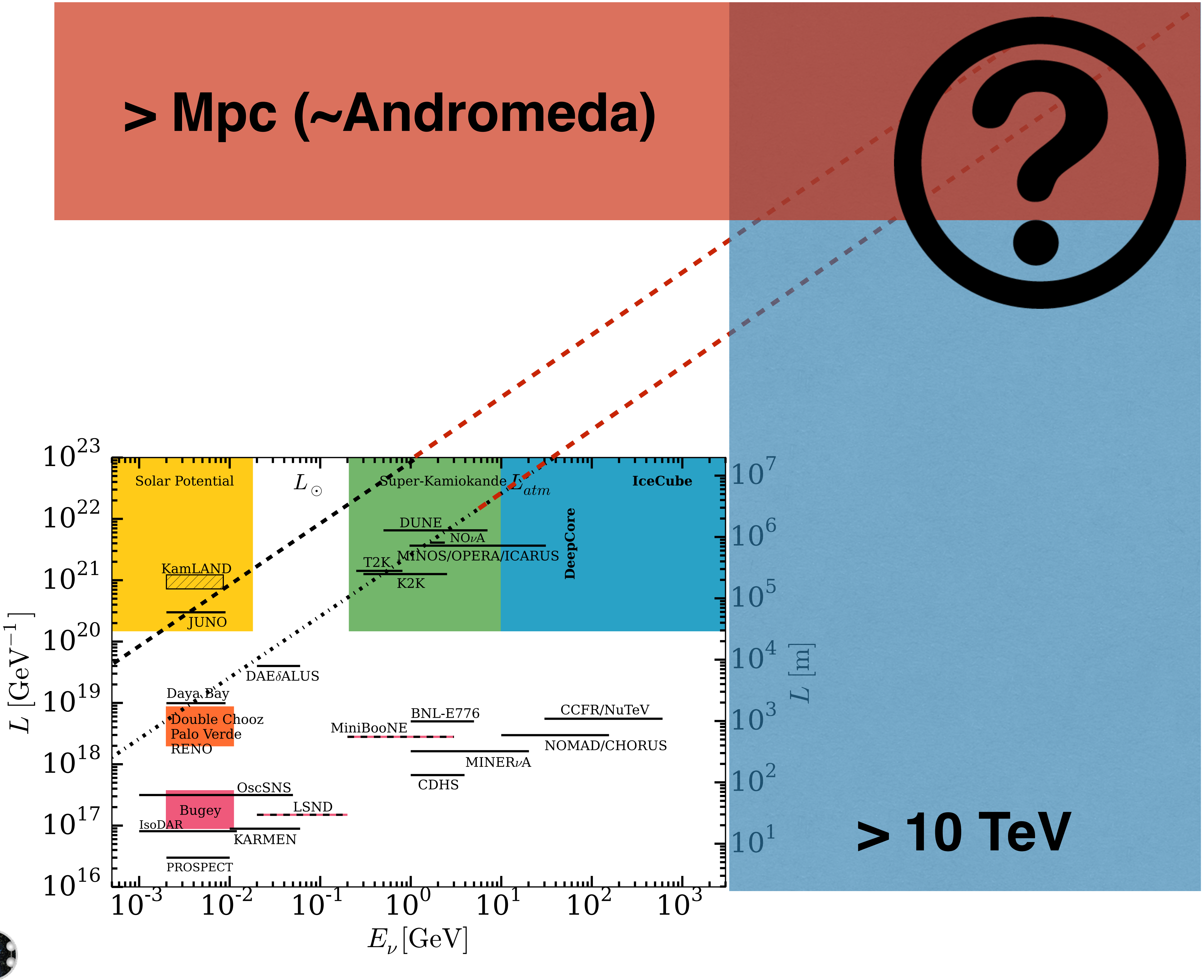
✤**Event #2 observed light arrival time pattern clearly favors the double cascade hypothesis.**

see J. STACHURSKA @Neutrino2018 10.5281/zenodo.1301121.

Terrestrial oscillation measurement landscape



Oscillation measurement ➡ *astrophysical* frontier



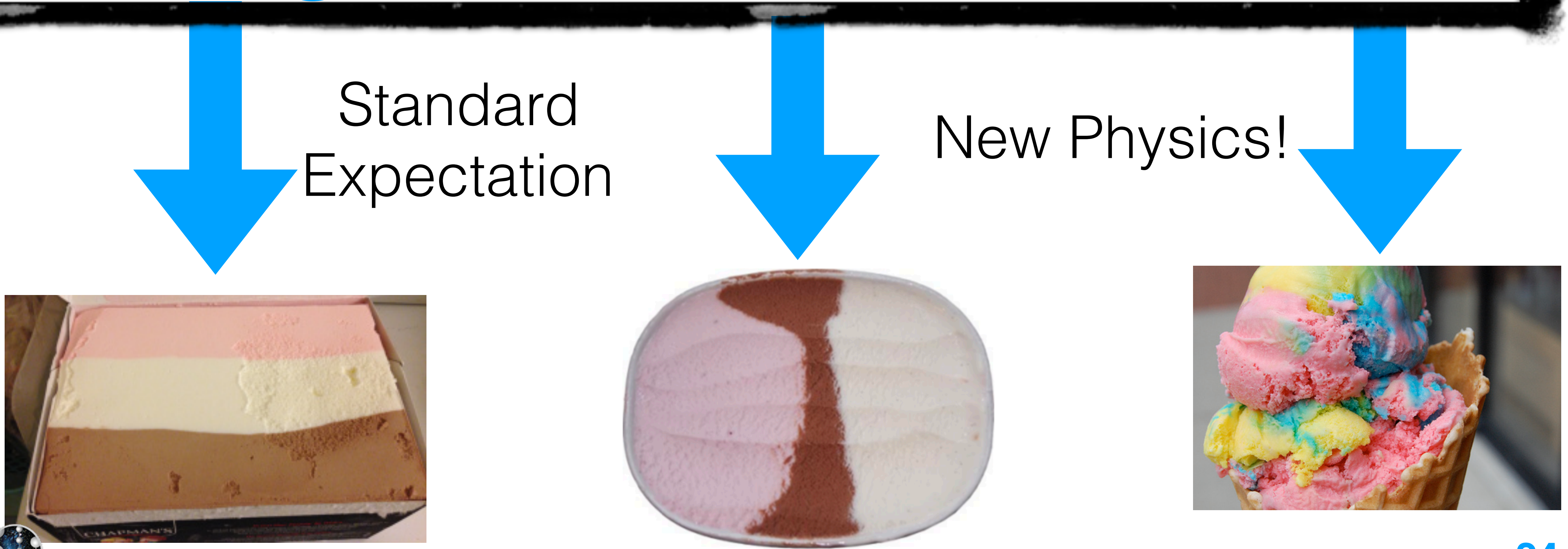
> Mpc (~Andromeda)

> 10 TeV

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!

Expected Sensitivity to Lorentz Violation with High-Energy Astrophysical Neutrinos

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

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

60 TeV ~ 1E4 GeV

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

10 PeV = 1E7 GeV

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

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

DIM 6

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

60 TeV ~ 1E4 GeV

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

10 PeV = 1E7 GeV

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

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

Note that this operators are *generic;* can arise from other physics that's not LV, e.g. see:

Capozzi et al. 1804.05117 for dark matter-neutrino couplings

Bustamante et al. 1808.02042 for long range forces

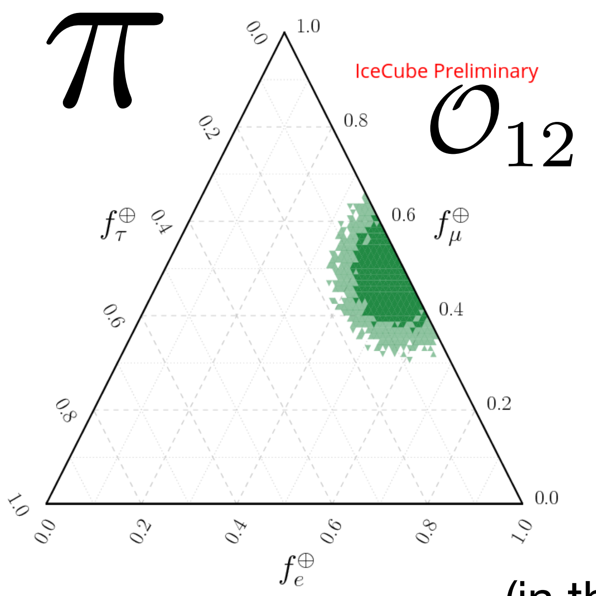
Limiting Specific Lorentz Violating Textures

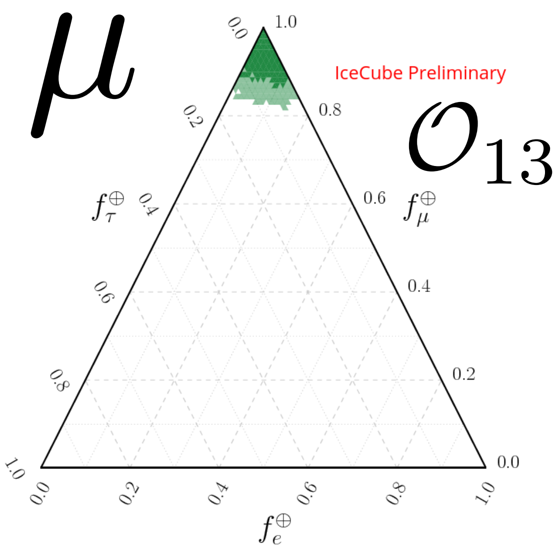
- **We will fix the initial flavor ratio to one of the usual scenarios.**
- **We will also study maximum flavor violating operators, *a la* Super-Kamiokande.**

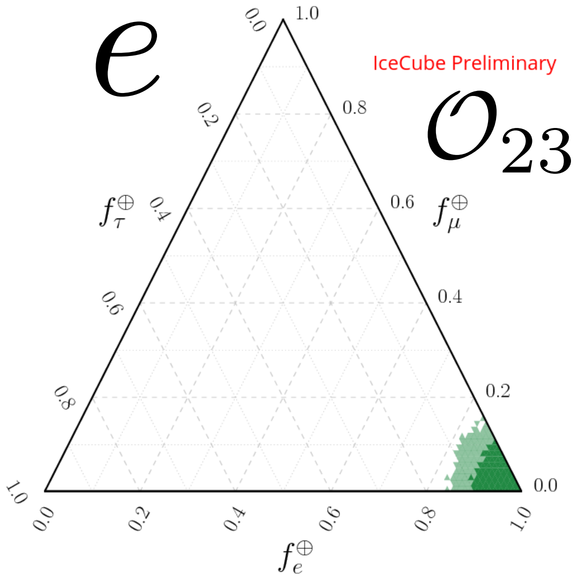
New Physics Mixing Matrix

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

How do some of these look in the flavor triangle?



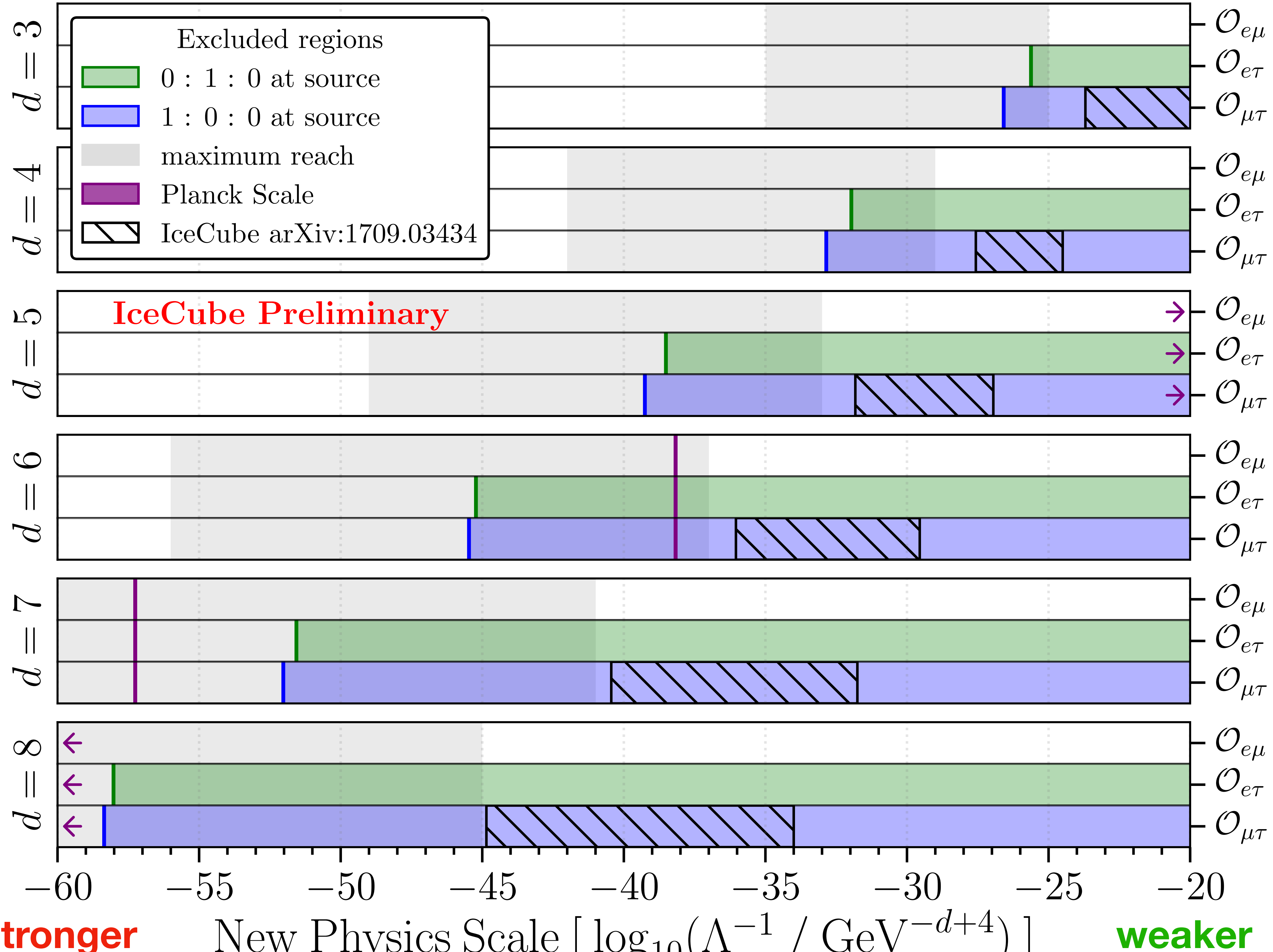




(in these triangles a gaussian detector smearing has been added)

New results **on high-dimensional LV operators**

hashed: atmospheric neutrinos, solid: astrophysical neutrinos

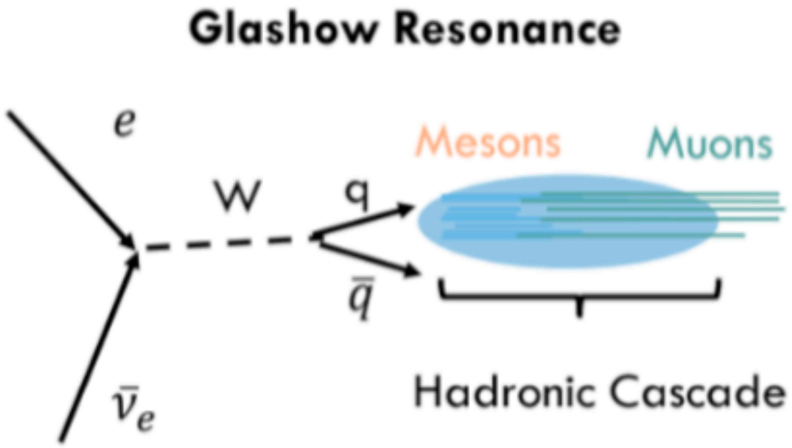


stronger constraint

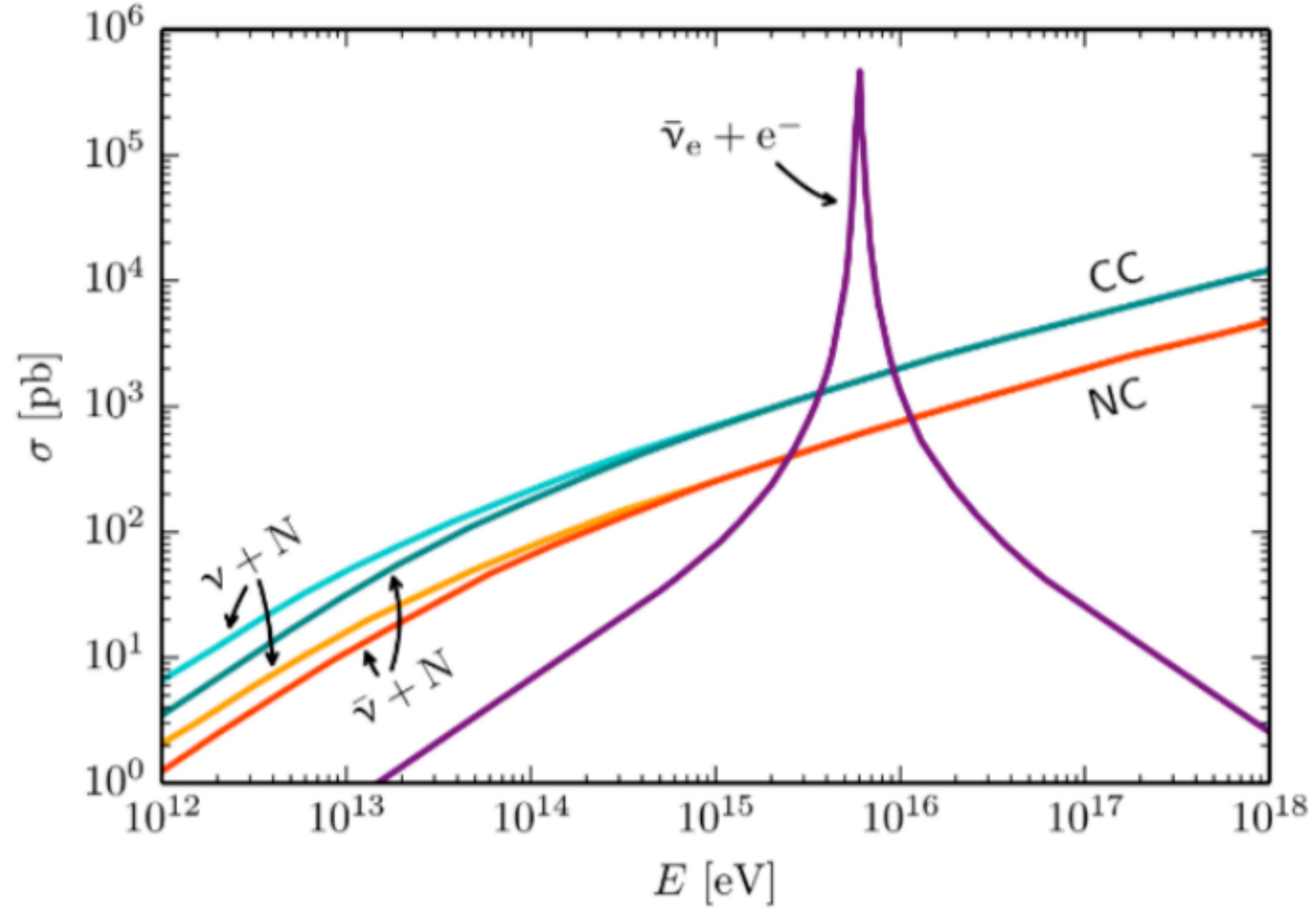
weaker constraint

see T. Yuan@Neutrino2018 10.5281/zenodo.1300505

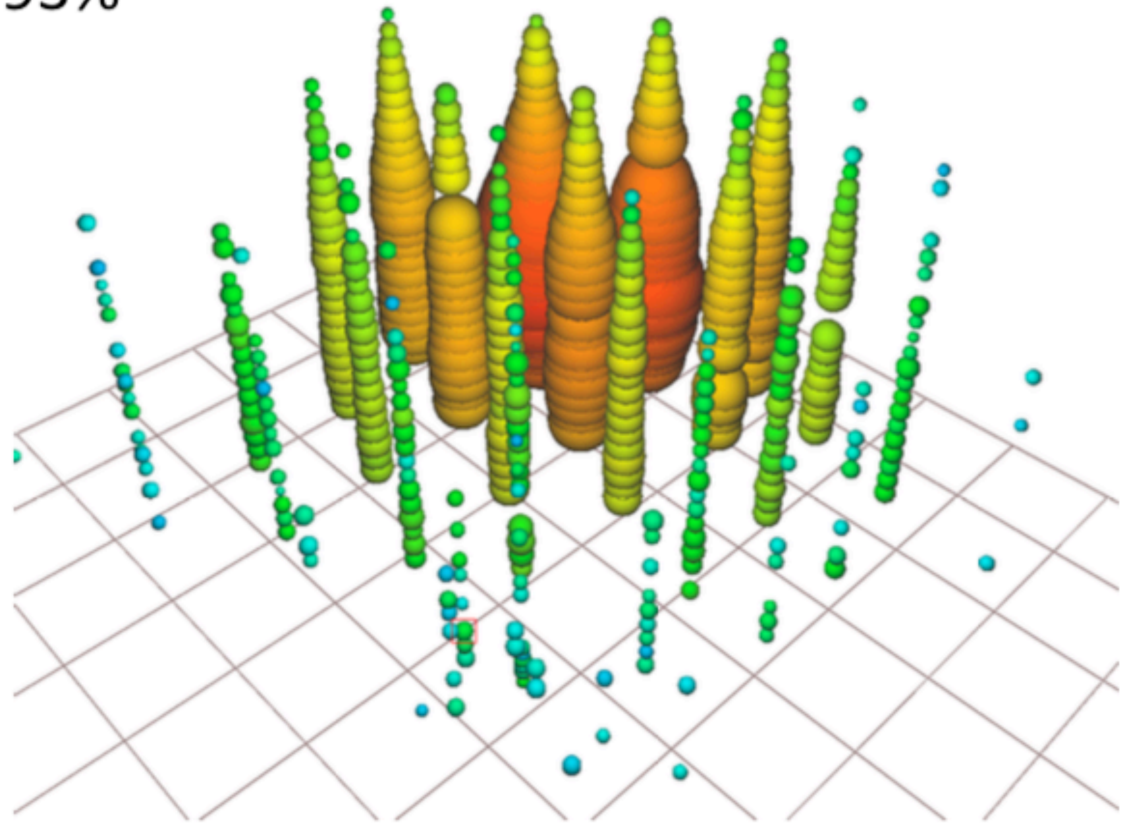
5.9 PeV **cascade in IceCube**



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%



IceCube Work In Progress



Non-starting, partially contained event

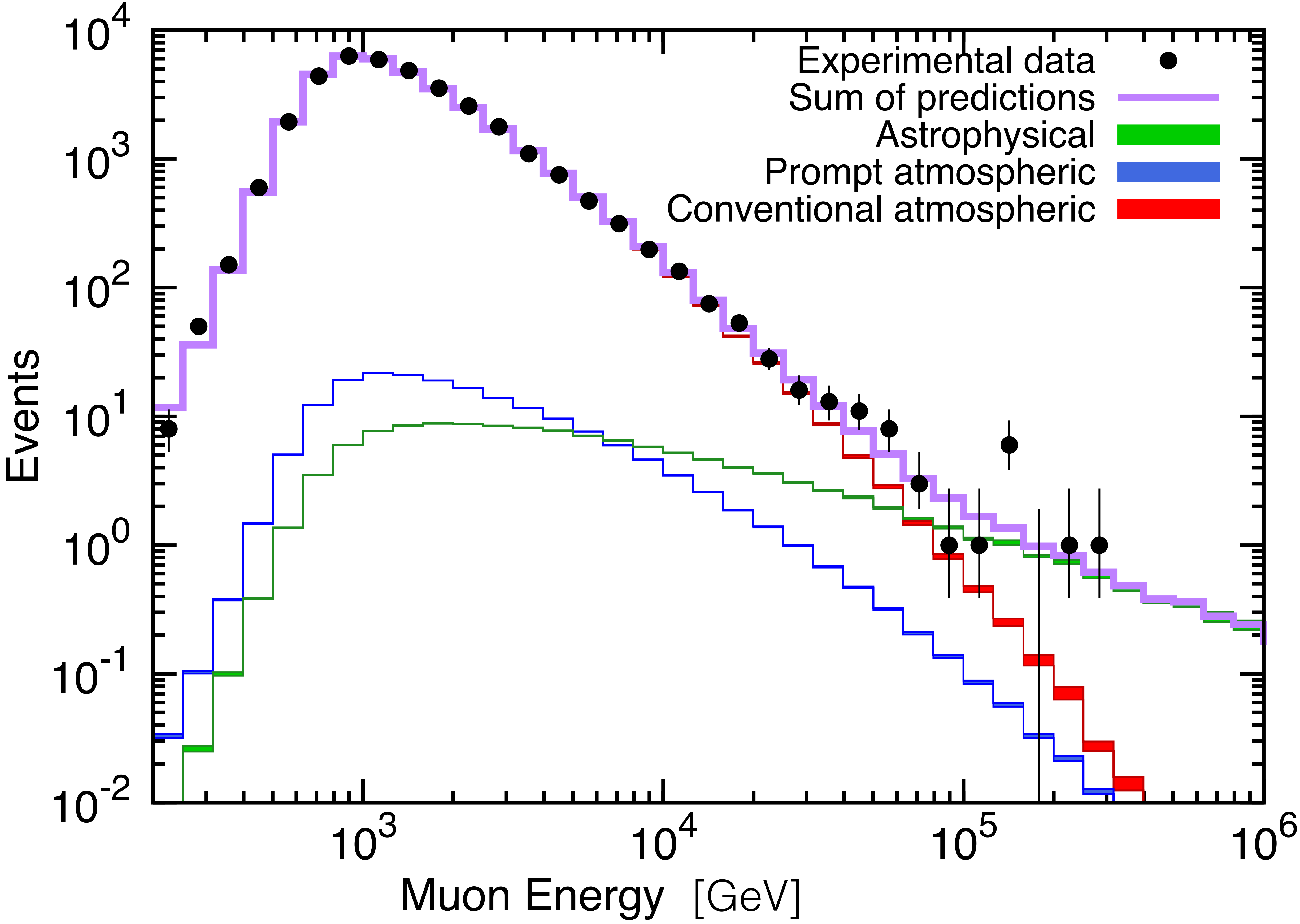
Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

Potential hadronic nature of this event under study

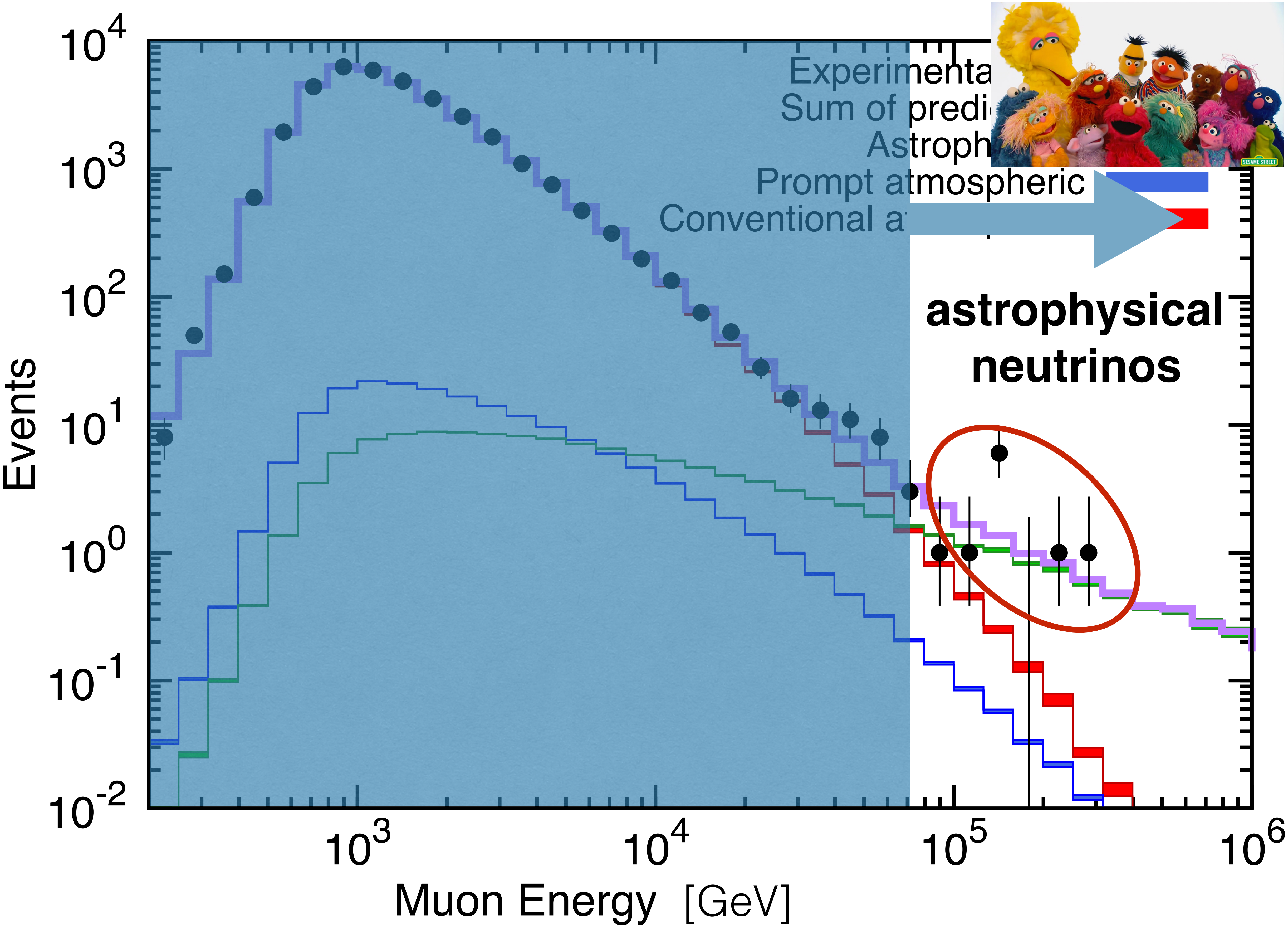
Measurements with Atmospheric Neutrinos

Through-going nu-mu energy distribution



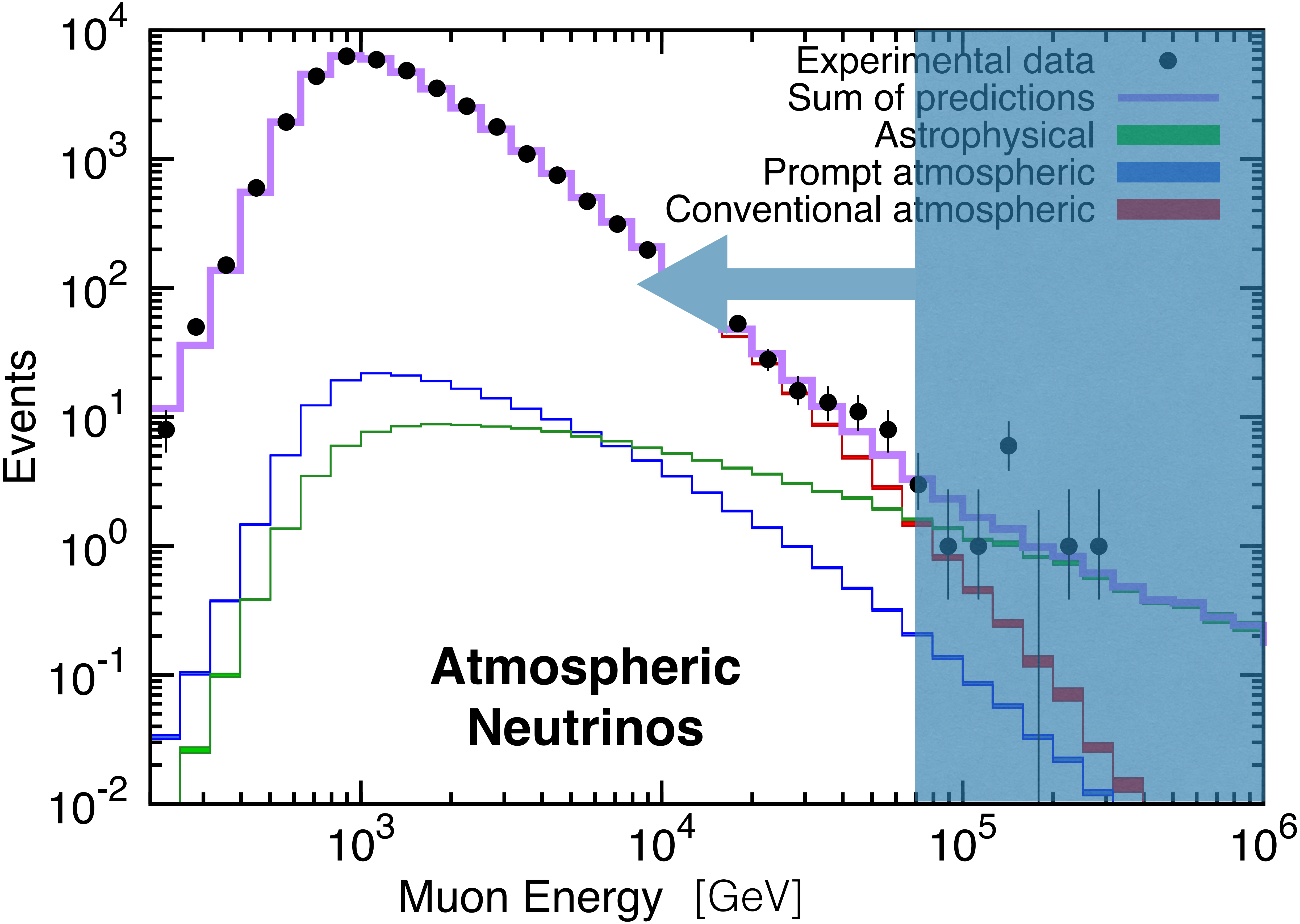
Phys. Rev. Lett. 115, 081102 (2015)

Astrophysical neutrino dominate at highest energies!



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

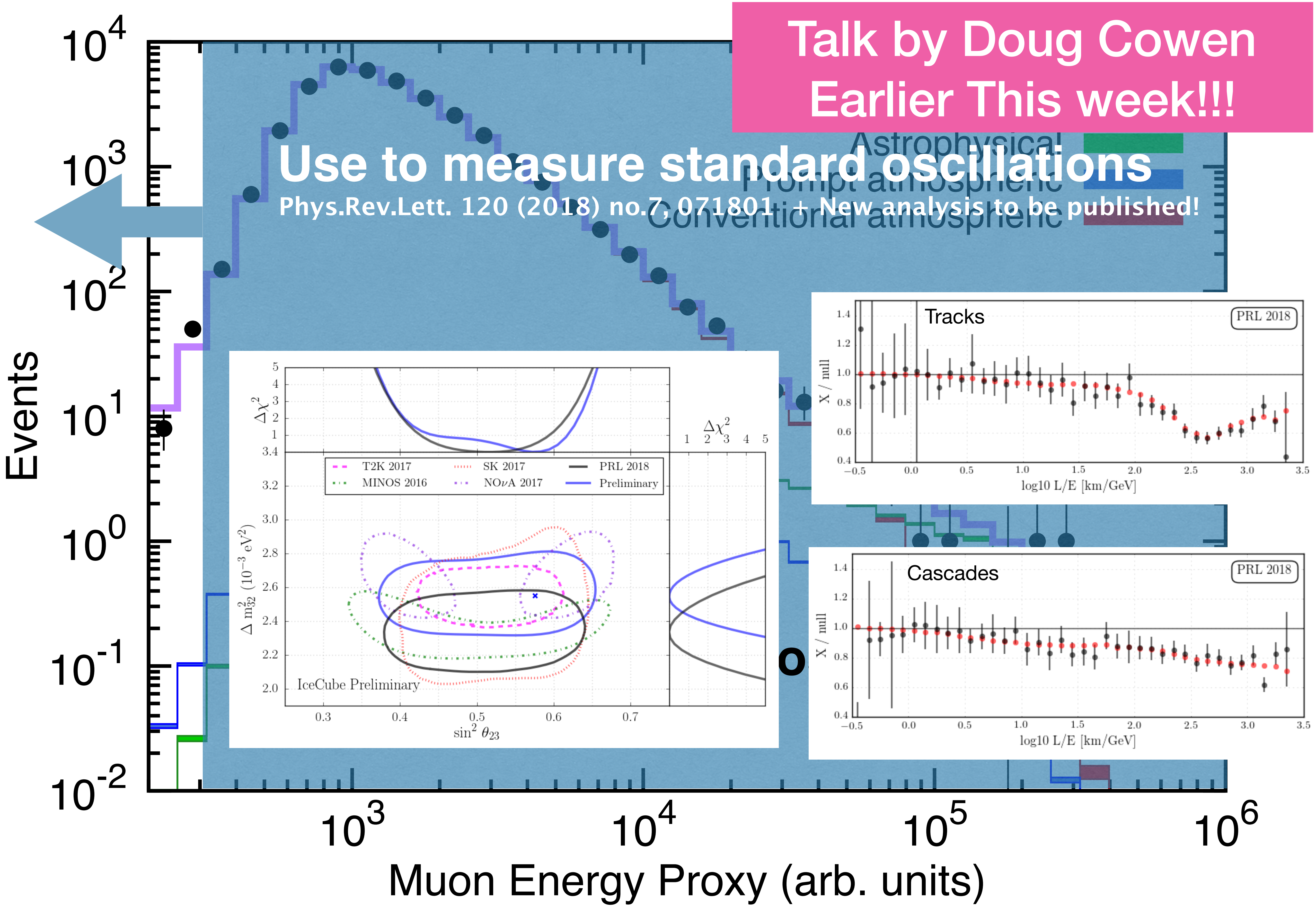
IceCube observes a lot of atmospheric neutrinos!



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

Through-going nu-mu energy distribution

Talk by Doug Cowen Earlier This week!!!



Use to measure standard oscillations

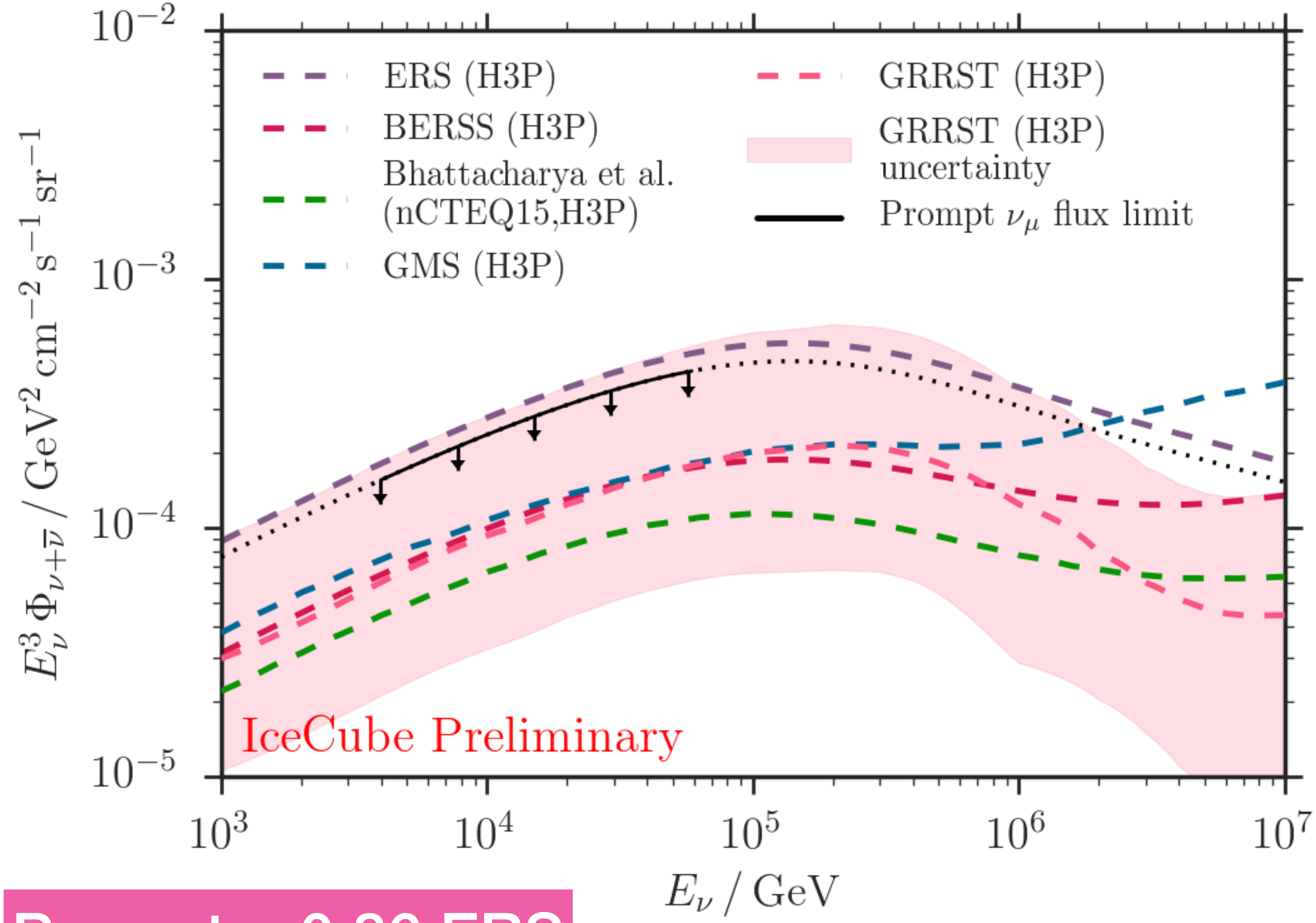
Phys.Rev.Lett. 120 (2018) no.7, 071801 + New analysis to be published!

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

What about the prompt neutrino flux?

Limits from 8 years of through-going muons

No prompt yet!

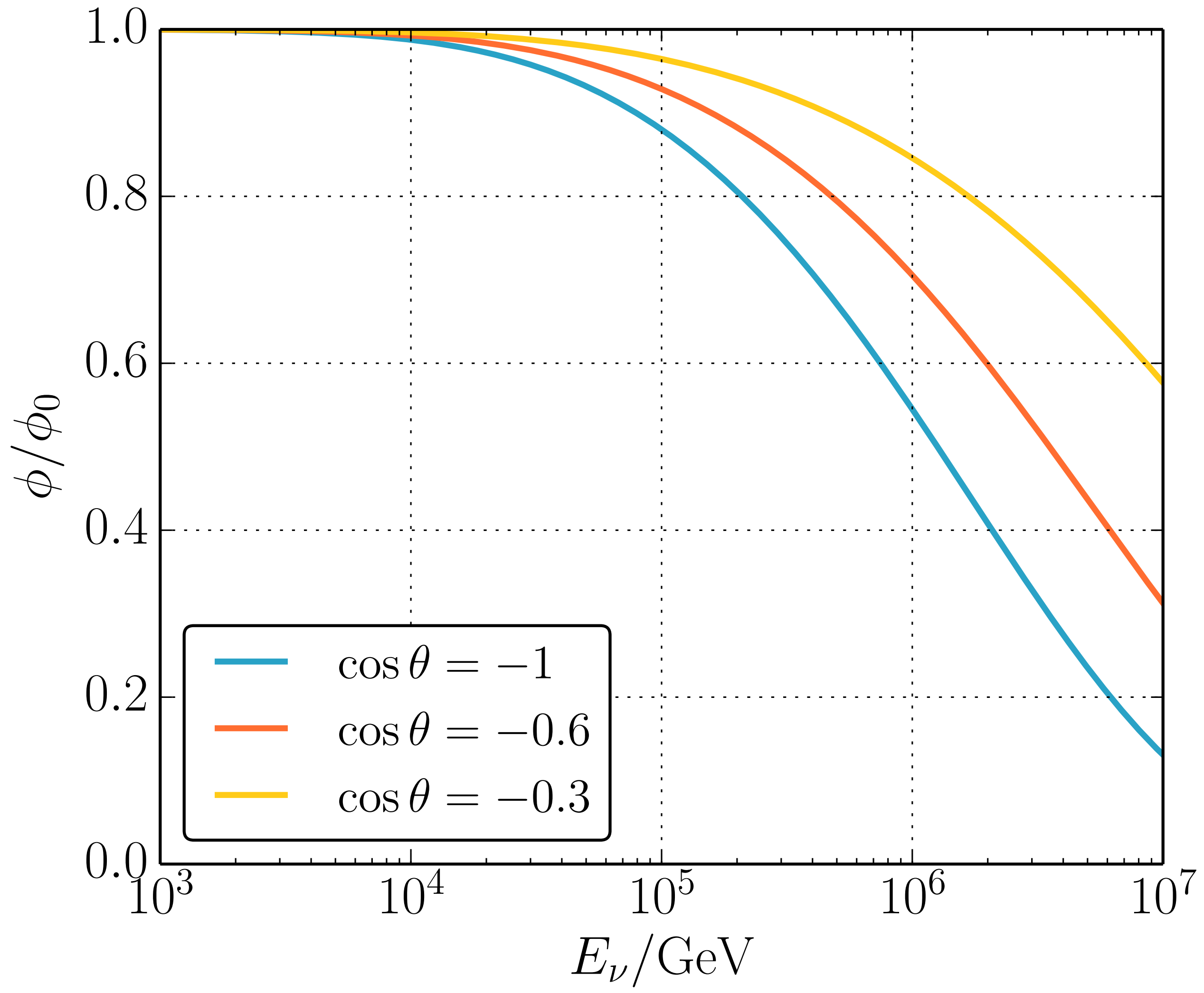


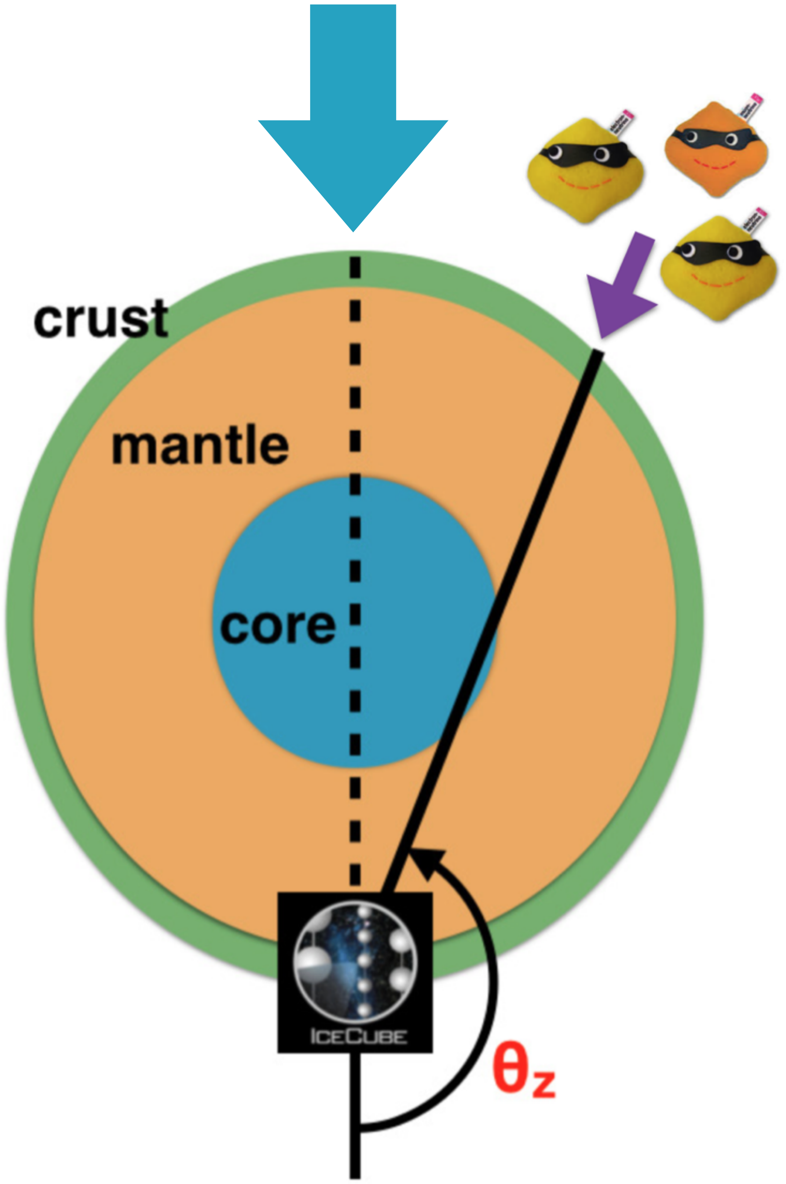
Prompt < 0.86 ERS

ERS=Enberg et al. Phys.Rev.D78:043005,2008

Measurement of the very high-energy neutrino cross section

High energy neutrinos experience zenith-dependent flux attenuation



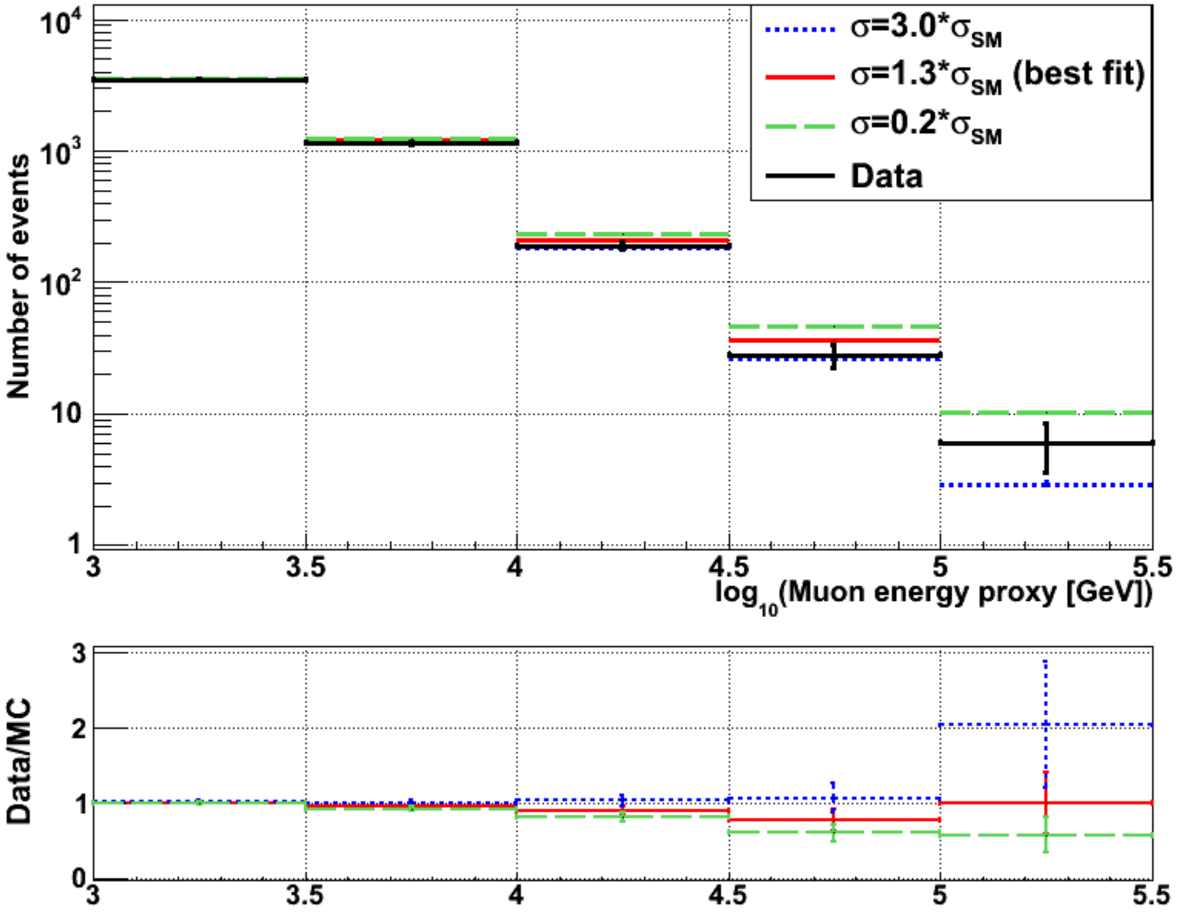


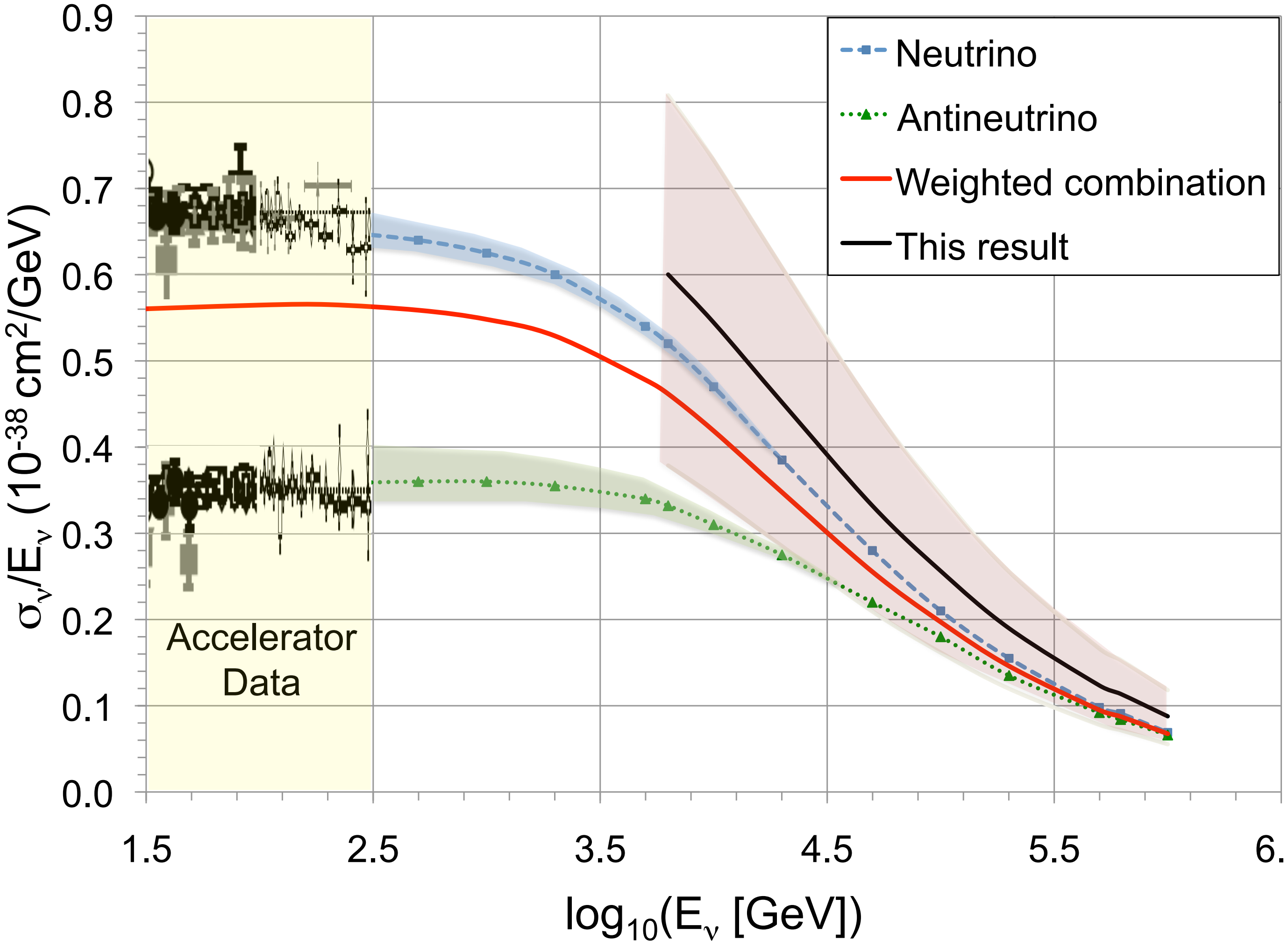
Ghandi et al. Astropart.Phys.5:81-110,1996
Connolly et al. Phys.Rev. D83 (2011) 113009

Vincent et al. JCAP 1711 (2017) 012
Bertone et al. arXiv:1808.02034

Measurement of the very high-energy neutrino cross section with through-going muons

Assume cross section increases by constant factor



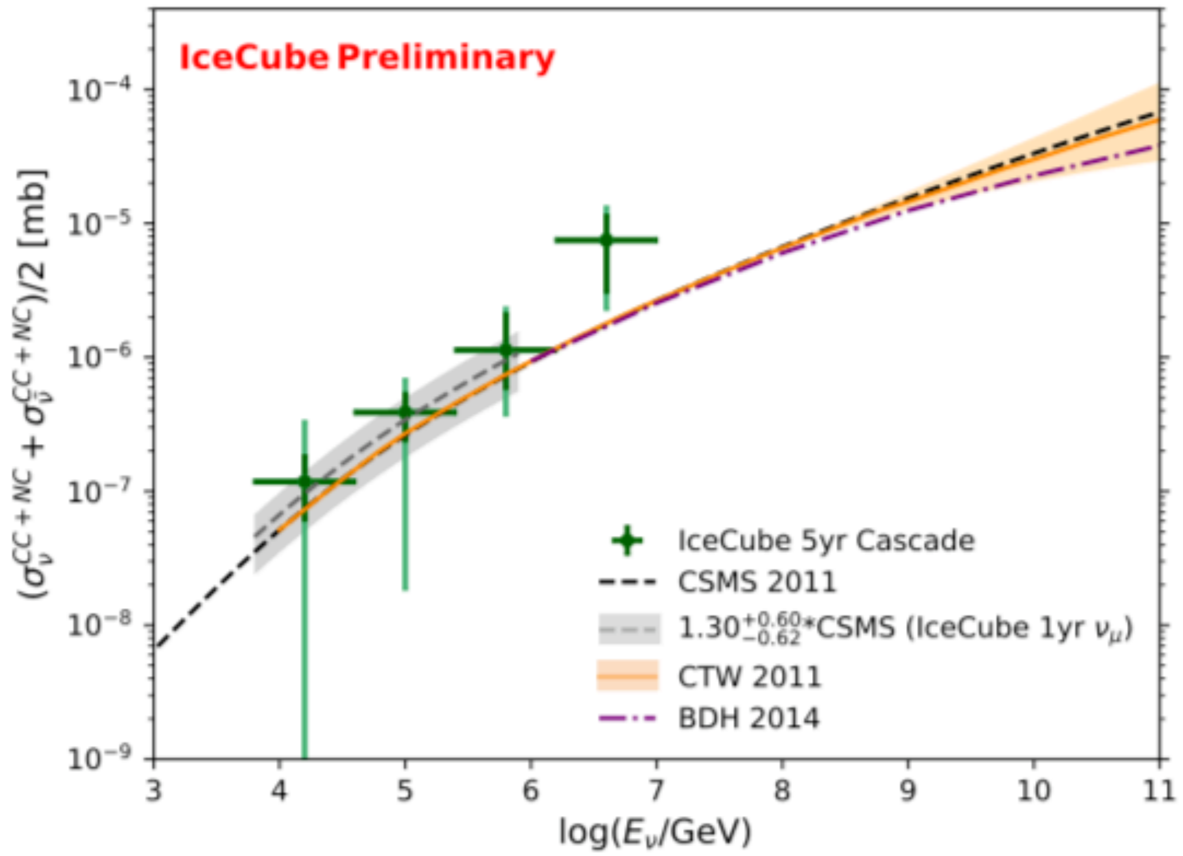


$$\kappa = 1.3^{+0.30(stat)+0.32(syst)}_{-0.26(stat)-0.40(syst)}$$

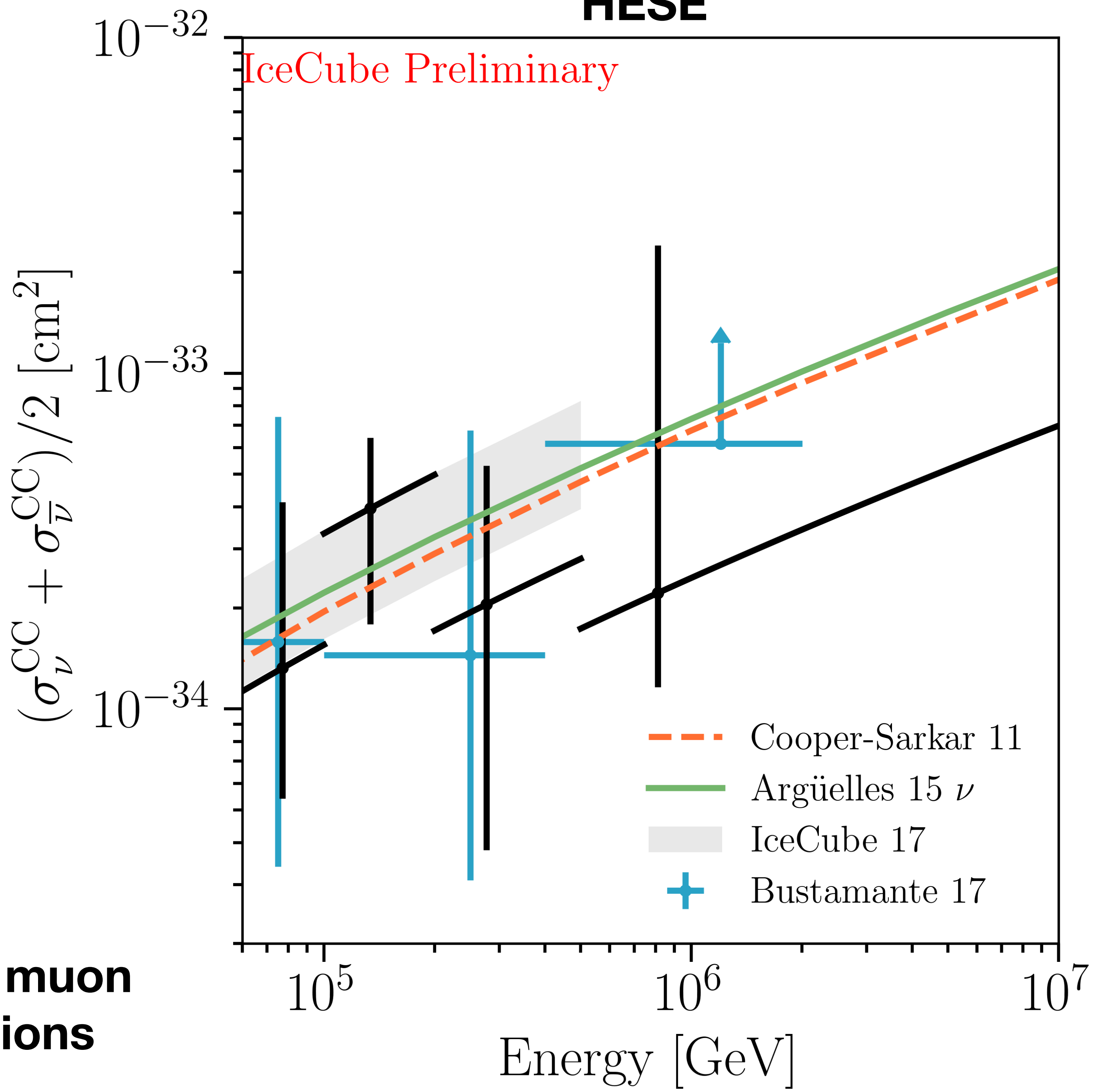
Nature 551 (2017) 596-600

New **measurement of the all-flavor neutrino cross section with cascades**

TeV-energy cascades



HESE

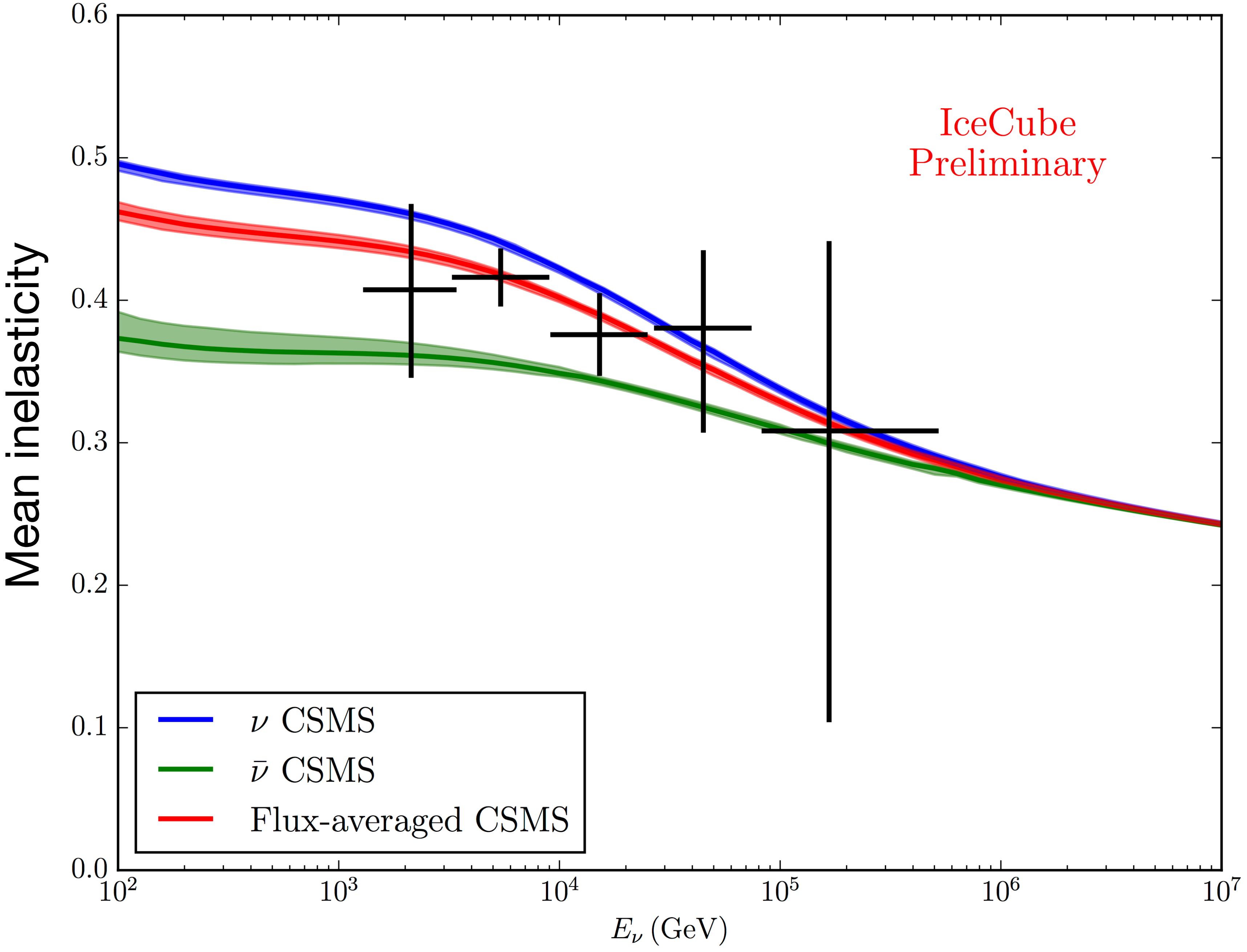


Results from cascades consistent with muon neutrino measurements and expectations

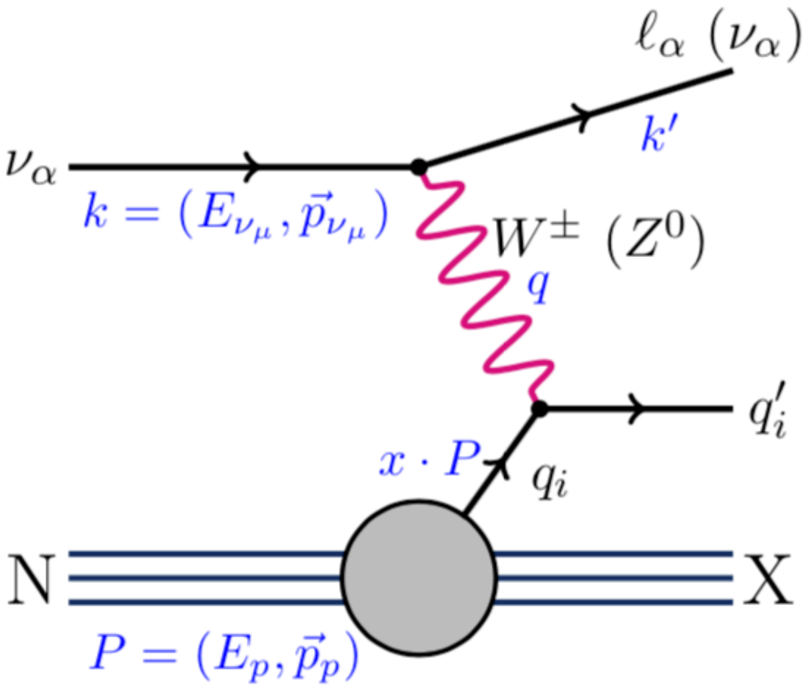
see T. Yuan@Neutrino2018
10.5281/zenodo.1300505

***HESE = high-energy starting events**

New **inelasticity measurement using starting events**



$$y = \frac{Q^2}{2mxE} = \frac{E_\nu - E_l}{E_\nu}$$

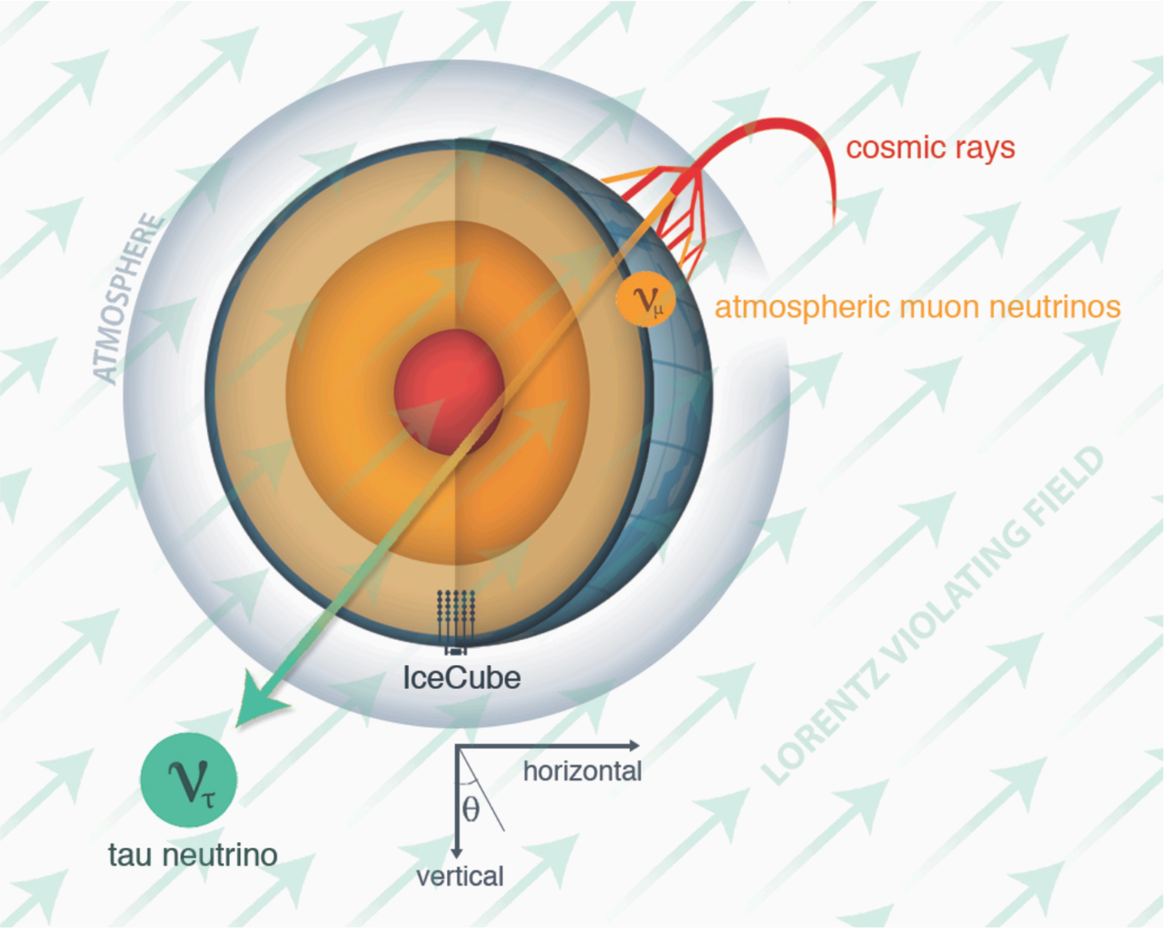


CSMS=A. Cooper-Sarkar, P. Mertsch and S. Sarkar, JHEP 08,042 (2011).

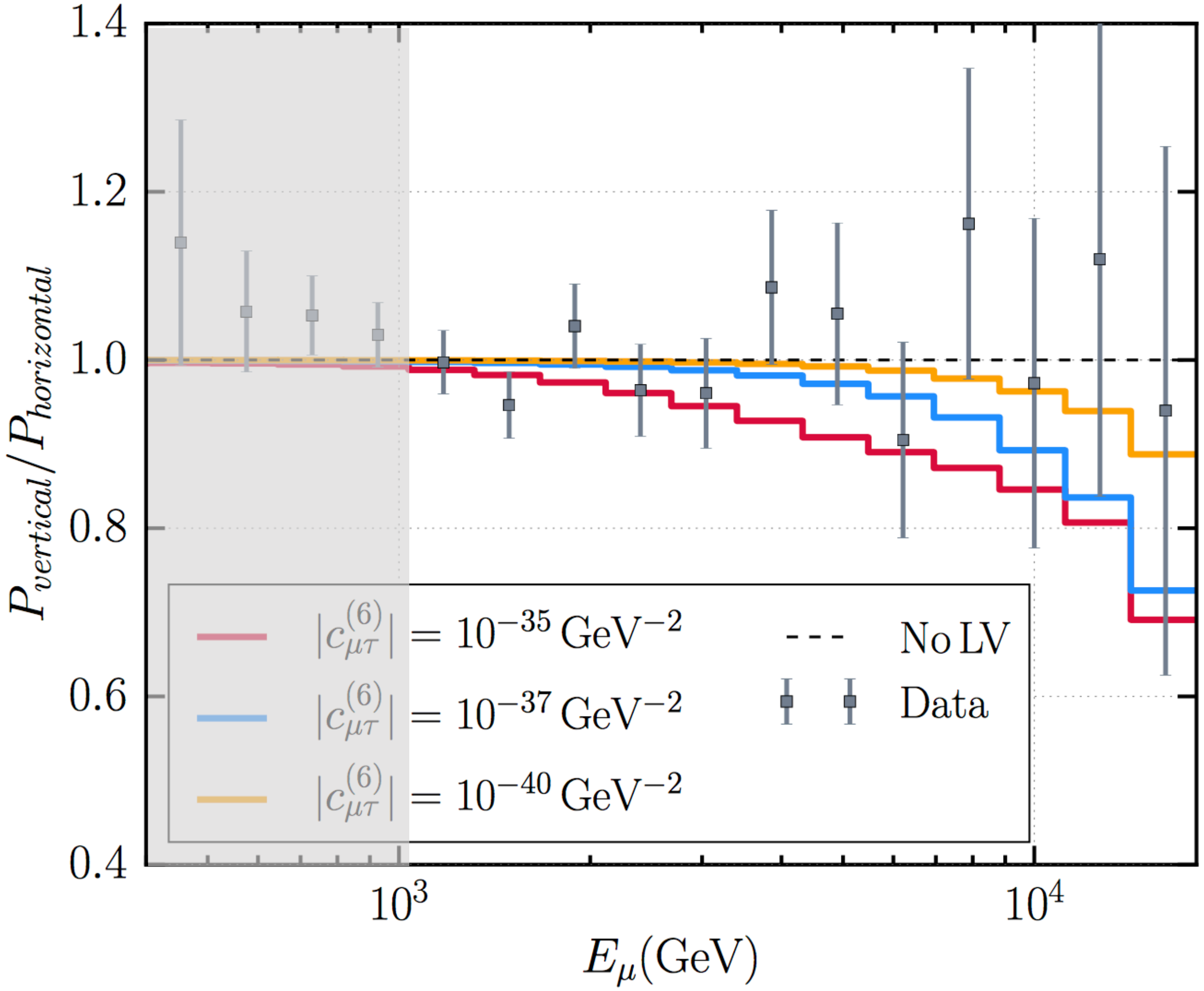
Search for Lorentz Violation with Atmospheric Neutrinos

The analysis sensitivity, especially for high-dimensional operators, is dominated by the highest-energy events.

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots .$$



$$P_{osc}(c^{(6)}_{\mu\tau} E_\nu L)$$



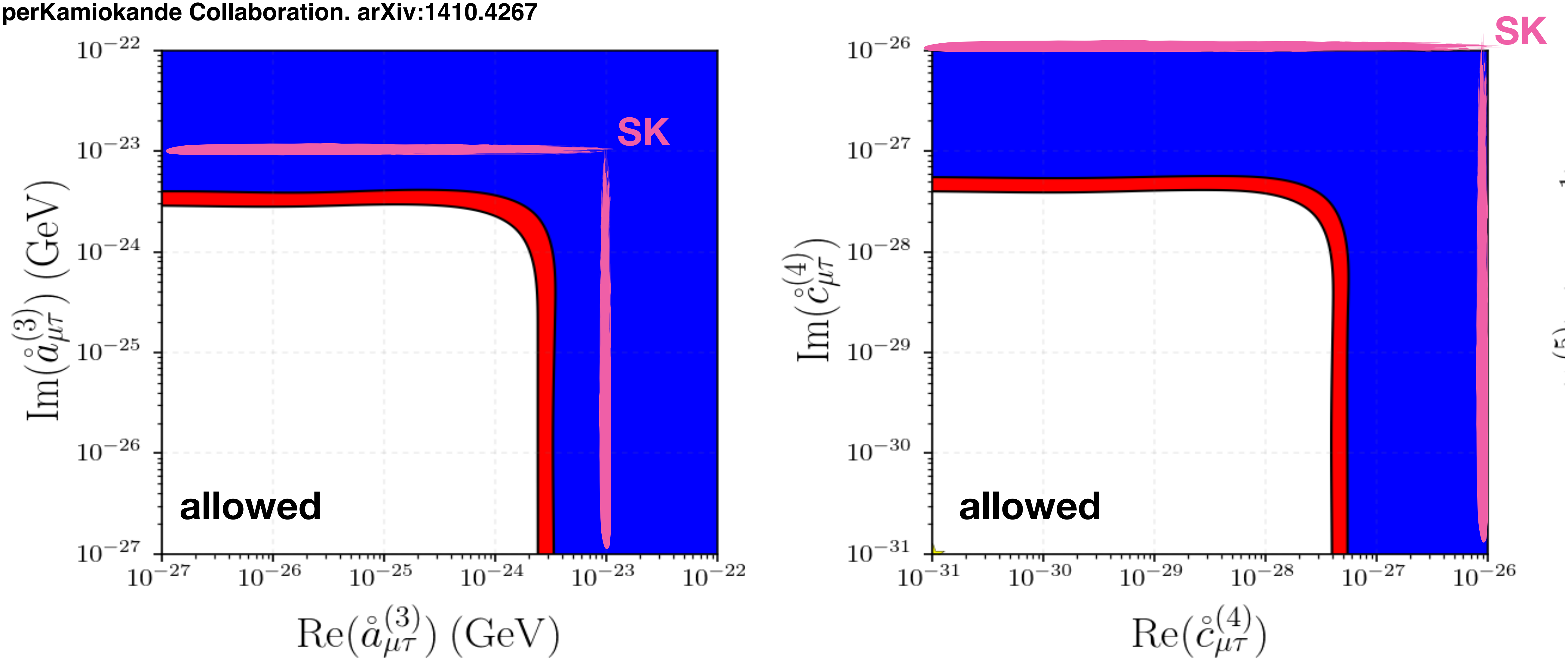
Our results in the maximum-flavor-violating assumption

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

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

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

SuperKamiokande Collaboration. arXiv:1410.4267



Nature Physics (2018) s41567-018-0172-2

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

Leading constraints across several fields of physics

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

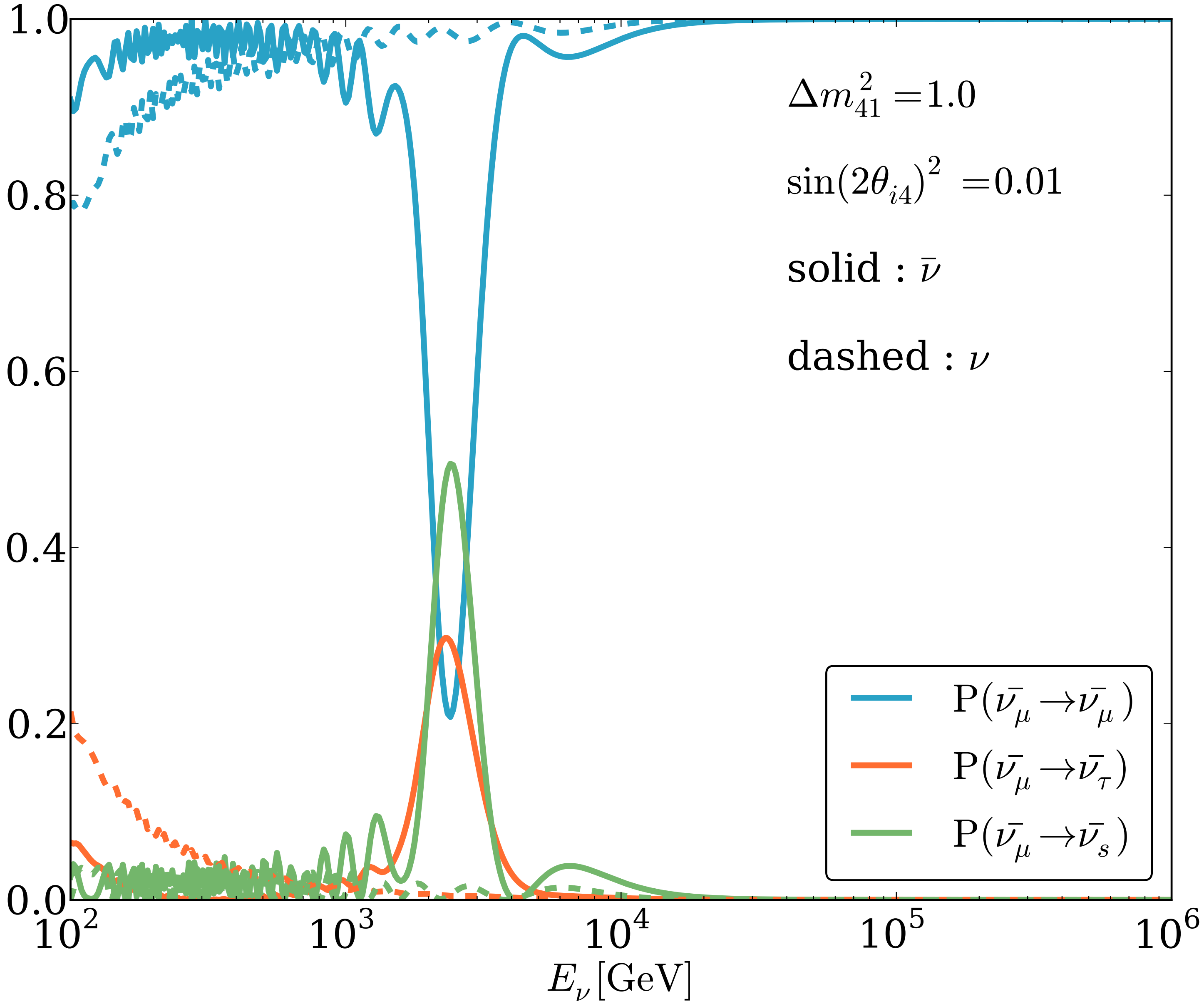
Very strong limits on Lorentz Violation induced by dimension-6 operators!

Nature Physics (2018) s41567-018-0172-2

Matter-Enhanced Oscillations With Steriles

In the **Earth**, for sterile neutrino of $\Delta m^2 = O(1eV^2)$ there is a matter resonant(*) effect when

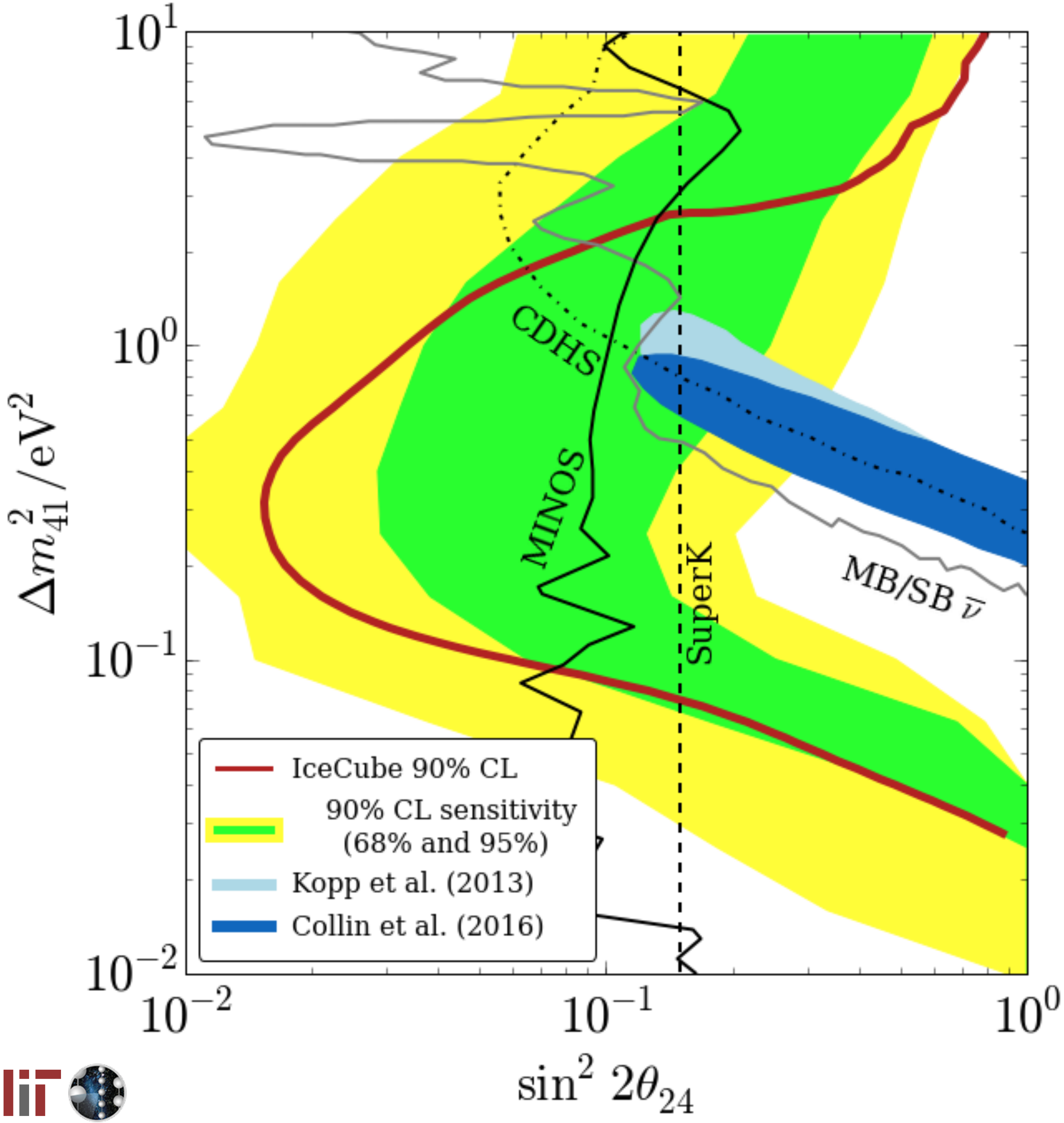
$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



(*parametric resonance)

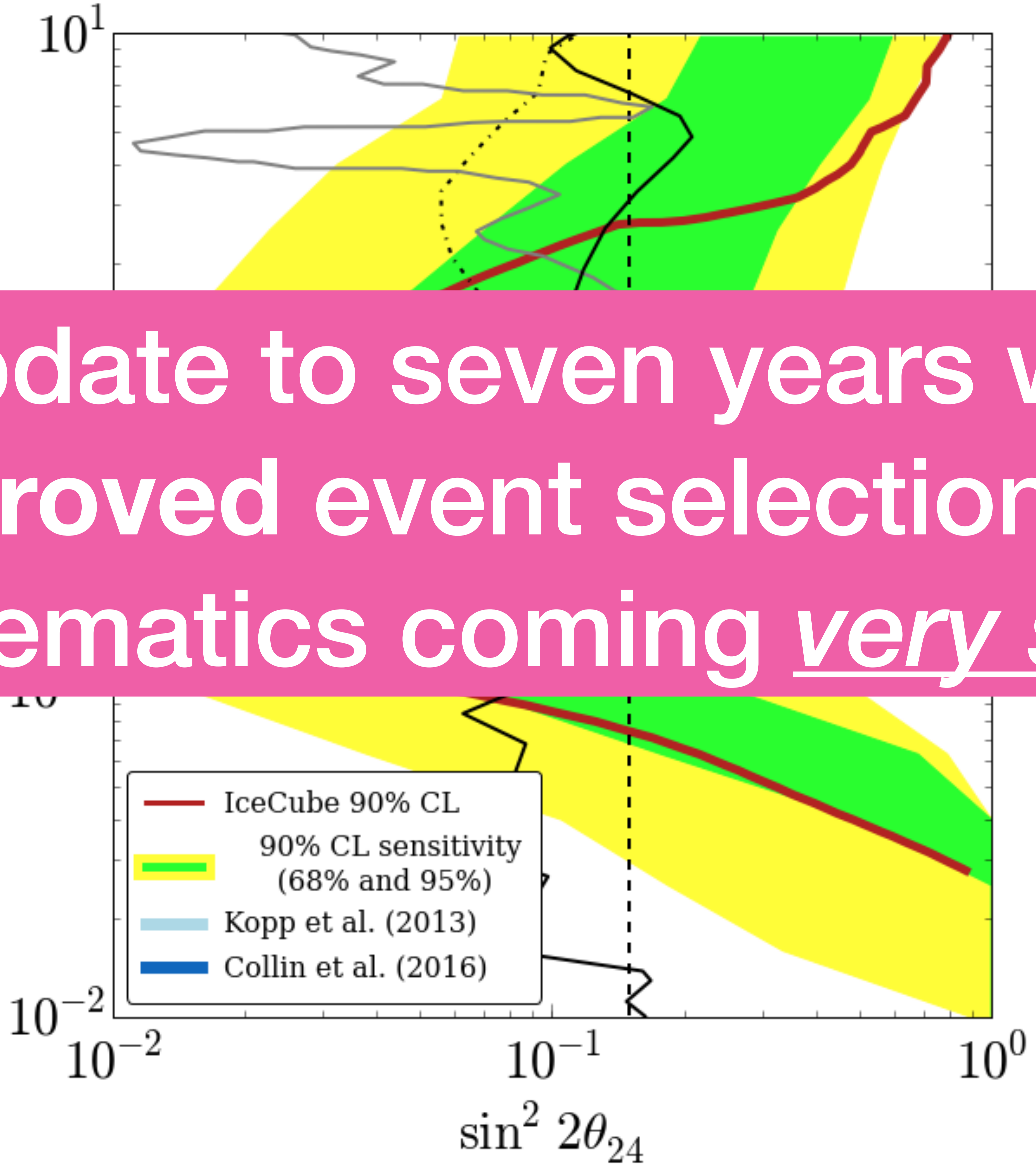
Nunokawa et al. PLB, B562, 279 (2003). arXiv:hep-ph/0302039

High-energy sterile bounds



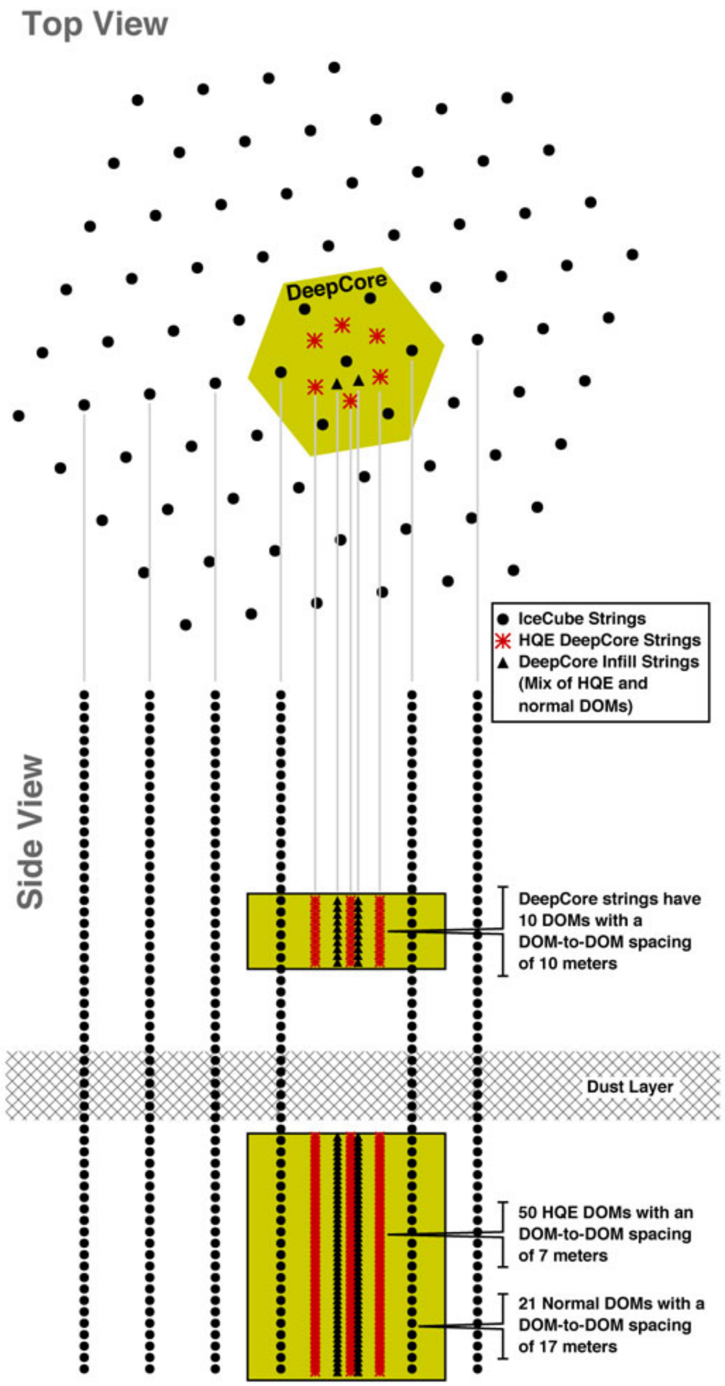
- ✤Several years ago … we unblinded one year of data which had ~ 20 000 neutrino events.
- ✤**Distributions compatible with the no sterile hypothesis.**

High-energy sterile bounds

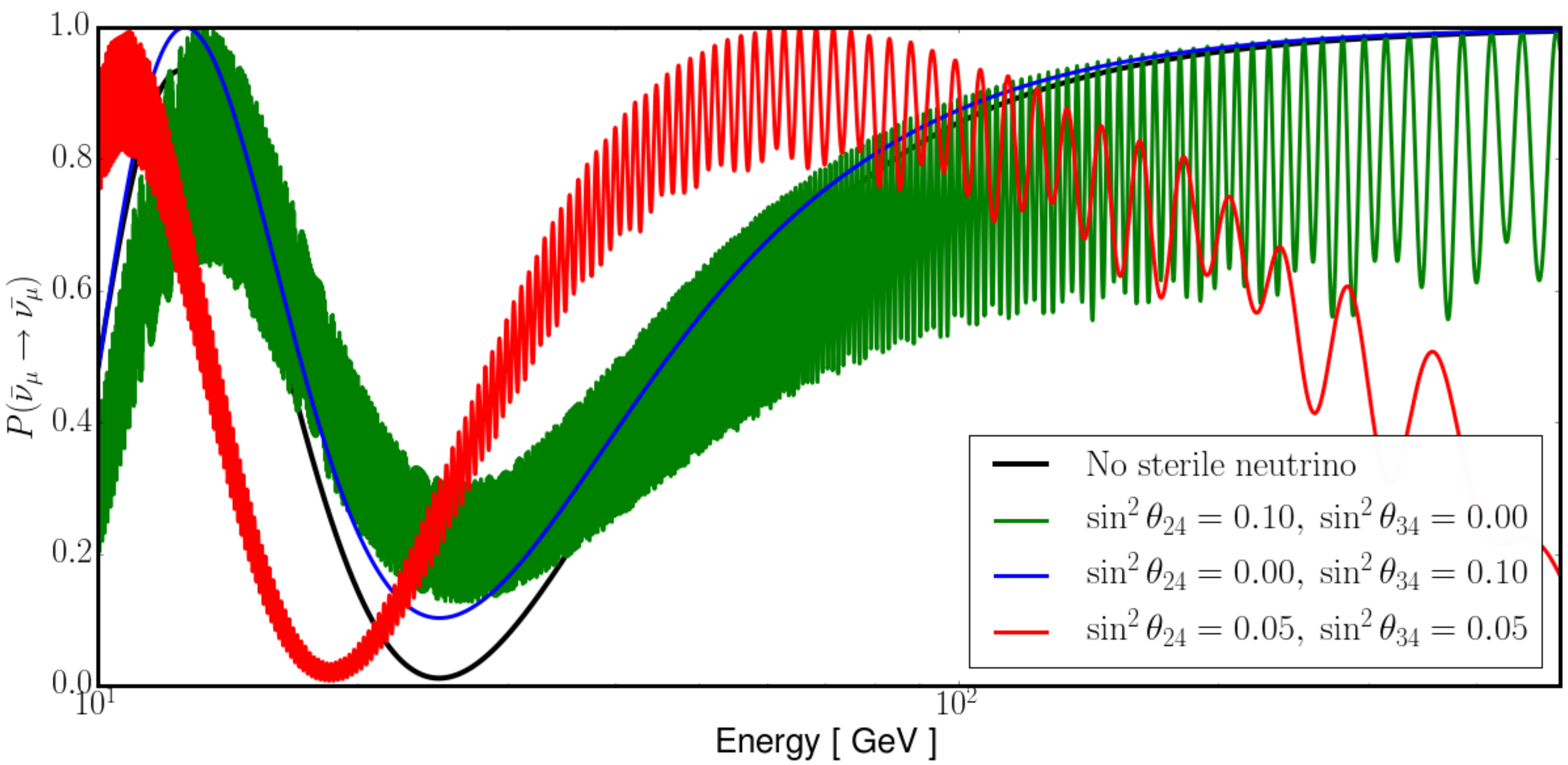


Update to seven years with improved event selection and systematics coming *very soon*!

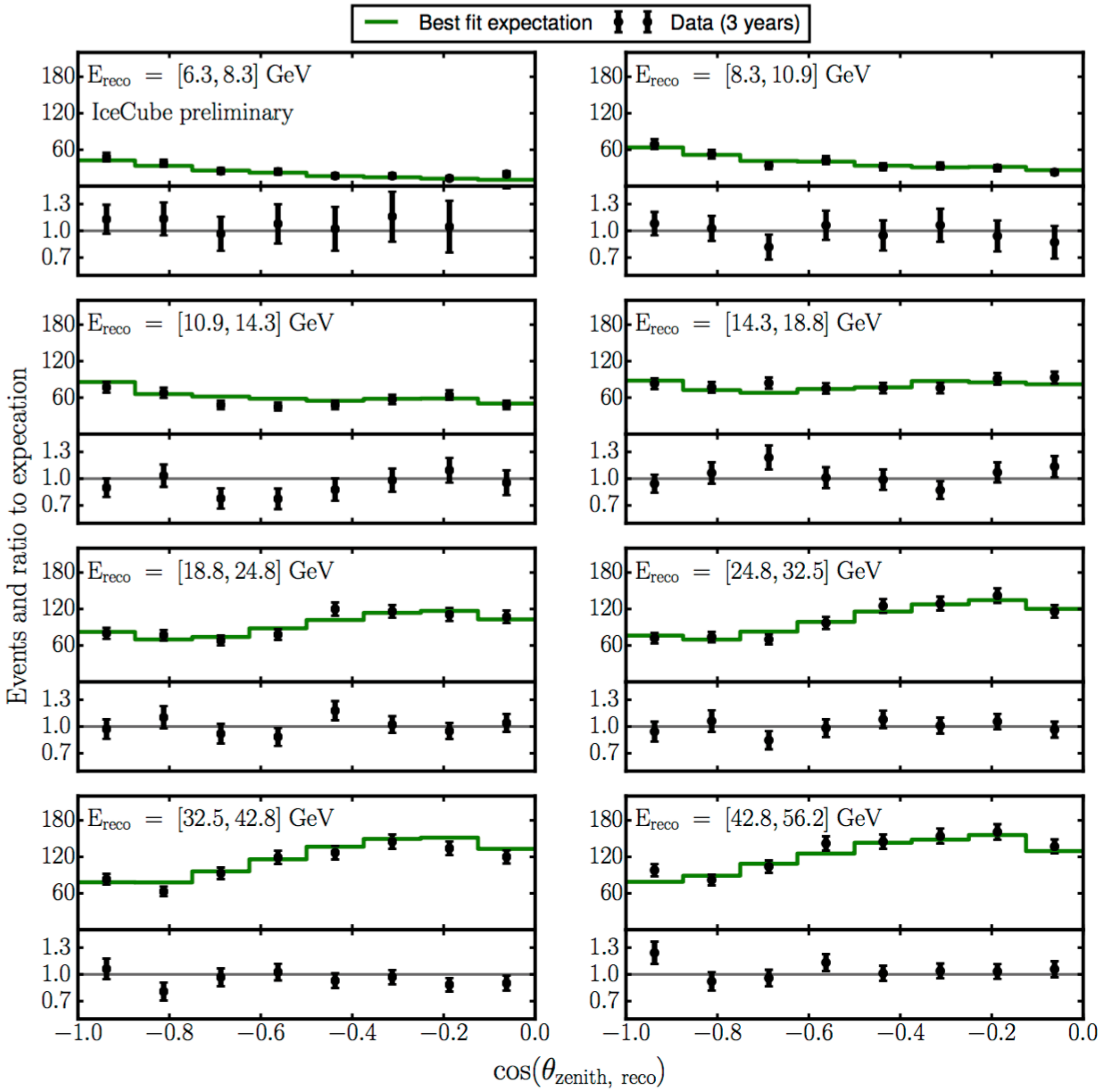
IceCube/DeepCore sterile analysis



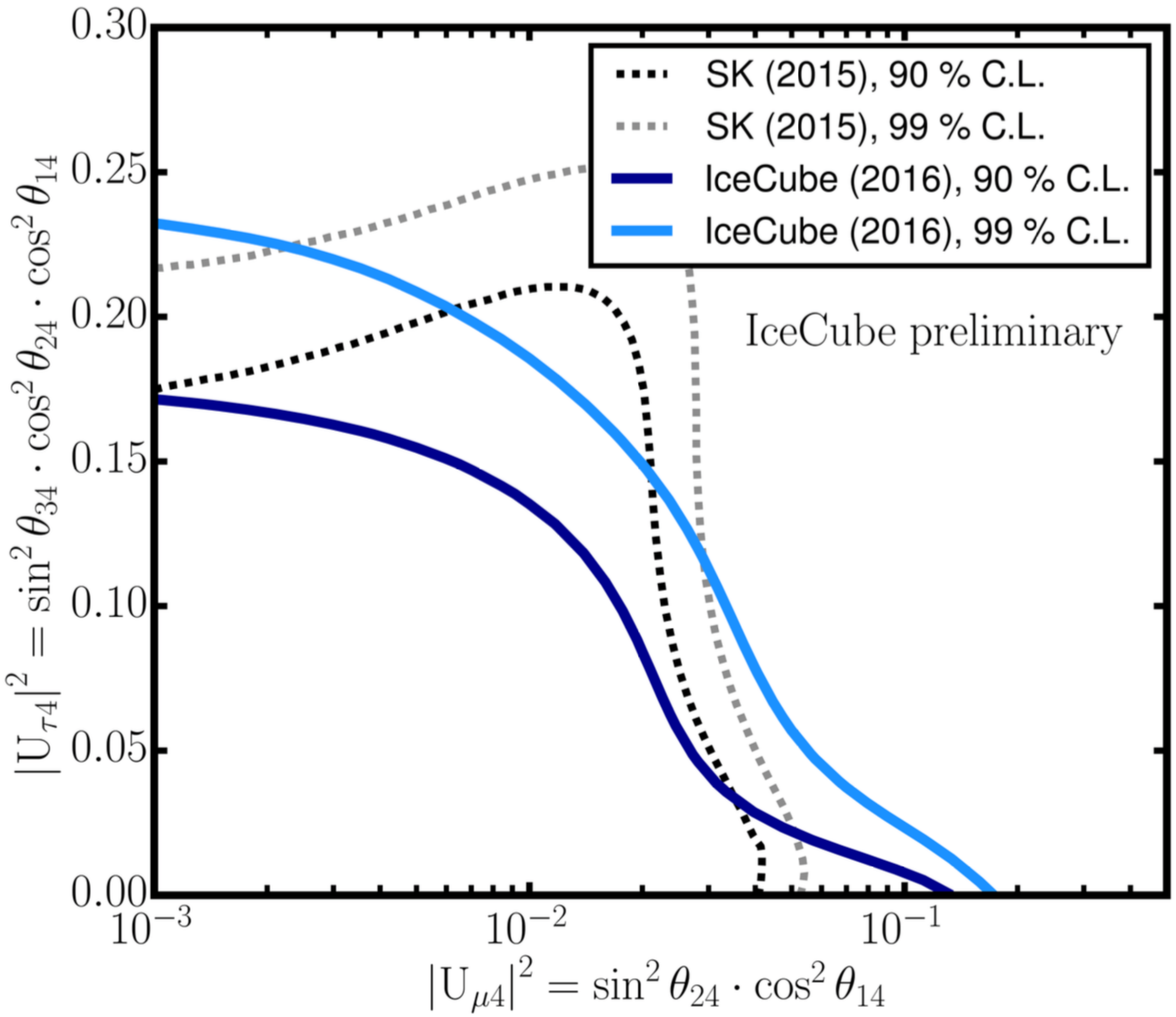
- DeepCore is a low energy extension of IceCube.
- We can look for distortions of the std. oscillations!
- We study θ_{34} and θ_{24}.



IceCube/DeepCore sterile analysis



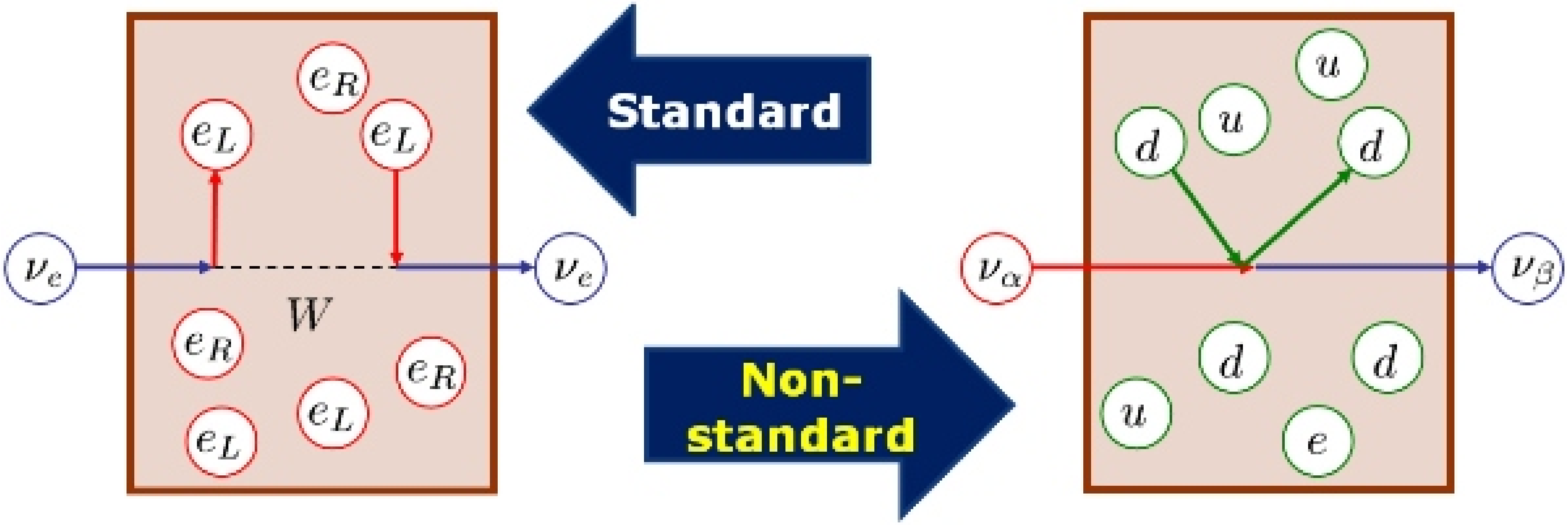
IceCube PRELIMINARY



Using events below a 100 GeV we can also obtain constraints on sterile neutrinos by deviations from standard oscillations.

Searches for non-standard interactions (NSI)

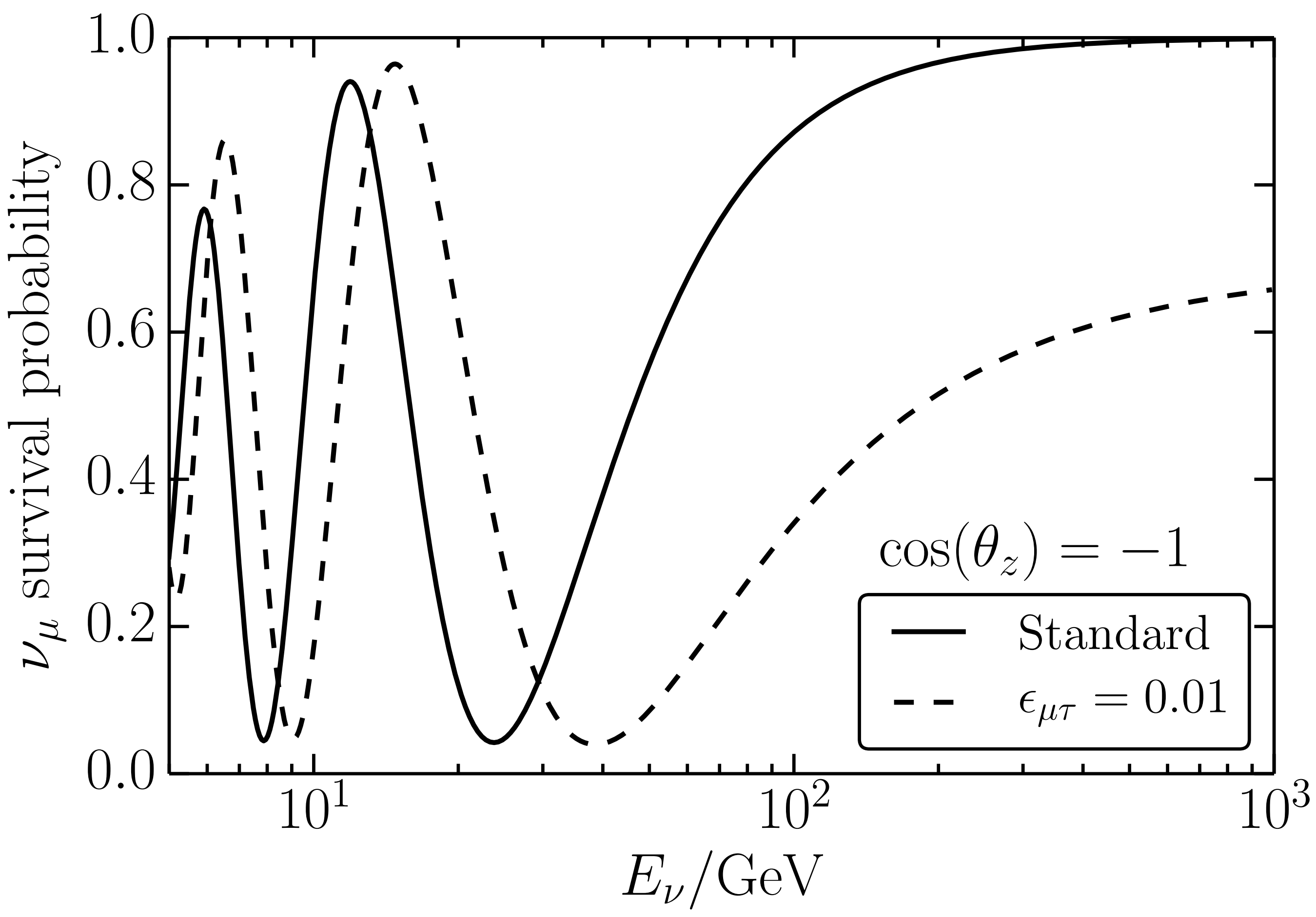
(from T. Ohlsson arXiv:1209.2710)

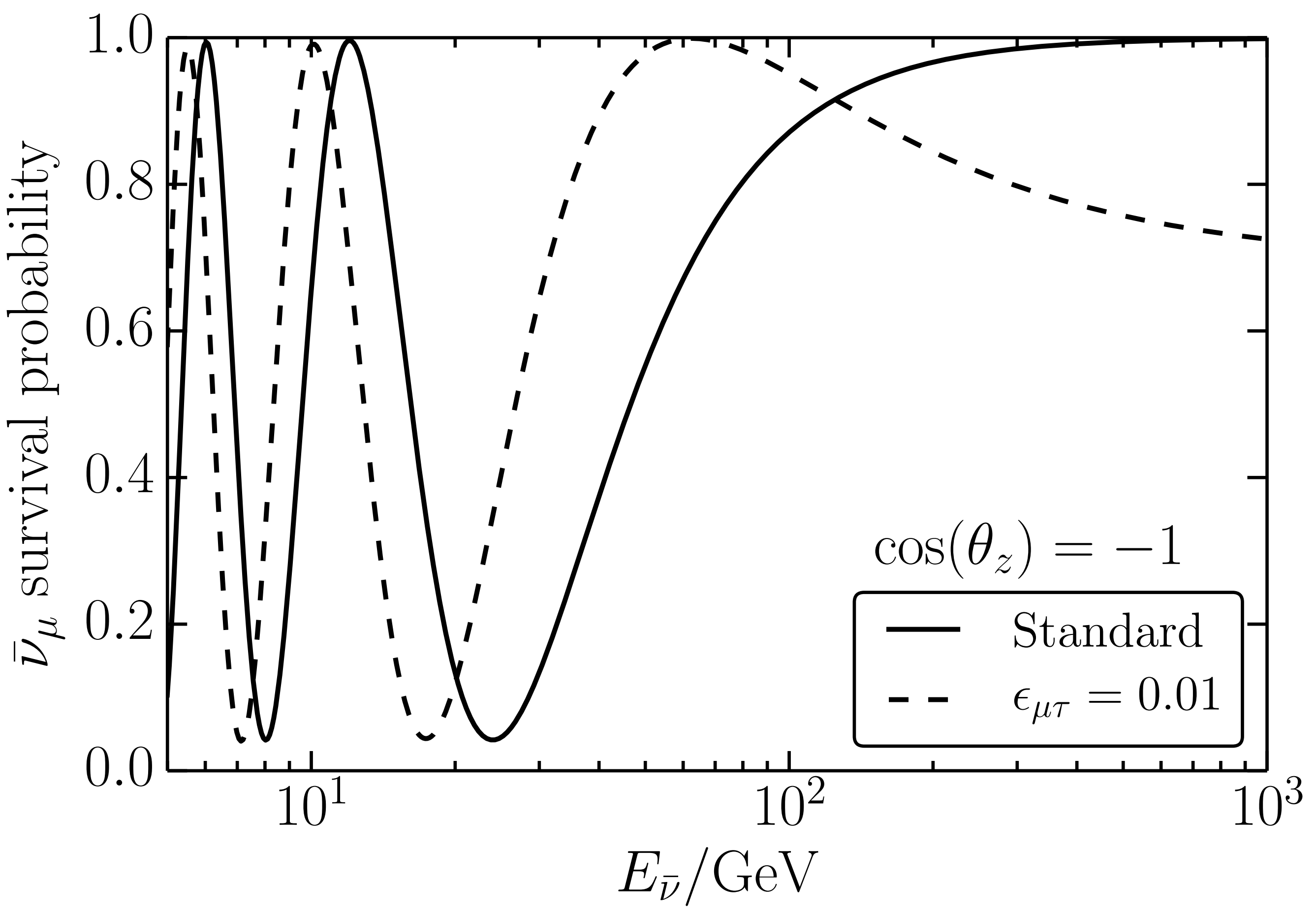


$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Searches for non-standard interactions (NSI)

- NSI interactions change the muon neutrino survival probability.
- We use an event selection based on our 3-year muon neutrino disappearance result (Phys. Rev. D 91, 072004 (2015)).

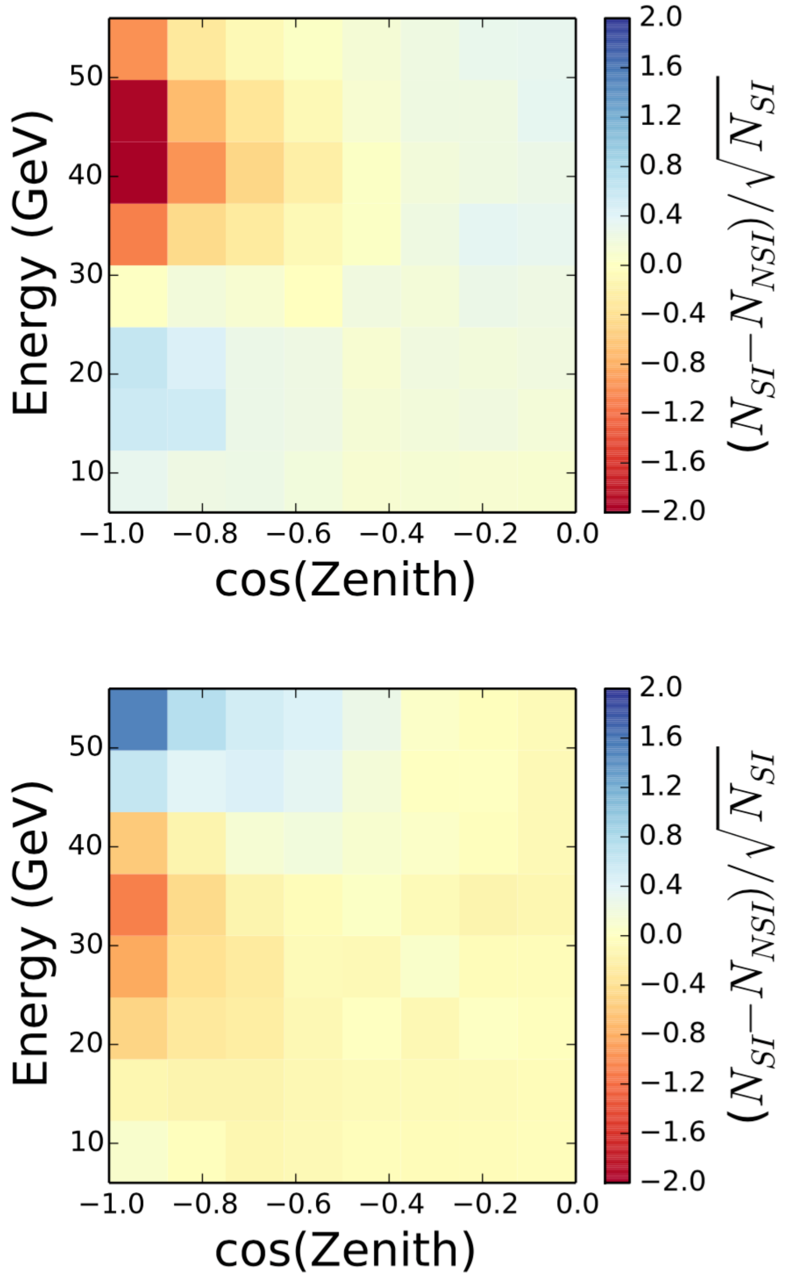


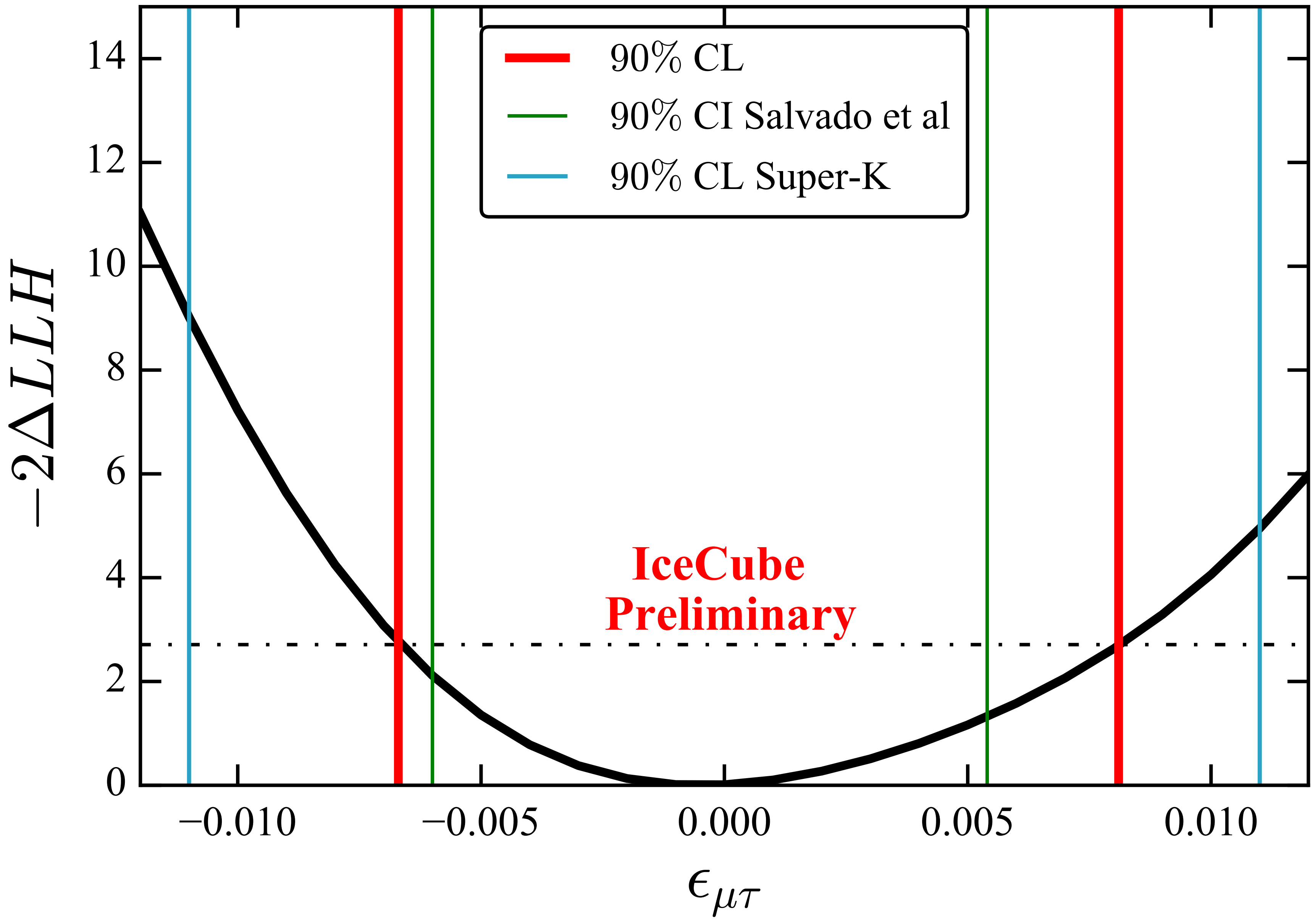


IceCube NSI result

$$\epsilon = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^{*} & \boldsymbol{\epsilon_{\mu\mu}} & \boxed{\boldsymbol{\epsilon_{\mu\tau}}} \\ \epsilon_{e\tau}^{*} & \boxed{\boldsymbol{\epsilon_{\mu\tau}^{*}}} & \boldsymbol{\epsilon_{\tau\tau}} \end{pmatrix}$$

$\epsilon_{\mu\tau} = 0.01$

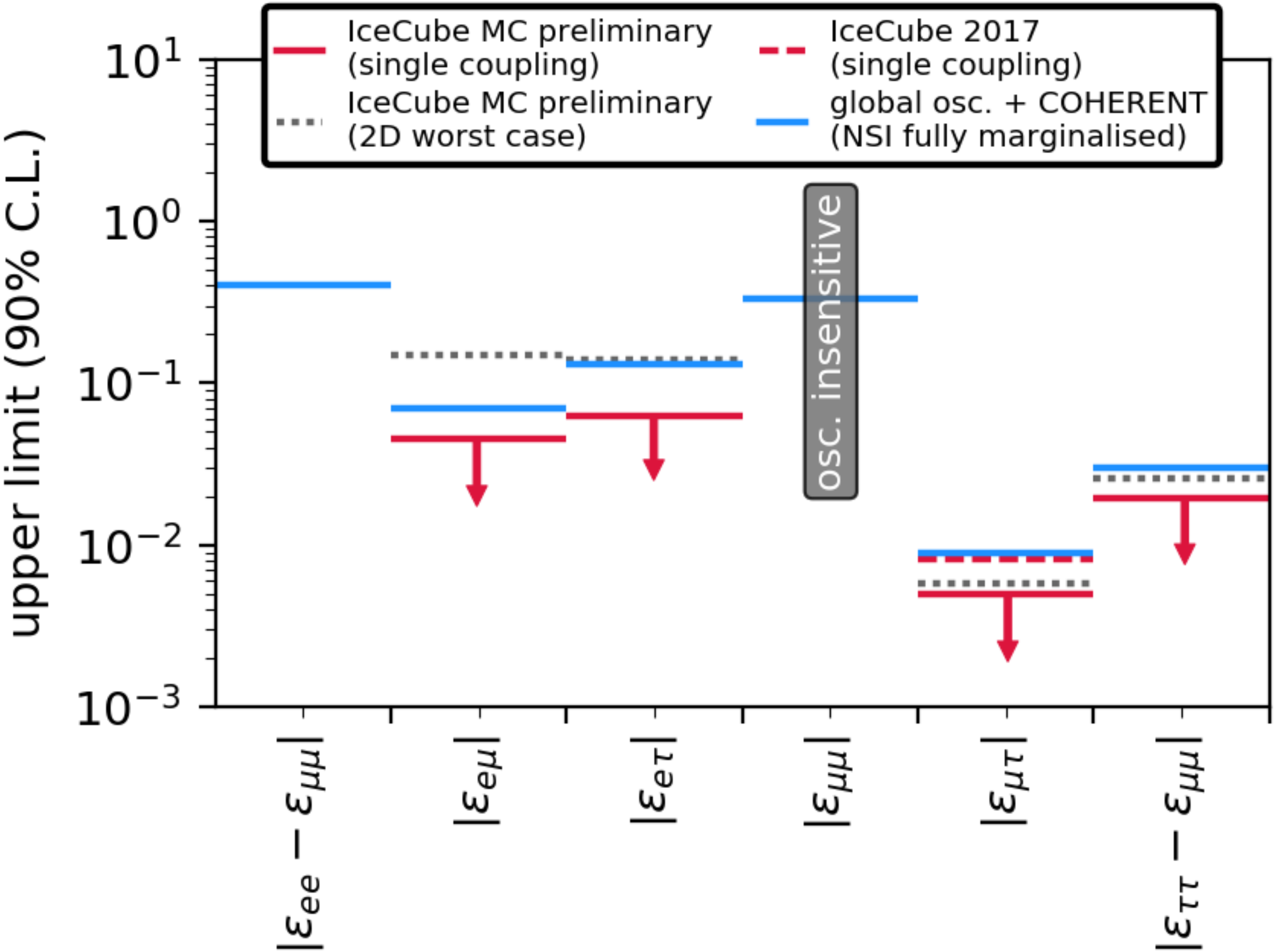




*Salvado et al. use public high-energy IceCube data

http://icecube.wisc.edu/science/data/IC86-sterile-neutrino

Updated NSI result with DeepCore on its way!



Take home message

- ✤**New** 7.5 year high-energy starting events result: softer spectrum, consistent with one power law.
- ✤Through-going nu-mu still consistent with starting events astrophysical spectrum. Hard spectrum preferred.
- ✤**First** double cascade spotted. Studies to determine its “tauness” underway.
- ✤**No** observation of prompt flux neutrinos.
- ✤**New** measurement of very high-energy neutrino cross section with nu-mu and all flavors.
- ✤**Best** limits on Lorentz Violation with atmospheric neutrinos.
- ✤**Soon.** Oscillation analysis in the TeV range looking for sterile neutrinos in preparation: increase from one to seven years!
- ✤Very competitive DeepCore-IceCube oscillation results in standard and new physics searches. Check out more details in Doug Cowen talk earlier this week!

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

We are friendly and curious *penguins* :)

Thank you!

THE ICECUBE COLLABORATION

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
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Technische Universität Dortmund
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Universität Mainz
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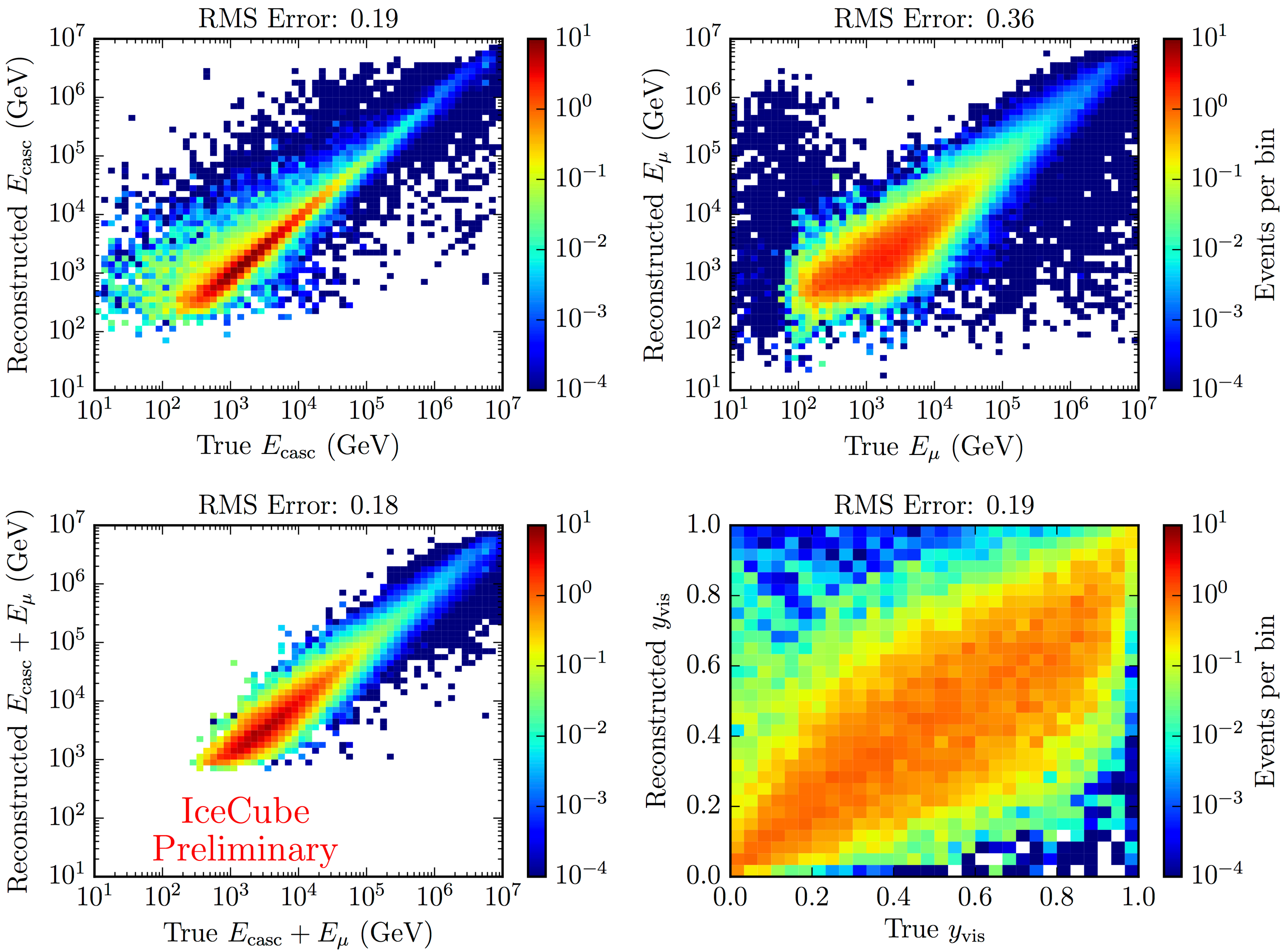
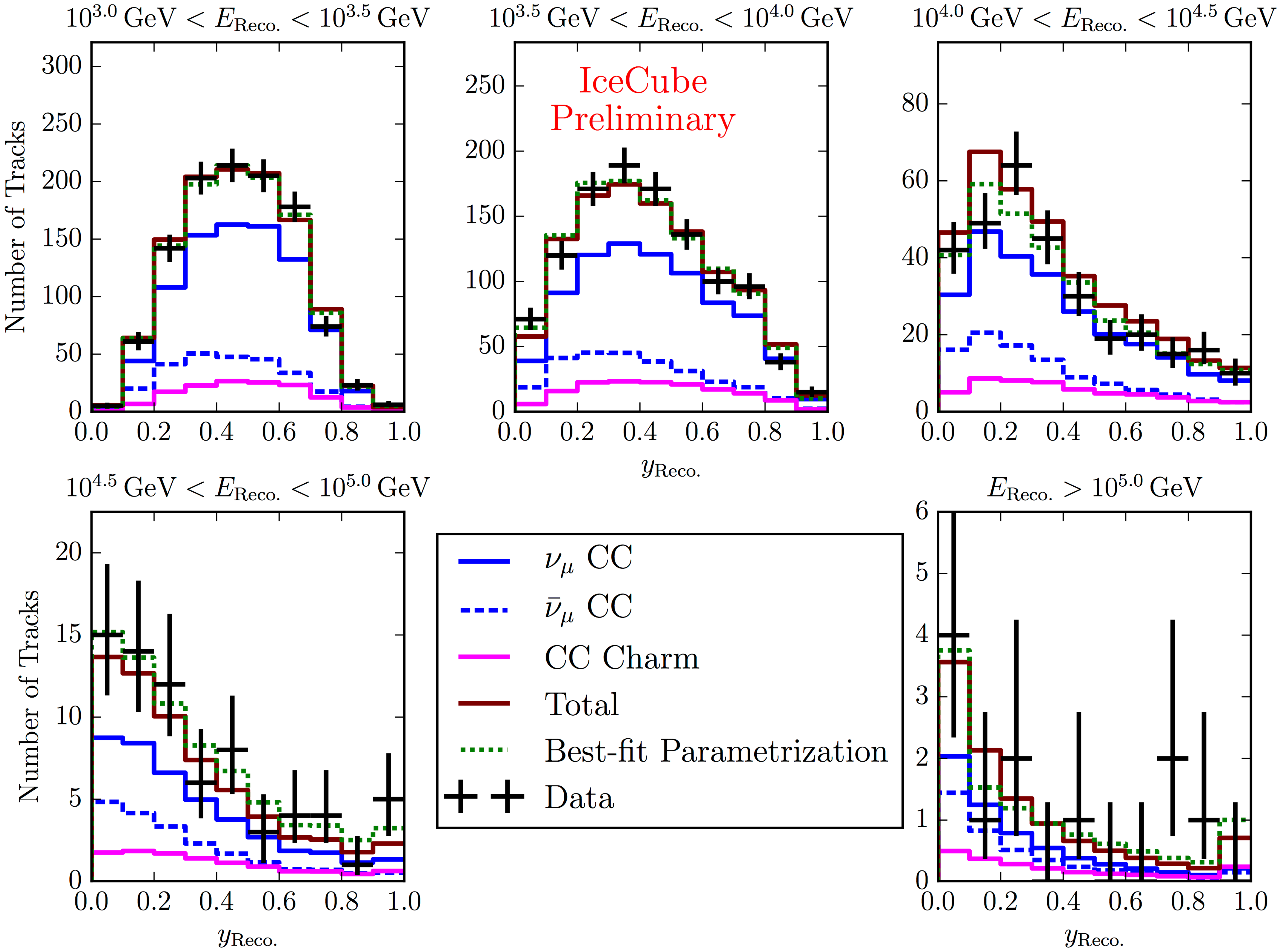
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

Bonus slides

Inelasticity analysis



Inelasticity distributions

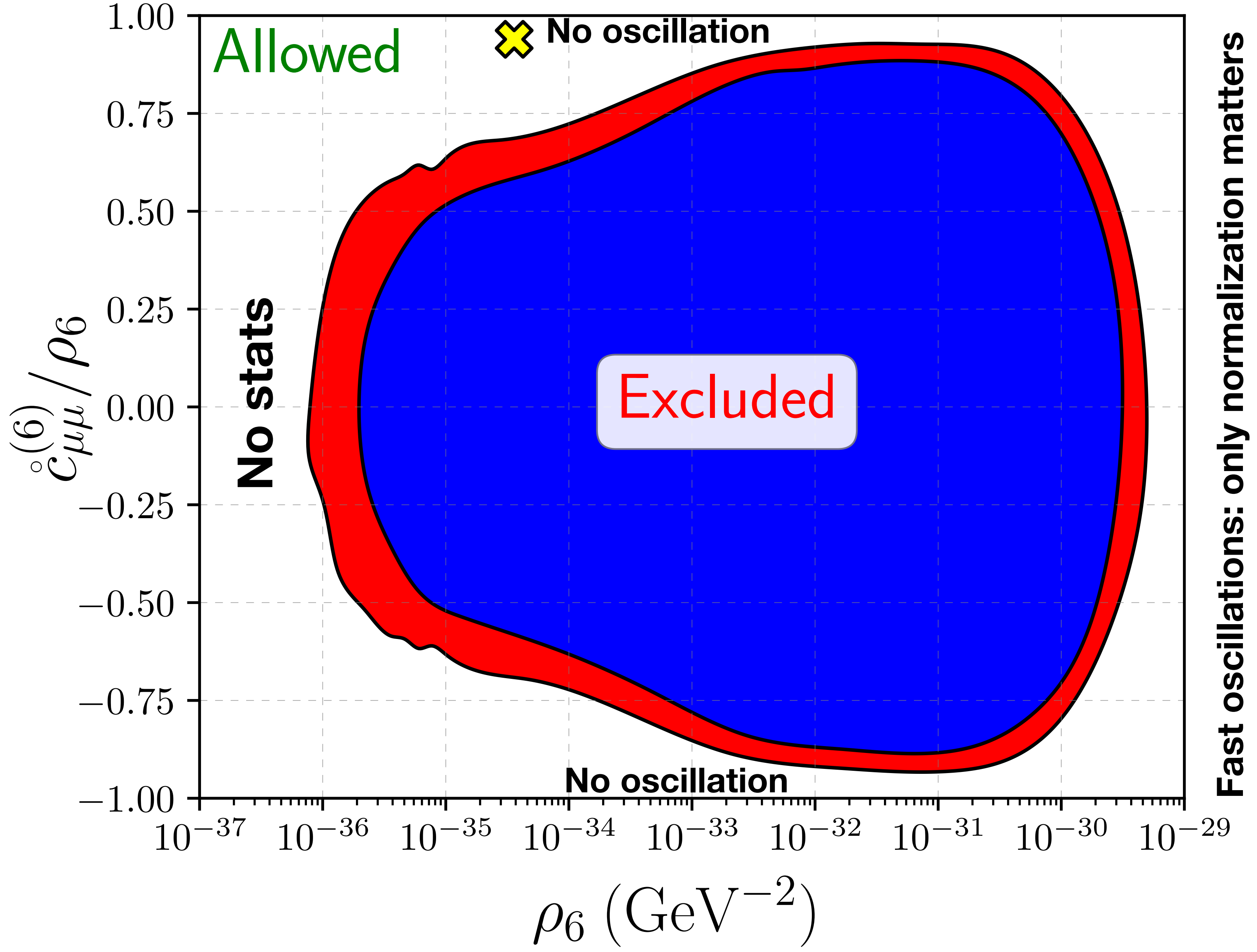


Anatomy of the dim-6 operator constraint

- 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

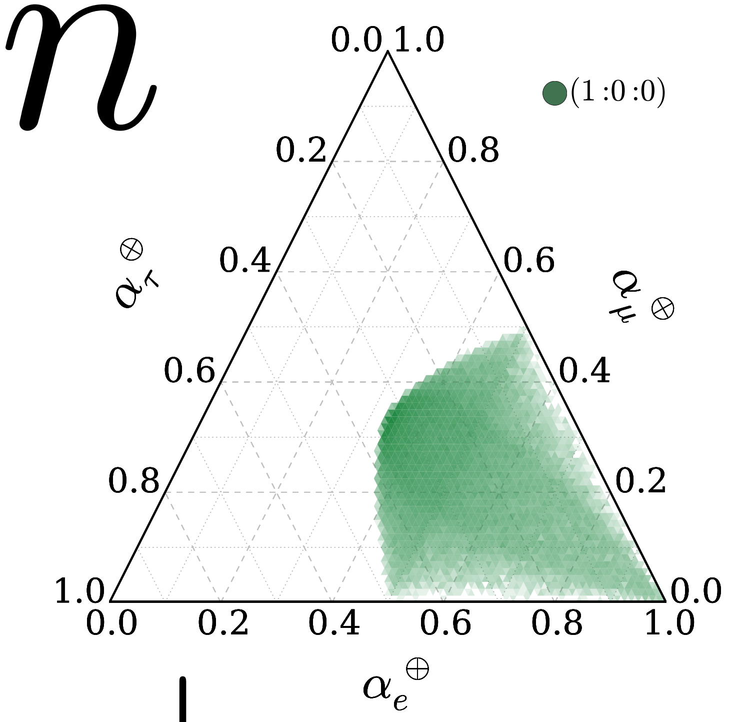
Flavor composition @ source

	(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)

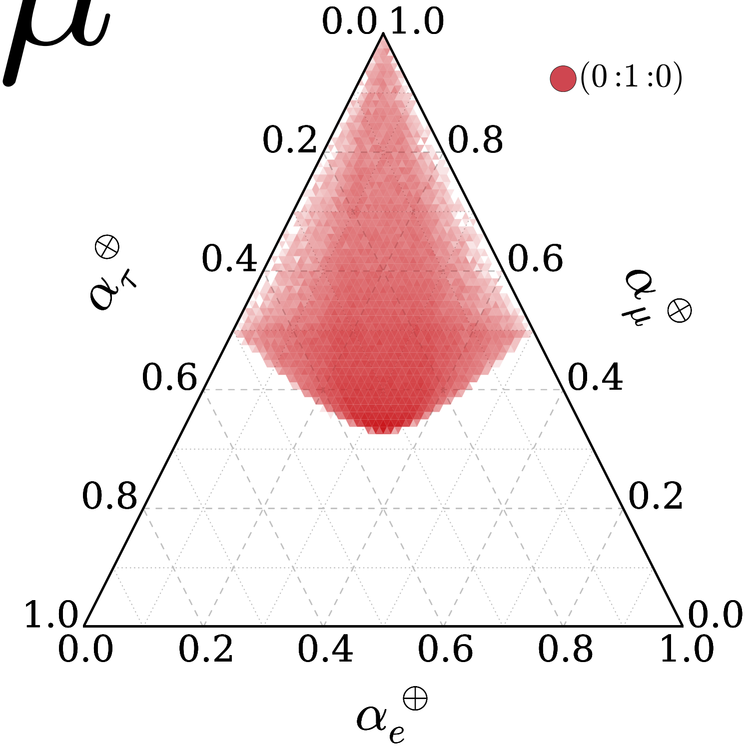
Possible flavor triangles

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

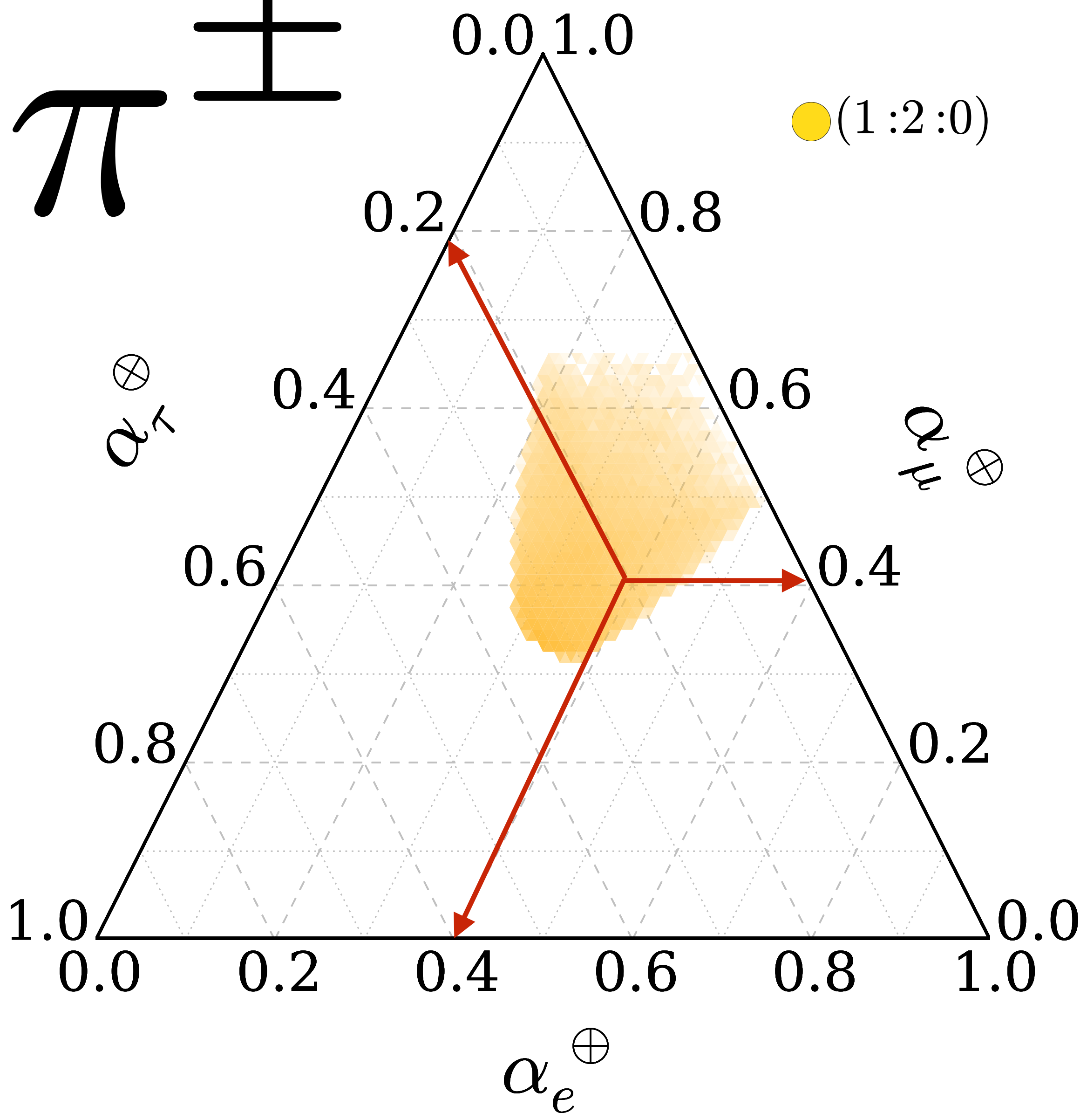
n



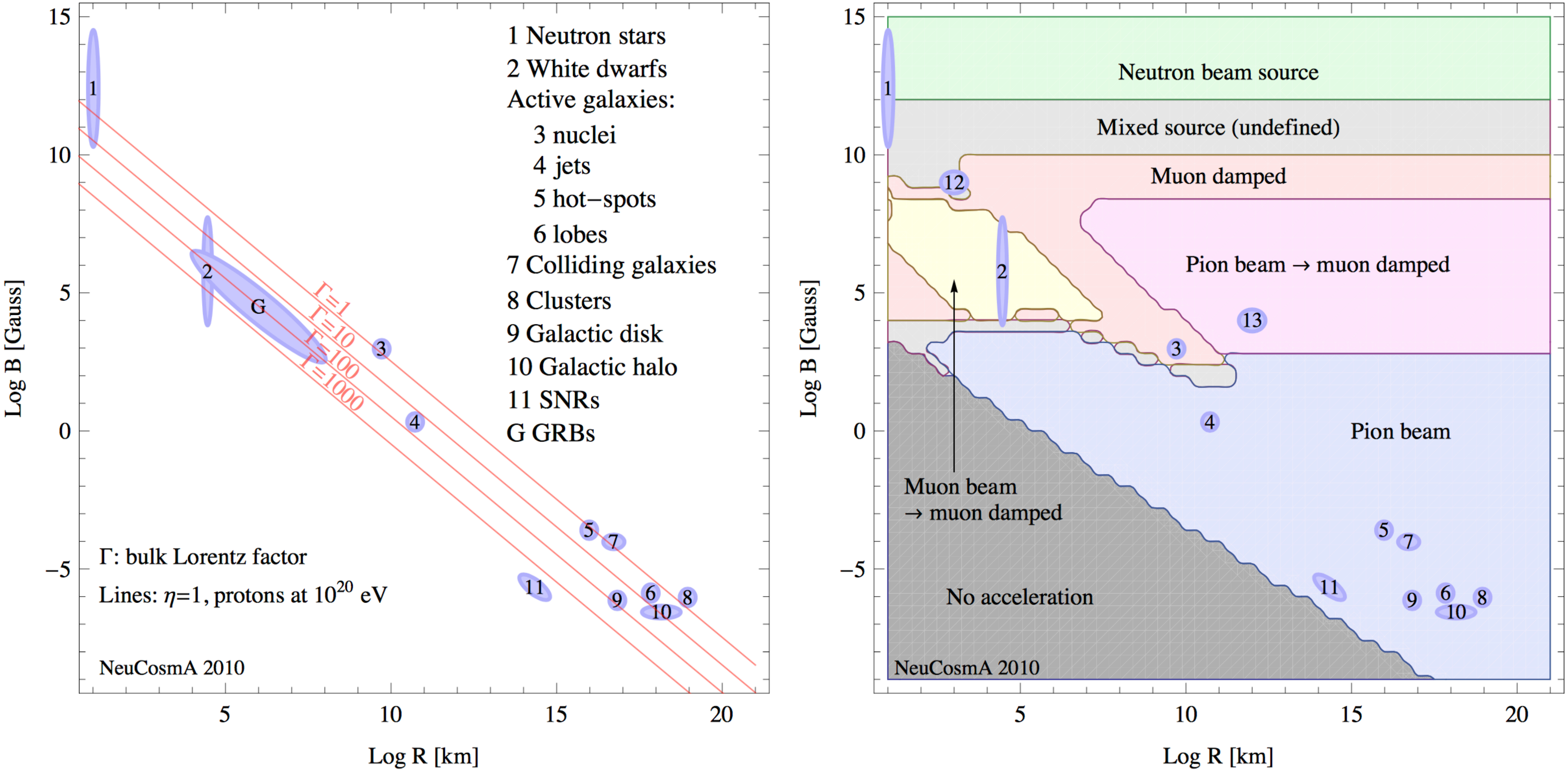
$\mu^{\pm}$



$\pi^{\pm}$

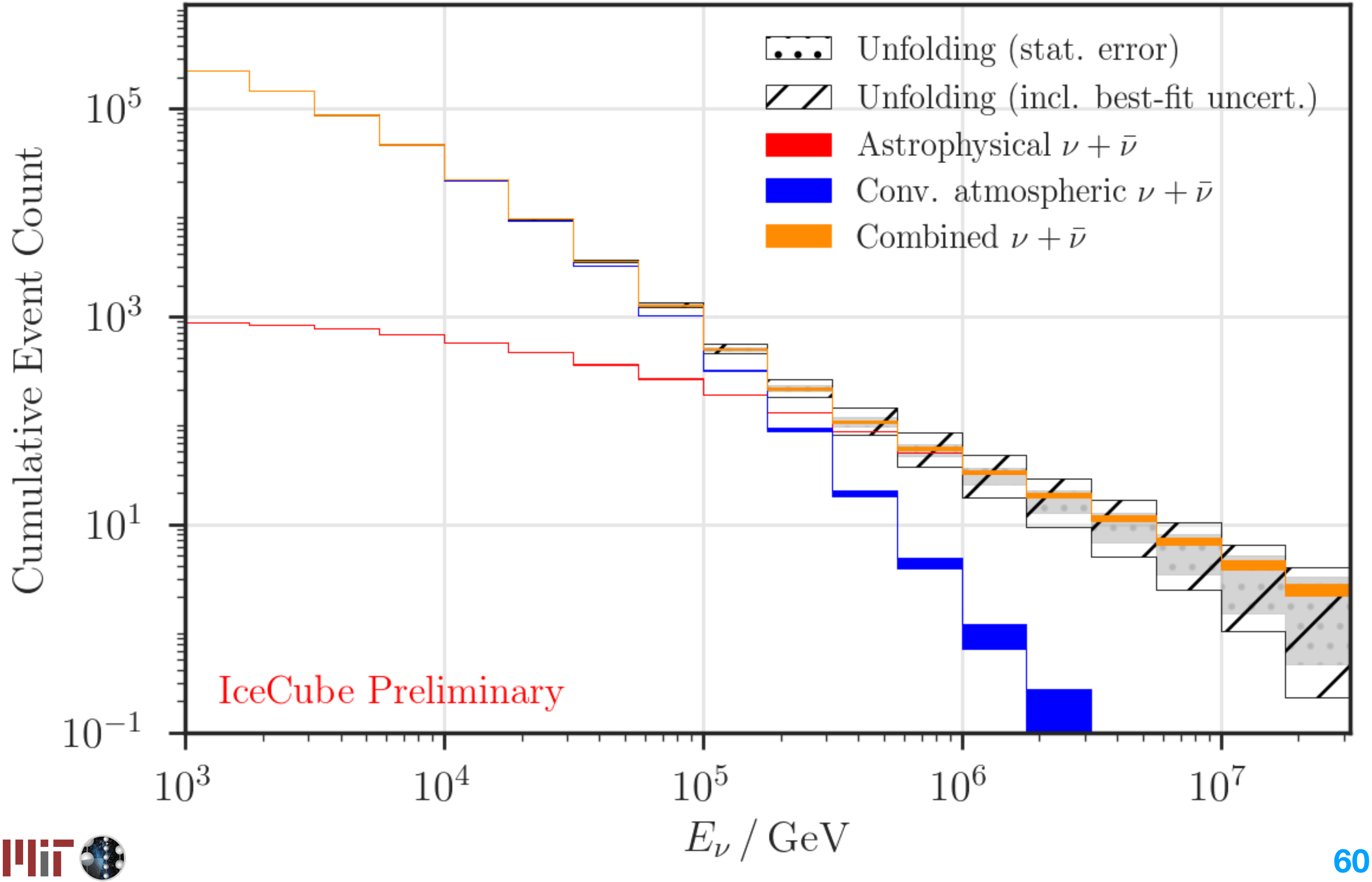


Due to unitarity the possible Earth flavor ratios for a given initial flavor composition is confined.



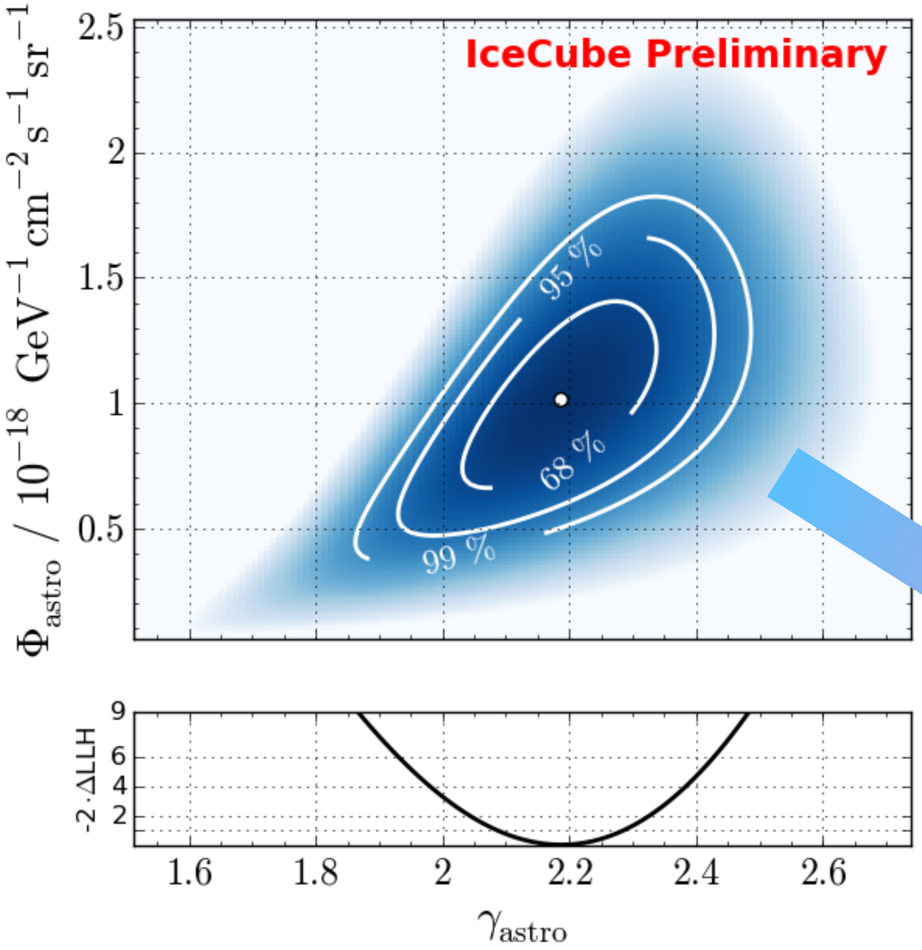
(arXiv:1007:0006)

Unfolded 8 year through-going distribution



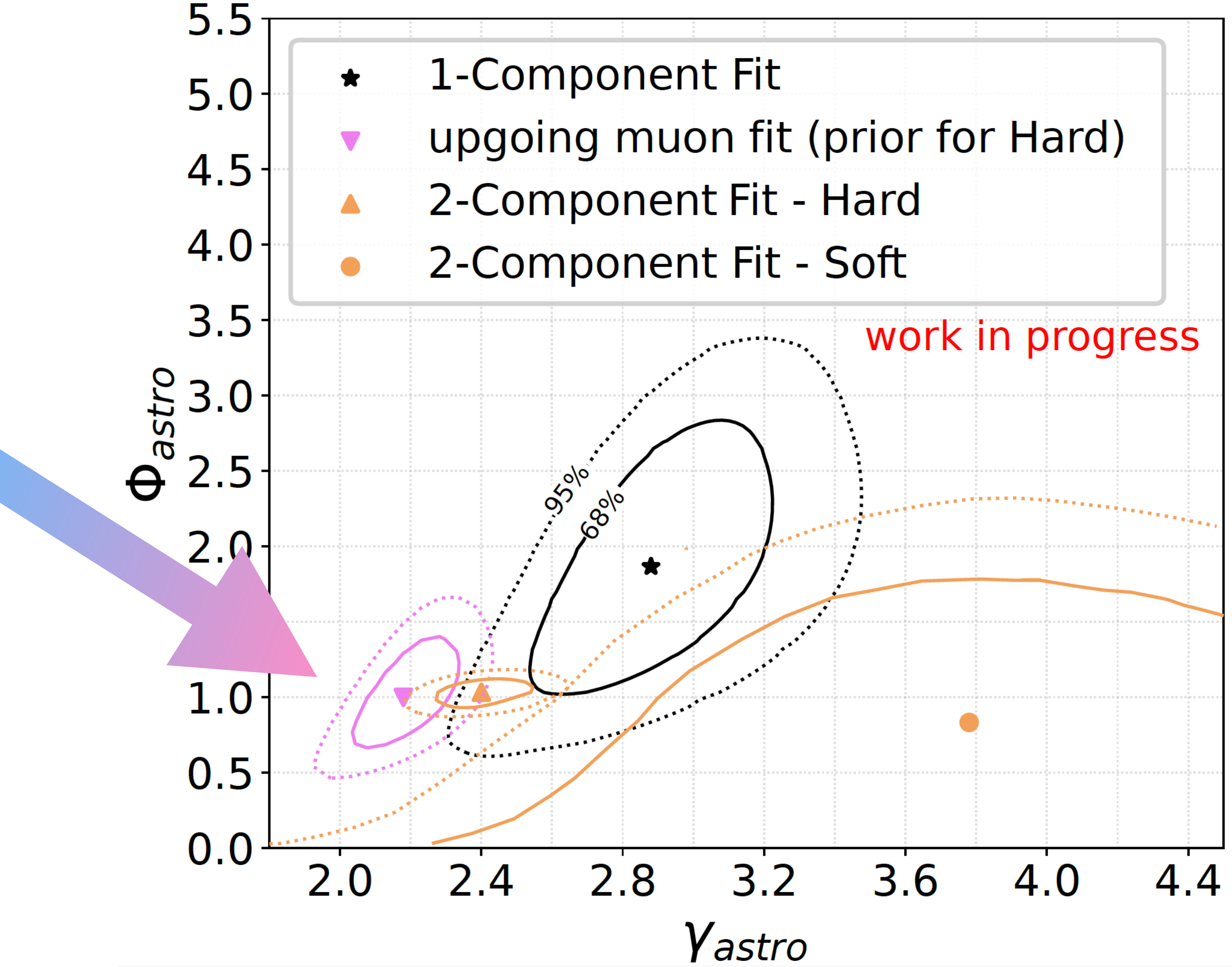
Astrophysical spectral index

From through-going muons



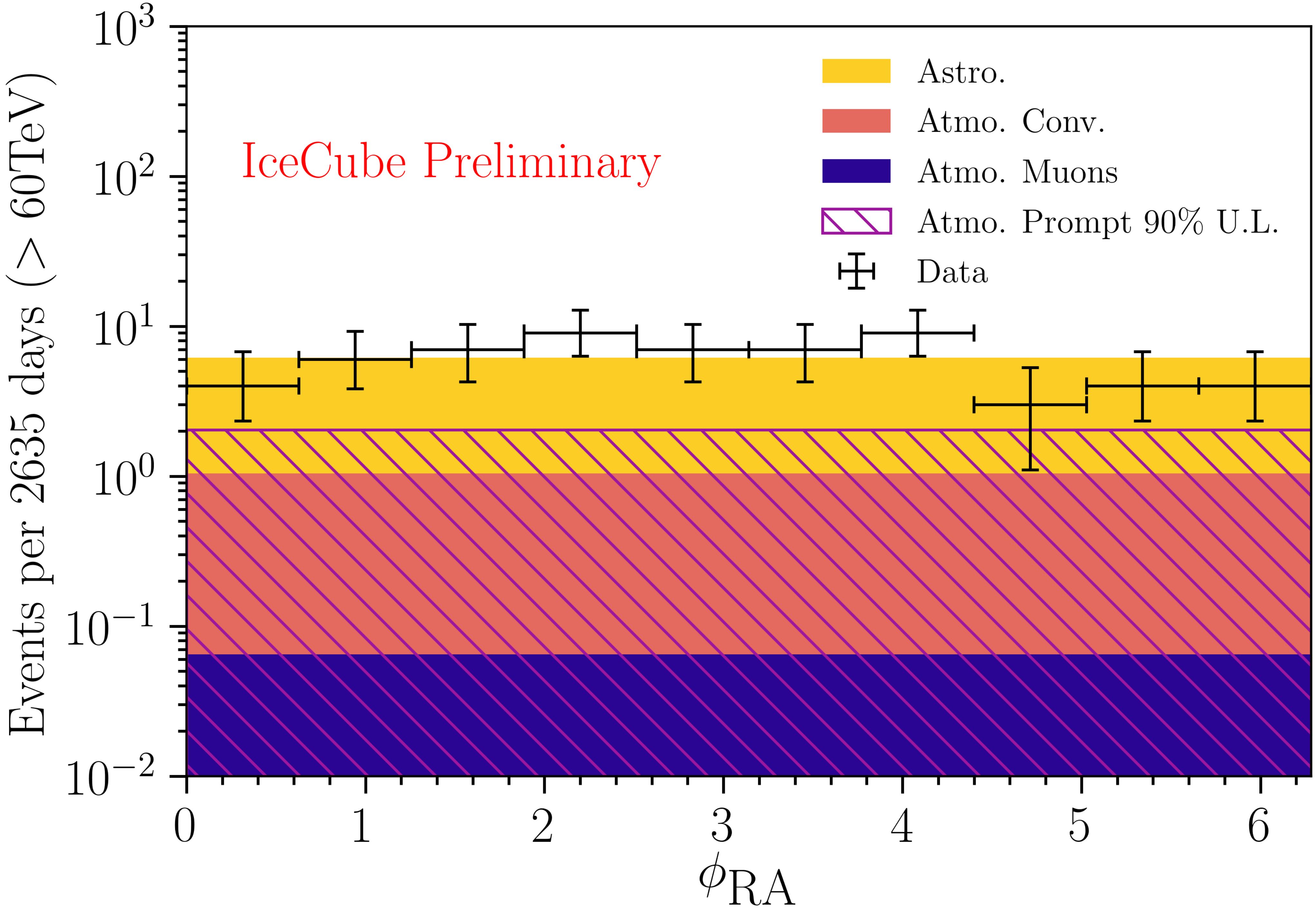
Single power law spectral index from through-going Muon neutrinos: 2.19±0.10

From high-energy starting events



No significant evidence for two power law solution!

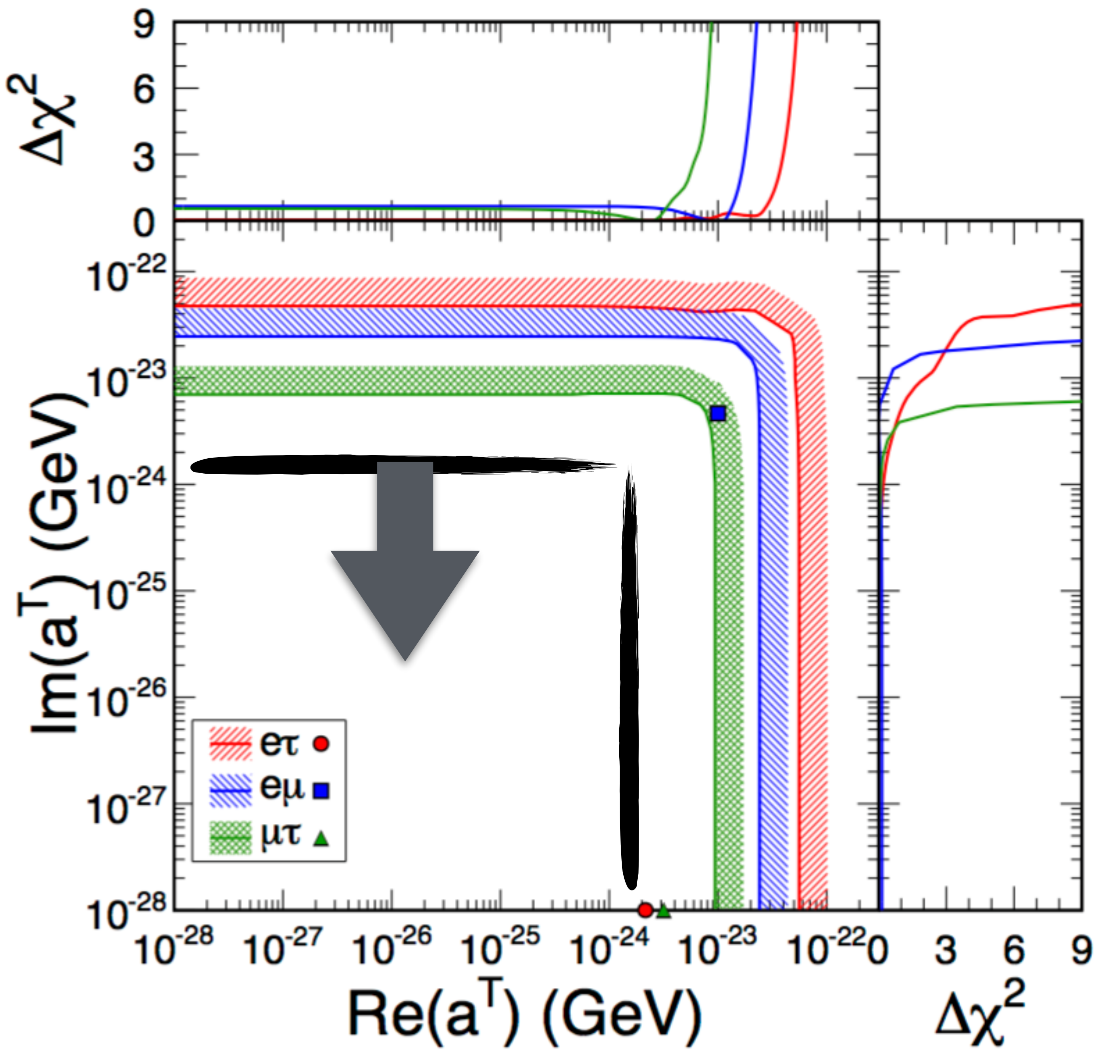
Right Ascension distribution HESE

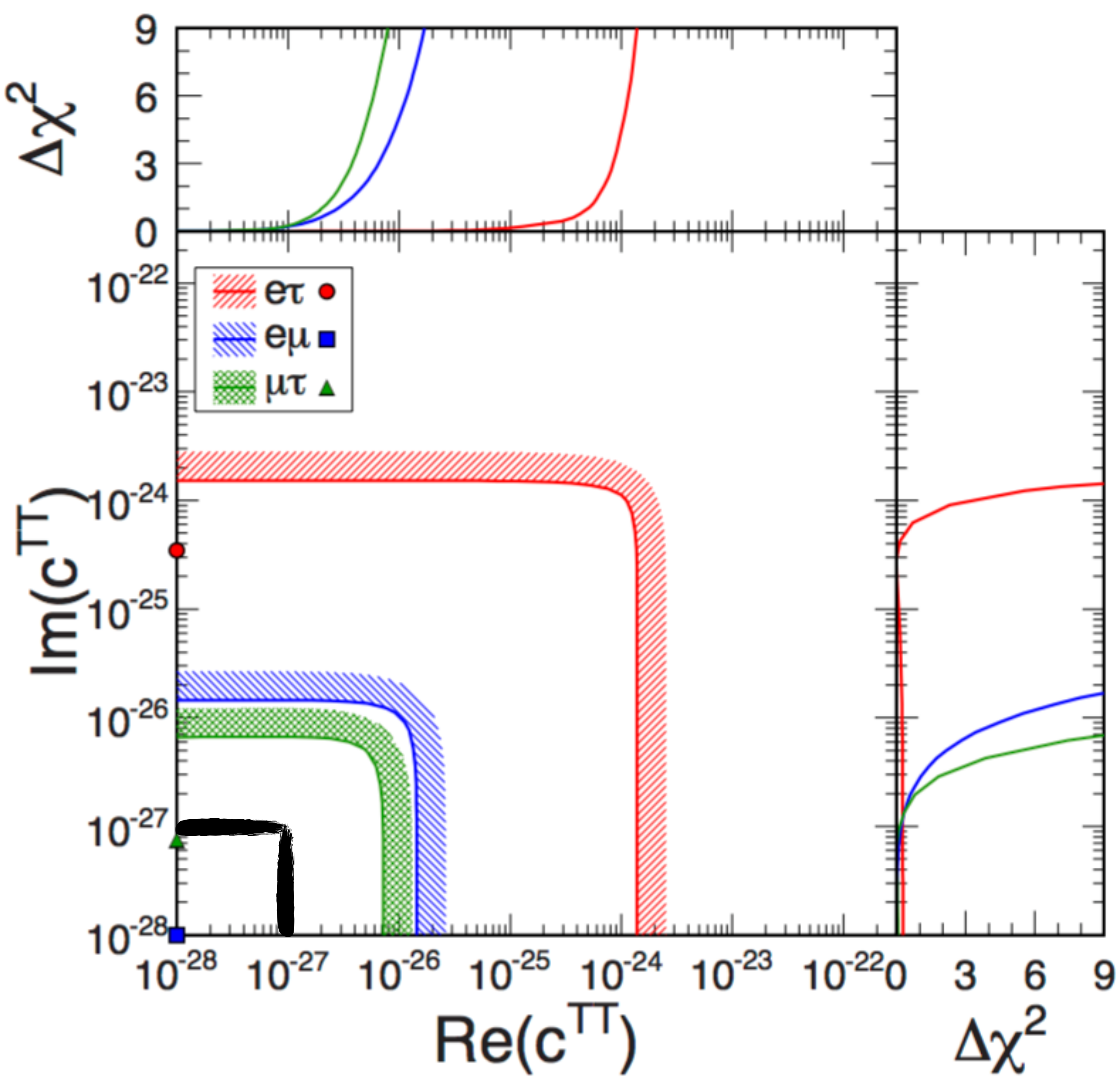


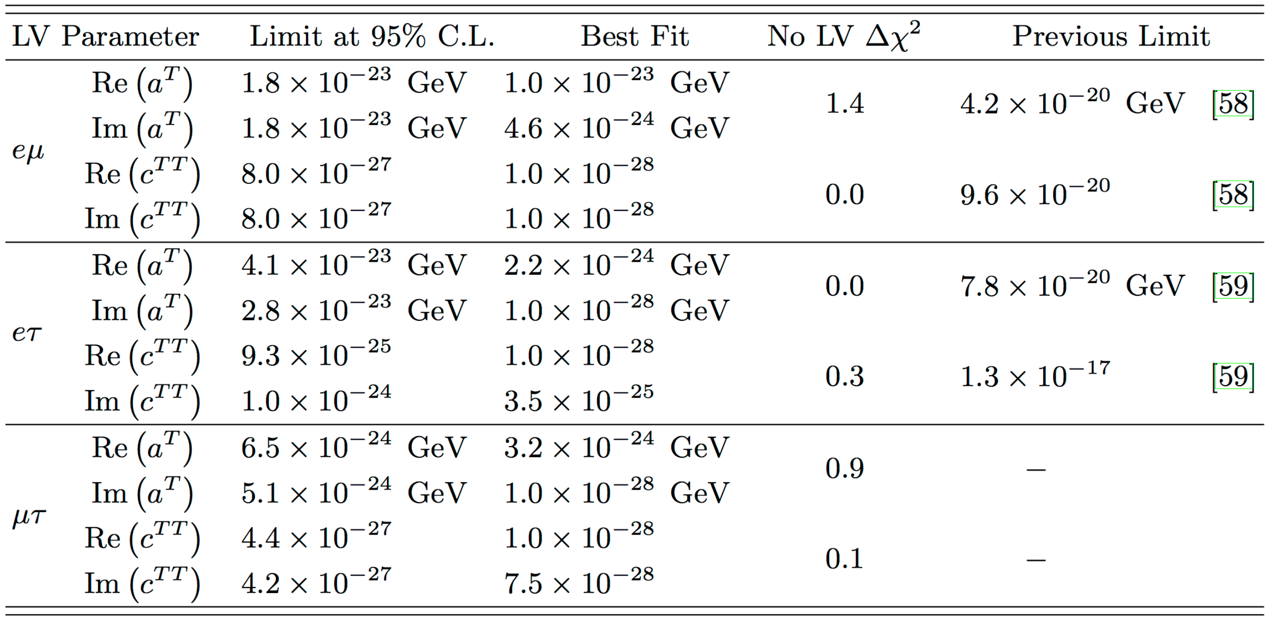
arXiv:1410.4267

Current bounds from SK

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



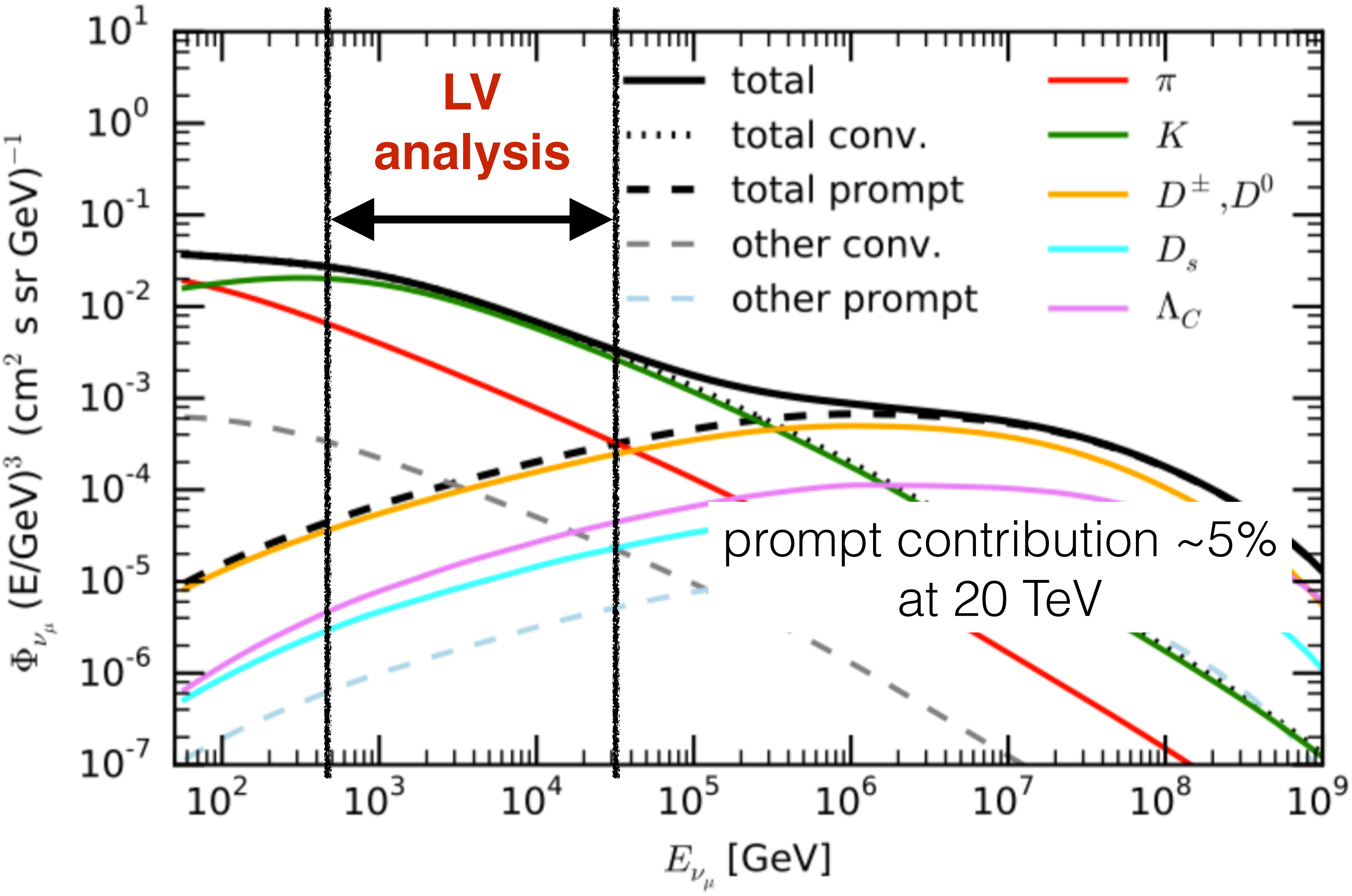




LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [58]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	Re (c^{TT})	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [58]
	Im (c^{TT})	8.0×10^{-27}	1.0×10^{-28}		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

IC wins a lot in c due to the E factor

Atmospheric flux decomposed



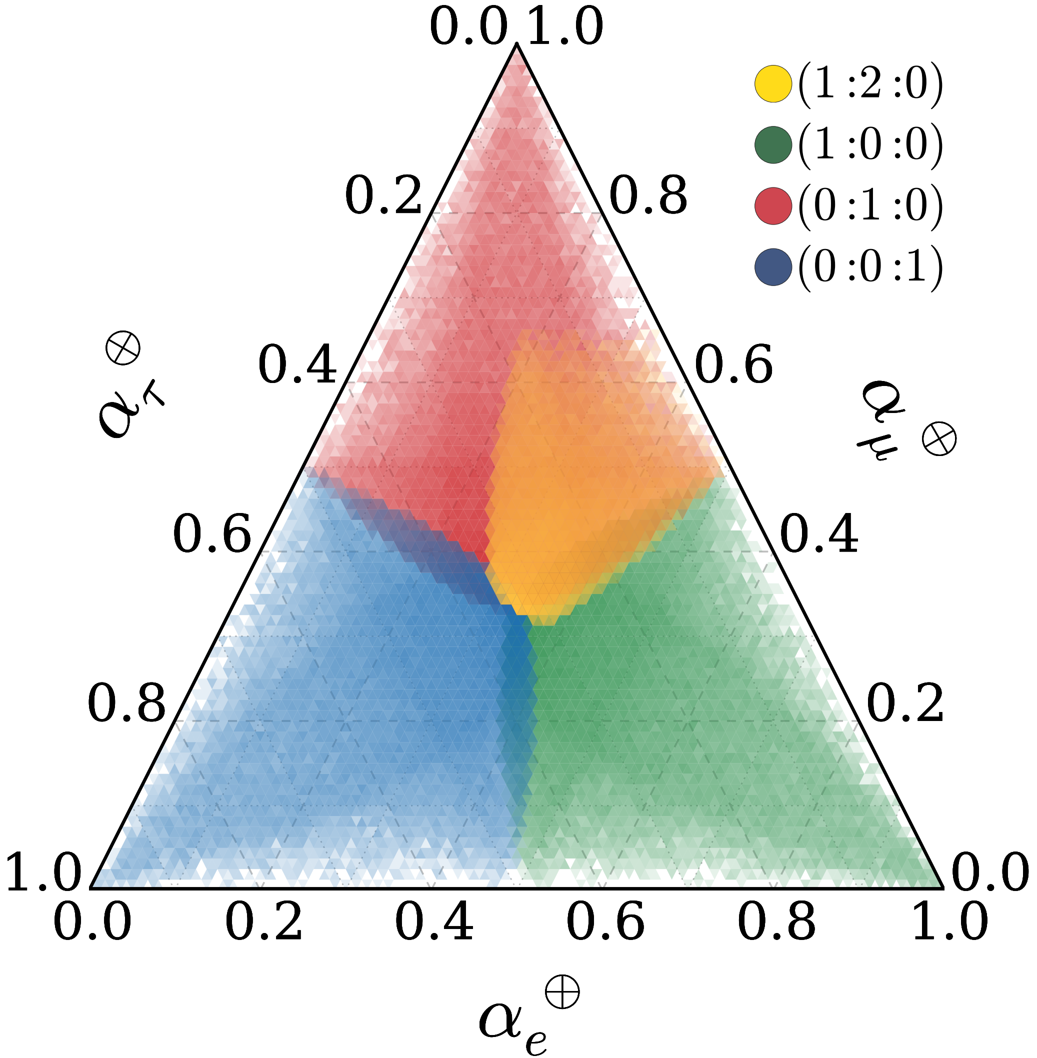
LV analysis

prompt contribution ~5% at 20 TeV

+ New physics: effective operators

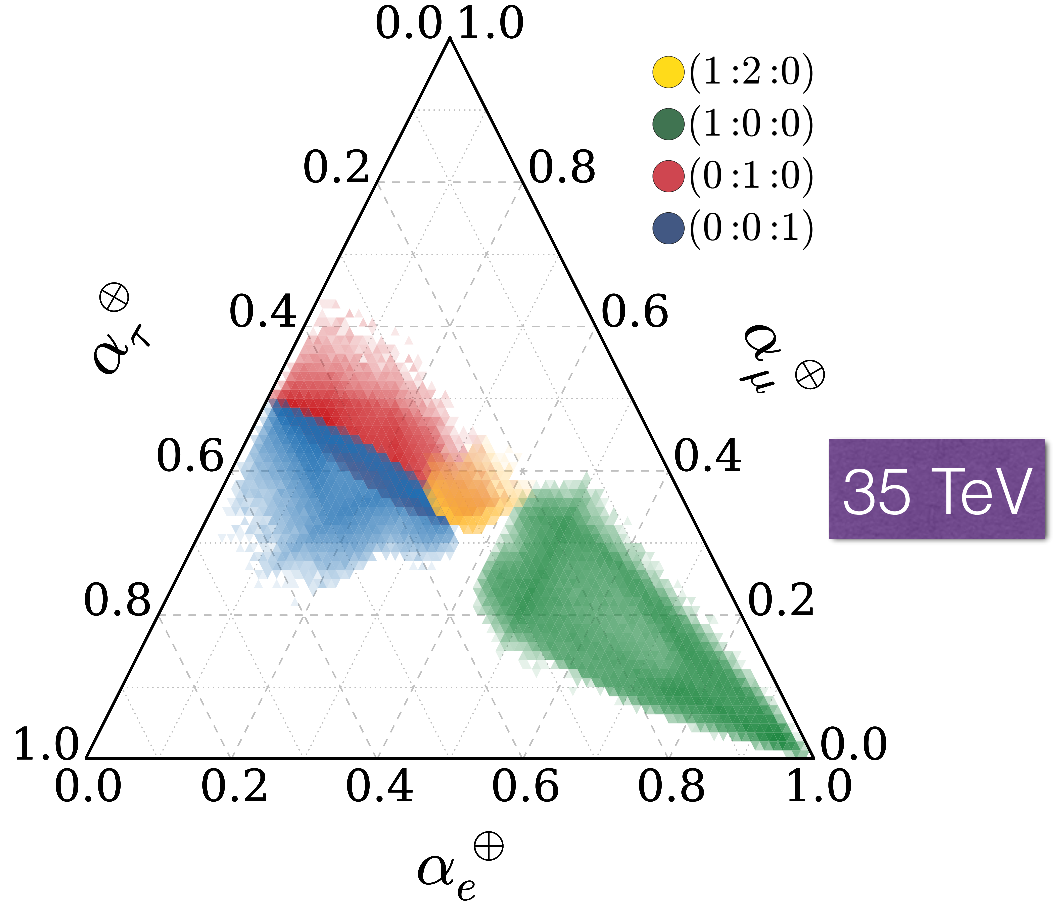
$$H = \frac{1}{2E} U M^2 U^\dagger + \boxed{\sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger}$$

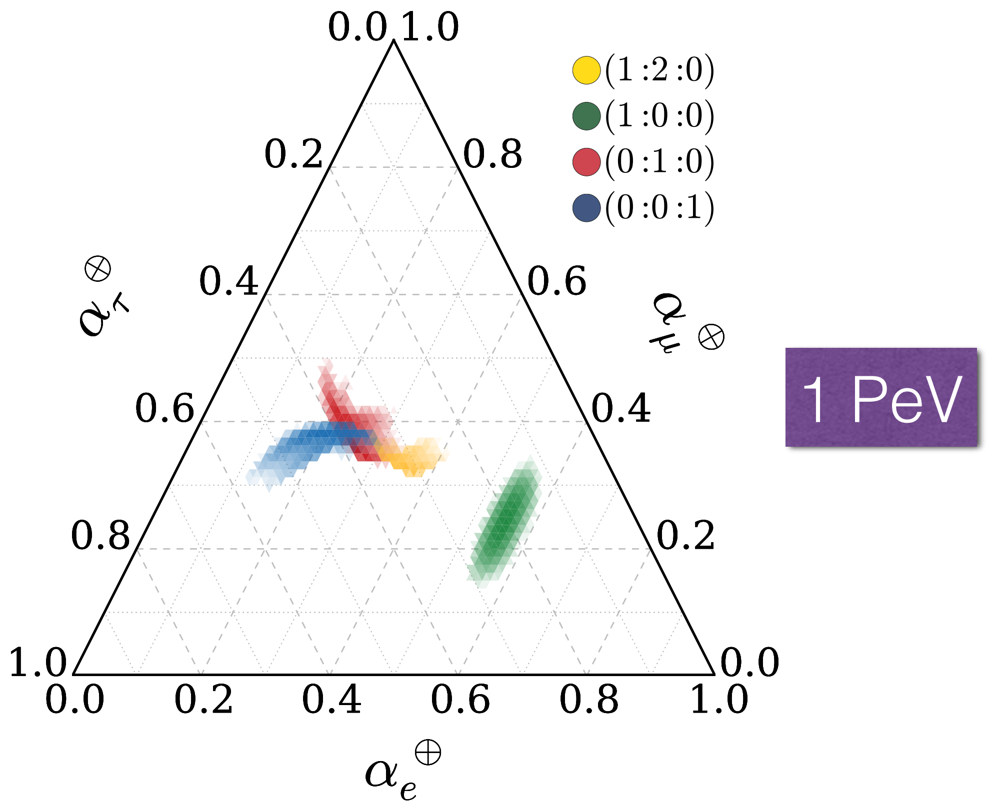
(setting operators scales to current SK bounds)



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

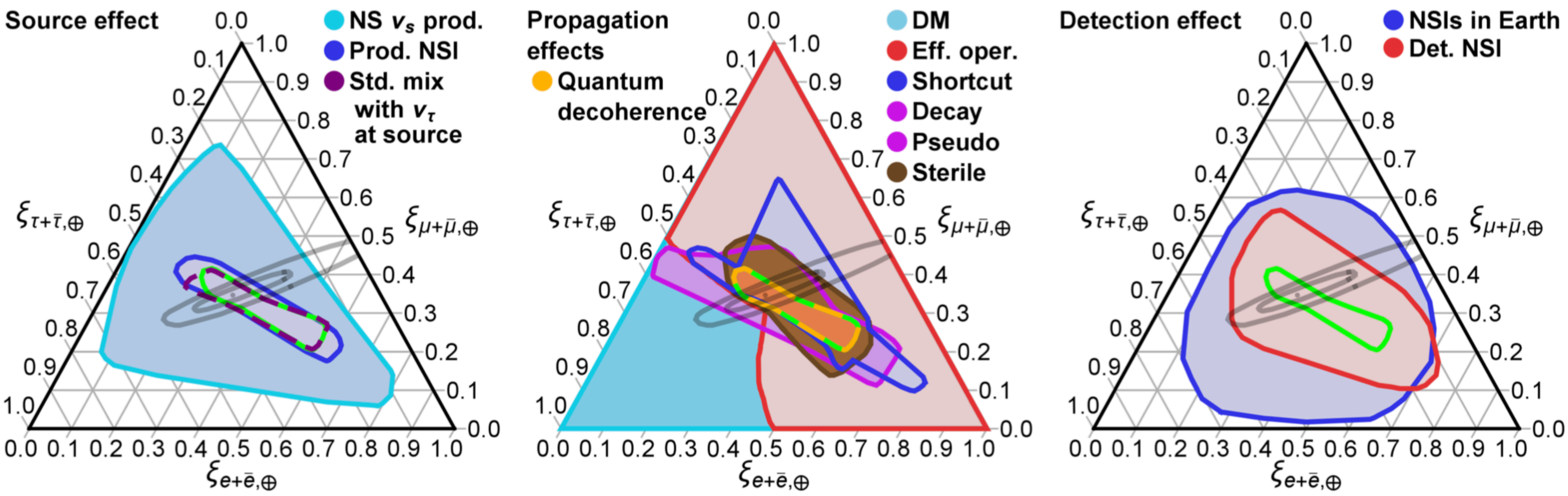
$O_0 \sim \mathrm{O}(10^{-26})$ GeV





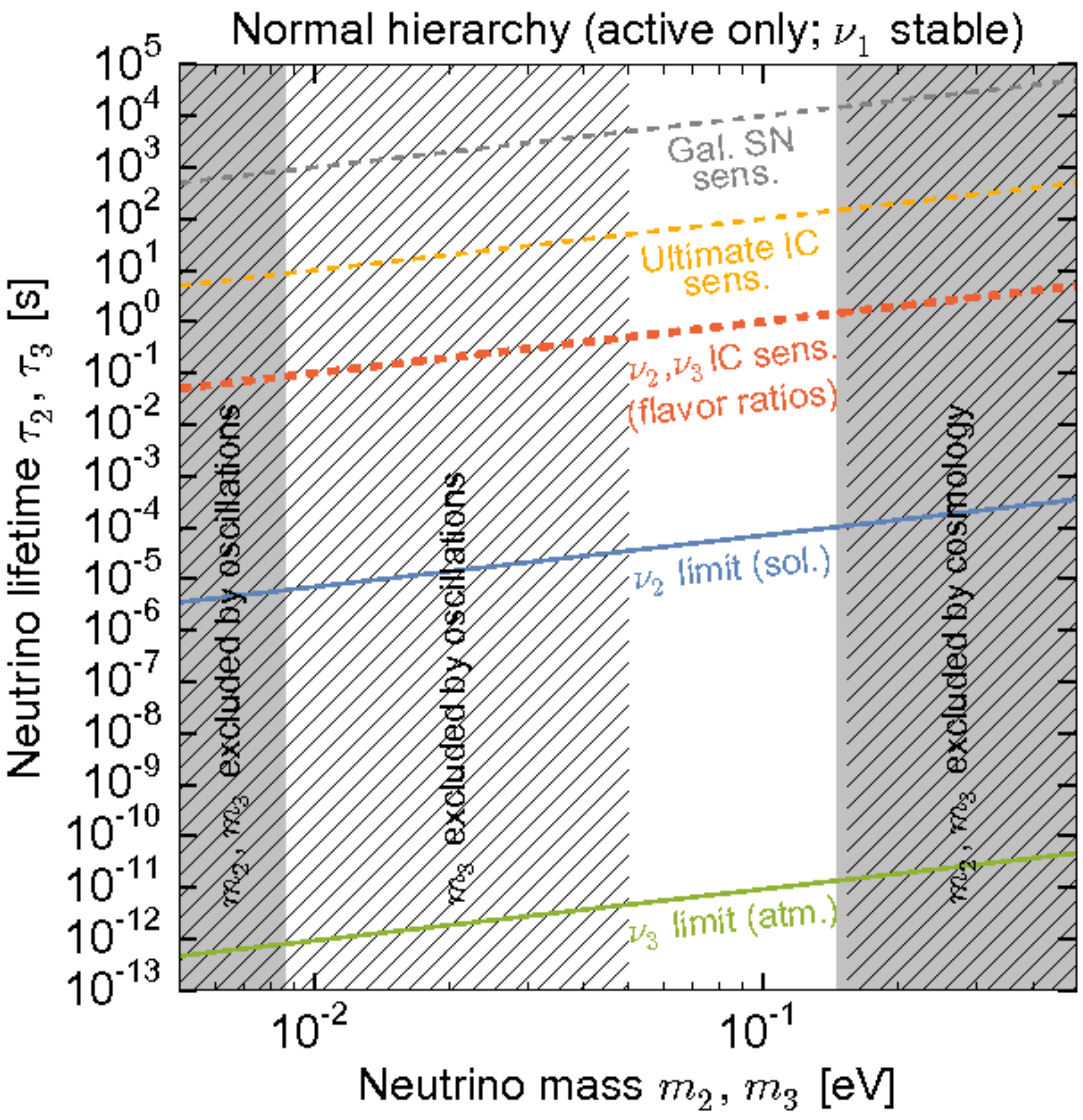
$O_0 \sim \mathrm{O}(10^{-29})$ GeV

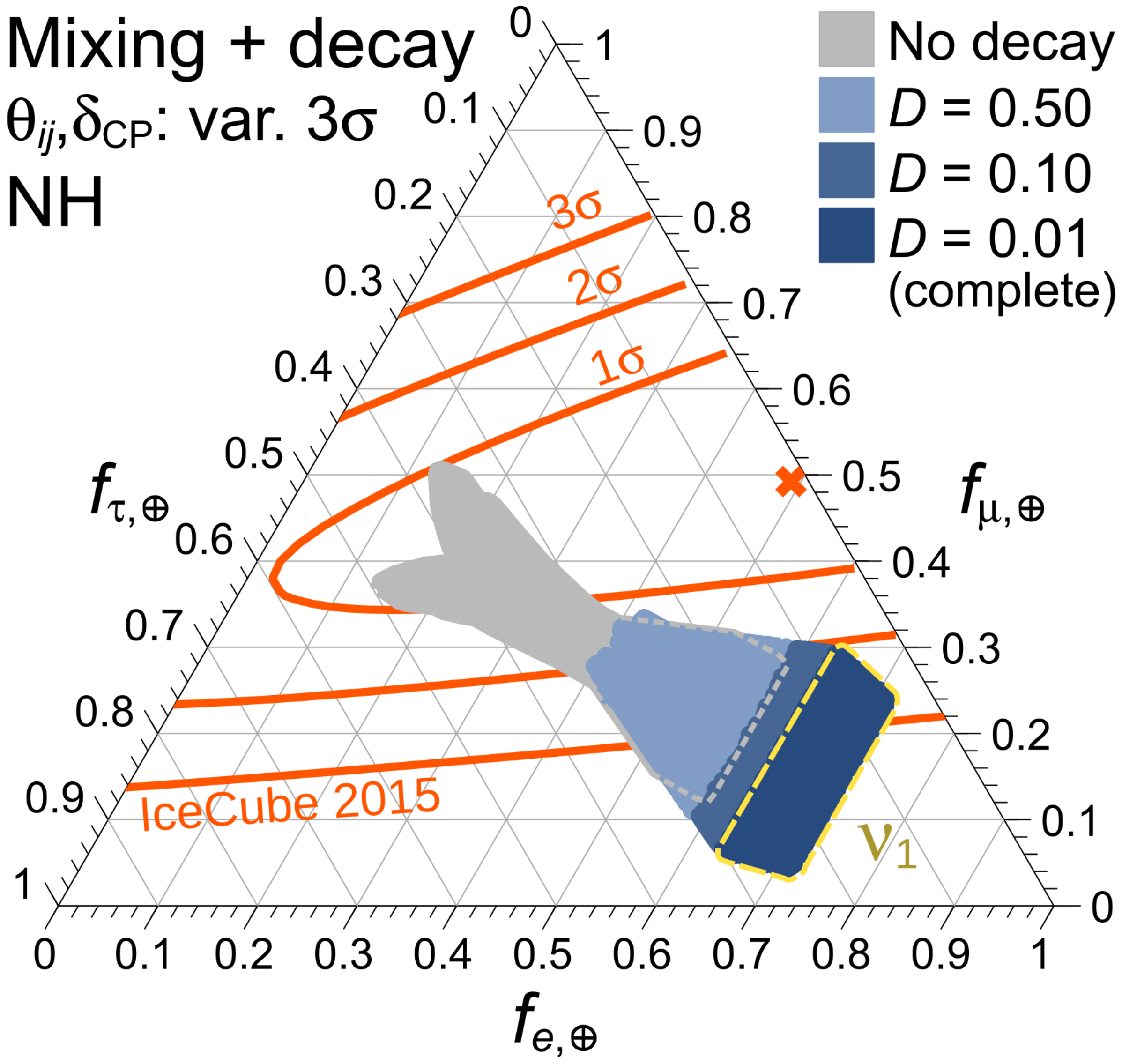
Note recent compilation on effects of BSM astrophysical neutrino flavor triangle



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

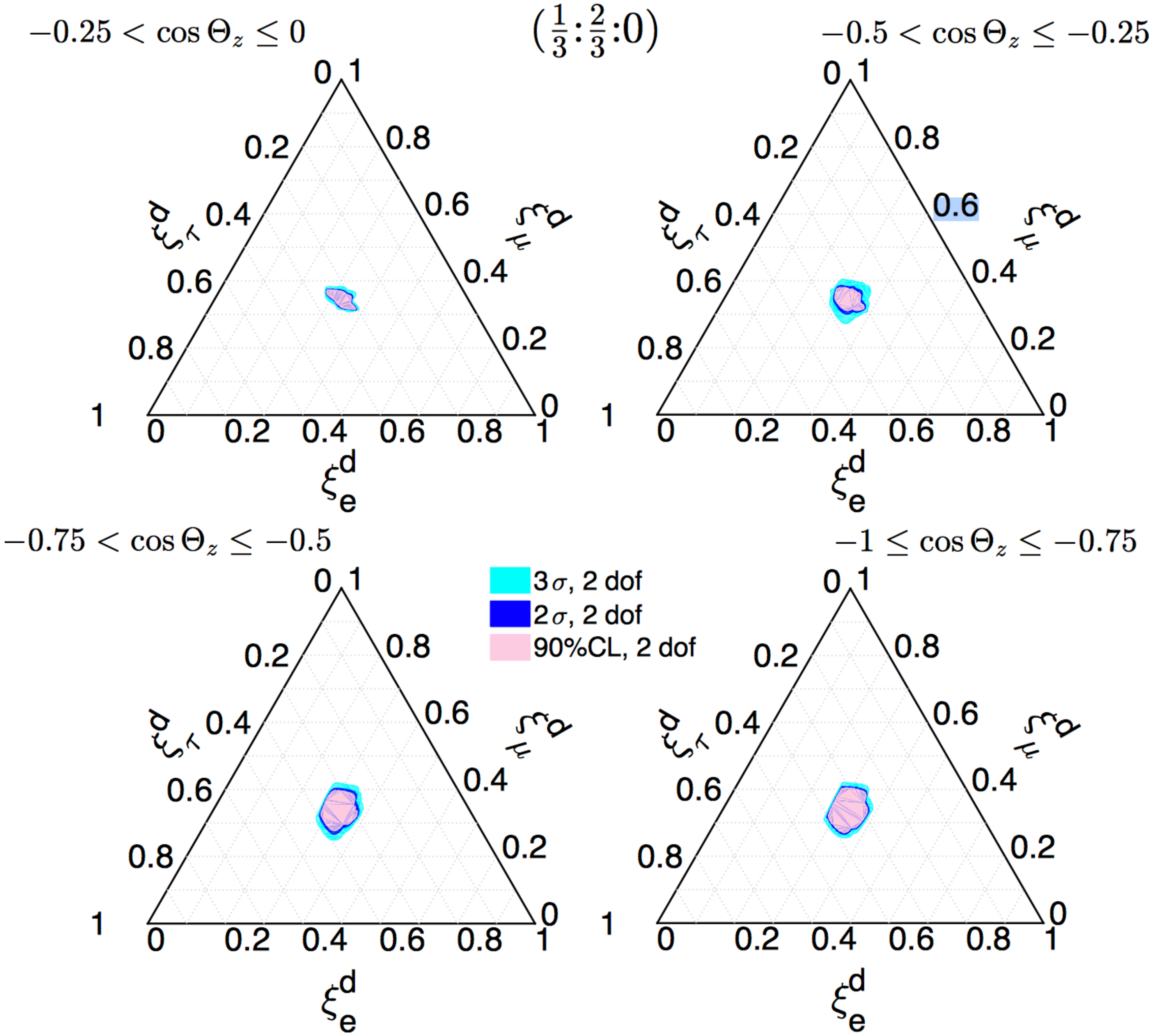
+Neutrino decay





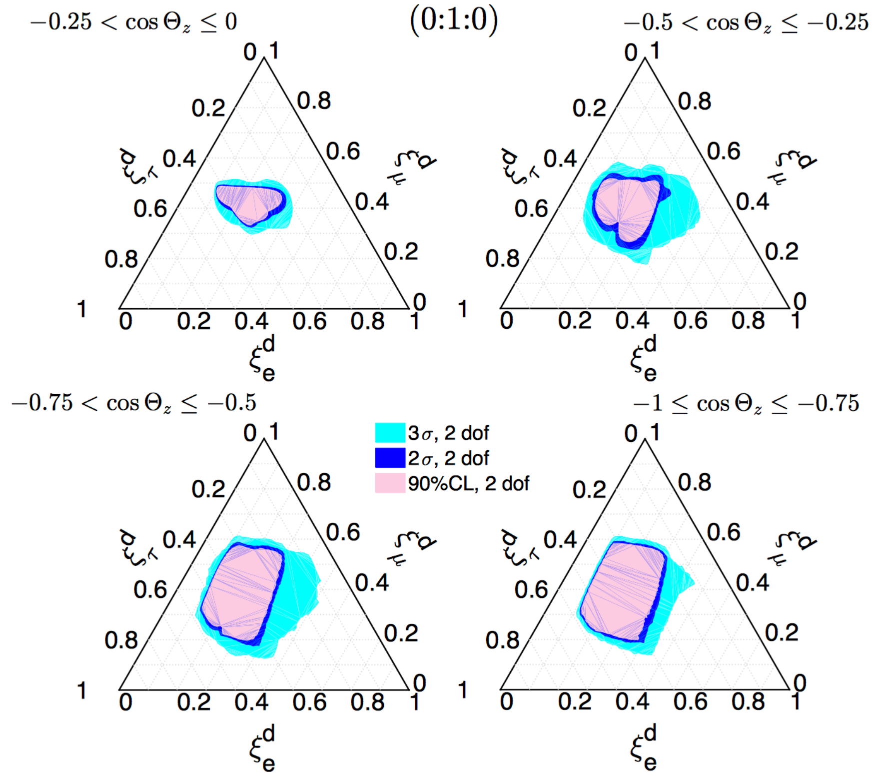
M. Bustamante, J. Beacom, K. Murase (1610.02096)

+ NSI@Earth



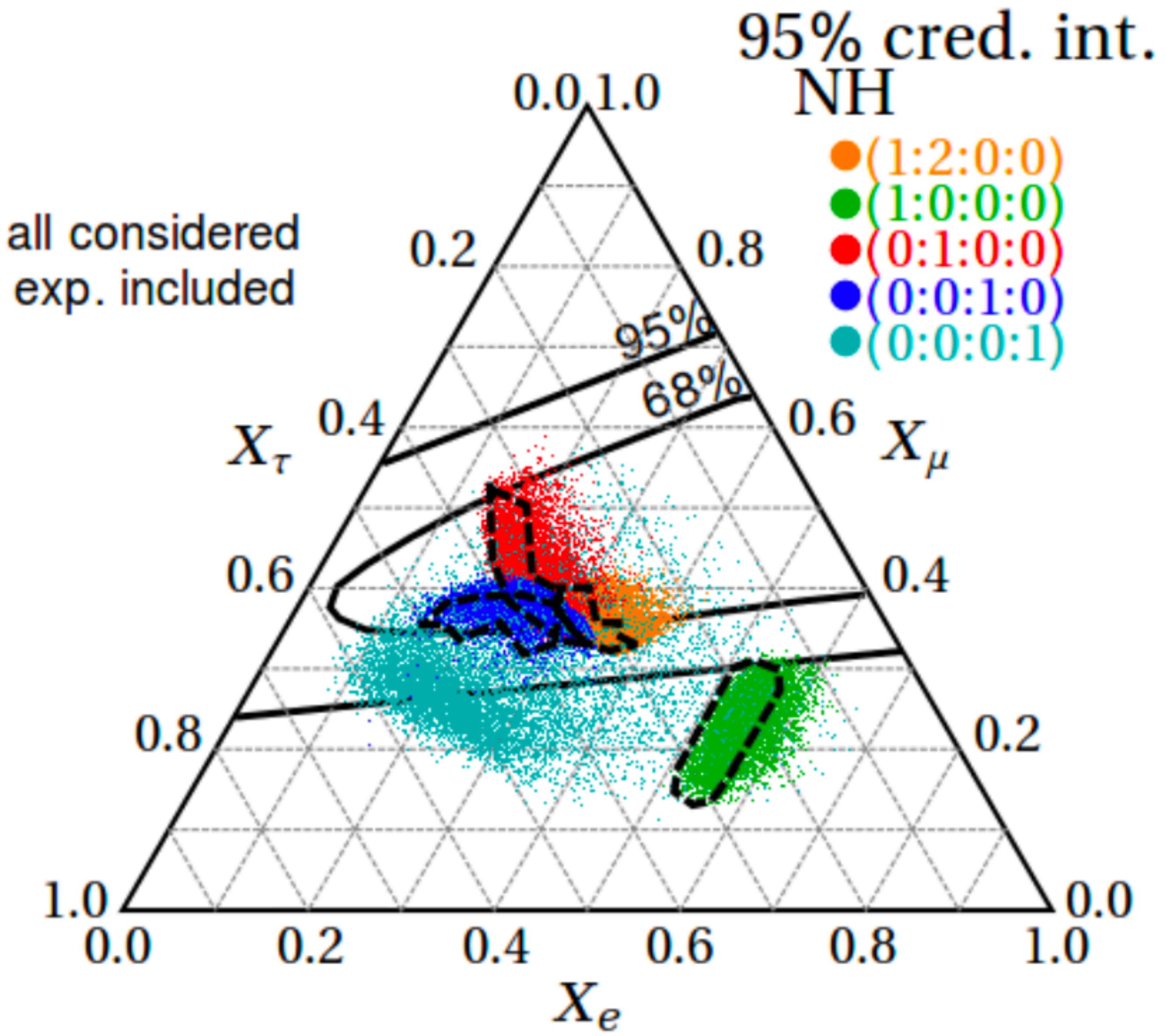
In the pion scenario NSI effects are small.

This is not the case for other initial flavor ratios.



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

+ (eV) sterile neutrino



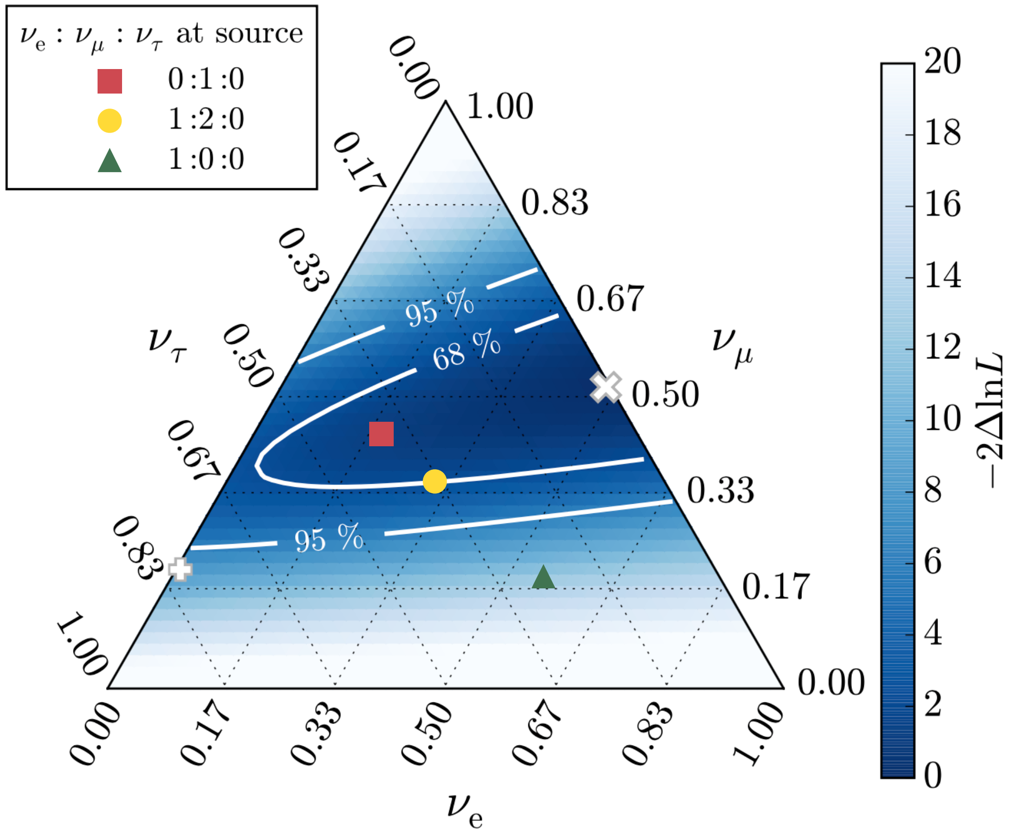
- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

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

IceCube -> IceCube-Upgrade!

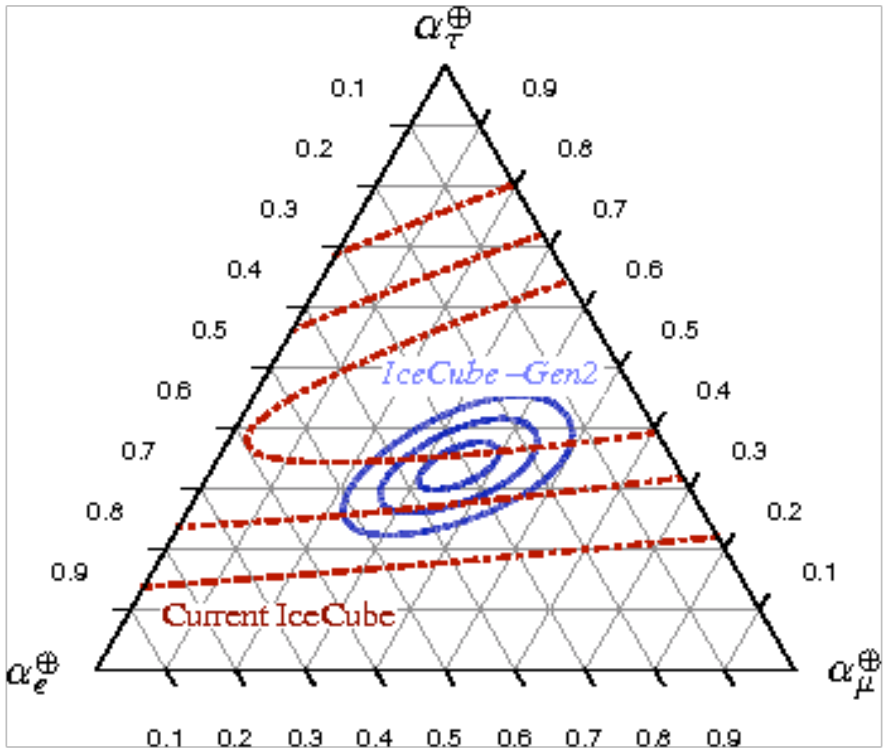
IceCube keeps collecting more data: triangle will improve!

(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