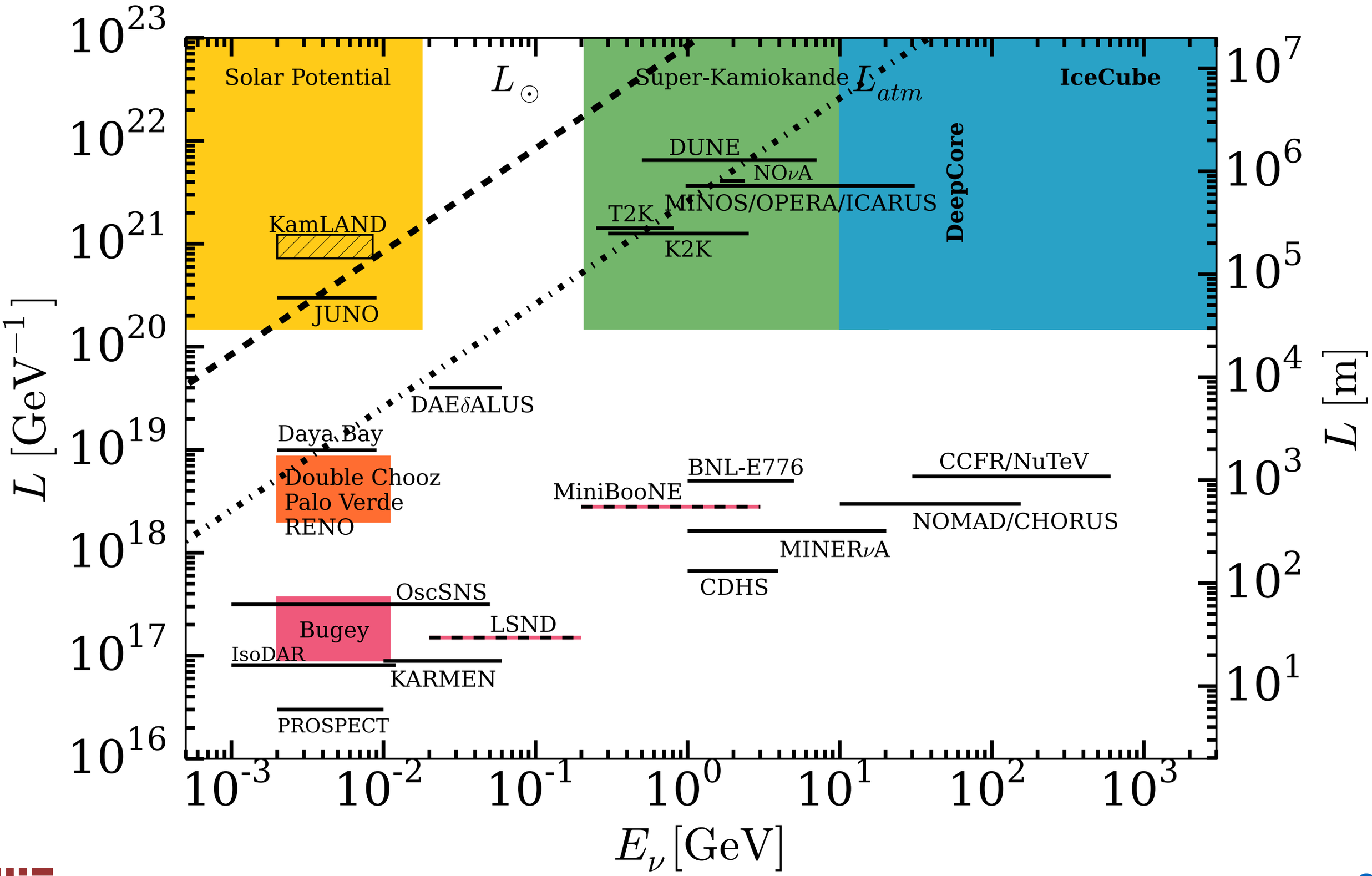
New physics searches with the >TeV neutrinos

Carlos Argüelles

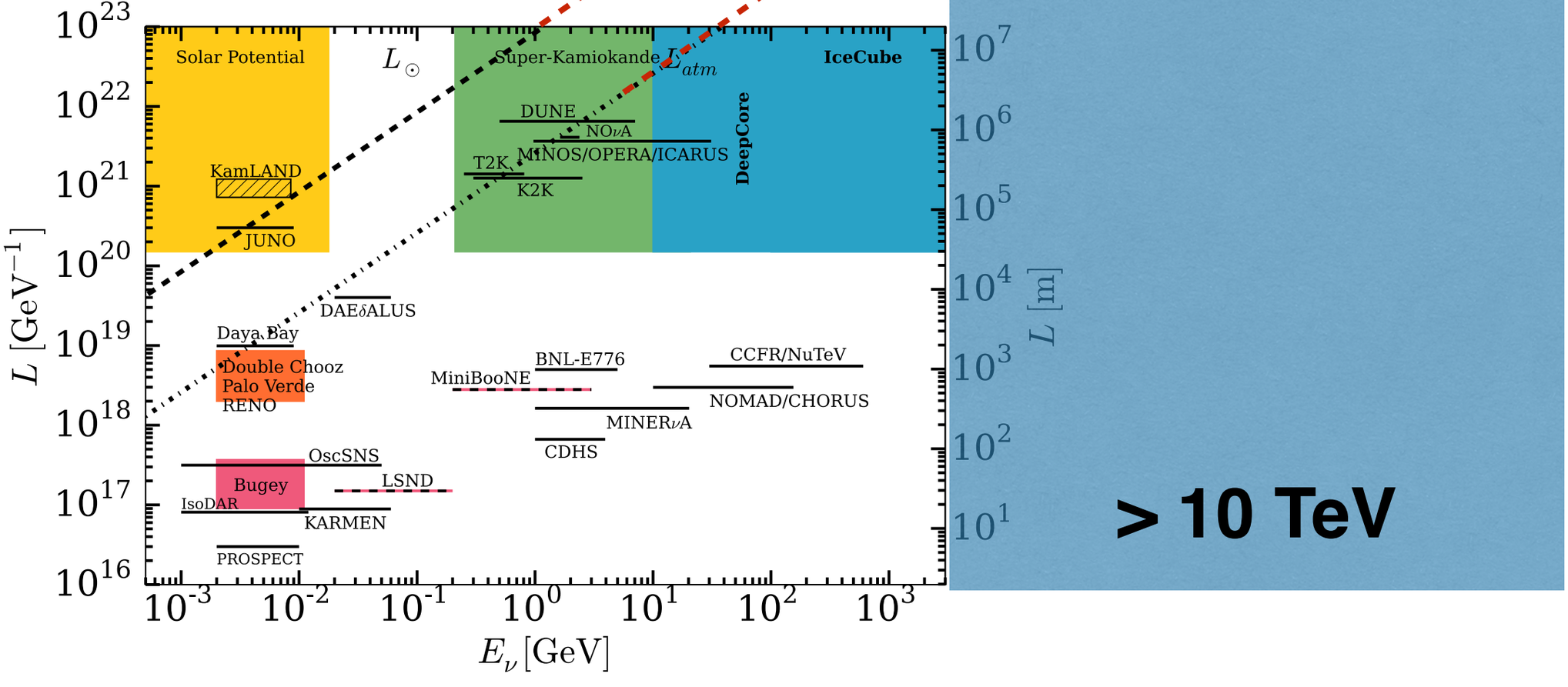
Fermilab Theory Seminar, August, 2017

What we have explored so far…



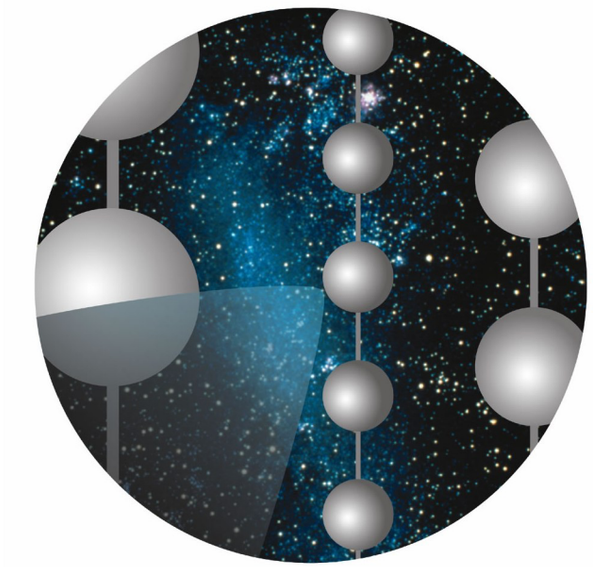
Cosmic neutrinos frontier

> Mpc (~Andromeda)



Basics of IceCube

The IceCube experiment

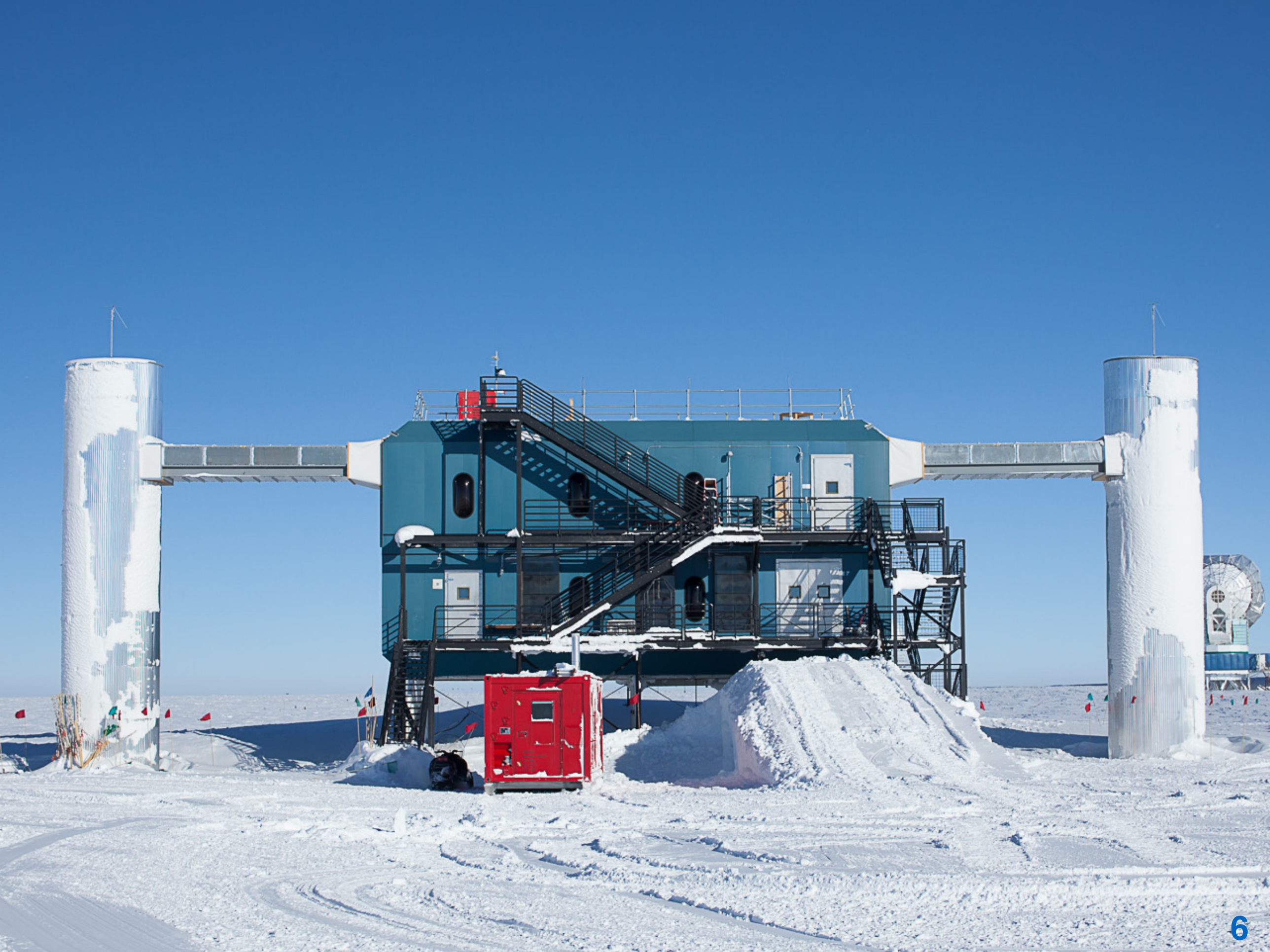


IceCube

Here

There

(to scale)



IceCube

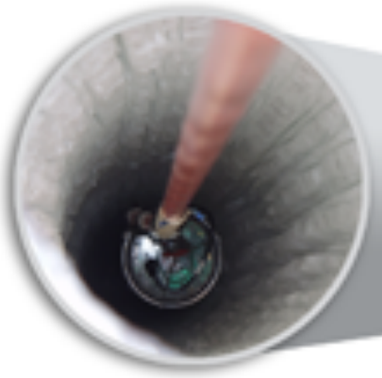
South Pole Neutrino Observatory

IceCube Laboratory

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

50 m

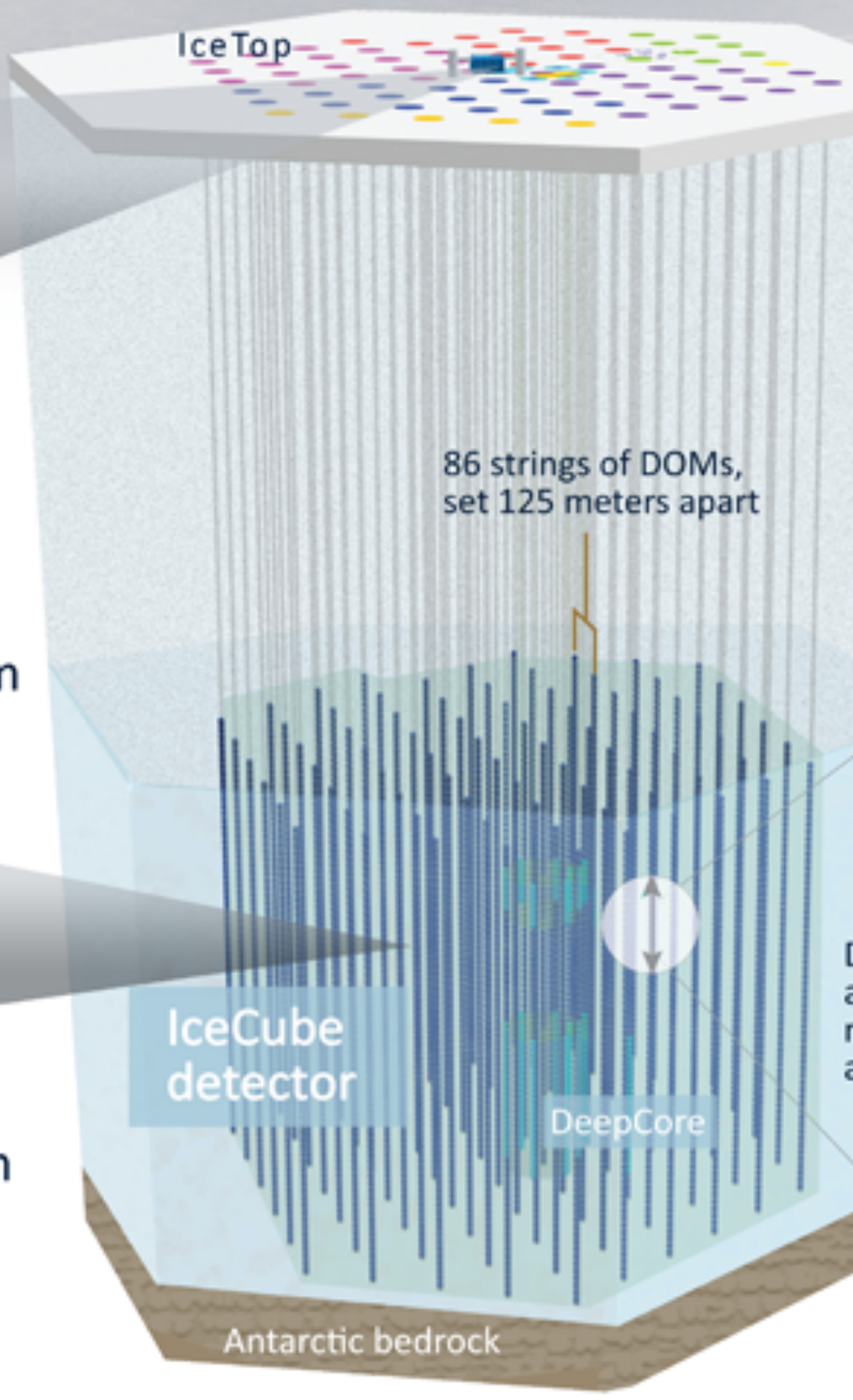
1450 m



Digital Optical Module (DOM)

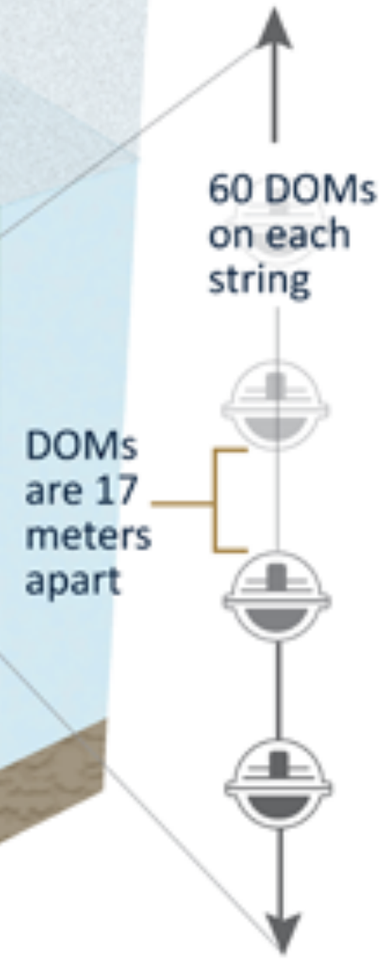
5,160 DOMs deployed in the ice

2450 m



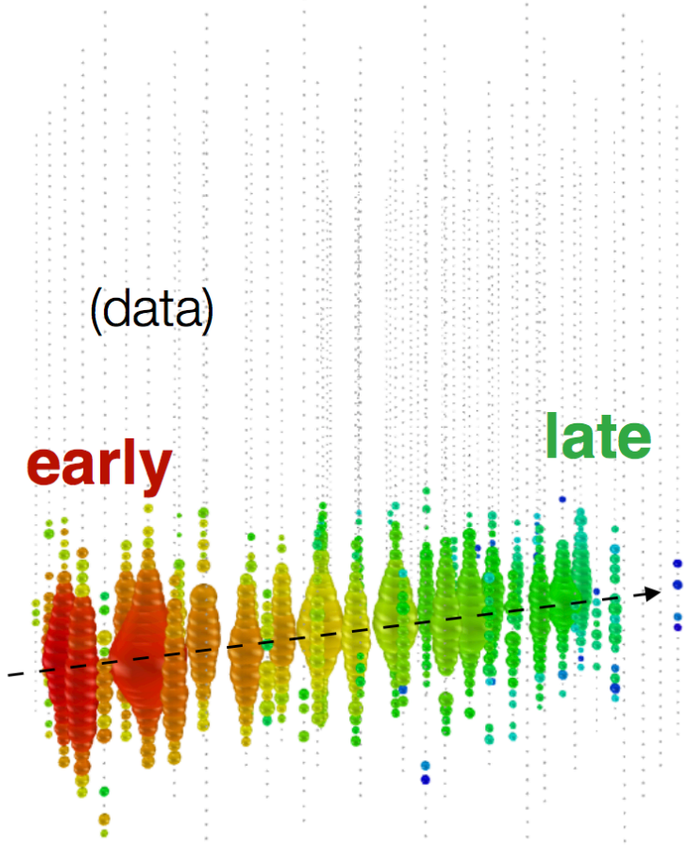
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



Event topologies

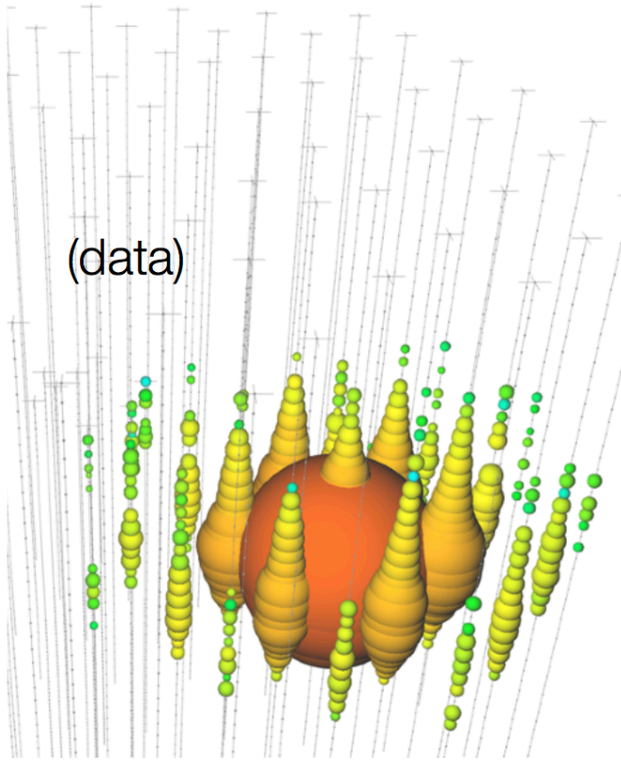
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

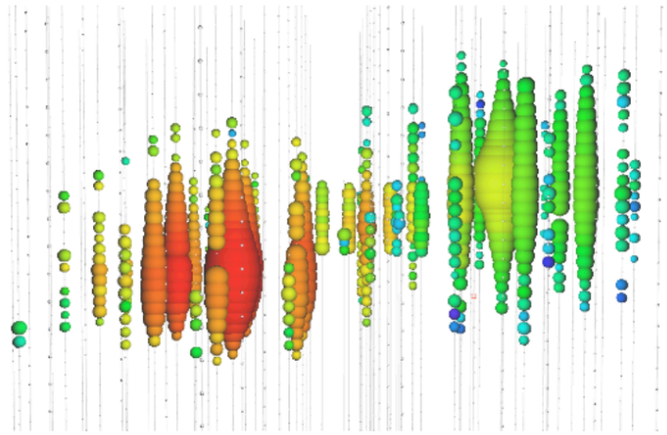
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

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

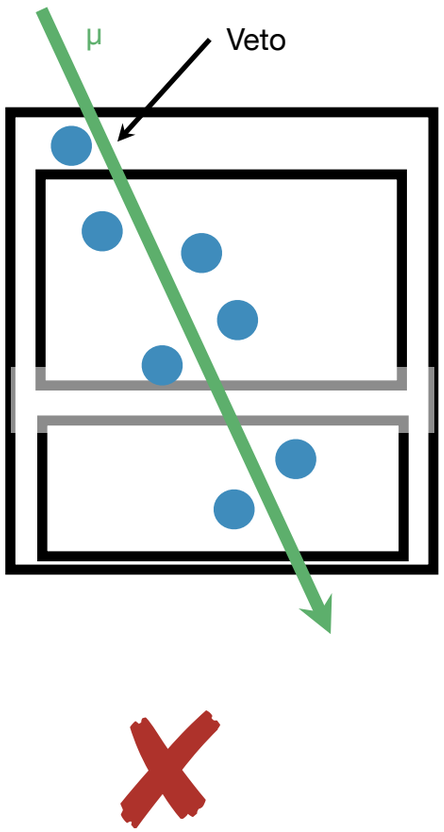
Charged-current ν_τ

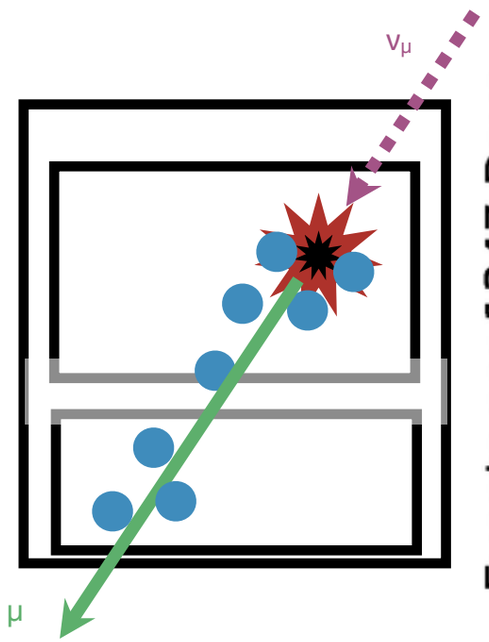


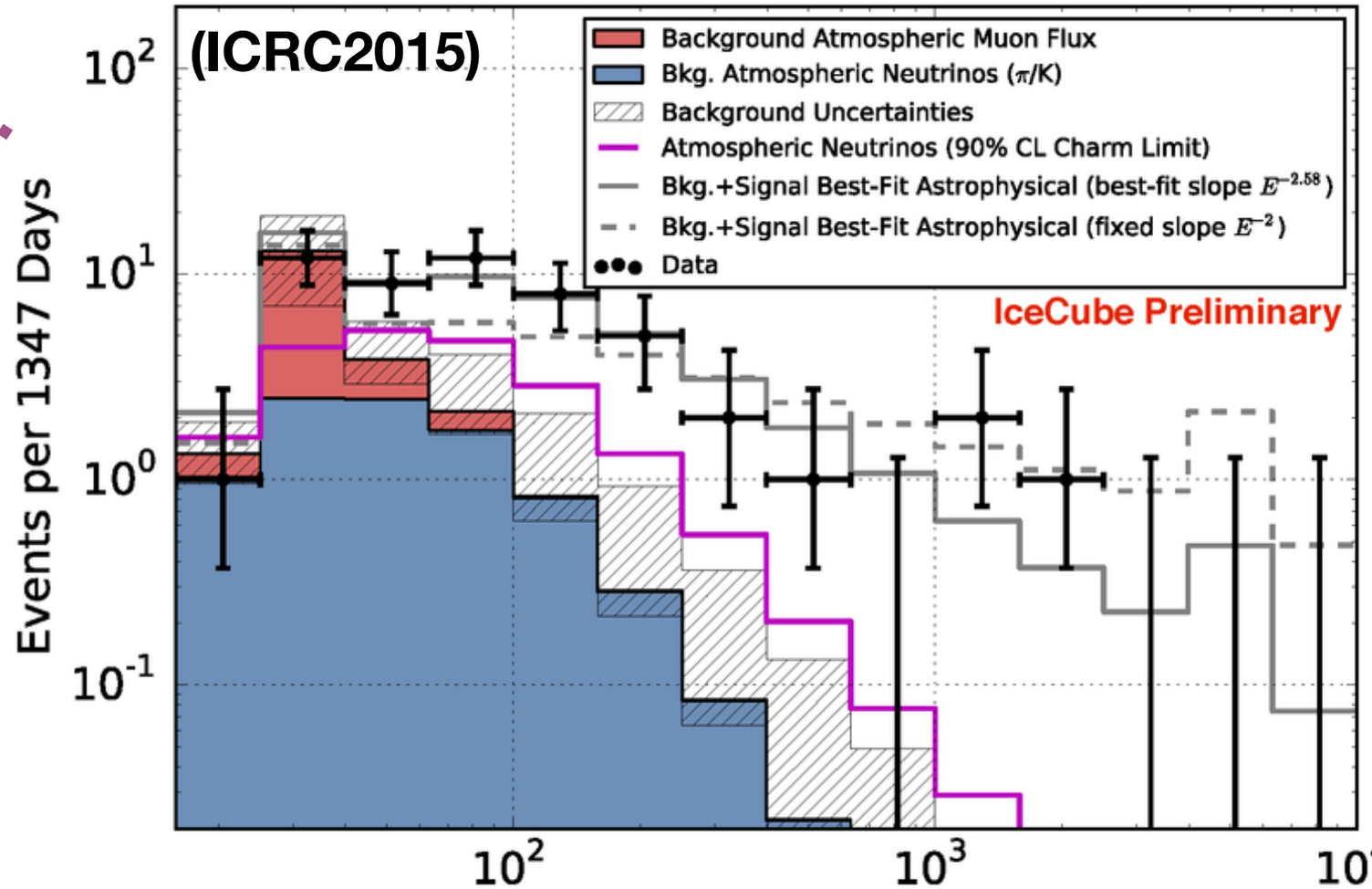
Double cascade

(resolvable above ~100 TeV deposited energy)

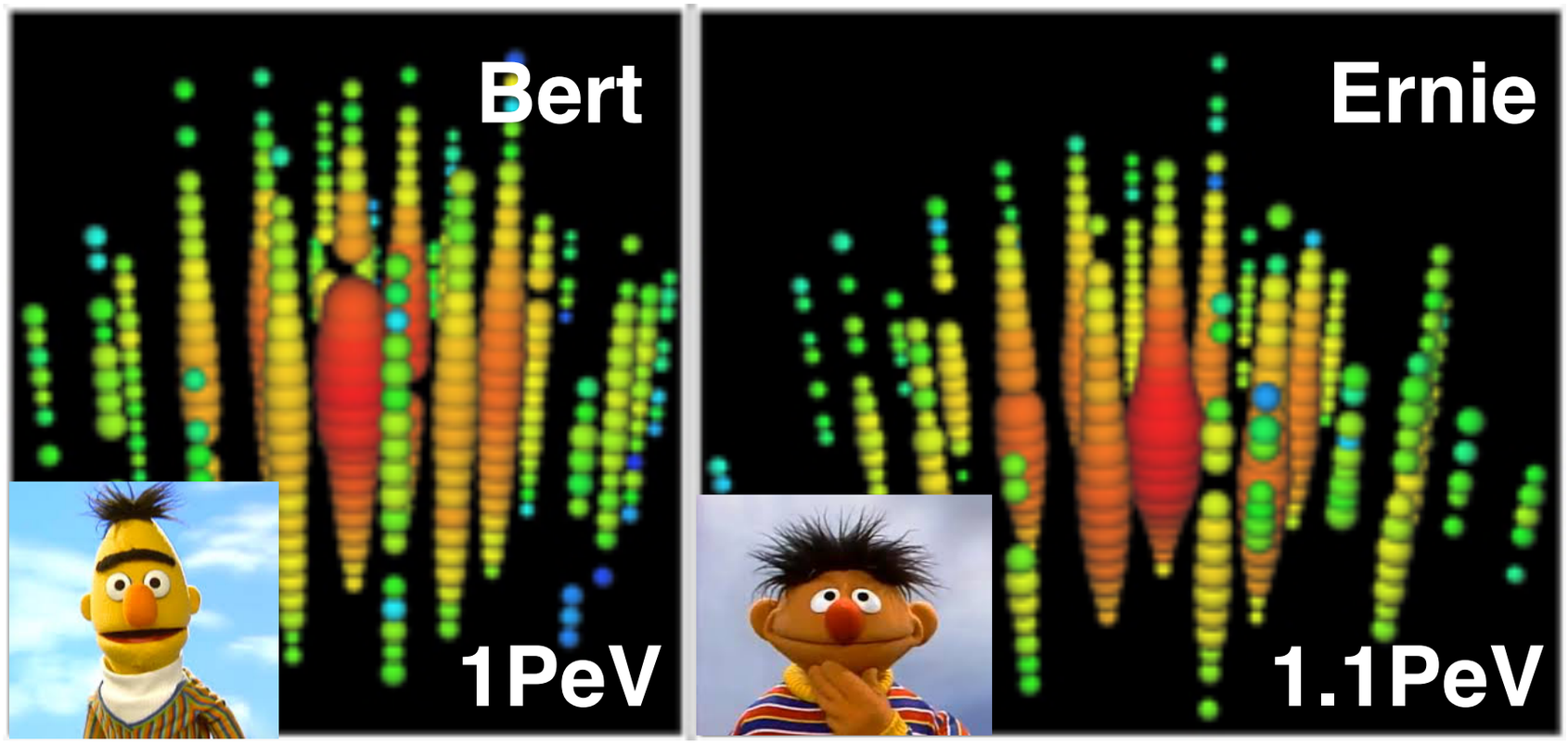
Astrophysical neutrinos



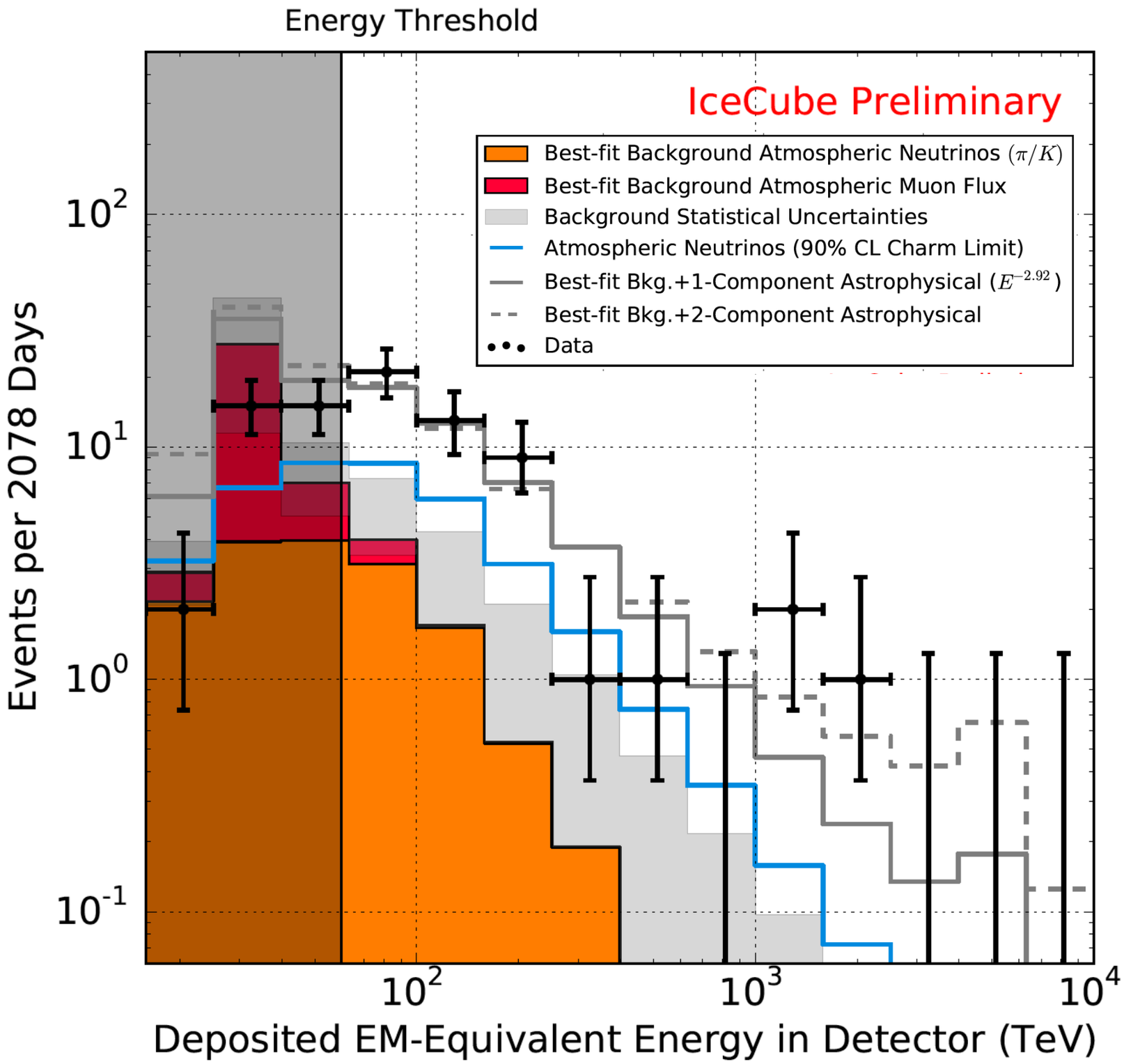




IceCube discovery of high energy astrophysical neutrinos

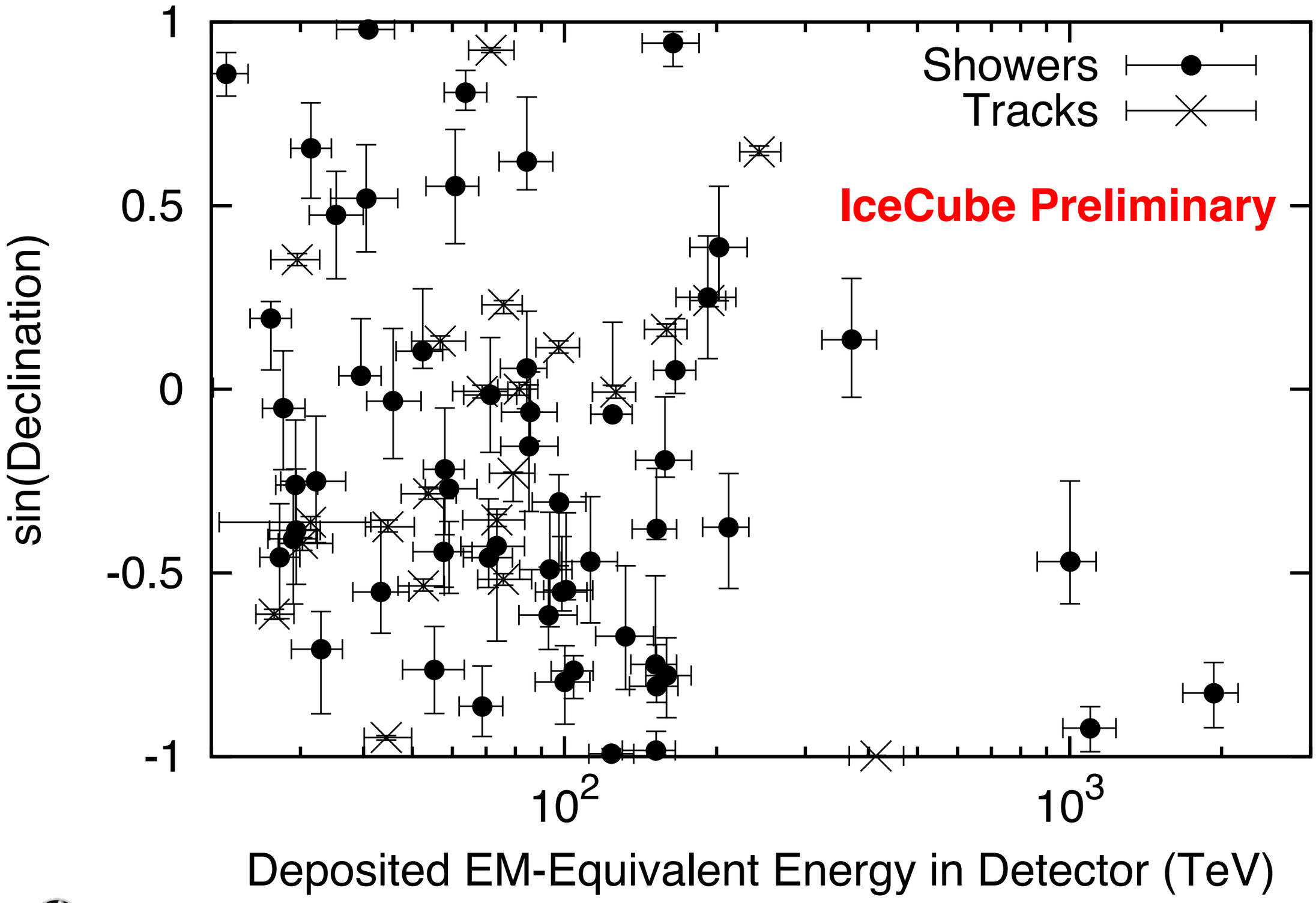


New **six years high energy starting events data!**

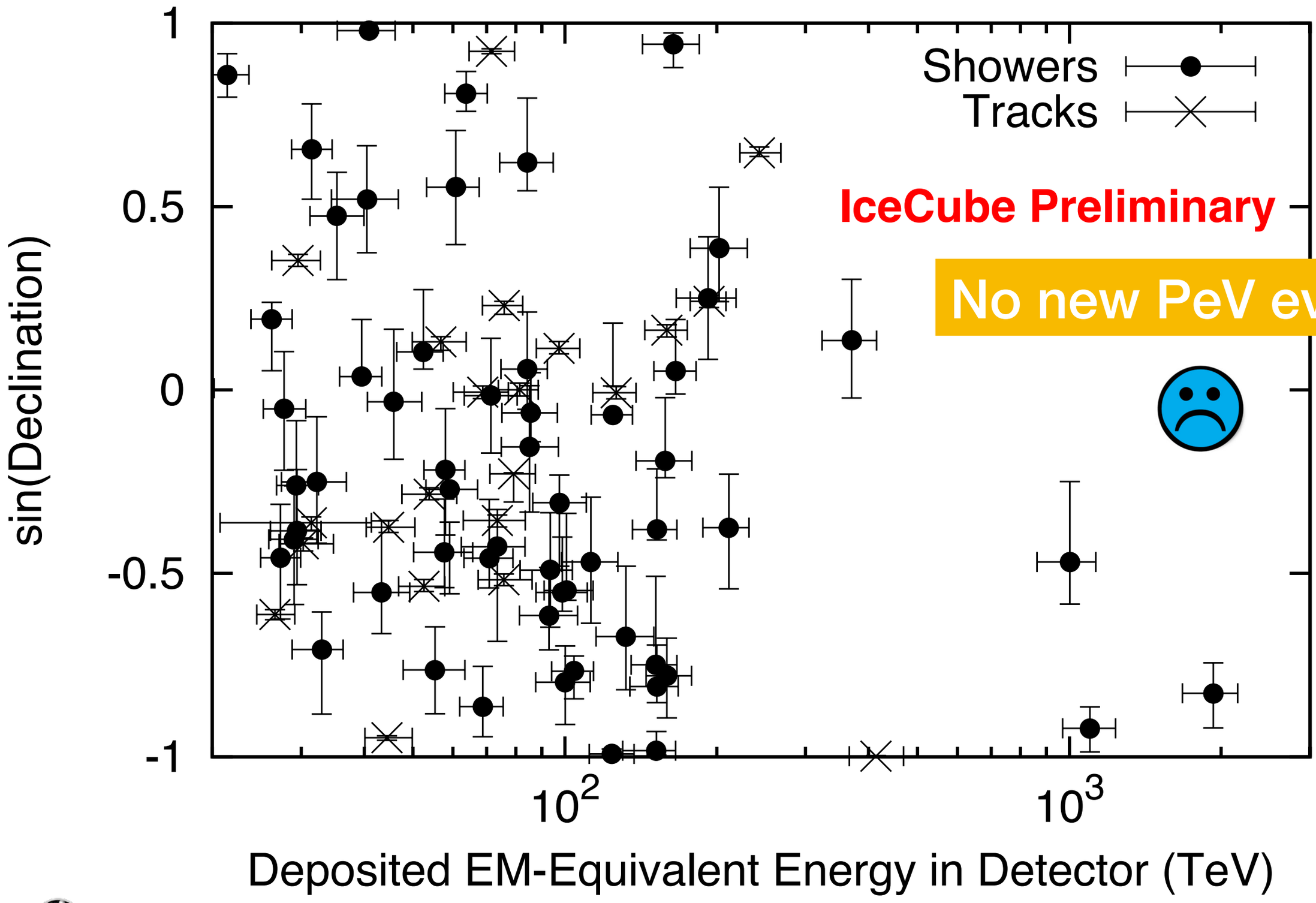


80+2 events in 6 years (54 in 4 years)

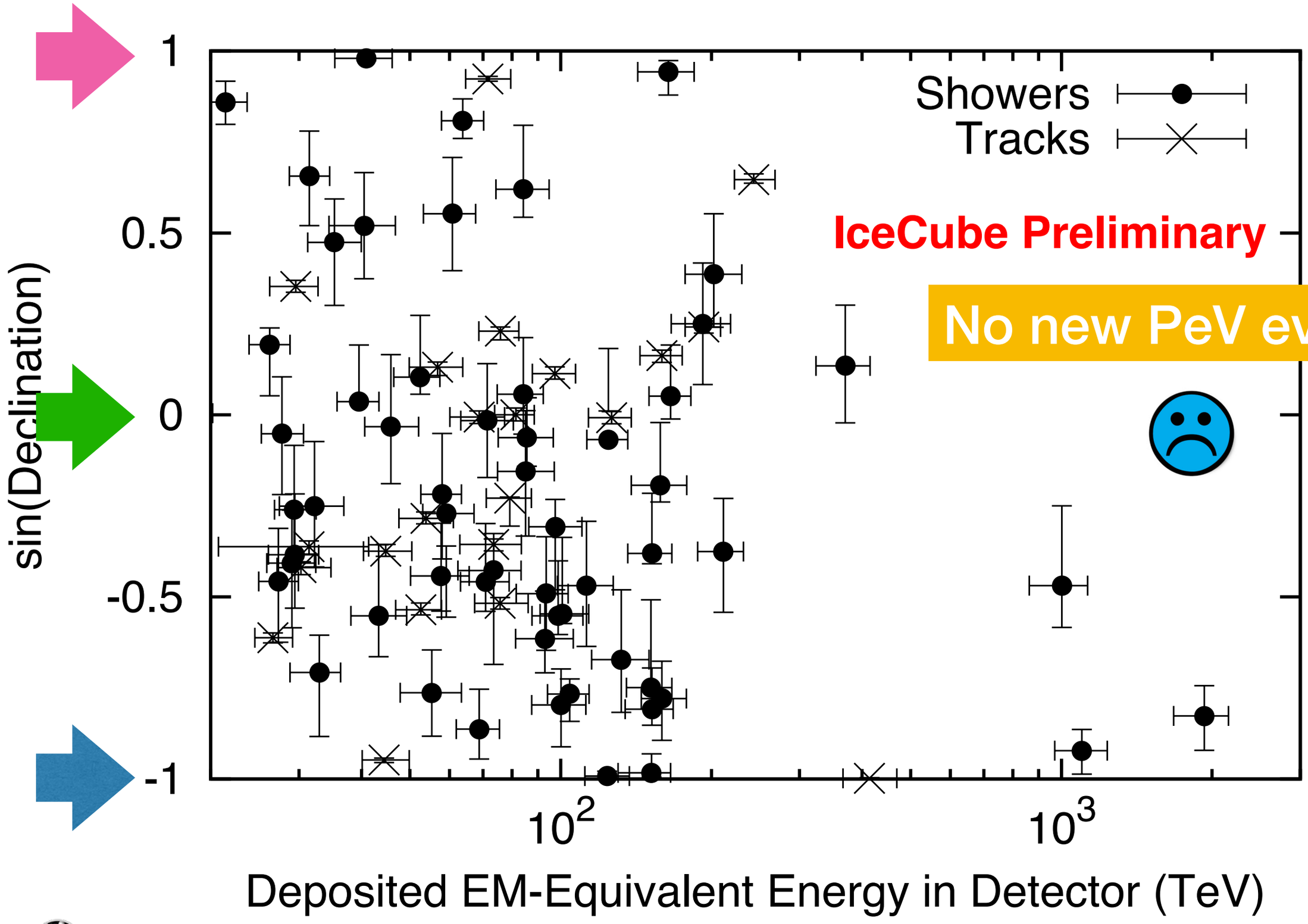
New HESE-6 years distribution



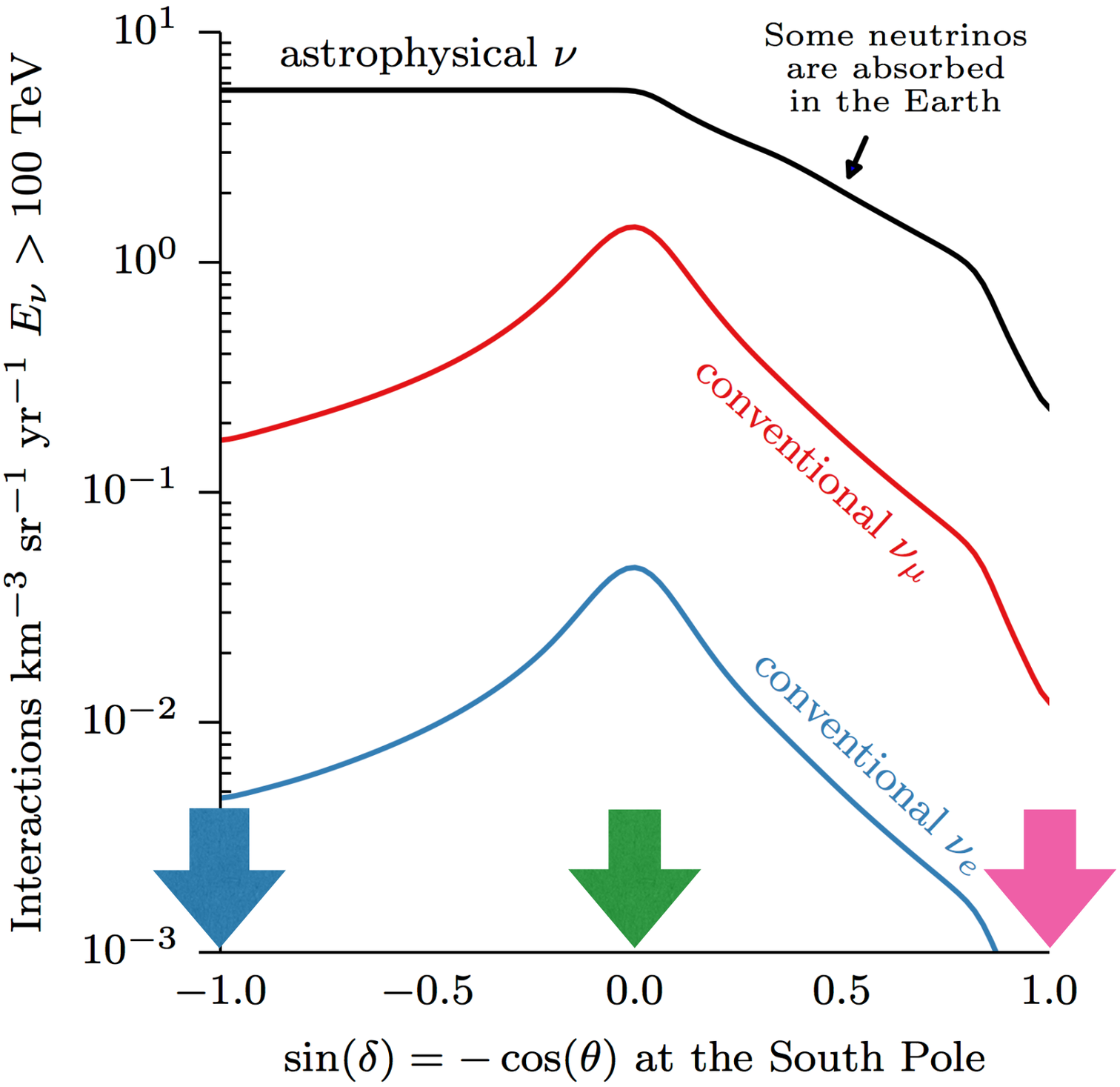
New HESE-6 years distribution

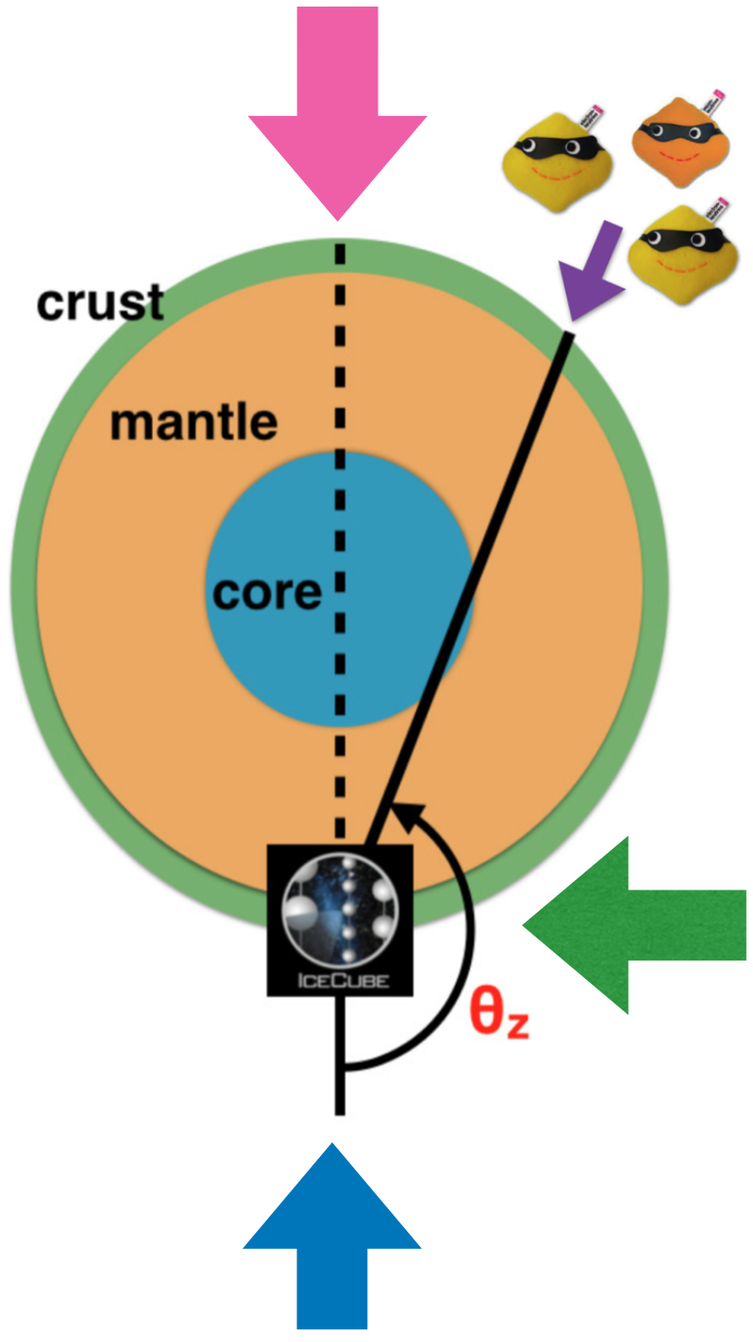


New HESE-6 years distribution

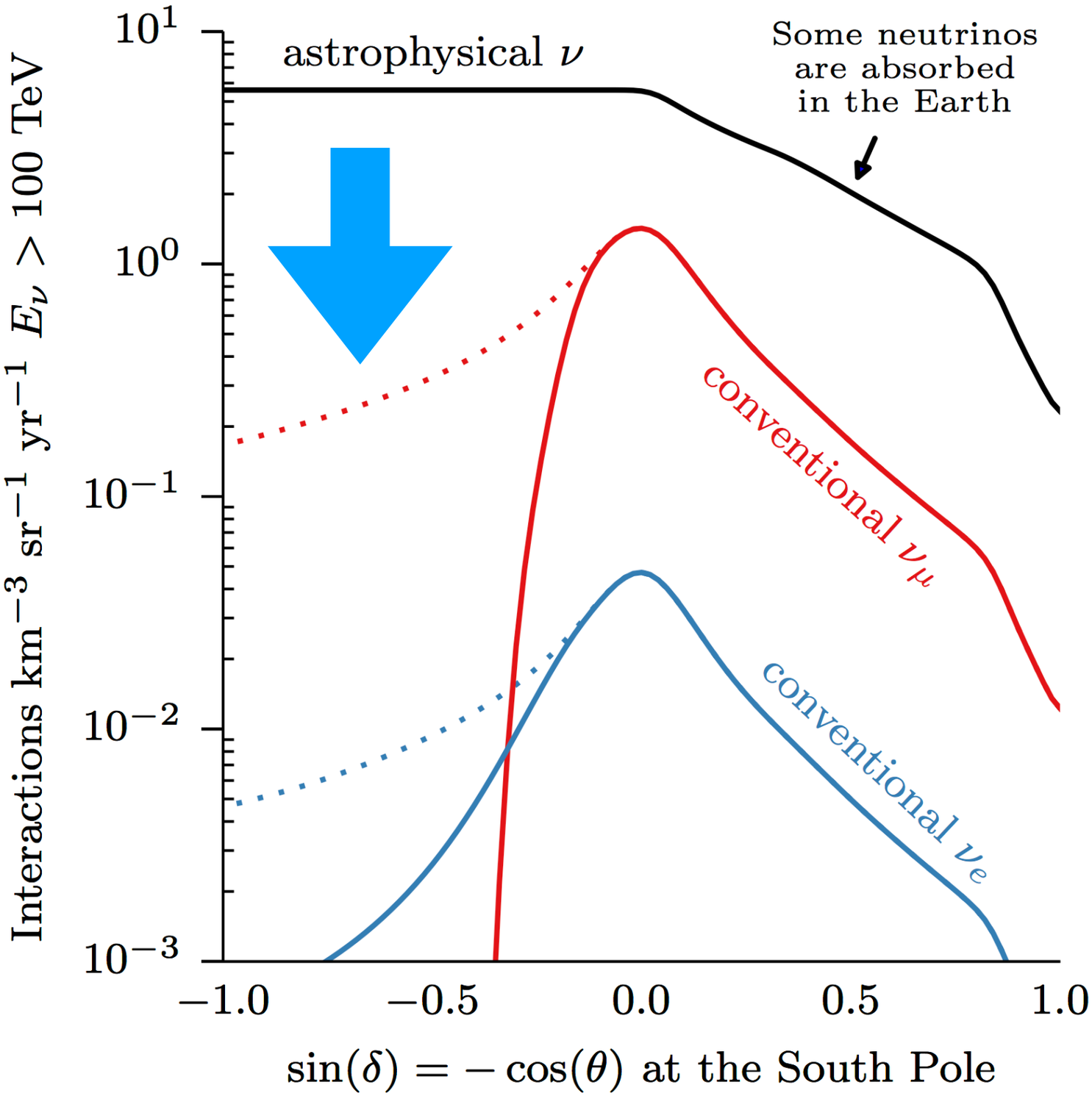


Expected angular distributions

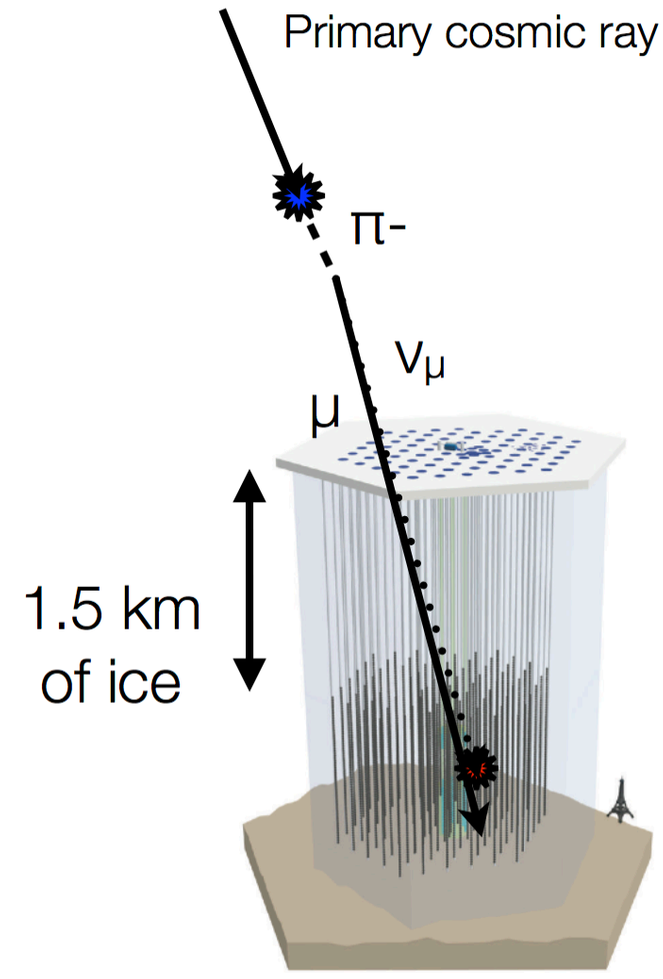




Selfveto!



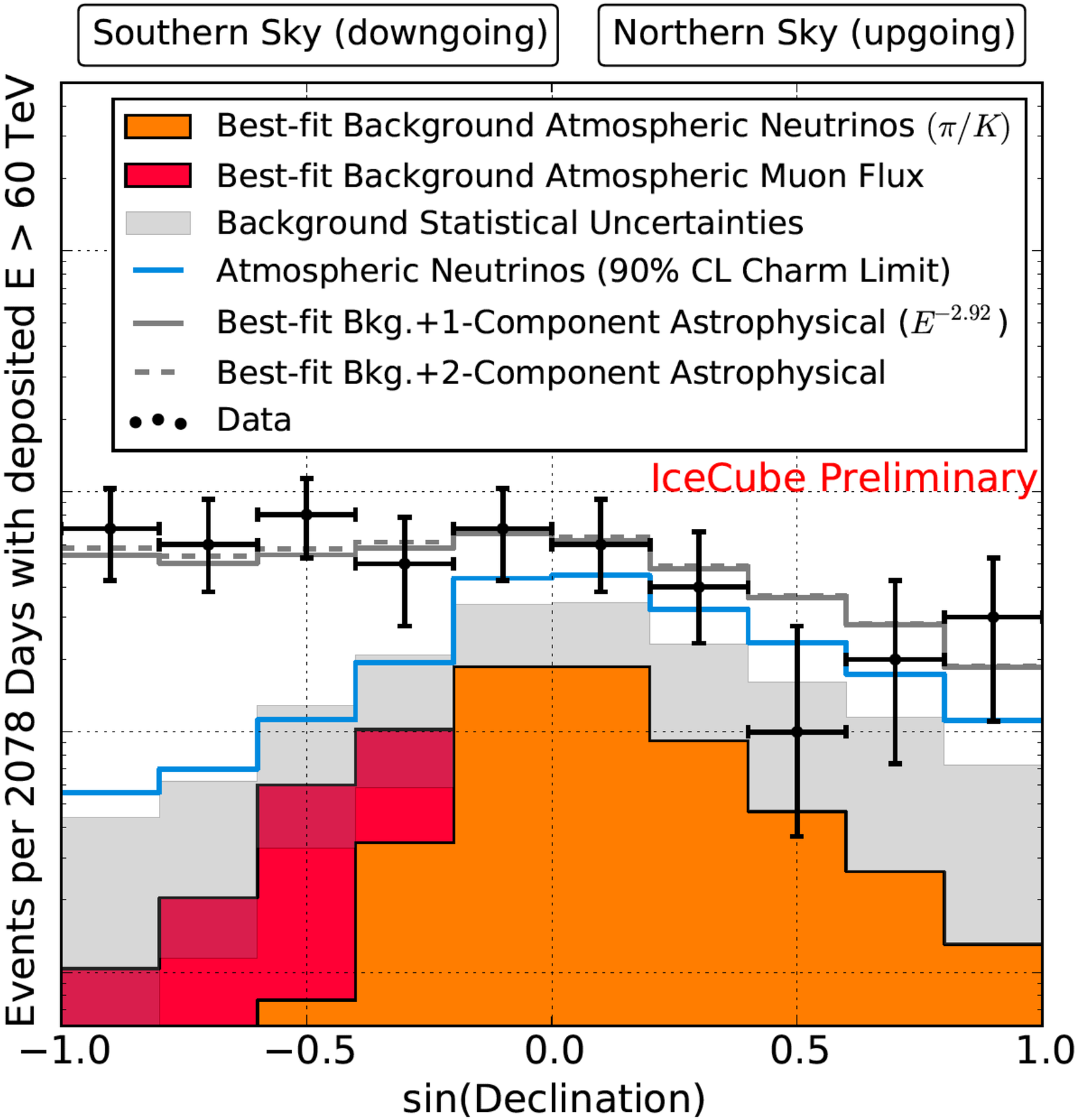
An active muon veto removes down-going atmospheric neutrinos.



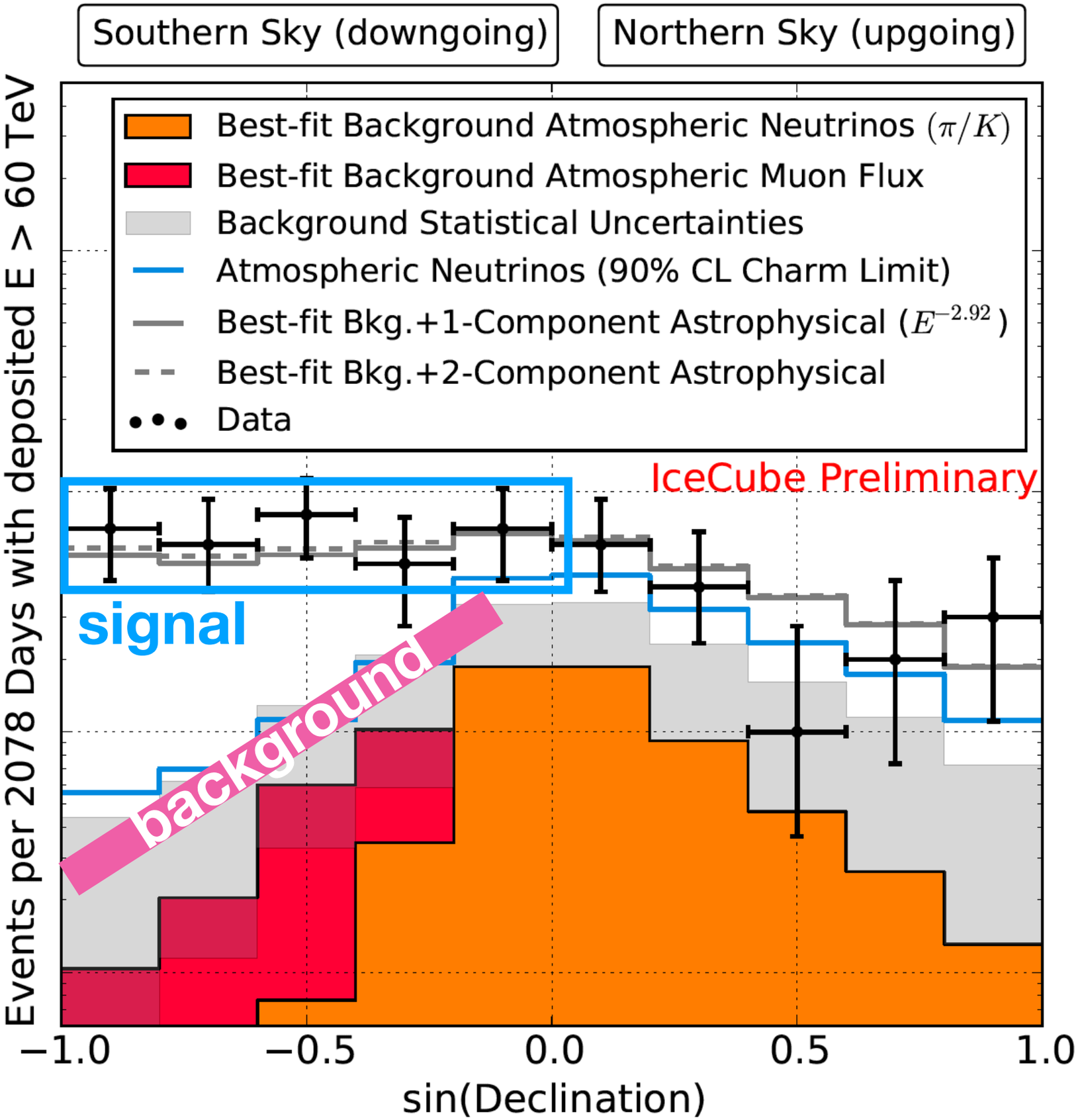
Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

New **six years high energy starting events data!**

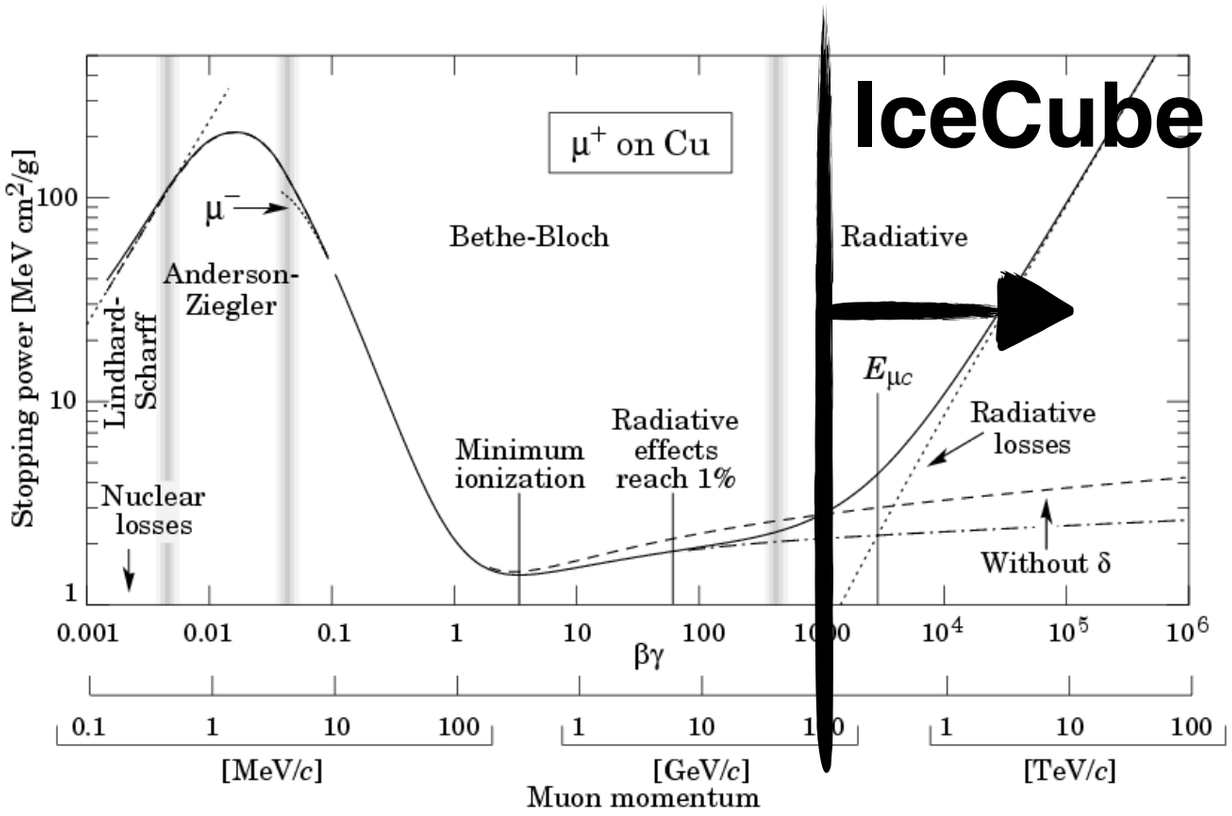


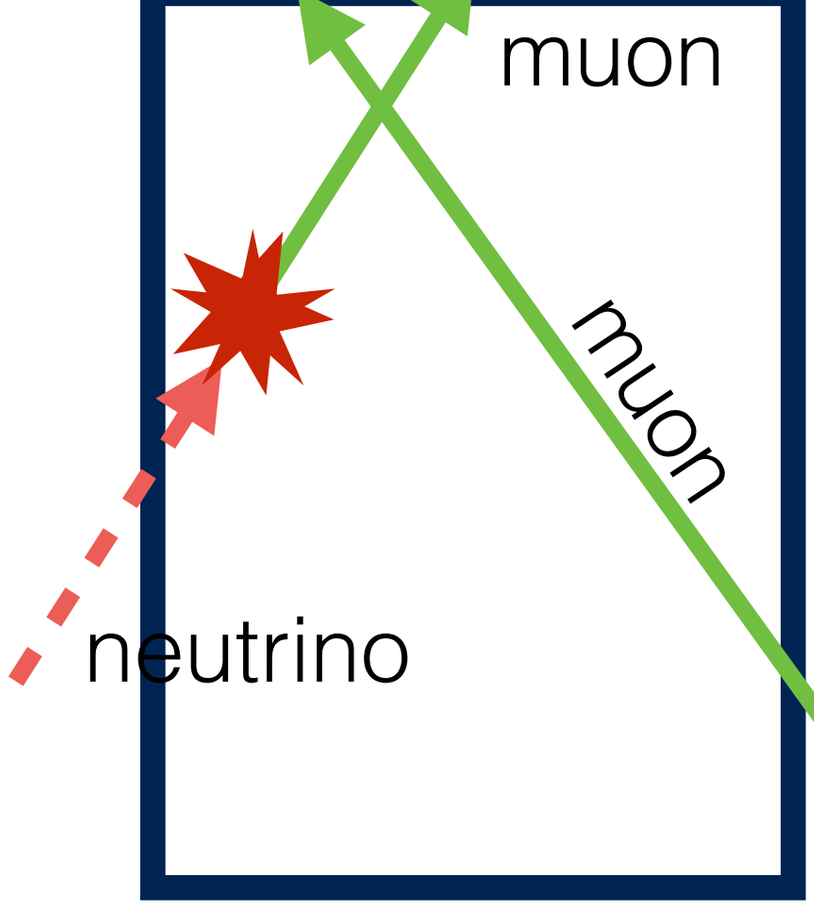
New **six years high energy starting events data!**

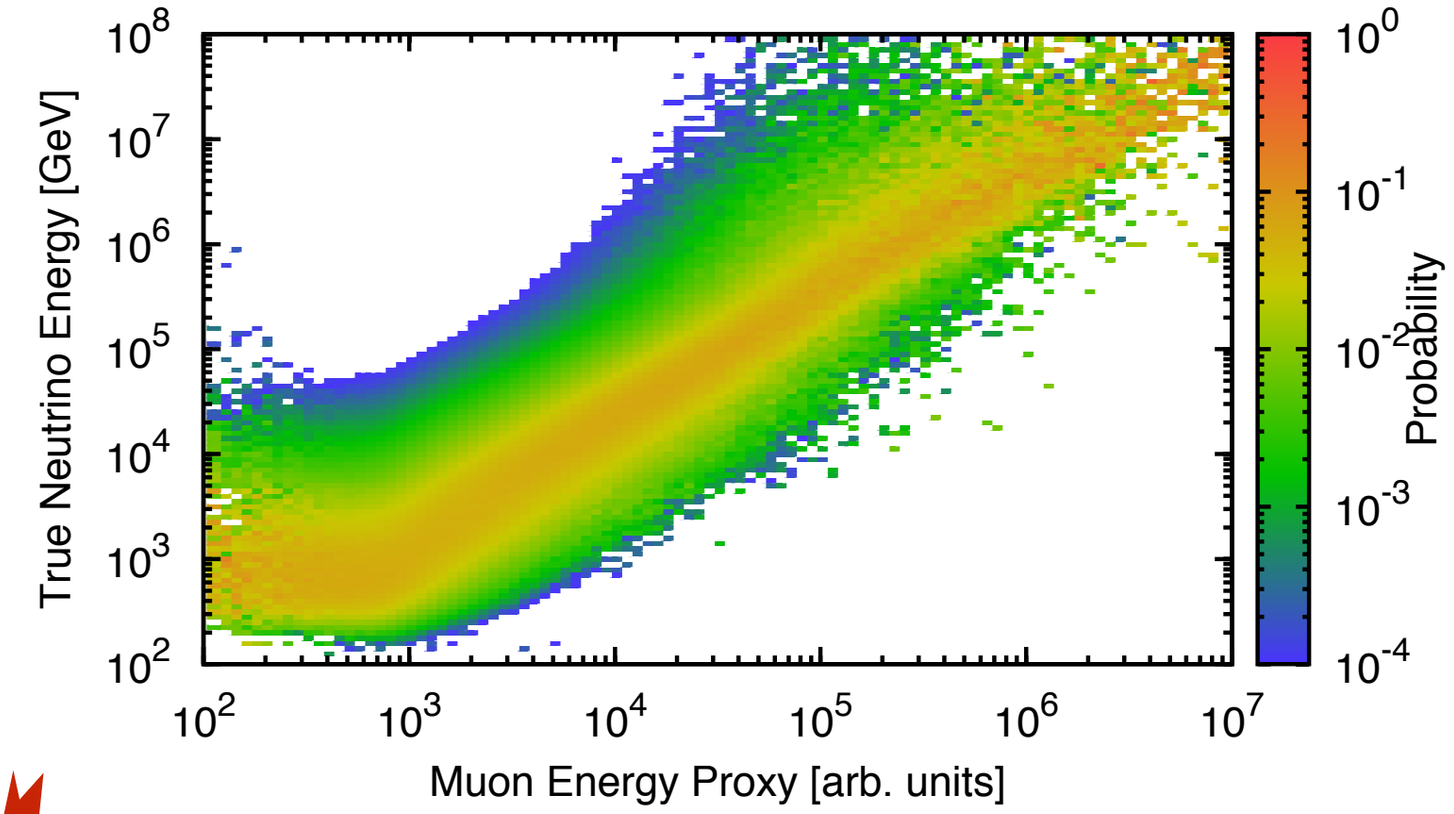


Through-going muons in IceCube

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



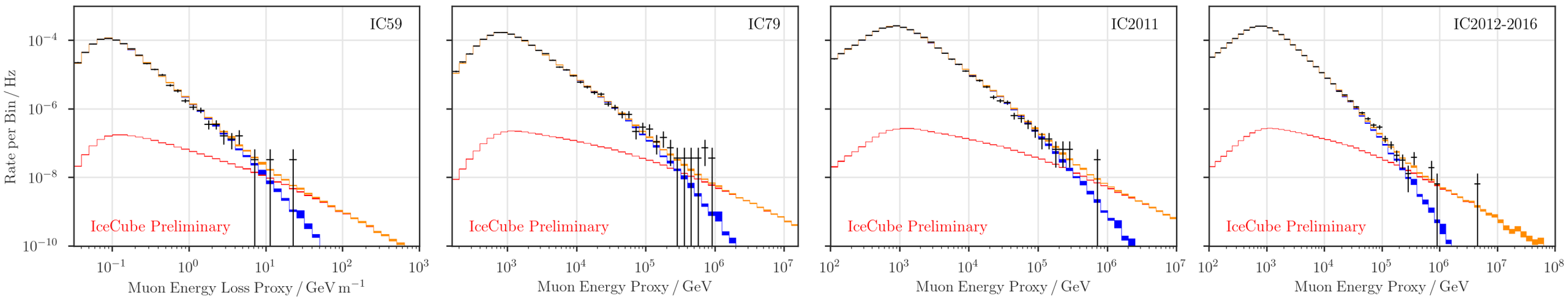


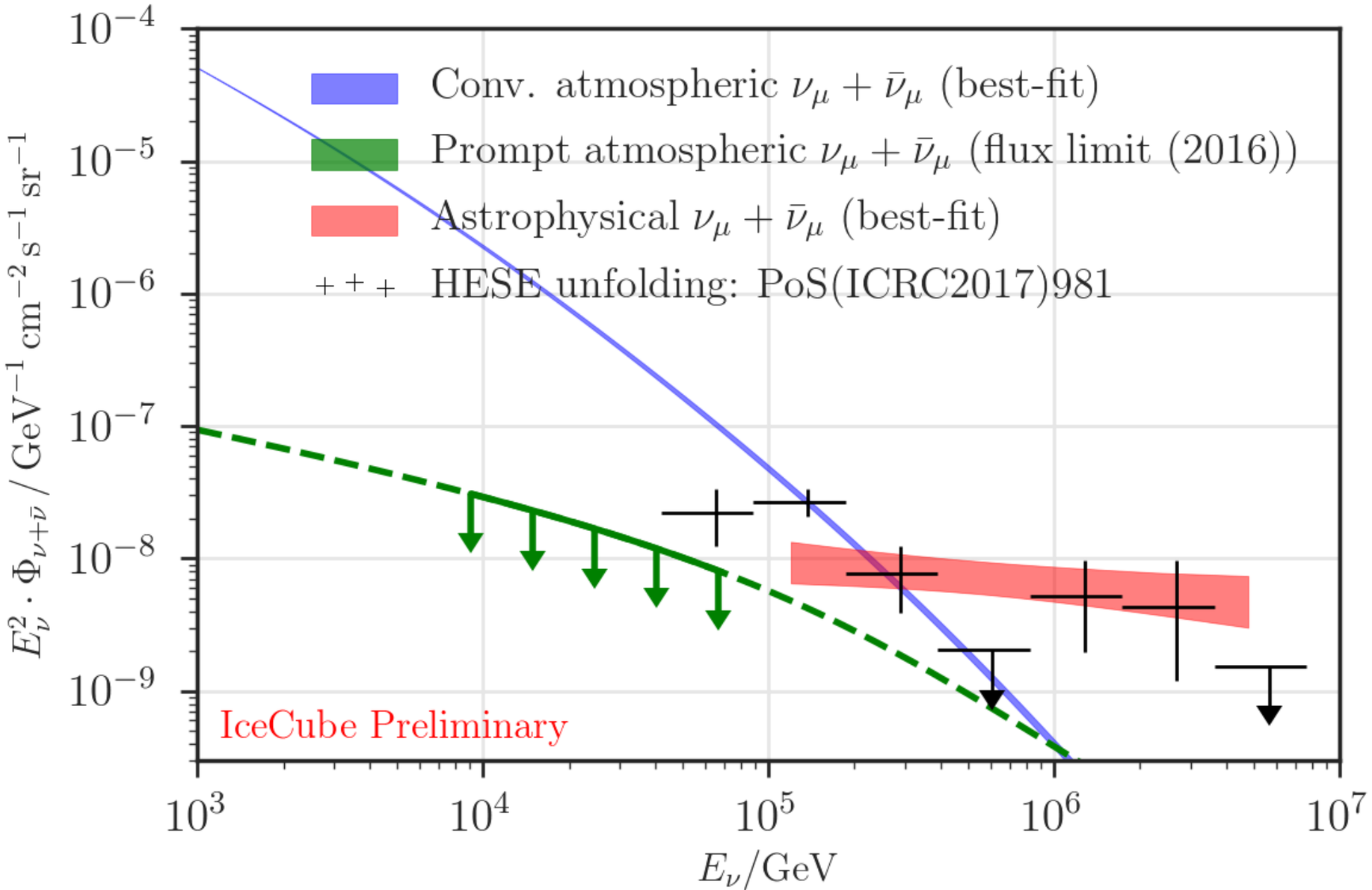


neutrino

(not to scale)

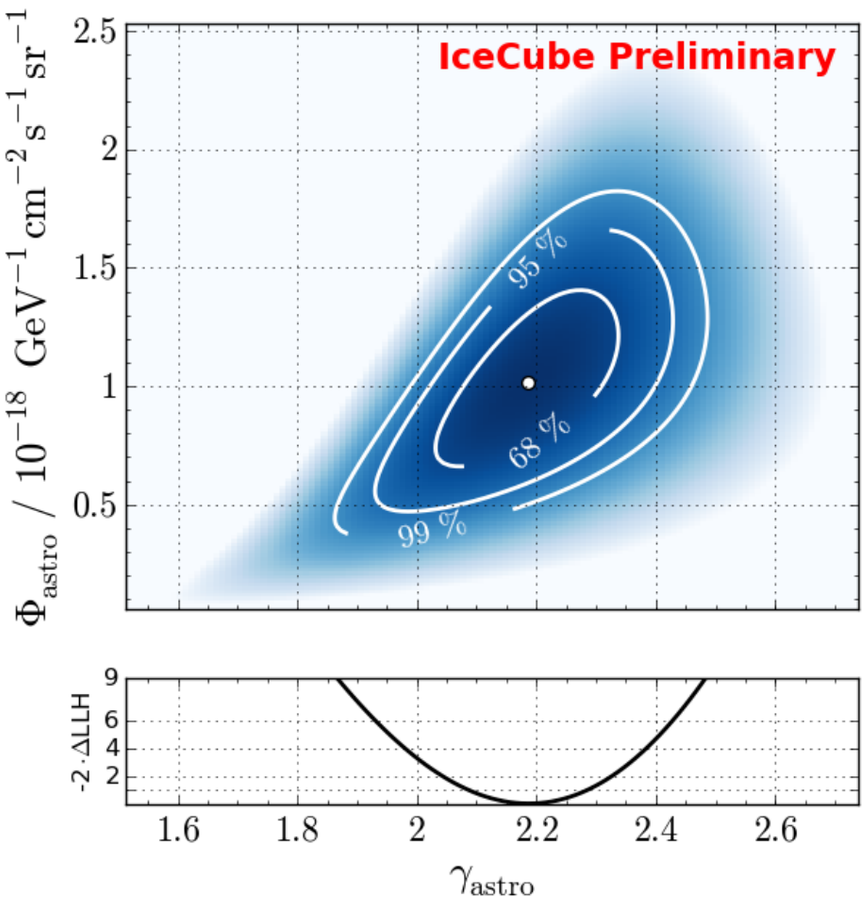
8 year through-going nu-mu!





Astrophysical spectral index

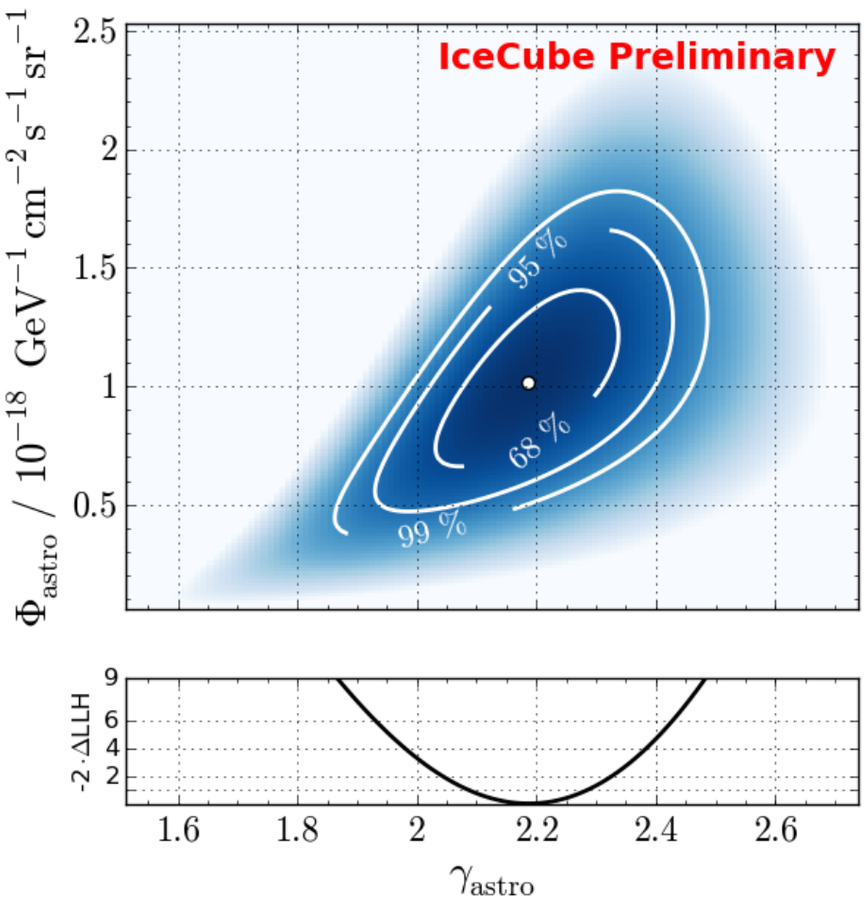
From through-going muons



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

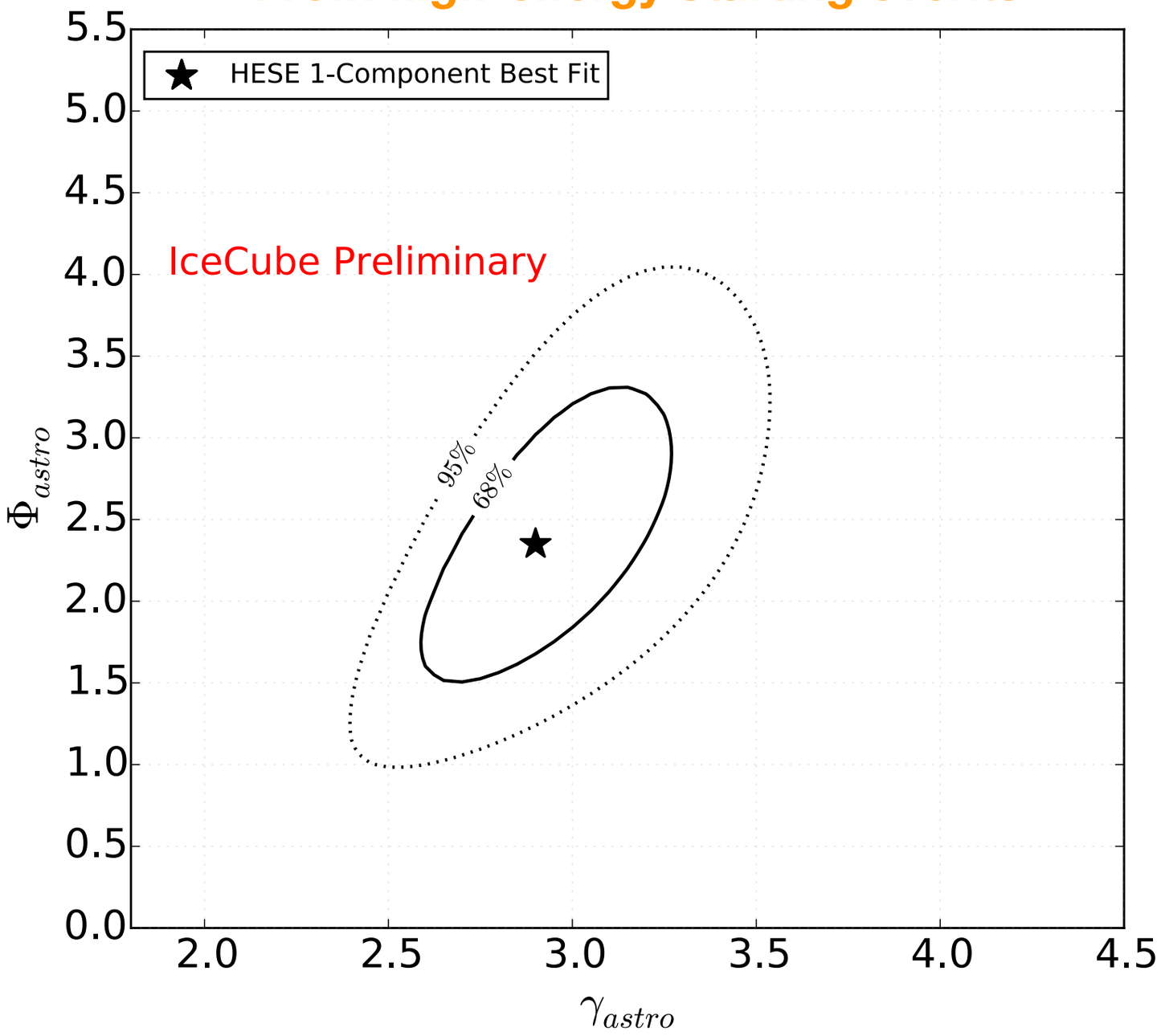
Astrophysical spectral index

From through-going muons



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

From high-energy starting events



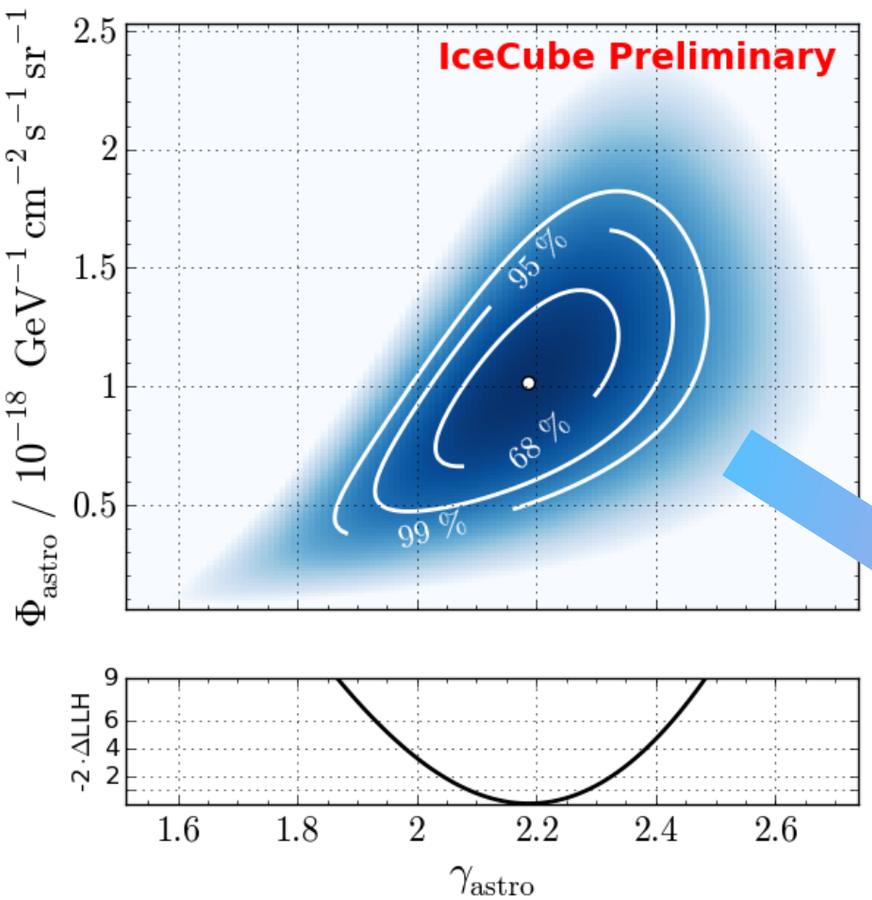
Single power law result from starting events:

$$E^2\phi(E) = 2.46 \pm 0.8 \times 10^{-8}(E/100\mathrm{TeV})^{-0.92}\mathrm{GeVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

$$\gamma = 2.93^{+0.33}_{-0.29}$$

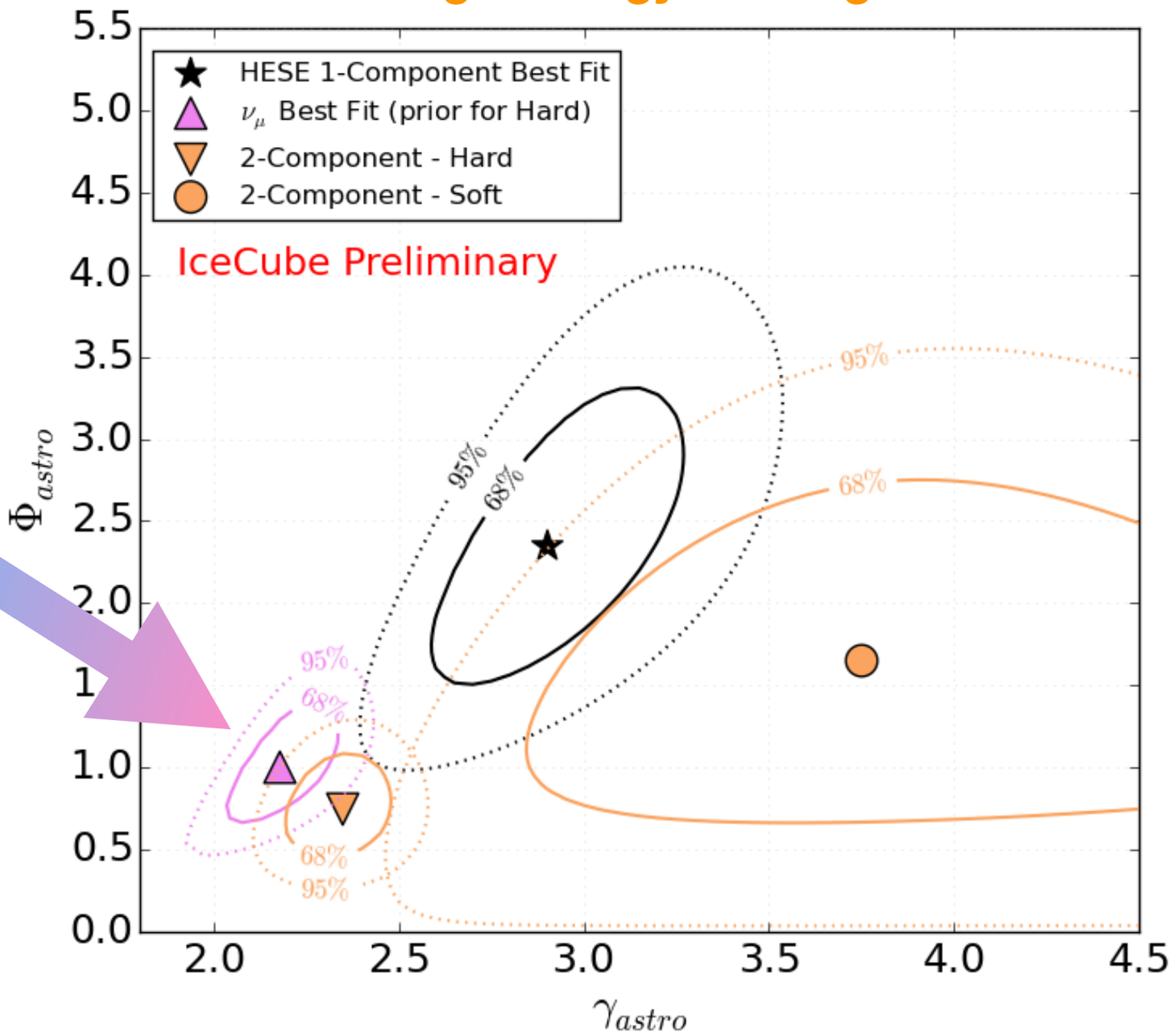
Astrophysical spectral index

From through-going muons



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

From high-energy starting events



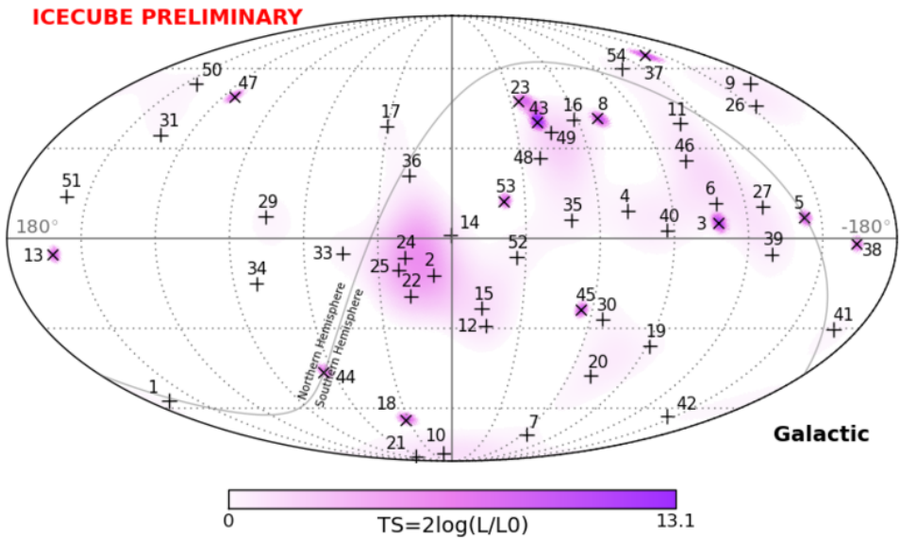
Single power law result from starting events:

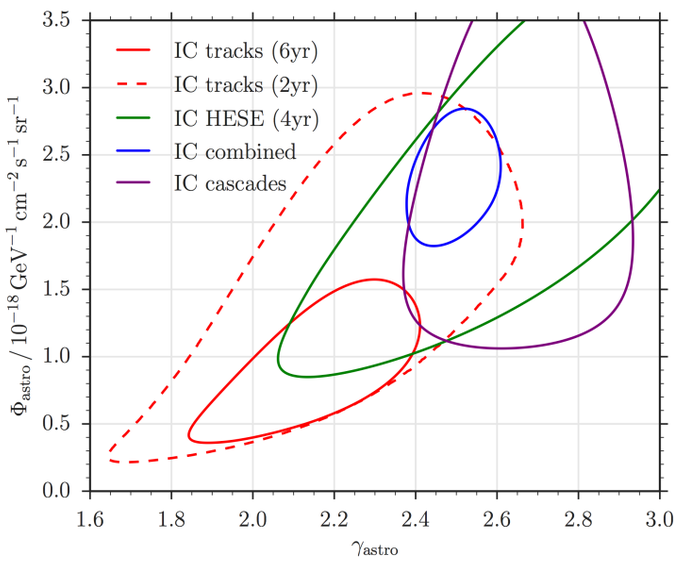
$$E^2\phi(E) = 2.46 \pm 0.8 \times 10^{-8}(E/100\mathrm{TeV})^{-0.92}\mathrm{GeVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

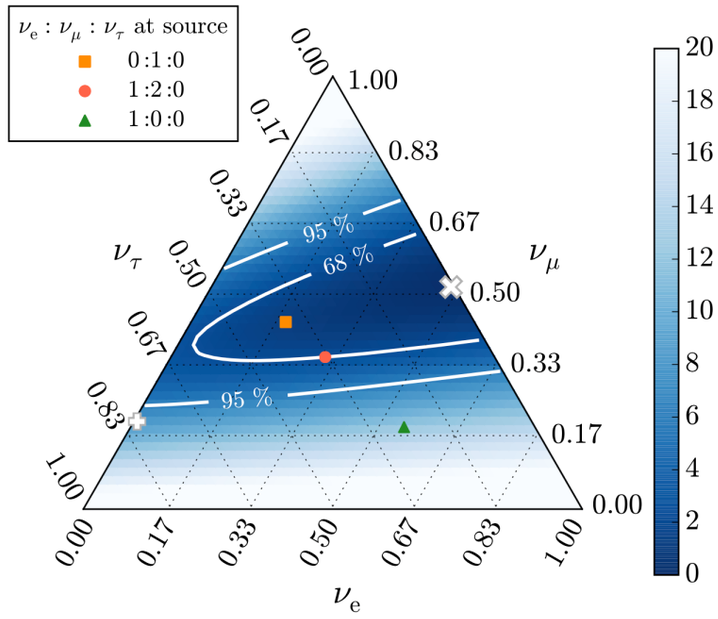
$$\gamma = 2.93^{+0.33}_{-0.29}$$

No significant evidence for two power law solution!

What do we know about astrophysical neutrinos?







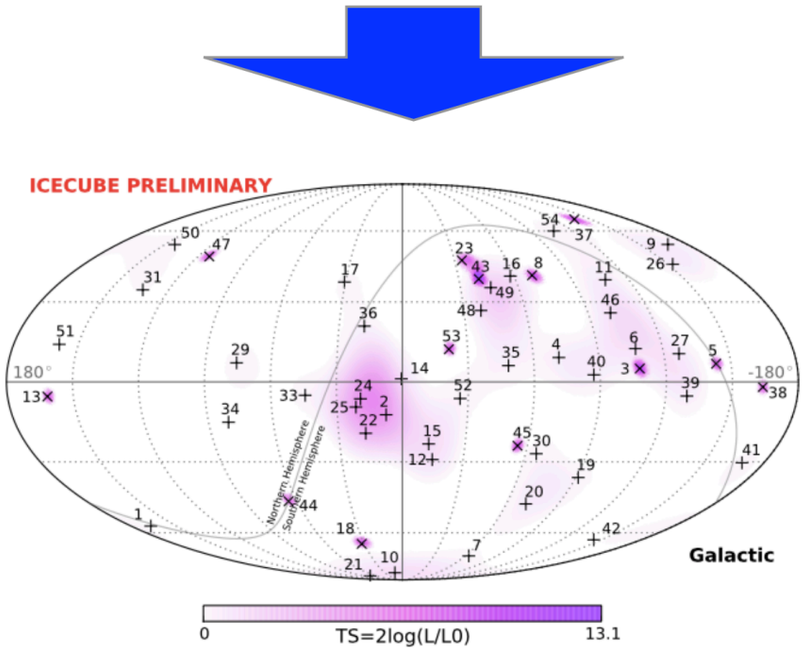
- ~80 Events in 6 years.
- Events spatial distribution compatible with **isotropic** hypothesis.
- **No statistically significant correlation** with Galactic plane.
- Event distribution suggests extragalactic origin for the majority of the events.
- **Flavor ratio** is consistent with 1:1:1 ratio.

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

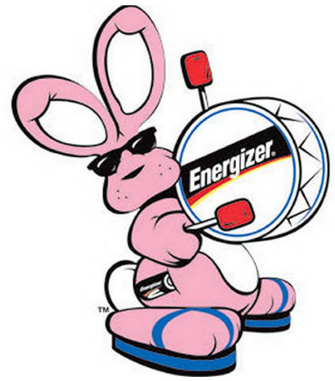
New Physics with Astrophysical Neutrinos

Astrophysical neutrino observables

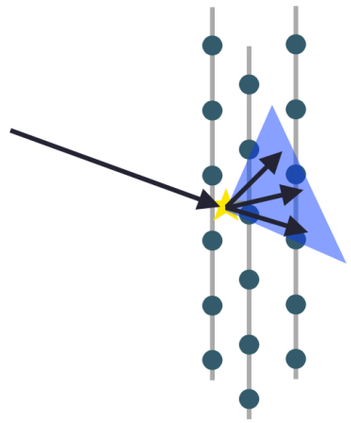
Arrival direction



Energy

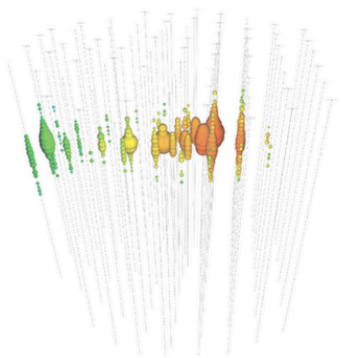


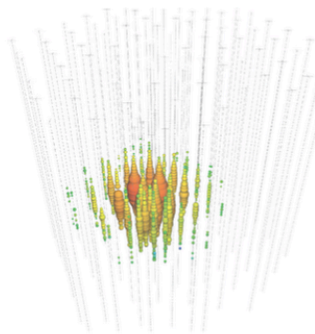
Deposited EM-equivalent



Flavour (e, μ, τ)

Topology





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, J. Salvado, S. Palomares-Ruiz, and A. Vincent *in preparation*)

New physics searches

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

T. Katori

Queen Mary University of London

J. Salvado

IFIC INSTITUT DE FÍSICA CORPUSCULAR

(C.A., M. Bustamante, J. Conrad, A. Kheirandish, J. Salvado, S. Palomares-Ruiz, 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 $\pi^+ \to \mu^+ + \nu_\mu$ $\downarrow$ $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$	(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

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

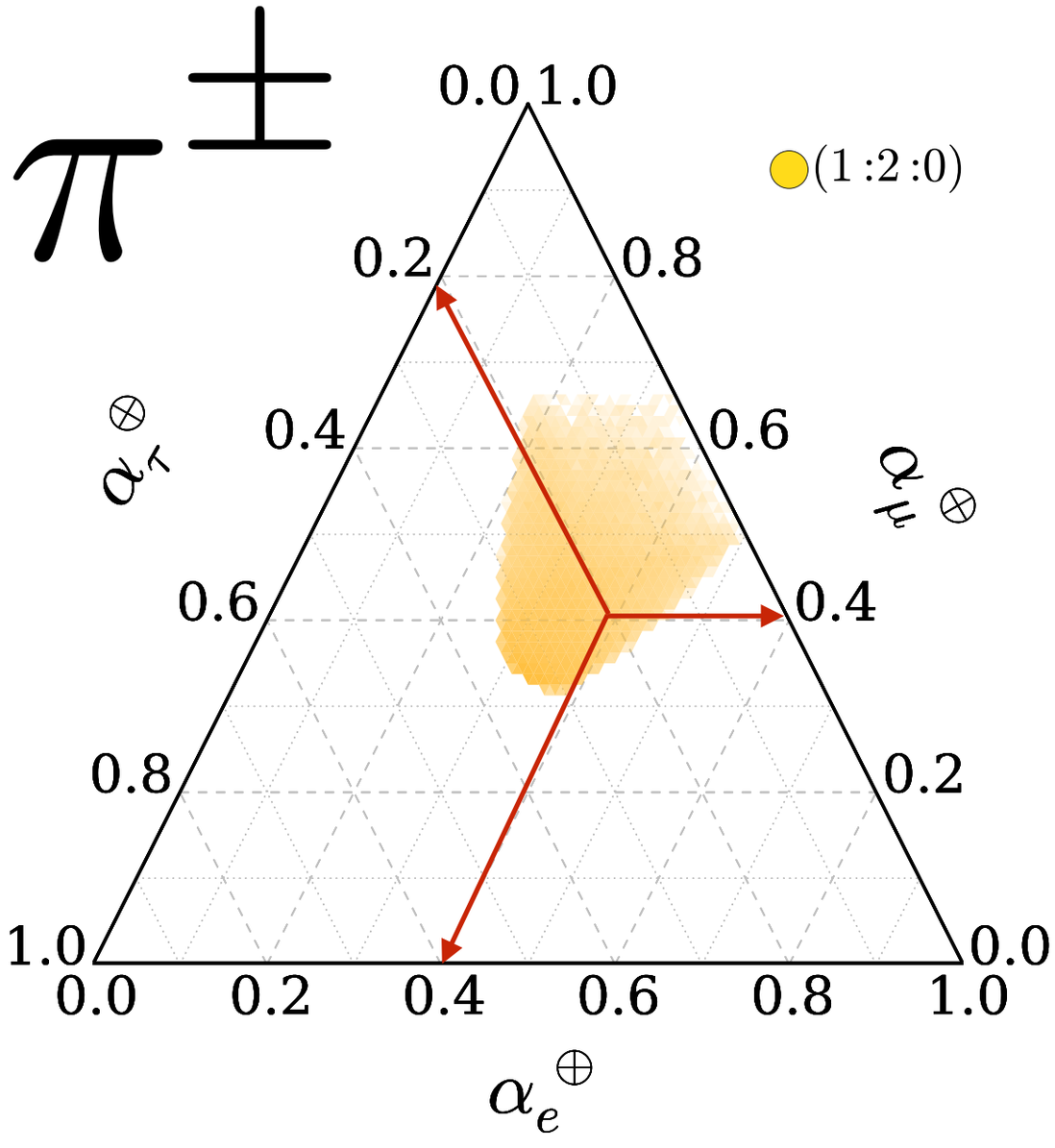
Since the oscillation length is much smaller than the distance of the sources

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

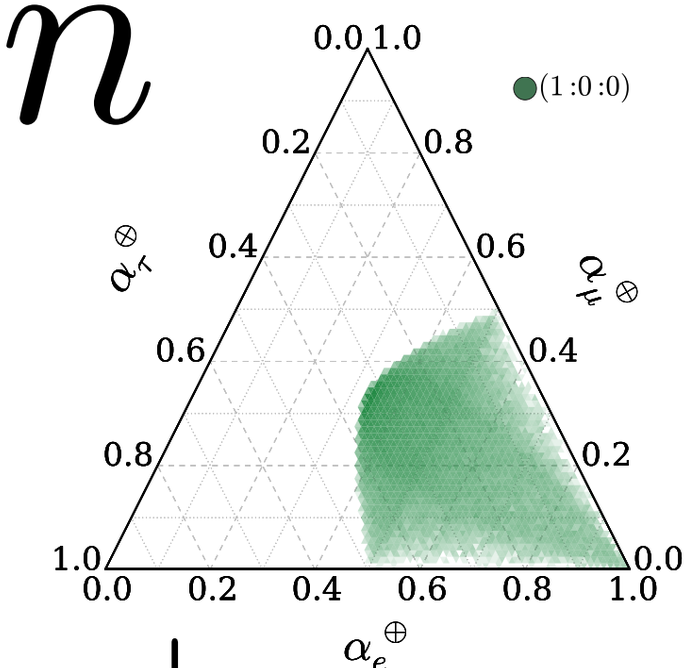
Oscillation probabilities depend only on the mixing elements!

Possible flavor triangles

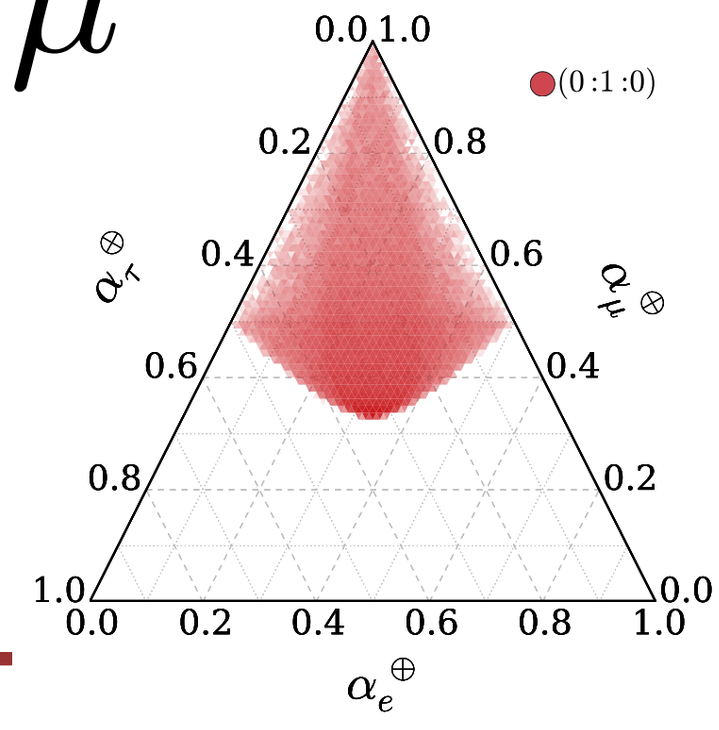
$\pi^{\pm}$



n



$\mu^{\pm}$



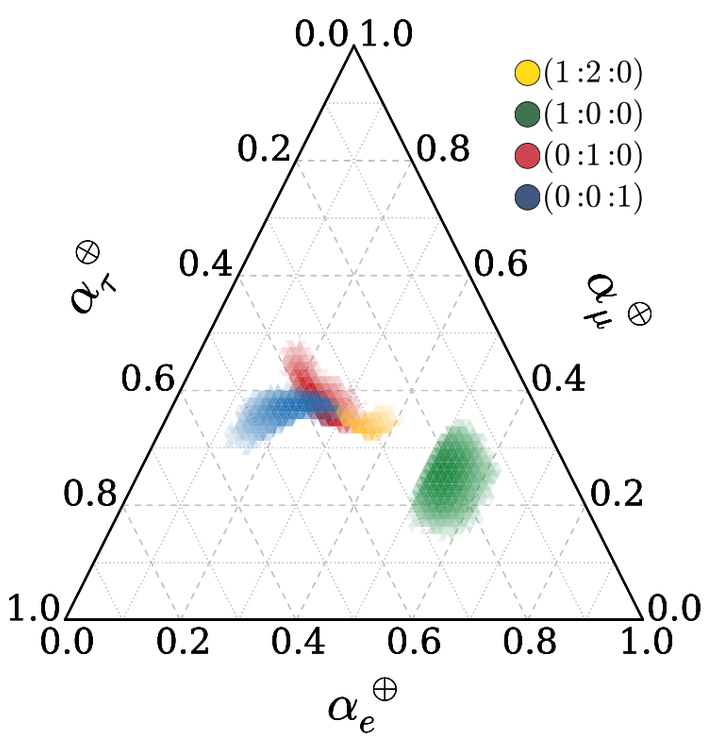
Due to unitarity the possible Earth flavor ratios for a given initial flavor composition is confined.

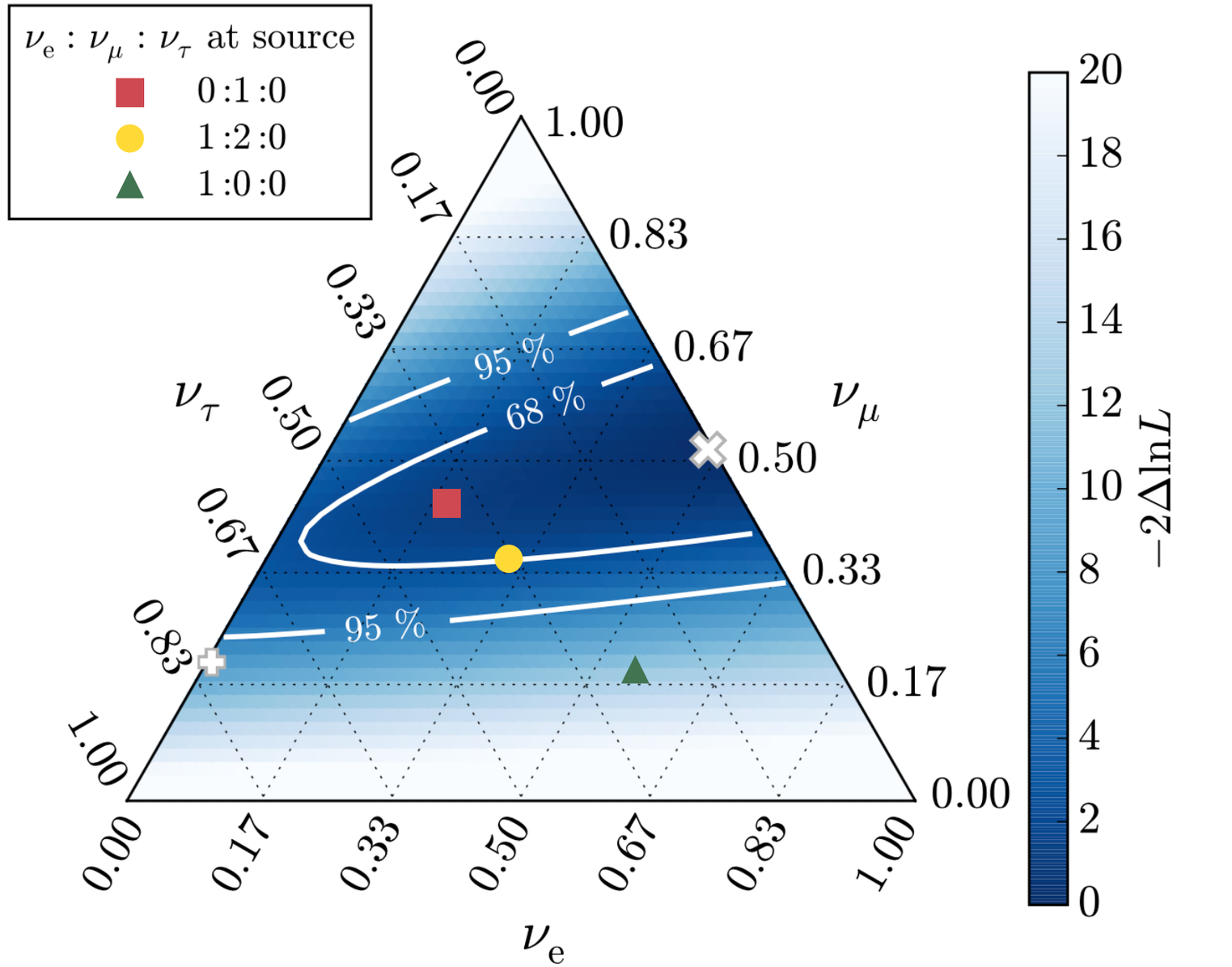
Astrophysical neutrino flavor

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

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: effective operators

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

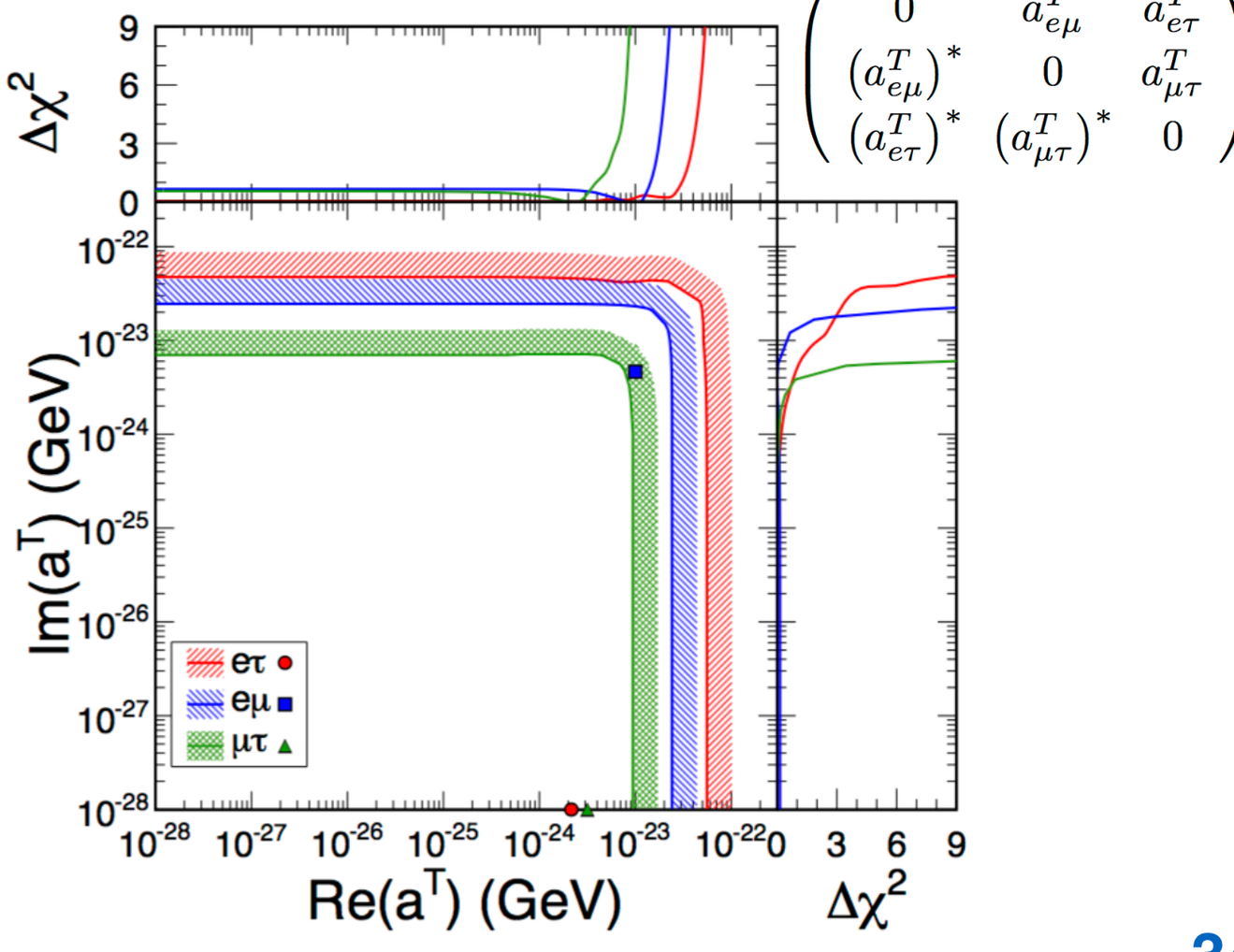
$$\sim 10^{-24}\text{GeV}\left(\frac{TeV}{E}\right)$$

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

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

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

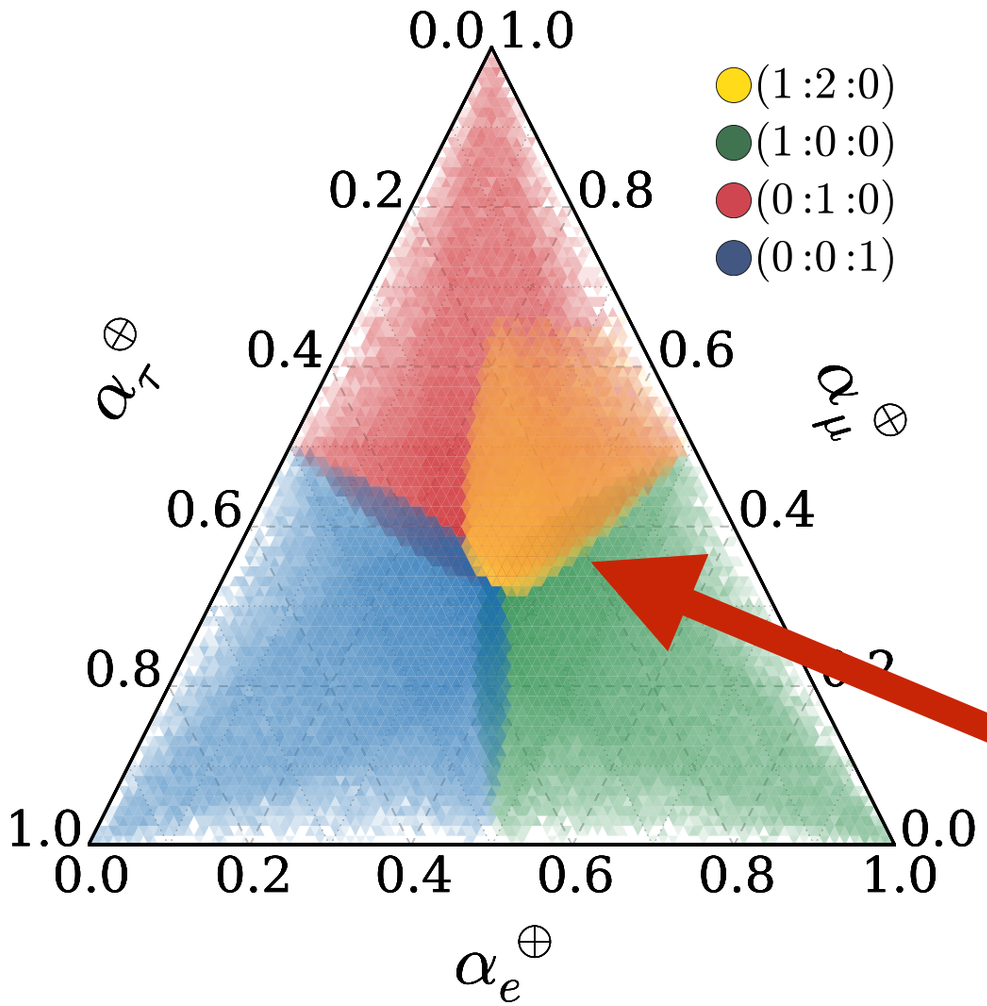
Phys.Rev. D91 (5) (2015) 052003,
Phys.Rev. D82 (2010) 112003.



+ 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

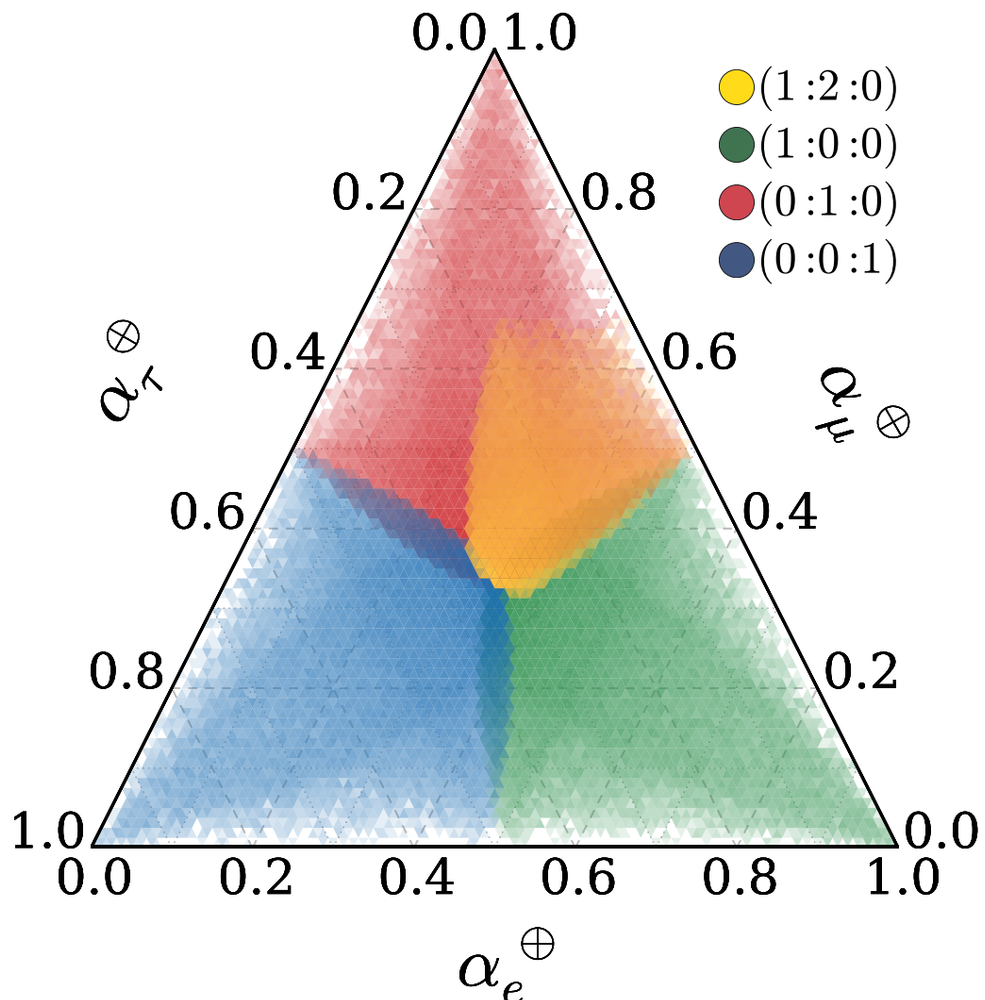
C.A., T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

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

+ New physics: effective operators

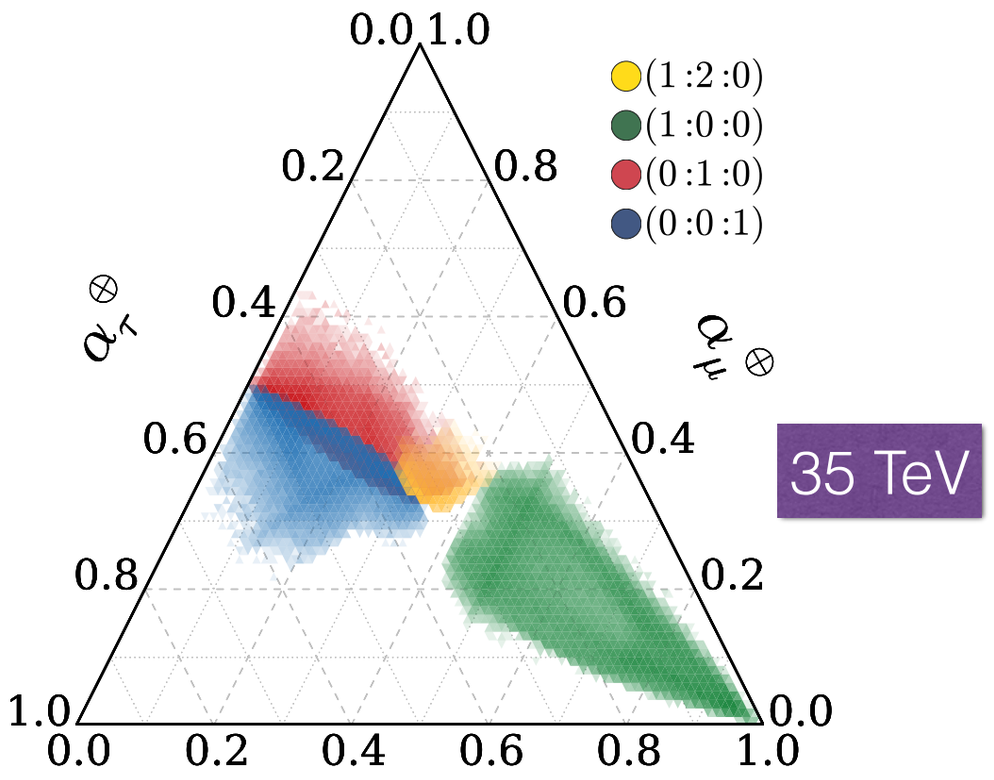
$$H = \frac{1}{2E} U M^2 U^\dagger + \boxed{\sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger}$$

(setting operators scales to current SK bounds)

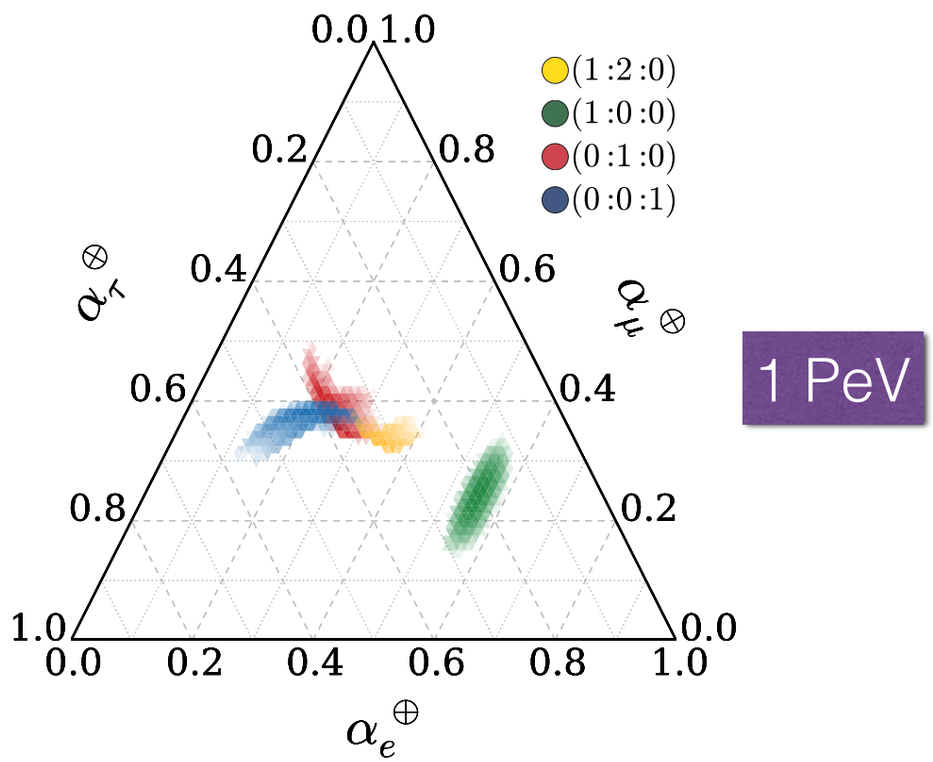


$O_0 \sim \mathrm{O}(10^{-23})$ GeV

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



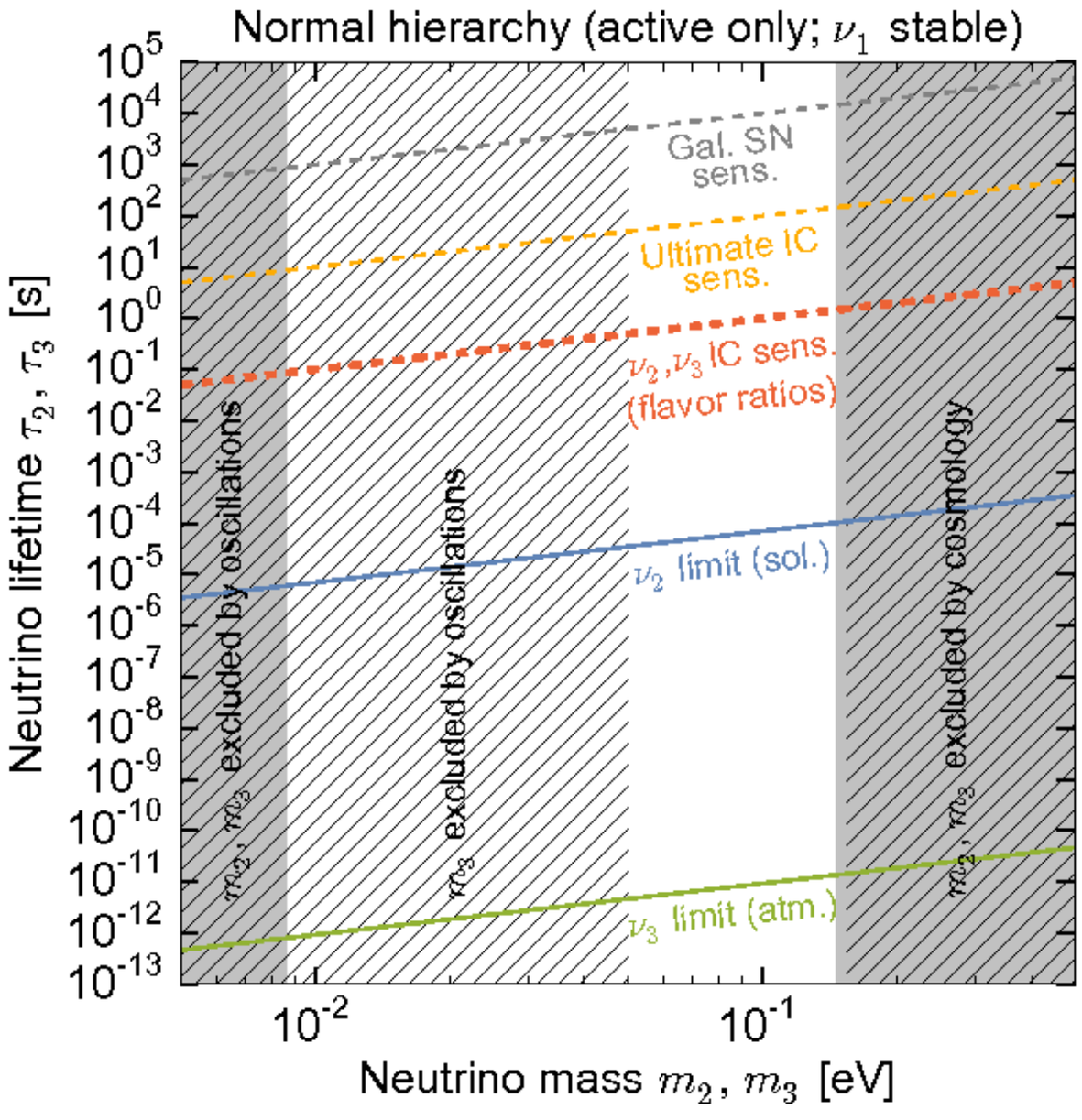
35 TeV

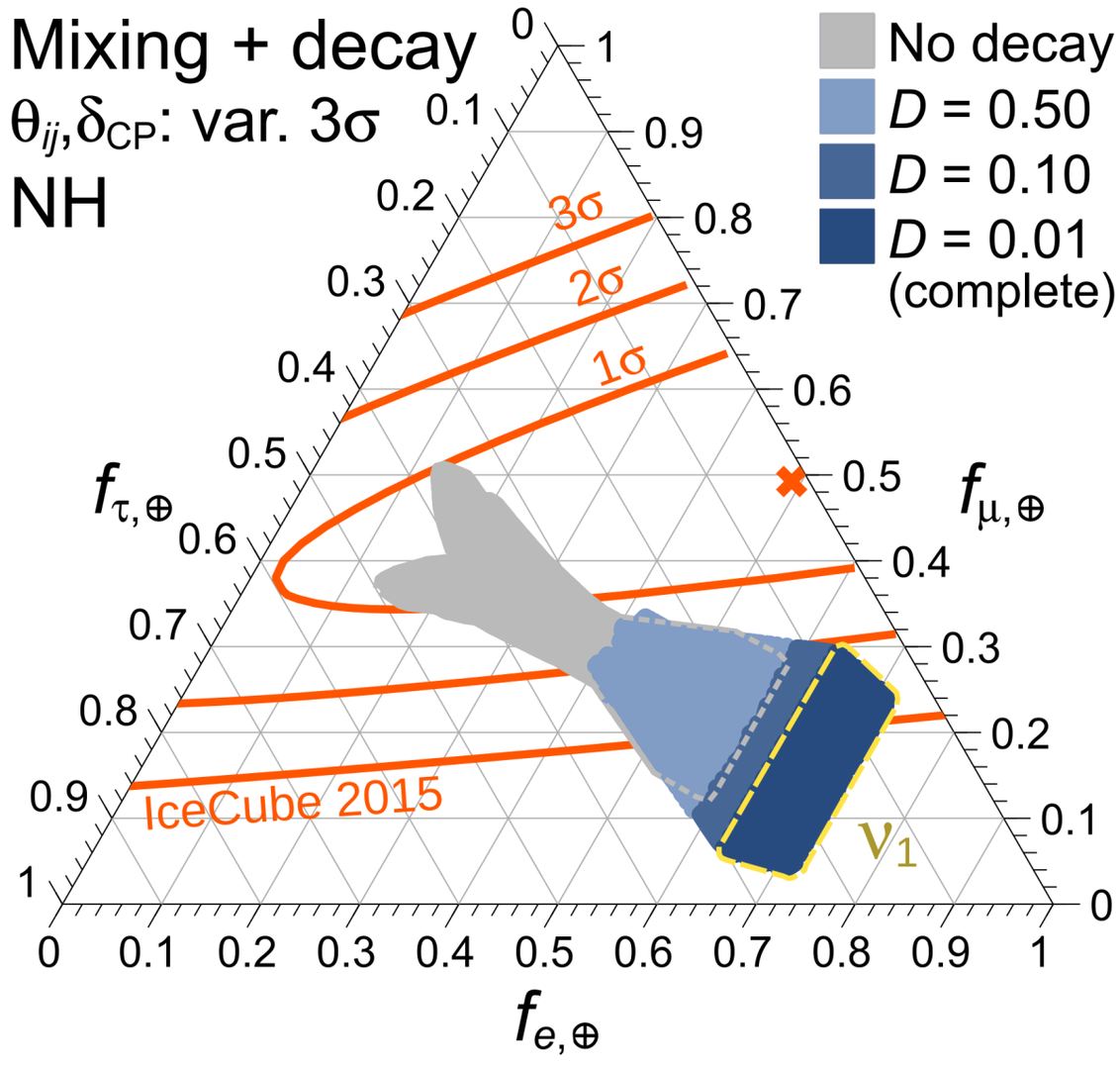


1 PeV

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

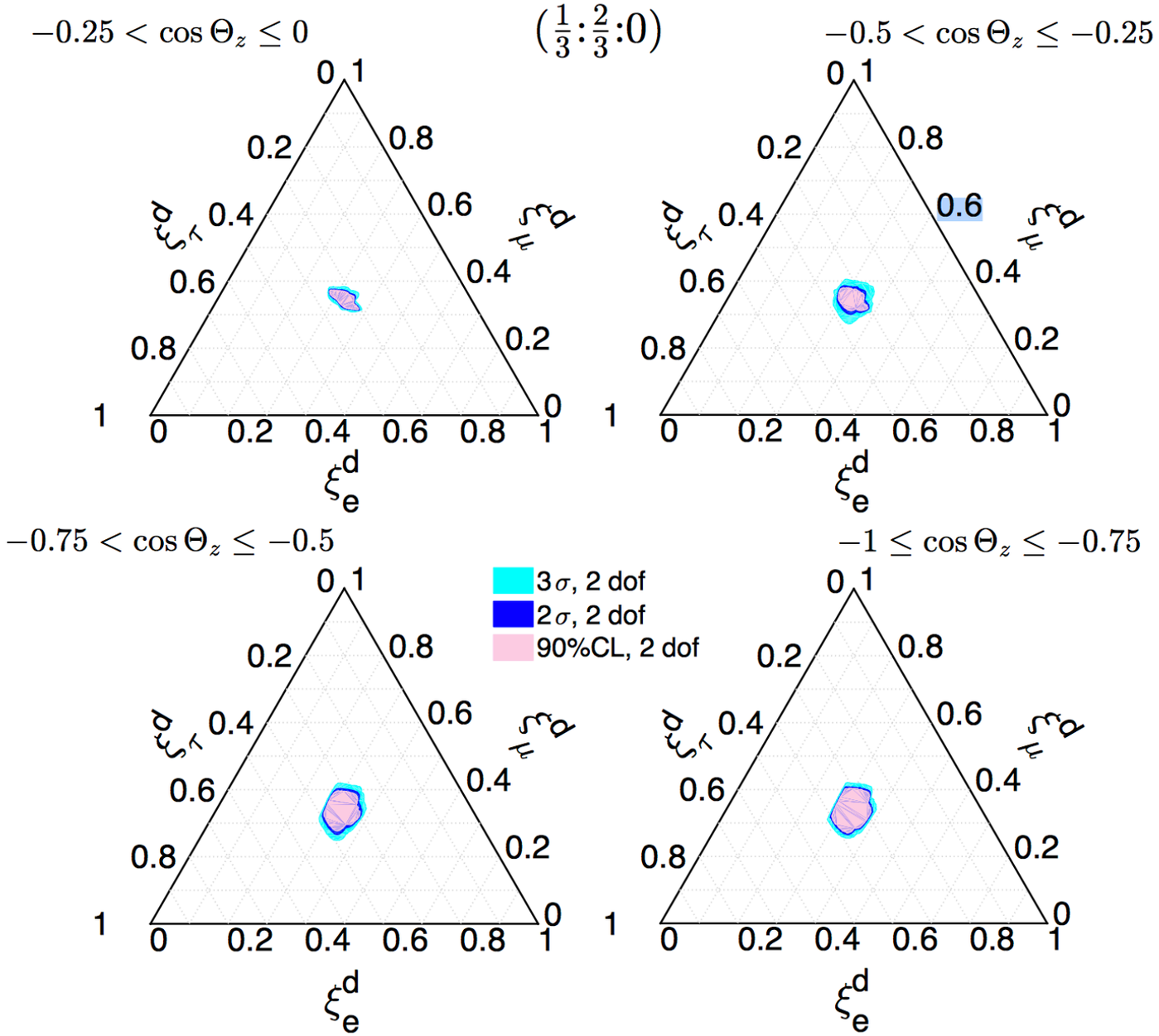
+Neutrino decay





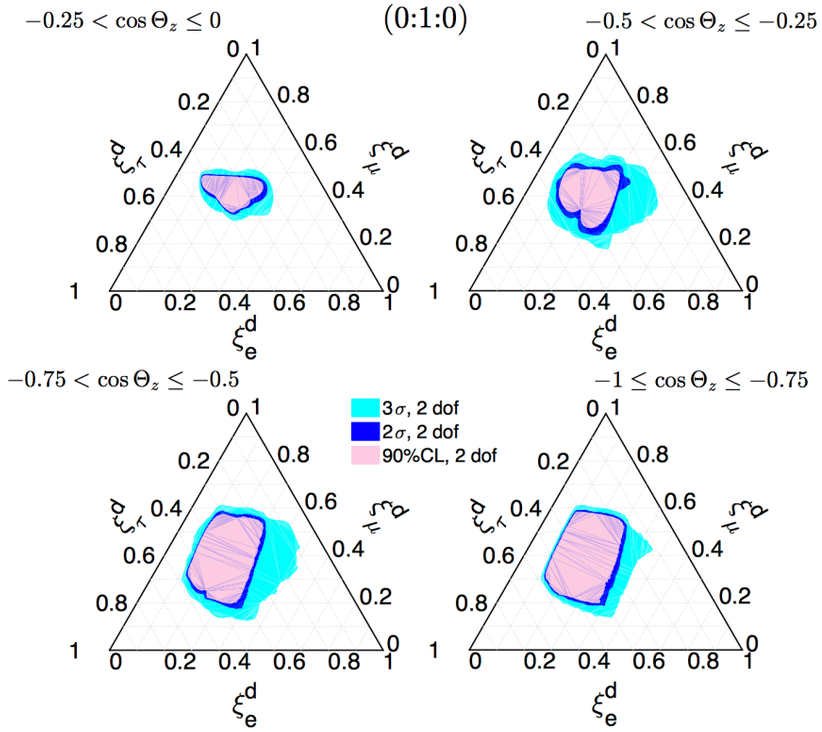
M. Bustamante, J. Beacom, K. Murase (1610.02096)

+ NSI@Earth

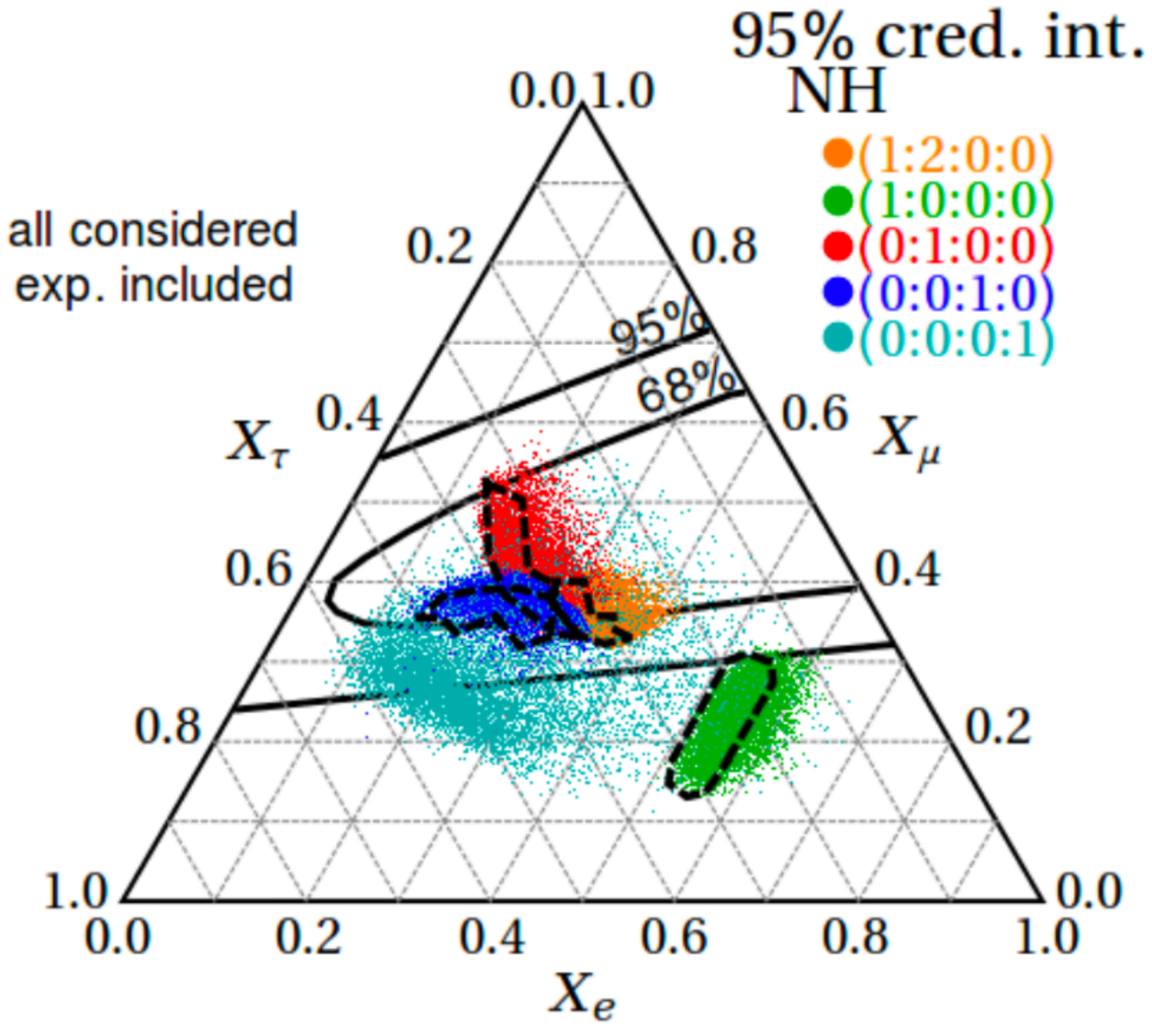


In the pion scenario NSI effects are small.

This is not the case for other initial flavor ratios.



+ (eV) sterile neutrino



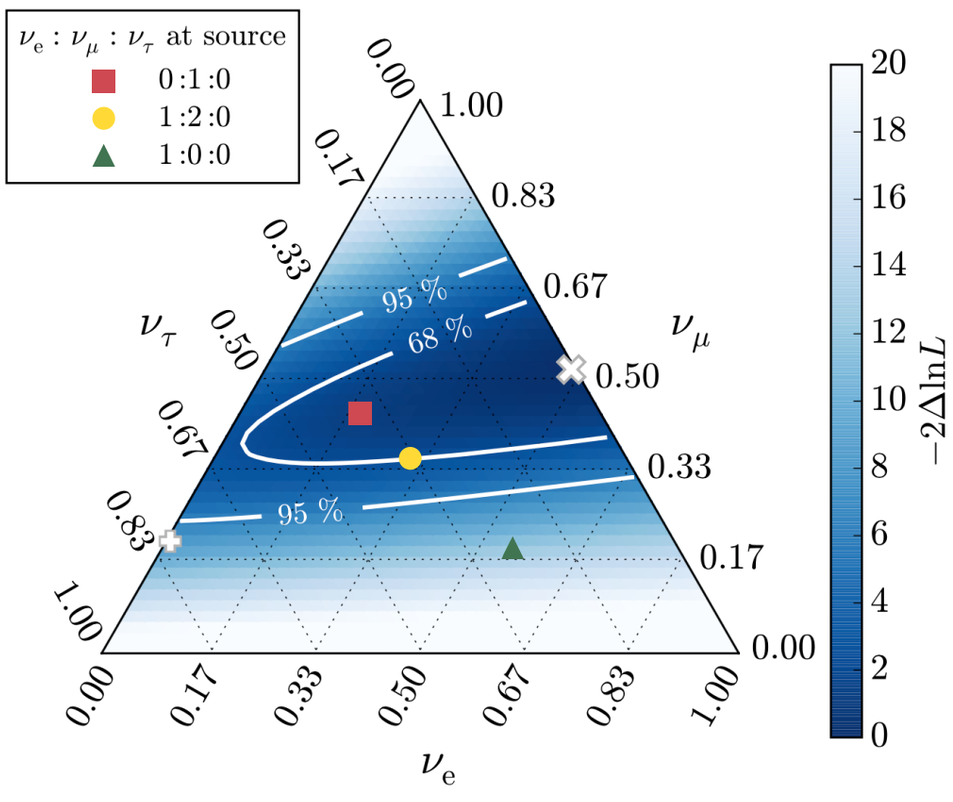
- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

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

IceCube -> IceCube-Gen2!

IceCube keeps collecting more data: triangle will improve!

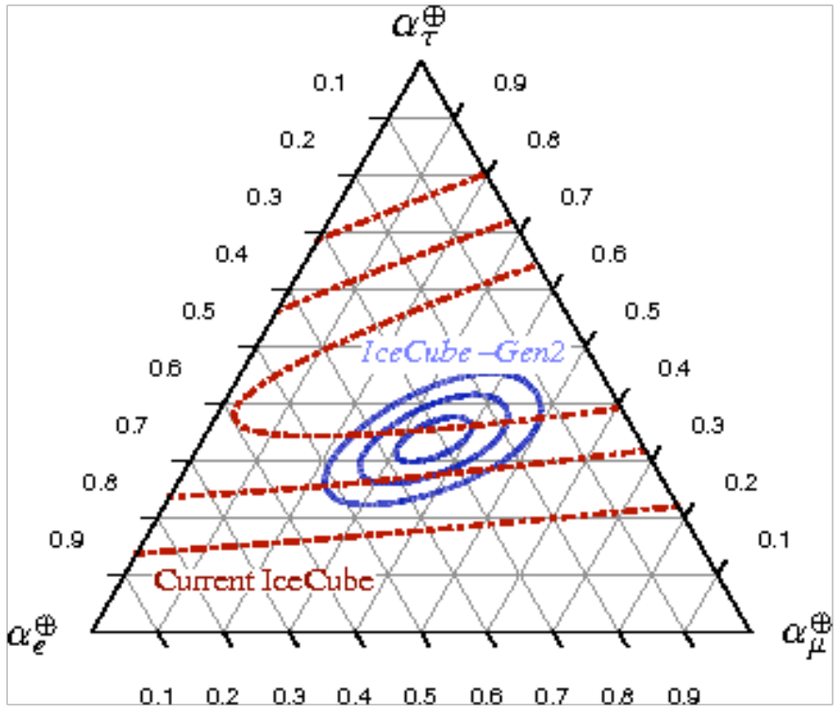
(current limits)



IceCube 1507.03991

Current limits is **statistically limited**!

An IceCube extension can help further constrain new physics!

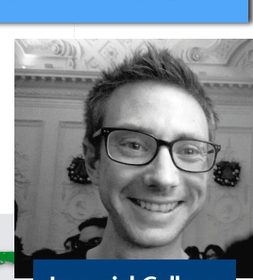


Shoemaker et al. Phys.Rev. D93 (2016) no.8, 085004

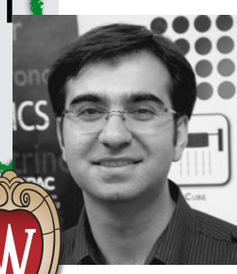
New physics searches

	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

A. Vincent



Imperial College London



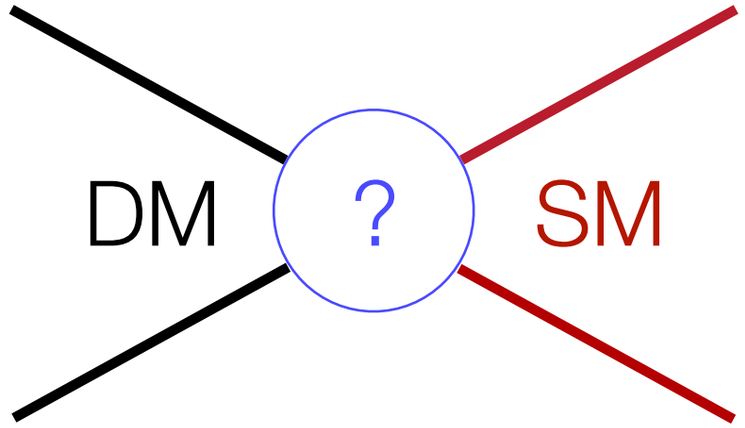
A. Kheirandish

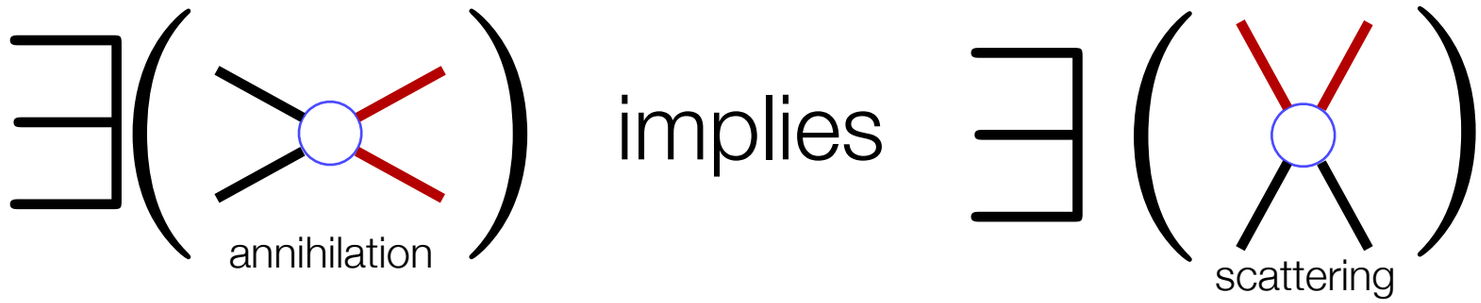
(C.A., M. Bustamante, J. Conrad, A. Kheirandish, J. Salvado, S. Palomares-Ruiz, and A. Vincent *in preparation*)

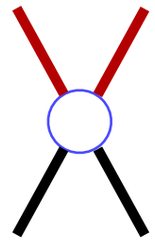
Argüelles, Kheirandish & Vincent 2017

Why DM-neutrino interactions?

- What is dark matter?
- What SM particles does dark matter interact with?
- How does it interact?





if —— = quarks, then  = direct detection (LUX, LZ, SuperCDMS, …)

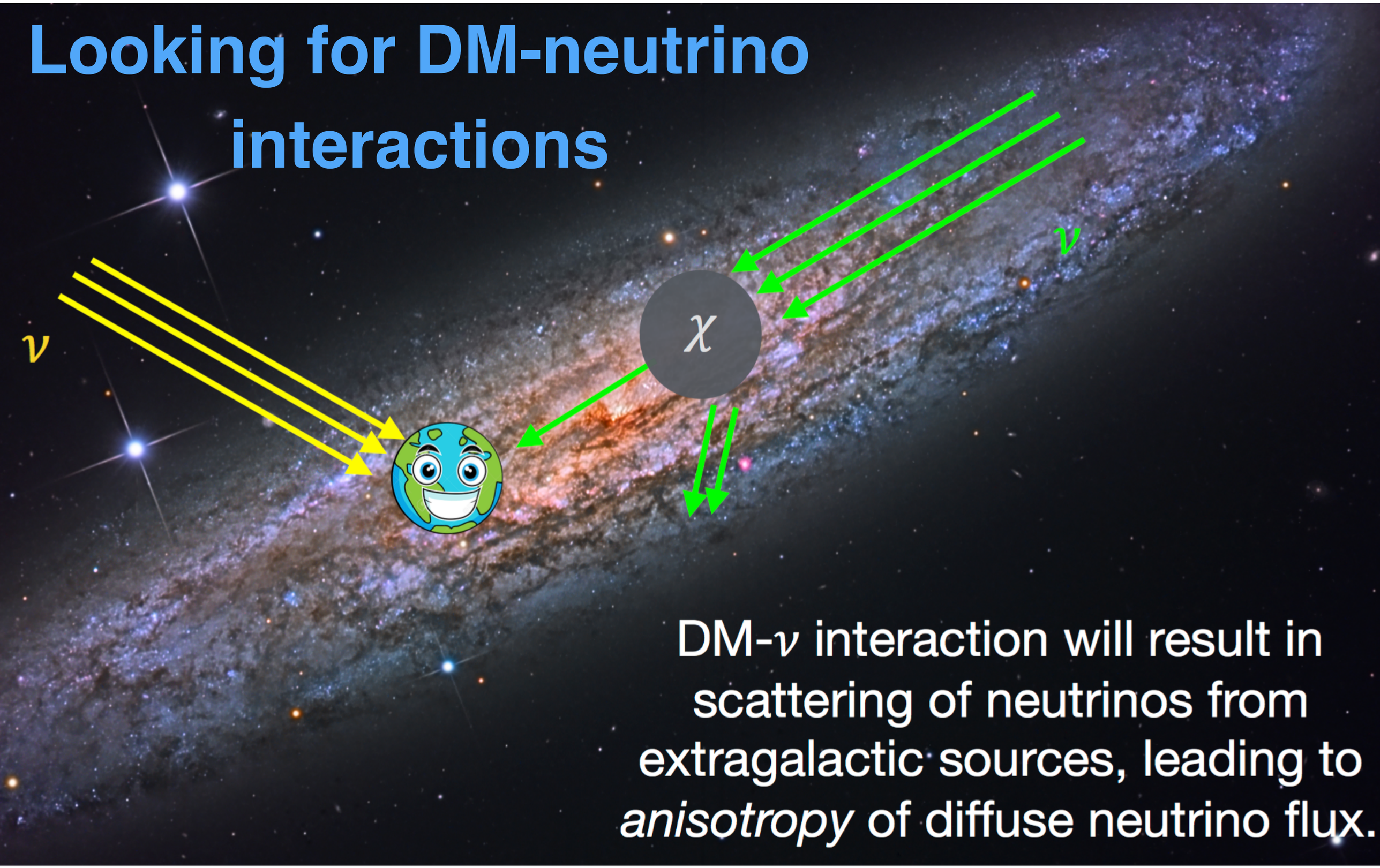
But if —— too light, or (?) does not talk to quarks, then

—— could be neutrinos

[Boehm+ 01, 02, 05, 14—Bertschinger+ 06— Mangano+ 06—Serra+ 10—Wilkinson+ 14—van den Aarssen+ 12—Farzan+ 14—Cherry+ 14—Bertoni+ 15—Chewtschenko+ 15]

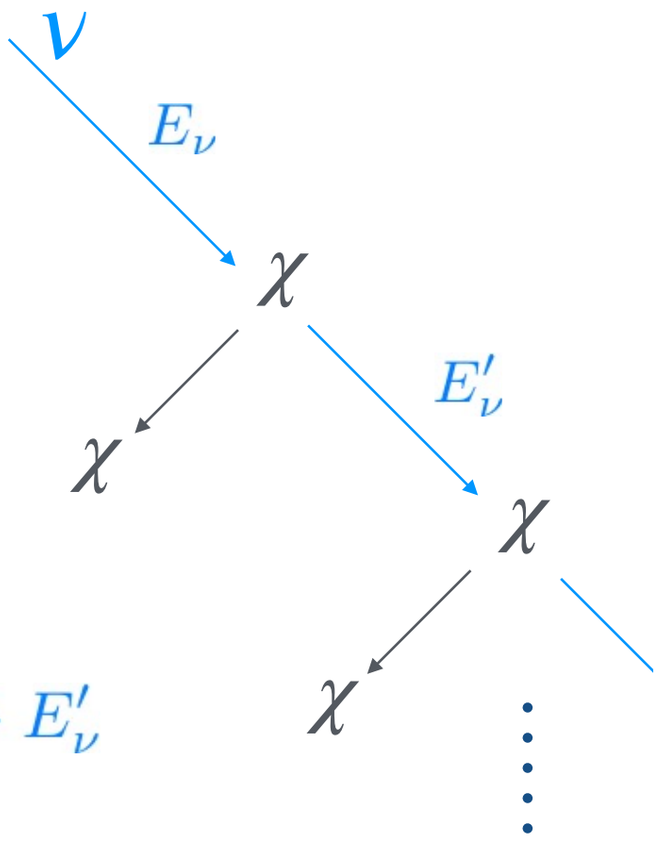
Argüelles, Kheirandish & Vincent 2017

Looking for DM-neutrino interactions

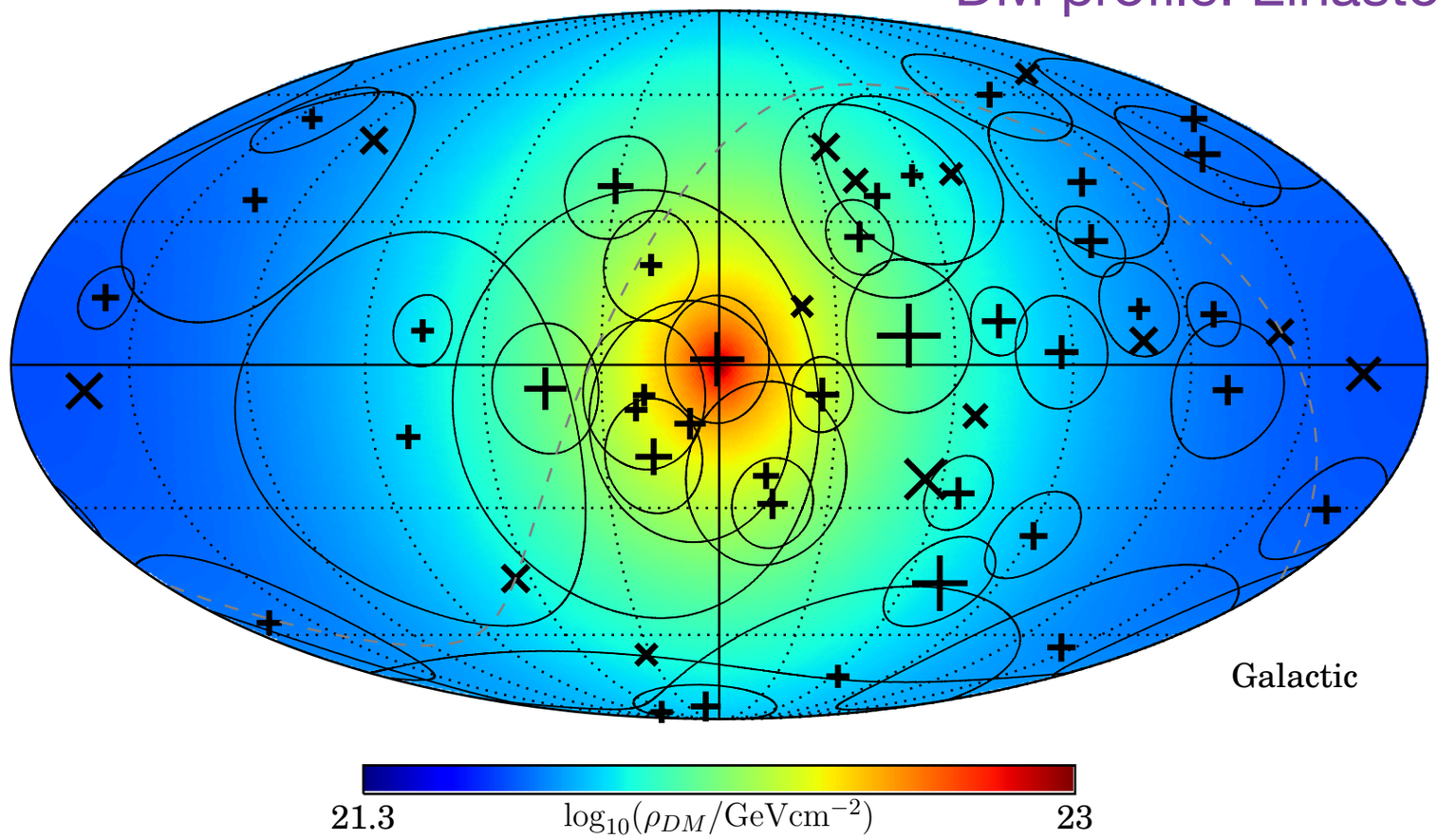


DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to *anisotropy* of diffuse neutrino flux.

Neutrino energy cascading down



DM profile: Einasto



$$\frac{d\phi(E)}{d\tau} = -\sigma(E)\phi(E) + \int d\tilde{E}\frac{d\sigma(\tilde{E},E)}{dE}\phi(\tilde{E})$$

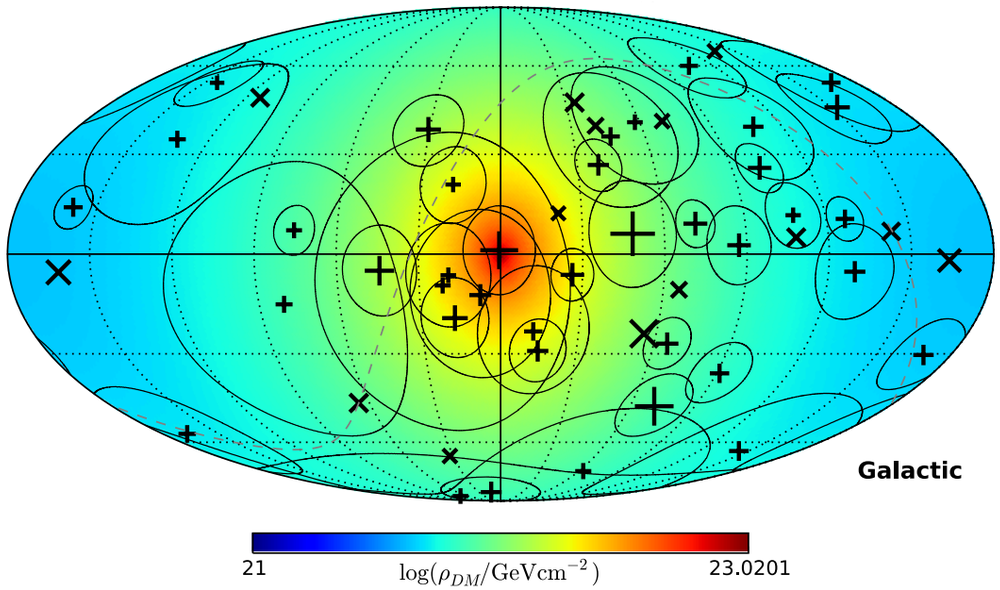
(flux loss) (flux gain)

b, *l*: galactic latitude, longitude

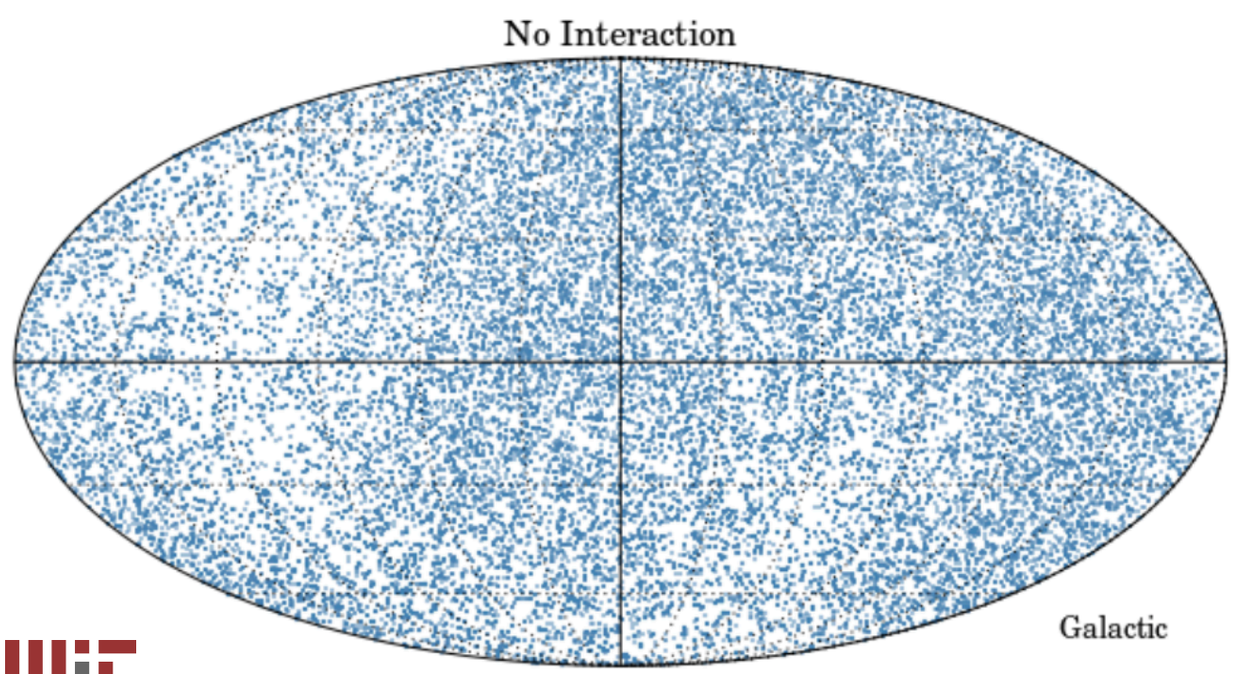
$$\tau(b,l) = \int_{l.o.s} n_\chi(x;b,l)dx$$

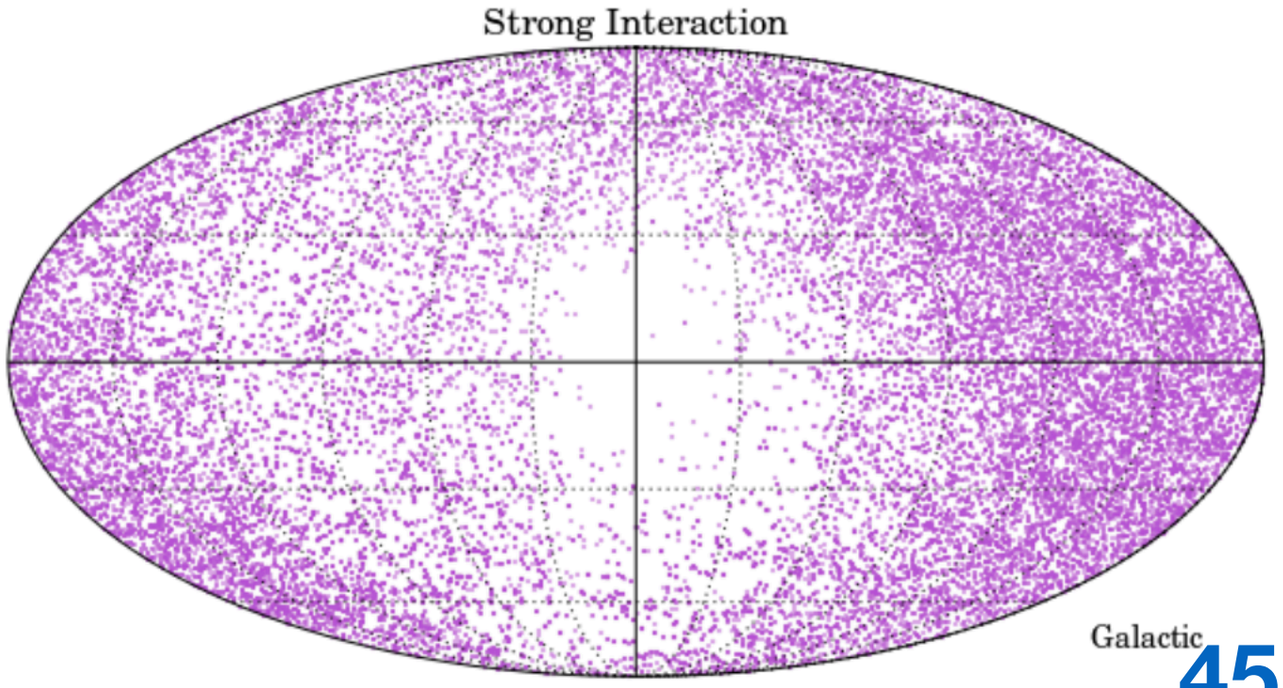
NUFATE github.com/aaronvincent/nuFATE

Dark matter column density seen from Earth



Simulation including effects of detector, Earth



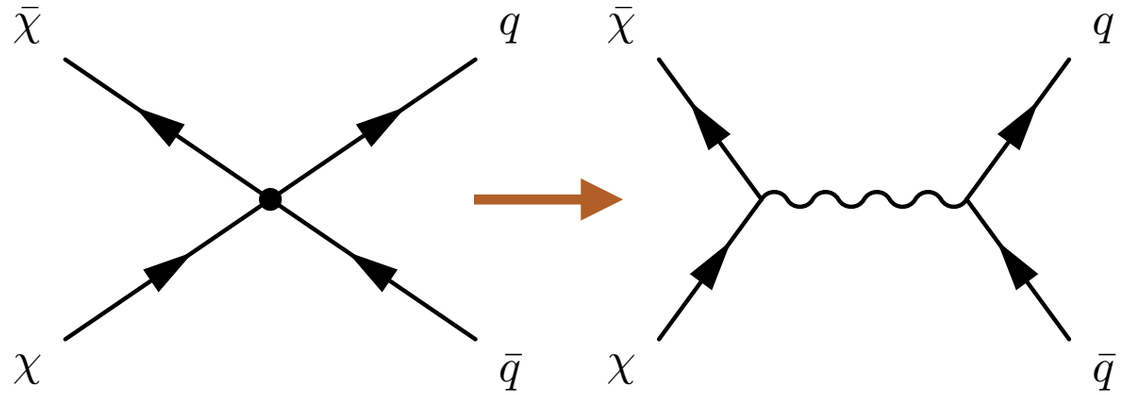


What about the cross section?

$$\sigma_{DM-\nu} \propto E_\nu^2 \xrightarrow[??]{} \left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

No!

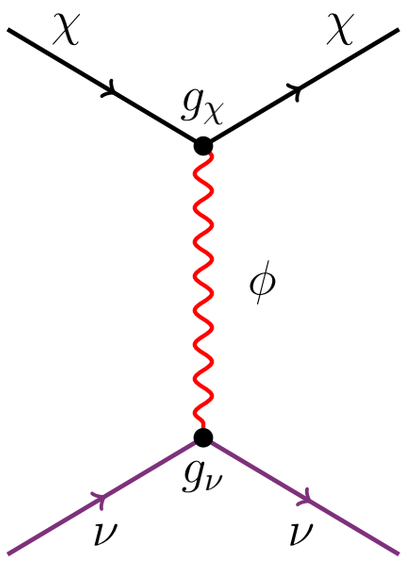
$$E \to \Lambda_{New\,physics}$$



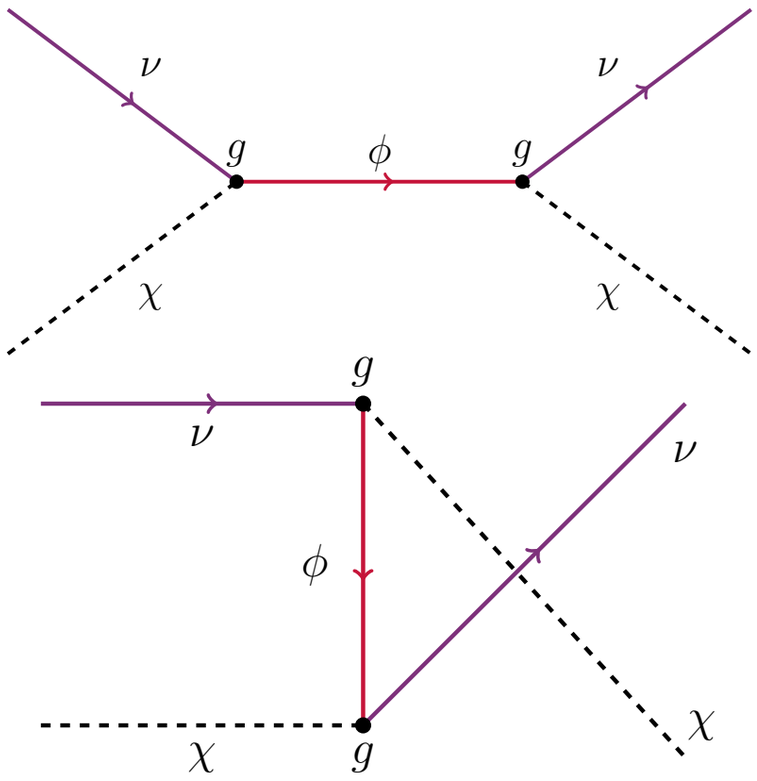
The low energy approximation does not work at a PeV!!

Begin to resolve microphysics: **need more concrete model**

Two Simplified models



Fermion DM, **vector mediator**:
similar to a leptophillic Z' model
Scales strongly with *E*

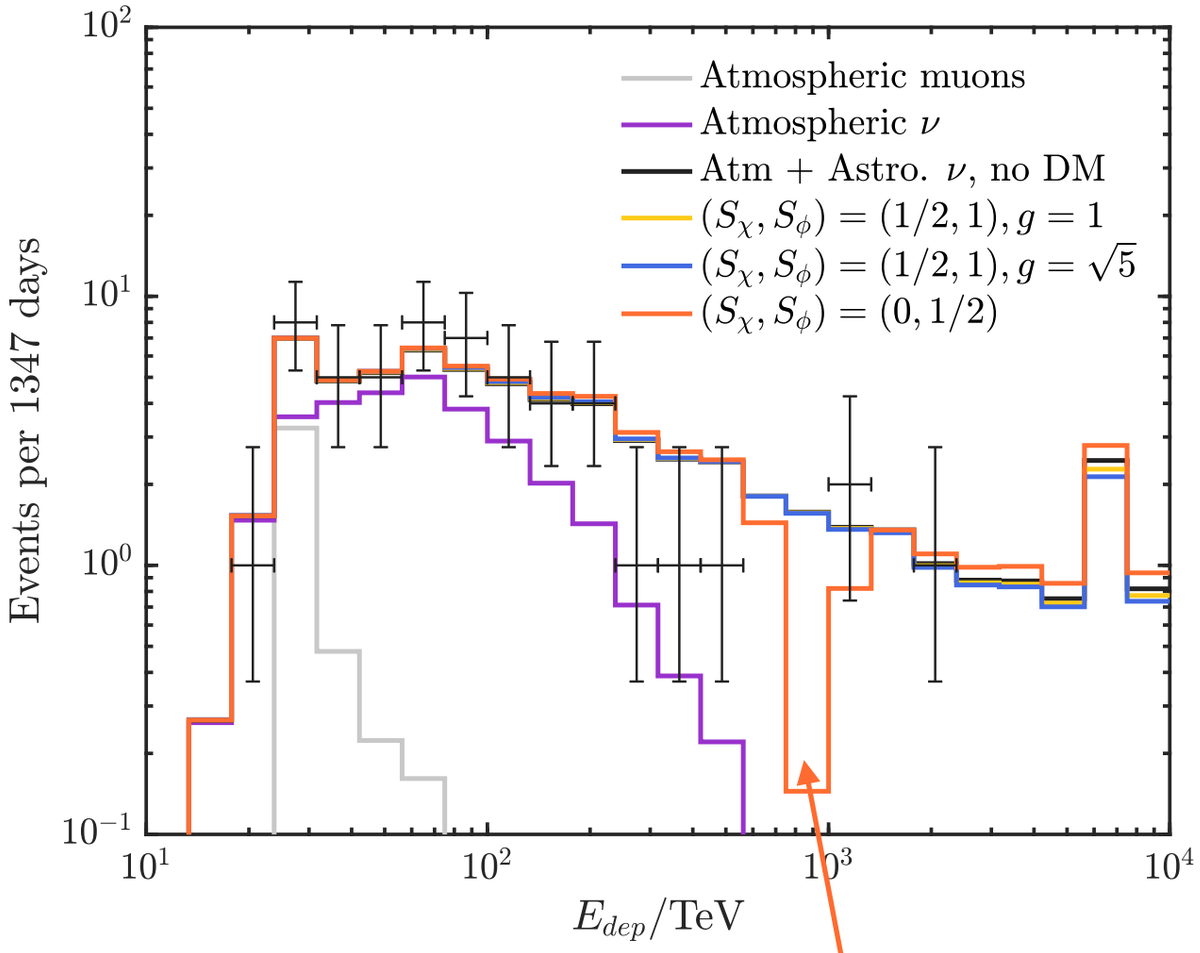


Scalar DM, **fermionic mediator**:
e.g. sneutrino dark matter,
neutralino mediator.
Resonant behaviour (s-channel)

Argüelles, Kheirandish & Vincent 2017

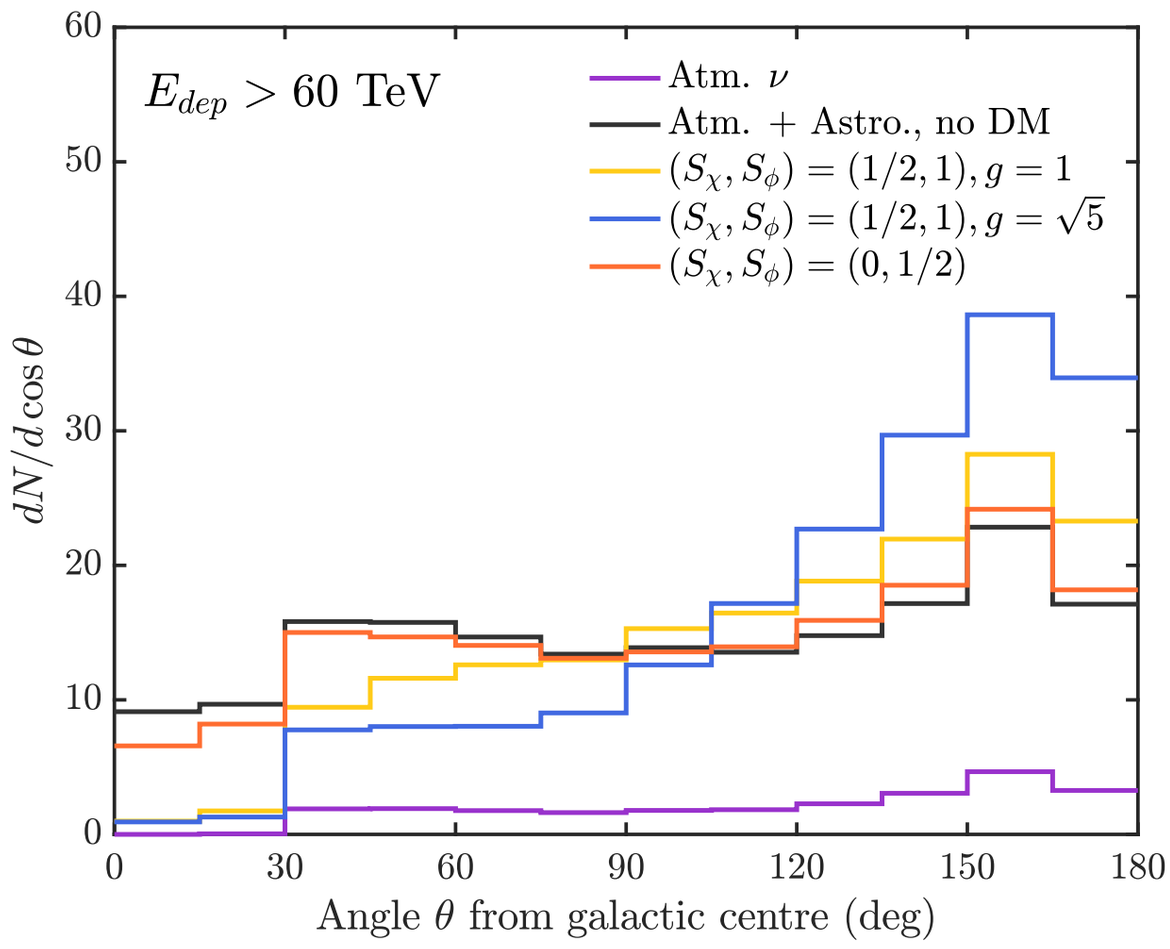
Effects in energy and direction

Energy



Resonance @ 810 TeV

Angle from galactic centre



IceCube HESE events

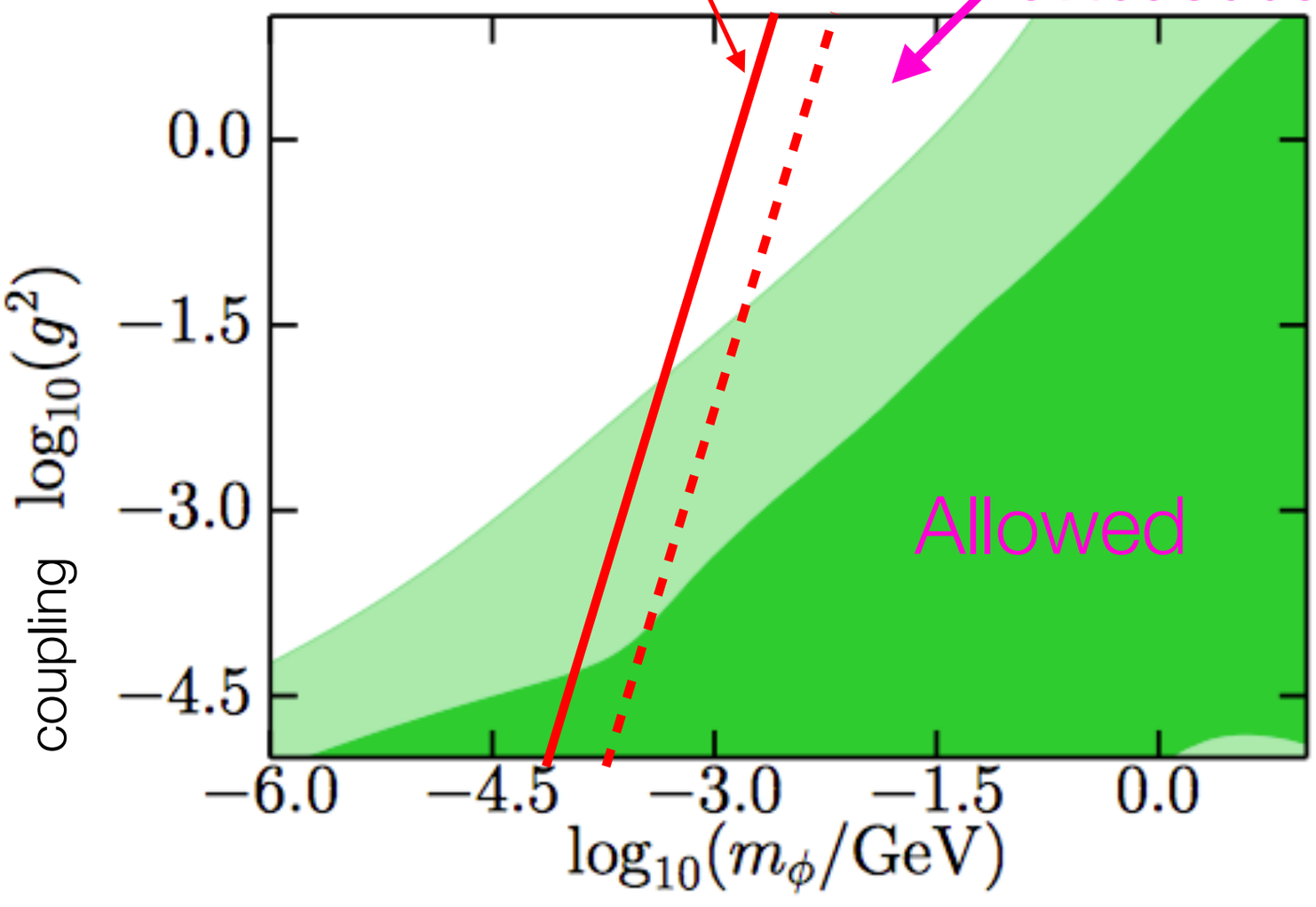
New limits!

Best constraints from Planck*

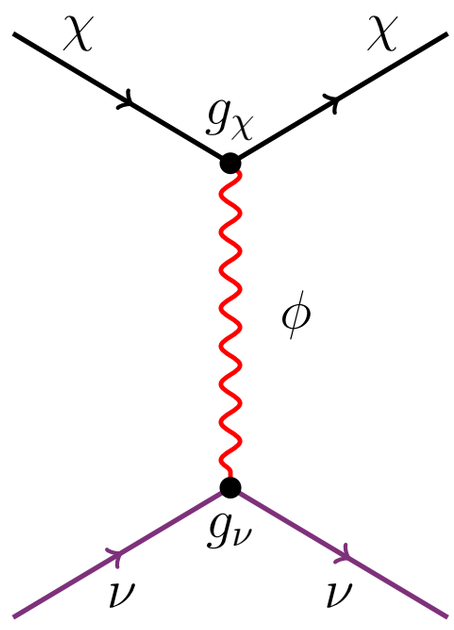
1 GeV DM

100 GeV DM

excluded by 53 events at IceCube



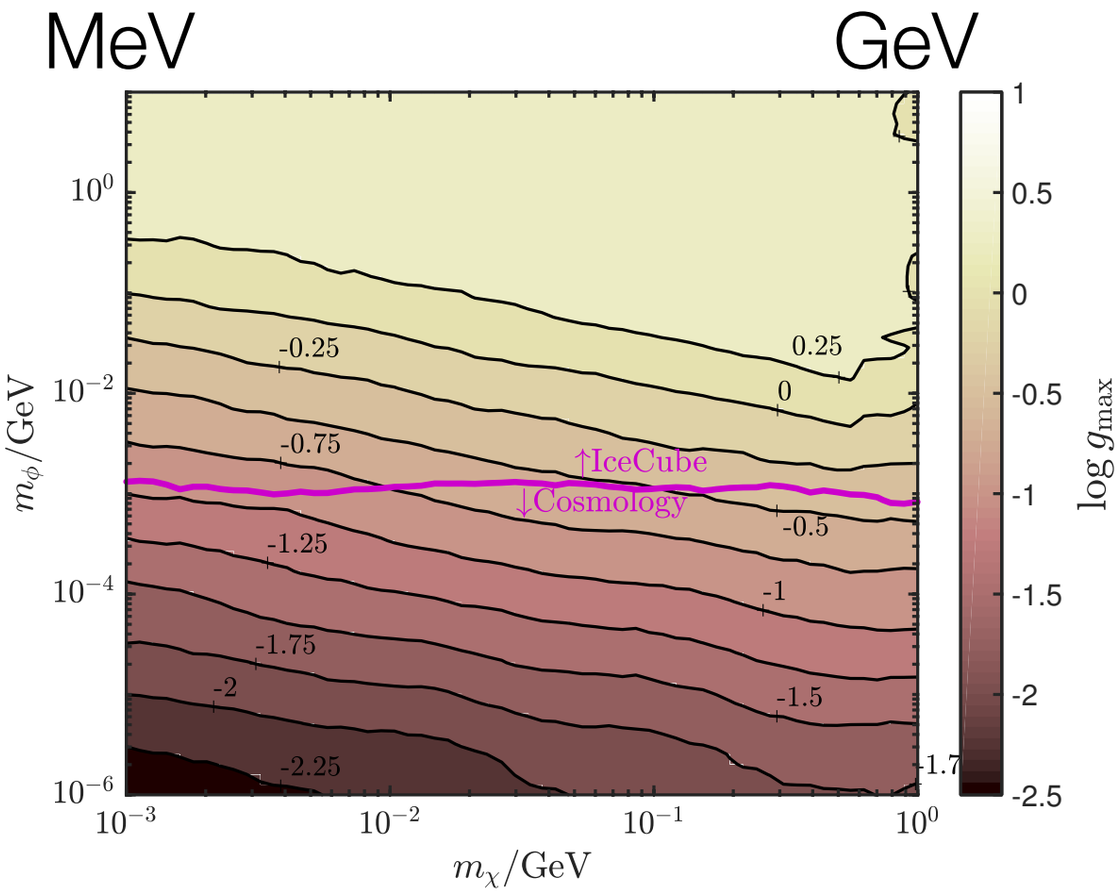
log mediator mass

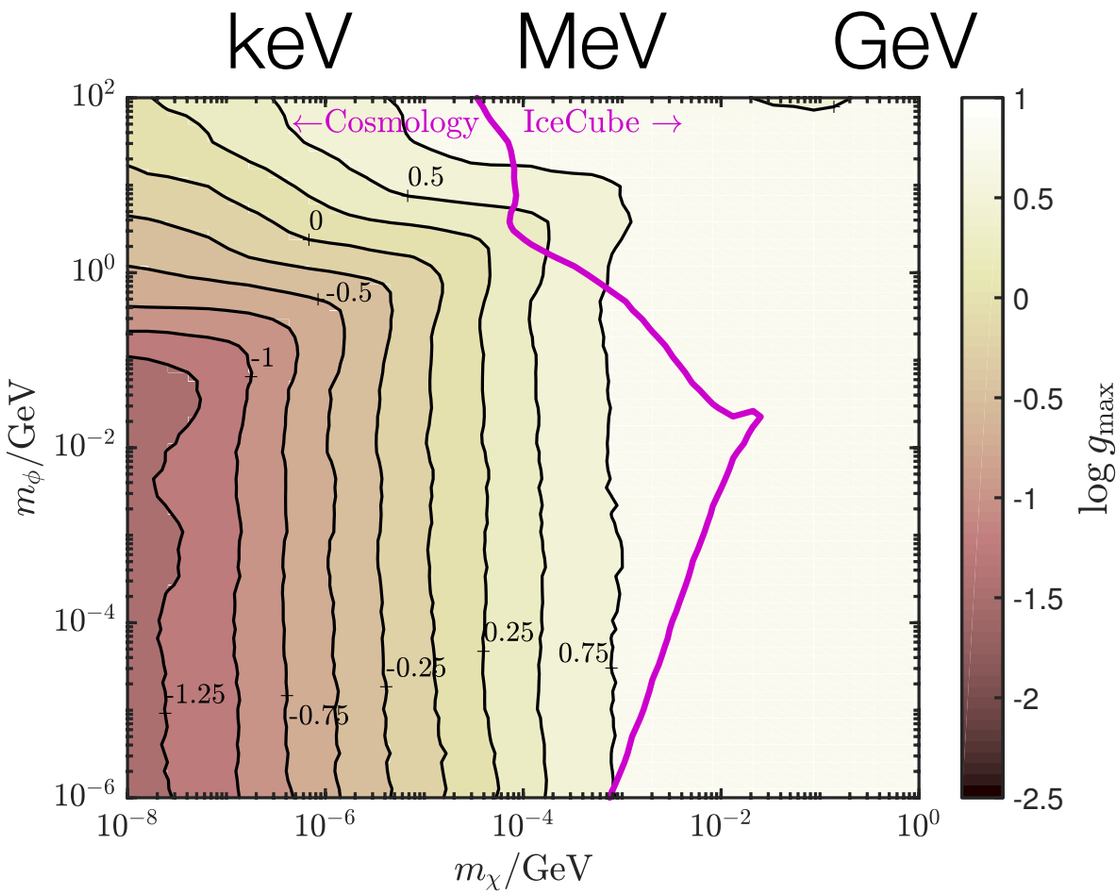


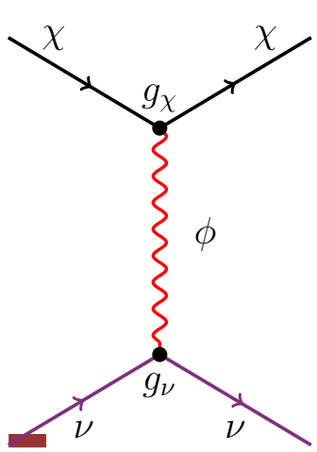
*Escudero et al 2016

Argüelles, Kheirandish & Vincent 2017

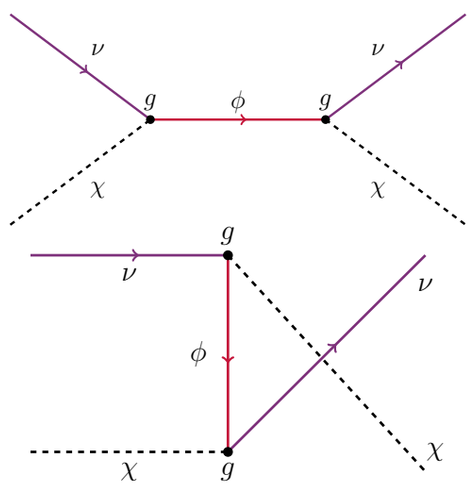
New limits!







Only 53 events:
already eating into
cosmology parameter
space



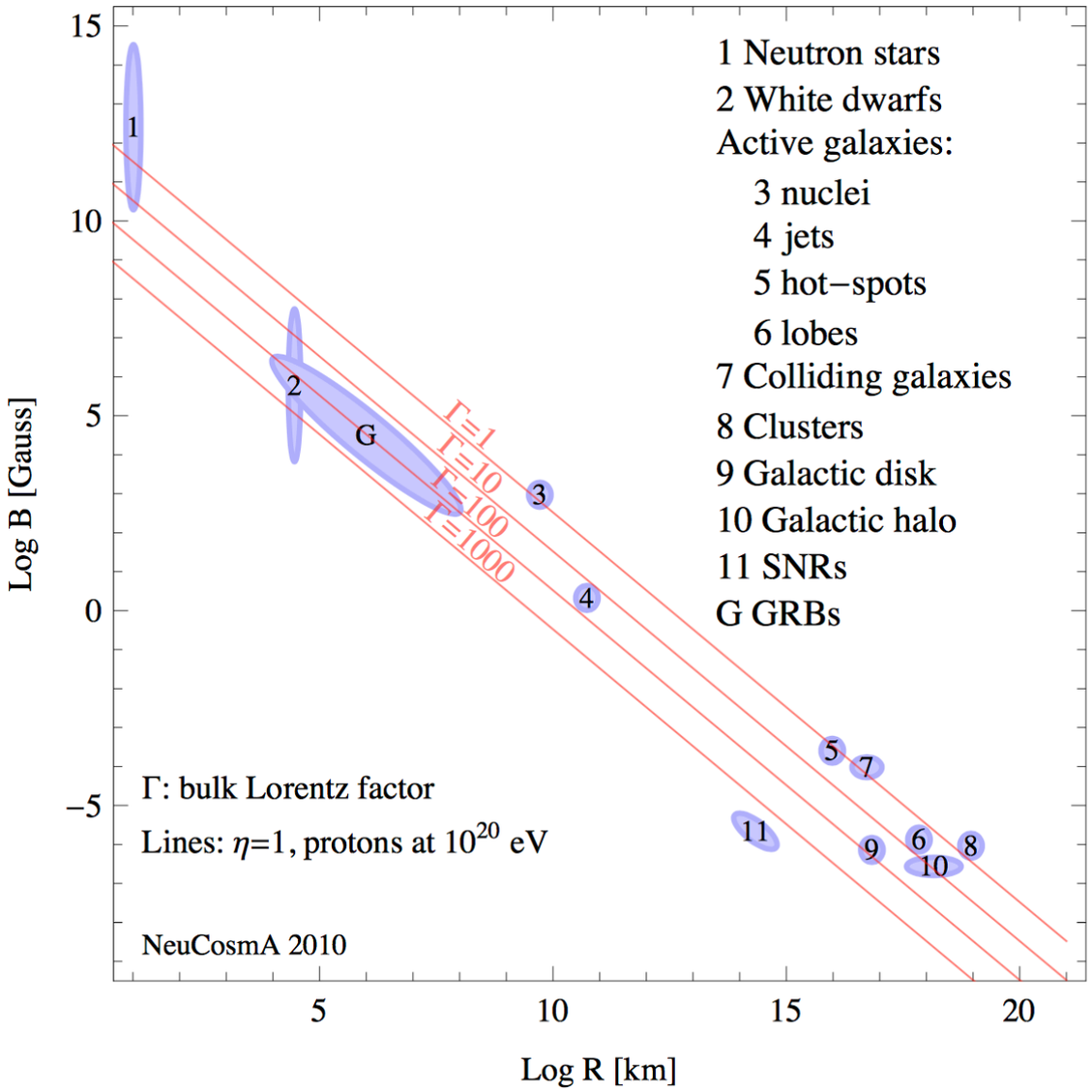
Take home message

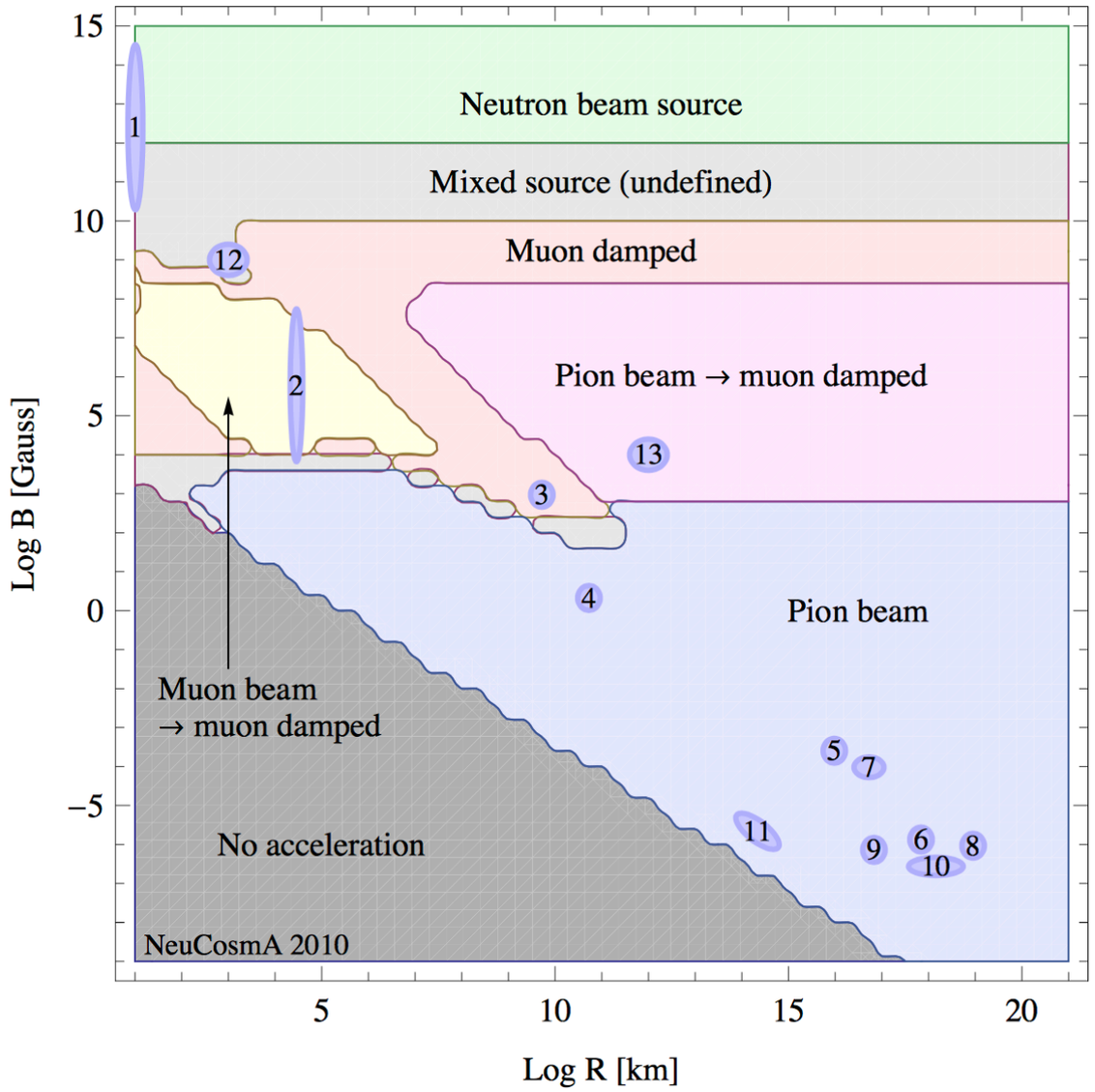
- **Current observations of the flavor triangle are already more restrictive than terrestrial measurements.**
- **Searches for anisotropies for dark-matter neutrino interactions already competitive with Plank data!**
- **Didn't have time to talk about: up coming measurements with atmospheric neutrinos: NSI, LV, and steriles!!! (Ask me later!)**
- Expect improvement on flavor measurements from IceCube-Gen2: **better systematics and more statistics**!

THANKS!

BONUS

SLIDES!

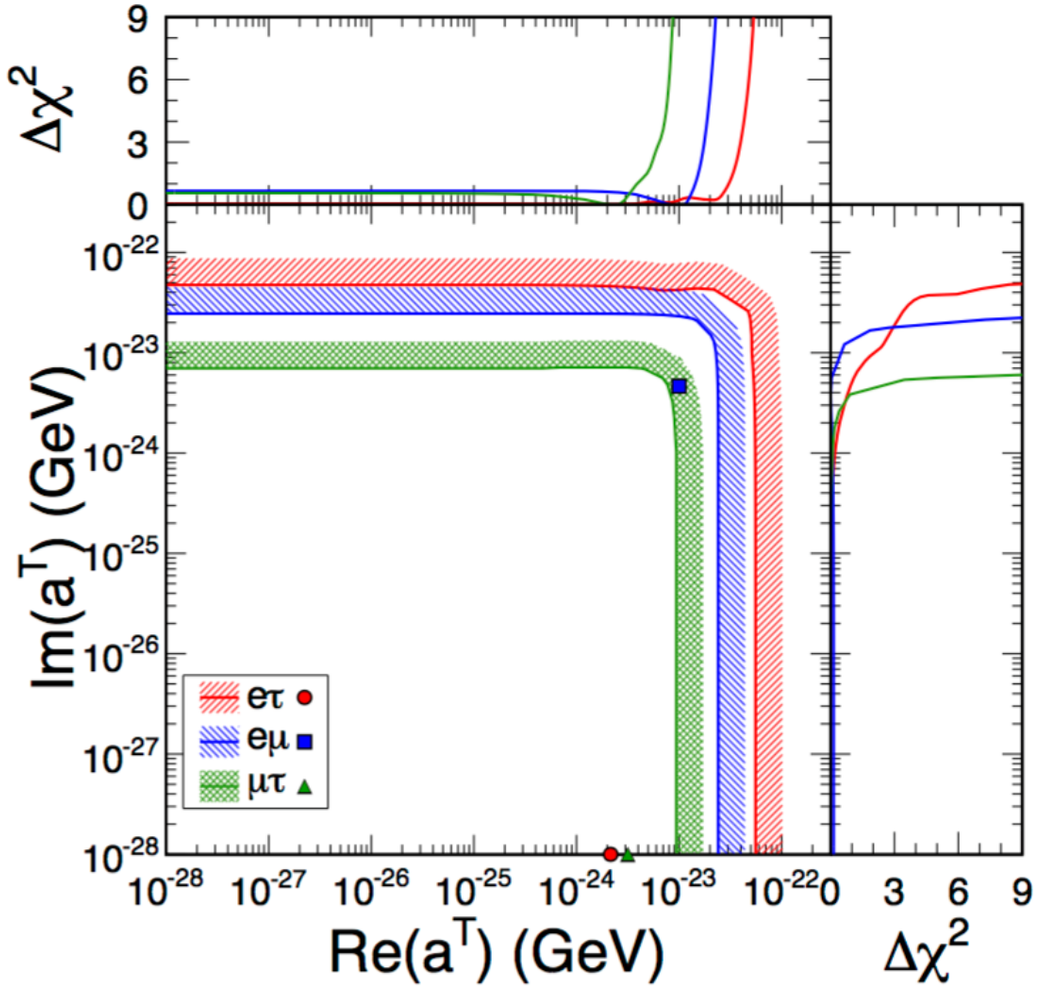




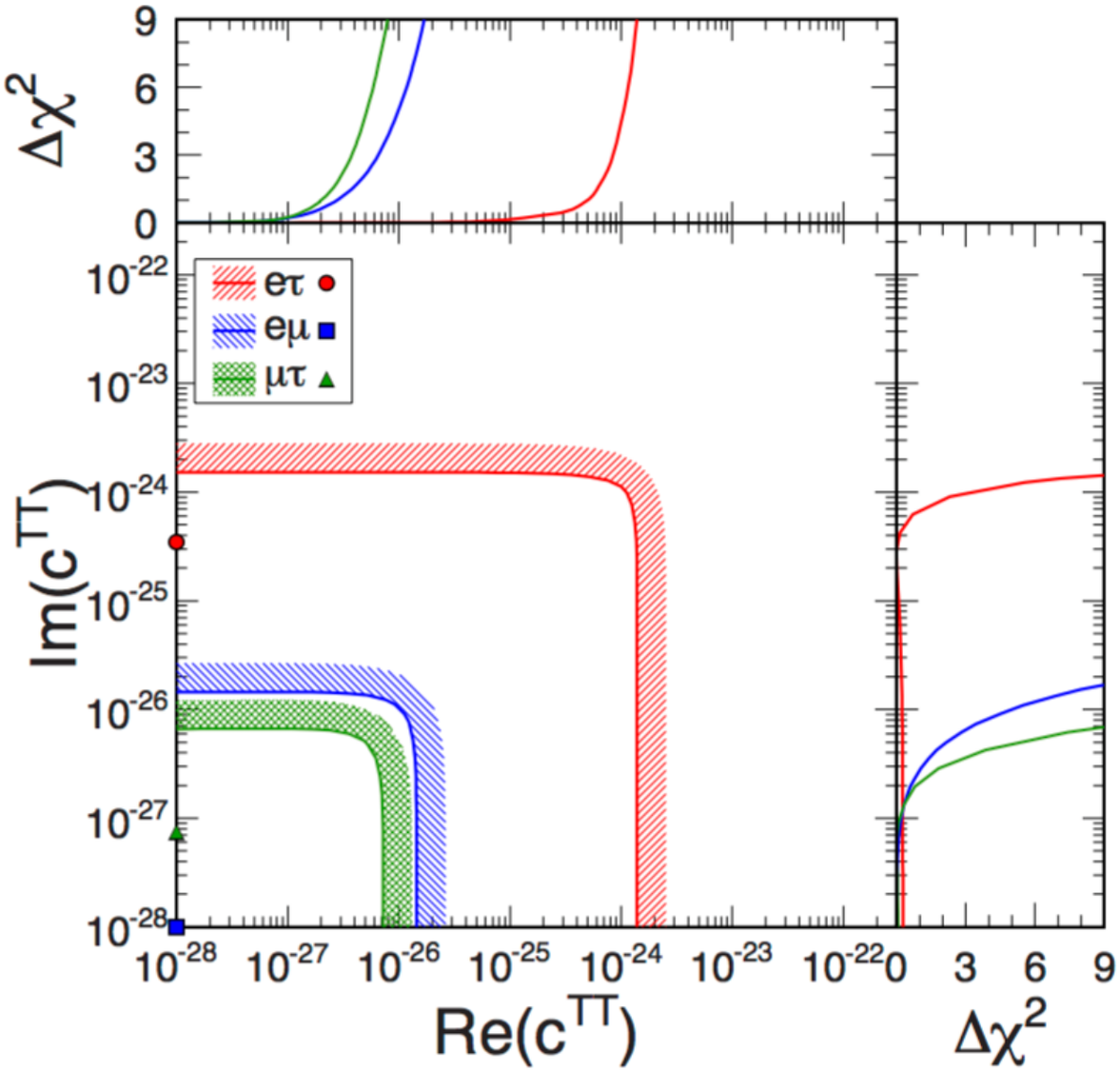
(arXiv:1007:0006)

arXiv:1410.4267

Current bounds from SK

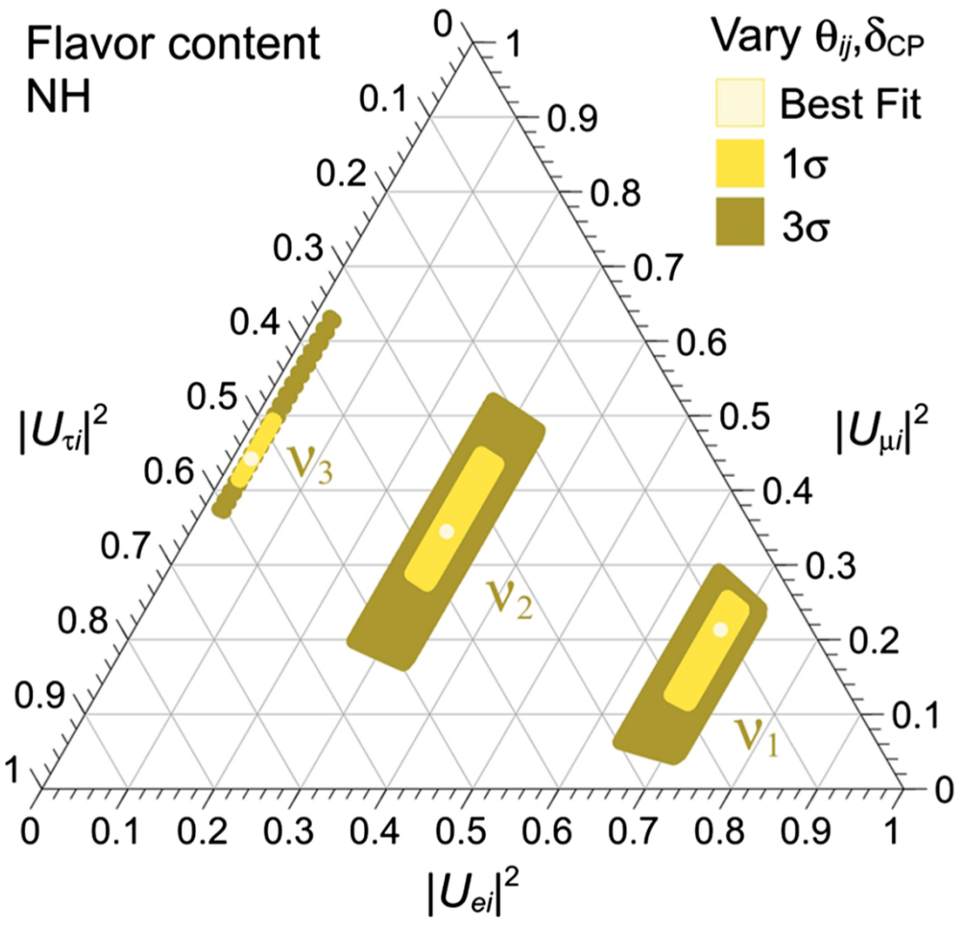


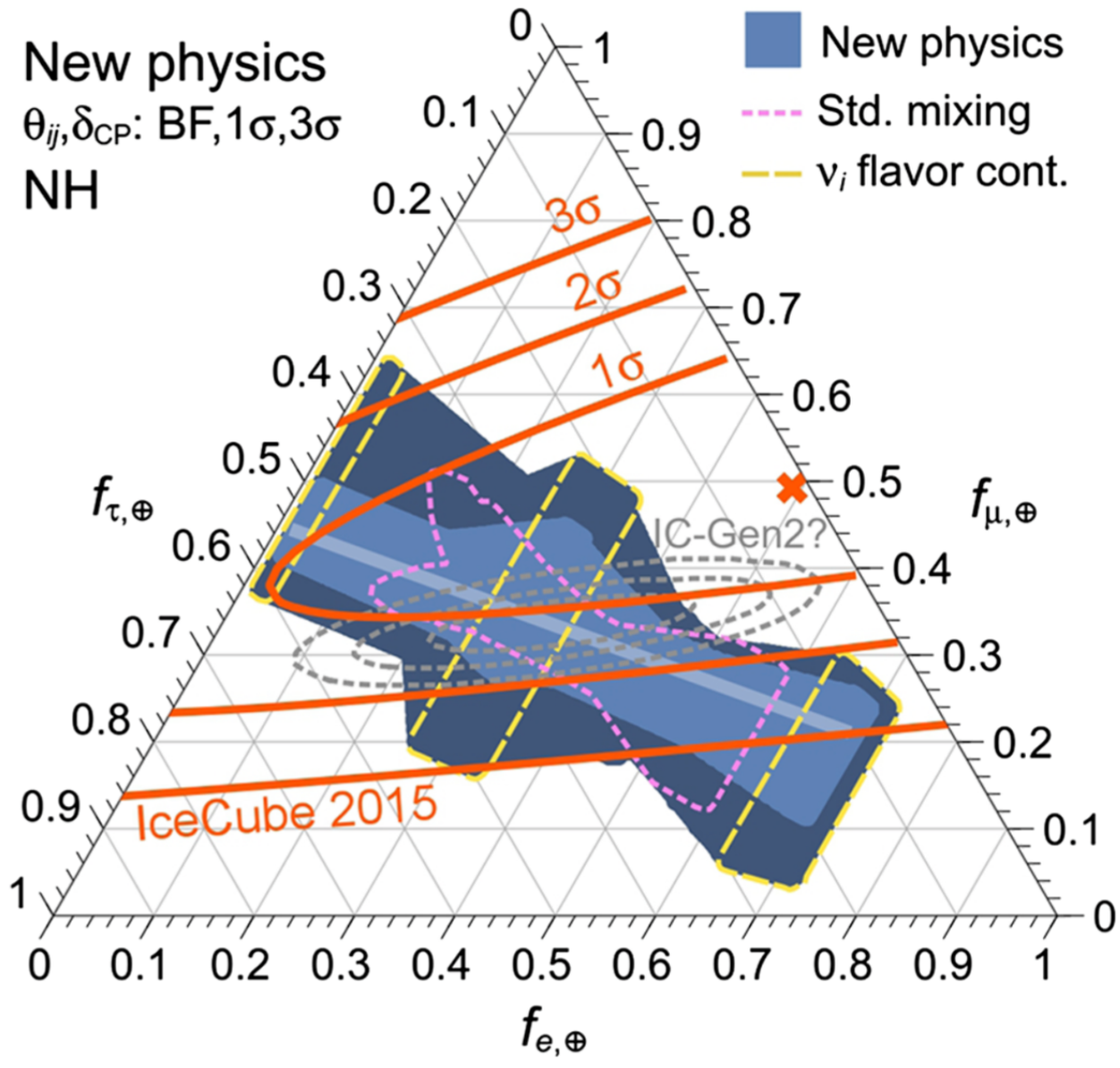
$$\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$



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}			

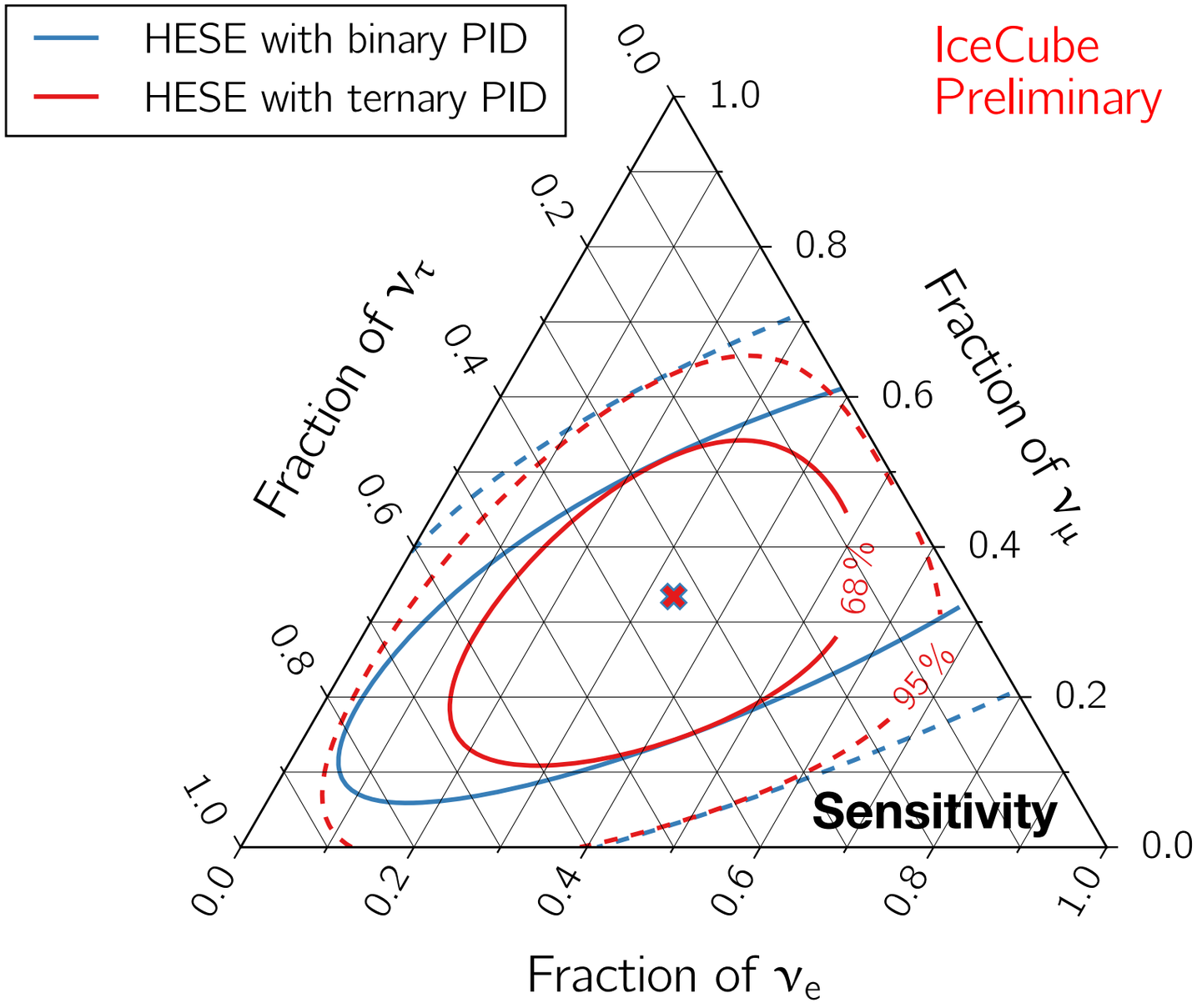
+ New physics mixing

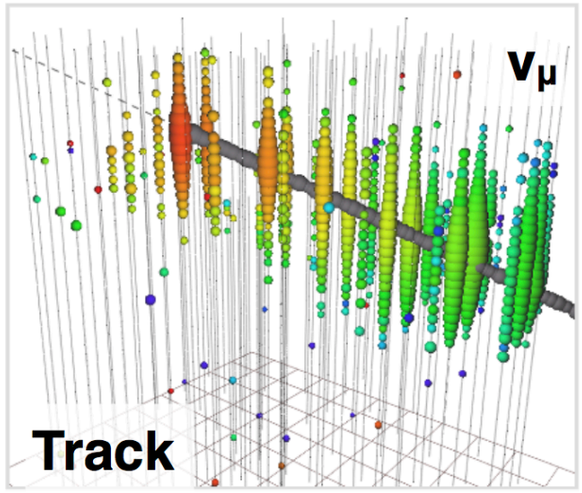


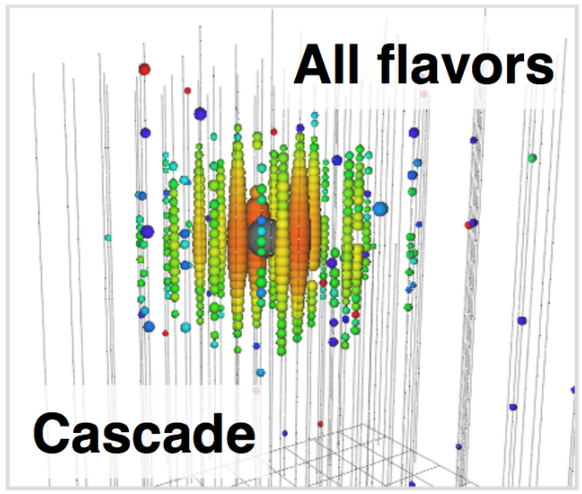


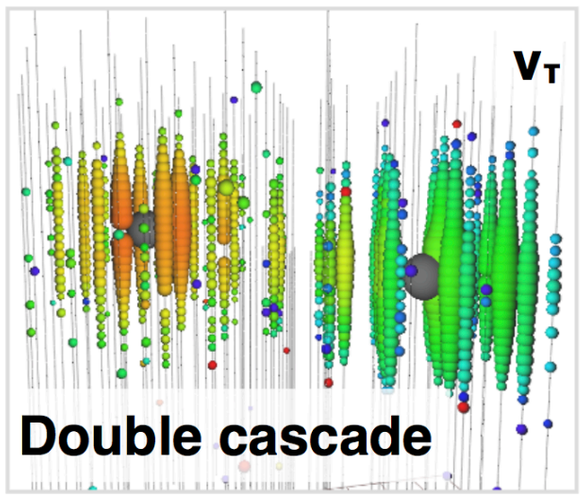
New search for astrophysical nu-tau with starting events

(6 year HESE)



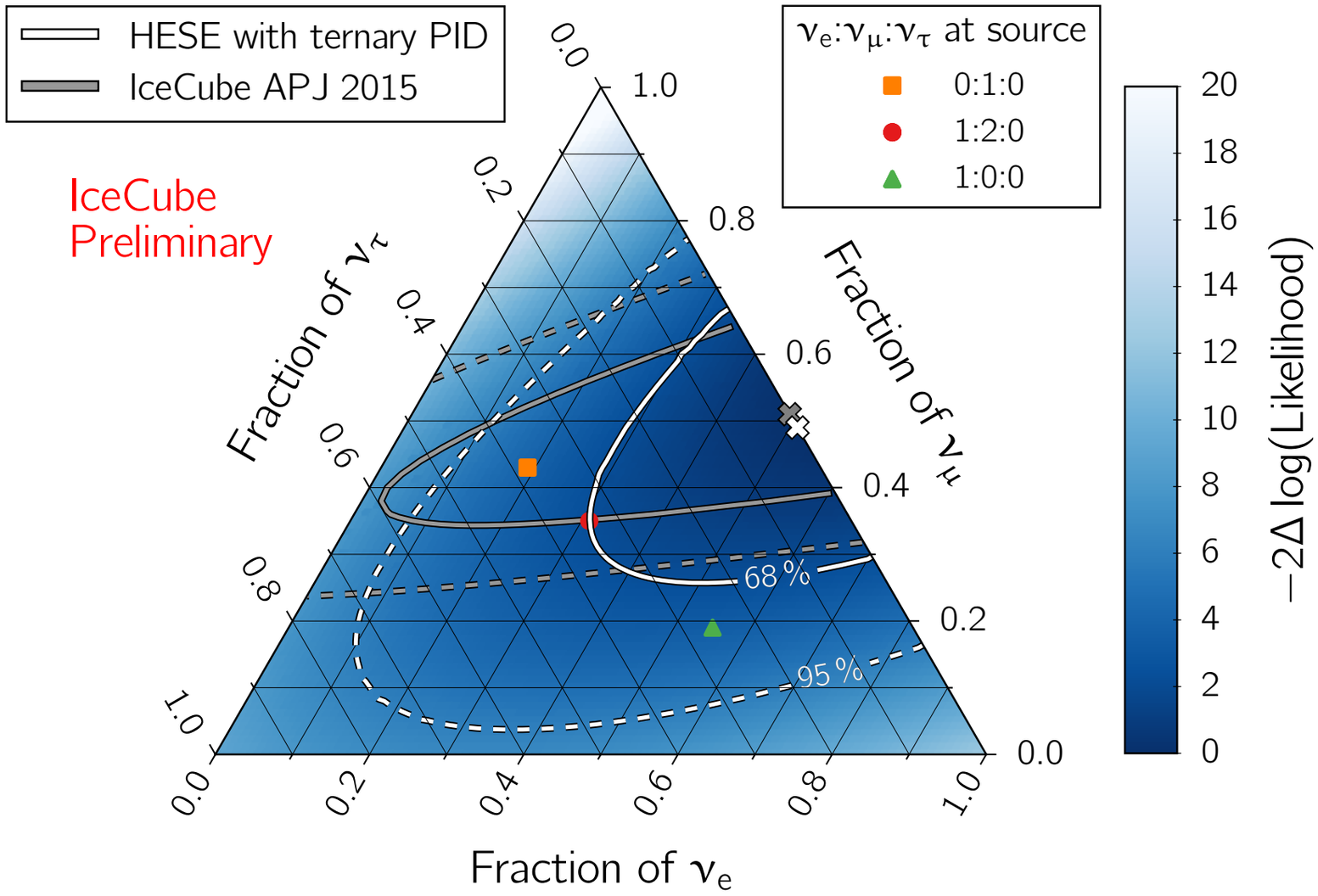


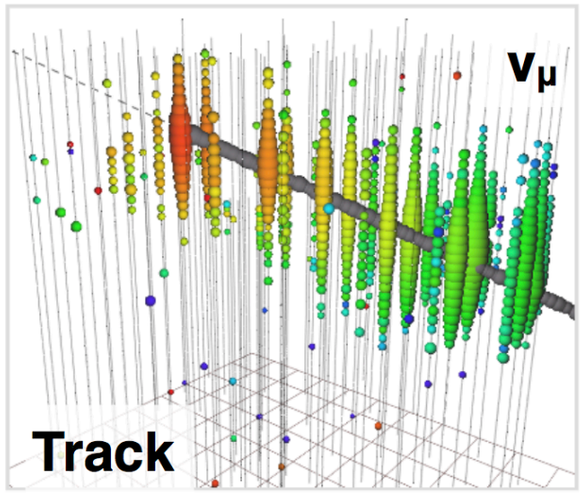


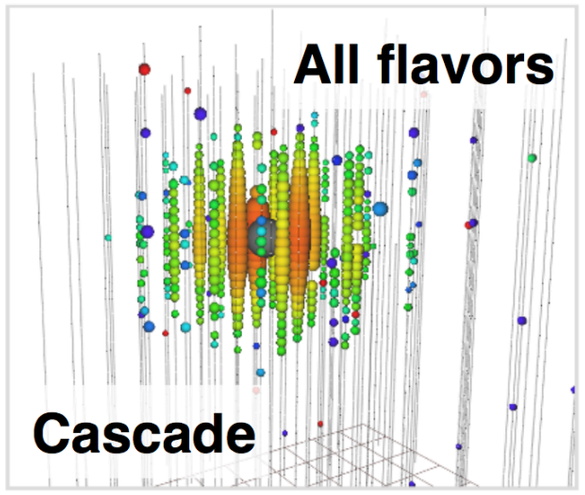


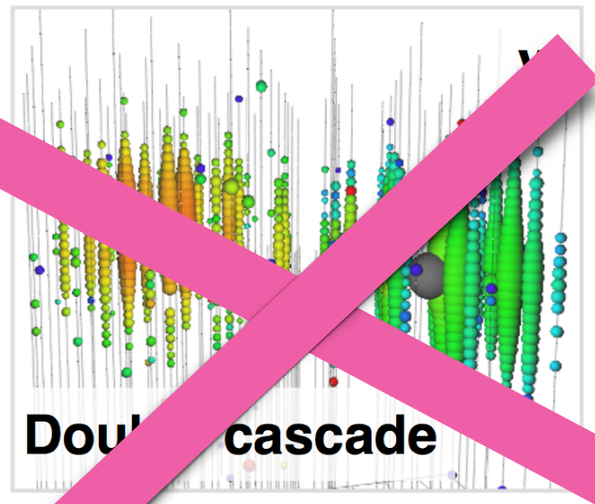
New search for astrophysical nu-tau with starting events

(6 years starting events)









No nu-tau observed!

DM-neutrino interactions: two constraints from cosmology

Extra radiation N_{eff}

If DM is light (< 10 MeV) it can dump entropy into neutrino sector as it becomes non-relativistic

BBN

neutrons less boltzmann suppressed at FO: more D, He

CMB

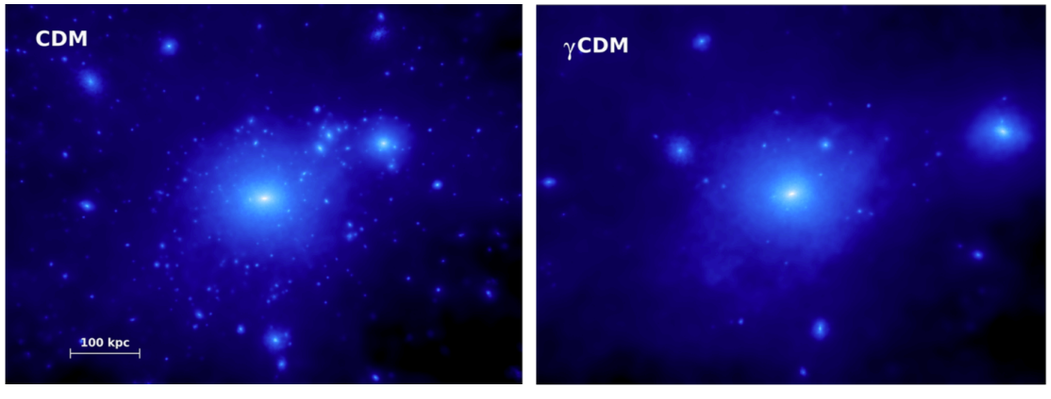
Shifted peaks from different sound propagation length

upper limit on DM mass

Aaron Vincent

Perturbation damping

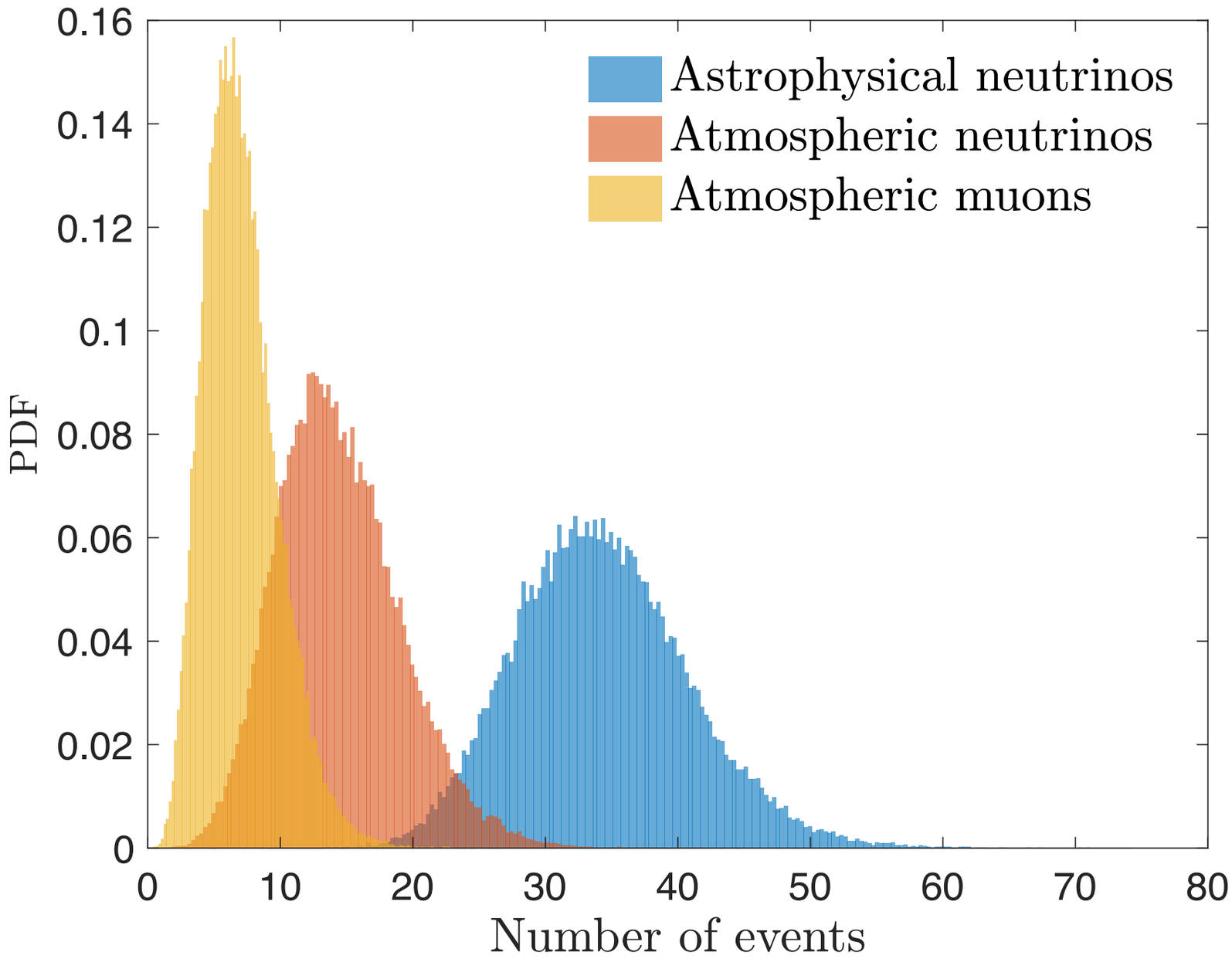
Scattering damps power spectrum of primordial fluctuations



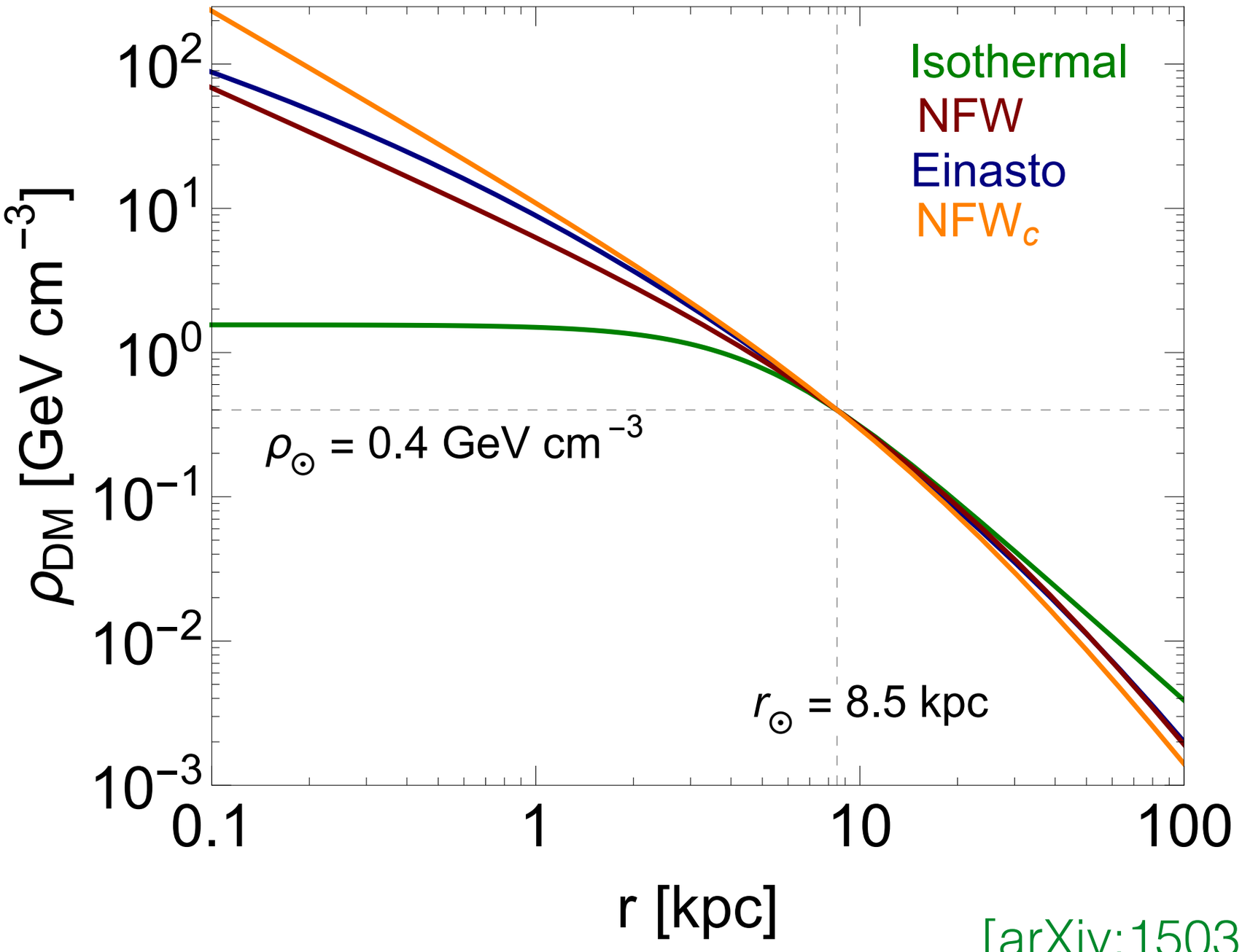
Boehm et. al 1404.7012

Upper limit on cross section

Distribution of flux components



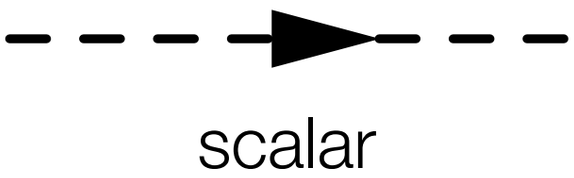
DM profiles



[arXiv:1503.07169]

Simplified models

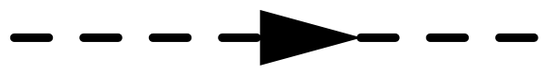
DM particle



scalar

fermion

mediator



scalar

fermion

vector

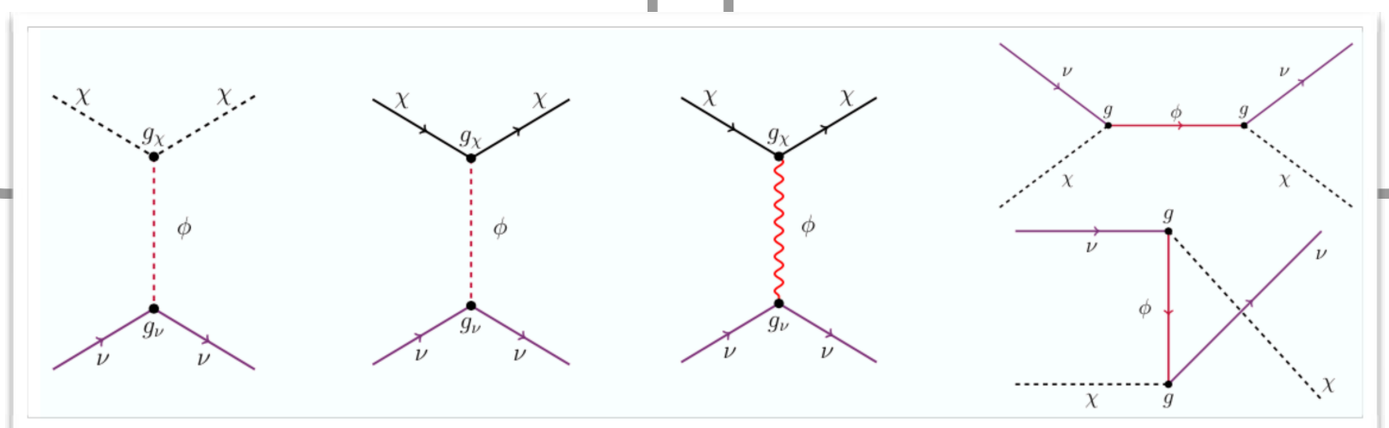
couplings

$$g_\nu g_\chi$$

scalar/scalar
fermion/scalar
fermion/vector

$$g^2$$

scalar/fermion



Cross Sections

Fermion DM—Vector Mediator

$$\frac{d\sigma}{d\cos\theta} = \frac{g^2 \left(g'\right)^2 E_\nu^2 m_\chi^2 \left(2(1-x)E_\nu + (1+x)m_\chi\right)}{4\pi \left((1-x)E_\nu + m_\chi\right)\left((1-x)E_\nu m_\phi^2 + m_\chi\left(m_\phi^2 - 2(x-1)E_\nu^2\right)\right)^2}$$

$$\sigma = \frac{g^2 g'^2}{16\pi E_\nu^2 m_\phi^2}\left(m_\phi^2 \log\left(\frac{m_\phi^2(2E_\nu + m_\chi)}{m_\chi(4E_\nu^2 + m_\chi^2) + 2E_\nu m_\phi^2}\right) + \frac{4m_\chi E_\nu^2}{m_\chi + \frac{2E_\nu m_\phi^2}{4E_\nu^2 + m_\phi^2}}\right)$$

Scalar DM—Fermion Mediator

$$\frac{d\sigma}{d\cos\theta} = \frac{g^4 E_\nu^2 m_\chi((x-1)m_\phi^6 - 2(x-1)m_\phi^4 m_\chi^2 + 8E_\nu^2((x-1)E_\nu - m_\chi)m_\chi^3 + (x-1)m_\phi^2 m_\chi^4)}{4\pi((x-1)E_\nu - m_\chi)^3((m_\phi^2 - m_\chi^2)^2 - 4E_\nu^2 m_\chi^2)^2}$$

$$\sigma = \frac{g^4 E_\nu^2(m_\phi^6 - 2m_\phi^4 m_\chi^2 + m_\phi^2 m_\chi^4 + 8E_\nu^2 m_\chi^3(2E_\nu + m_\chi))}{2\pi(2E_\nu + m_\chi)^2((m_\chi^2 - m_\phi^2)^2 - 4E_\nu^2 m_\chi^2)^2}$$