Results from IceCube High-Energy Starting-Event Analysis

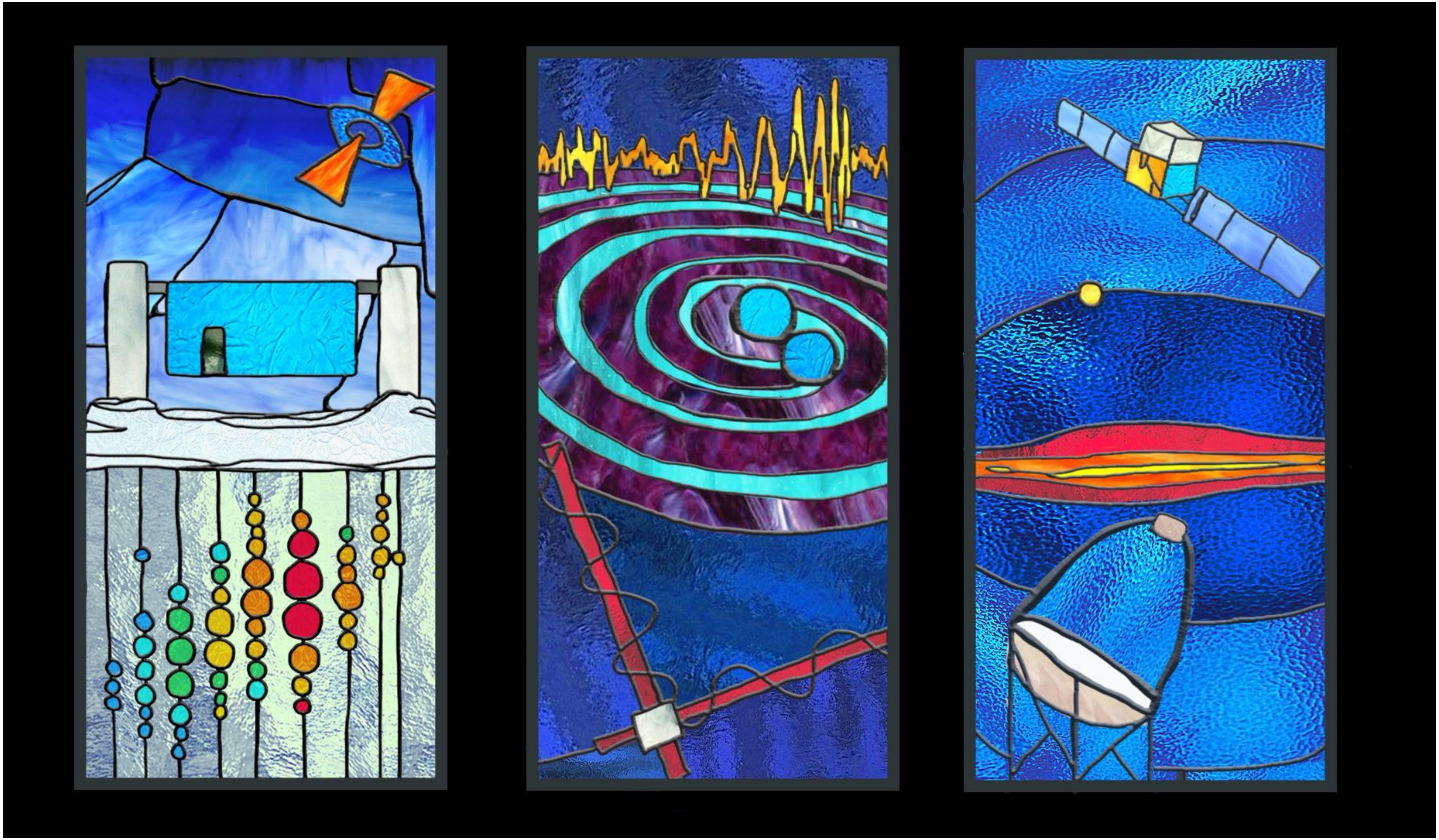
This talk is based on
arXiv:2011.03545, 2011.03561, 2011.03560, and 2012.12893

APEC Seminar at IPMU 29 of June 2021

Carlos Argüelles

HARVARD UNIVERSITY

How does the Universe look in neutrinos?



How do high-energy neutrinos behave?

Outline of the rest of this talk:

1. Neutrinos in IceCube
2. Measuring High-Energy Astrophysical Neutrinos
3. Searching for new forces:
   - Measuring the Neutrino-Nucleon cross section
4. Searching for dark matter:
   - Neutrino-Dark Matter Interactions
5. Searching for a new symmetry:
   - Lorentz Violation Effects on Flavor
6. The future

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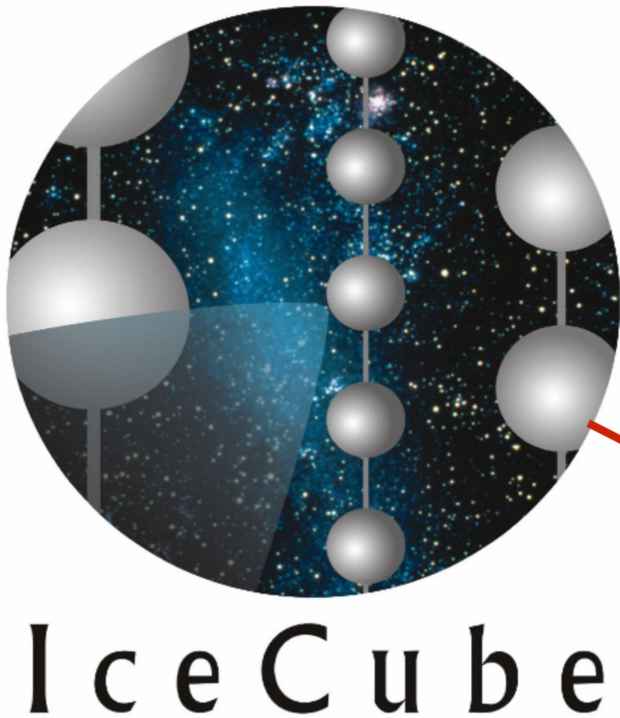
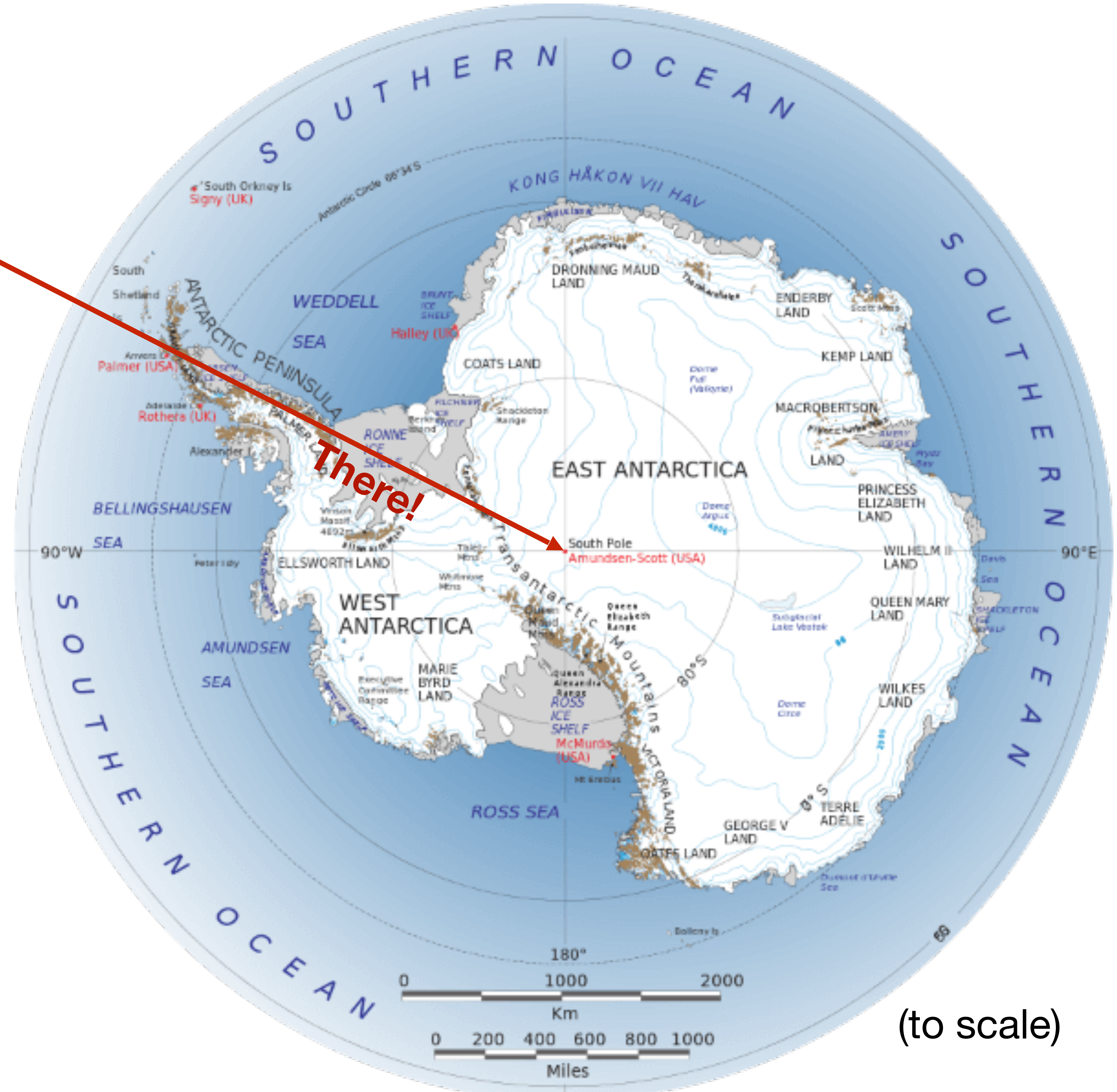

IceCube


SOUTHERN OCEAN
SOUTHERN OCEAN
SOUTHERN OCEAN
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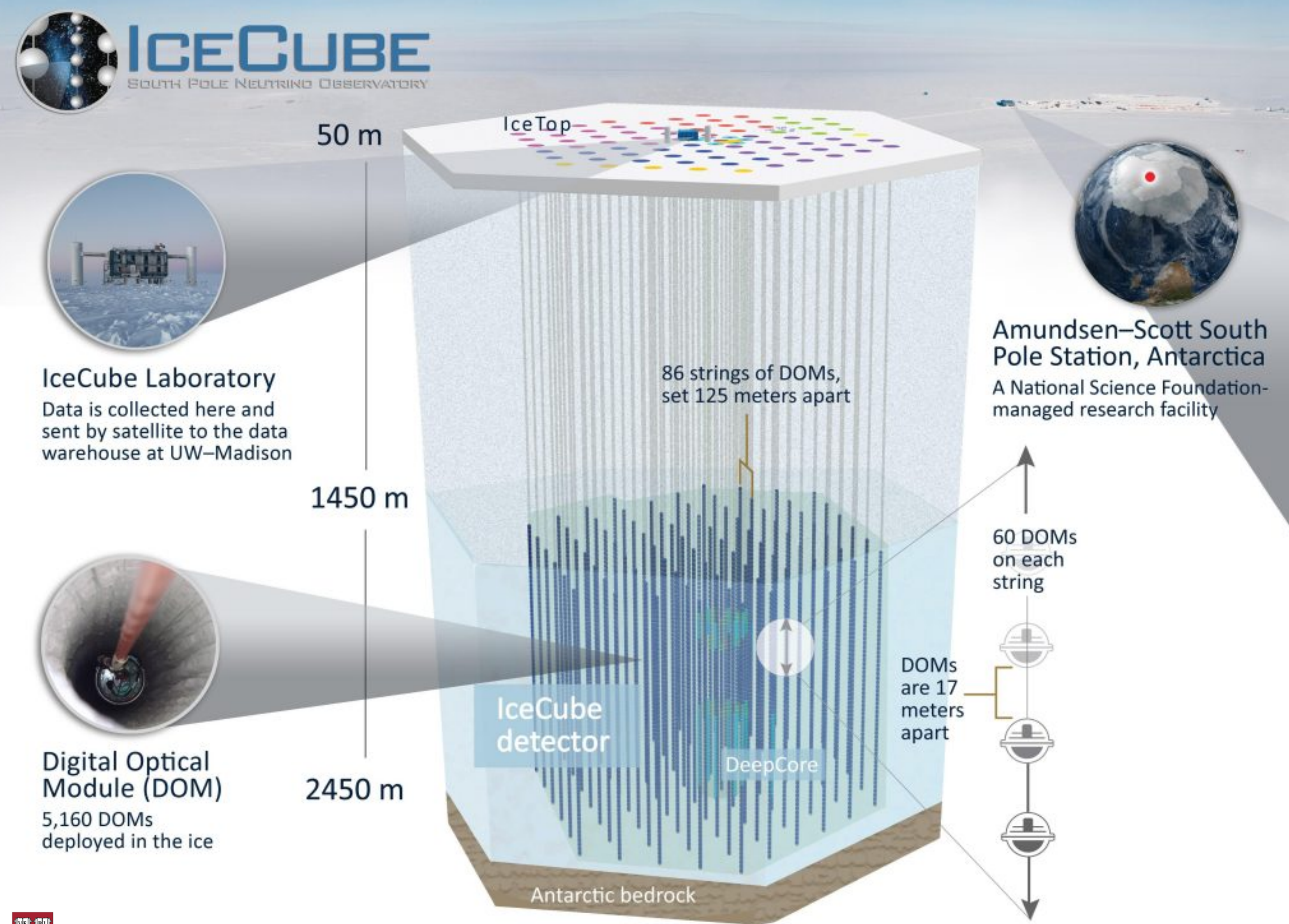
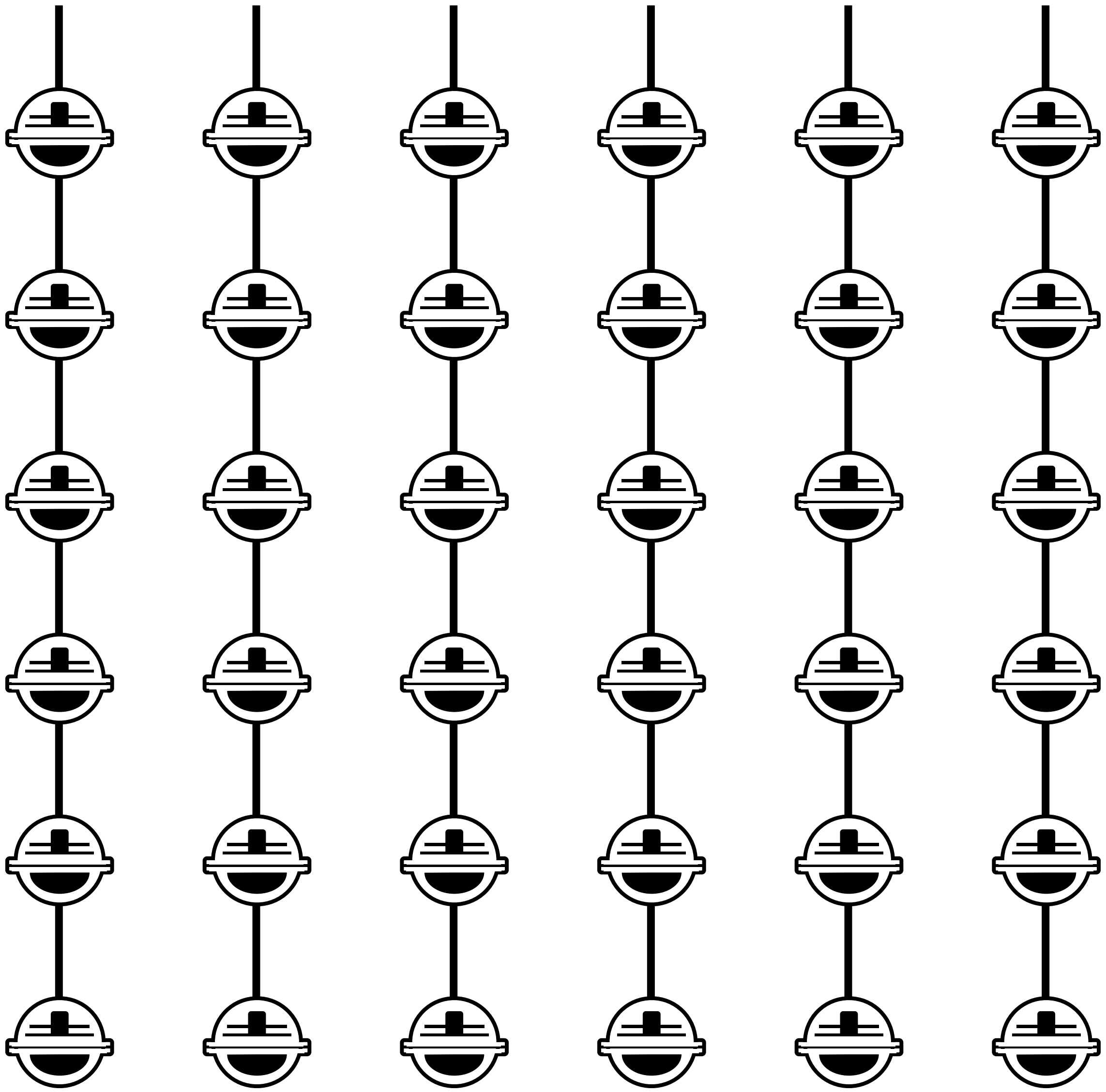
KONG HÅKON VII HAV
WEDDELL SEA
BELLINGSHAUSEN SEA
AMUNDSEN SEA
ROSS SEA
ANTARCTIC PENINSULA
EAST ANTARCTICA
WEST ANTARCTICA
There!
South Pole
Amundsen-Scott (USA)
DRONNING MAUD LAND
ENDERBY LAND
KEMP LAND
MACROBERTSON LAND
PRINCESS ELIZABETH LAND
WILHELM II LAND
QUEEN MARY LAND
WILKES LAND
TERRE ADÉLIE
GEORGE V LAND
OATES LAND
VICTORIA LAND
COATS LAND
ELLSWORTH LAND
MARIE BYRD LAND
RONNE ICE SHELF
ROSS ICE SHELF
McMurdo (USA)
Halley (UK)
Palmer (USA)
Rothera (UK)
South Orkney Is
Signy (UK)
South Shetland
Transantarctic Mountains
Antarctic Circle 66°34'S
80°S
90°W
90°E
180°
0
1000
2000
Km
0
200
400
600
800
1000
Miles

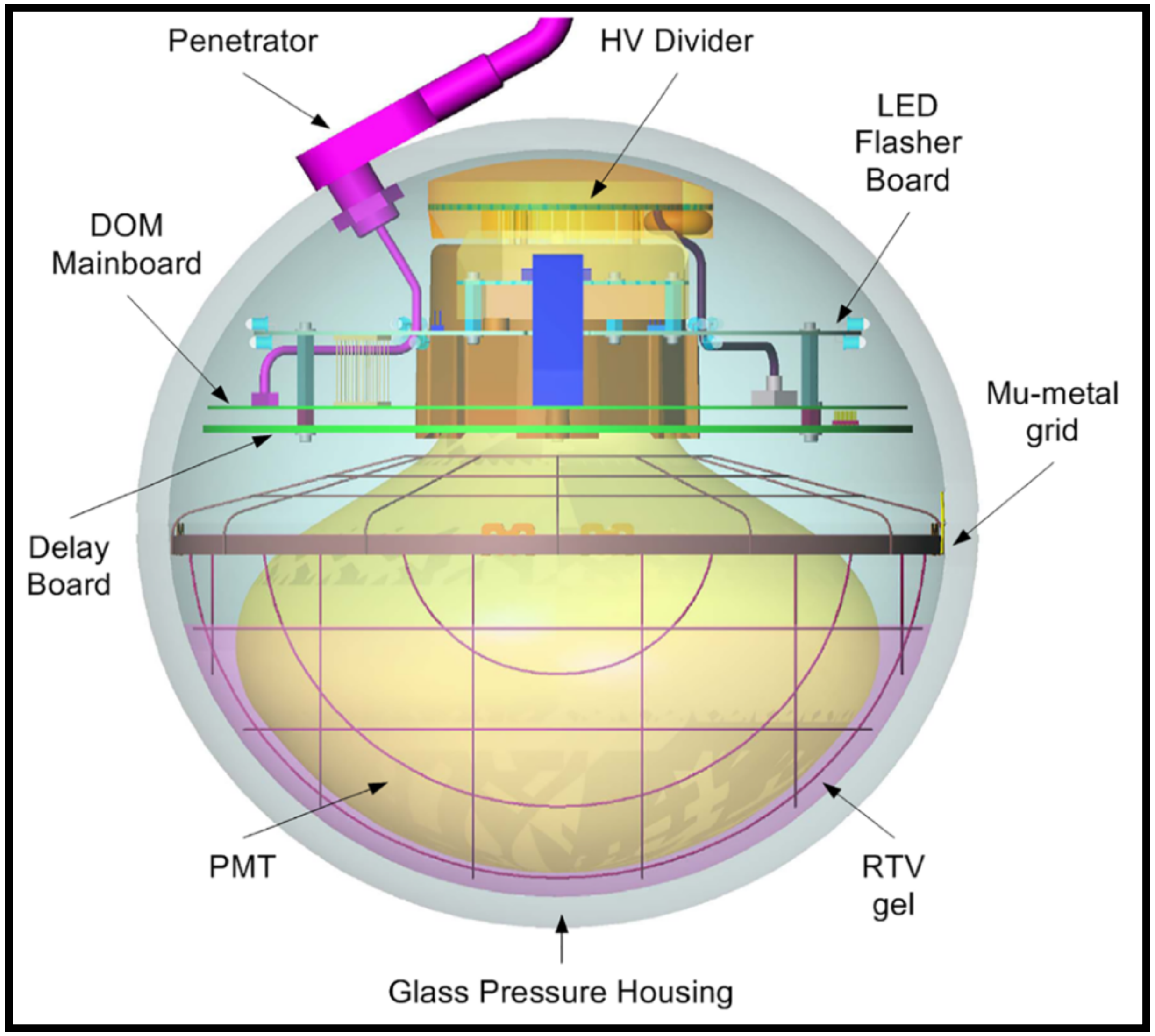
(to scale)

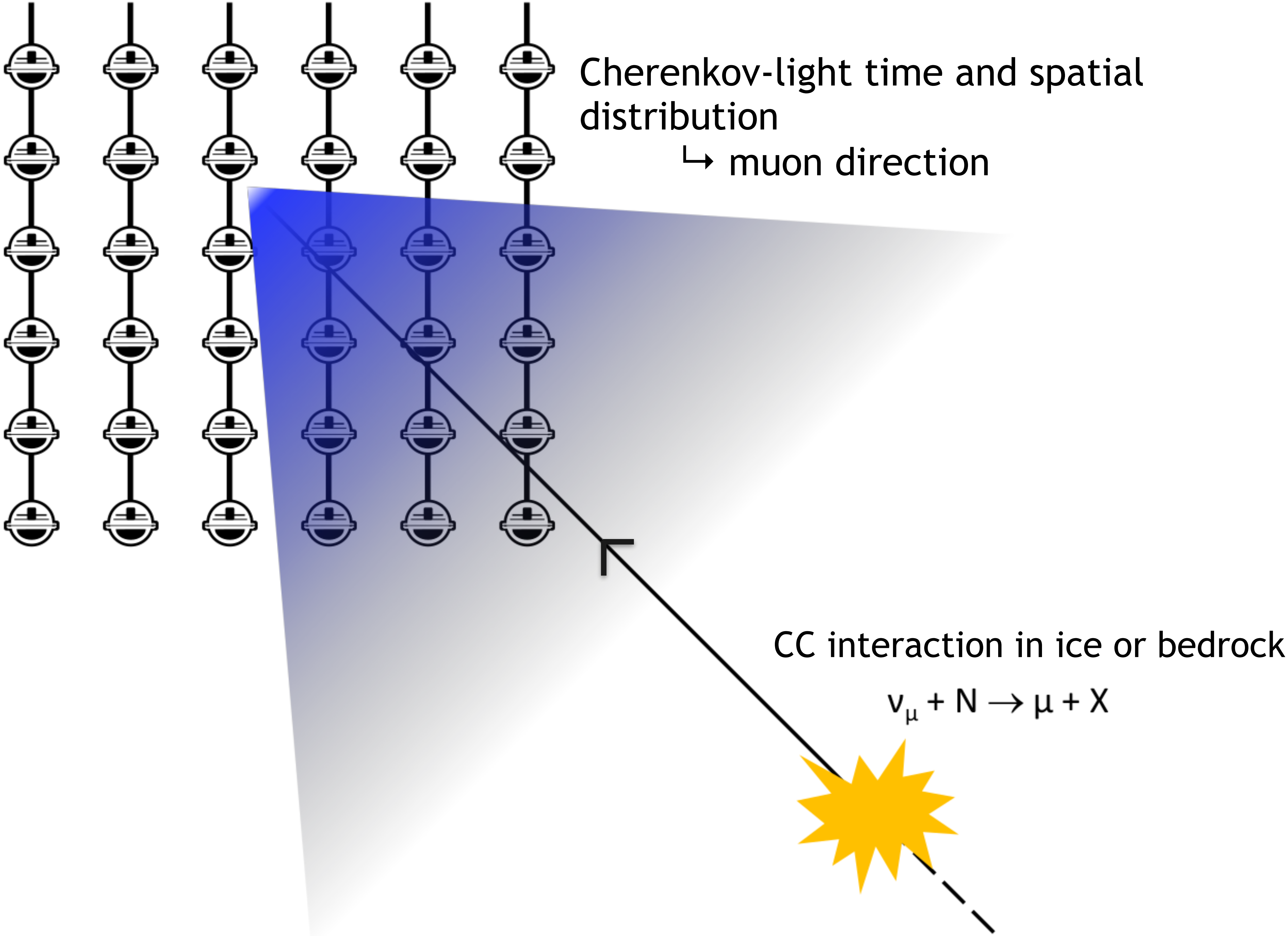
Looking at it
from our point of view
here in the northern hemisphere:

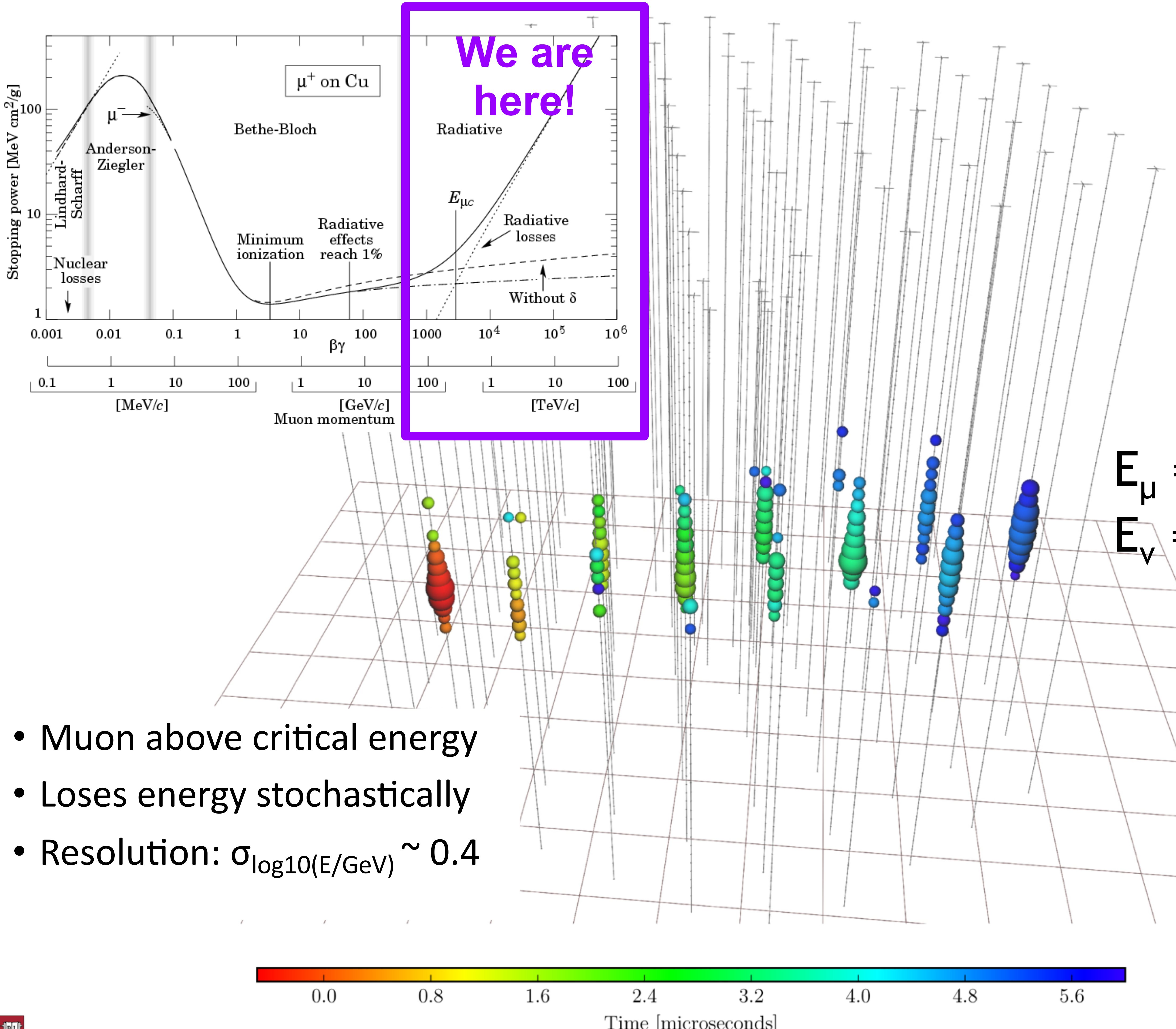

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock

Digital Optical Module (DOM)






Cherenkov-light time and spatial distribution
↳ muon direction
CC interaction in ice or bedrock
$\nu_\mu + N \rightarrow \mu + X$

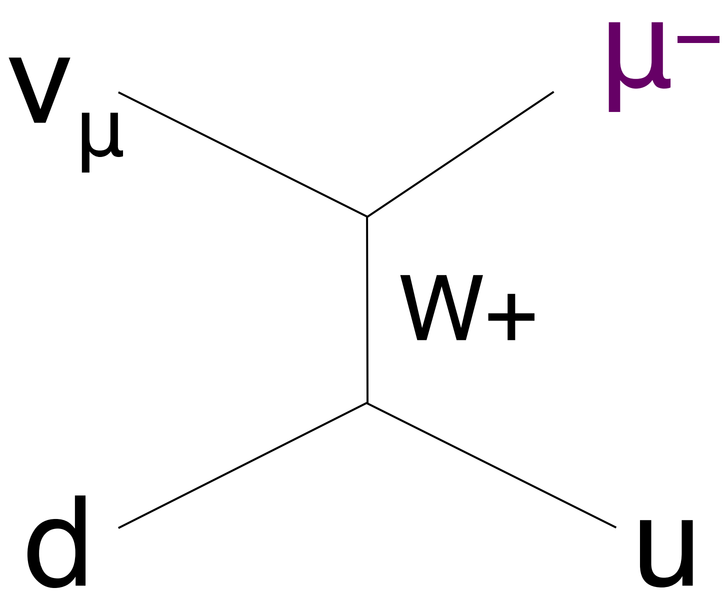


E_μ = 139 TeV

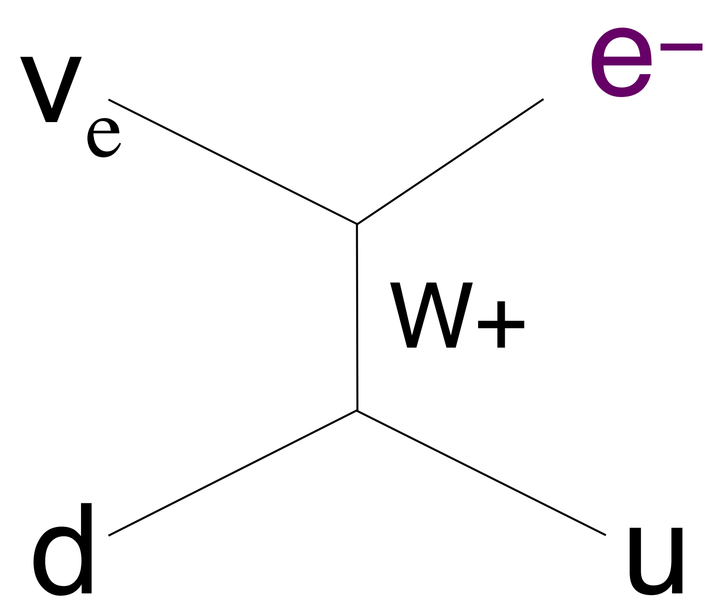
E_ν = 179 TeV

- Muon above critical energy
- Loses energy stochastically
- Resolution: $\sigma_{\log10(E/GeV)} \sim 0.4$

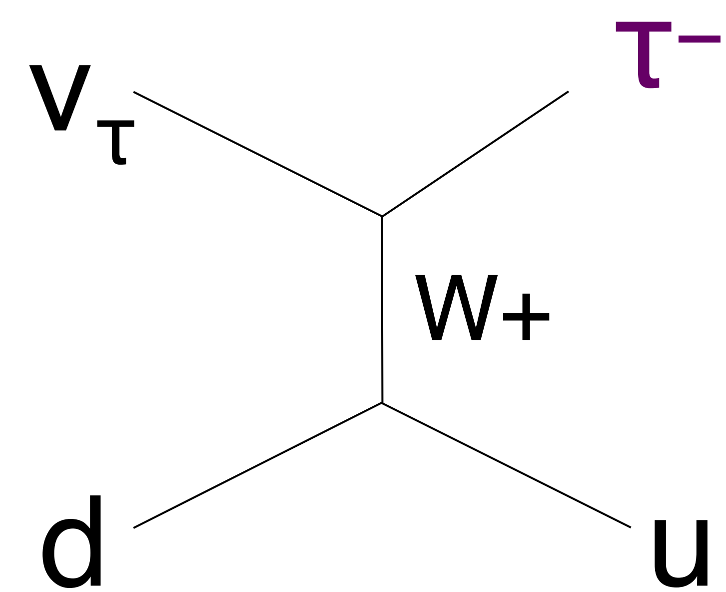
All CC Interactions



Events can start in the detector or below it (through-going).



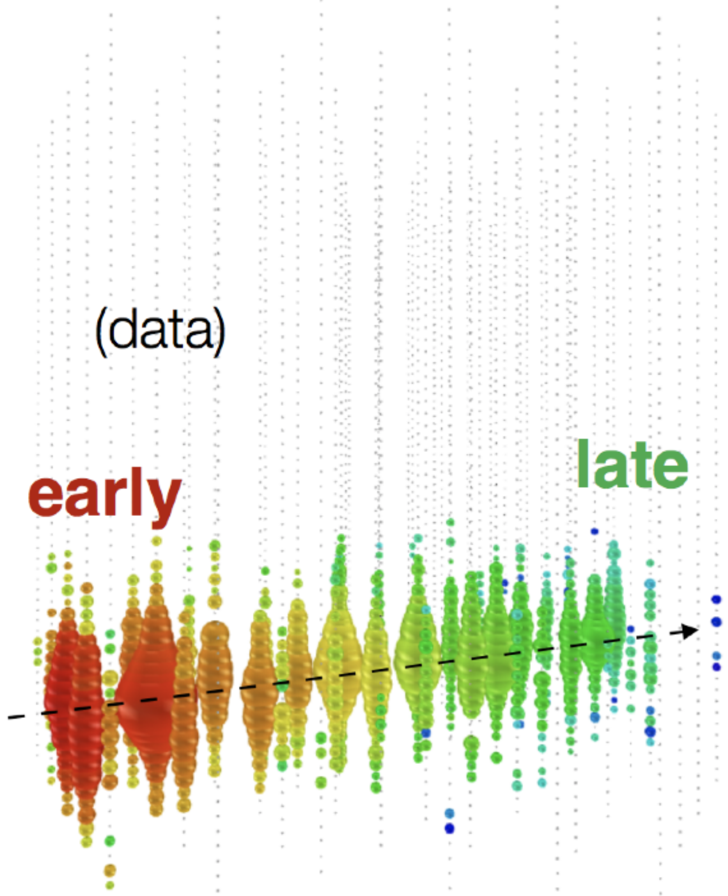
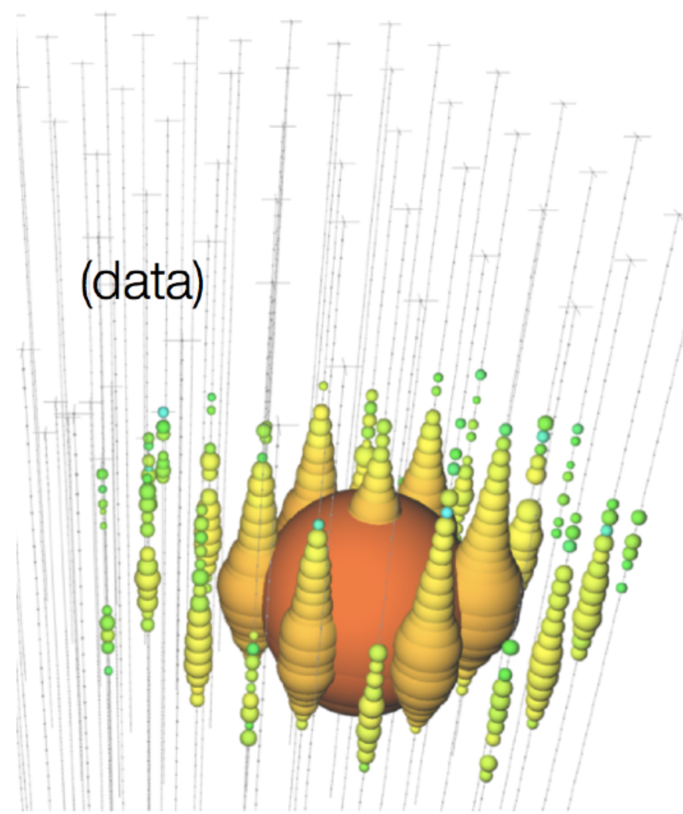
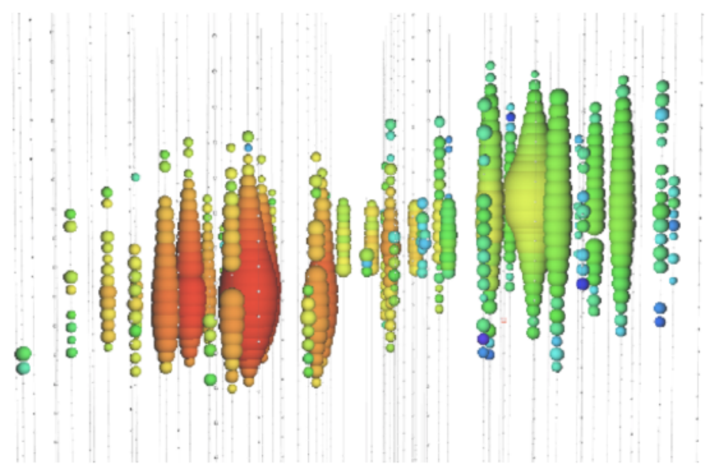
Events must be contained or partially contained in the detector.



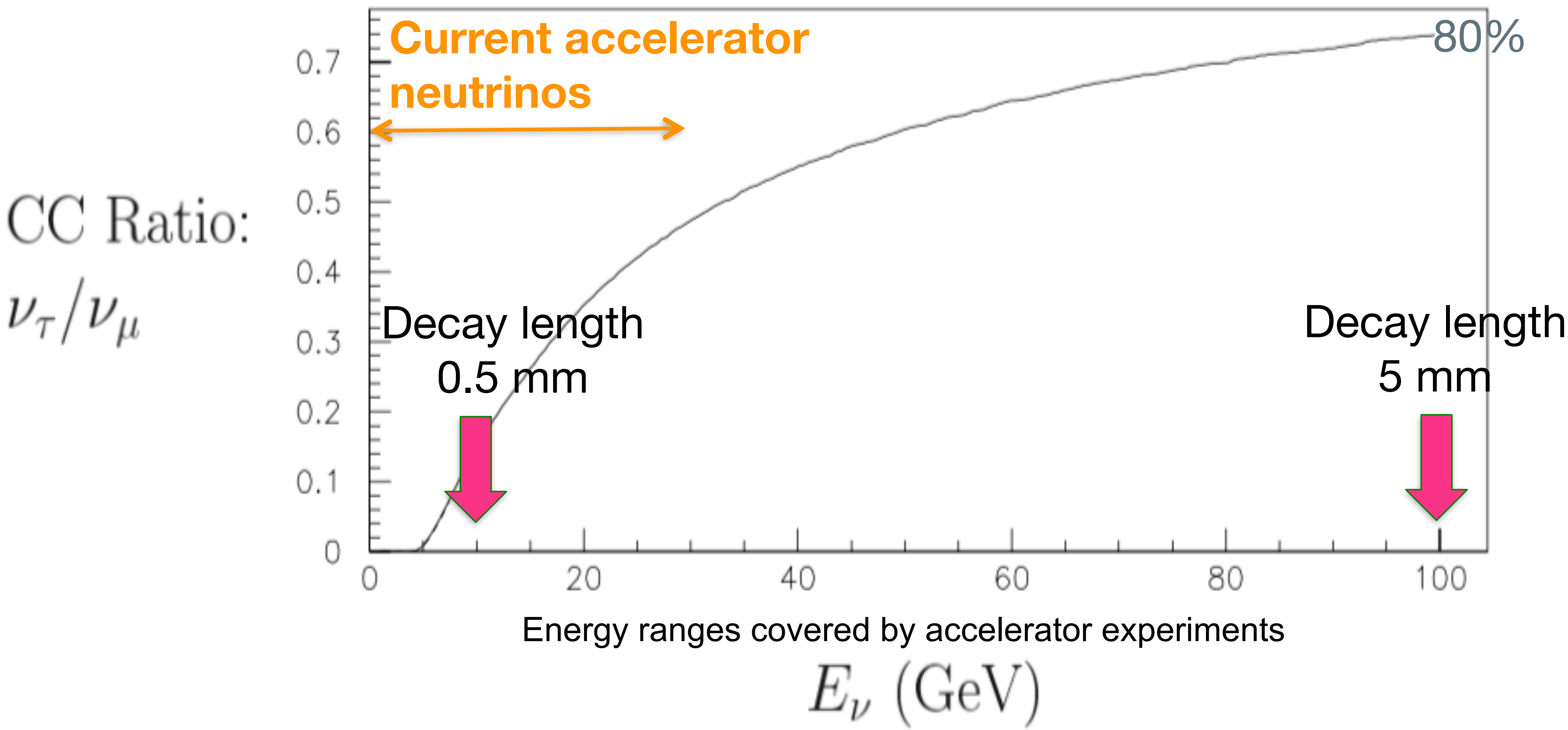
Events must be contained in the detector

I will show you our first candidate event!

All event morphologies

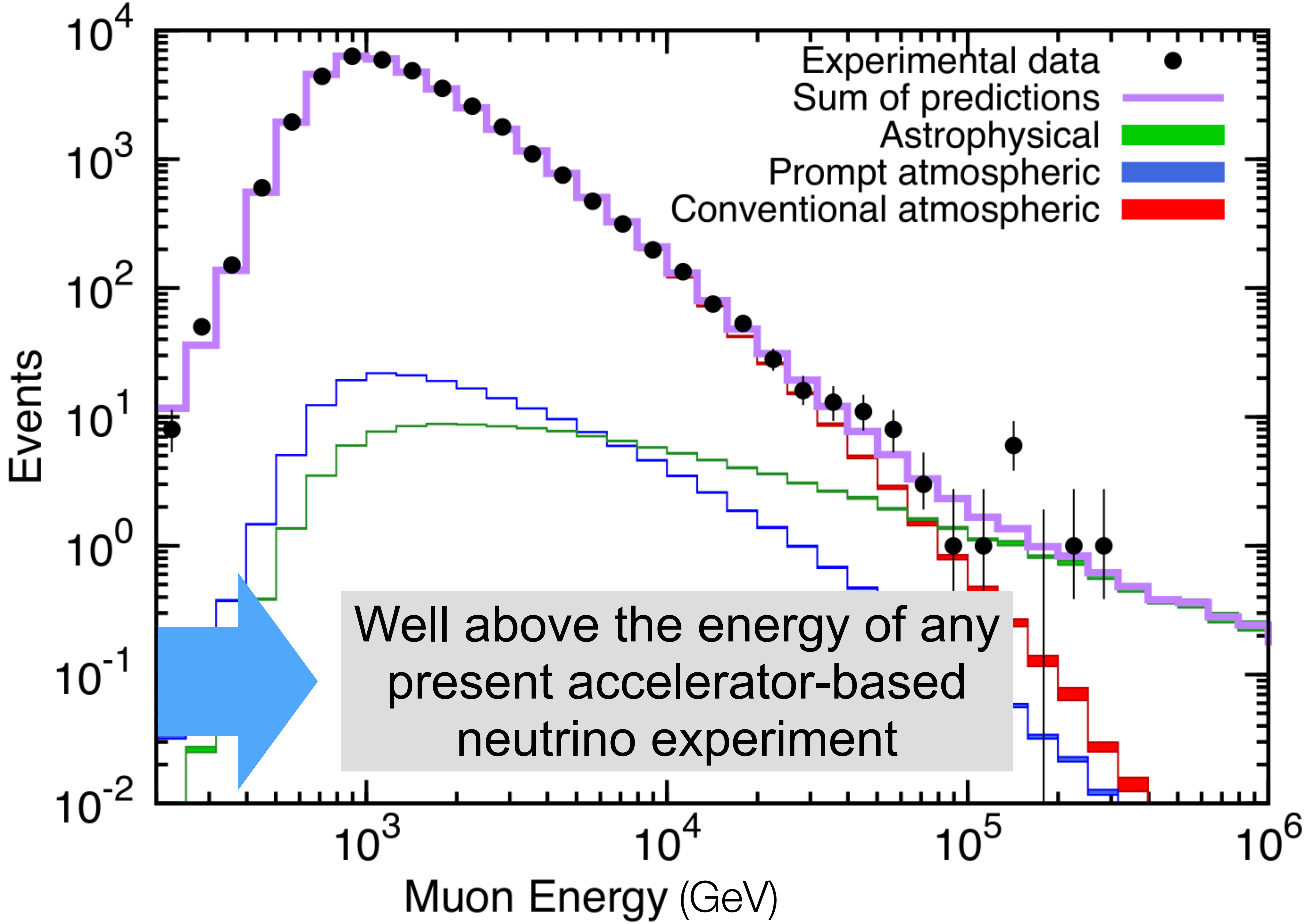
Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ
		
Up-going track	Isolated energy deposition (cascade) with no track	Double cascade
Factor of ~ 2 energy resolution < 1 degree angular resolution	15% deposited energy resolution 10 degree angular resolution (above 100 TeV)	(resolvable above ~ 100 TeV deposited energy)

The ν_τ interaction is very hard to see in other experiments...



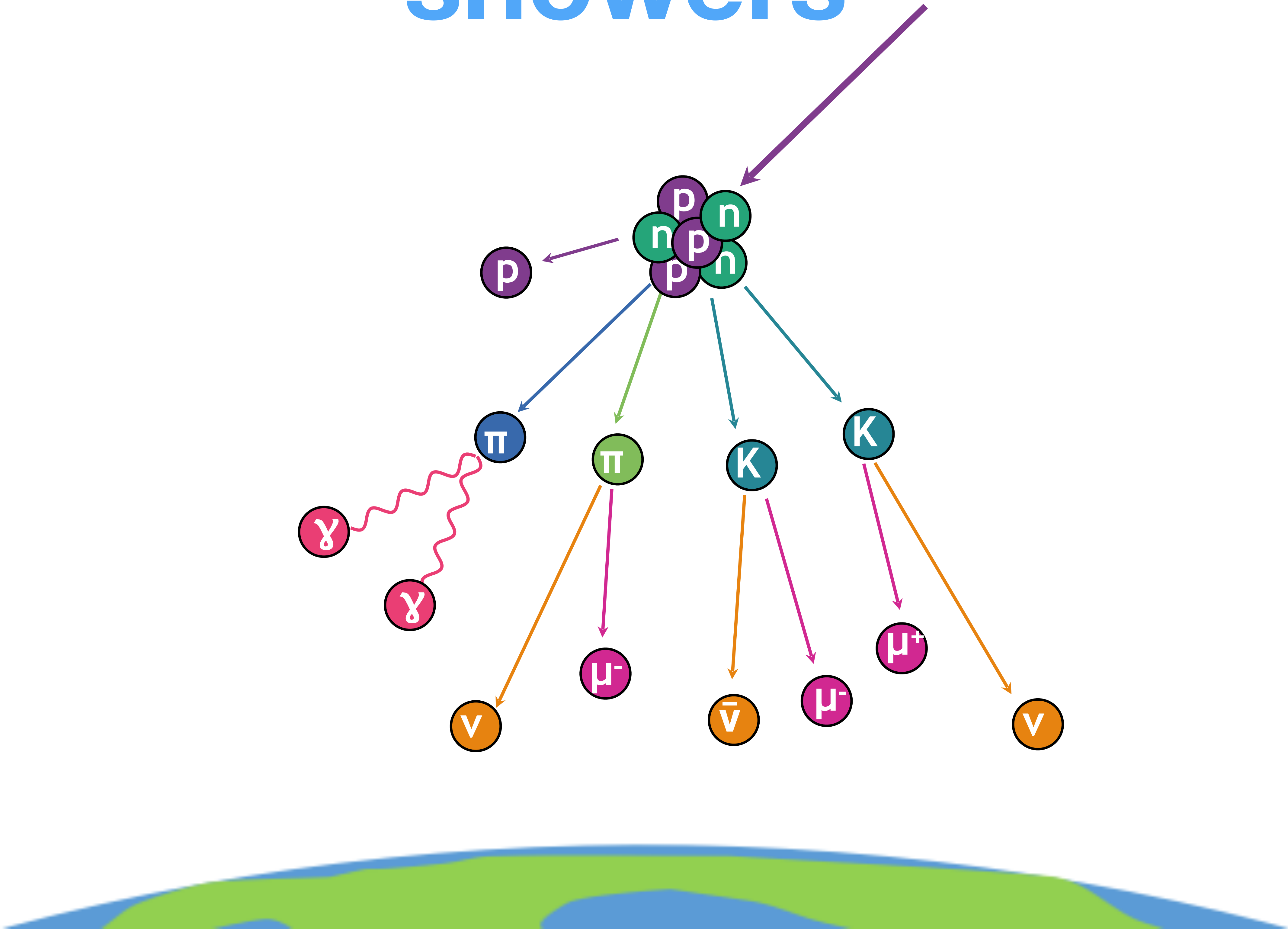
It is hard to build an enormous detector with this resolution at reasonable cost

Luckily IceCube Events are Very High Energy!

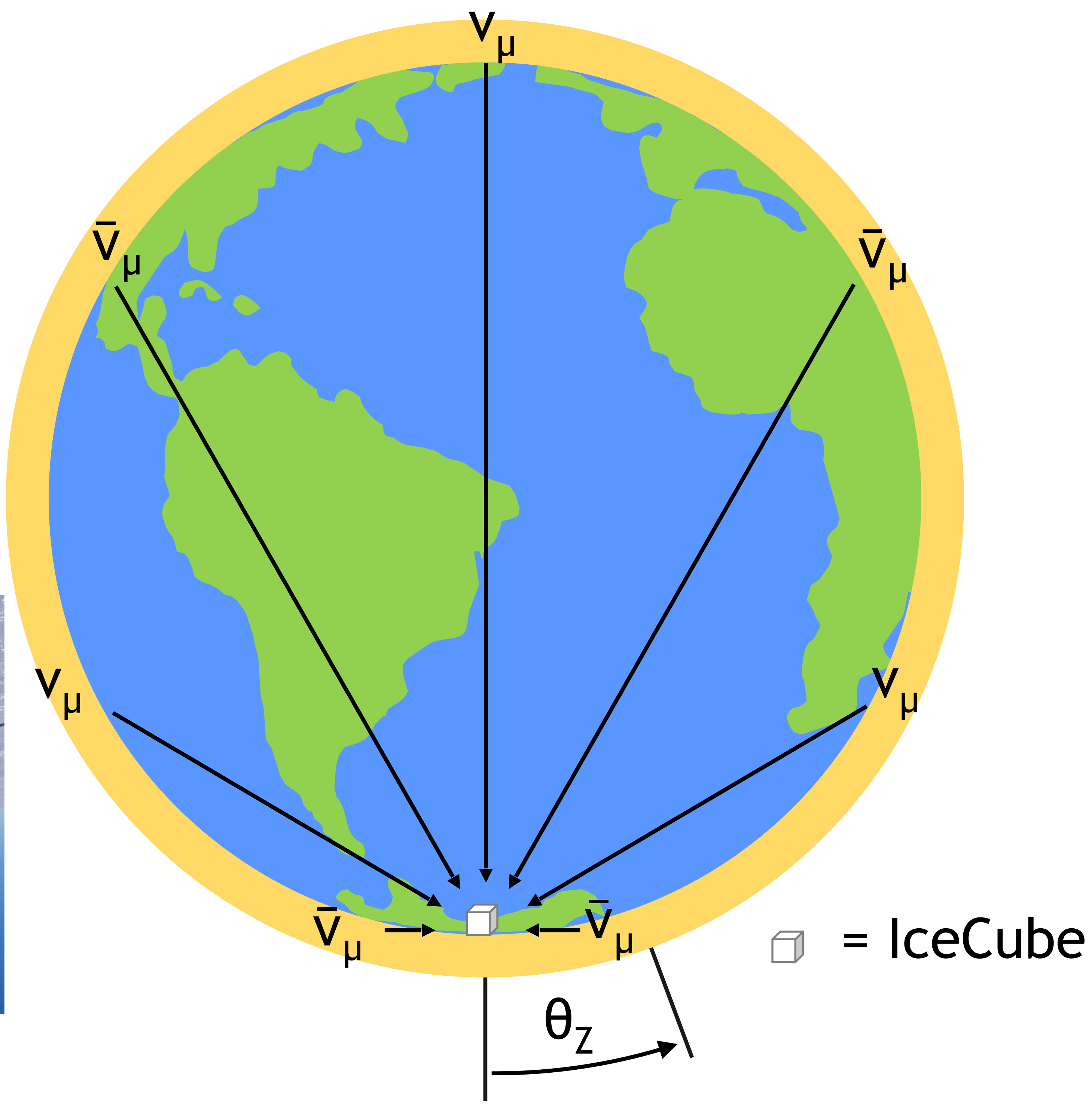


Phys. Rev. Lett. 115, 081102 (2015)

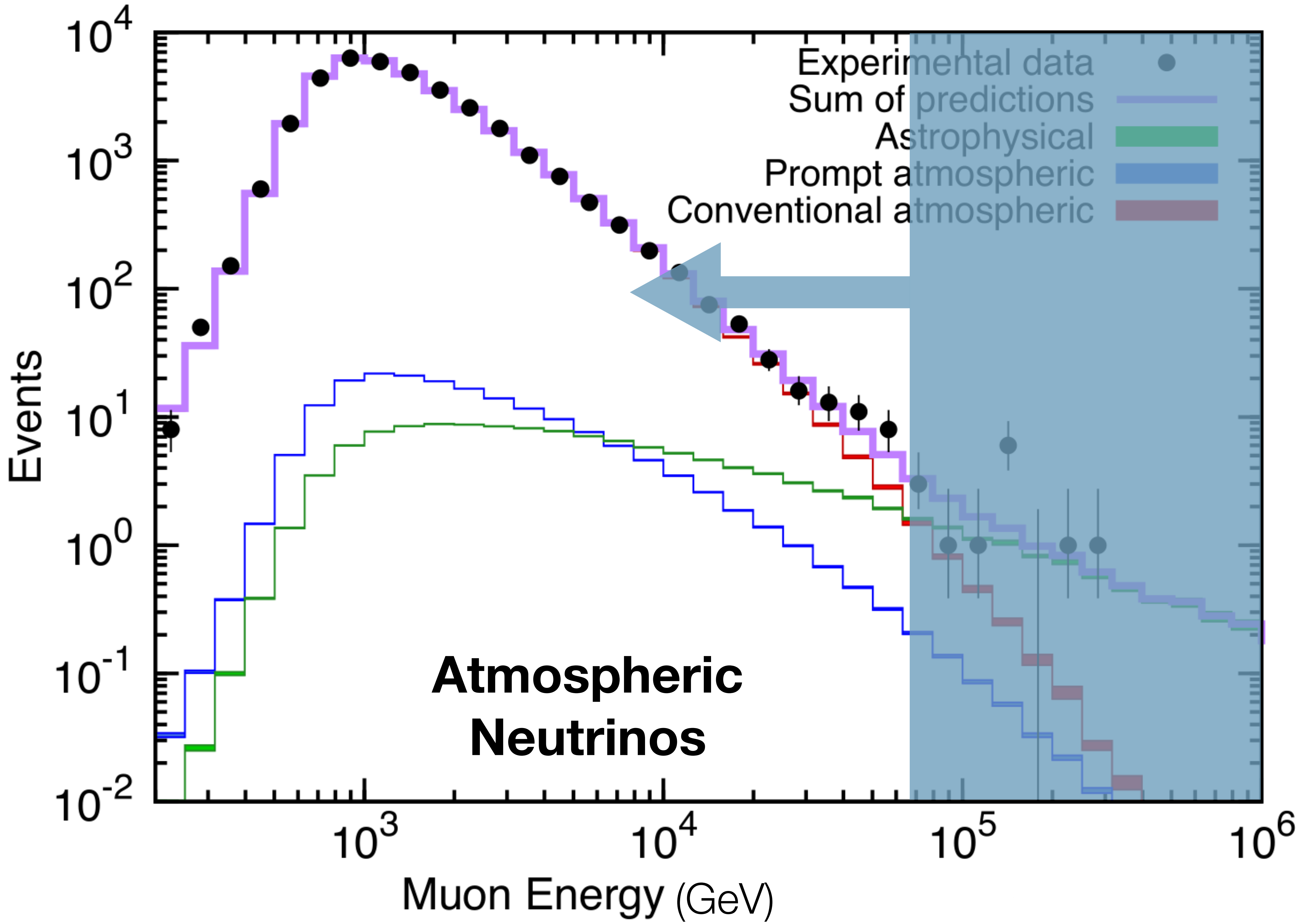
Neutrinos from cosmic-ray air showers



Atmospheric neutrinos come from all directions

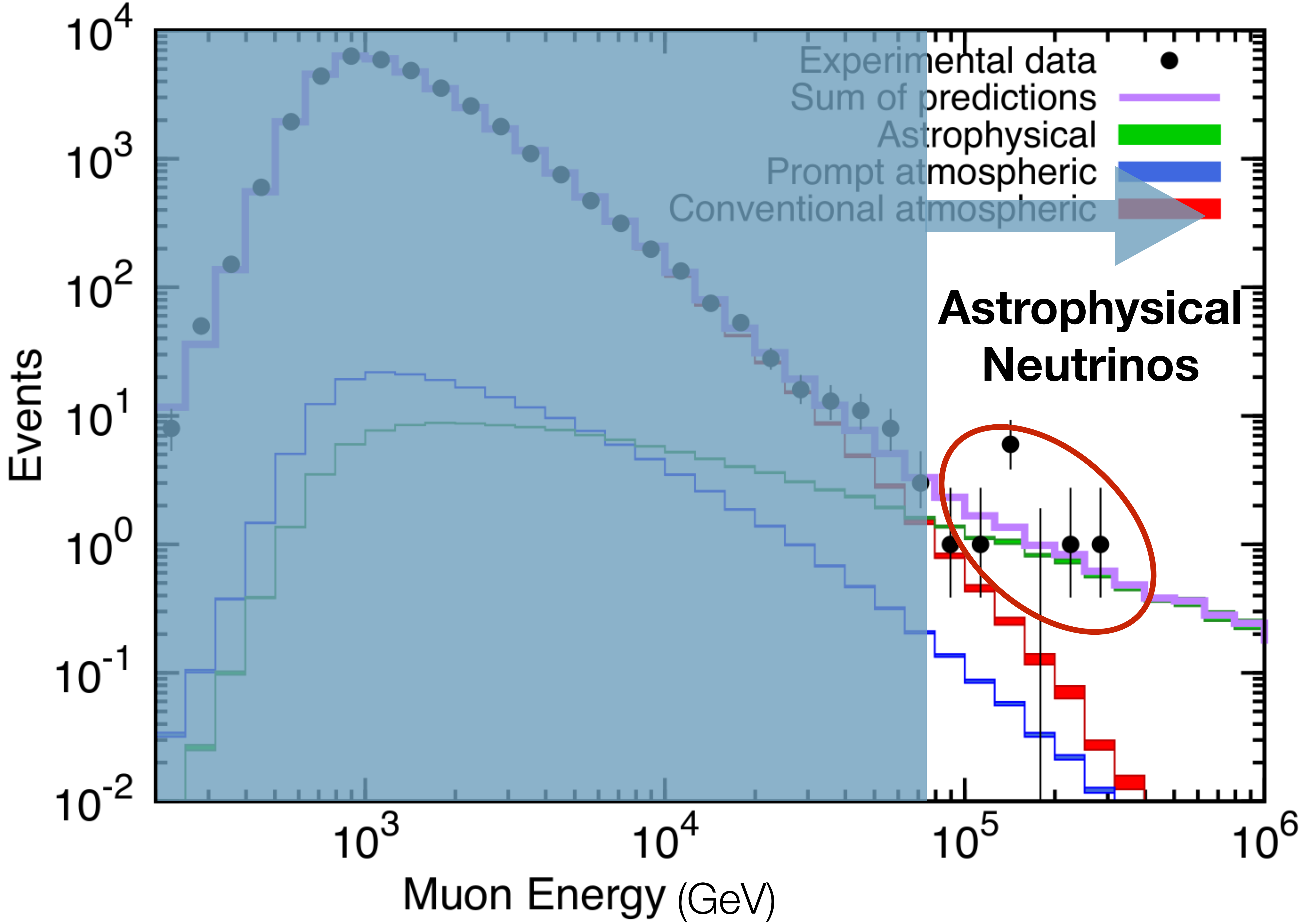


IceCube observes a lot of atmospheric neutrinos!



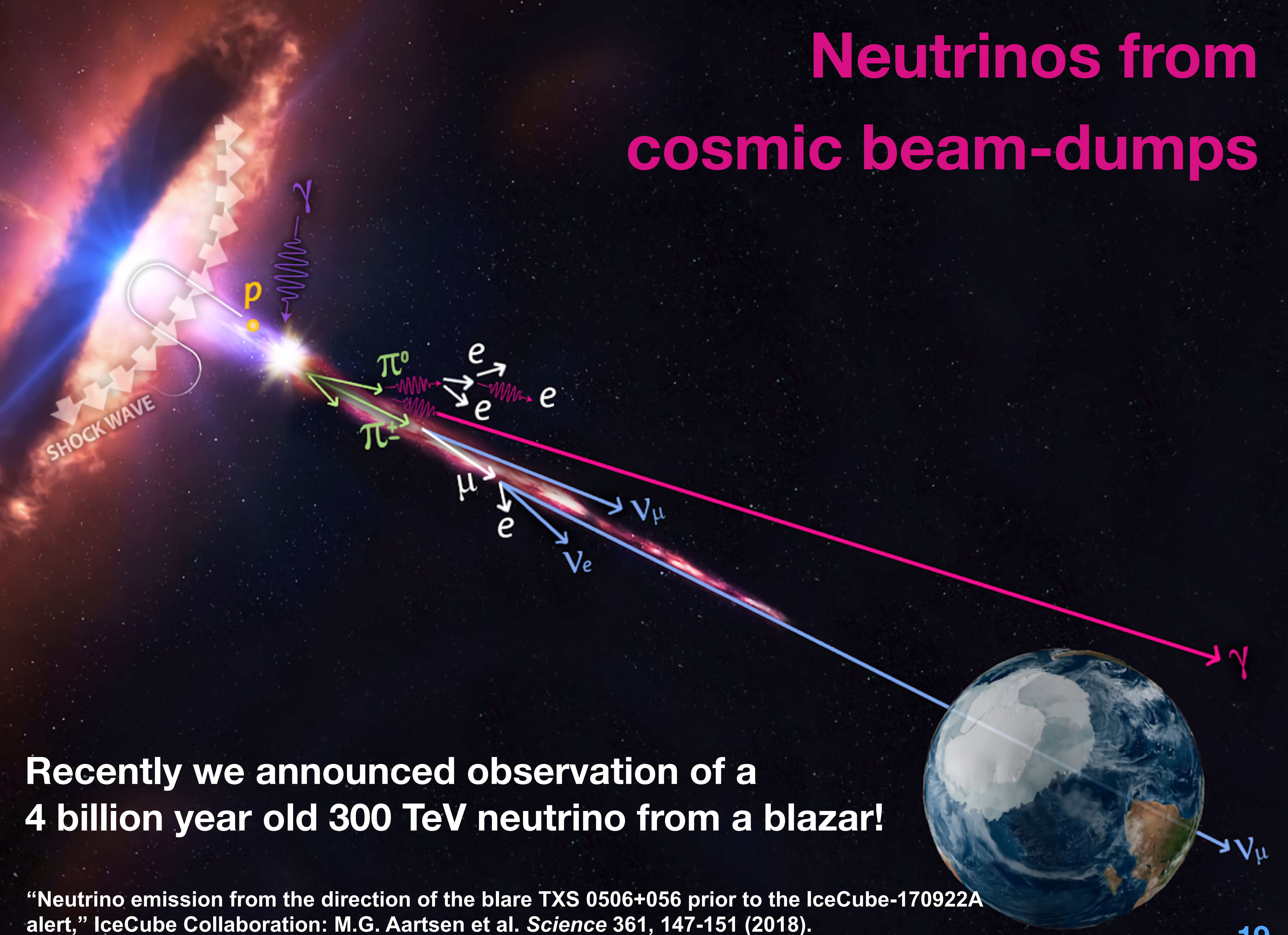
Phys. Rev. Lett. 115, 081102 (2015)

But wait, there's more!



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

Neutrinos from cosmic beam-dumps



Recently we announced observation of a 4 billion year old 300 TeV neutrino from a blazar!

"Neutrino emission from the direction of the blare TXS 0506+056 prior to the IceCube-170922A alert," IceCube Collaboration: M.G. Aartsen et al. *Science* 361, 147-151 (2018).

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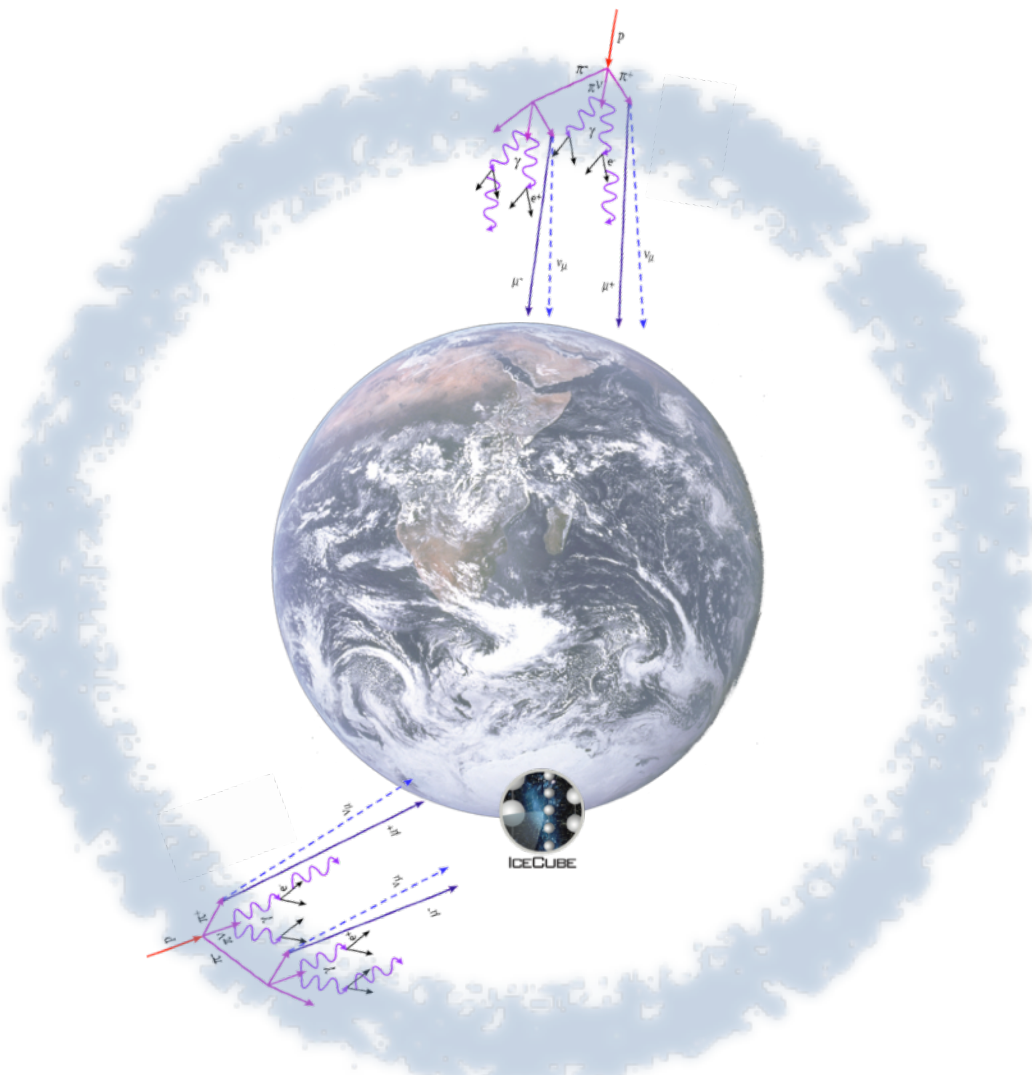
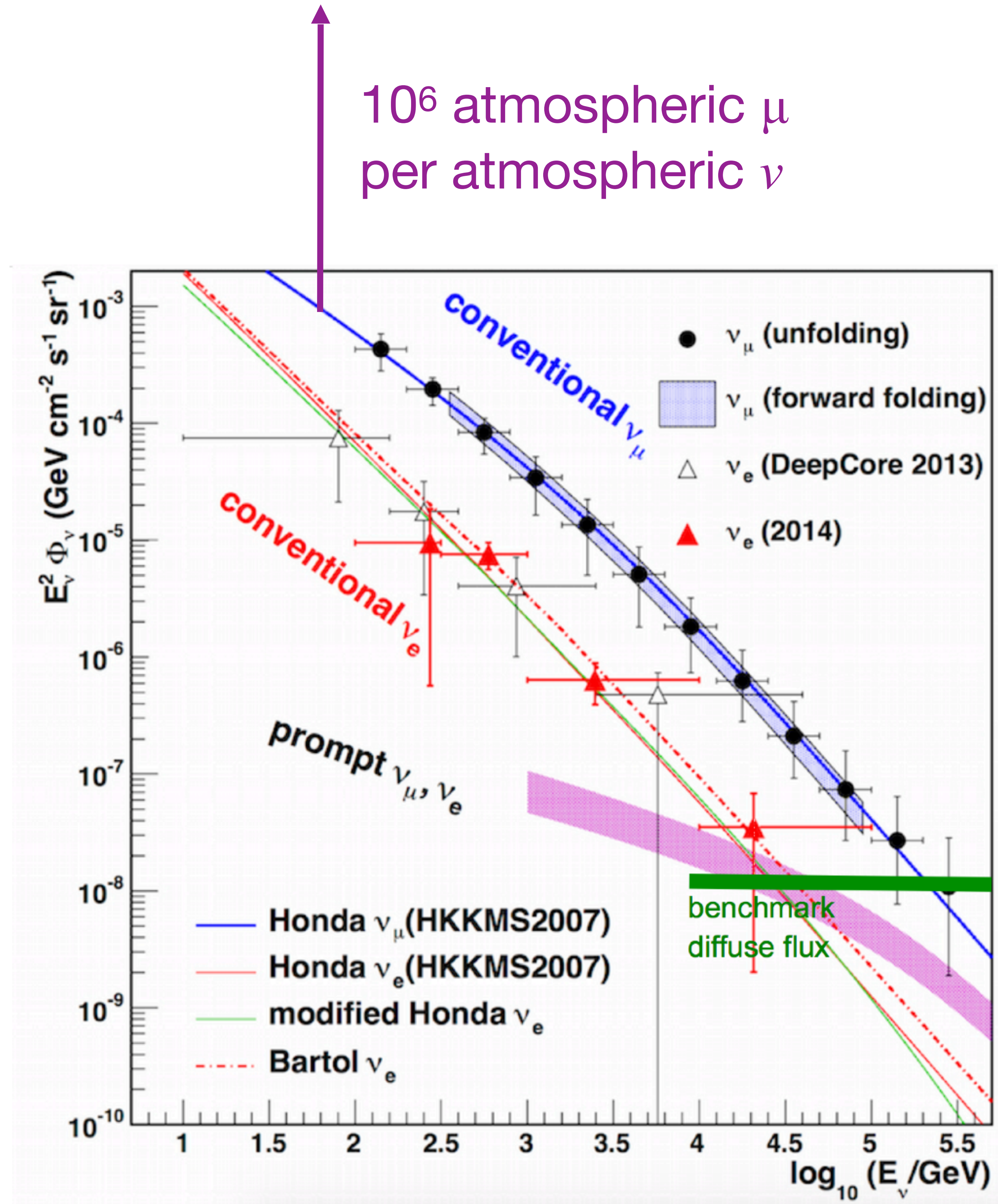


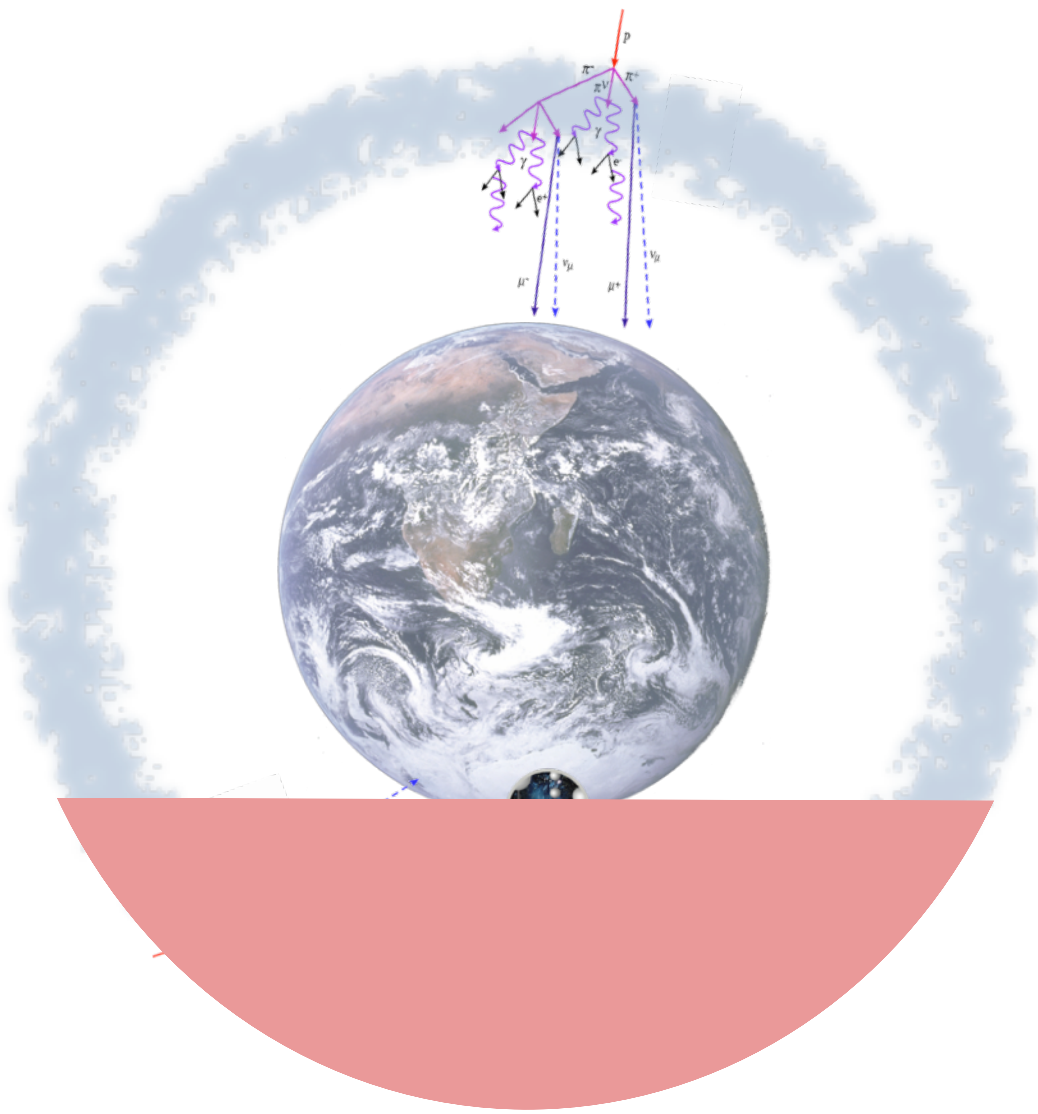


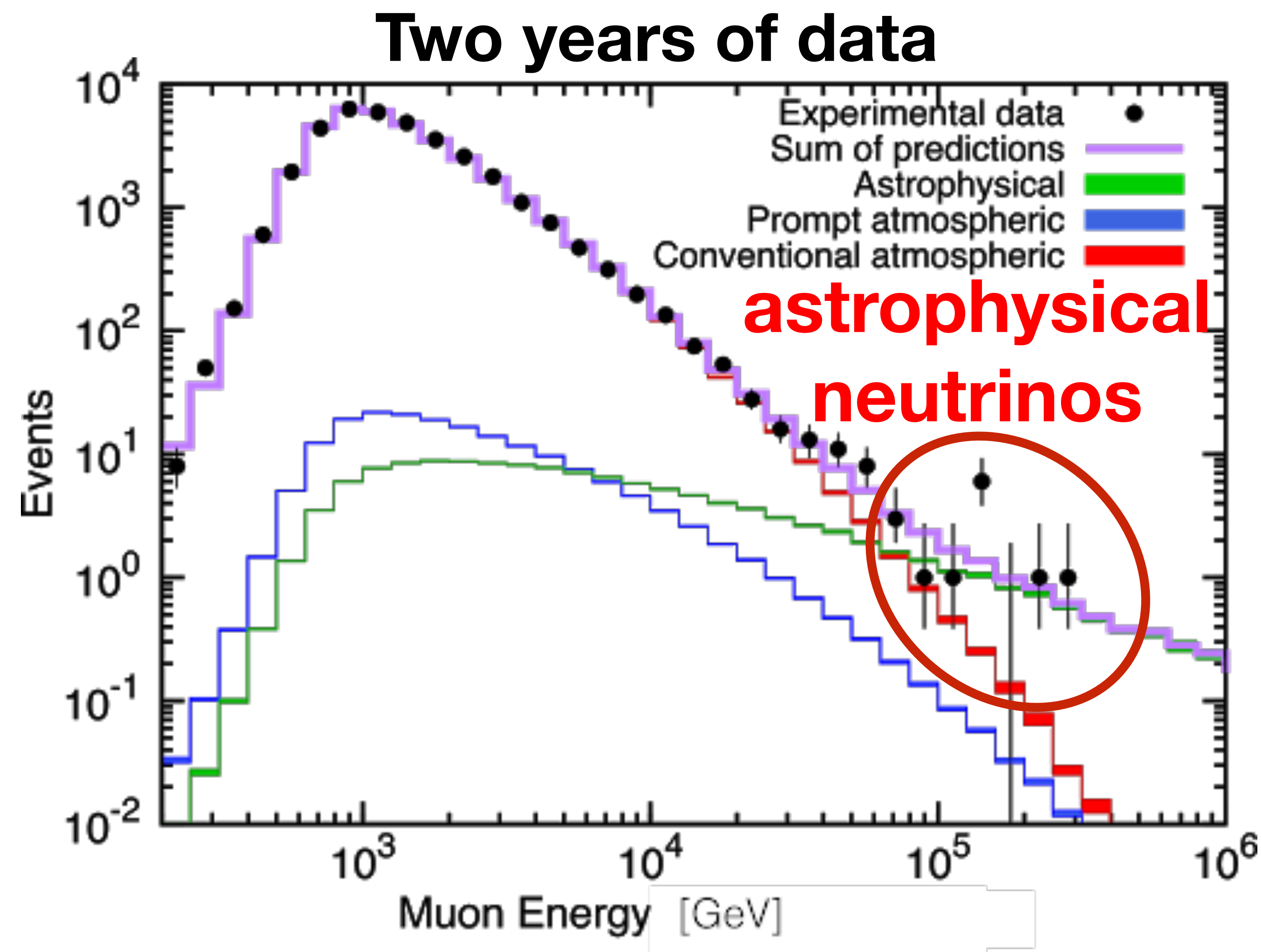
Challenges:

Astrophysical neutrino flux is very small

Large atmospheric neutrino and muon backgrounds

Strategy One: look at the Northern Sky

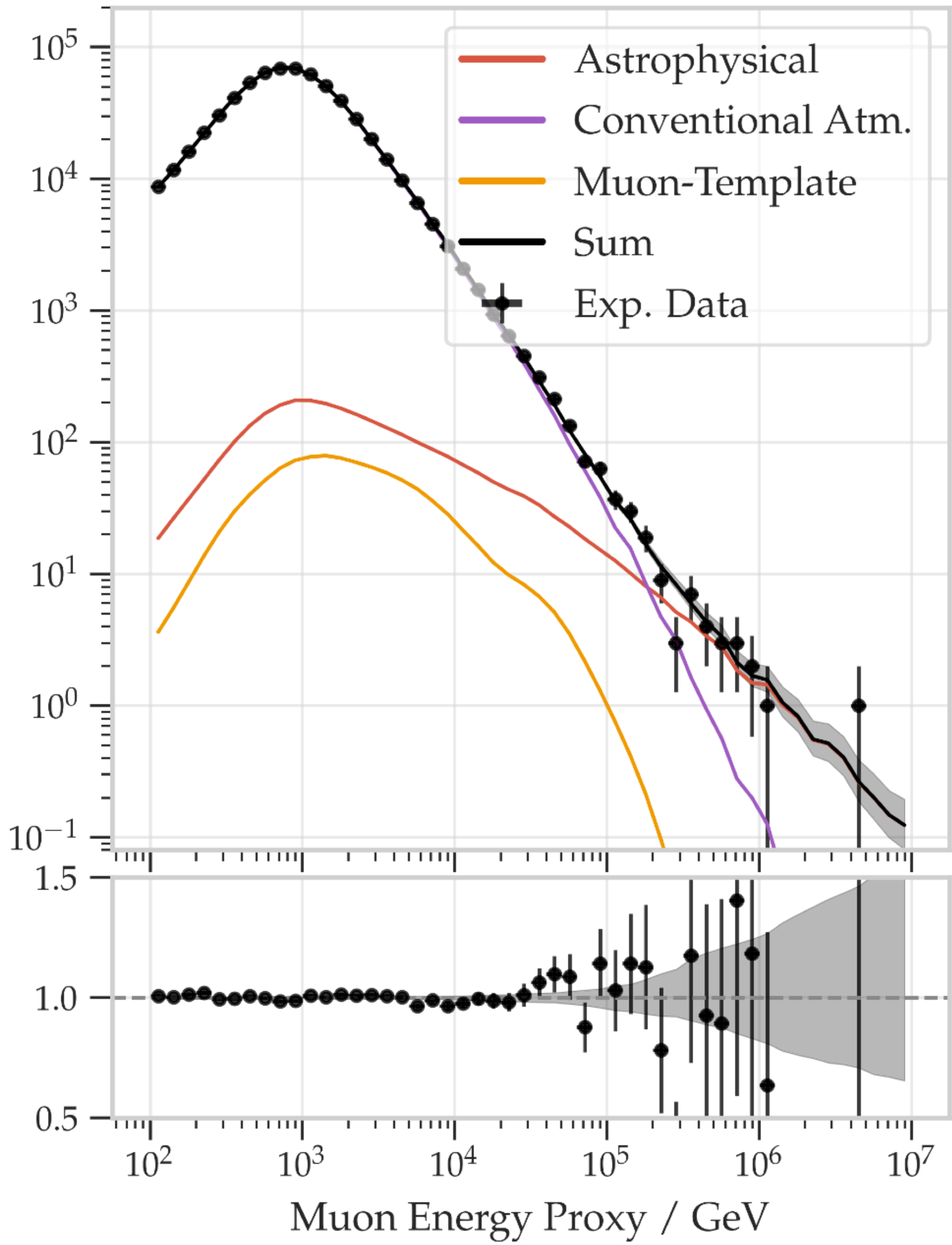


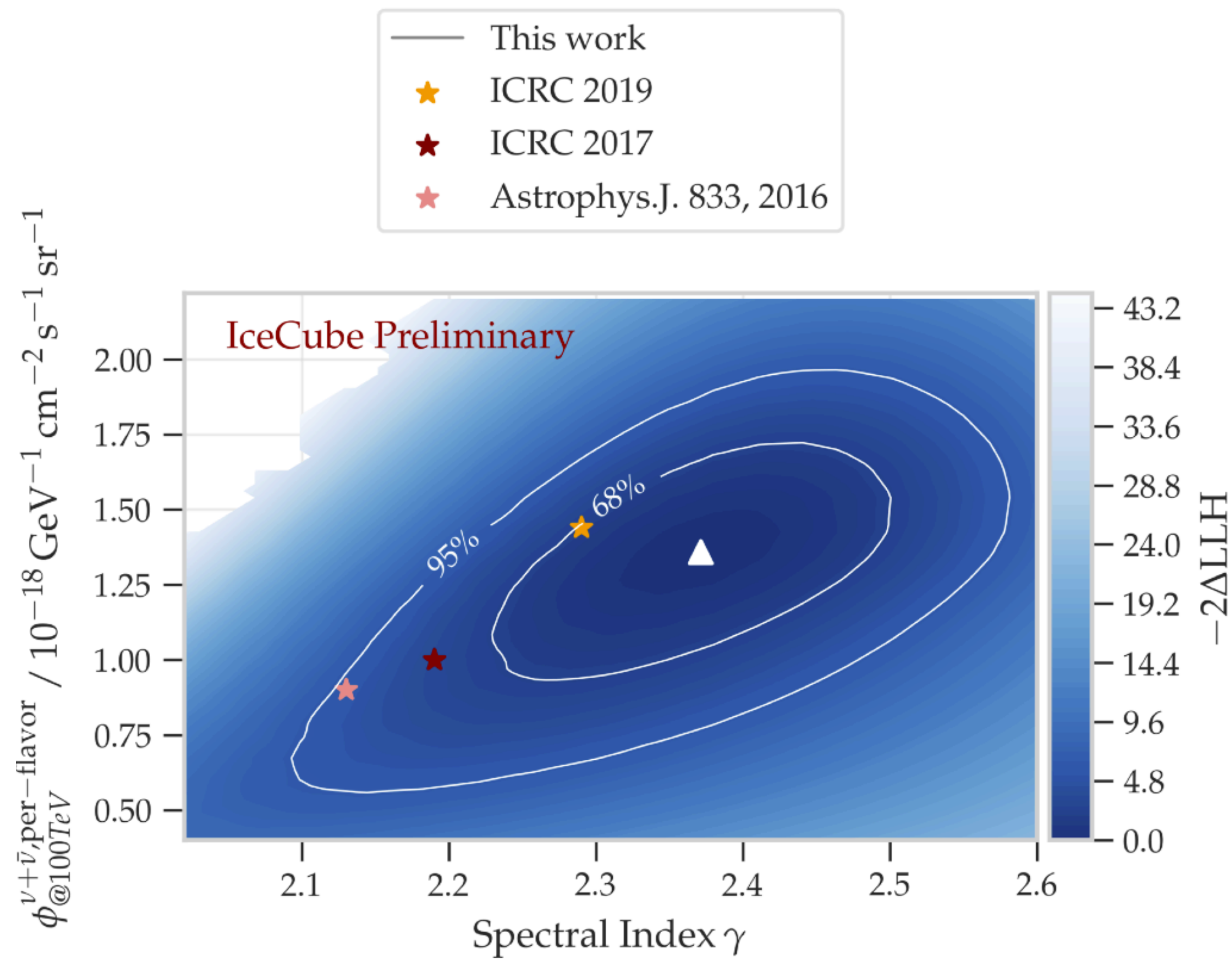


Strategy:

- Use the Earth to block the large atmospheric muon flux
- Look at the highest energy where the atmosphric neutrino flux is smallest

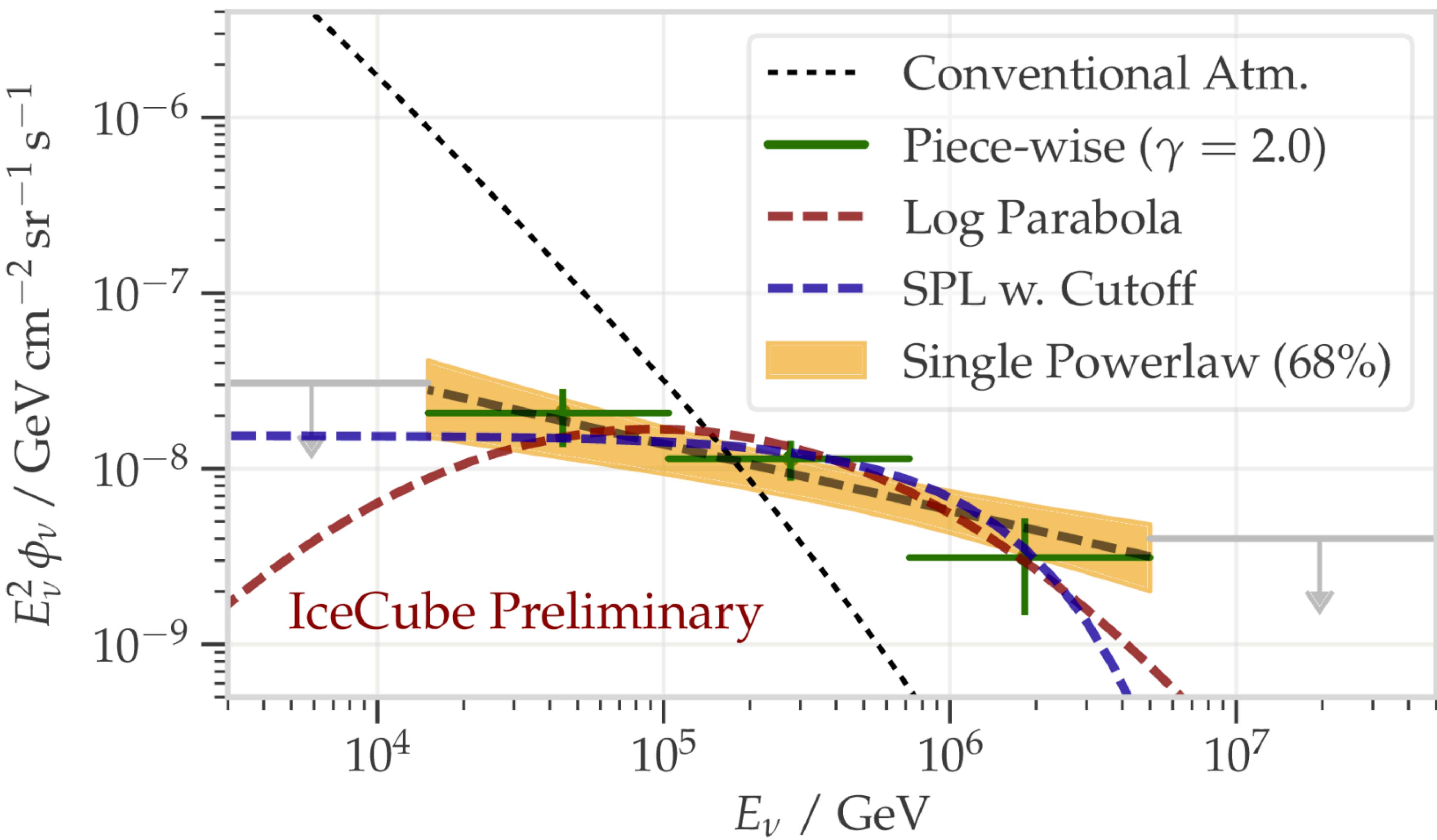
9.5 years of northern-sky neutrinos show consistent excess over atmospheric background





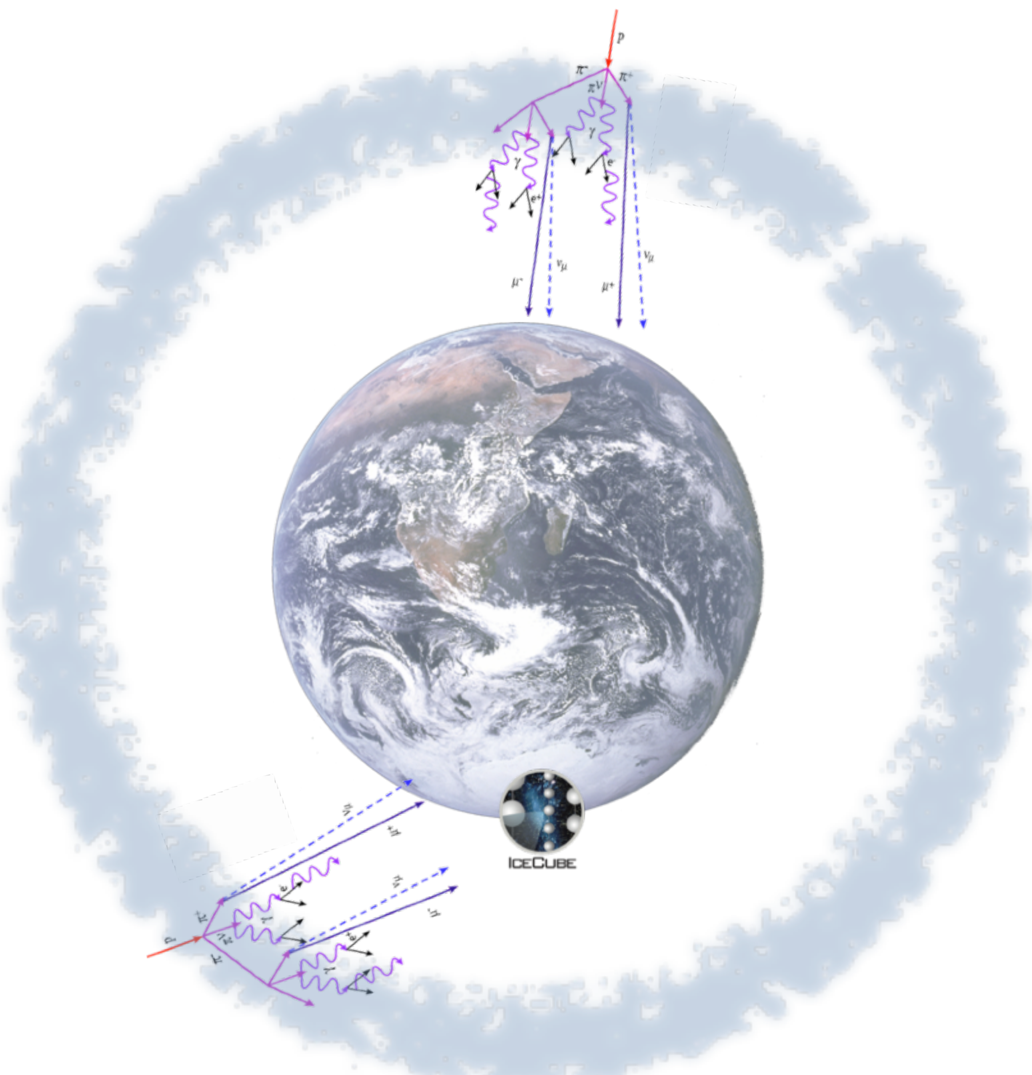
$$\gamma = 2.37 \pm 0.1$$

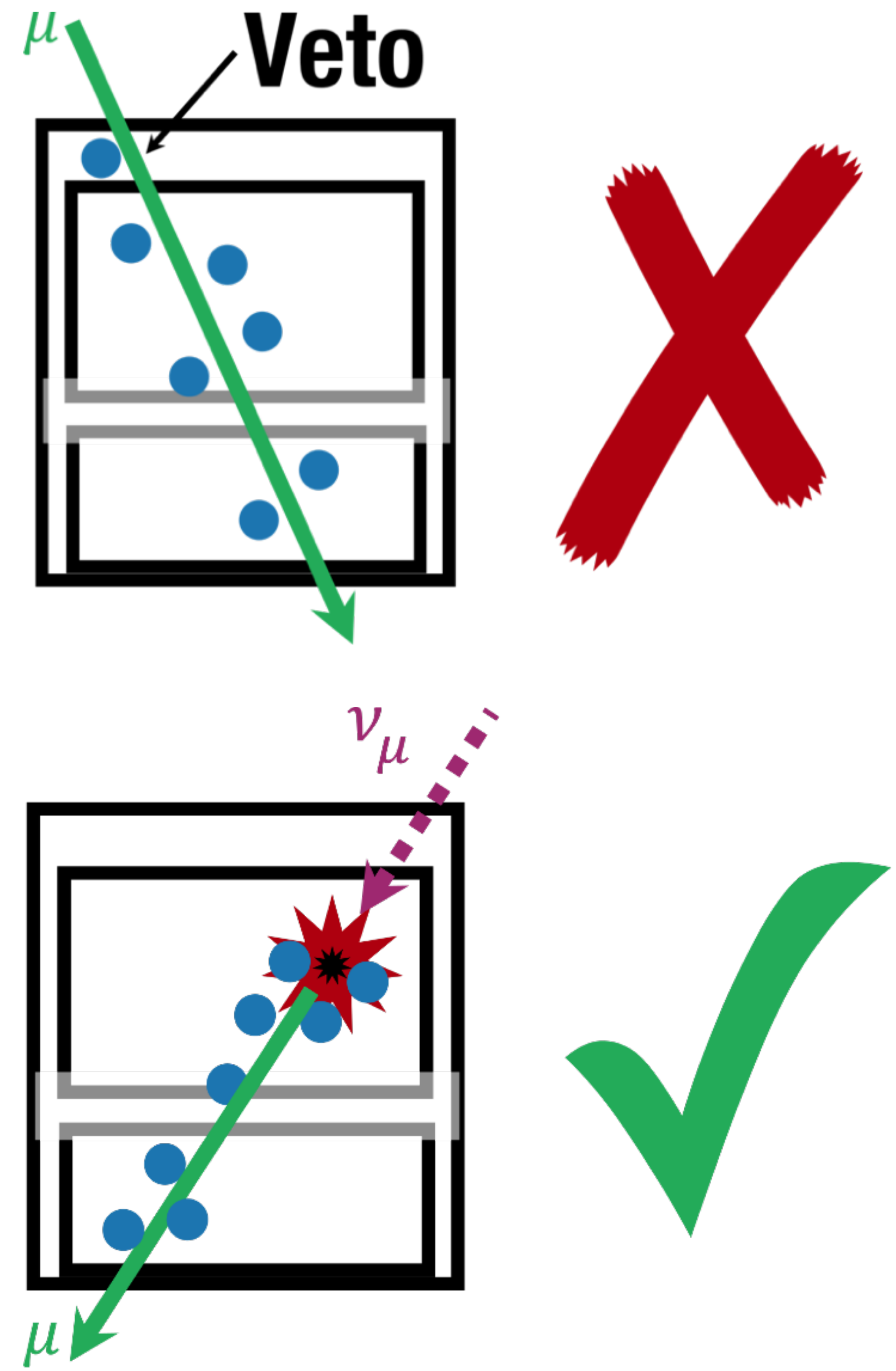
9.5 years of northern-sky neutrinos show consistent excess over atmospheric background



Northern-sky astrophysical neutrino flux is well characterized by single power-law with spectral index: 2.37±0.10

Strategy Two: Use the other detector as a veto

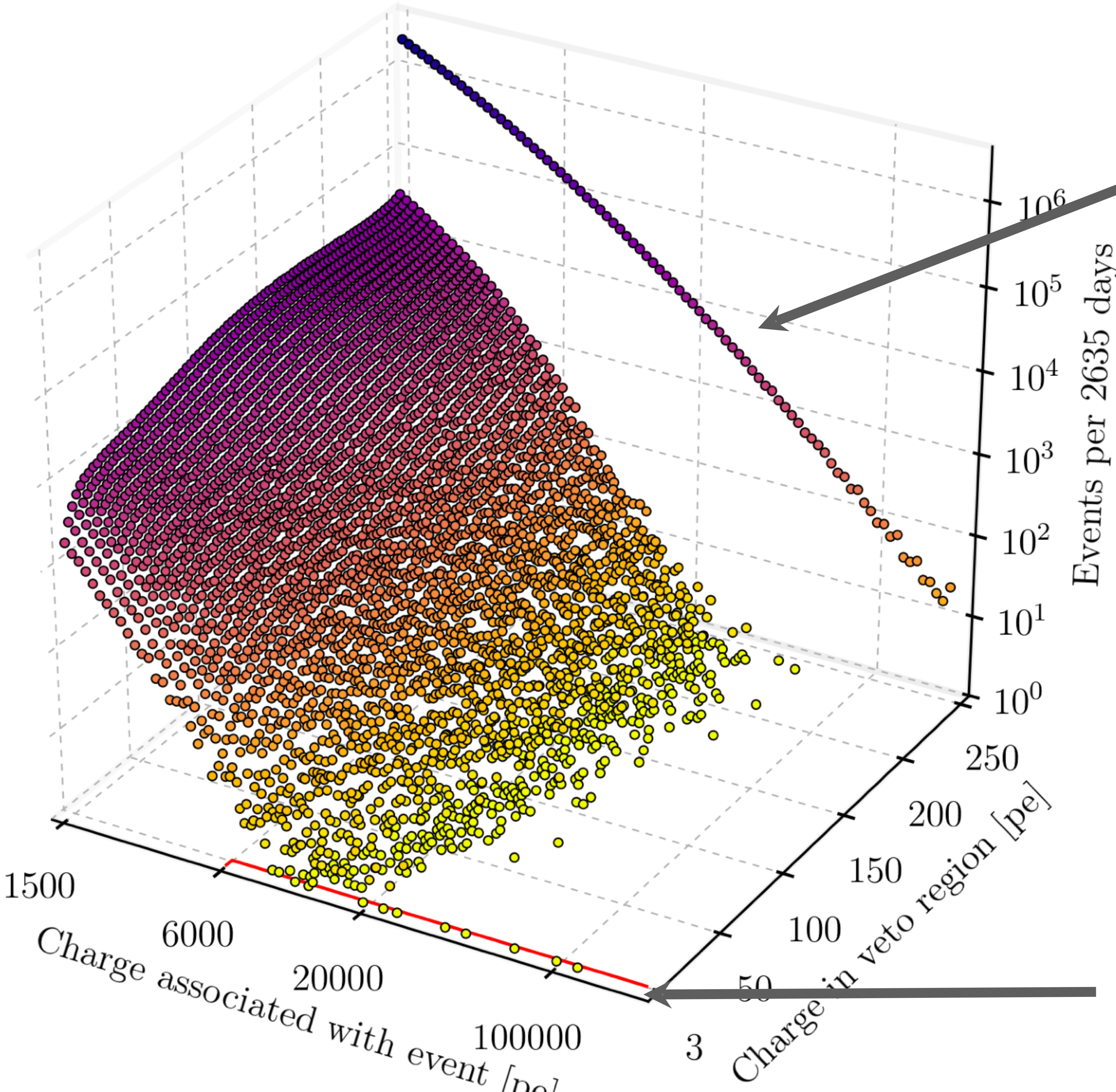




Strategy:

- Define a veto region in the detector to supress the atmospheric background,
- Advantage: All-sky vision

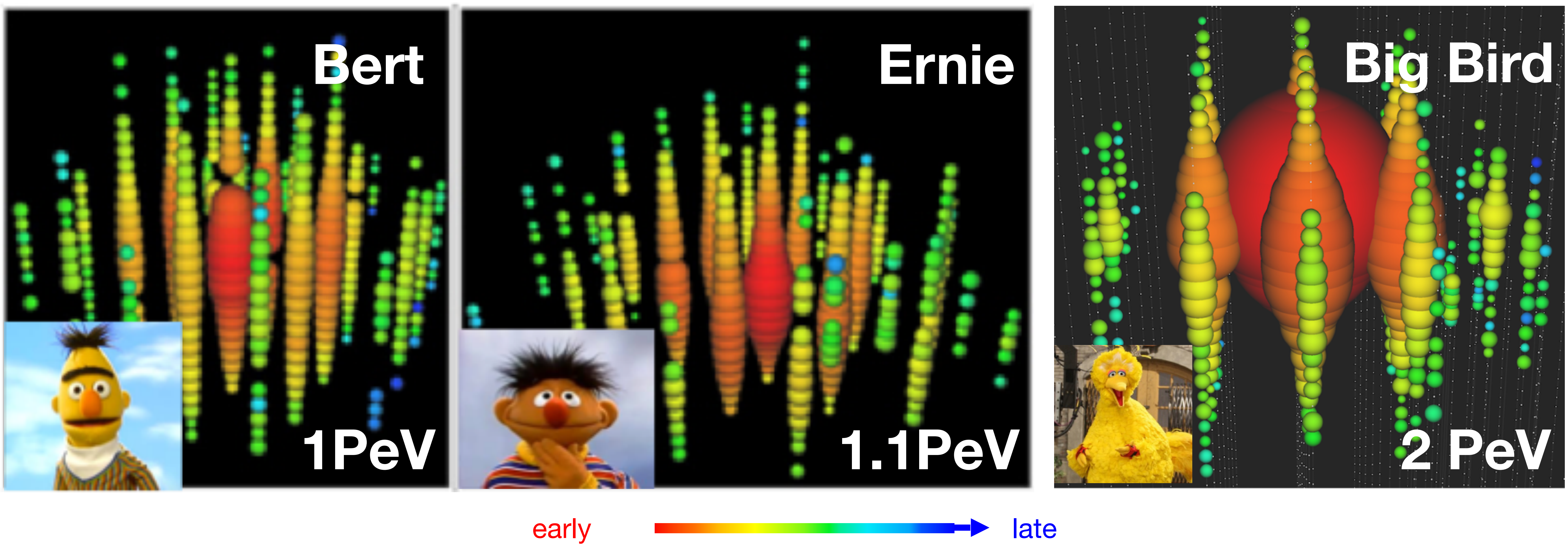
High-Energy Starting Events (HESE)



Large muon background is well-separated

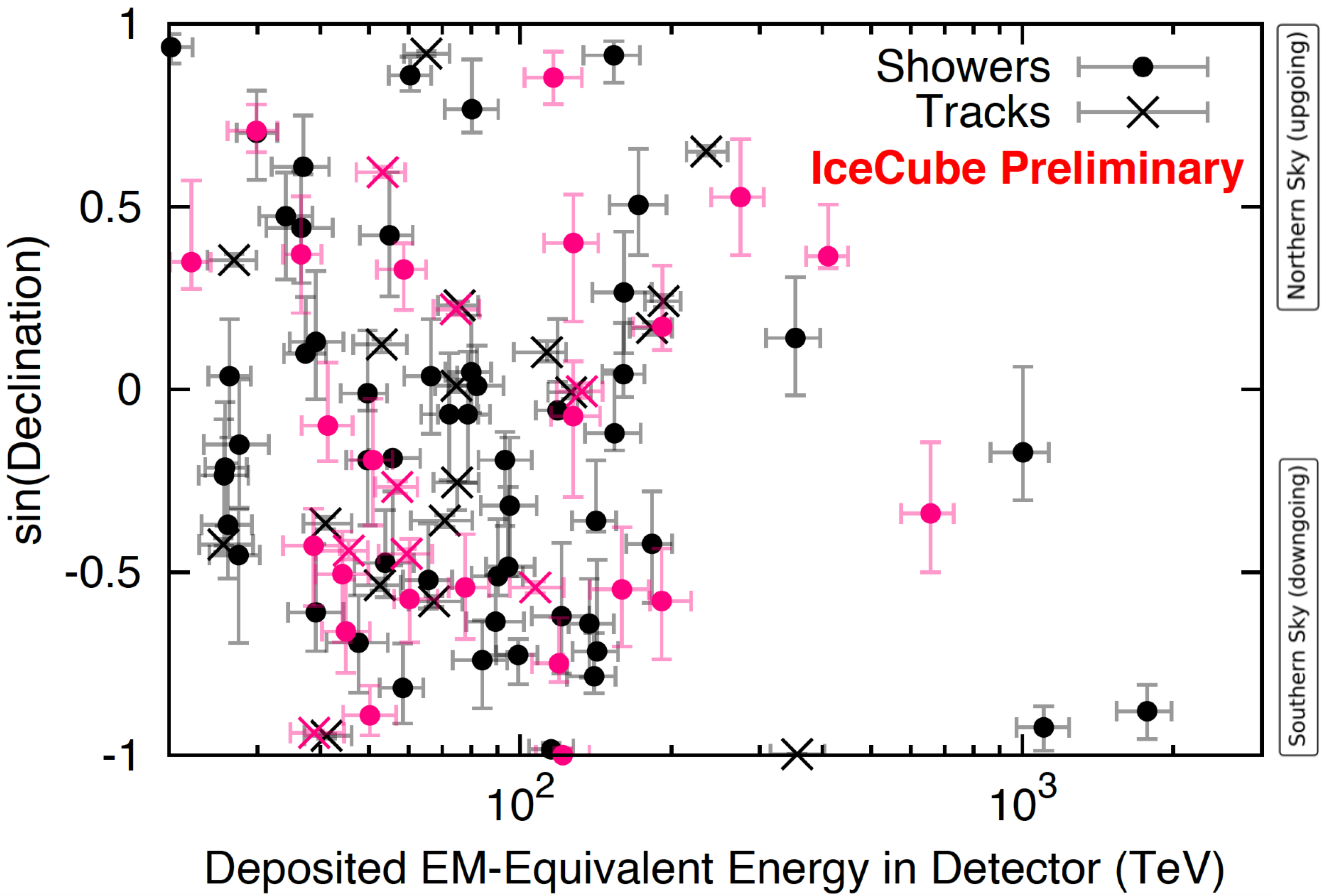
Astrophysical neutrinos candidates!

This event selection contains some of the highest energy neutrinos ever observed



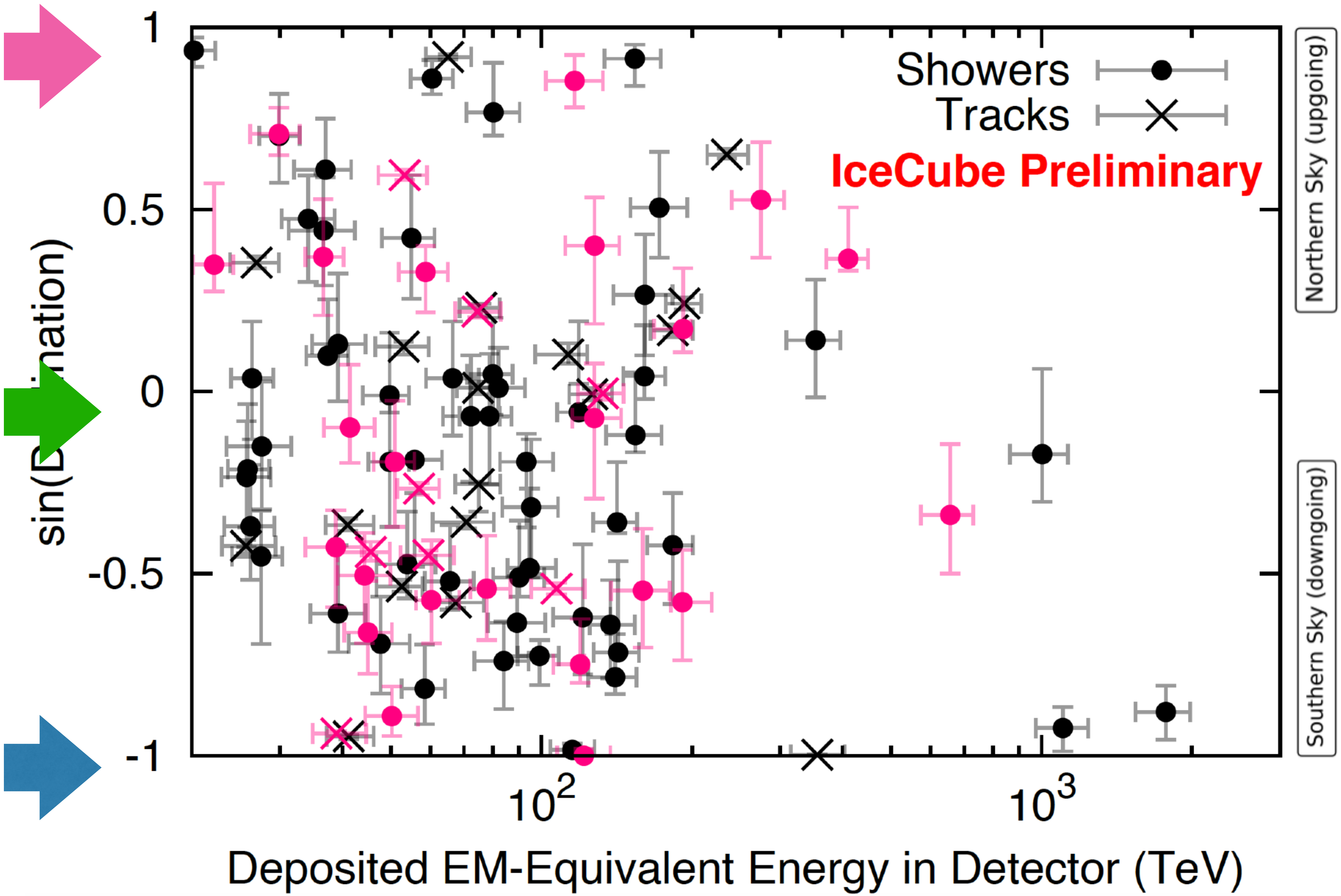
Color indicates time (red earlier, green later)
Sphere sizes indicate charge deposited.

HESE-7.5 years distribution



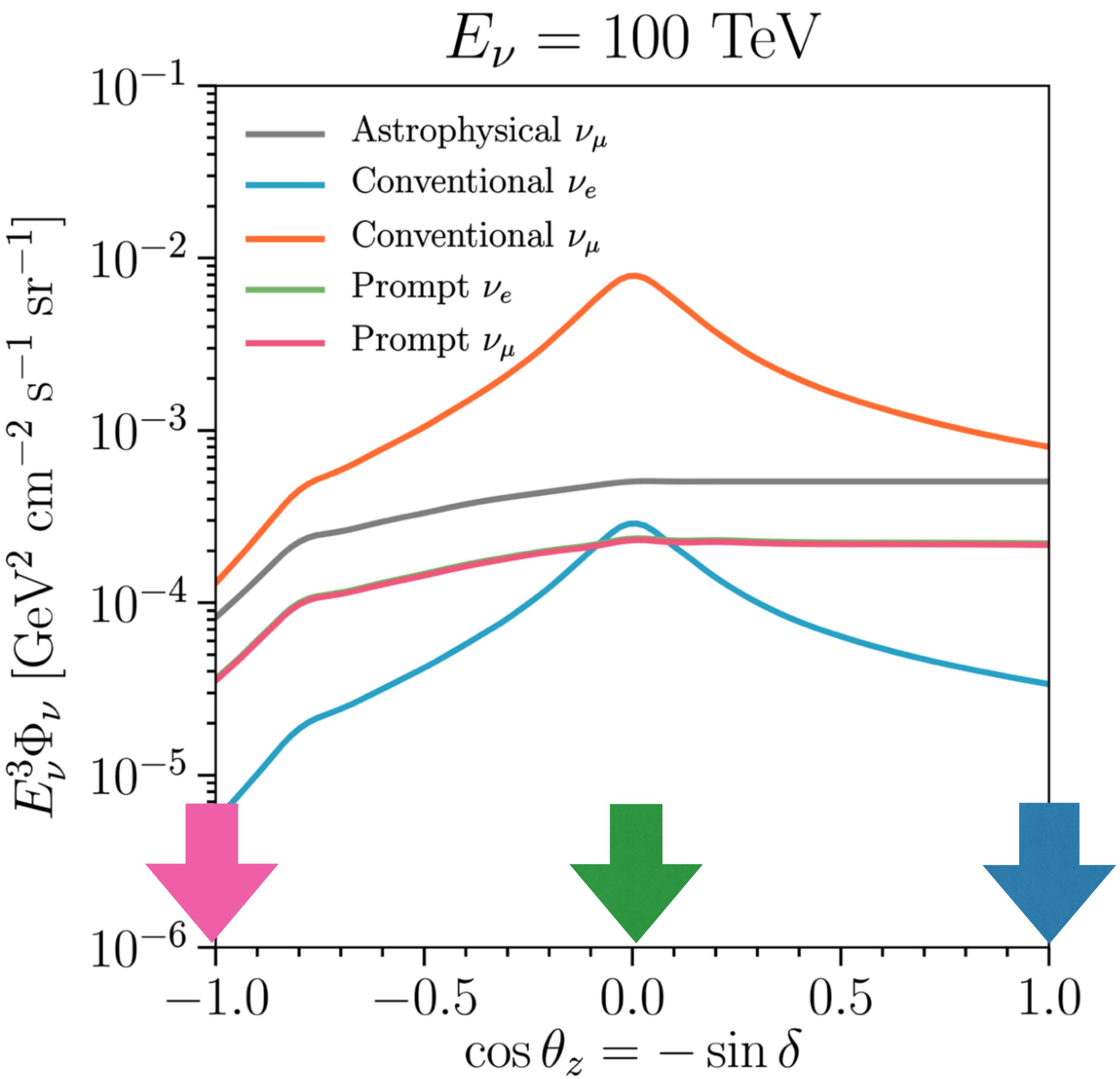
*HESE = high-energy starting events

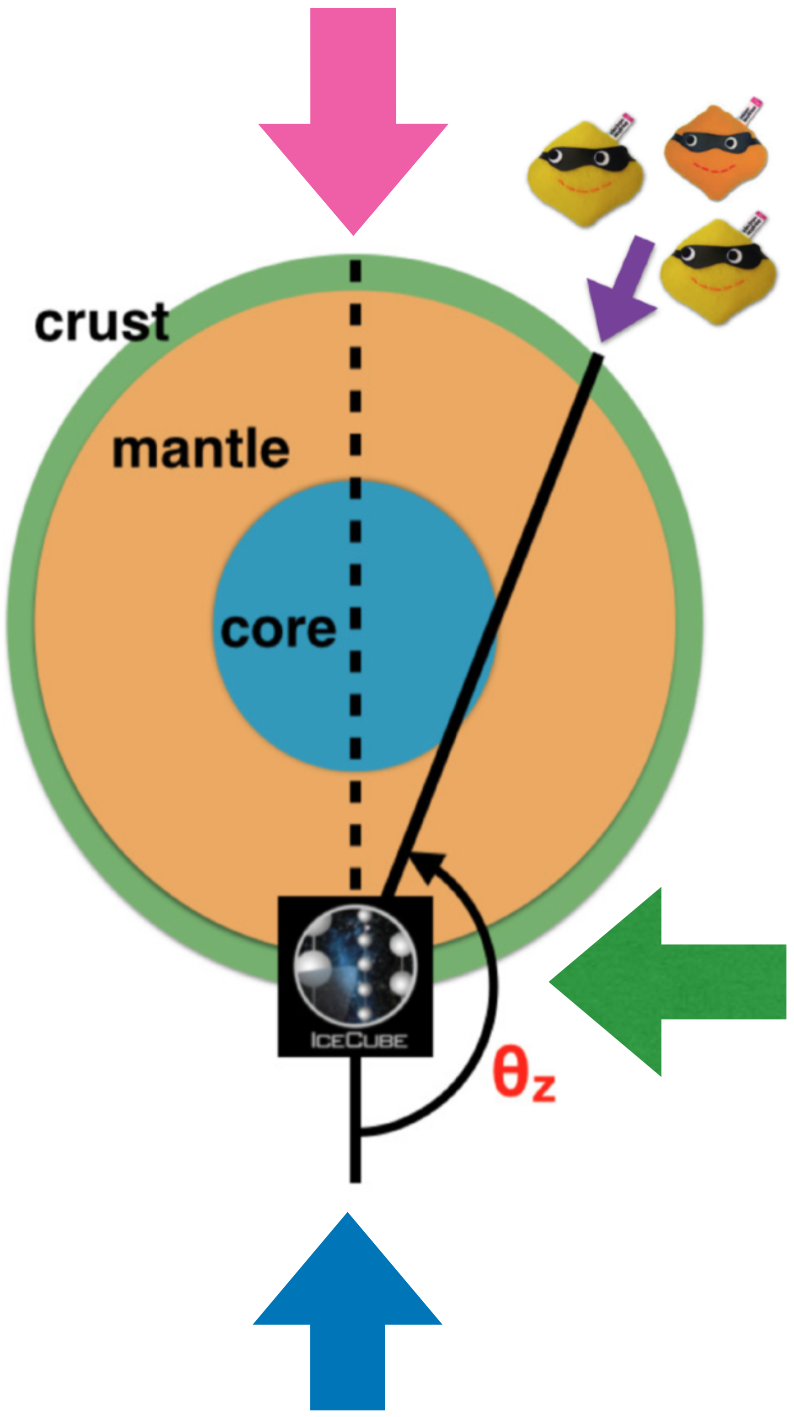
HESE-7.5 years distribution



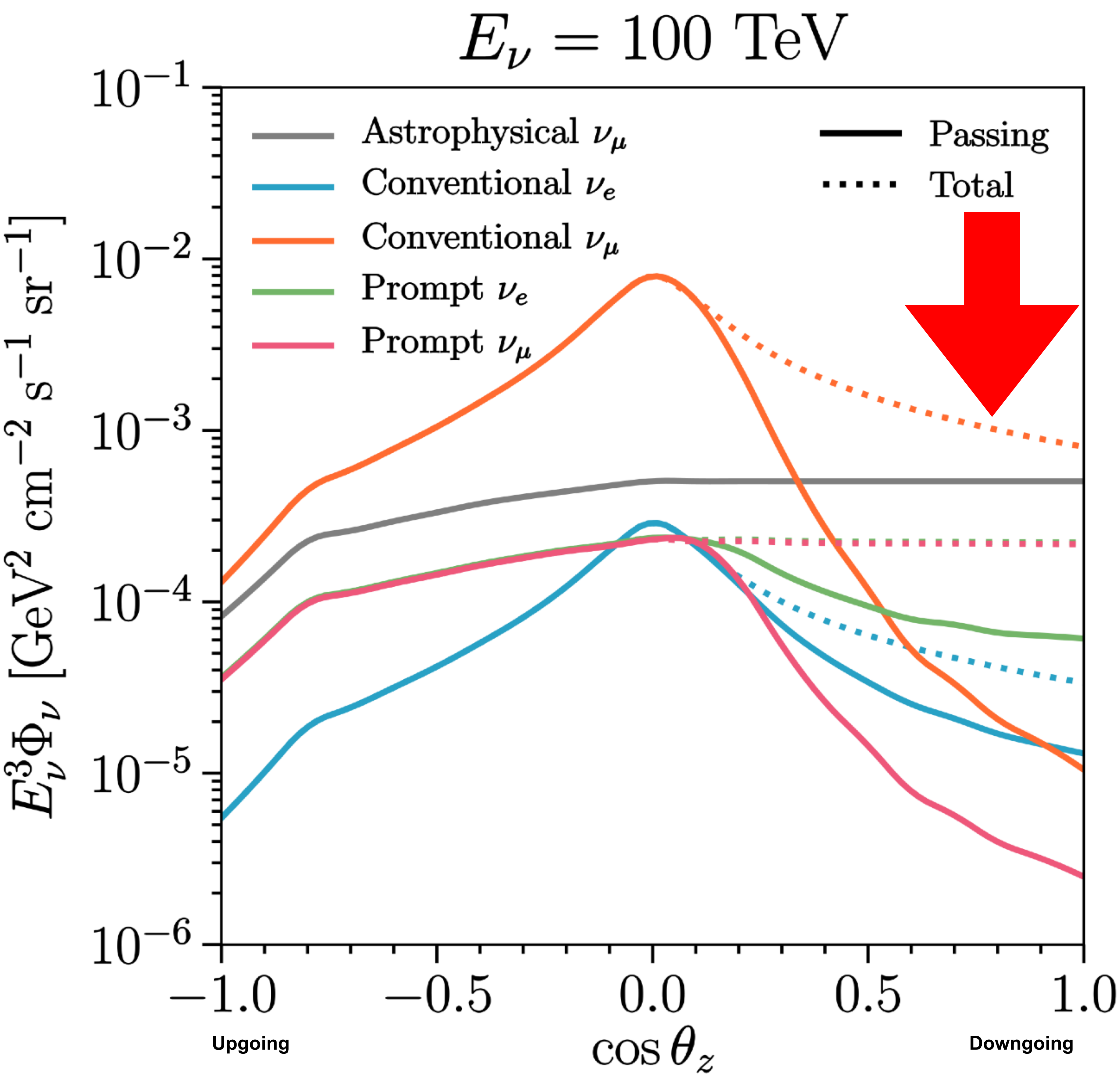
*HESE = high-energy starting events

Expected angular distributions

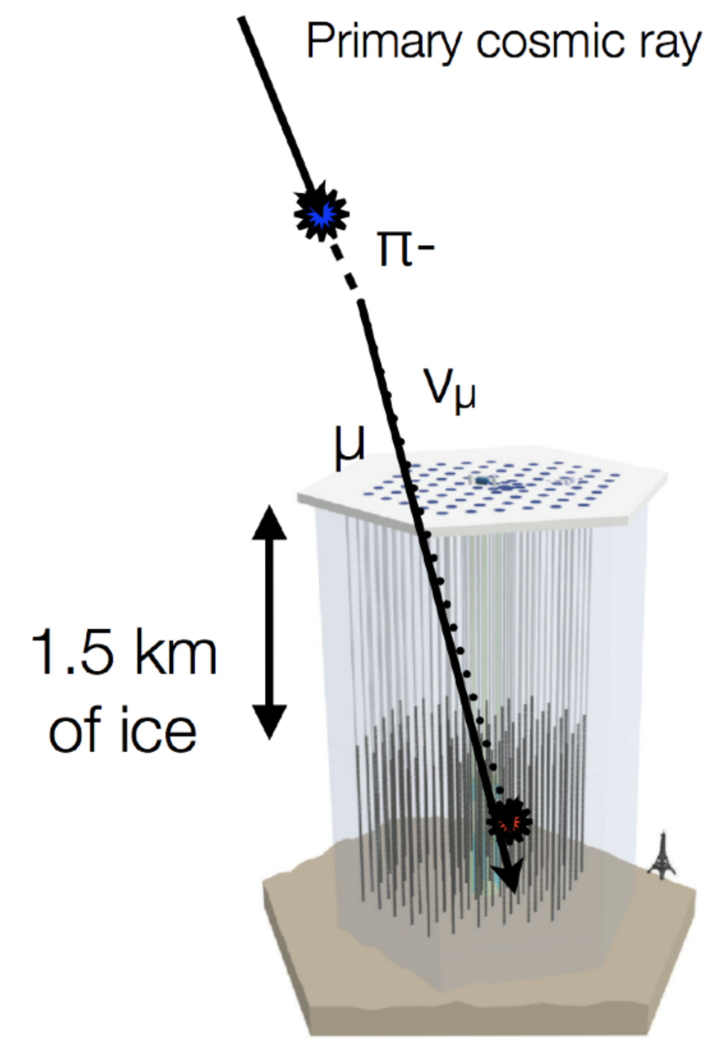




Coincident muons supress neutrino flux!

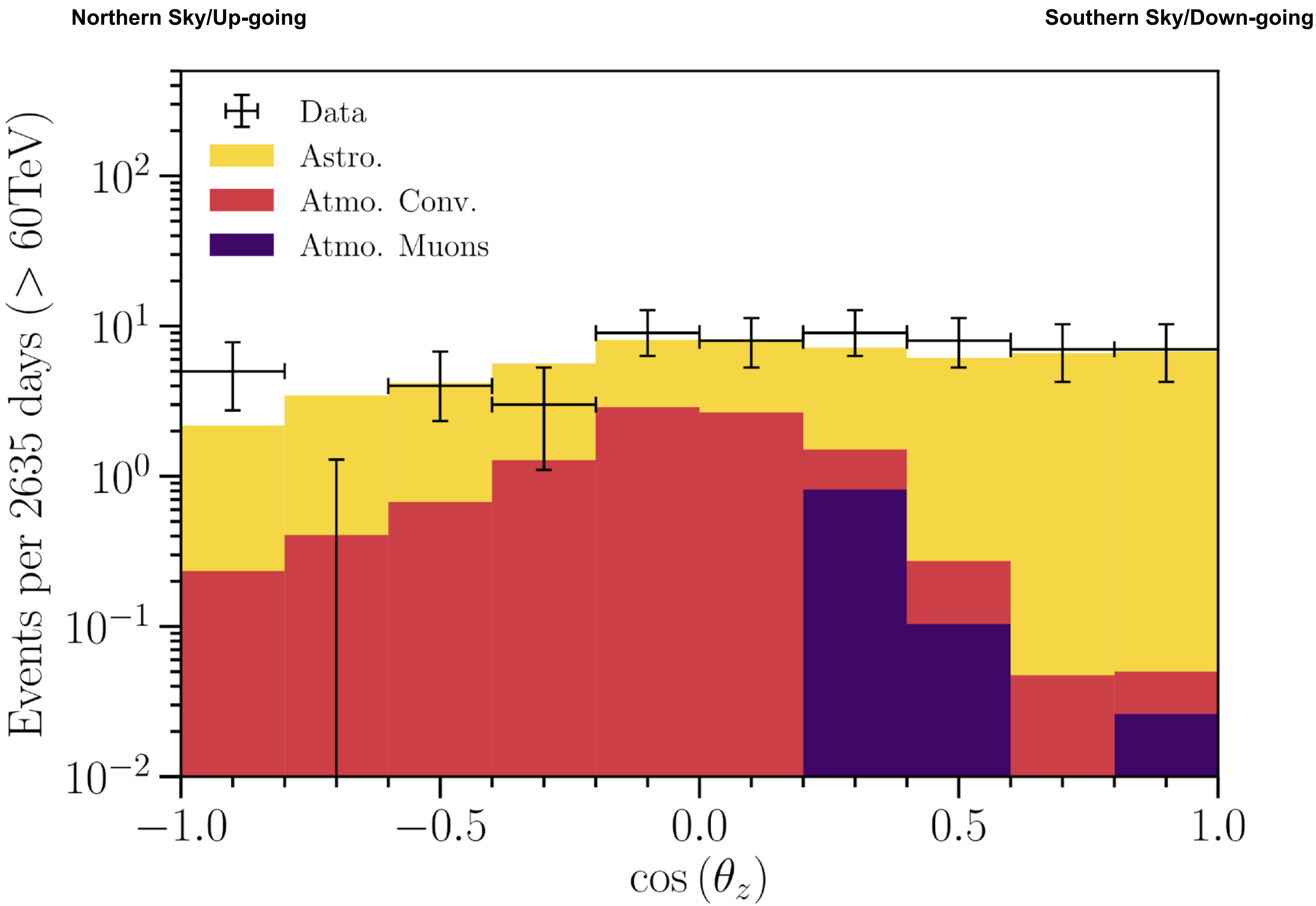


An active muon veto removes down-going atmospheric neutrinos.

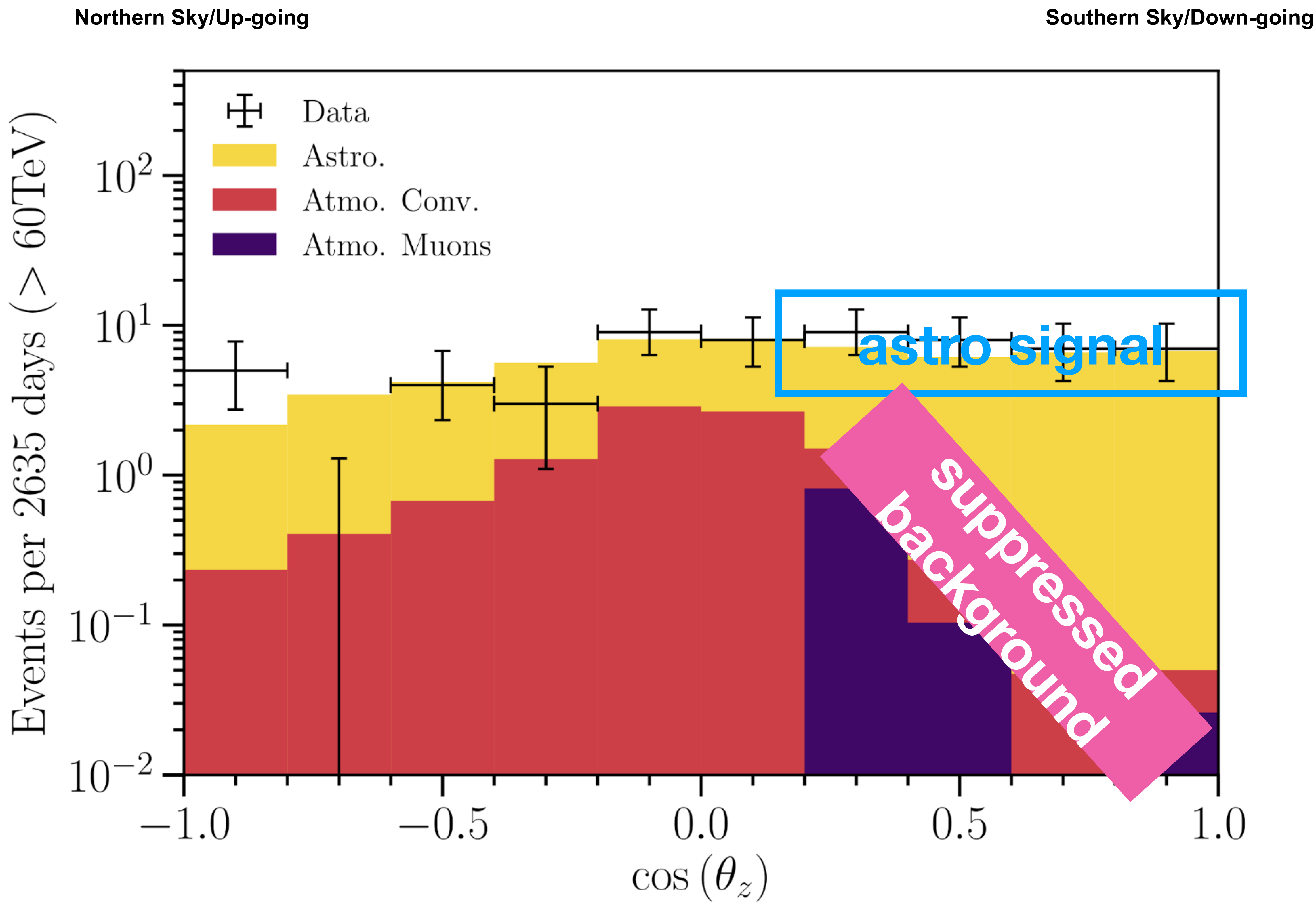


Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
CA, Palomares-Ruiz, Austin Schneider, Wille, Yuan
JCAP 1807 (2018) no.07, 047

HESE-7.5 years angular distribution

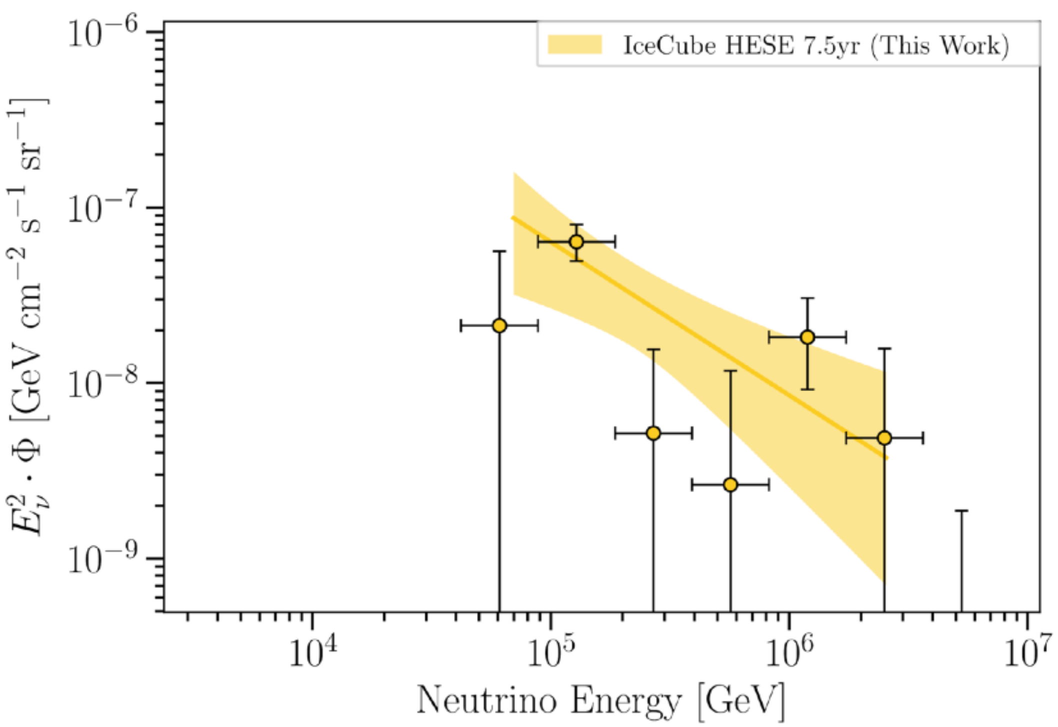


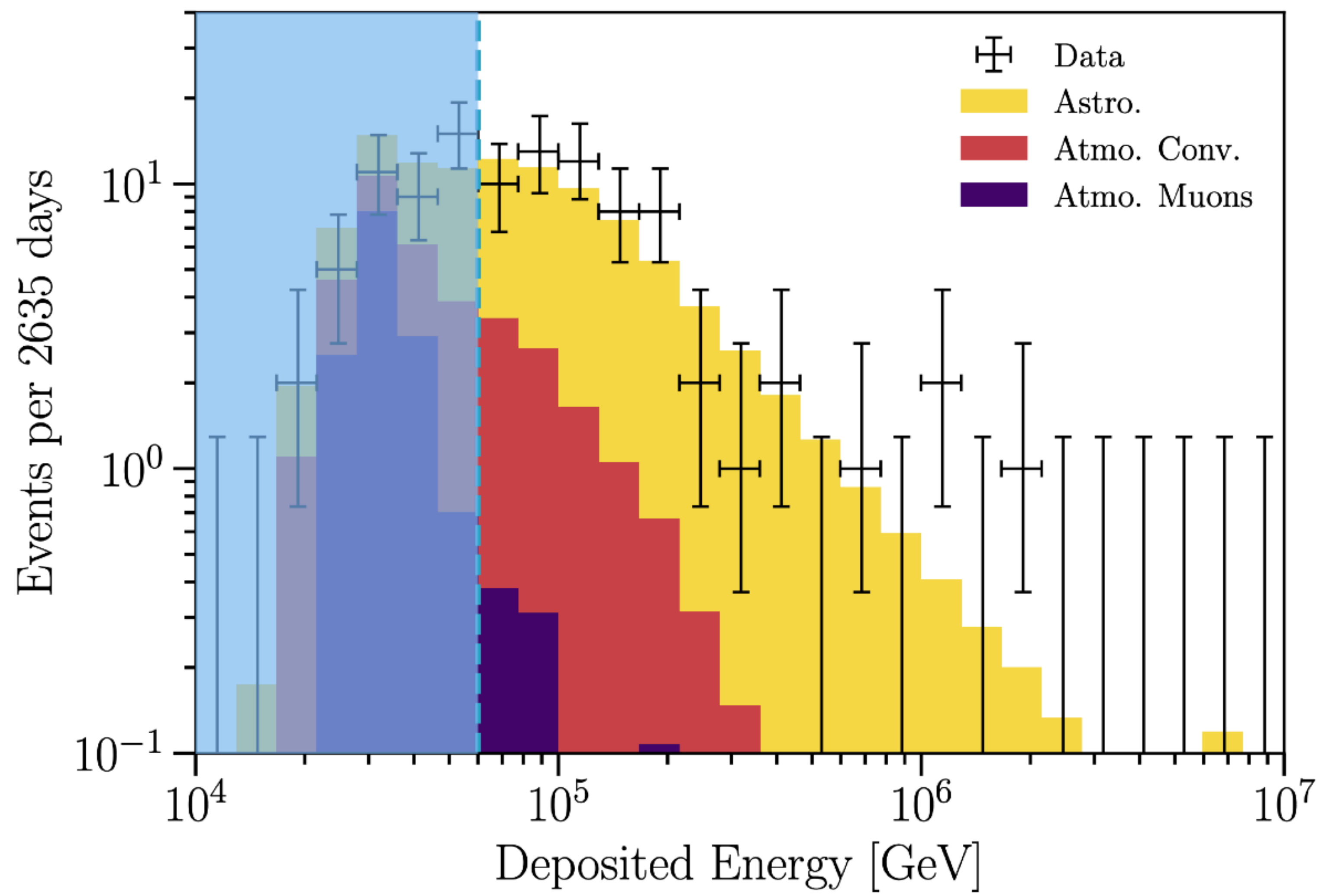
HESE-7.5 years angular distribution



Starting Events Energy Distribution And Inferred Spectrum

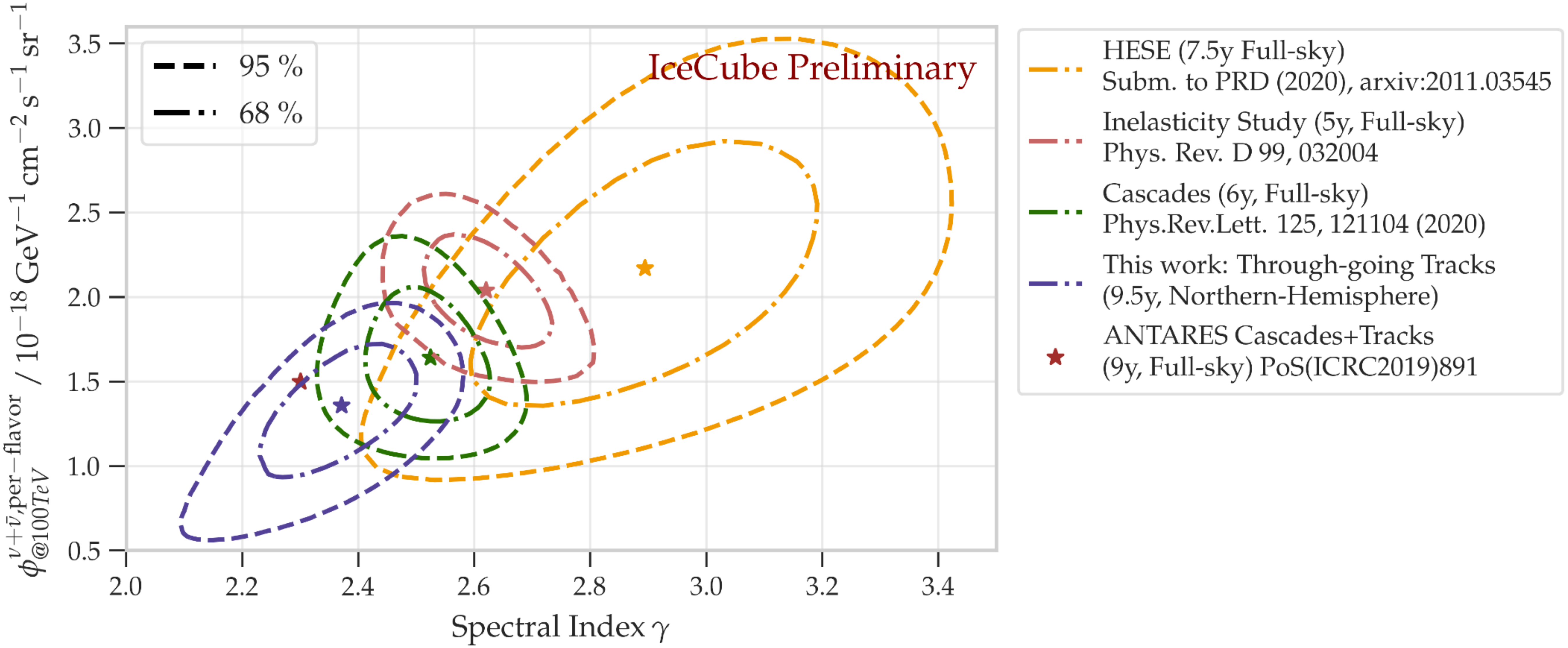
$$\gamma = 2.9 \pm 0.2$$





High-Energy Starting Events energy distribution is well described by a single power-law, but with a spectral index softer than the northern tracks!

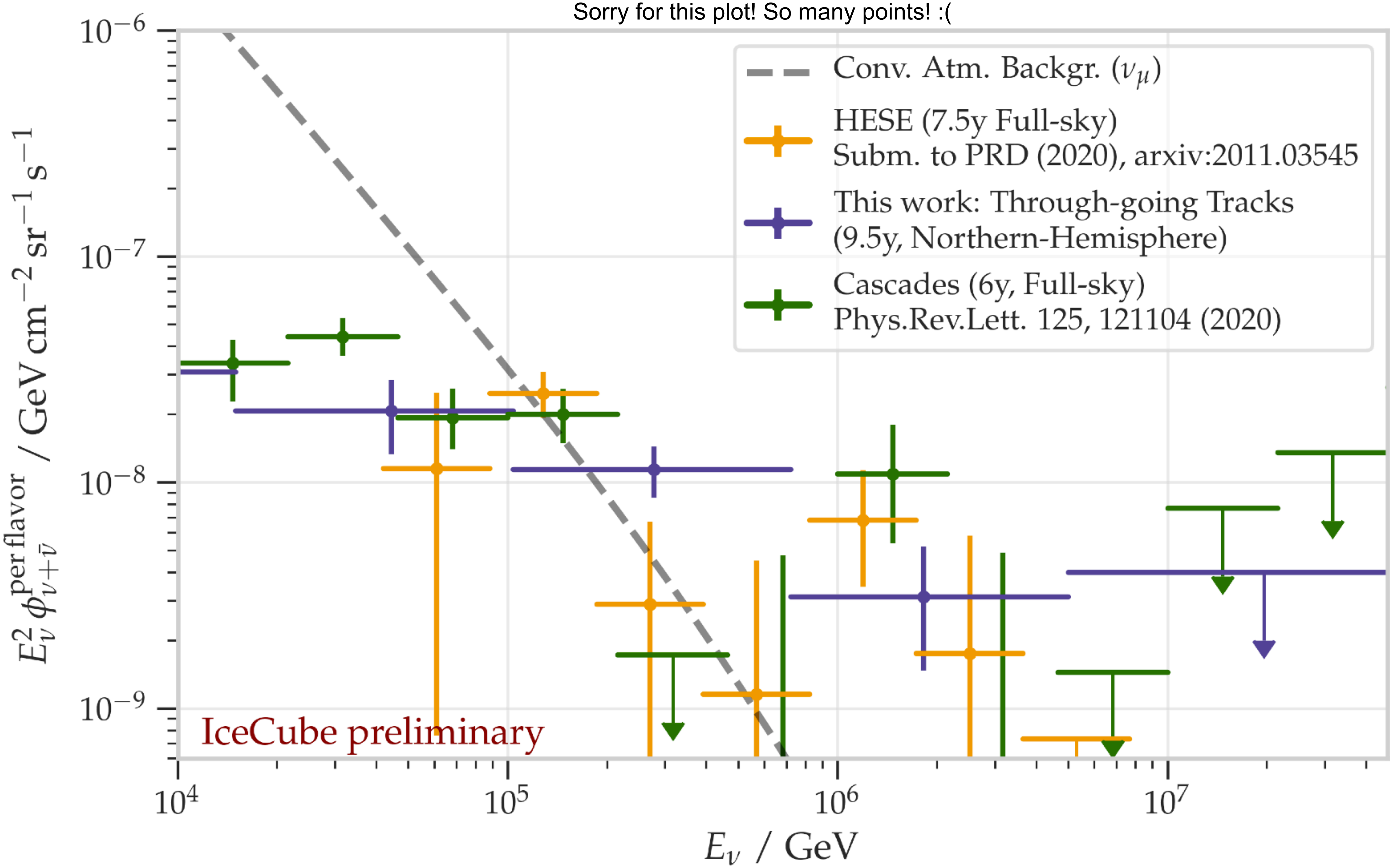
Comparison of different single power-law spectra



- ❖Shower power (hep-ph/0409046): Cascade-only event selections also produce very pure astrophysical neutrino samples!
- ❖Multiyear cascade analysis extends to TeV energies, yields a harder spectrum. Restricting this above 60 TeV, HESE spectrum is recovered.
- ❖First hints of a diffuse component in the ANTARES data!

Trying to go beyond a Power Law ...

Sorry for this plot! So many points! :(



❖Statistics is not high enough to infer a specific pattern.
❖Small hint of hardening below 60 TeV. LogParabola spectra?

Take away so far:

1. IceCube is sensitive to all neutrino flavors.

2. We have measured the diffuse astrophysical neutrino flux using track and cascade morphologies. We have done all-sky and northern-sky.

3. Small discrepancies between the spectra inferred from one analysis to another hints a more complex spectral dependence!

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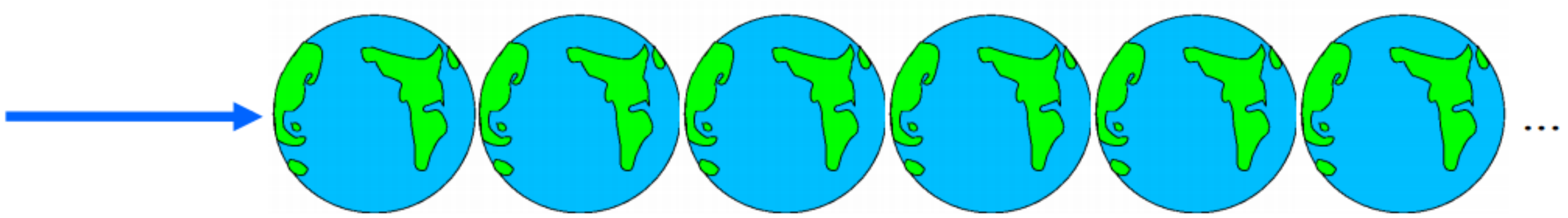
We are used to neutrinos just passing through

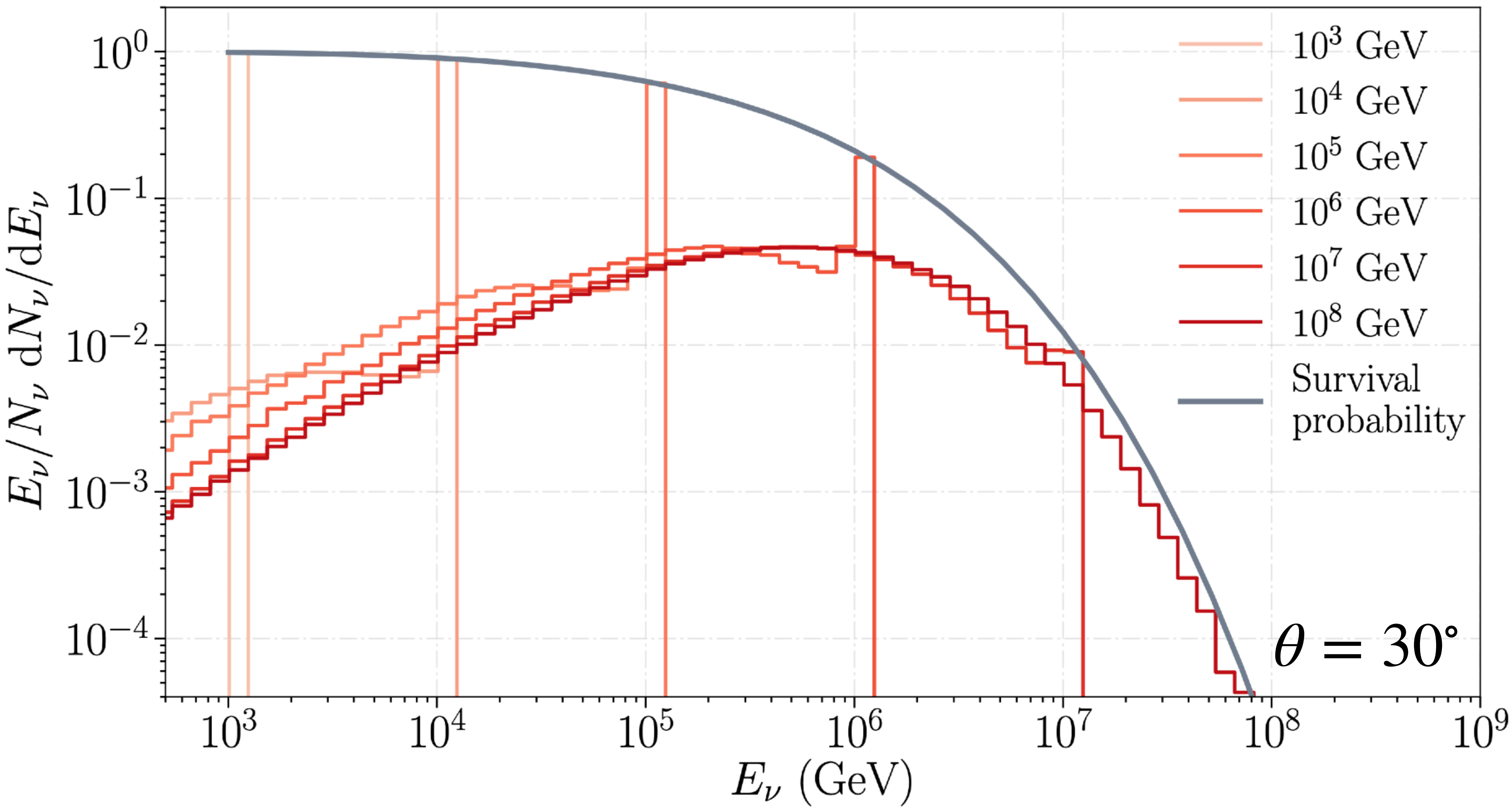
Solar neutrino cross section ~ 10^{-43} cm^2

Compare to pp fixed target ~ 10^{-24} cm^2



A neutrino has a good chance of travelling through 200 earths before interacting at all!

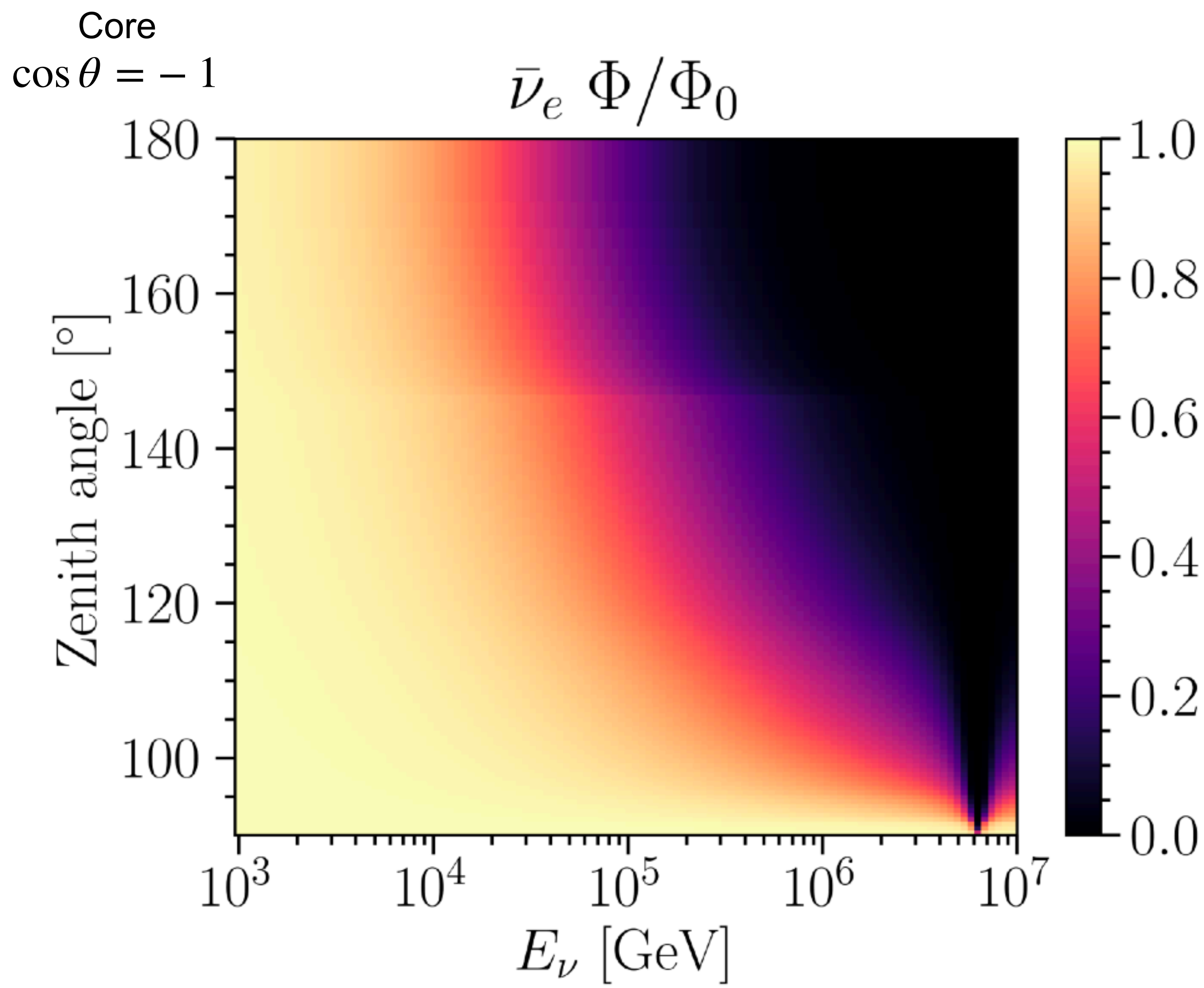
At High-Energies The Neutrino Interaction Length Becomes Smaller

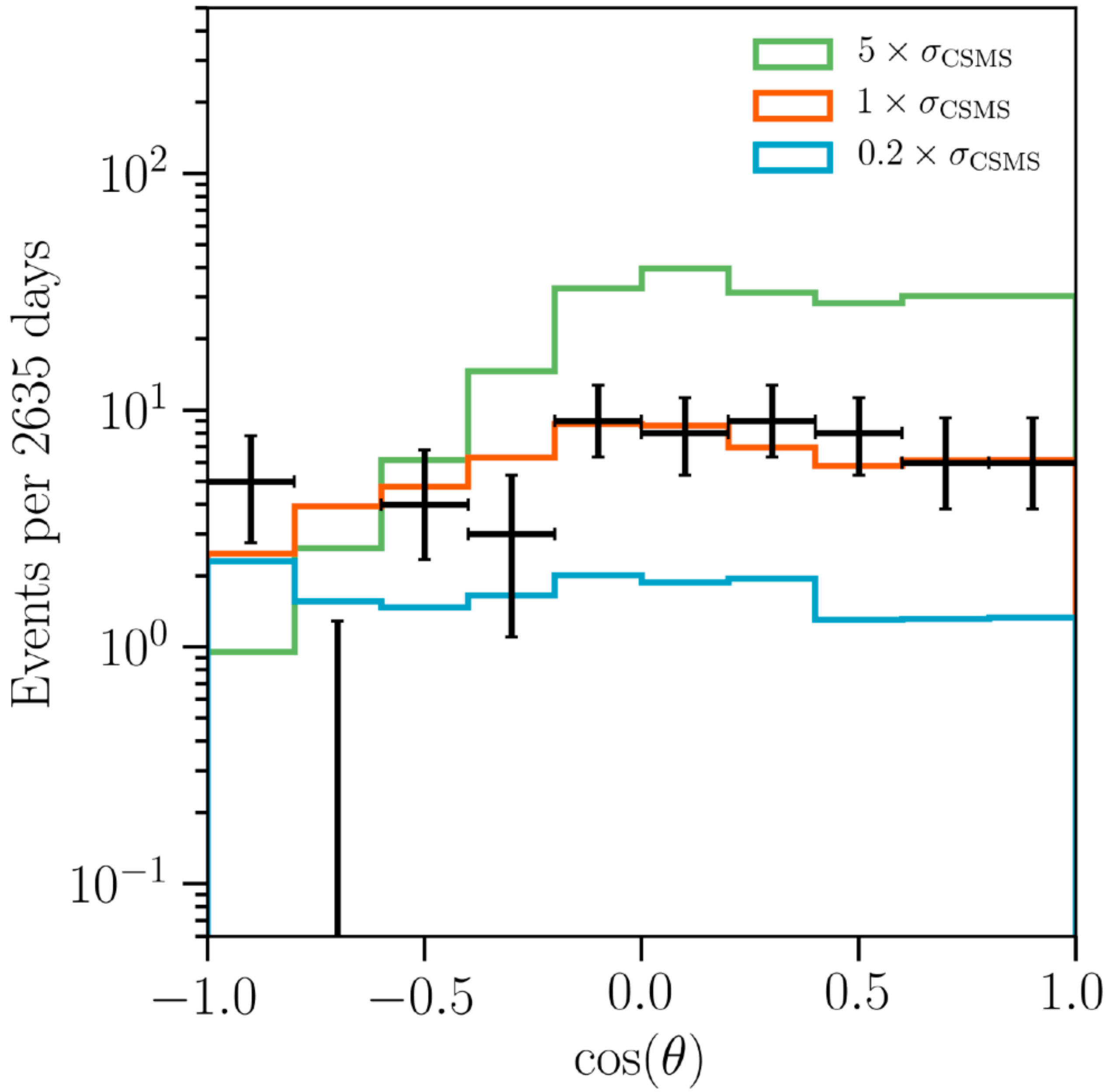


I. Safa et al. https://arxiv.org/pdf/1909.10487.pdf

We can use the Earth opacity to infer the neutrino cross section*

*or the Earth column density see Donini *et al Nature Physics* 15, 37-40 (2019)

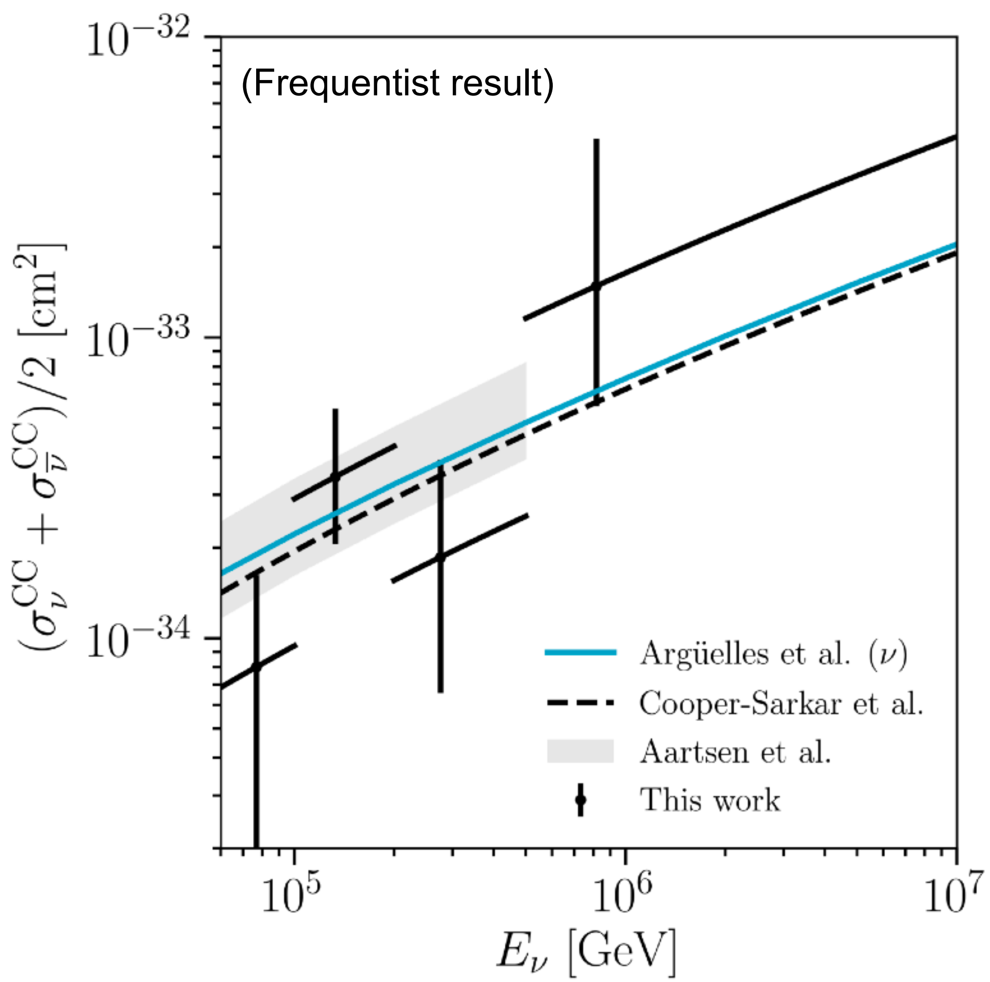


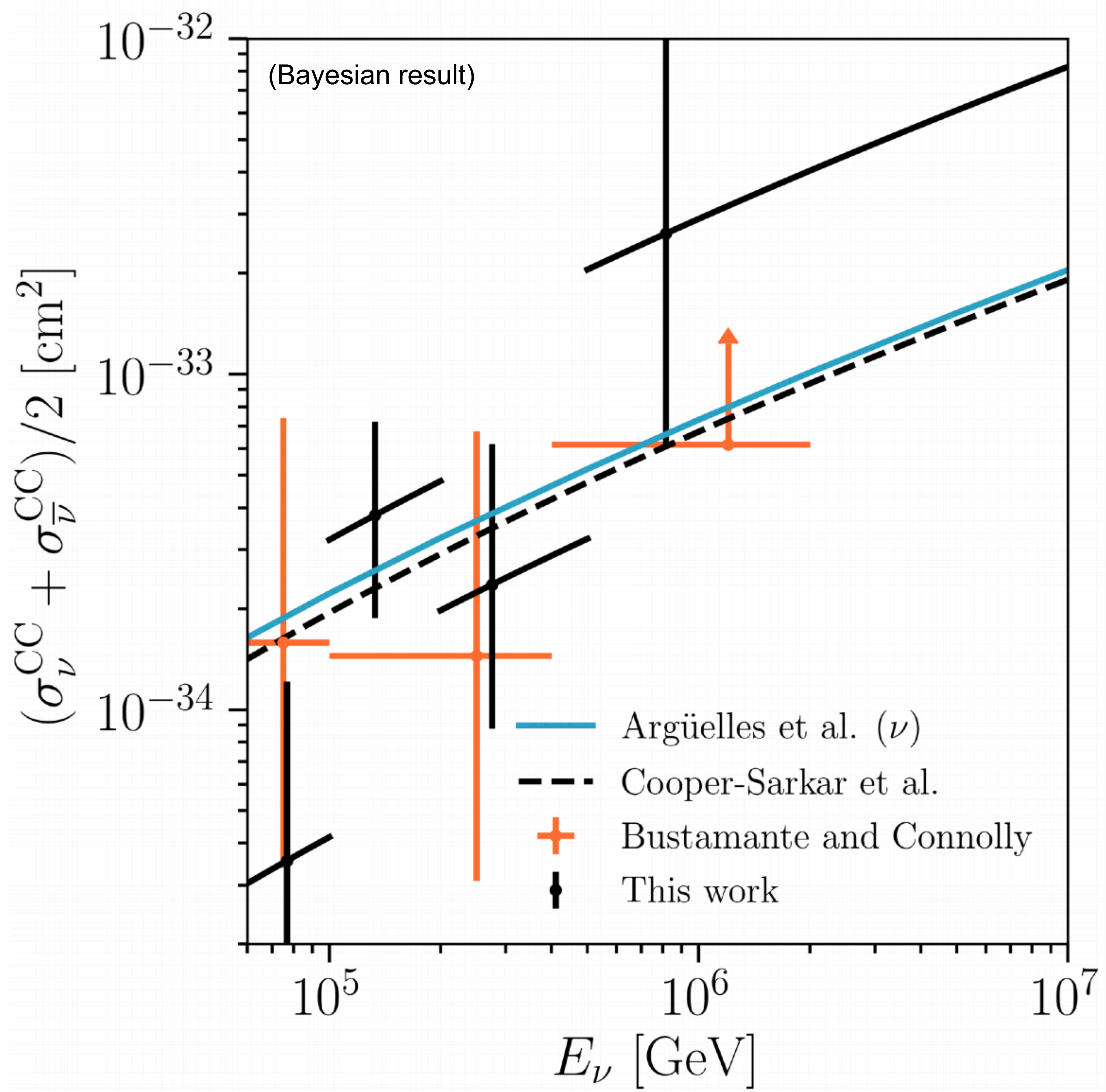


CSMS: is a NLO pQCD reference calculation of the neutrino-nucleon cross section, Cooper-Sarkar et al, JHEP 08 (2011) 042. See also A. Garcia et al JCAP 09 (2020) 025; CA, F. Halzen, L. Wille, M. Kroll, MH Reno, Phys. Rev. D92: 074040 (2015); A. Connolly *et al* Phys. Rev. D83: 113009,2011; R. Gandhi et al. Astropart. Phys. 5: 81-110 (1996).

Measurements of the Neutrino Cross Section With Starting Events

Parameter	Energy range	68.3% HPD	68.3% CI
x_0	60 TeV to 100 TeV	$0.21^{+0.52}_{-0.21}$	$0.48^{+0.49}_{-0.37}$
x_1	100 TeV to 200 TeV	$1.65^{+1.49}_{-0.84}$	$1.50^{+1.03}_{-0.60}$
x_2	200 TeV to 500 TeV	$0.68^{+1.11}_{-0.43}$	$0.54^{+0.60}_{-0.35}$
x_3	500 TeV to 10 PeV	$4.31^{+13.26}_{-3.32}$	$2.44^{+5.10}_{-1.47}$





Bustamante & Connolly: PRL 122, 041101 (2019)
Argüelles: Phys. Rev. D92: 074040 (2015)
Cooper-Sarkar: JHEP 08 (2011) 042

Take Away on Cross Section Measurements

1. All-flavor measurements of the neutrino interaction cross section at 10TeV to PeV energies are compatible with SM predictions.

2. IceCube brings unique capabilities to study neutrino interactions! (Also “weight” the Earth)

3. Future radio detectors can also explore high-energy neutrino interactions. Will the SM trend hold?

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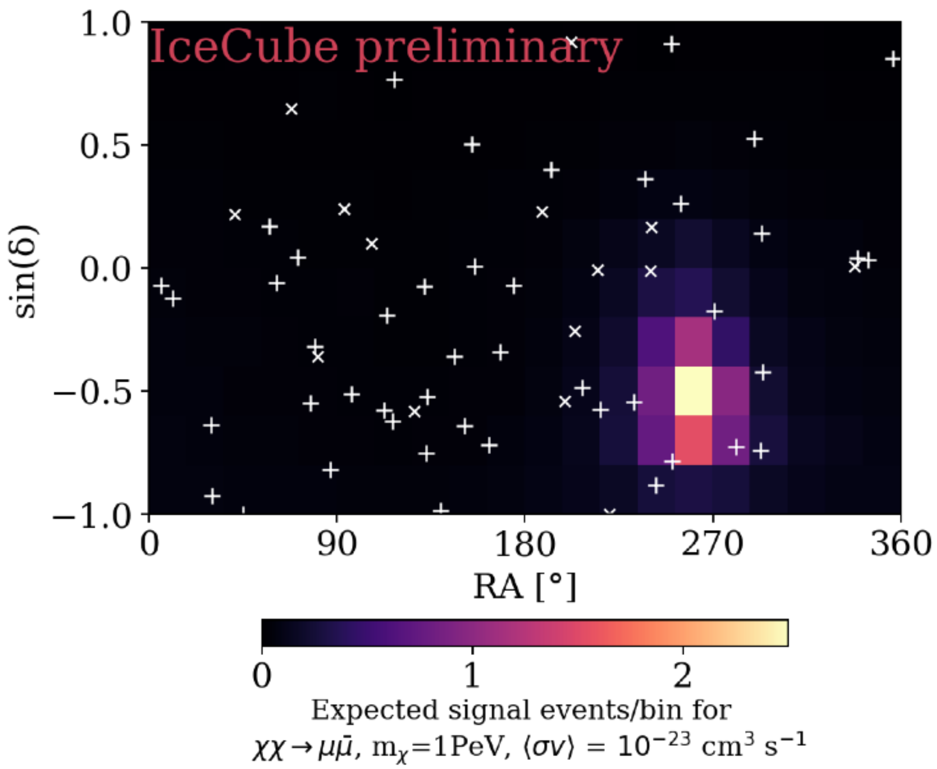
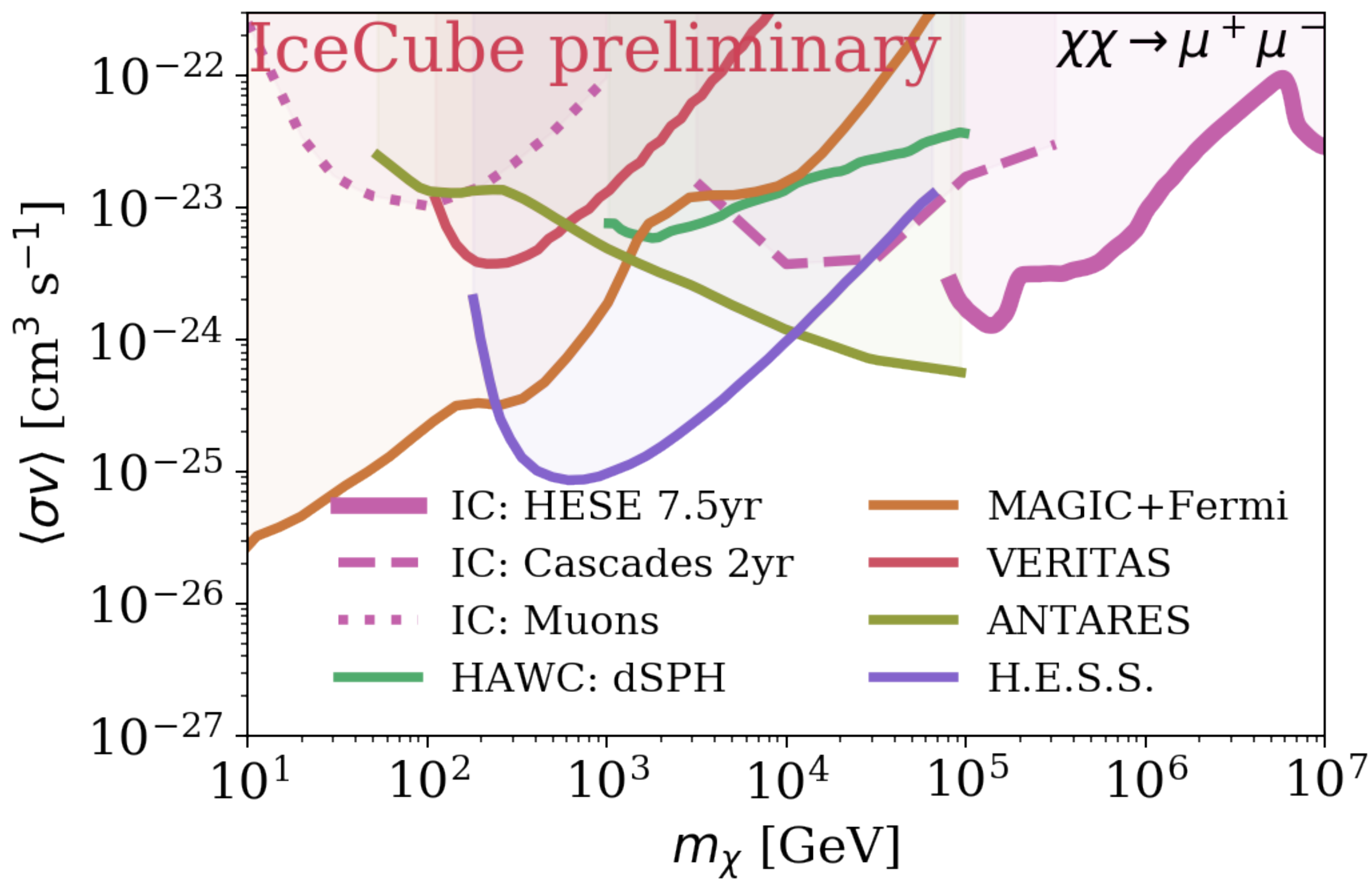
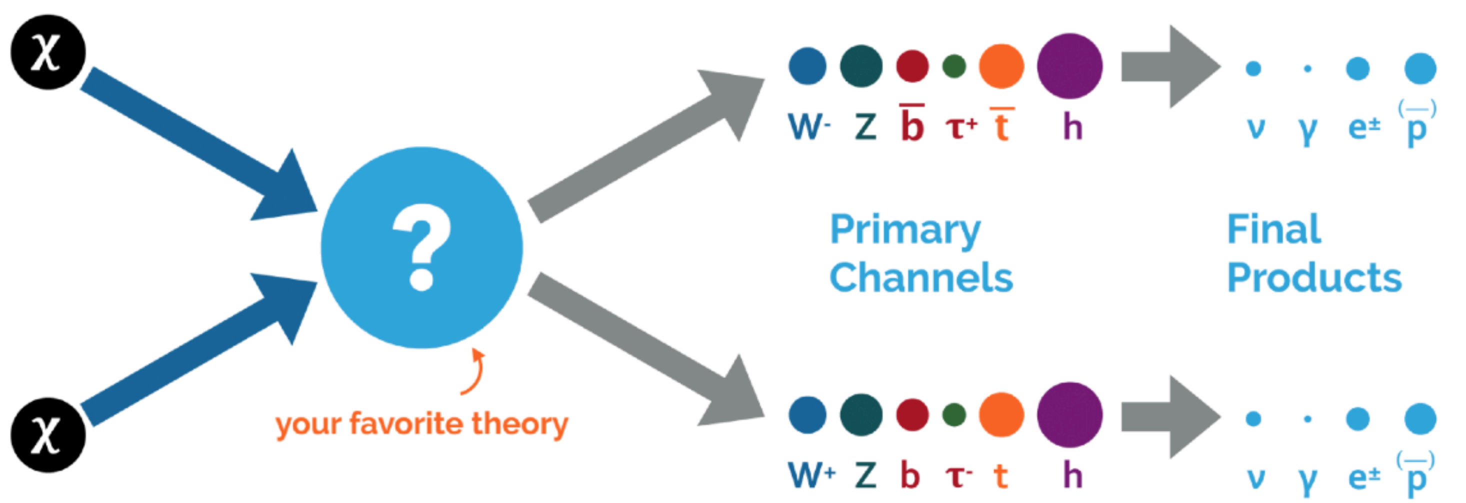
   -Lorentz Violation Effects on Flavor
6. The future

Dark matter annihilation



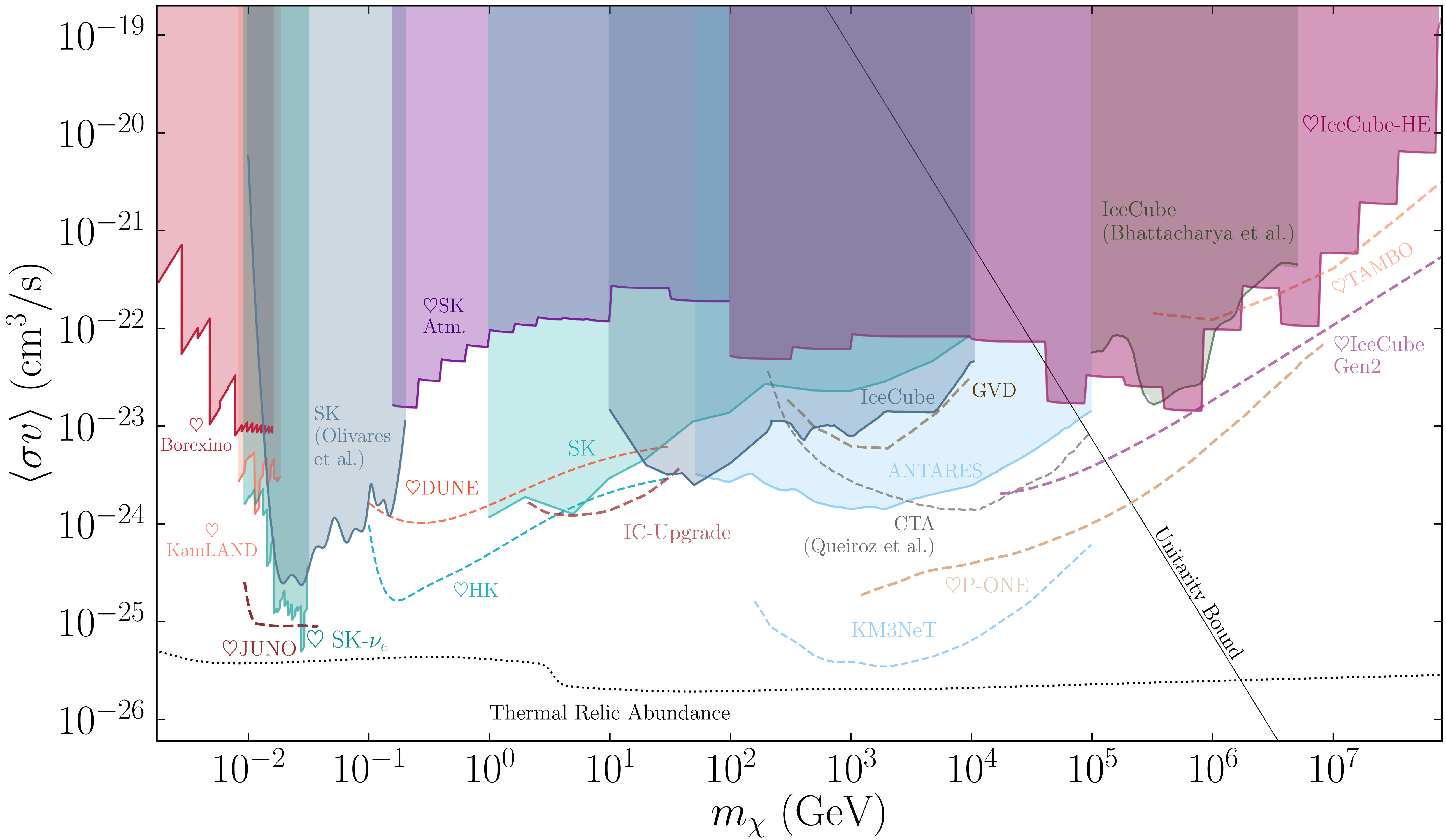




CA, H. Dujmovic arXiv 1907.11193.

See also Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

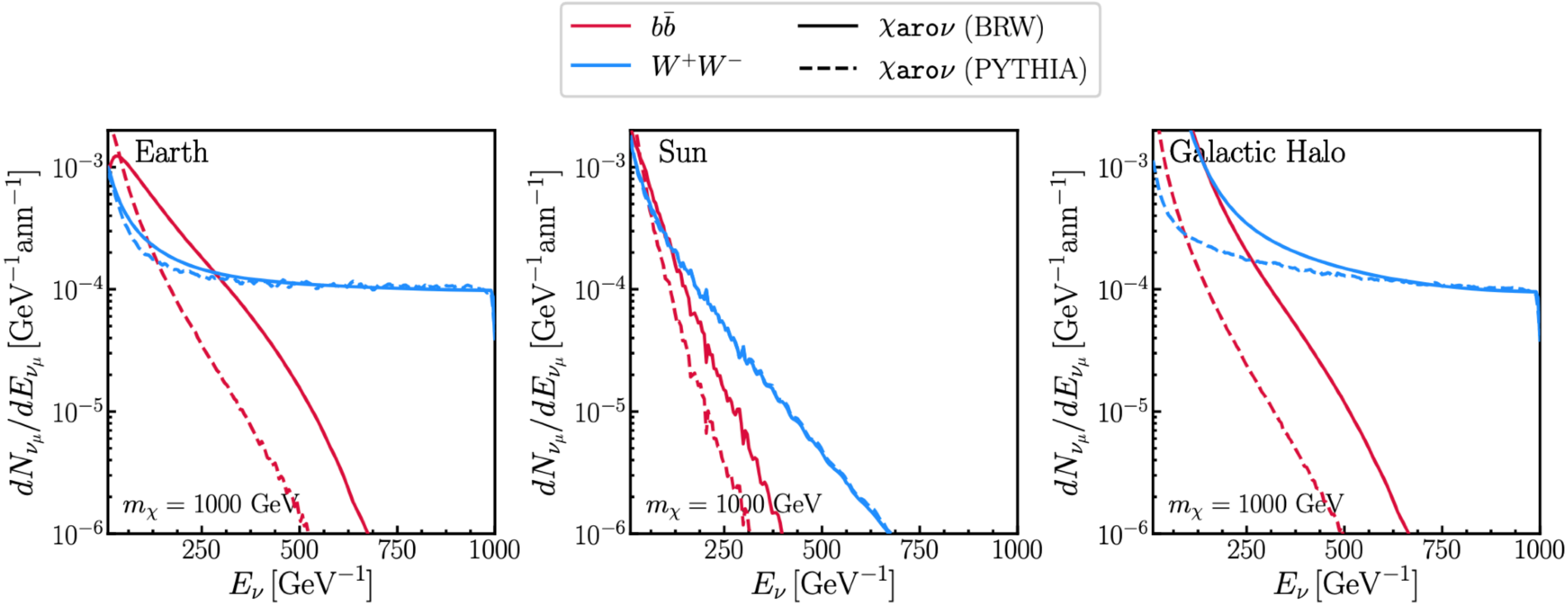
And many more measurements ...



CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent (arXiv:1912.09486);
See also Beacom et al. PRL 99: 231301, 2007.

For good results, we need good predictions!

https://github.com/IceCube/charon

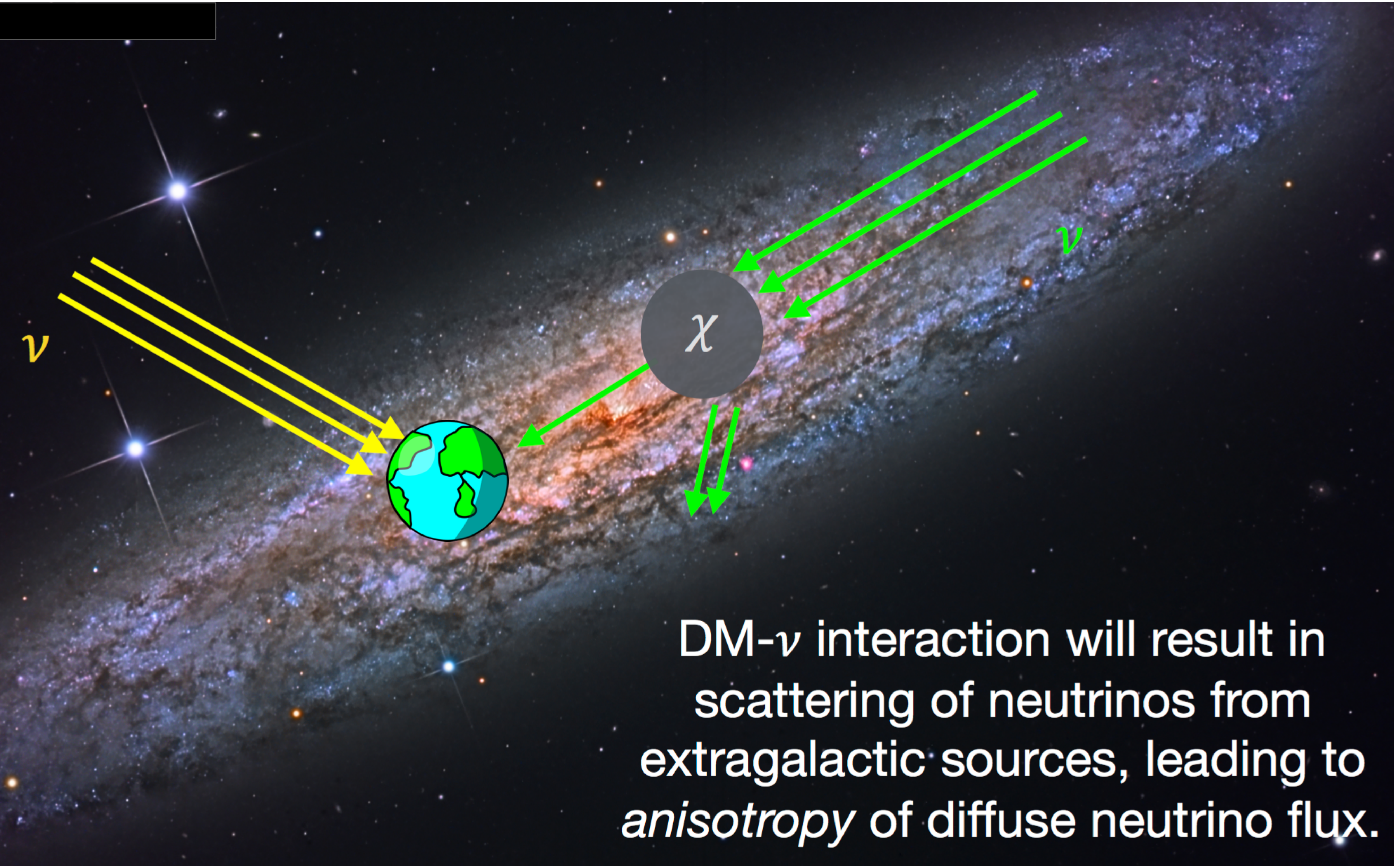


IceCube results with updated calculations to appear soon!

Q. Liu & J. Lazar *et al* 2007.15010

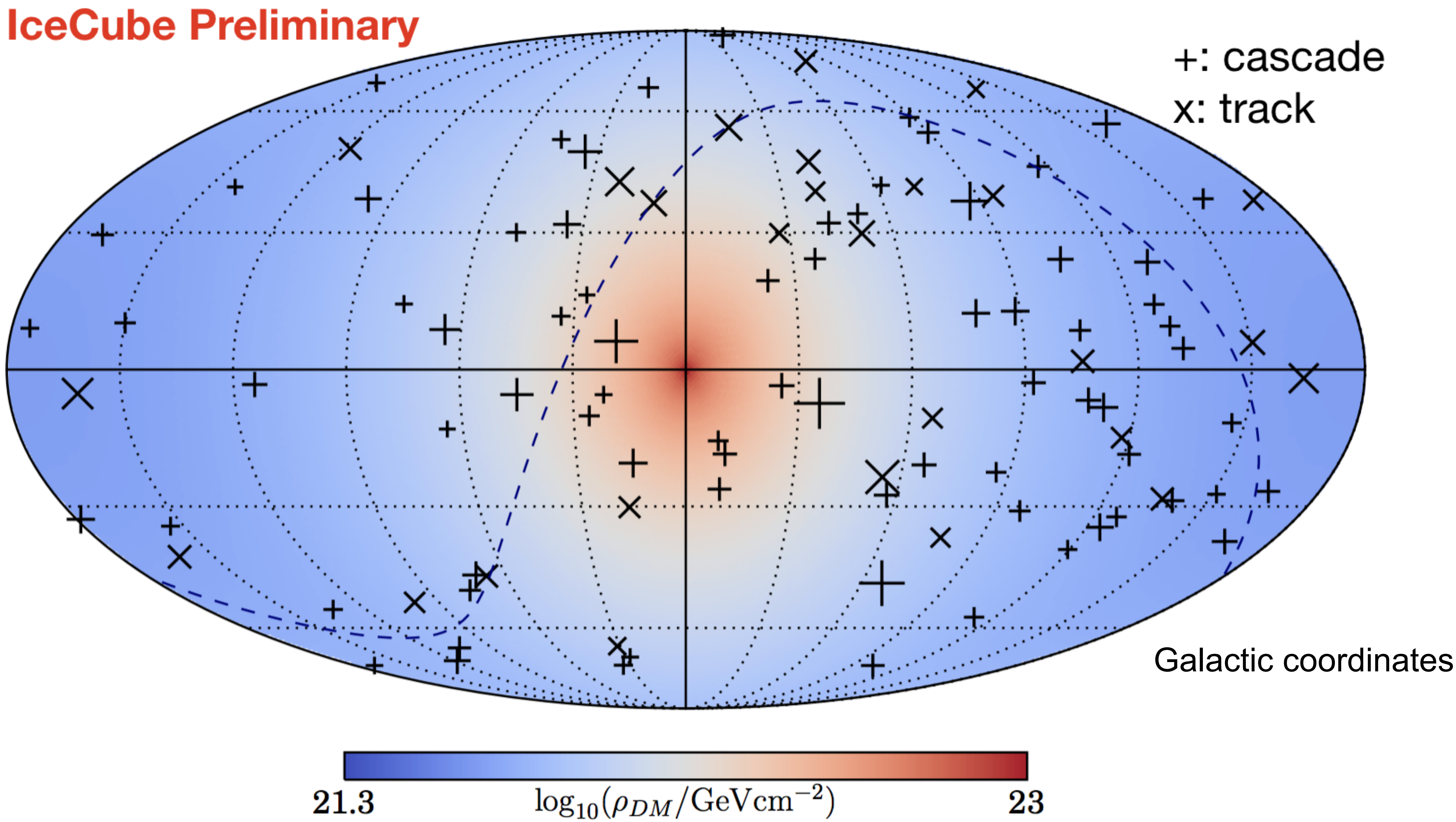
Bauer, Rodd & Webber *et al* 2007.15001

Dark matter neutrino incoherent **scattering**



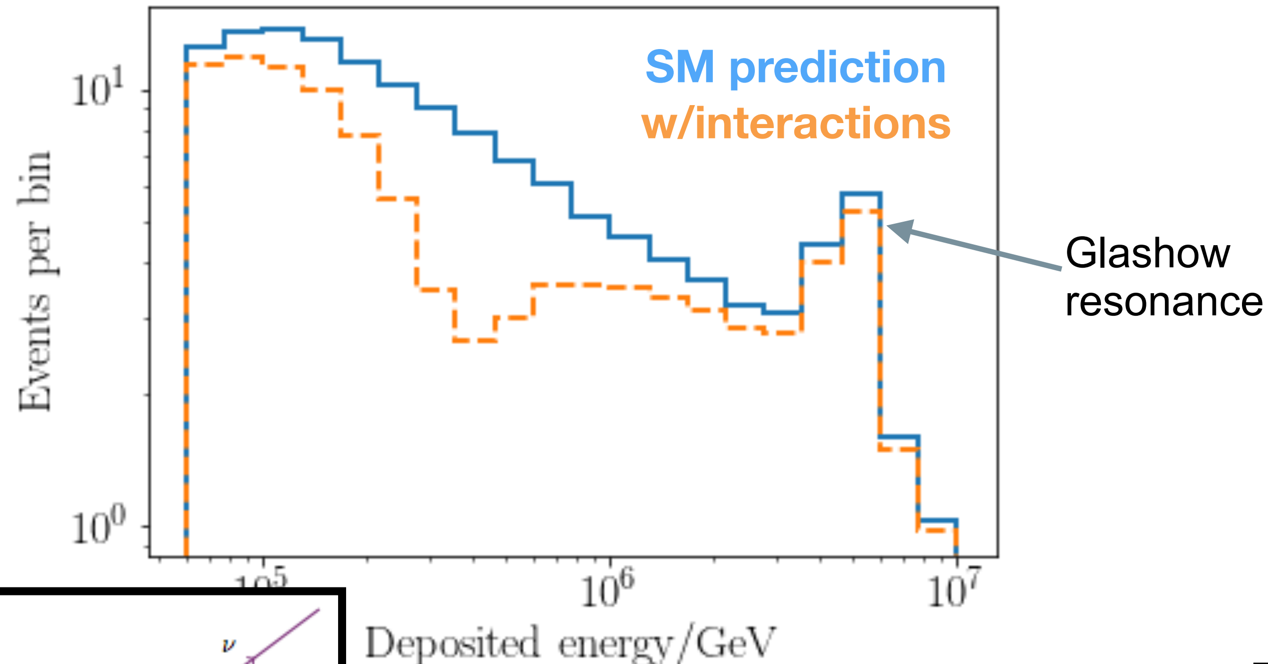
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

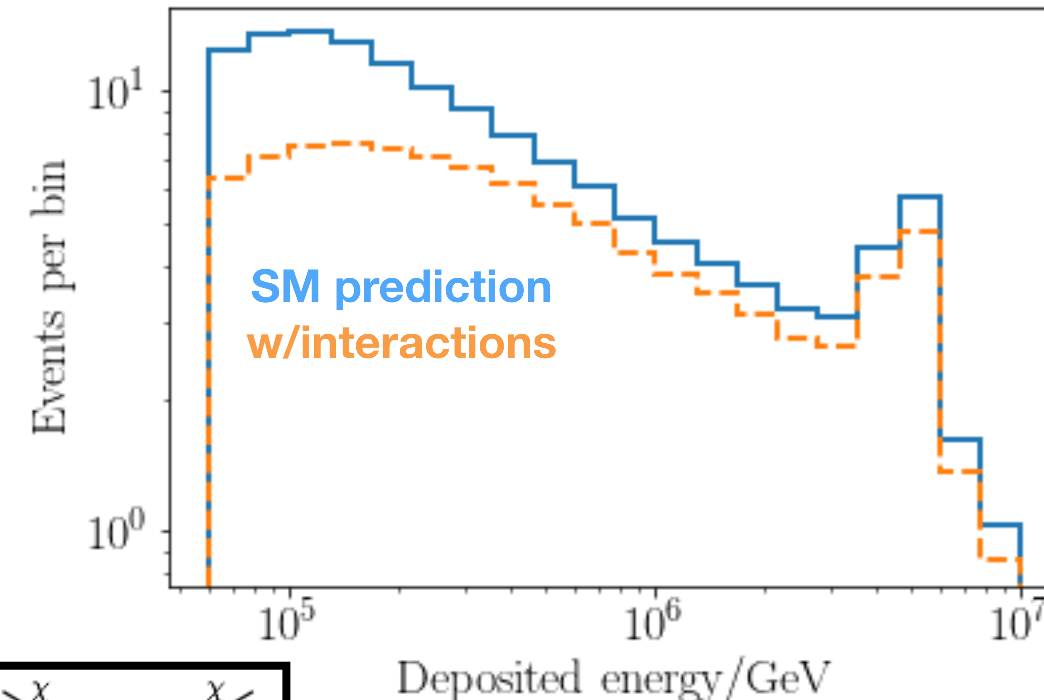
Neutrino skymap

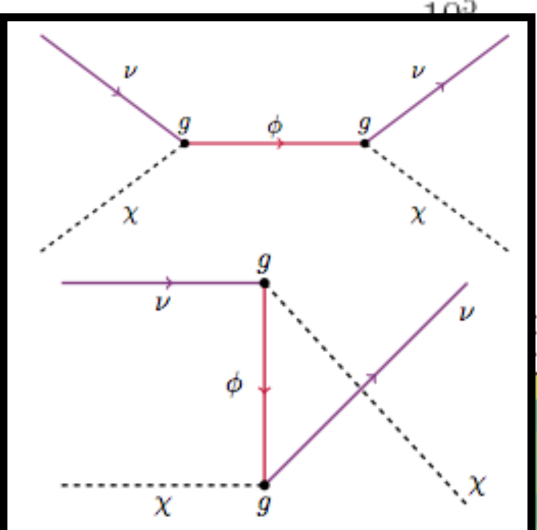


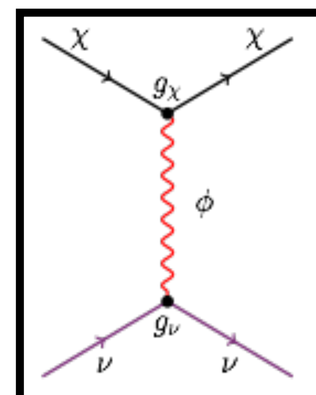
Events are compatible with an isotropic distribution: found no signal!

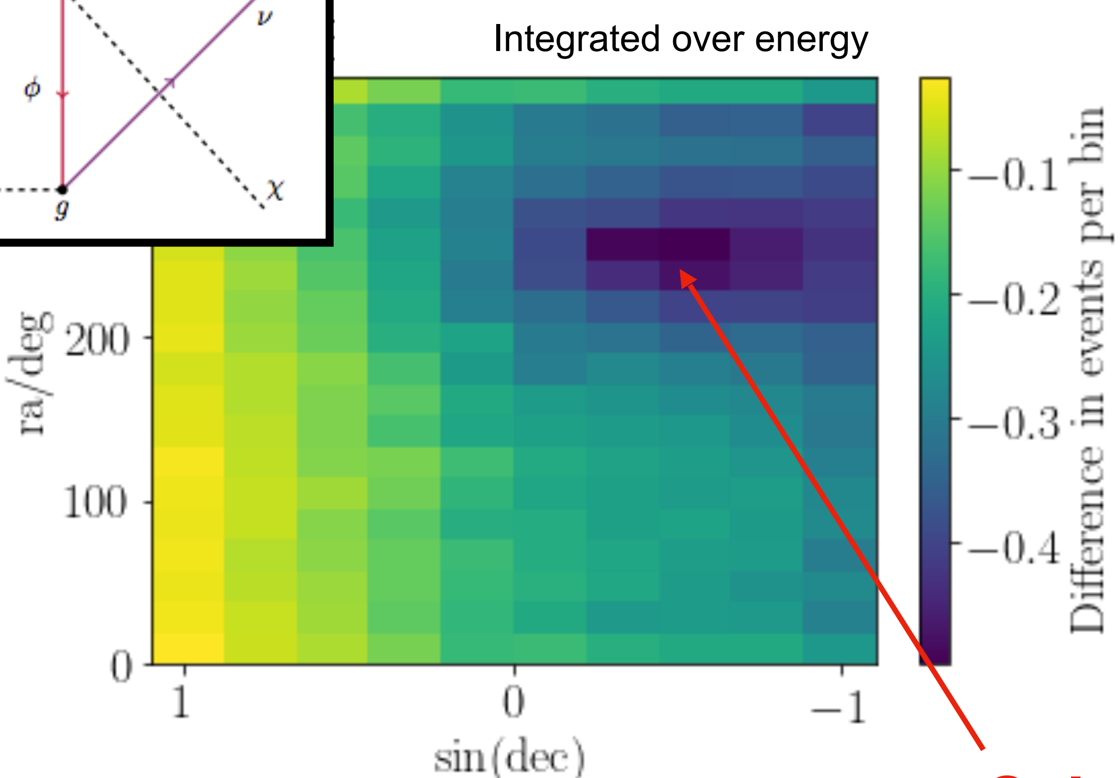
Also include effects in energy and direction

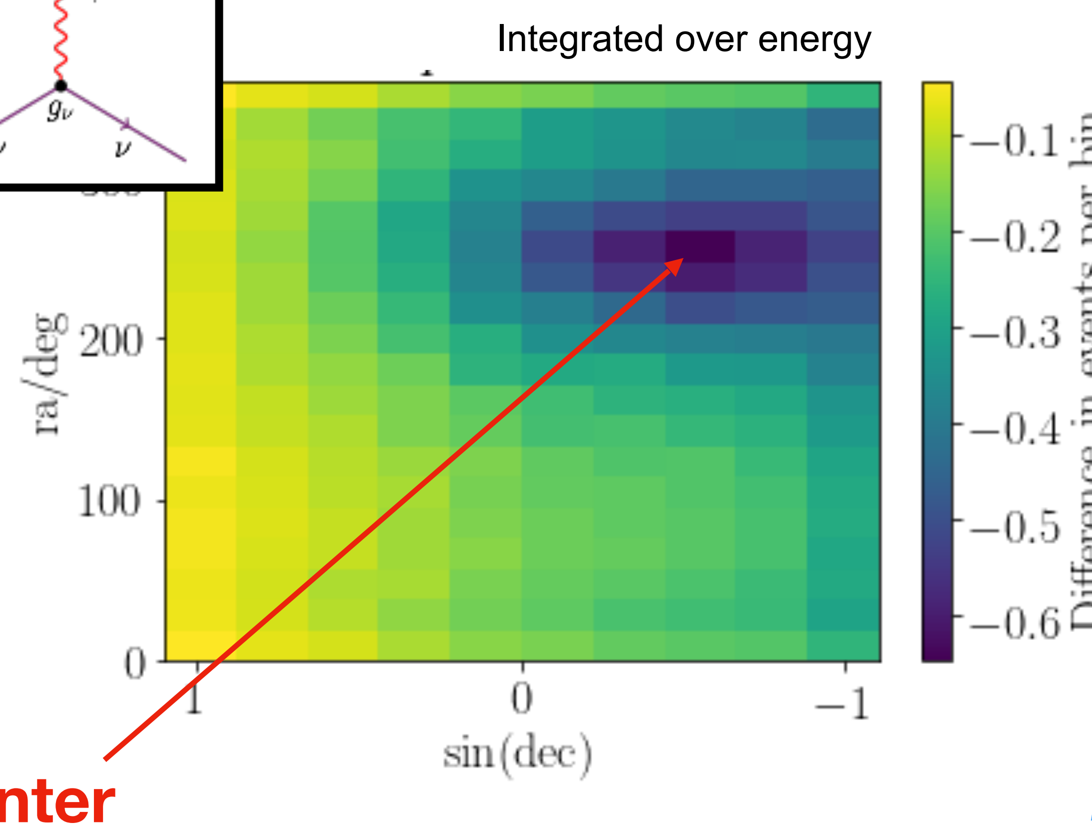




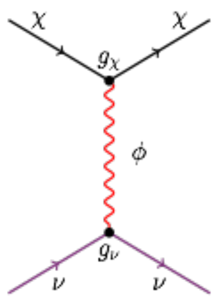




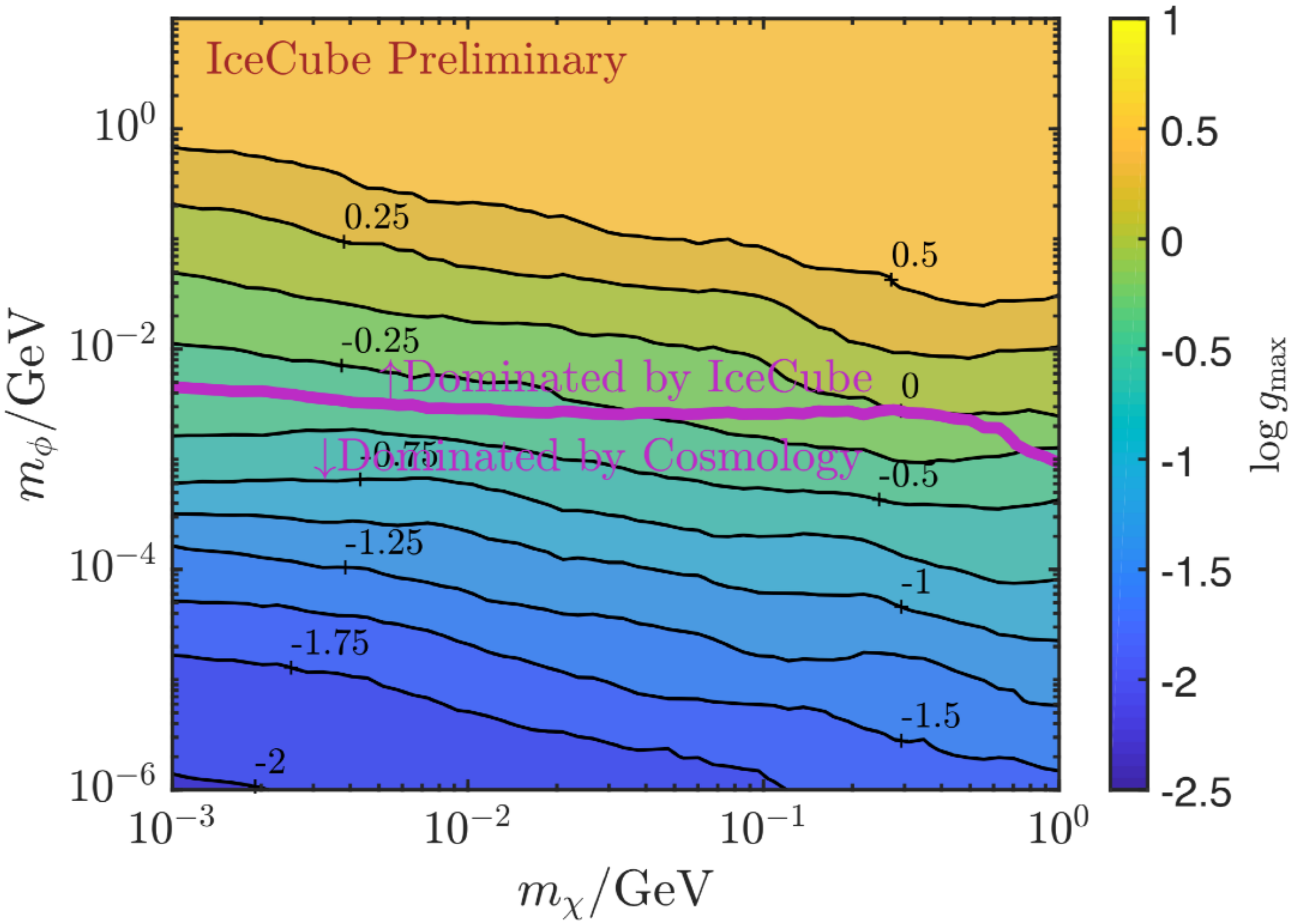


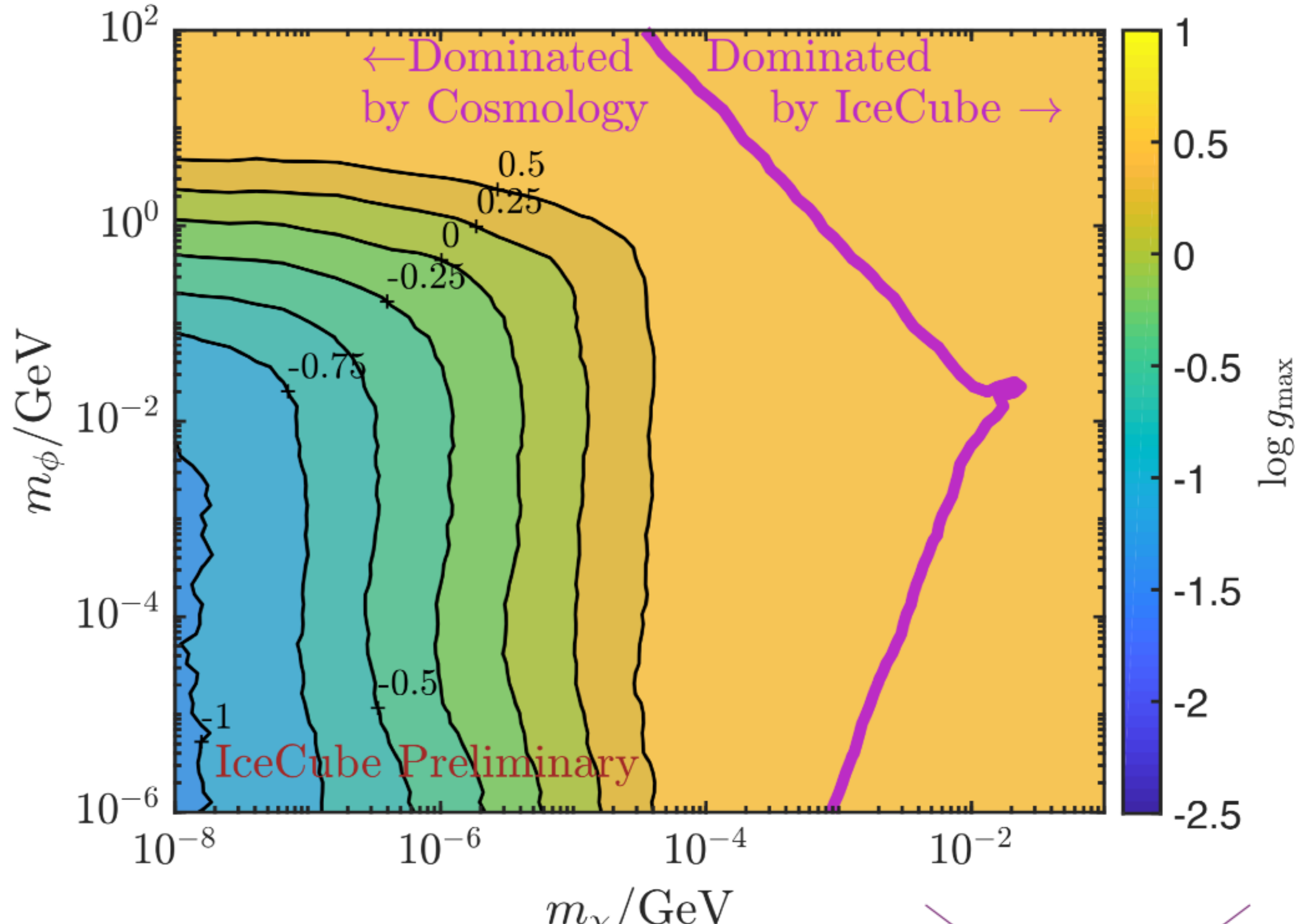


New constraints on neutrino-dark matter interactions



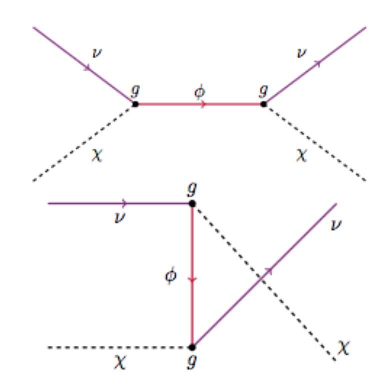
IceCube Work In Progress





Color scale is the maximum allowed coupling.

Cosmological bounds using Large Scale Structure from Escudero et al 2016



Take aways on
Neutrino-dark matter interactions

1. IceCube brings unique capabilities to understanding dark matter.

2. We are now competitive with cosmology, and getting better with improved analyses

   and more data to come!

Outline of the rest of this talk:

1. Neutrinos in IceCube
2. Measuring High-Energy Astrophysical Neutrinos
3. Searching for new forces:
    -Measuring the Neutrino-Nucleon cross section
4. Searching for dark matter:
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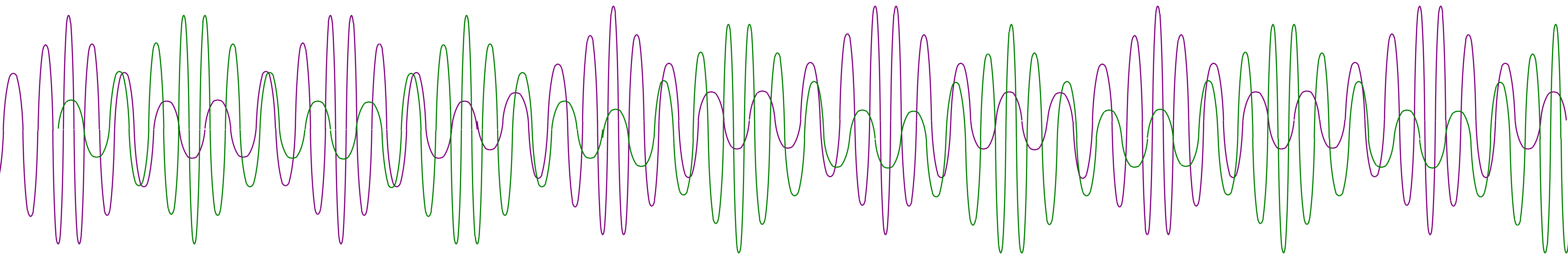
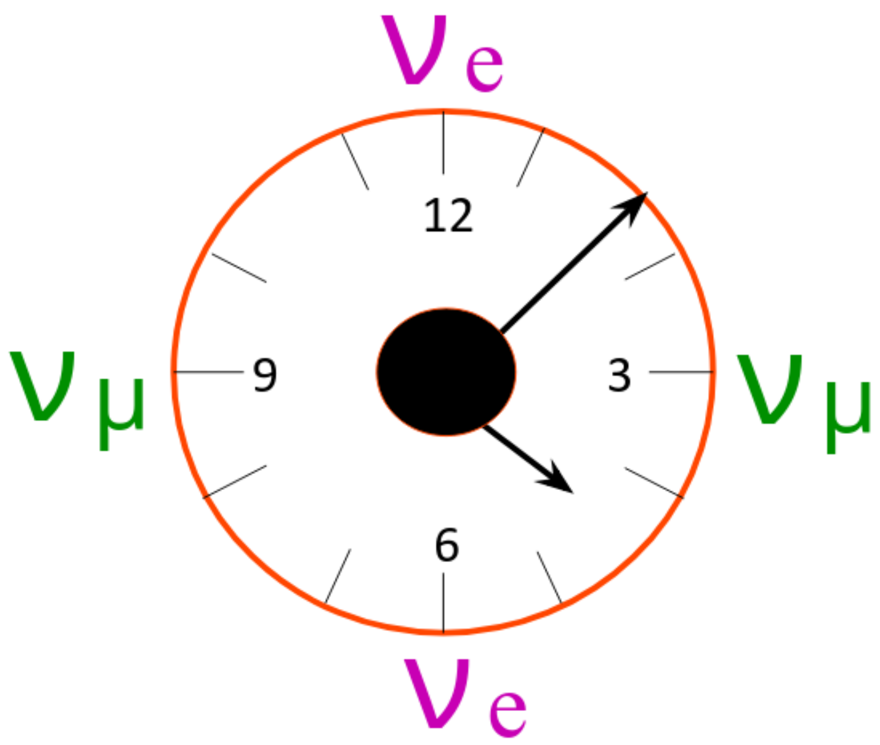


Because of oscillations, neutrinos are natural clocks.
As time passes, they change from one flavor to the other, and back.

$$|\nu(t)\rangle = e^{-iHt/\hbar}\,|\nu_\alpha\rangle$$



Lorentz violation will change the neutrino oscillation frequency producing **new flavor conversion**

Flavor composition @ source

(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

(1:2:0)

Muon-damped

$$\pi^+ \to \cancel{\mu^+} + \nu_\mu$$

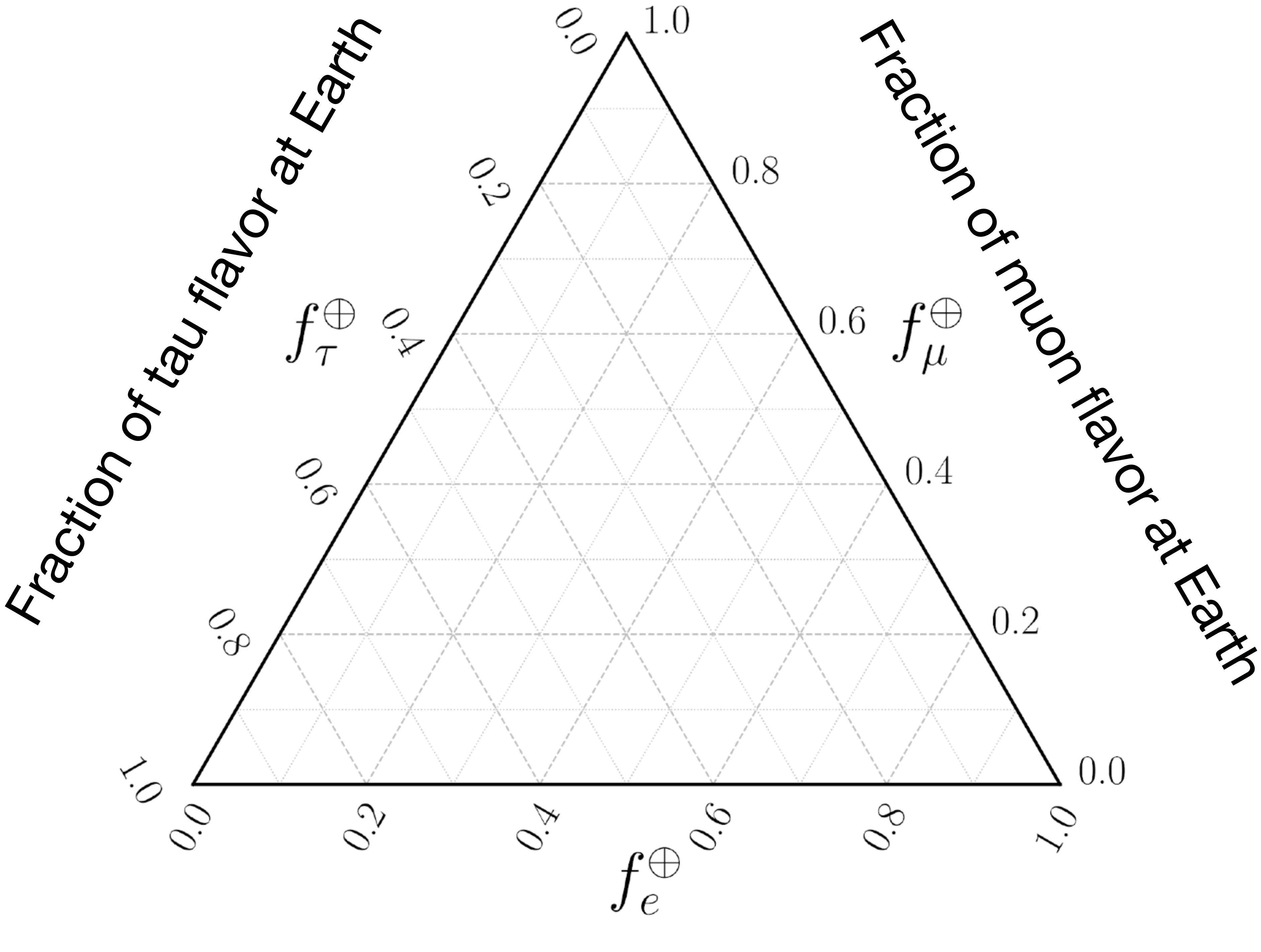
(0:1:0)

Neutron

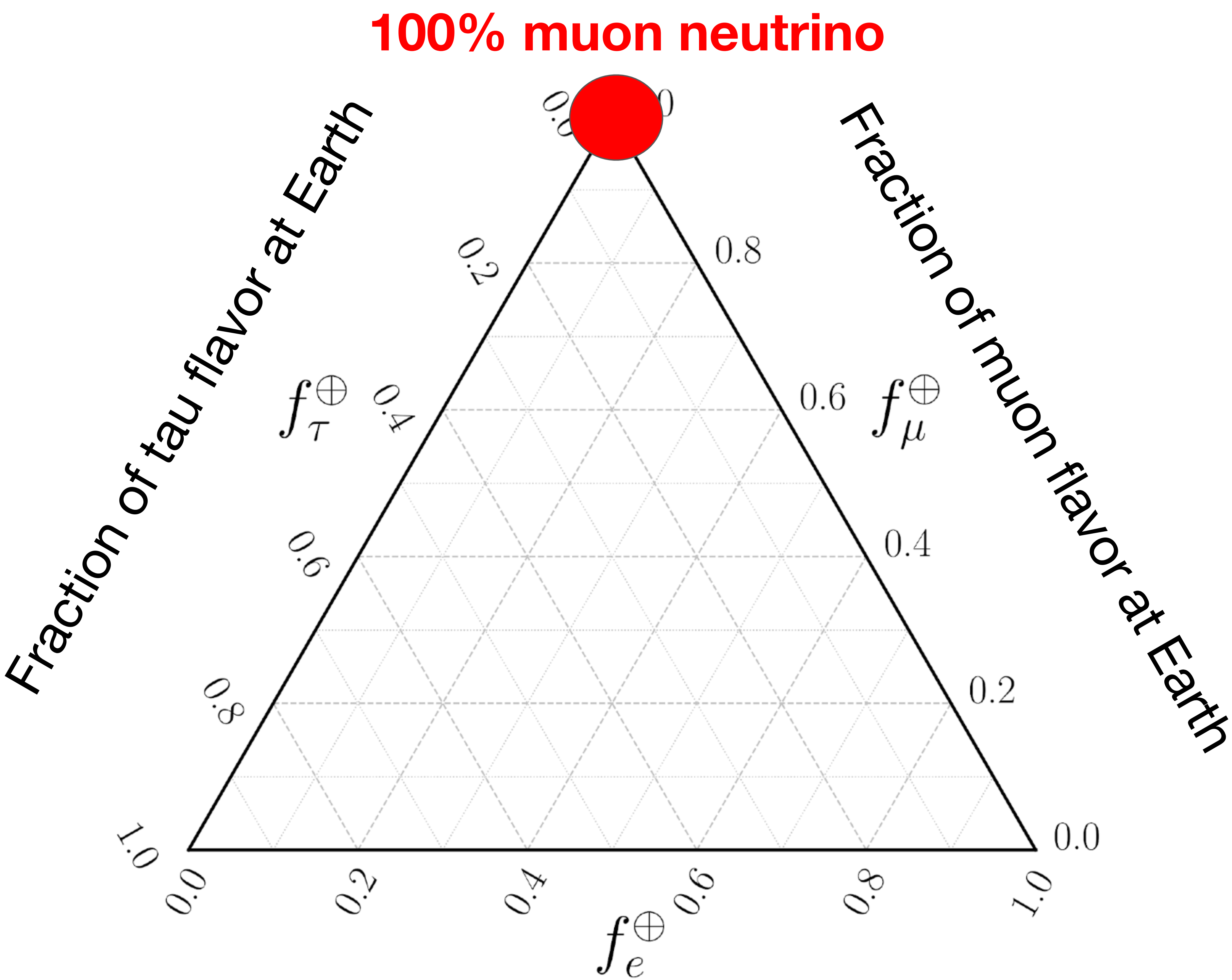
$$n \to p + e^- + \bar{\nu}_e$$

(1:0:0)

The flavor triangle

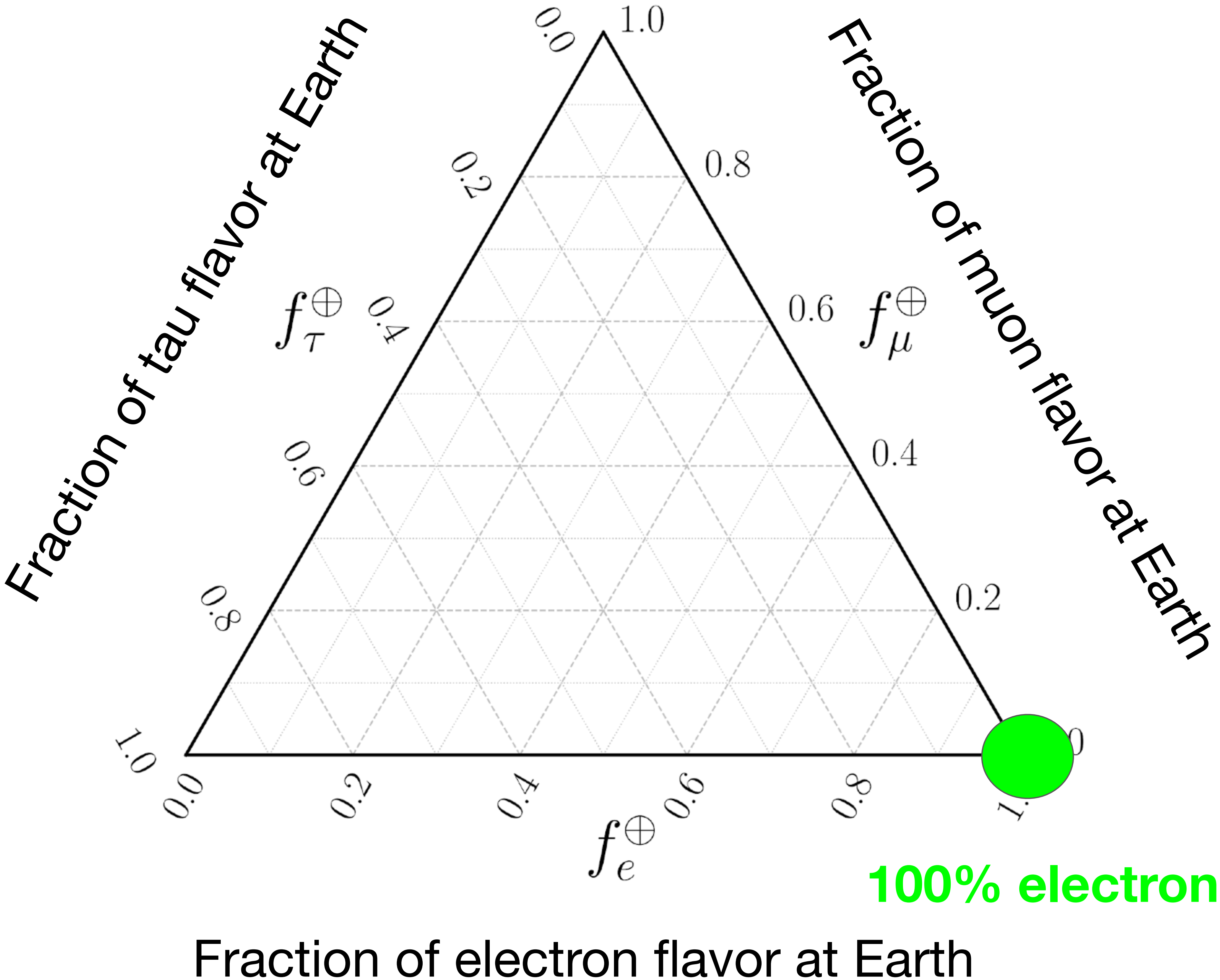


The flavor triangle

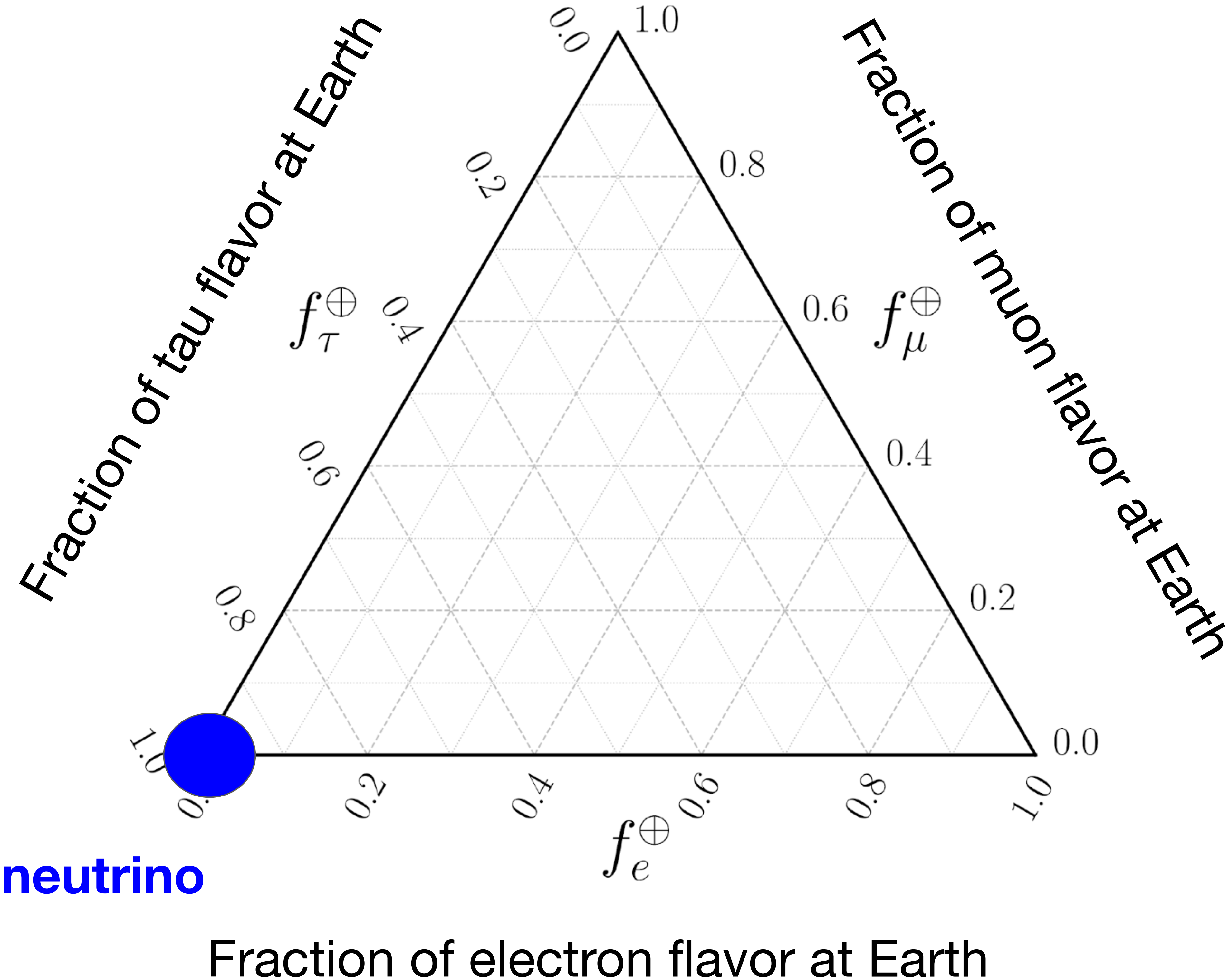


Fraction of electron flavor at Earth

The flavor triangle

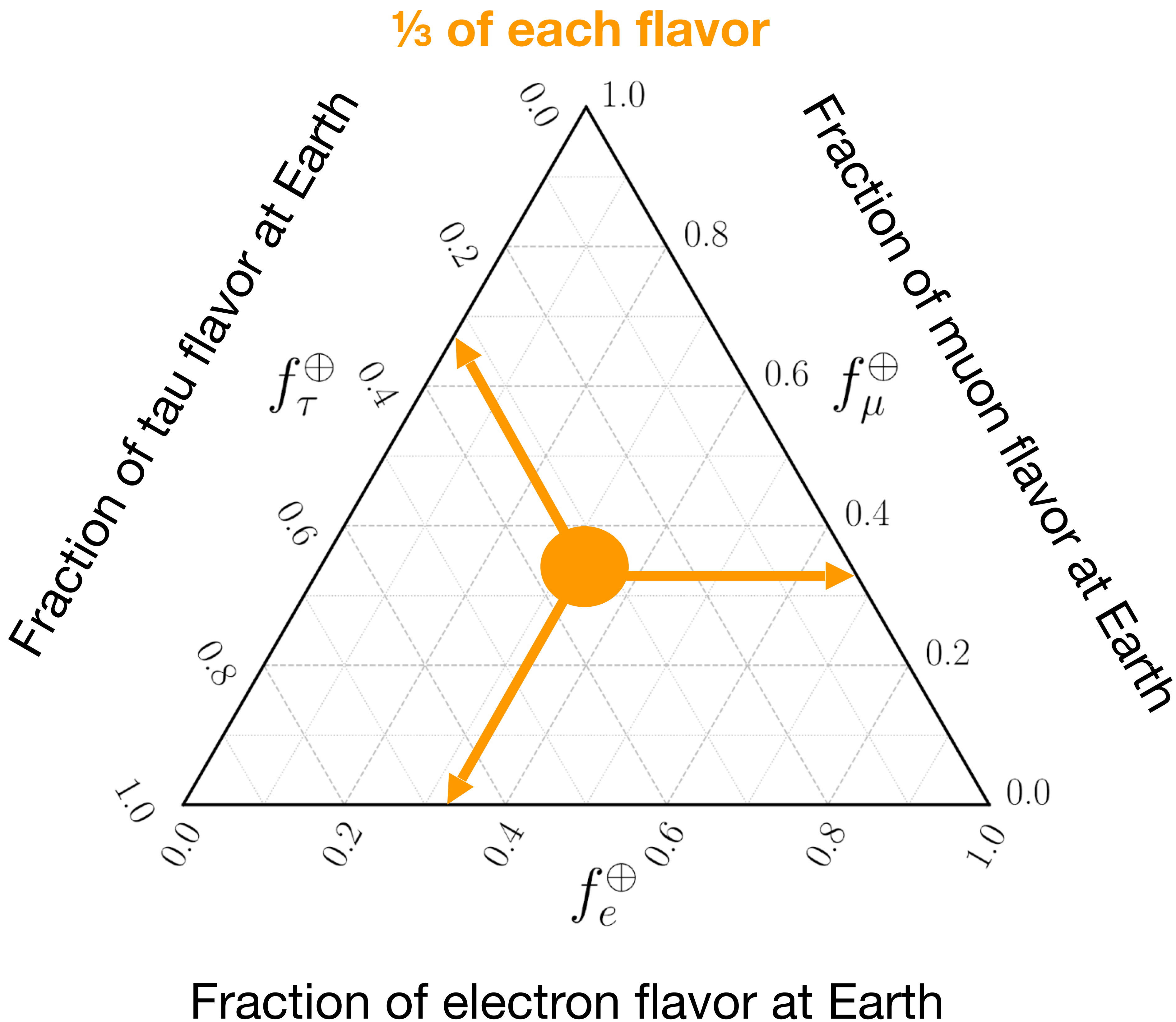


The flavor triangle



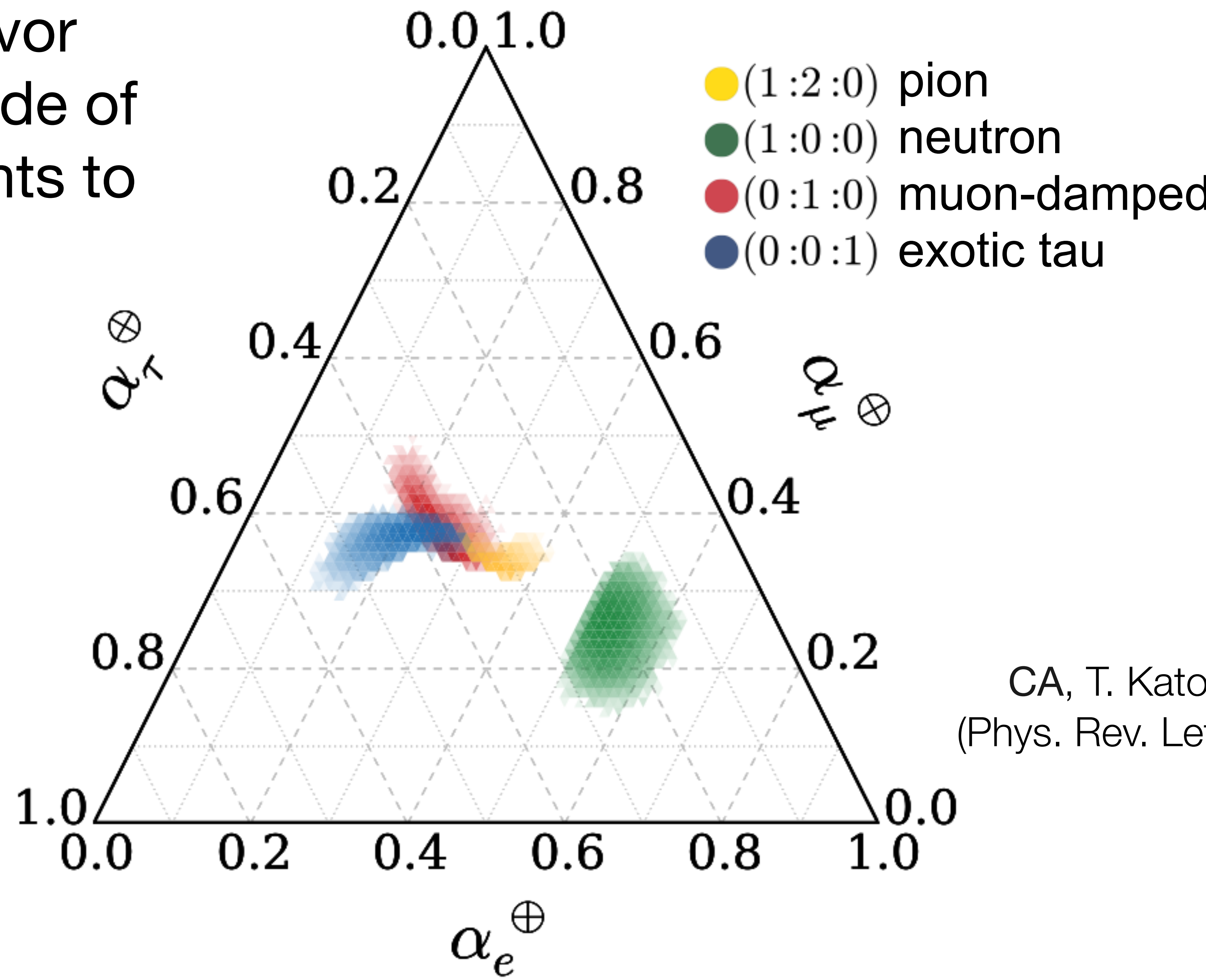
100% tau neutrino

The flavor triangle



After oscillations where will the different sources end up?

Measuring a flavor composition outside of these regions points to new physics!



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

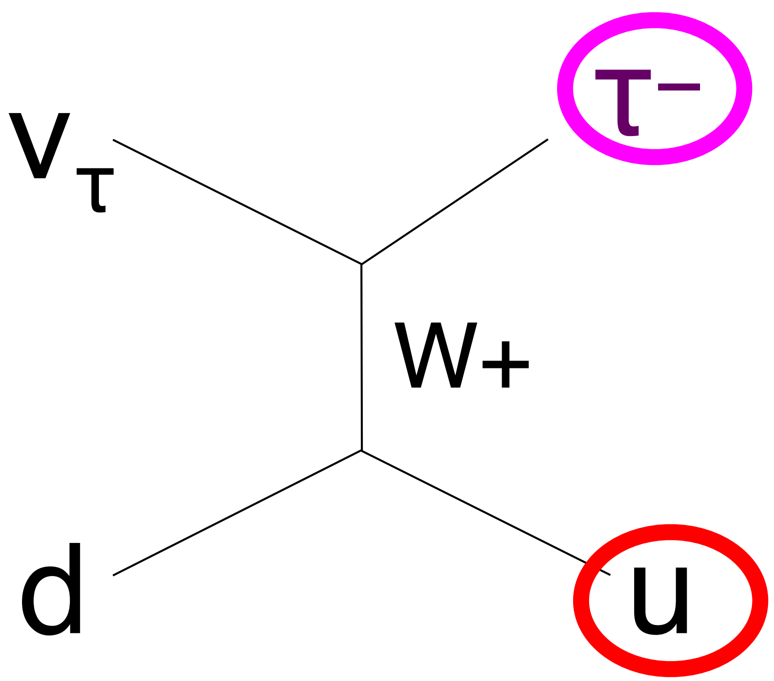
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

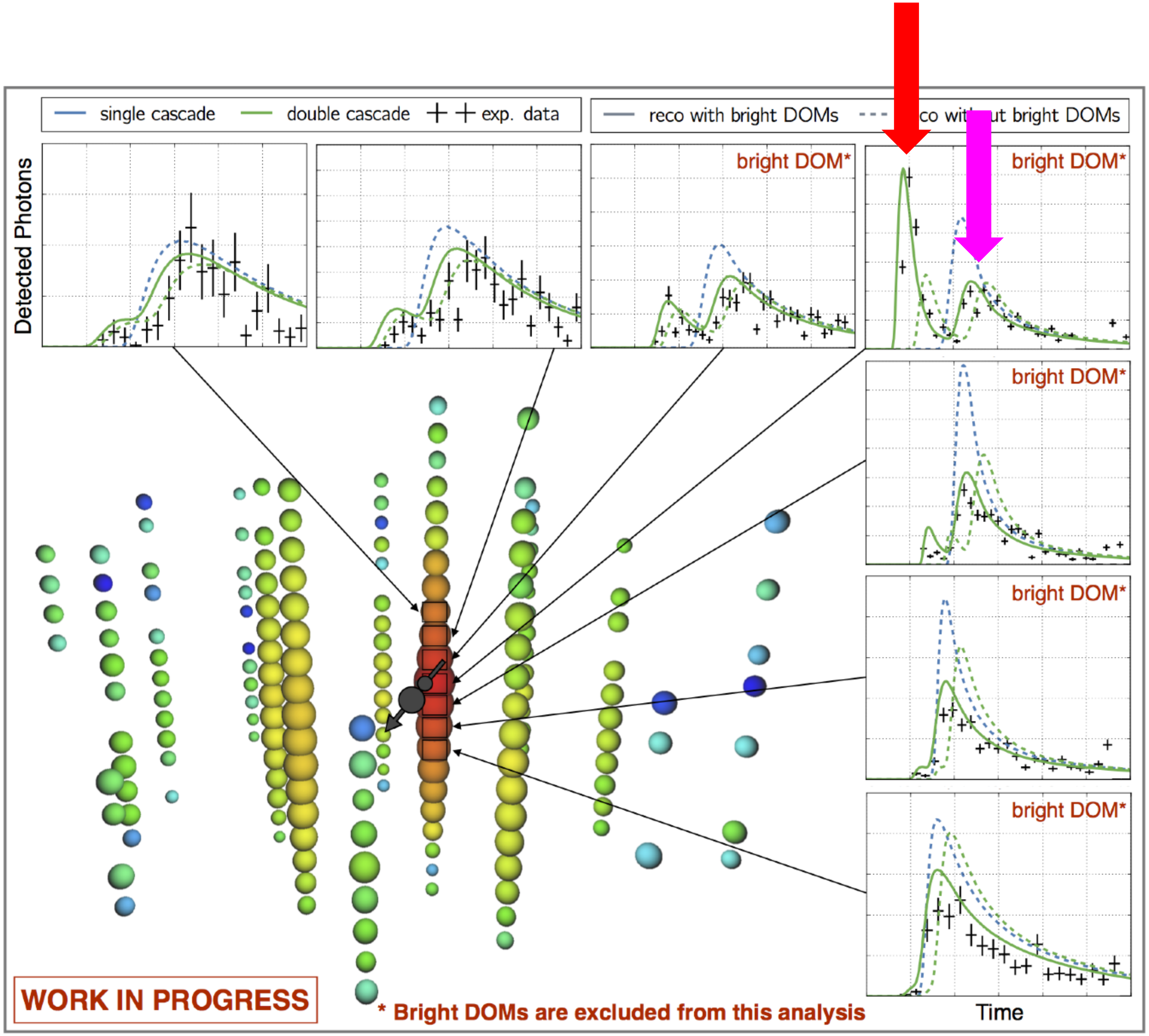
First astrophysical ν_τ candidate found!

Total deposited energy ~ 90 TeV.

First “bang” in time (shower)

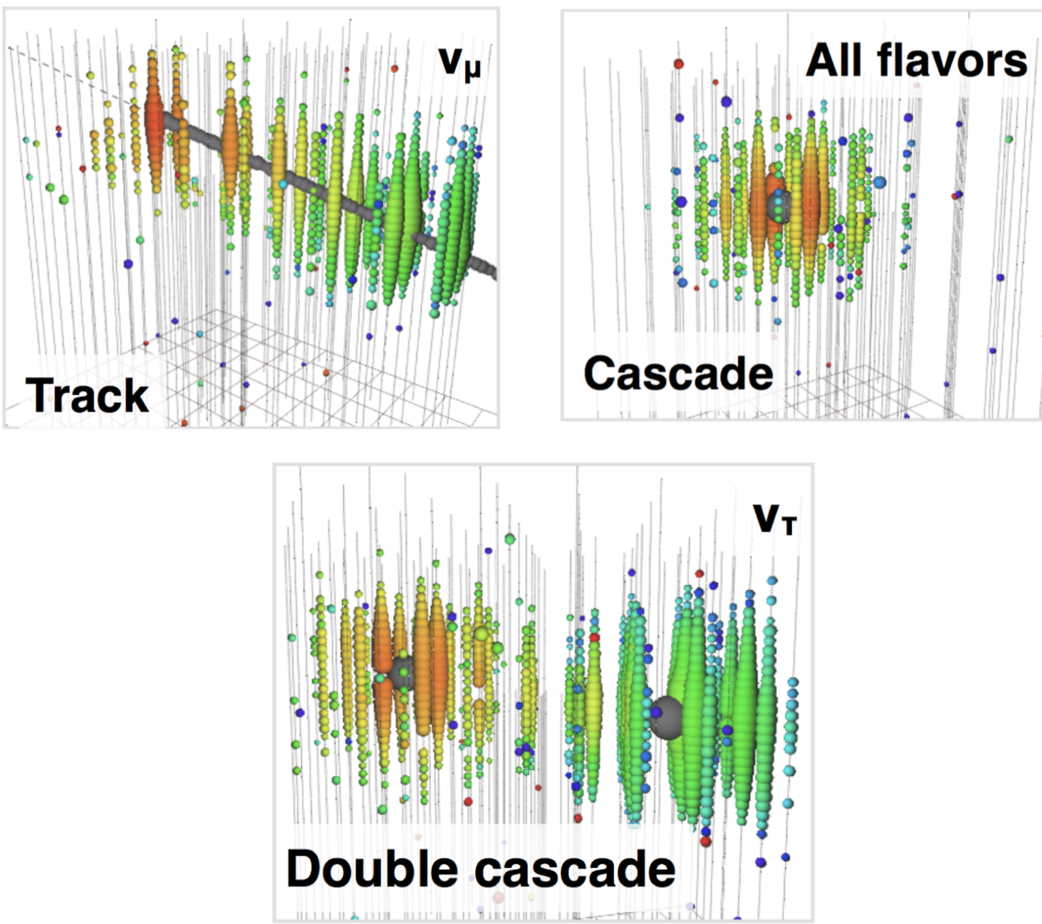
Second “bang” in time (tau decay)

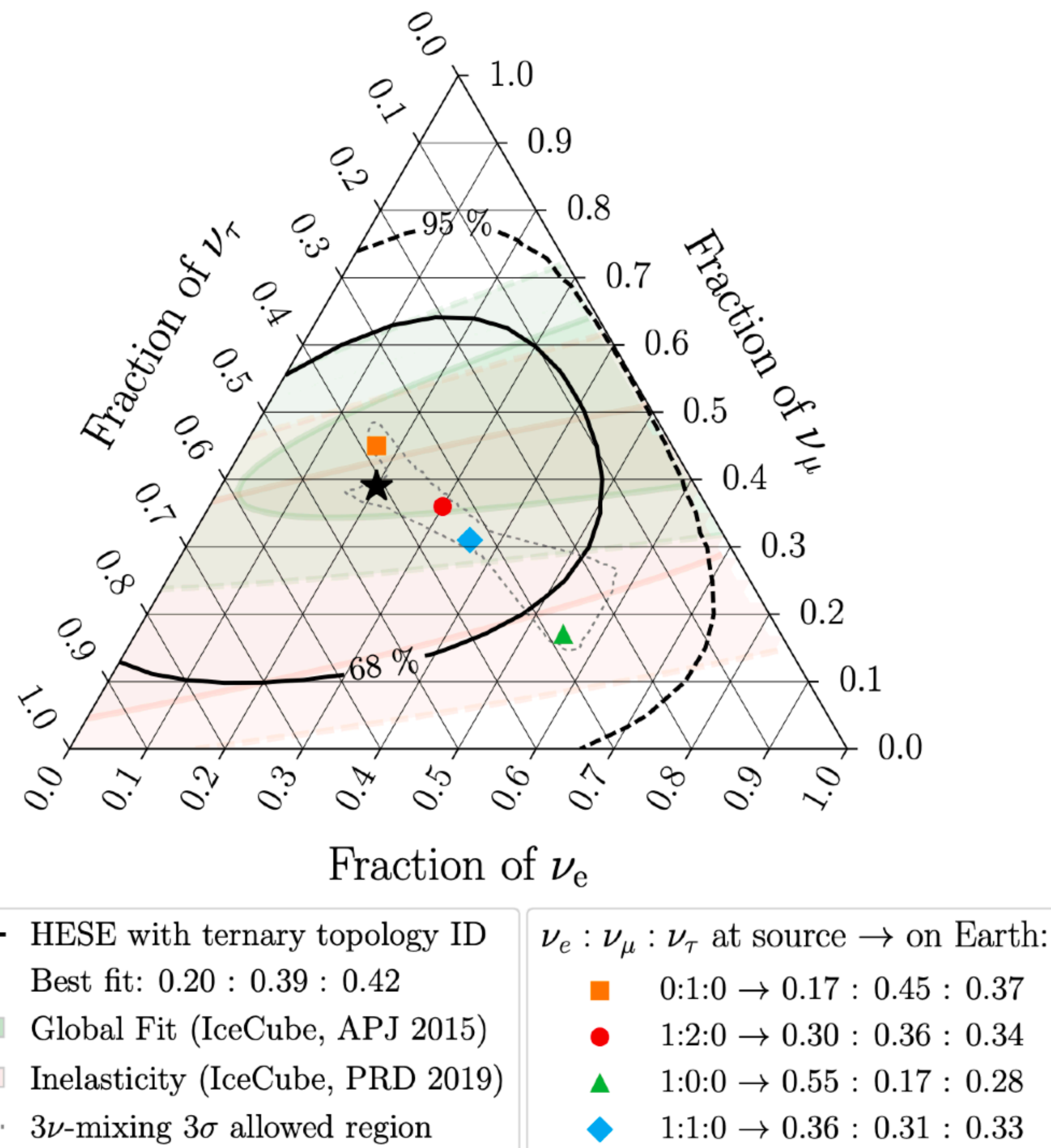




IceCube Collaboration, https://arxiv.org/abs/2011.03561

Astrophysical neutrino flavor measurements with high-energy starting events





IceCube Collaboration, https://arxiv.org/abs/2011.03561

Search for Lorentz Violation via Flavor Morphing

As neutrinos travel from their far away source they can interact with a Lorentz violating field.

Effects expected at the Planck Scale.

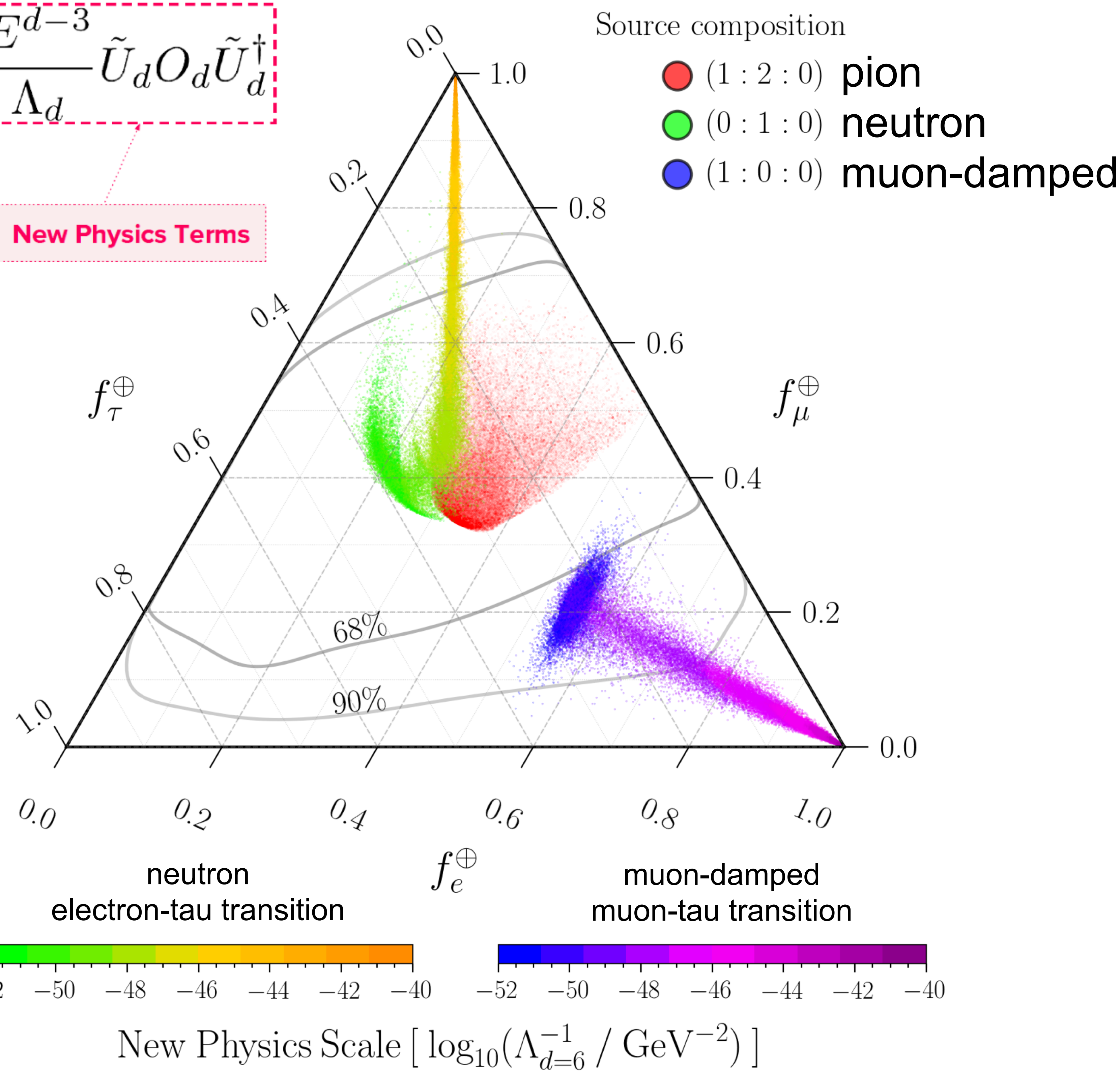
Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)

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

Dimension

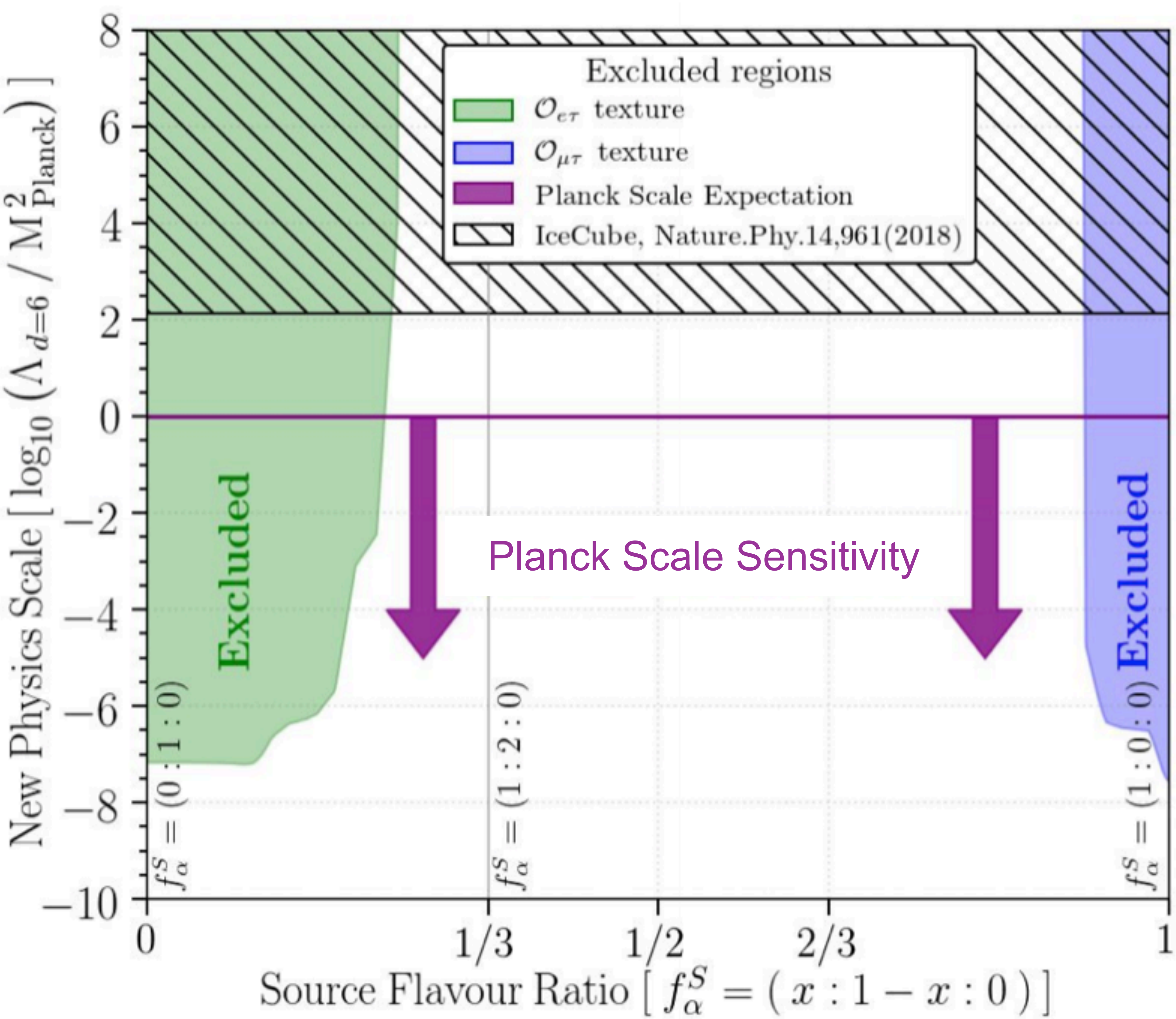
Standard Mixing

New Physics Terms



Katori, CA, Farrag, Mandalia for the IceCube collaboration https://arxiv.org/abs/1906.09240

Results on high-dimensional LV operators



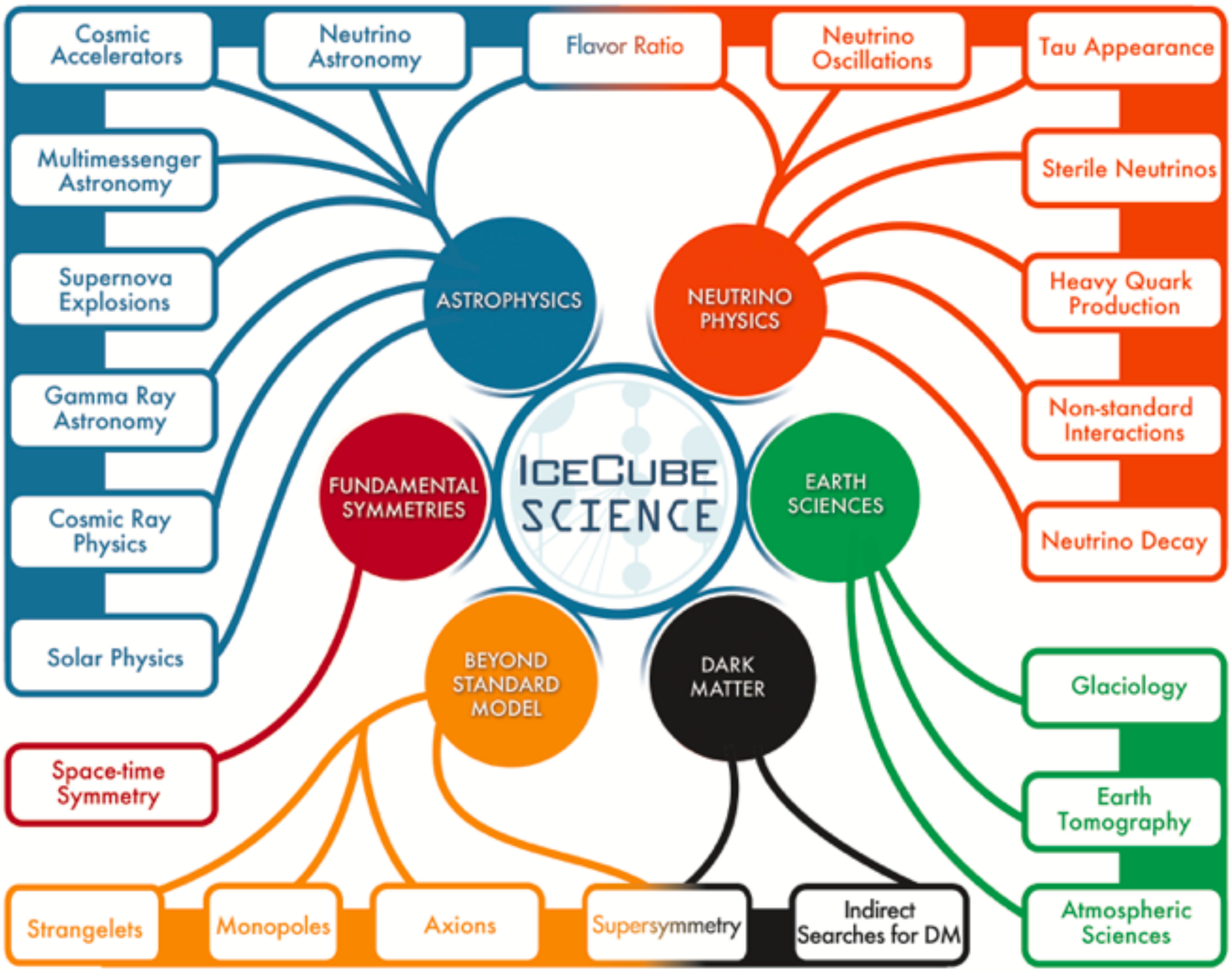
Katori, CA, Farrag, Mandalia for the IceCube collaboration https://arxiv.org/abs/1906.09240

Take away of the Lorentz Violation search:

1. IceCube astrophysical neutrinos allow physics-reach into the Planck scale.

2. We are beginning to enter territory of string theory and other GUTs.

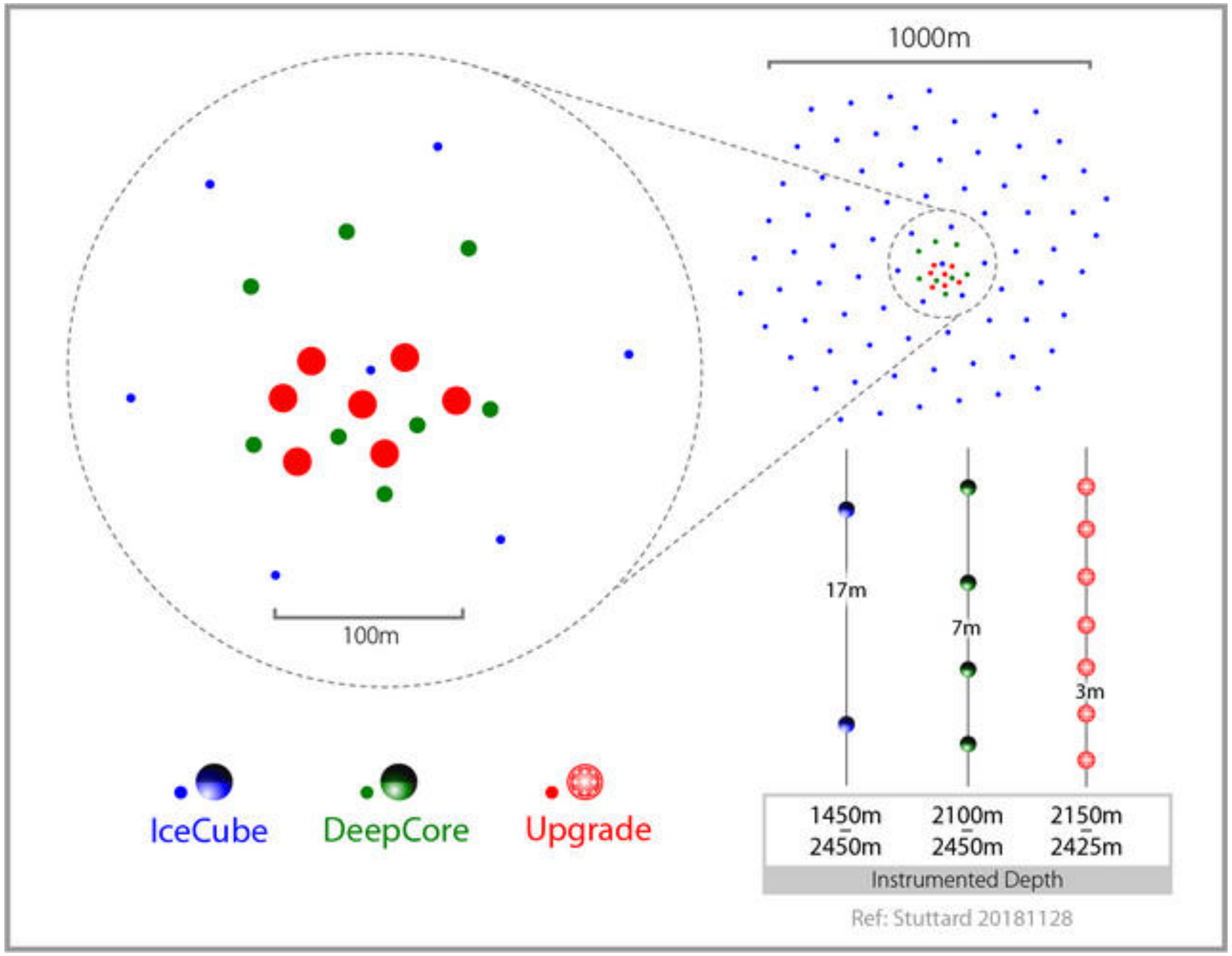
I hope I have convinced you that ...



IceCube has great potential for discovery

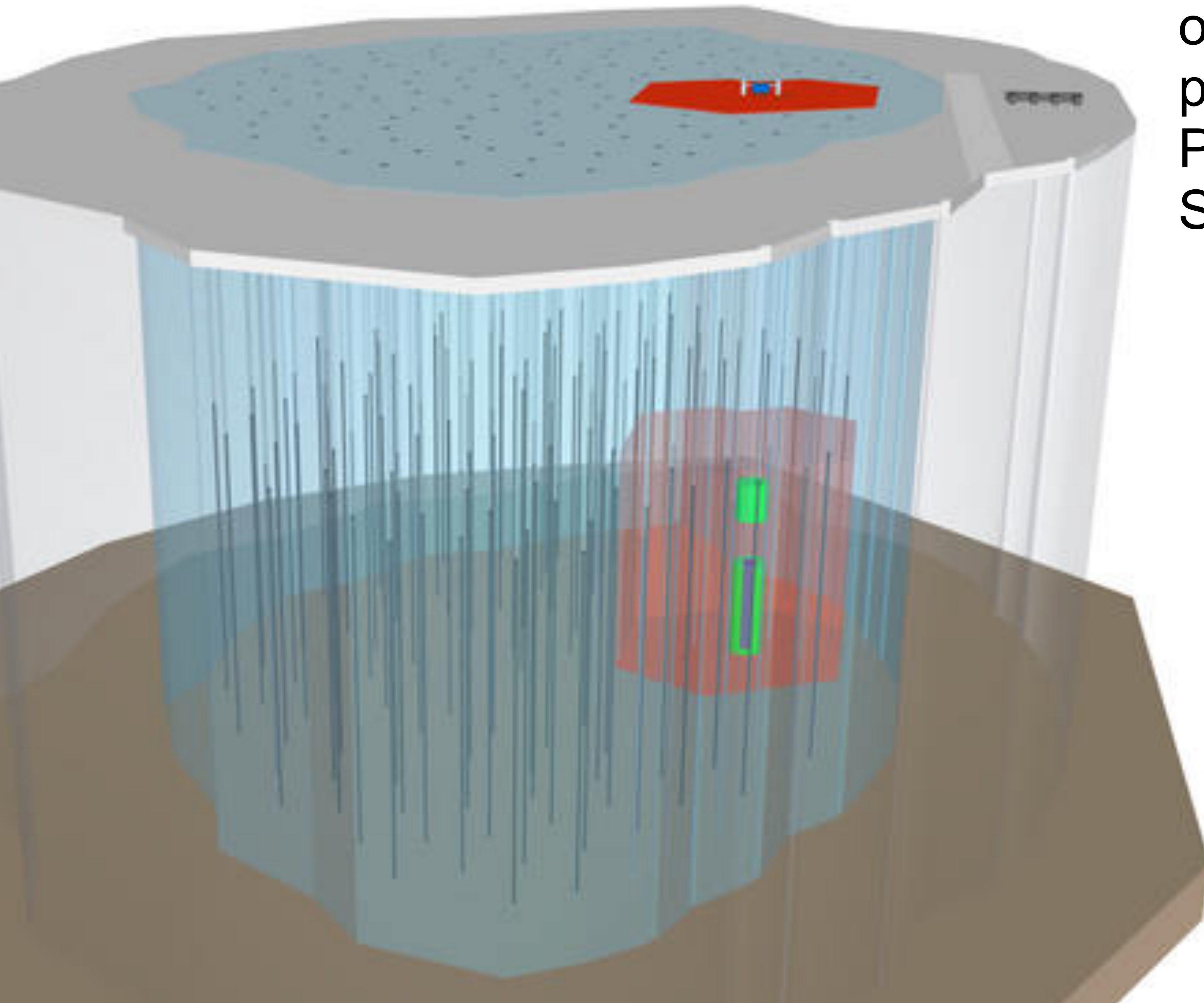
That potential is growing: The Upgrades

Phase 1: 7 new, high-precision strings in
the central, densely instrumented region.
Funded, installation in 2023(?).



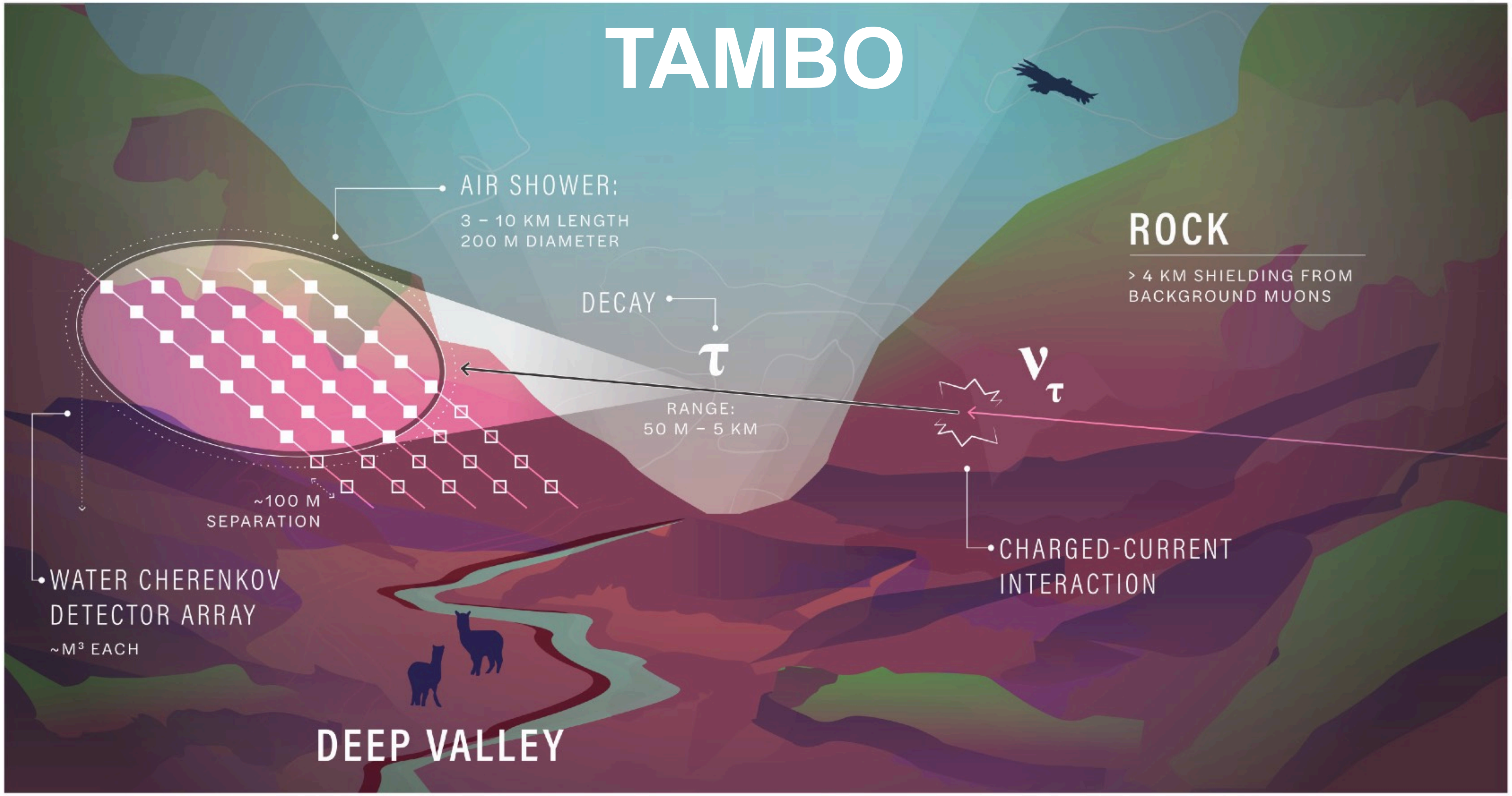
New detector technologies.
Better low energy reconstruction.
Improved flavor identification.

That potential is growing: The Upgrades

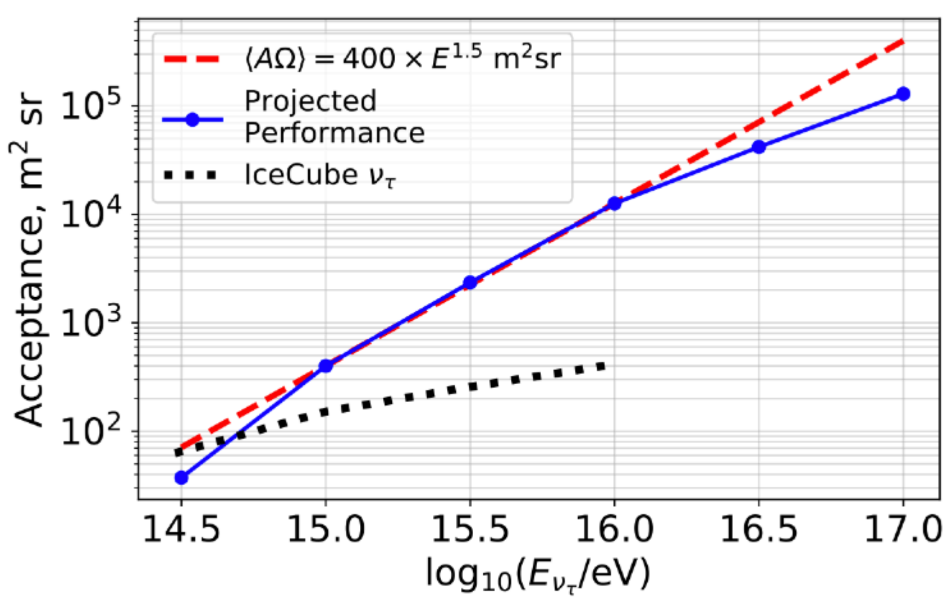


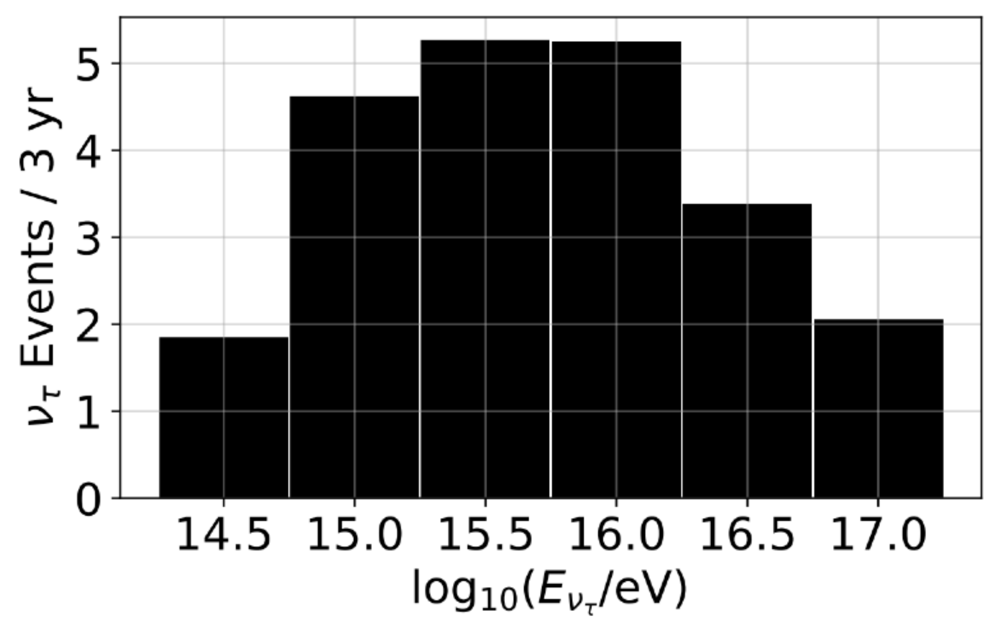
Phase 2: x10 the volume of present IceCube, plus additional detectors. Progressing through NSF Science Board approval.

TAMBO



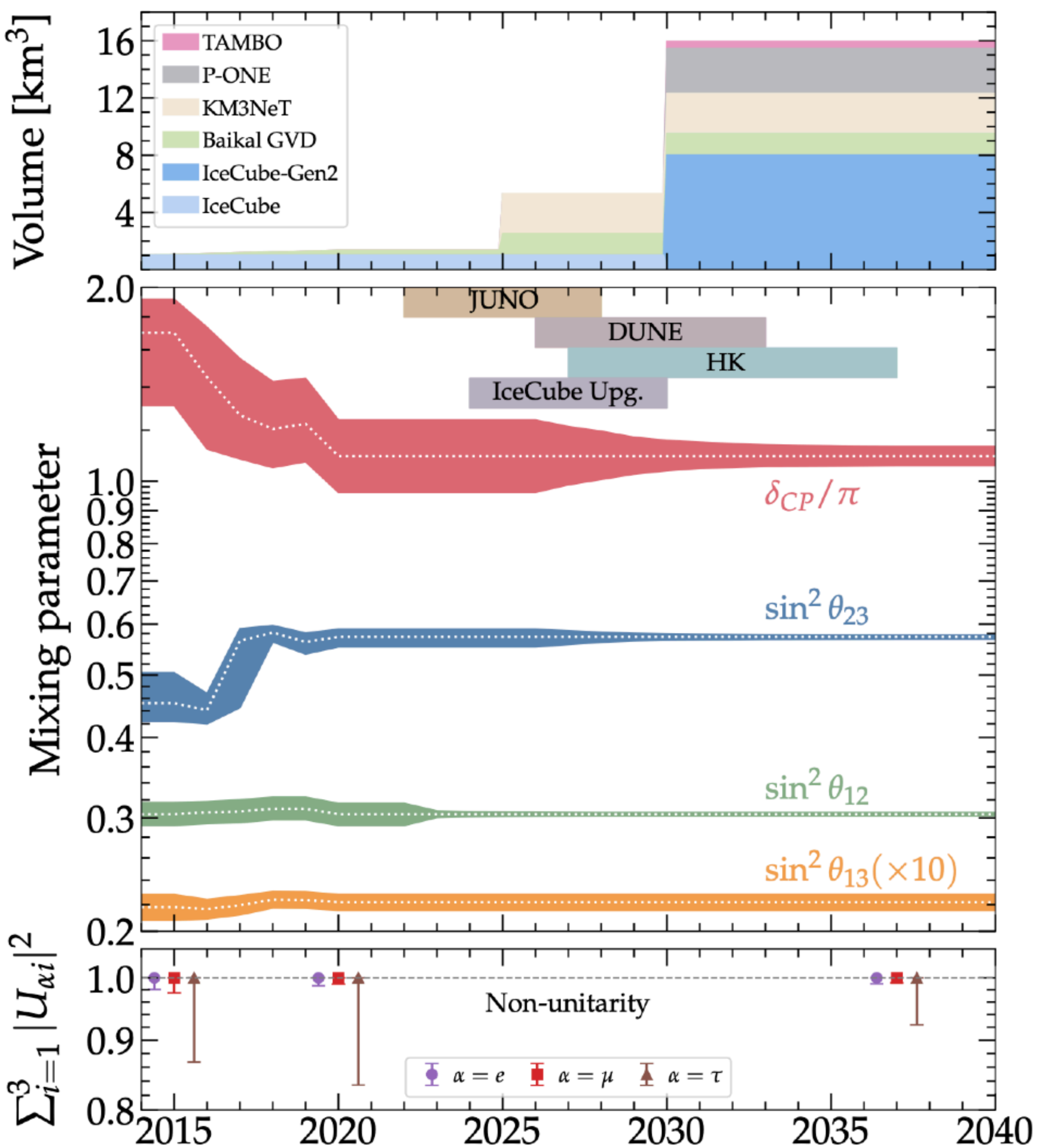
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

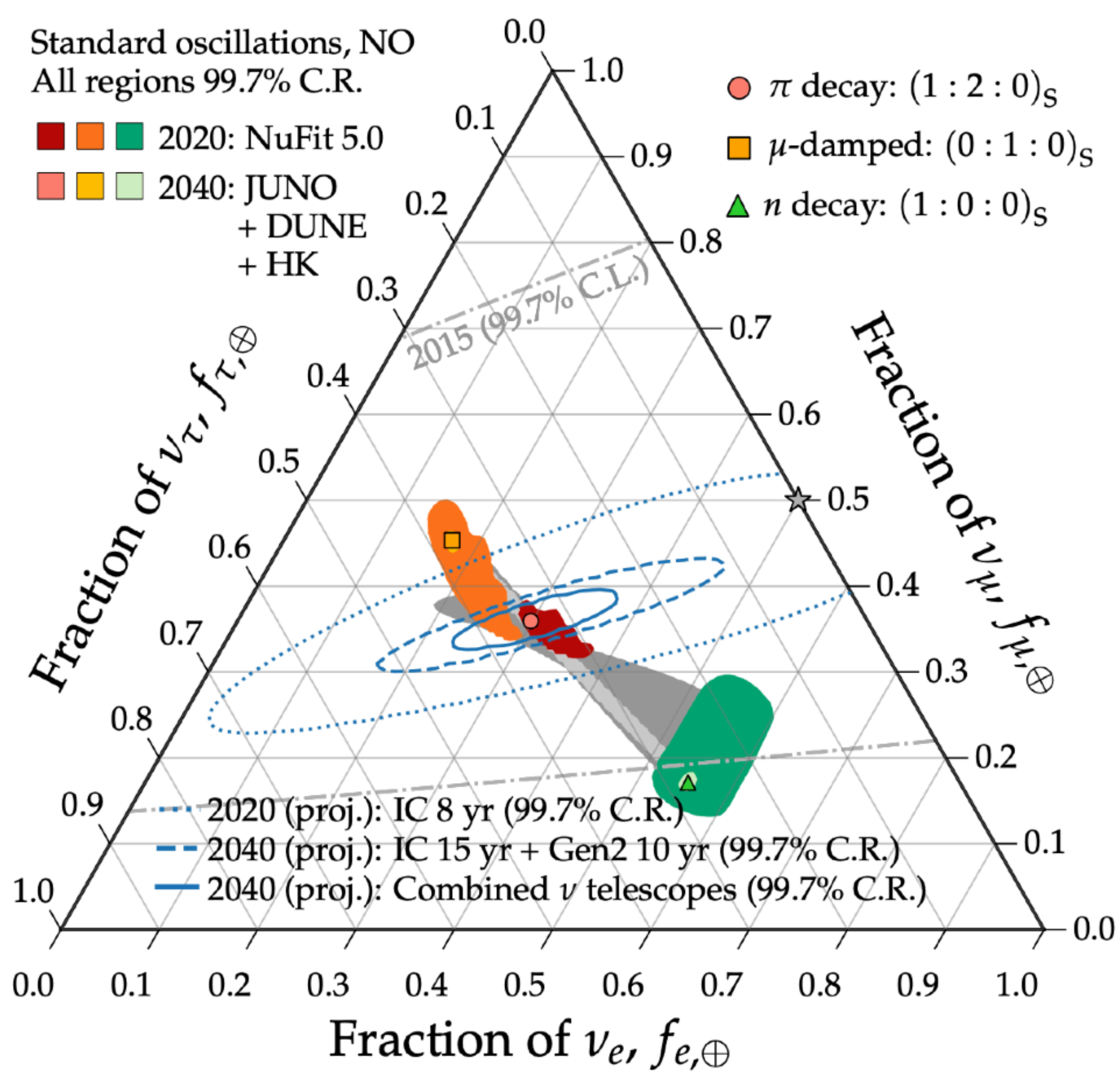




Romero-Wolf *et al* https://arxiv.org/abs/2002.06475

Projected Upgrade Flavor Measurement





N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)

Conclusion

Neutrino Physics is truly in the midst of interesting times:

- First candidate astrophysical neutrino sources have been detected.
- Spectral measurements of the high-energy diffuse spectra start to give hint of structure.
- We are studying neutrino properties at PeV energies!
- We have the Dark Matter problem that maybe related to neutrinos.
- We have reached extreme regimes that lets us explore into the Planck scale.

We also have great possibilities for the future:

- Combination of IceCube measurements
- New results from Km3NeT and GVD-Baikal
- Next generation neutrino observatories will provide a *nu* picture of the Universe.

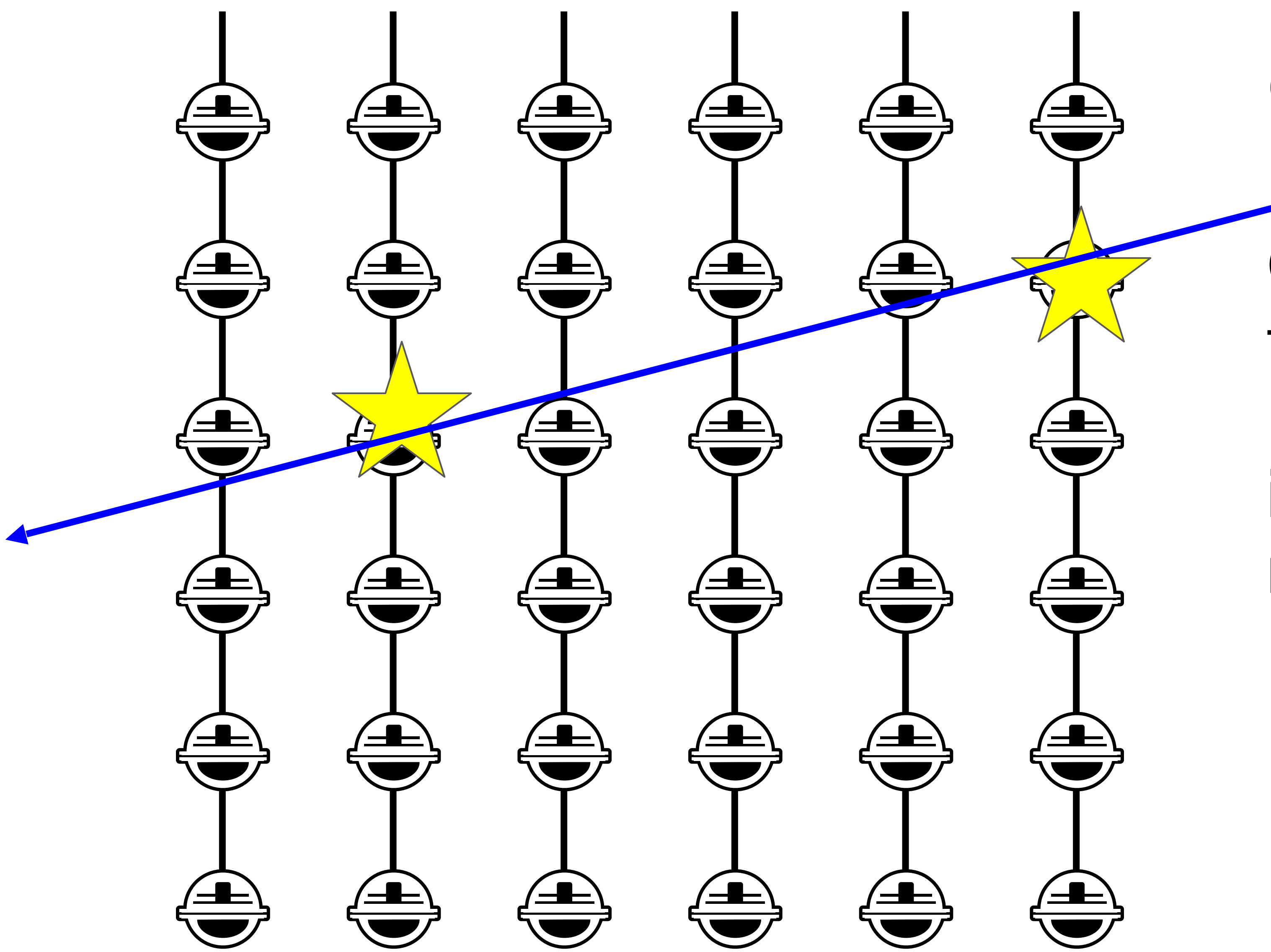
Thanks!


mass →
charge →
spin →
2.4 MeV/c²
2/3
1/2
u
up
1.27 GeV/c²
2/3
1/2
c
charm
171.2 GeV/c²
2/3
1/2
t
top
0
0
1
γ
photon
≈126 GeV/c²
0
0
H
Higgs boson
4.8 MeV/c²
-1/3
1/2
d
down
104 MeV/c²
-1/3
1/2
s
strange
4.2 GeV/c²
-1/3
1/2
b
bottom
0
0
1
g
gluon
QUARKS
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
LEPTONS
GAUGE BOSONS
???

Bonus slides

What are mTOMs?

Muon Tagging Optical Modules (mTOMs)
875 optically isolate scintillator blocks within DOMs;
If a muon goes through, scintillator tags the track
with very high precision.



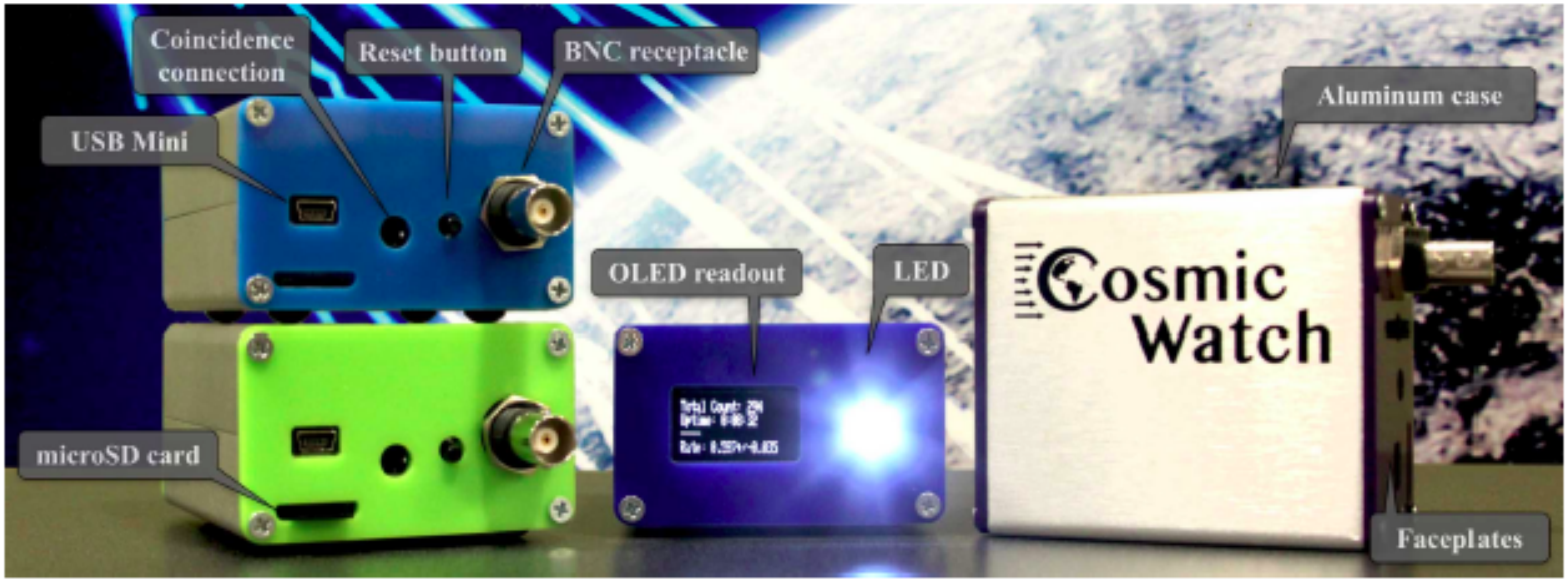
Goal:

Collect ~10k cosmic muon tracks per year for study

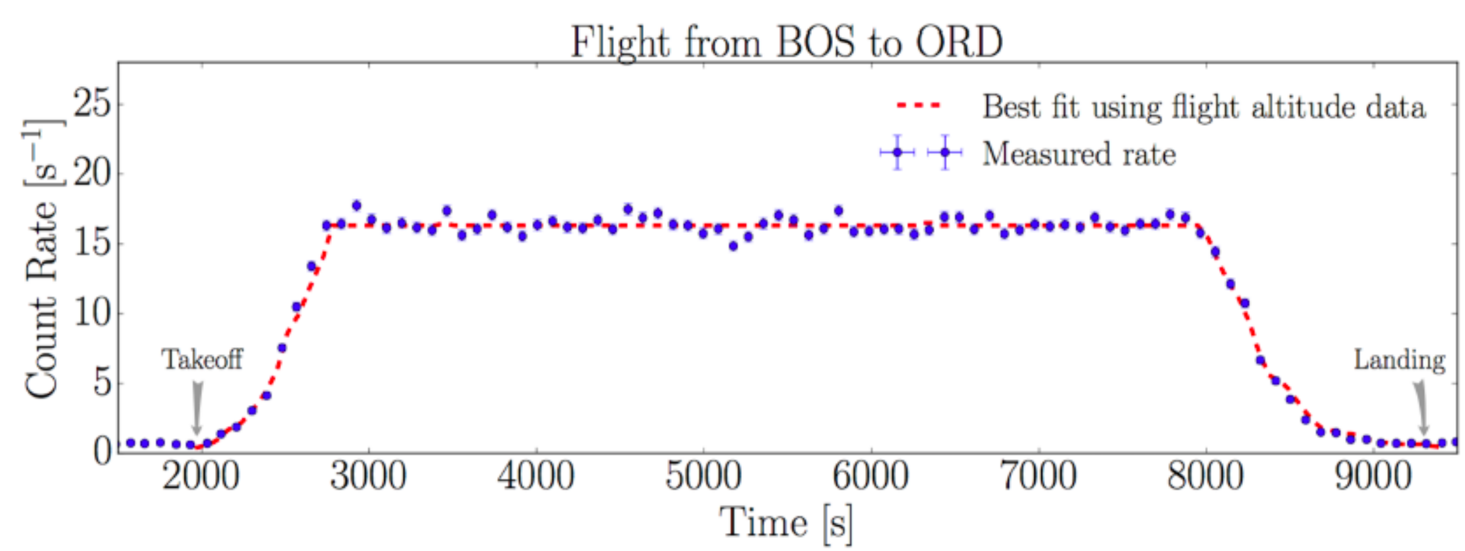
improve down-going muon reconstruction to

1) increase ν event sample
2) improve the cosmic veto

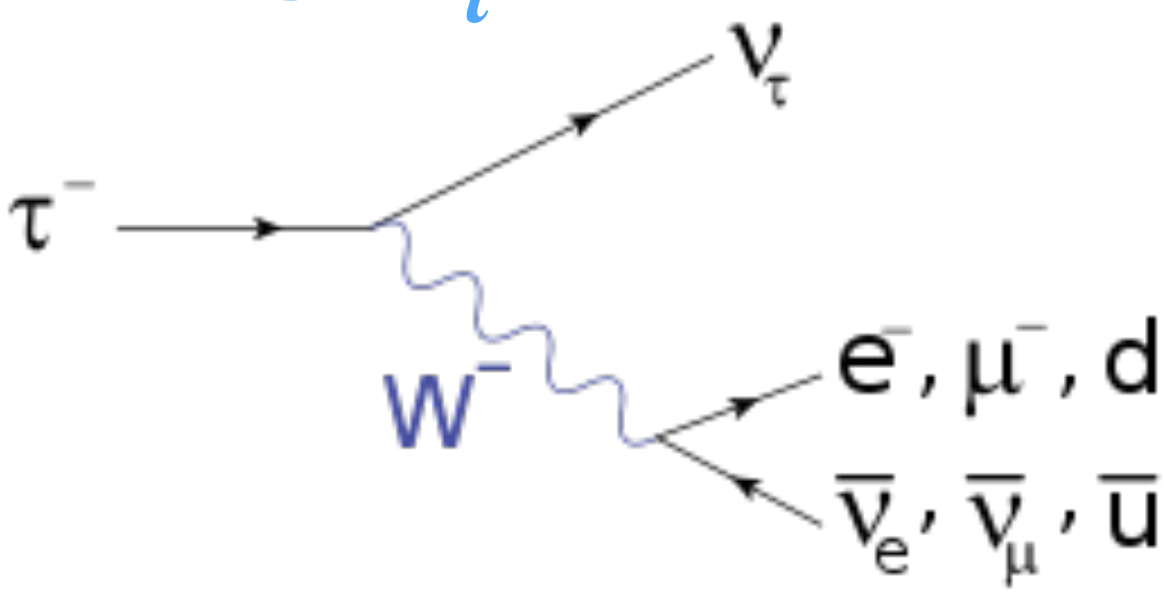
Prototype mTOMs ⇒ CosmicWatch!



Our prototype has become … the $100 portable muon counter.
Easily constructed by undergraduates.
All kinds of cool projects!



Why ν_τ at DUNE?



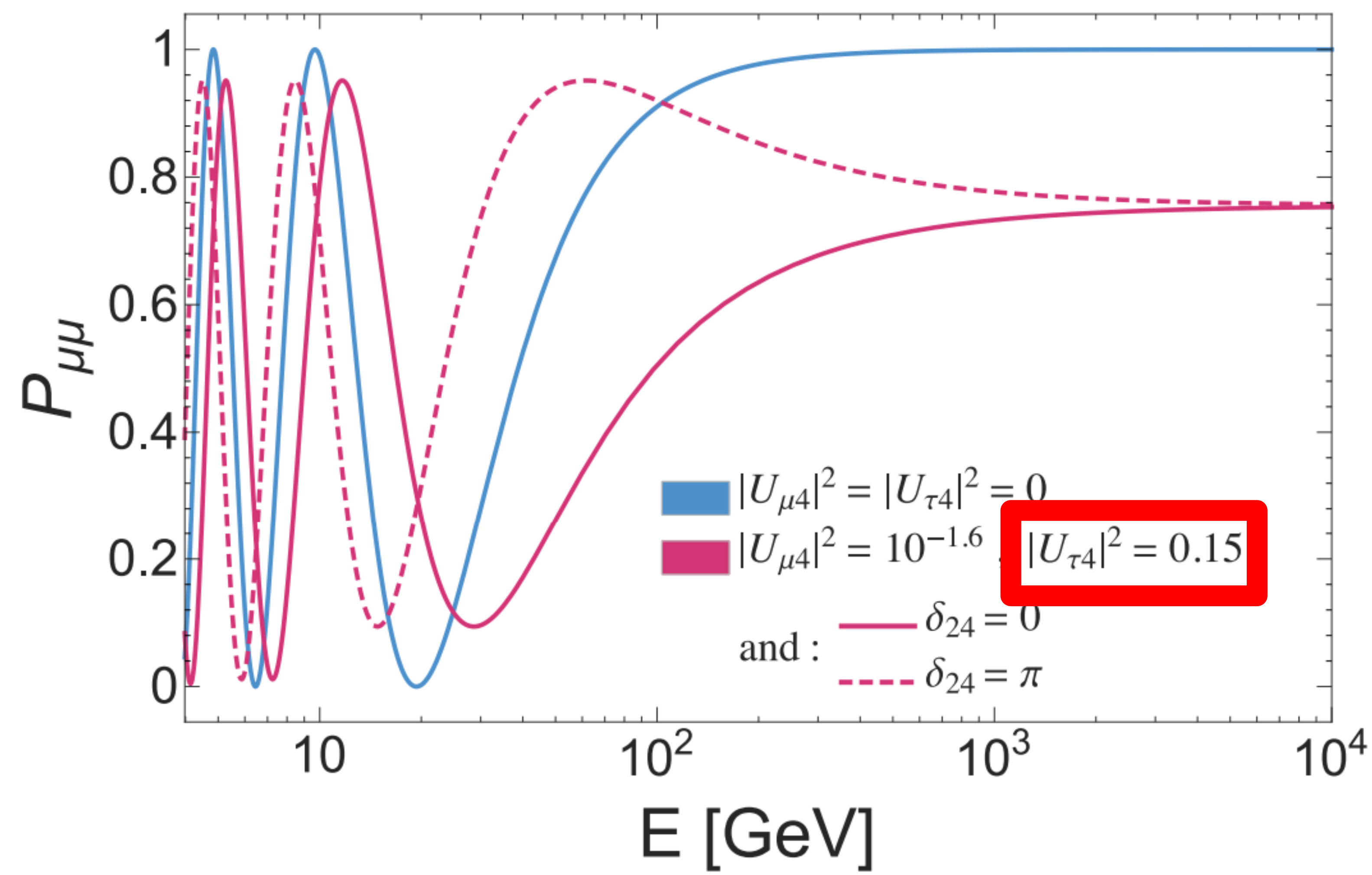
Once you produce the τ you have to identify it via the decay!

DUNE excellent vertex resolution

Decay length:

- ~ 50 m @ 1 PeV
- ~ 5 cm @ 1 TeV
- ~ 0.5 mm @ 10 GeV

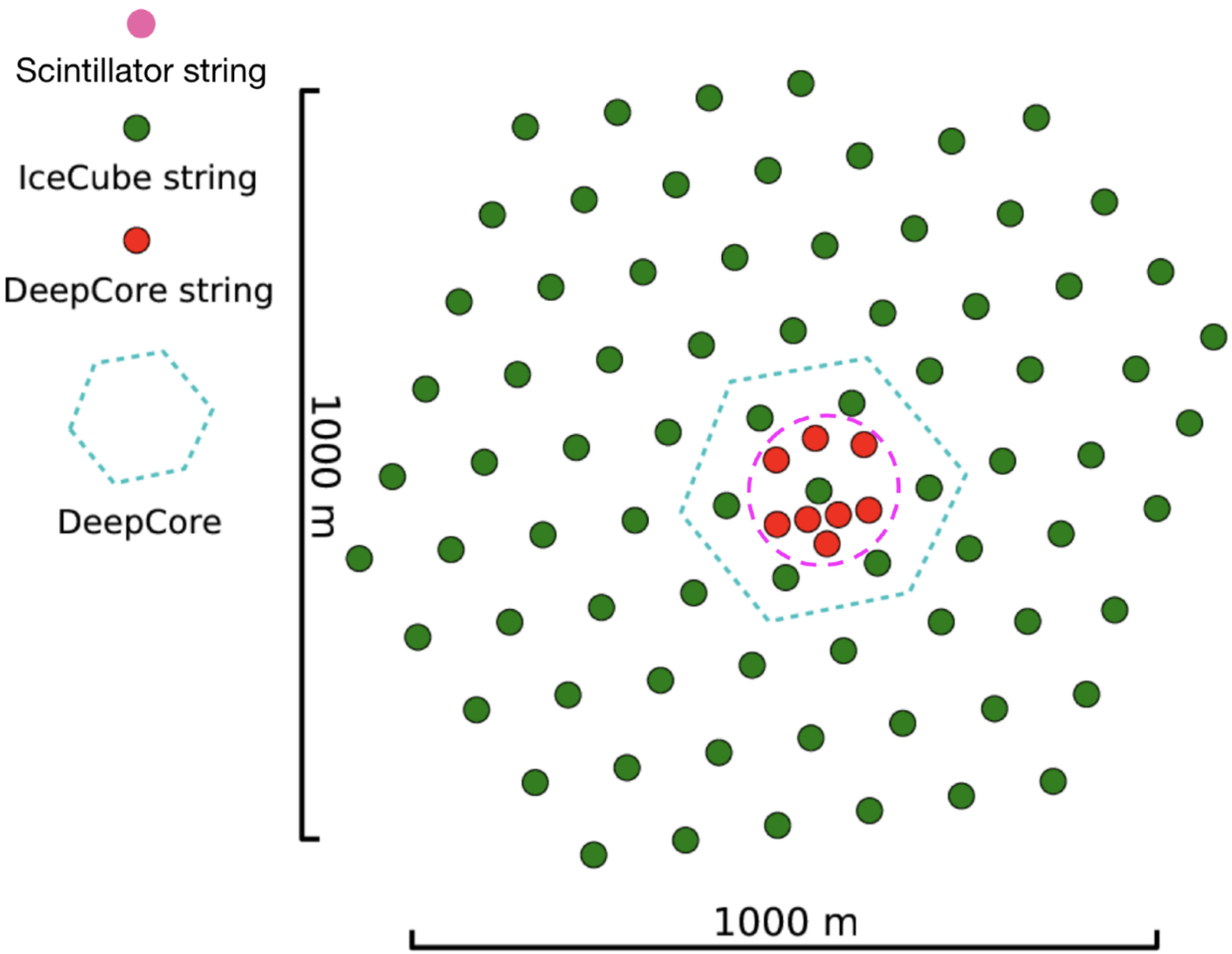
& other BSM physics with displaced vertex can be studied with similar techniques.

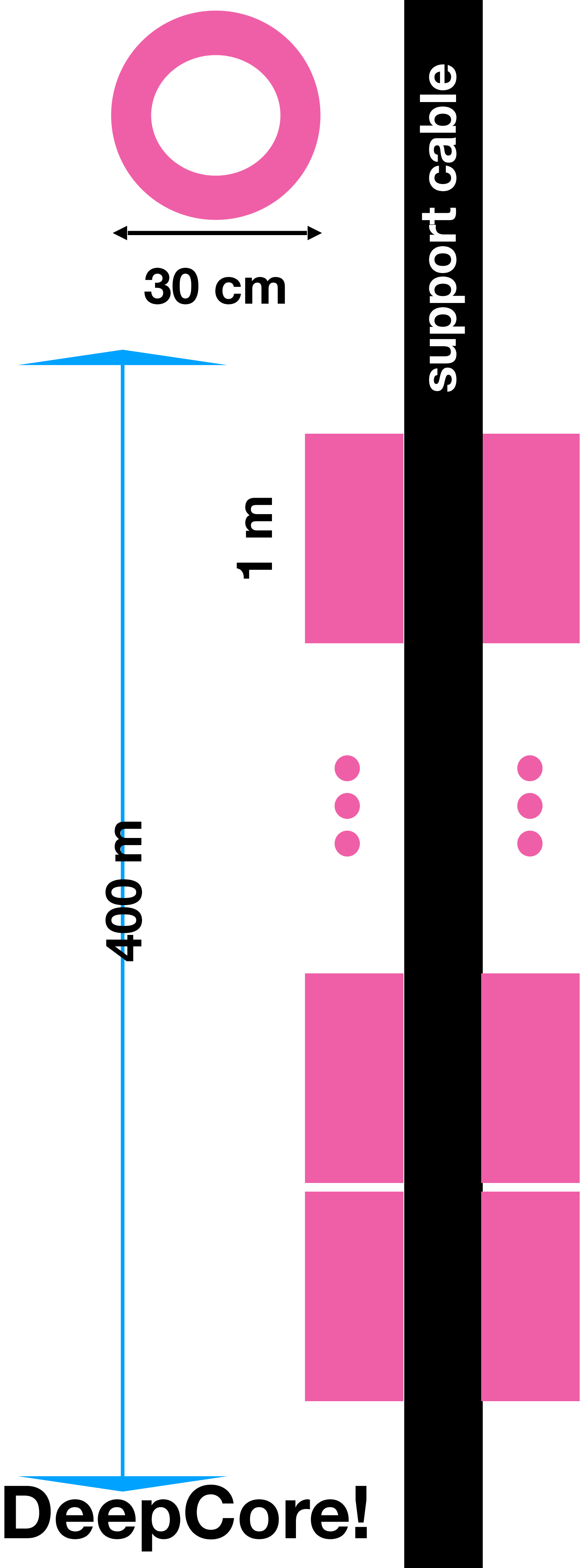


Appearance of tau neutrinos via sterile mixing and matter effects.

ADELIE:The Idea

- ✤We deploy plastic scintillator inside the IceCube instrumented volume.
- ✤No PMTs, no electronics, no new DAQ.
- ✤Light seen by existing DOMs.

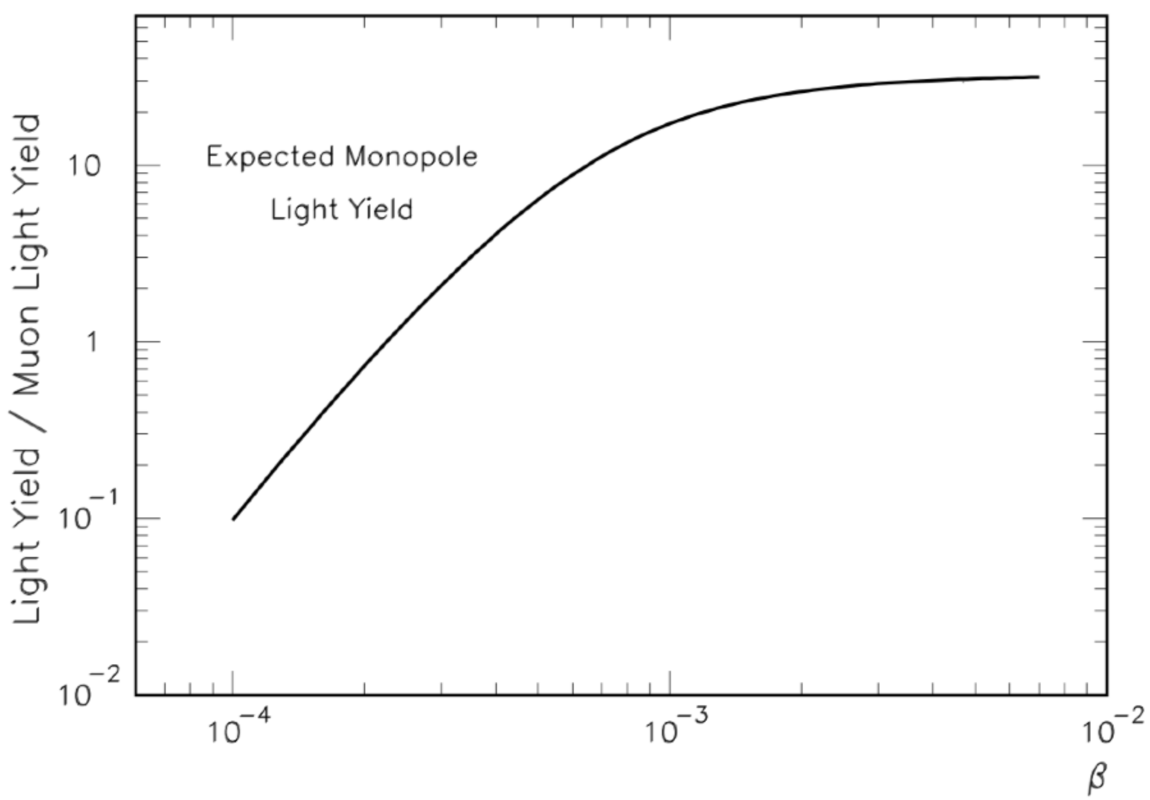




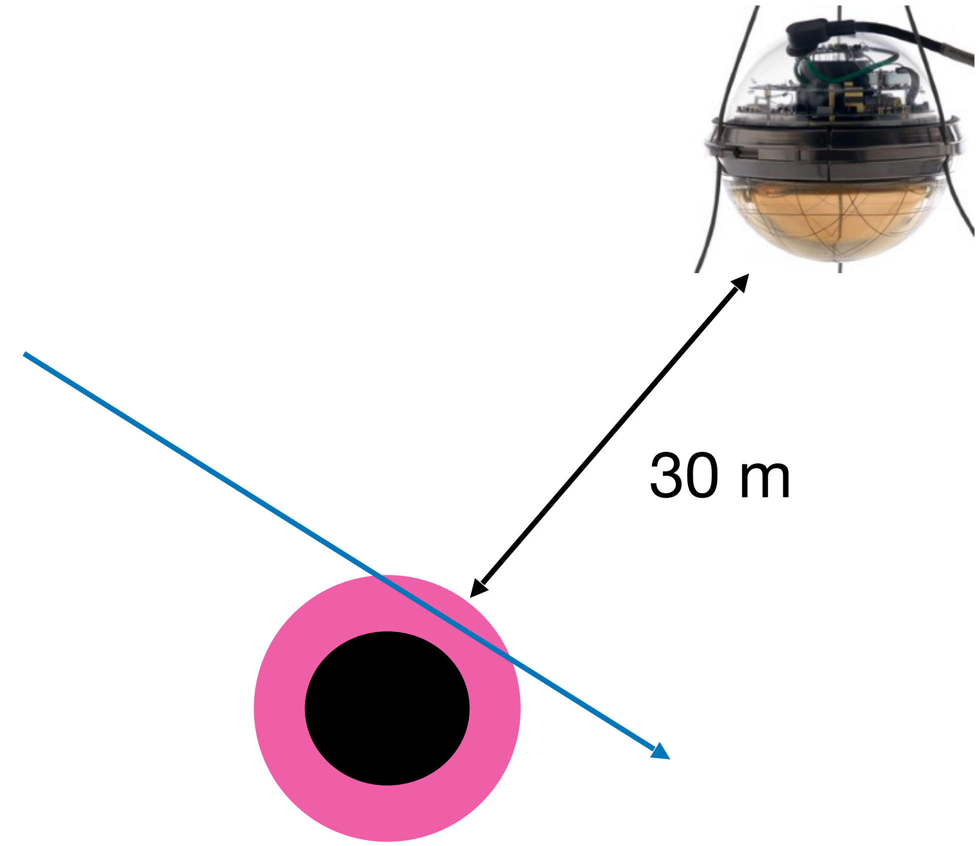
Scintillator strings surrounding IceCubeDeepCore!

Monopoles in ADELIE

Slow monopoles produce no Cherenkov light, so we can veto muons.

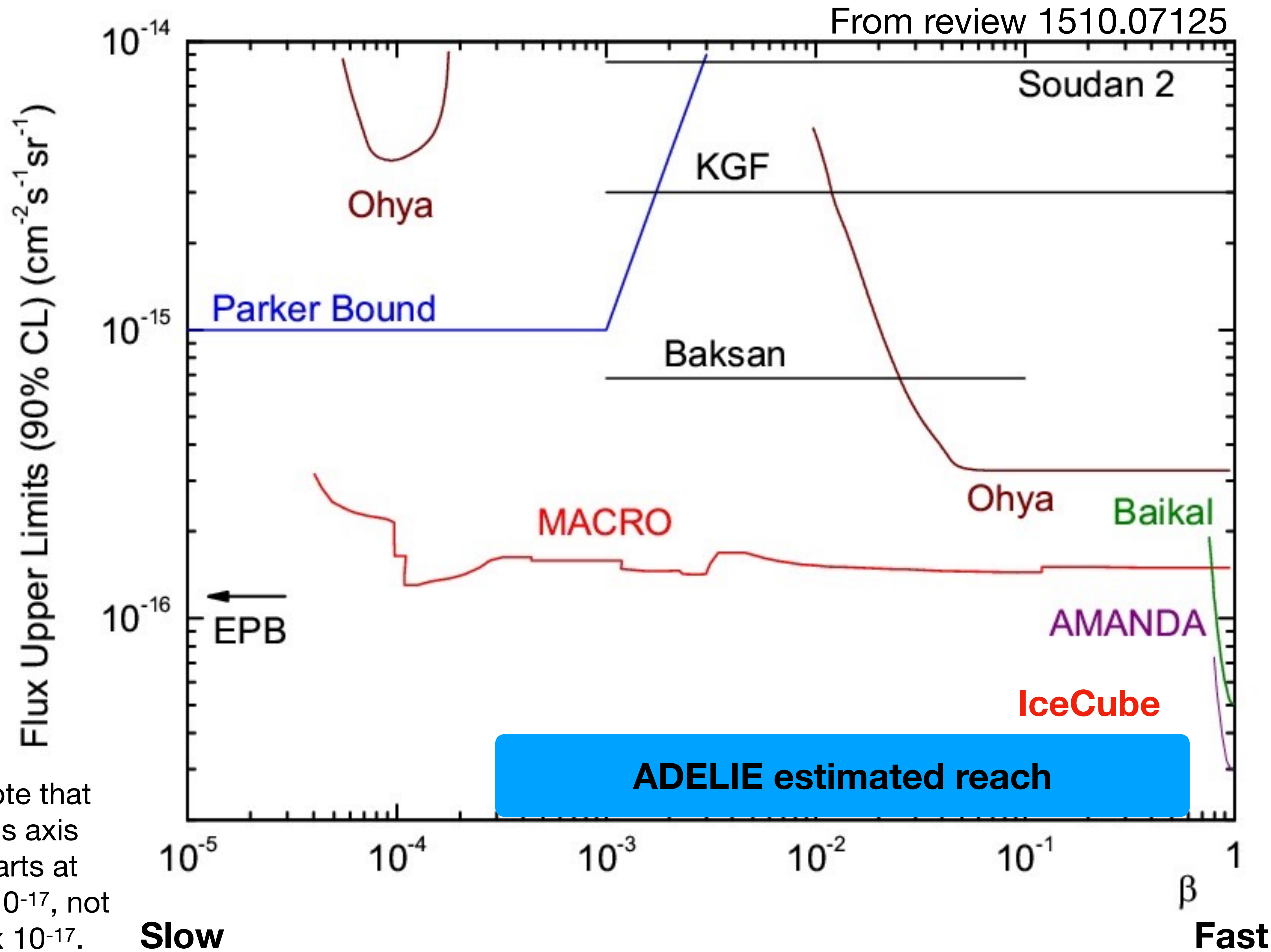


Monopoles emit 3 to 30 times more light than MIPs.



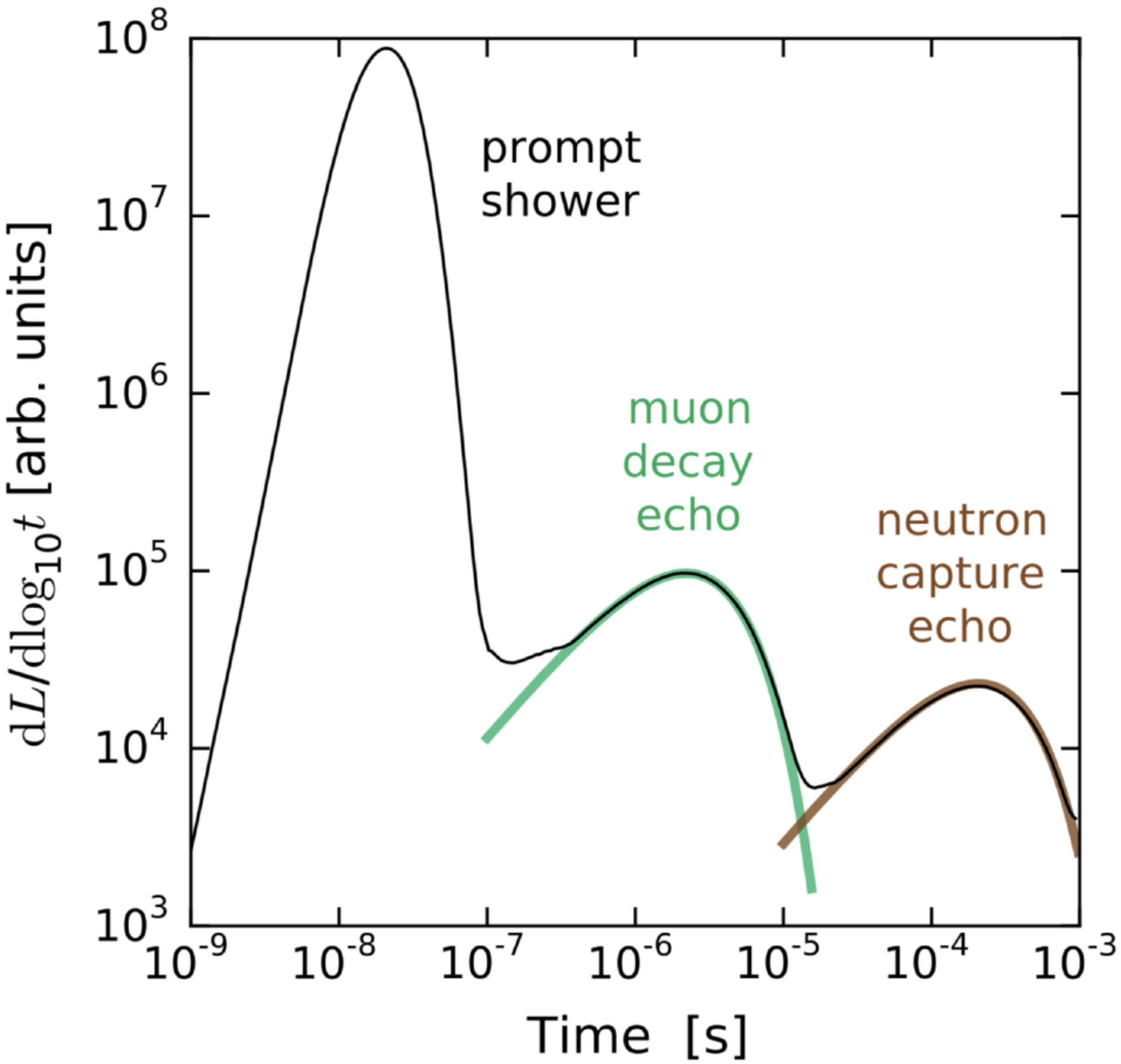
We estimate ~ 5 p.e. per MIP crossing our scintillator. Or up to 150 p.e. if it's a monopole!

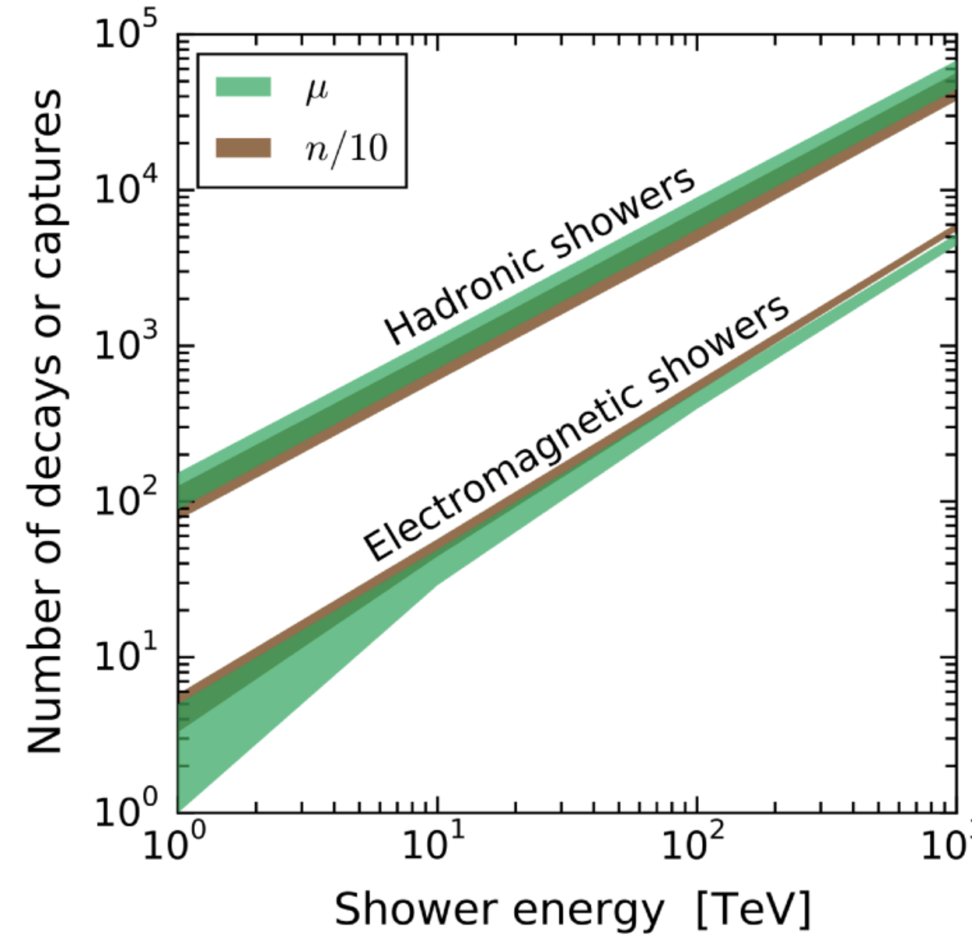
Monopoles sensitivity with ADELIE



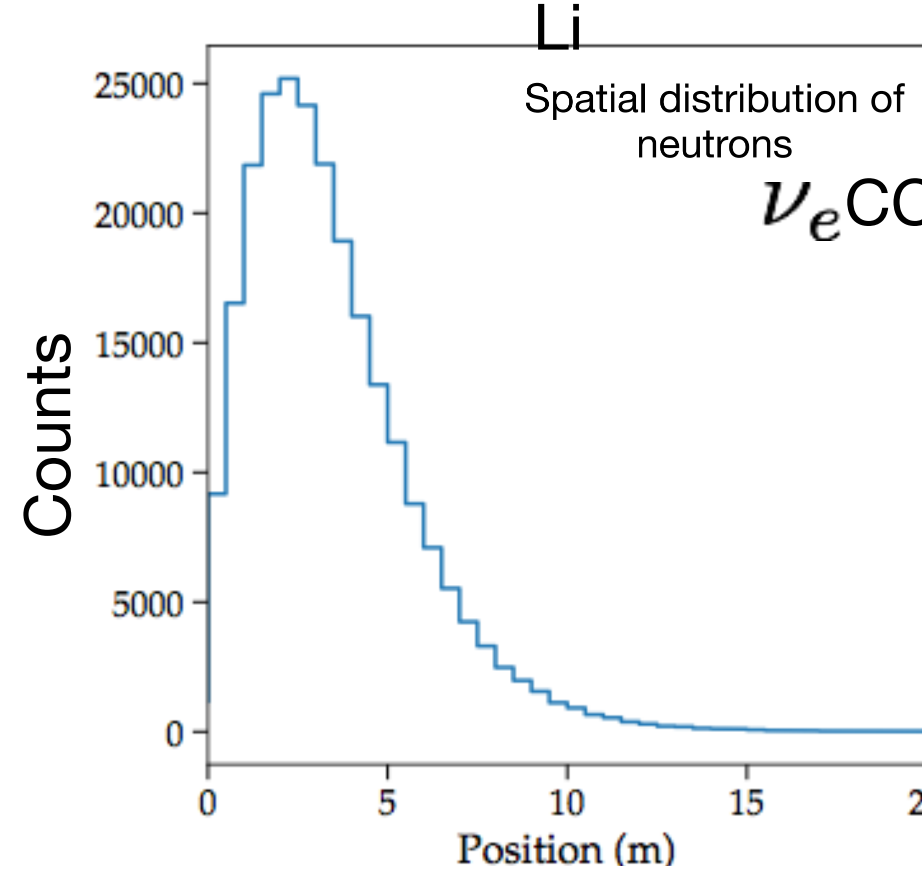
*Note that this axis starts at 2 x 10^{-17}, not 1 x 10^{-17}.

Hadronic identification with ADELIE





Plot courtesy of Shirley Li



Distance from vertex (m)

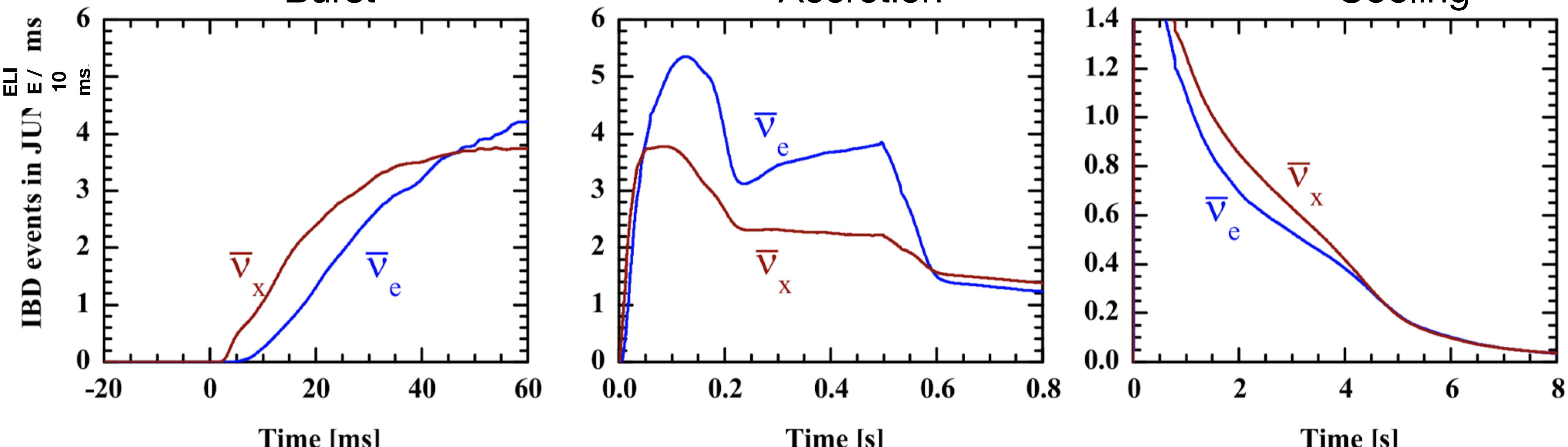
Expect ~ 1% of HESE/MESE-like events to have hadronic shower close to ADELIE.

https://arxiv.org/abs/1606.06290

Galactic Supernovae in ADELIE

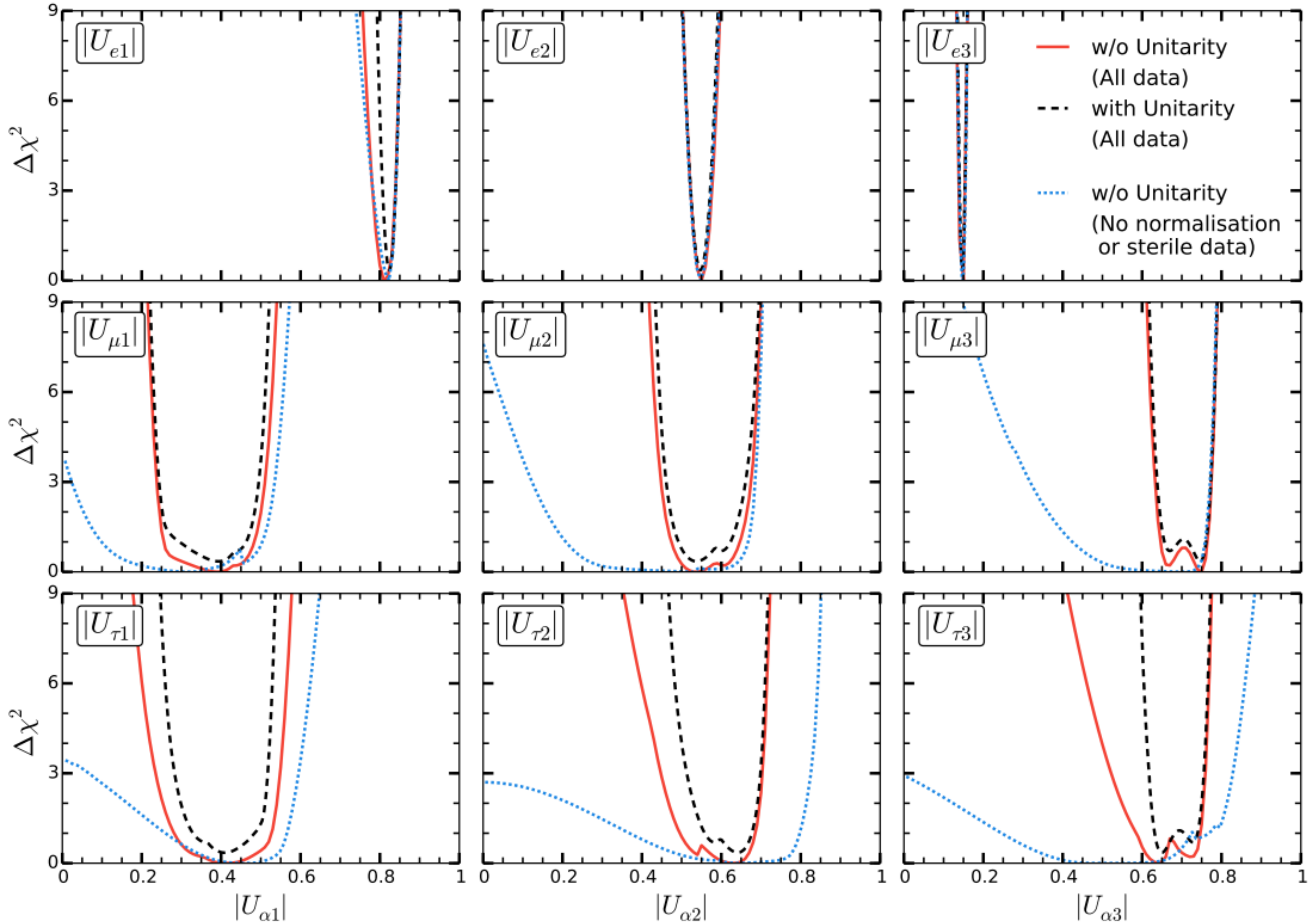
- For IBD: With Gd secondary light from IBD after ~ 30 microsecond producing ~ 8 MeV gamma; without Gd secondary light ~ 200 microsecond producing ~ 2 MeV gamma.
- Different intensity and time distributions for antineutrinos due to the IBD contribution may give us a handle on nu/nubar ratio for SN.

Burst Accretion Cooling



Adapted from JUNO
1507.05613

Tau sector of PMNS matrix poorly explored



Parket et al. Phys. Rev. D 93, 113009 (2016)

Beyond the Lorentz Violation interpretation

Our analysis is performed by introducing *effective terms*, which can be due to by other new physics beyond Lorentz Violation.

Standard term | New physics term

$$H = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{V_{\text{new physics}}}$$

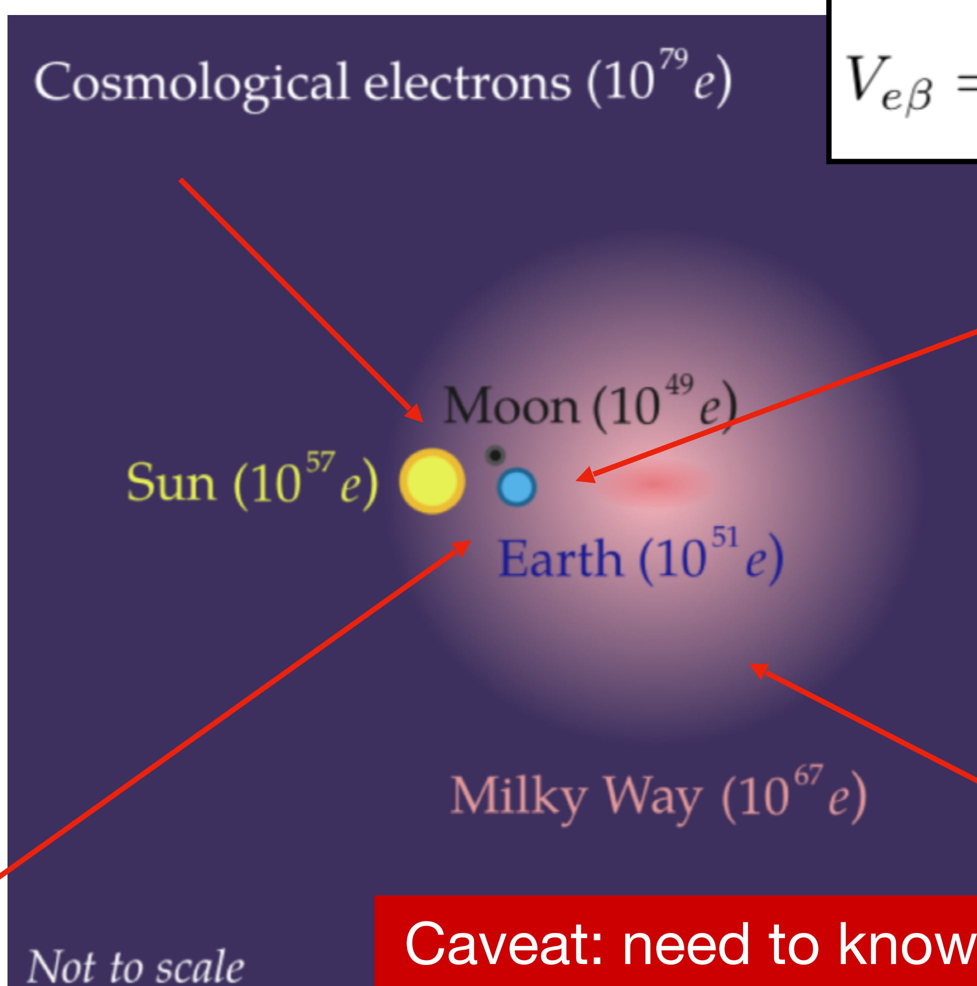
$V_{e\tau} < 10^{-27}\,\text{GeV}$ (0:1:0) source

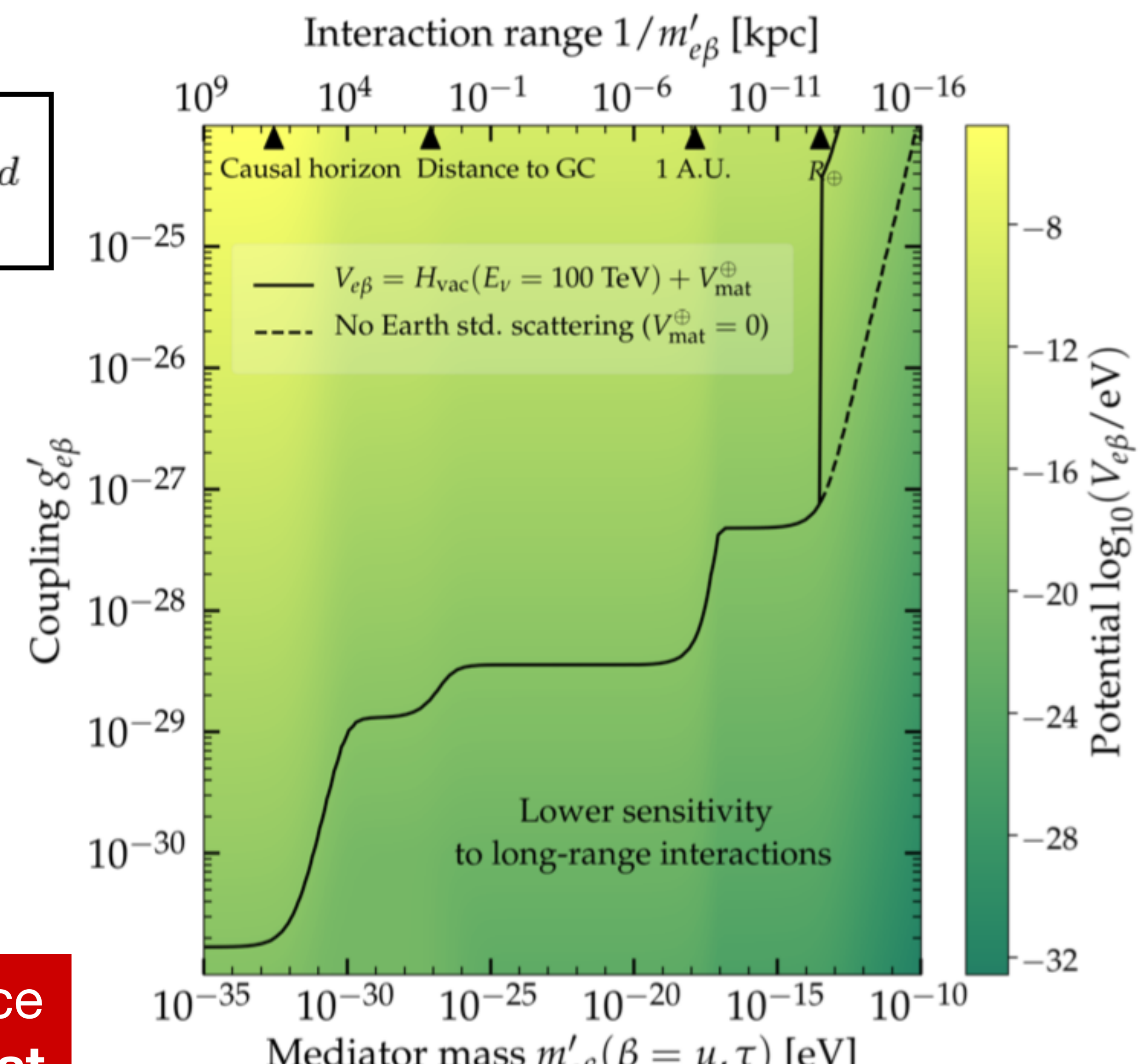
$V_{\mu\tau} < 10^{-28}\,\text{GeV}$ (1:0:0) source

New long range forces gauged on

$$L_e - L_\alpha$$

$$V_{e\beta} = -\frac{g'^2_{e\beta}}{4\pi d} e^{-m'_{e\beta} d}$$





Bustamante et al. Phys.Rev.Lett. 122 (2019) no.6, 061103

Caveat: need to know neutrino source initial flavor composition to get **robust** bounds with current limits.

Coherent **Dark Matter Scattering**

Standard term New physics term

$$H = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{V_{\text{new physics}}}$$

$V_{e\tau} < 10^{-27}\text{GeV}$
(0:1:0) source

$V_{\mu\tau} < 10^{-28}\text{GeV}$
(1:0:0) source

Coherent scattering with dark cosmic background

Our analysis is performed by introducing *effective terms*, which can be due to by other new physics beyond Lorentz Violation.

$$V_D \sim G_D N_D$$

$$G_D \sim \frac{g_d^2}{M_D^2}$$

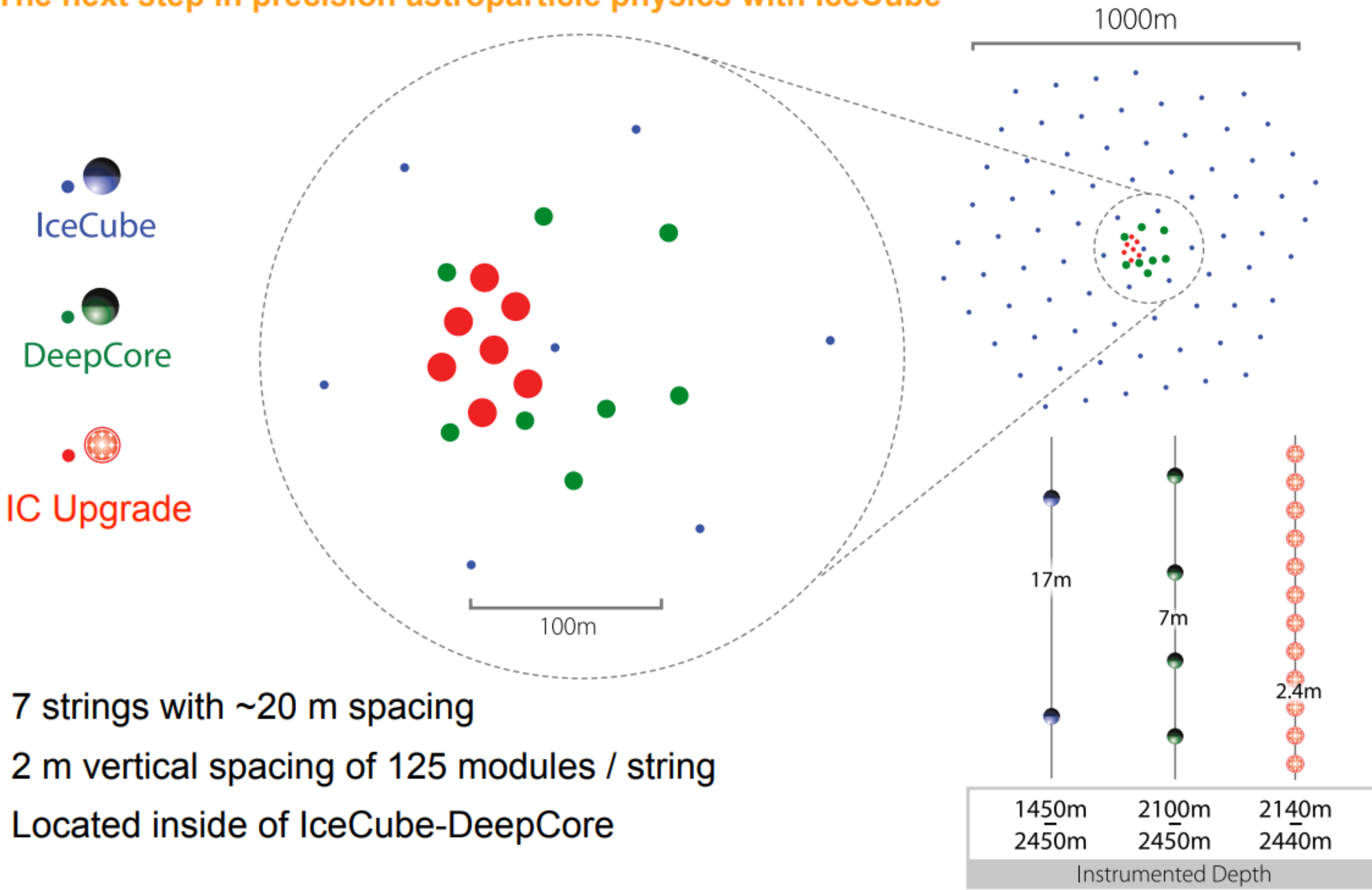
Caveat: need to know neutrino source initial flavor composition to get **robust** bounds with current limits.

de Salas, et al. Phys. Rev. D94 (2016) 123001

Capozzi et al. 1804.05117

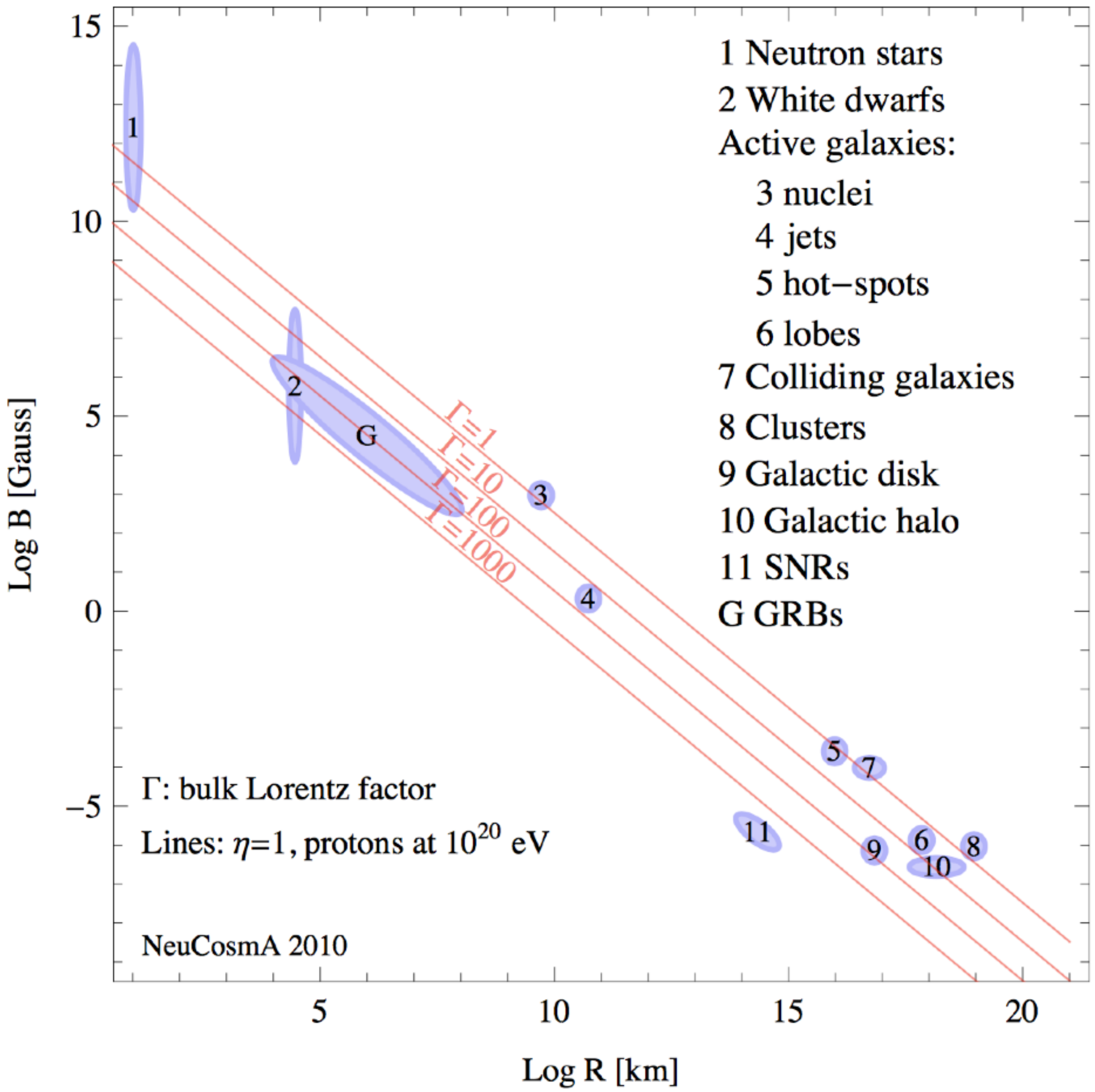
The IceCube Upgrade

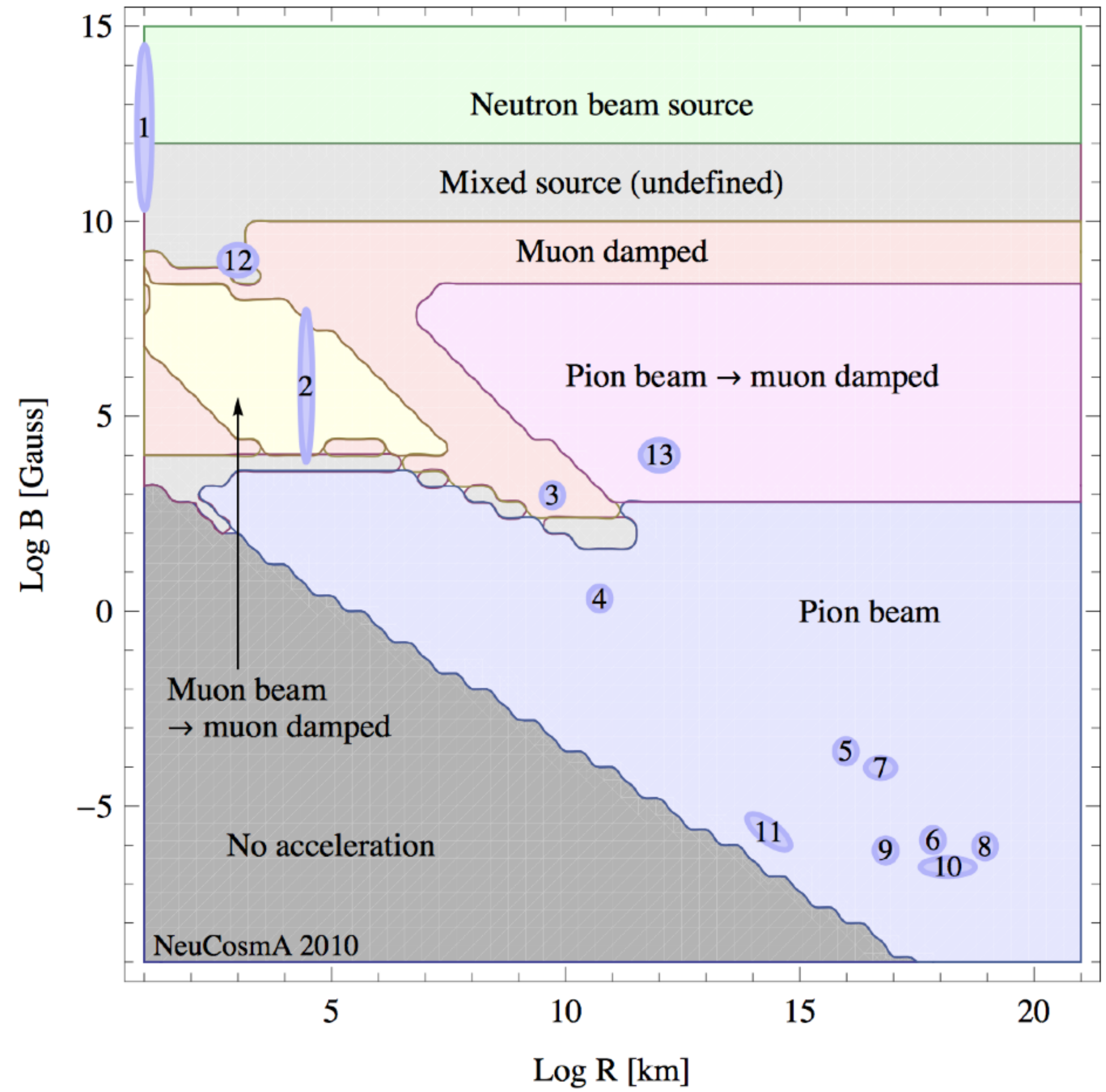
The next step in precision astroparticle physics with IceCube



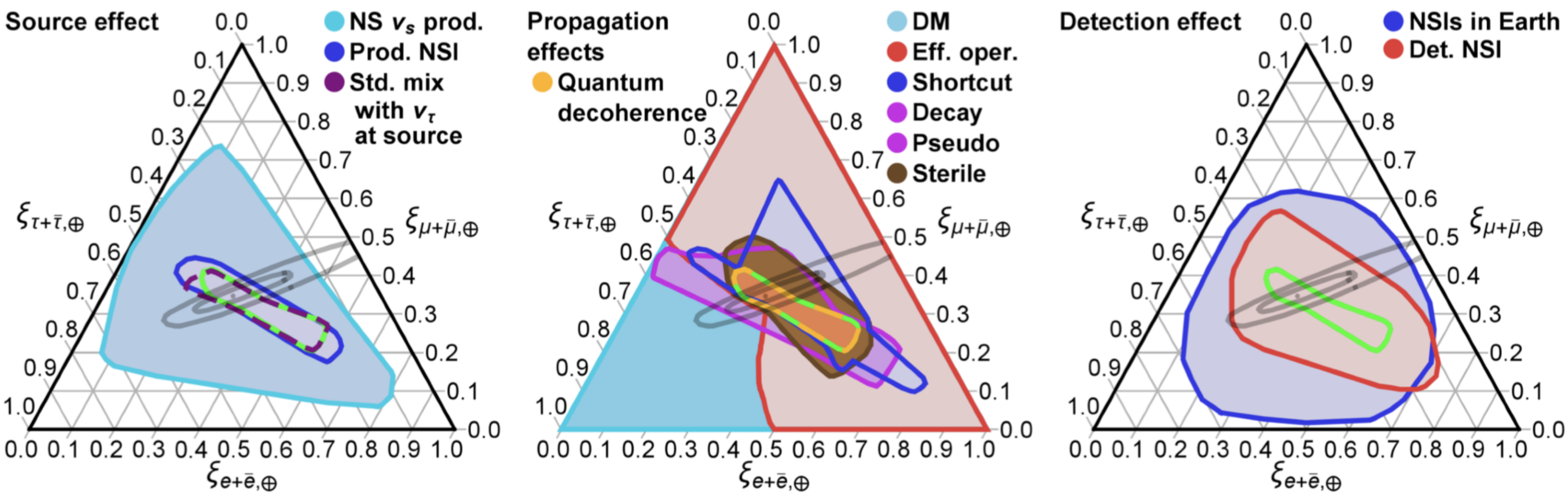
- 7 strings with ~20 m spacing
- 2 m vertical spacing of 125 modules / string
- Located inside of IceCube-DeepCore

Sources of Astrophysical Neutrinos

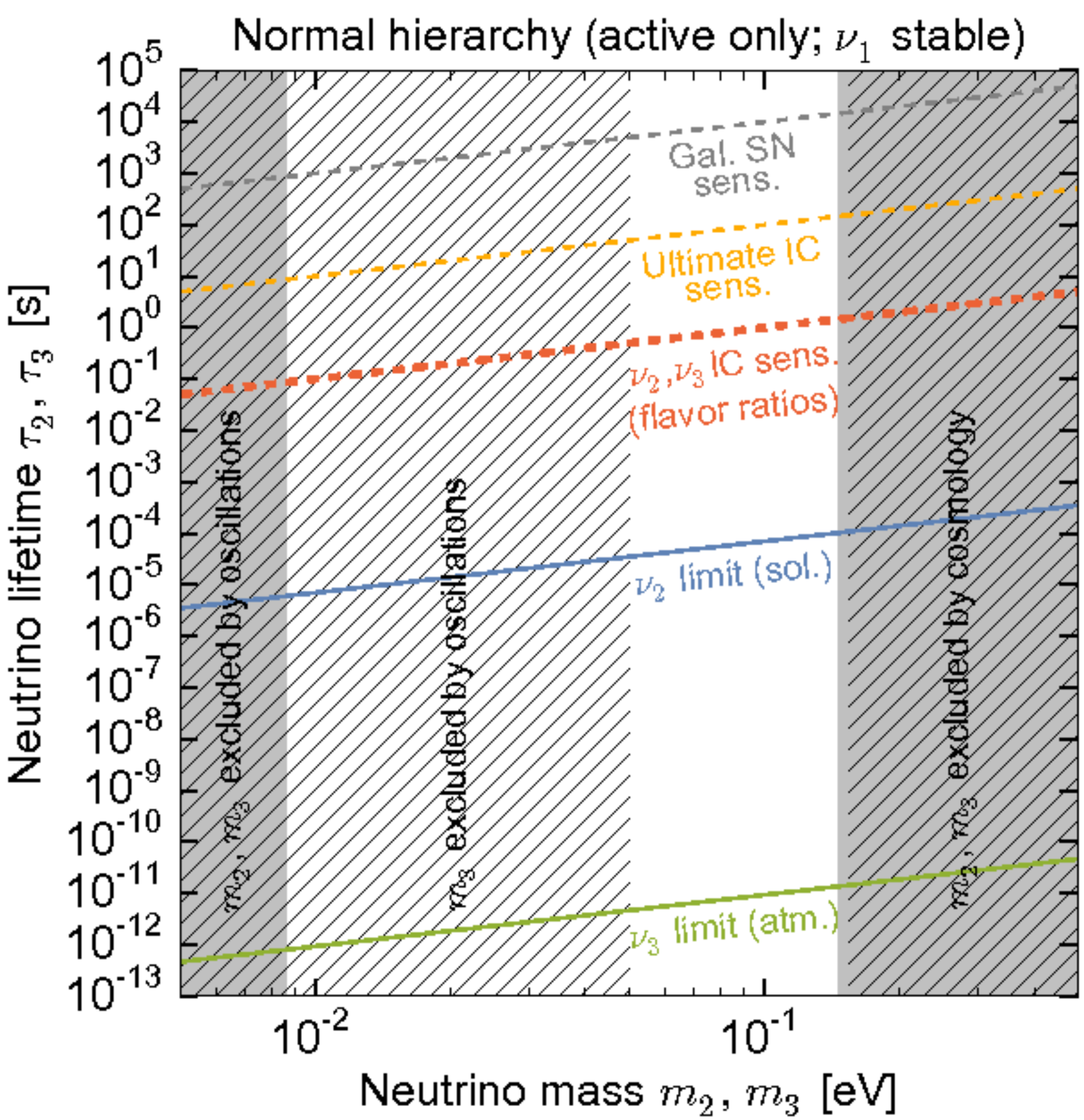


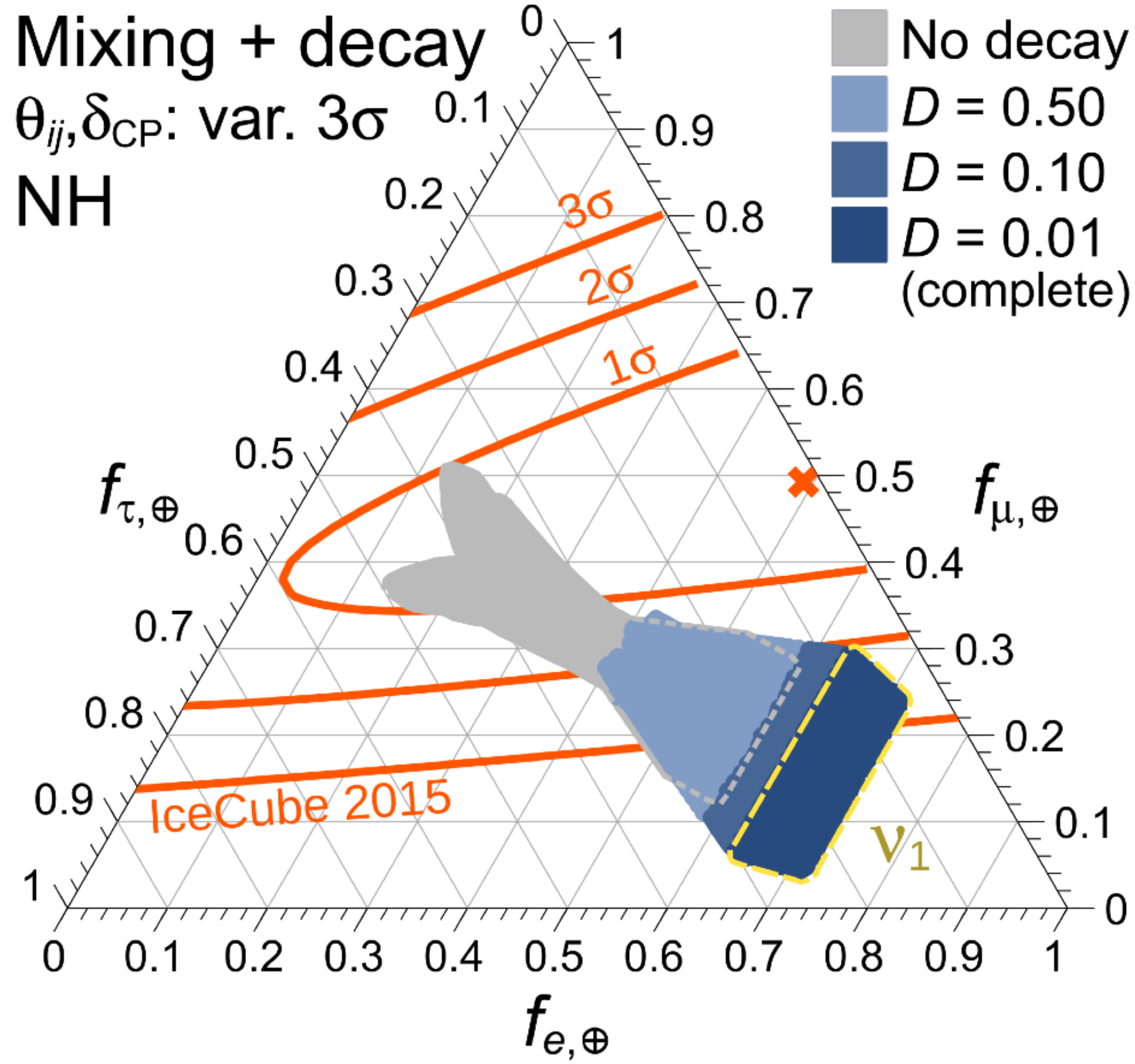


(arXiv:1007:0006)



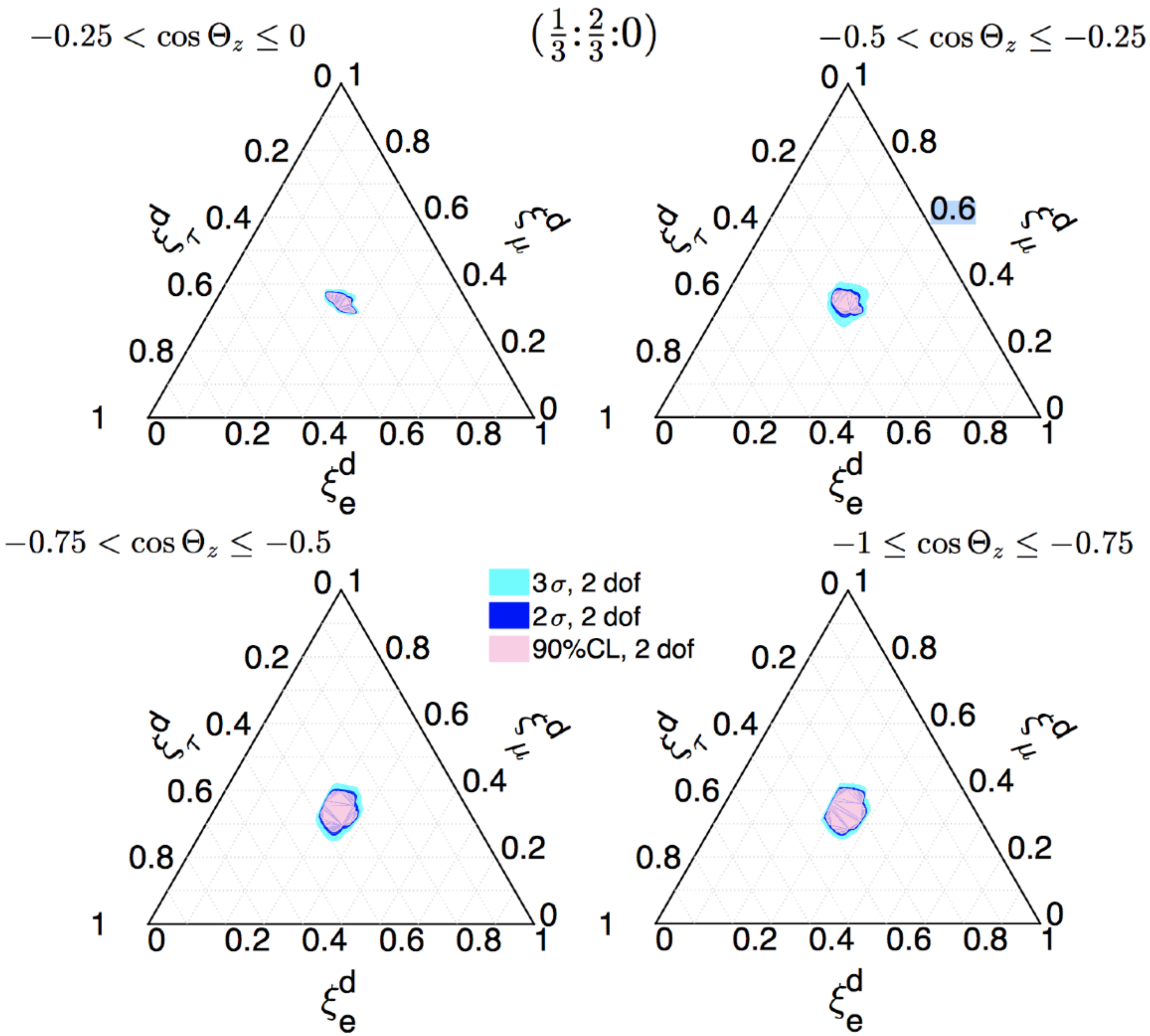
Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684

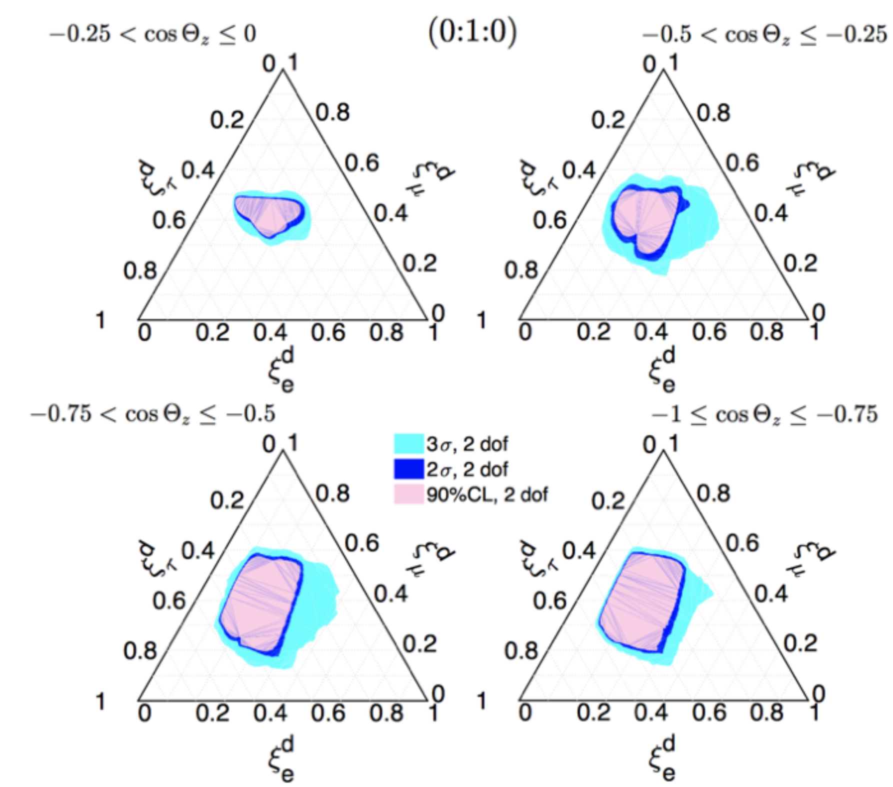




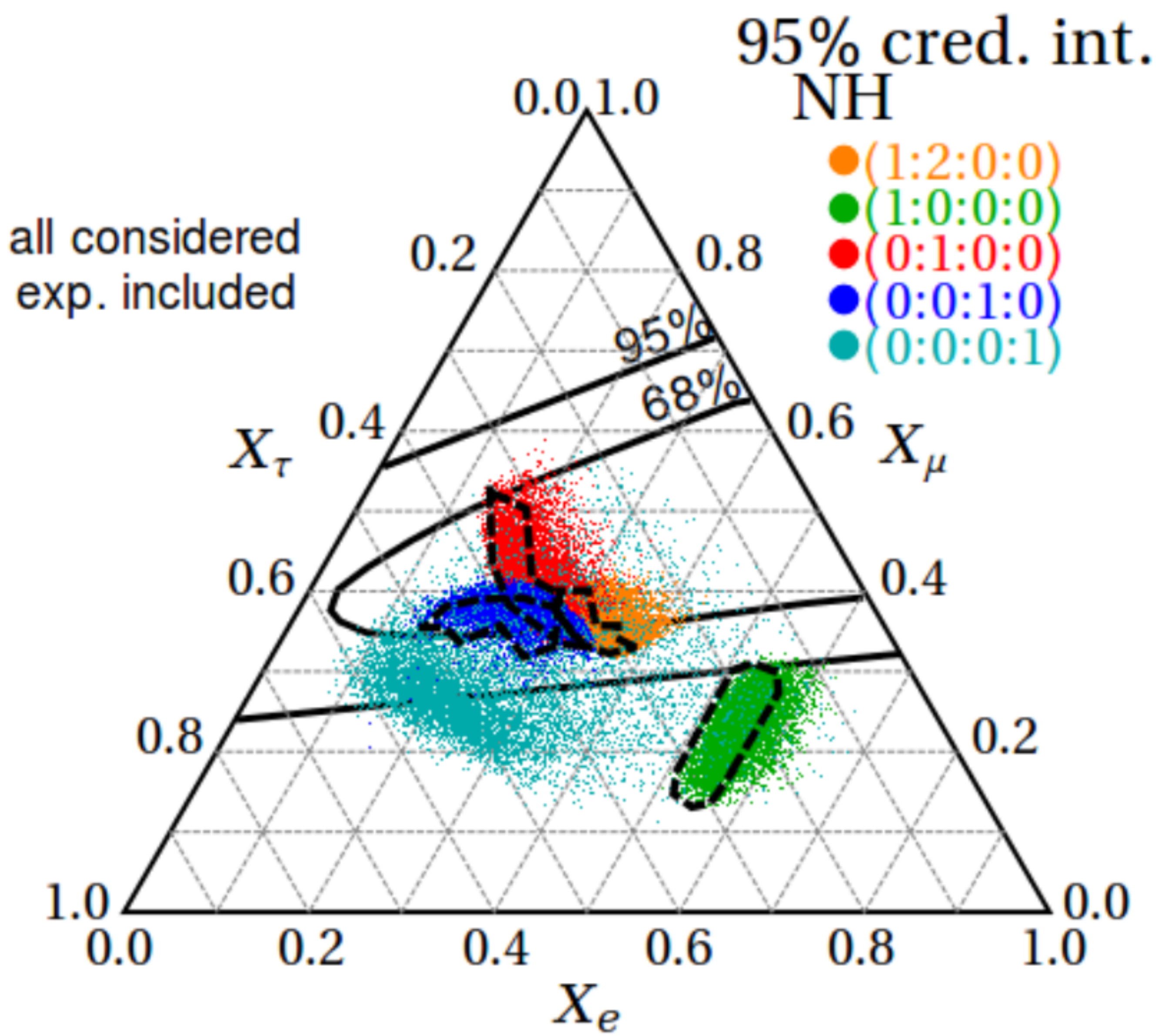
M. Bustamante, J. Beacom, K. Murase (1610.02096)

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





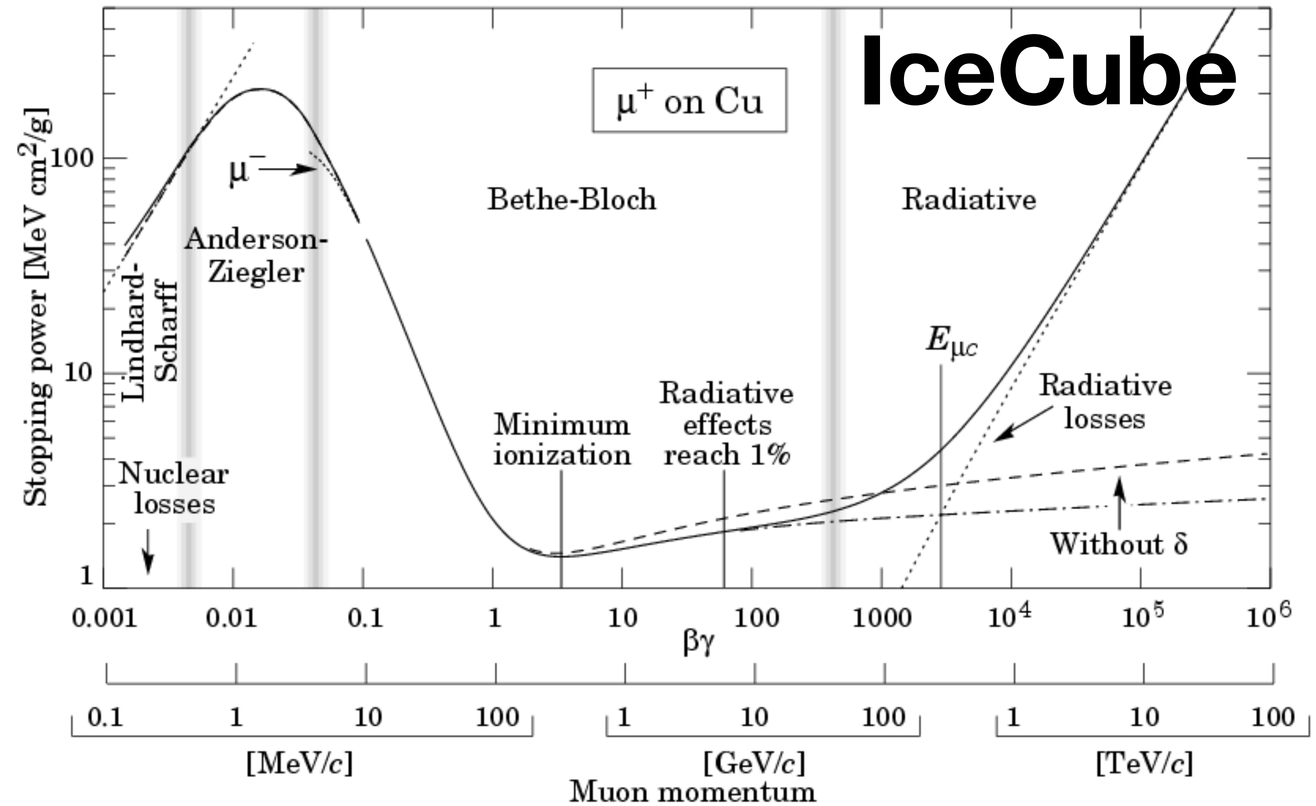
Gonzalez-Garcia et al. Astroparticle Physics 84 (2016) 15-22



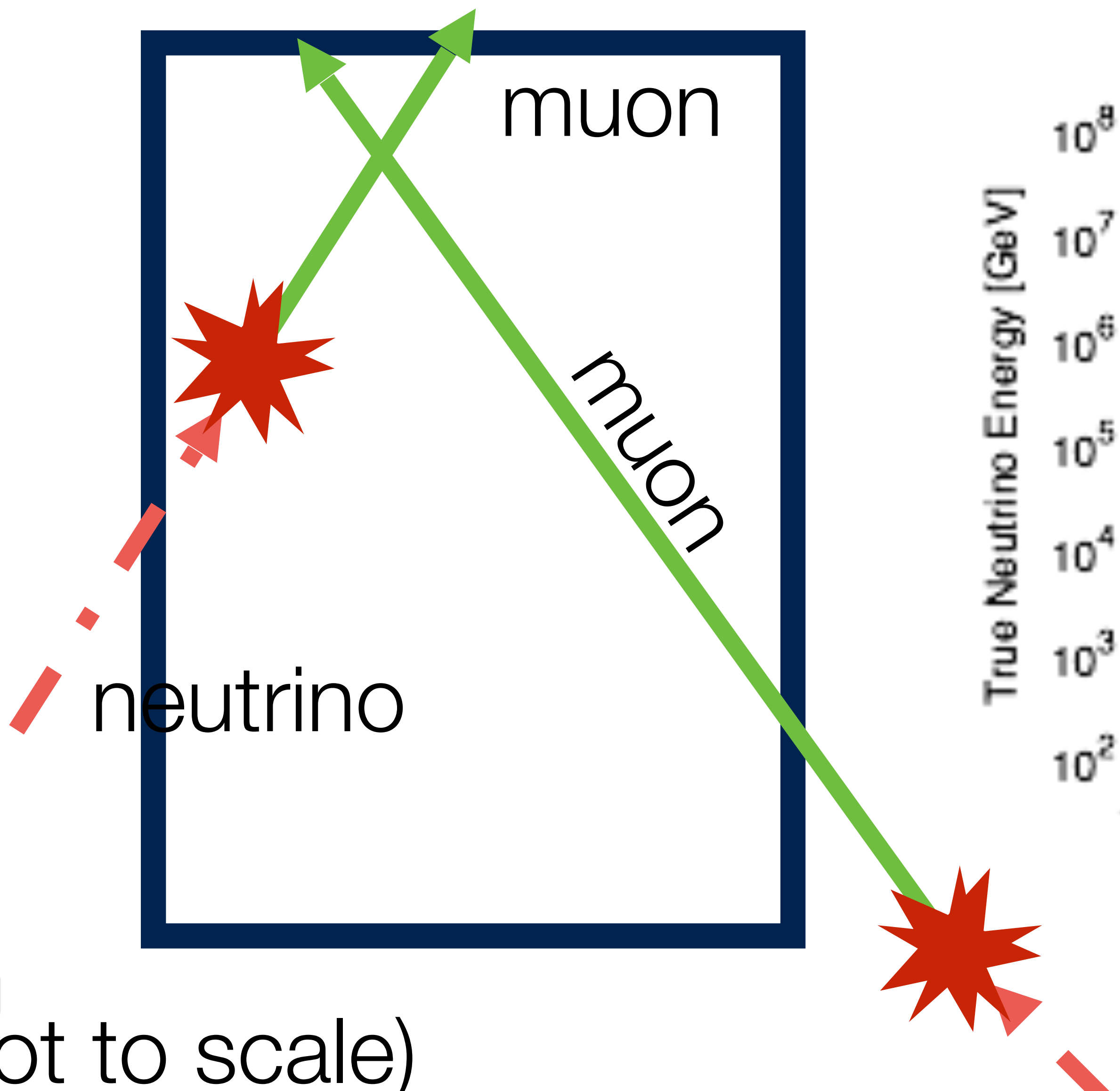
- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

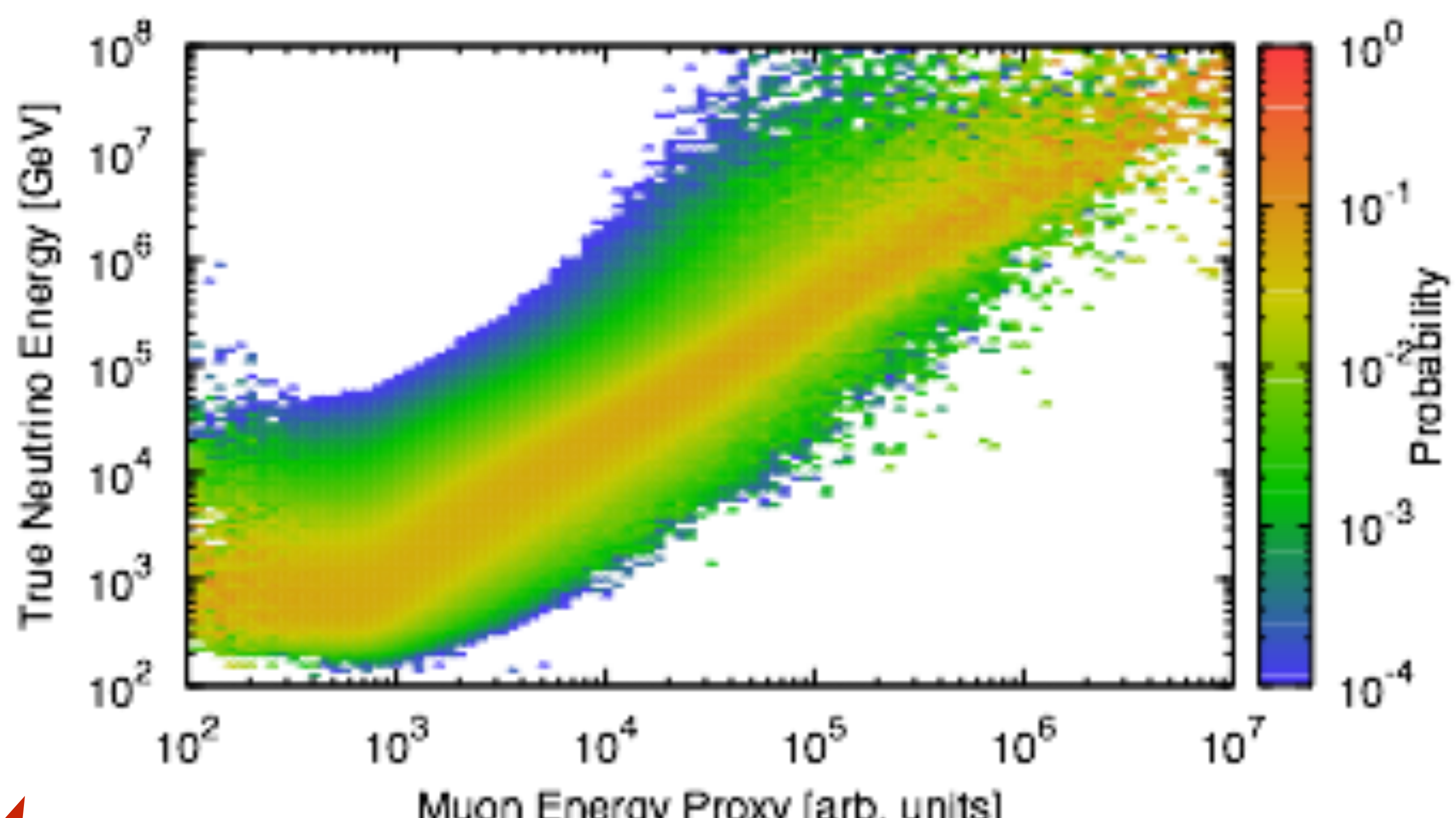
Brdar et al. JCAP 1701 (2017) no.01, 026

Through-going muons in IceCube



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





(not to scale)

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

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

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

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

back of the envelope sensitivity

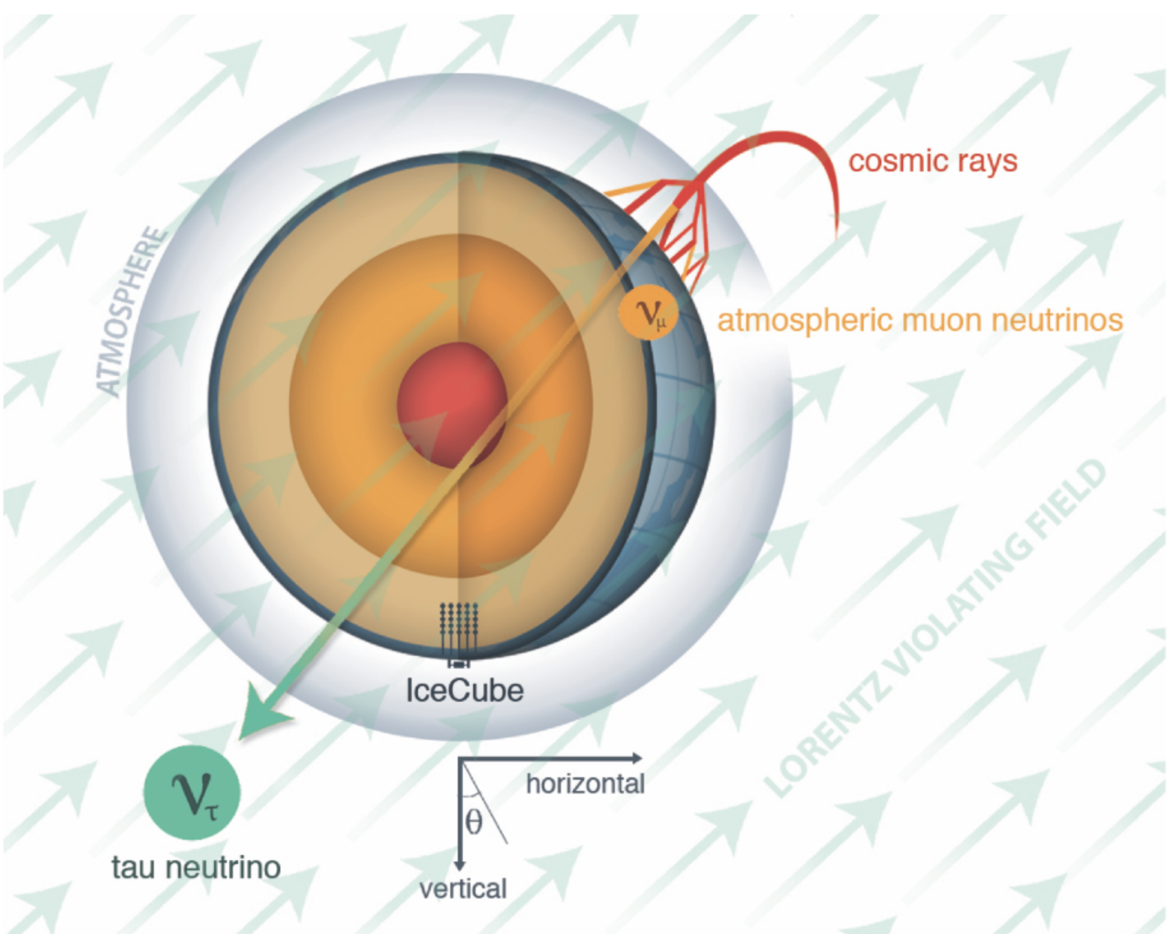
$$\tilde{a}^{T} \sim 10^{-24}\text{GeV} \to 10^{-27}\text{GeV}$$

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

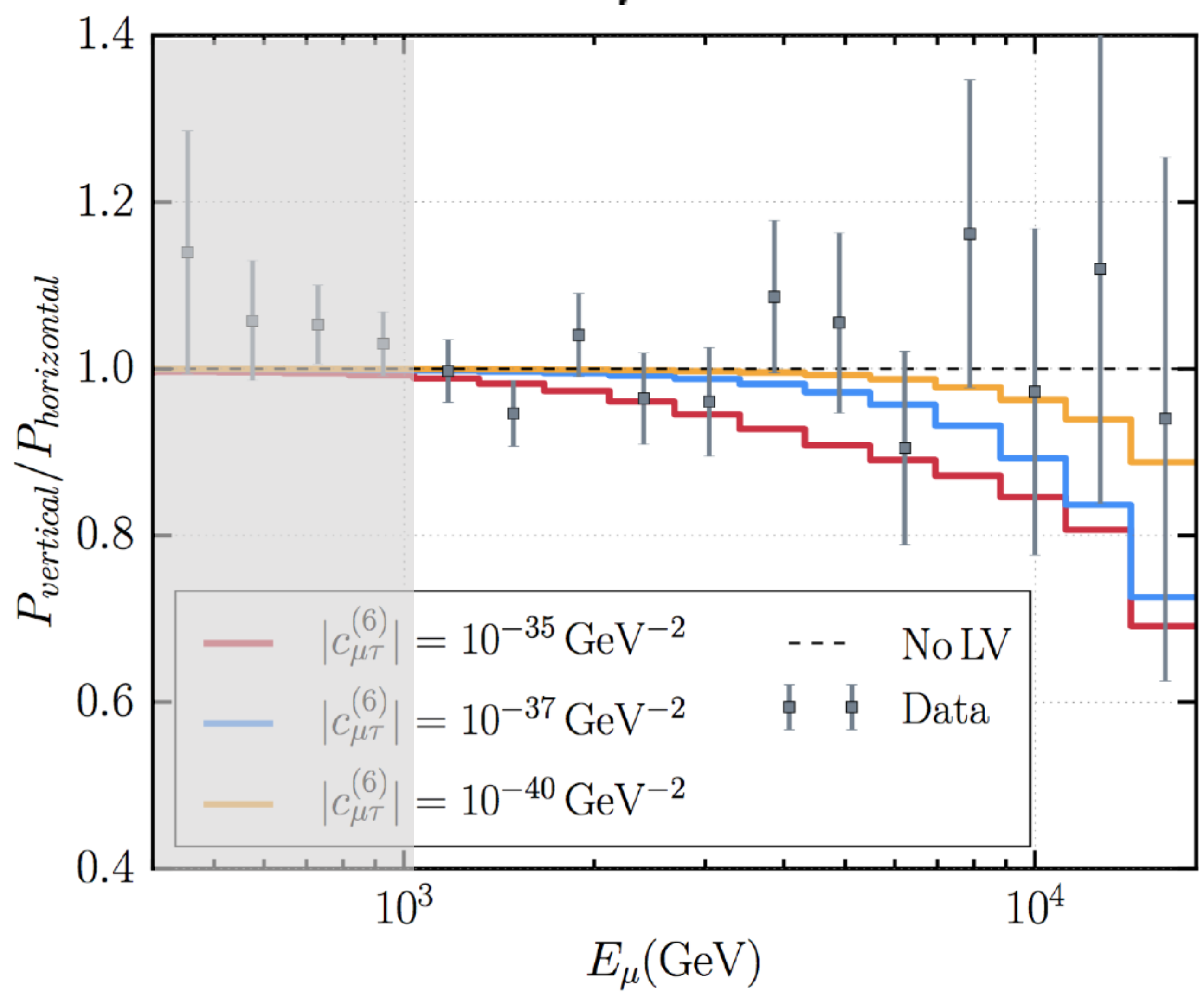
Search for Lorentz Violation with High-energy Atmospheric Neutrinos

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

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



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



Lorentz violation changes the ratio of horizontal to vertical events.

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

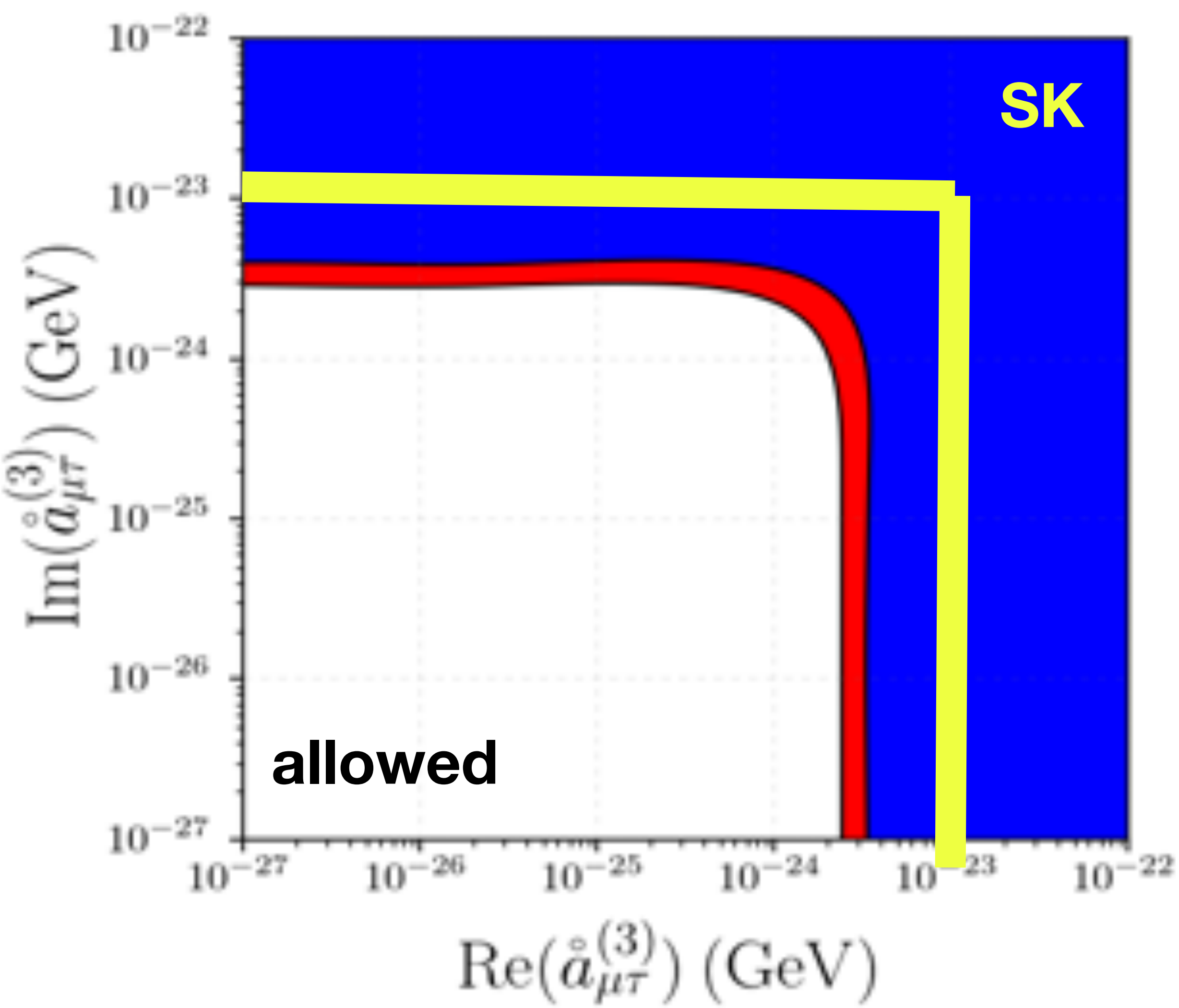
Our results in the maximum-flav violating assumption

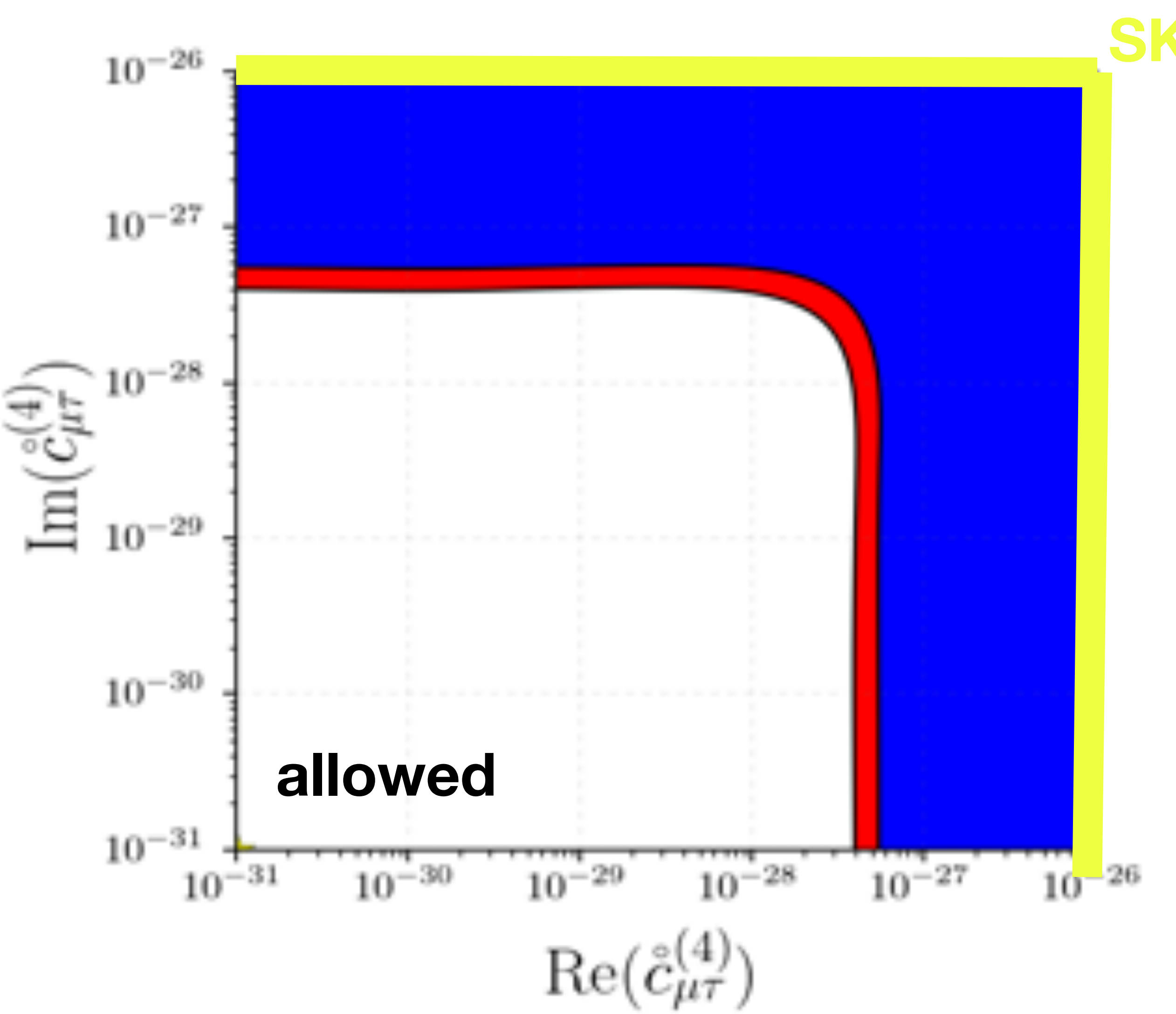
$$\begin{pmatrix} 0 & c_{e\mu}^{TT} & c_{e\tau}^{TT} \\ (c_{e\mu}^{TT})^* & 0 & c_{\mu\tau}^{TT} \\ (c_{e\tau}^{TT})^* & (c_{\mu\tau}^{TT})^* & 0 \end{pmatrix}$$

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

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

SuperKamiokande Collaboration. arXiv:1410.4267





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

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

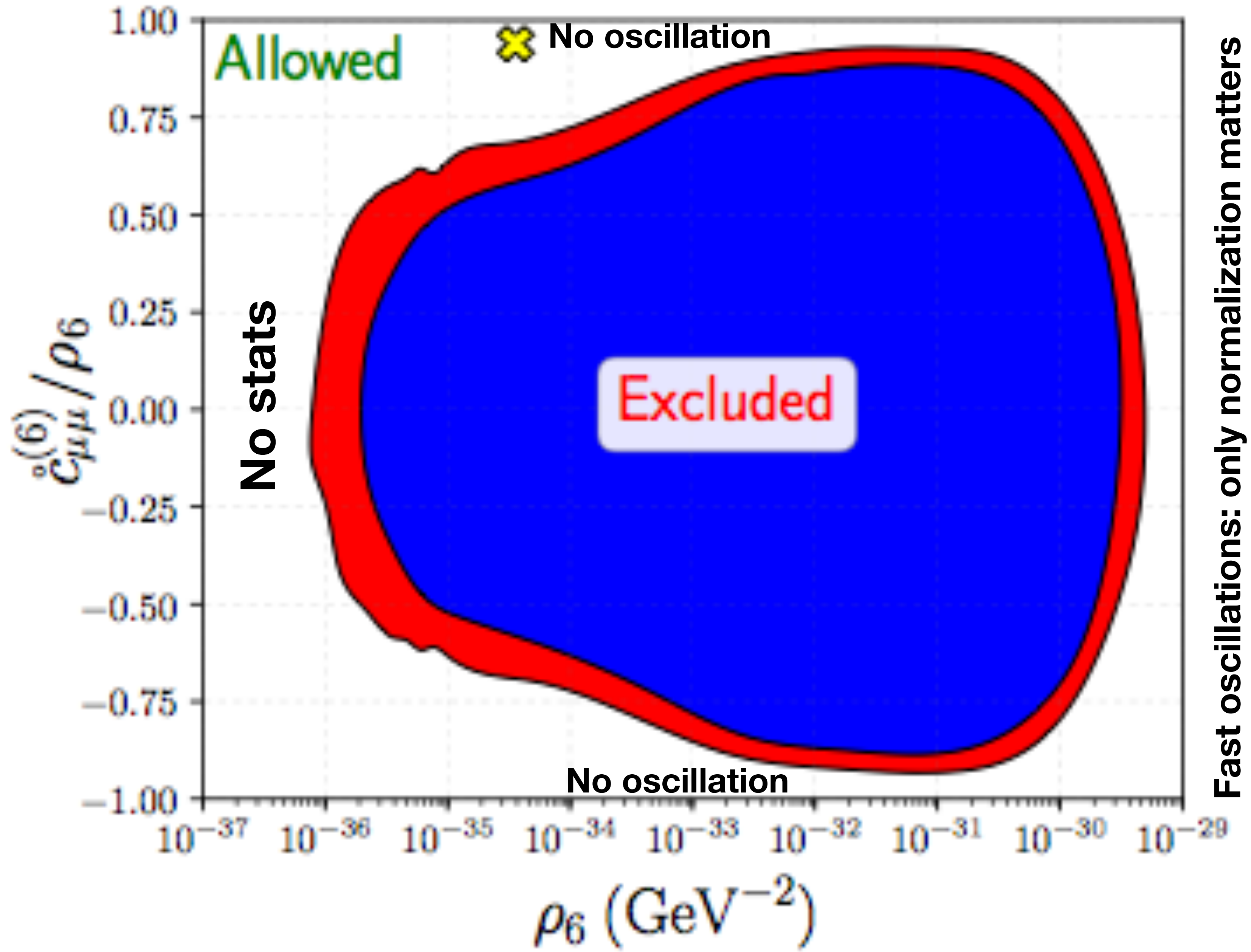
Anatomy of the dim-6 operator constraint

$$H \sim \frac{m^2}{2E} - E^3 \cdot \mathring{c}^{(6)}$$

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

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

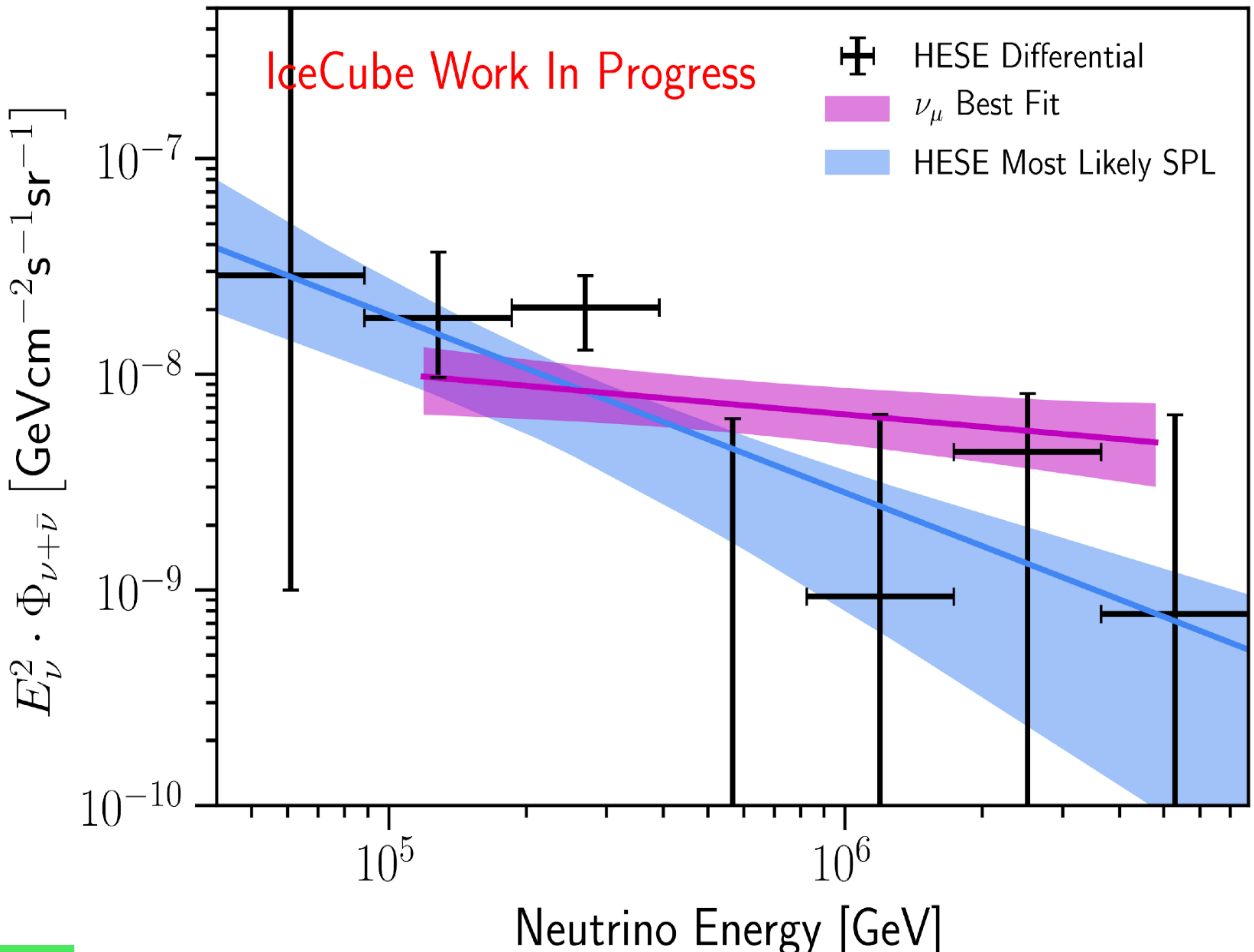
$$P(\nu_\mu \to \nu_\tau) \sim \left(\frac{\mathring{a}^{(d)}_{\mu\tau} - \mathring{c}^{(d)}_{\mu\tau}}{\rho_d}\right)^2 \sin^2(L\rho_d \cdot E^{d-}$$



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

IceCube Collaboration, arXiv:1709.03434

HESE and through-going muons

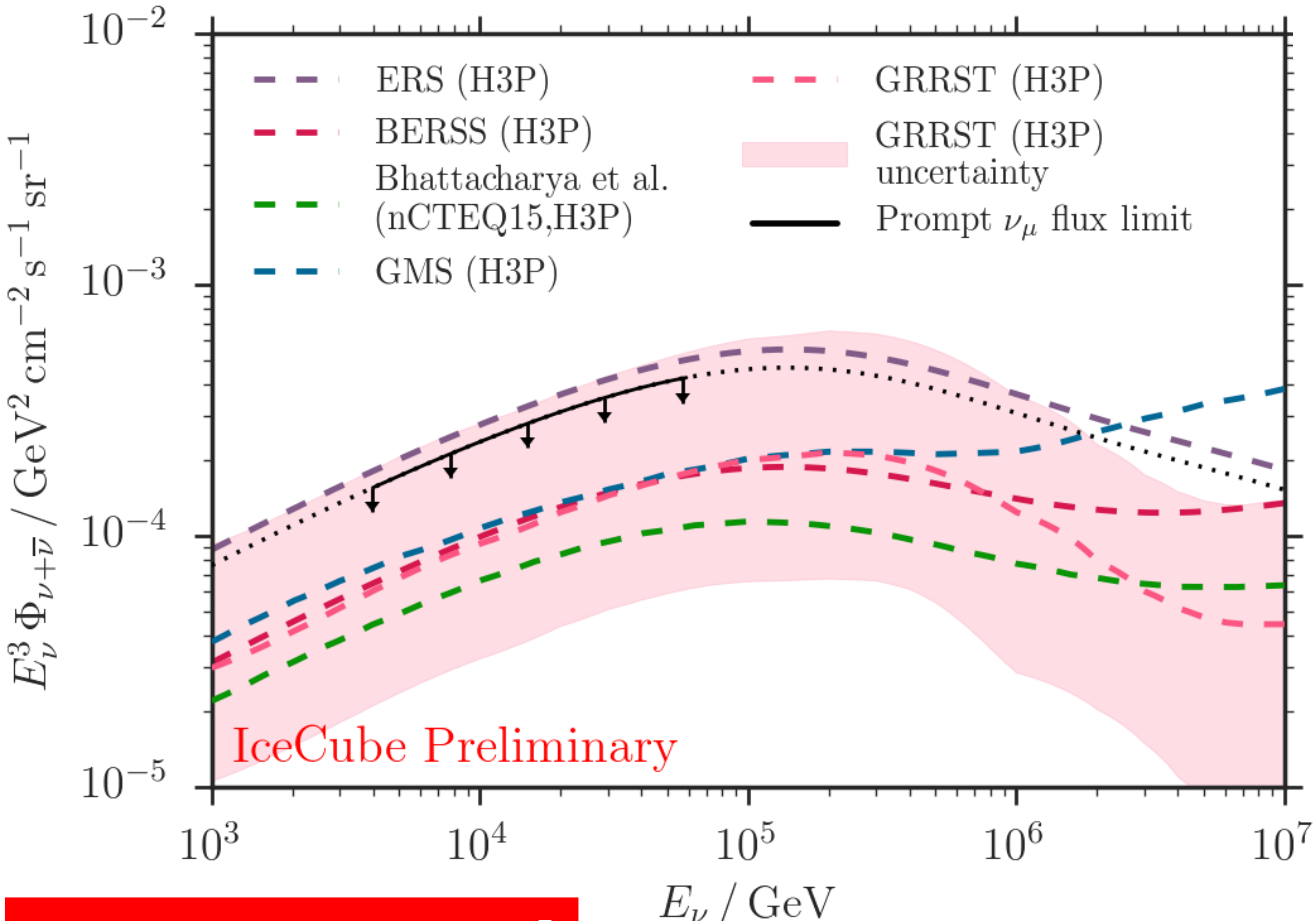


Data

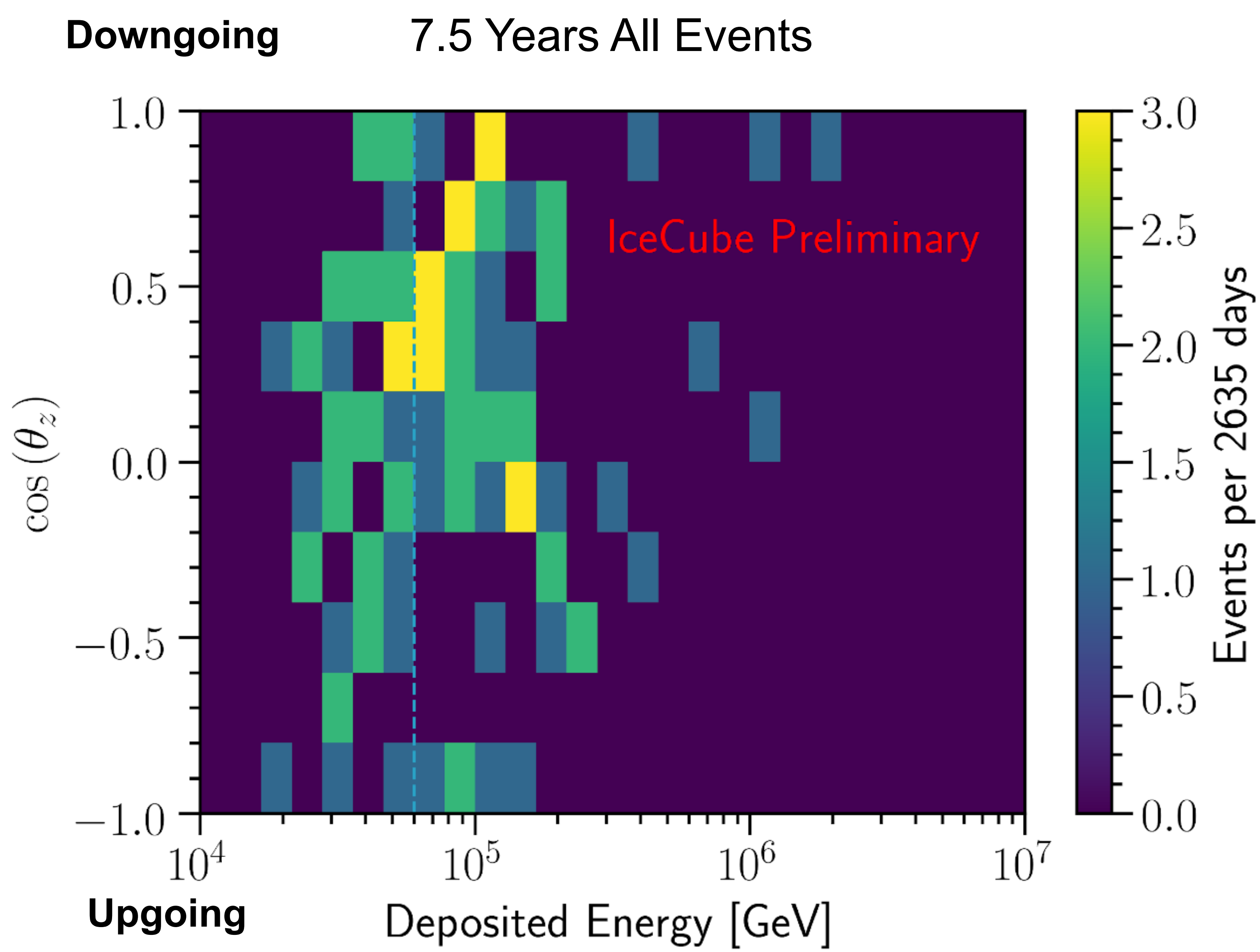
Also, constraints from the Northern Sky

Limits from 8 years of through-going muons

No prompt yet!



Prompt < 0.86 ERS

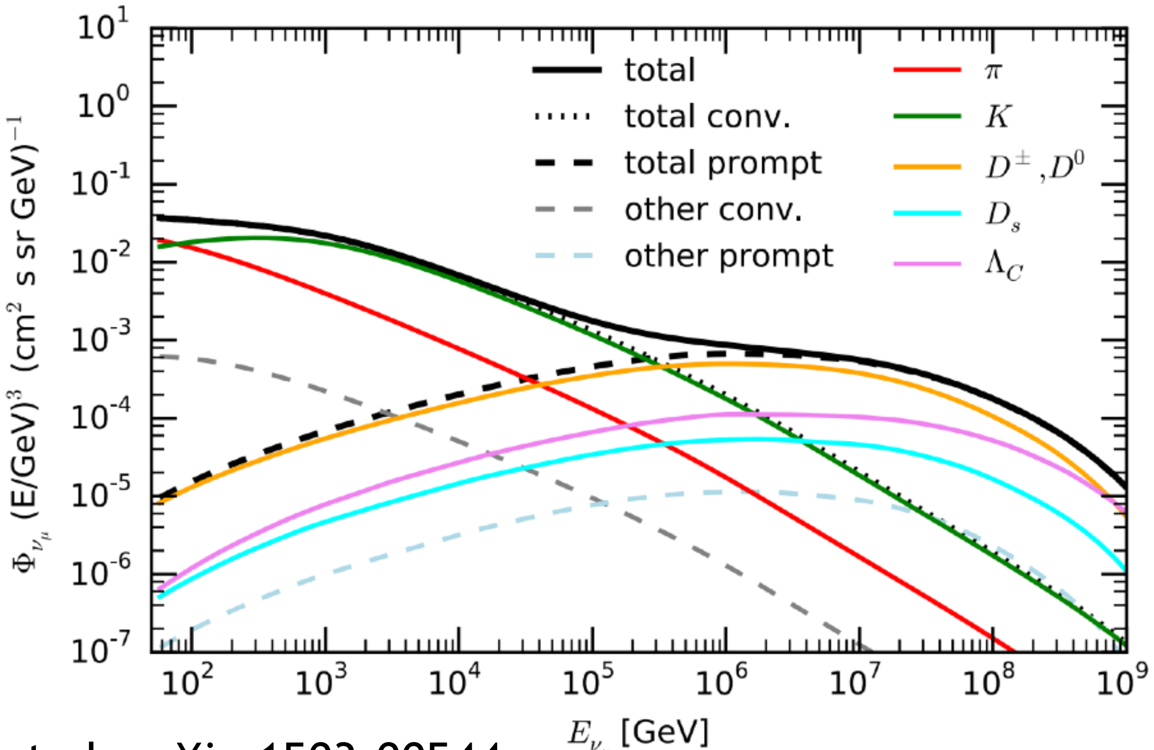


Above 60TeV: 60 events
12 new events in 2016 season
5 new events in 2017 season

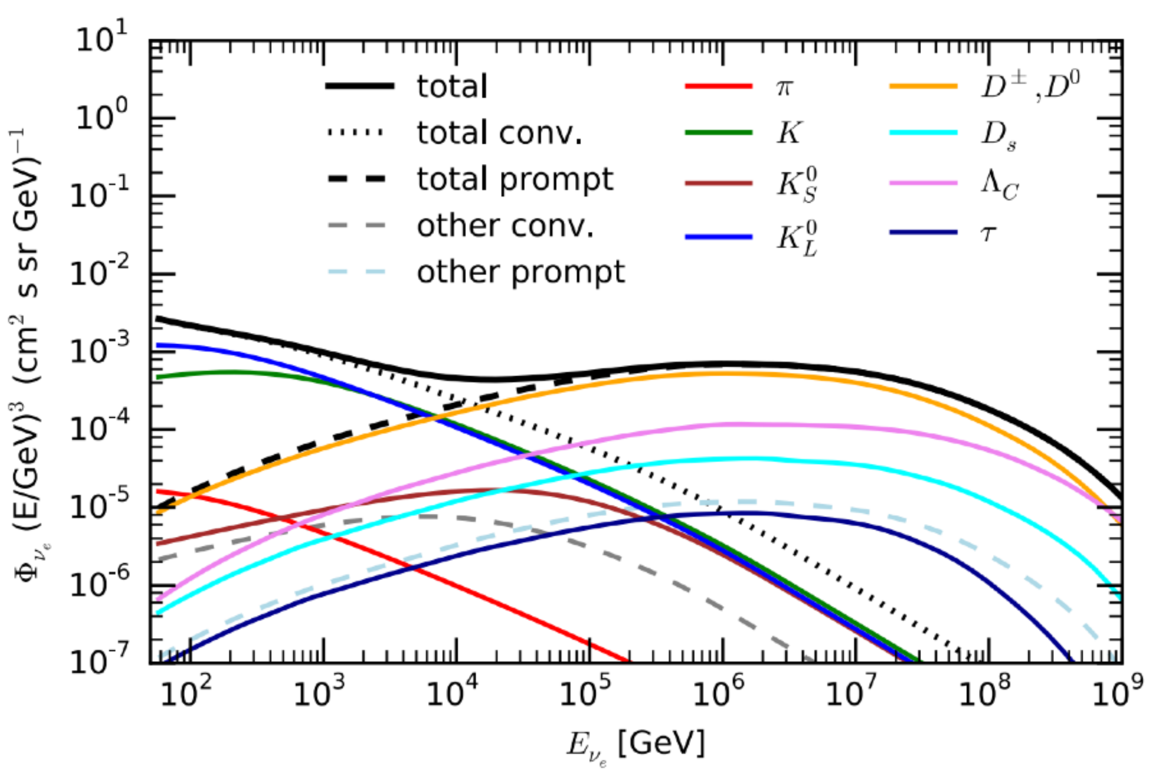
All energies: 102 events
22 new events in 2016 season
9 new events in 2017 season

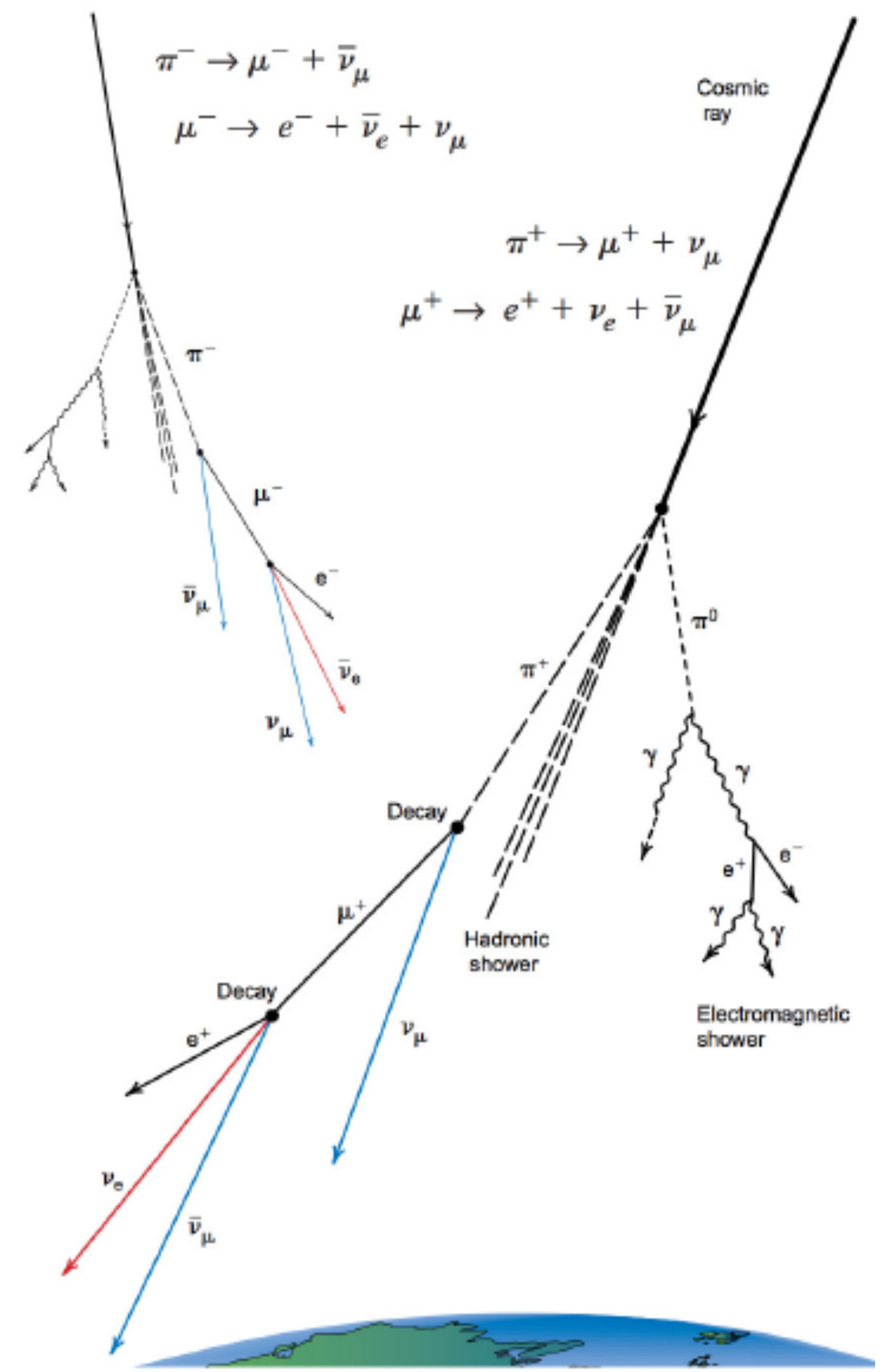
Atmospheric neutrinos

The conventional atmospheric neutrino (muon) flux originates from the decay of $\pi^{\pm}$ and $K^{\pm}$ in the atmosphere.

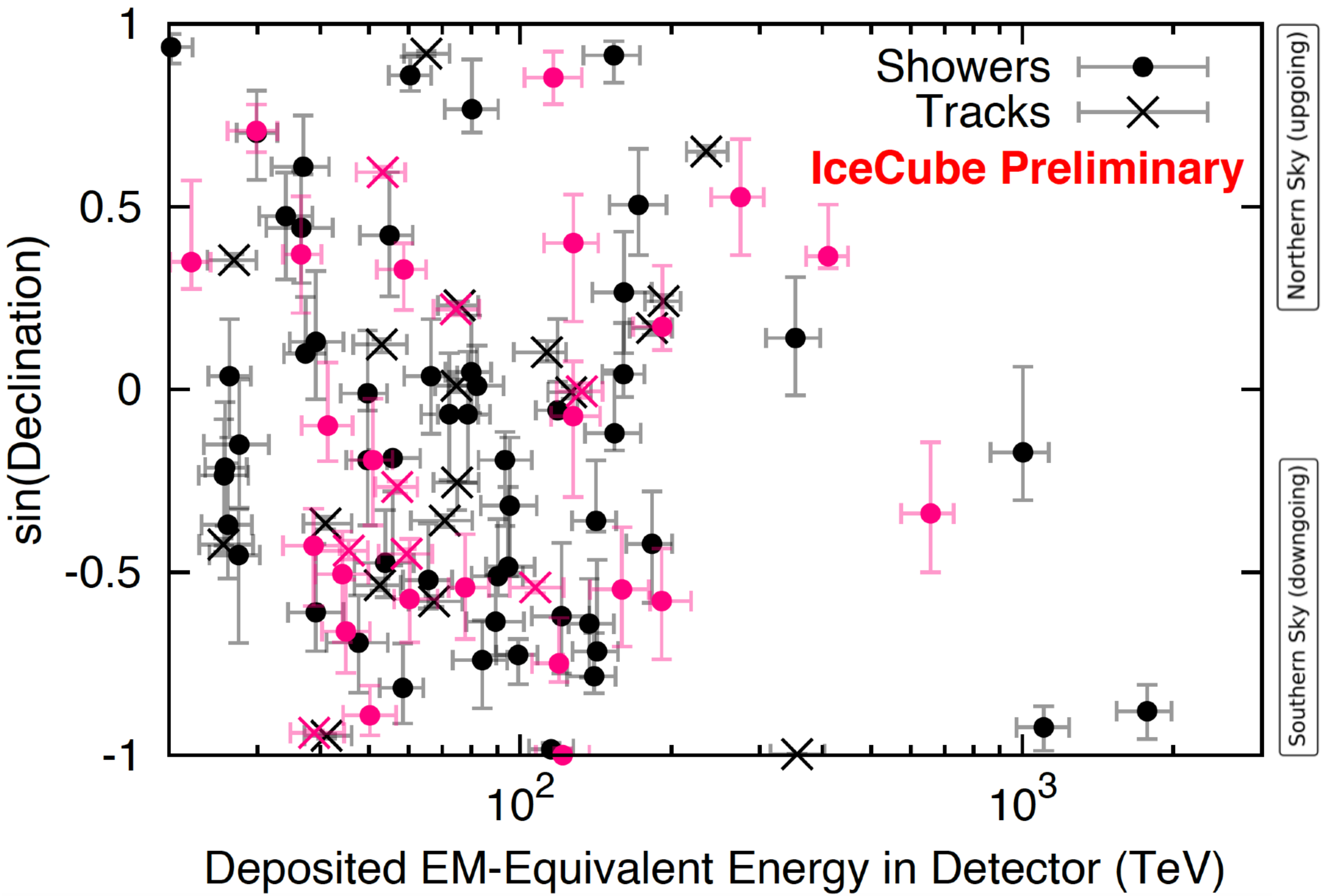


Fedynitch et al. arXiv:1503.00544



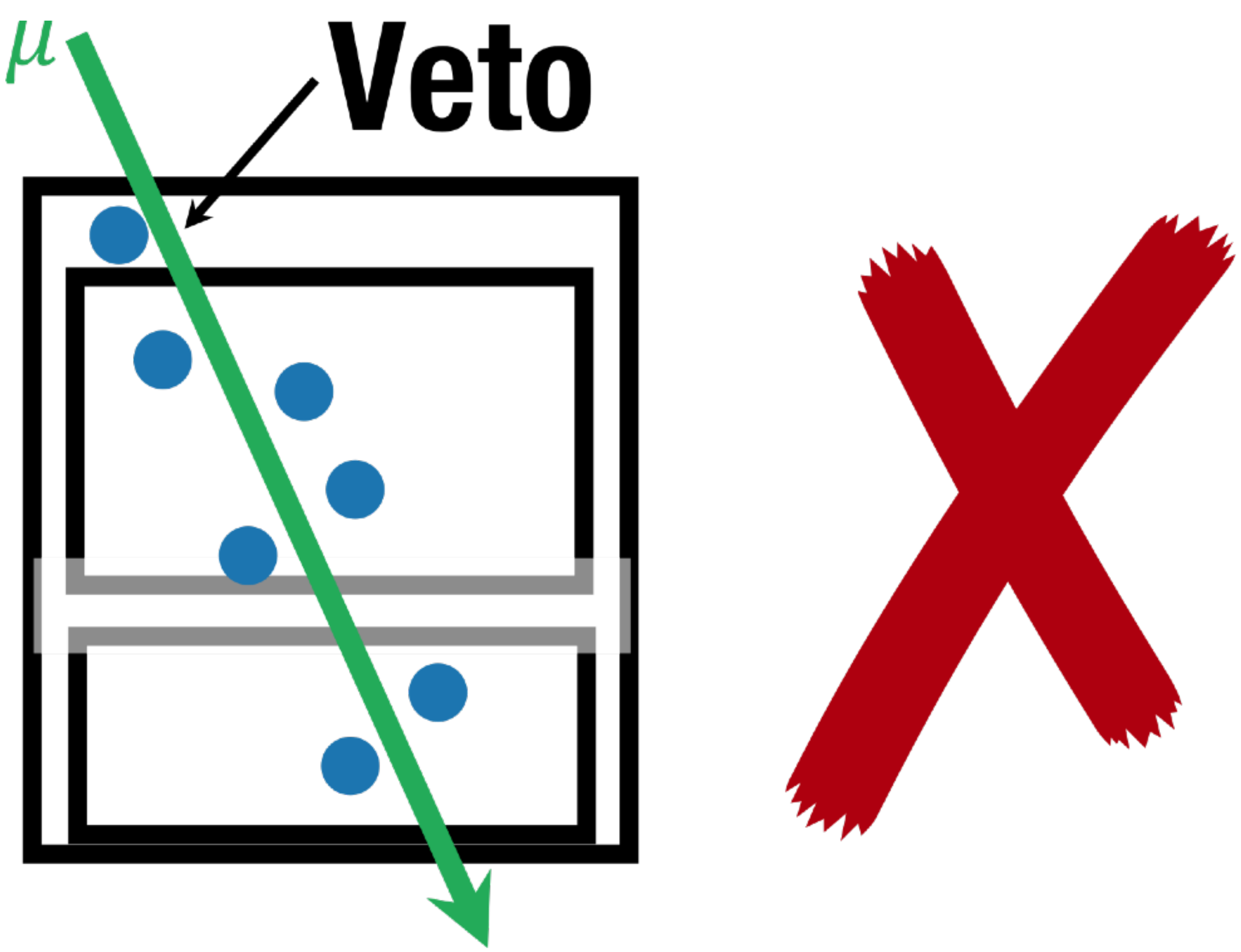


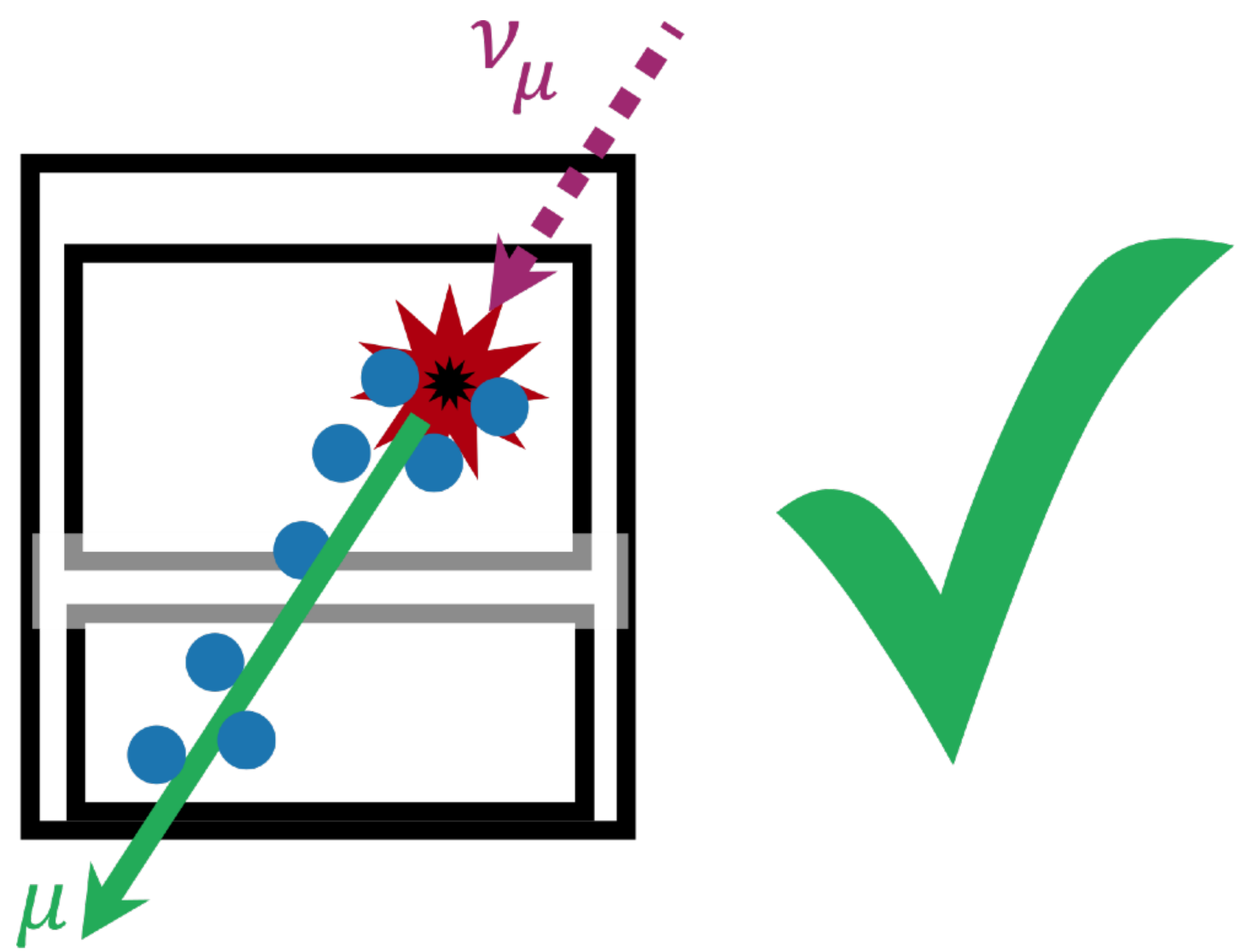
Highest energy neutrinos distribution



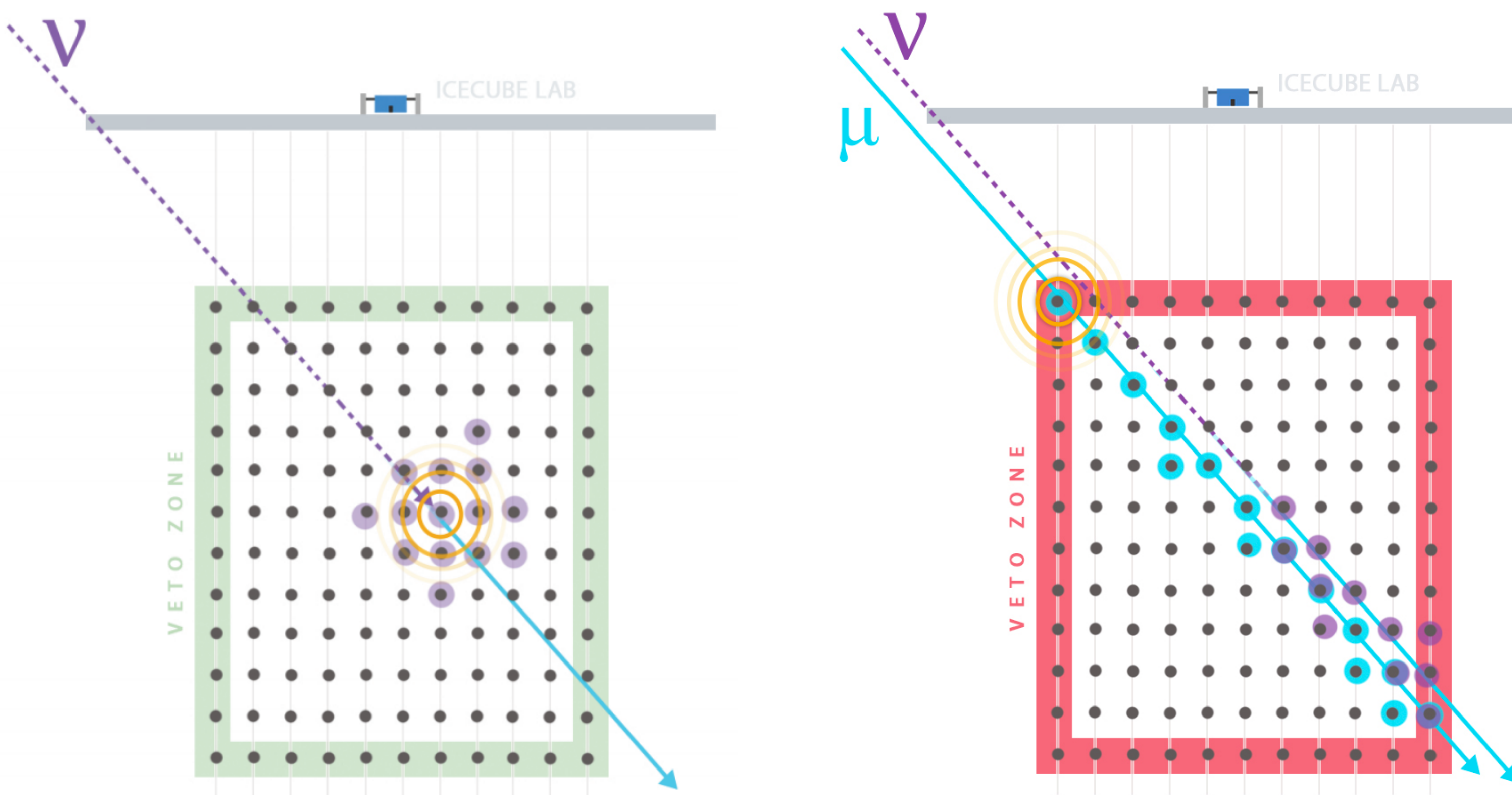
Veto region rejects atmospheric muons and neutrinos

High neutrino signal purity at high energy





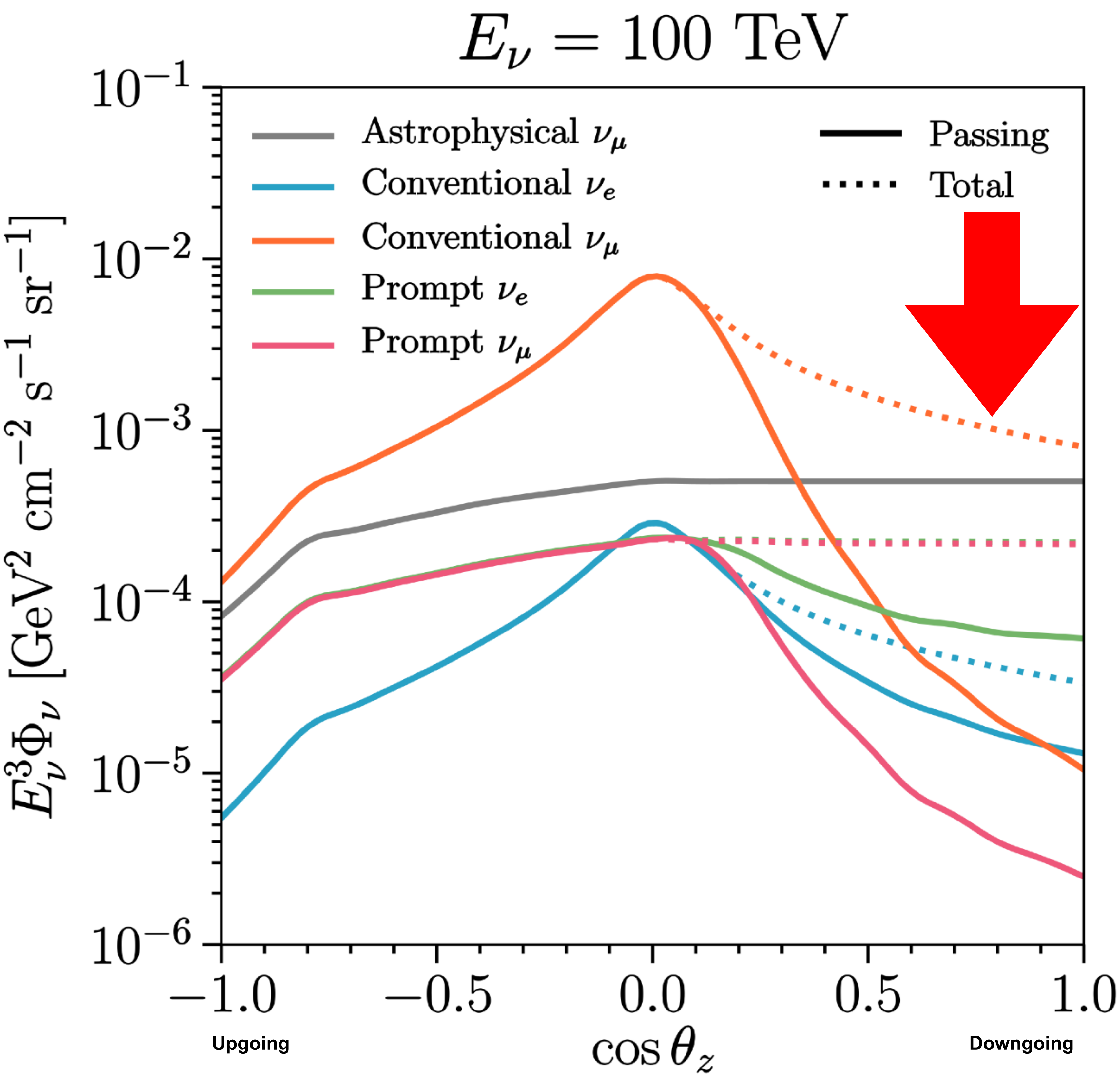
Coincident muons suppress atmospheric neutrino flux!



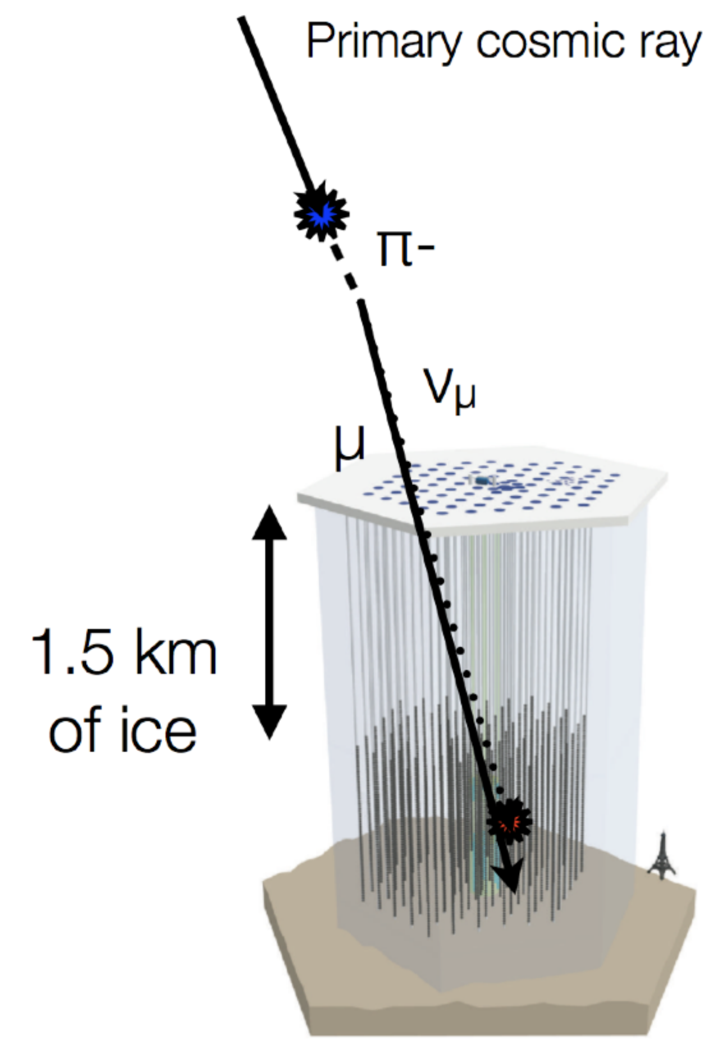
Veto not only suppresses large atmospheric muon flux, but also correlated atmospheric neutrinos produced in the same shower.

CA, Palomares-Ruiz, Schneider, Wille, Yuan
JCAP 1807 (2018) no.07, 047

Coincident muons suppress neutrino flux!

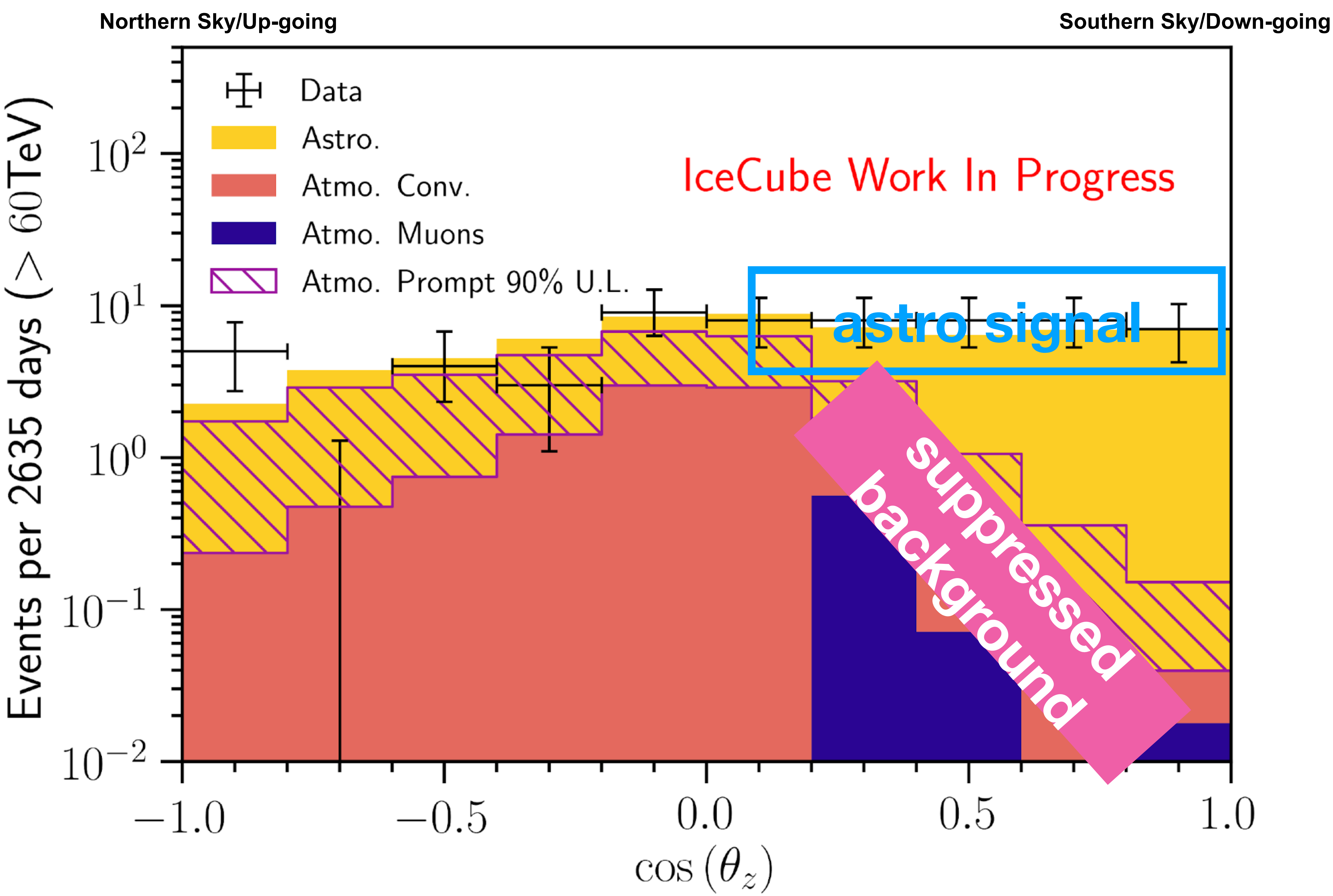


An active muon veto removes down-going atmospheric neutrinos.

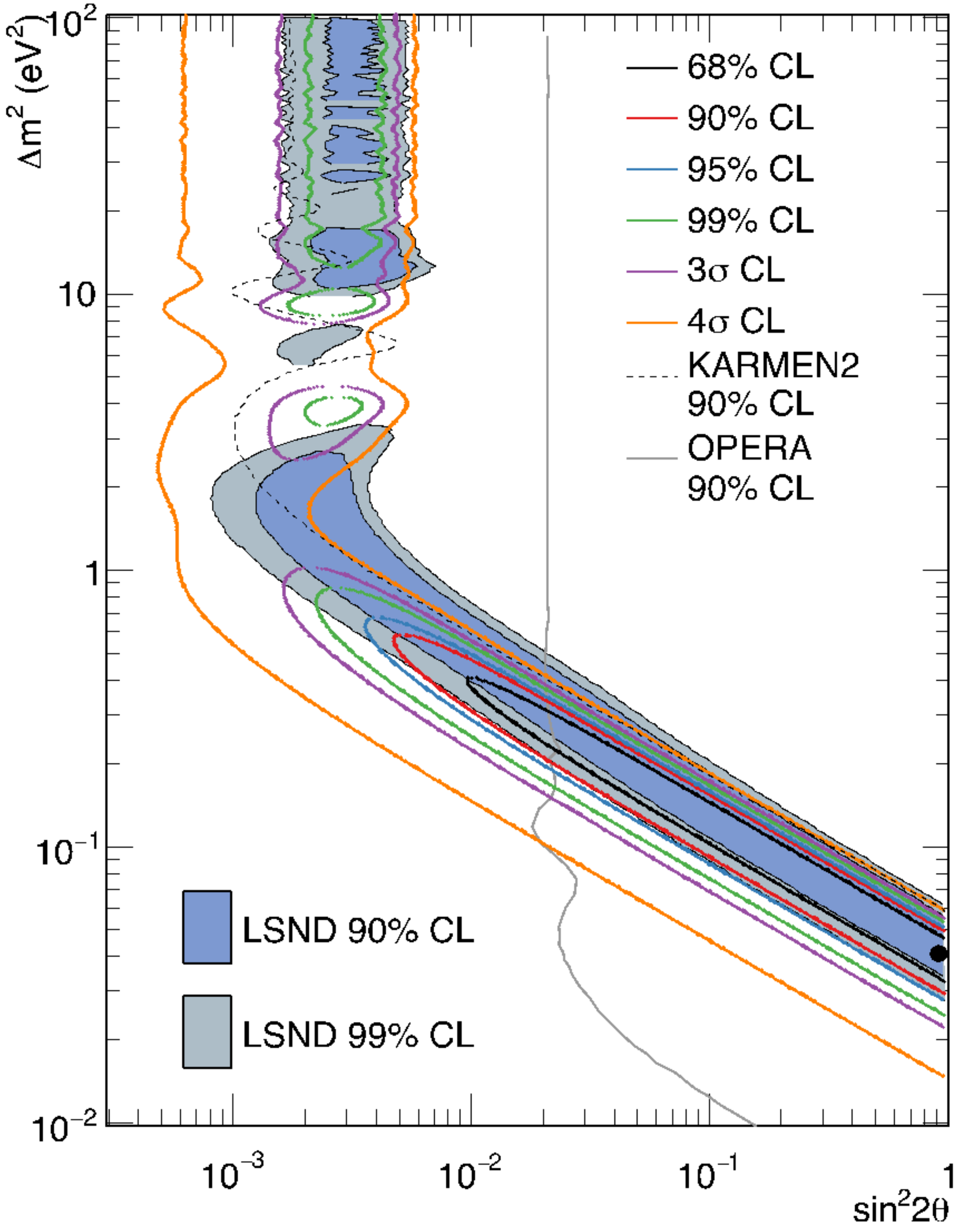


CA, Palomares-Ruiz, Schneider, Wille, Yuan
JCAP 1807 (2018) no.07, 047

Angular distribution of highest-energy neutrinos

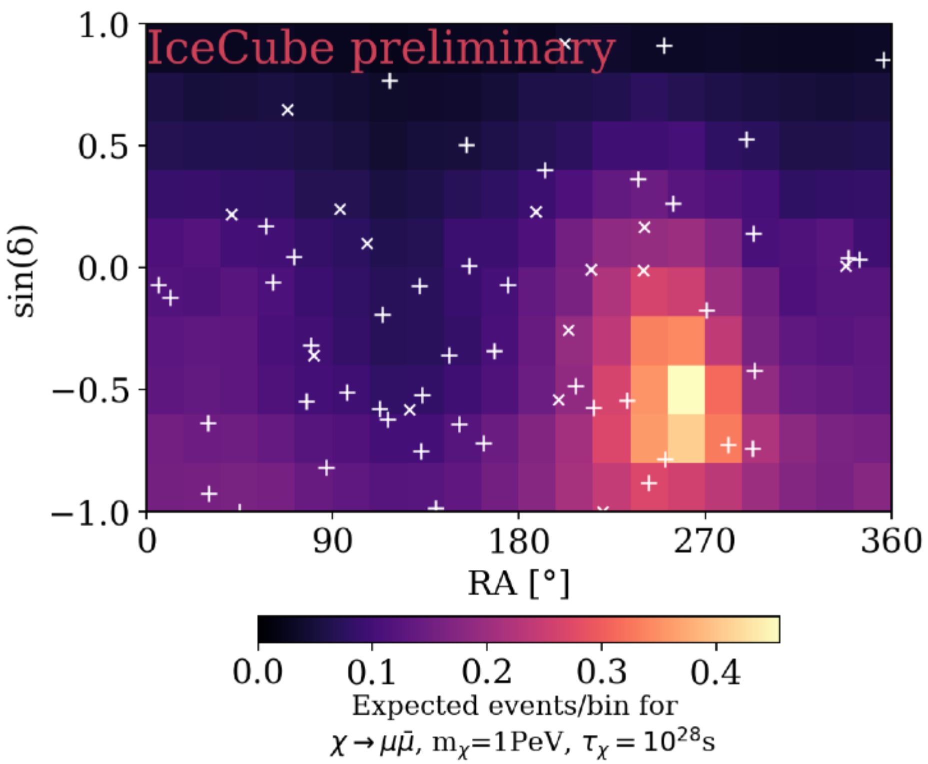


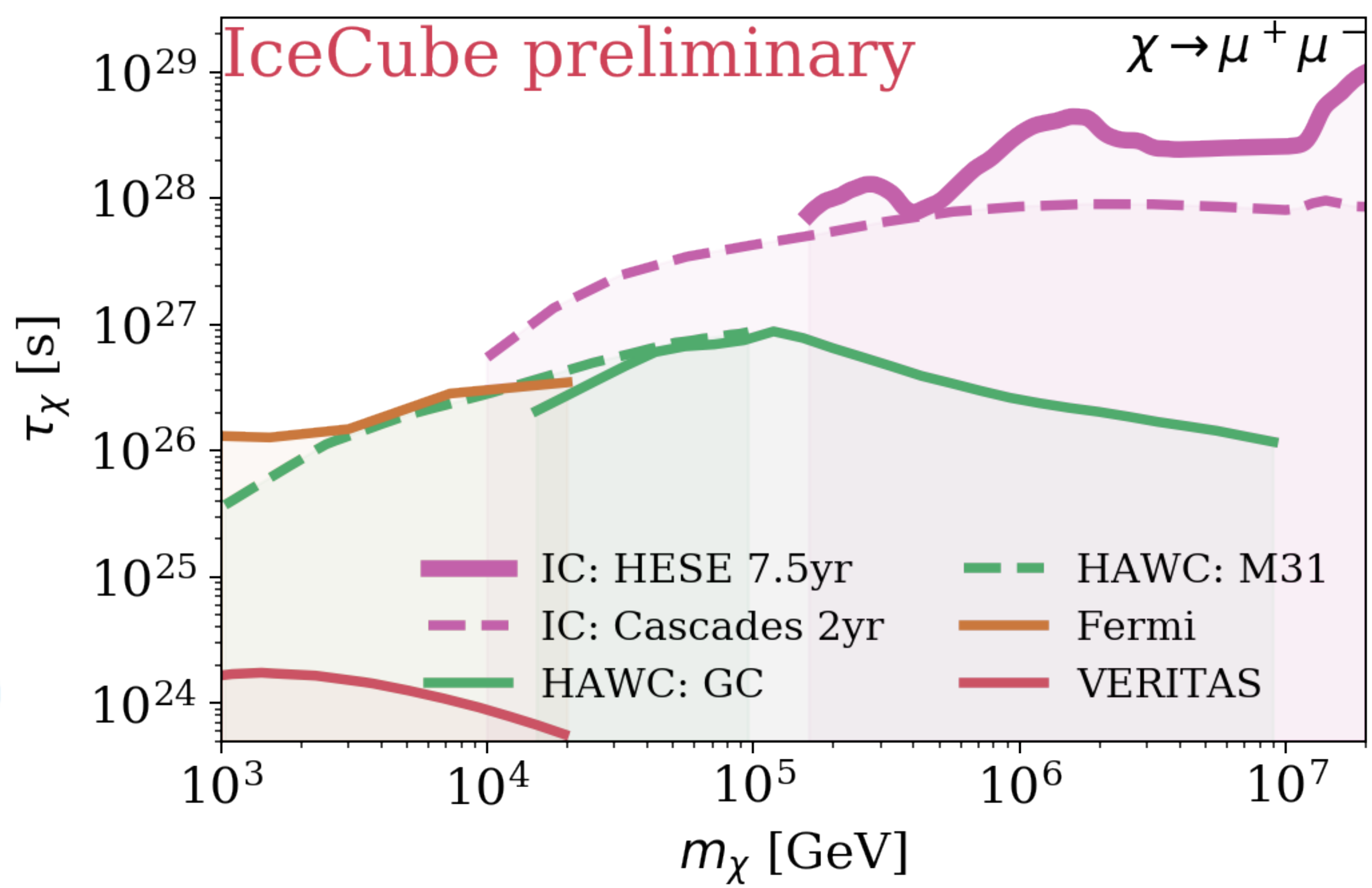
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

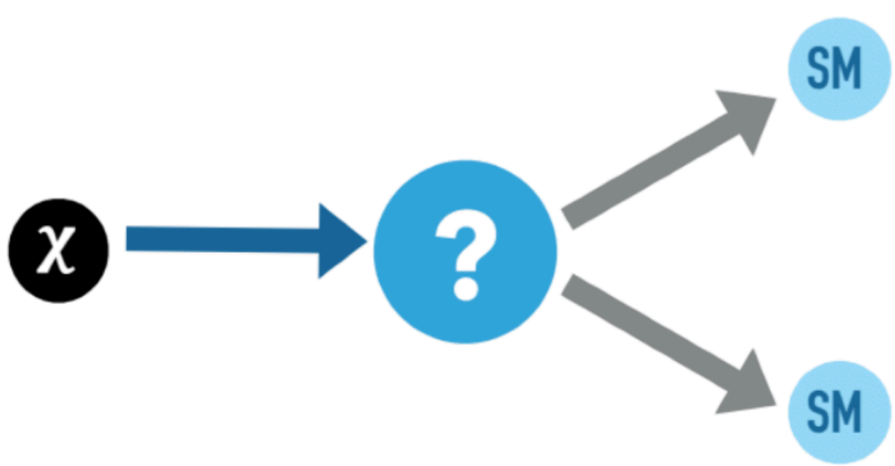


MiniBooNE,
arXiv:1805.12028

Dark matter decay







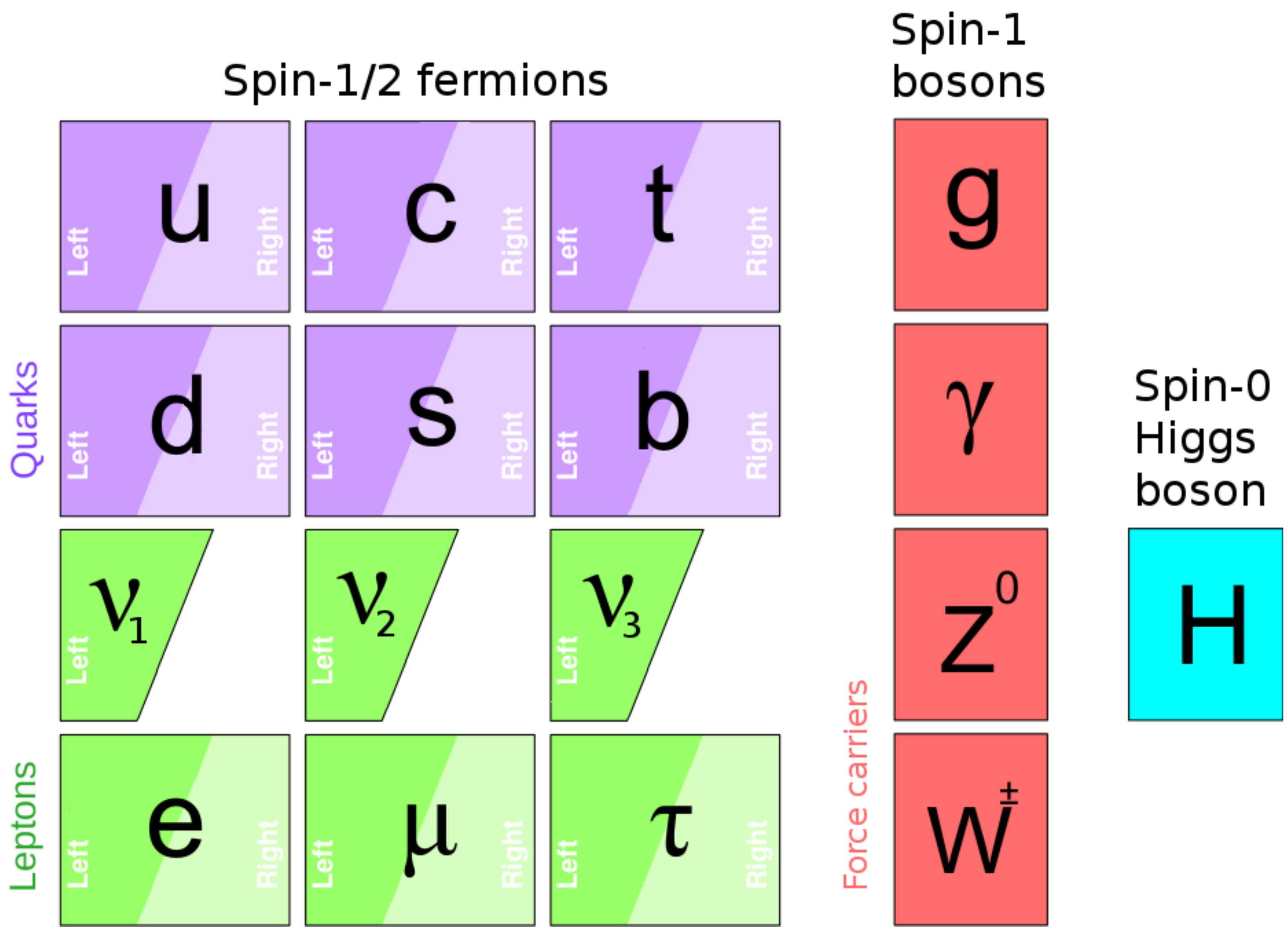
CA, H. Dujmovic arXiv 1907.11193

Outline of the rest of this talk:

1. Neutrinos in general and in IceCube
2. Searching for a new kind of neutrino:
    -The Sterile Neutrino
3. Searching for a new force:
    -Neutrino-Dark Matter Interactions
4. Searching for a new symmetry:
    -Lorentz Violation Effects on Flavor

Two funny things about neutrinos...

One theoretical: where's the right-handed partner?

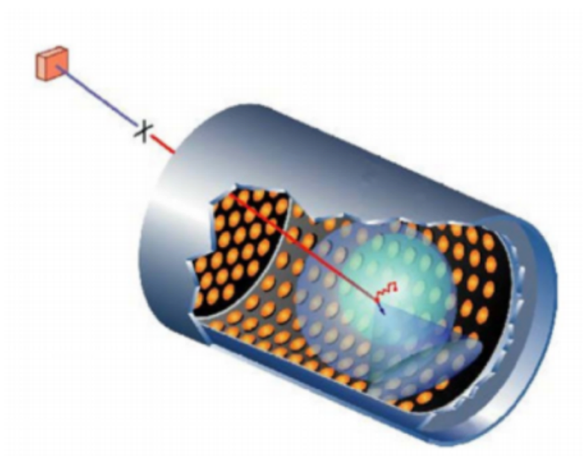


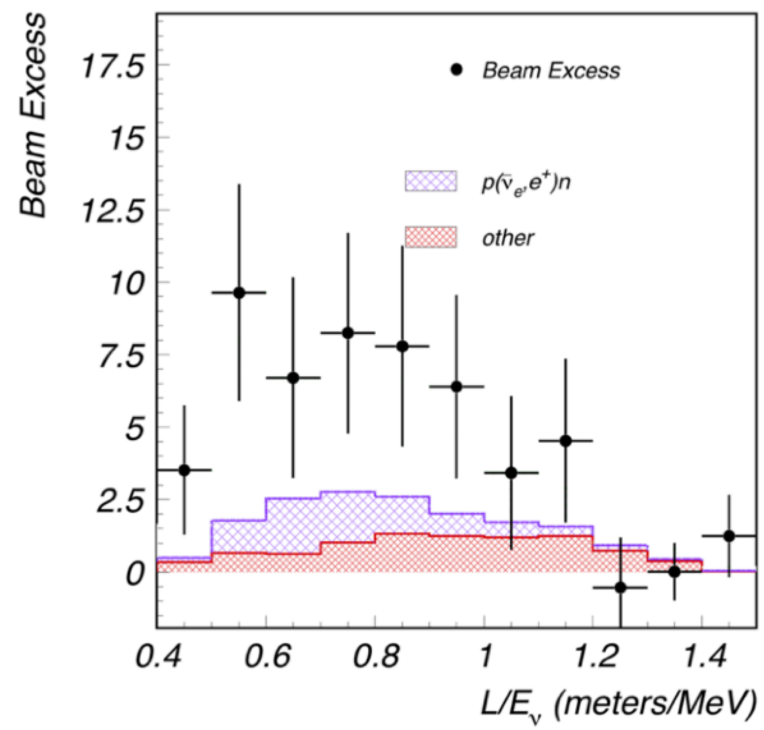
… and one experimental: what are those anomalies?

Long-standing “appearance” oscillation anomalies

LSND

(3.8σ!)



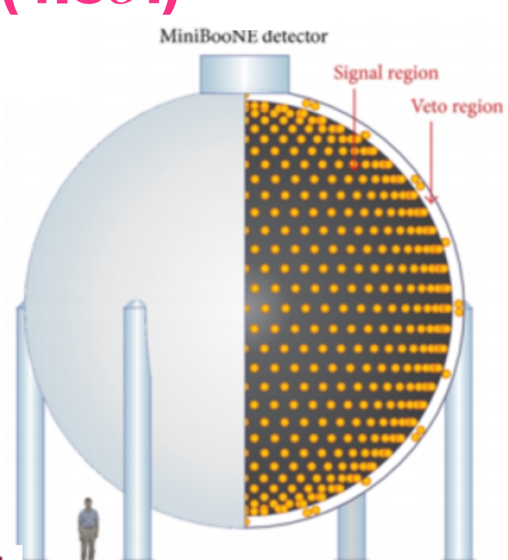


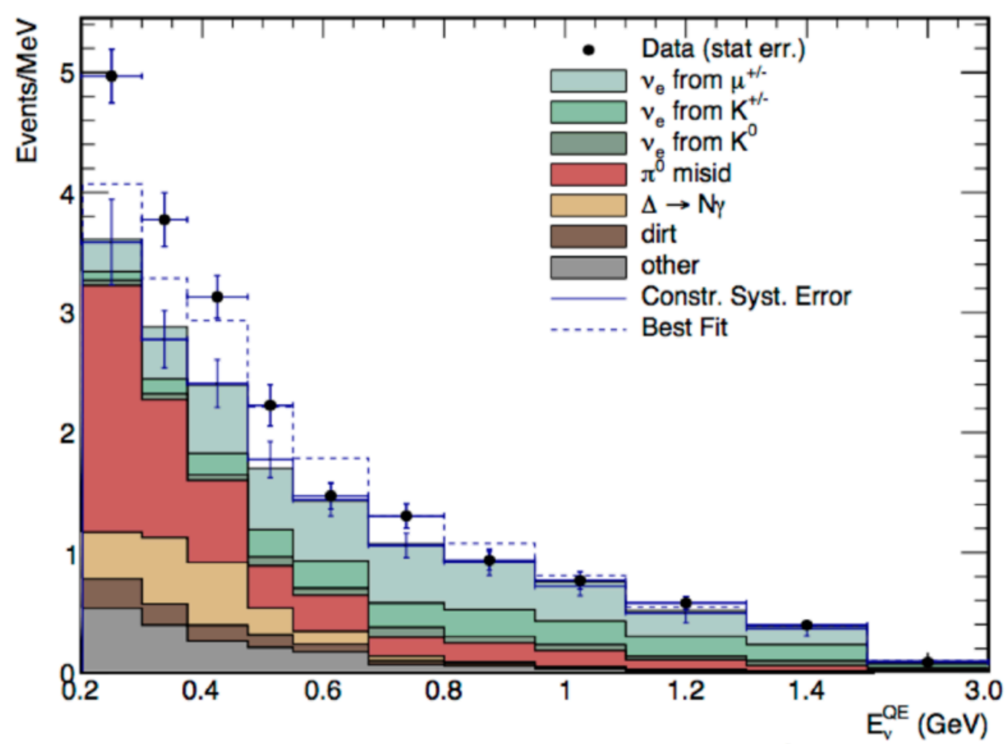
These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

This points to Δm^2~1eV^2

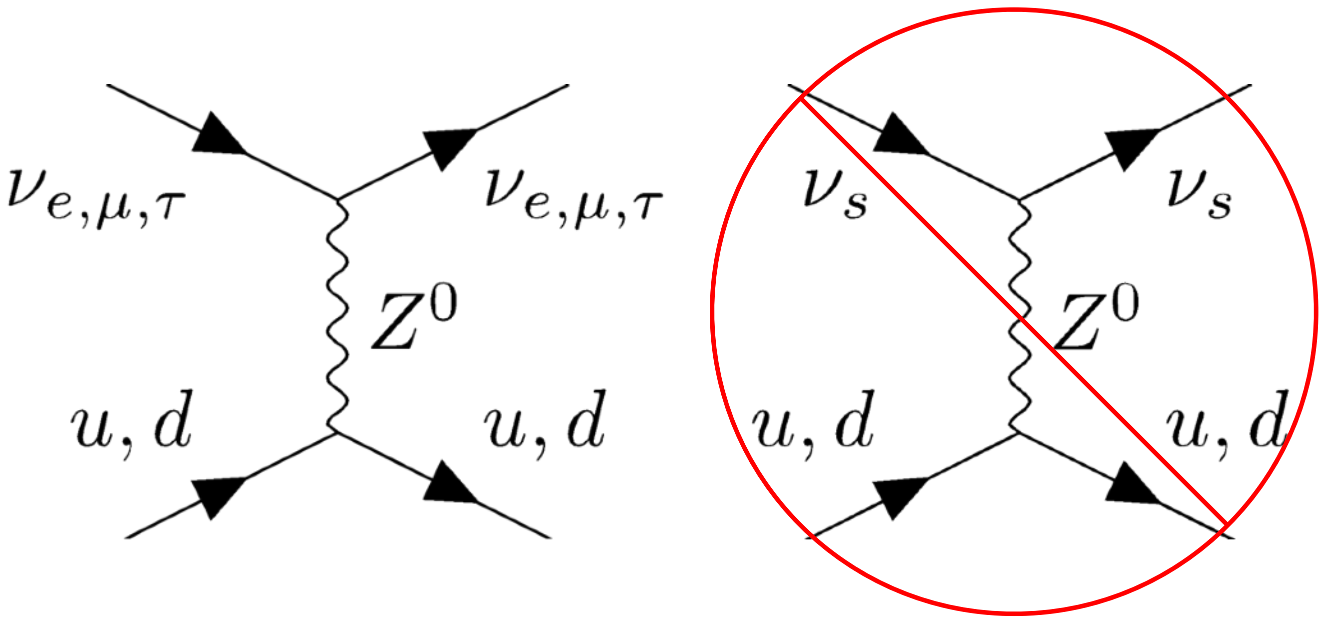
MiniBooNE

(4.8σ!)

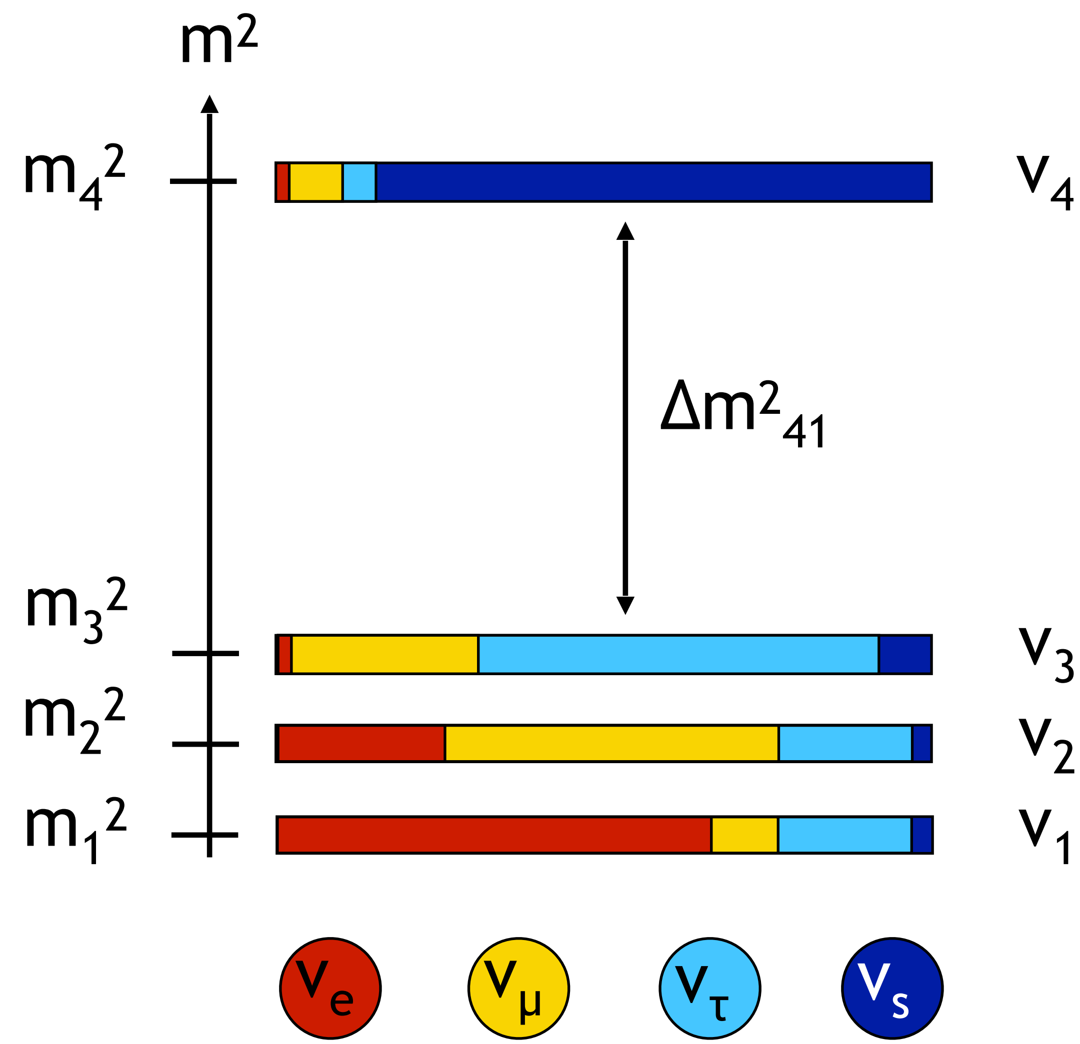




Introducing a sterile neutrino



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



Assuming Normal Ordering

Appearance and Disappearance signals should be related!

$$\nu_\mu \to \nu_e$$
$$\nu_e \to \nu_e$$
$$\nu_\mu \to \nu_\mu$$

$\Rightarrow$ $\boxed{U_{e4}}$ $\boxed{U_{\mu 4}}$ $\boxed{\Delta m^2}$

$$P_{\nu_e\to\nu_e} = 1 - 4\boxed{(1-|U_{e4}|^2)|U_{e4}|^2}\sin^2(1.27\boxed{\Delta m^2_{41}}L/E)$$

$$P_{\nu_\mu\to\nu_e} = 4\boxed{|U_{e4}|^2}\boxed{|U_{\mu 4}|^2}\sin^2(1.27\boxed{\Delta m^2_{41}}L/E)$$

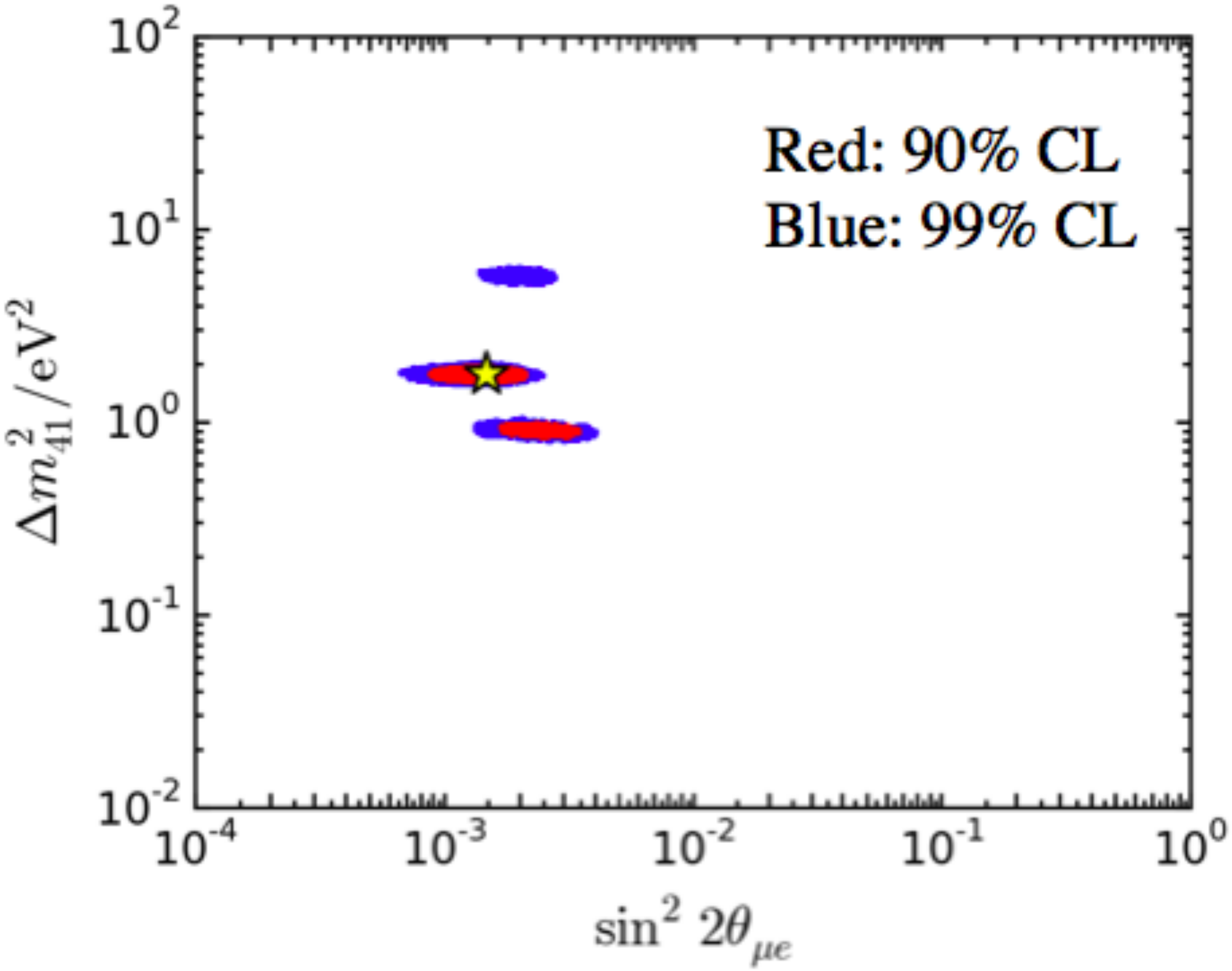
$$P_{\nu_\mu\to\nu_\mu} = 1 - 4\boxed{(1-|U_{\mu 4}|^2)|U_{\mu 4}|^2}\sin^2(1.27\boxed{\Delta m^2_{41}}L/E)$$

$$\sin^2 2\theta_{ee} = 4(1-\boxed{|U_{e4}|^2)|U_{e4}|^2}$$

$$\sin^2 2\theta_{\mu\mu} = 4(1-\boxed{|U_{\mu 4}|^2)|U_{\mu 4}|^2}$$

$$\sin^2 2\theta_{\mu e} = 4\boxed{|U_{\mu 4}|^2}\boxed{|U_{e4}|^2}$$

Global fit solution



Best fit point:

Δm^2_{41} : 1.75 eV^2

$\sin^2 2\theta_{\mu e}$: 1.45×10^{-3}

χ^2 : 306.81 (312 dof)

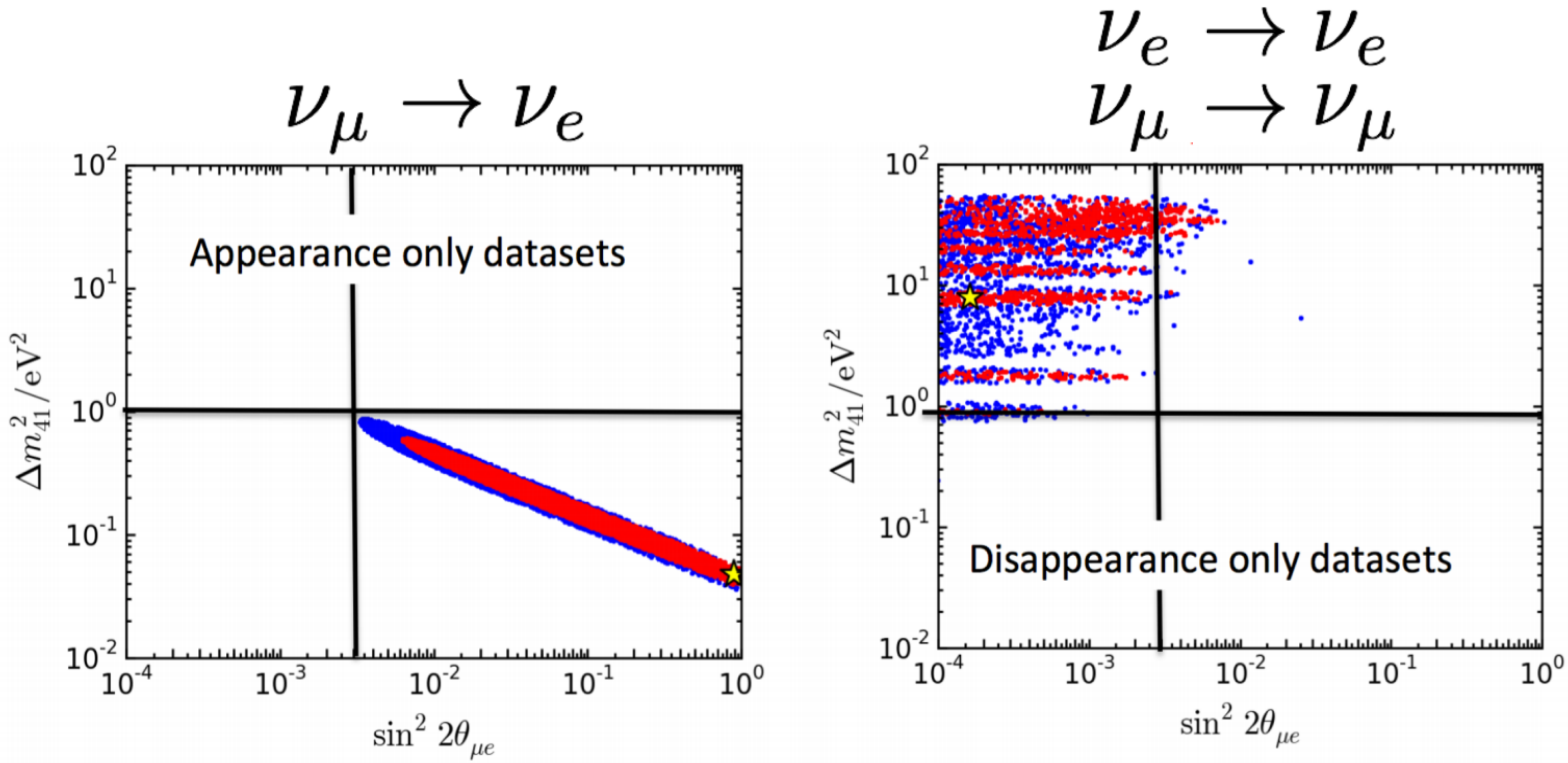
χ^2_{null} : 359.15 (315 dof)

$\Delta\chi^2$: 52.34 (3 dof)

Data strongly prefers
a model with
a sterile neutrino

Collin, CA, Conrad, and Shaevitz Nucl.Phys. B908 (2016) 354-365
arXiv:1602.00671; see also Diaz, CA, Collin, Conrad, Shaevitz arXiv:1906.00045.

Appearance and disappearance "preference regions" don't overlap!



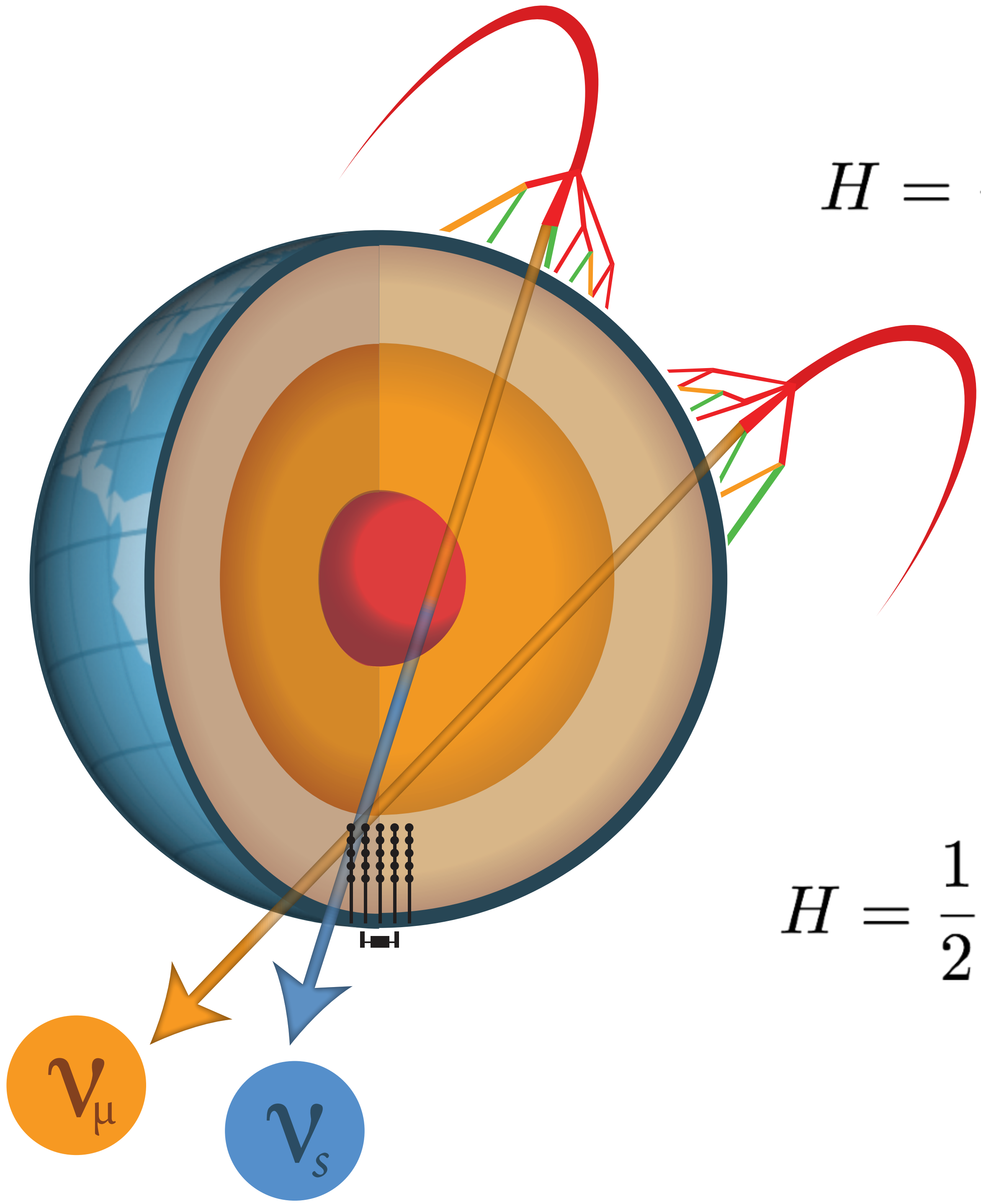
From Collin, CA, Conrad, and Shaevitz 1602.00671, similar conclusions from other groups see Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018). See Diaz…CA arXiv:1906.00045 for more discussion.

IceCube has a novel way of addressing muon-neutrino disappearance.

The channel in which no signal is yet seen.

Our neutrinos traverse a lot of matter!

For simplicity consider a 2-neutrino transition : $\nu_\mu \rightarrow \nu_\mathrm{s}$

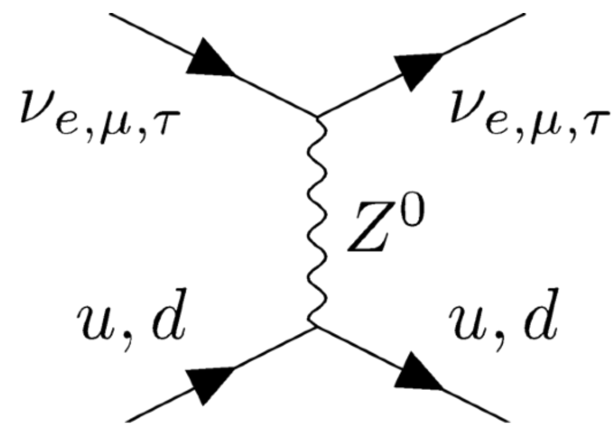


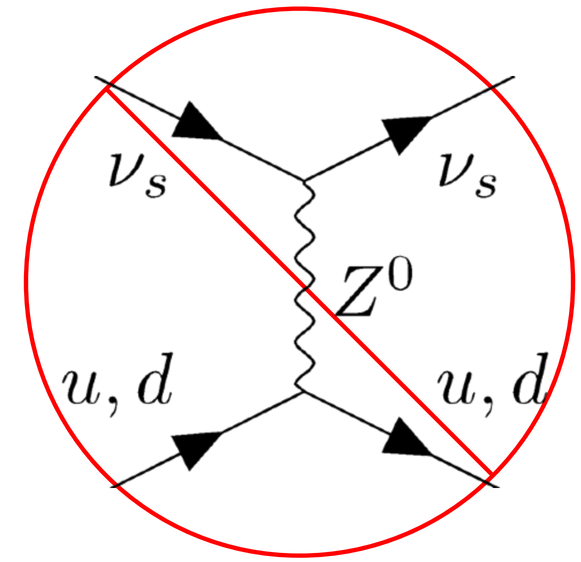
$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U$$

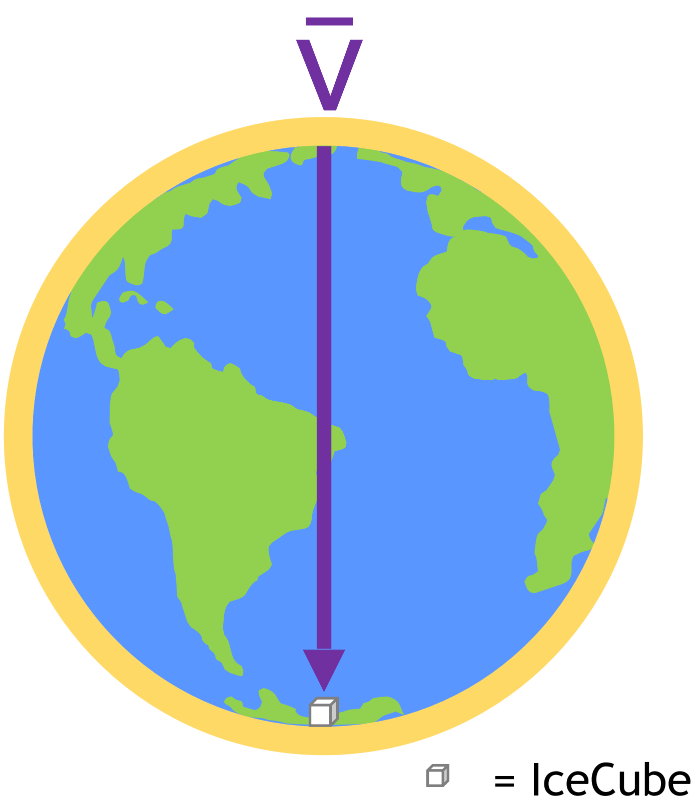
IceCube atmospheric neutrinos traverse large regions of matter.

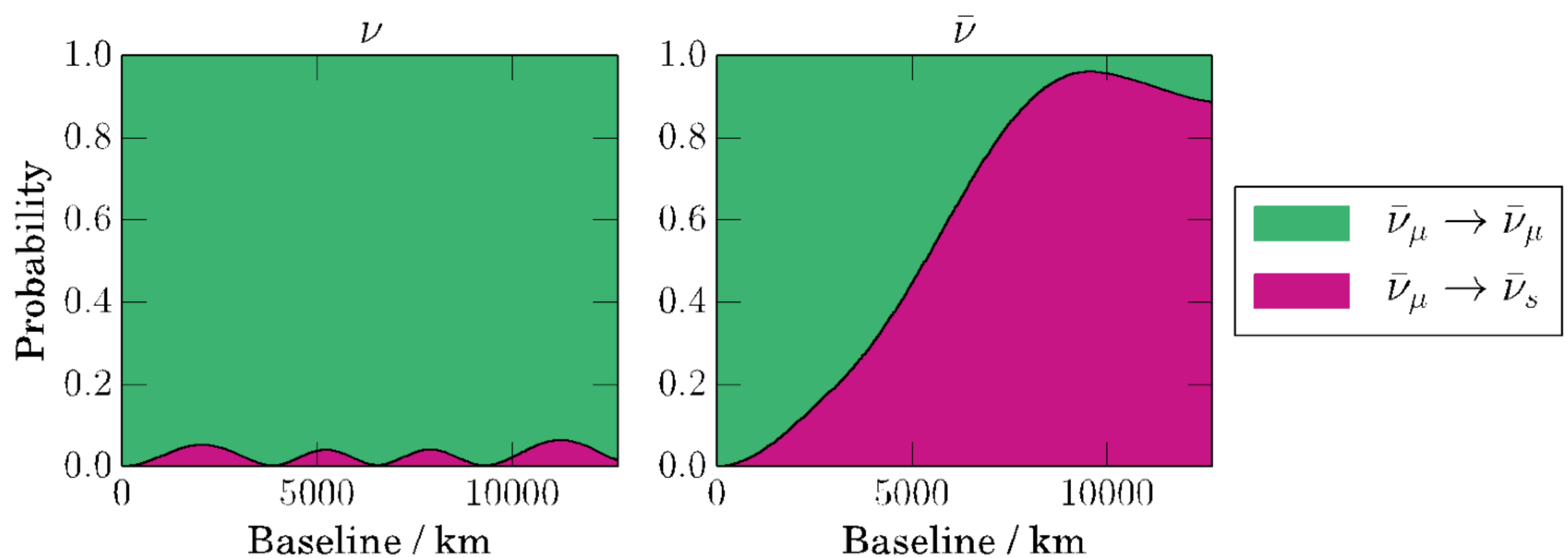
$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U \mp \frac{G_F}{\sqrt{2}} \begin{pmatrix} N_\mathrm{nuc} & 0 \\ 0 & 0 \end{pmatrix}$$

Effects of Matter Effects





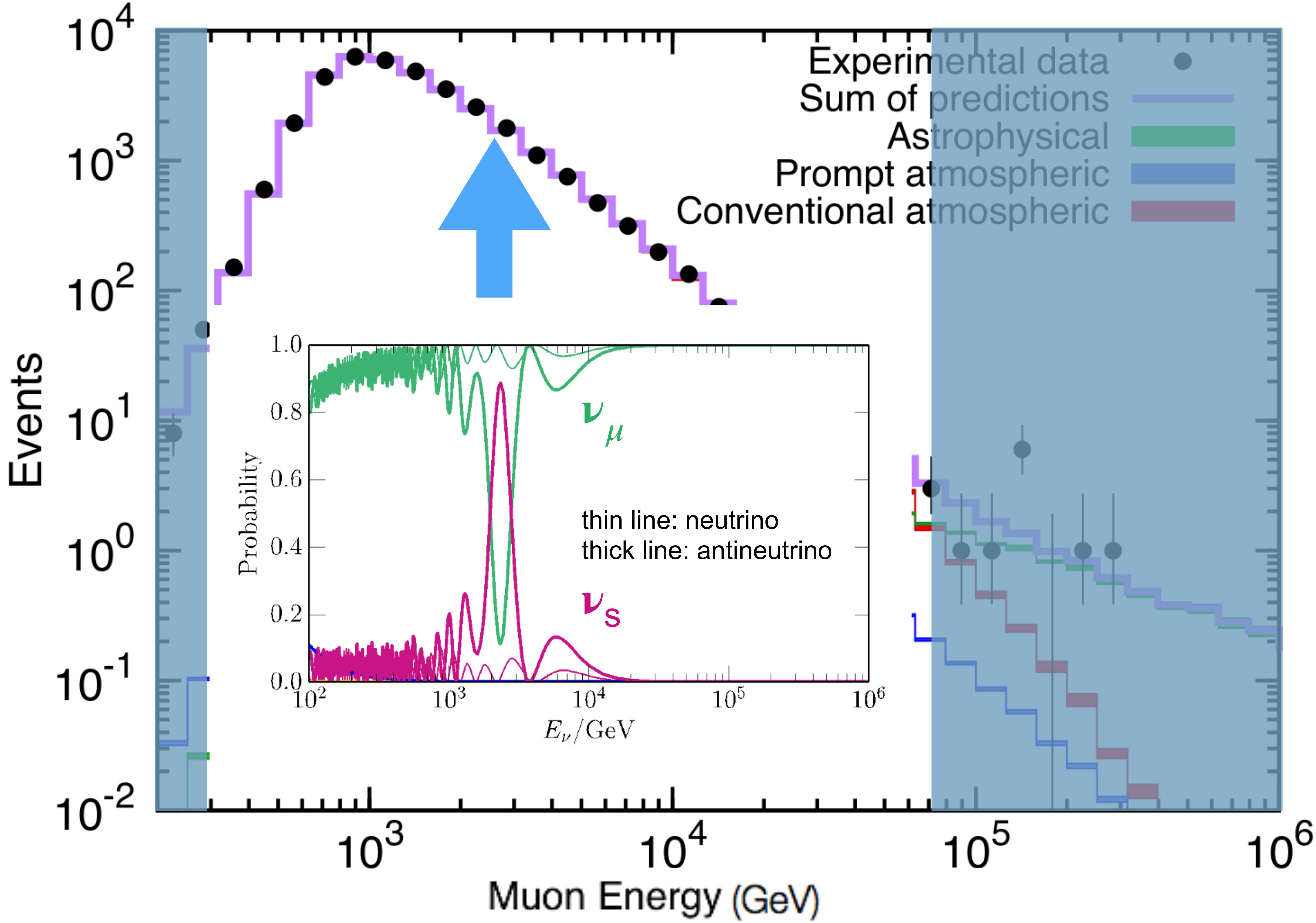




Plotted for:

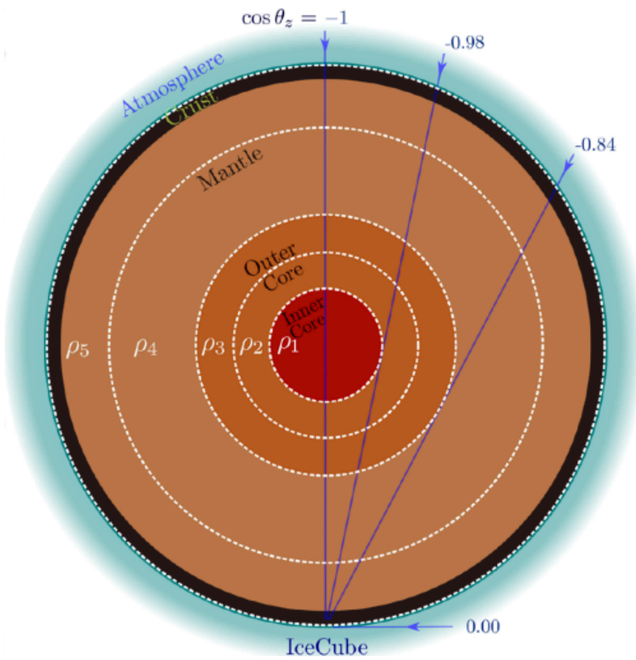
- 2.3 TeV
- Δm^2_{41} = 1 eV^2, $\sin^2 2\theta_{24}$ = 0.1 (compatible with best fit)

Where is the resonance effect?



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

Position of resonance maps onto sterile parameter space

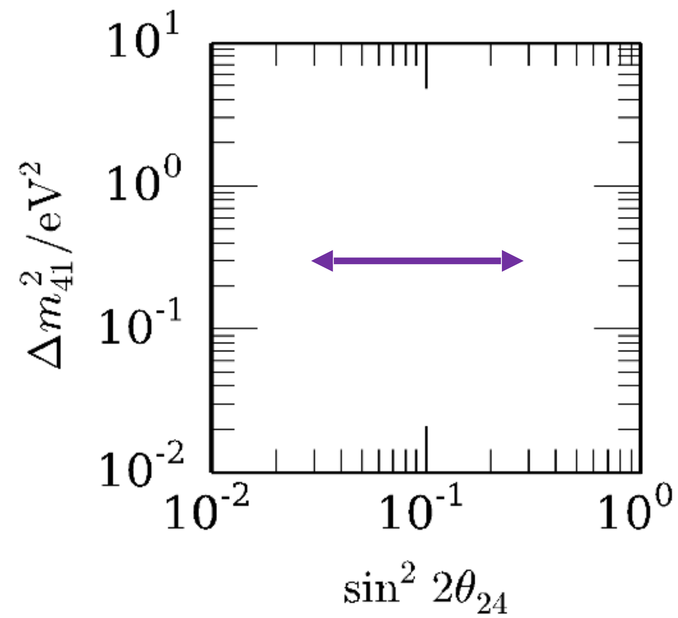


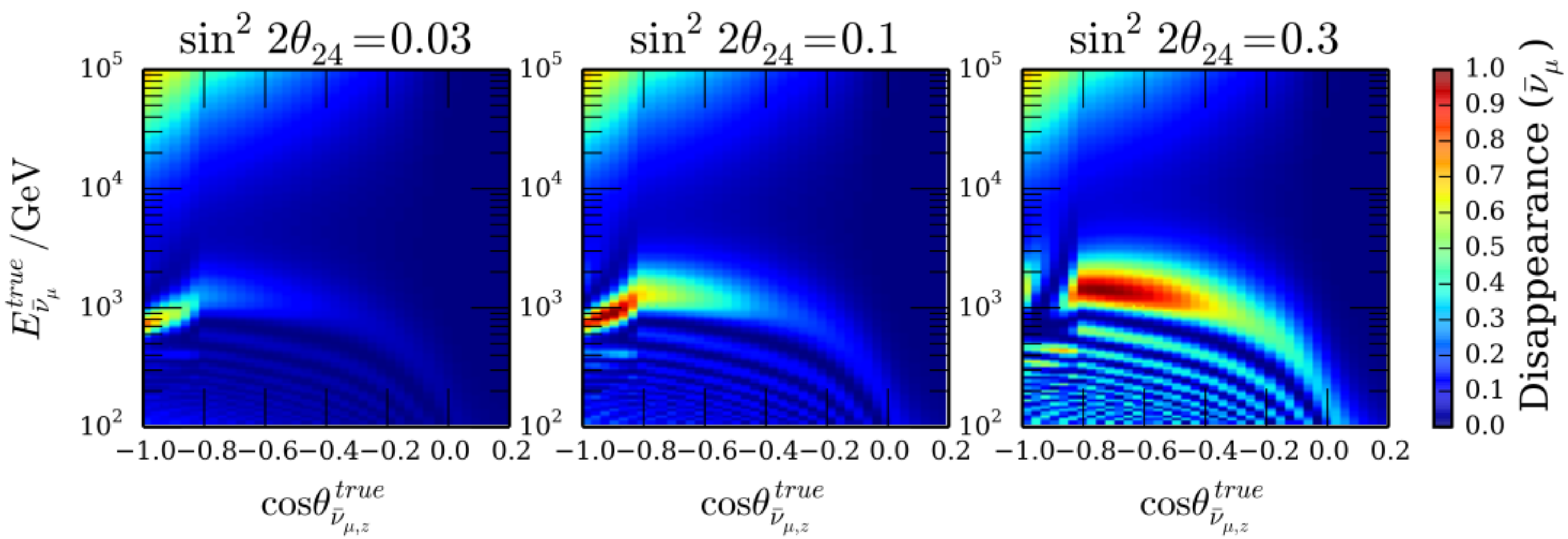
We measure two things:

- $\cos\theta$ ⇨ length
- energy

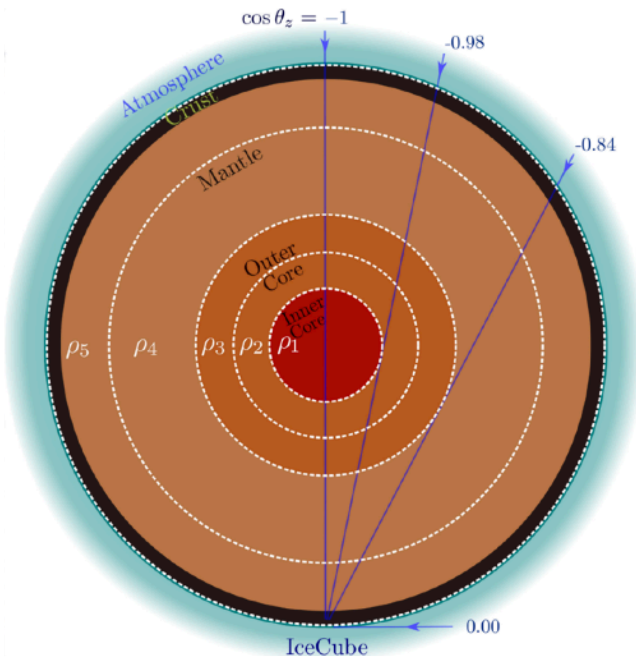
We extract two parameters:

- squared mass difference
- mixing angle





Position of resonance maps onto sterile parameter space



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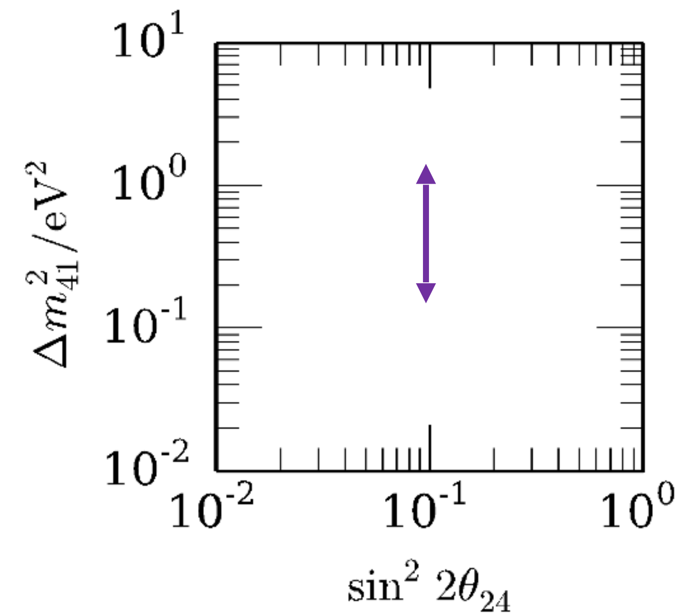
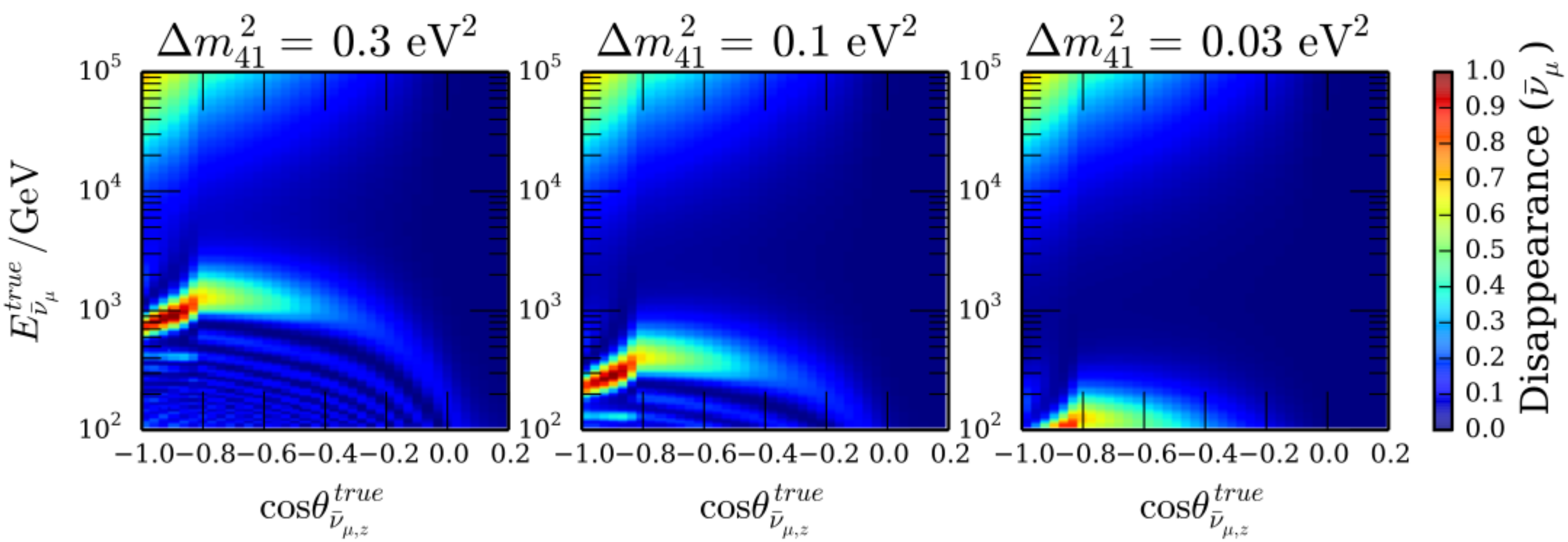
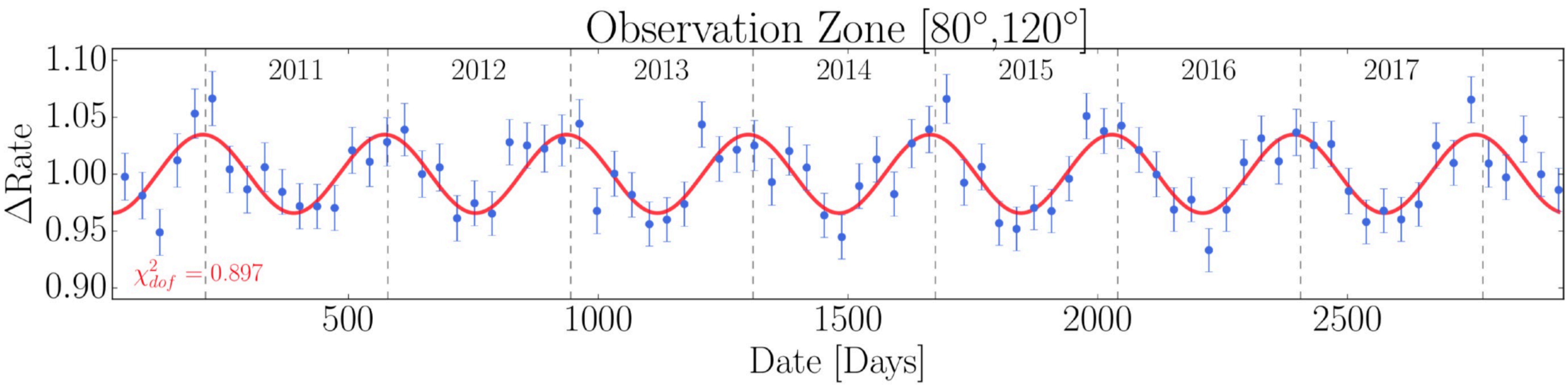




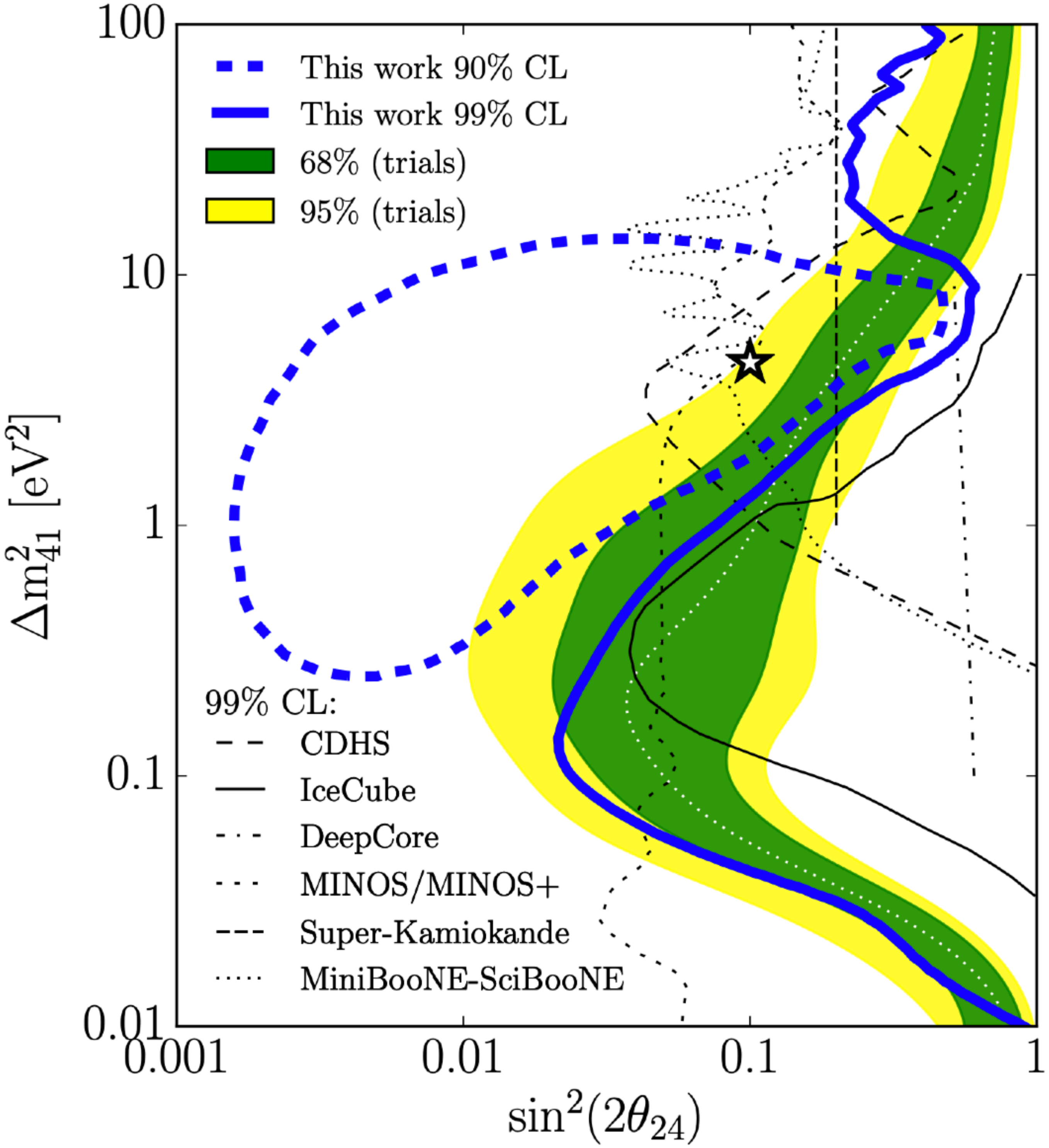
8-year search in IceCube

Matter-Enhanced Oscillations With Steriles (MEOWS)



✤Optimized event selection: 300k events!
✤Improved systematic treatment
✤**New results to be be published soon!**

New results from 8-year sterile search



Though no significance evidence. Small hint of disappearance.

Is this the ν_μ disappearance we have been looking for?

IceCube Coll. arXiv:2005.12942 and 2005.12943