A Tour Of Recent IceCube Searches For New Physics And Future Prospects

Seminar at Fermilab, Batavia, IL
May 5, 2022

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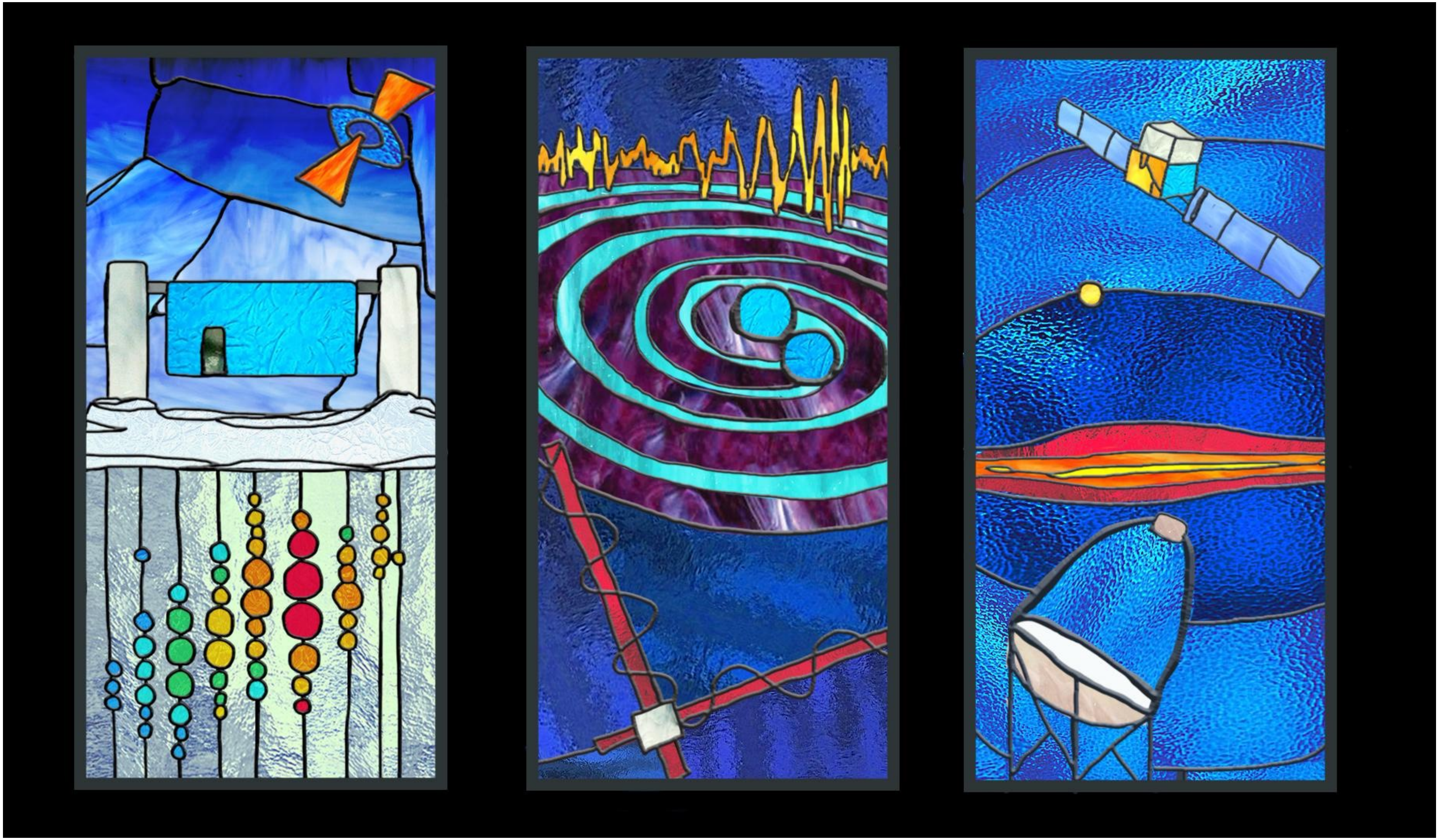
HARVARD UNIVERSITY

How does the Universe look in neutrinos?



How do high-energy neutrinos behave?

Outline of the rest of this talk:

1. Neutrinos from cosmic beam dumps & IceCube
2. Searching for a new kind of neutrino:
   - -The Sterile Neutrino
3. Searching for new forces
   - -Non-standard Neutrino Interactions
4. Searching for a dark sector:
   - -Neutrino-Dark Matter Interactions
5. Searching for a new symmetry:
   - -Lorentz Violation Effects on Flavor

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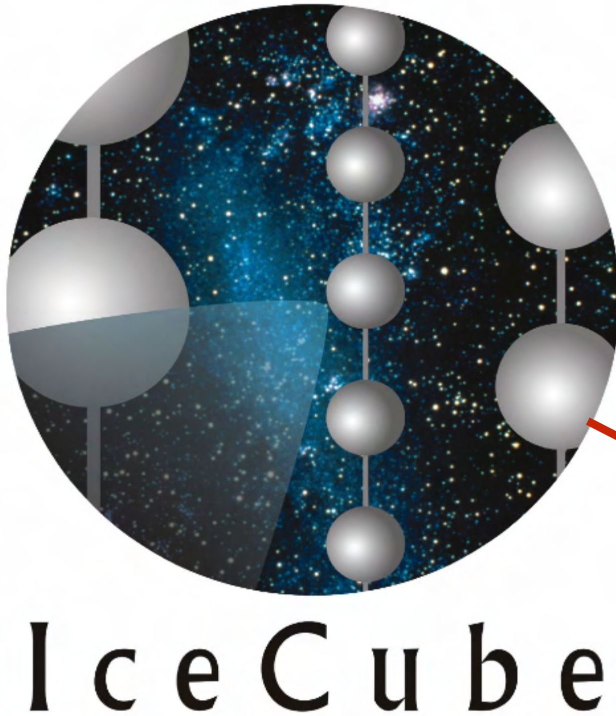
The IceCube Neutrino Observatory

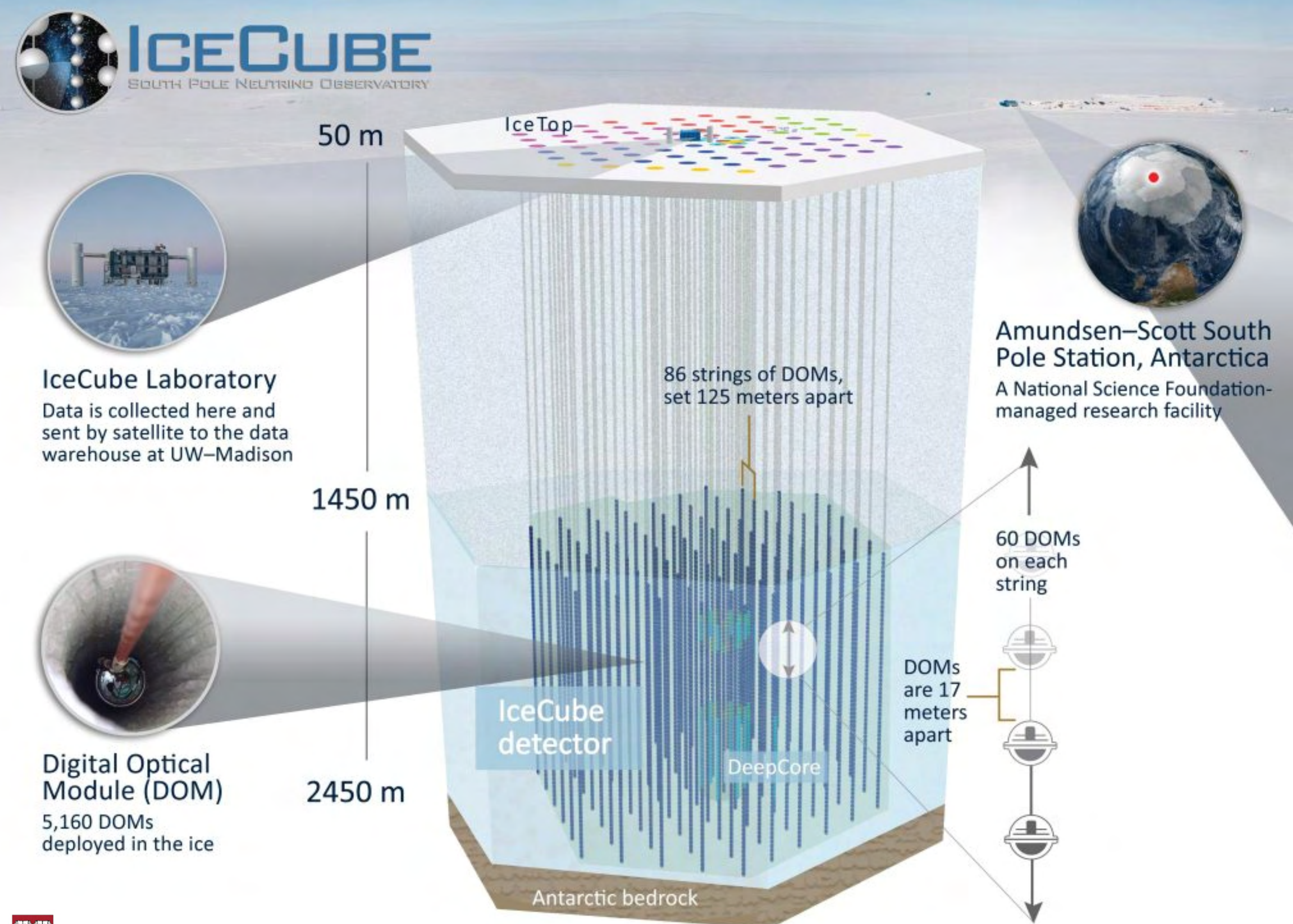

IceCube


Here!
CANADA
MONTANA
WYOMING
SOUTH DAKOTA
NEBRASKA
IOWA
ILLINOIS
INDIANA
OHIO
PENNSYLVANIA
NEW YORK
KANSAS
MISSOURI
KENTUCKY
COLORADO
UTAH
OKLAHOMA
ARKANSAS
TENNESSEE
NORTH CAROLINA
ARIZONA
NEW MEXICO
TEXAS
LOUISIANA
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
MEXICO
GULF OF MEXICO
ATLANTIC OCEAN
THE BAHAMAS
ALASKA
MAINE

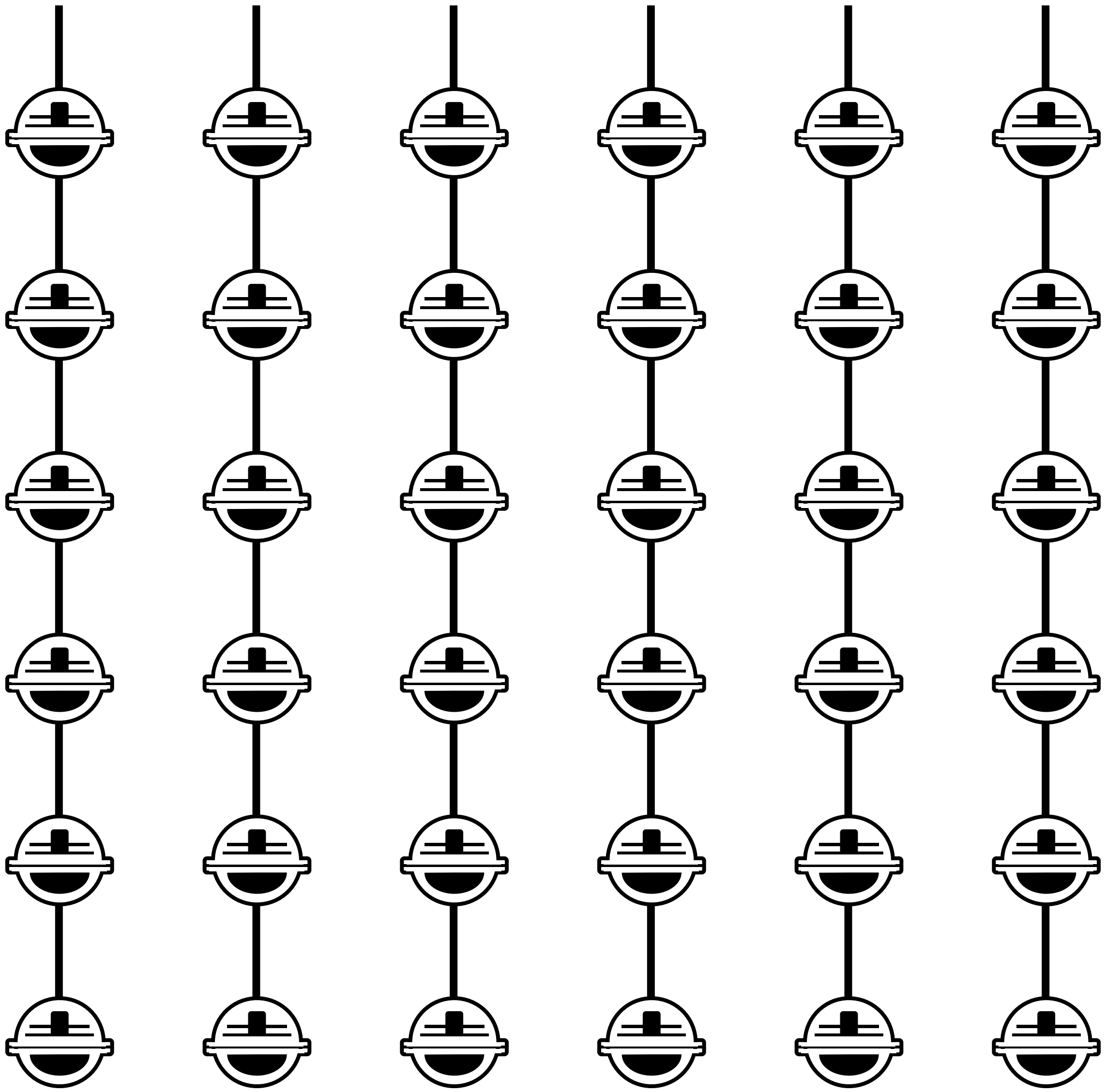

There!
SOUTHERN OCEAN
KONG HÅKON VII HAV
WEDDELL SEA
ANTARCTIC PENINSULA
DRONNING MAUD LAND
ENDERBY LAND
KEMP LAND
COATS LAND
MACROBERTSON LAND
EAST ANTARCTICA
PRINCESS ELIZABETH LAND
South Pole
Amundsen-Scott (USA)
WILHELM II LAND
QUEEN MARY LAND
WILKES LAND
BELLINGSHAUSEN SEA
90°W
90°E
ELLSWORTH LAND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

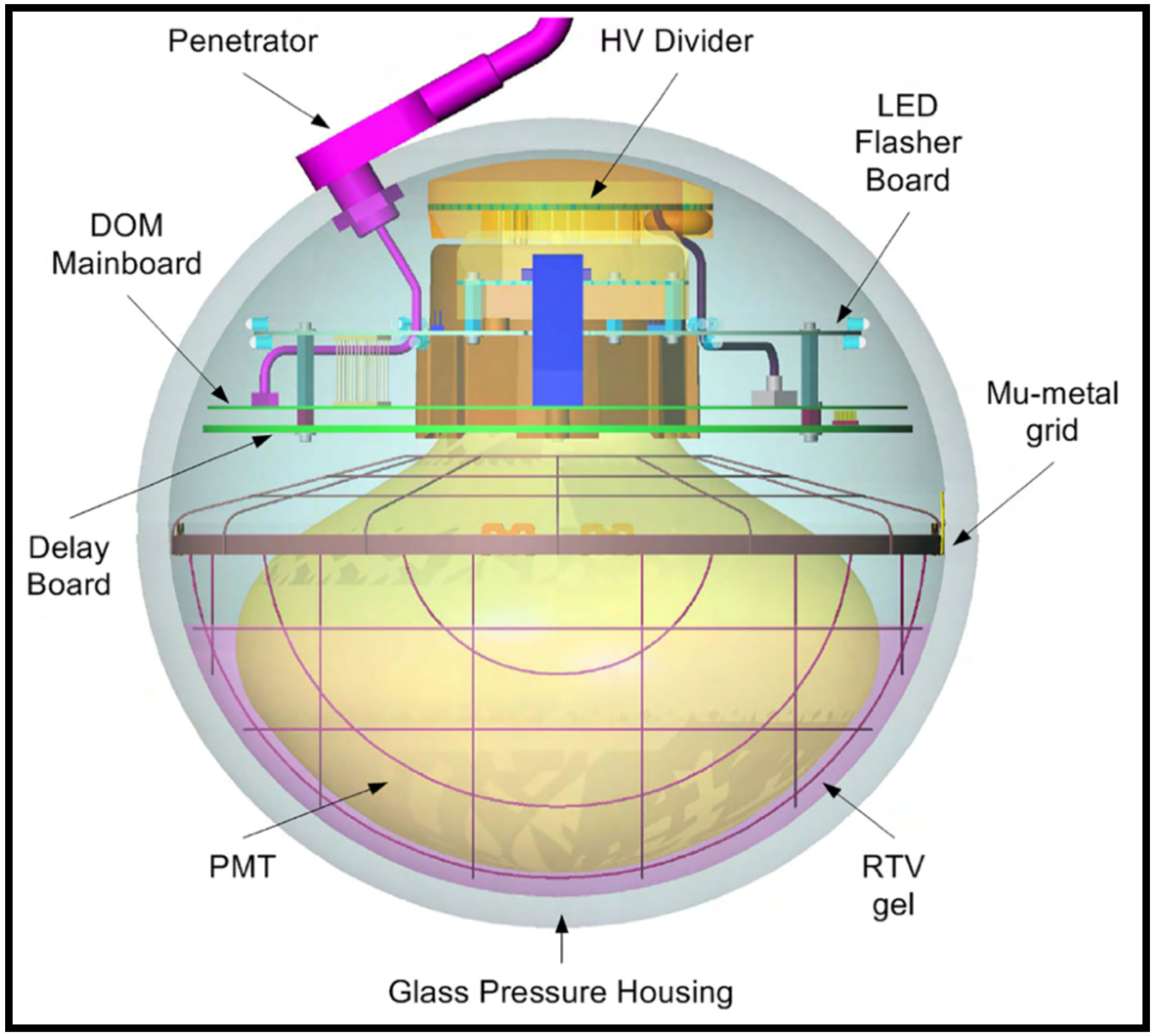
(to scale)

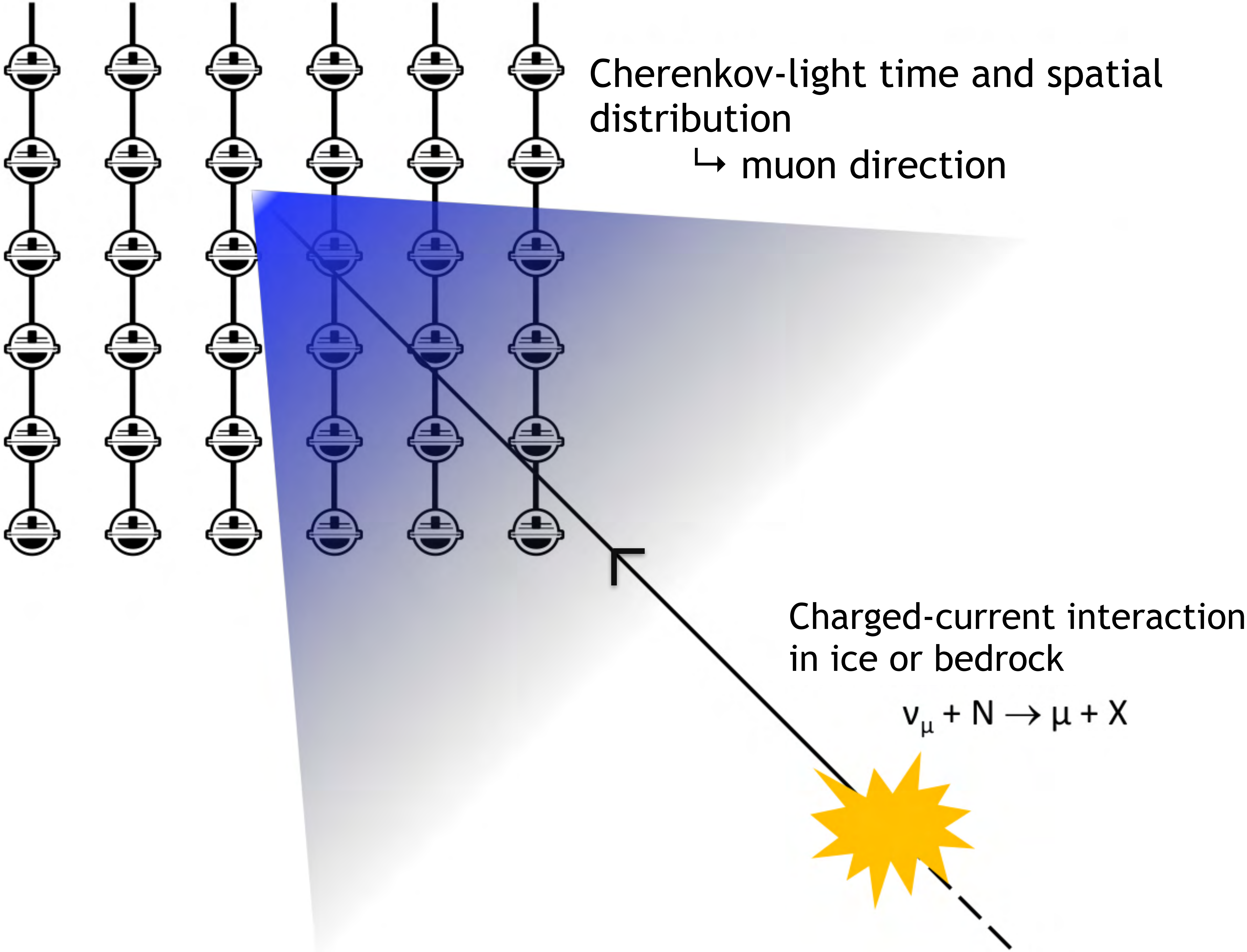
Looking at it from our point of view here in the northern hemisphere:

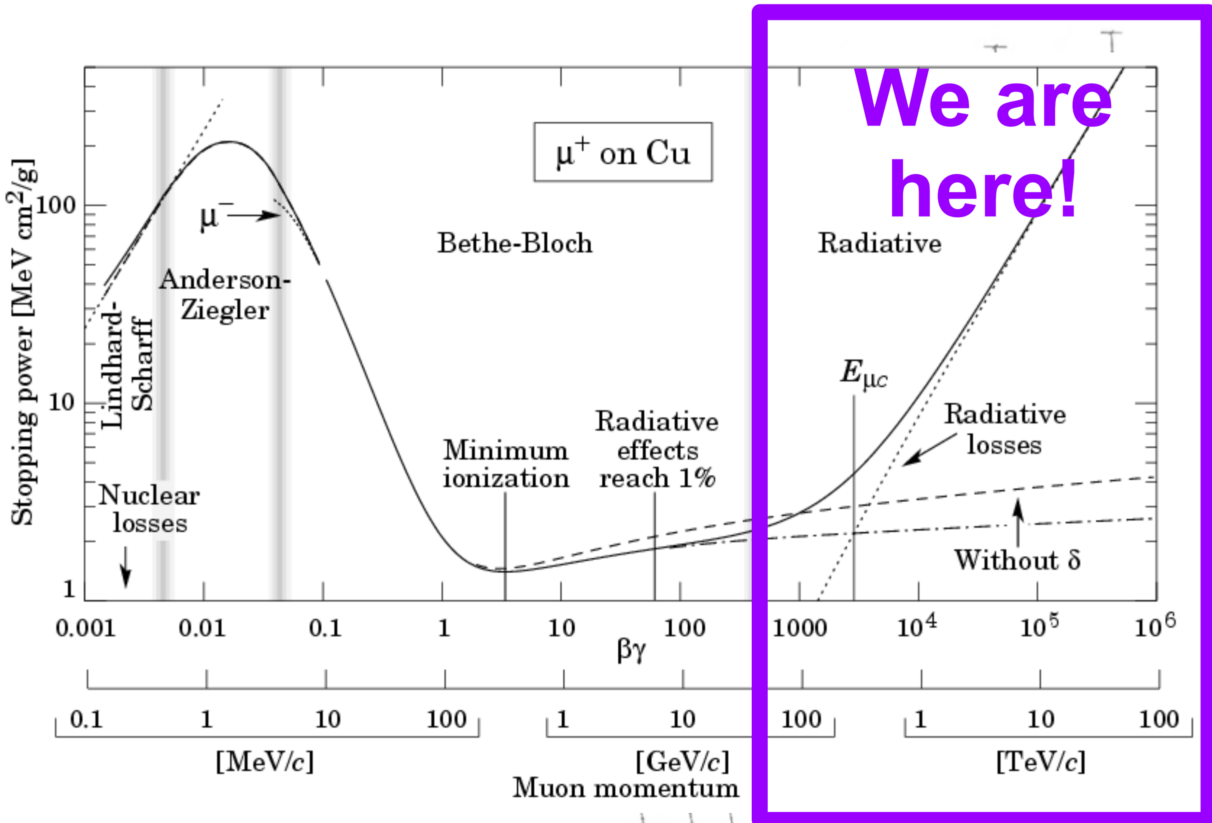

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility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

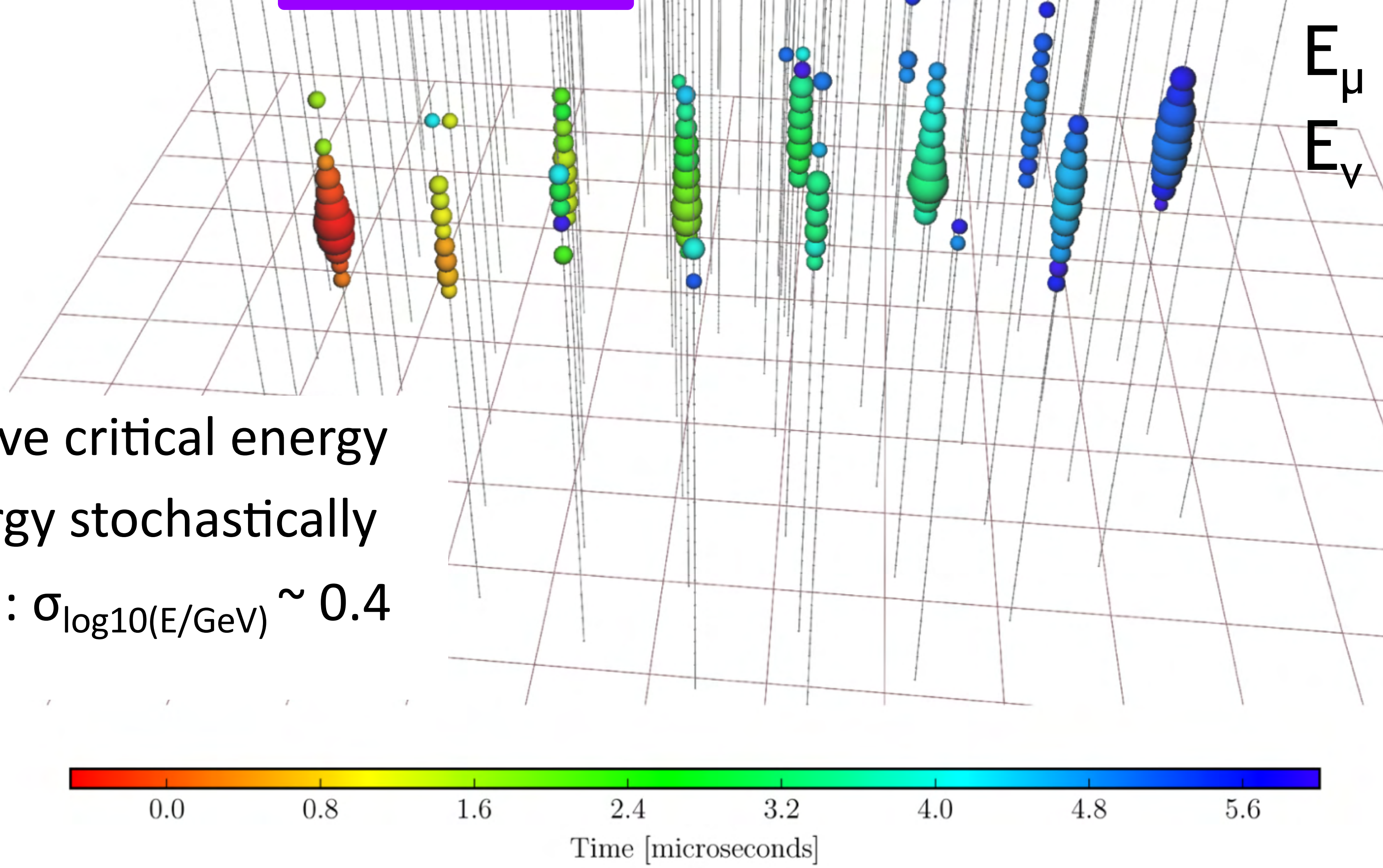
Digital Optical Module (DOM)






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



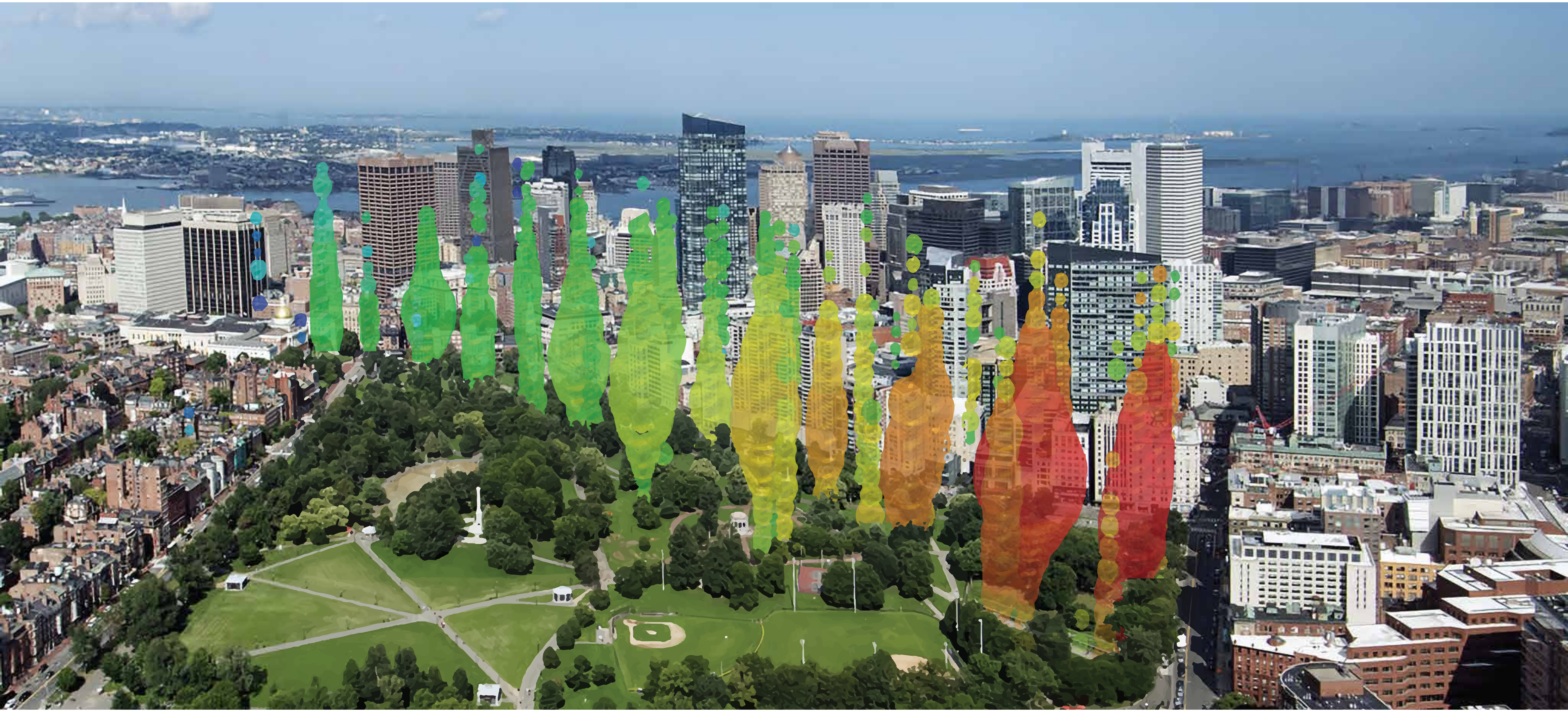


E_μ = 139 TeV

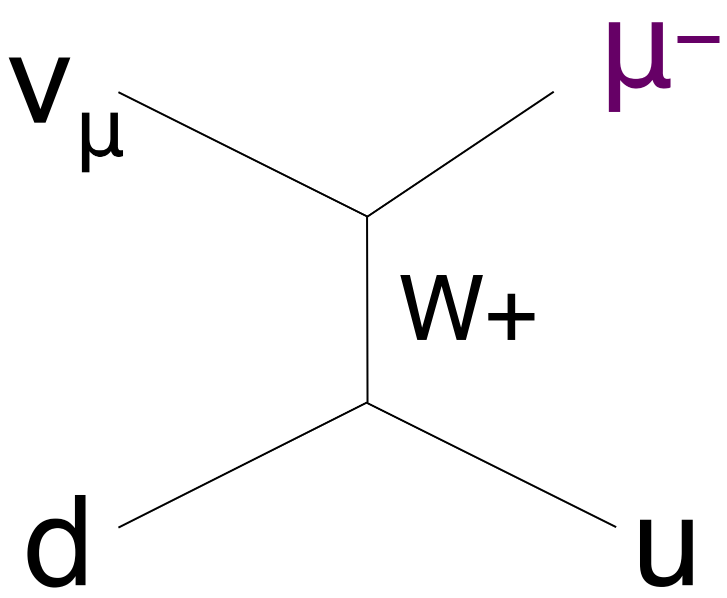
E_ν = 179 TeV

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

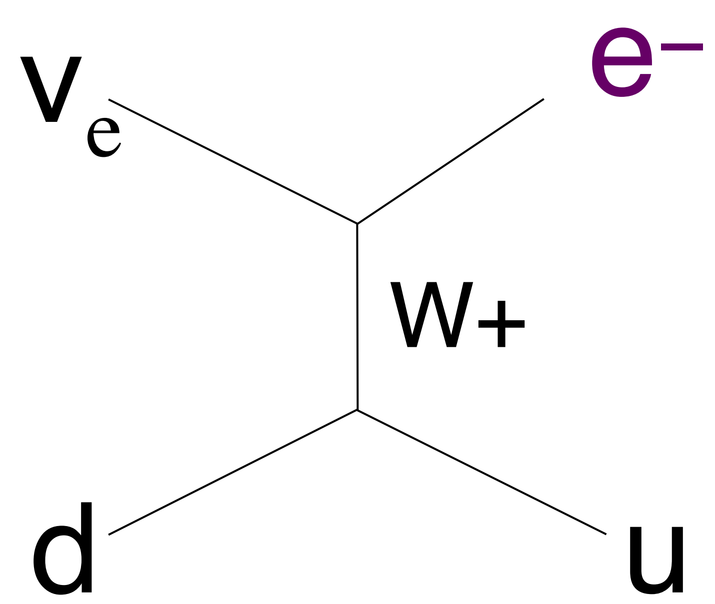
These events are really big!



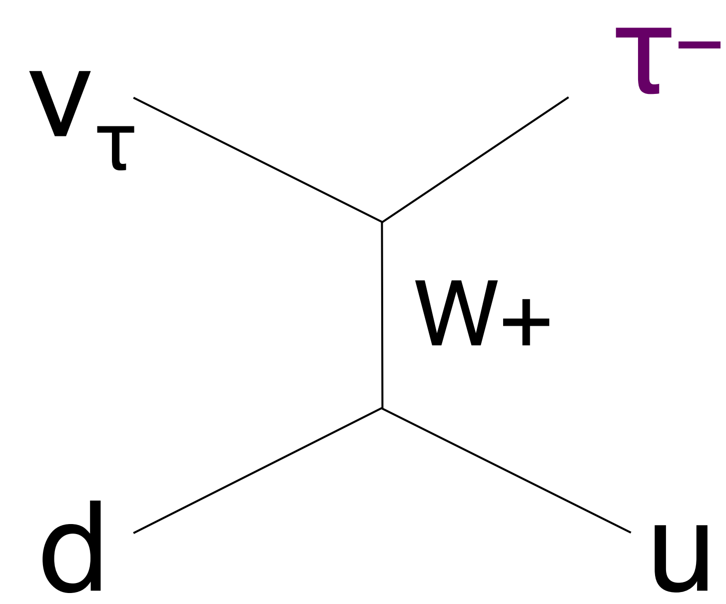
Remember our interactions?



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



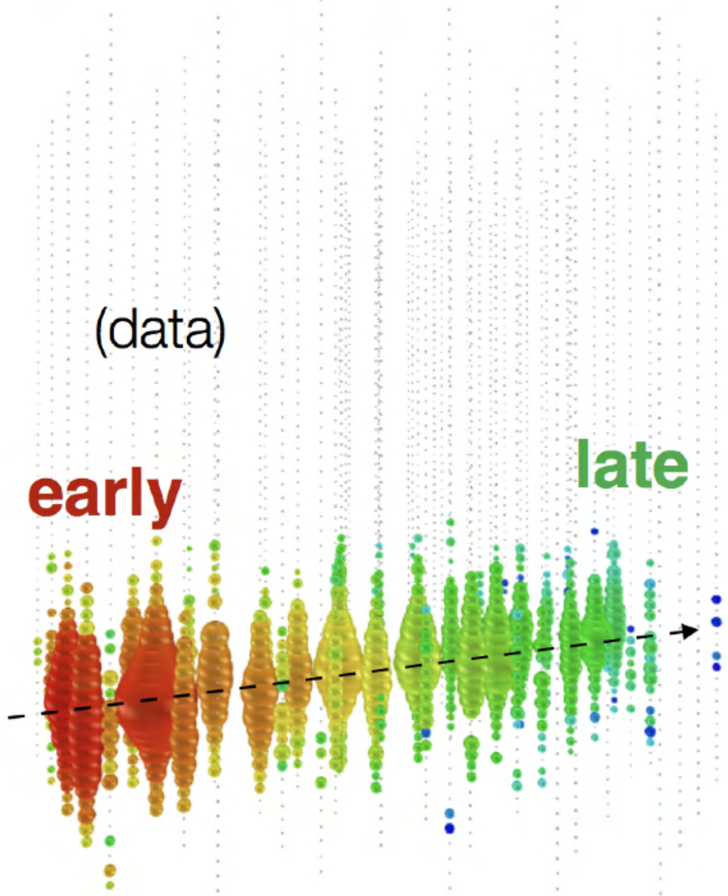
Events must be contained or partially contained in the detector.



Events must be contained in the detector

All event morphologies

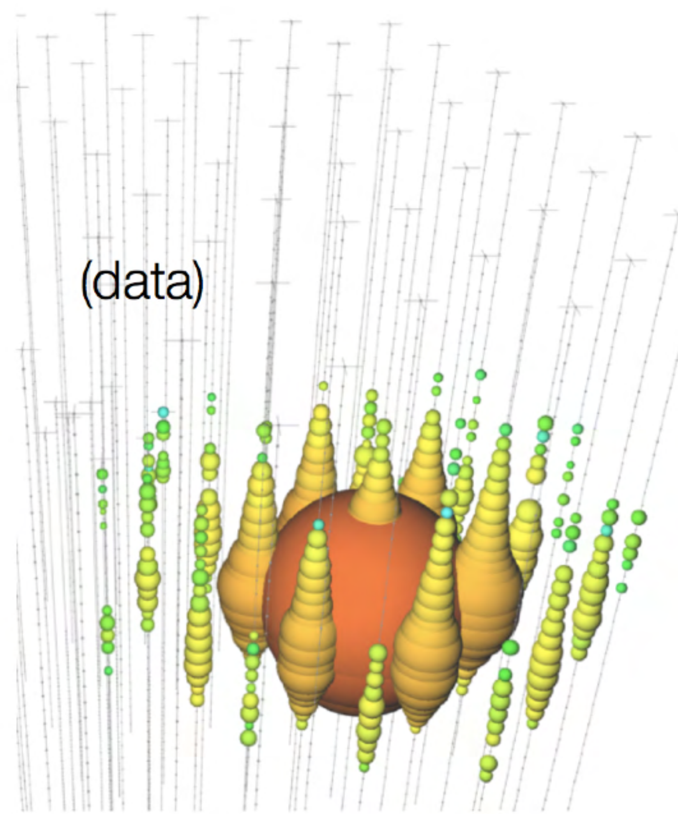
Charged-current ν_μ



Up-going track

Factor of ~ 2 energy resolution
< 1 degree angular resolution

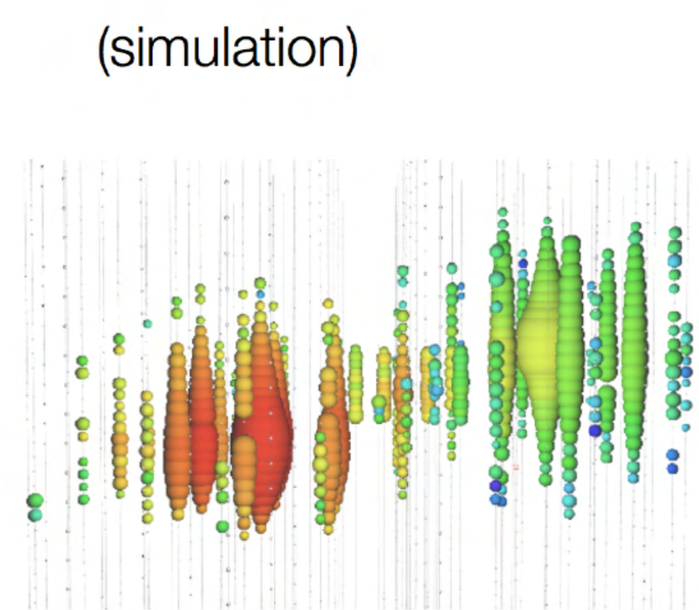
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

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

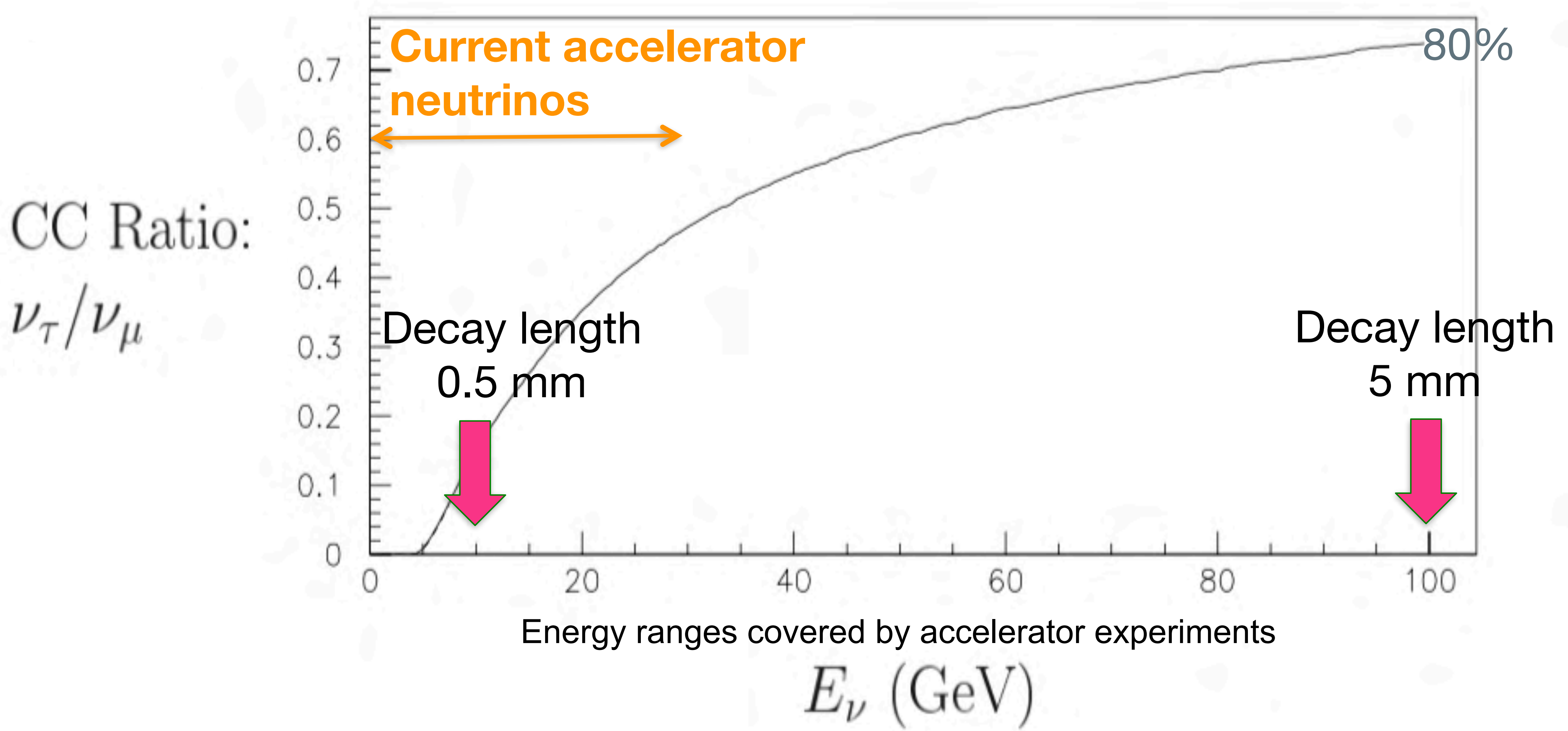
Charged-current ν_τ



Double cascade

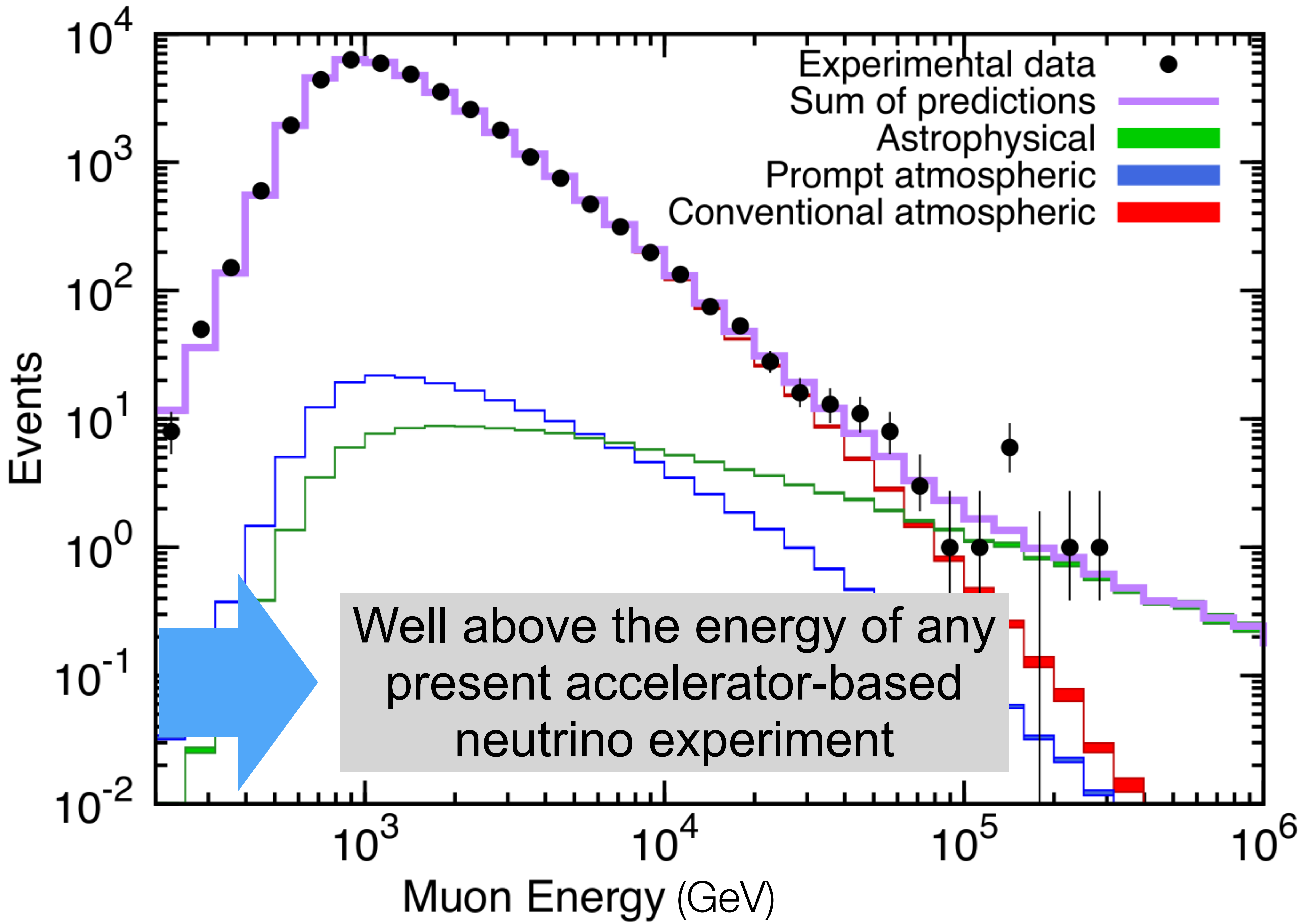
(resolvable above ~ 100 TeV deposited energy)

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



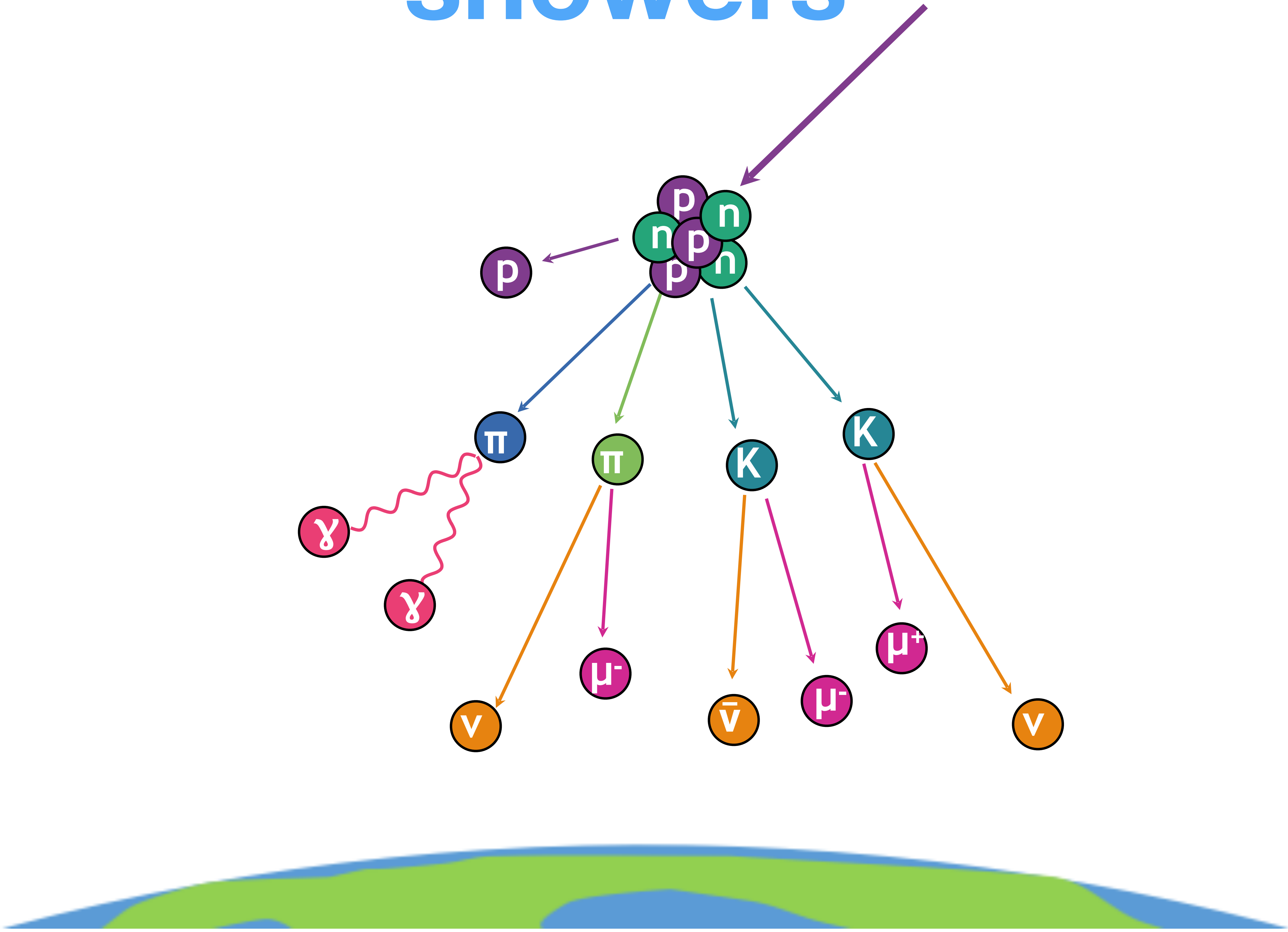
It is hard to build an enormous detector with this resolution at reasonable cost

Luckily IceCube Events are Very High Energy!

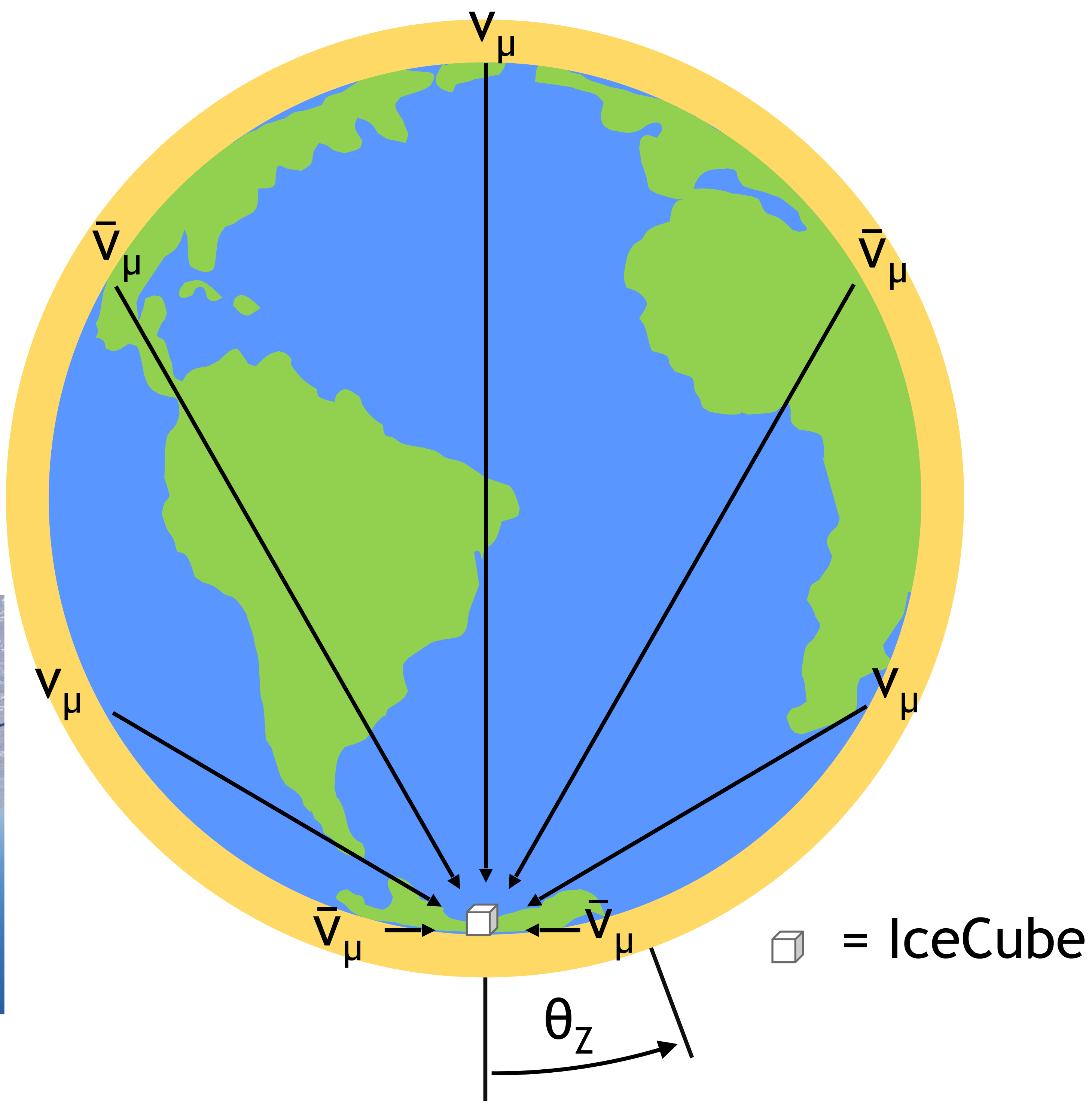


Phys. Rev. Lett. 115, 081102 (2015)

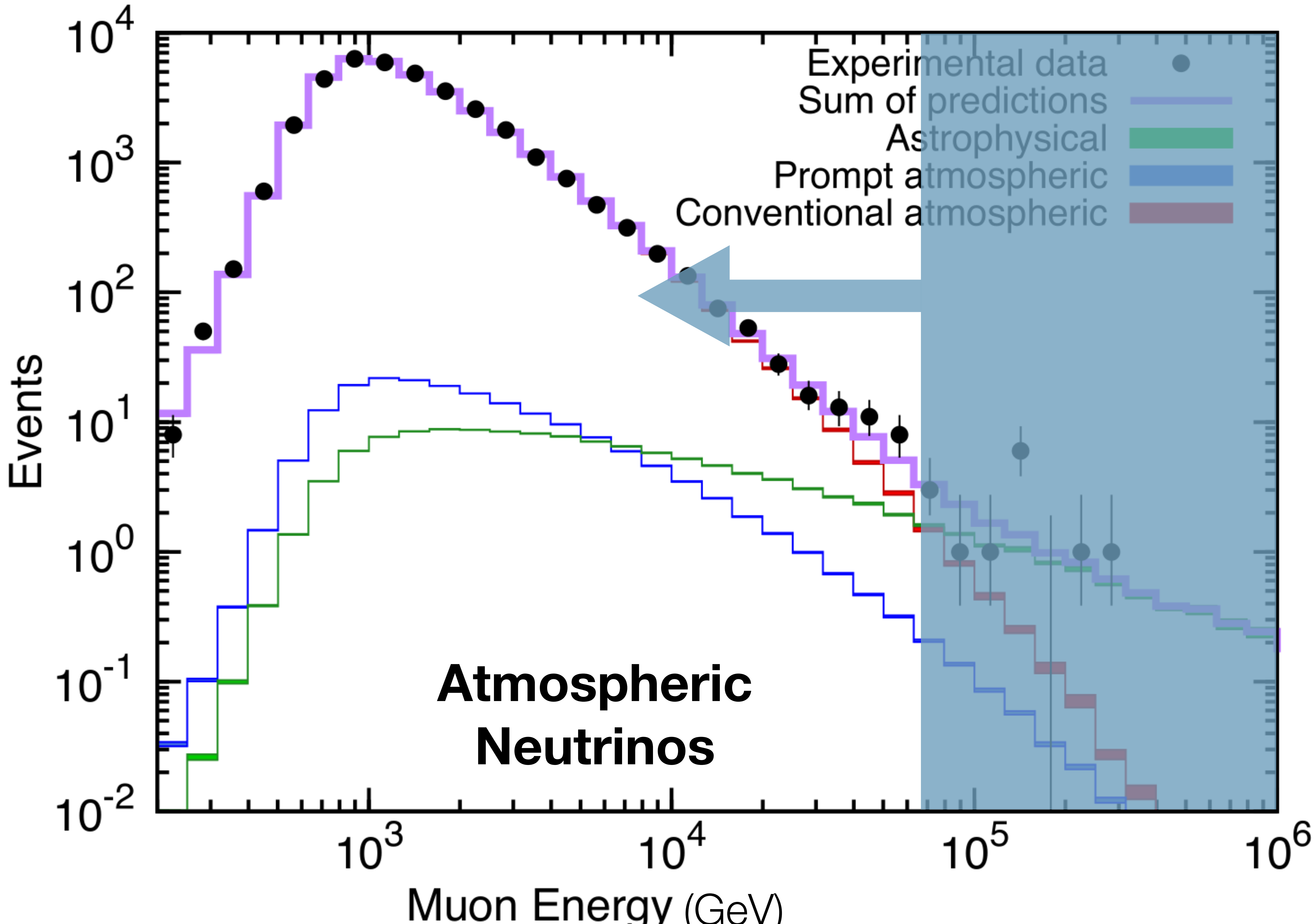
Neutrinos from cosmic-ray air showers



Atmospheric neutrinos come from all directions



IceCube observes a lot of atmospheric neutrinos!

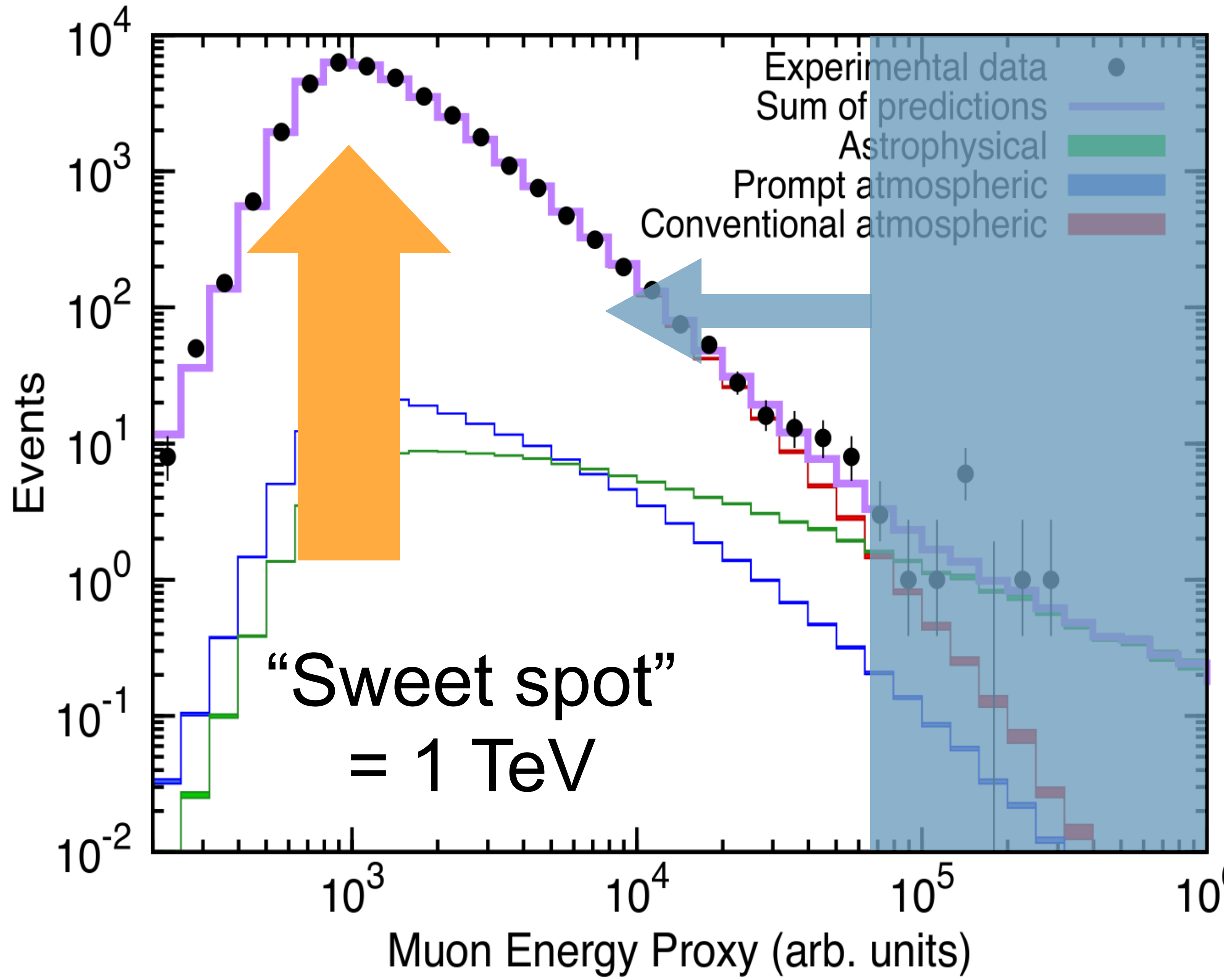


Phys. Rev. Lett. 115, 081102 (2015)

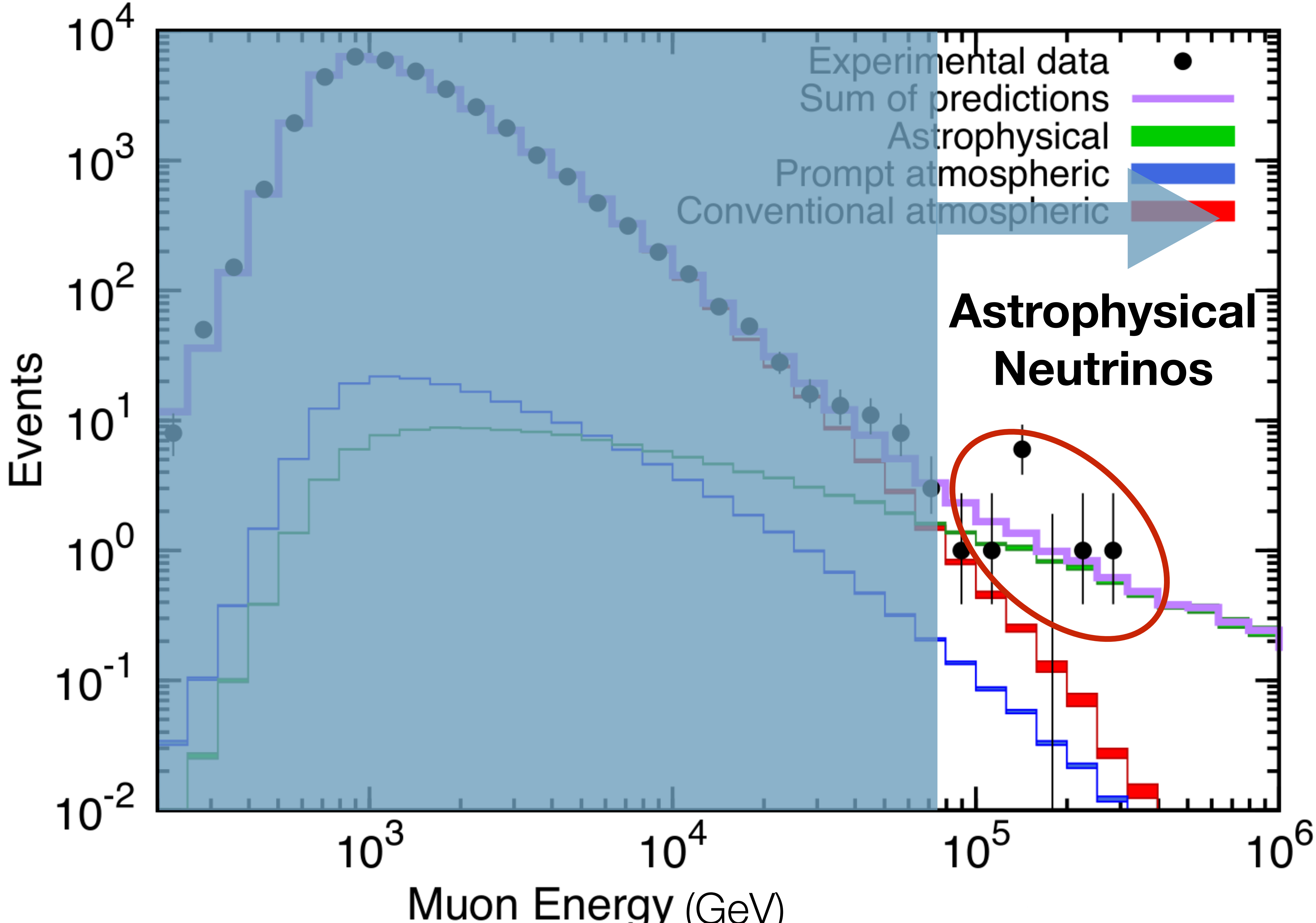
This may not be the atmospheric spectrum you expected …

Atmospheric flux rises with decreasing energy

Turn–over happens because detector is inefficient at "low" energy (detector spacing)



But wait, there's more!

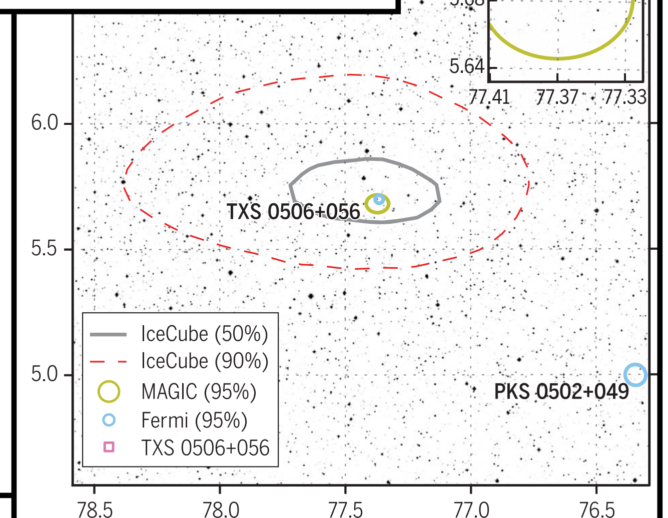


Phys. Rev. Lett. 115, 081102 (2015)

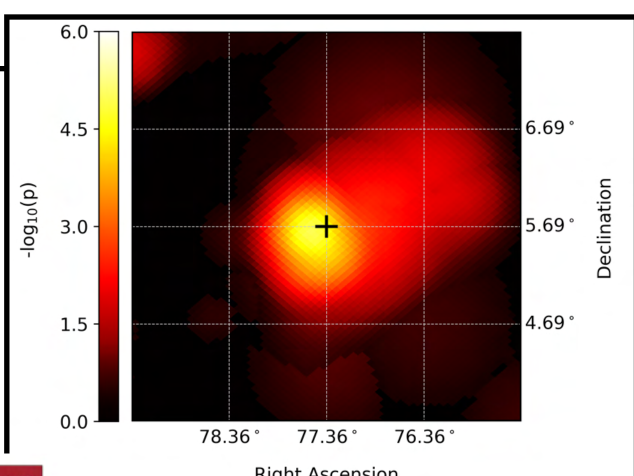
Neutrinos From Cosmic Beam dump
Blazar: TXS 0506+056

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

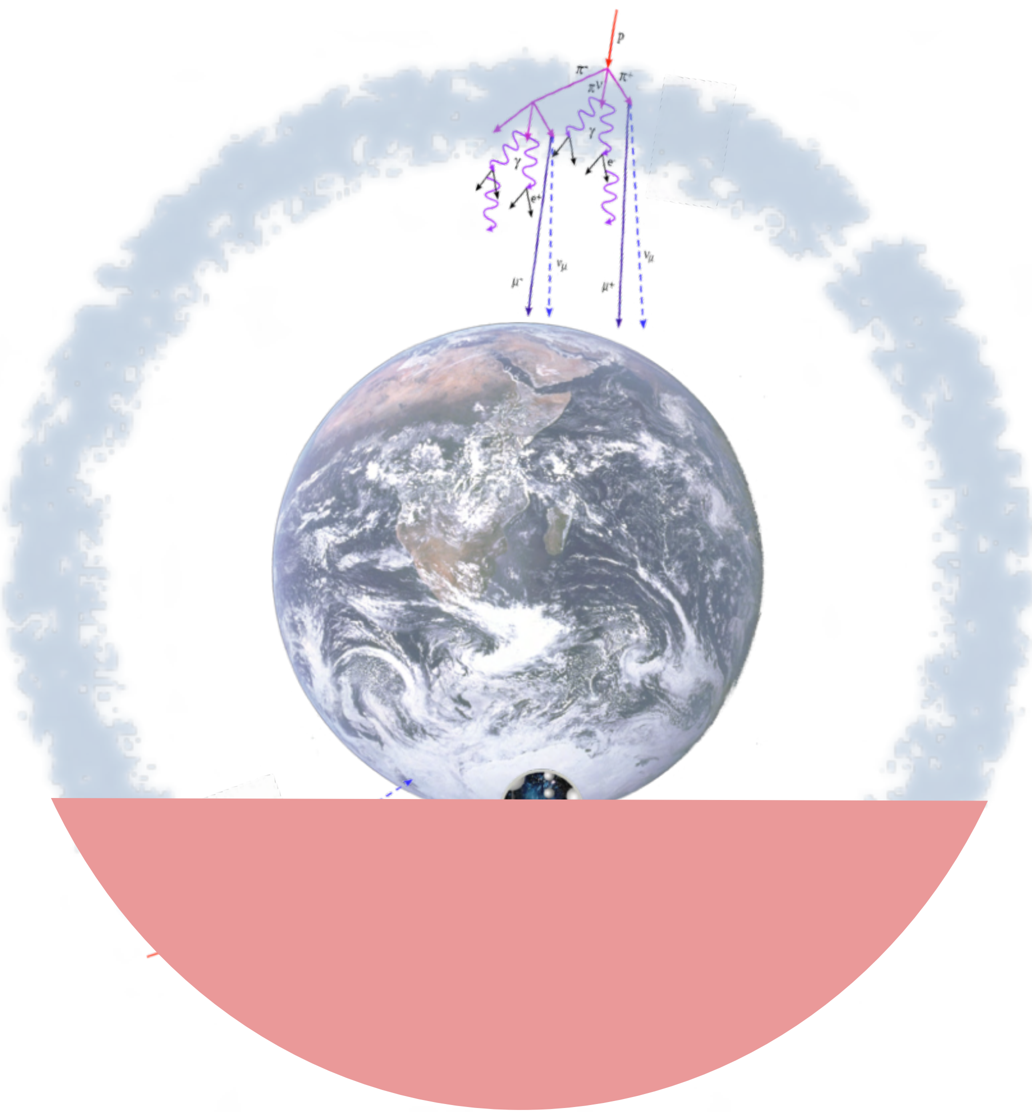
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

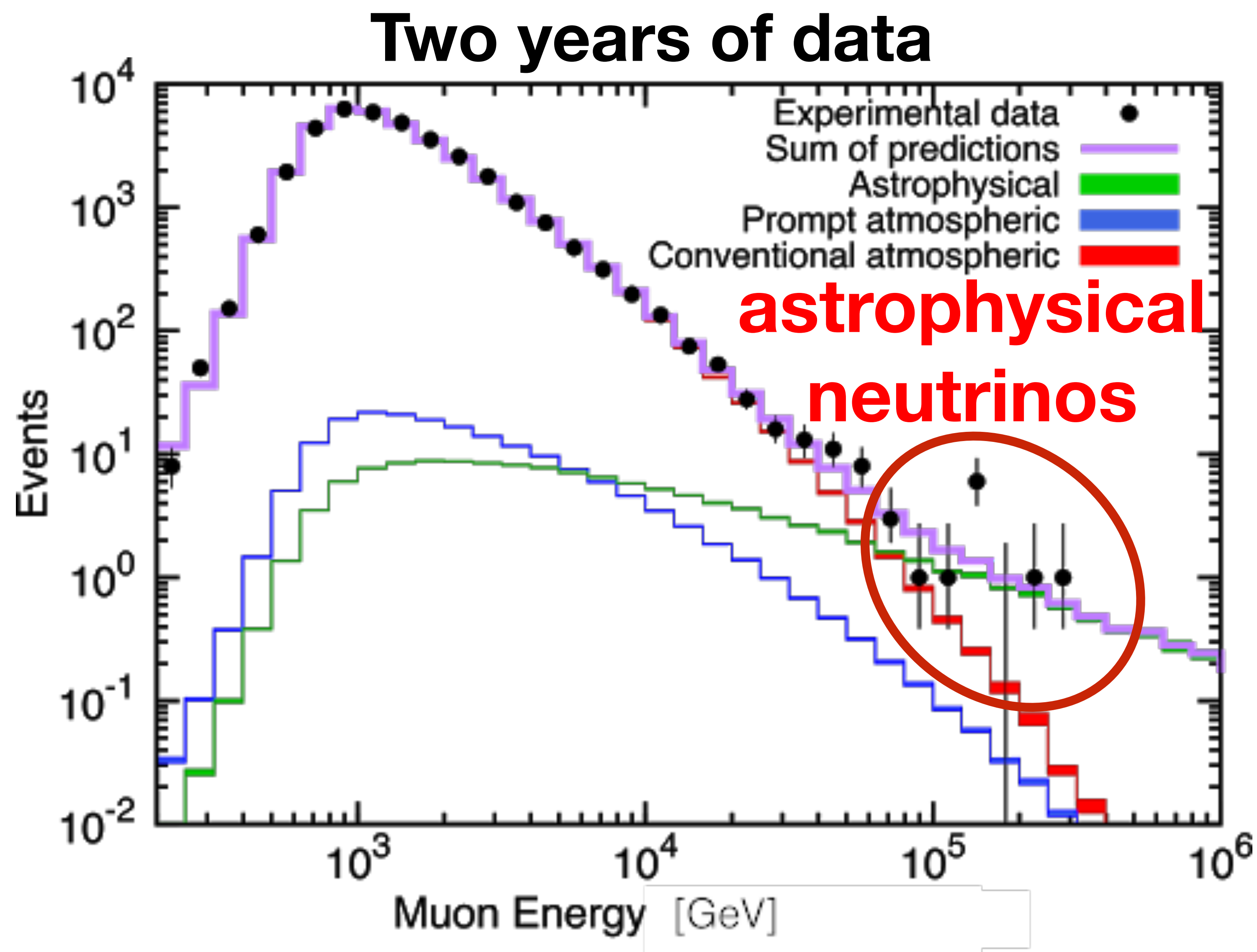


Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert



Strategy One: look at the Northern Sky



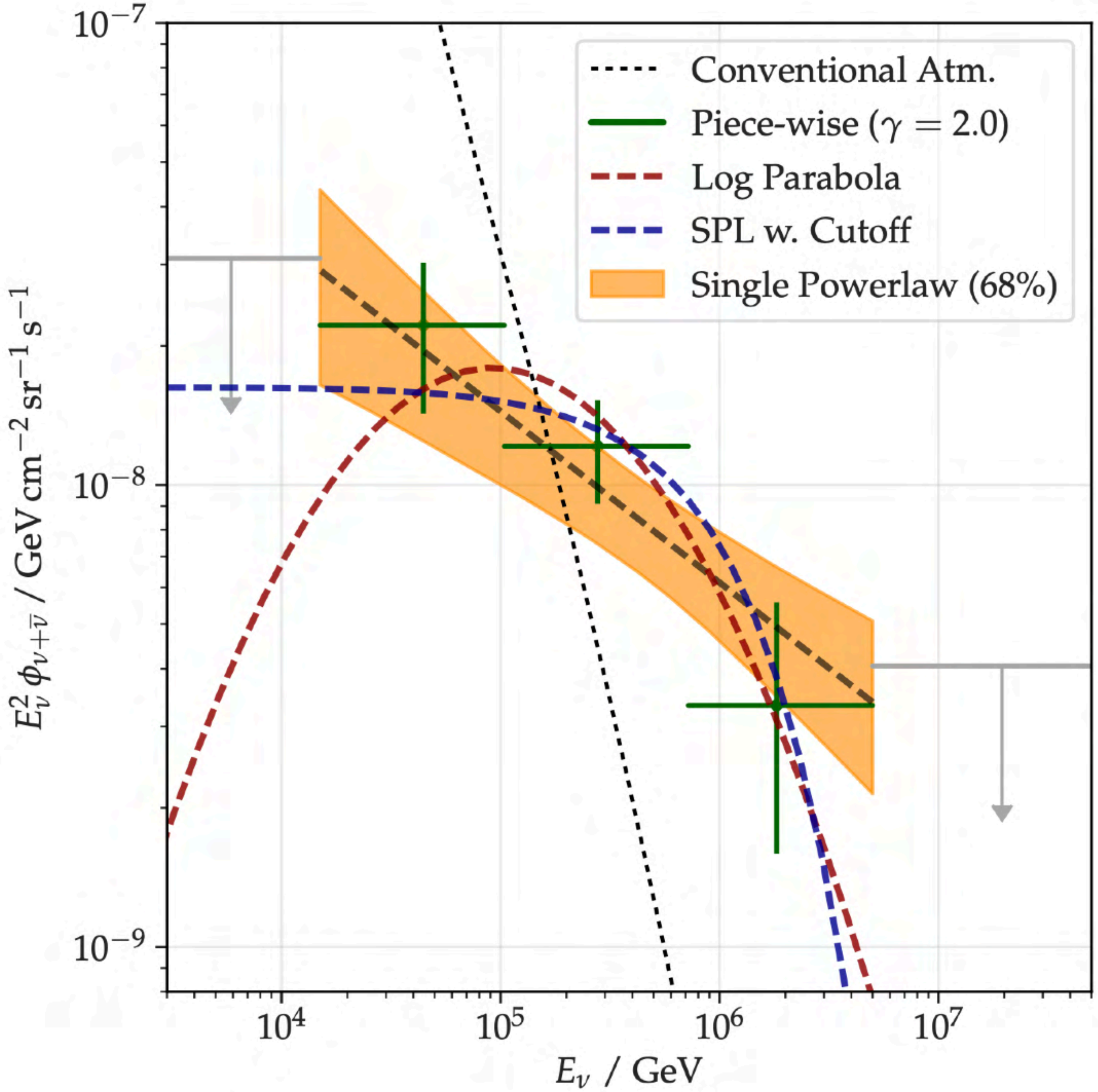


Strategy:

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

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

IceCube Coll. arXiv:2111.10299



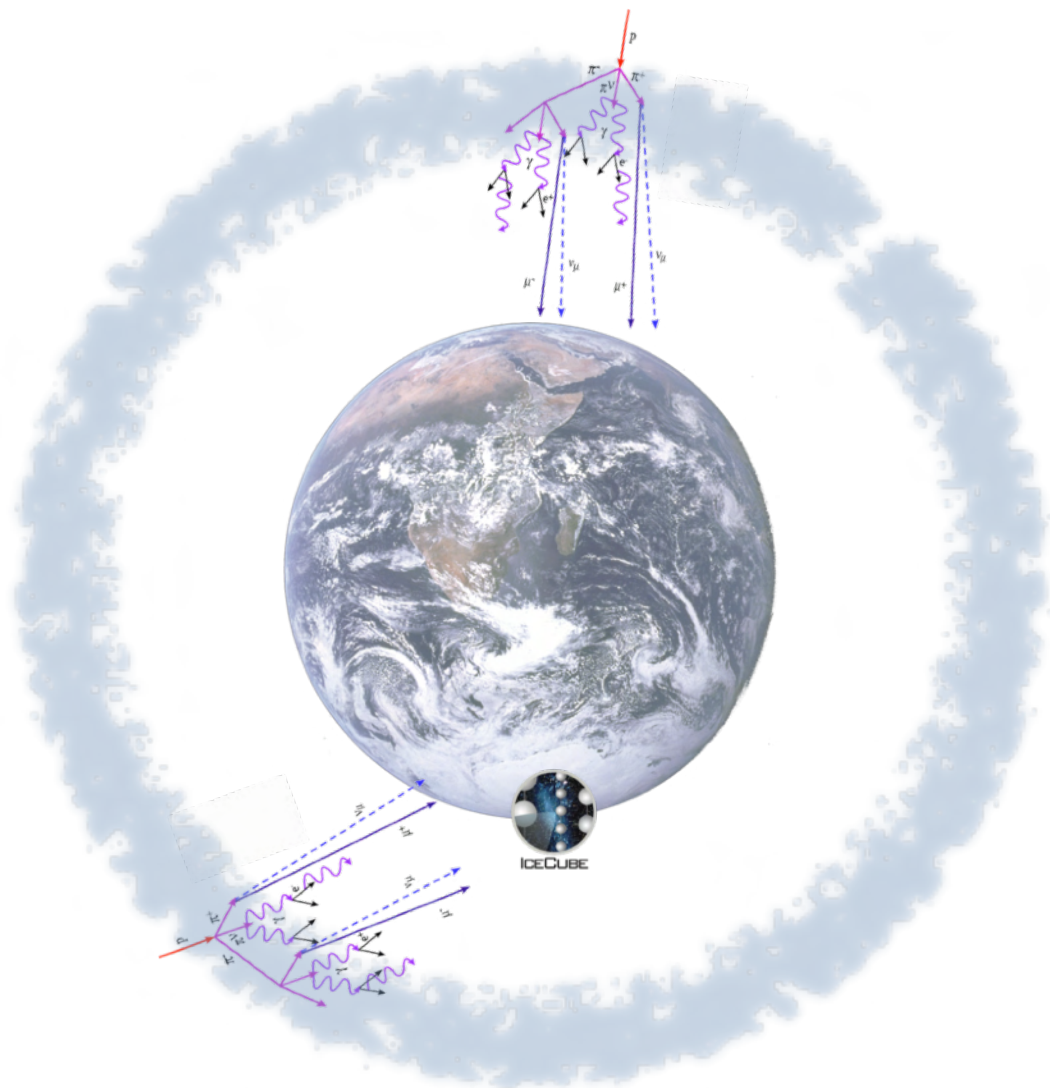
Simple power-law (SPL) *versus* more *ad hoc* complex models

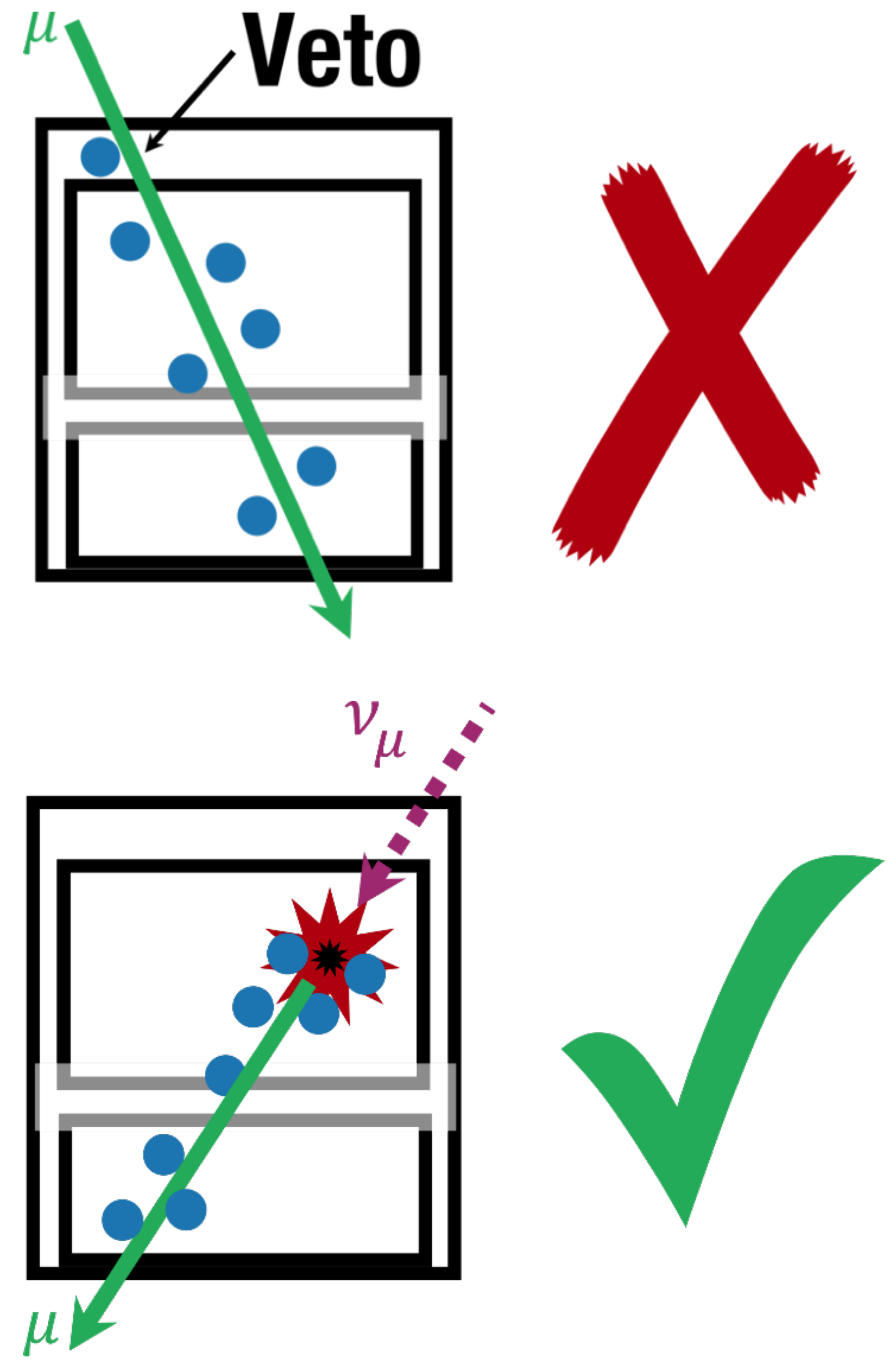
Astrophysical Norm. $\phi_{\rm cutoff}/C_{\rm units}$	$1.64^{+0.39}_{-0.36}$
Spectral Index $\gamma_{\rm cutoff}$	$2.0^{+0.22}_{-0.28}$
Cut-off Energy $E_{\rm cutoff}$/ PeV	$1.25^{+1.72}_{-0.56}$
Significance over SPL	$2\Delta\mathrm{LLH} = 4.24$
	$\mathrm{p}(> 2\Delta\mathrm{LLH}\|\mathrm{SPL}) = 6.1\%$

Log-parabola Norm. $\phi_{\rm LogParab.}/C_{\rm units}$	$1.79^{+0.40}_{-0.38}$
Spectral Index $\alpha_{\rm LogParab.}$	$2.03^{+0.22}_{-0.31}$
Curvature parameter $\beta_{\rm LogParab.}$	$0.45^{+0.29}_{-0.22}$
Significance over SPL	$2\Delta\mathrm{LLH} = 6.82$
	$\mathrm{p}(> 2\Delta\mathrm{LLH}\|\mathrm{SPL}) = 1.3\%$

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



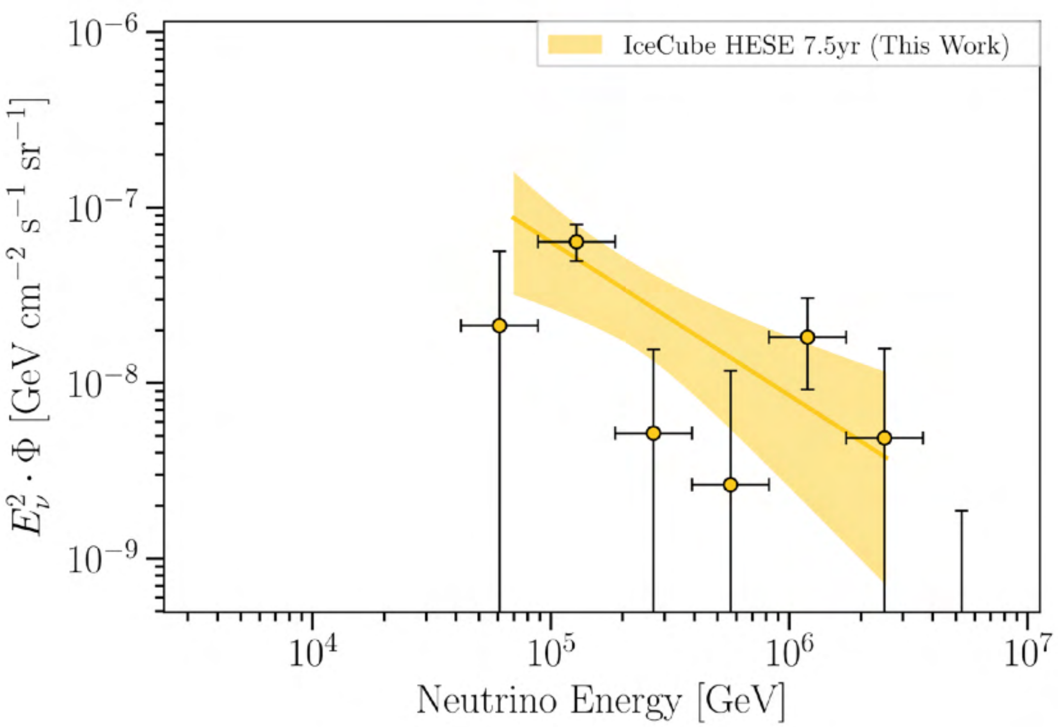


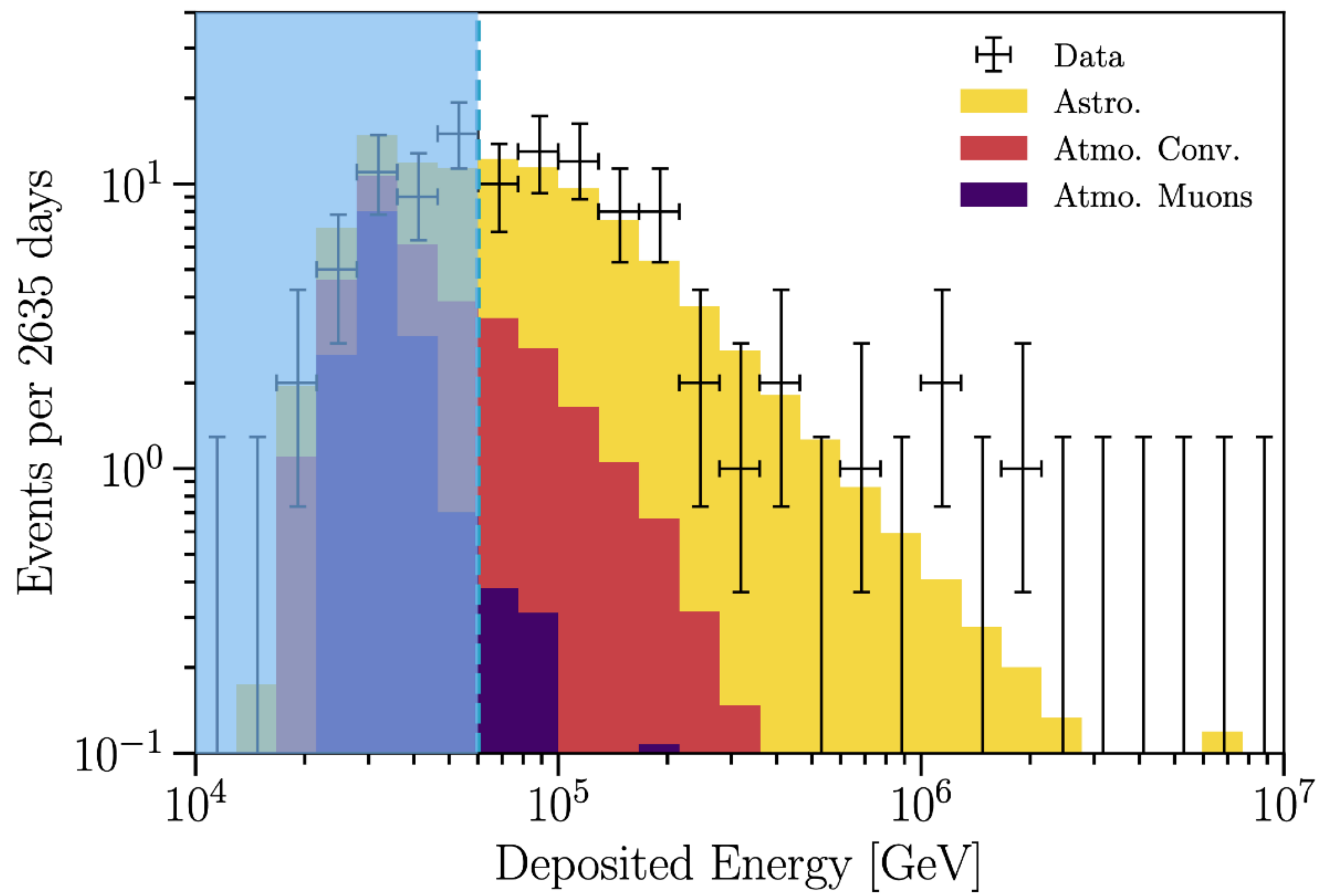
Strategy:

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

Starting Events Energy Distribution And Inferred Spectrum

$$\gamma = 2.9 \pm 0.2$$

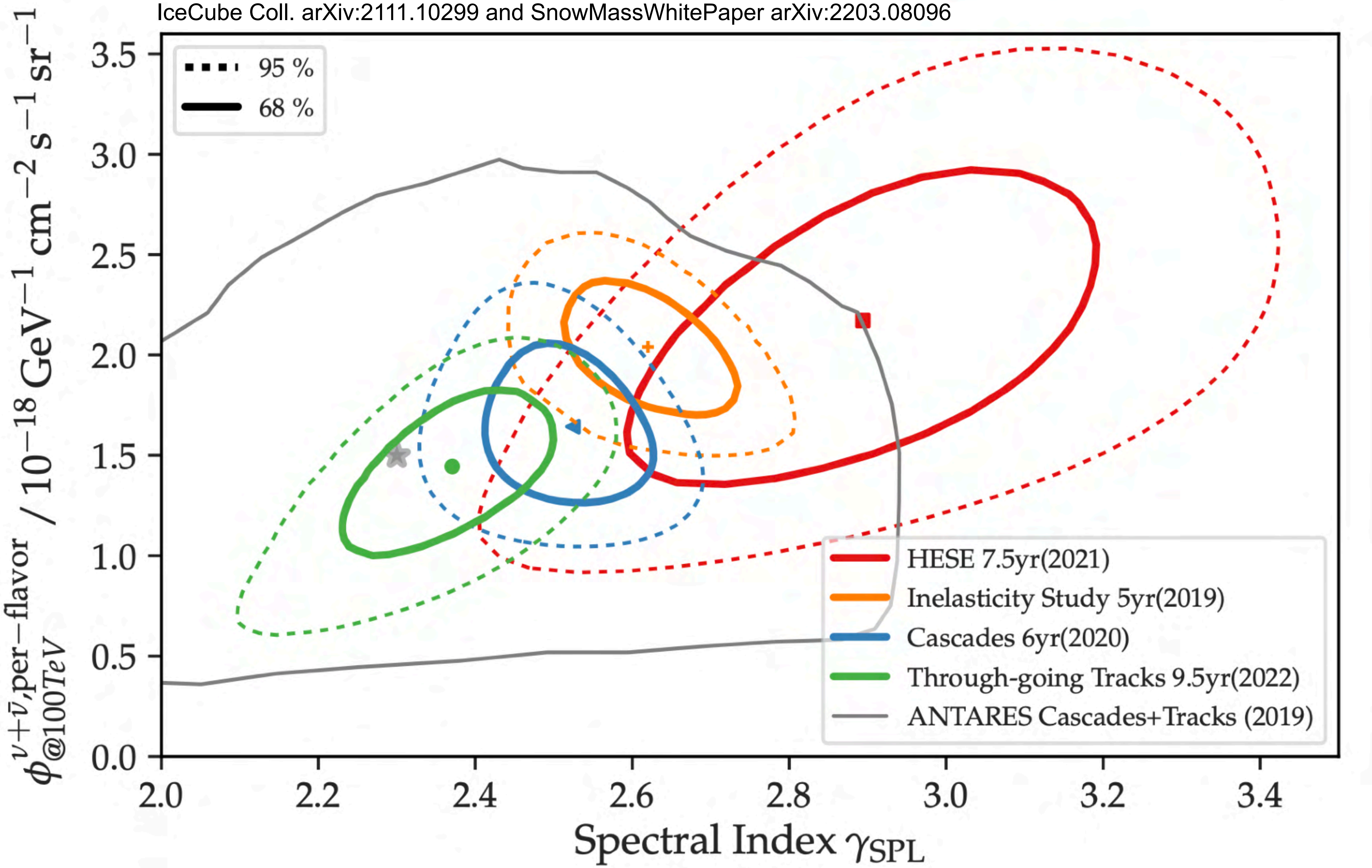




High-Energy Starting Events energy distribution is well described by a single power-law, but with a *spectral index softer* than the northern tracks!

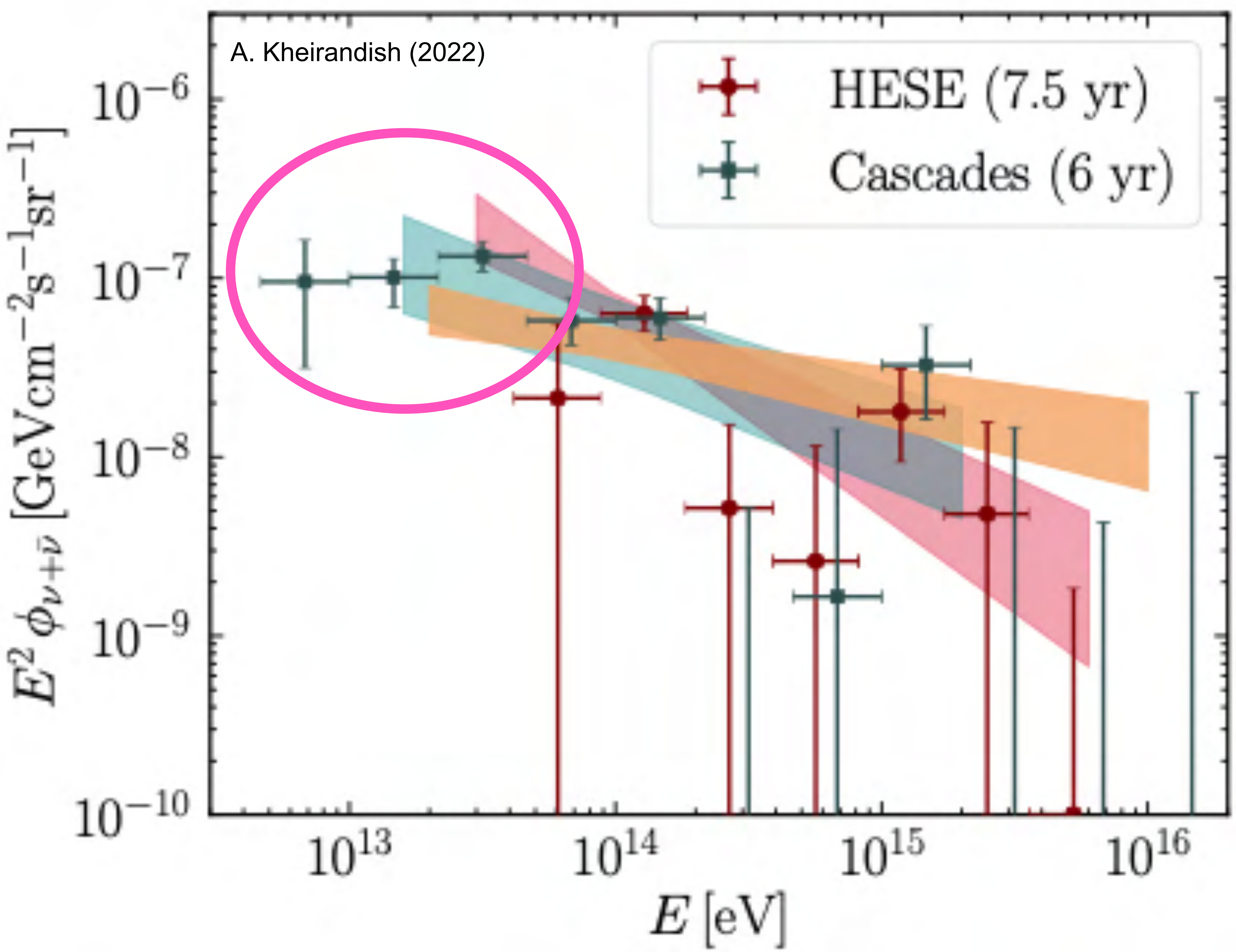
Comparison of different single power-law spectra

IceCube Coll. arXiv:2111.10299 and SnowMassWhitePaper arXiv:2203.08096



- ❖ 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 ...



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

Take away so far:

1. We are interested in anomalies related to neutrino flavor.

2. IceCube is a unique neutrino detector with interactions at CM energies similar to LHC. This allows us to access unusual interactions, like ν_τ interactions.

3. It has a well-understood atmospheric flux and a newly discovered astrophysical one.

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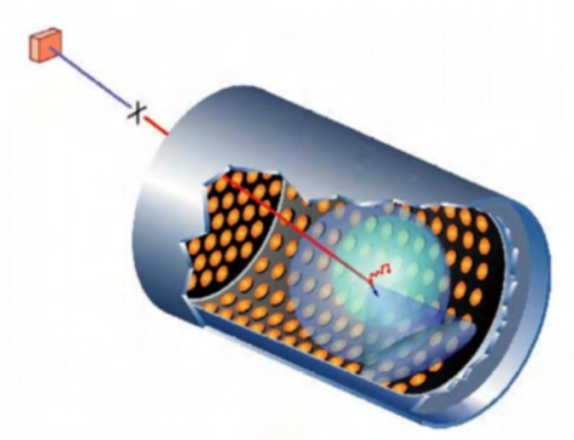
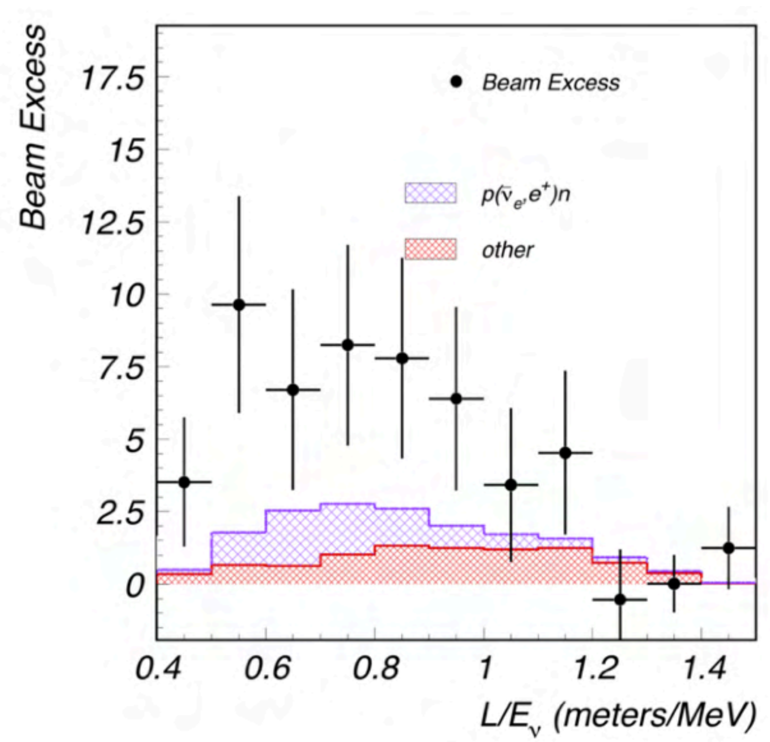
Long-standing "appearance" oscillation anomalies

LSND

(3.8σ!)



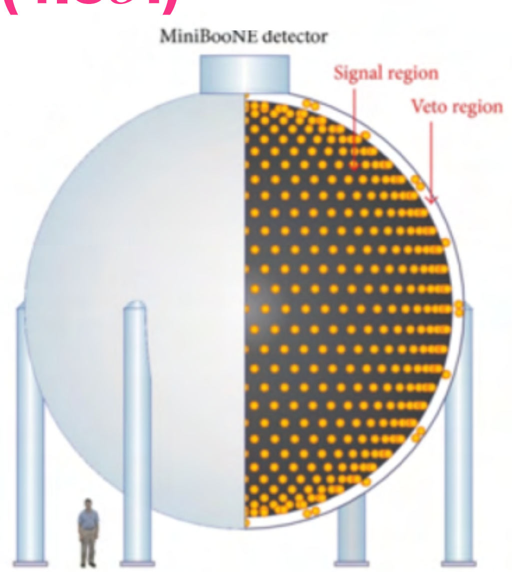


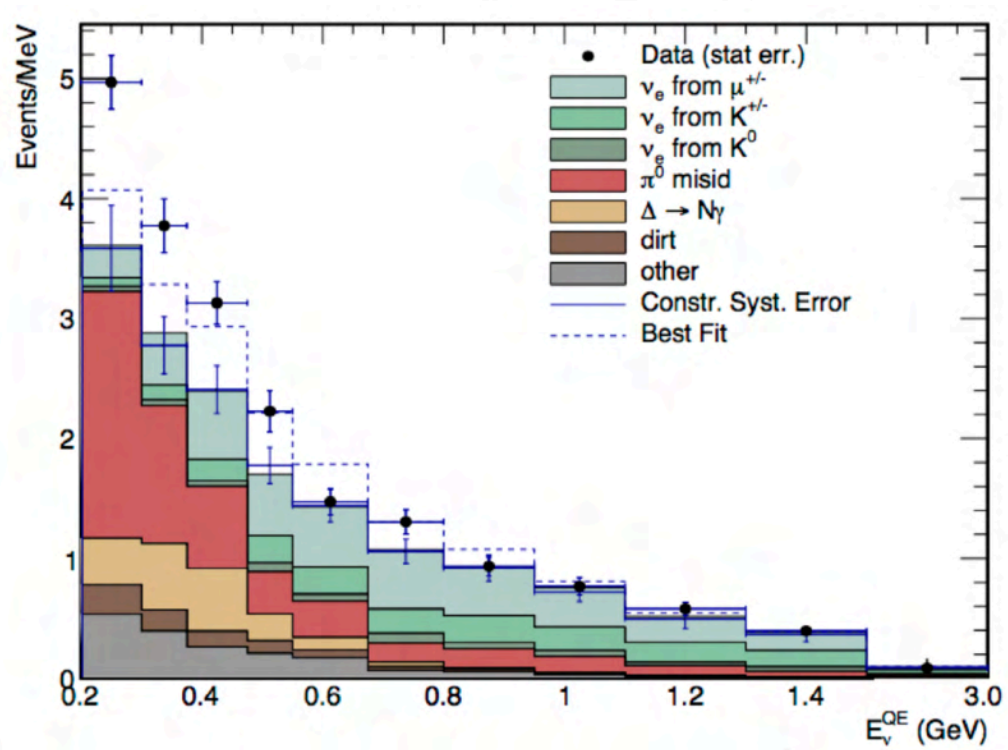
These experiments observe ν_e appearance at L/E ~ 1 km/ GeV!

This points to Δm^2~1eV^2

MiniBooNE

(4.8σ!)



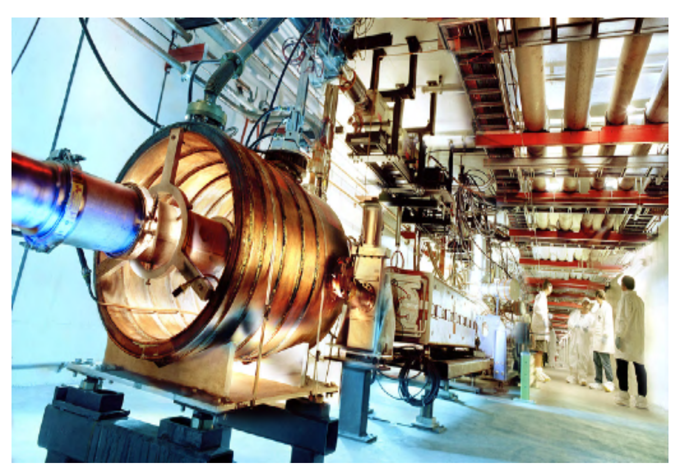
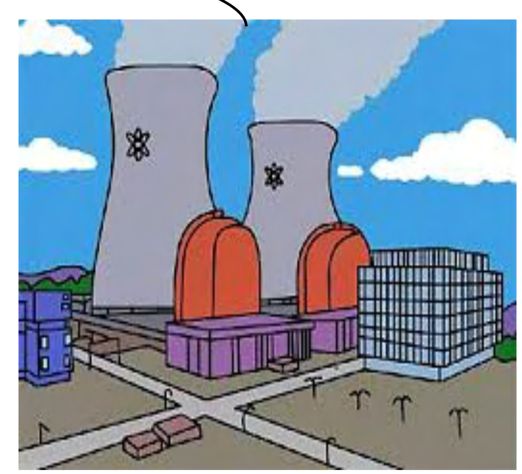


These are not alone, other interesting observations

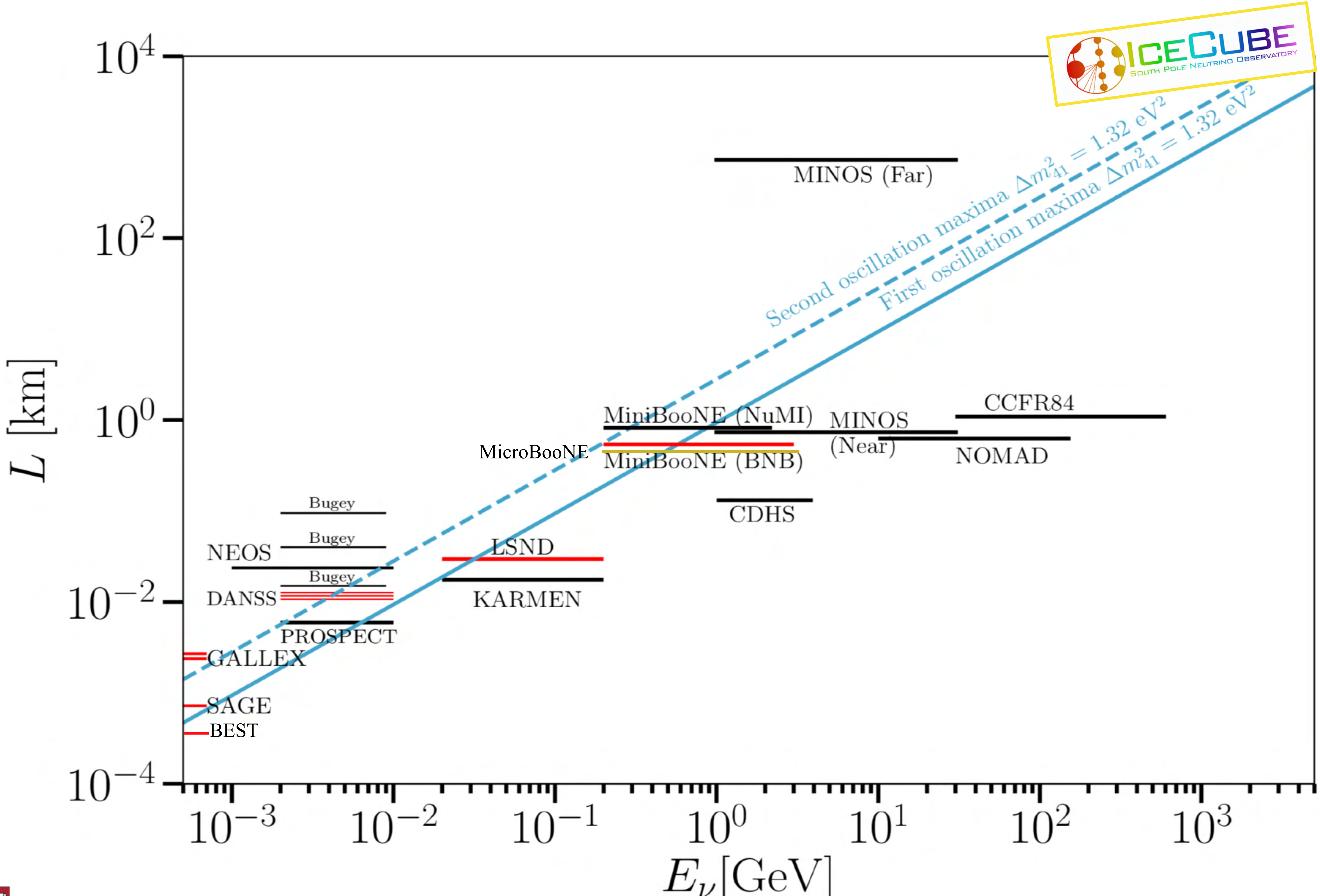
	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) $*$	SciBooNE/MiniBooNE	KARMEN/LSND Cross Section
	MiniBooNE(NuMI)	CCFR	Gallium $*$
	NOMAD	CDHS	BEST $*$
	MicroBooNE (BNB) $(*?)$	MINOS IceCube	
Antineutrino	LSND $*$	SciBooNE/MiniBooNE	Bugey Daya Bay
	KARMEN	CCFR	NEOS PROSPECT
	MiniBooNE (BNB) $*$	MINOS	DANSS STEREO
		IceCube $(*?)$	Neutrino-4 $*$

$*$ $\Longrightarrow$ >2σ "signal"

$*$ $\Longrightarrow$ unclear "signal"/work in progress

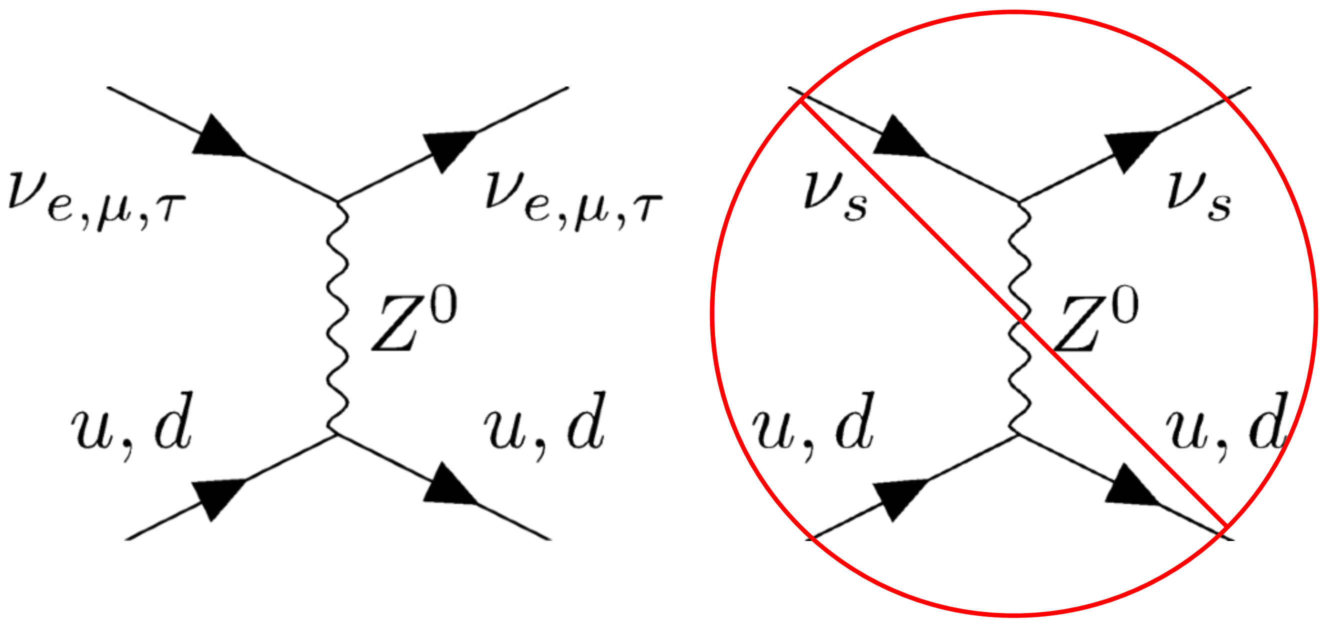




The anomalies lie ~ in a line

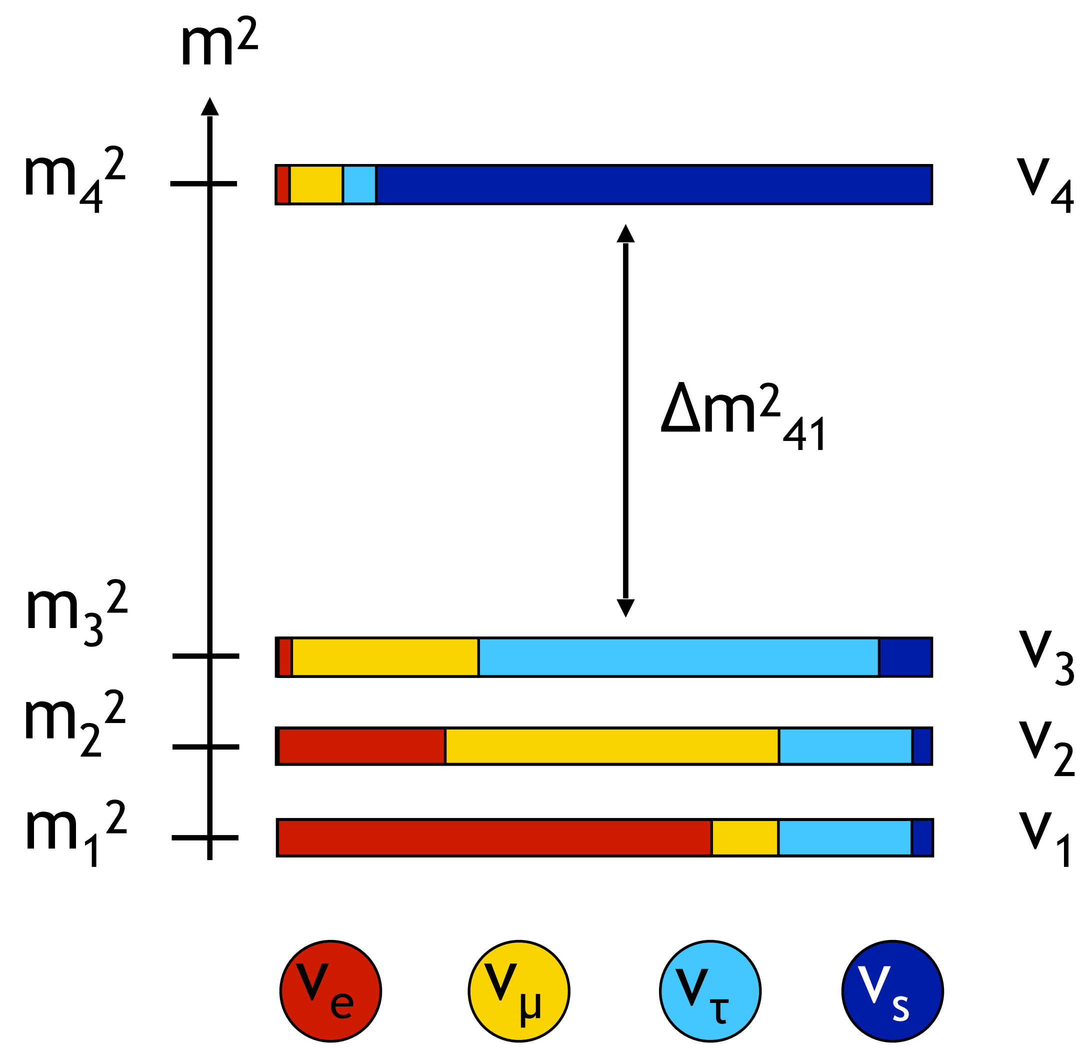


Diaz *et al.* arXiv:1906.00045

Vanilla solution: light sterile neutrino



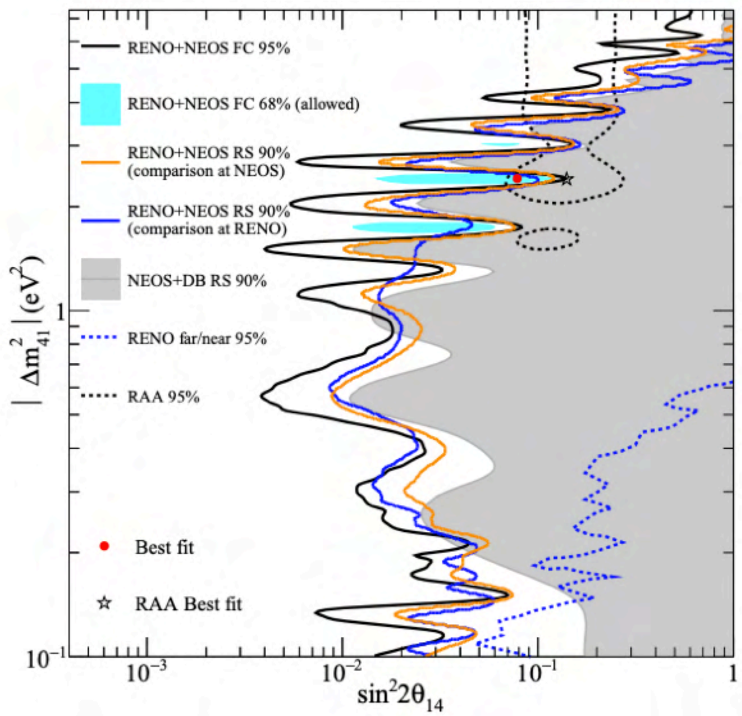
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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



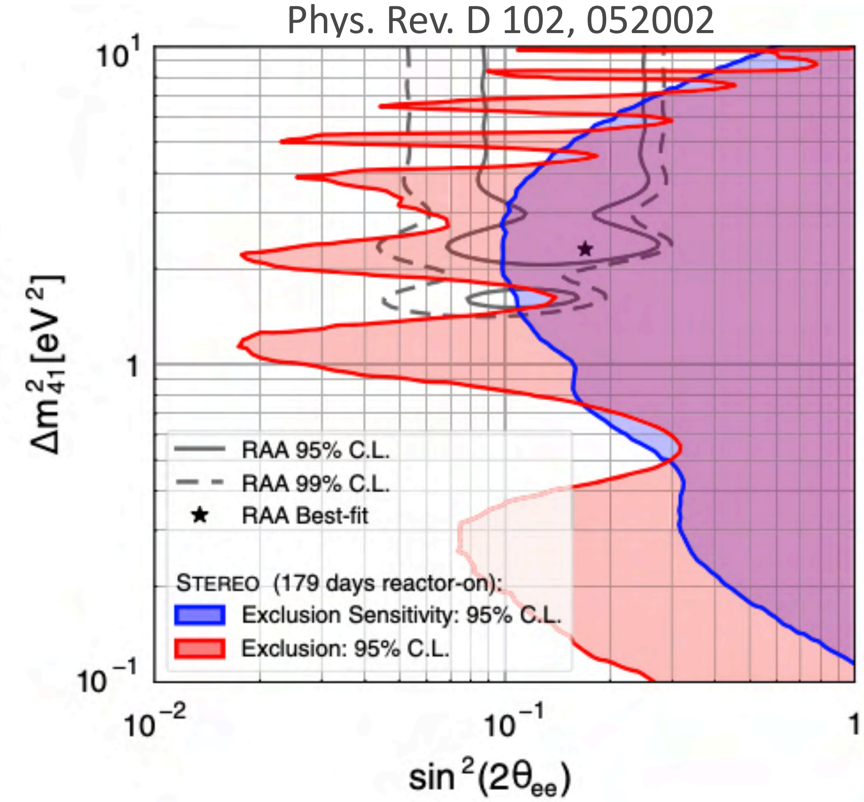
Assuming Normal Ordering

Constraints from $\nu_e \rightarrow \nu_e$ searches on 3+1

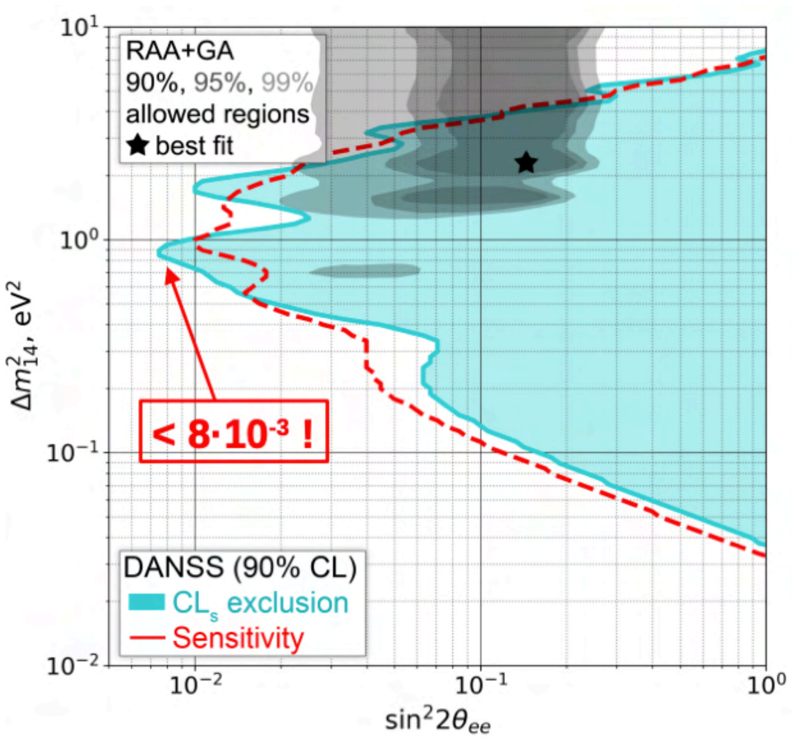
NEOS+RENO
arXiv:2011.00896



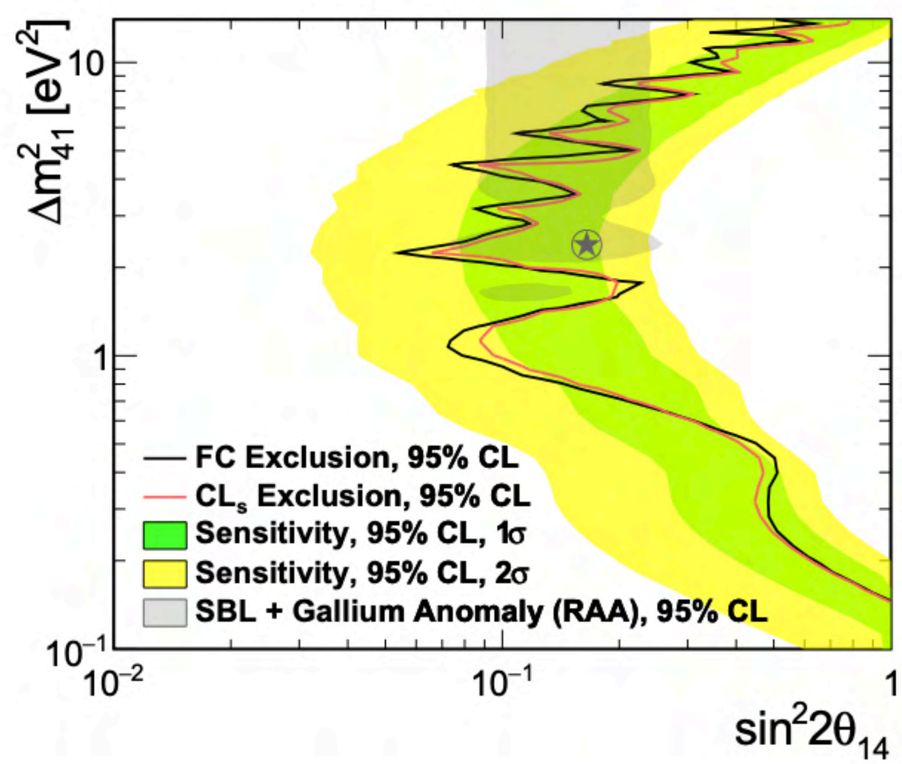
STEREO Collaboration
Phys. Rev. D 102, 052002



DANSS

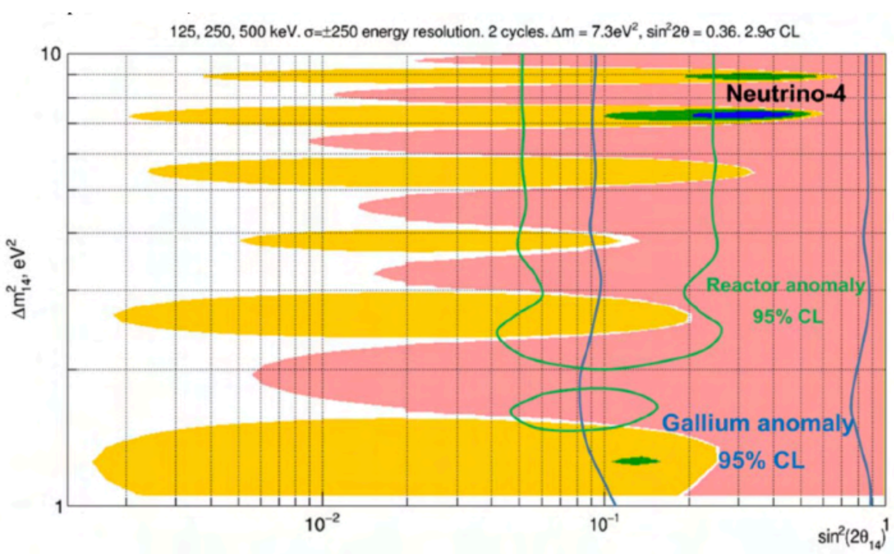


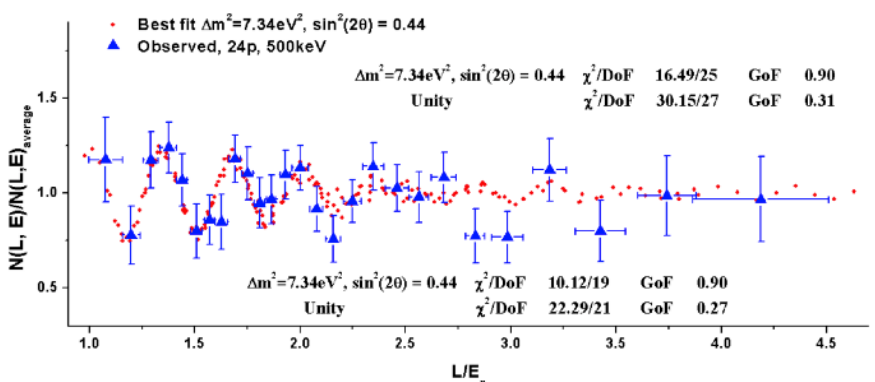
PROSPECT
Phys. Rev. D 103, 032001 (2021)



Indications from $\nu_e \rightarrow \nu_e$ searches for 3+1

Neutrino-4 arXiv:2005.05301

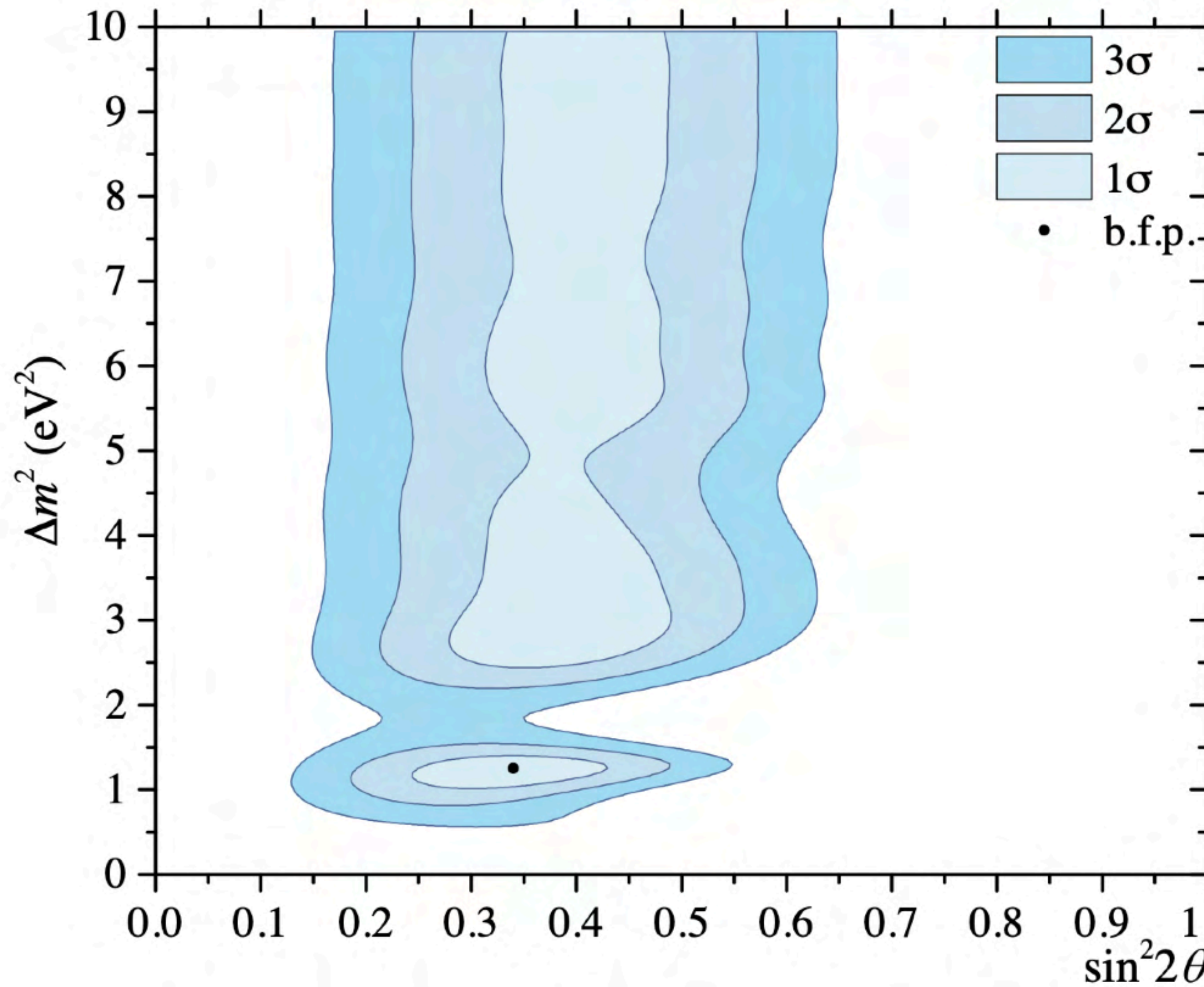




Wiggles or fluctuations?

See C. Giunti arXiv:2101.06785
Neutrino-4 Coll. arXiv:2005.05301

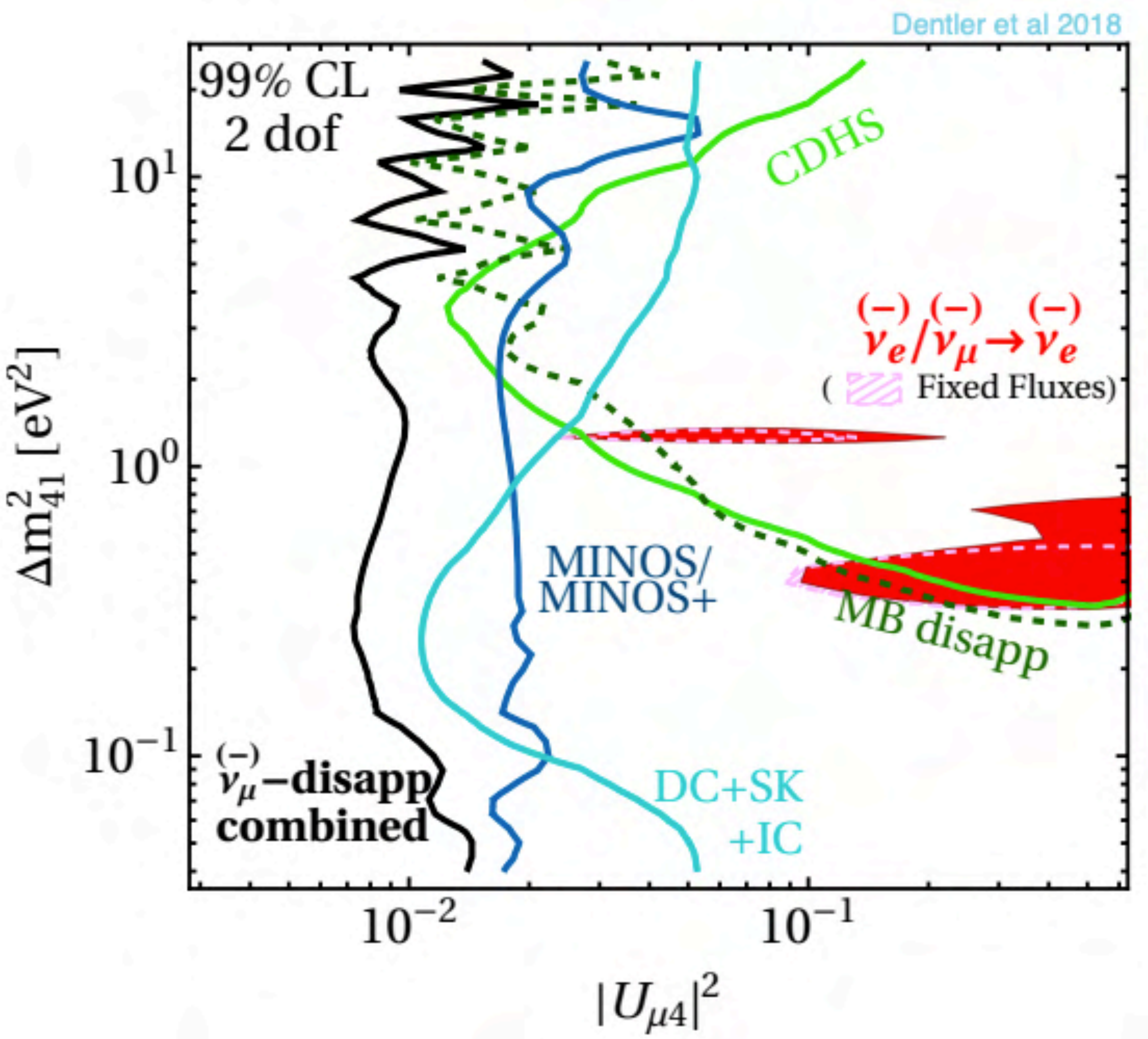
BEST arXiv:2109.11482



More than 5 sigma observation of electron neutrino disappearance!

New physics, cross sections, or flux?

Constraints from $\nu_\mu \to \nu_\mu$ searches on 3+1



Accelerator neutrinos
CDHS, MiniBooNE, NOvA NC, MINOS/MINOS+

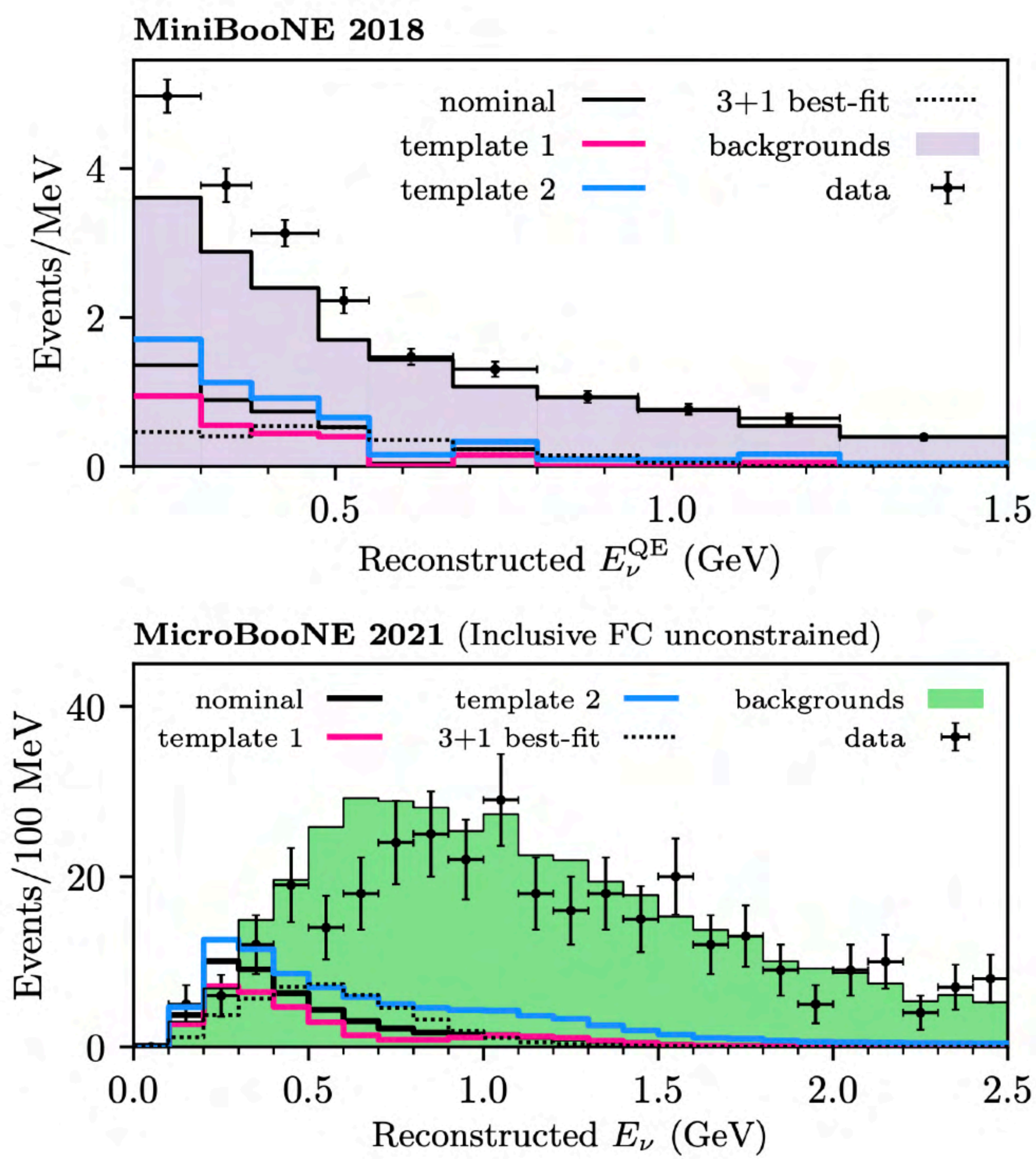
Atmospheric neutrinos
IceCube, SK, DeepCore

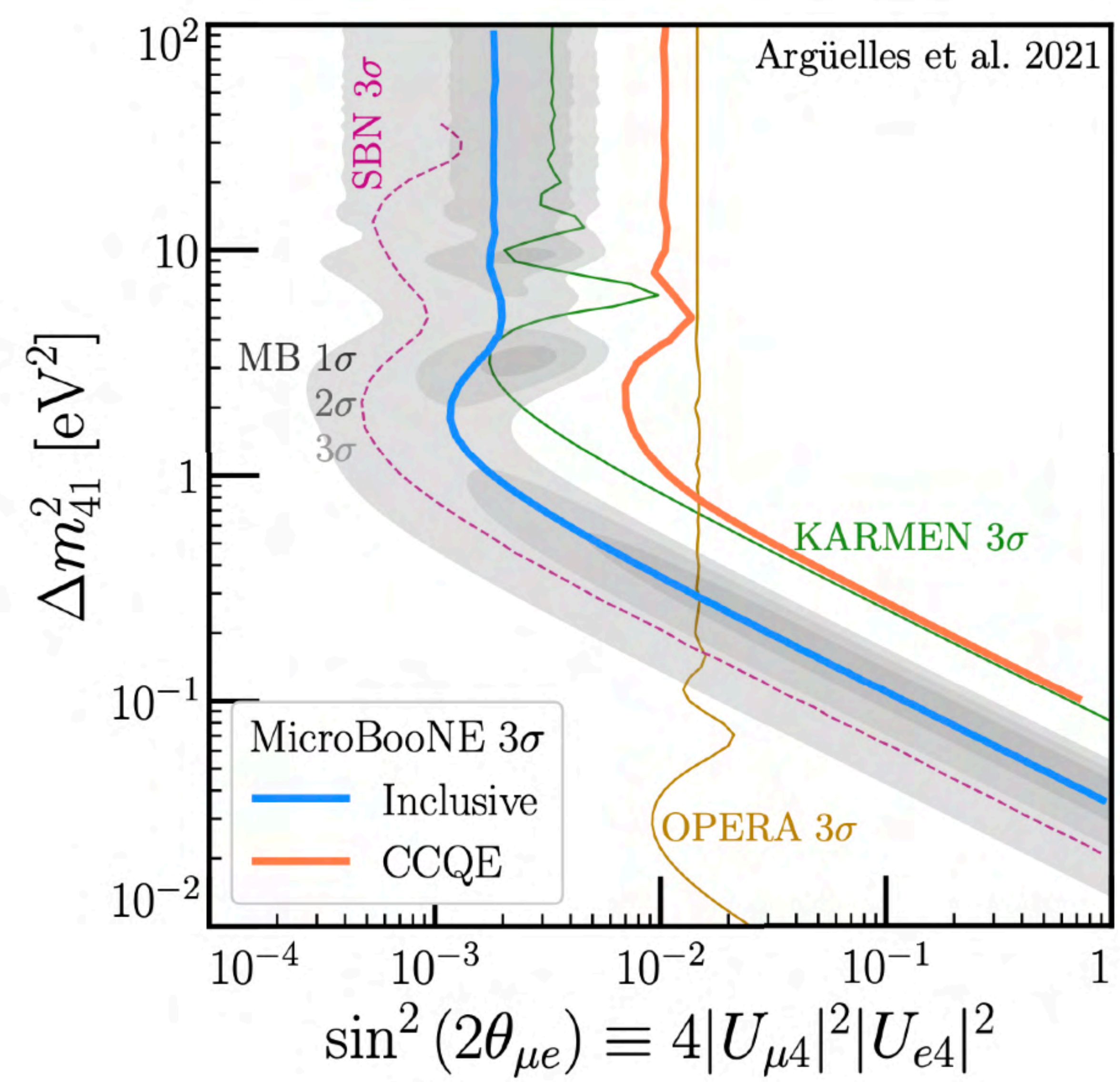
No anomaly there

Very strong constraint

Dominated by IceCube and MINOS/MINOS+, then CDHS and MiniBooNE

Additionally, recent results from MicroBooNE see no *significant* hints!





MicroBooNE collaboration arXiv:2110.14054,2110.13978,2110.14080

CA, I. Esteban, M. Hostert, K.J. Kelly, J. Kopp, P.A.N. Machado, I. Martinez-Soler, Y. F. Perez-Gonzalez, arXiv:2111.10359
See also Denton arXiv:2111.05793

Appearance and Disappearance signals should be related!

$\nu_\mu \to \nu_e$

$\nu_e \to \nu_e$

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

$\Rightarrow$ U_{e4} $U_{\mu 4}$ Δm^2

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

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

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

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

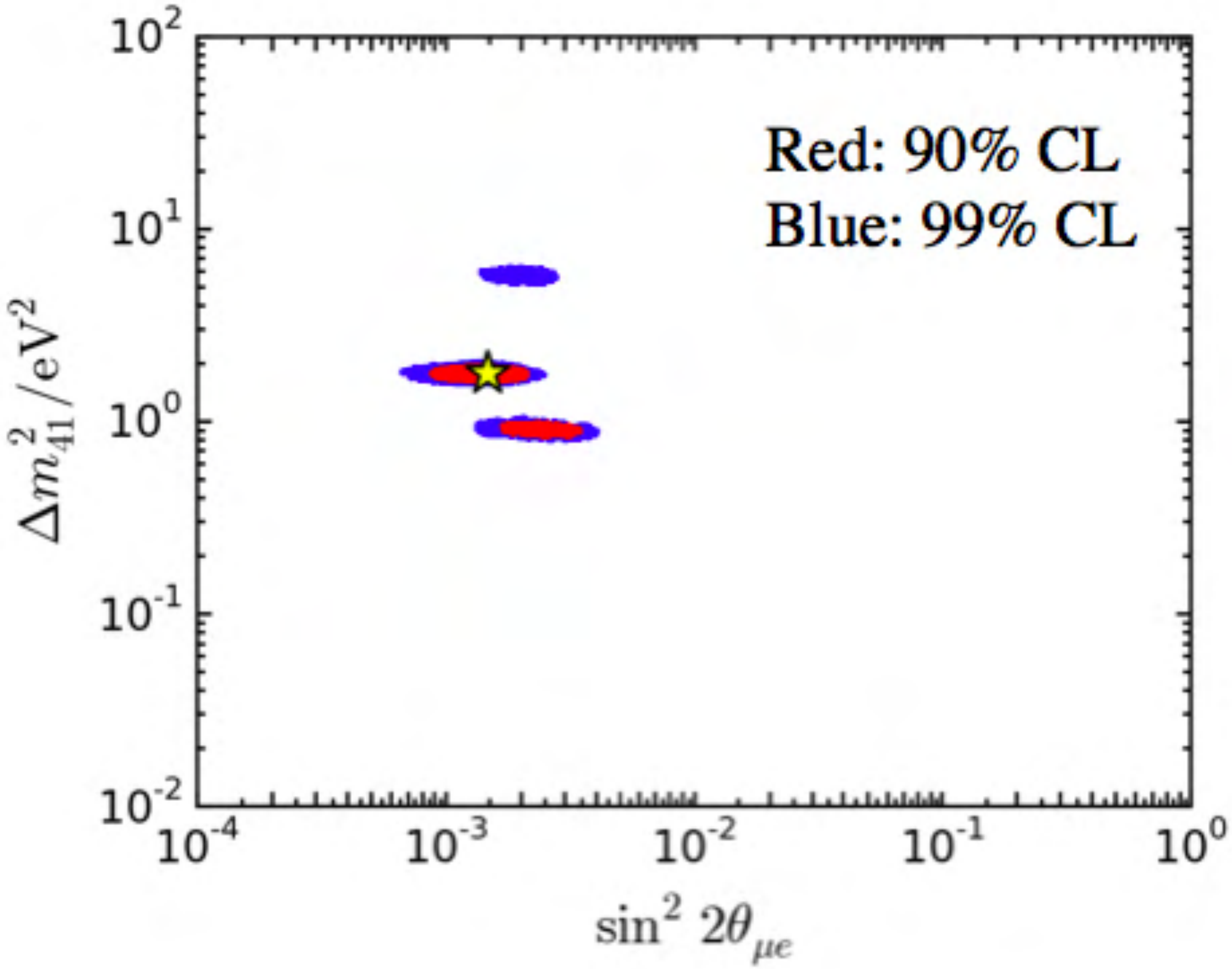
$$\sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2$$

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

This is a VERY confusing situation …

What happens if we add *everything* together?

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)

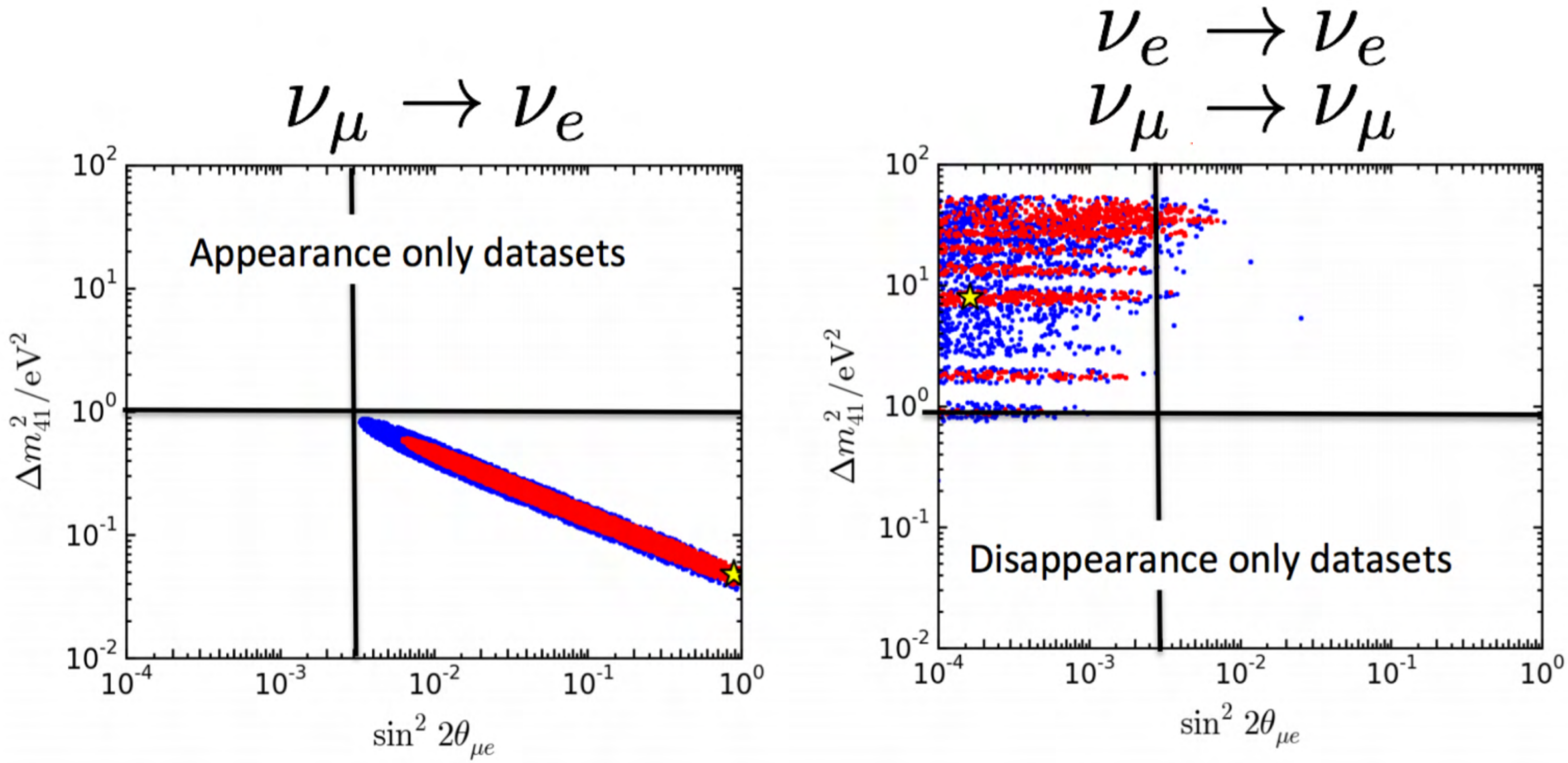
$\Delta\chi^2$: 52.34 (3 dof)

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.

*Recent measurements not added

Appearance and disappearance “preference regions” don’t overlap!



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

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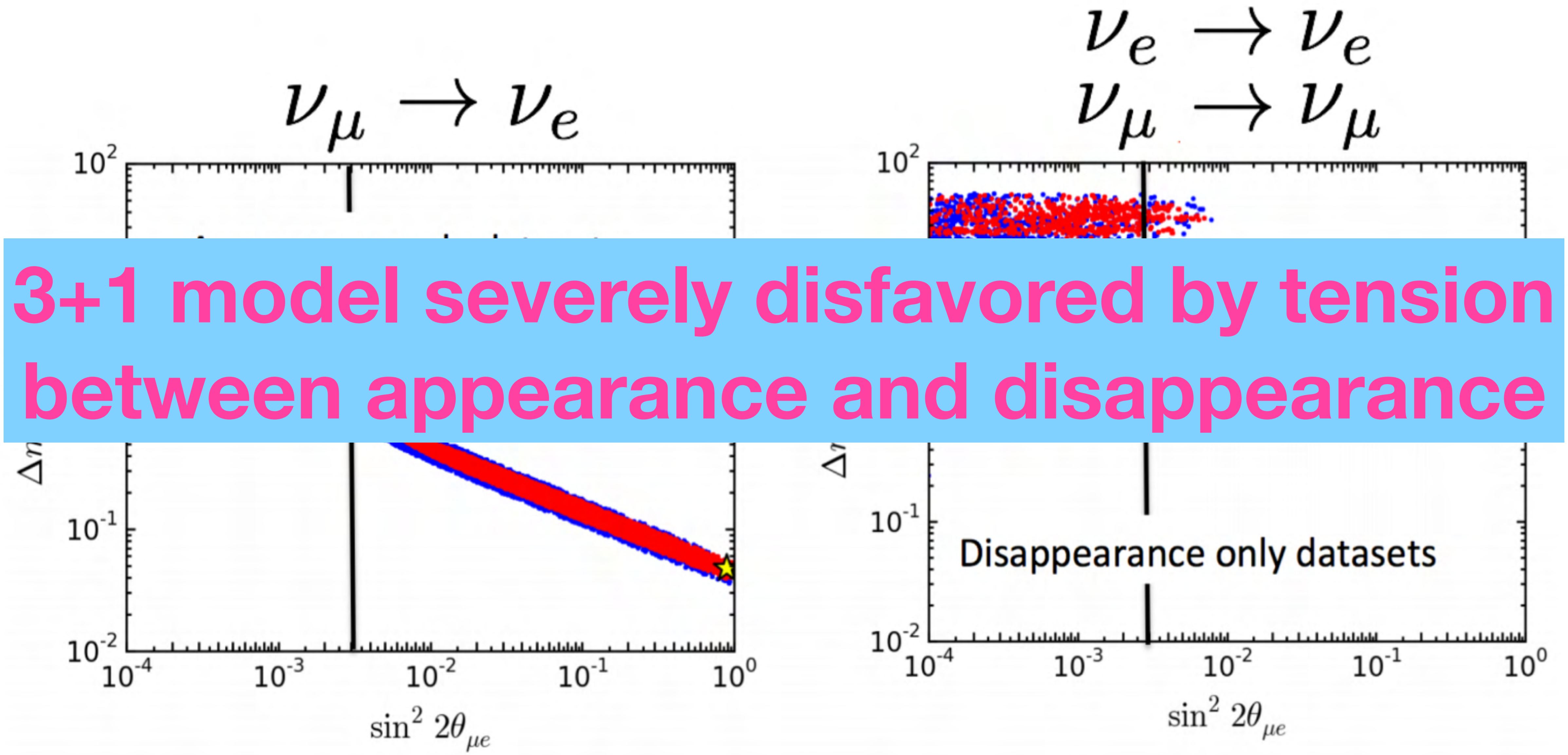


3+1 model severely disfavored by tension between appearance and disappearance

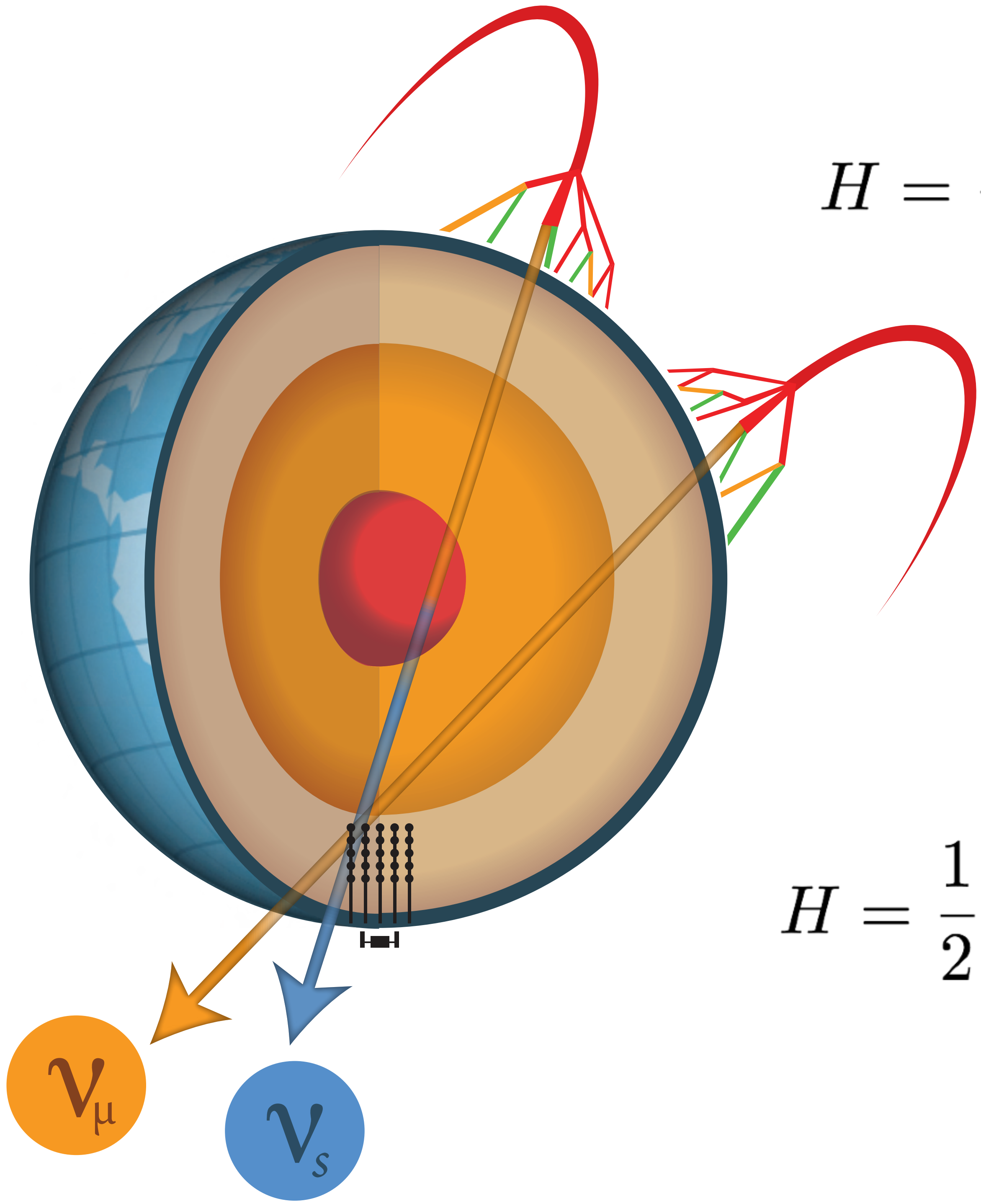
From Collin et al. 1602.00671, similar conclusions from other groups see Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018). See Diaz et al. arXiv:1906.00045 for more discussion.

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 : $\nu_\mu \to \nu_\mathrm{s}$

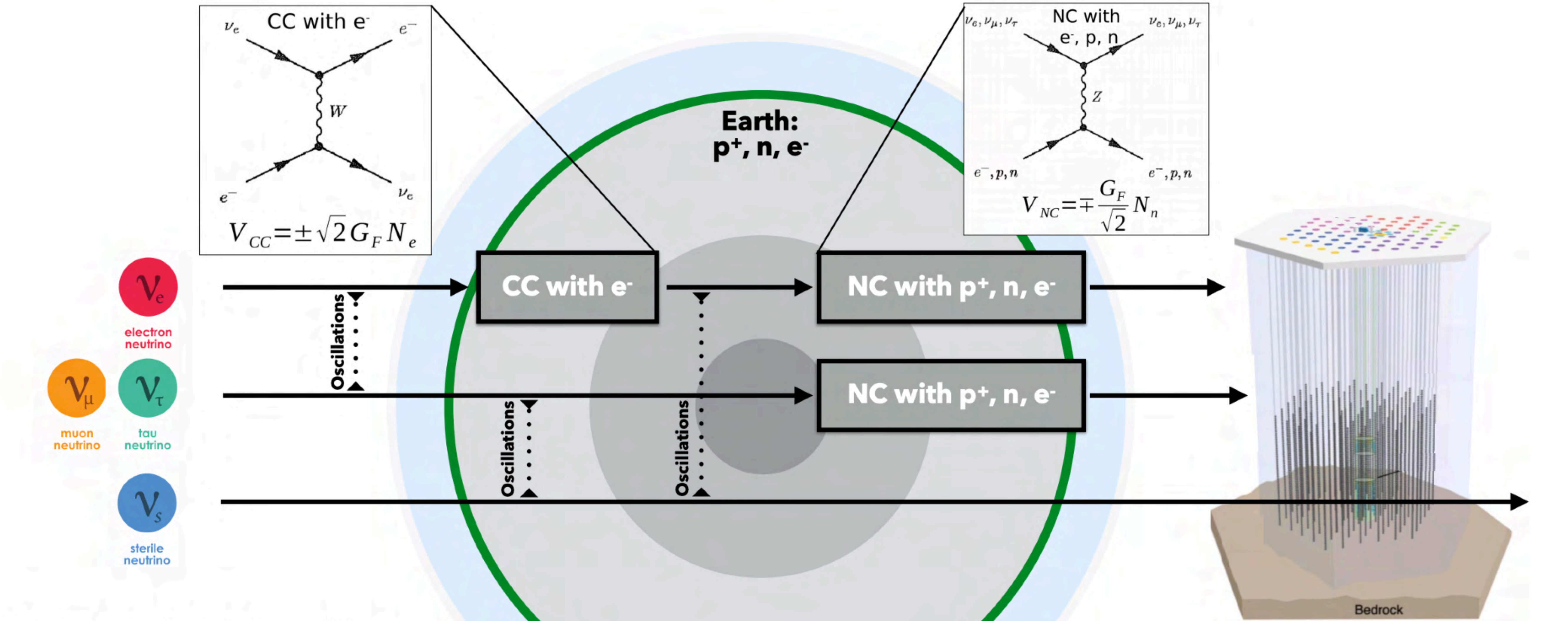


$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U$$

IceCube atmospheric neutrinos traverse large regions of matter.

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

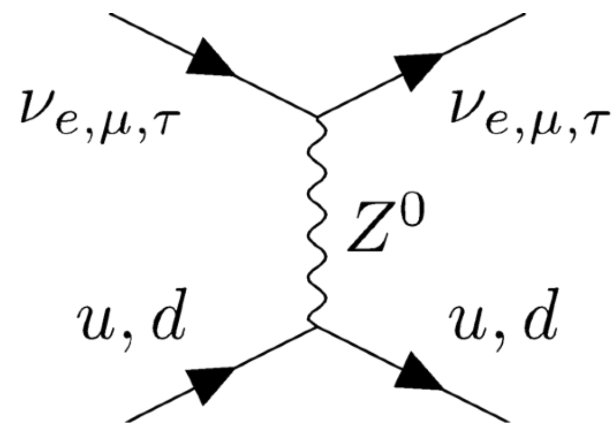
Neutrino oscillations in matter

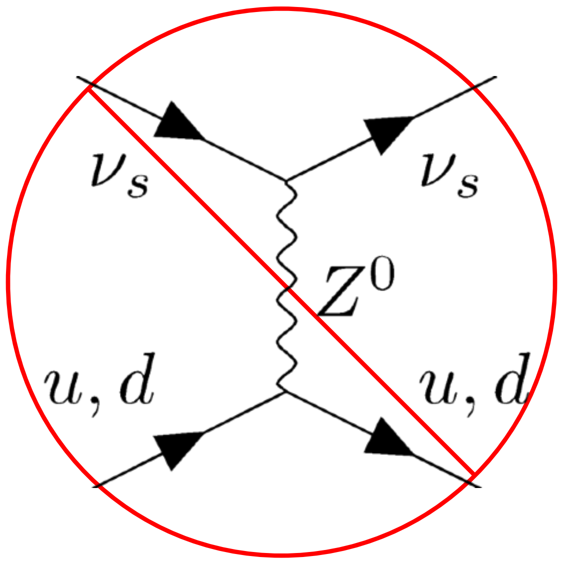


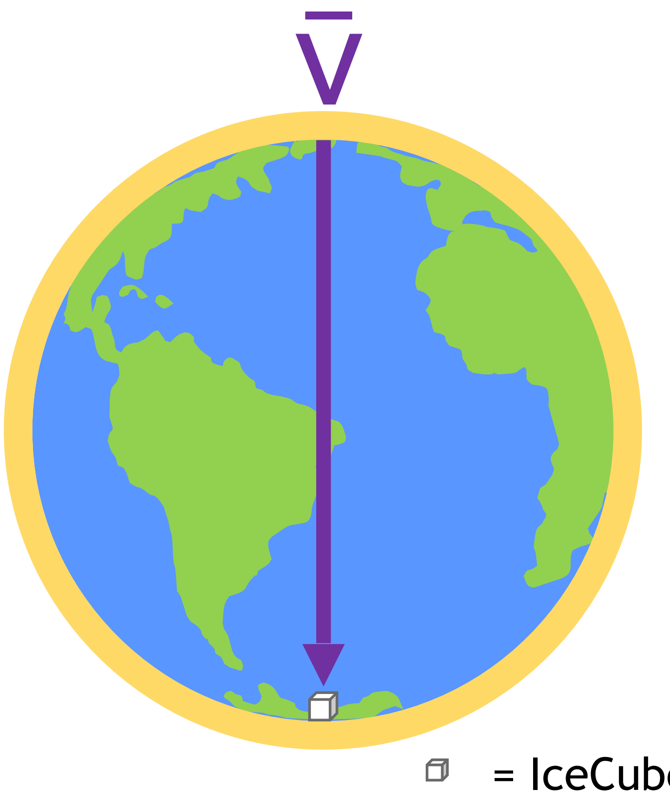
Presence of matter modifies neutrino oscillations

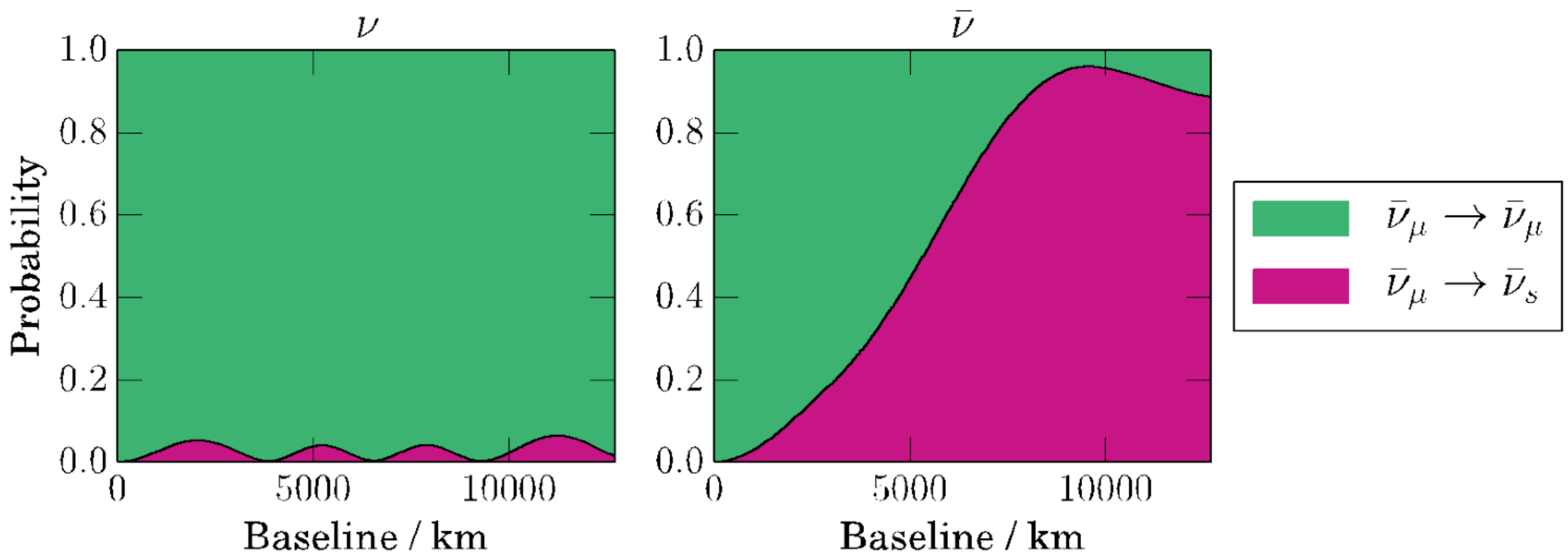
Leads to enhancements responsible for the MSW effect, parametric resonance...

Effects of Matter Effects





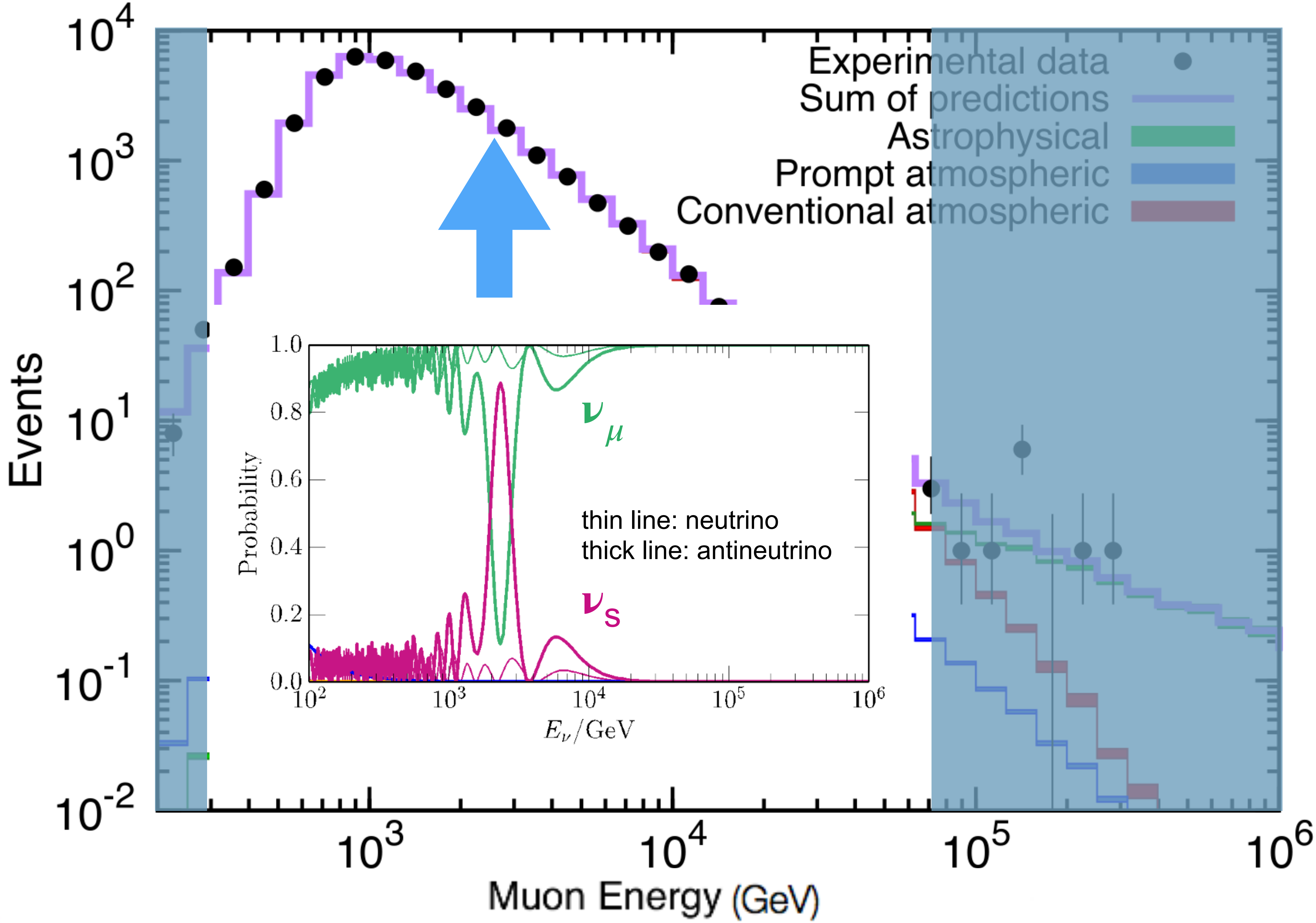




Plotted for:

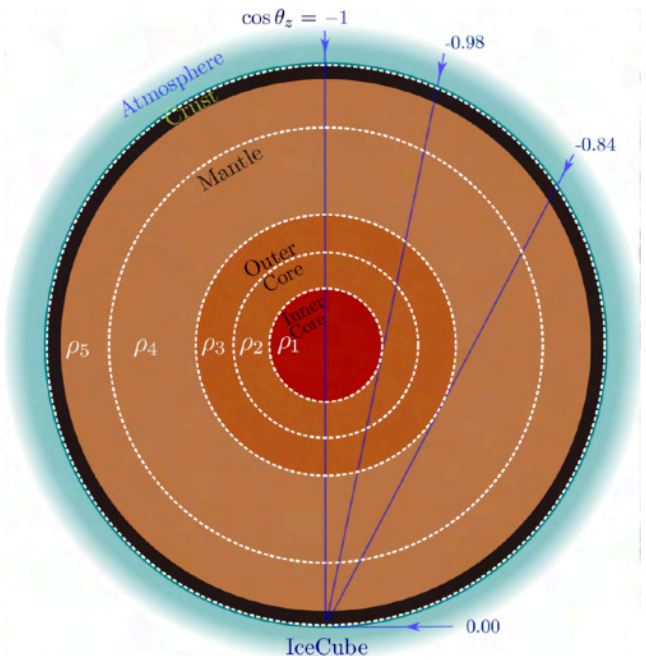
- ❖ 2.3 TeV
- ❖ Δm^2_{41} = 1 eV^2, $\sin^2 2\theta_{24}$ = 0.1 (compatible with best fit)

Where is the resonance effect?



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

Position of resonance maps onto sterile parameter space

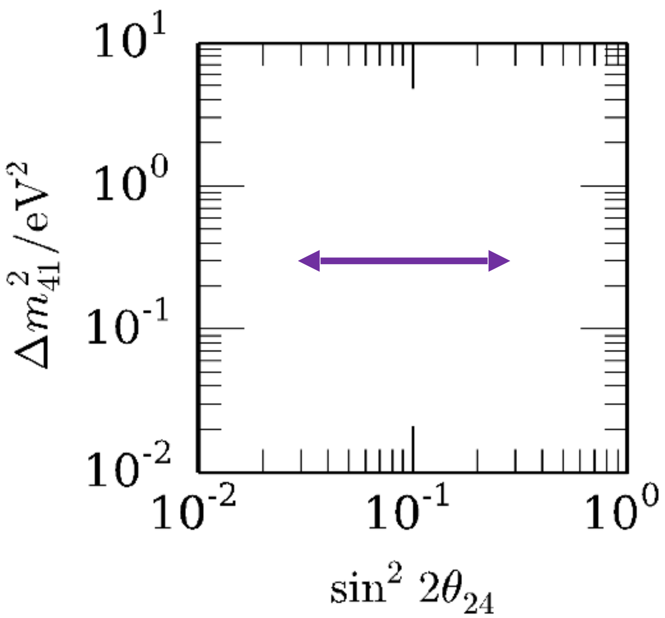


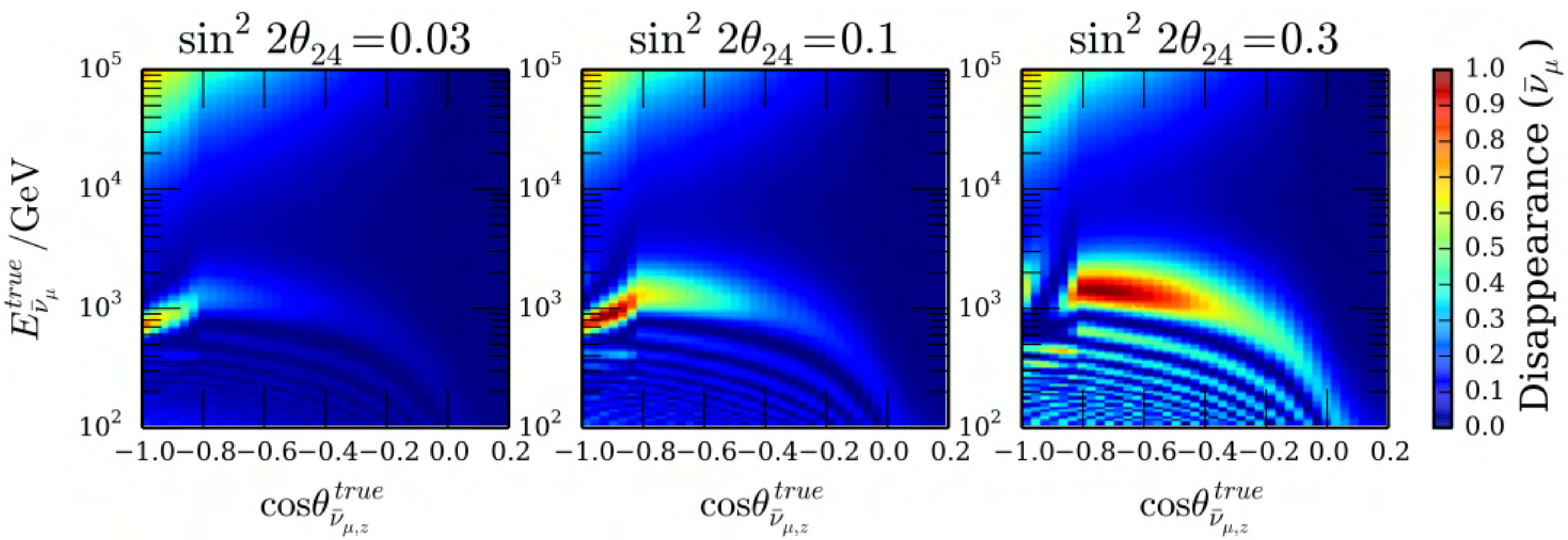
We measure two things:

- $\cos\theta$ ⇨ length
- energy

We extract two parameters:

- squared mass difference
- mixing angle





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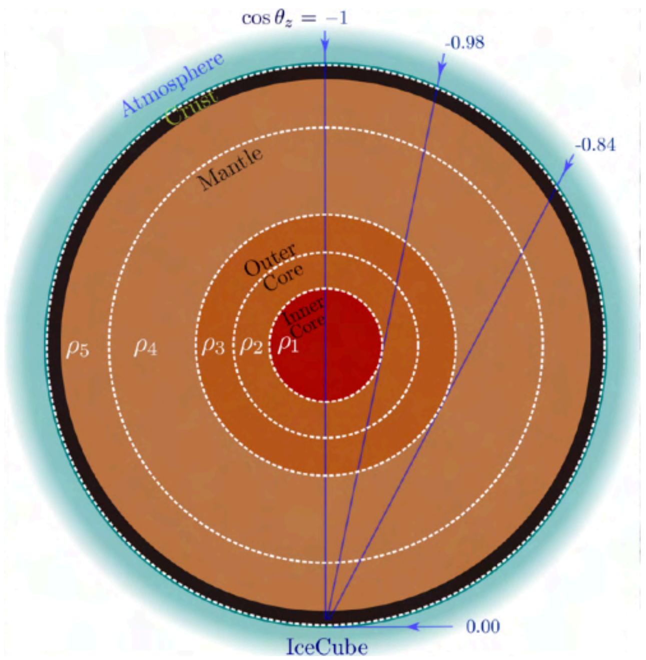

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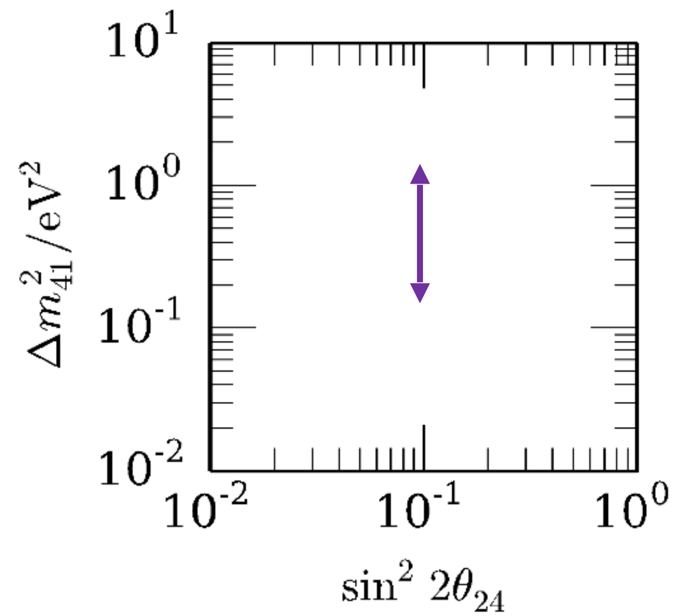
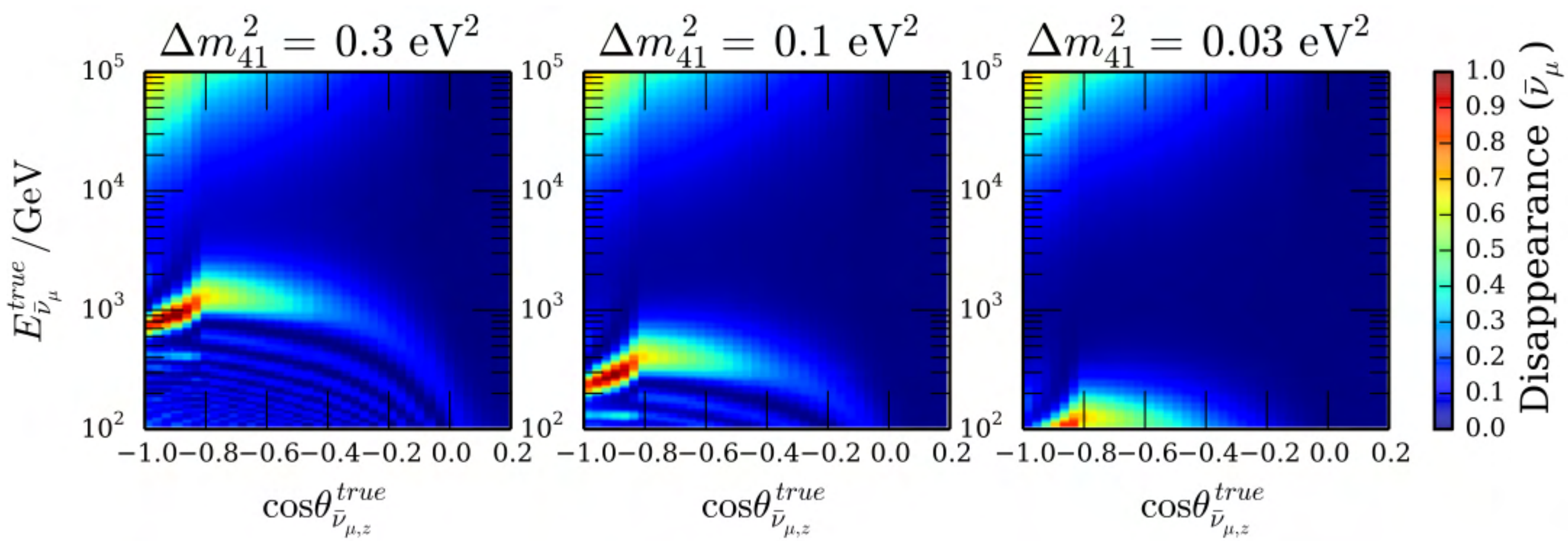
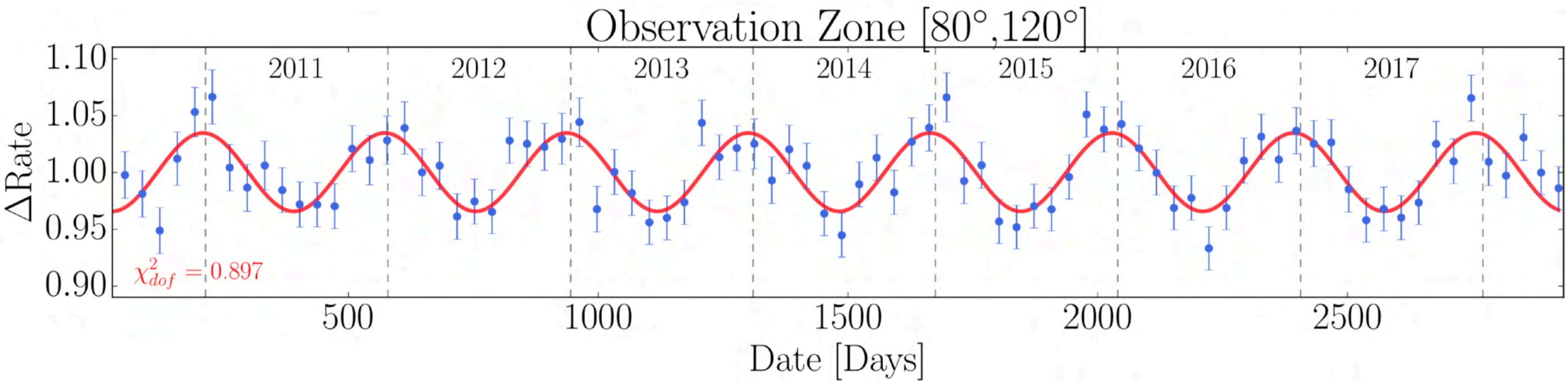


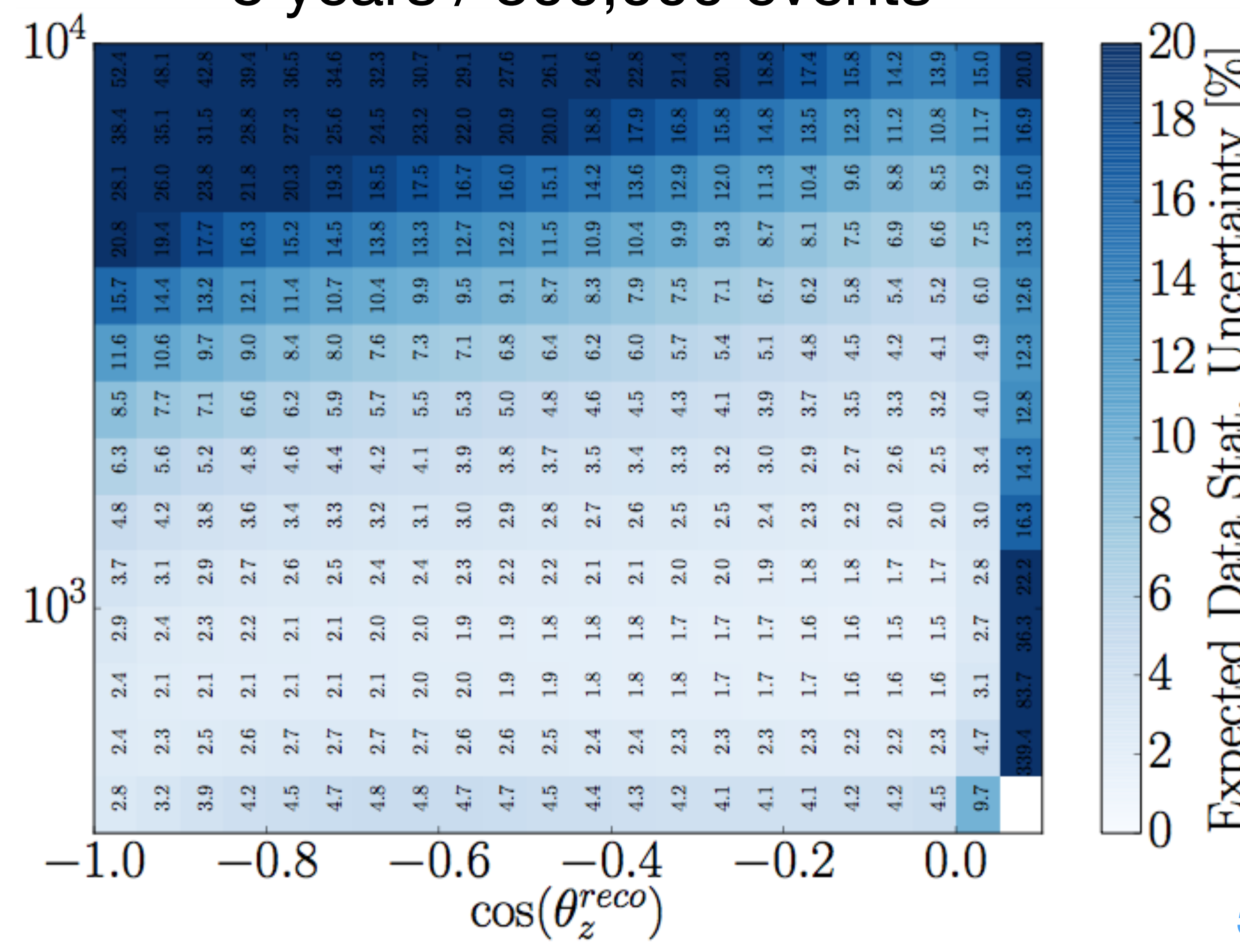


8-year search in IceCube

Matter-Enhanced Oscillations With Steriles (MEOWS)

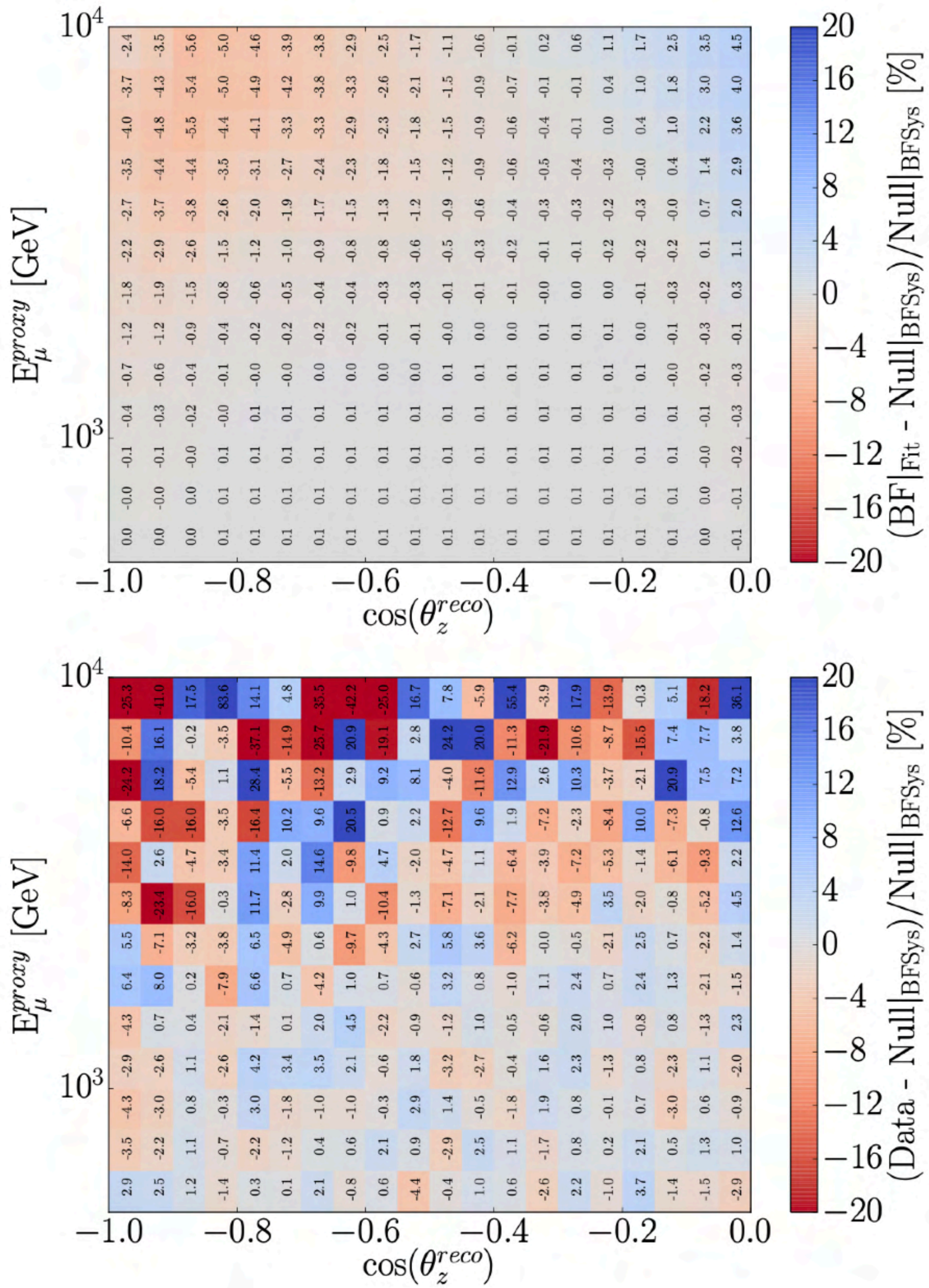


8 years / 300,000 events



- ✤Optimized event selection
- ✤Improved systematic treatment

IceCube Hints



- ❖ Best fit:

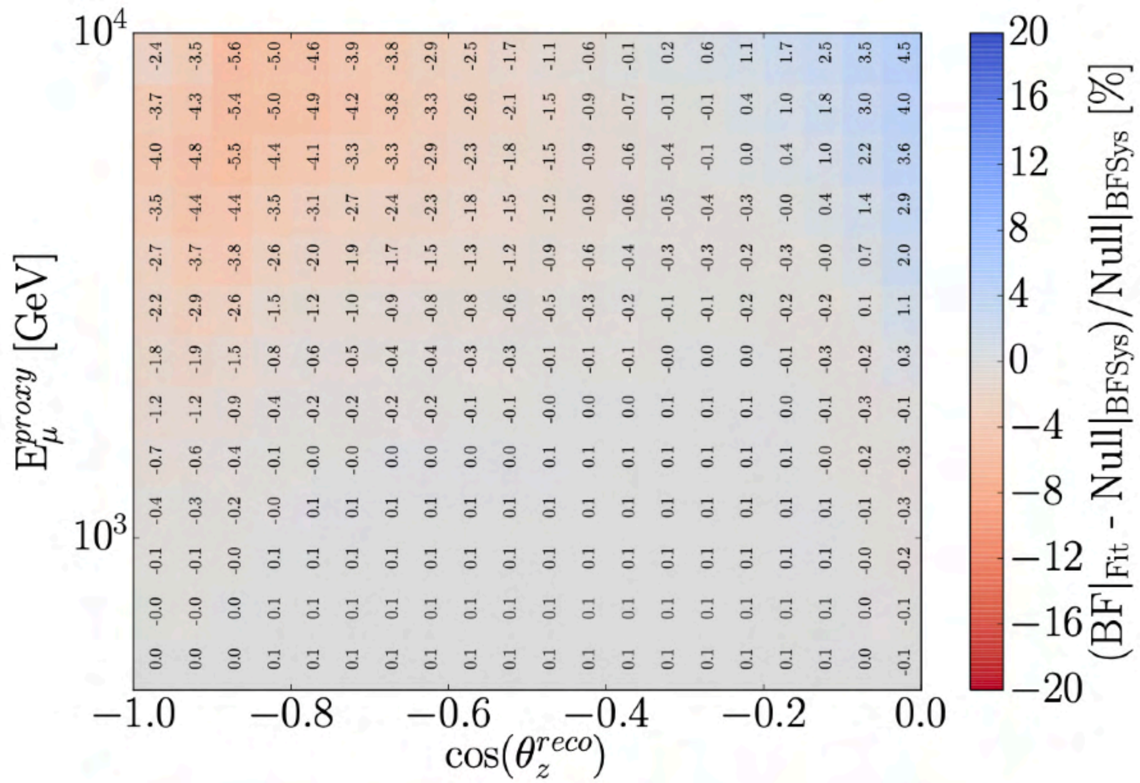
$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$$

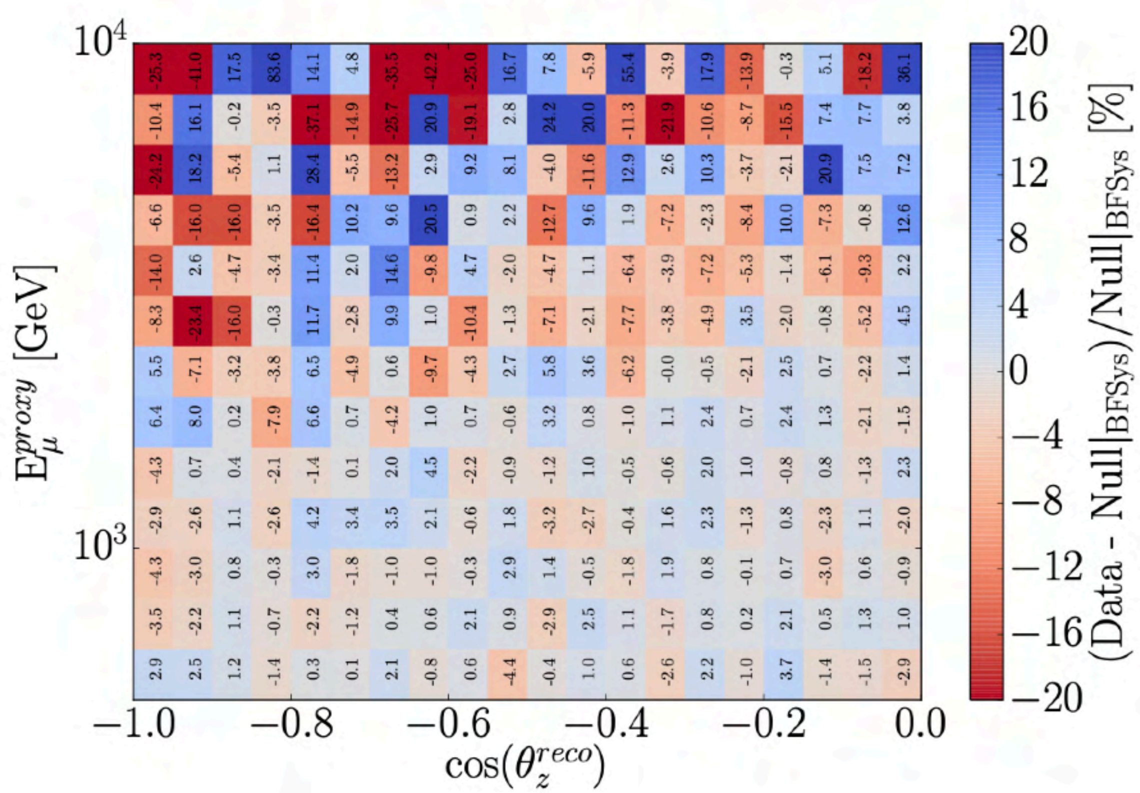
$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$

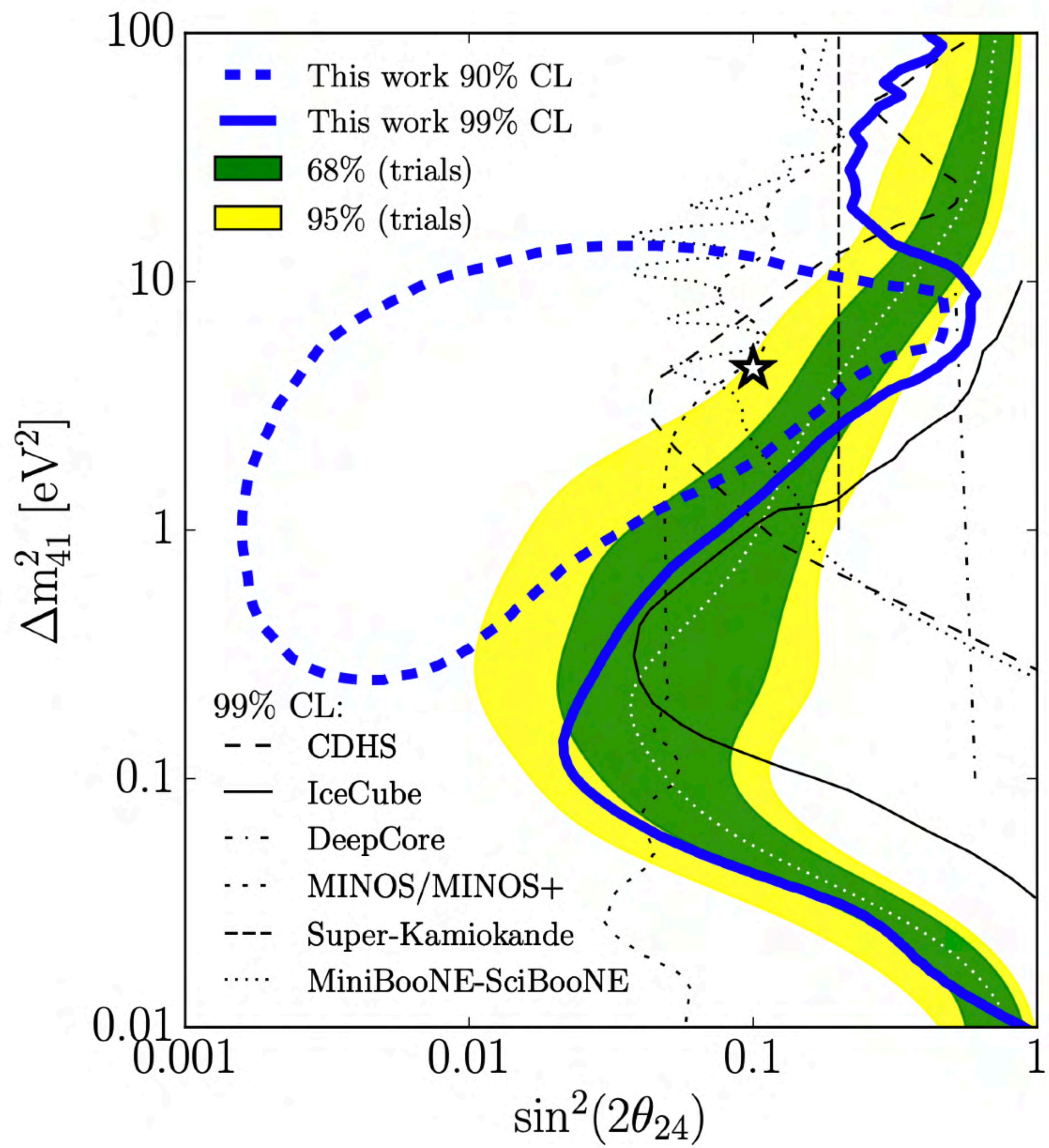
- ❖ Sterile neutrino hypothesis is preferred to null
- ❖ Null is rejected at 8% p-value

IceCube Collaboration Phys. Rev. Lett. 125, 141801 (2020)
IceCube Collaboration Phys. Rev. D 102, 052009 (2020)

IceCube Hints







IceCube Collaboration Phys. Rev. Lett. 125, 141801 (2020)
IceCube Collaboration Phys. Rev. D 102, 052009 (2020)

See talk by B. Smithers S11.00004@APS2022 for prospects with cascades

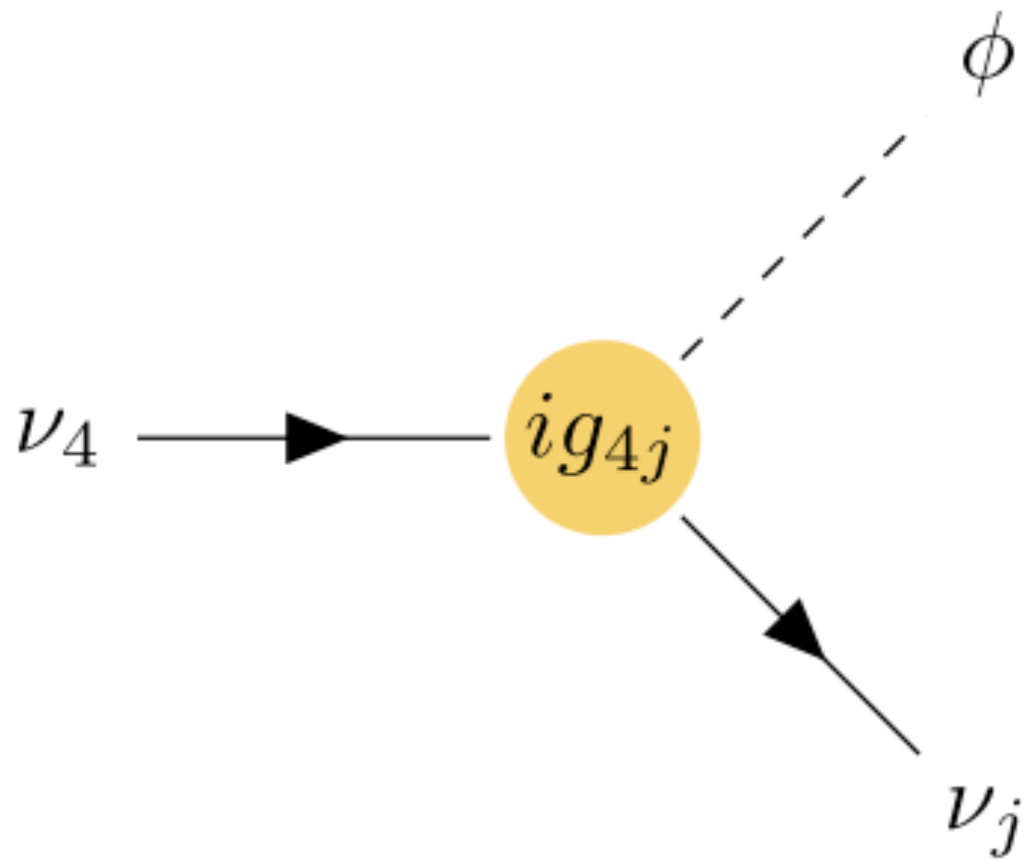
Reexamining IceCube

IceCube muon-neutrino disappearance result is in a very interesting part of parameter space, but has low significance.

Is IceCube significance low because we are not looking for the right model?

"Sterile" Neutrino Decay

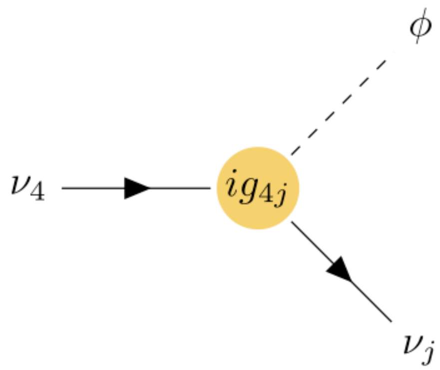
Moss et al https://arxiv.org/abs/1711.05921
Dentler *et al* https://arxiv.org/abs/1911.01427
Gouvea *et al* https://arxiv.org/abs/1911.01447



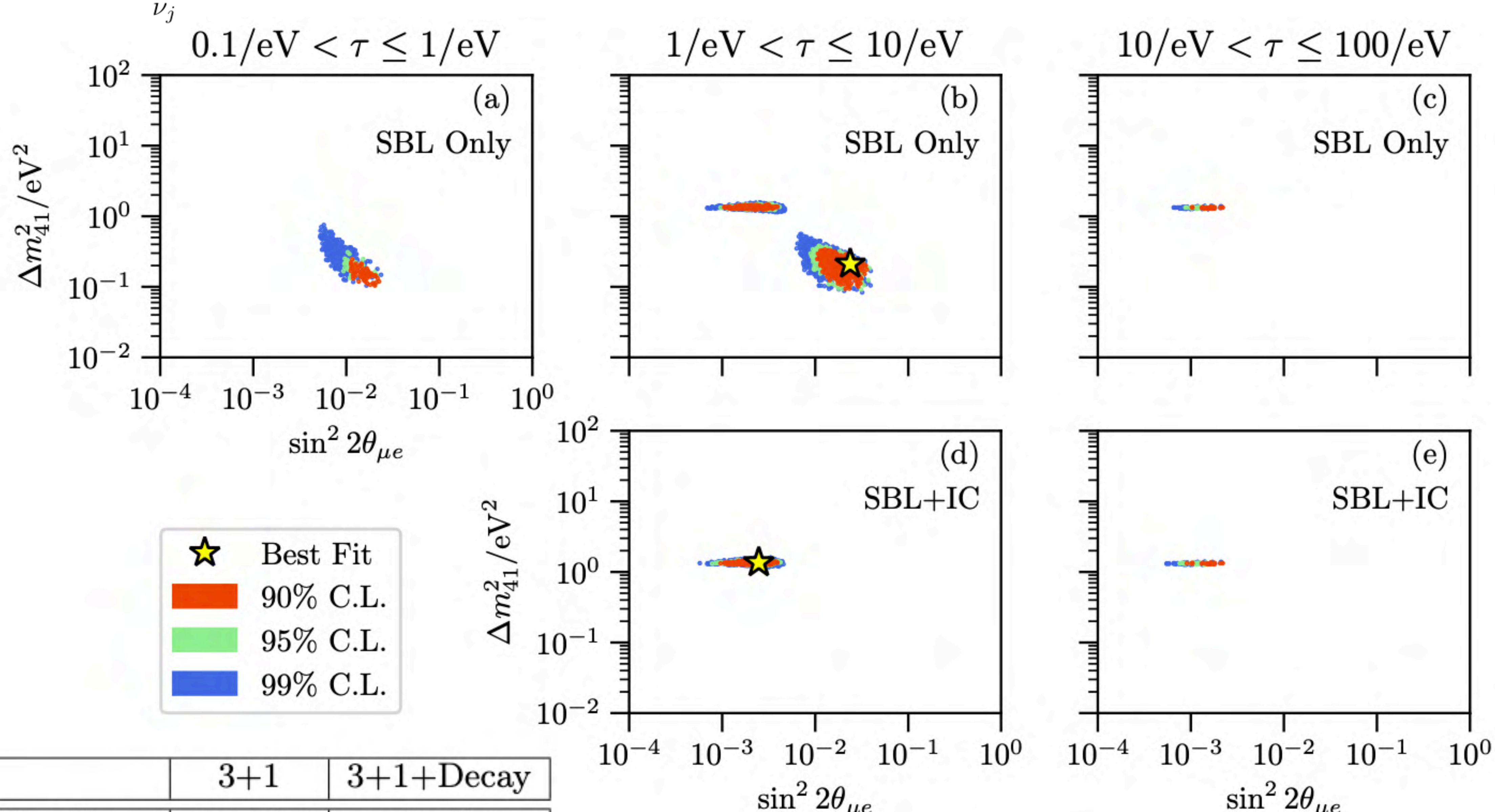
$$\tau = \frac{16\pi}{g^2 m_4}$$

Decay can be visible or invisible.

If neutrinos are Dirac -> invisible
If neutrinos are Majorana -> visible



Sterile Neutrino Decay (3+1+Invisible-Decay)

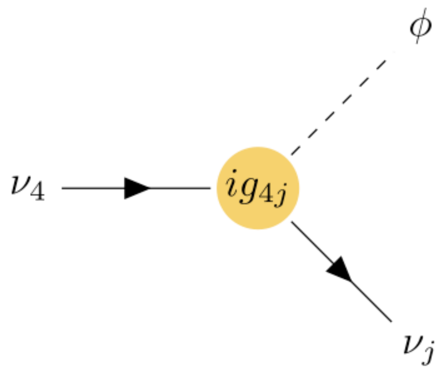


	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\text{dof})_{\text{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\text{dof})_{3+1}$	–	9.1 / 1

Moss Moss et al https://arxiv.org/abs/1711.05921
Moulai et al https://arxiv.org/abs/1910.13456

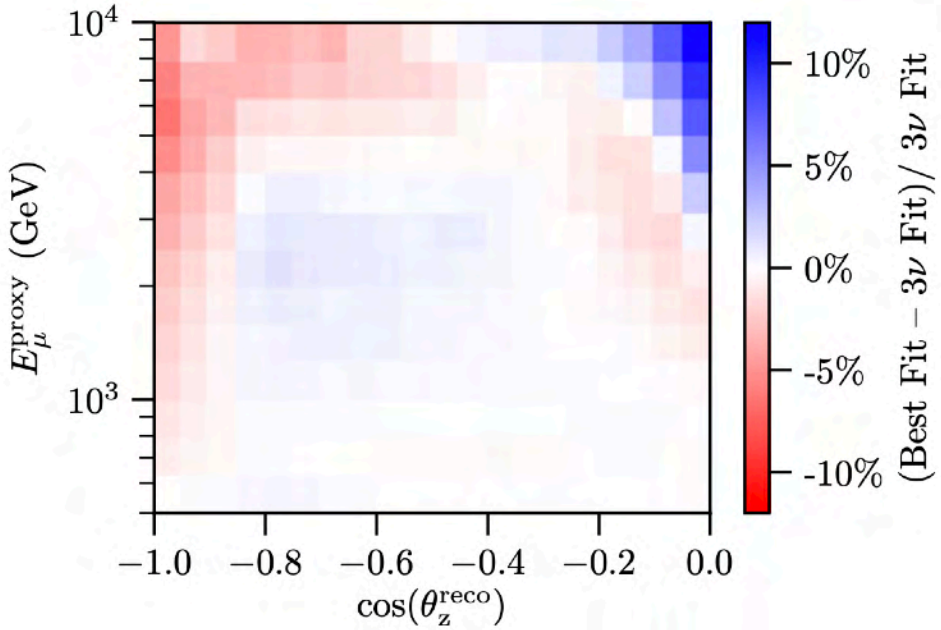
See also Berryman *et al* https://arxiv.org/abs/1407.6631

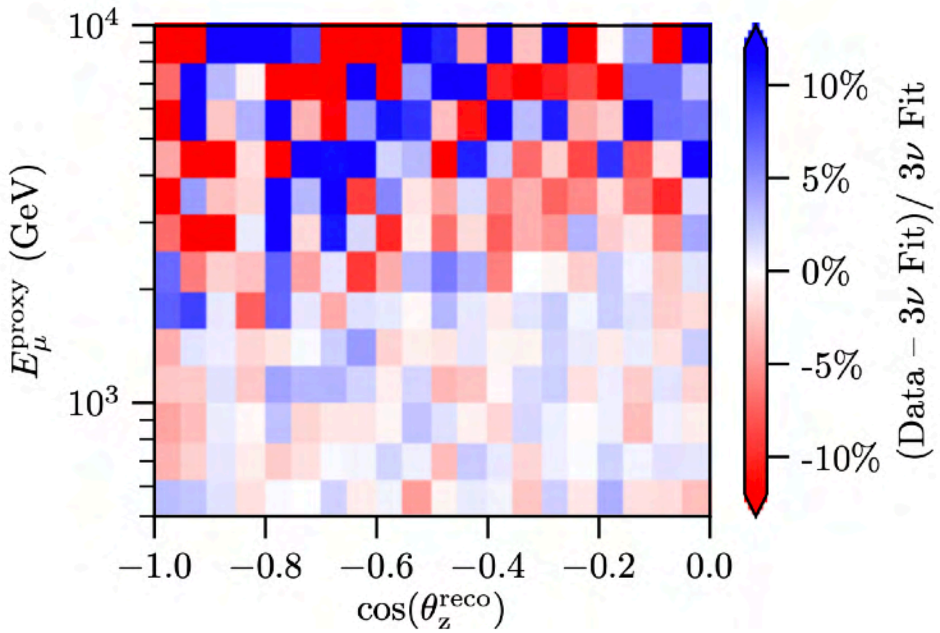
Global data prefers 3+1+Decay!



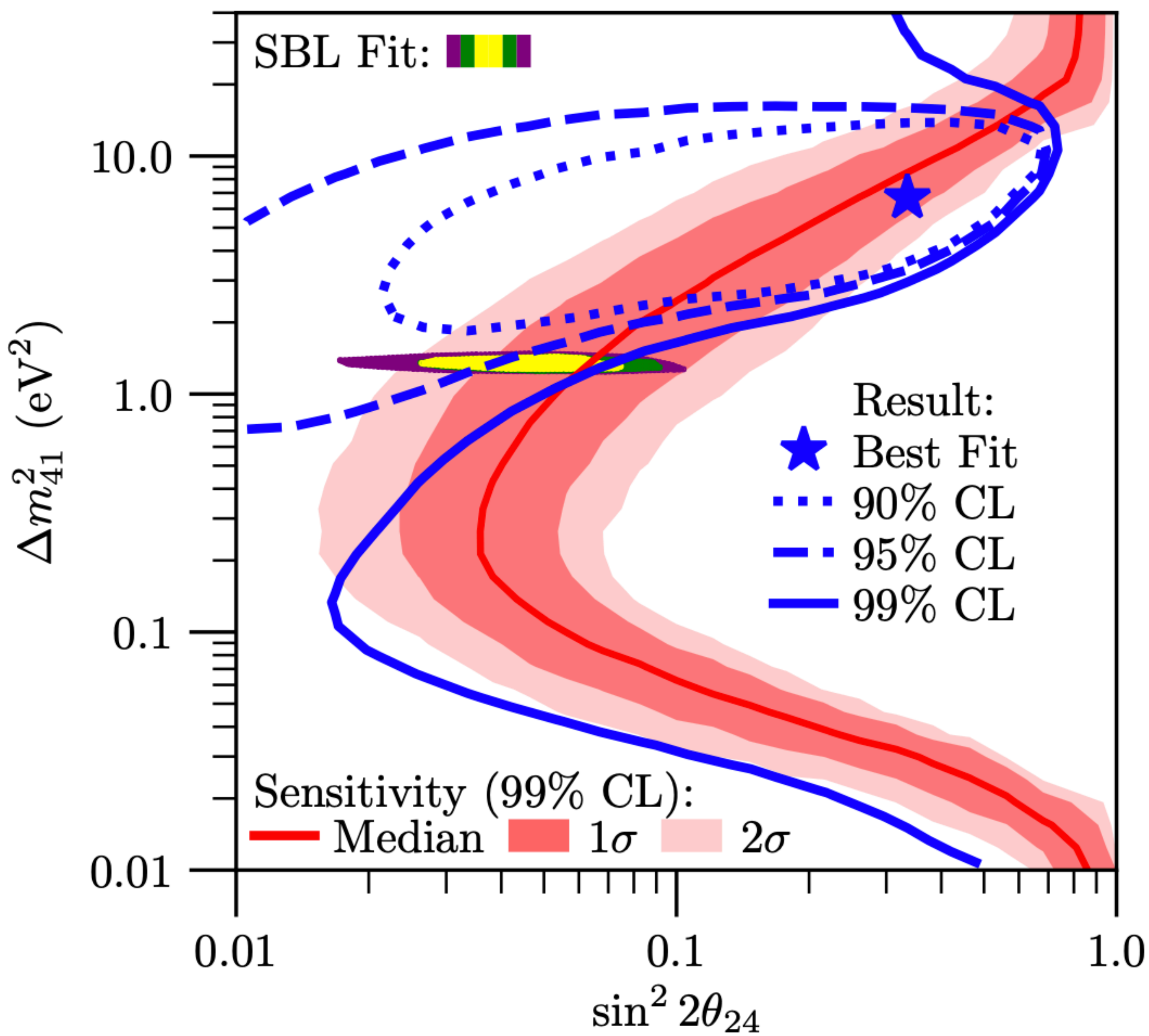
First Search For Unstable Sterile Neutrinos In IceCube!

$$\Delta m^2_{41} = 6.7^{+3.9}_{-2.5}\text{eV}^2 \quad \sin^2 2\theta_{24} = 0.33^{+0.20}_{-0.17} \quad g^2 = 2.5\pi \pm 1.5\pi$$





(slice for best-fit decay constant)



IceCube Collaboration arXiv:2204.00612

See talk by J. Milis for similar work on MicroBooNE

IceCube also prefers 3+1+Decay, though at small significance!

Take Away on Sterile Neutrinos

1. IceCube brings unique capabilities to new particle searches through oscillations!

2. New results from IceCube on ν_μ disappearance are in agreement with global-fit solutions, and hint at an effect in this channel.

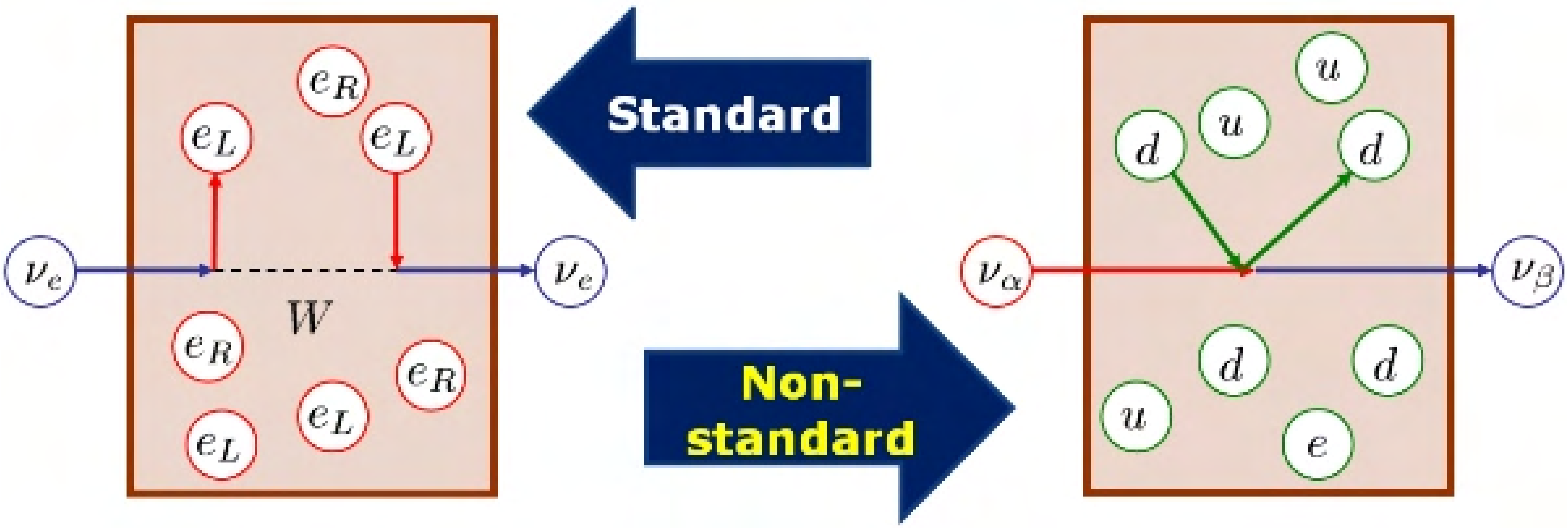
3. Situation is very confusing …

Outline of the rest of this talk:

1. Neutrinos from cosmic beam dumps & IceCube
2. Searching for a new kind of neutrino:
   - -The Sterile Neutrino
3. Searching for new forces
   - -Non-standard Neutrino Interactions
4. Searching for a dark sector:
   - -Neutrino-Dark Matter Interactions
5. Searching for a new symmetry:
   - -Lorentz Violation Effects on Flavor

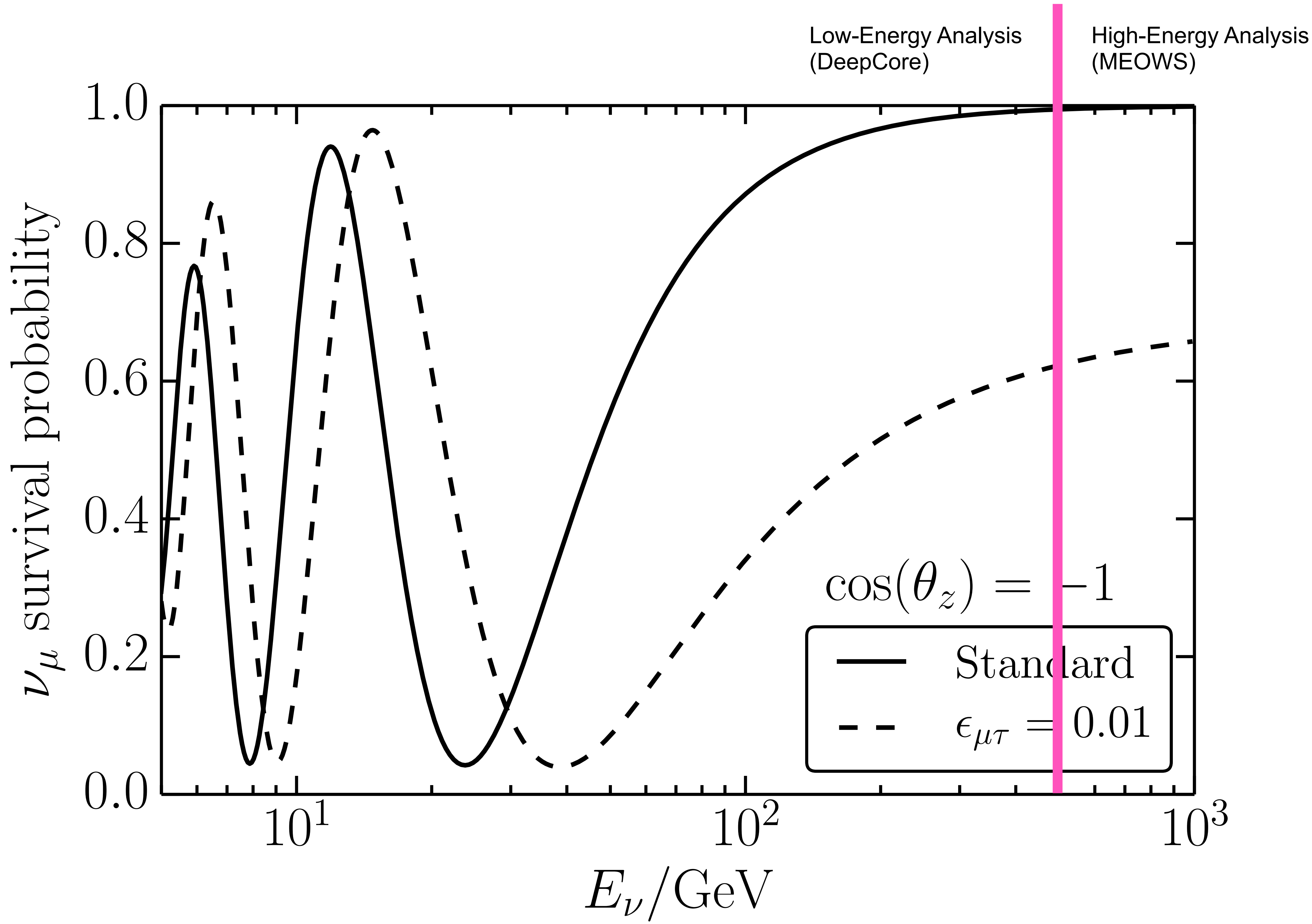
Searches for non-standard interactions (NSI)

(from T. Ohlsson arXiv:1209.2710)



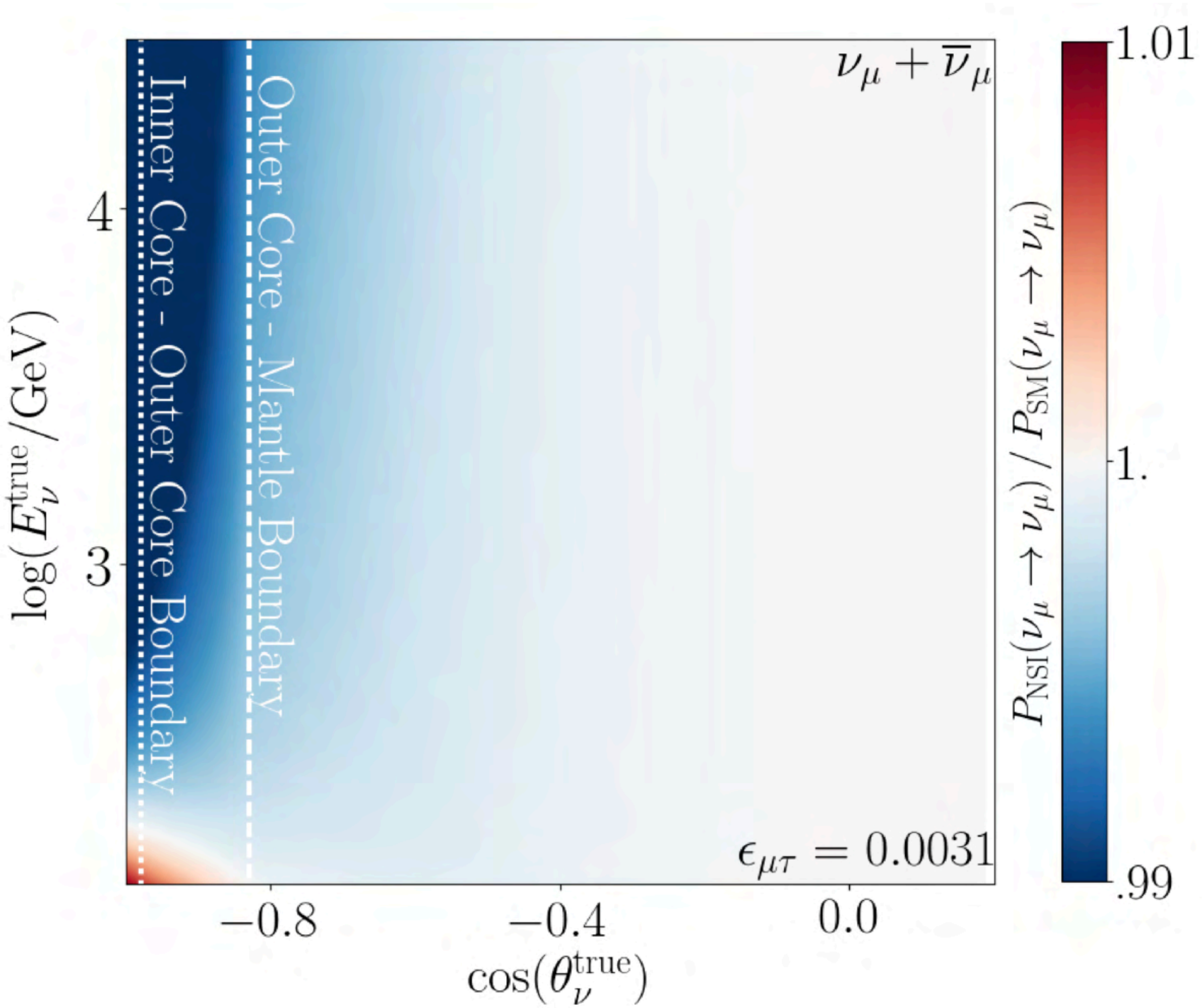
$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\frac{1}{2E}\left[U\begin{pmatrix}0&0&0\\0&\Delta m_{21}^2&0\\0&0&\Delta m_{31}^2\end{pmatrix}U^\dagger+A\begin{pmatrix}1+\varepsilon_{ee}&\varepsilon_{e\mu}&\varepsilon_{e\tau}\\ \varepsilon_{e\mu}^*&\varepsilon_{\mu\mu}&\varepsilon_{\mu\tau}\\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

Searches for non-standard interactions (NSI)



- Low-energy analysis fits simultaneously std. osc. parameters + NSI parameters
- High-energy analysis only fits NSI

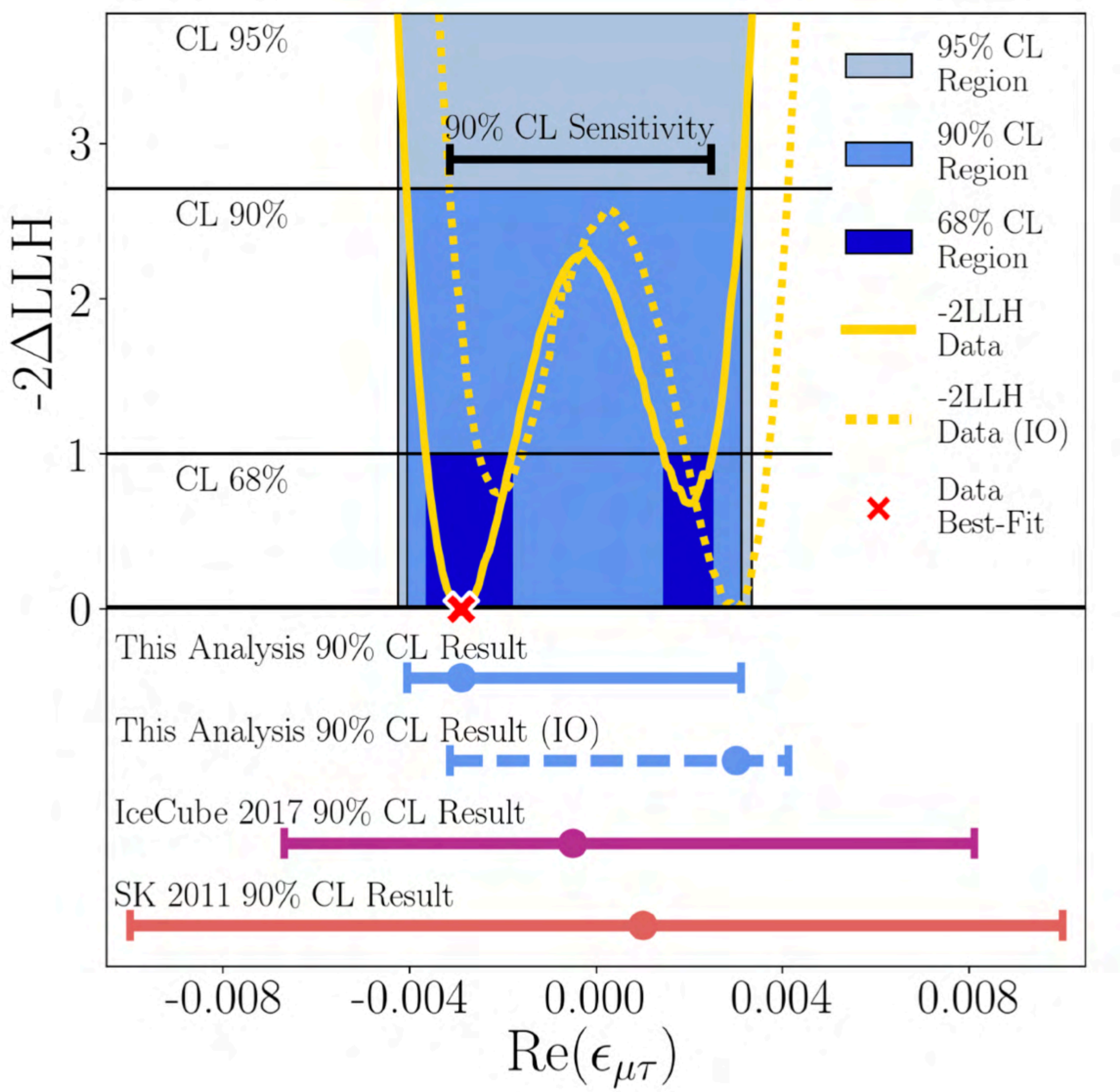
NSI Searches With TeV Neutrinos



- NSI effect is a change in the neutrino angular distribution.
- Most sensitive parameter is $\epsilon_{\mu\tau}$.
- We perform our analysis in the maximum-flavor-violating scenario.
- Large diagonal NSI is to first order the same as the null hypothesis due to lack of std. oscillations.

$$H_{\rm mat+NSI} = V_{CC}(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

NSI Searches With TeV Neutrinos



IceCube Collaboration arXiv:2201.03566

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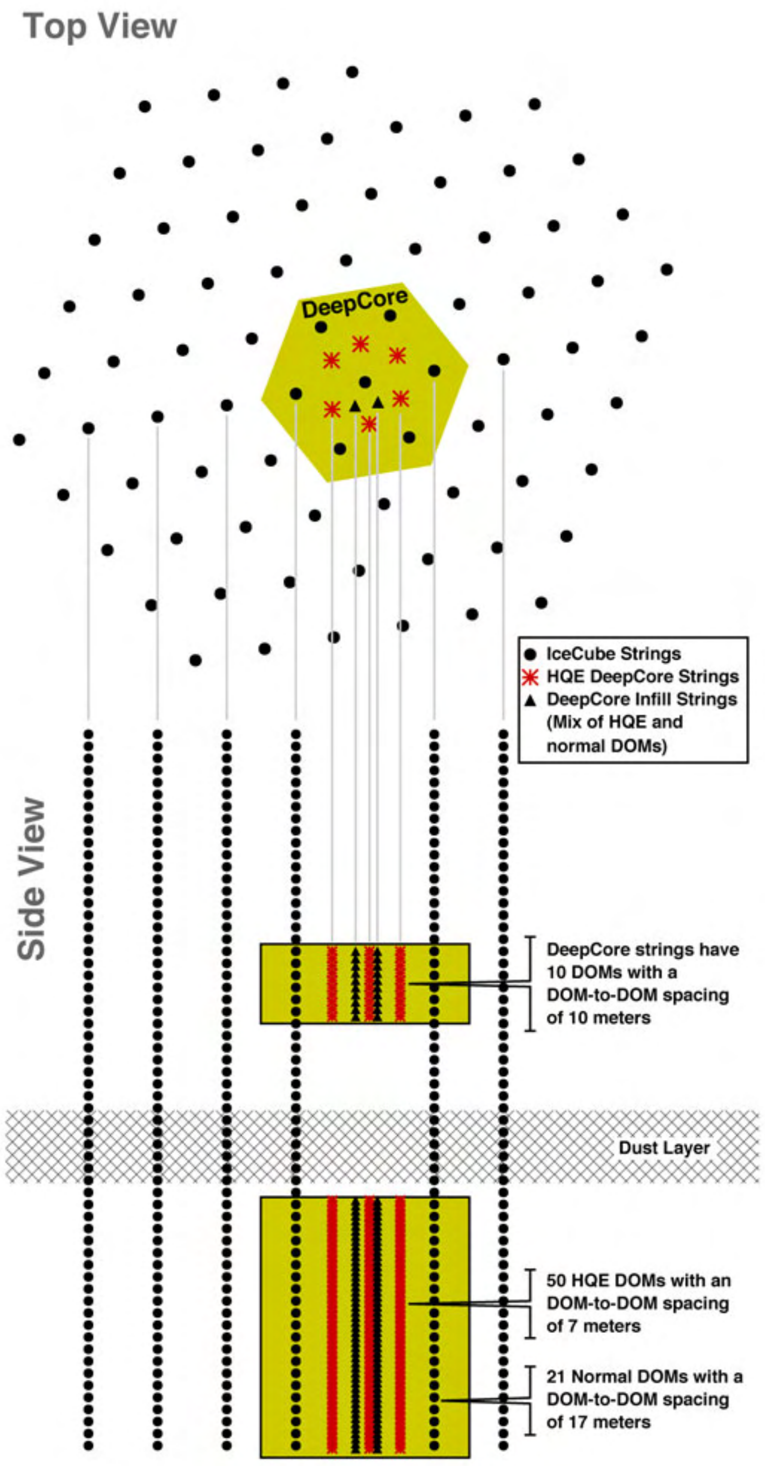
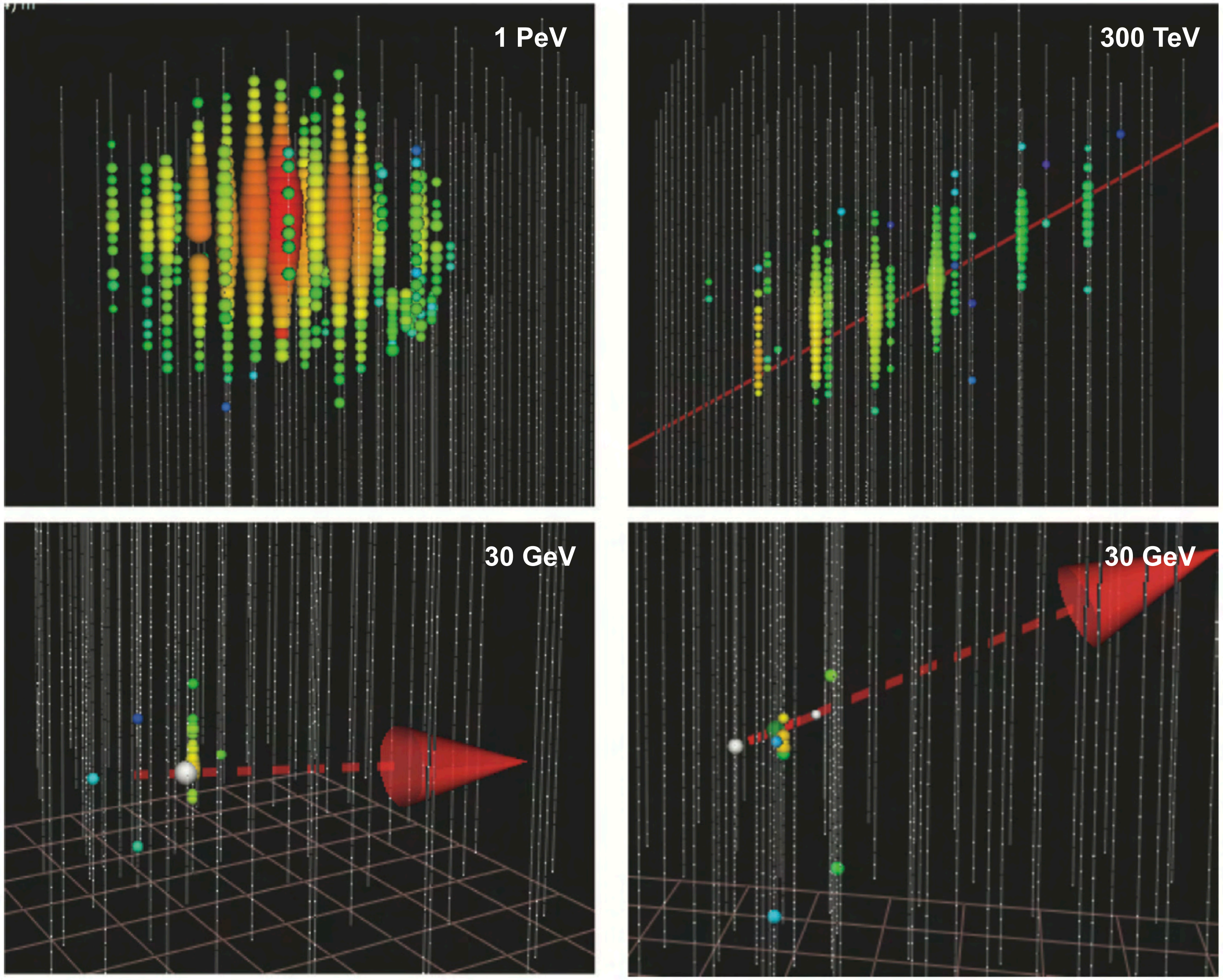
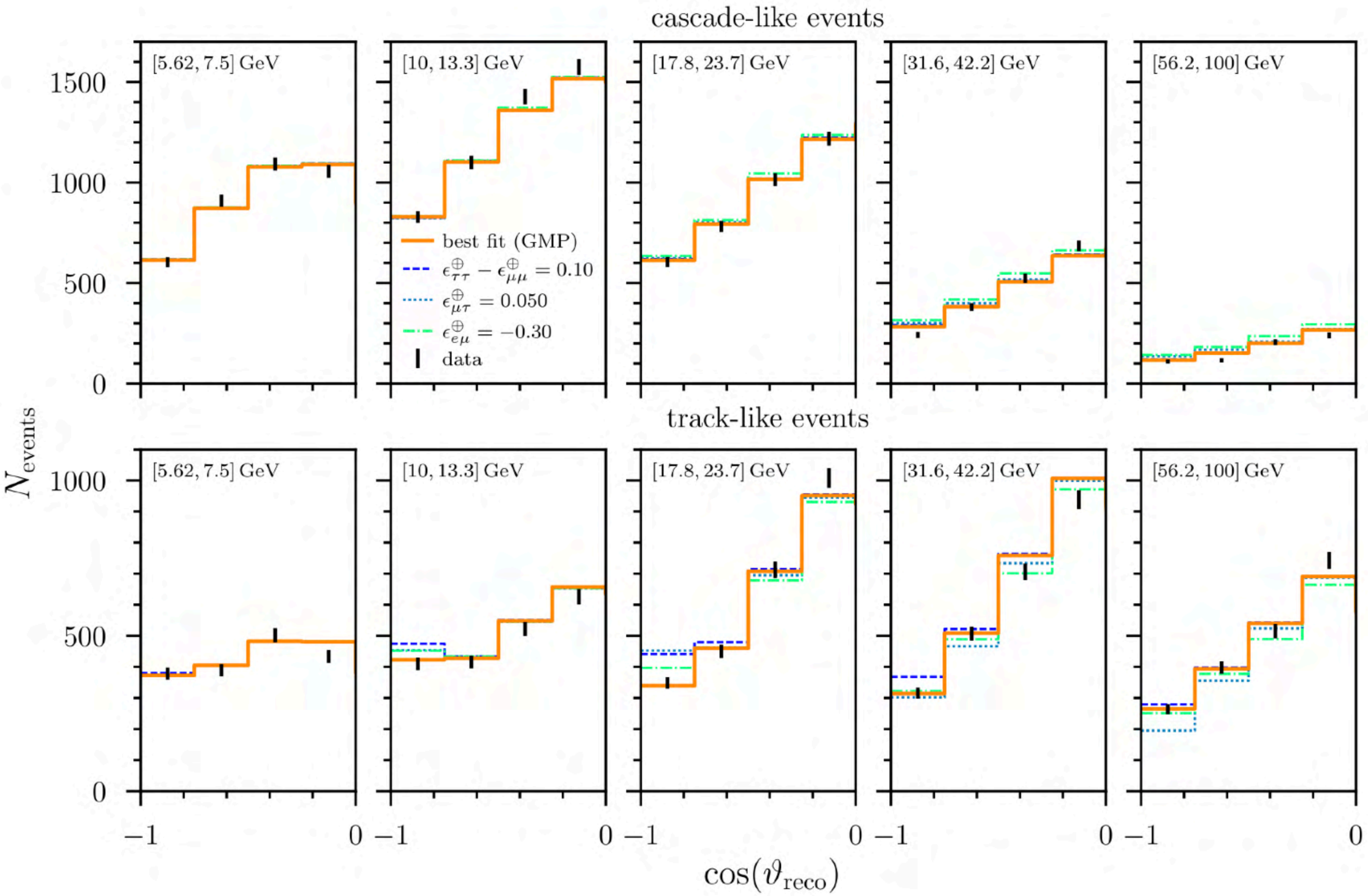
General NSI Searches With sub-TeV Neutrinos





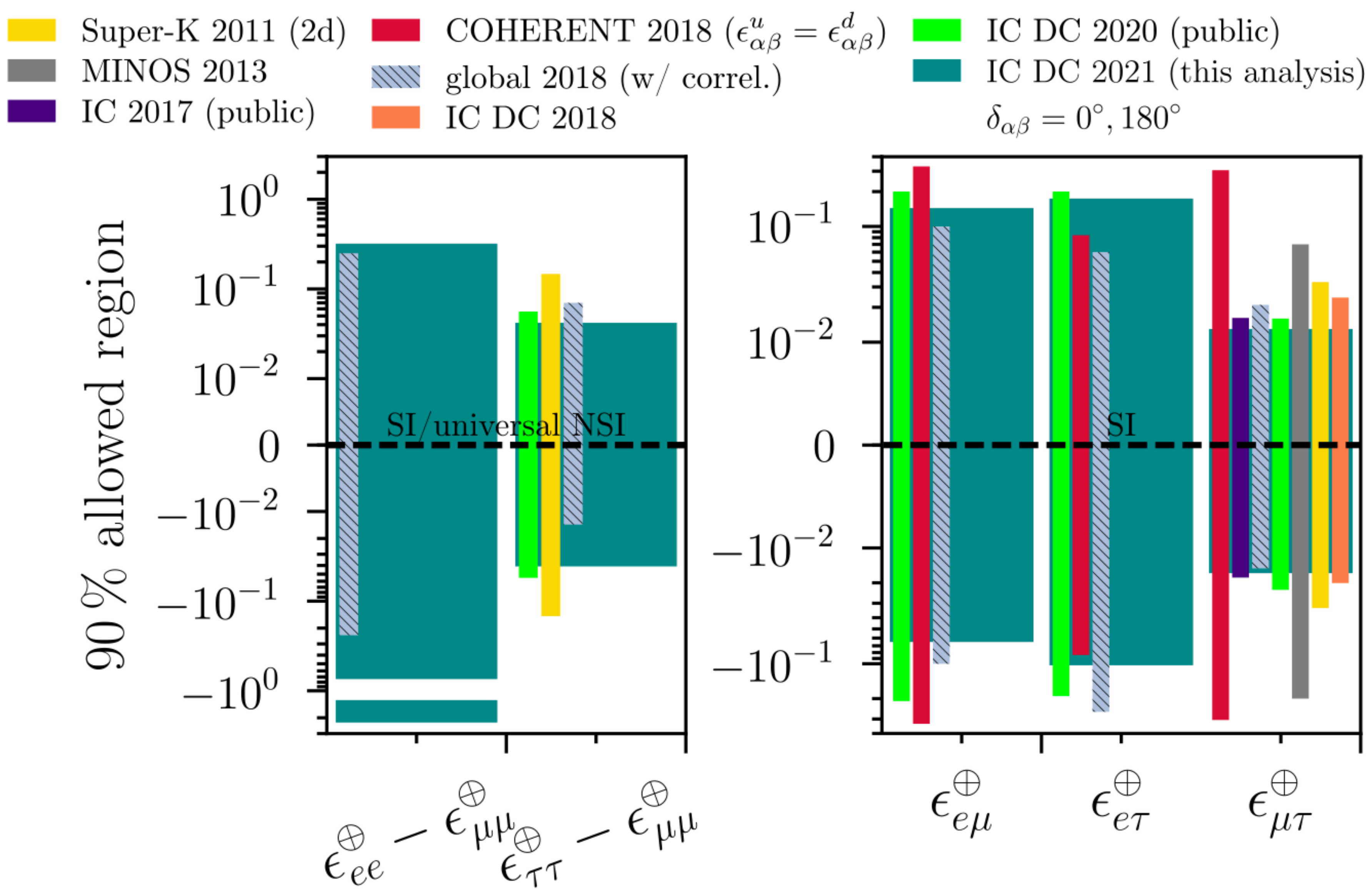
General NSI Searches With sub-TeV Neutrinos



IceCube Collaboration arXiv:2106.07755

Current published analysis uses three years of data

General NSI Searches With sub-TeV Neutrinos



Current published analysis uses three years of data

IceCube Collaboration arXiv:2106.07755

Take aways on
Non-Standard Neutrino Interactions

1. IceCube can look for NSI using TeV and sub-TeV neutrinos.

2. TeV NSI searches have focused on muon-neutrino disappearance. Strongest constraints on $\epsilon_{\mu\tau}$.

3. sub-TeV analyses fit std. oscillation and all NSI couplings

Outline of the rest of this talk:

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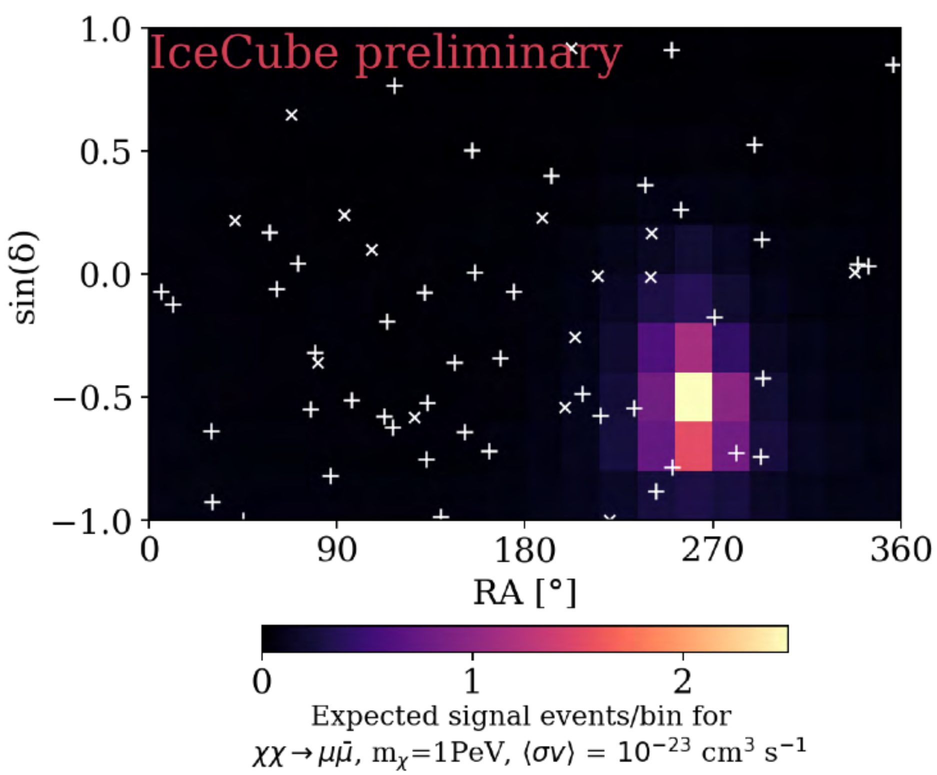
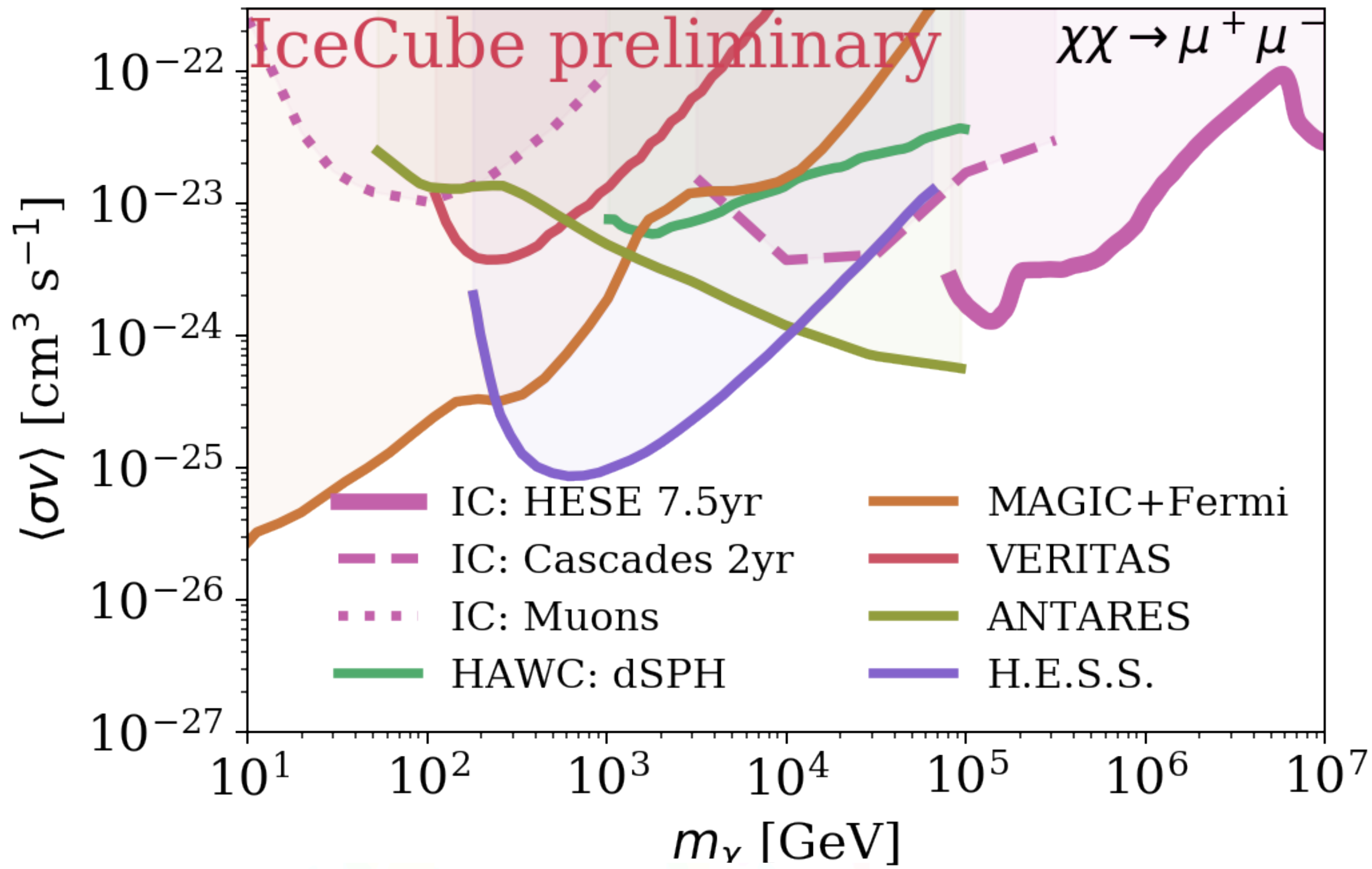
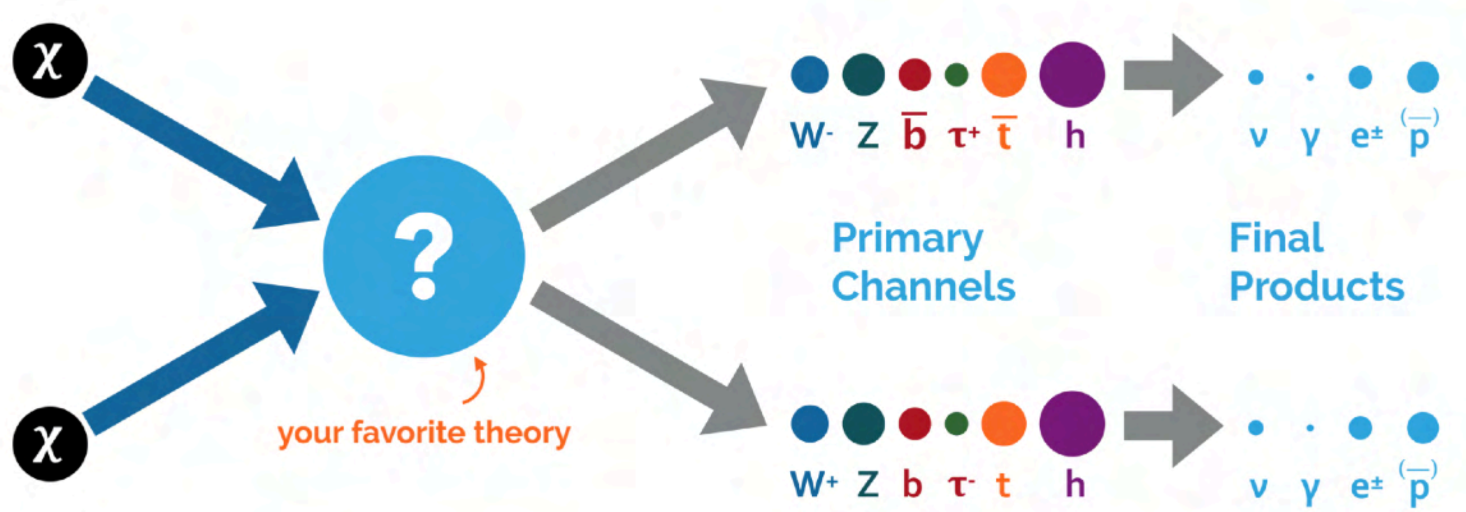
   - Lorentz Violation Effects on Flavor

Dark matter annihilation

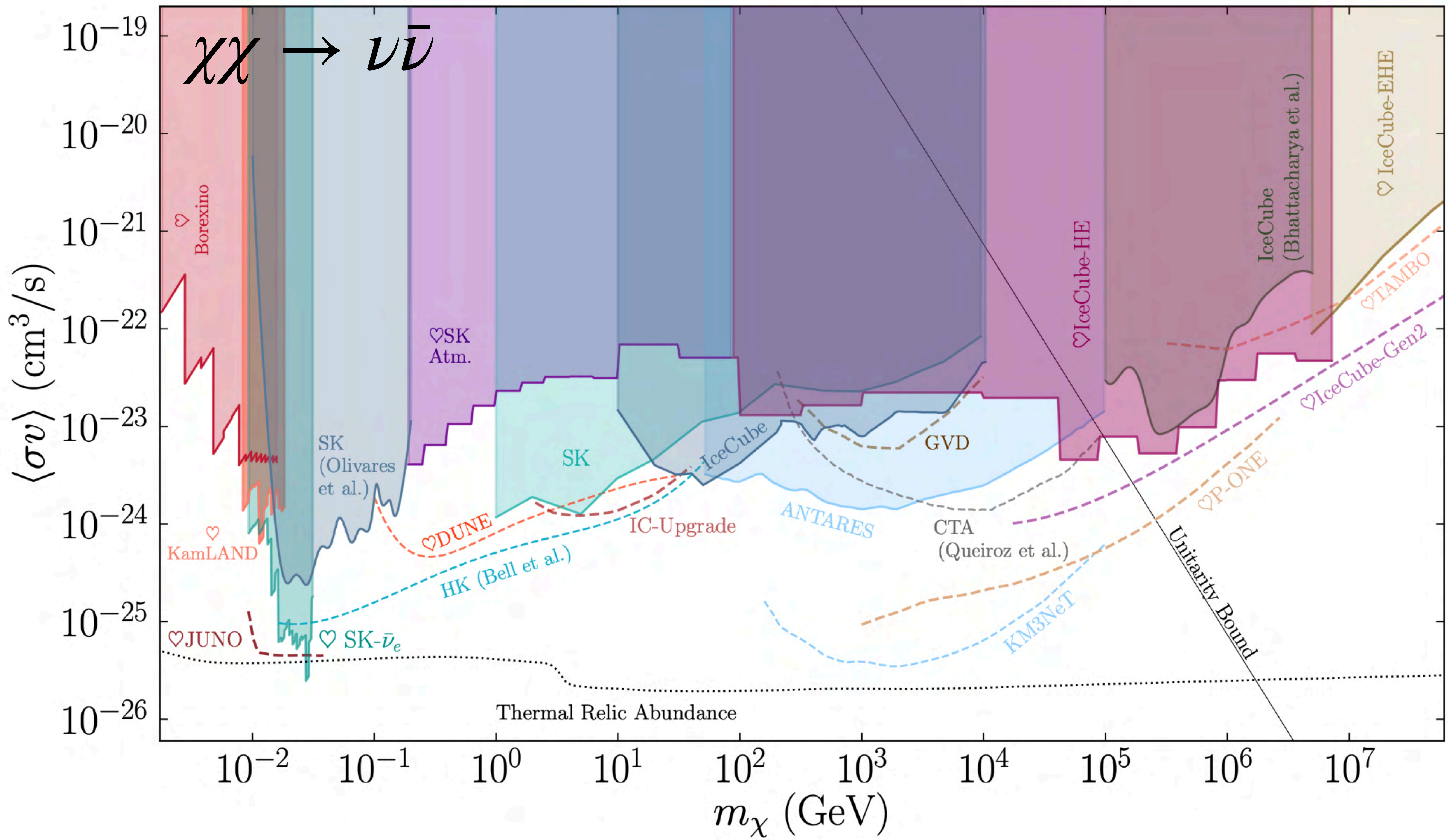






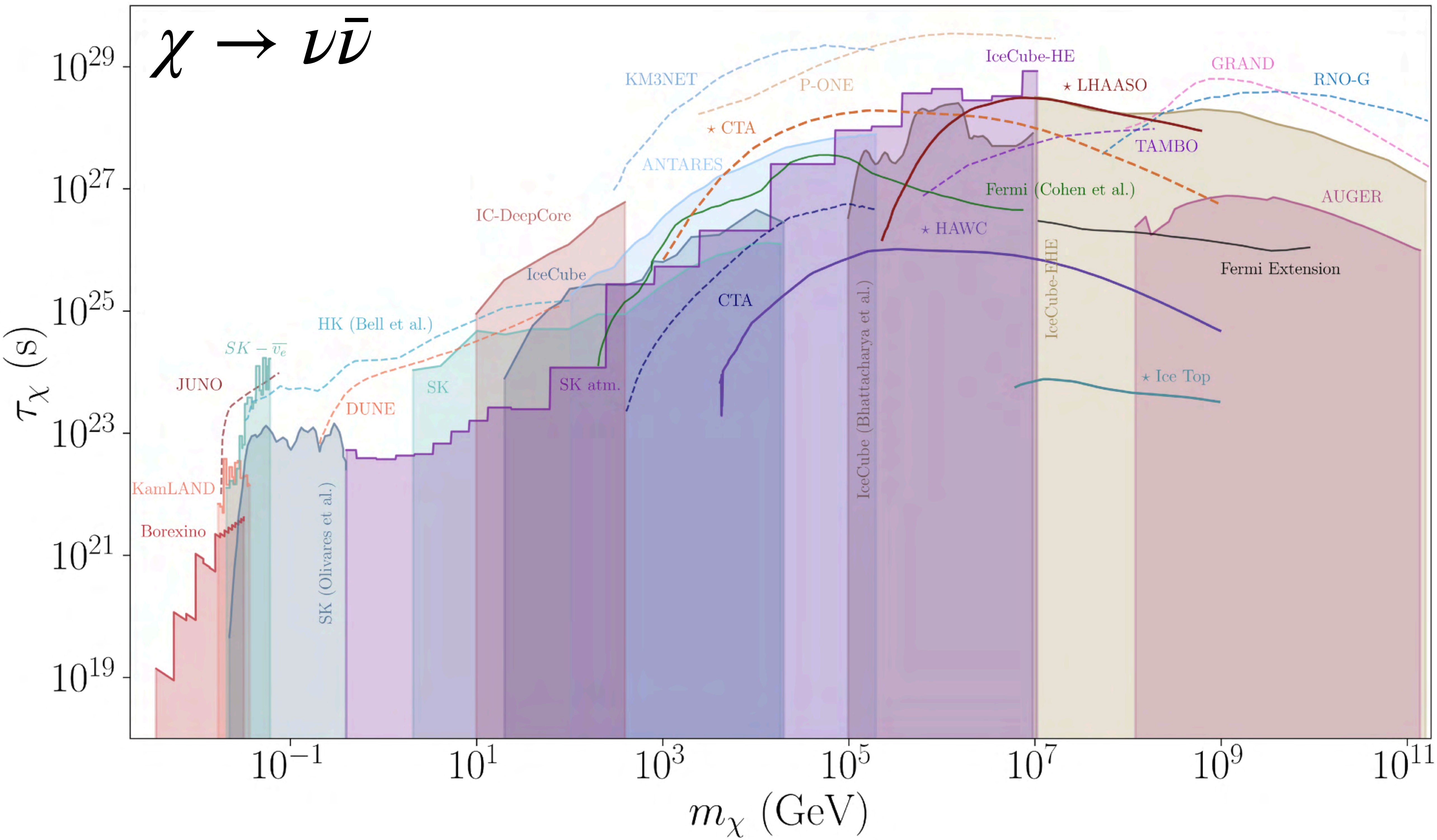
CA, H. Dujmovic arXiv 1907.11193

And many more measurements ...



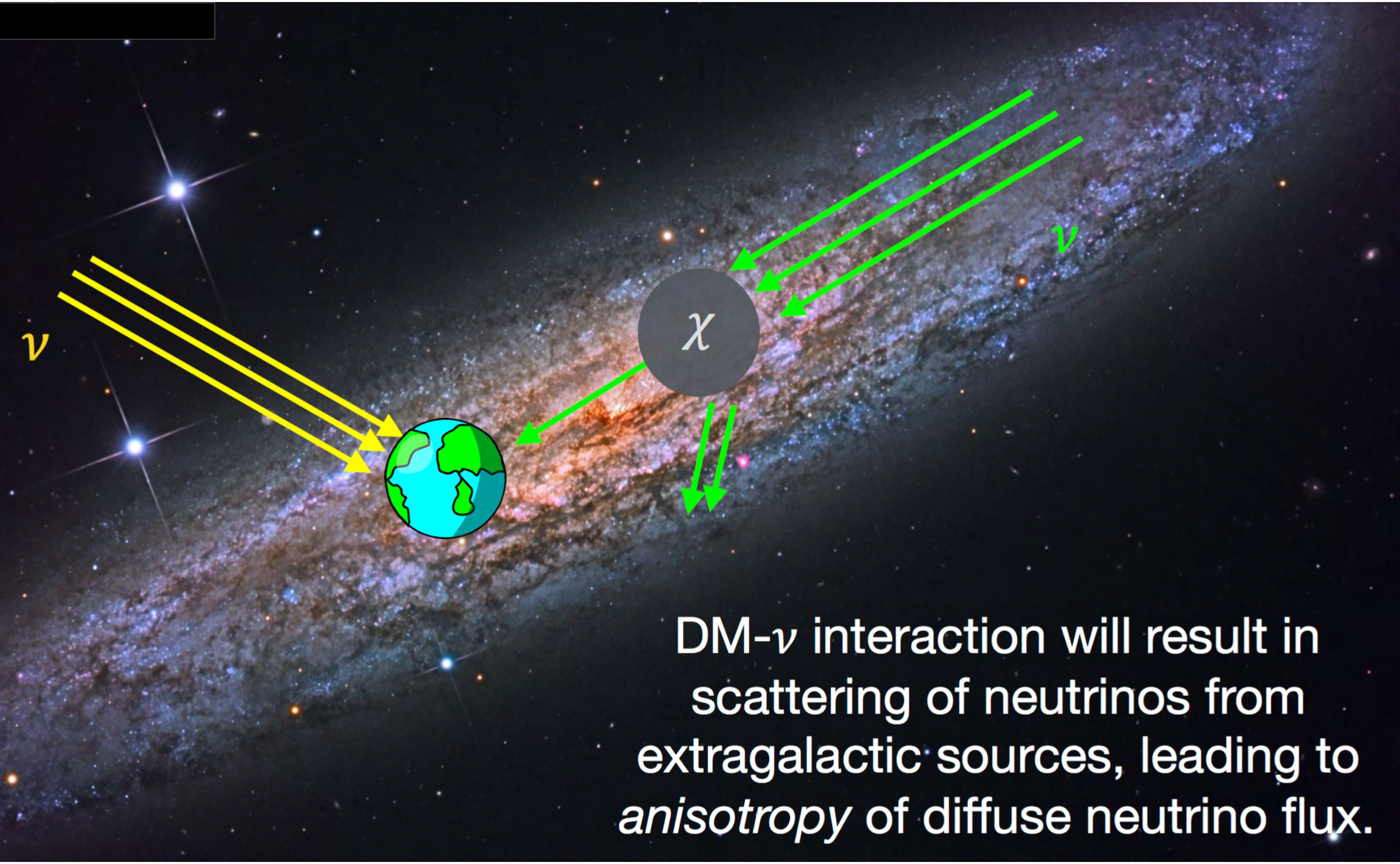
CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.

And many more measurements ...



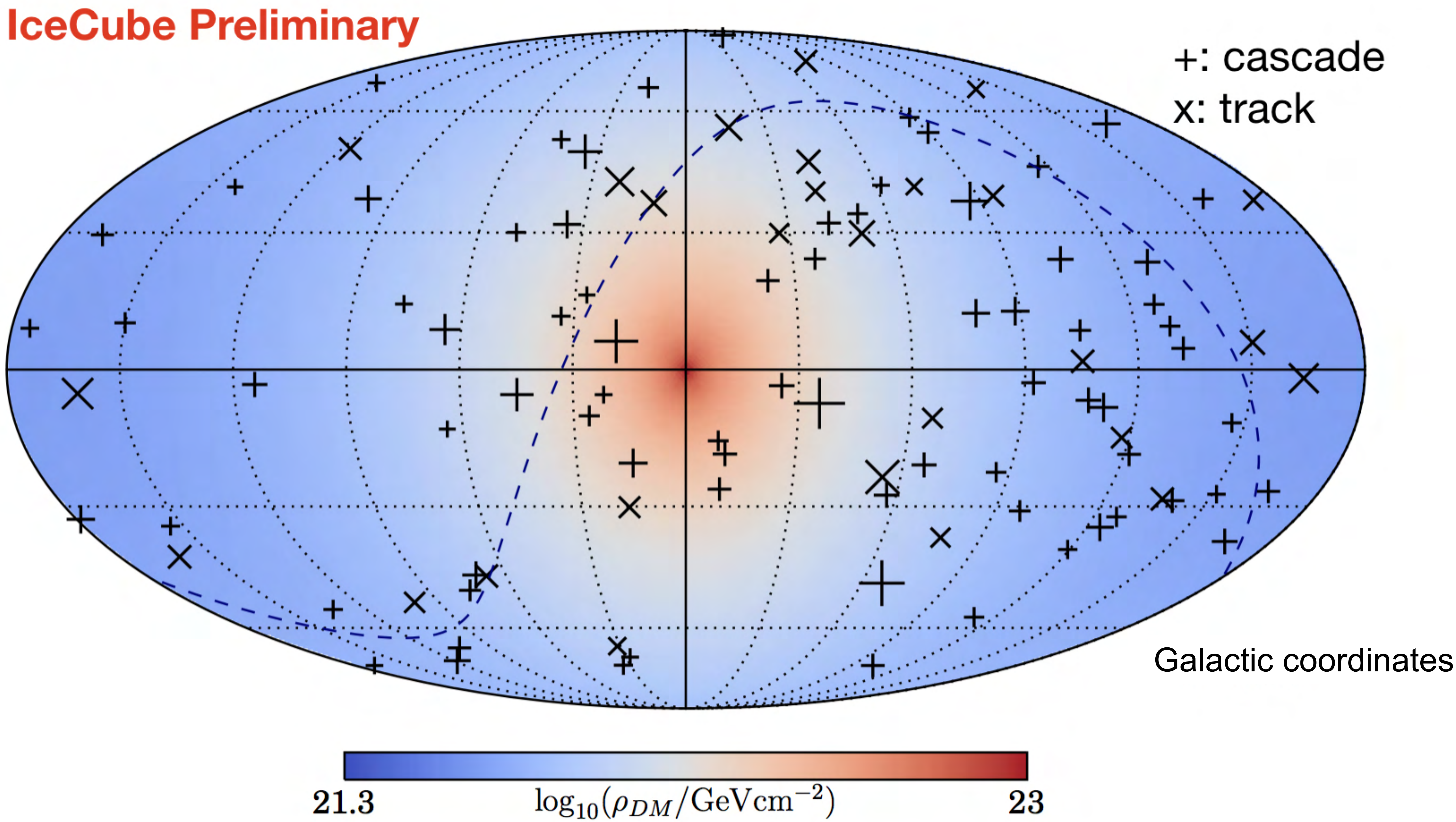
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White
to appear soon…

Dark matter neutrino incoherent **scattering**



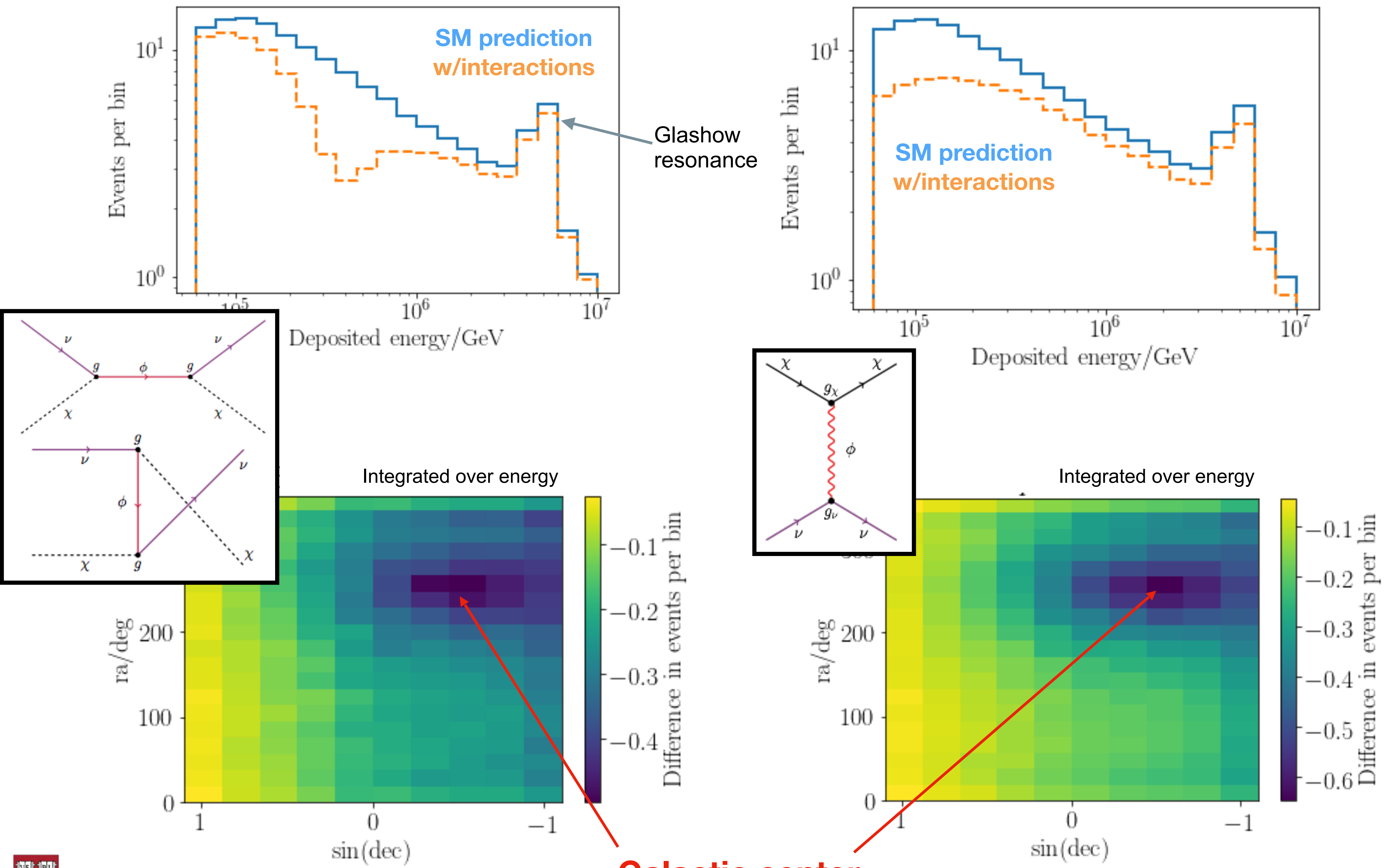
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

Neutrino skymap

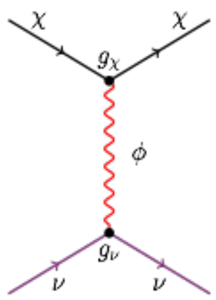


Events are compatible with an isotropic distribution: found no signal!

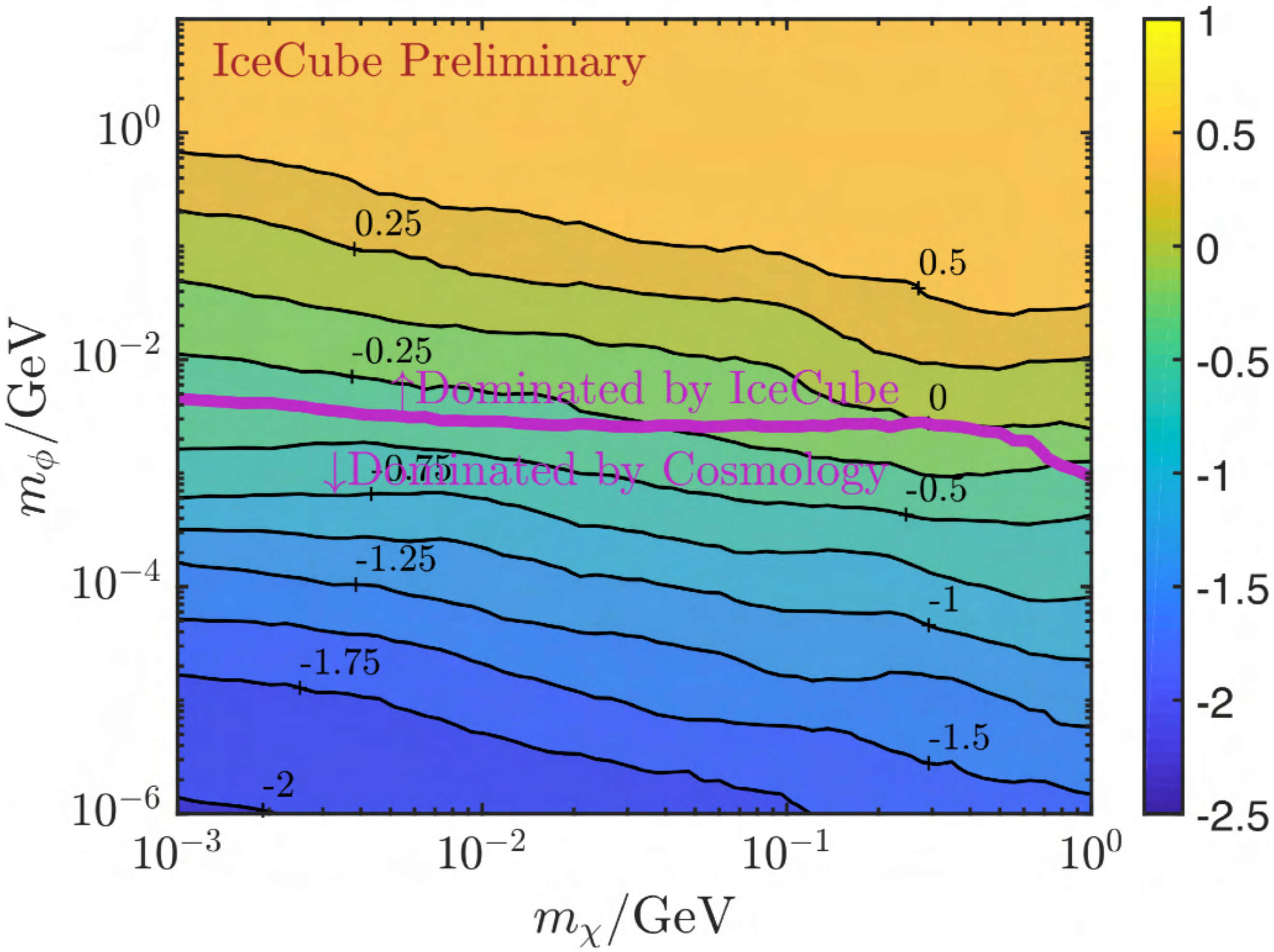
Also include effects in energy and direction

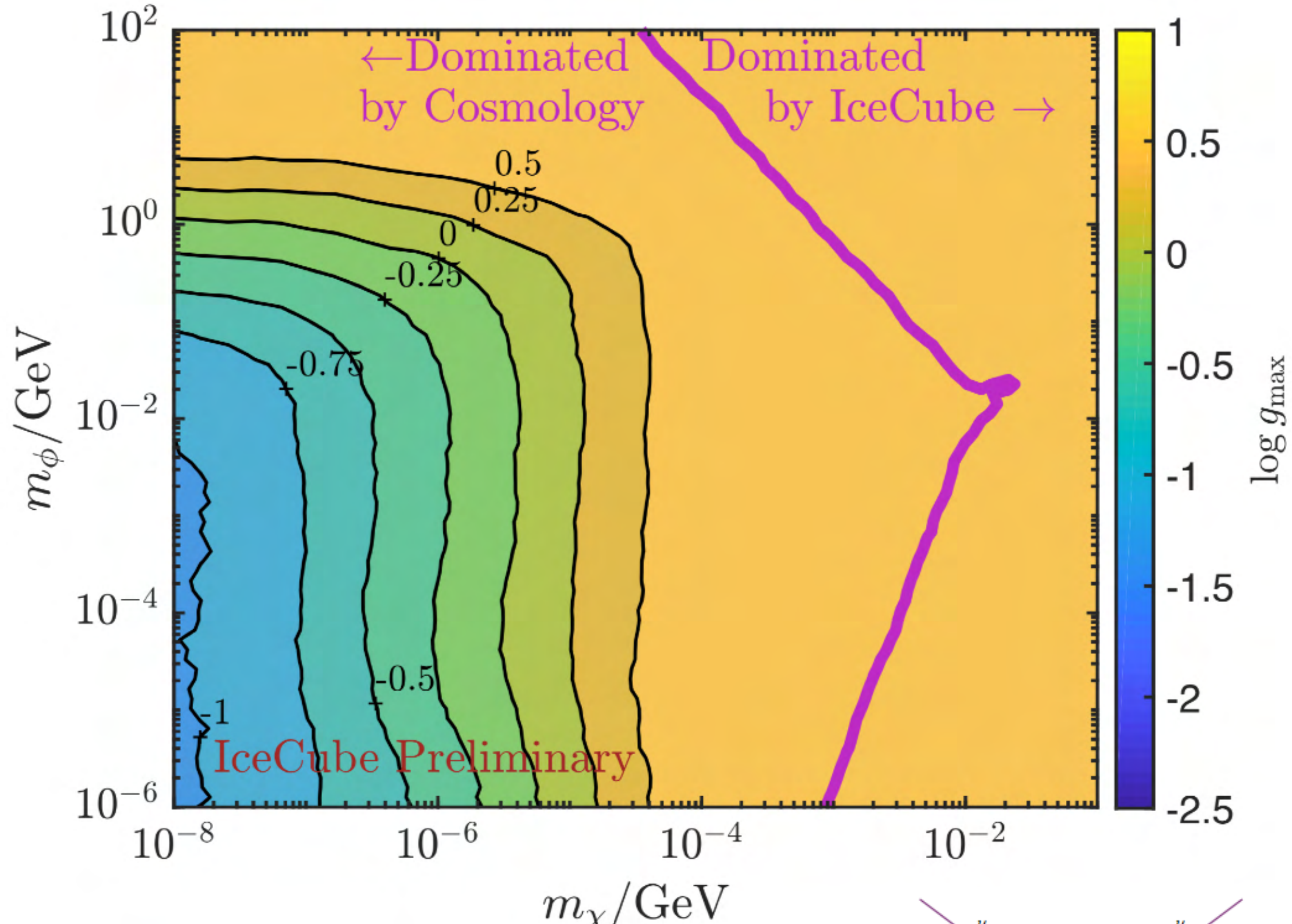


New constraints on neutrino-dark matter interactions



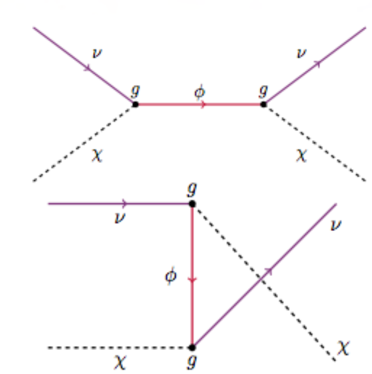
IceCube Work In Progress





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

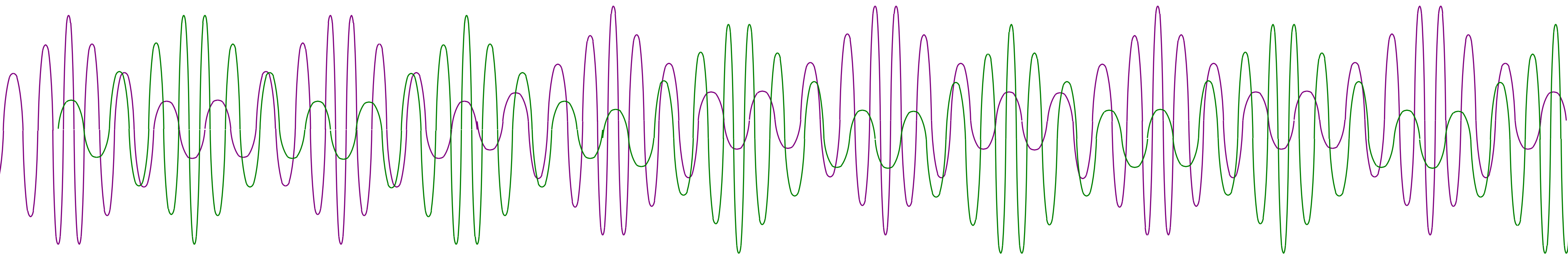
1. IceCube brings unique capabilities to understanding dark matter.

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

   and more data to come!

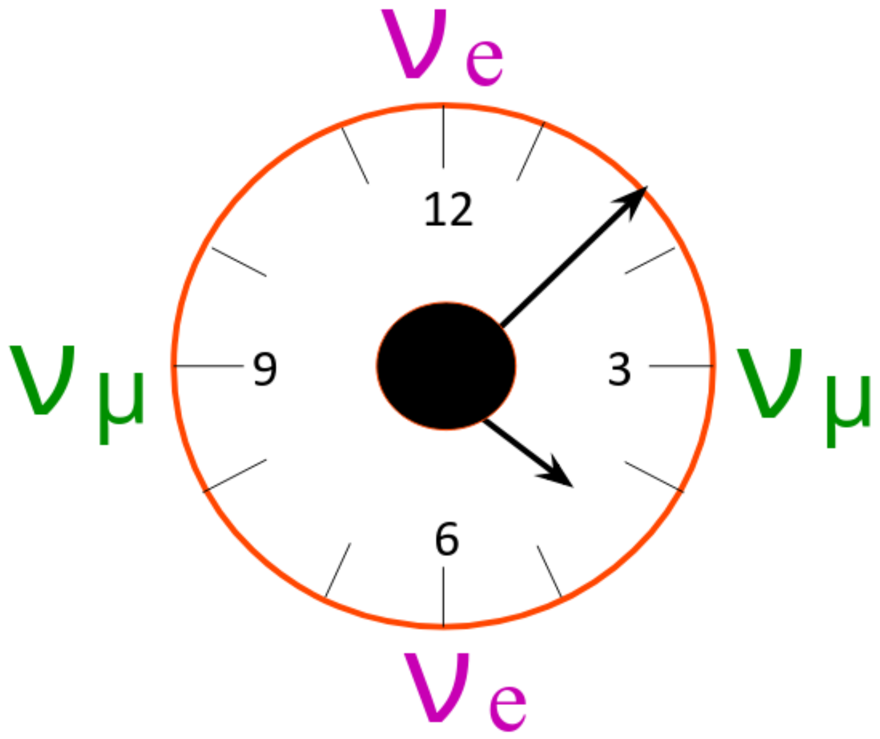
Outline of the rest of this talk:

1. Neutrinos from cosmic beam dumps & IceCube
2. Searching for a new kind of neutrino:
   -The Sterile Neutrino
3. Searching for new forces
   -Non-standard Neutrino Interactions
4. Searching for a dark sector:
   -Neutrino-Dark Matter Interactions
5. Searching for a new symmetry:
   -Lorentz Violation Effects on Flavor



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

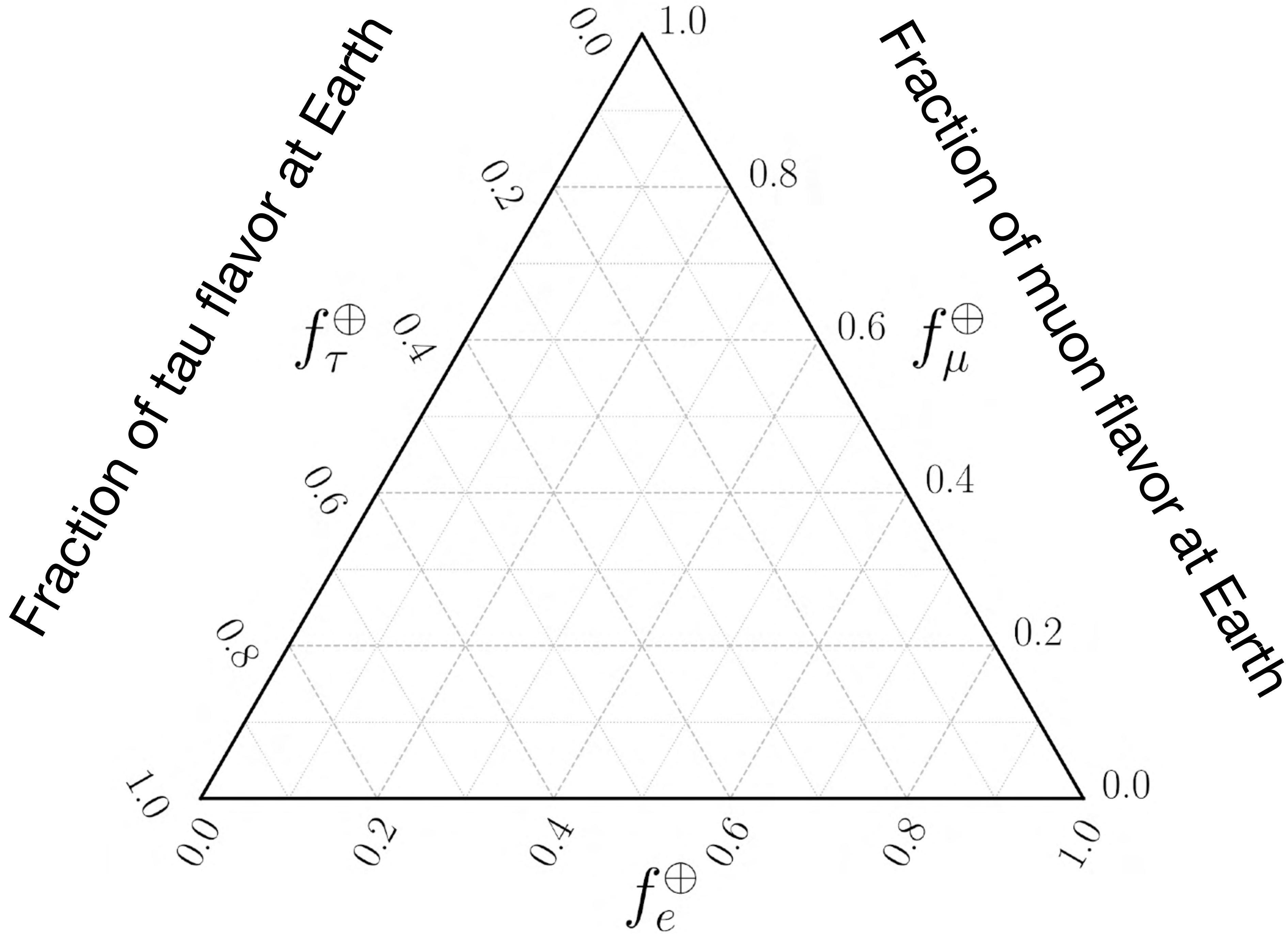
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_\mu + \bar{\nu}_e$$

(1:2:0)

Muon-damped $\pi^+ \rightarrow \cancel{\mu^+} + \nu_\mu$ (0:1:0)

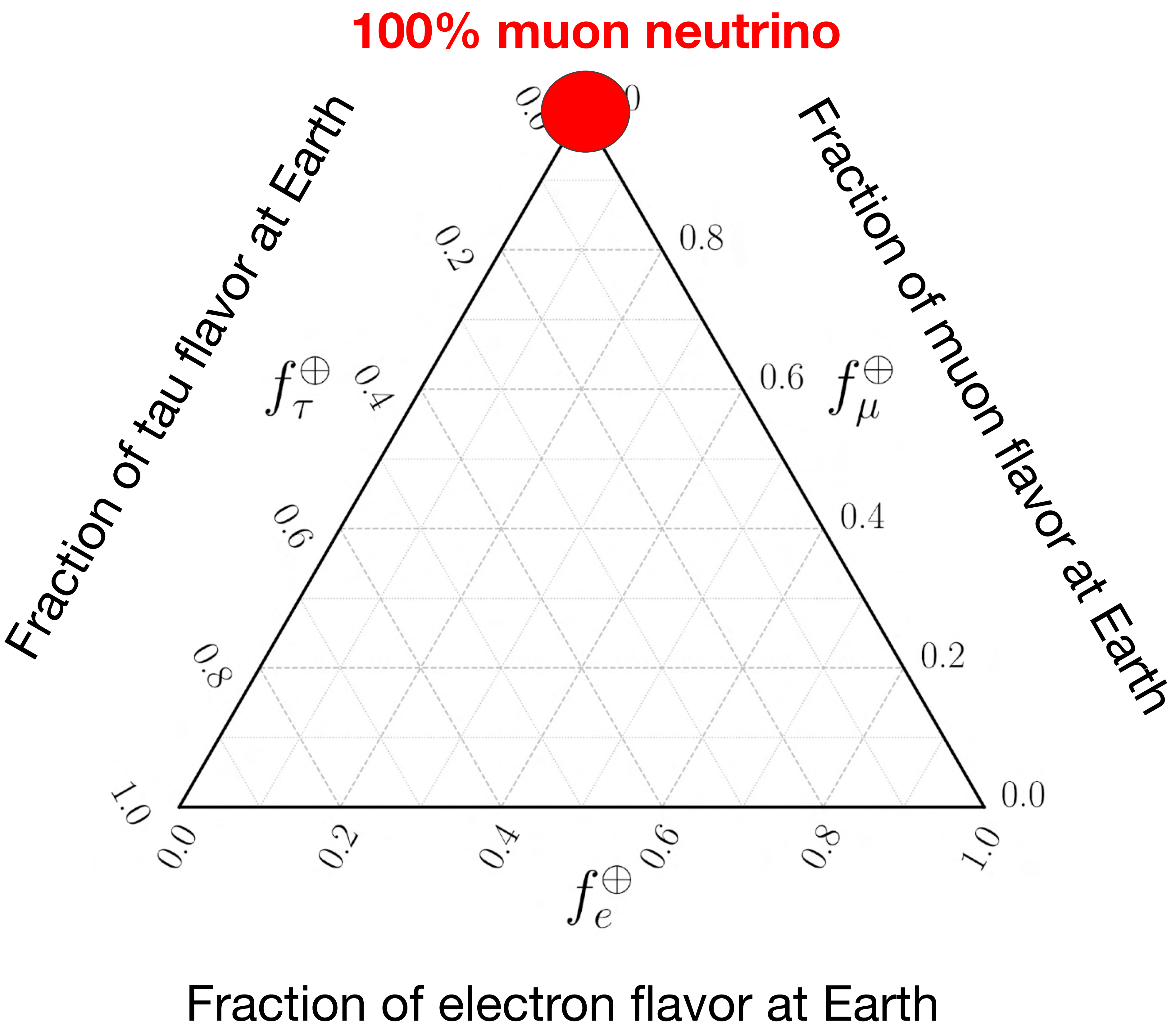
Neutron $n \rightarrow p + e^- + \bar{\nu}_e$ (1:0:0)

The flavor triangle

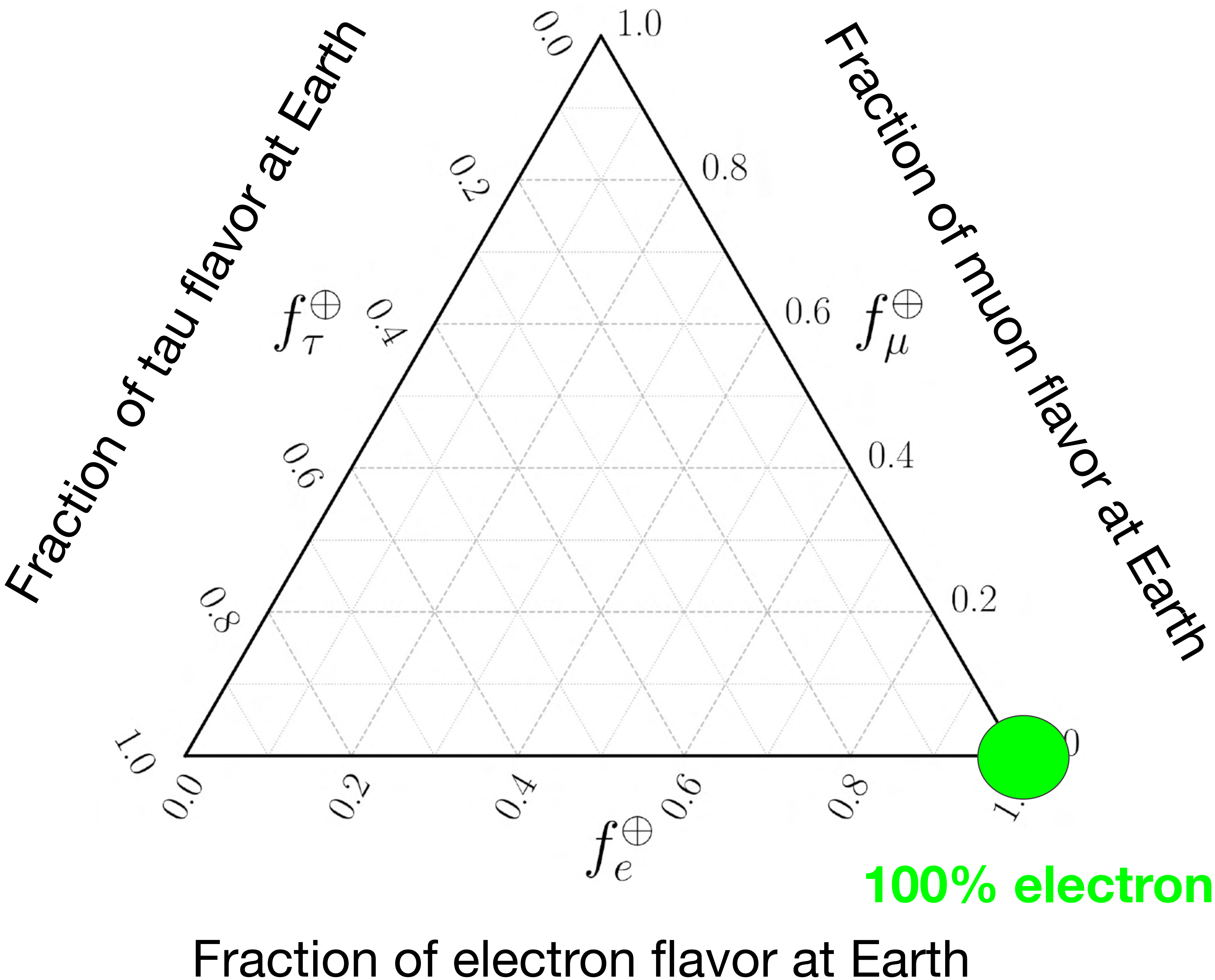


Fraction of electron flavor at Earth

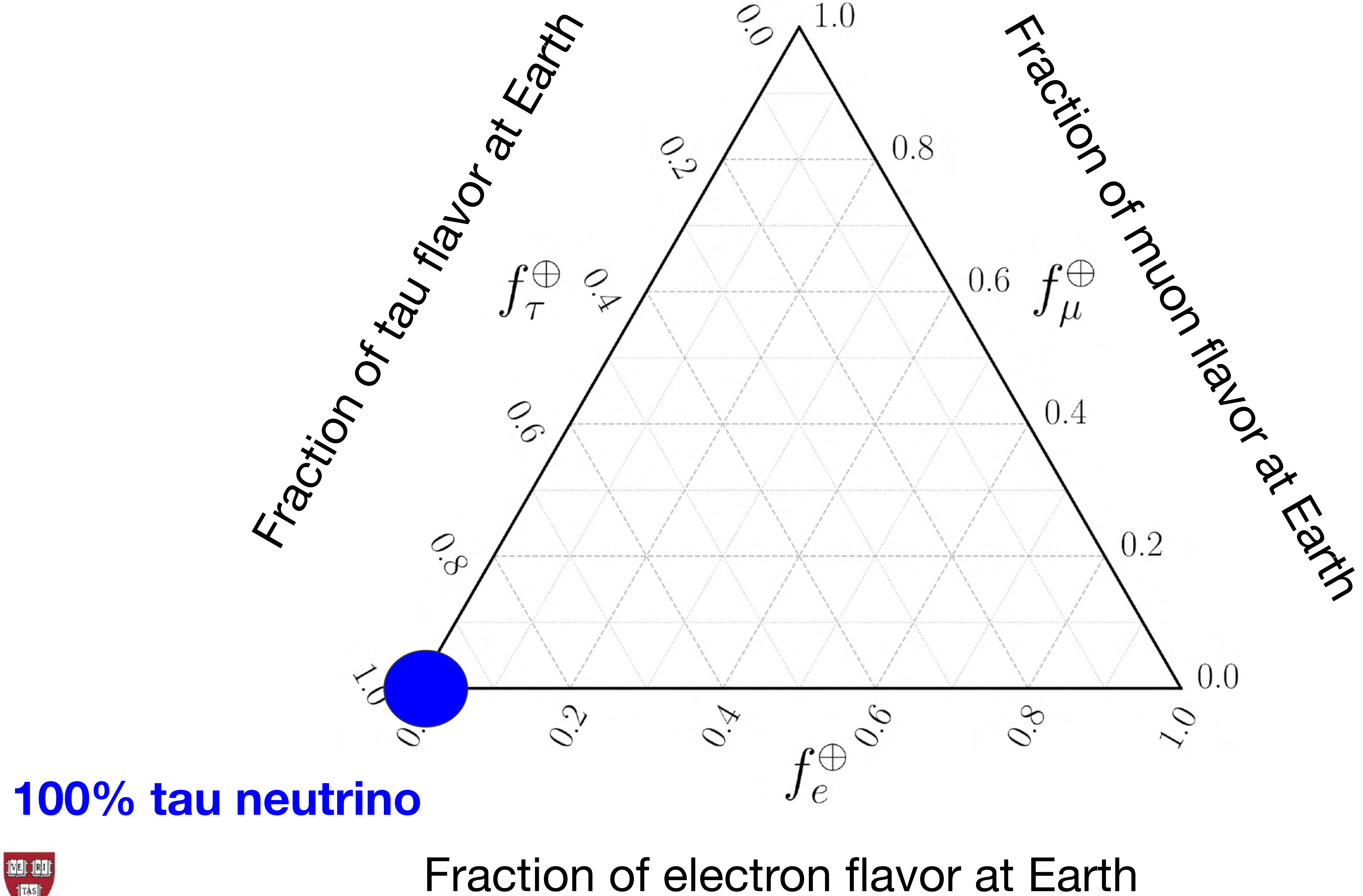
The flavor triangle



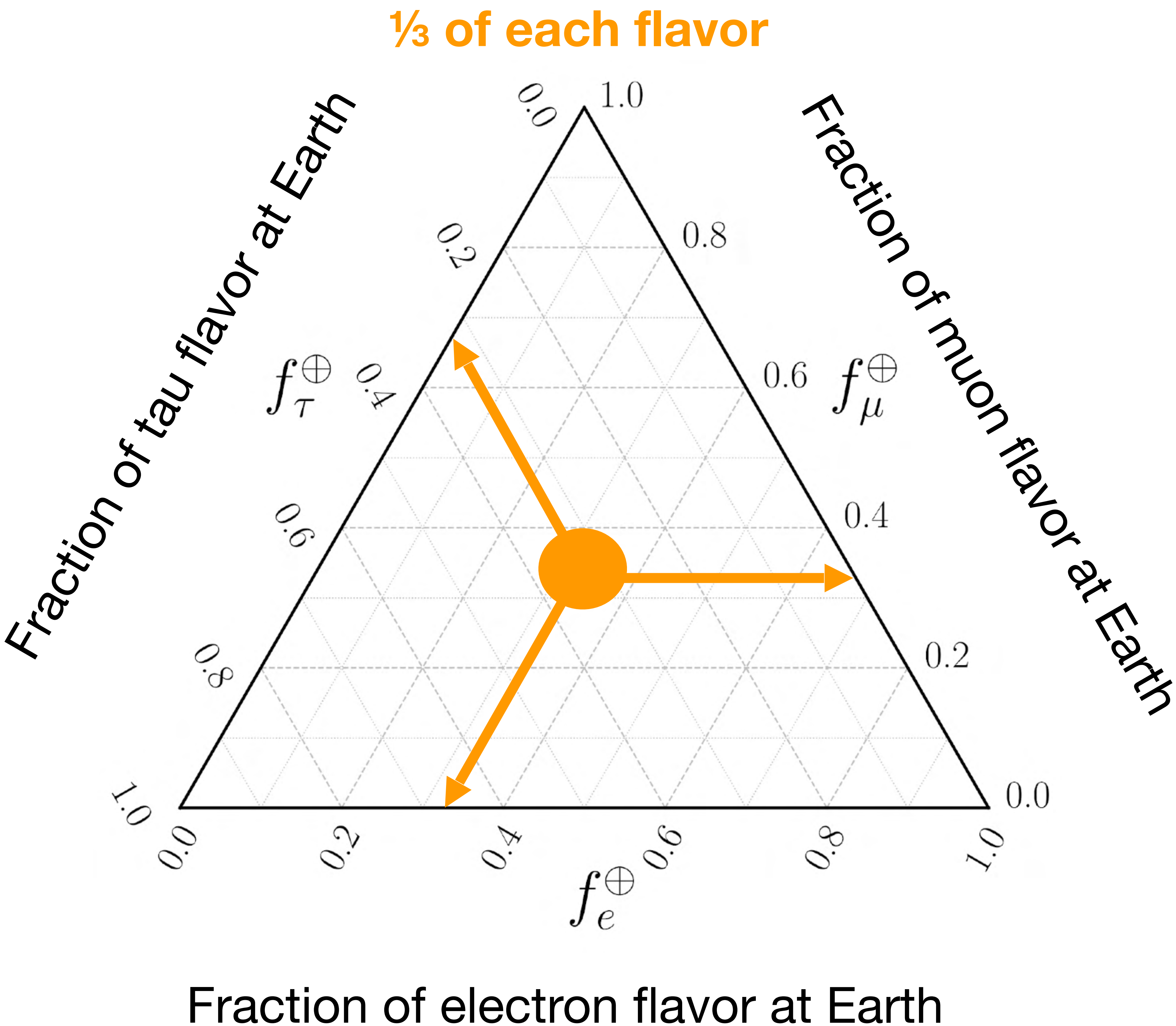
The flavor triangle



The flavor triangle

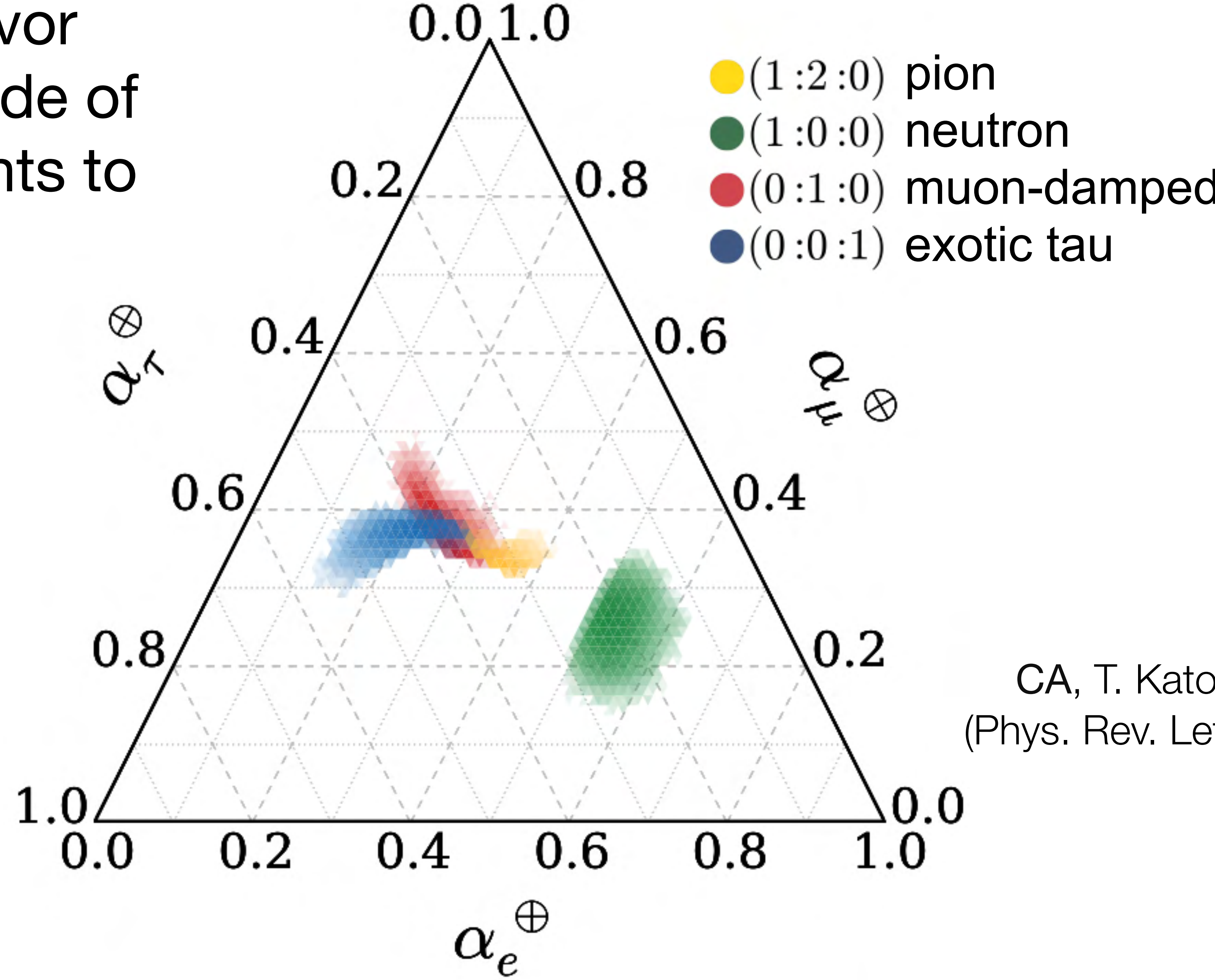


The flavor triangle



After oscillations where will the different sources end up?

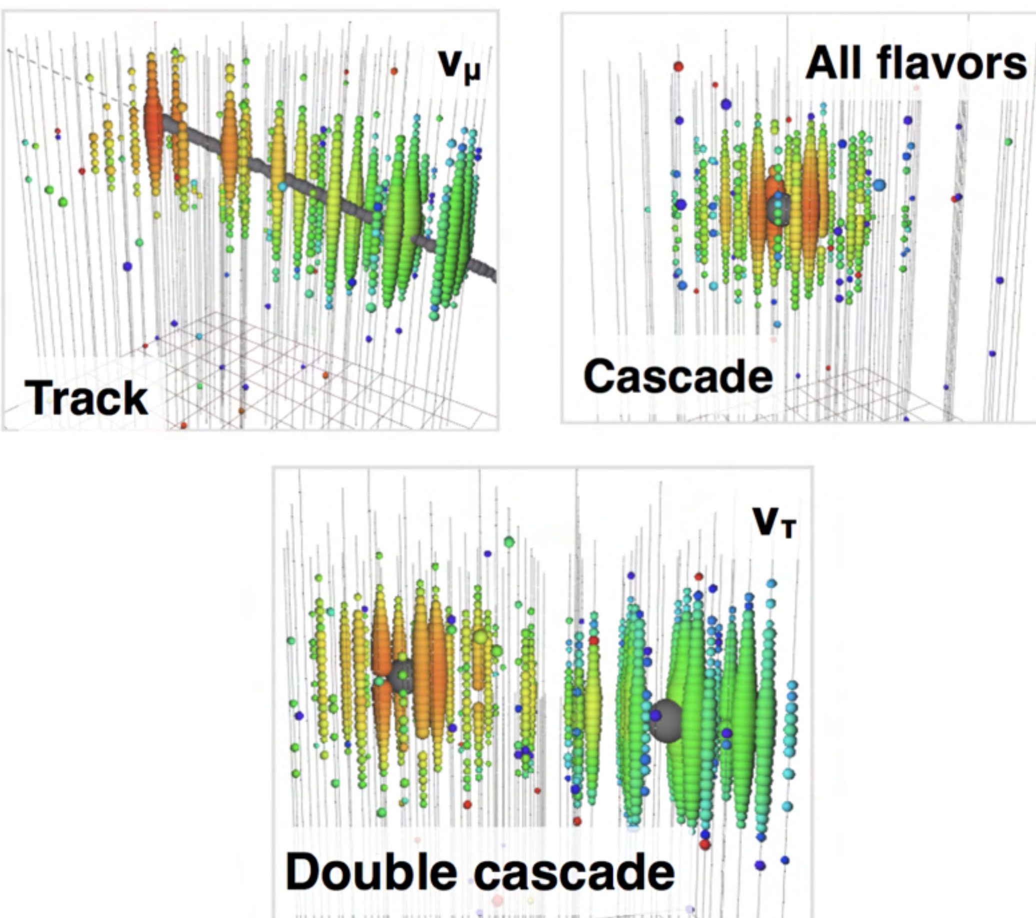
Measuring a flavor composition outside of these regions points to new physics!



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

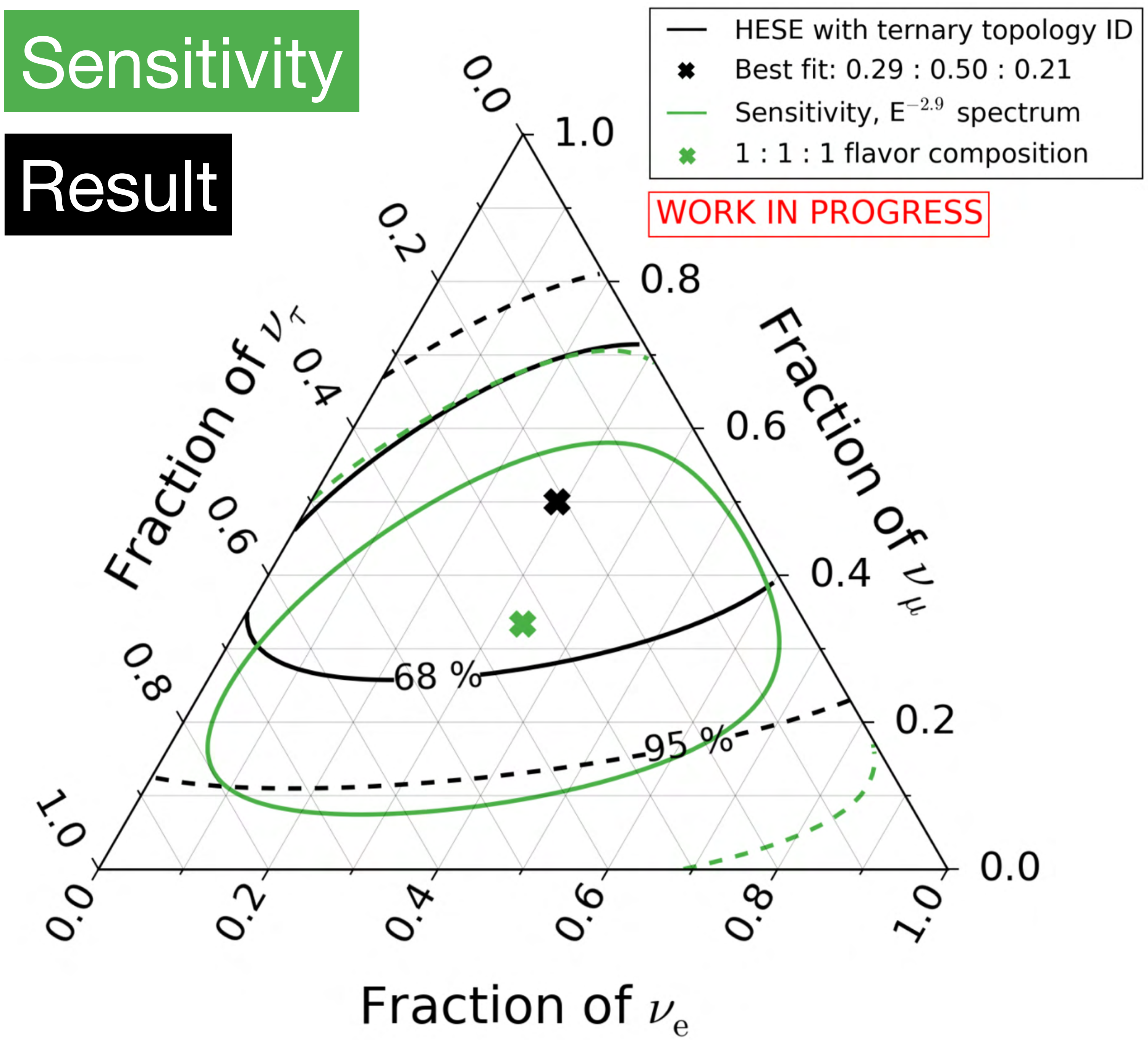
See also Bustamante *et al. PRL 115, 161302 (2015);* CA *et al.* JCAP 2019 arXiv:1909.05341

Latest astrophysical neutrino flavor measurement



Sensitivity

Result



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)

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

Dimension

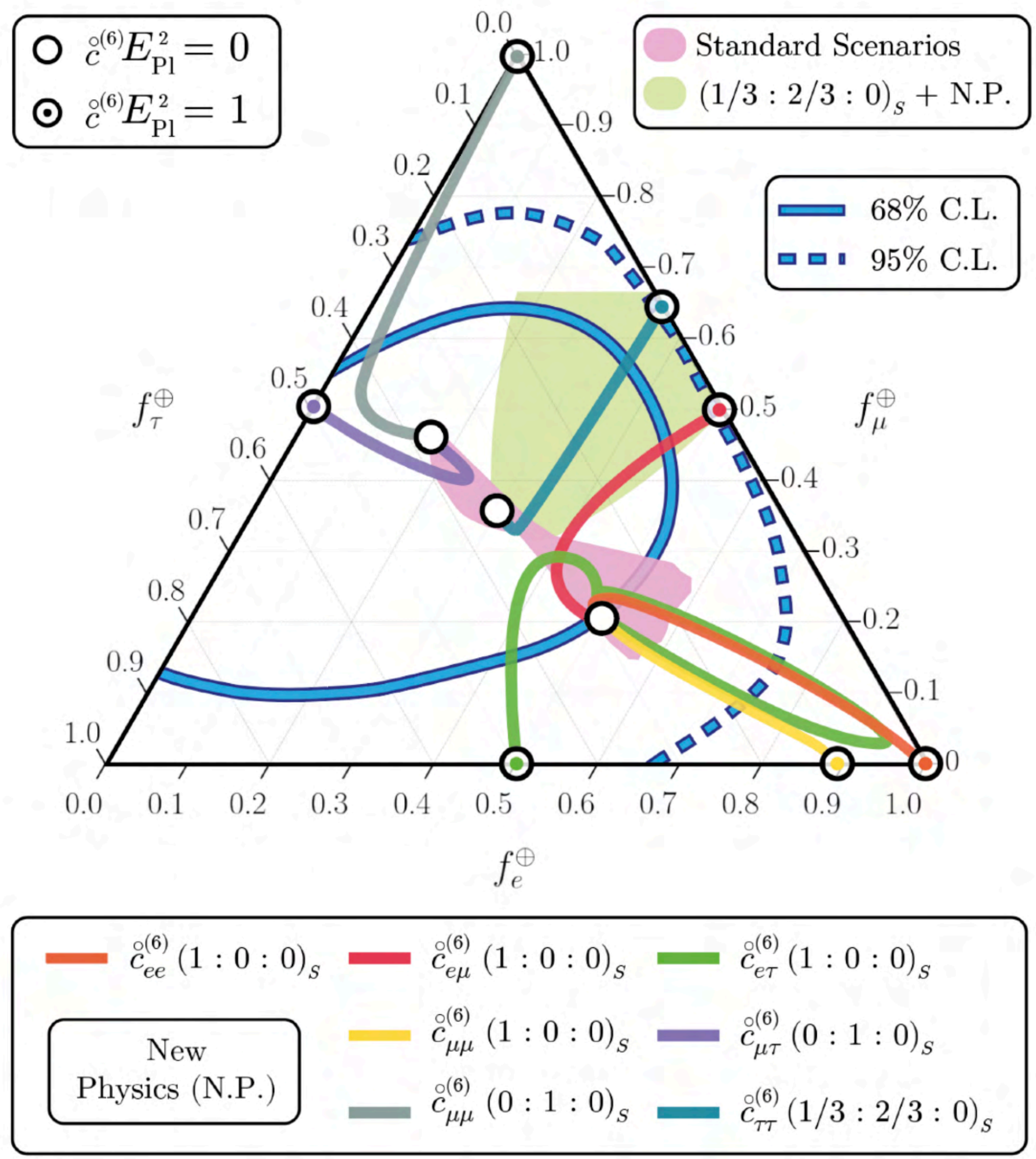
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

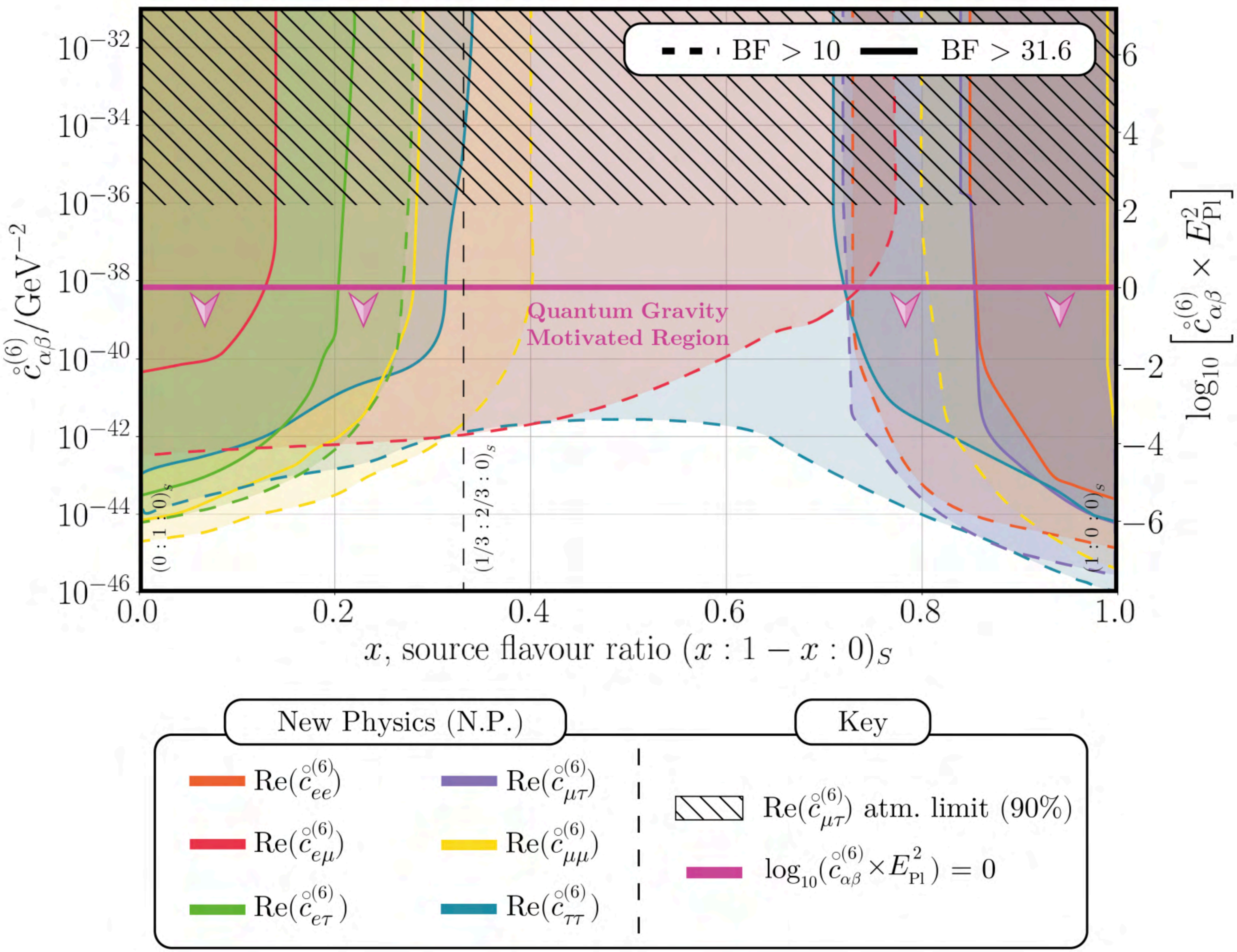
$(0:1:0)$ neutron

$(1:0:0)$ muon-damped



IceCube collaboration arXiv:2111.04654

Results on high-dimensional LV operators



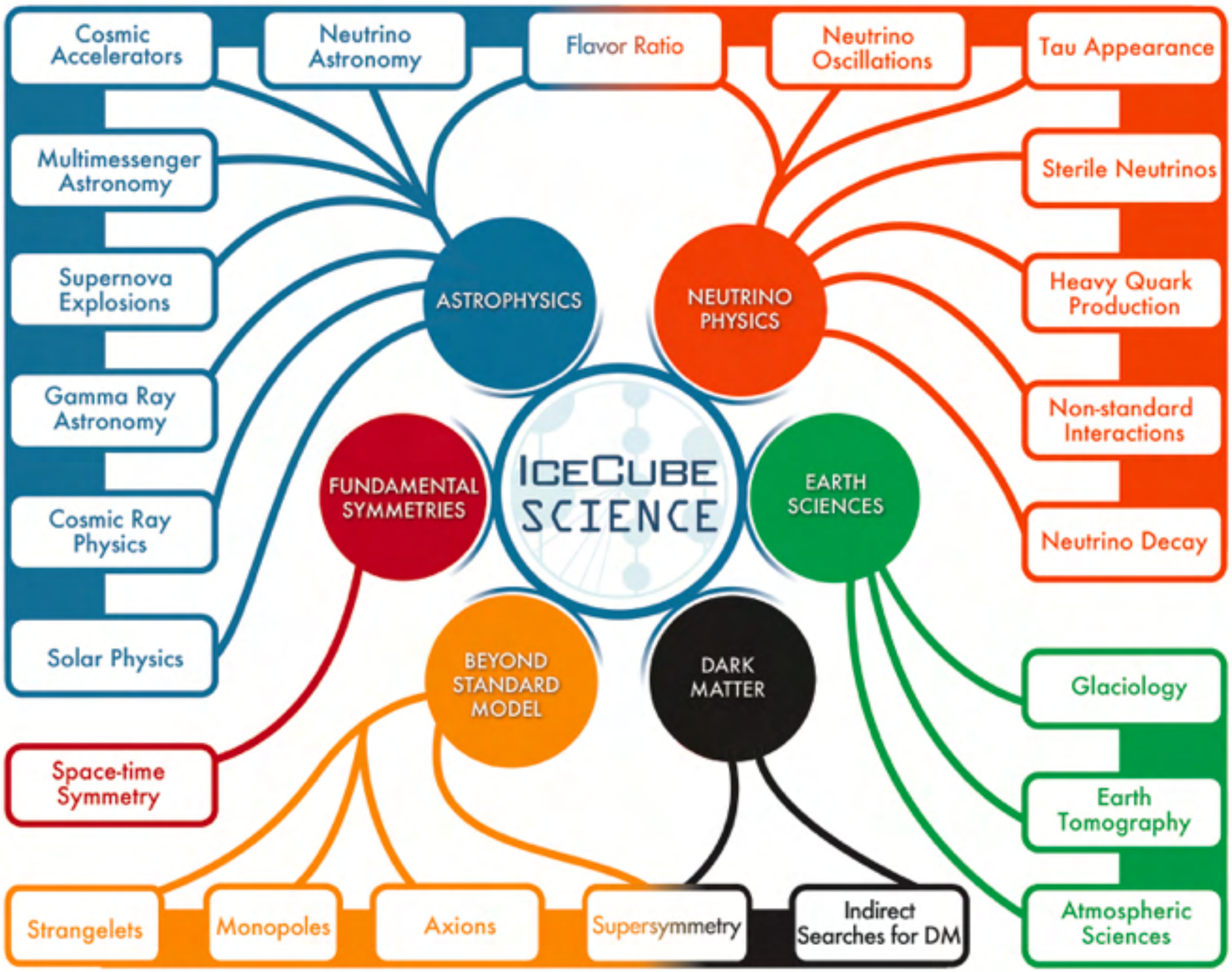
IceCube collaboration arXiv:2111.04654

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 quantum gravity

I hope I have convinced you that ...

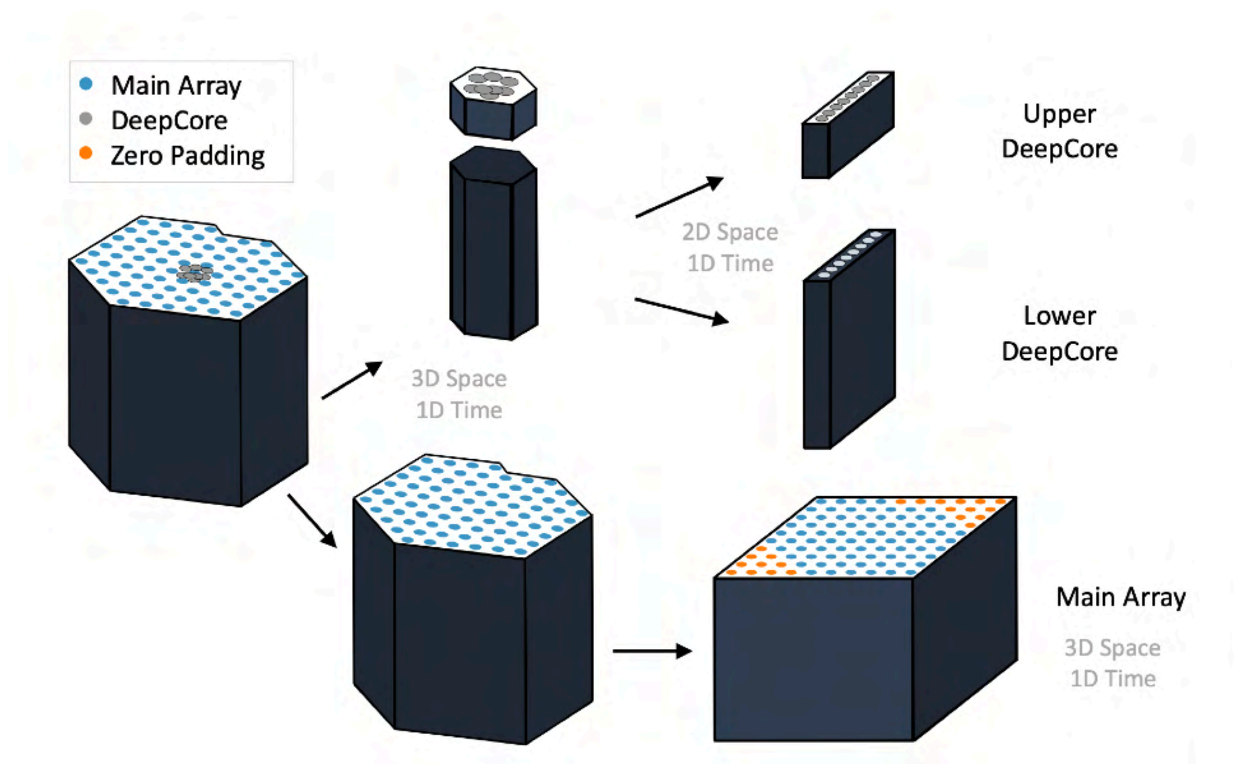


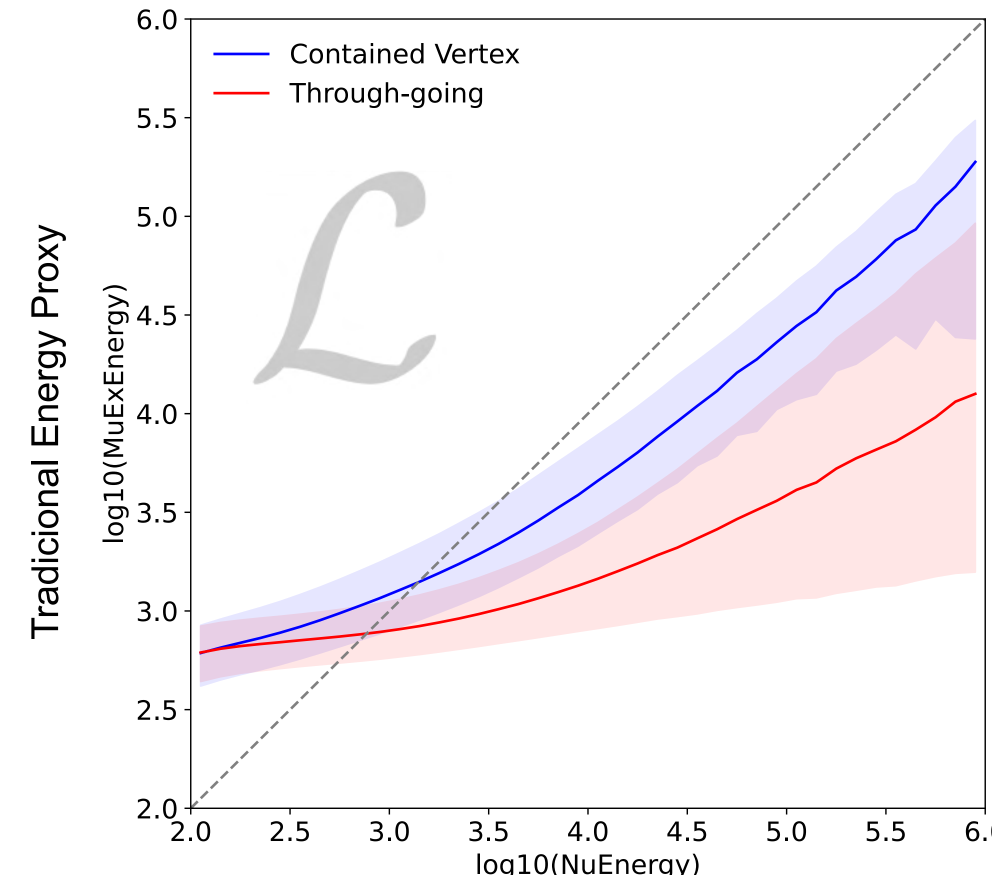
IceCube has great potential for discovery

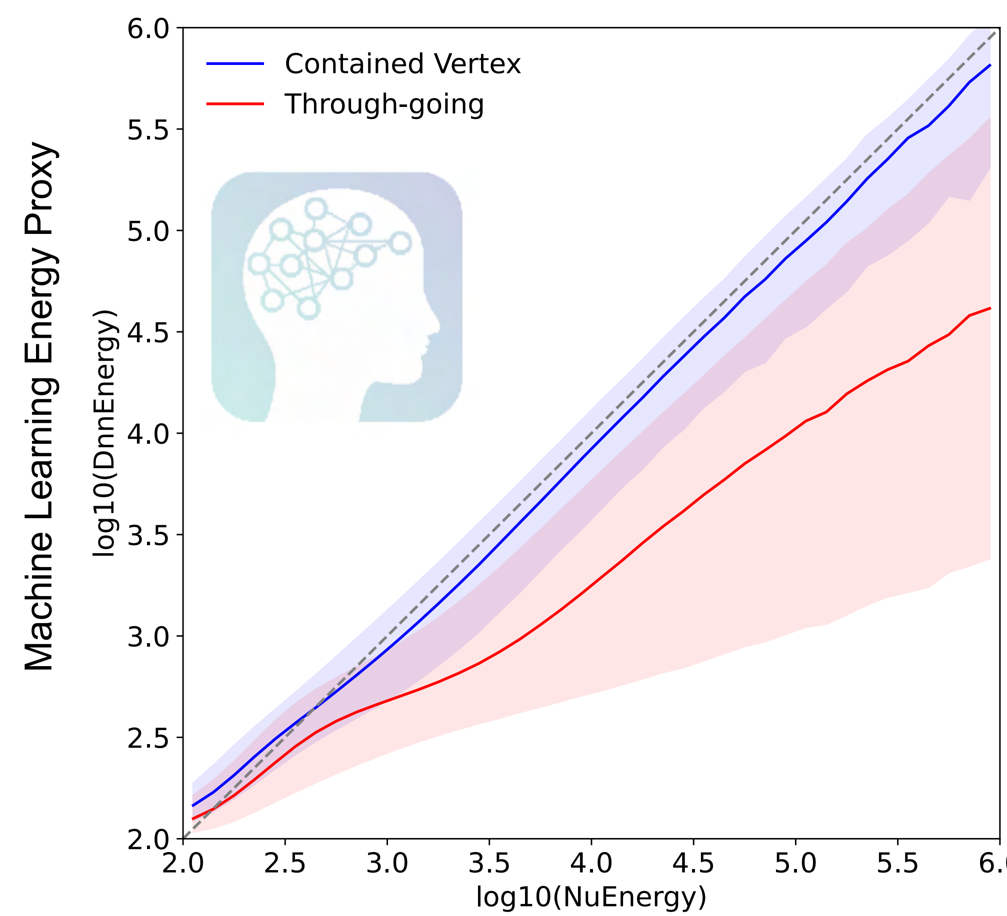
That potential is growing:

Machine learning

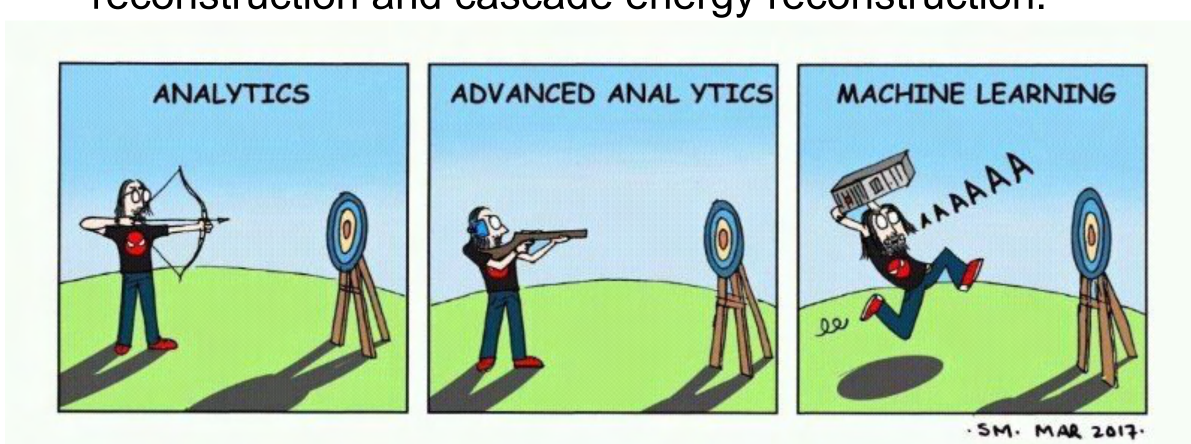
IceCube Collaboration arXiv:2101.11589





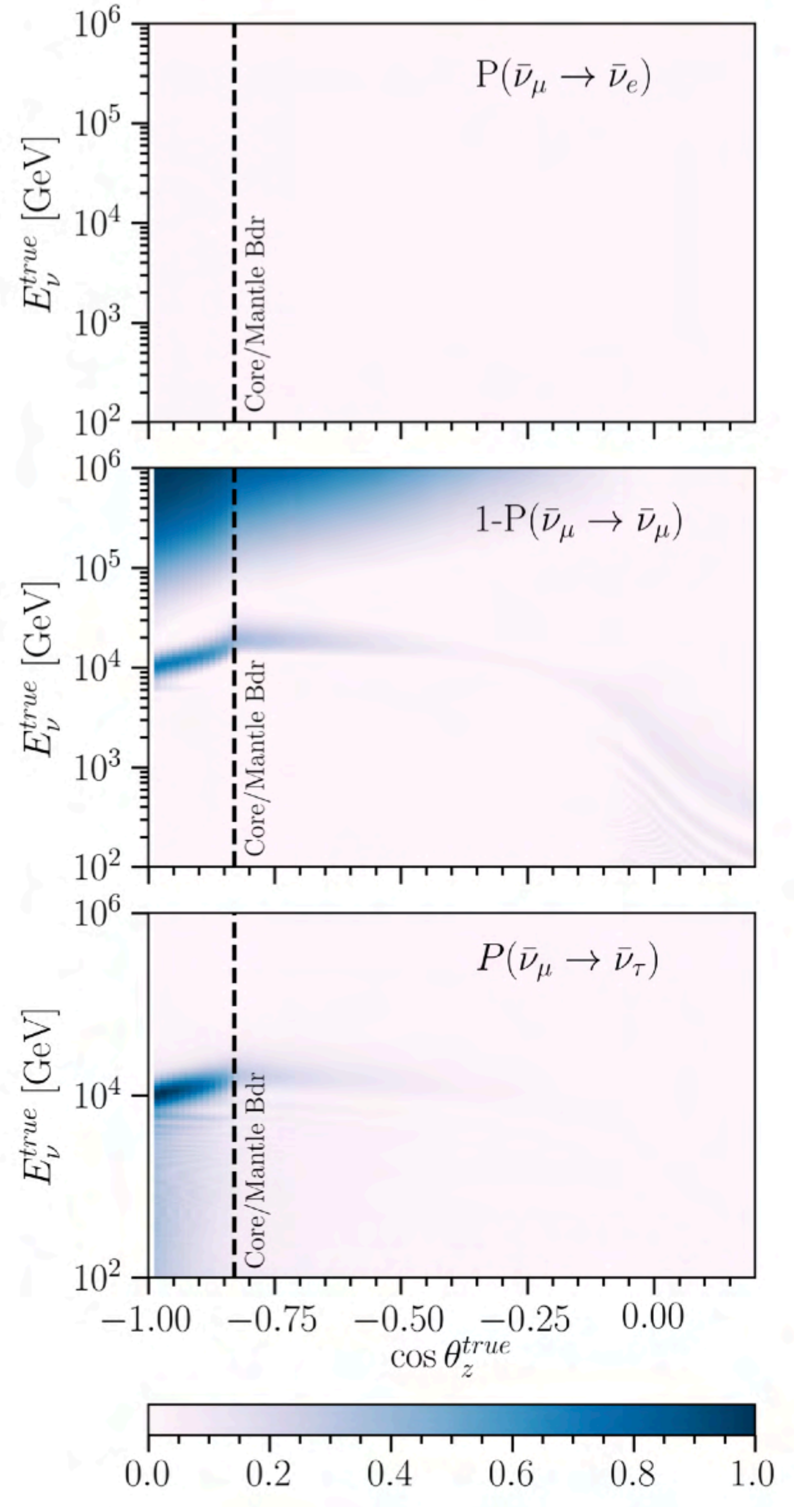


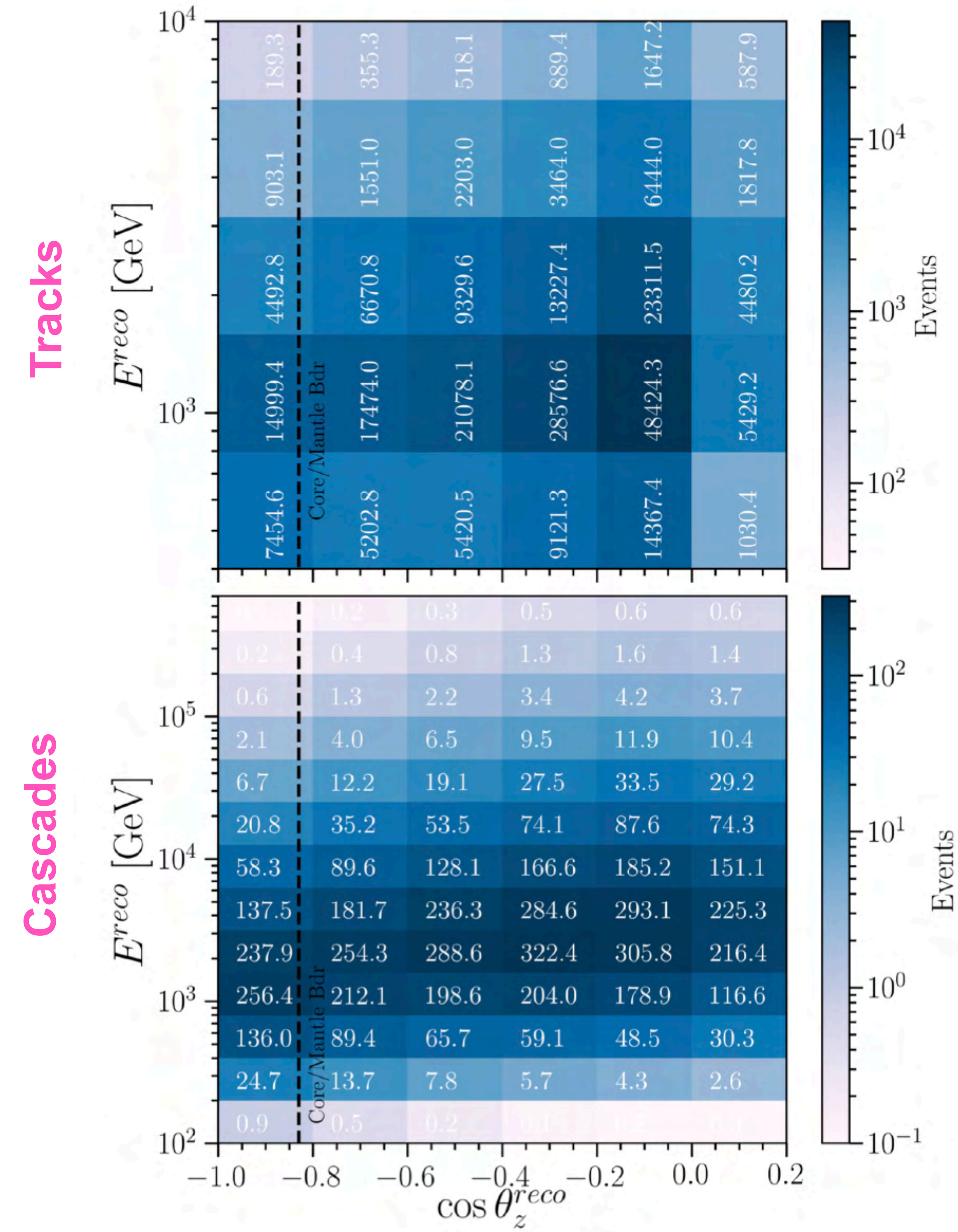
Also significant improvements on direction reconstruction and cascade energy reconstruction.



That potential is growing:

Untapped potential of medium-energy cascades





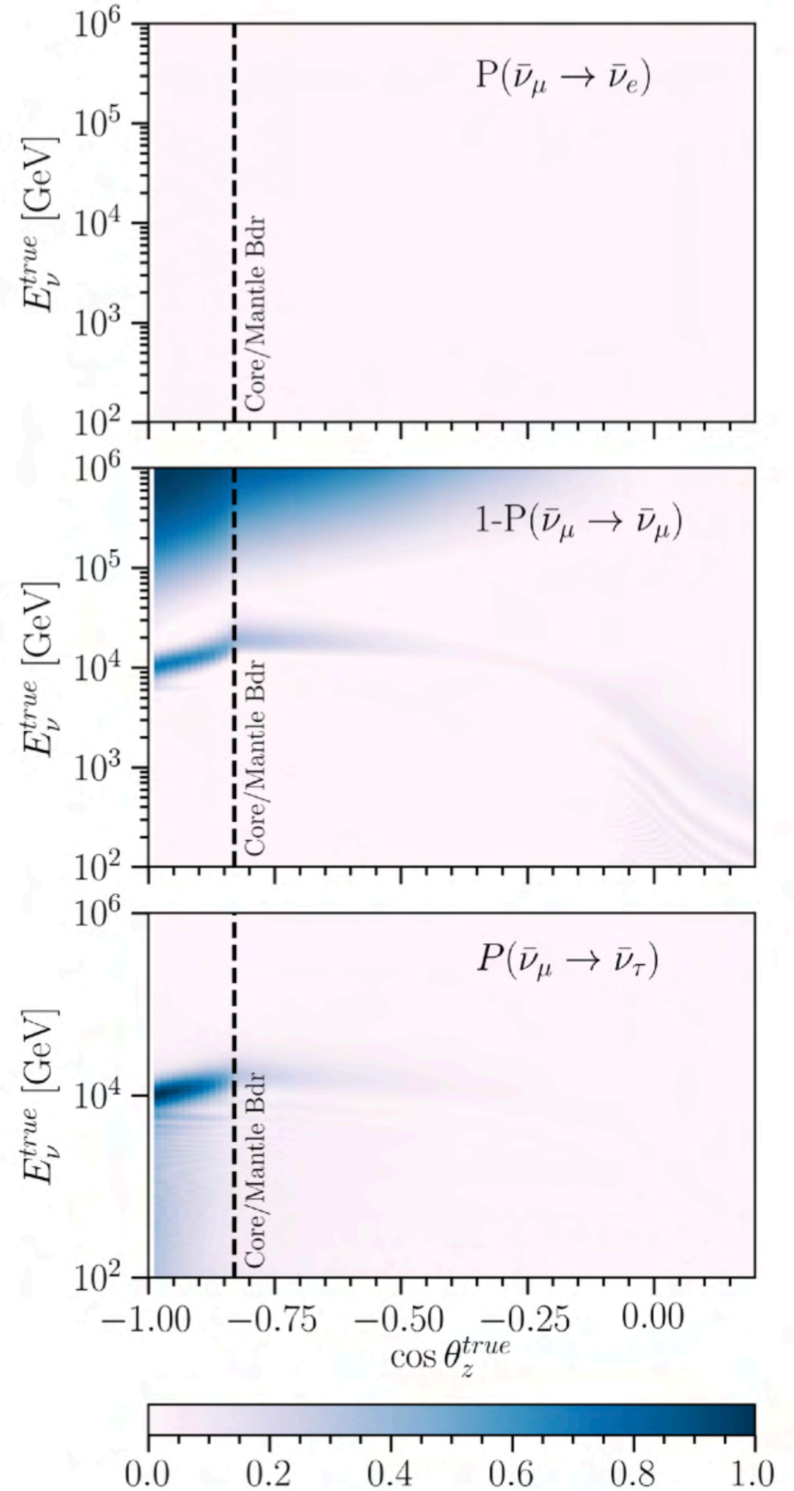
$\sin^2 2\theta_{34} = 0.2 \quad \sin^2 2\theta_{24} = 0.1$

$\Delta m^2 = 4.5\text{eV}^2$

Smithers, Jones, CA, & Conrad arXiv:2111.08722

That potential is growing:

Untapped potential of medium-energy cascades



$\sin^2 2\theta_{34} = 0.2 \quad \sin^2 2\theta_{24} = 0.1$

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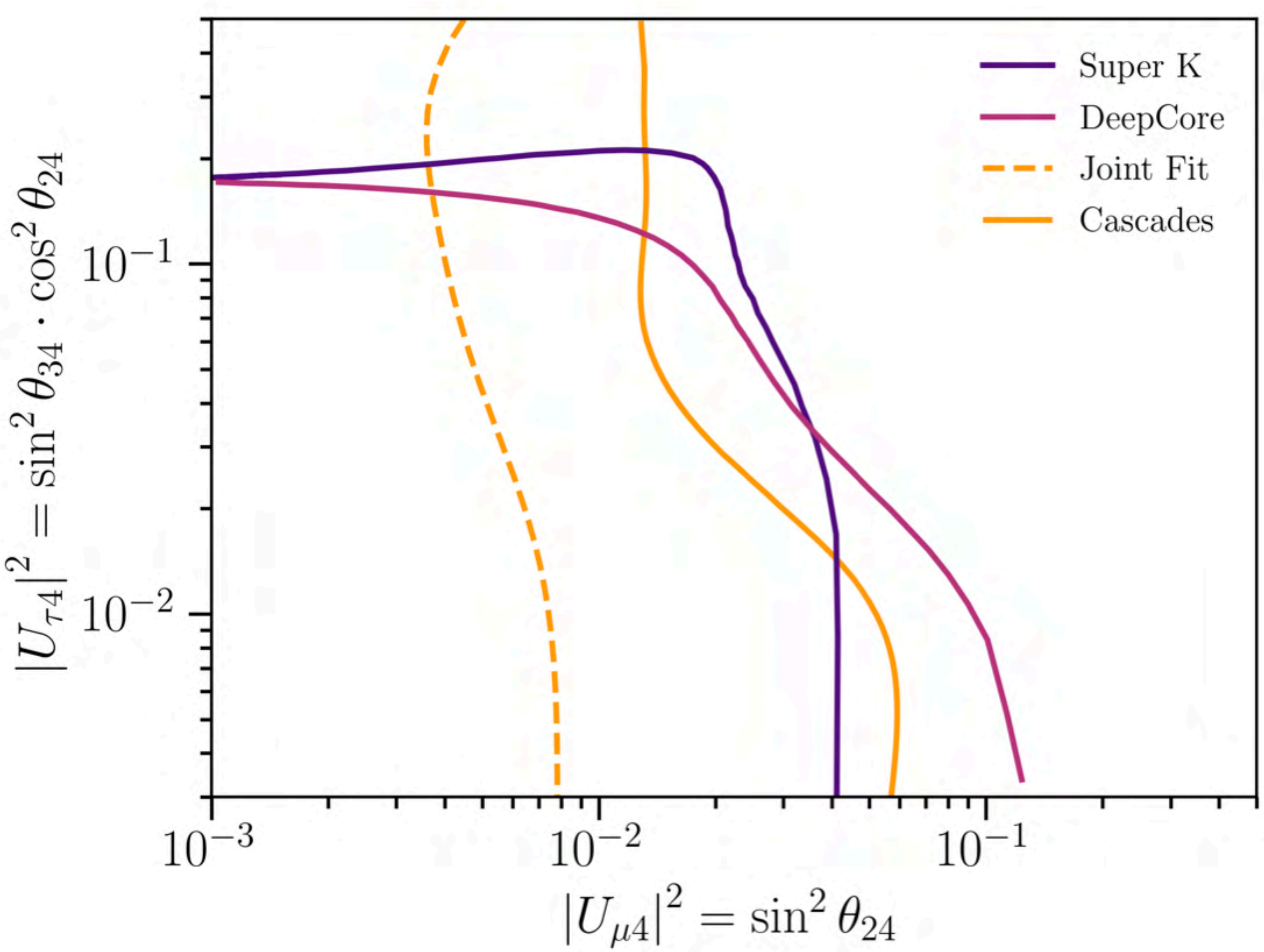

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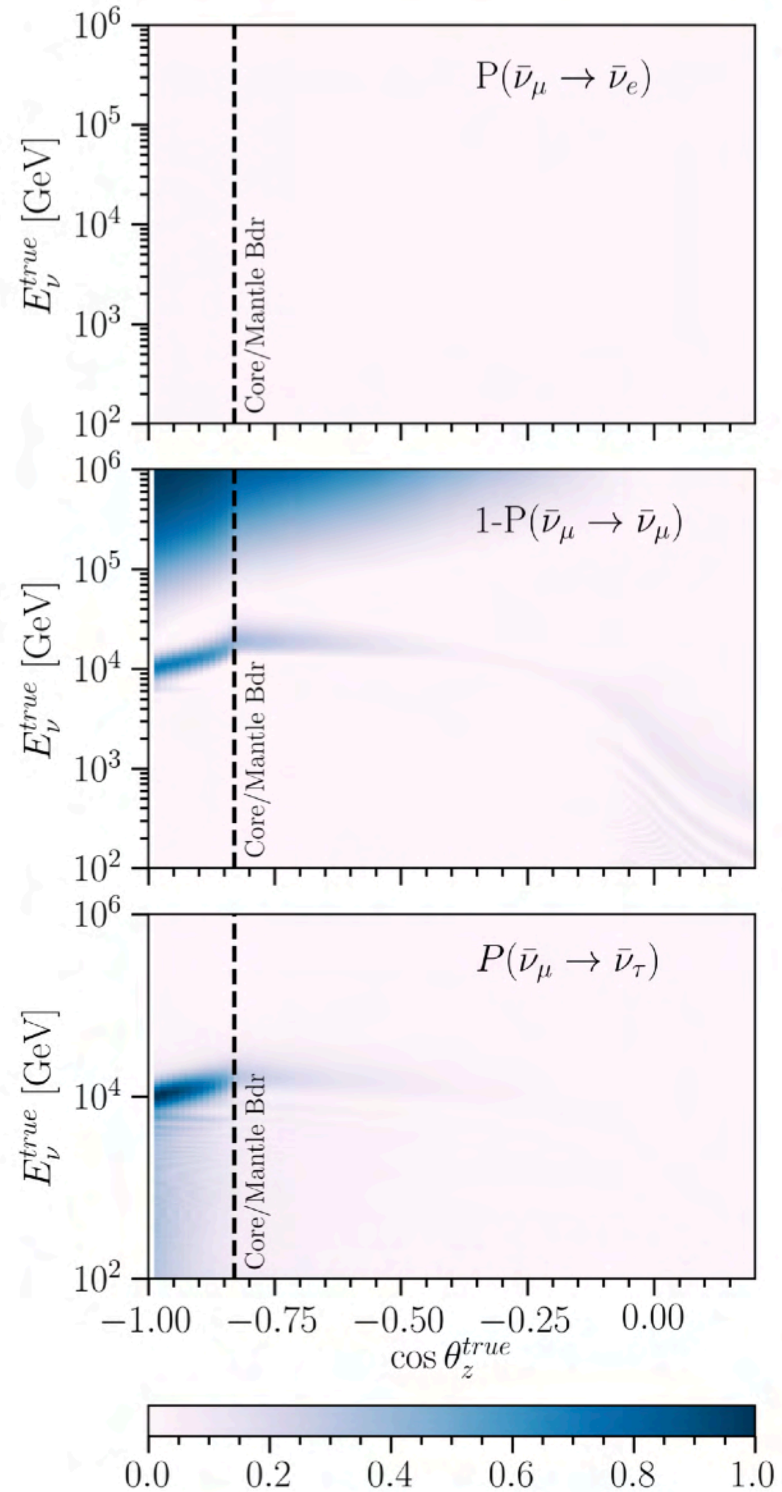

$\sin^2 2\theta_{34} = 0.2 \quad \sin^2 2\theta_{24} = 0.1$

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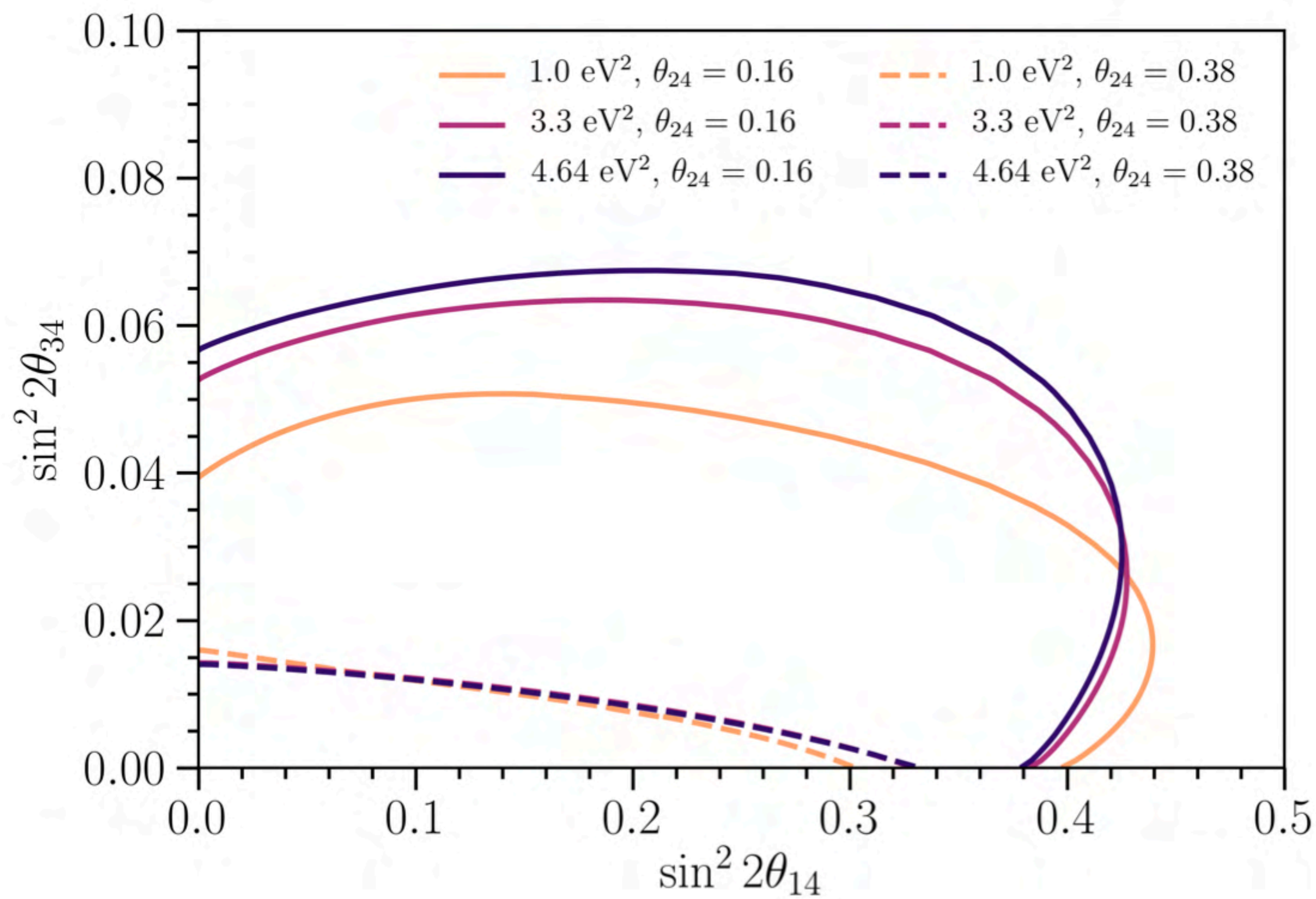
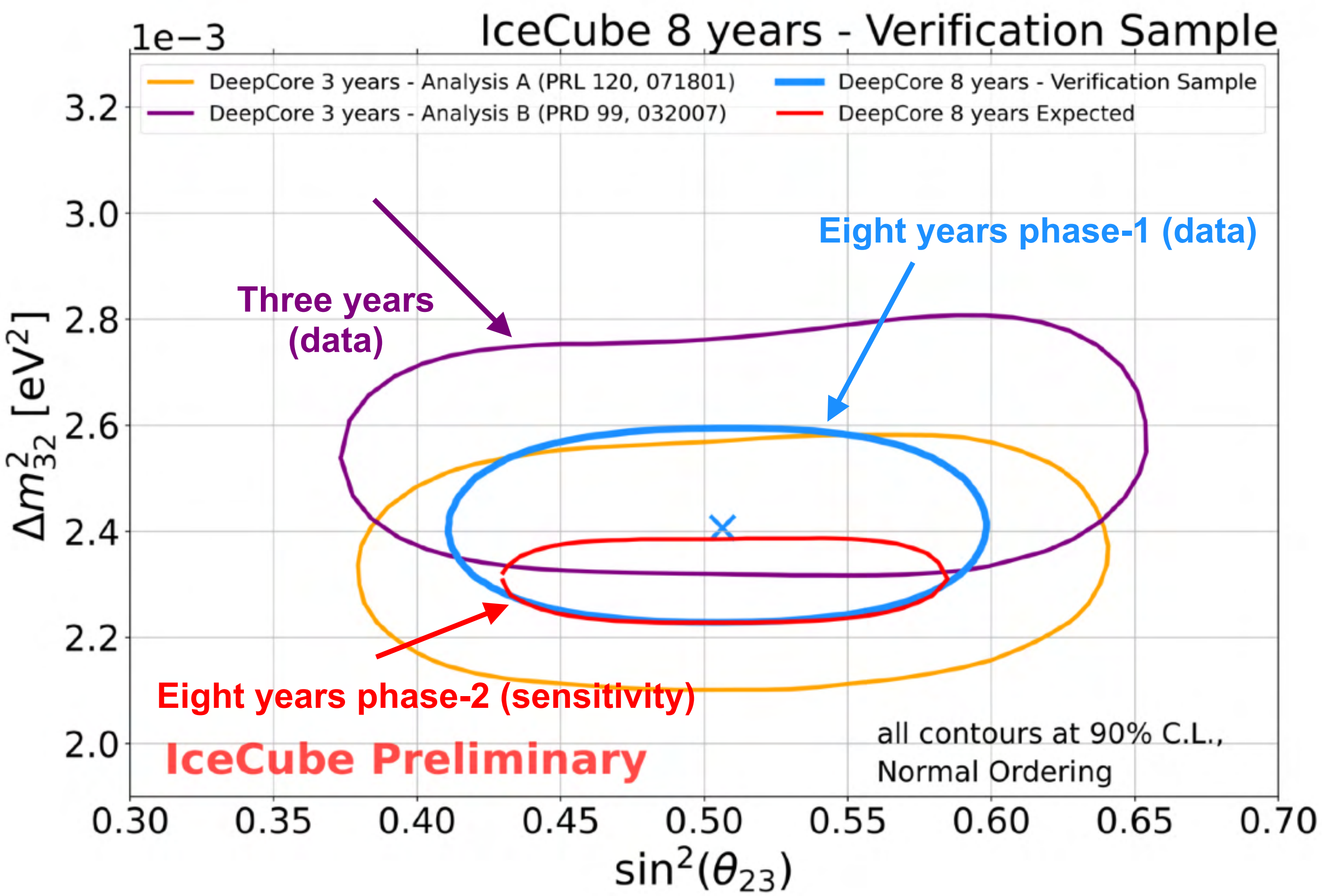


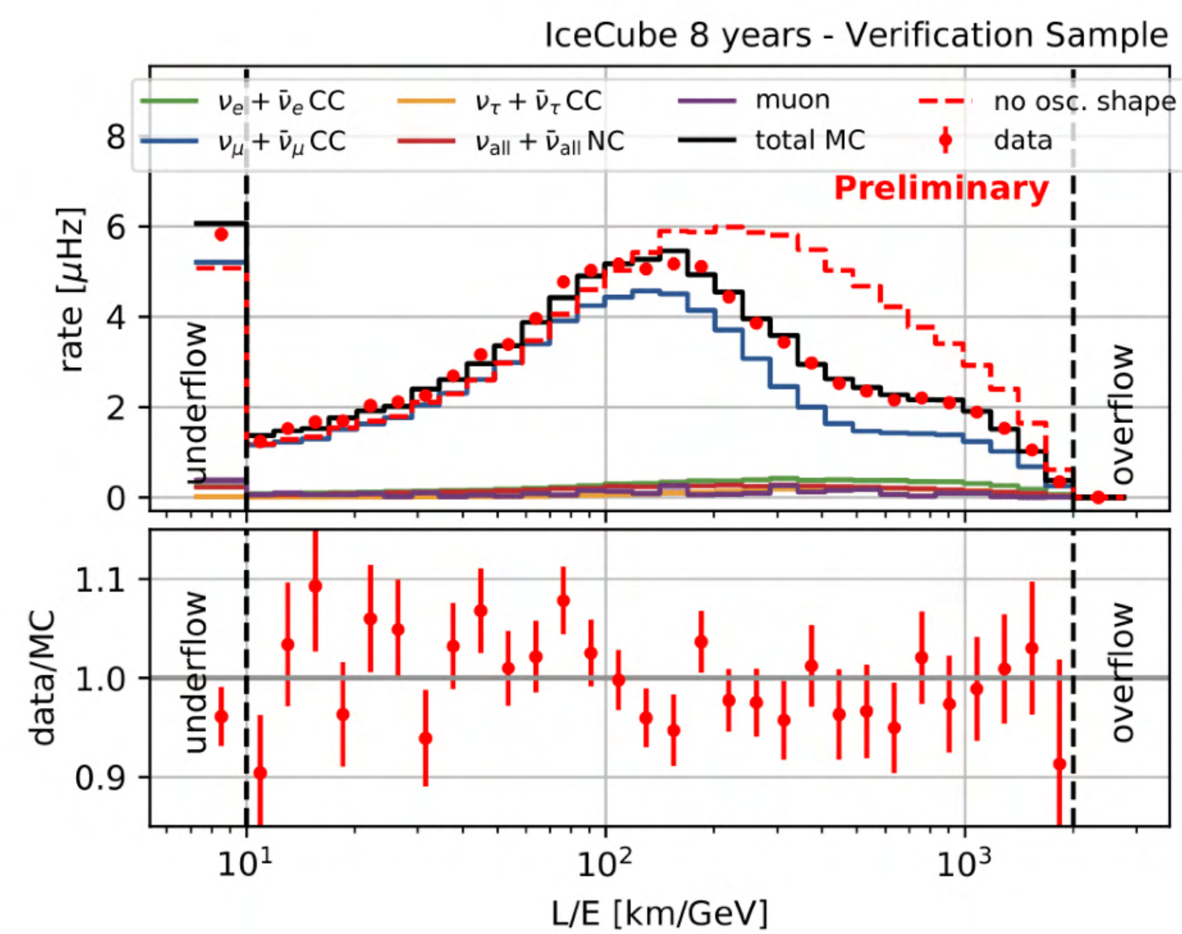
Smithers, Jones, CA, & Conrad arXiv:2111.08722

That potential is growing:

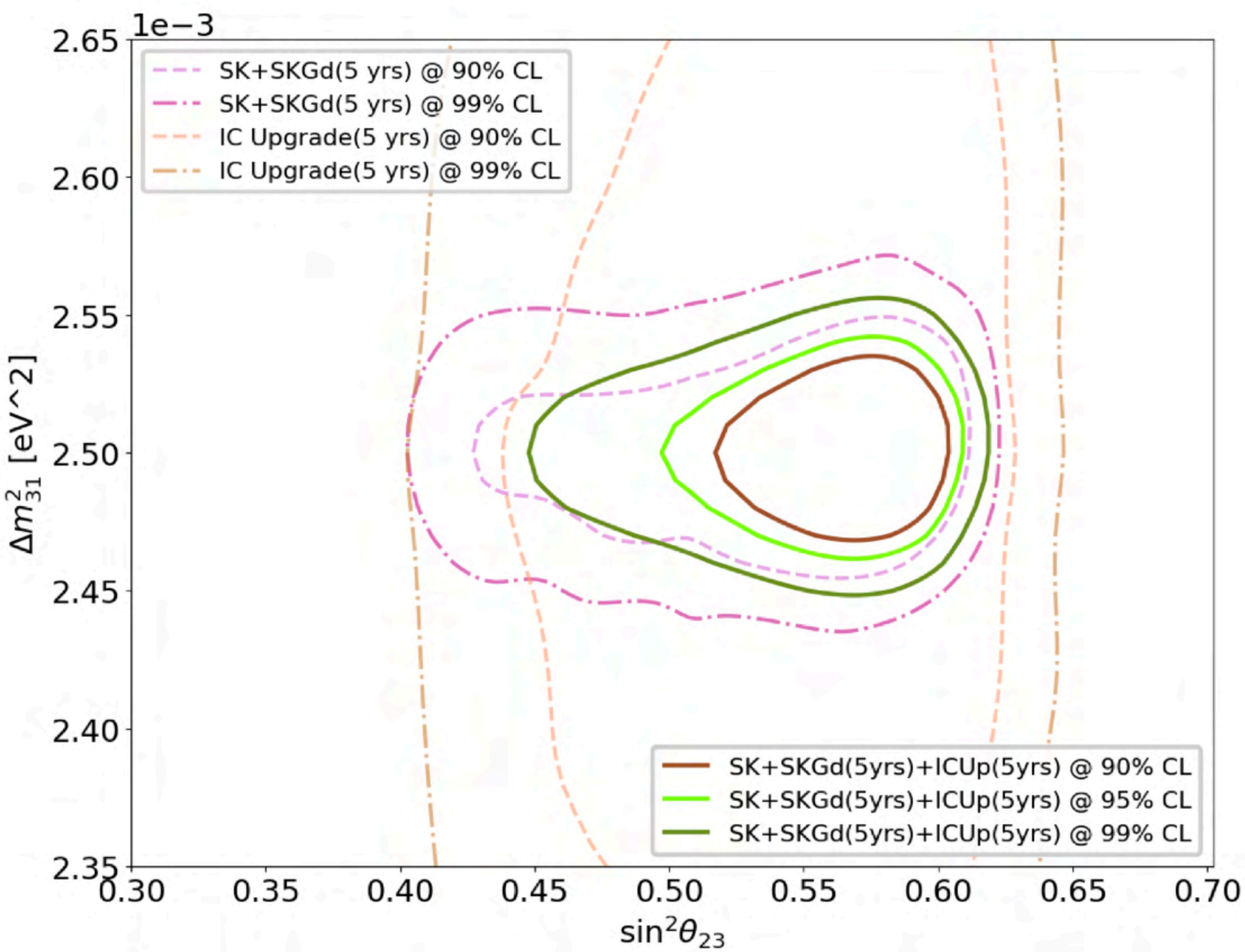
Full ~ 8 years of IceCube/DeepCore

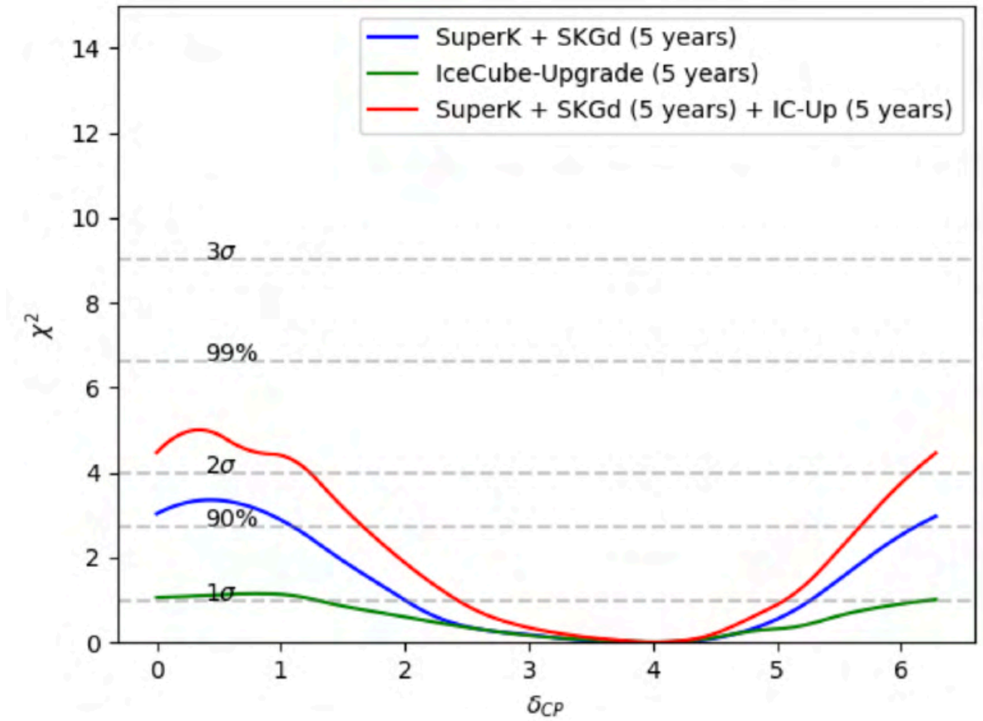


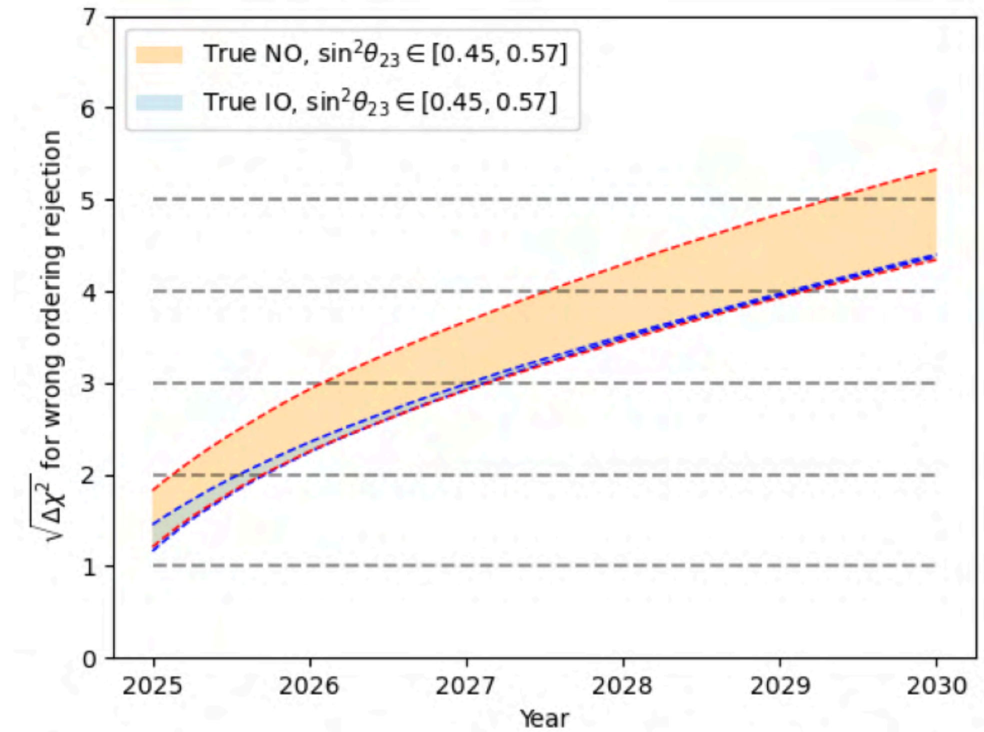
- IceCube/DeepCore analyses have used three years of data, but more than eight on disk.
- Performed new analysis with improved systematics on 8 years with golden events ("verification sample")
- Upcoming new analysis with high-statistics and new systematics with 8 years.



That potential is growing:
Synergies with other water Cherenkov atm. exp.





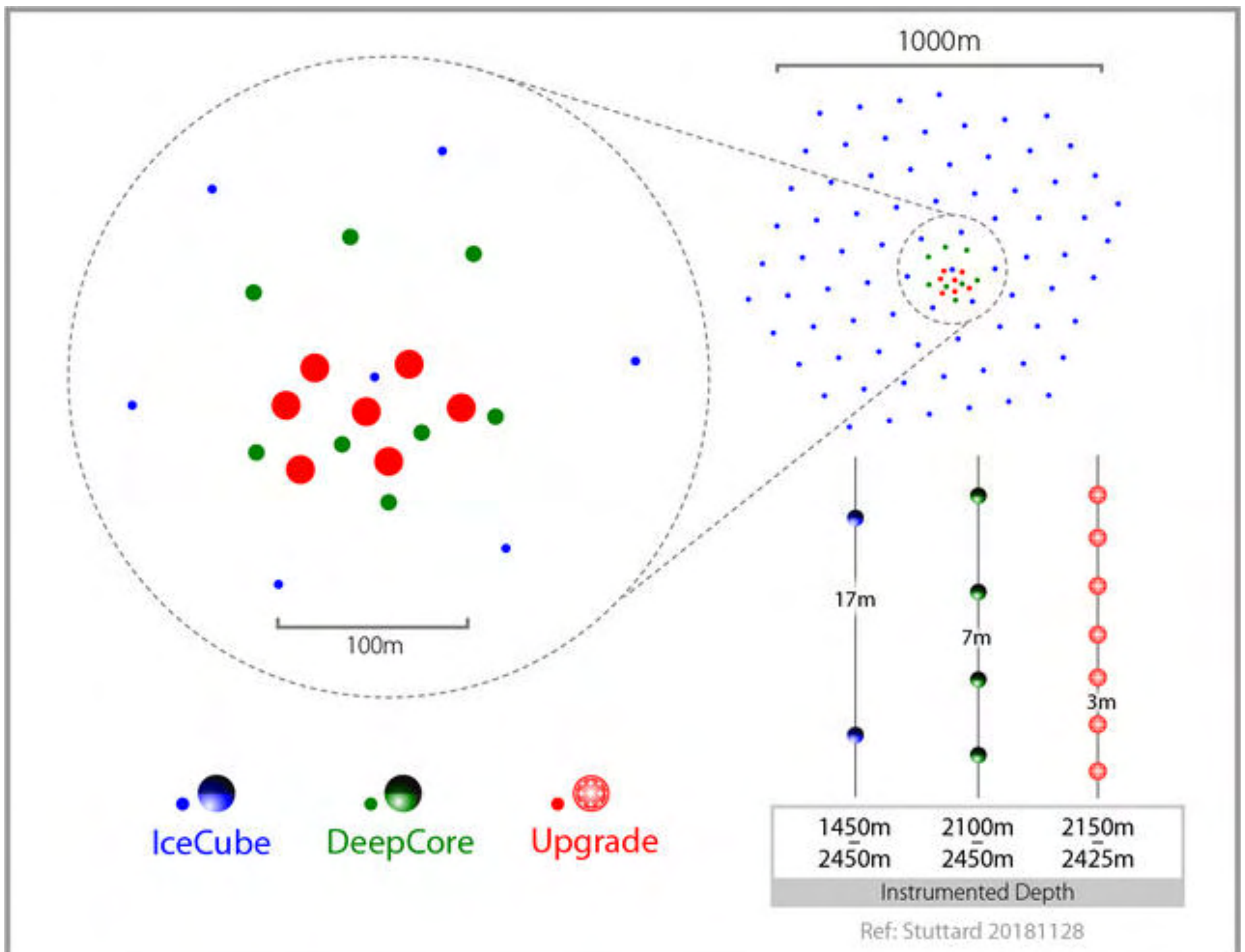


- Combination of IceCube + SK is natural since they use the same target and flux.
- IceCube can constrain the atmospheric parameters better, but SK brings enhanced sensitivity to ordering, octant, and CP-phase.

CA, P. Fernandez, I. Martínez-Soler, and M. Jin *to appear soon*

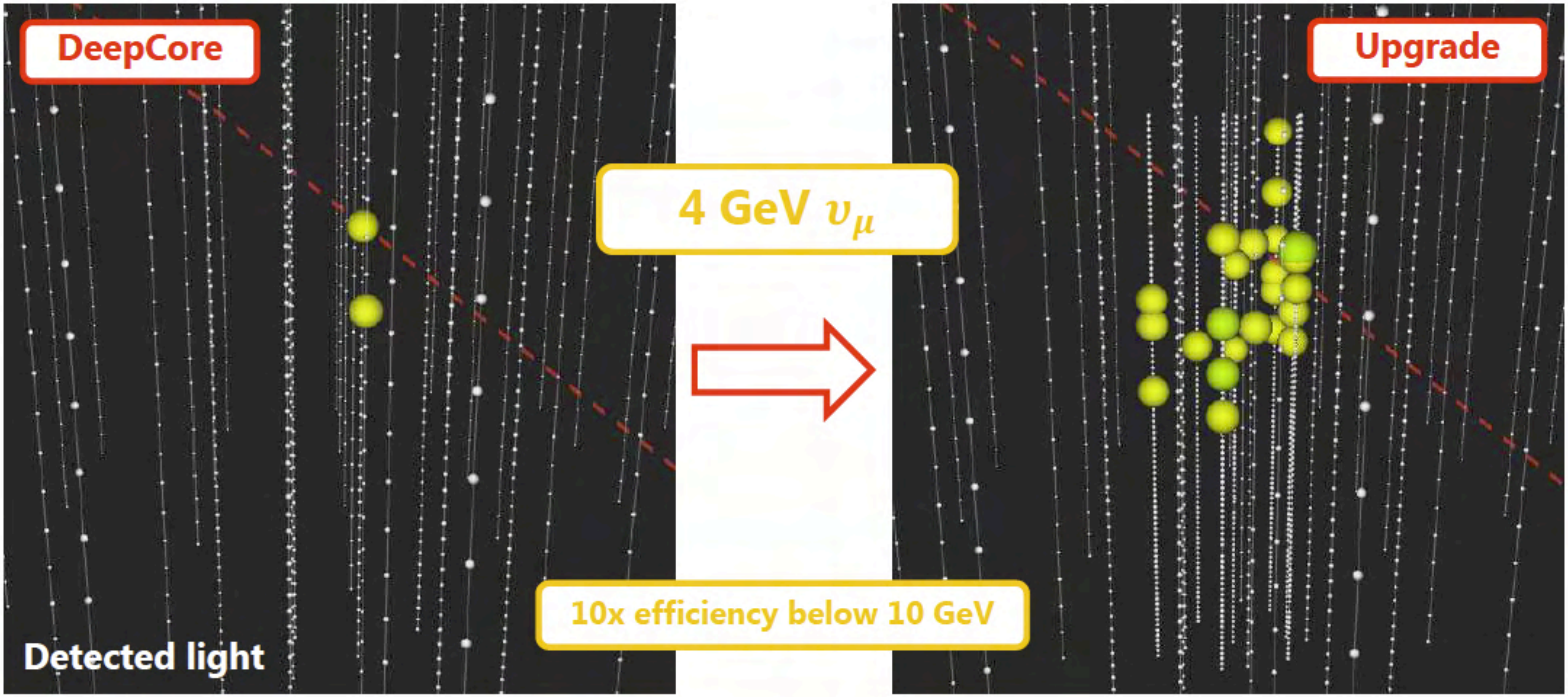
That potential is growing: The Upgrades

Phase 1: 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2024-2026.



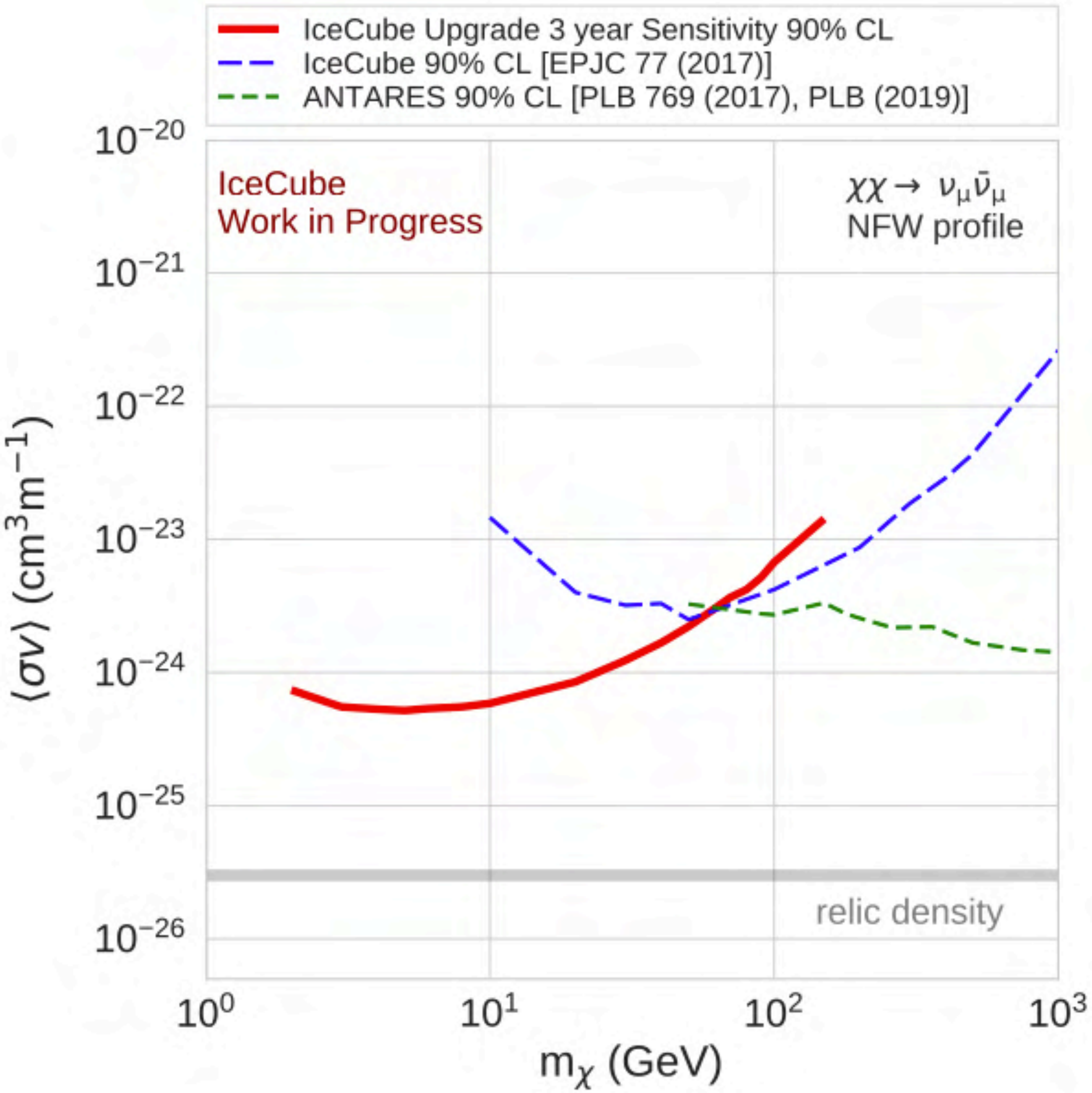
New detector technologies.
Better low energy reconstruction.
Improved flavor identification.

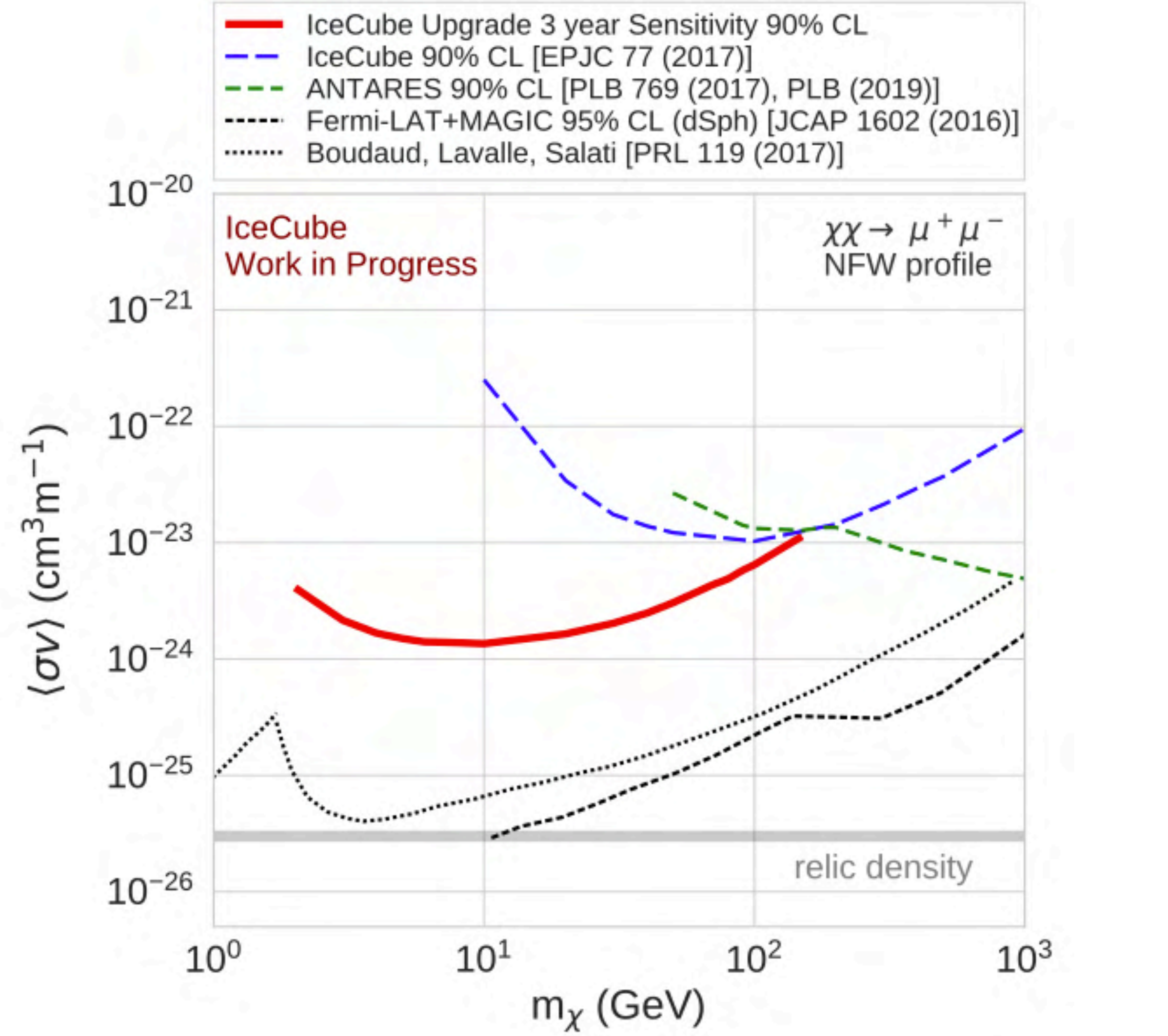
Improved light-collection for low-energy events

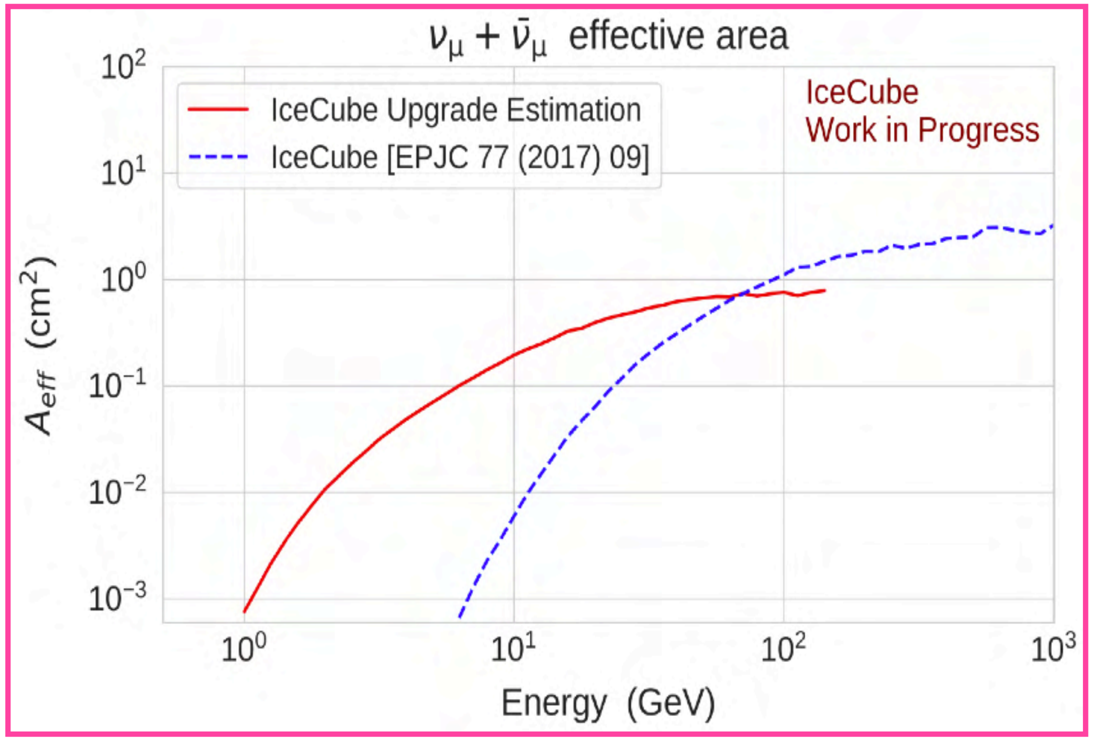


*DeepCore (shown on the left) is the current low-energy extension of IceCube

IceCube-Upgrade DM Sensitivity

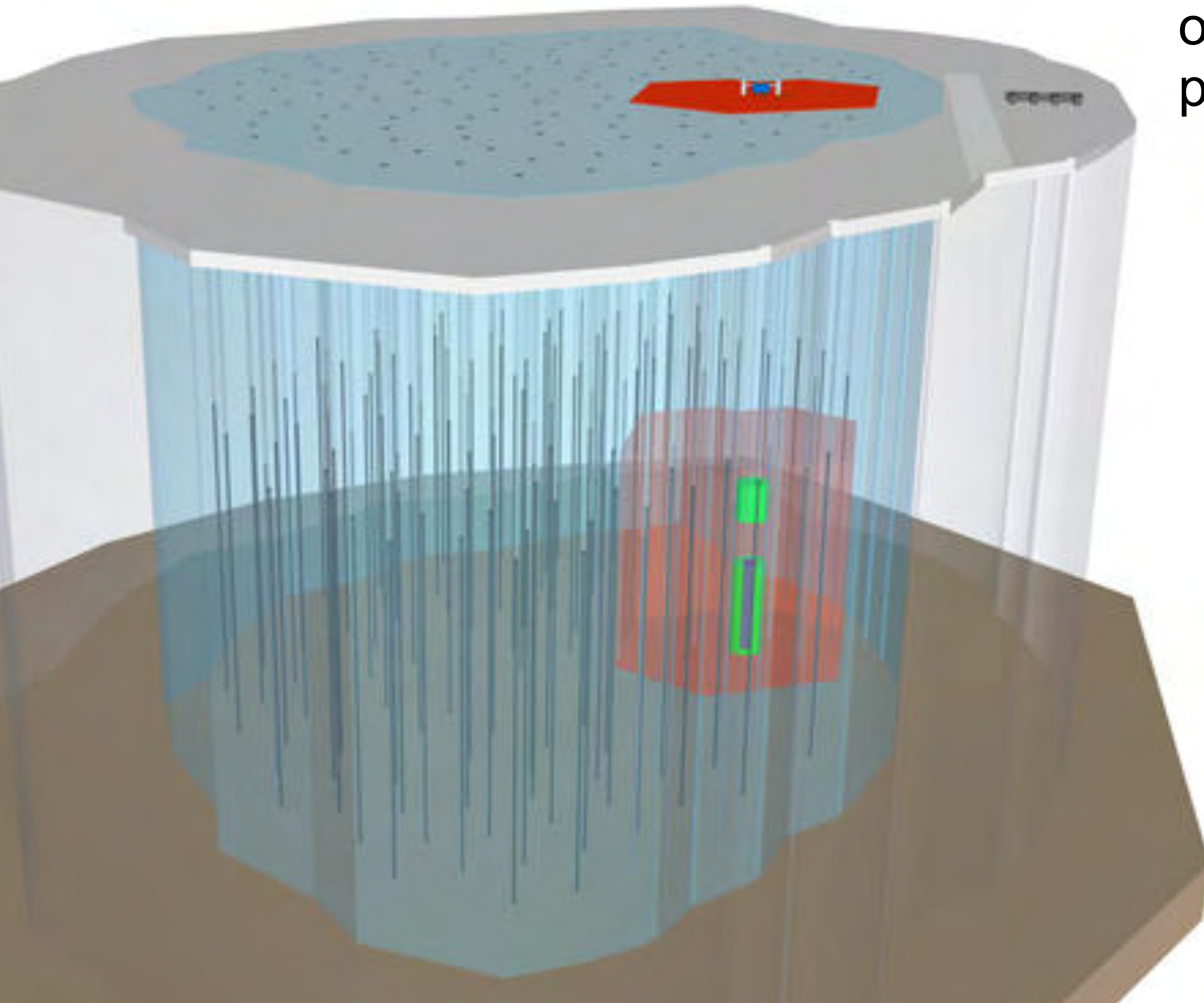






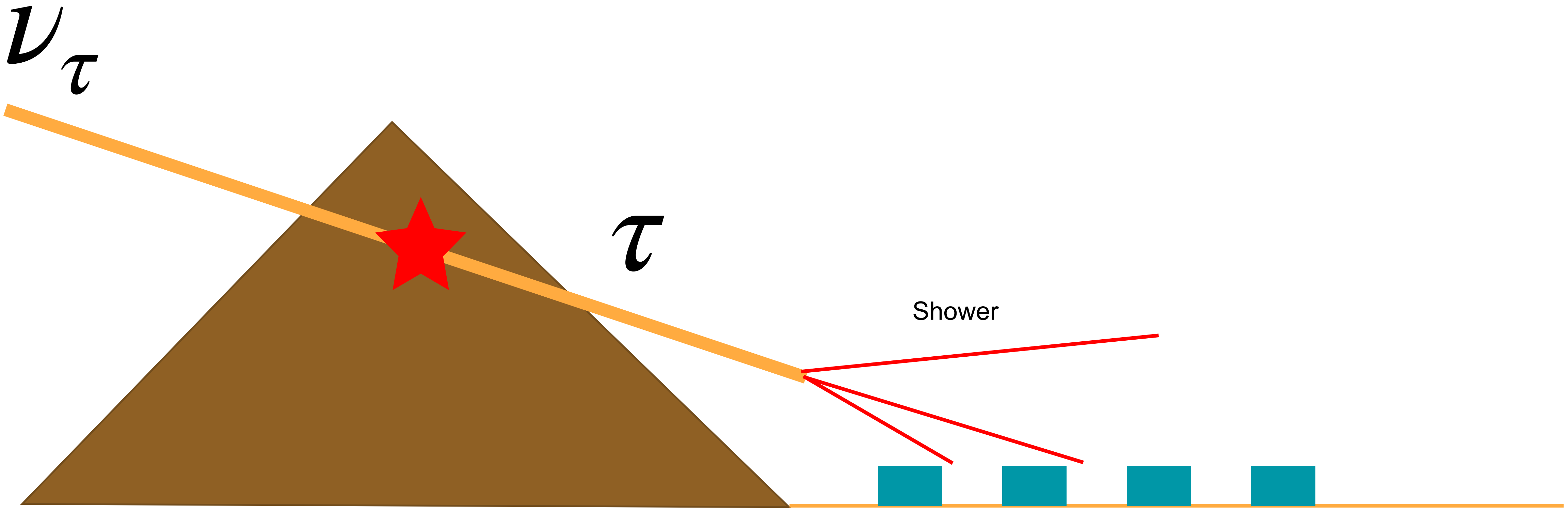
S. Baur arXiv:1908.08236

That potential is growing: The Upgrades



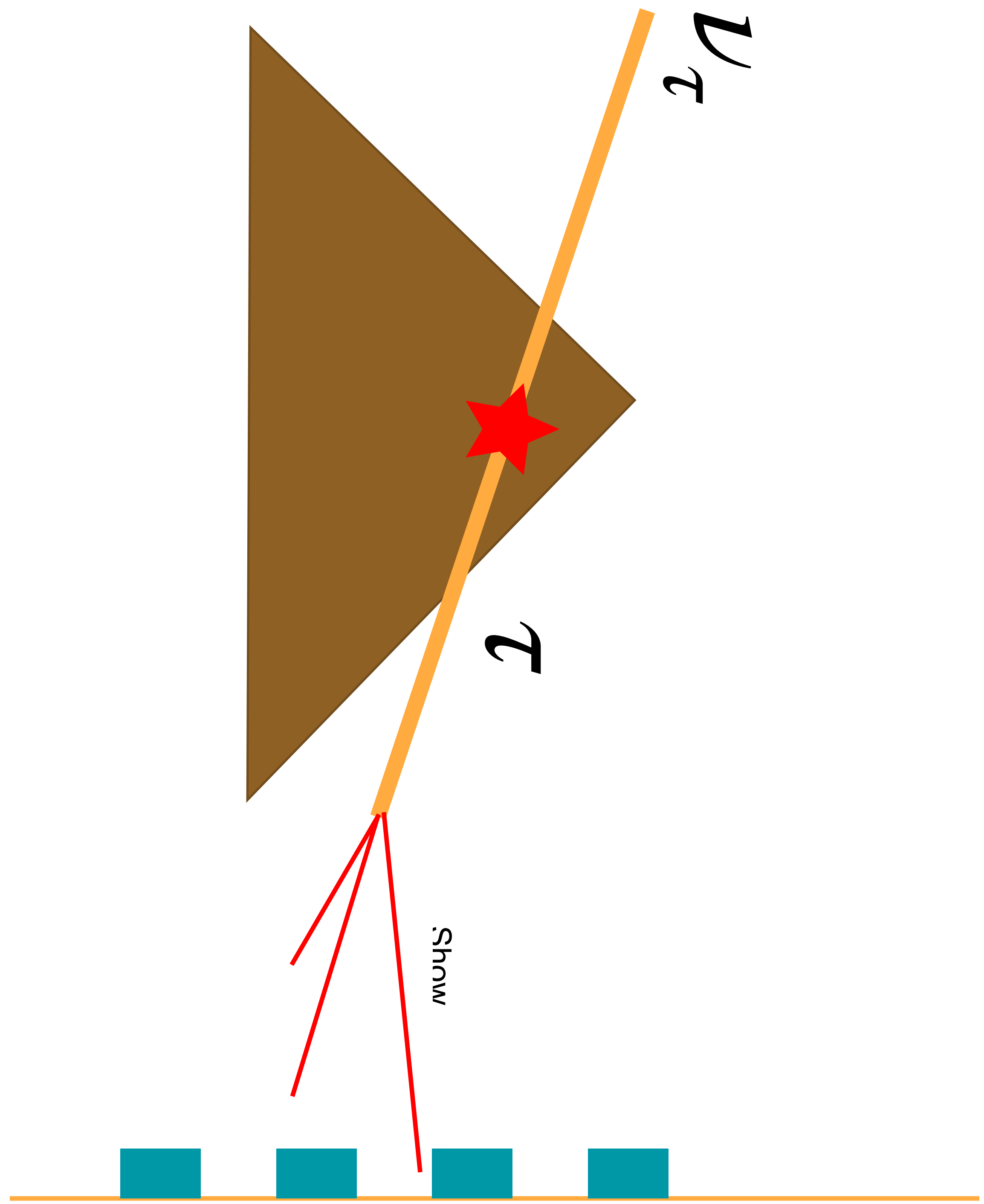
Phase 2: x10 the volume of present IceCube, plus additional detectors.

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

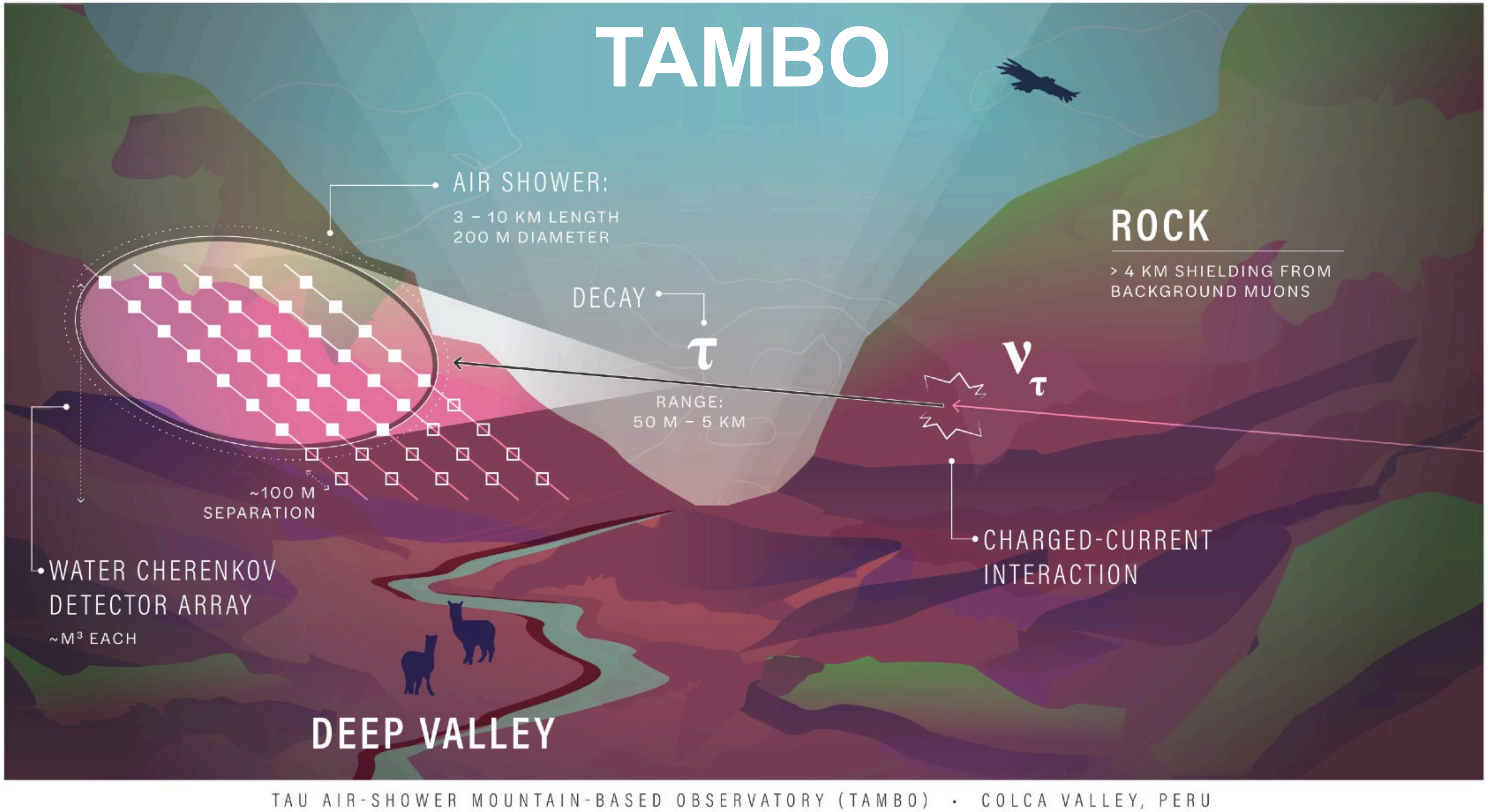
Thinking about Earth-skimming neutrino detectors

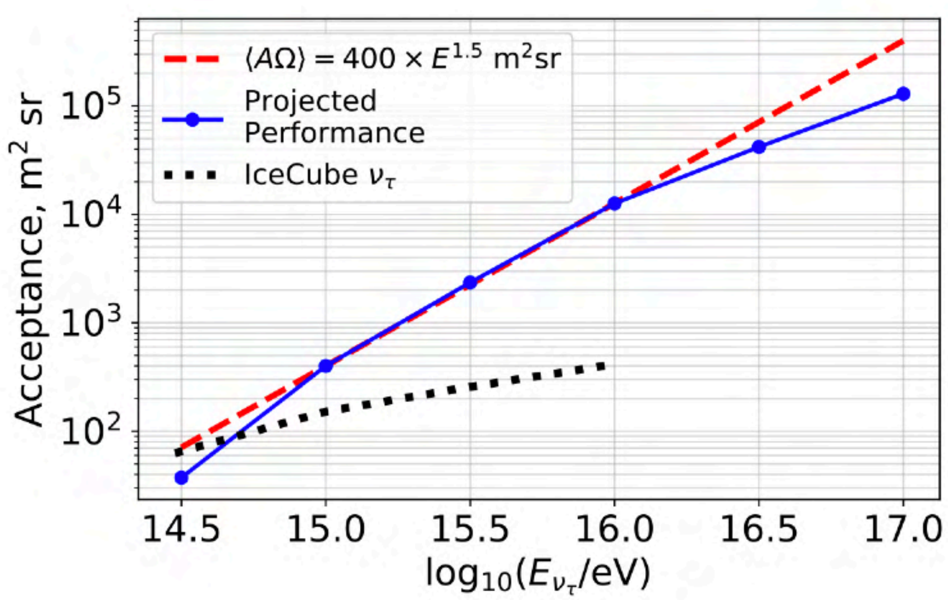


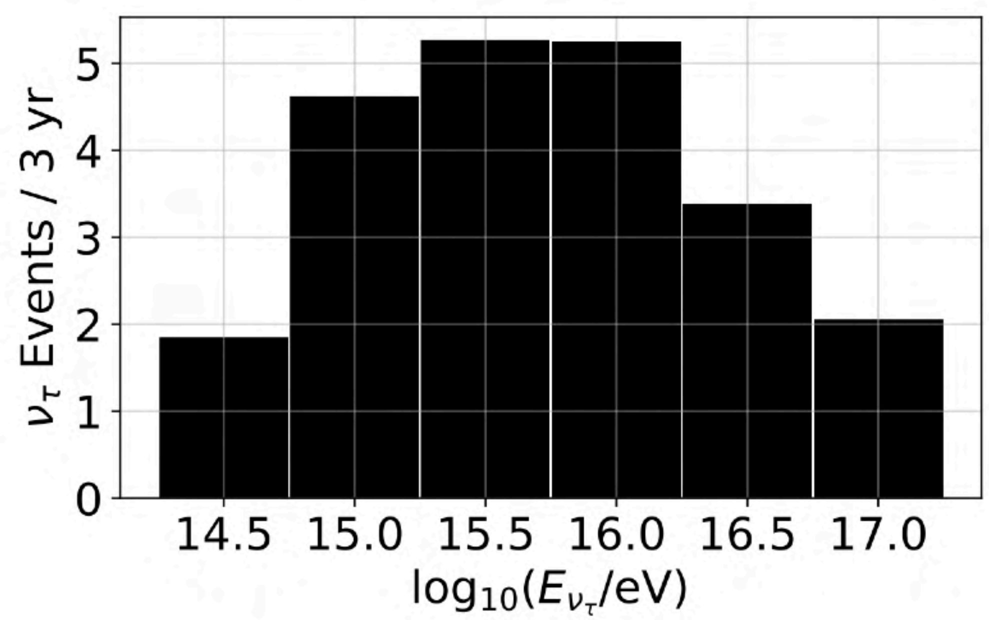
The geometry here is key for the acceptance of neutrino detection

This would be a more ideal scenario, but can’t put mountain over detector

TAMBO



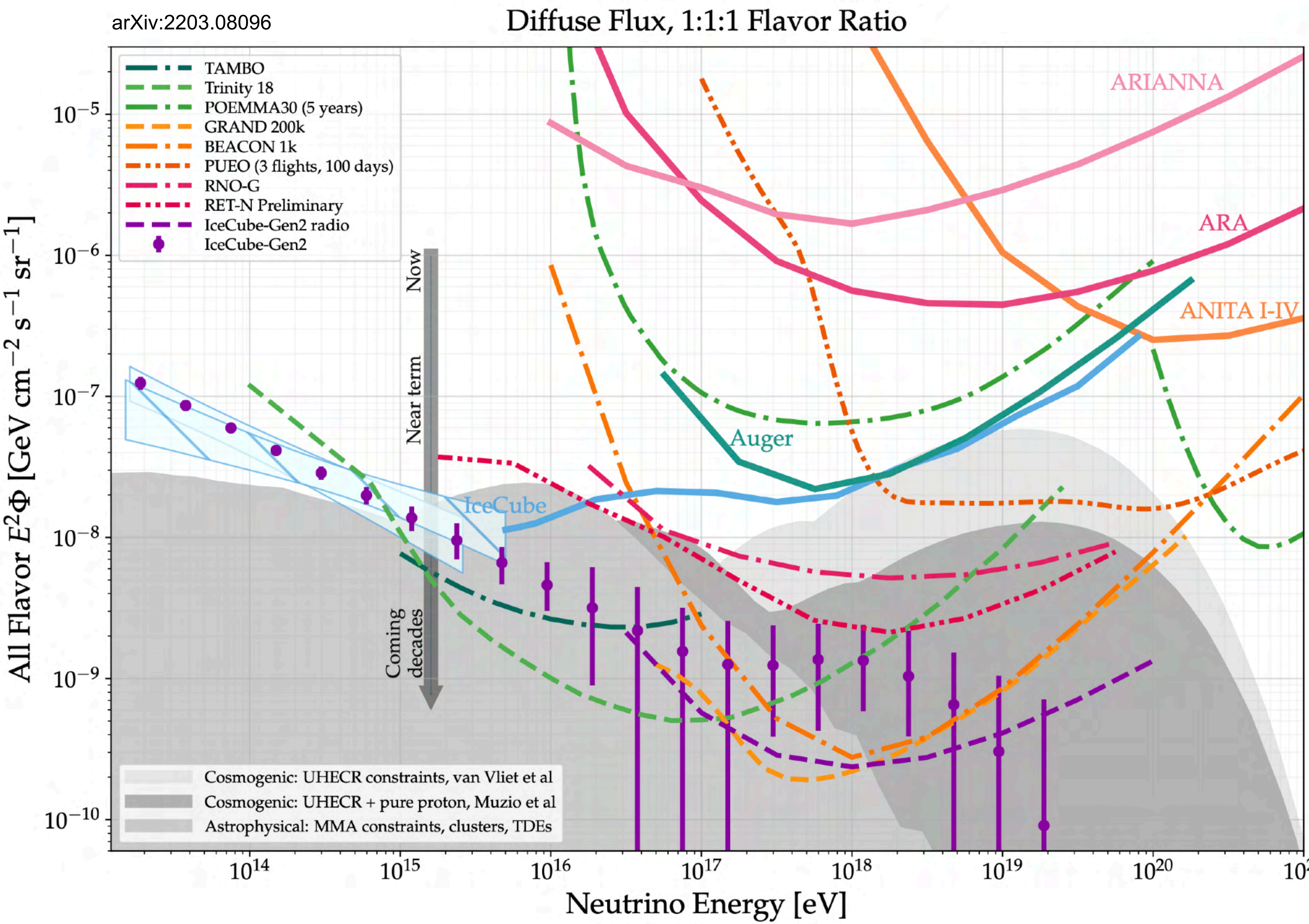




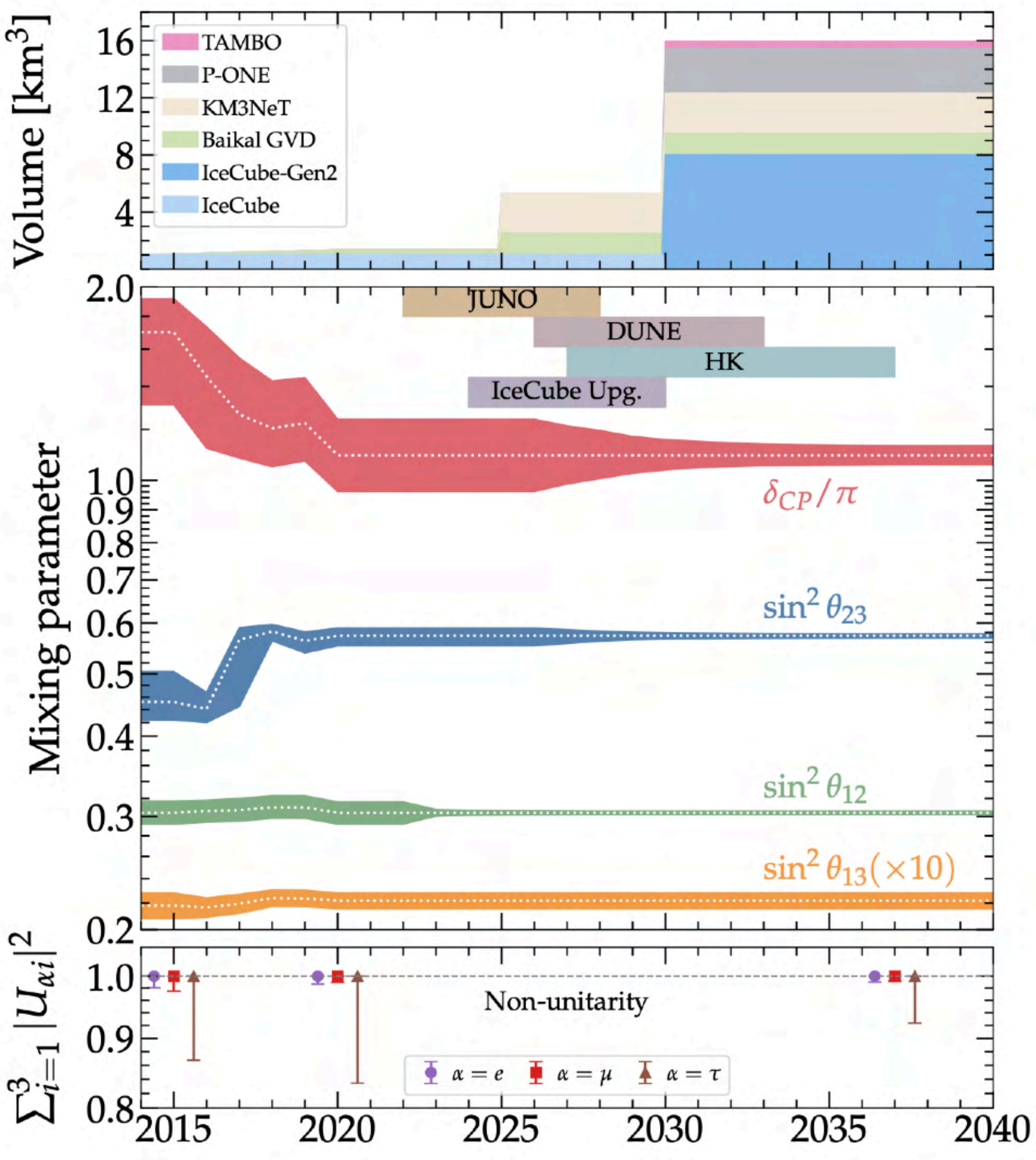
Romero-Wolf *et al* https://arxiv.org/abs/2002.06475

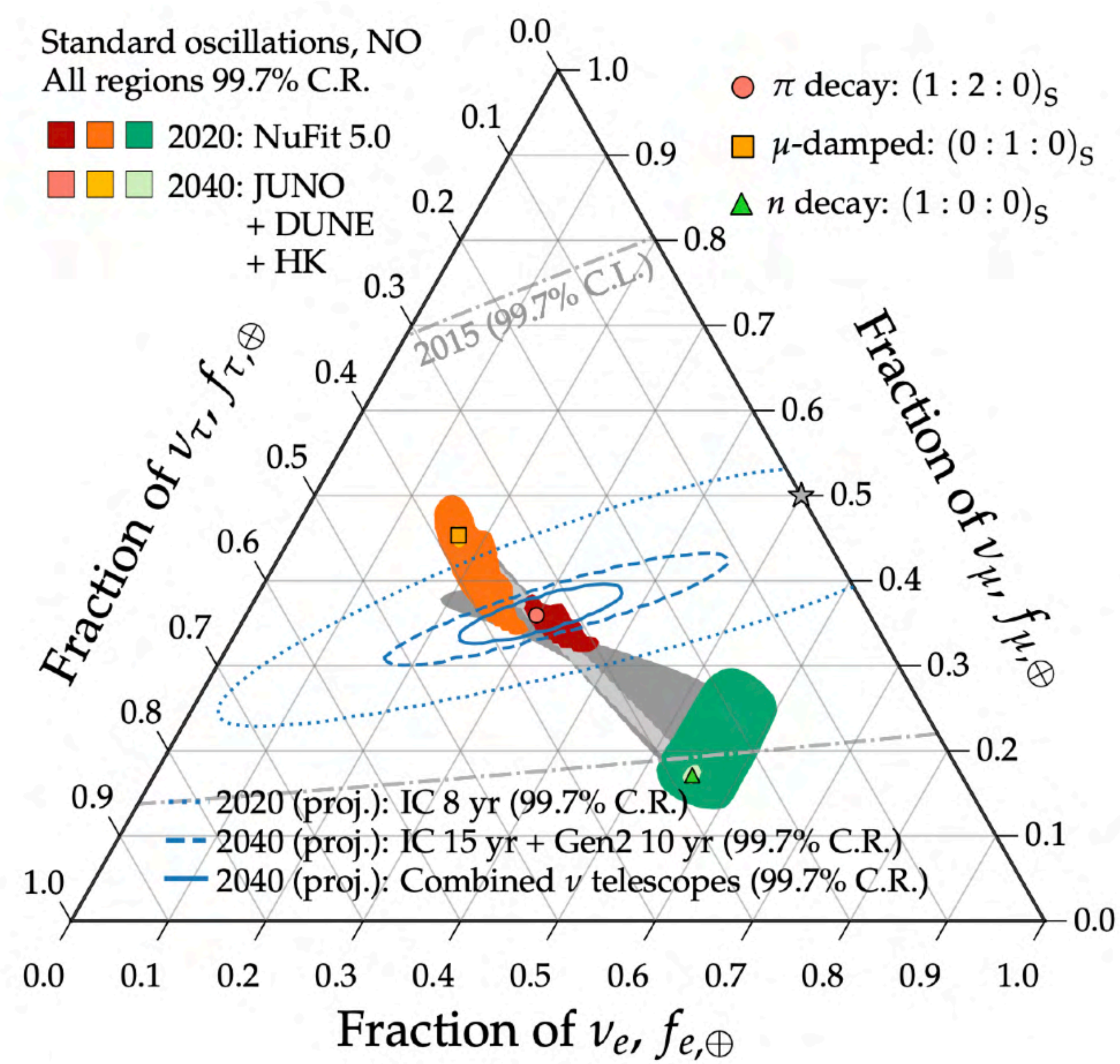
Next Generation Experiments Flux Sensitivity

arXiv:2203.08096



Projected Upgrade Flavor Measurement





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

Conclusion

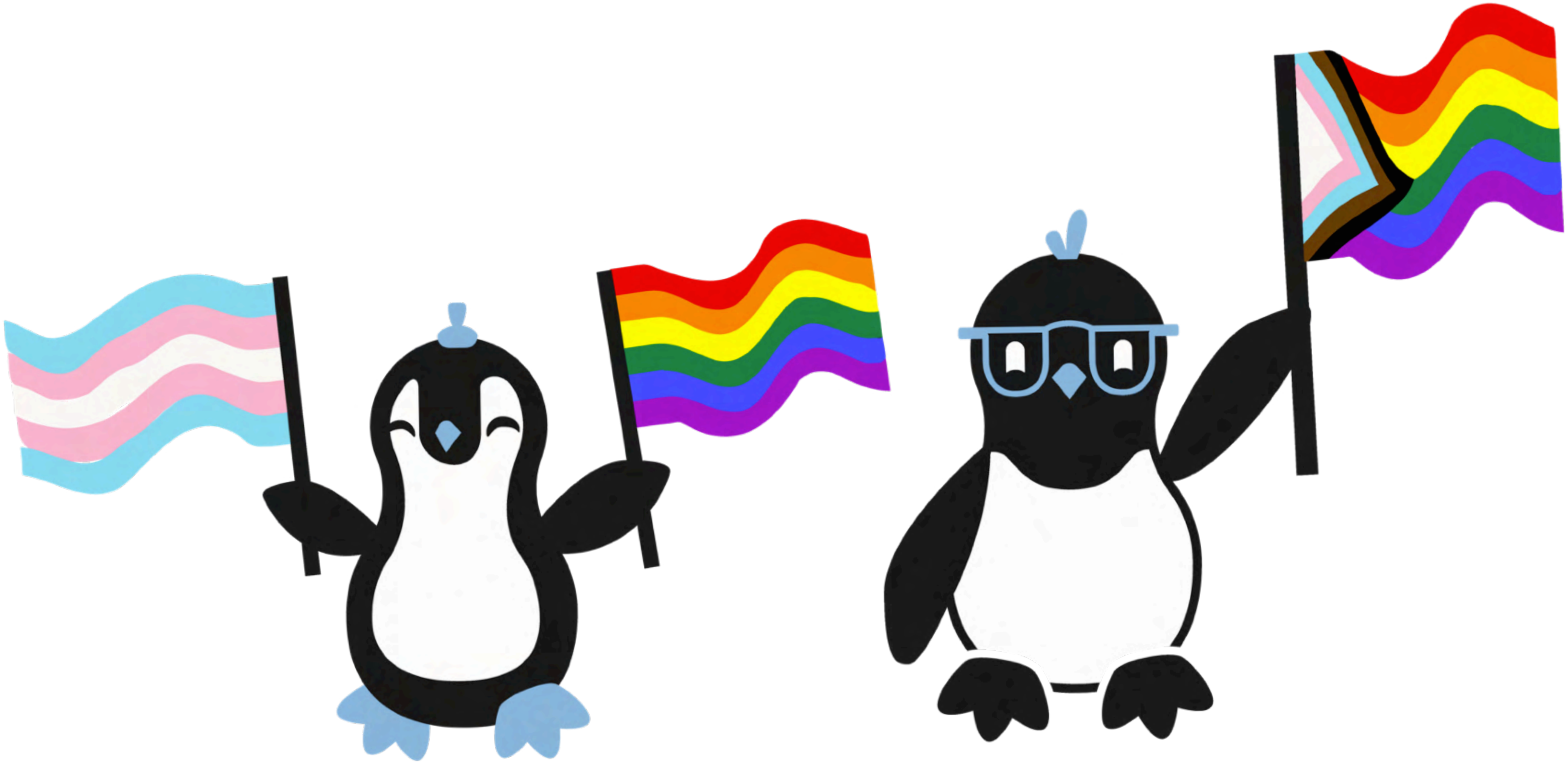
Neutrino Physics is truly in the midst of interesting times:

✤We have persistent oscillation anomalies to pursue.
✤We have the Dark Matter problem that may be related to neutrinos.
✤We have reached extreme regimes that lets us explore into the Planck scale.

We also have great possibilities for the future:

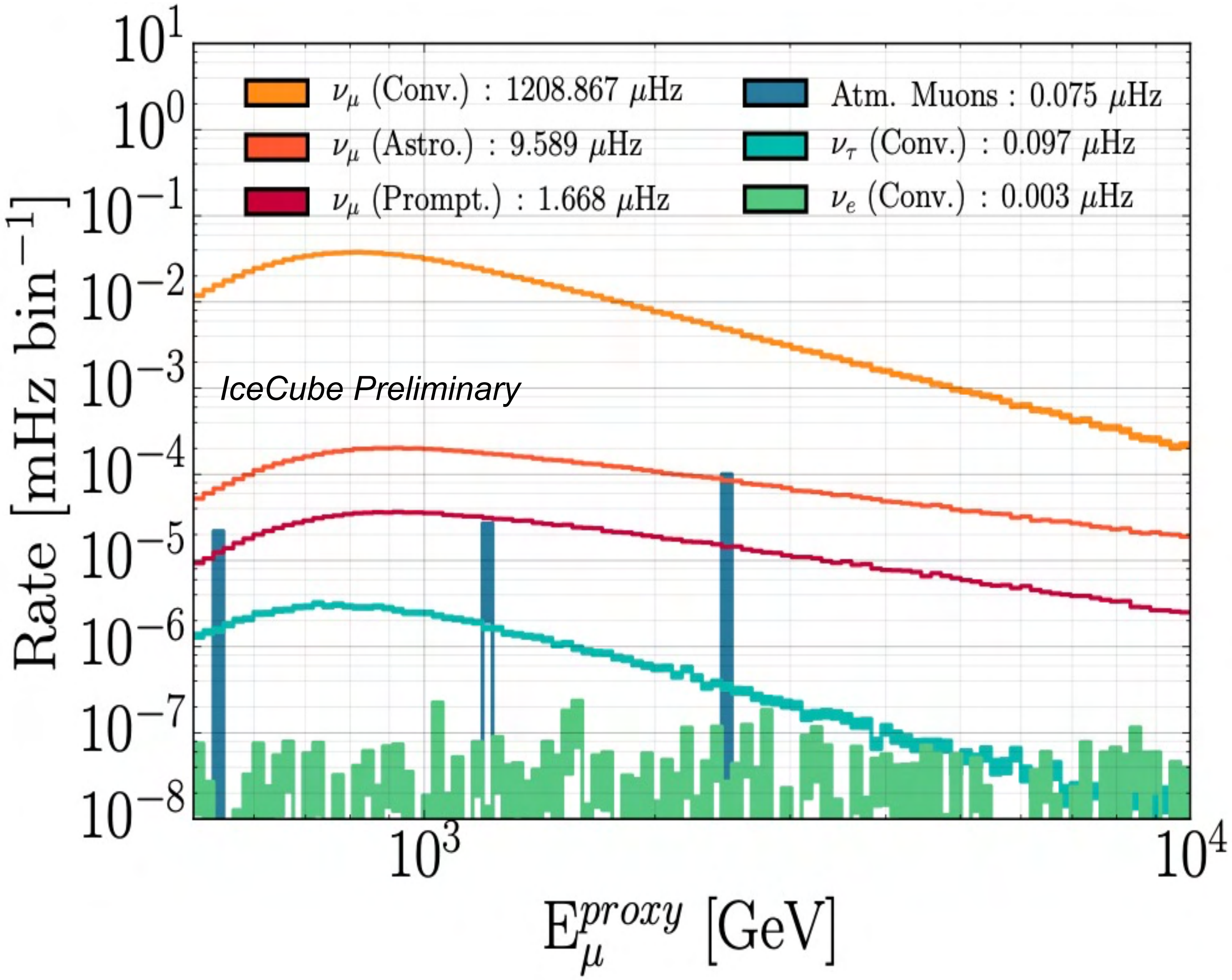
✤With IceCube we have a rich data set for continued searches.
✤With the IceCube Upgrade we will have great new precision.

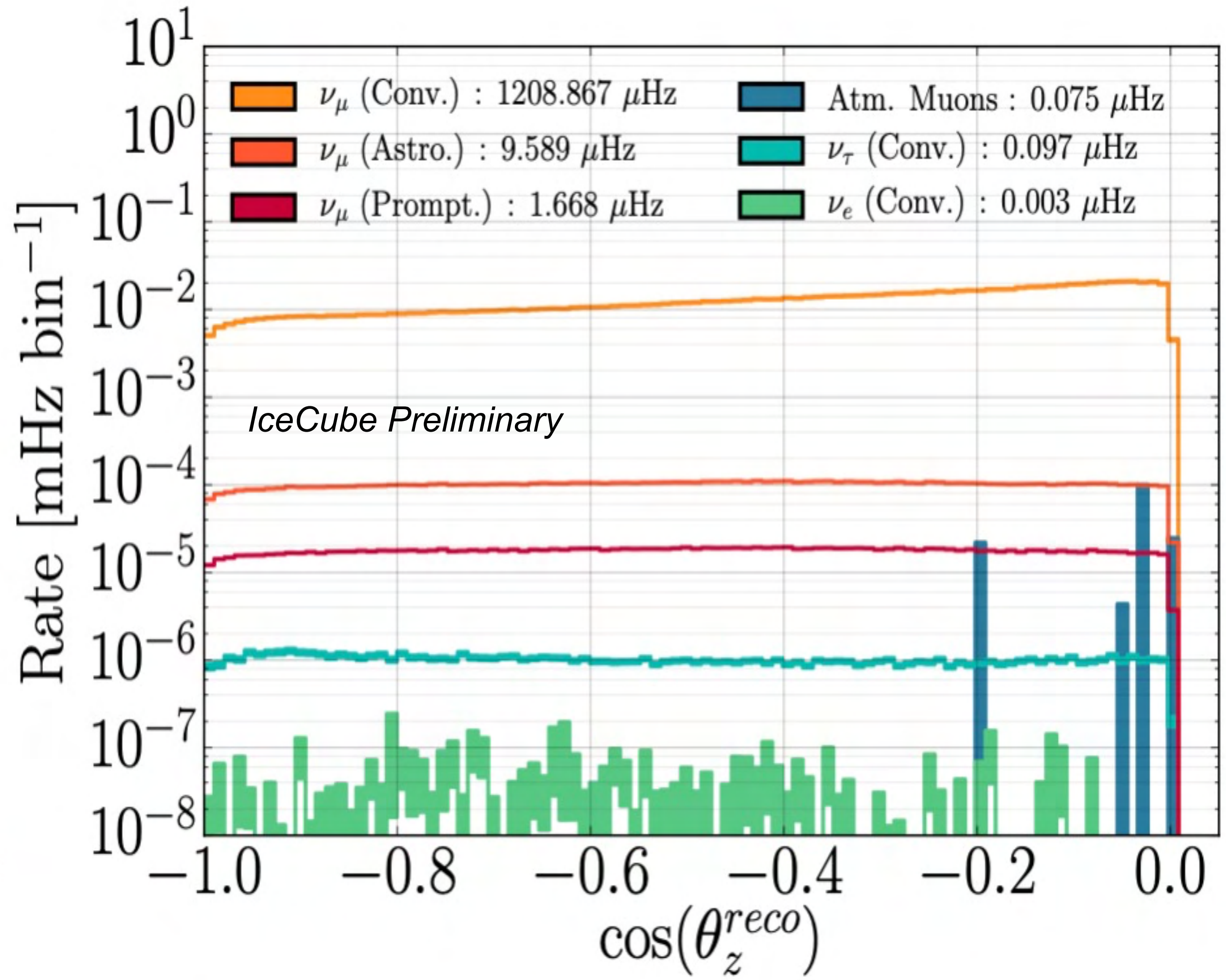
Thanks!



Bonus slides

Improved event selection:
13x stats of the 1-year analysis.





❖**Large dataset:** 315,000 events predicted for 7.6 years livetime

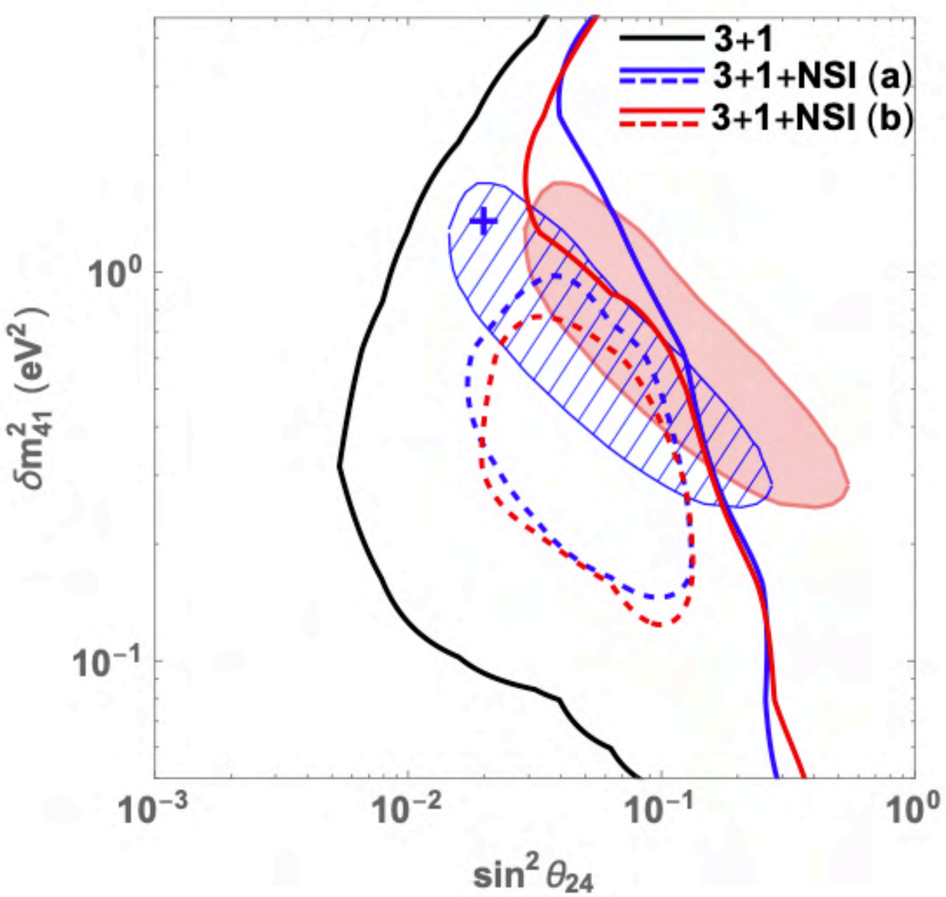
❖**Low muon contamination:** < 0.1%

Non-Standard Matter Effects (3+1+NSI)

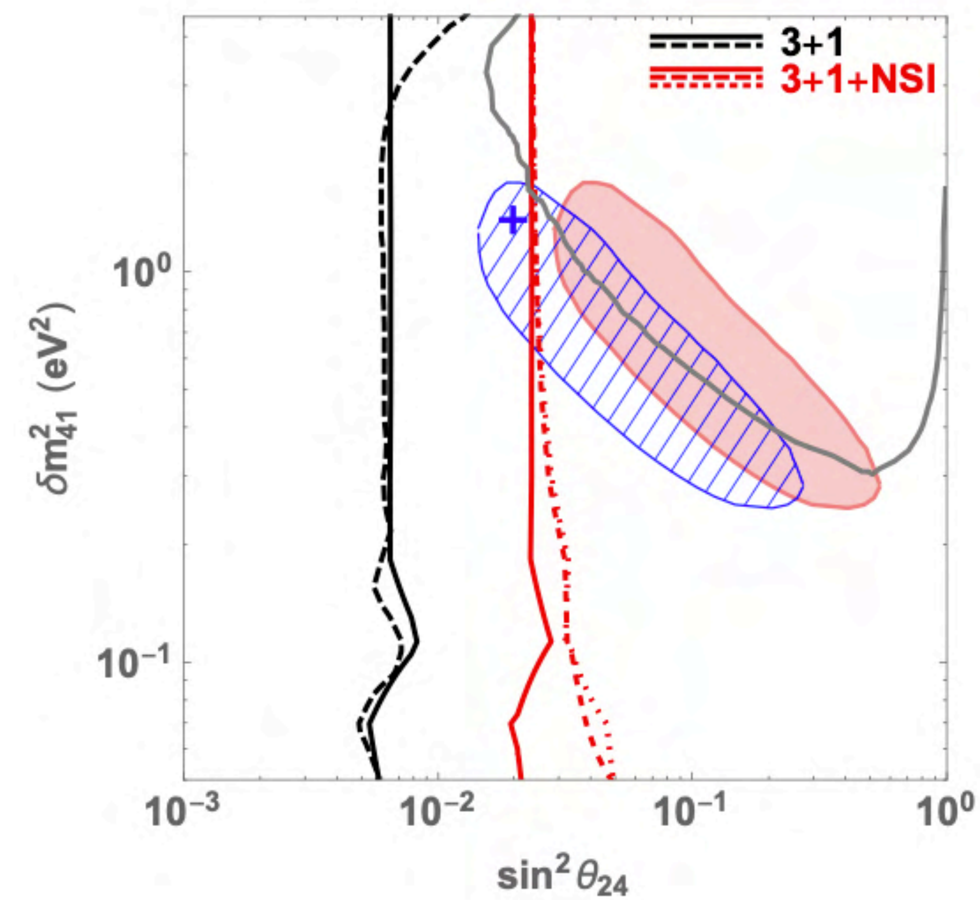
J. Liao et al

A. Esmaili et al https://arxiv.org/abs/1810.11940

IceCube modified by NSI



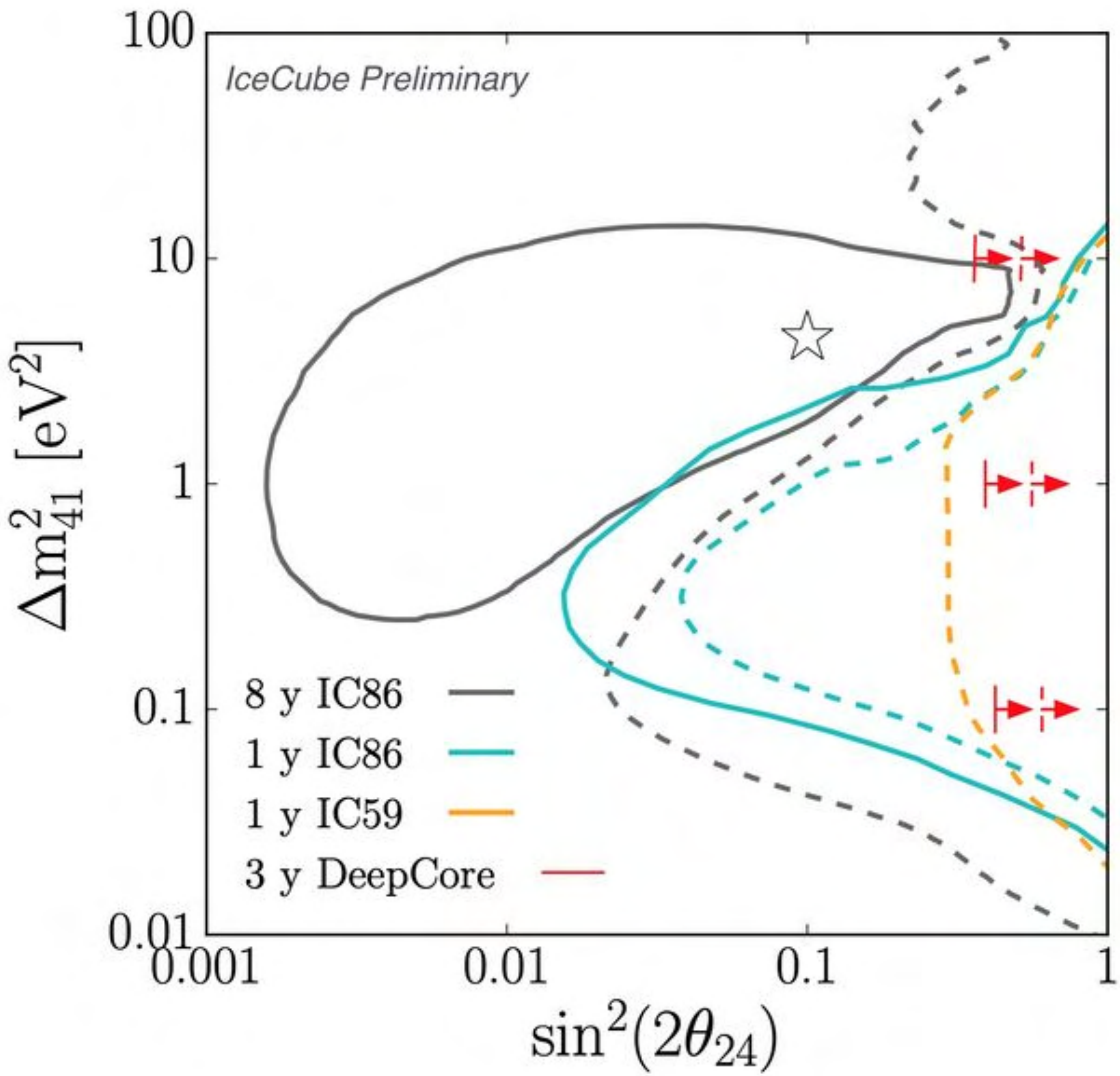
MINOS modified by NSI



See also Denton et al
Bhupal Dev et al

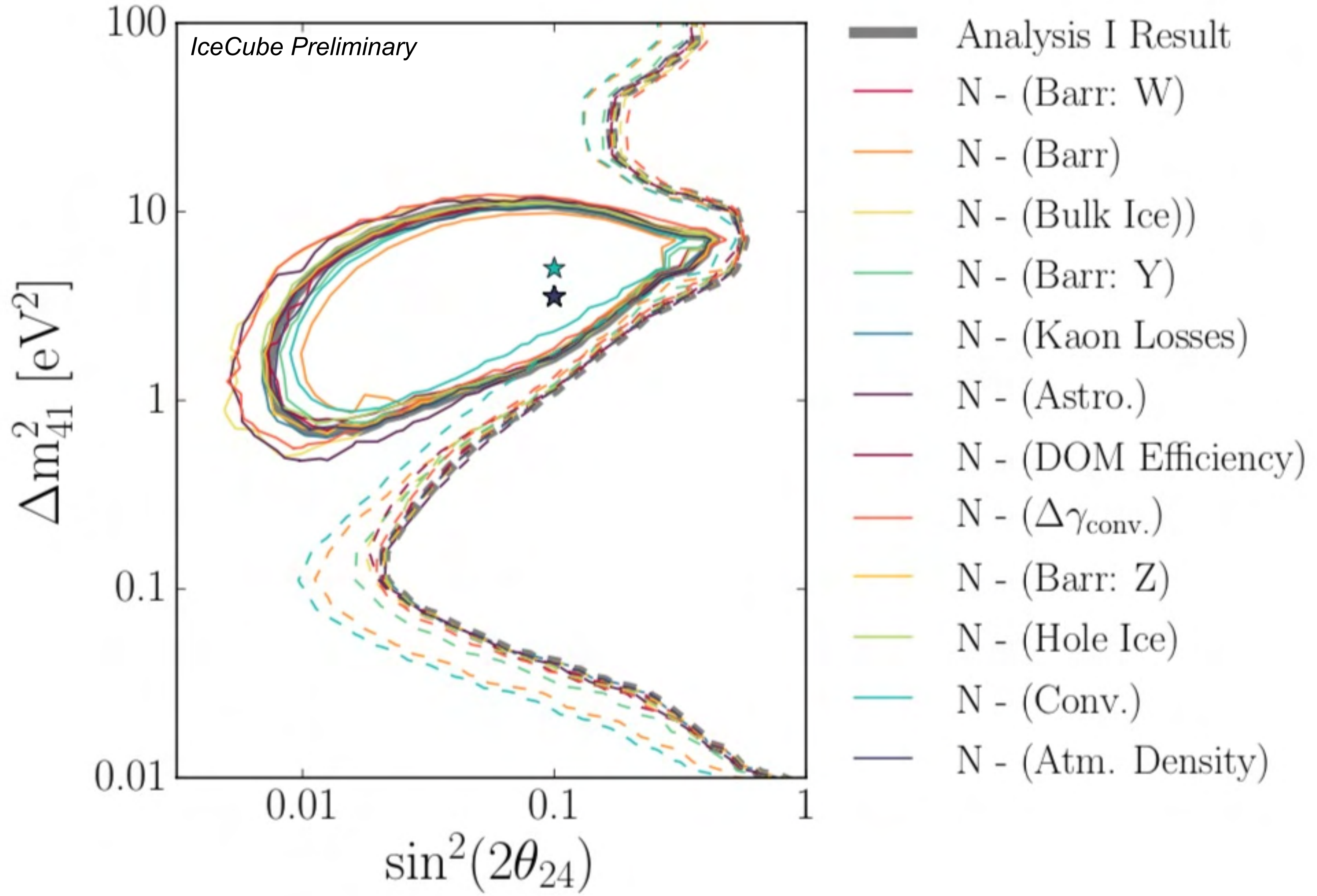
Direct Probes of Matter Effects In Neutrino Oscillations
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)

All IceCube's sterile neutrino results



- ❖90% CL: solid
- ❖99% CL: dashed
- ❖DeepCore results use energies: < 100 GeV.

Impact of the systematic uncertainties on our new result



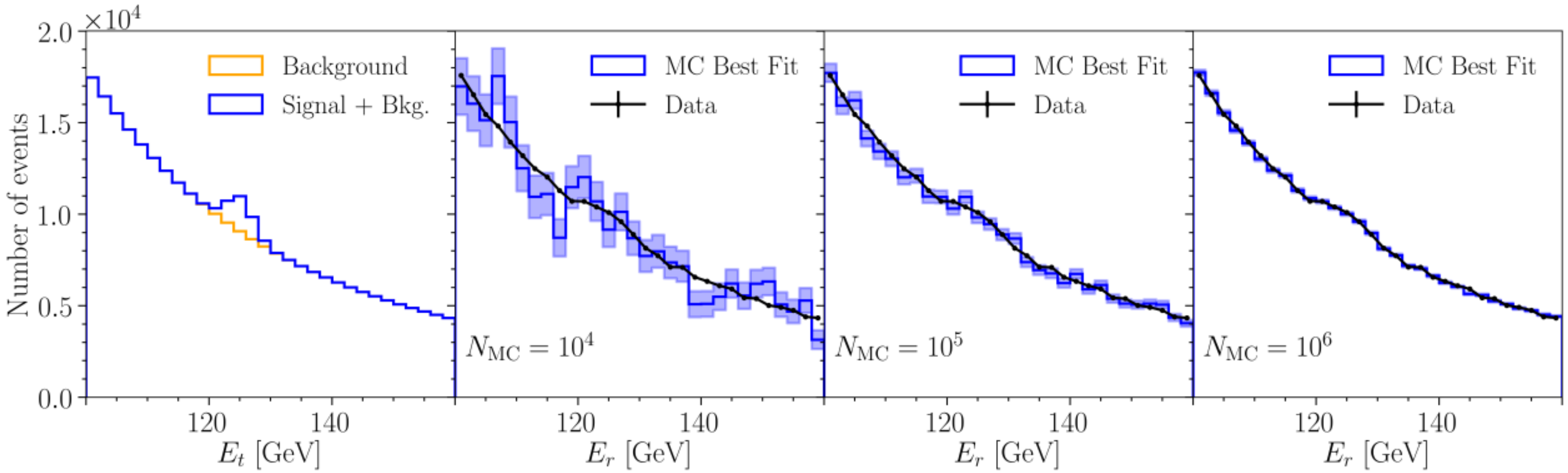
We remove one systematic uncertainty at a time and redo the analysis to assess how relevant each systematic was to the analysis.

Systematics Overview

	Systematic	Central value	Prior width (1σ)	Range
Conventional Atmospheric Neutrino Flux	Conventional norm	1	0.4	--
	CR spectral index	0	0.03	--
	Atmospheric density	0	1	--
	Barr WM	0	0.4	-0.5 – 0.5
	Barr WP	0	0.4	-0.5 – 0.5
	Barr YM	0	0.3	-0.5 – 0.5
	Barr YP	0	0.3	-0.5 – 0.5
	Barr ZM	0	0.12	-0.2 – 0.5
	Barr ZP	0	0.12	-0.2 – 0.5
	Kaon E loss	1	0.05	
Astrophysical Neutrino Flux	Astro norm	1	0.36	--
	Astro spectral index	0	0.36	--
Neutrino Cross Sections	Neutrino xs	1	0.03	0.5 – 1.5
	Antineutrino xs	1	0.075	0.5 – 1.5
IceCube Detector	IceGradient0	0	1	--
	IceGradient1	0	1	--
	Hole Ice	-1	10	-5.0 – 2.0
	DOM efficiency	0.97	0.1	0.92 – 1.03

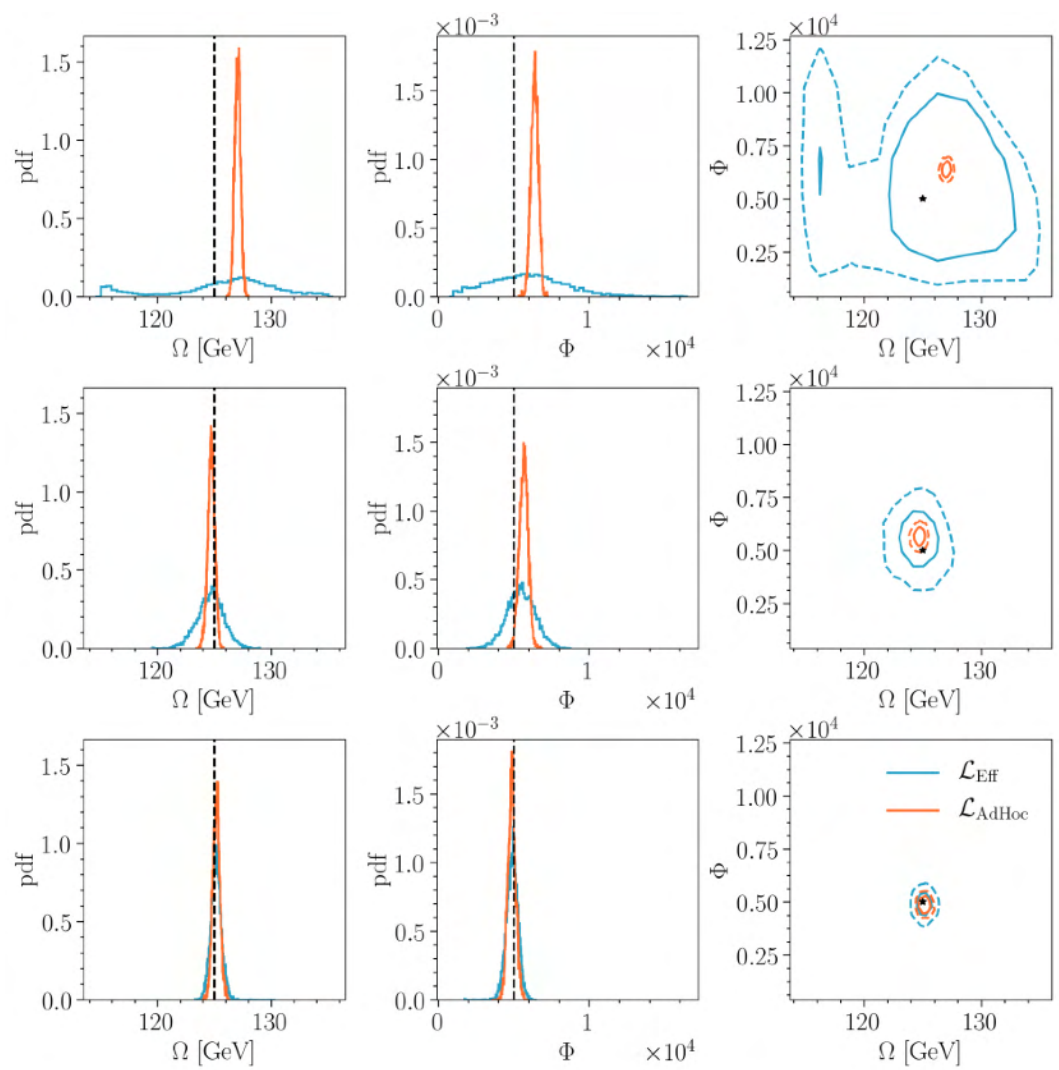
Each source of uncertainty has been parameterized and included as a nuisance parameter in the likelihood problem.

Improved statistical treatment to account for Monte Carlo statistical uncertainties



Various ideas in the literature:

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

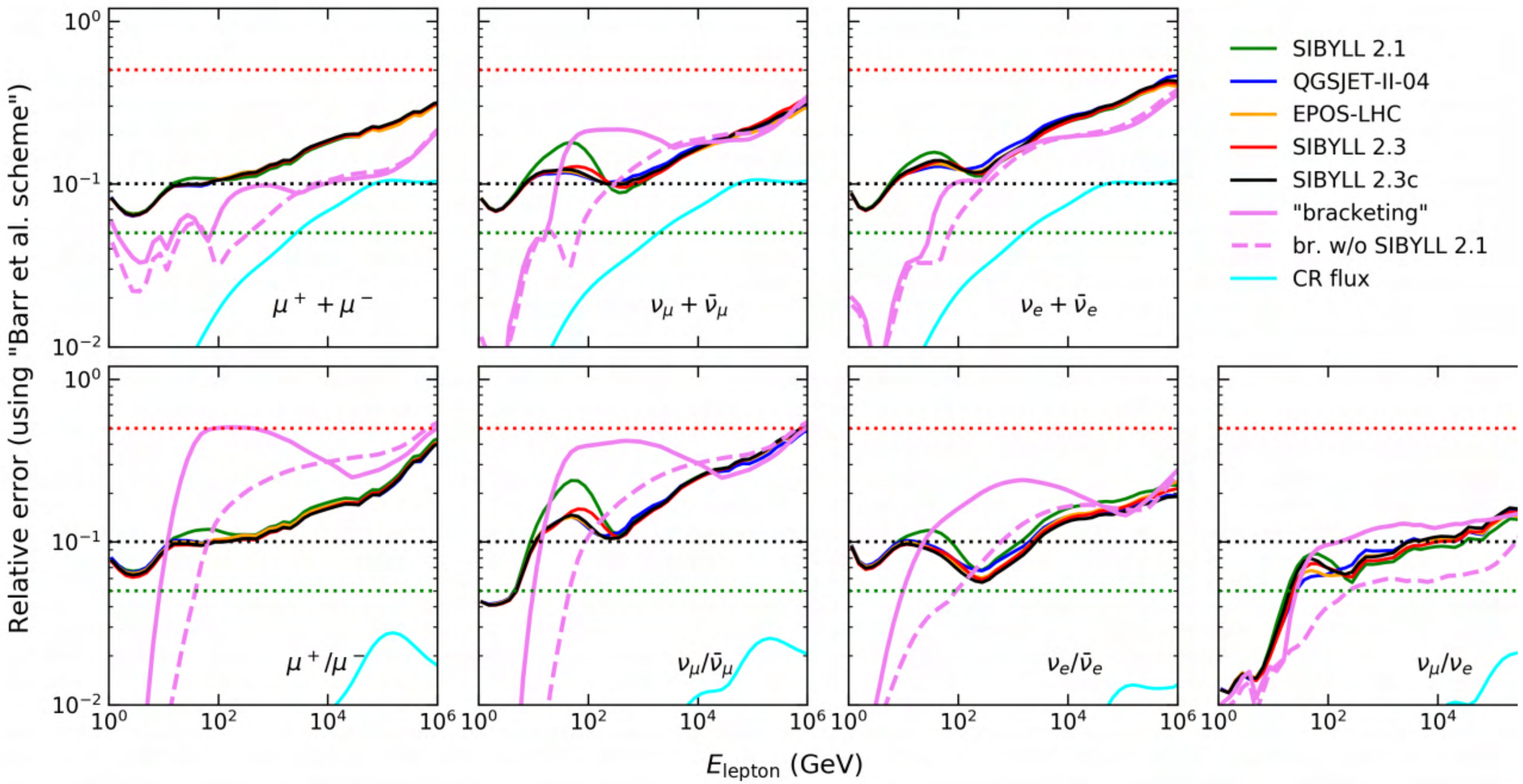


$$\mathcal{L}_{\rm General}(\vec{\theta}|k) = \int_0^\infty \frac{\lambda^k e^{-\lambda}}{k!} \mathcal{P}\left(\lambda|\vec{w}(\vec{\theta})\right)\, d\lambda$$

Parameters	$\mu \equiv \sum_{i=1}^m w_i,\ \sigma^2 \equiv \sum_{i=1}^m w_i^2$
$\mathcal{L}_{\rm AdHoc}$	$\frac{\mu^k e^{-\mu}}{k!}$
$\chi^2_{\rm mod}$	$\frac{(k-\mu)^2}{\mu+\sigma^2}$
$\mathcal{L}_{\rm BB}^{s=1}$	$\max_{\bar{m}} \left\{ \frac{1}{k!m!} \left(\frac{\mu \bar{m}}{m}\right)^k \bar{m}^m e^{-\frac{\mu\bar{m}}{m} - \bar{m}} \right\}$
$\mathcal{L}_{\rm Mean}$	$\left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}} \Gamma\left(k + \frac{\mu^2}{\sigma^2}\right) \left[k! \left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}} \Gamma\left(\frac{\mu^2}{\sigma^2}\right)\right]^{-1}$
$\mathcal{L}_{\rm Eff}$	$\left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}+1} \Gamma\left(k + \frac{\mu^2}{\sigma^2}+1\right) \left[k! \left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}+1} \Gamma\left(\frac{\mu^2}{\sigma^2}+1\right)\right]^{-1}$

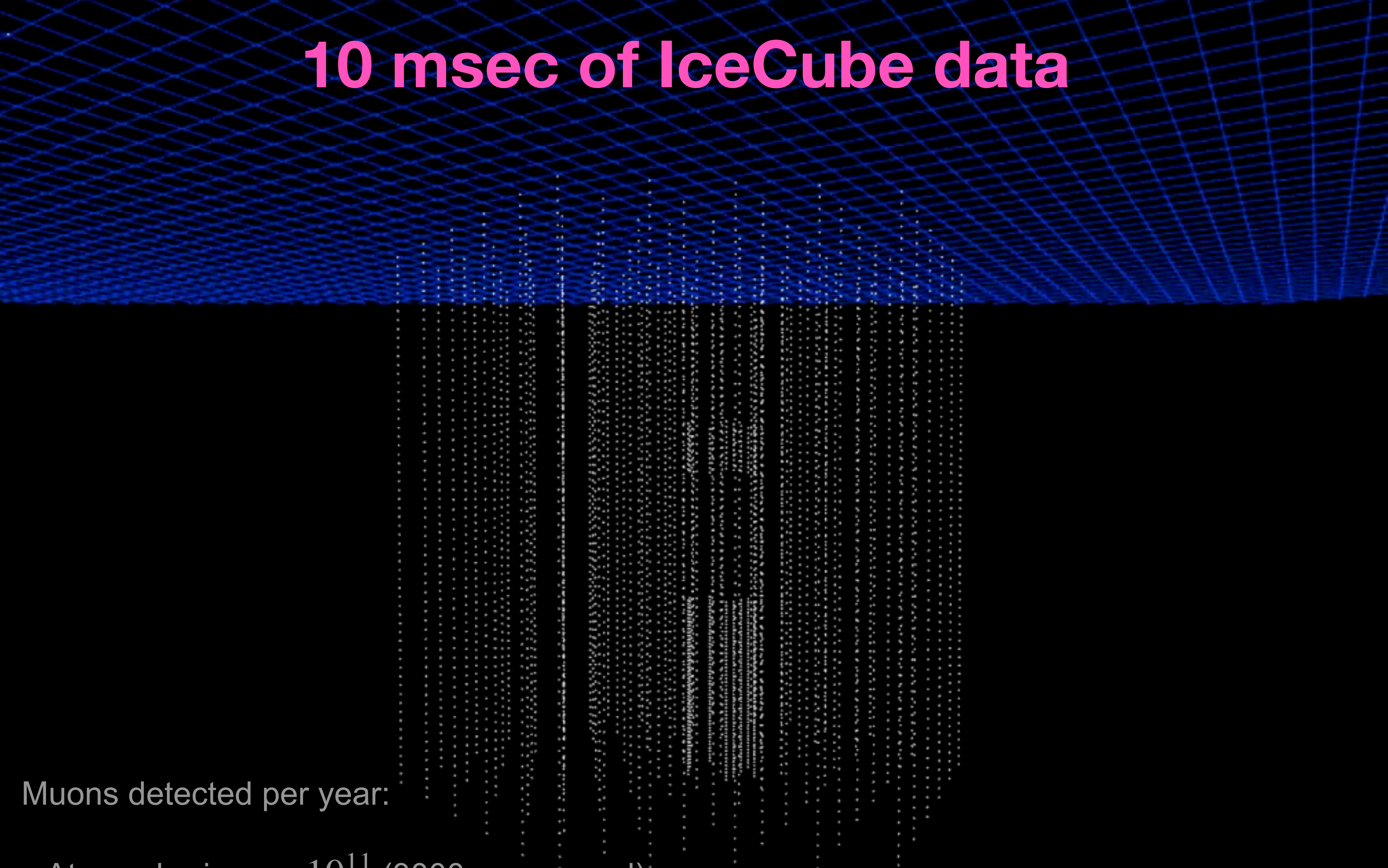
CA, A. Schneider, T. Yuan, arXiv:1901.04645

Improved treatment of atmospheric flux uncertainties



Fedynitch et al. arXiv:1806.04140
Fedynitch PANE2018.

10 msec of IceCube data

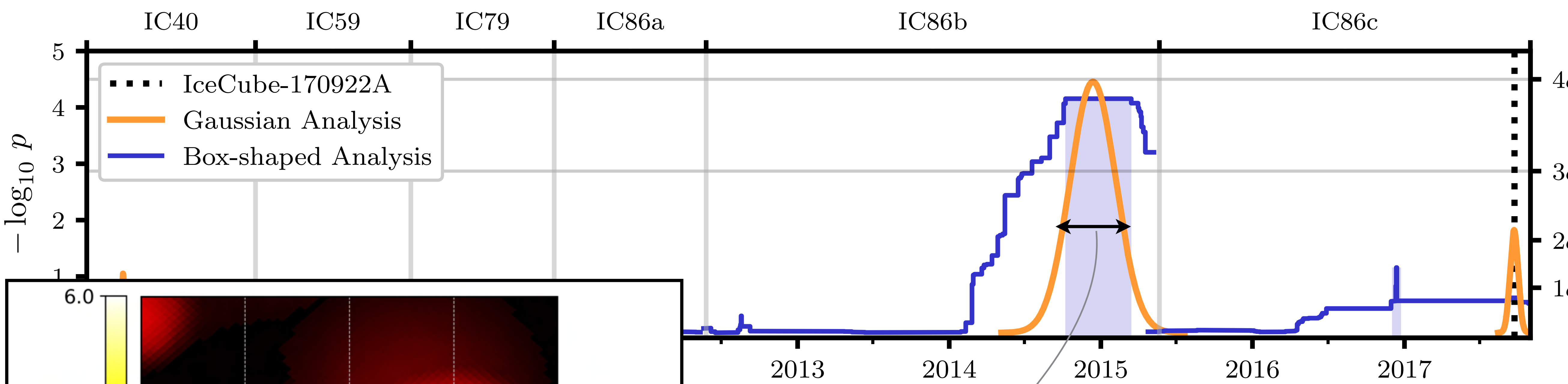


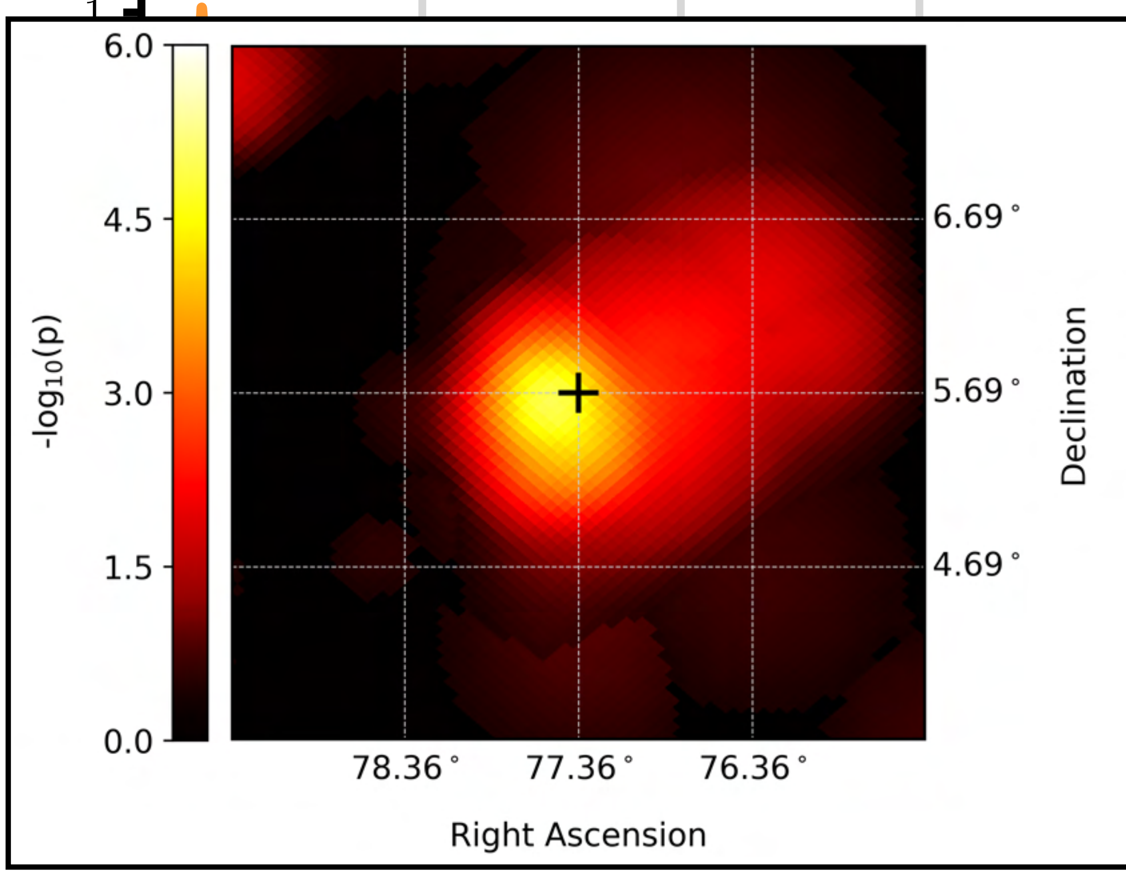
Muons detected per year:

- Atmospheric $\mu \sim 10^{11}$ (3000 per second)
- Atmospheric* $\nu \to \mu \sim 10^{5}$ (1 every 6 minutes)
- Cosmic** $\nu \to \mu \sim 10^{2}$

Neutrino Flare in 2014

Time-dependent search in the direction of TXS 0506+056 revealed a **neutrino flare** in December 2014.





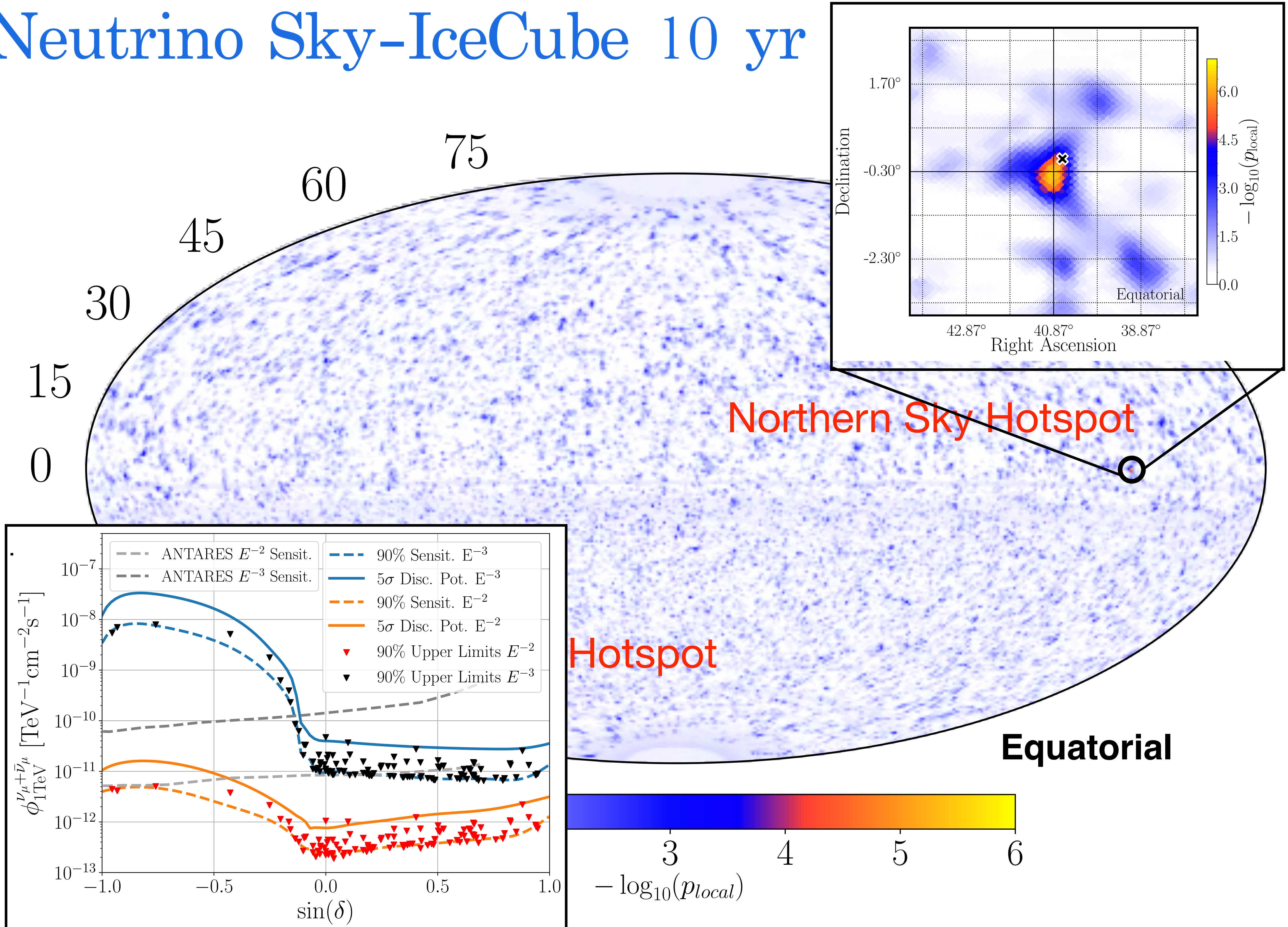
$$T_{\mathrm{W}} = 110^{+35}_{-24} \text{ days}$$

$$\Phi_{100} = \left(1.6^{+0.7}_{-0.6}\right) \times 10^{-15} \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

13±5 signal events rejecting background hypothesis at 3.5σ

[IceCube, Science 2018]

Neutrino Sky-IceCube 10 yr



[IceCube 2019]

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

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

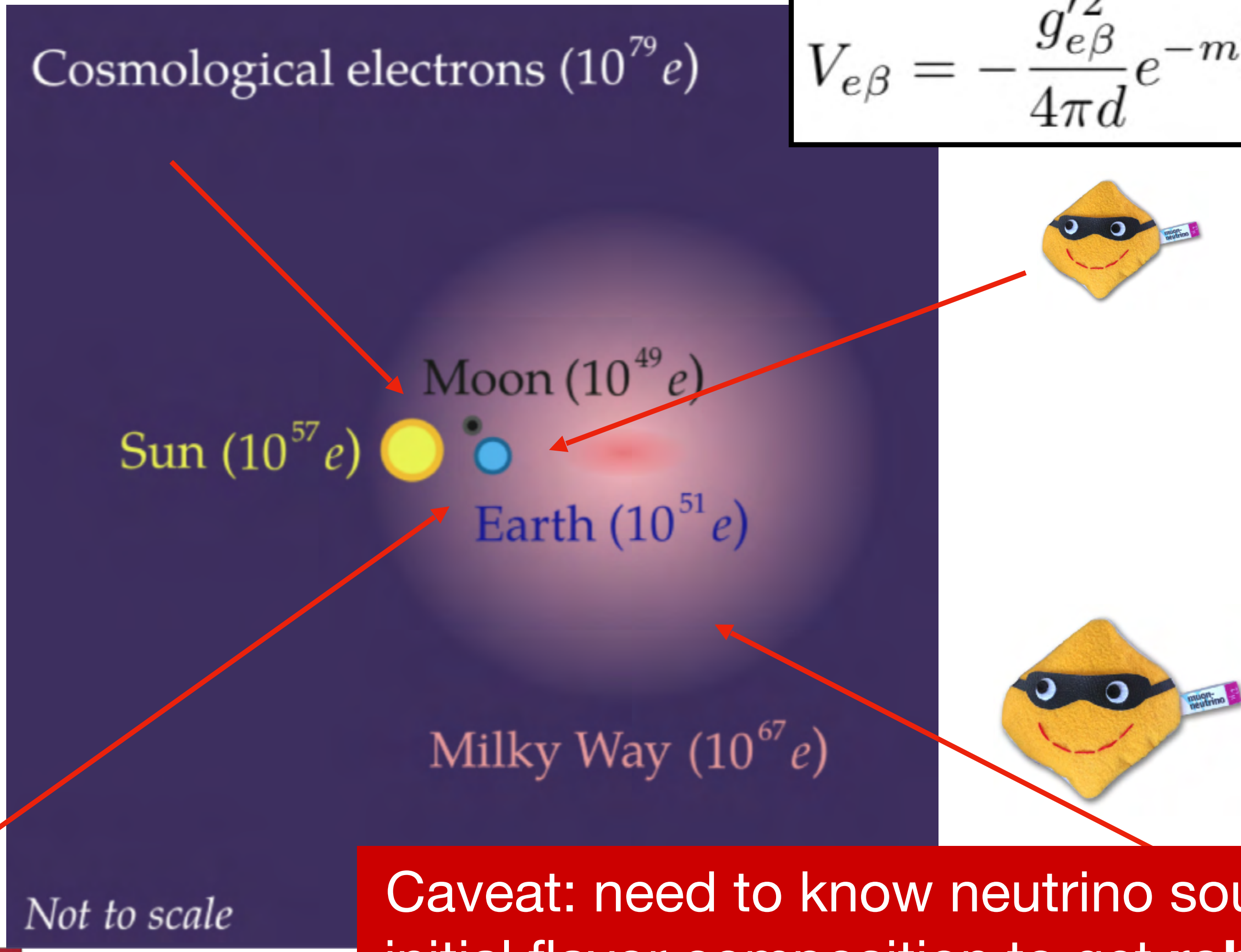
$V_{e\tau} < 10^{-27}\,\text{GeV}$ (0:1:0) source

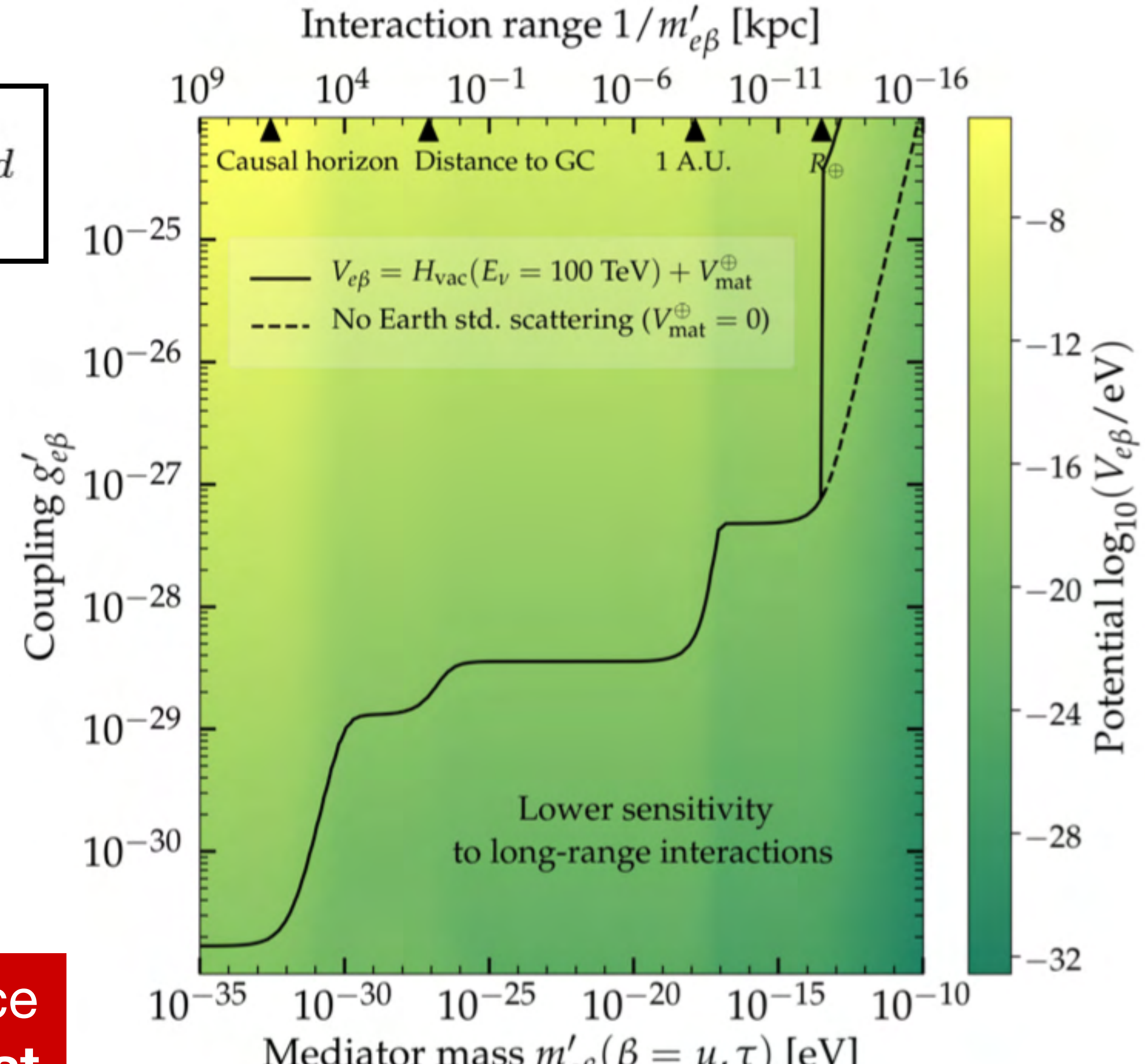
$V_{\mu\tau} < 10^{-28}\,\text{GeV}$ (1:0:0) source

New long range forces gauged on

$$L_e - L_\alpha$$

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





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

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

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.

$$V_D \sim G_D N_D$$

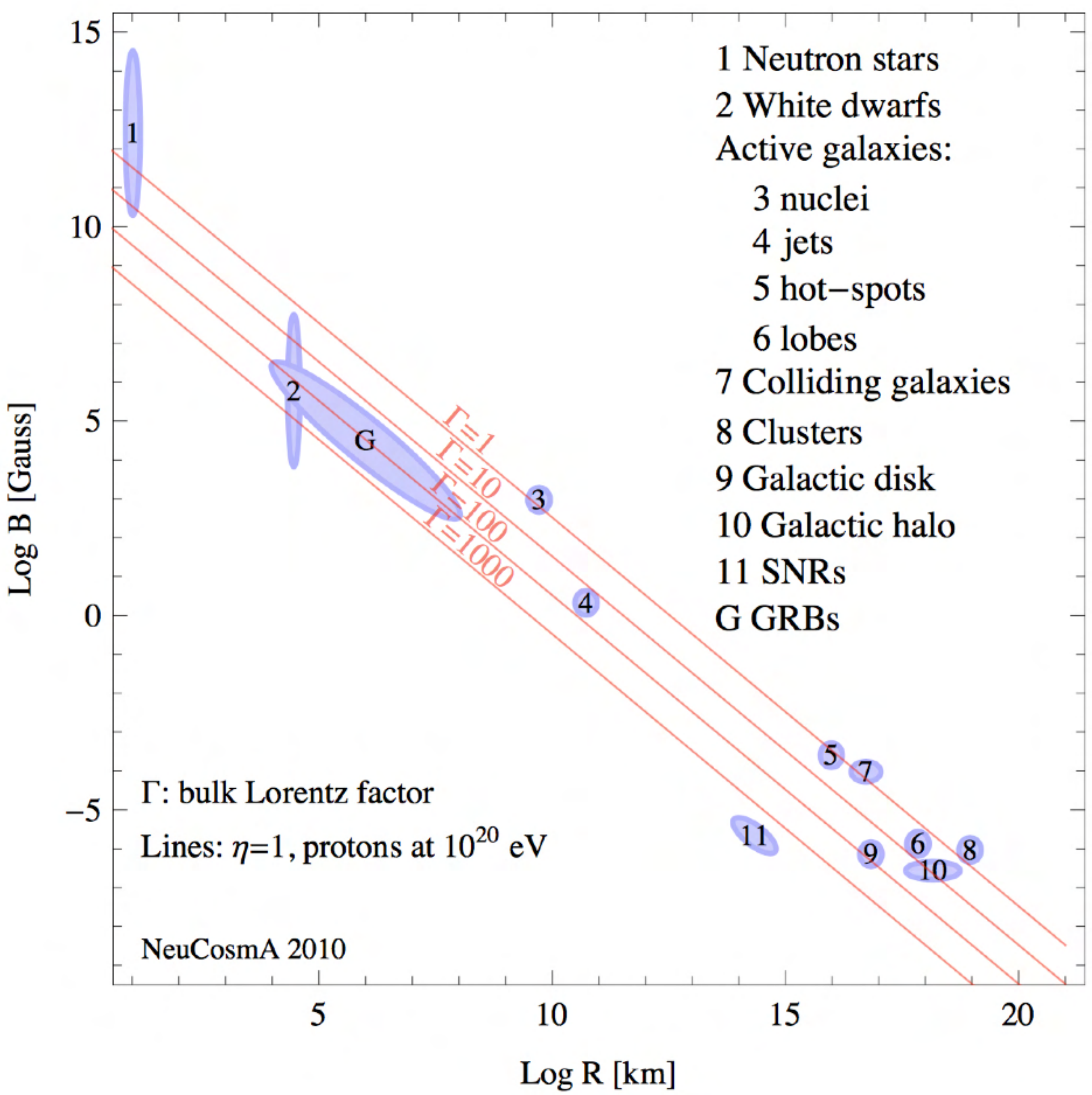
$$G_D \sim \frac{g_d^2}{M_D^2}$$

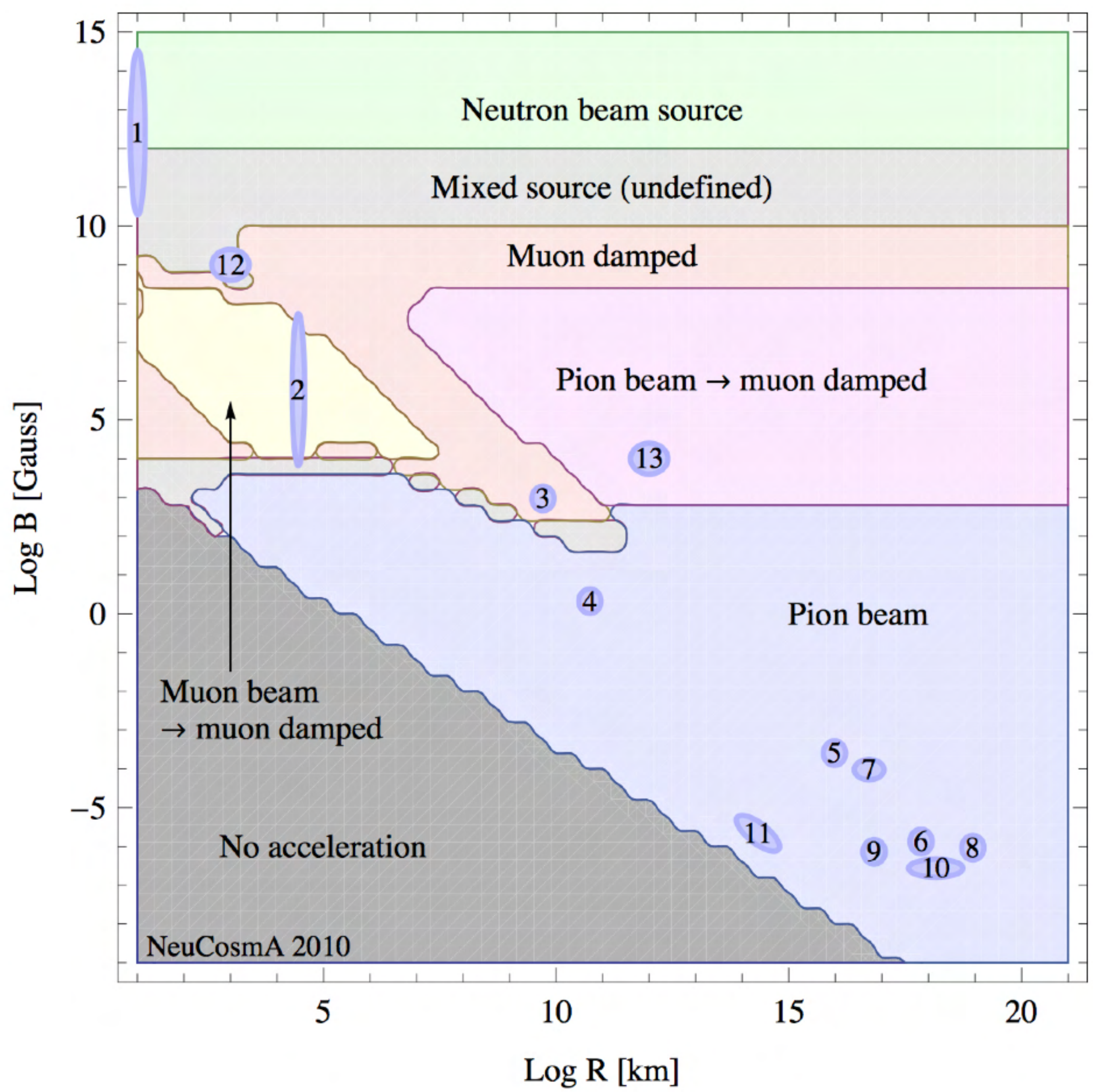
Caveat: need to know neutrino source initial flavor composition to get **robust** bounds with current limits.

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

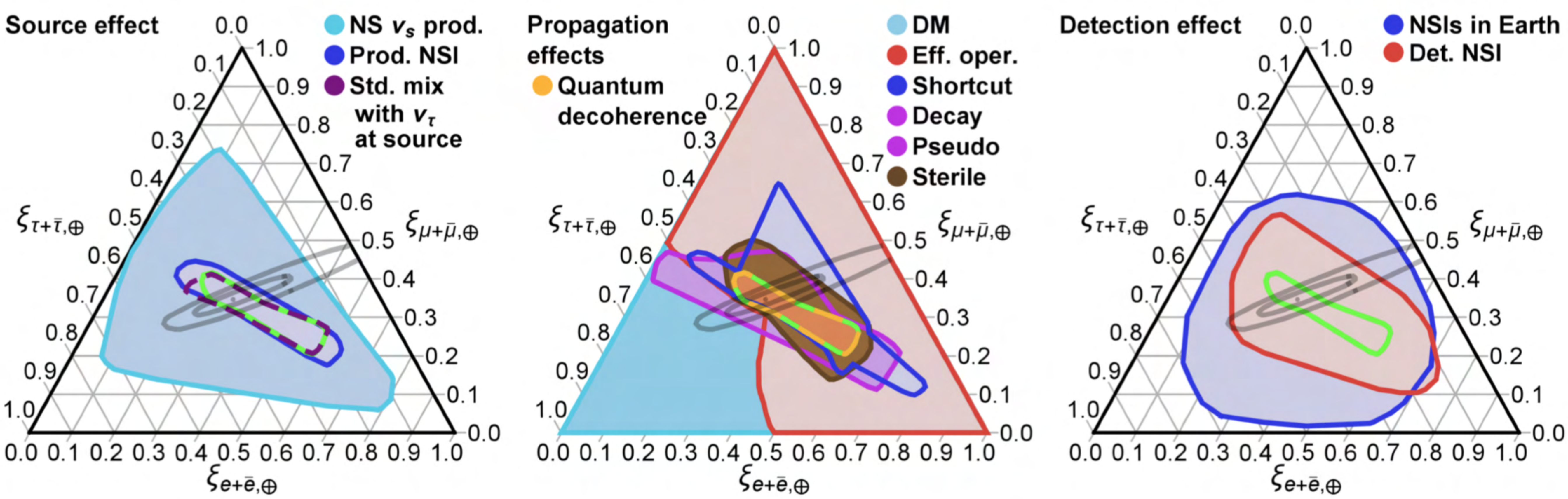
Capozzi et al. 1804.05117

Sources of Astrophysical Neutrinos





(arXiv:1007:0006)

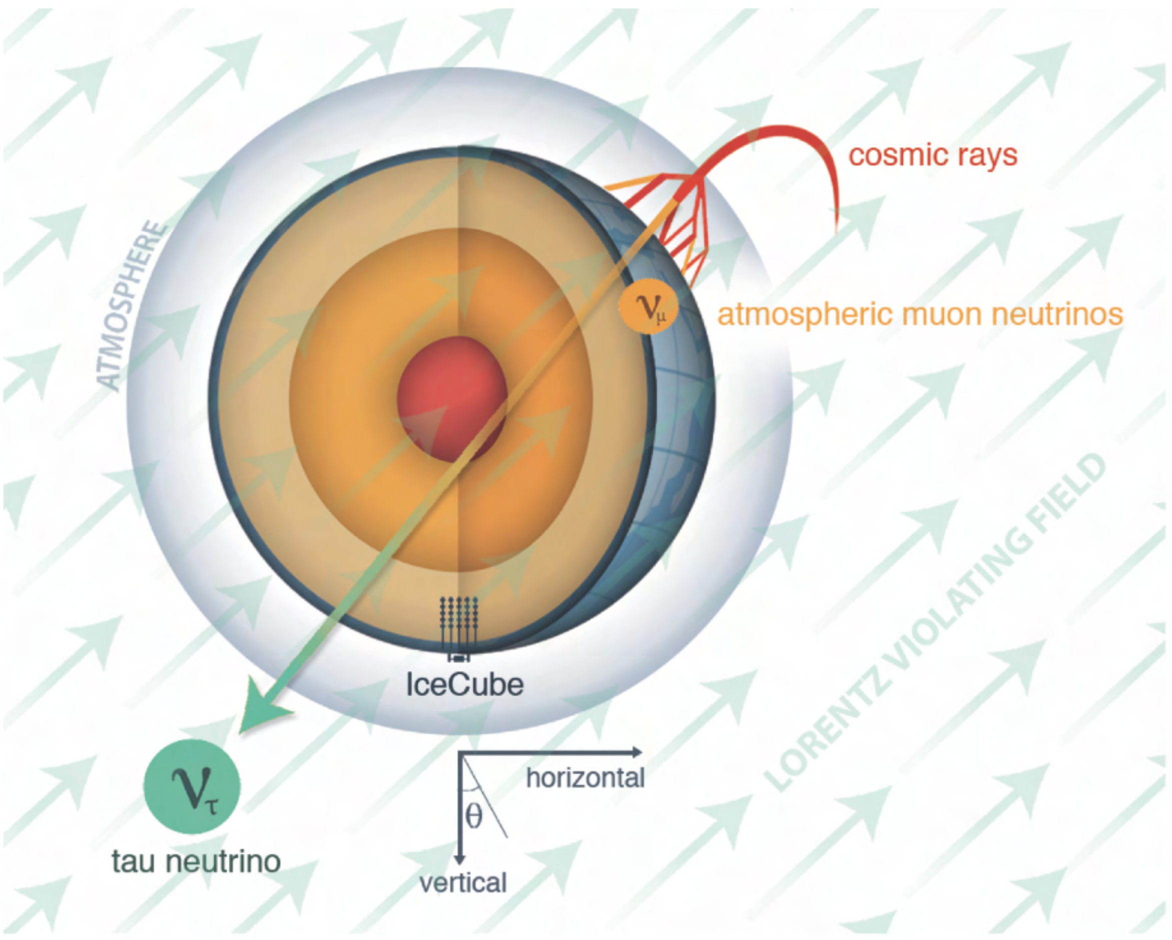


Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684

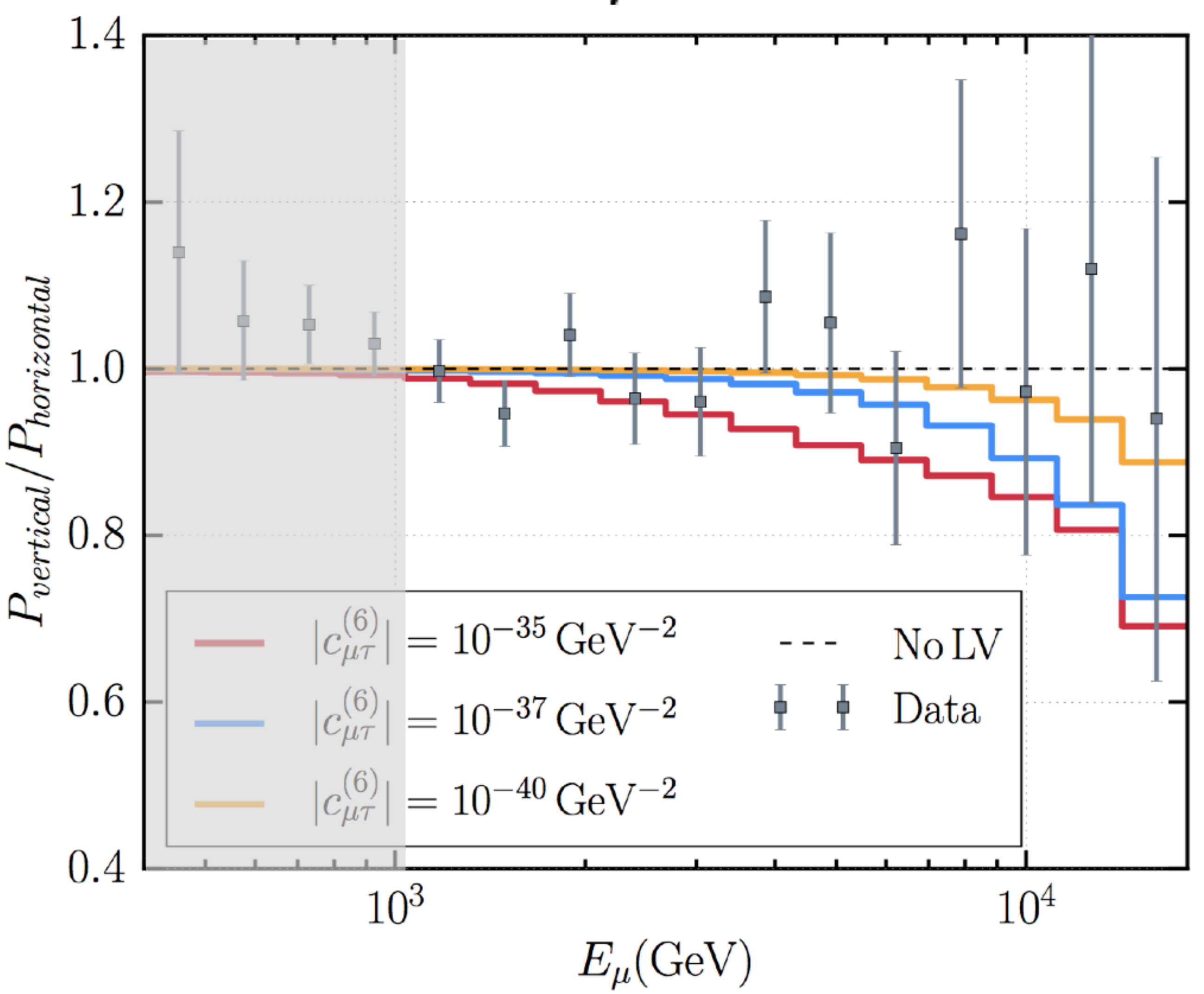
Search for Lorentz Violation with High-energy Atmospheric Neutrinos

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

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



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



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

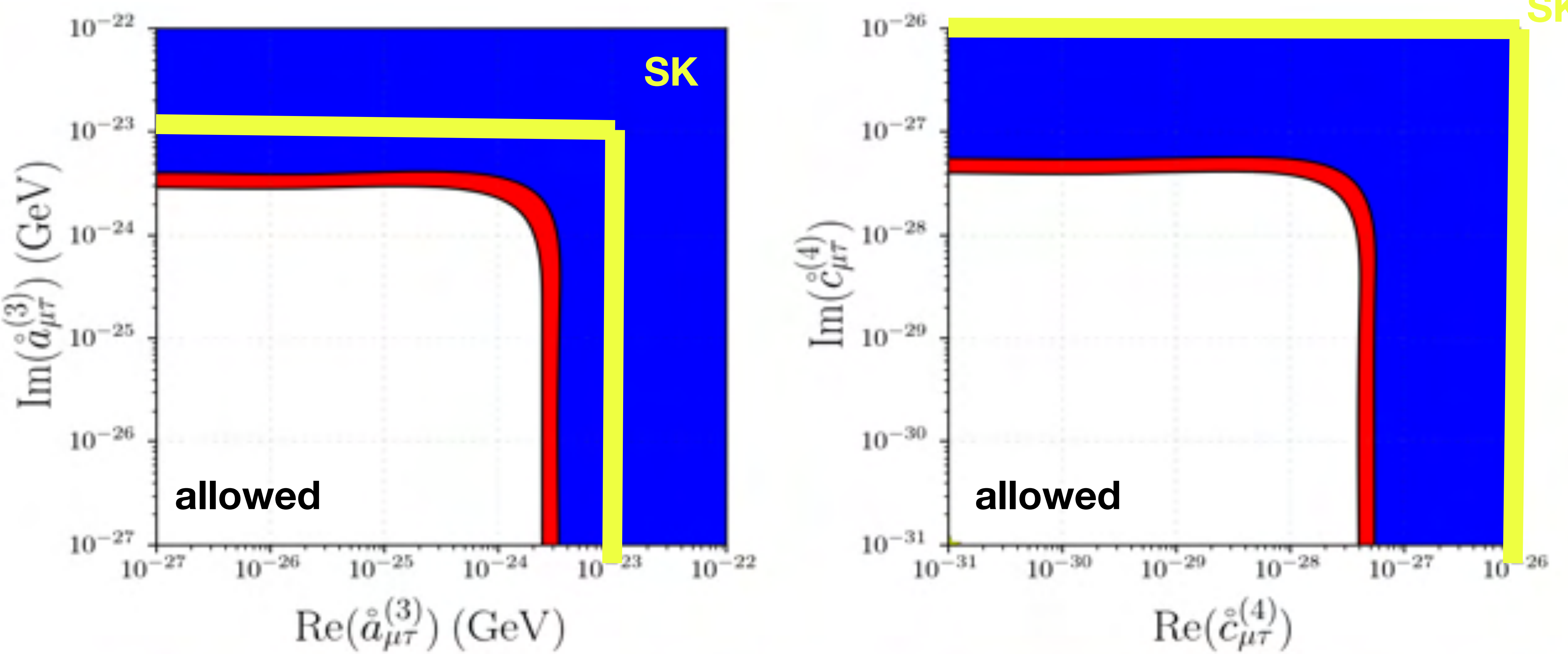
Our results in the maximum-flav
violating assumption

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

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

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

SuperKamiokande Collaboration. arXiv:1410.4267



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

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

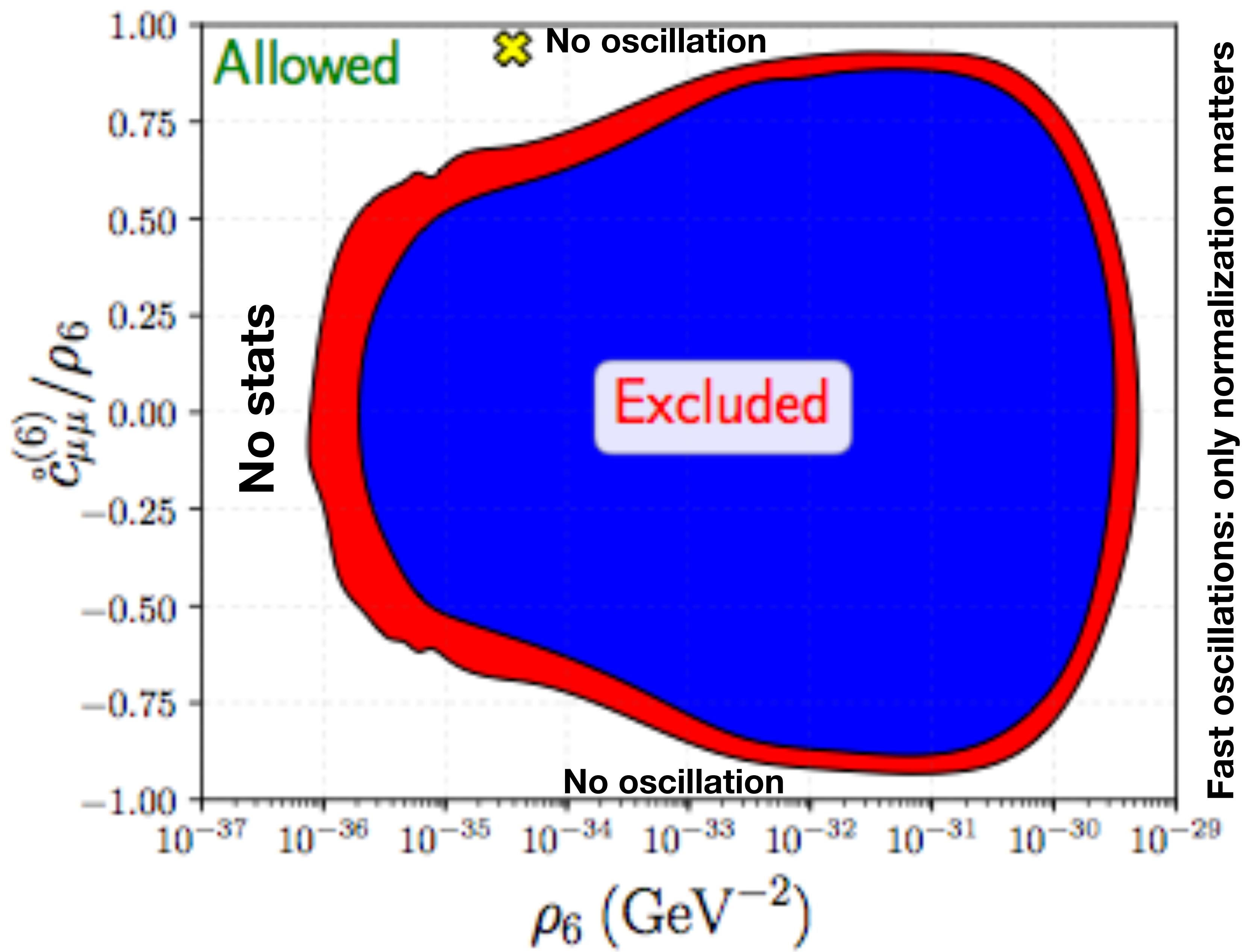
Anatomy of the dim-6 operator constraint

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

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

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

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

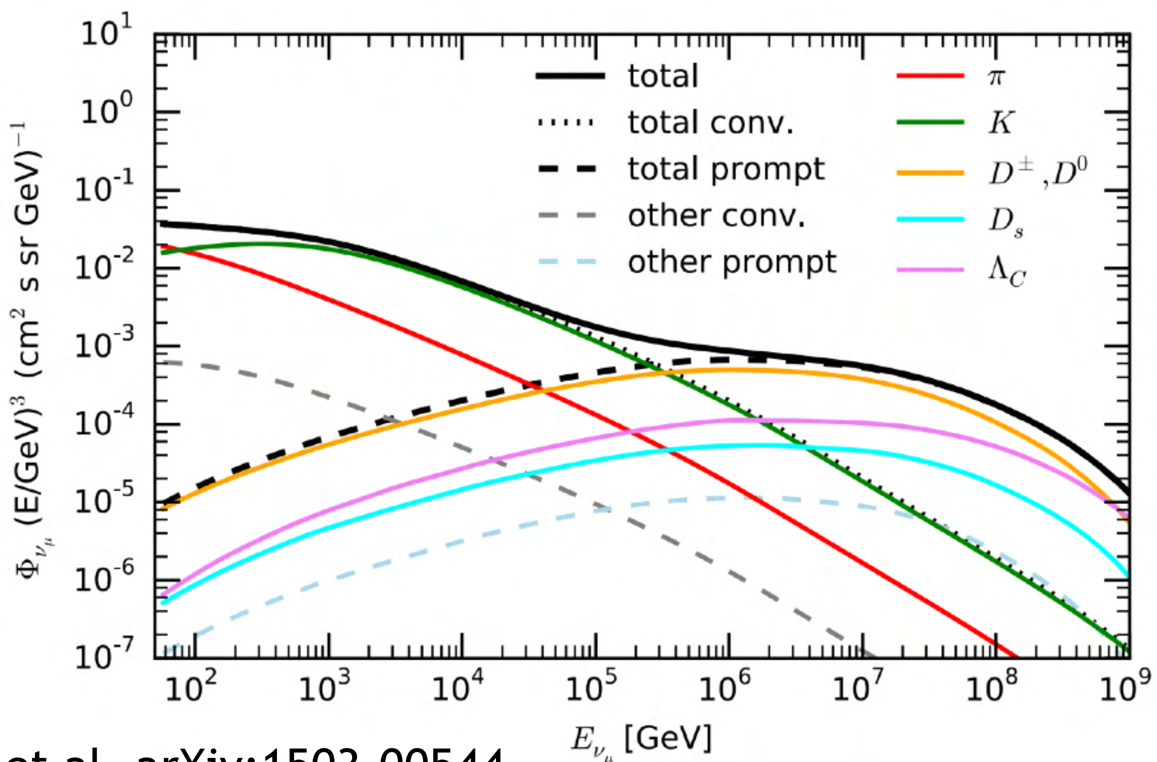


$$\rho_d \equiv \sqrt{(\mathring{c}^{(d)}_{\mu\mu})^2 + \mathrm{Re}\,(\mathring{c}^{(d)}_{\mu\tau})^2 + \mathrm{Im}\,(\mathring{c}^{(d)}_{\mu\tau})^2}$$

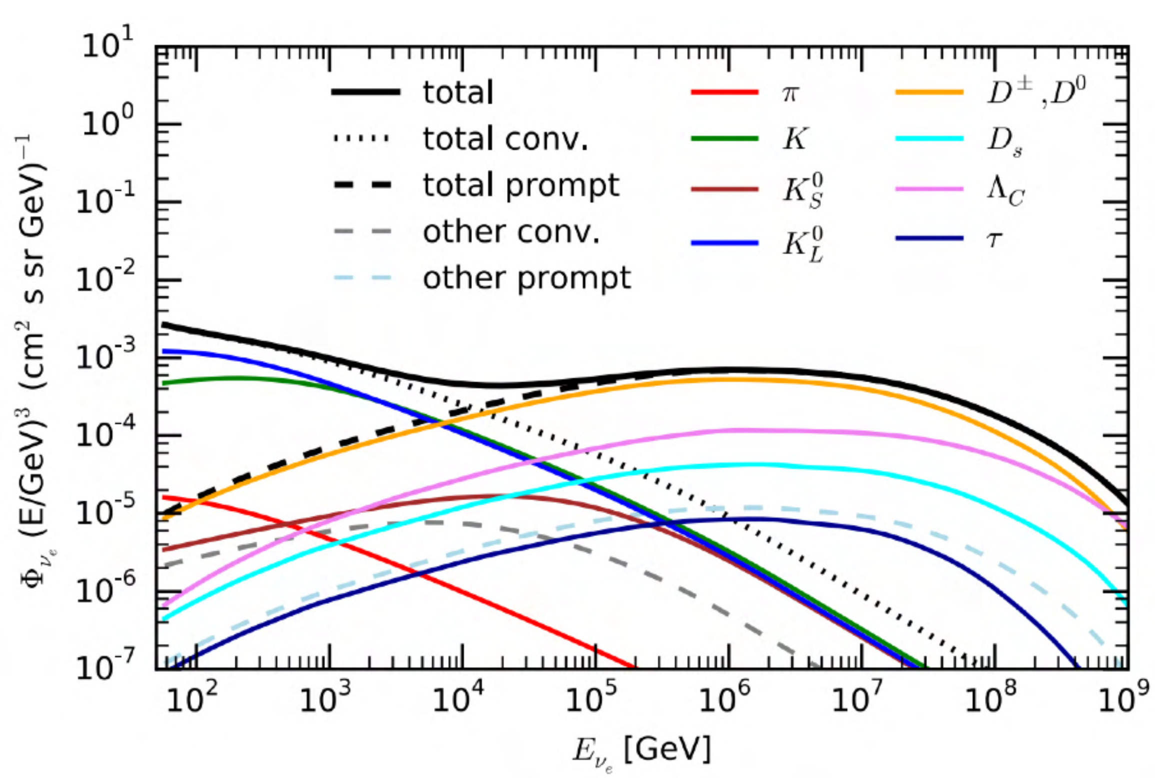
IceCube Collaboration, arXiv:1709.03434

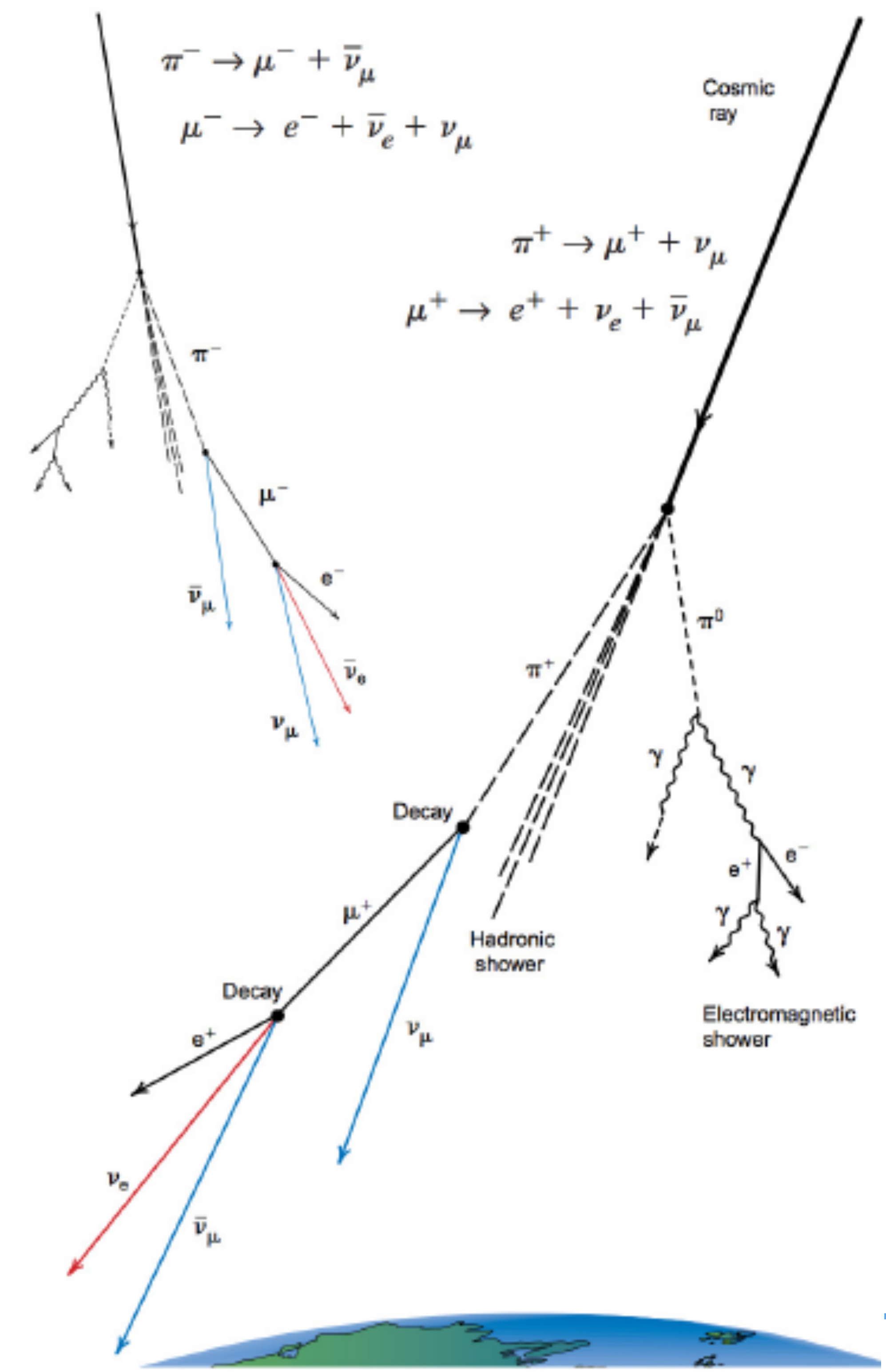
Atmospheric neutrinos

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

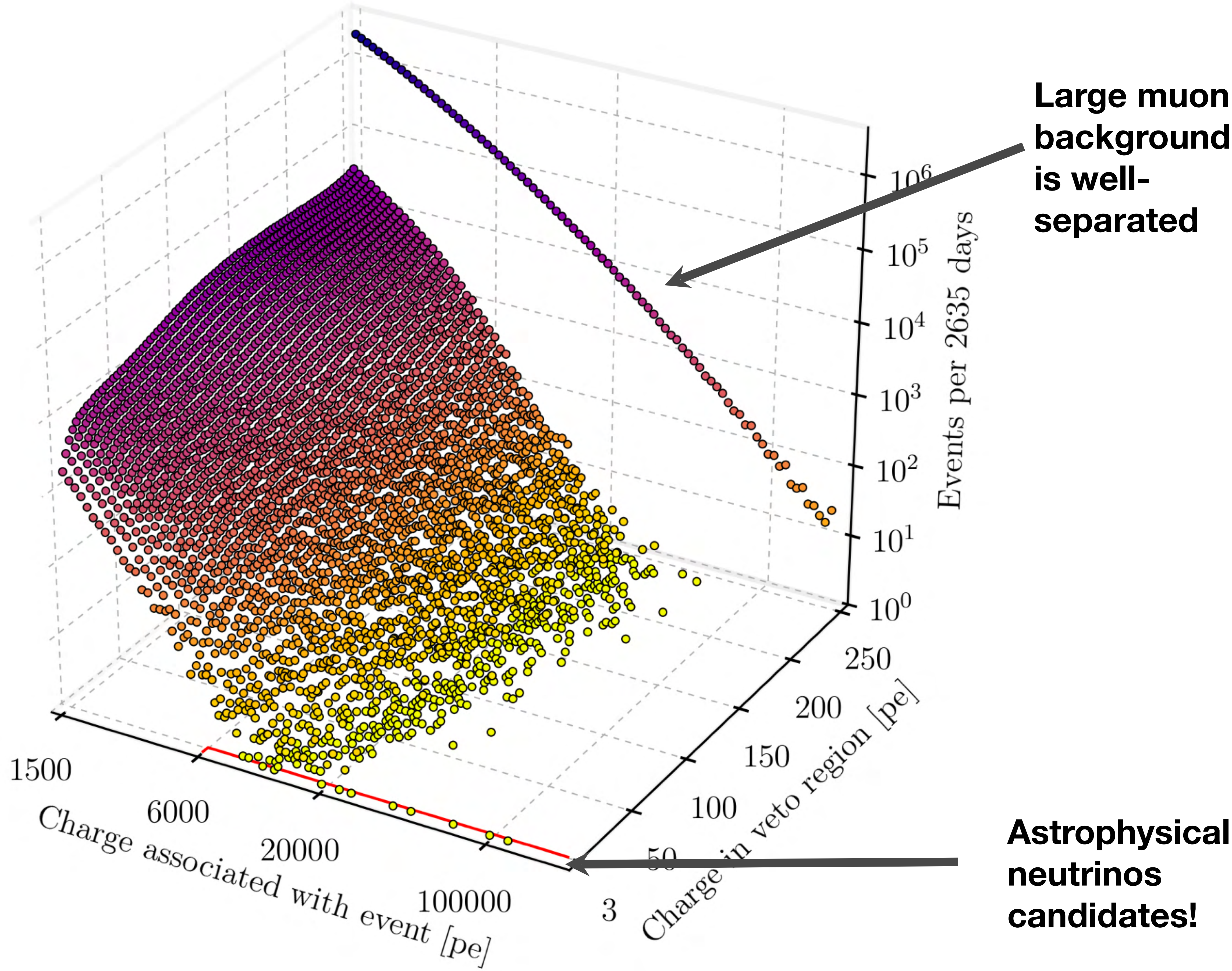


Fedynitch et al. arXiv:1503.00544





High-Energy Starting Events (HESE)

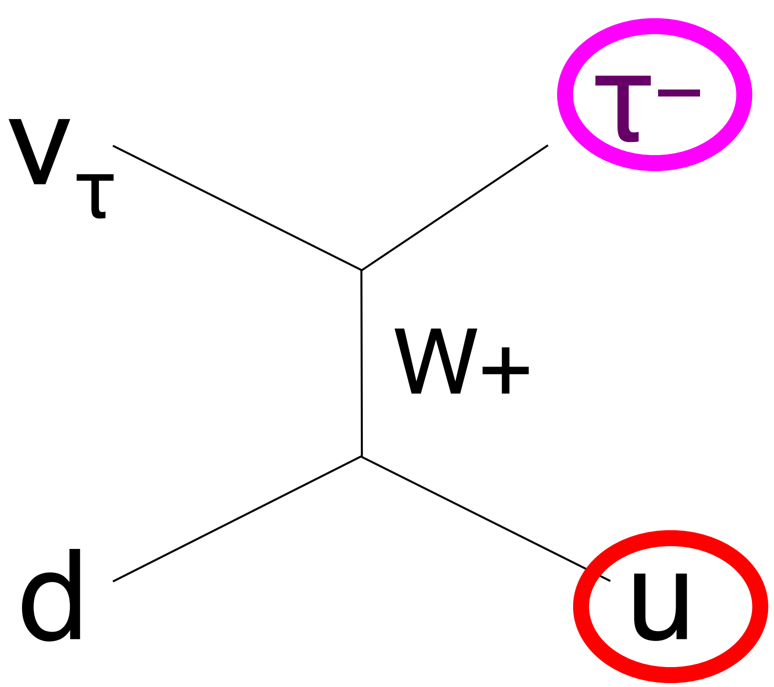


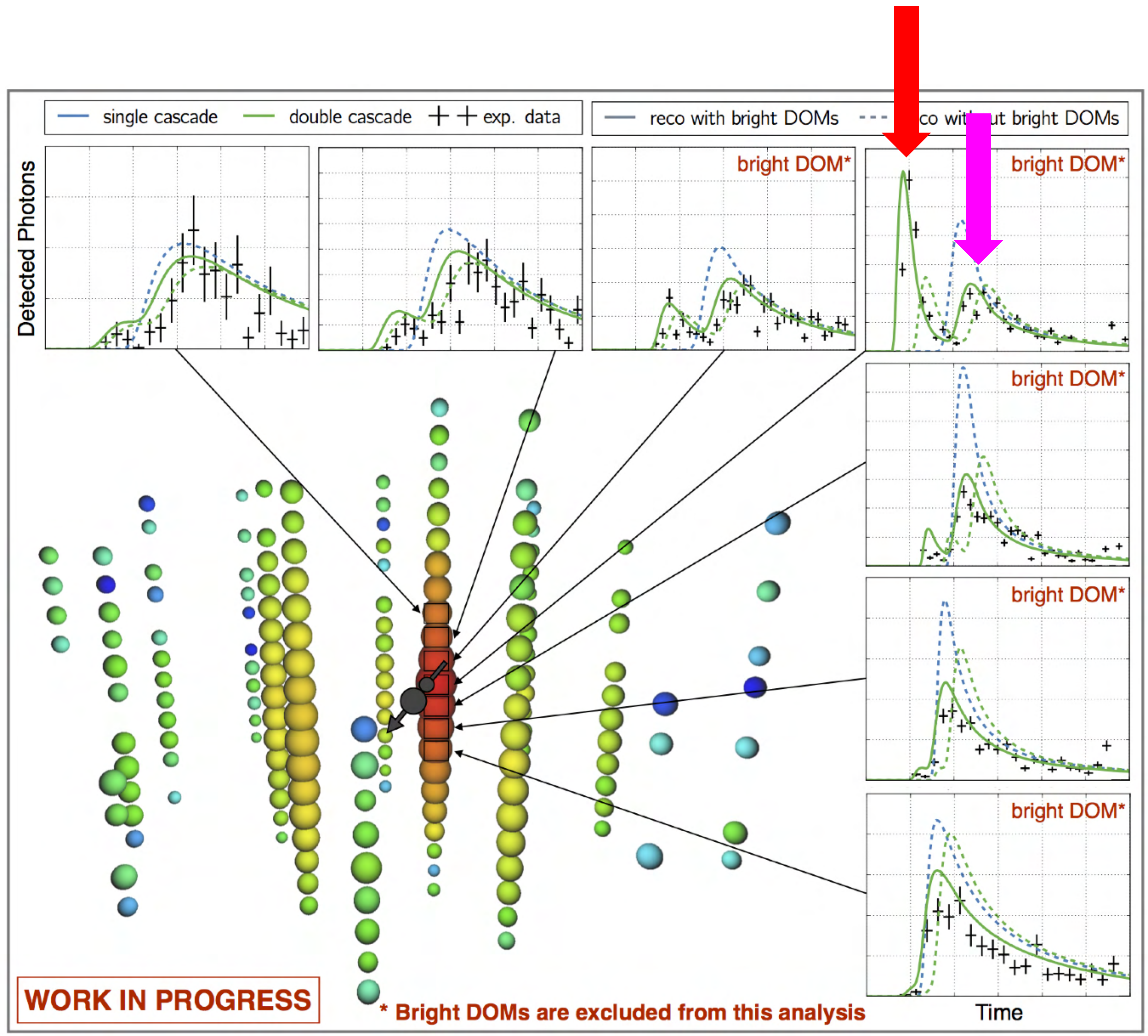
First astrophysical ν_τ candidate found!

Total deposited energy ~ 90 TeV.

First "bang" in time (shower)

Second "bang" in time (tau decay)



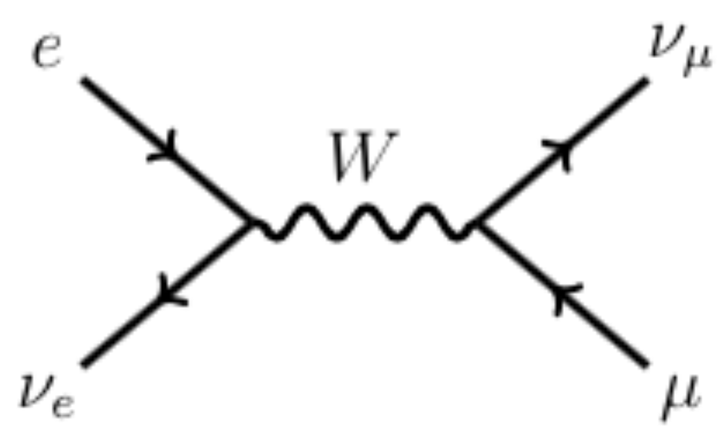


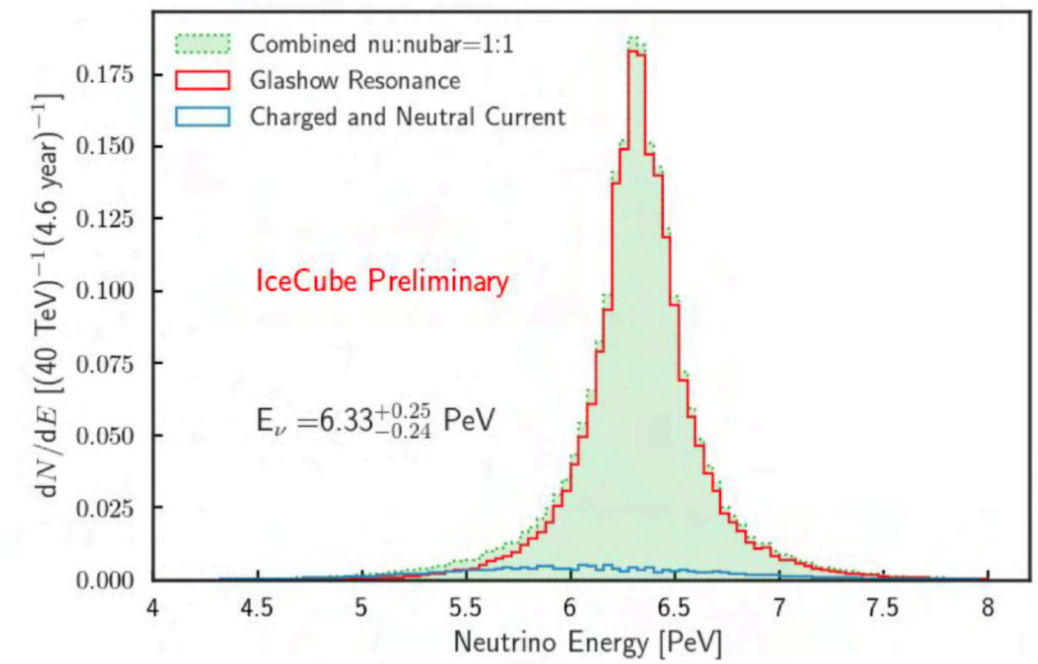
Cosmic-neutrino decay length ~ 17 m!

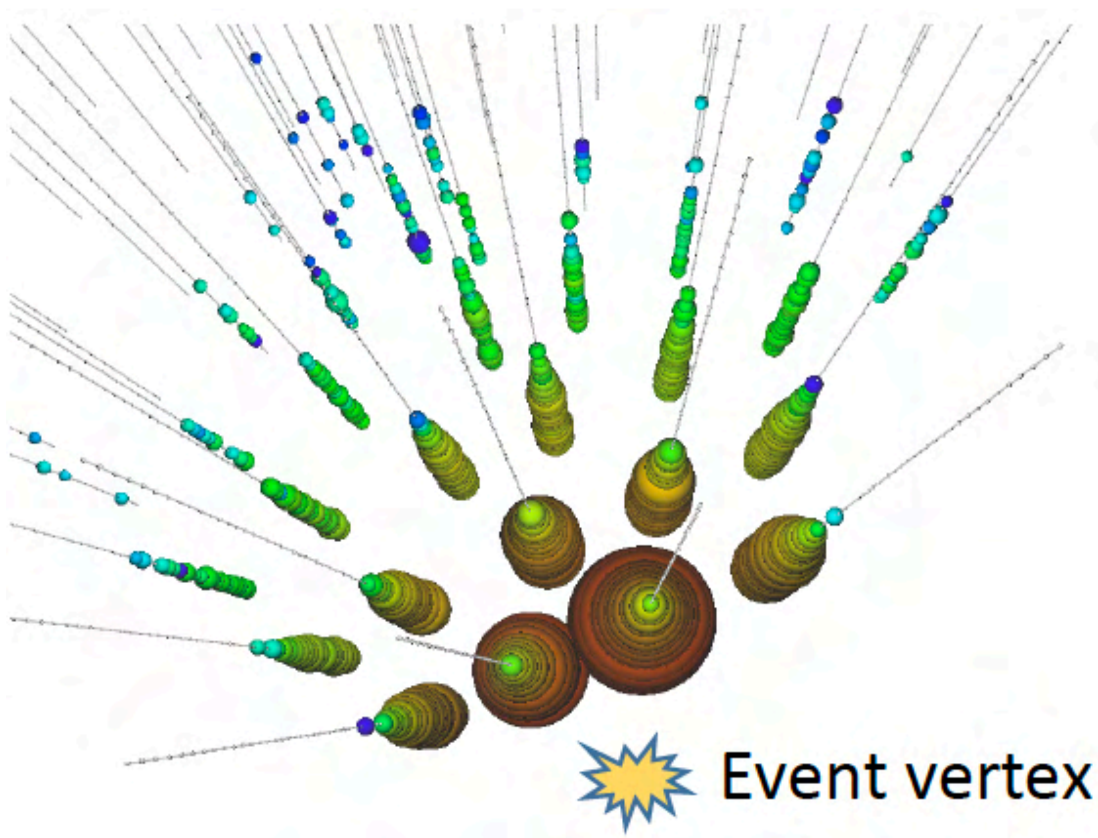
The first Glashow resonance event:

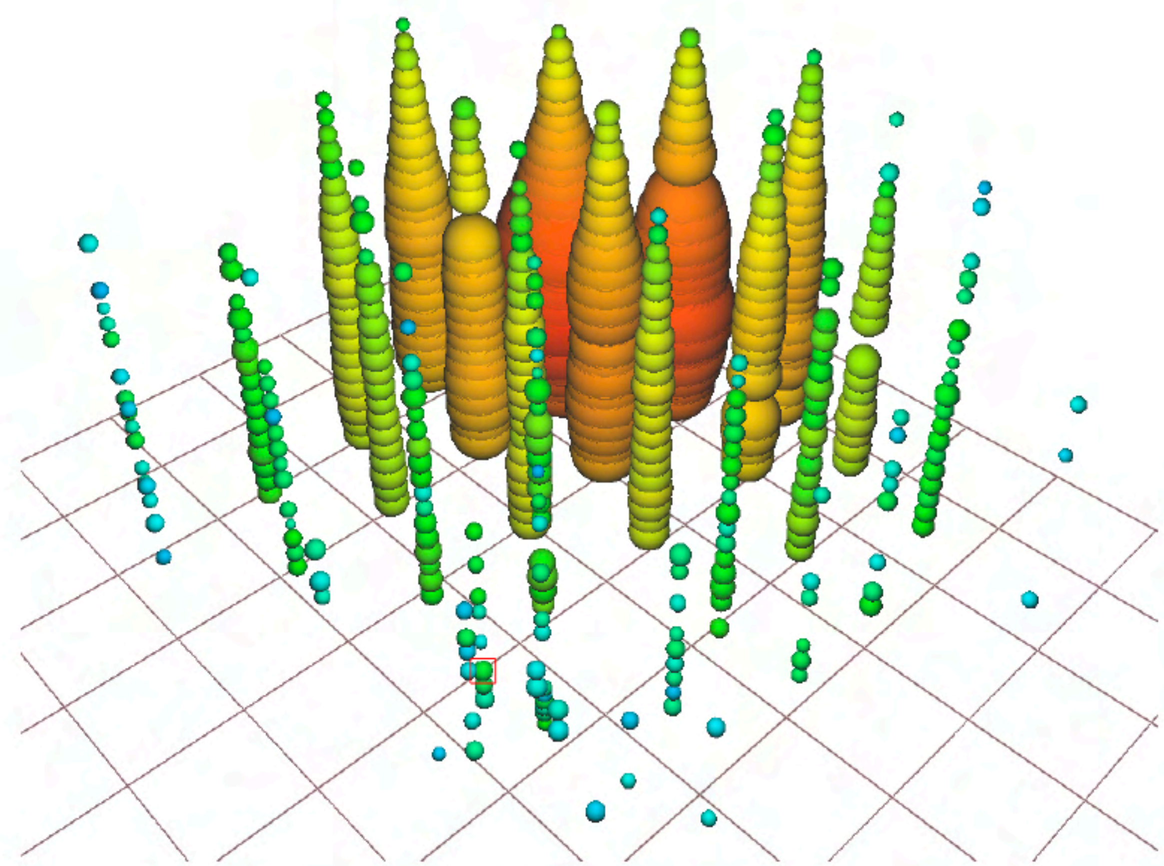
anti-ν_e + atomic electron → real W at 6.3 PeV

Resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron









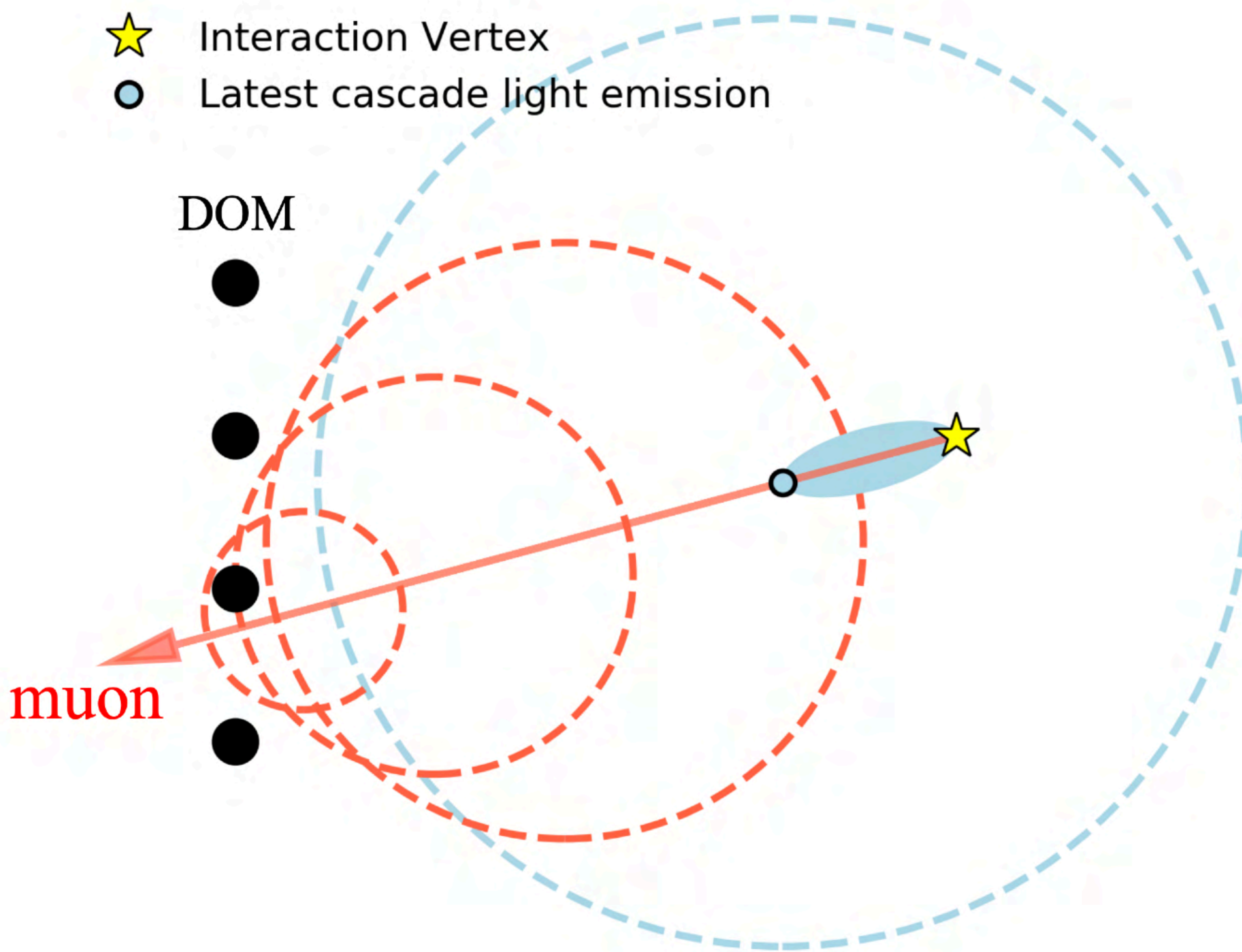
W production or background?

Signal:
hadronic (quark-antiquark decay of the W)

Or

Background:
electromagnetic shower radiated by a high energy background cosmic-ray muon

muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)



Hadronic shower from W-decay:

Early muons followed by electromagnetic shower