Measuring the high-energy astrophysical flux with IceCube

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Santa Barbara, USA
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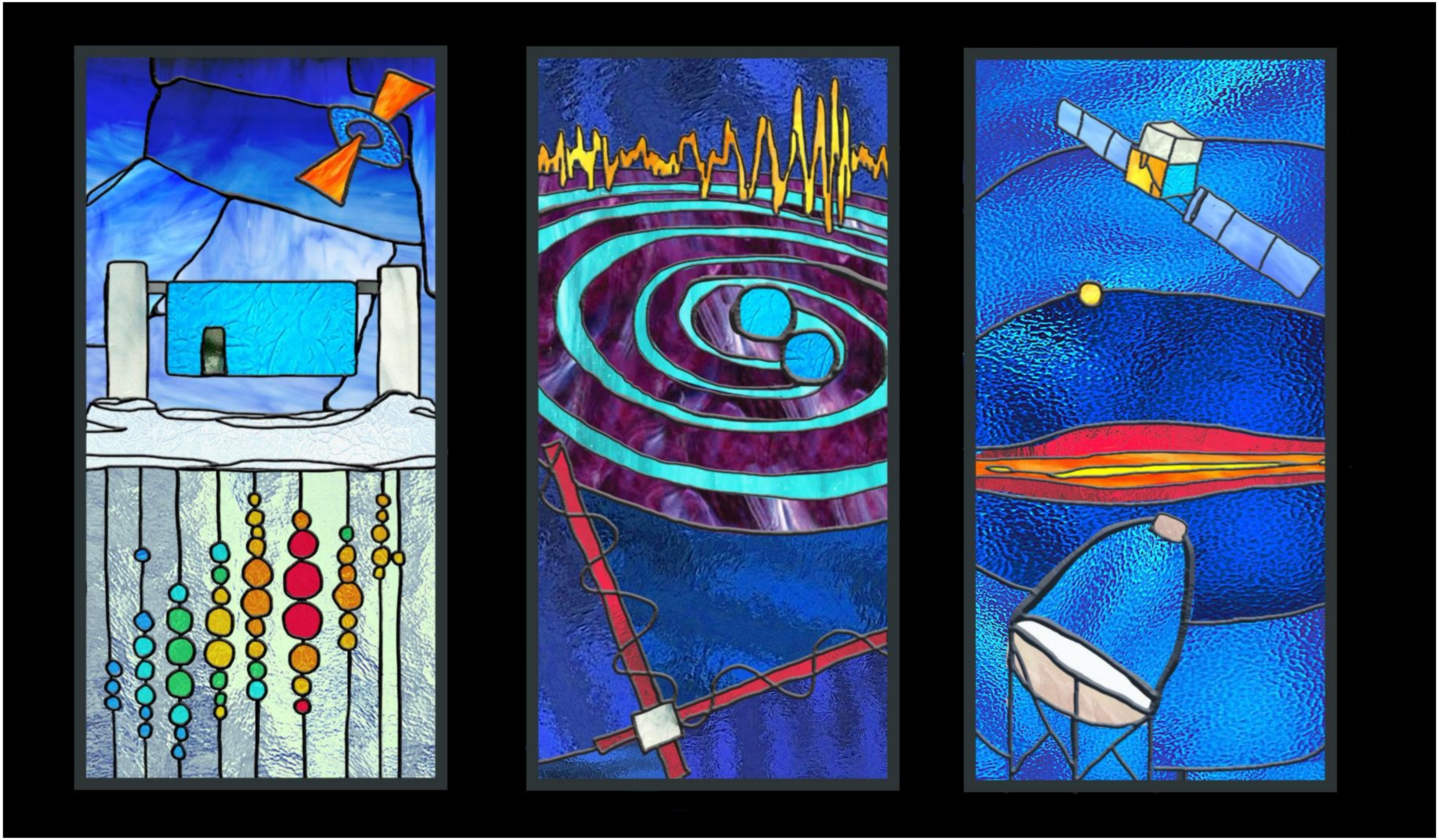
How does the Universe look in neutrinos?



How do high-energy neutrinos behave?

Outline of the rest of this talk:

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

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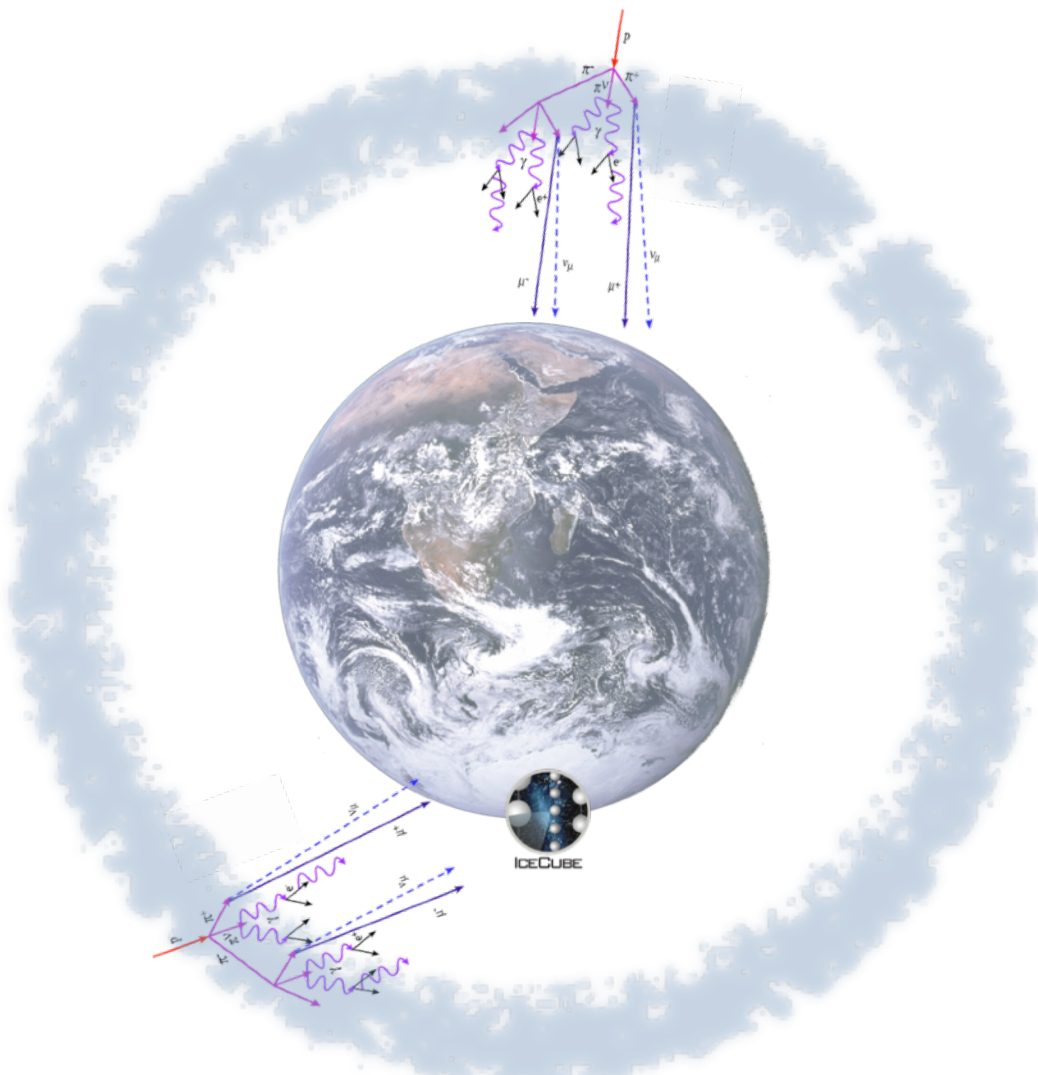
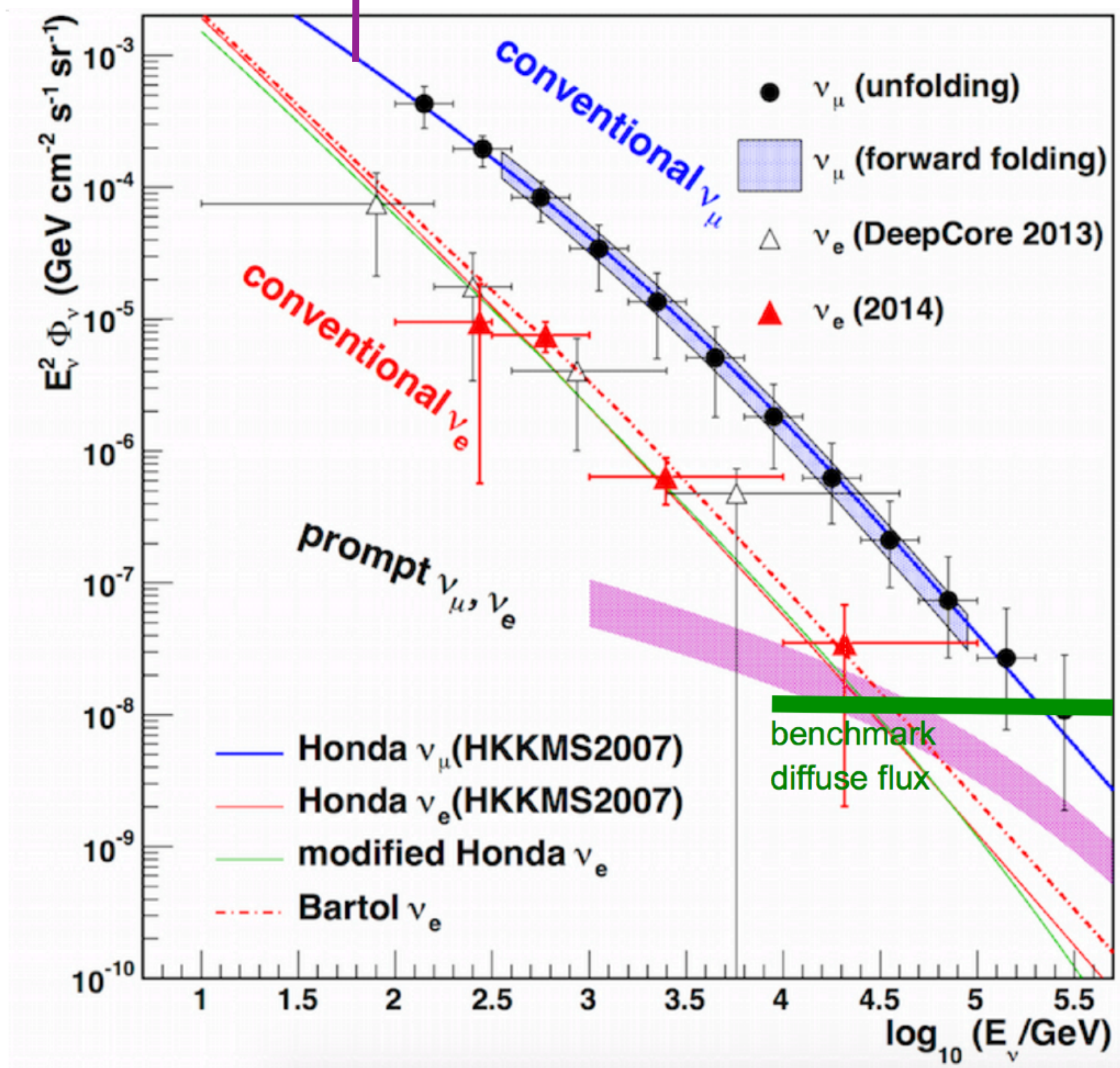


10^6 atmospheric μ
per atmospheric ν

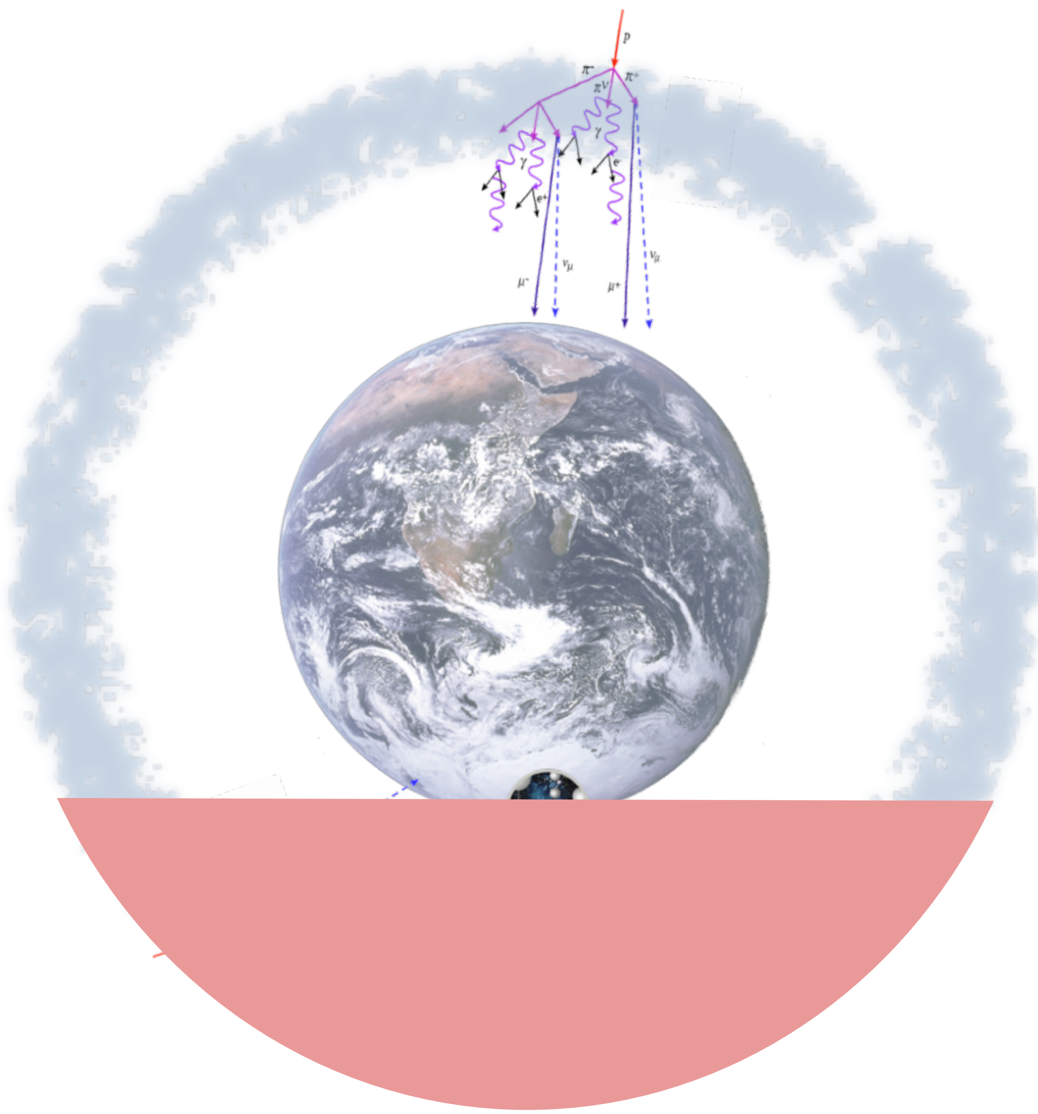


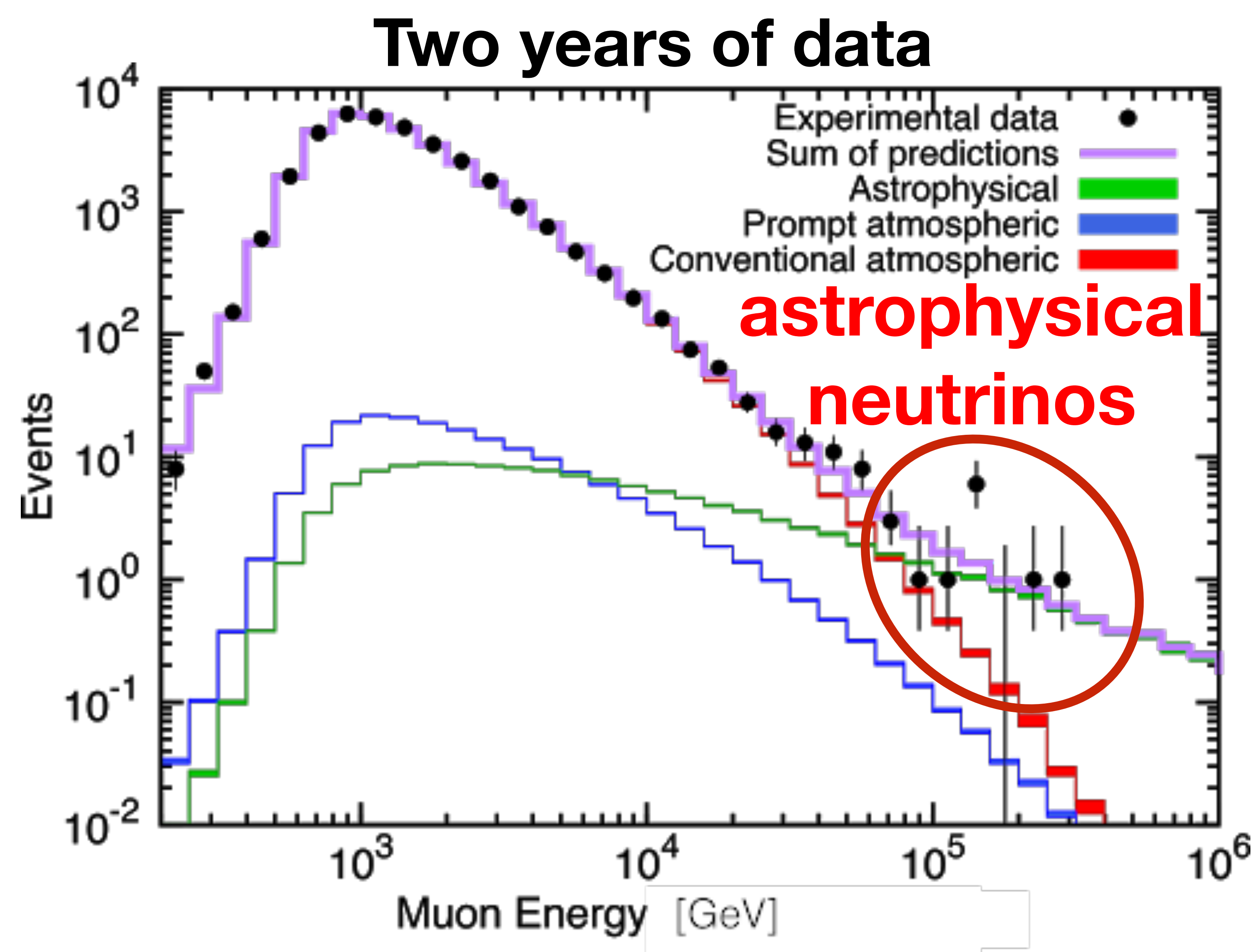
Challenges:

Astrophysical neutrino flux is very small

Large atmospheric neutrino and muon backgrounds

Strategy One: look at the Northern Sky

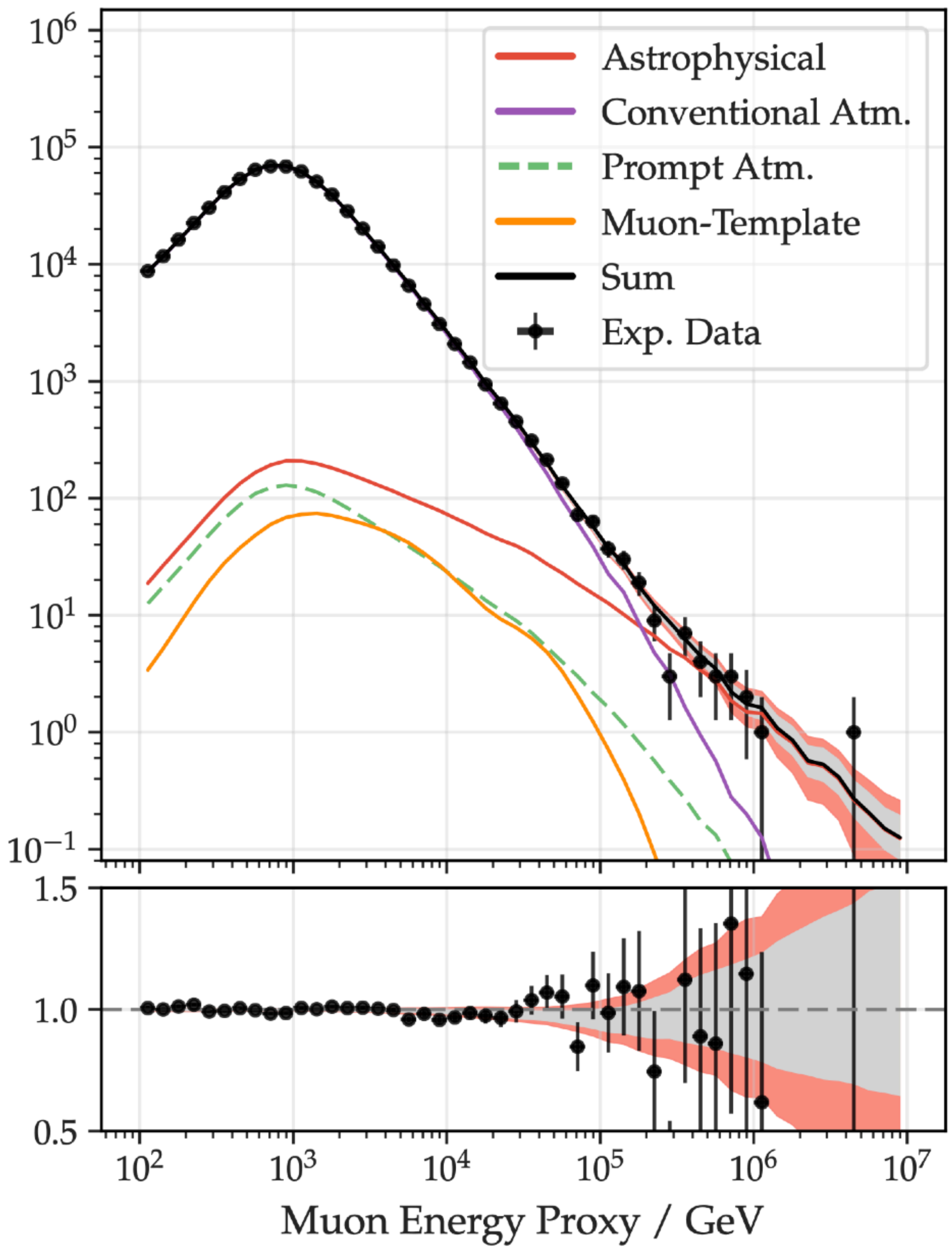




Strategy:

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

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



IceCube Coll. arXiv:2111.10299

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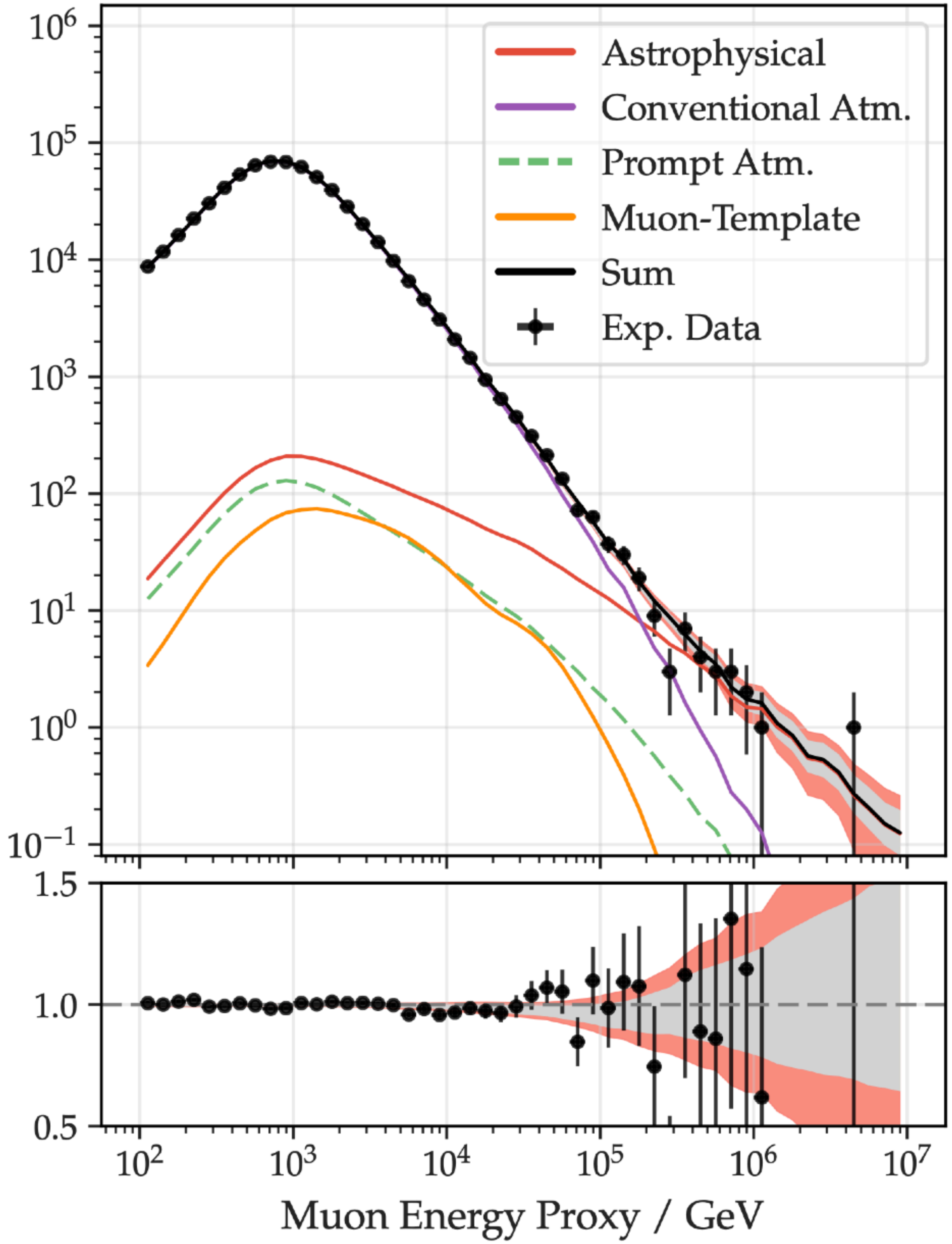

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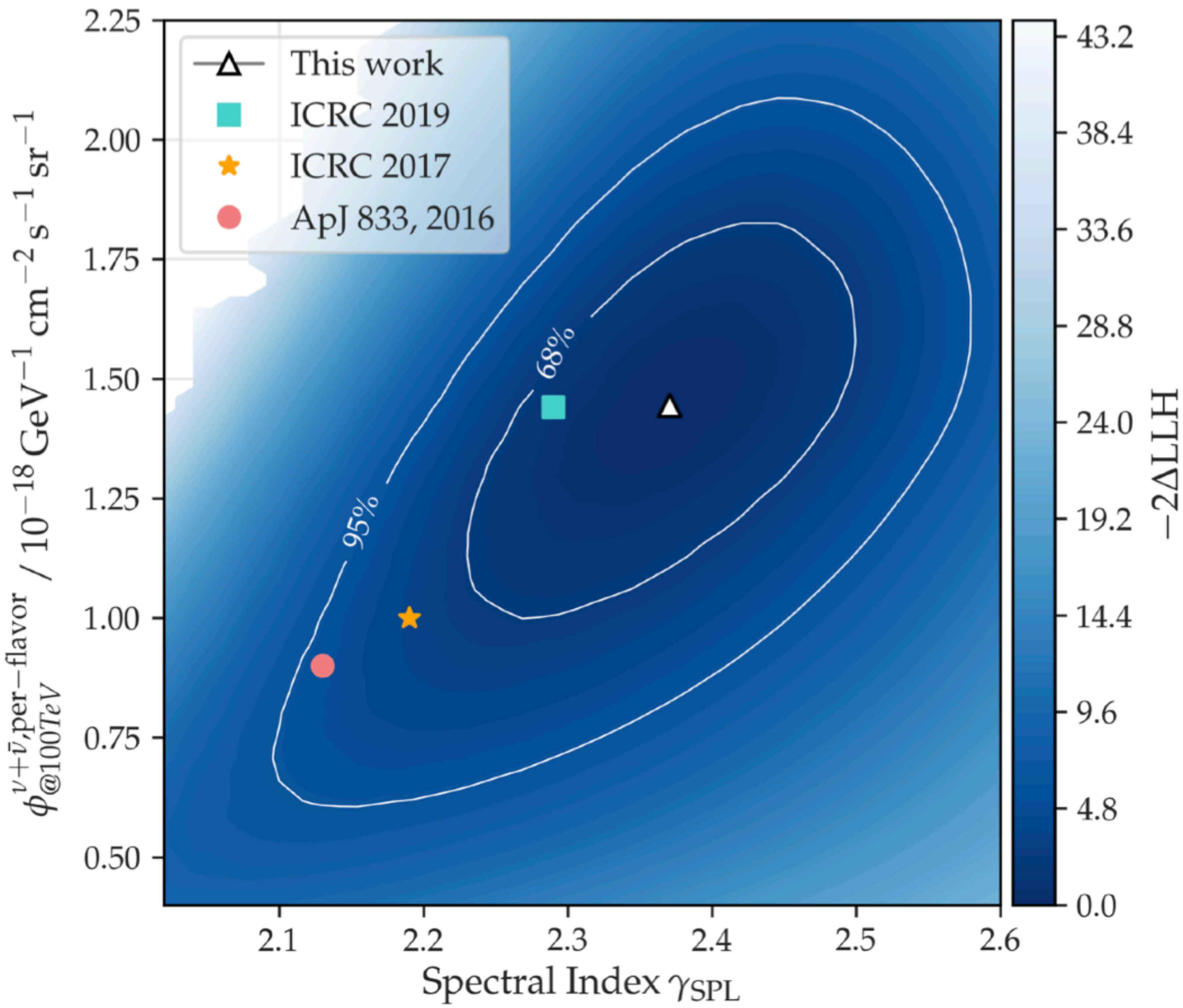
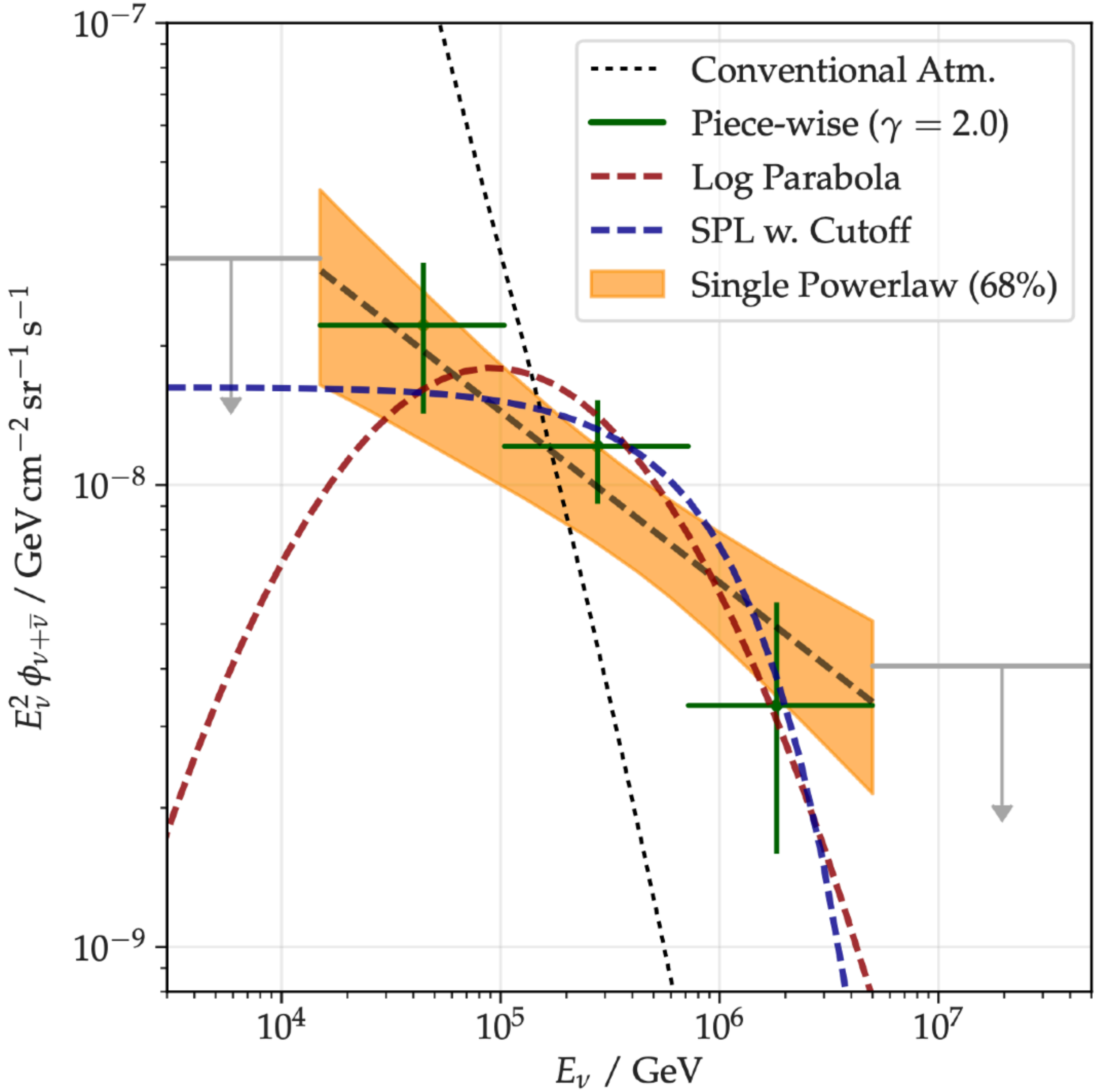


$$\gamma = 2.37 \pm 0.1$$

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

IceCube Coll. arXiv:2111.10299



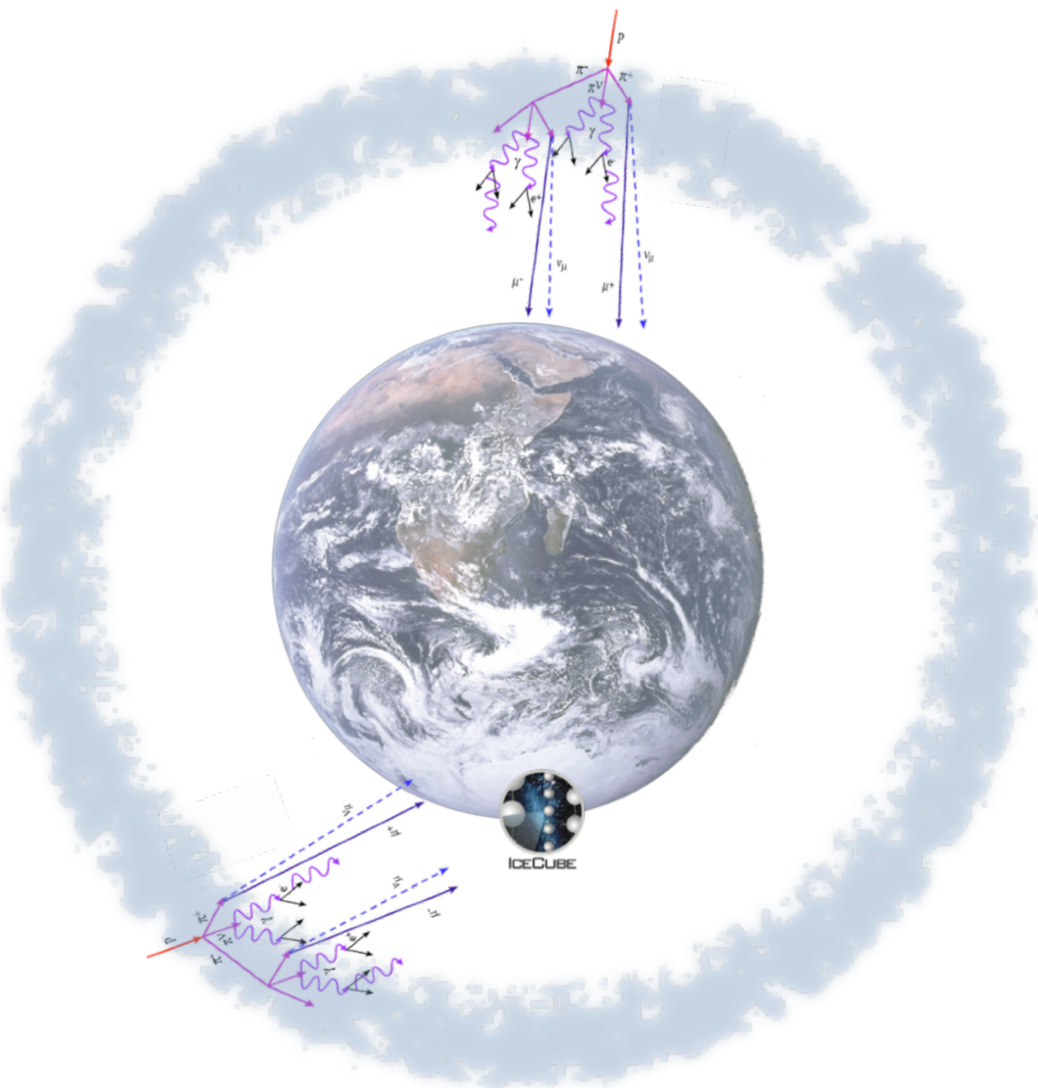
Simple power-law (SPL)
versus more *ad hoc*
complex models

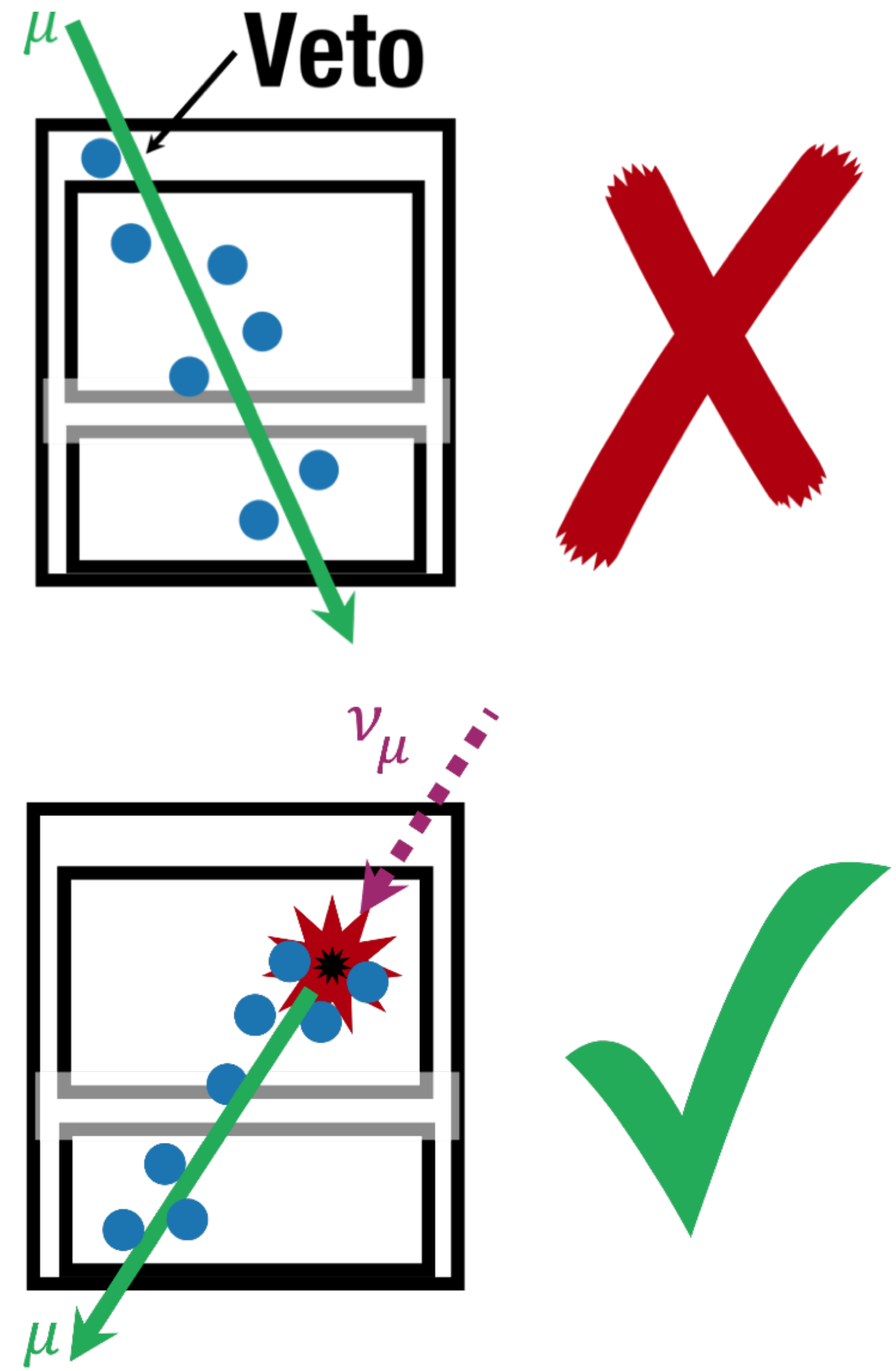
Astrophysical Norm. $\phi_{\mathrm{cutoff}} / C_{\mathrm{units}}$	$1.64^{+0.39}_{-0.36}$
Spectral Index γ_{cutoff}	$2.0^{+0.22}_{-0.28}$
Cut-off Energy E_{cutoff}/ PeV	$1.25^{+1.72}_{-0.56}$
Significance over SPL	$2\Delta\mathrm{LLH} = 4.24$
	$\mathrm{p}(> 2\Delta\mathrm{LLH}\vert\mathrm{SPL}) = 6.1\%$

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

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

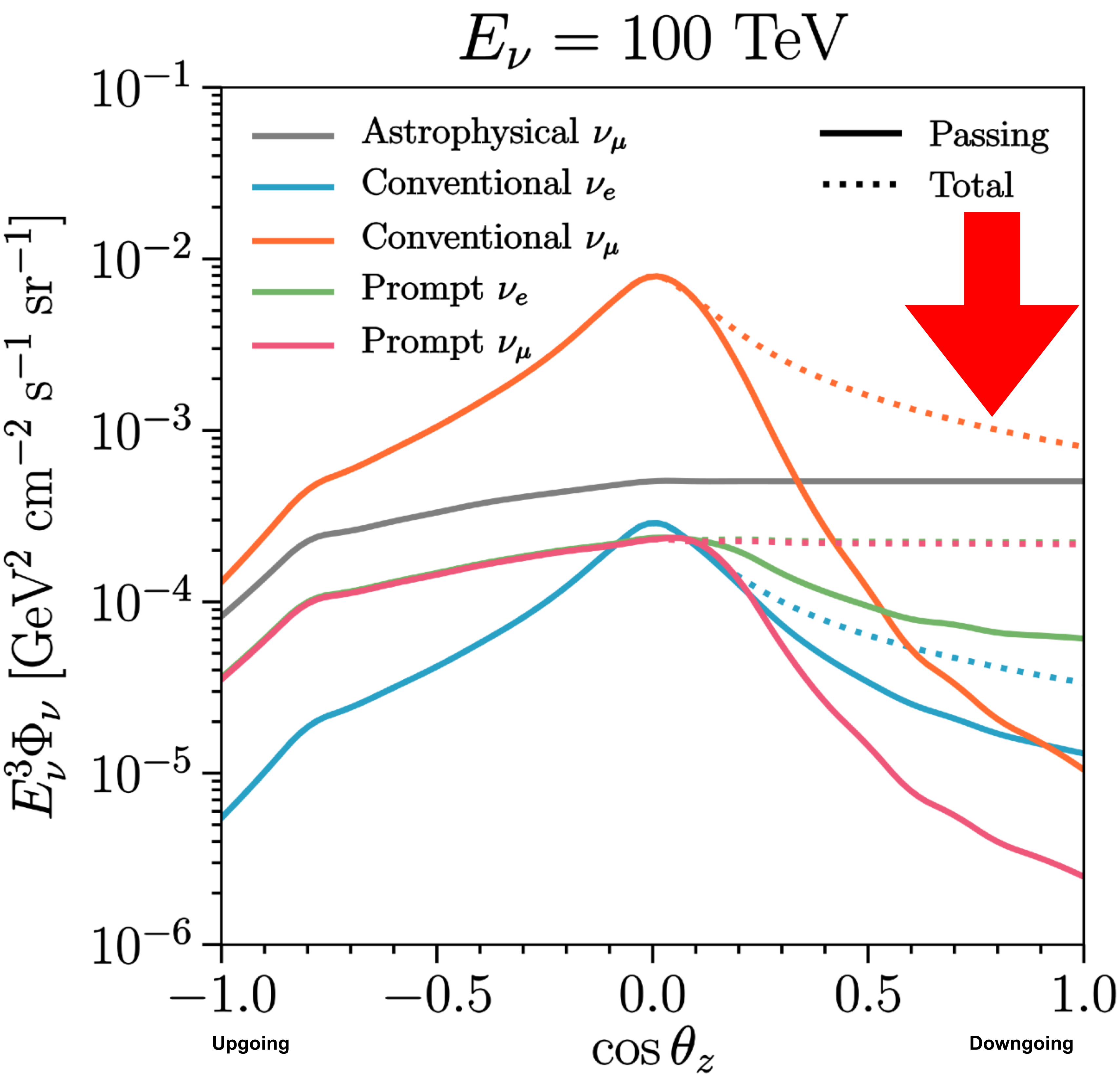




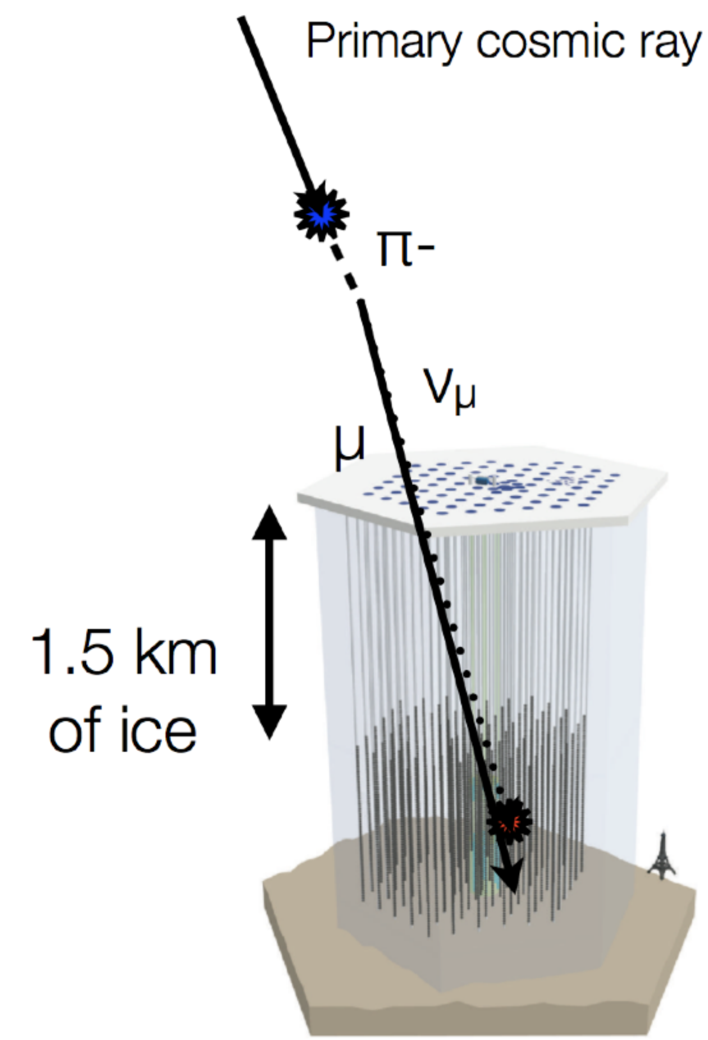
Strategy:

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

Coincident muons supress neutrino flux!

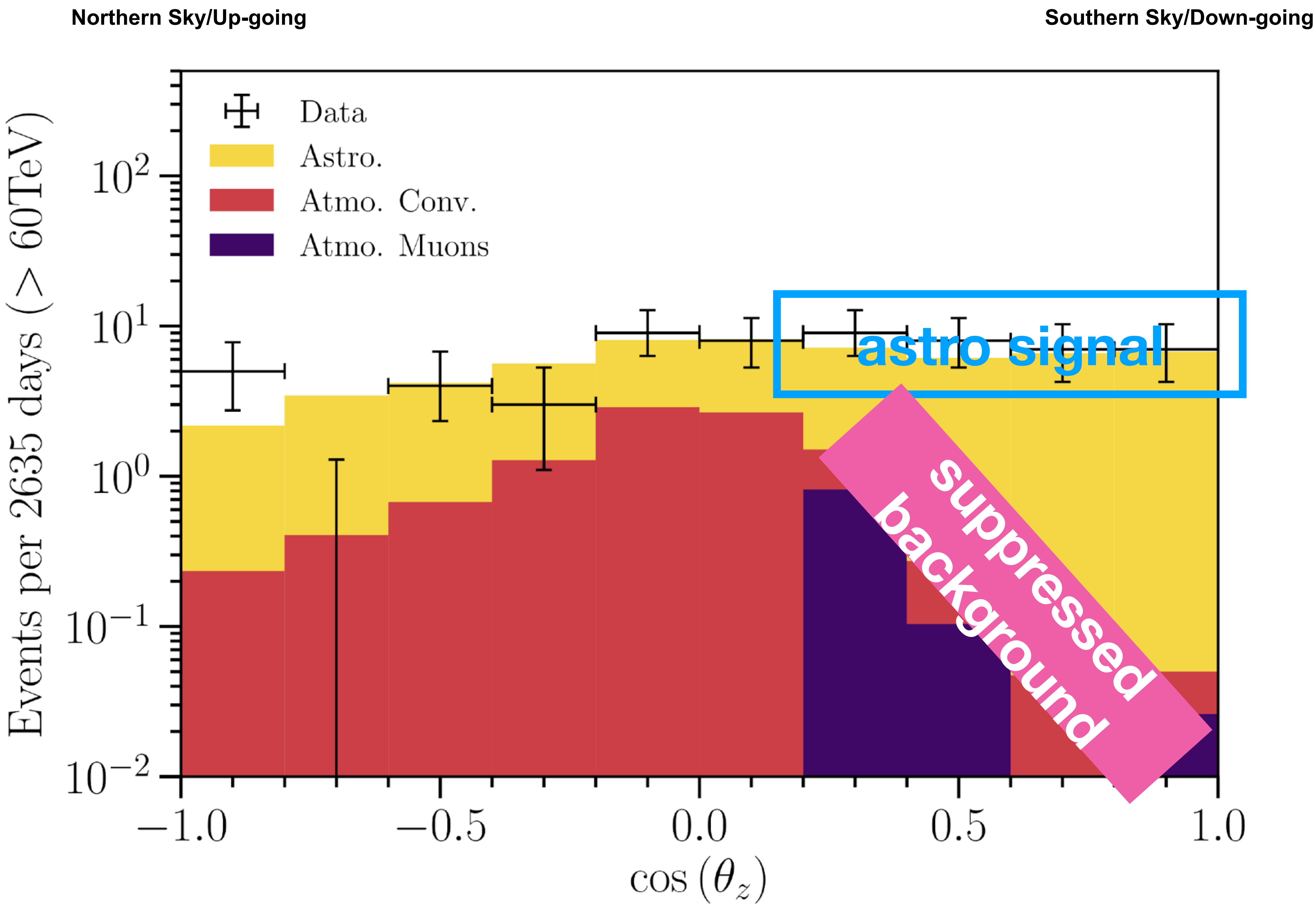


An active muon veto removes down-going atmospheric neutrinos.



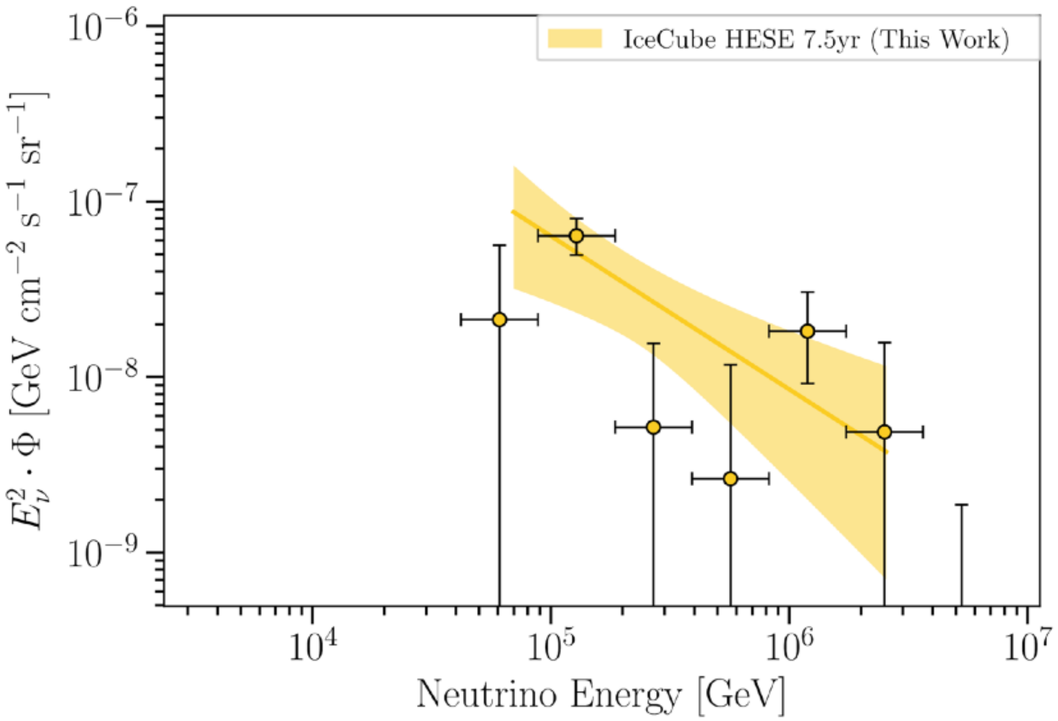
Schönert, Gaisser, Resconi, Schulz Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen Phys. Rev. D 90; 023009(2014)
CA, Palomares-Ruiz, Austin Schneider, Wille, Yuan JCAP 1807 (2018) no.07, 047

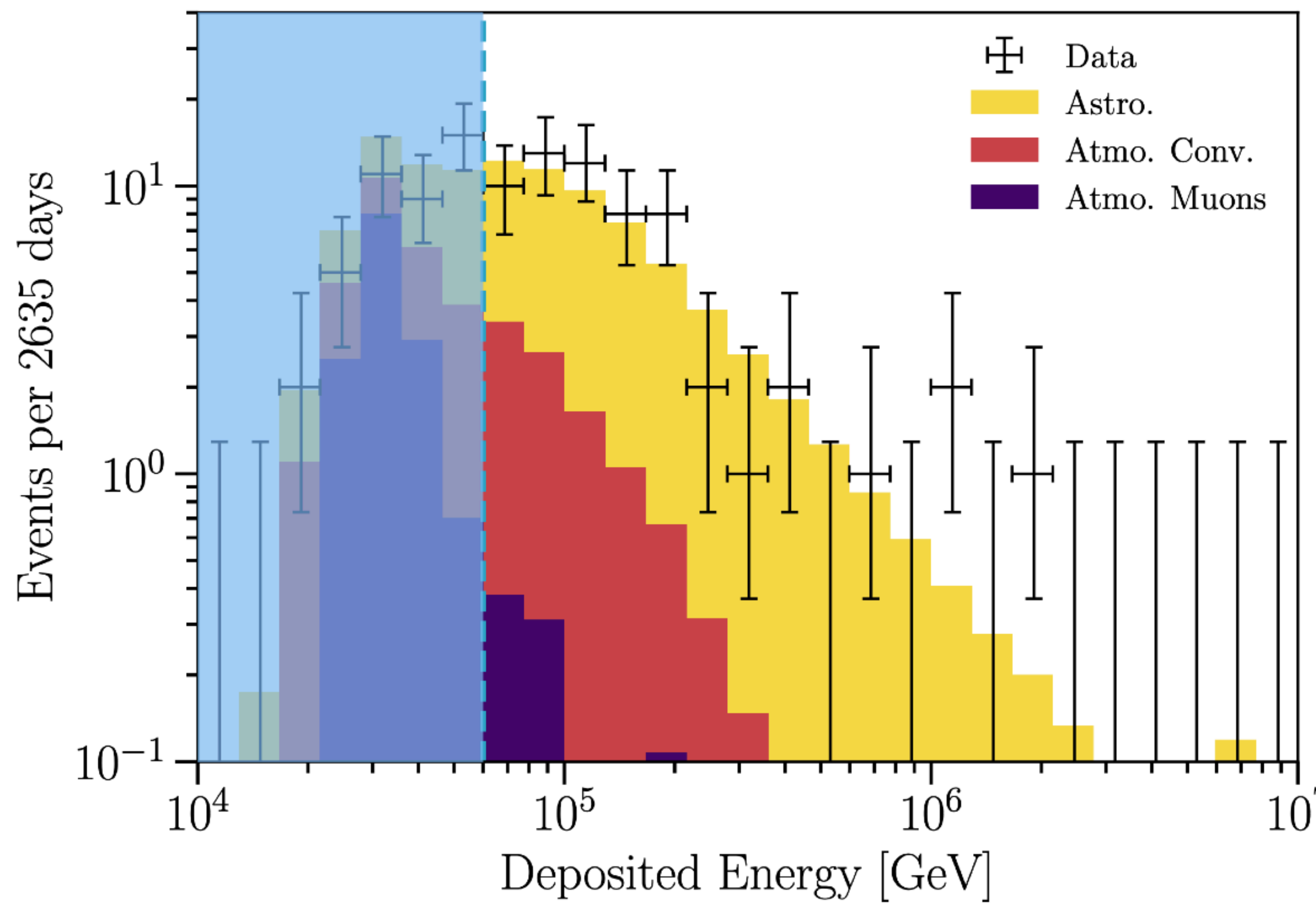
HESE-7.5 years angular distribution



Starting Events Energy Distribution And Inferred Spectrum

$$\gamma = 2.9 \pm 0.2$$

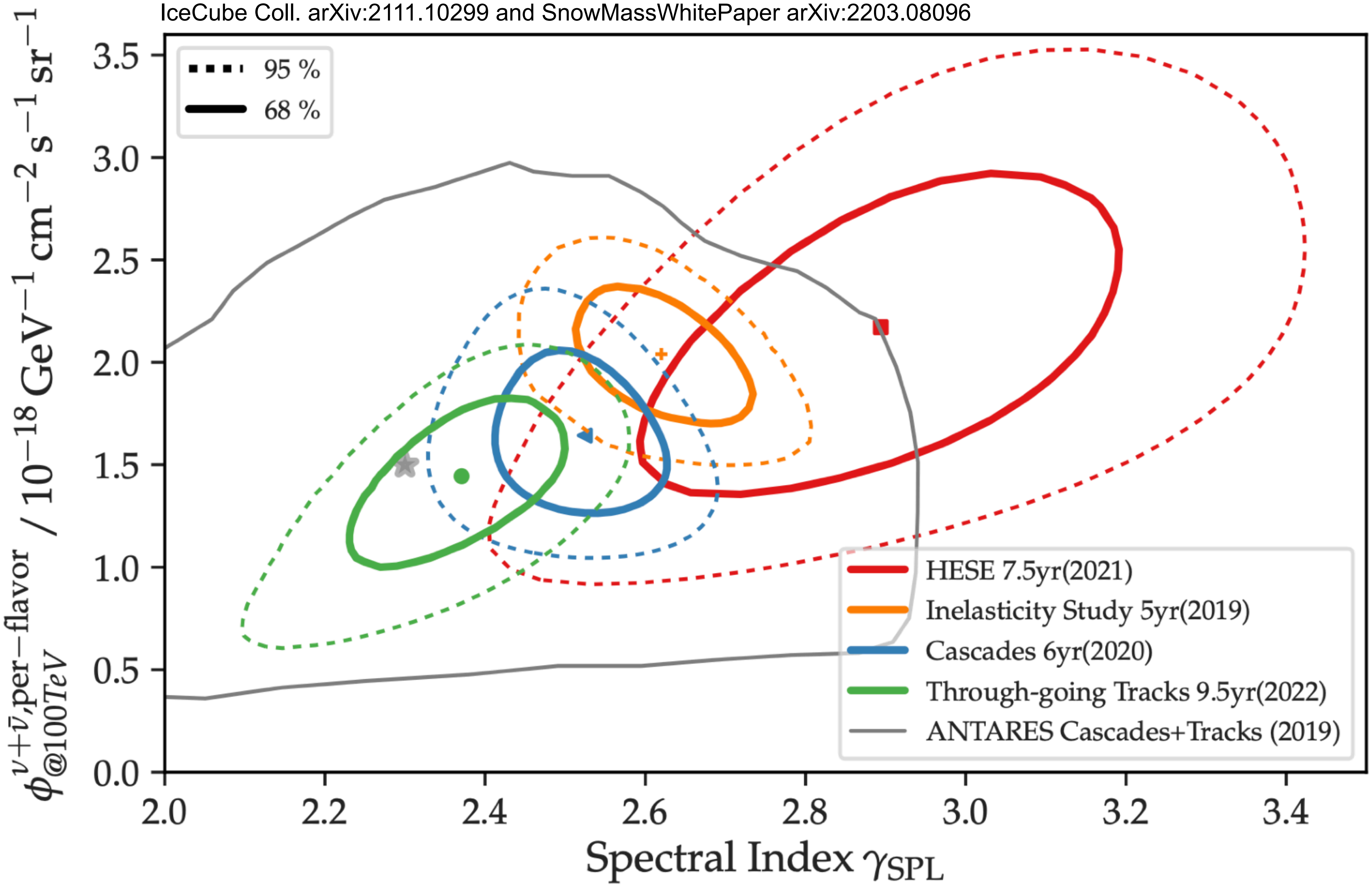




High-Energy Starting Events energy distribution is well described by a single power-law, but with a *spectral index softer* than the northern tracks!

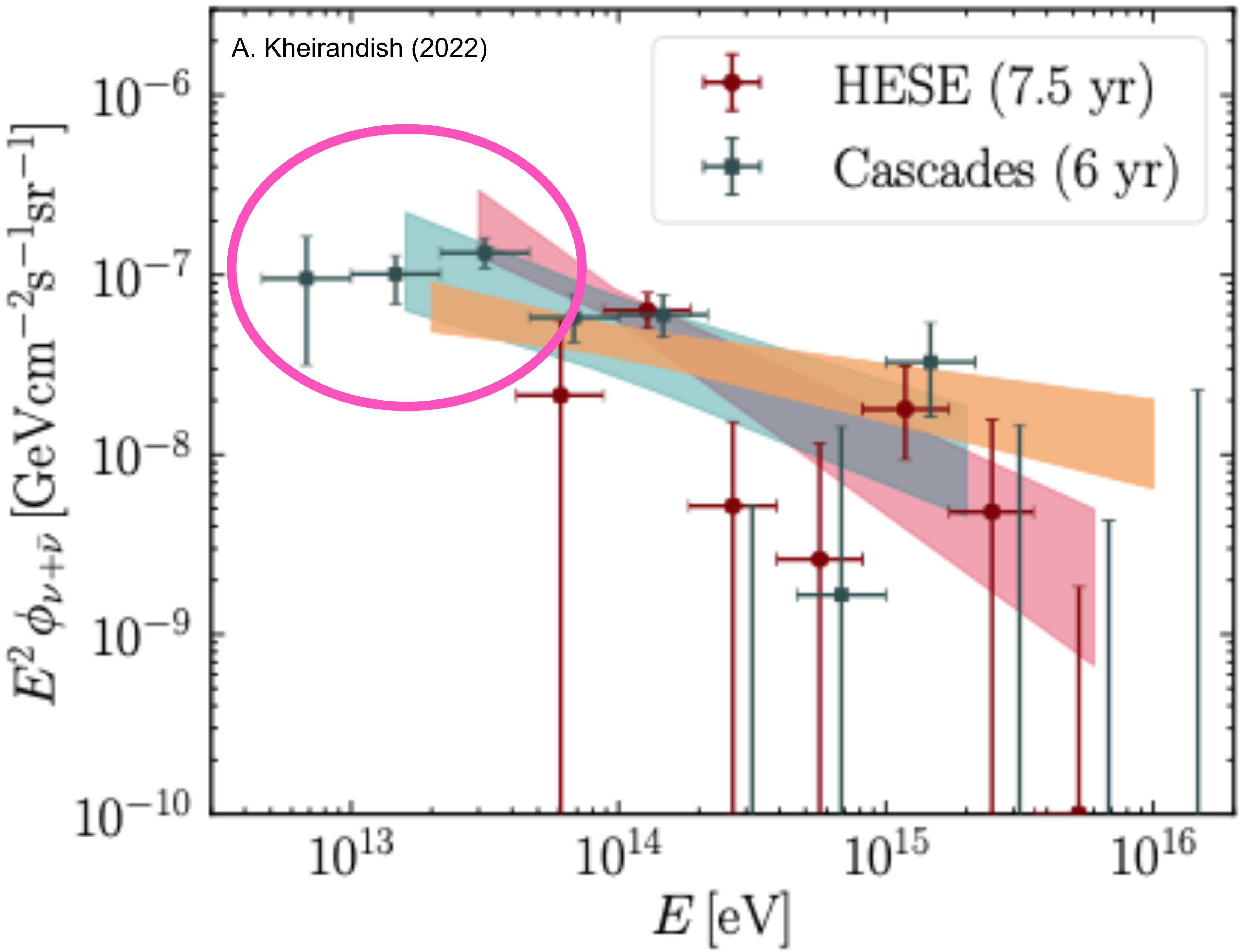
Comparison of different single power-law spectra

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?

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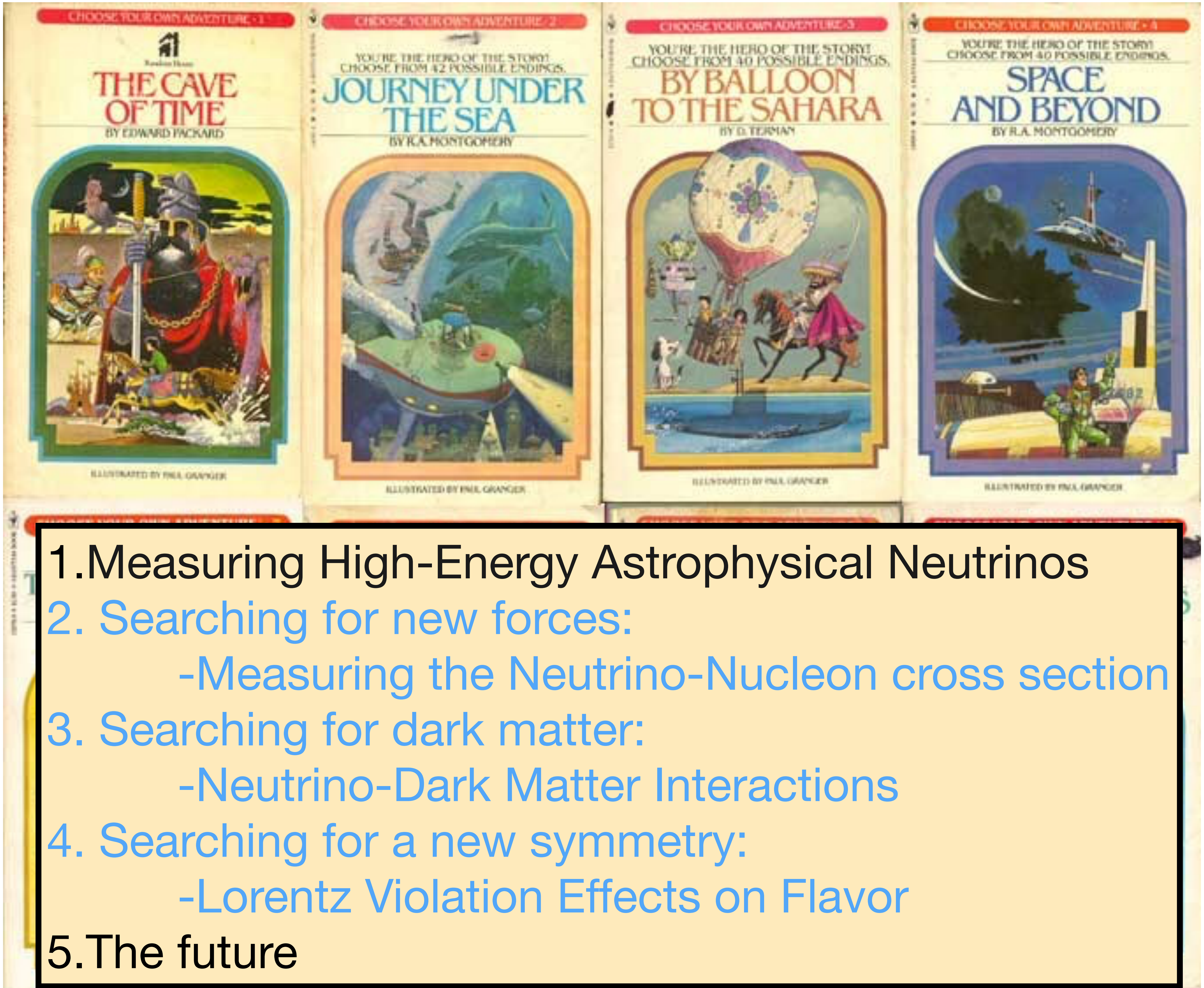
5.The future

Choose your own adventure!



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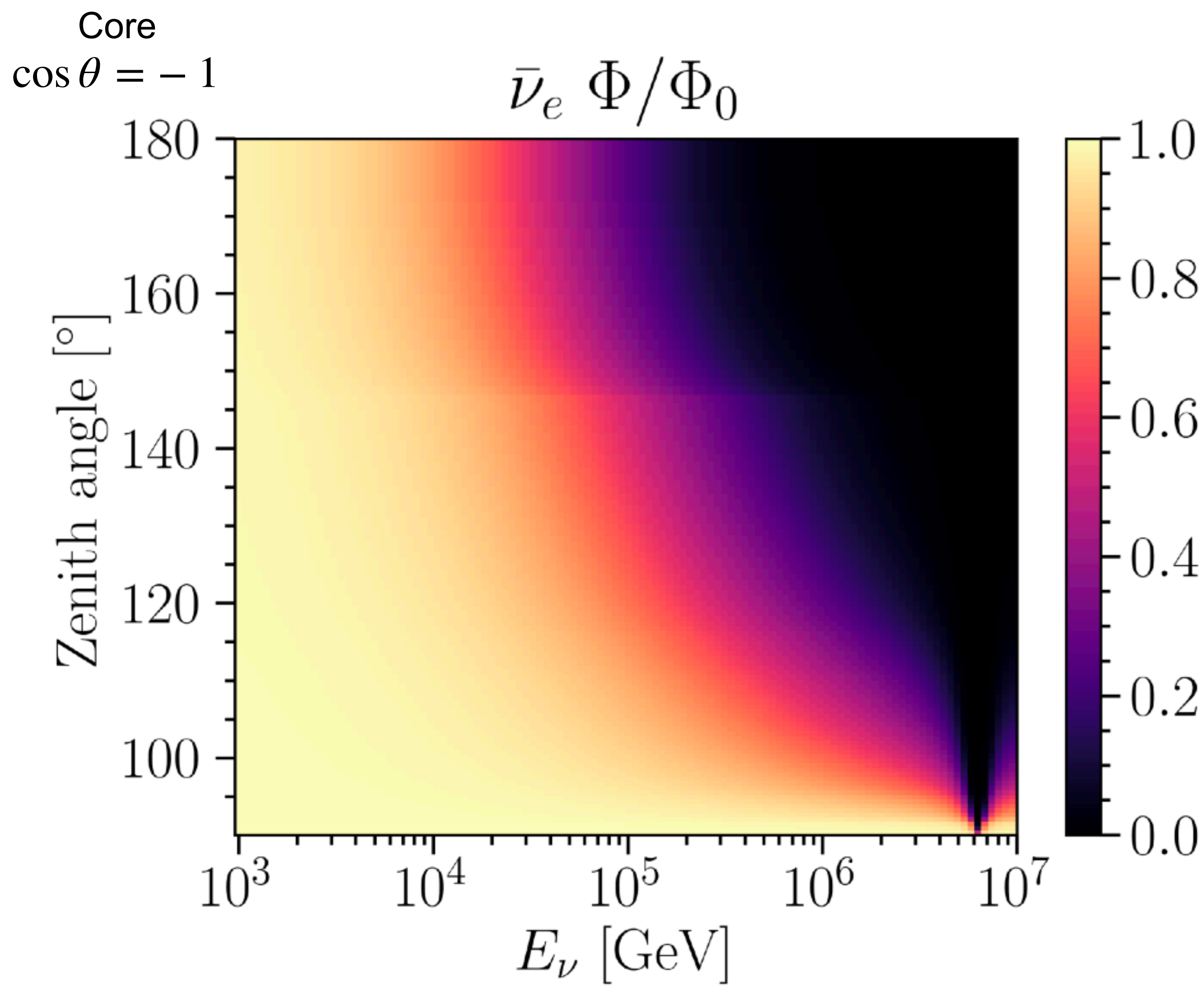
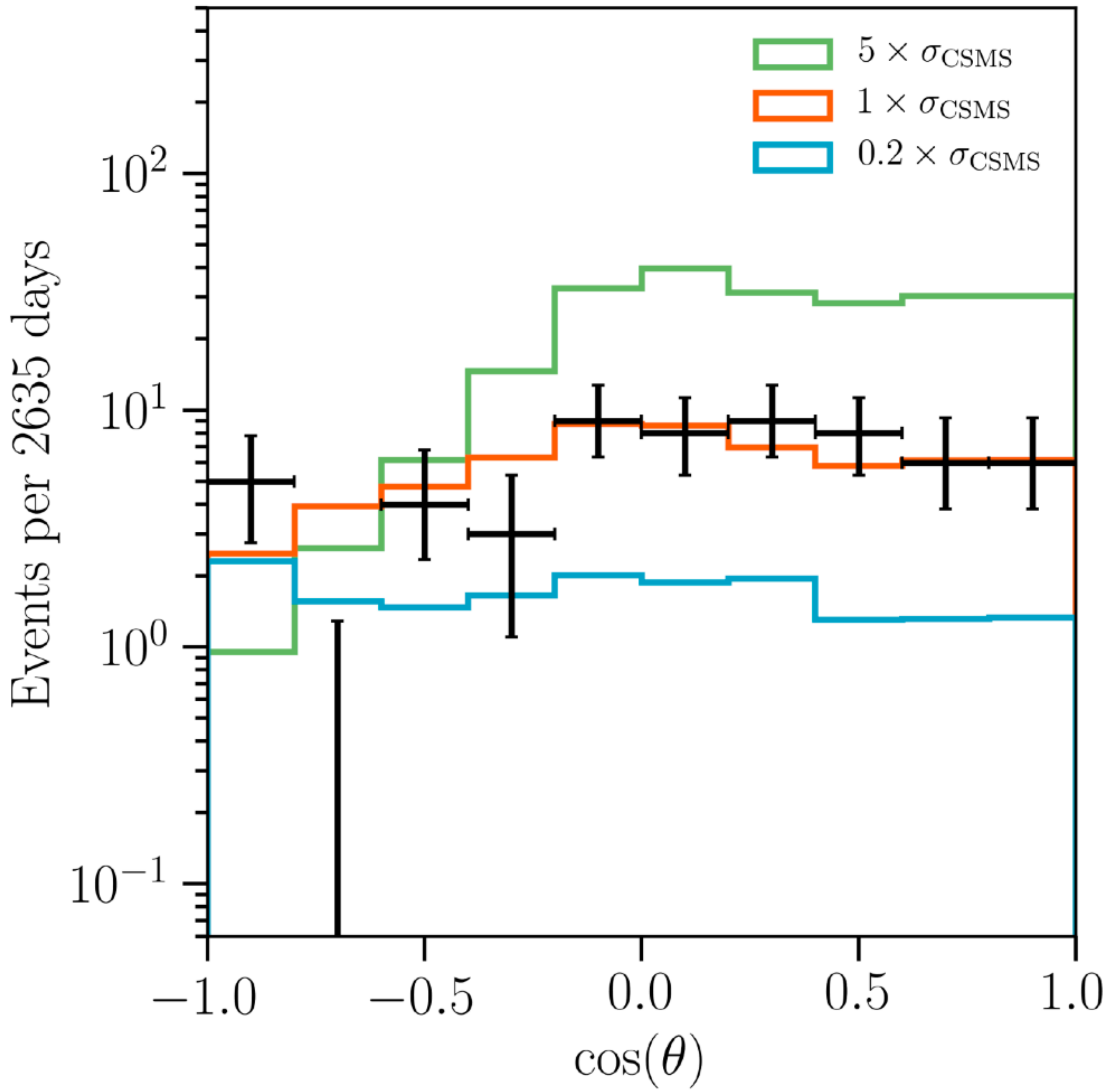
We can use the Earth opacity to infer the neutrino deep-inelastic cross section*

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

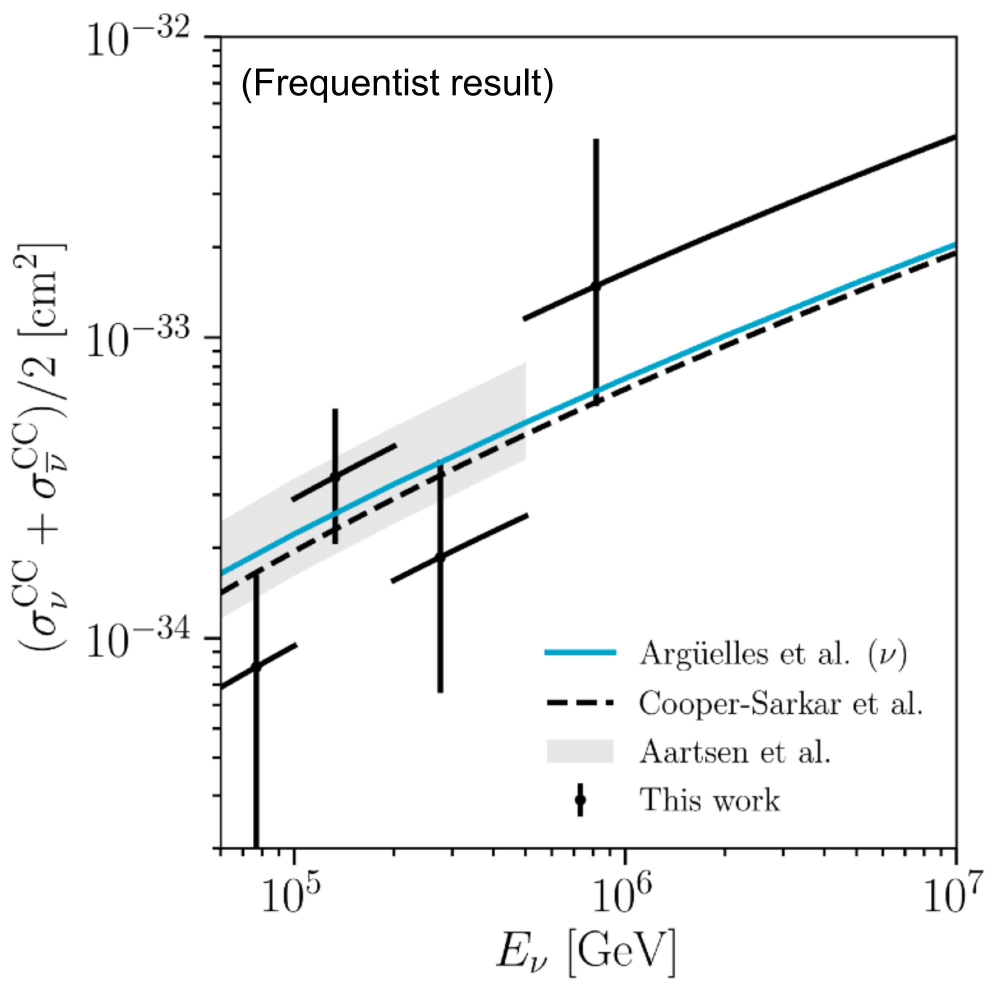


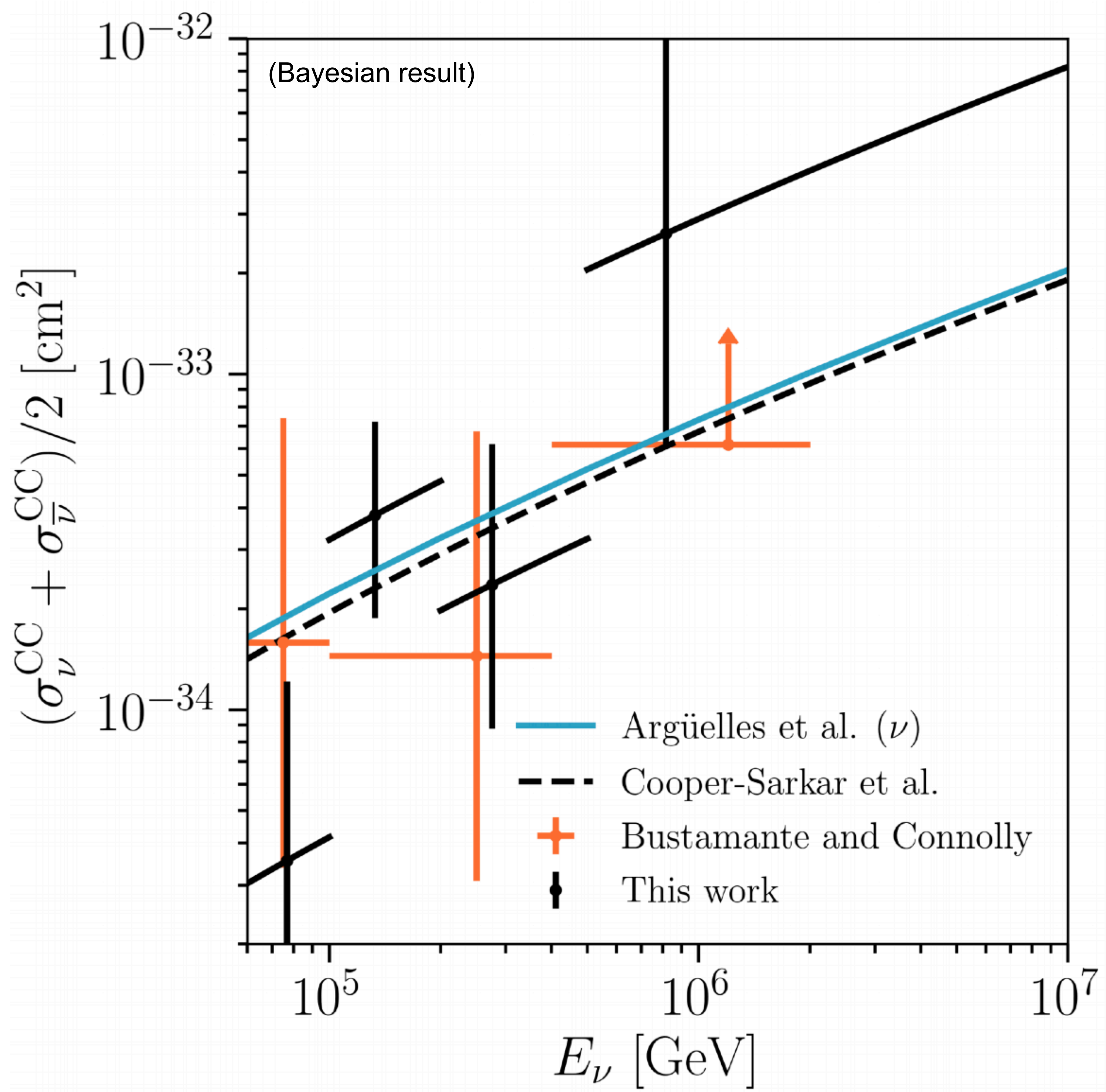


CSMS: is a NLO pQCD reference calculation of the neutrino-nucleon cross section, Cooper-Sarkar et al, JHEP 08 (2011) 042. See also A. Garcia et al JCAP 09 (2020) 025; CA, F. Halzen, L. Wille, M. Kroll, MH Reno, Phys. Rev. D92: 074040 (2015); A. Connolly *et al* Phys. Rev. D83: 113009,2011; R. Gandhi 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	$4.31^{+13.26}_{-3.32}$	$2.44^{+5.10}_{-1.47}$



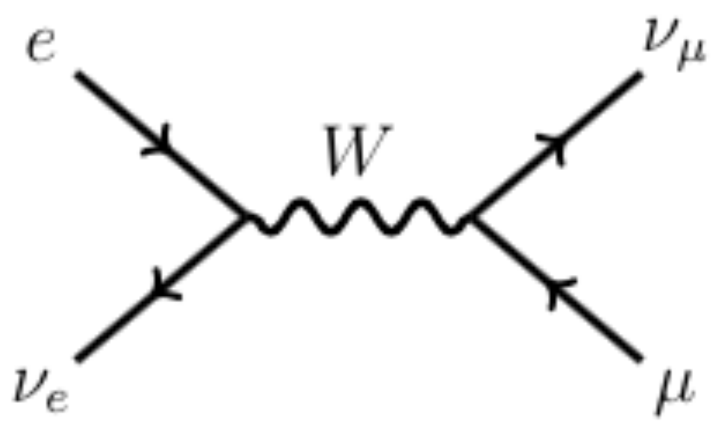


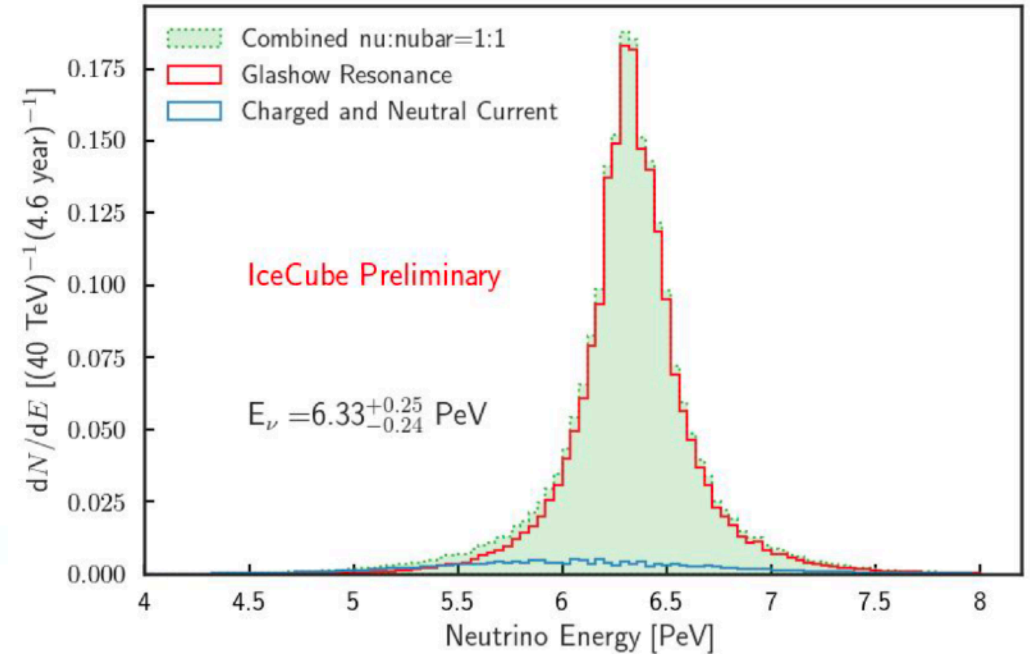
Bustamante & Connolly: PRL 122, 041101 (2019)
Argüelles: Phys. Rev. D92: 074040 (2015)
Cooper-Sarkar: JHEP 08 (2011) 042

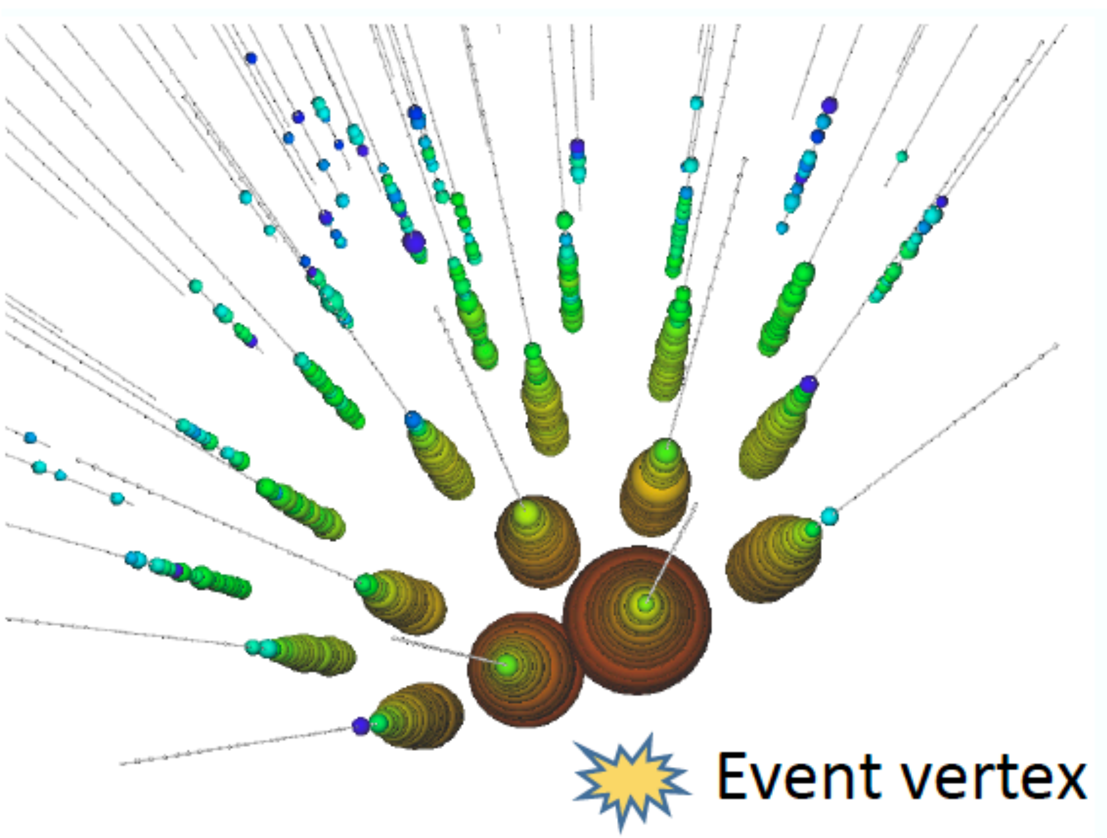
The first Glashow resonance event:

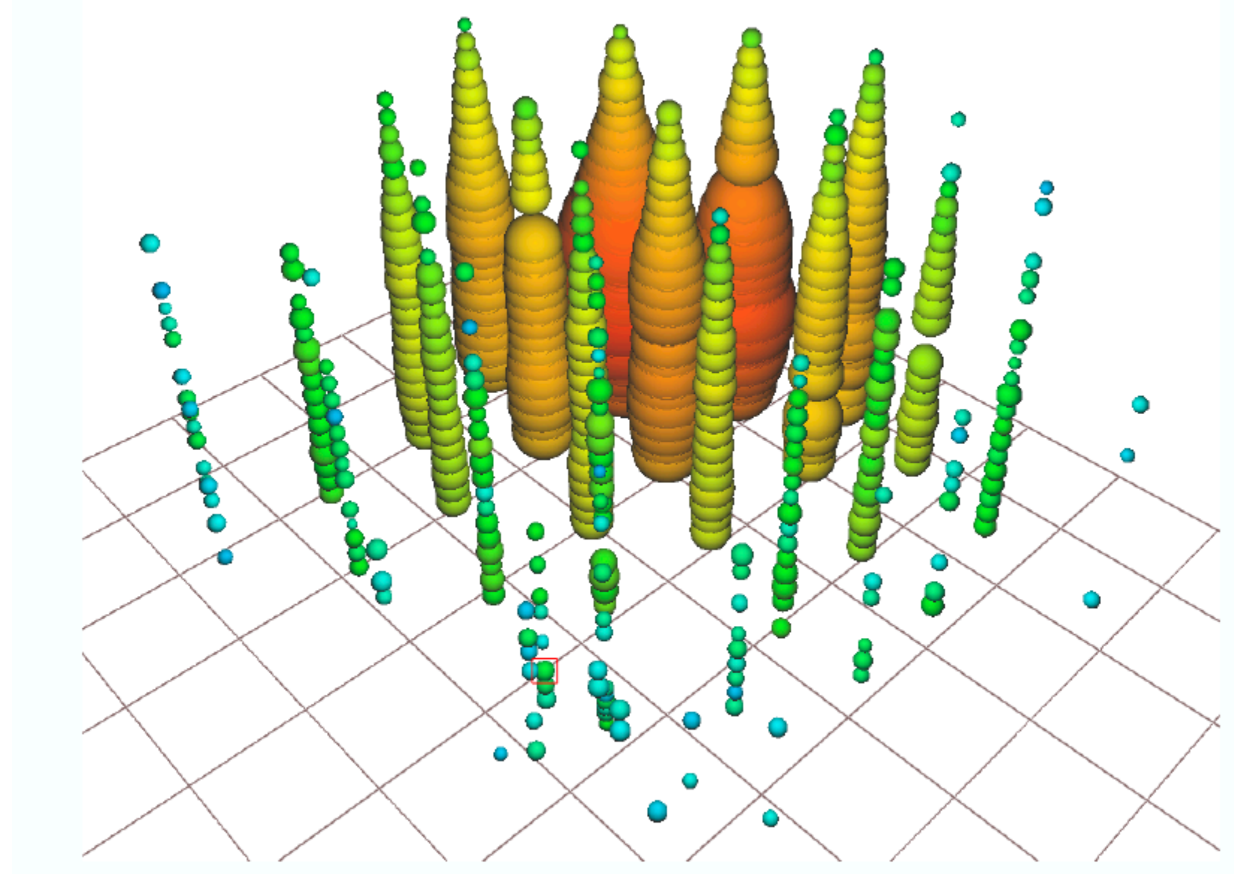
anti-ν_e + atomic electron → real W at 6.3 PeV

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









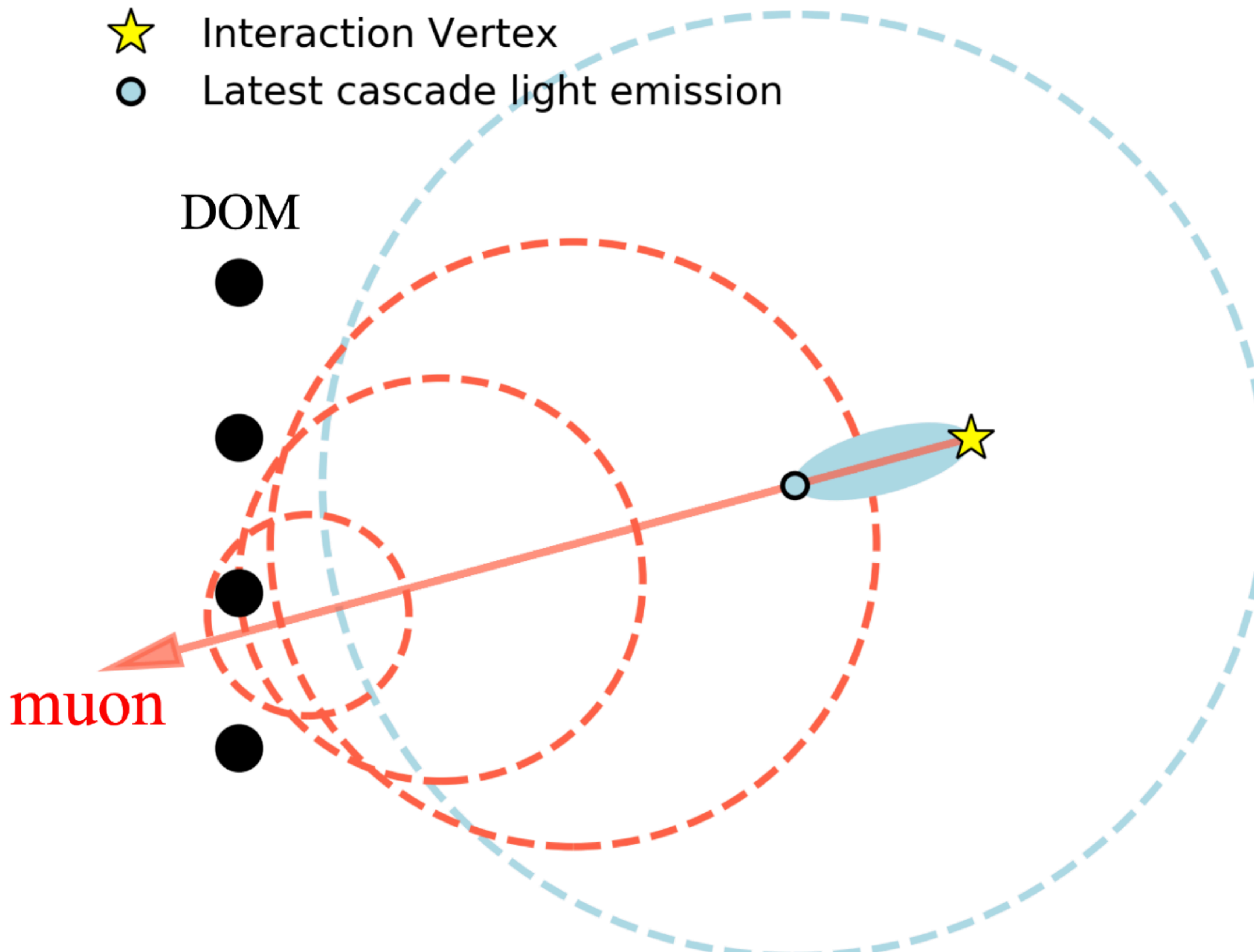
W production or background?

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

Or

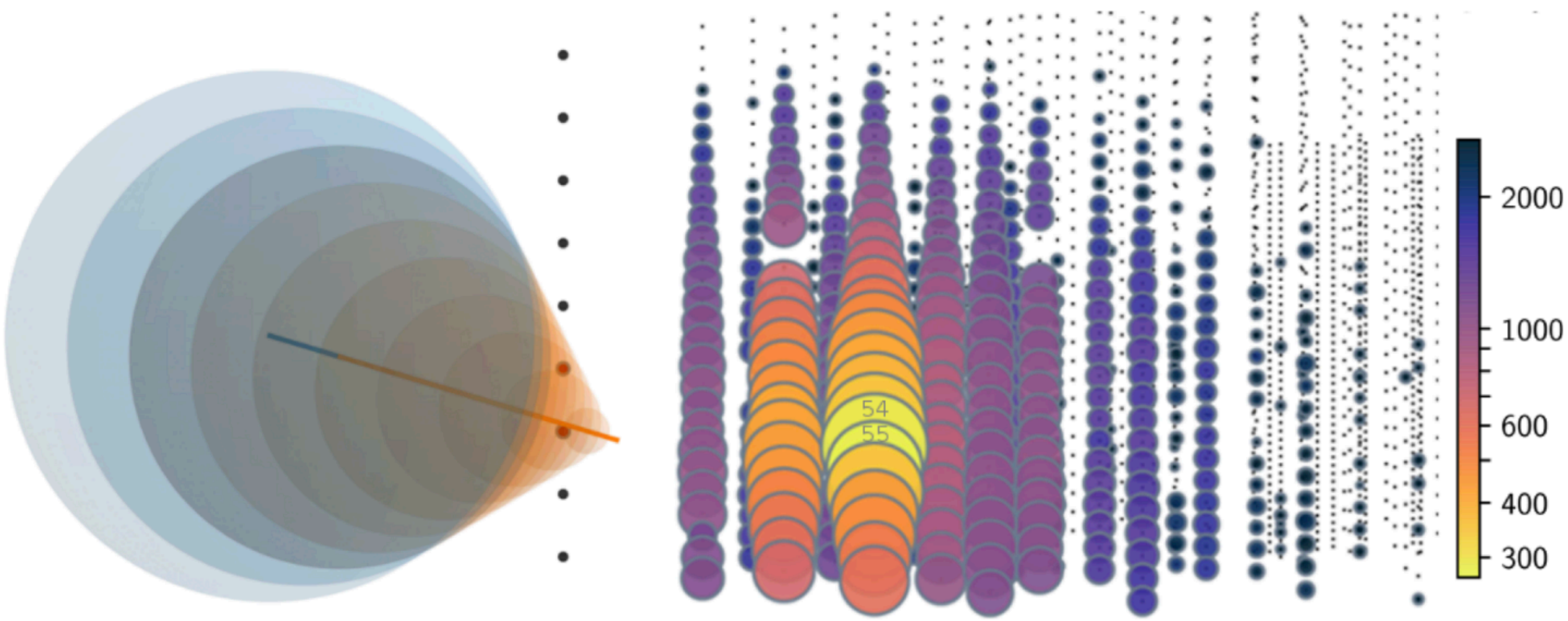
Background:
electromagnetic shower radiated by a high energy background cosmic-ray muon

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



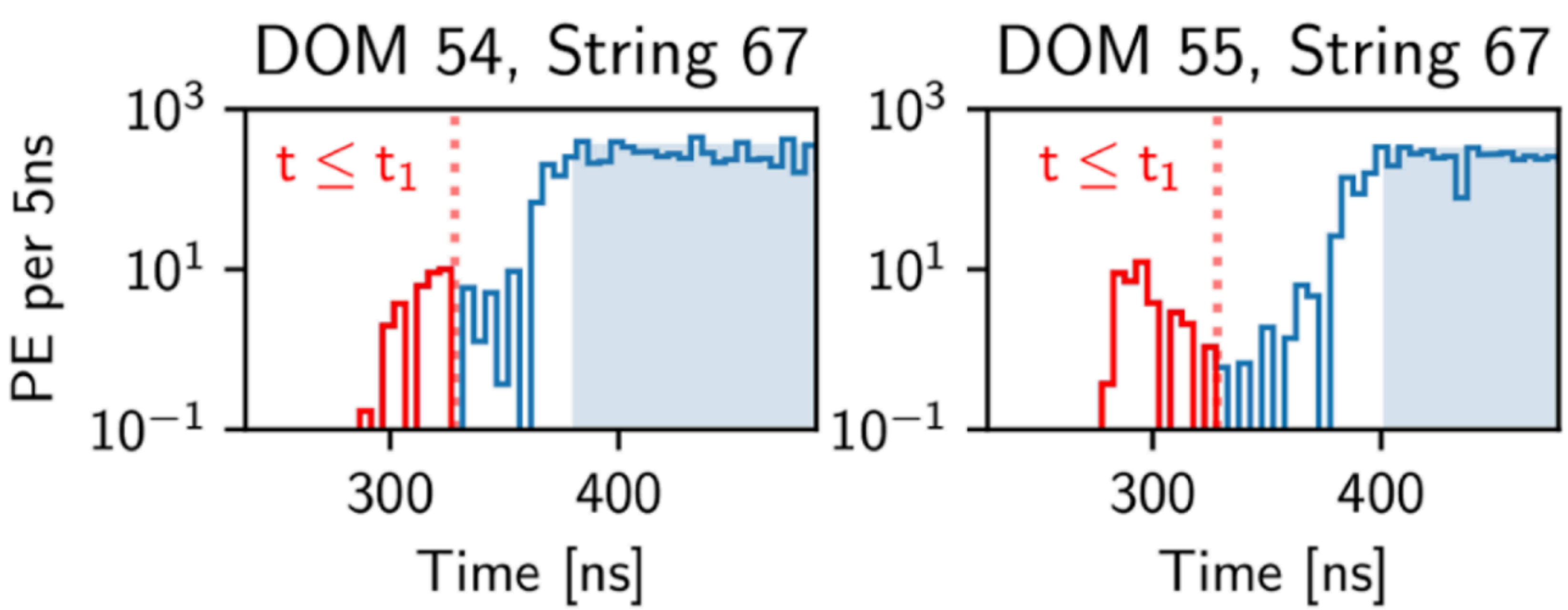
Hadronic shower from W-decay:

Early muons followed by electromagnetic shower



t_1=328 ns

3μs after t_1



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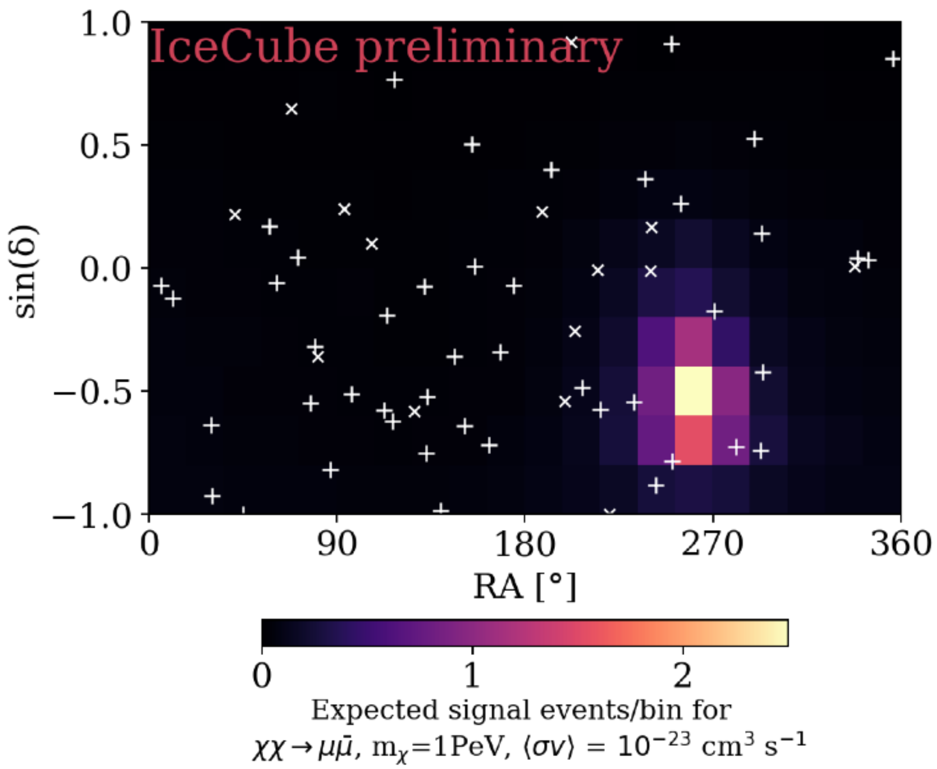
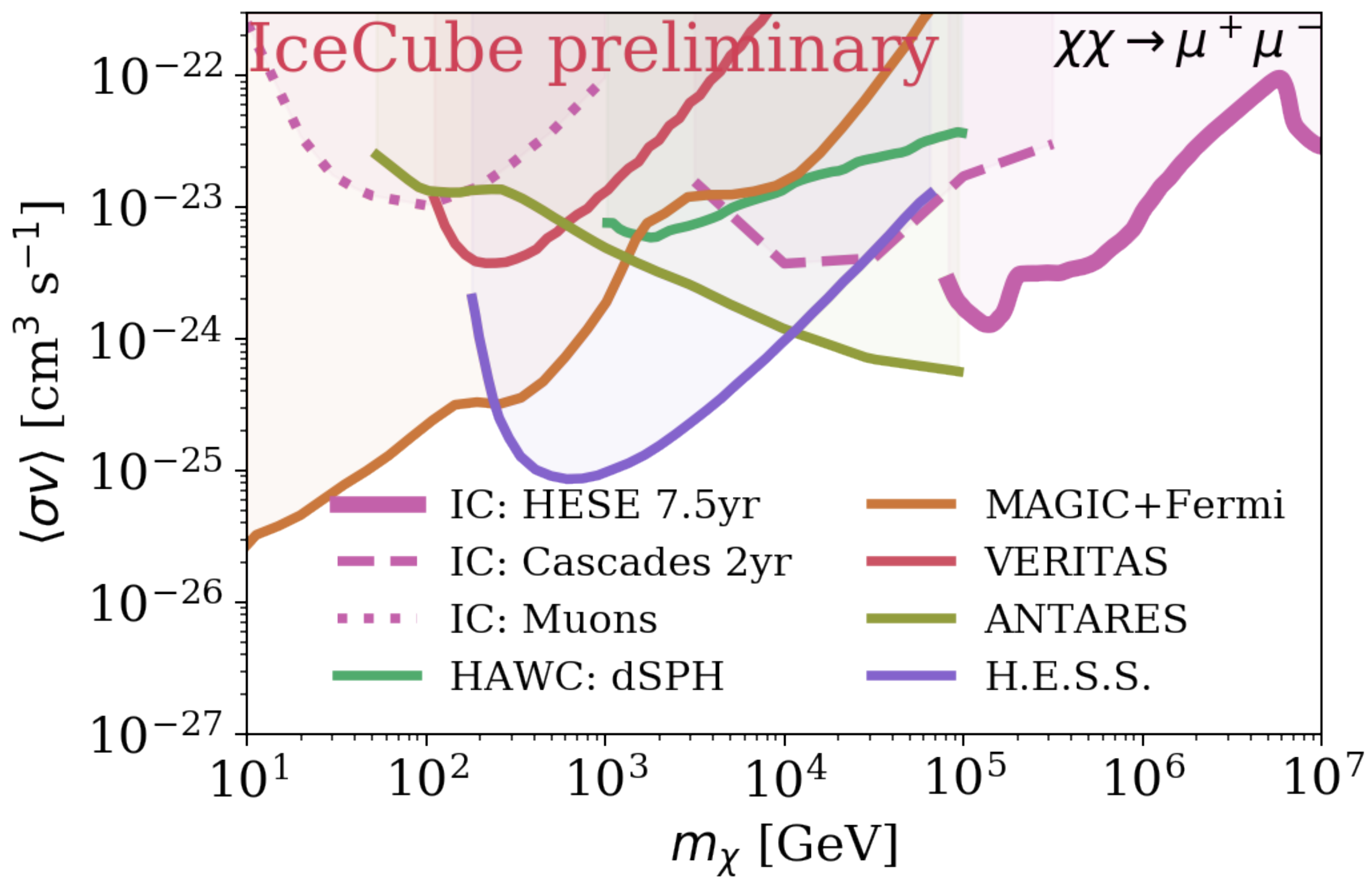
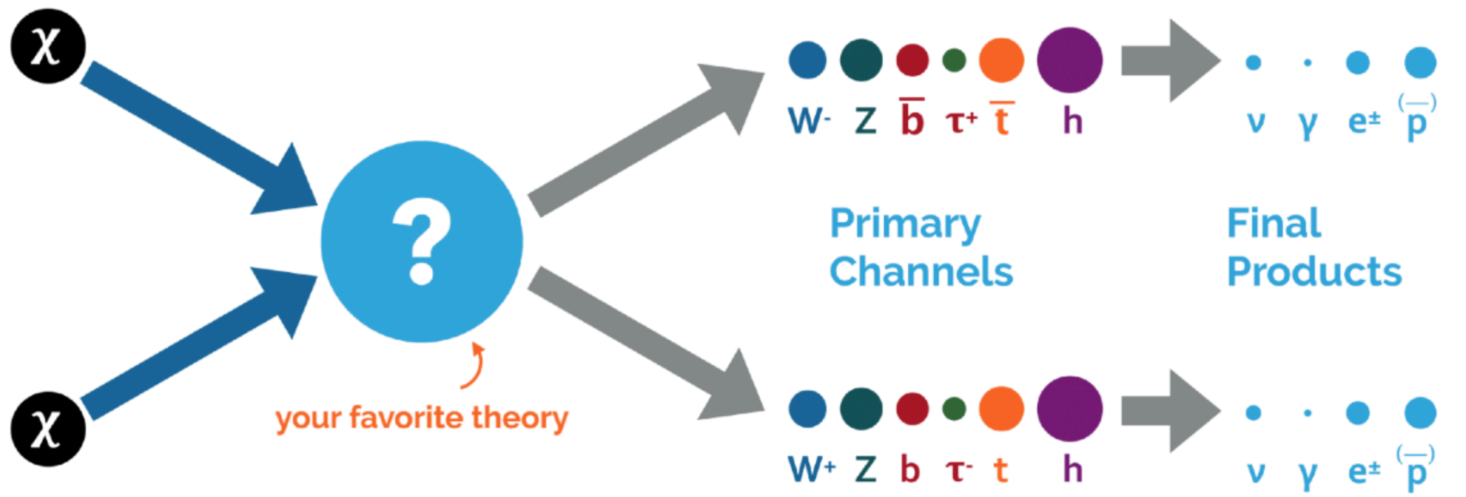
Dark matter annihilation

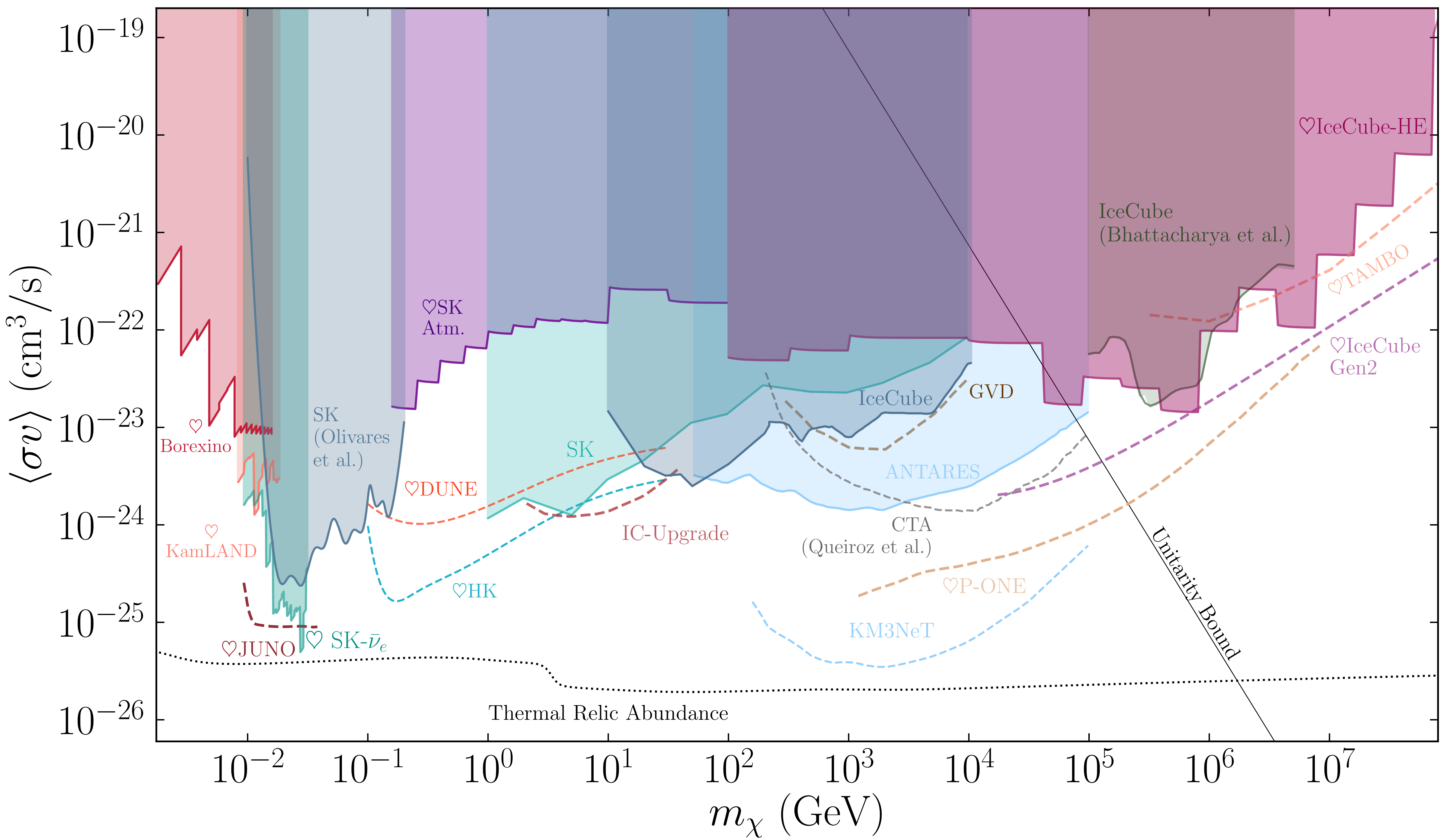






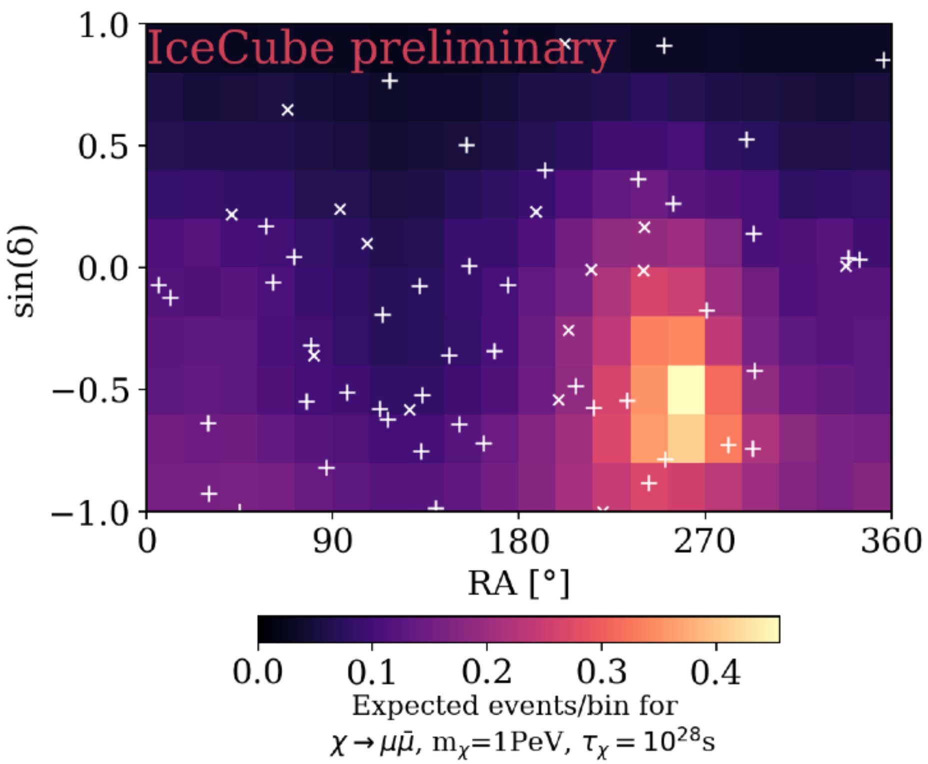
CA, H. Dujmovic arXiv 1907.11193.
See also Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

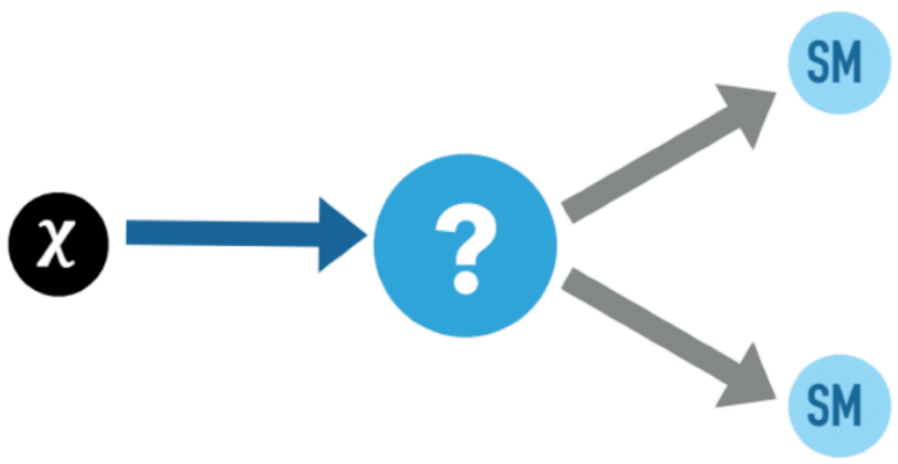
And many more measurements ...

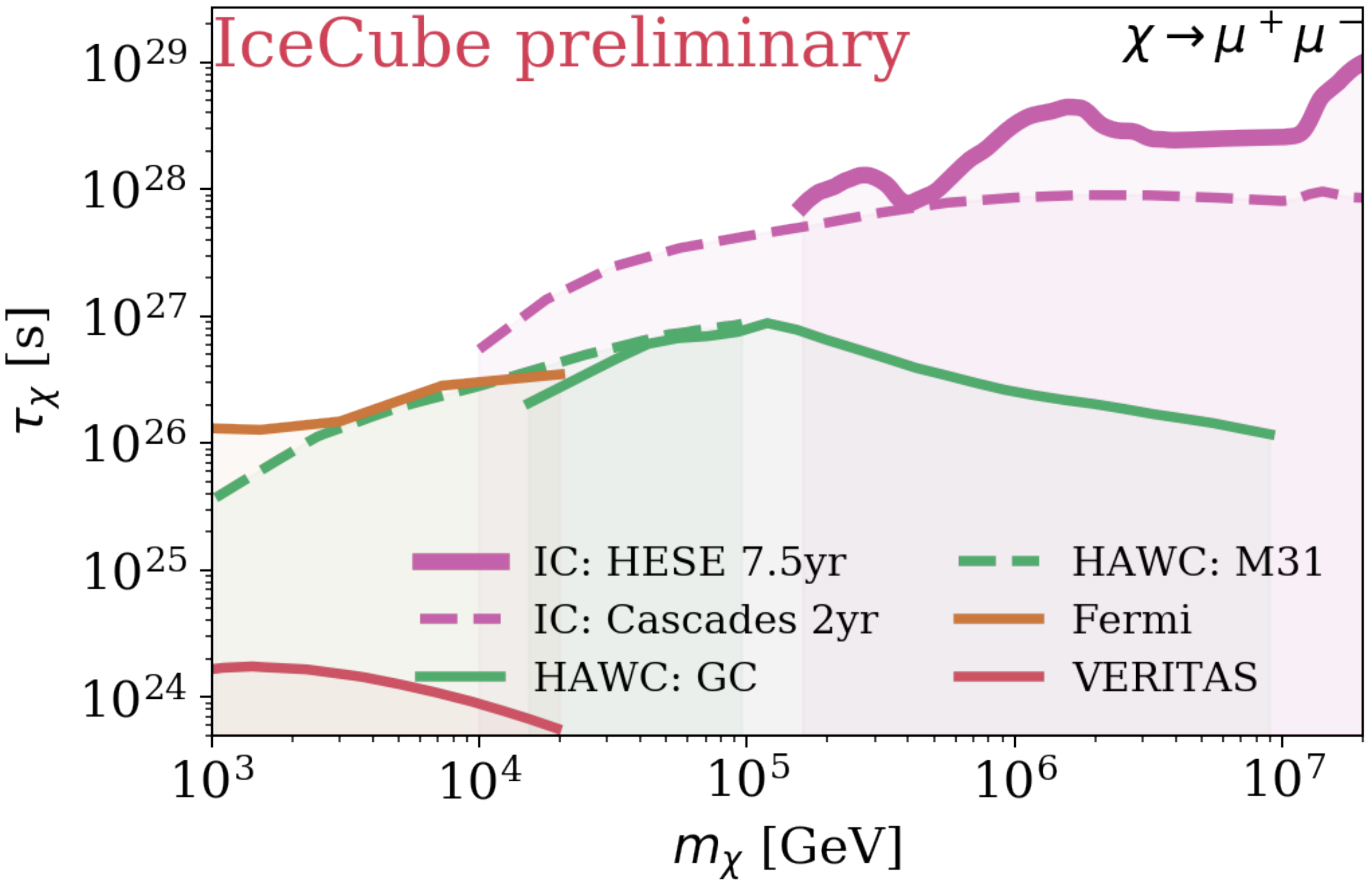


CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.

Dark matter decay







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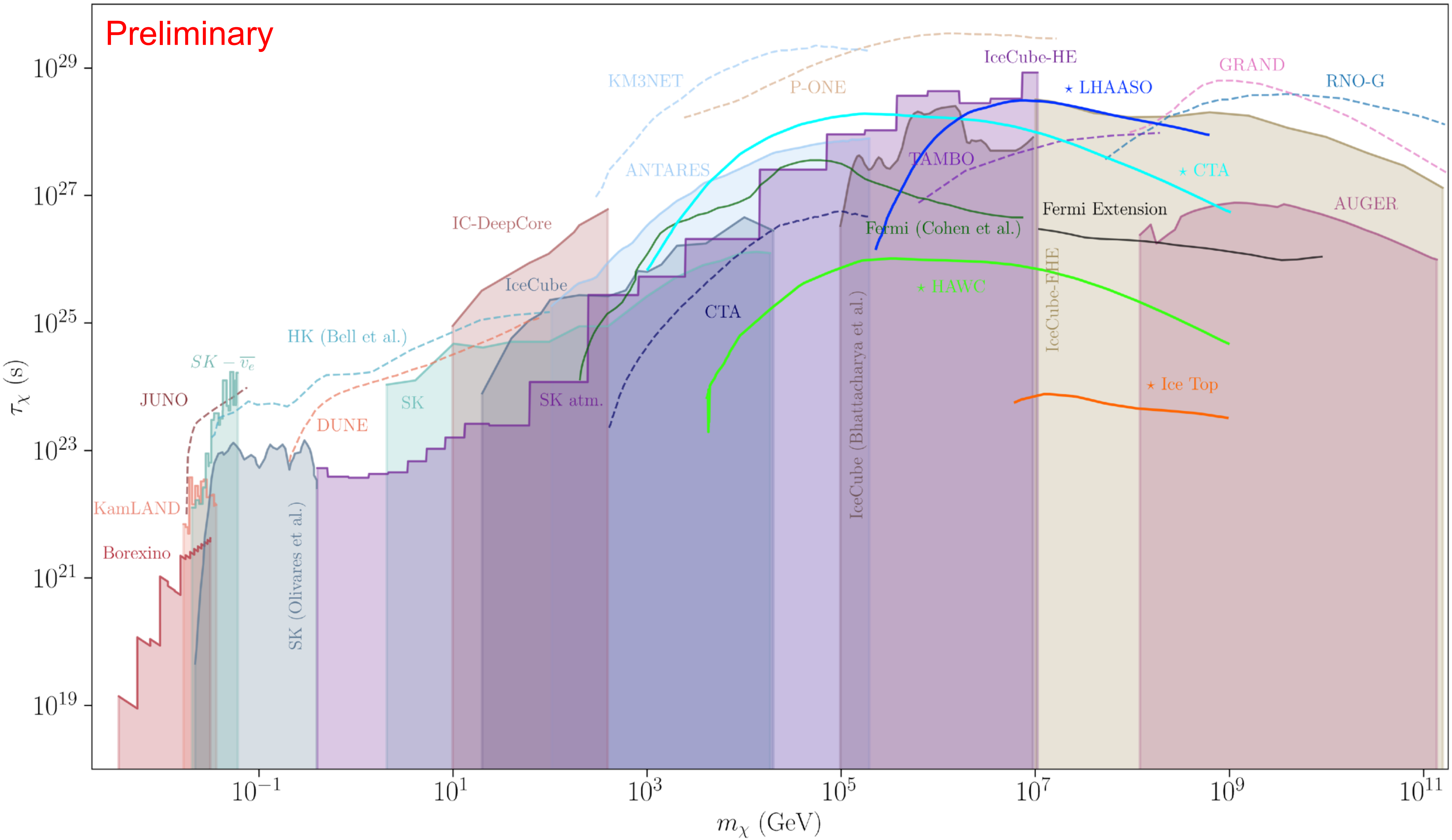
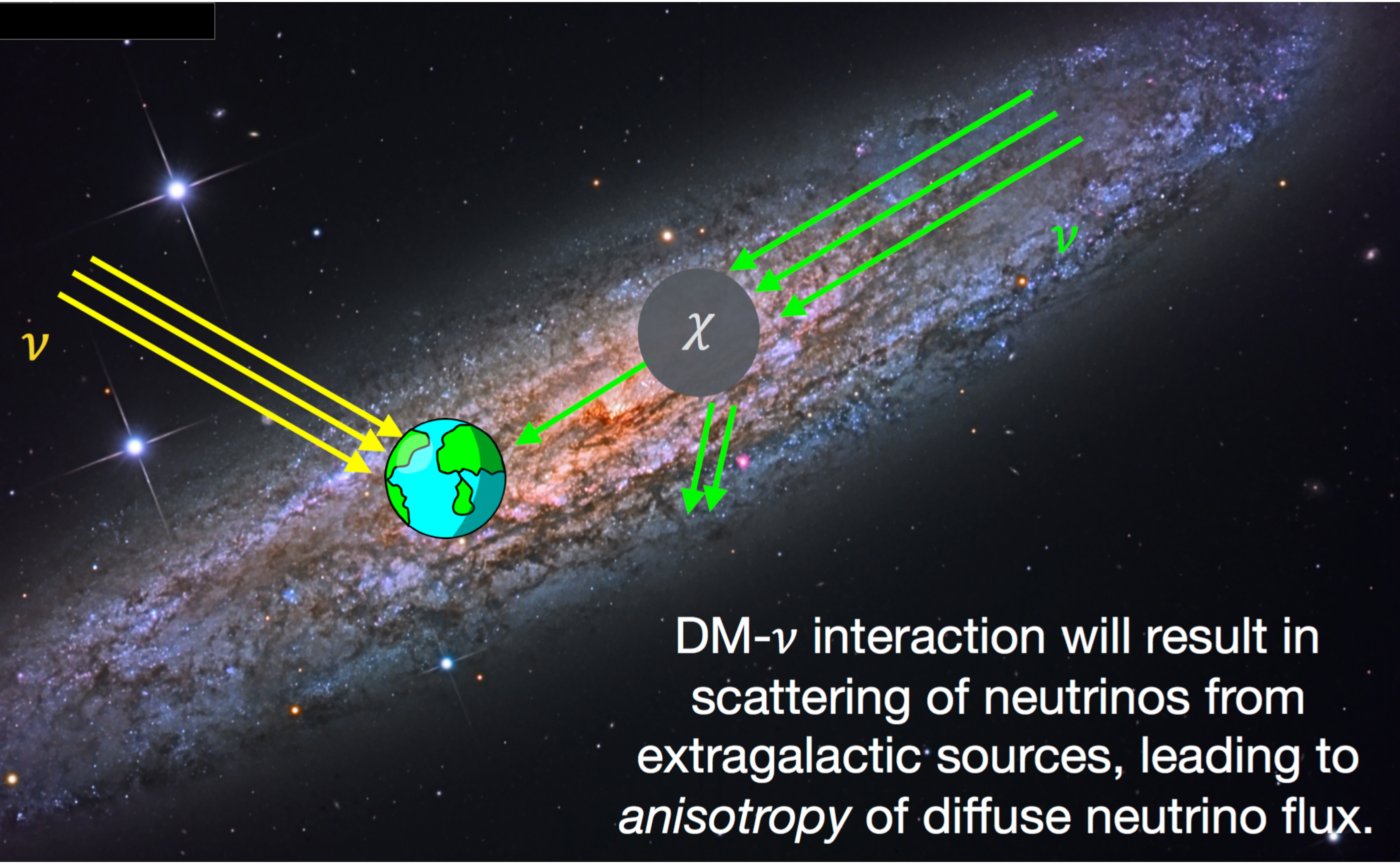


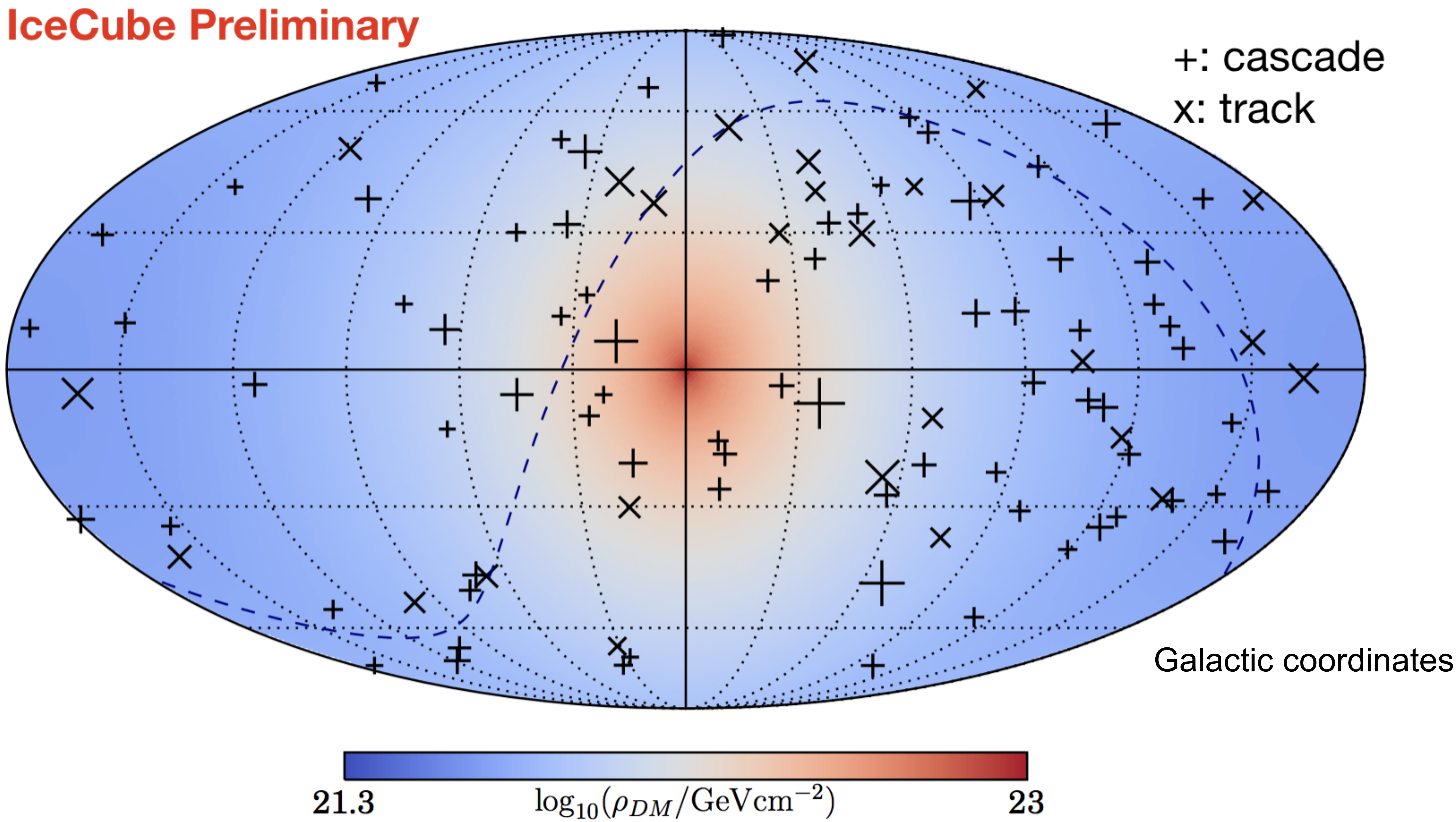
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White
to appear soon…

Dark matter neutrino scattering



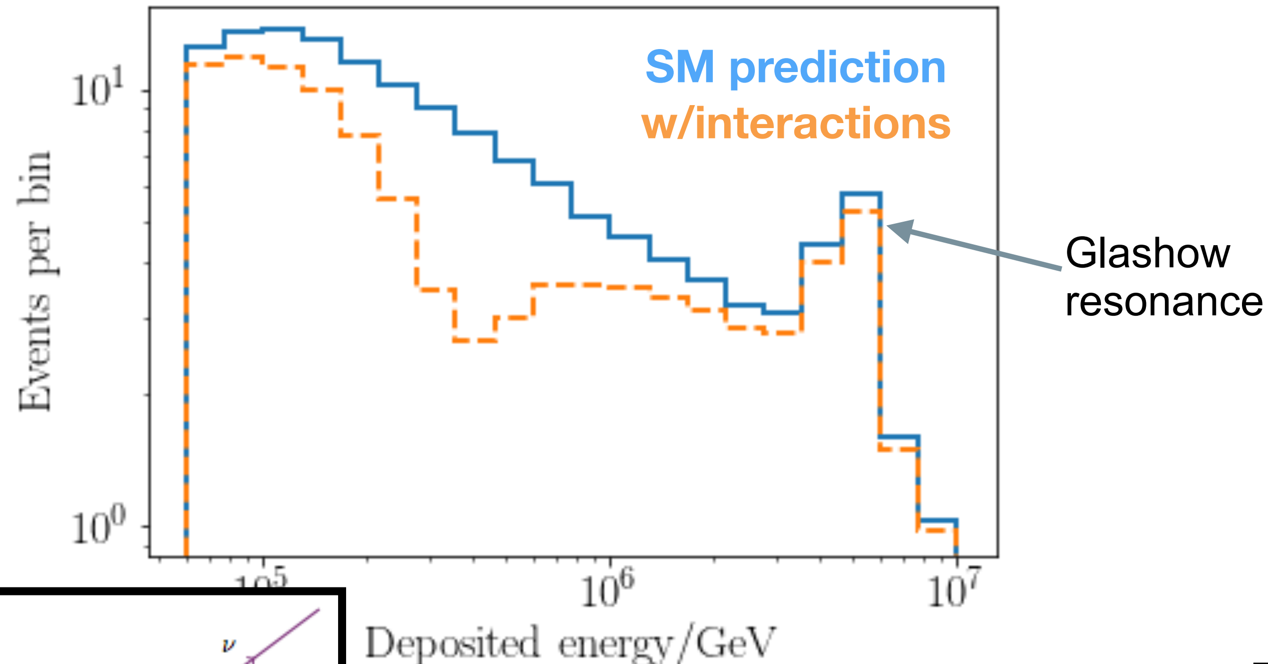
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

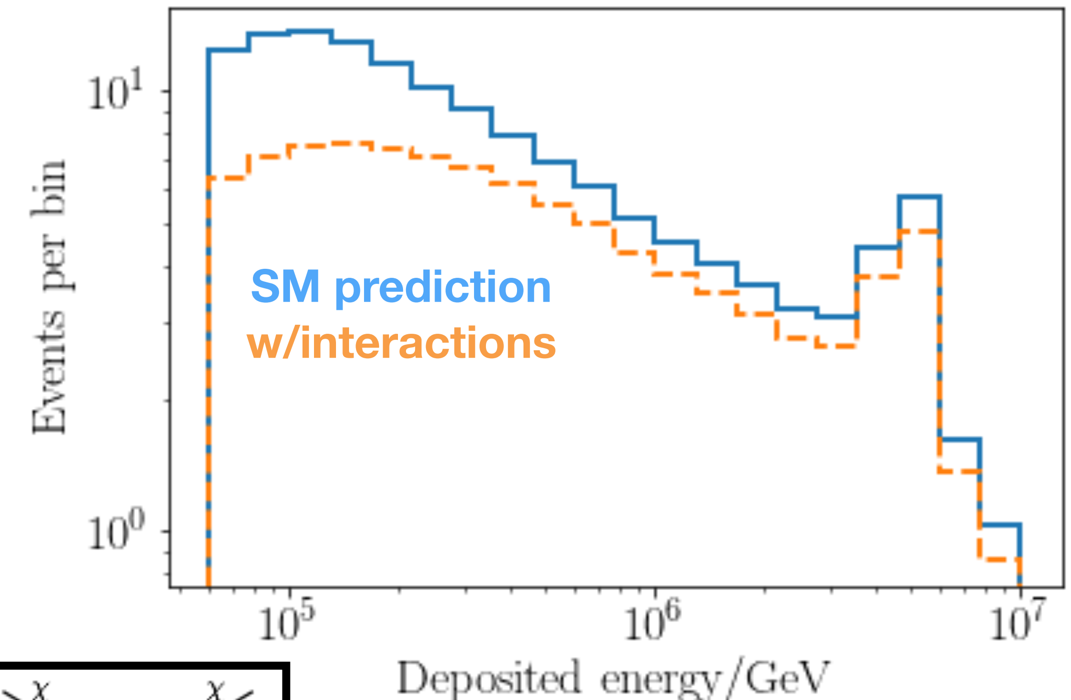
HESE Neutrino skymap

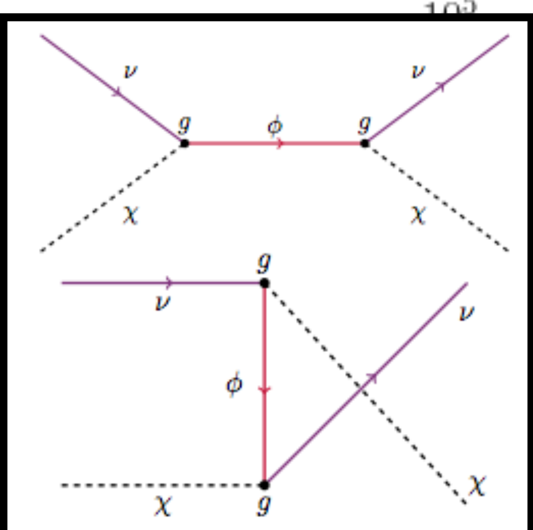


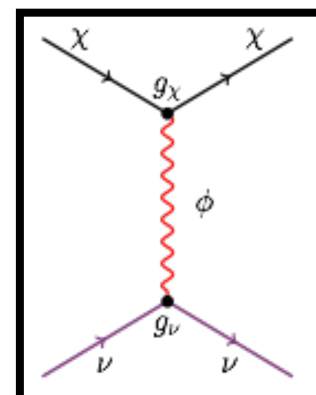
Events are compatible with an isotropic distribution: found no signal!

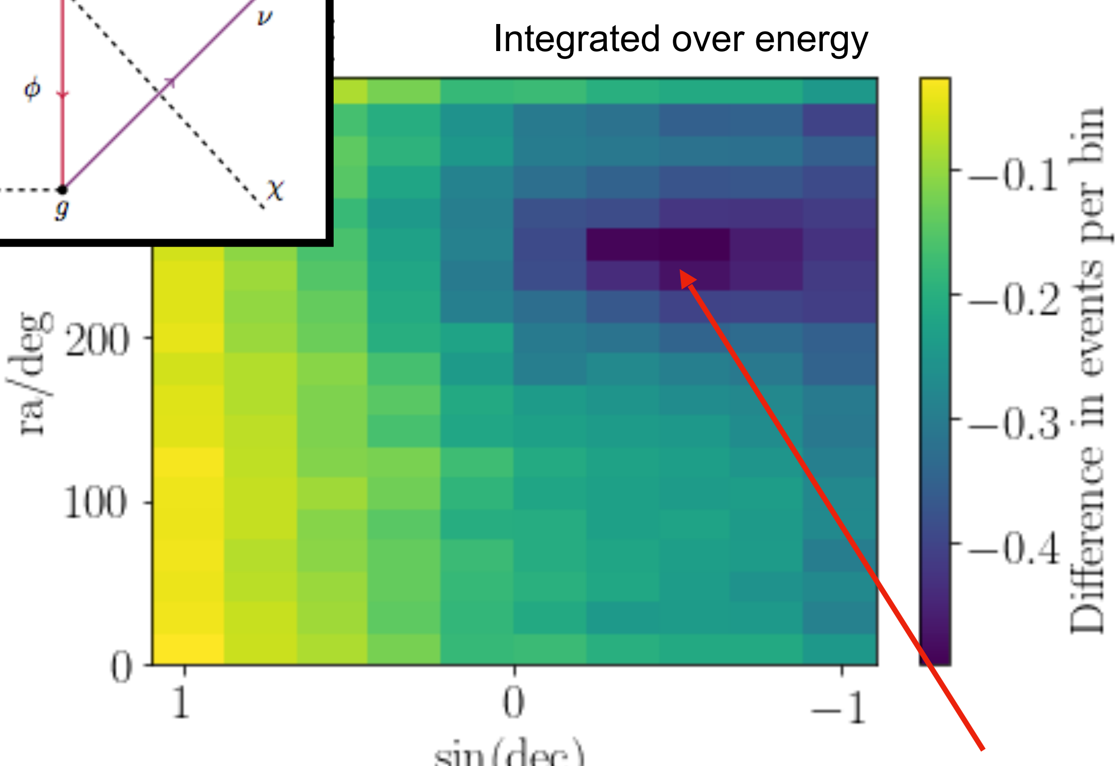
Also include effects in energy and direction

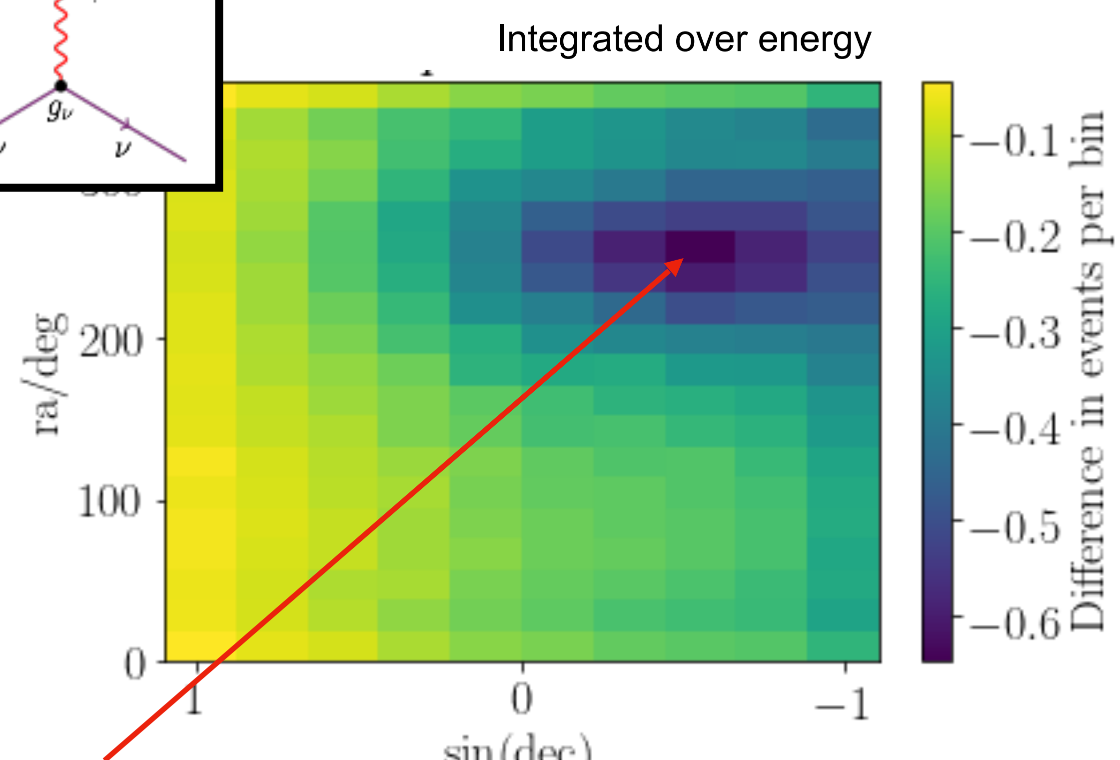






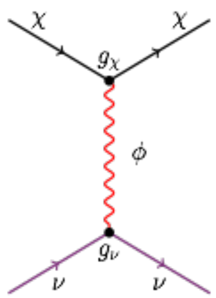




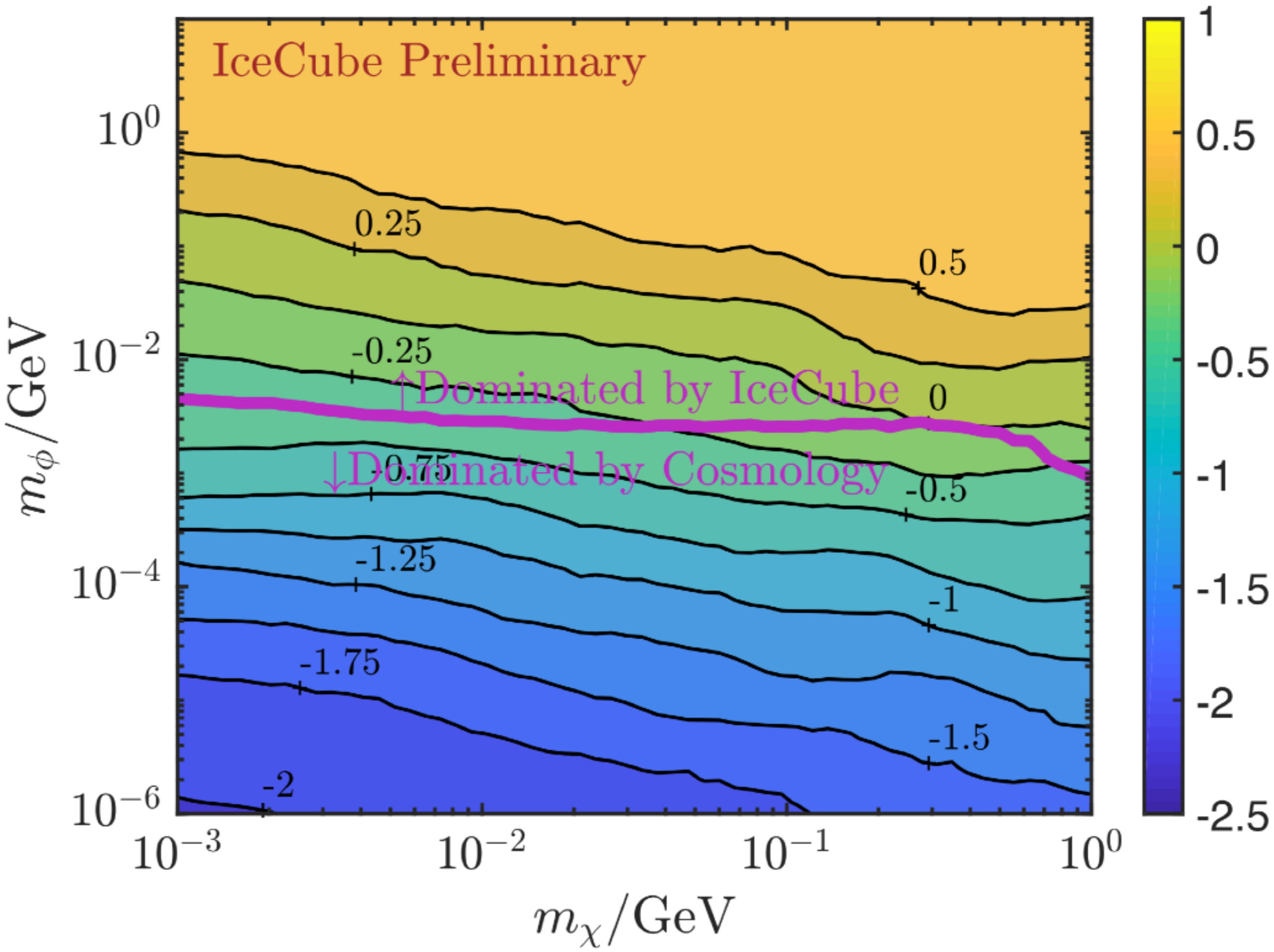


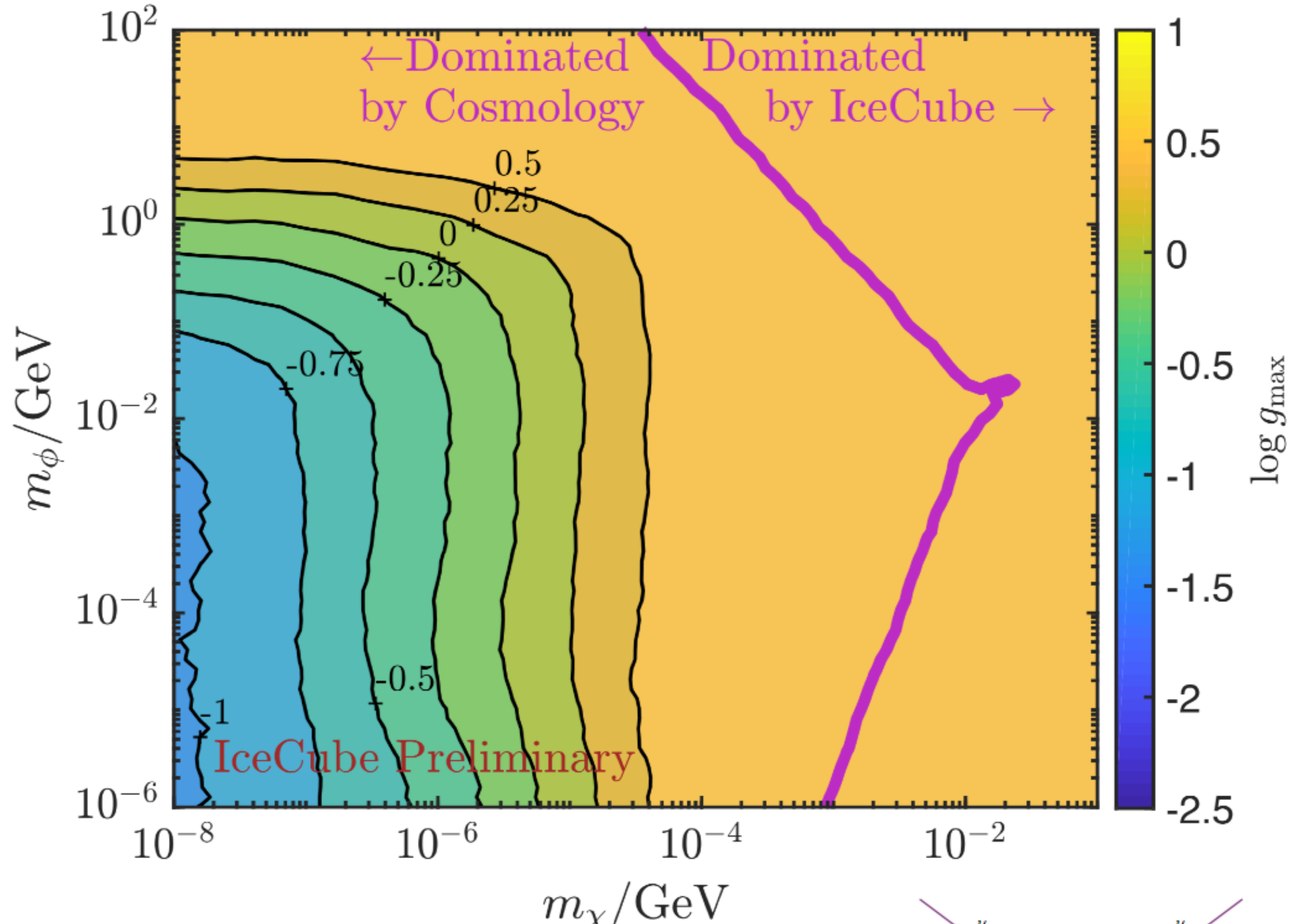
Galactic center

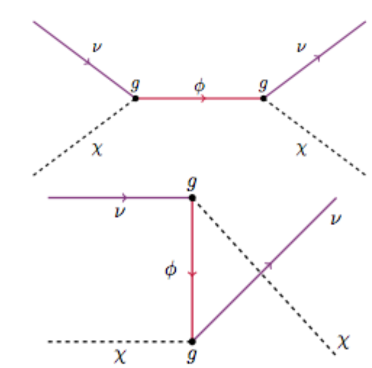
New constraints on neutrino-dark matter interactions



IceCube Work In Progress







Color scale is the maximum allowed coupling.

Cosmological bounds using Large Scale Structure from Escudero et al 2016

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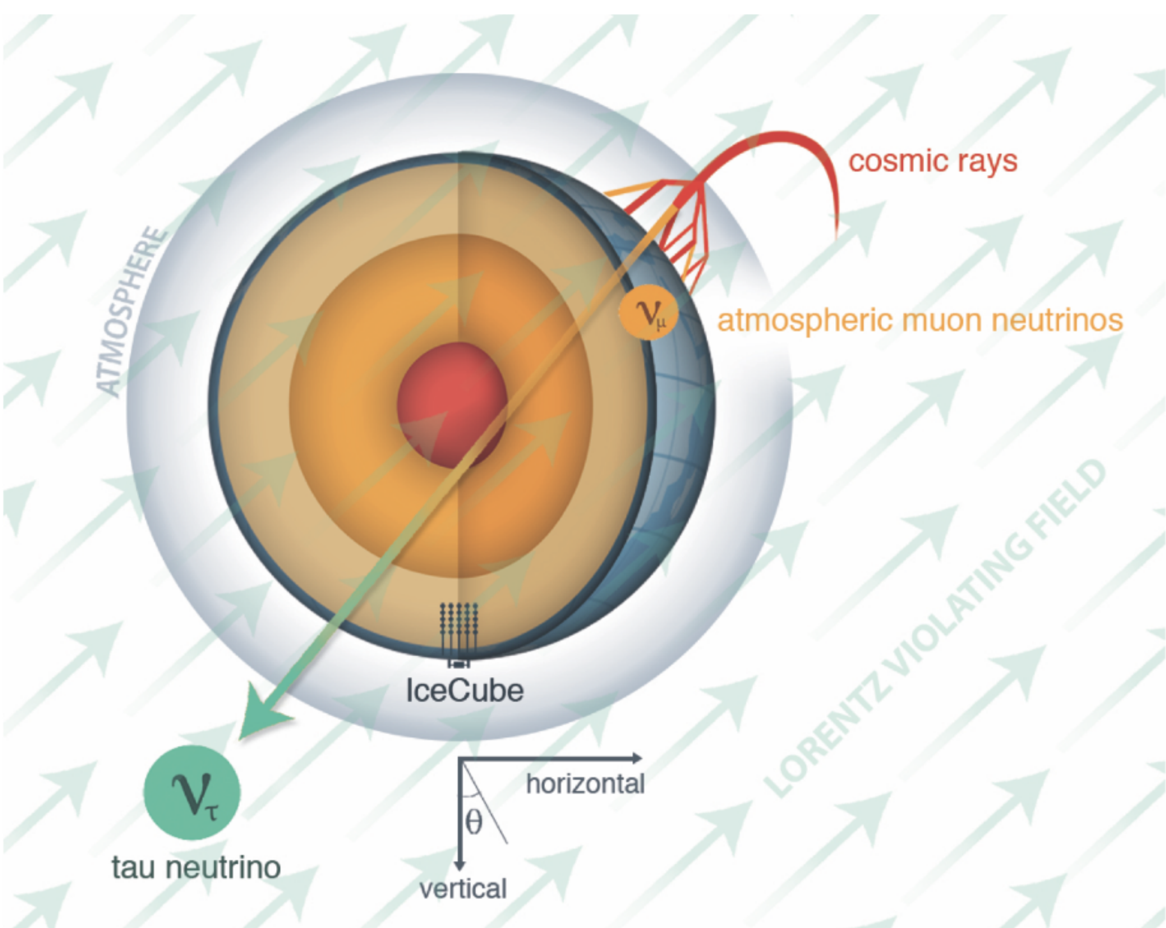
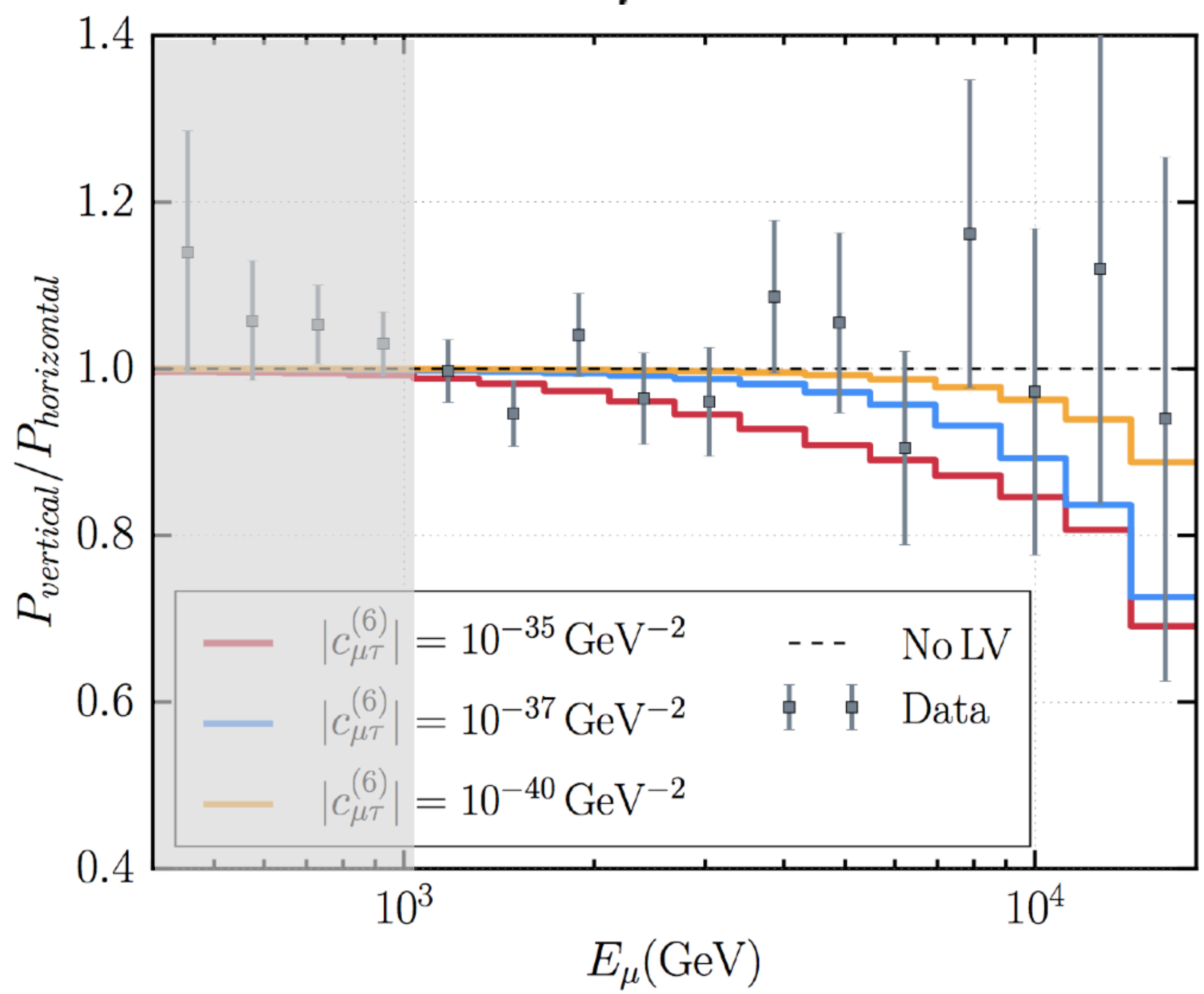
Search for Lorentz Violation with High-energy Atmospheric Neutrinos

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.

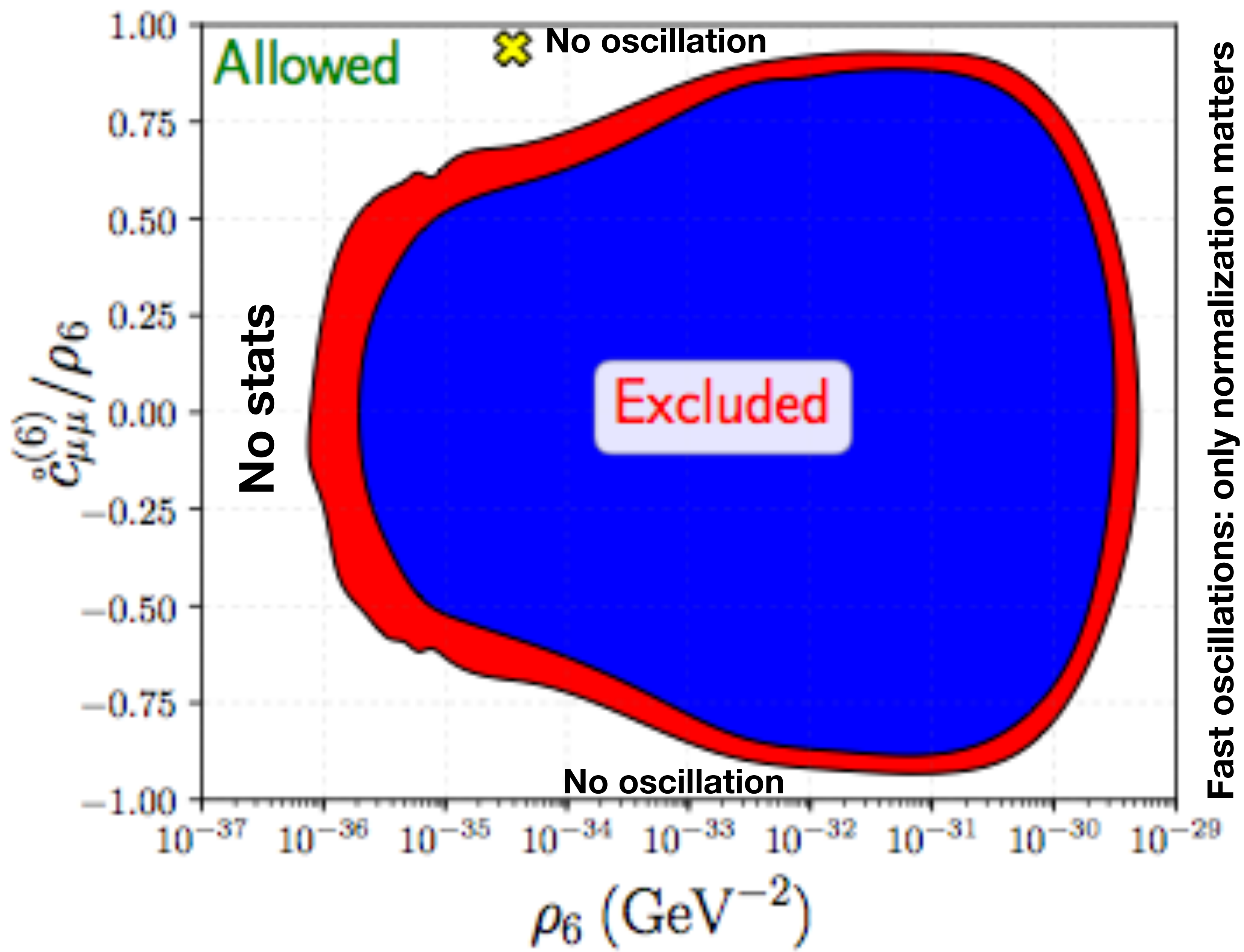
Anatomy of the dim-6 operator constraint

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

- 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

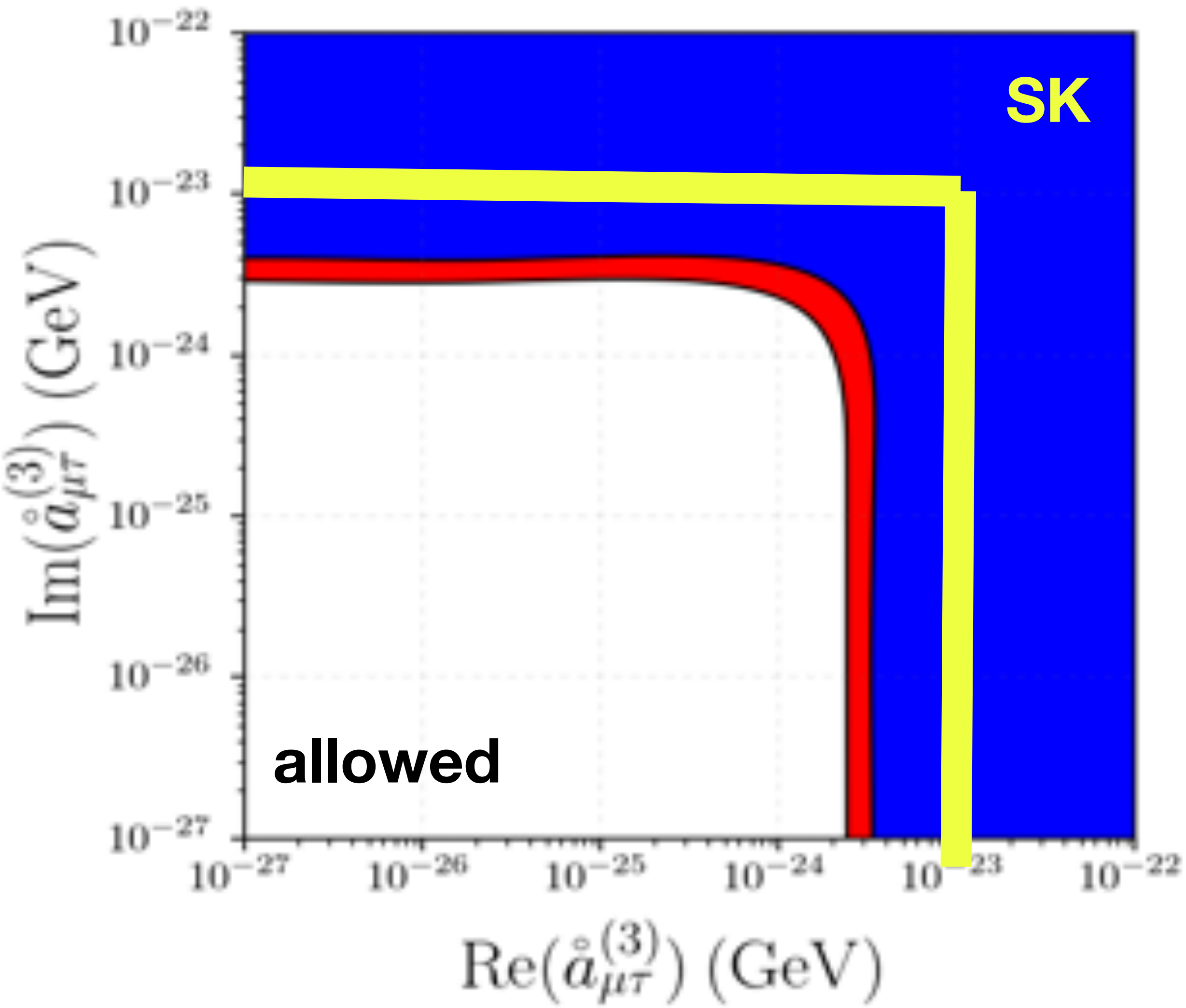
Our results in the maximum-flavor-violating assumption

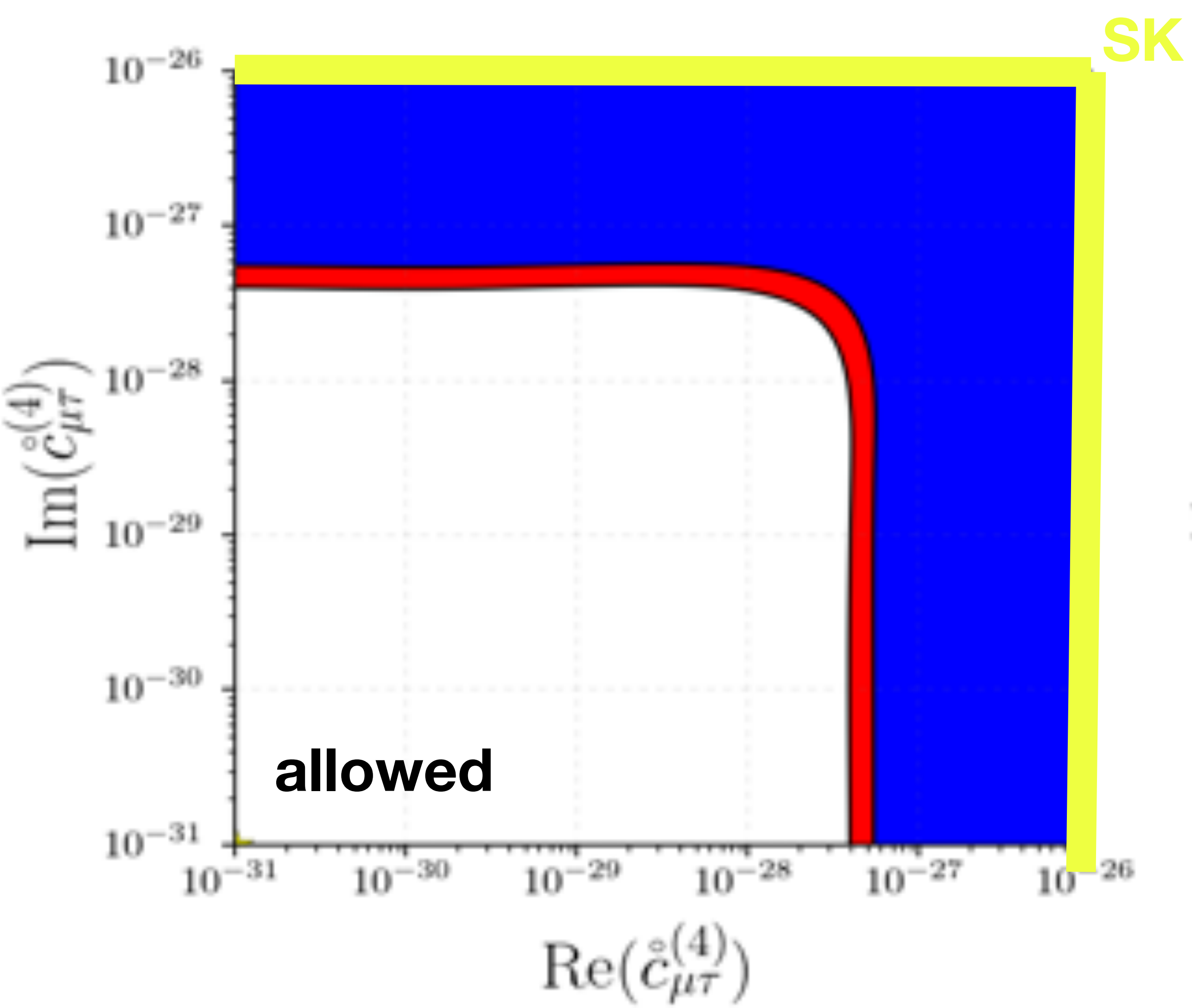
$$\begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

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.

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

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.

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

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

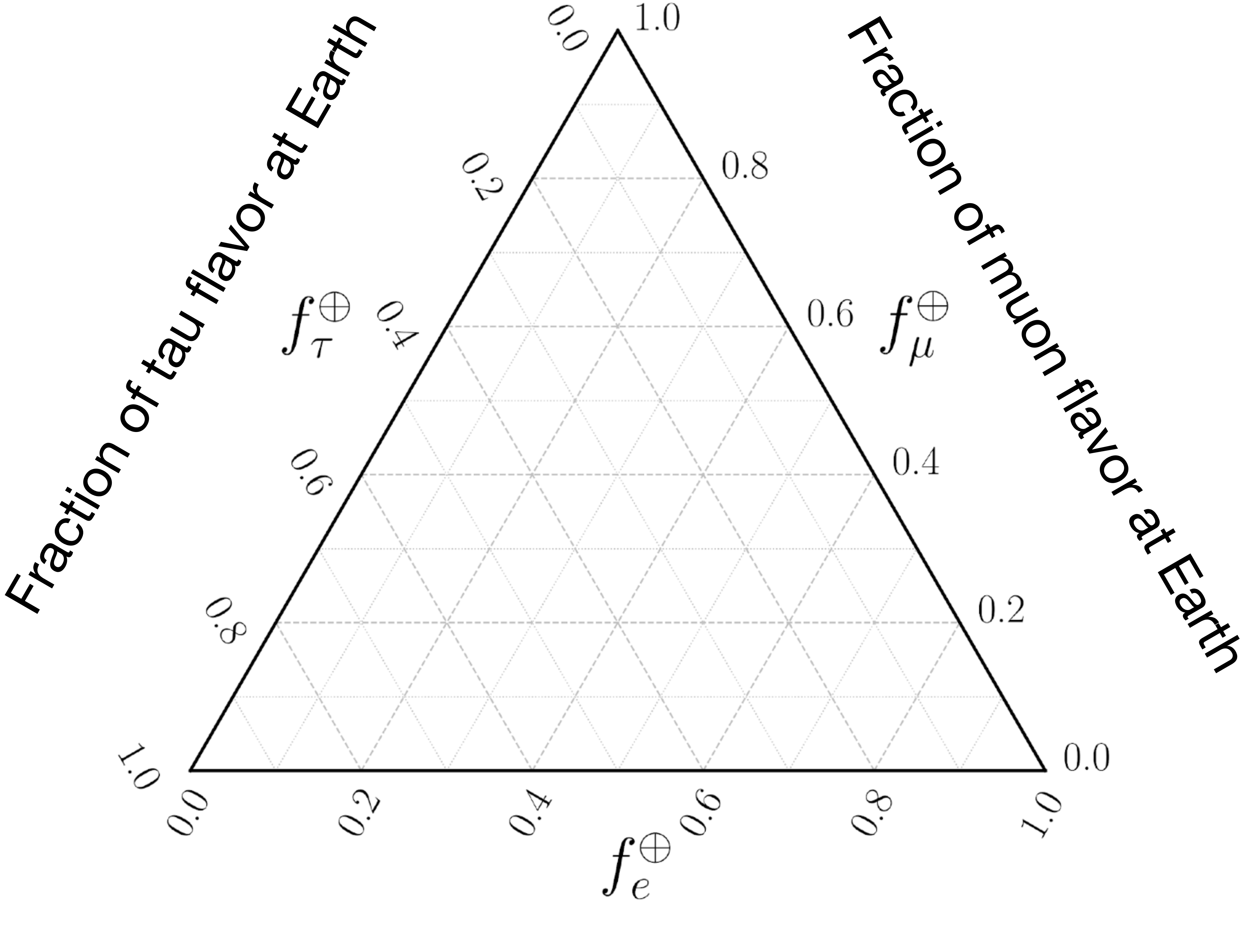
(0:1:0)

Neutron

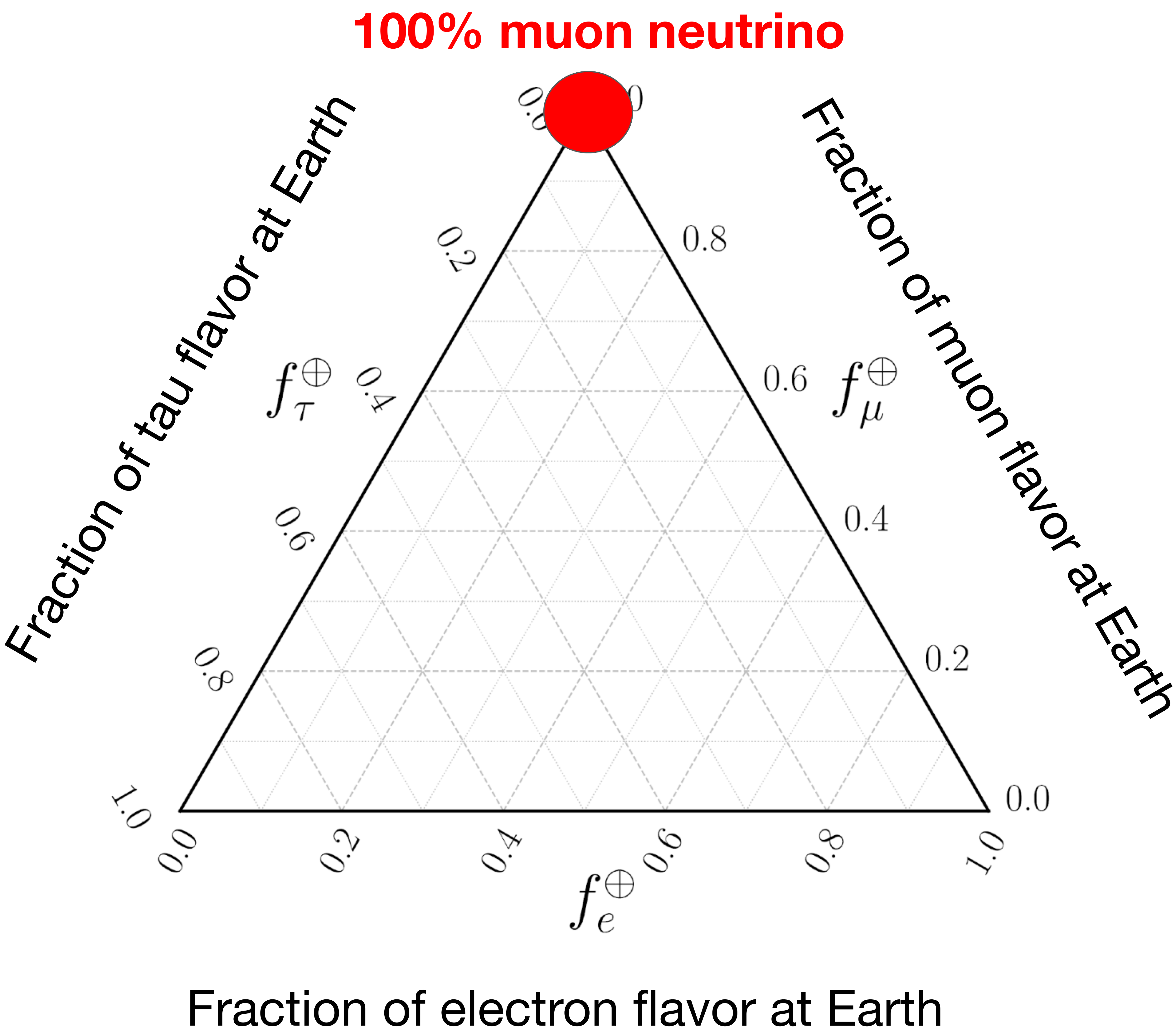
$$n \to p + e^- + \bar{\nu}_e$$

(1:0:0)

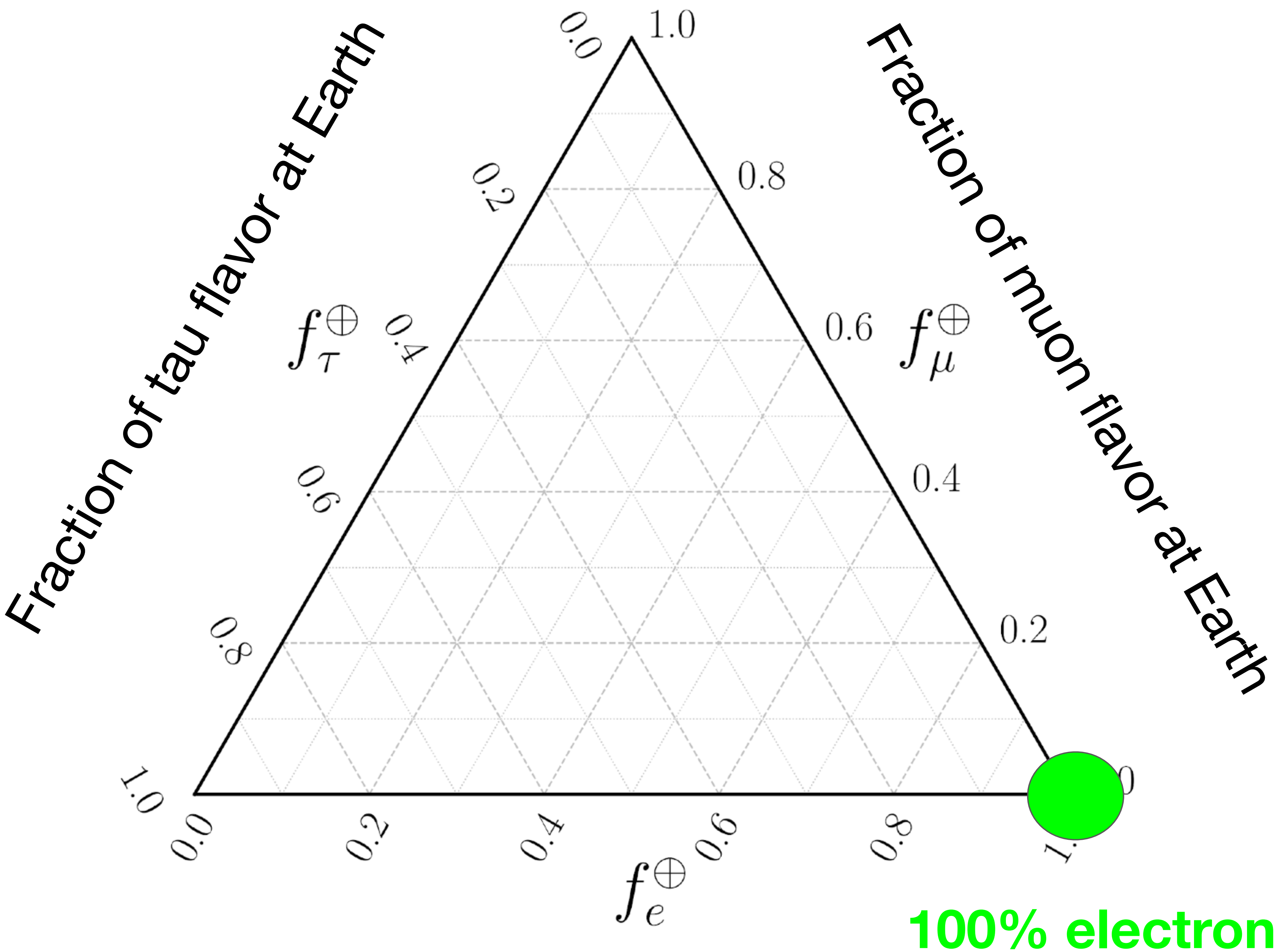
The flavor triangle



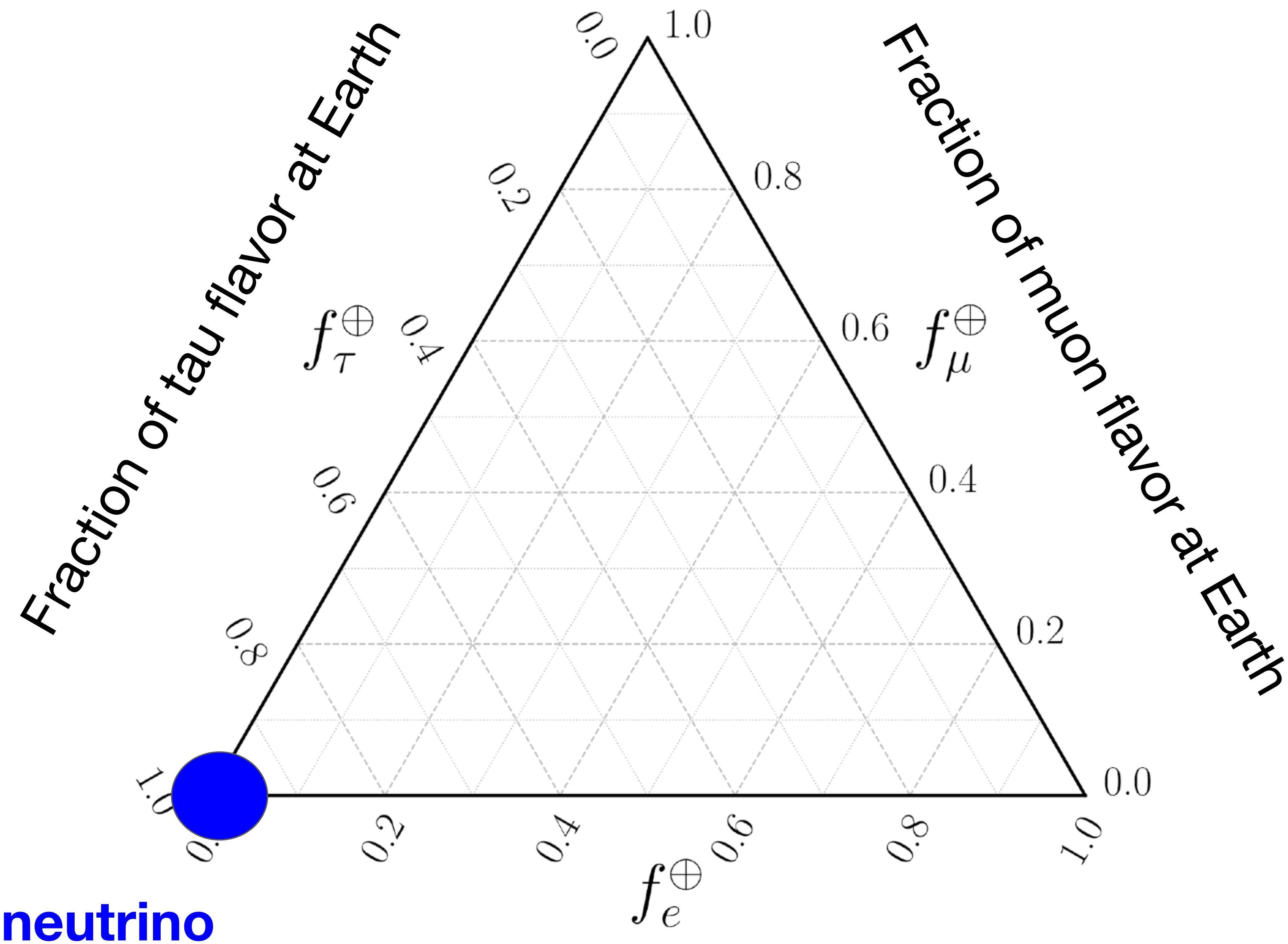
The flavor triangle



The flavor triangle



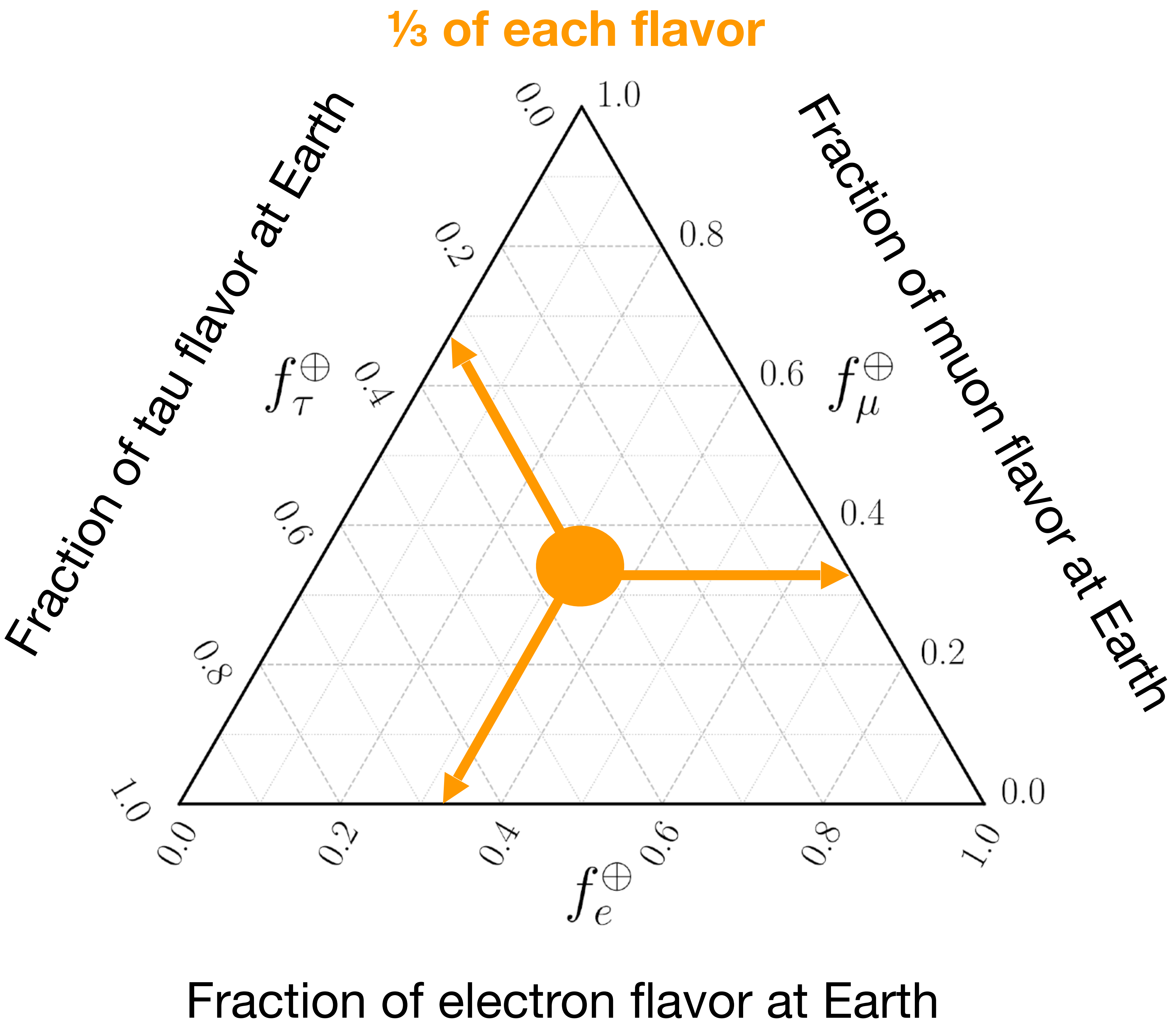
The flavor triangle



100% tau neutrino

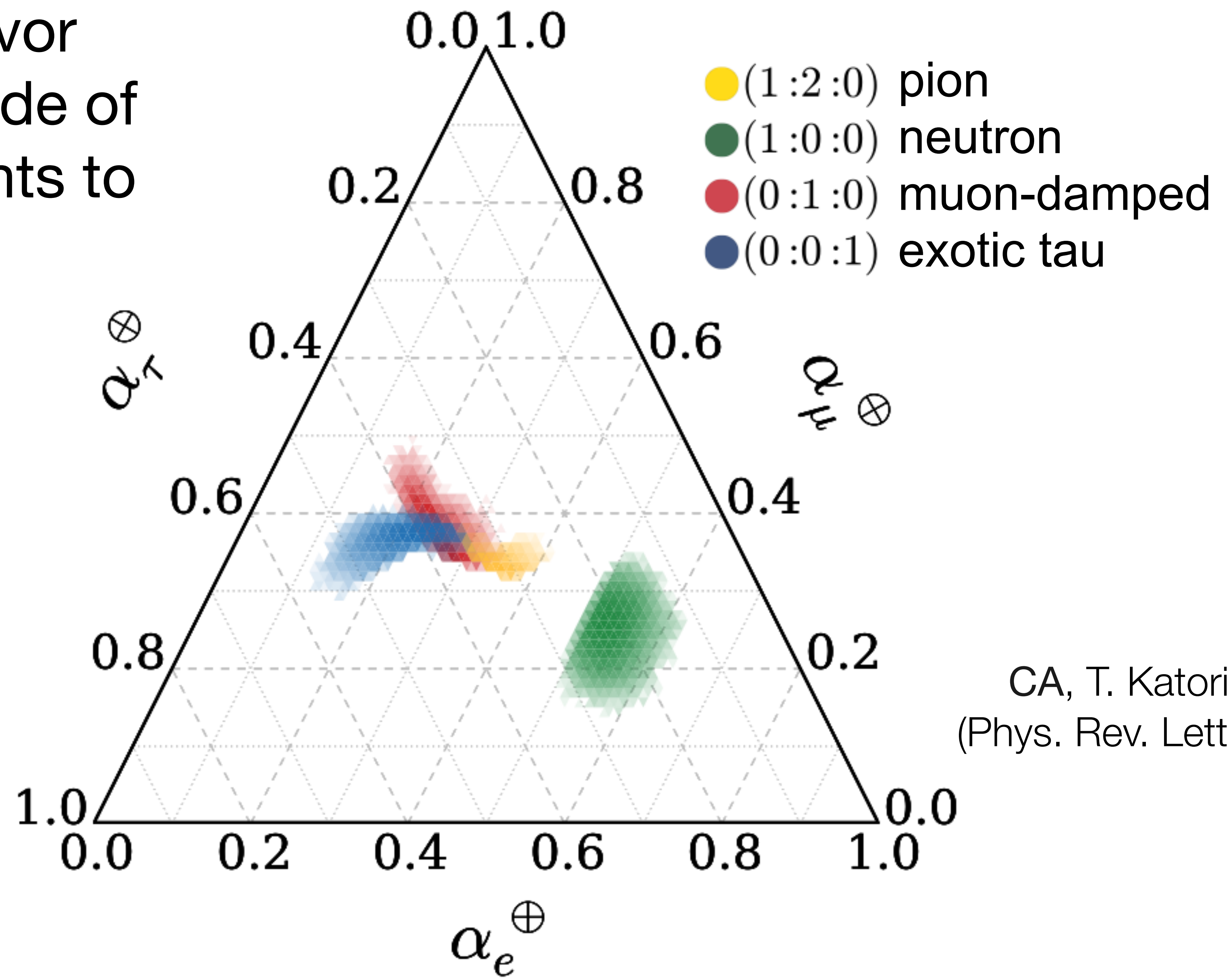
Fraction of electron flavor at Earth

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)

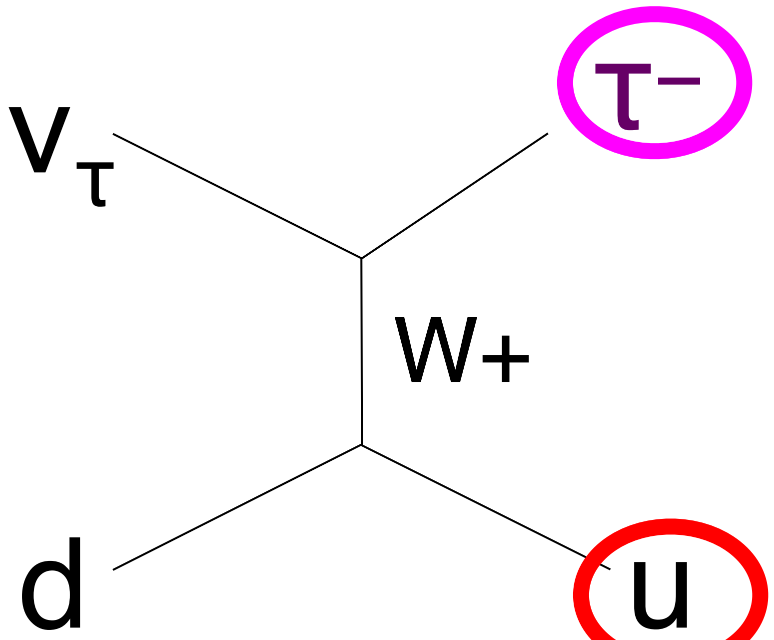
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

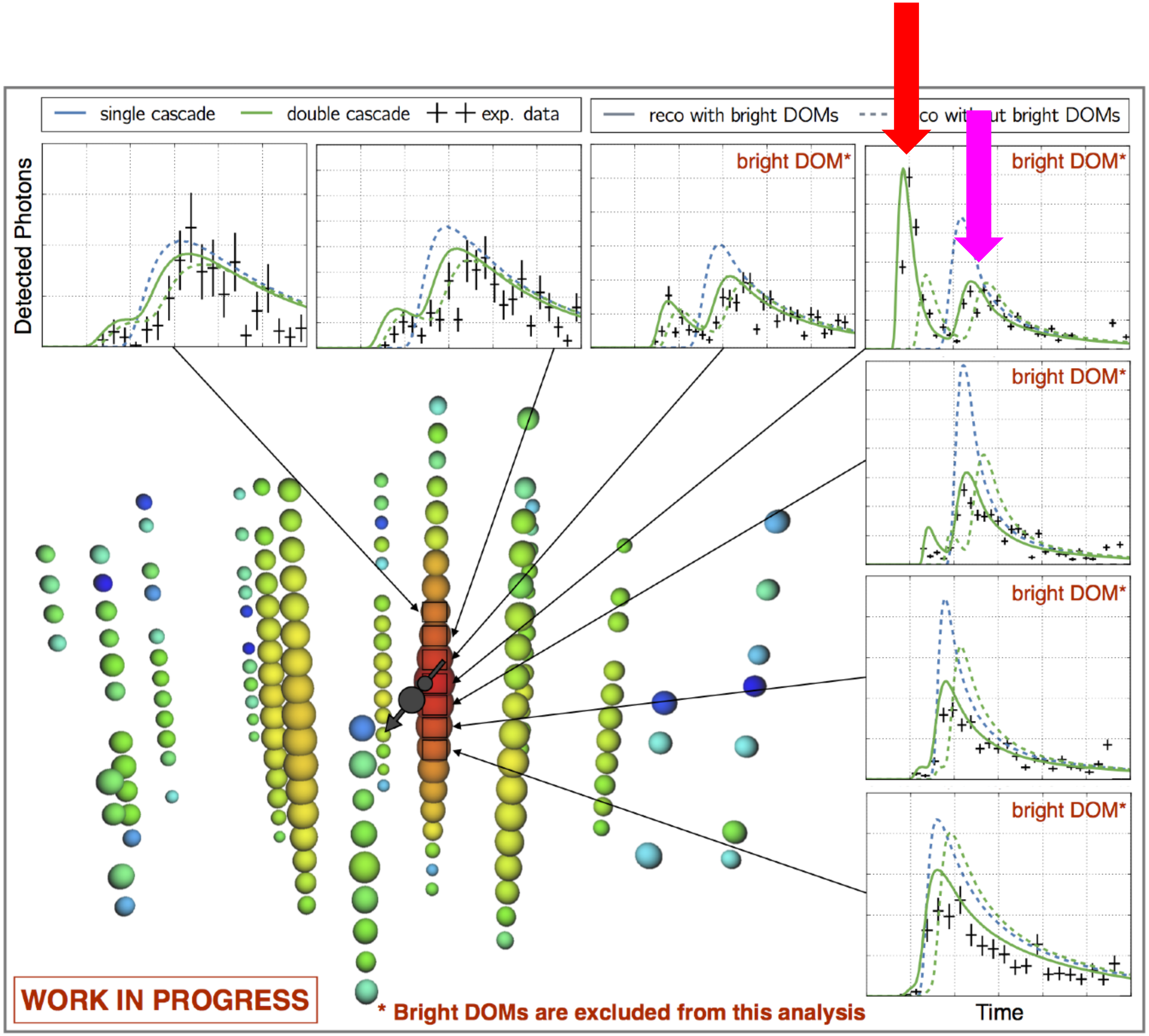
First astrophysical ν_τ candidate found!

Total deposited energy ~ 90 TeV.

First "bang" in time (shower)

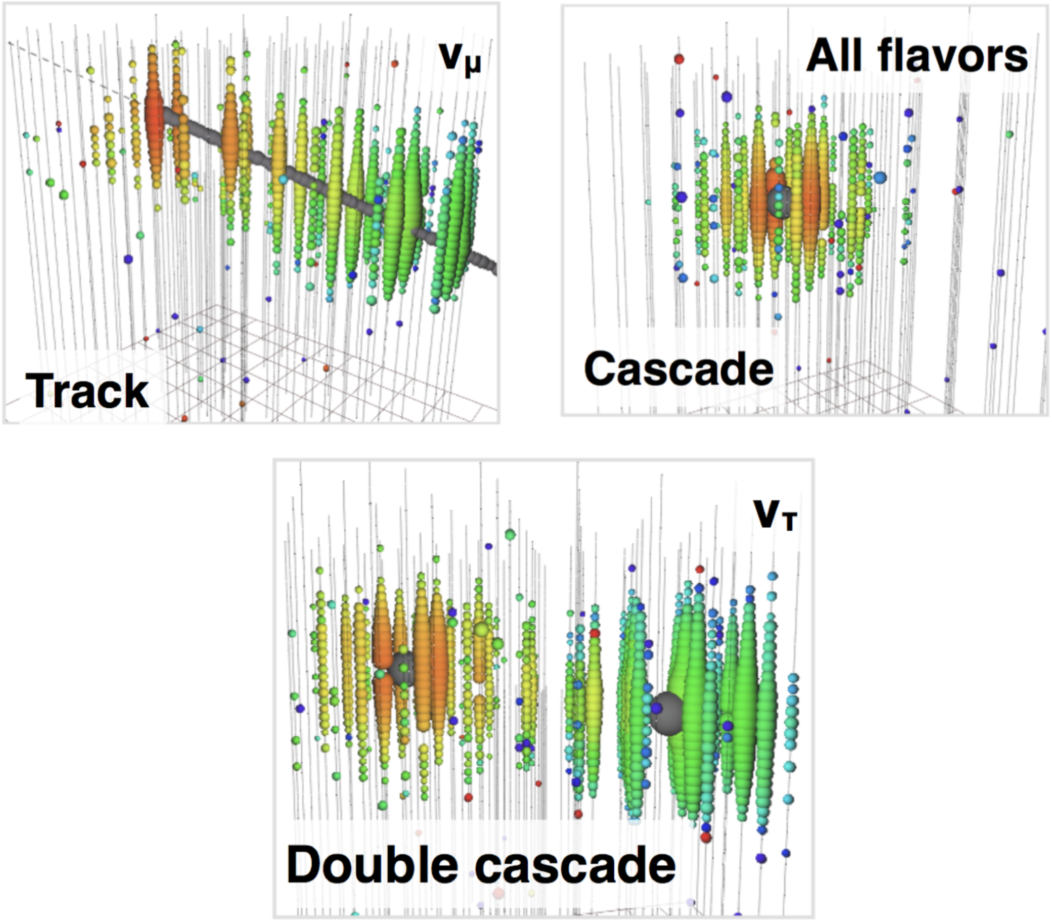
Second "bang" in time (tau decay)

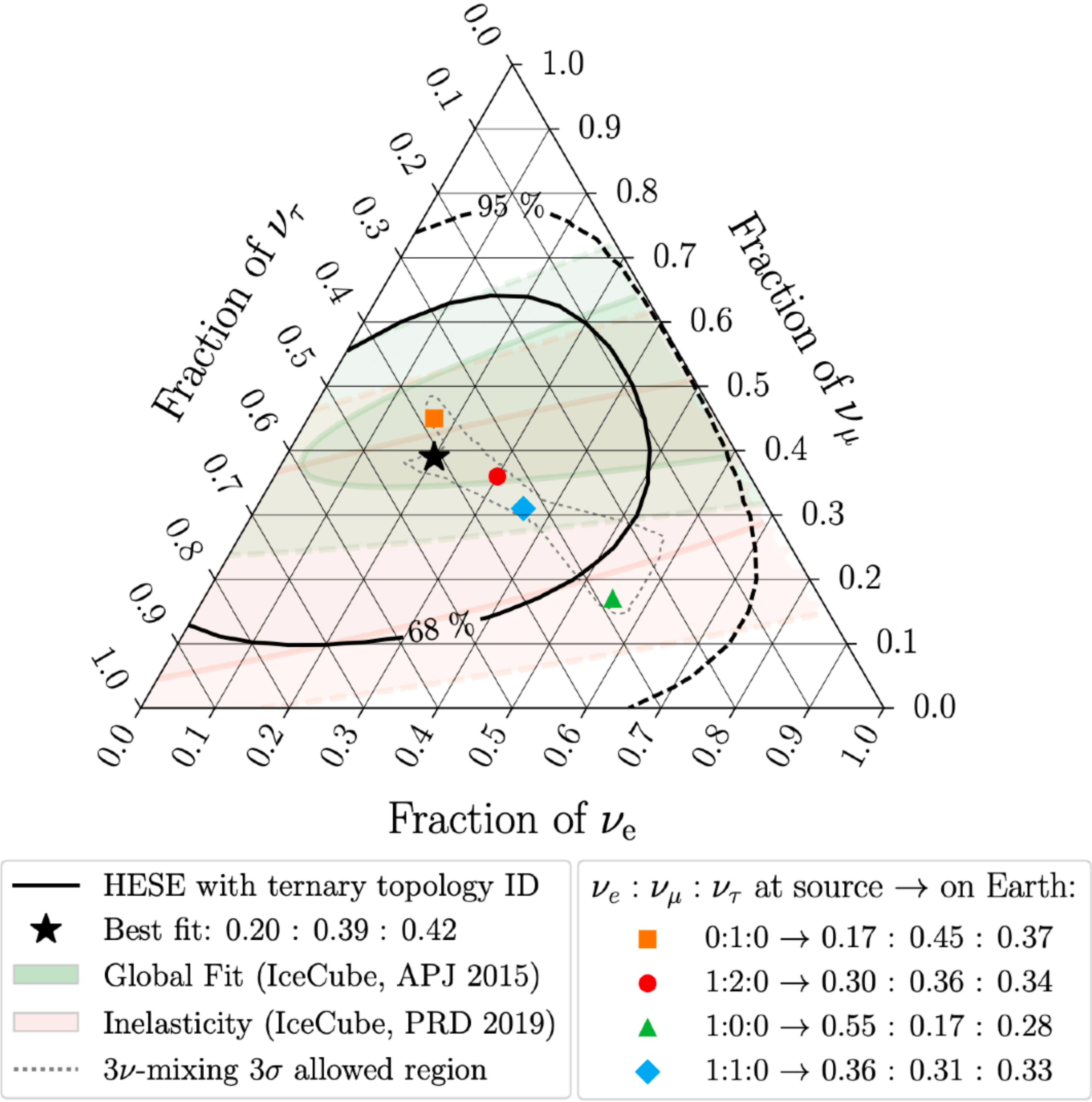




IceCube Collaboration, https://arxiv.org/abs/2011.03561

Astrophysical neutrino flavor measurements with High-Energy Starting Events





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

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

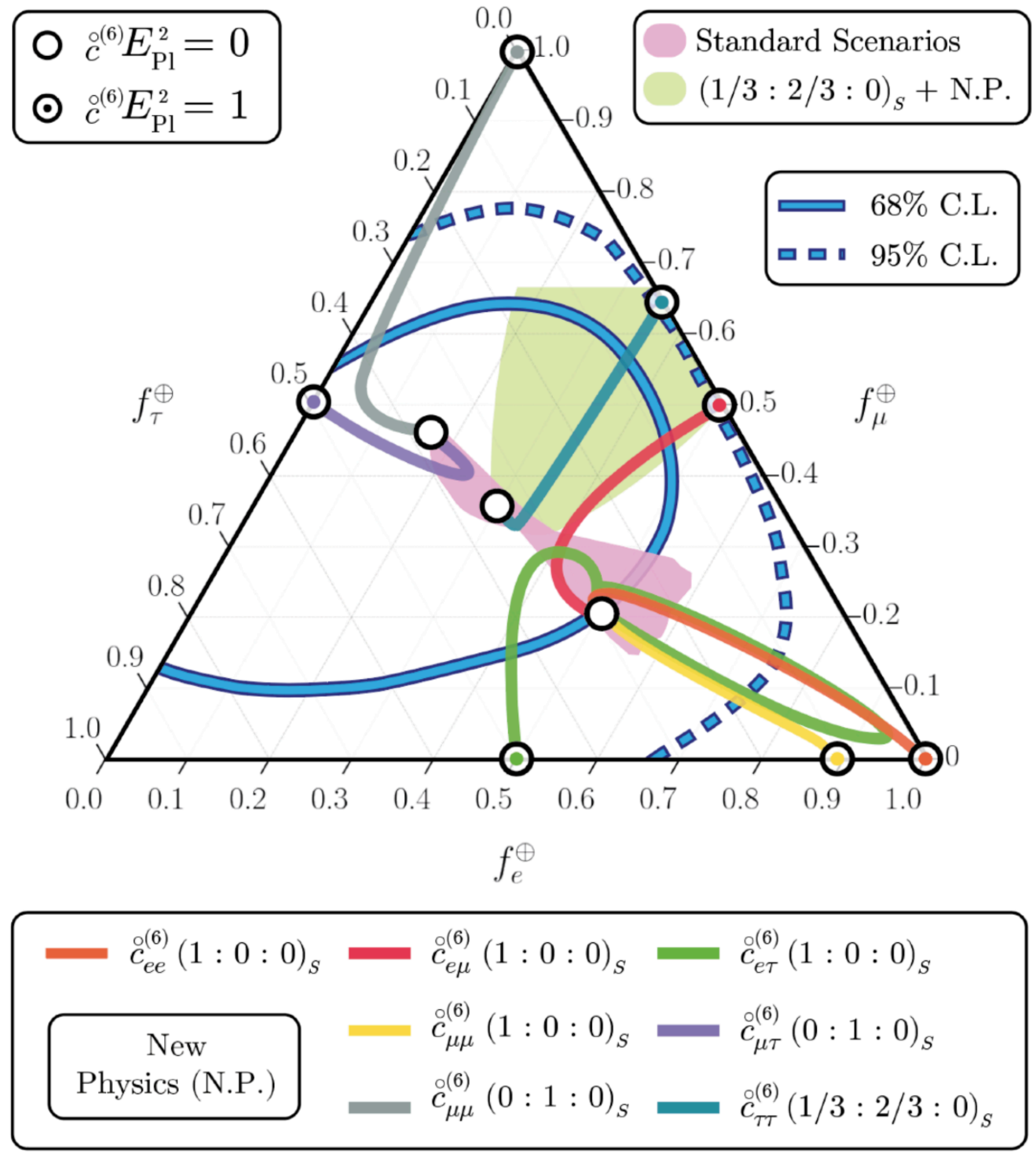
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

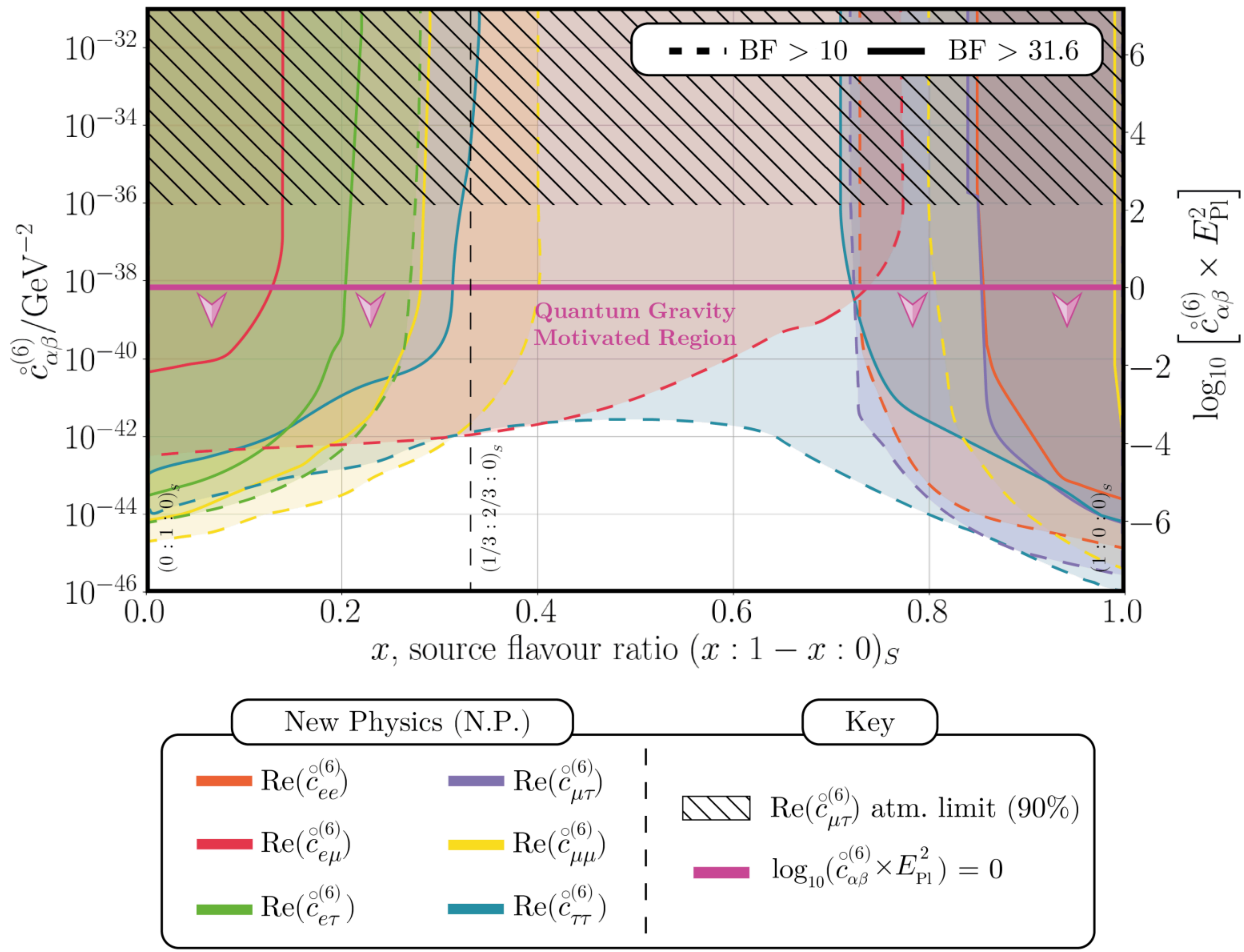
$(0:1:0)$ neutron

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



IceCube collaboration arXiv:2111.04654

Results on high-dimensional LV operators

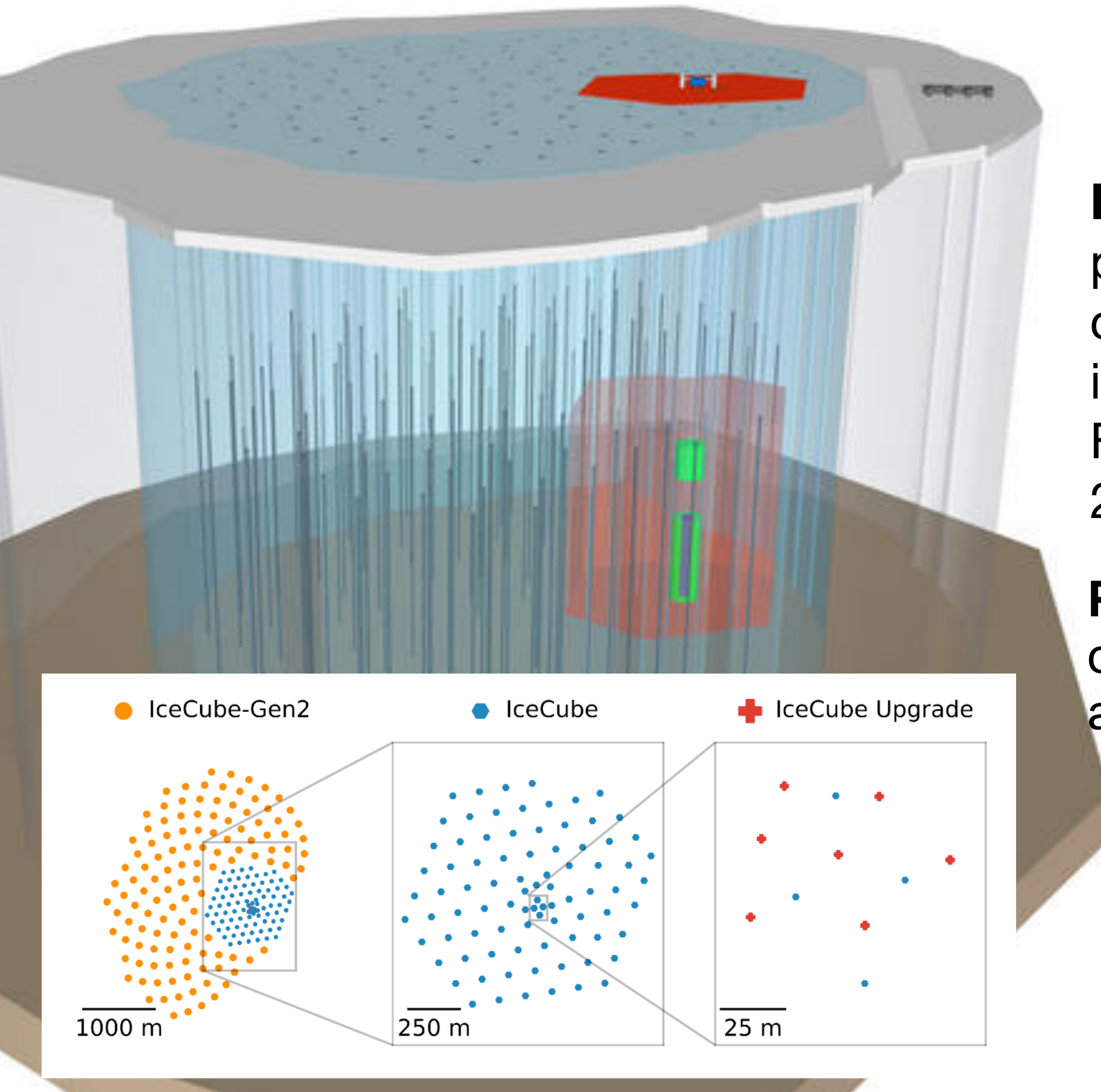


IceCube collaboration arXiv:2111.04654

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

The IceCube Upgrades

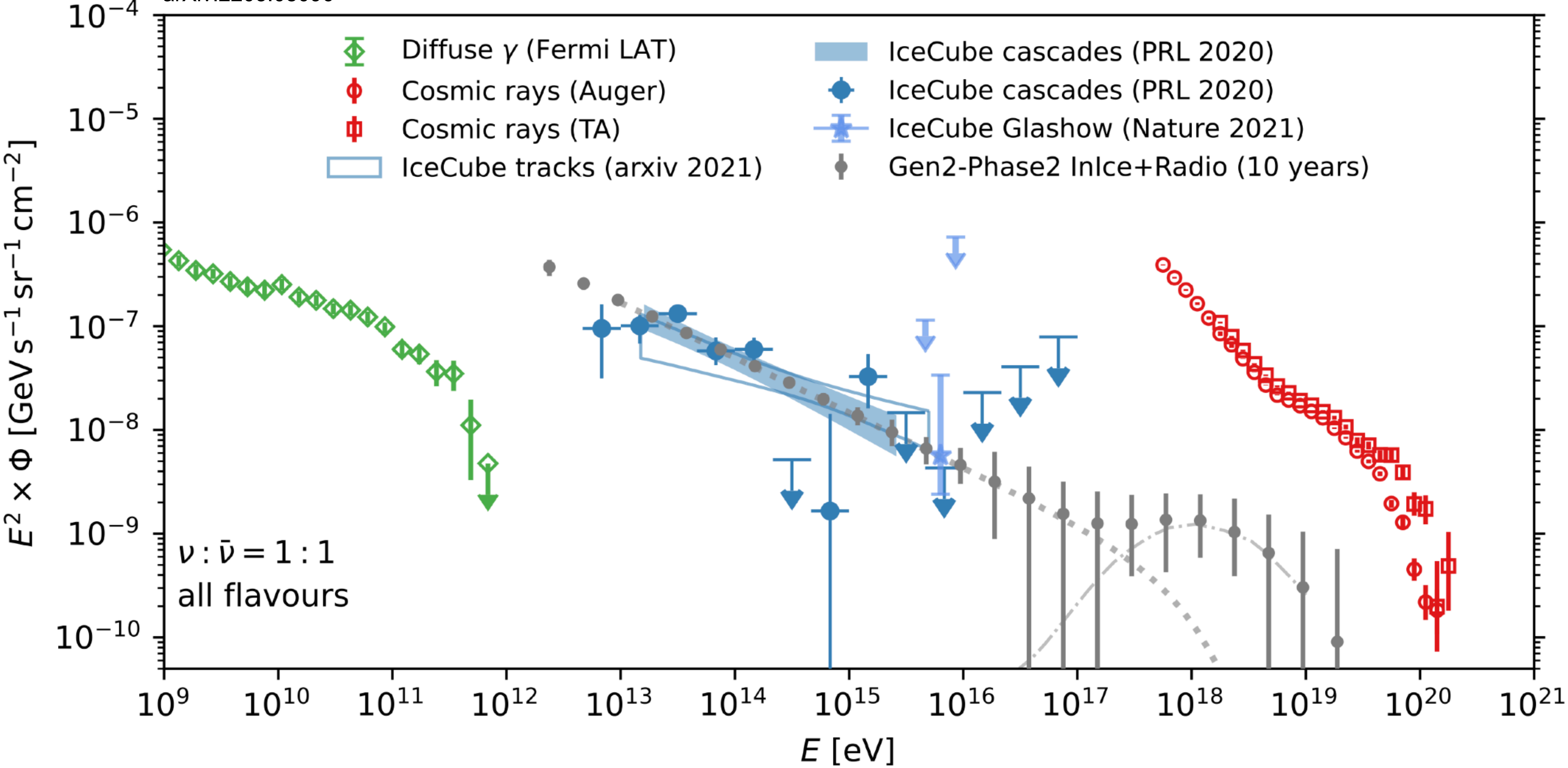


Phase 1: 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2024-2026.

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

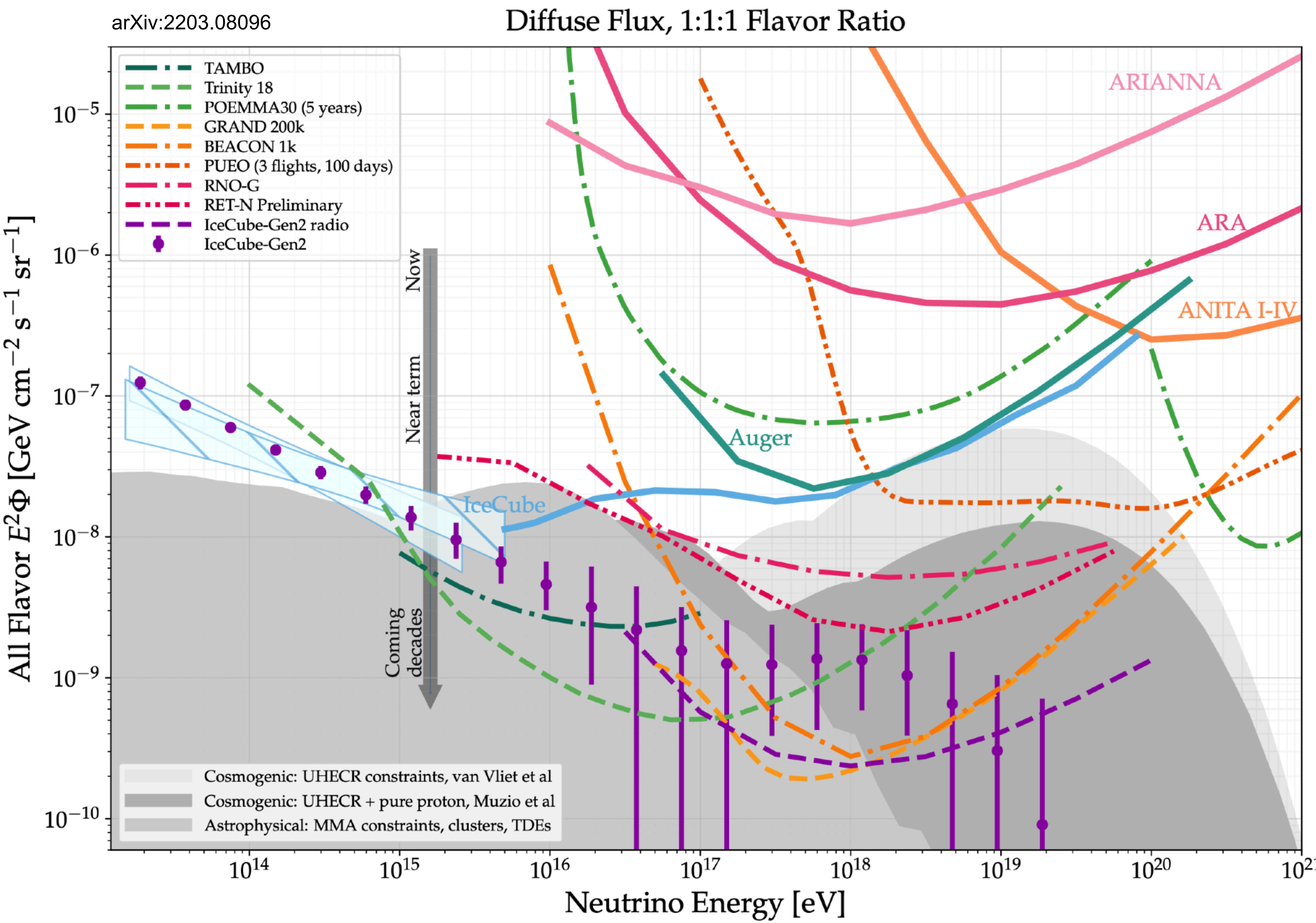
IceCube-Gen2
Expected Measurement of Astrophysical Flux

arXiv:2203.08096

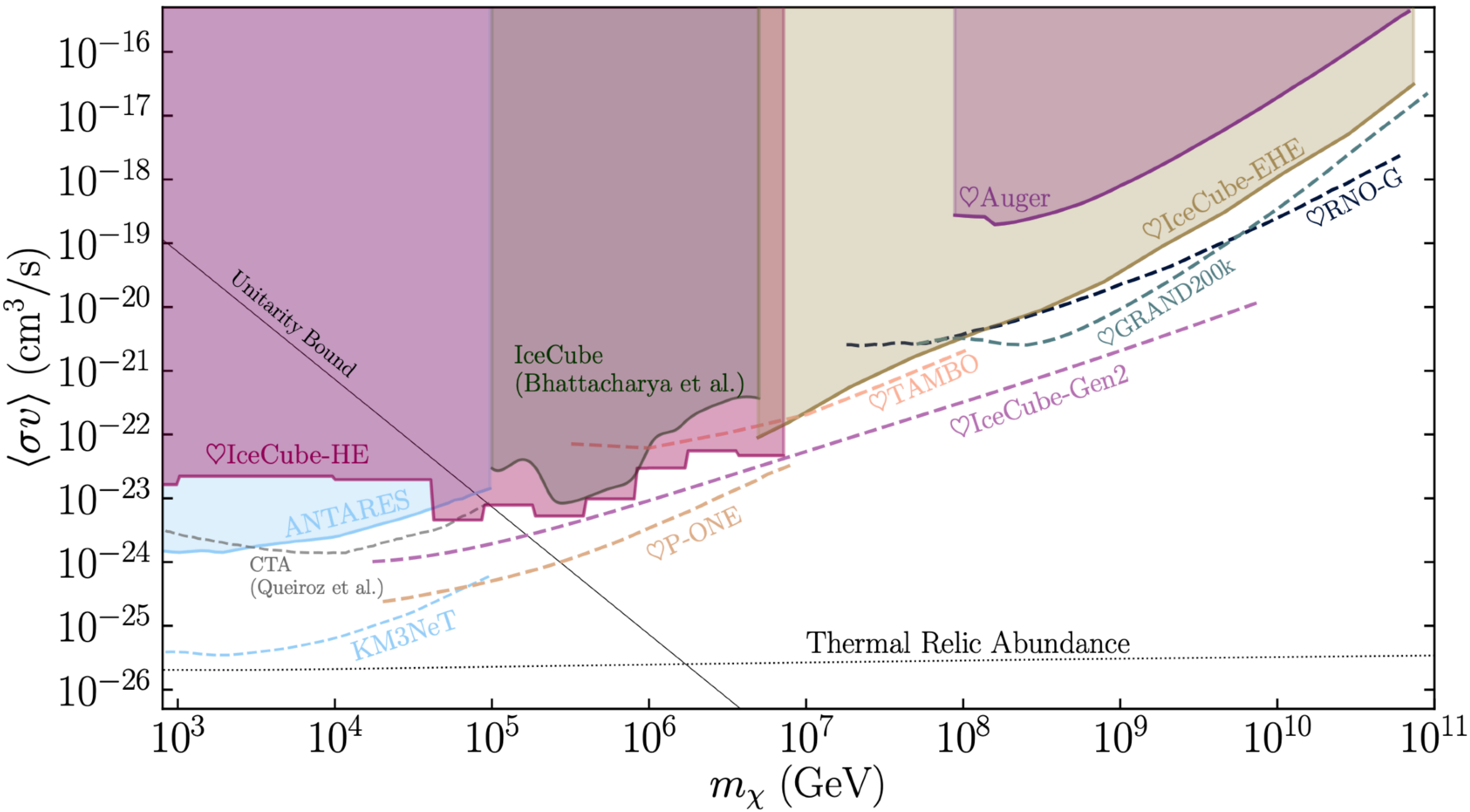


Next Generation Experiments Flux Sensitivity

arXiv:2203.08096

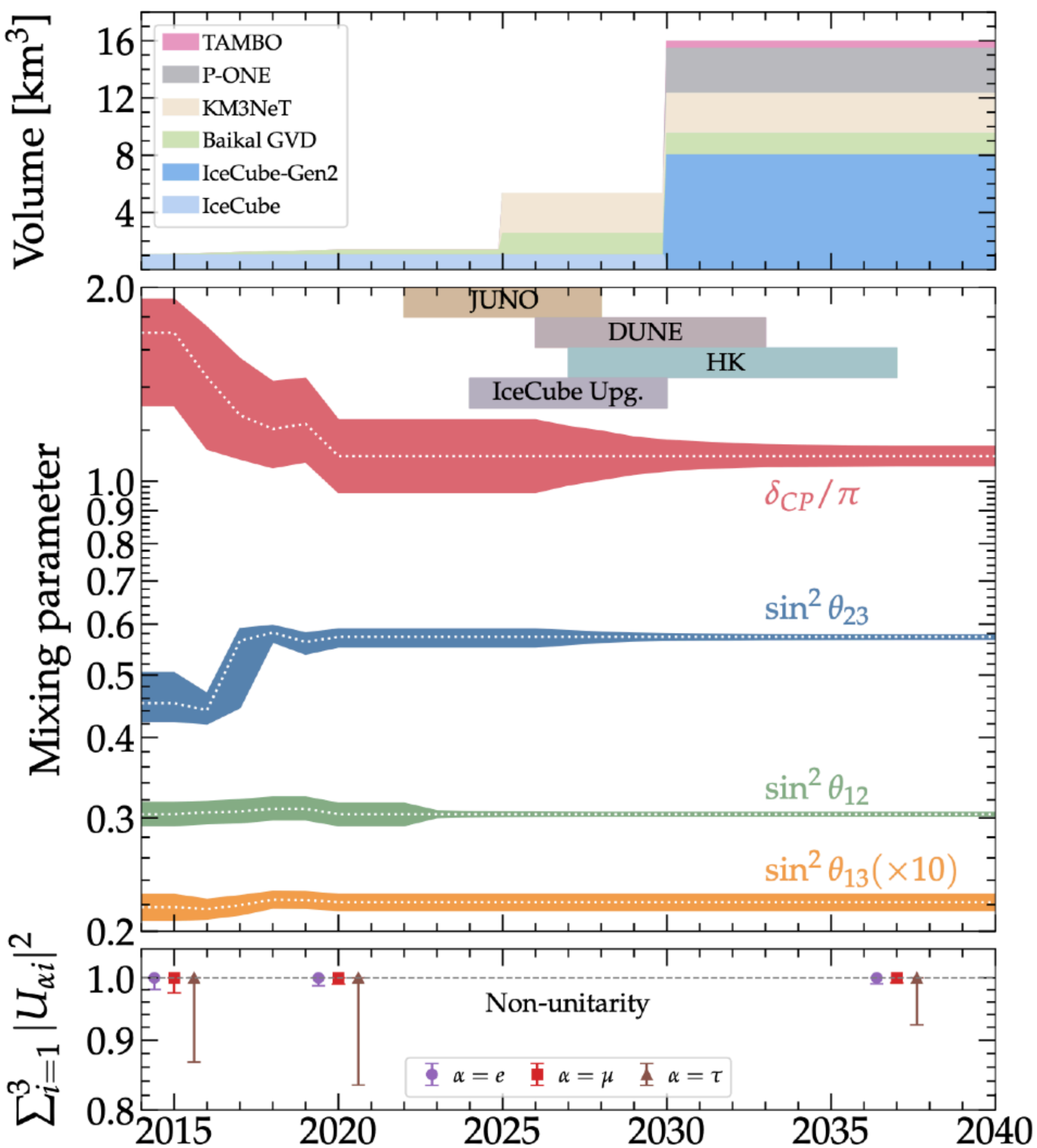


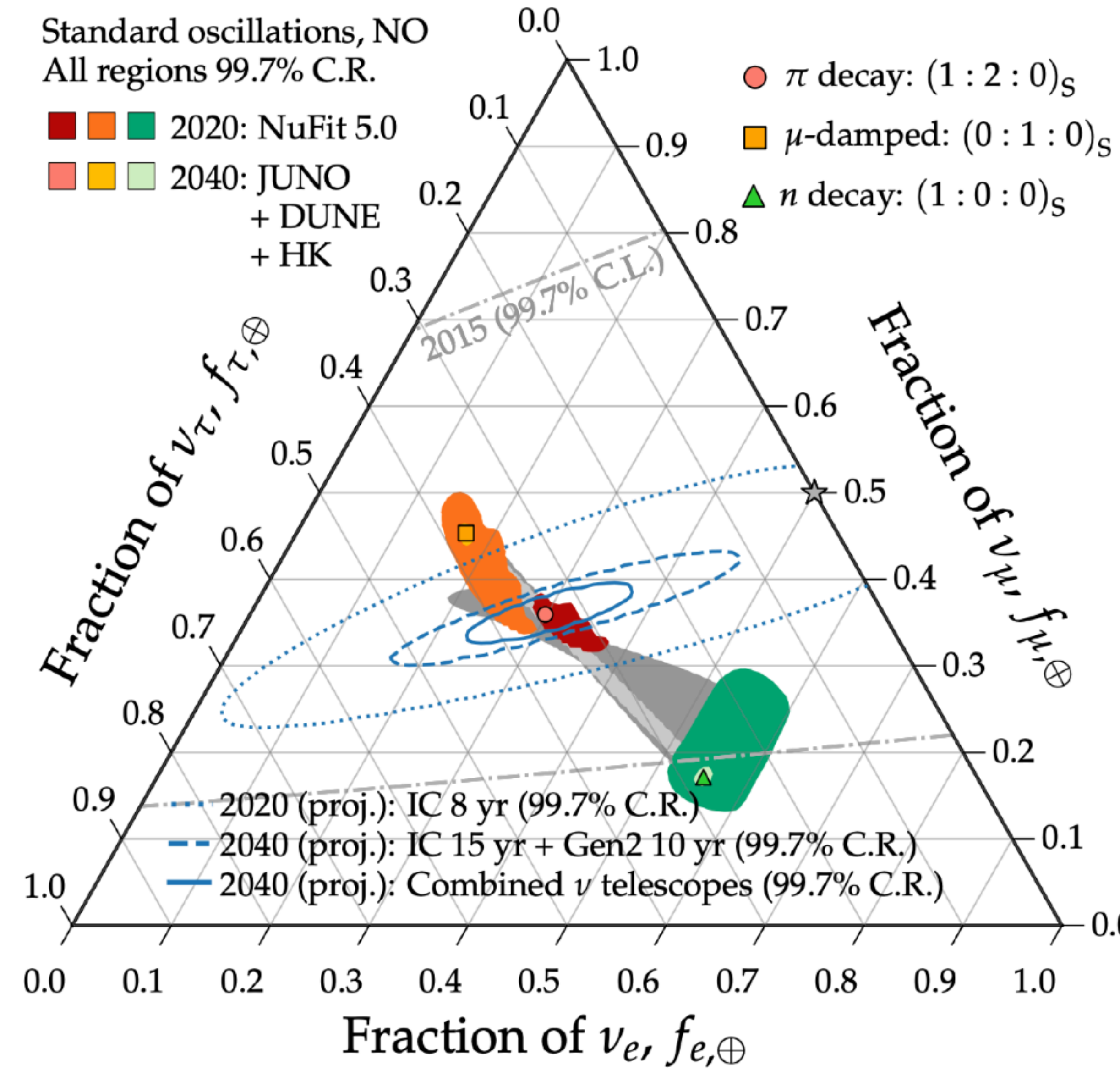
Next Generation Dark Matter Searches



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*.

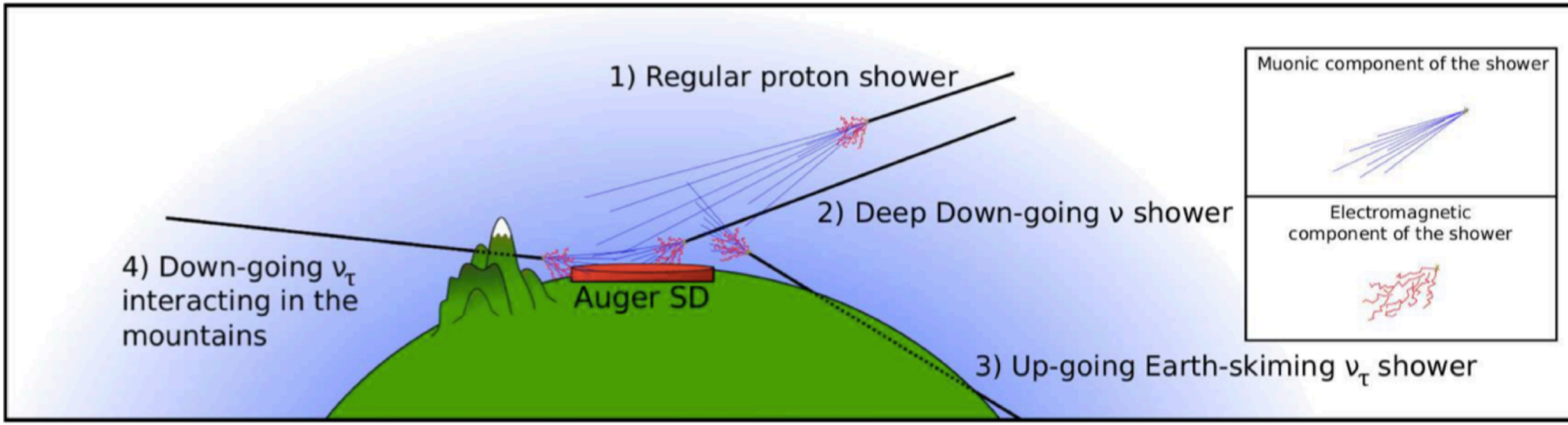
Projected Upgrade Flavor Measurement

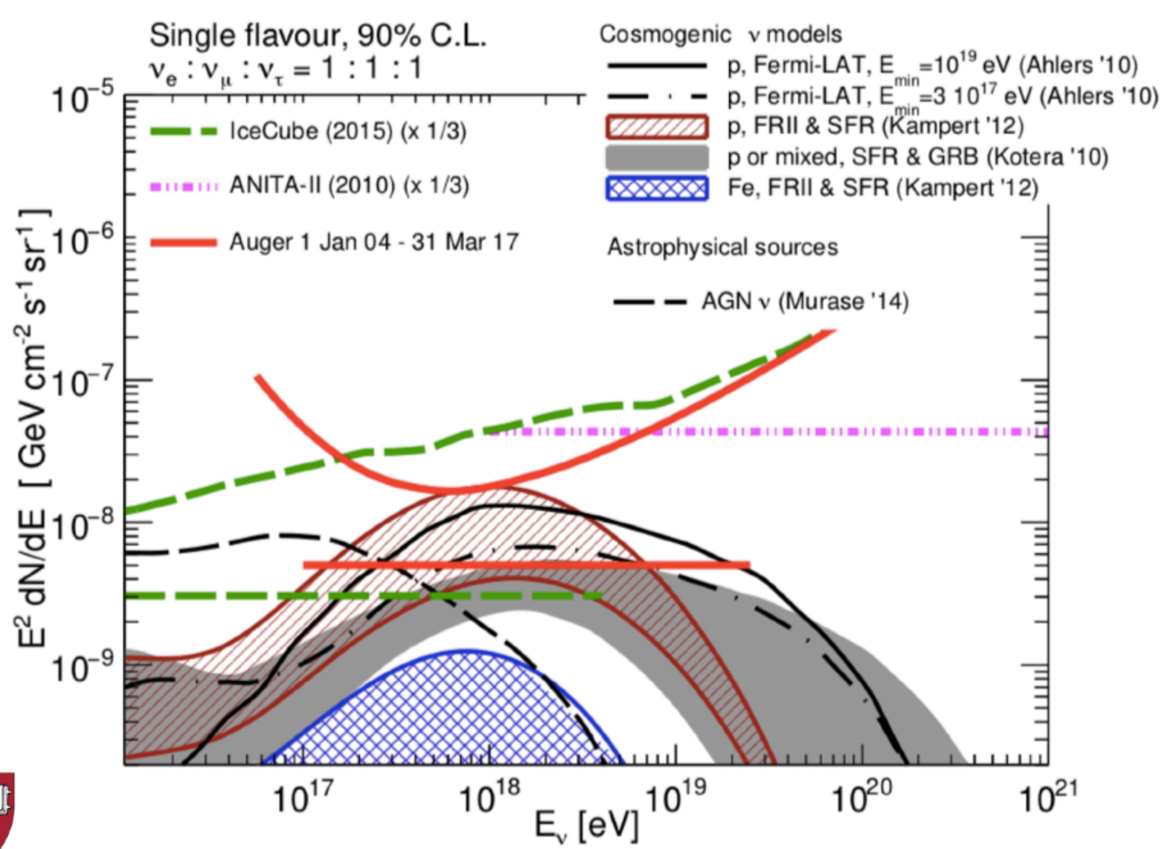




N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)

Earth-skimming neutrino detectors

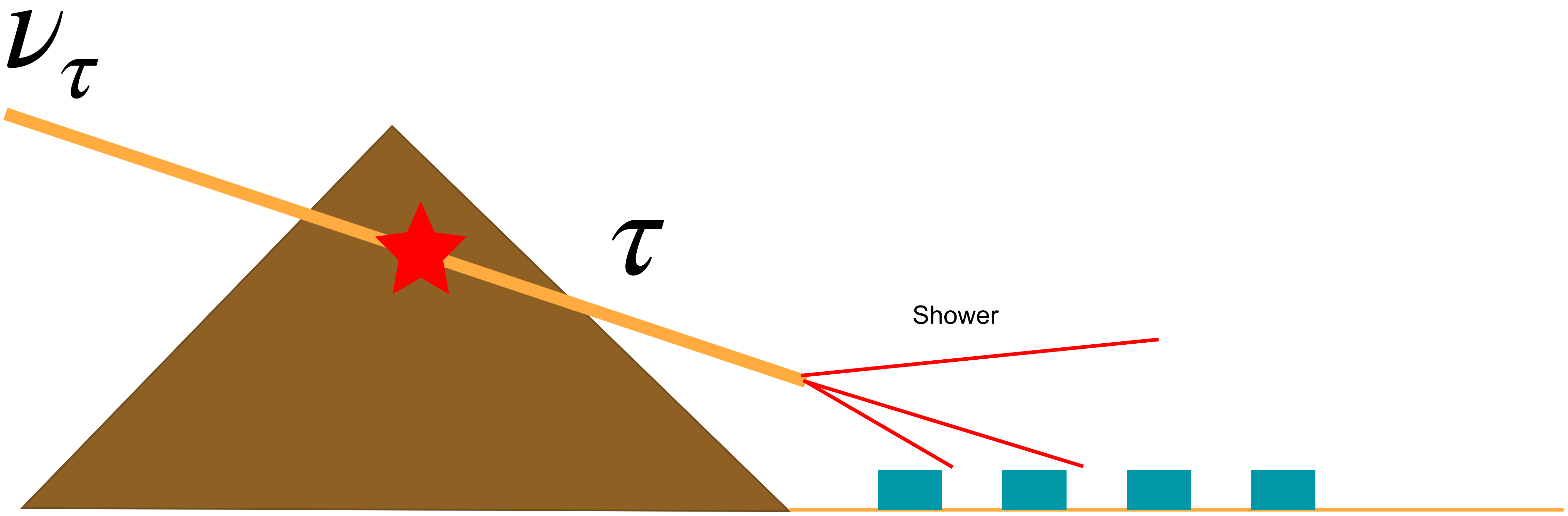




Earth-skimming neutrino detection uses mountains as the neutrino target and then detects the tau shower using Cherenkov detectors (Auger) or radio antennas (GRAND, proposed).

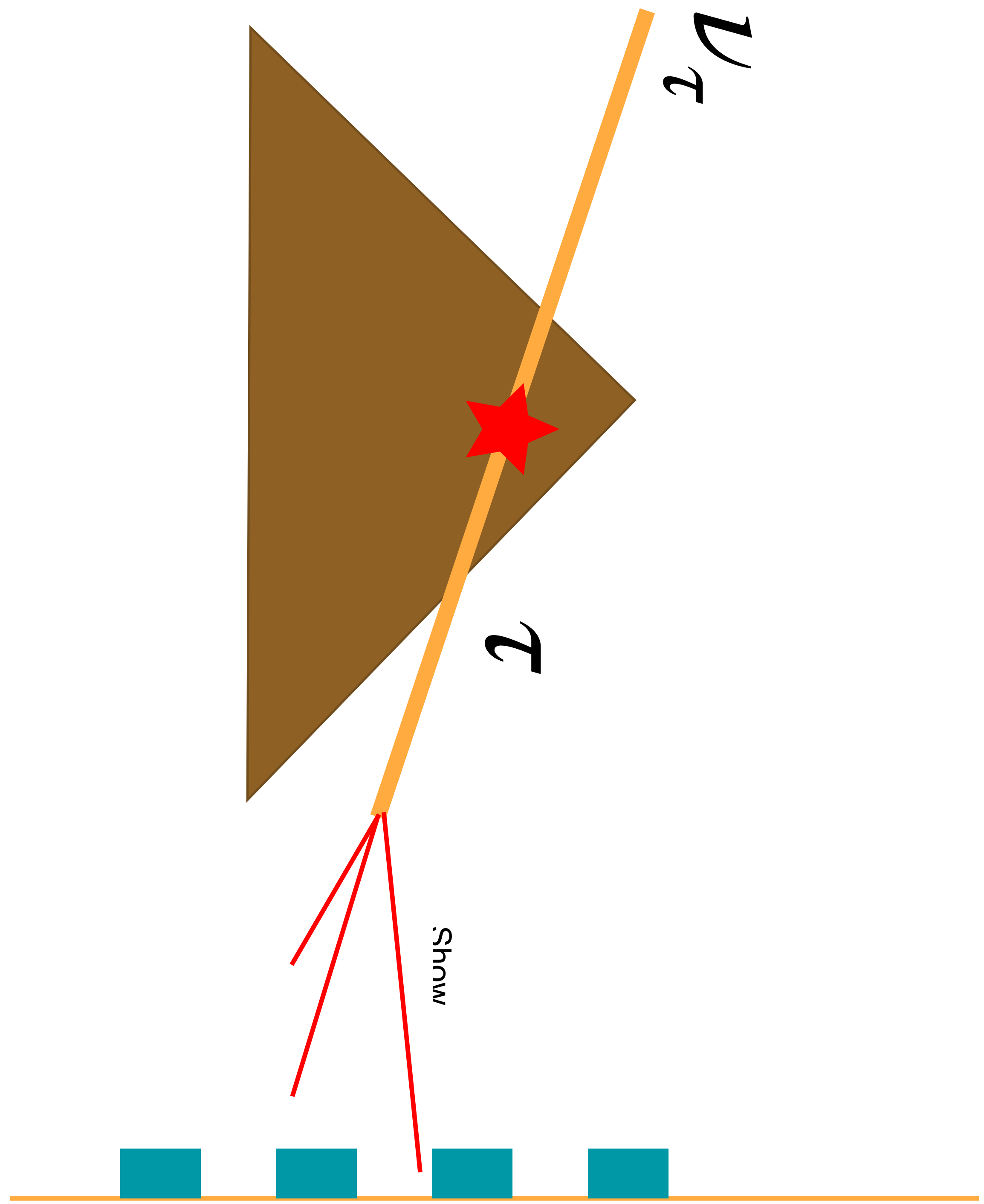
Angular acceptance is limited.

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

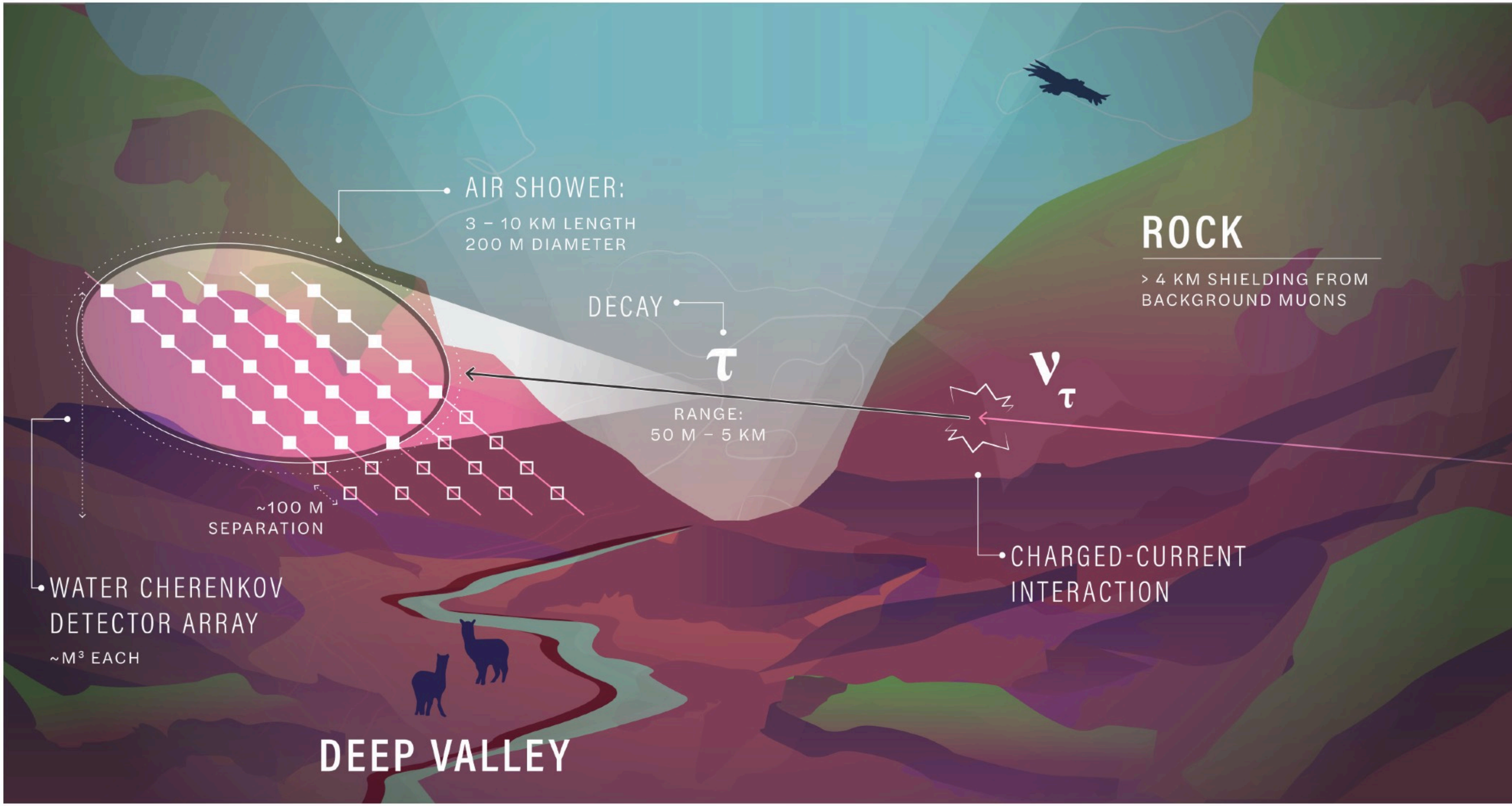
Thinking about Earth-skimming neutrino detectors



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

Solution: TAMBO*!

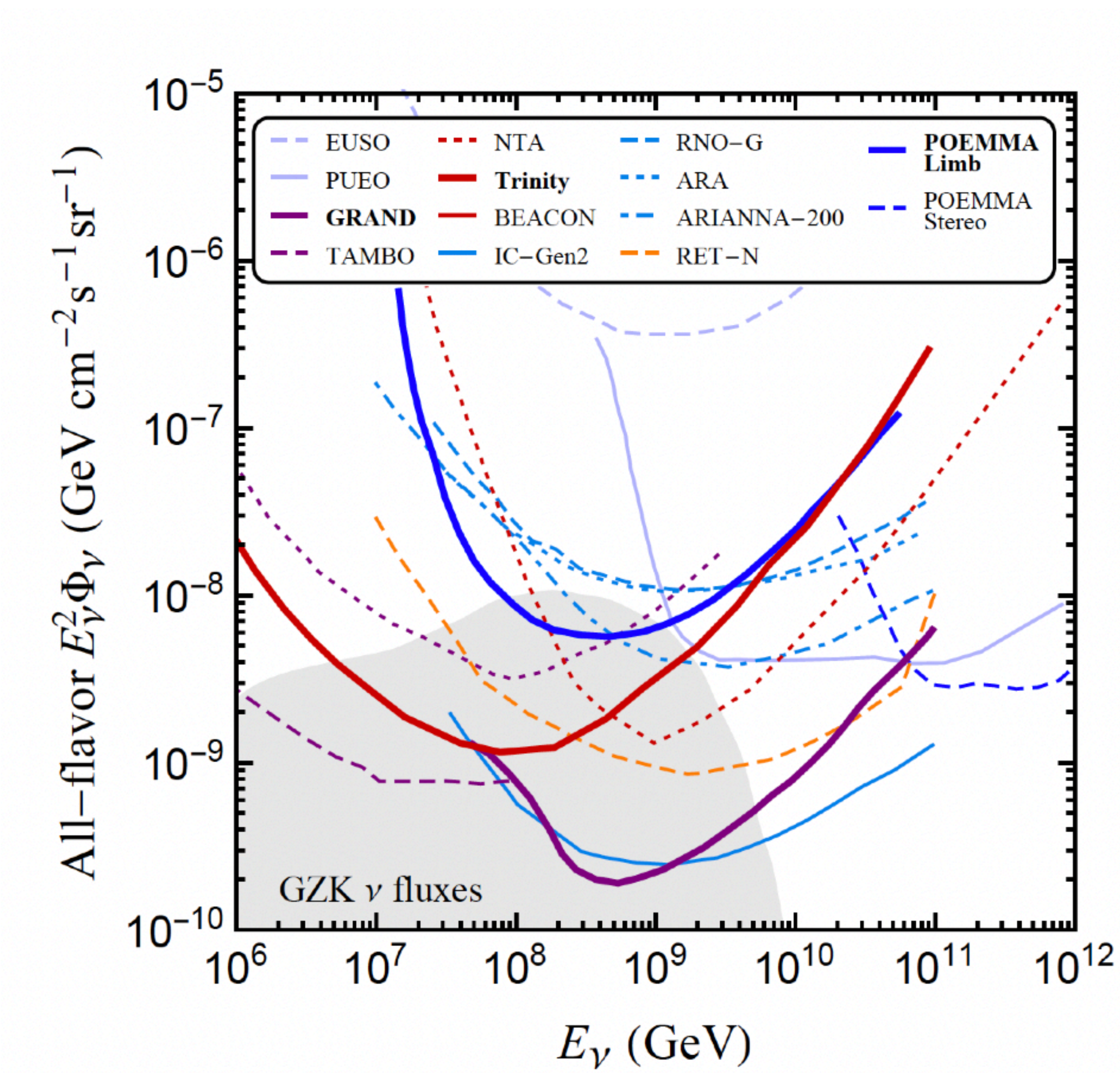


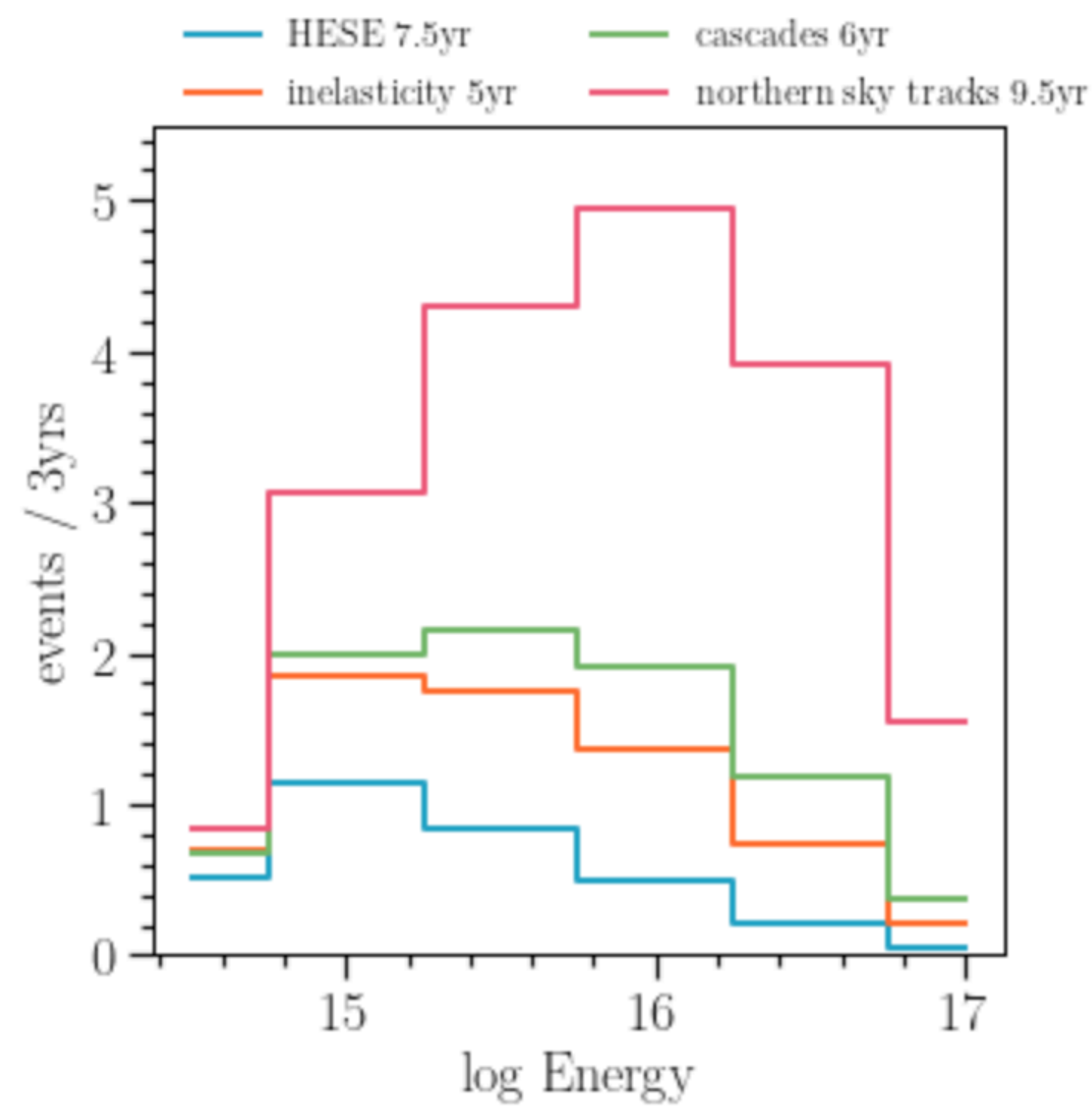
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

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

*TAMBO means house or inn in Quechua.

Preliminary Sensitivities

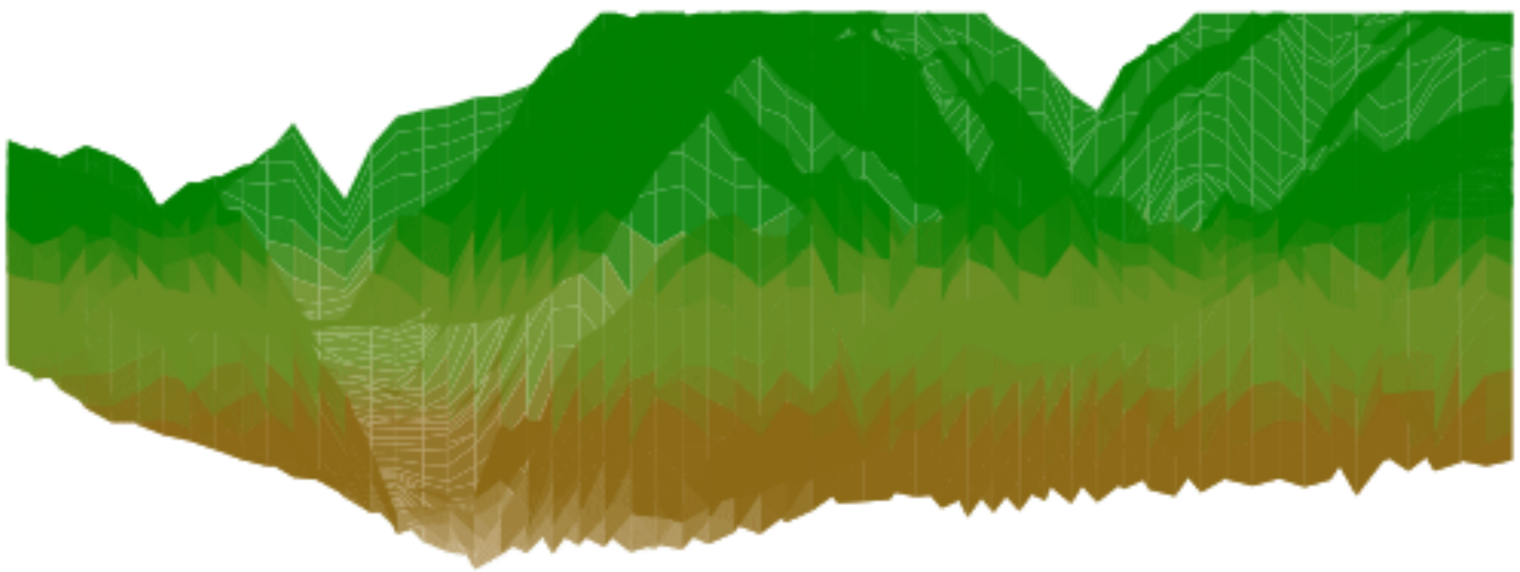




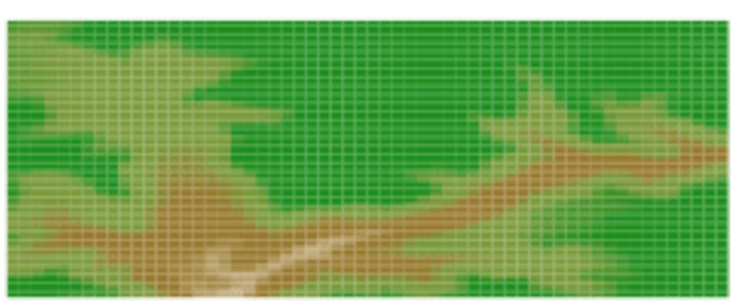
Sensitivities to E_ν^{-2} flux for next generation experiments: Note that almost the entire energy range from 10^6 GeV to 10^{11} GeV can be optimally covered by TAMBO and IceCube-Gen2

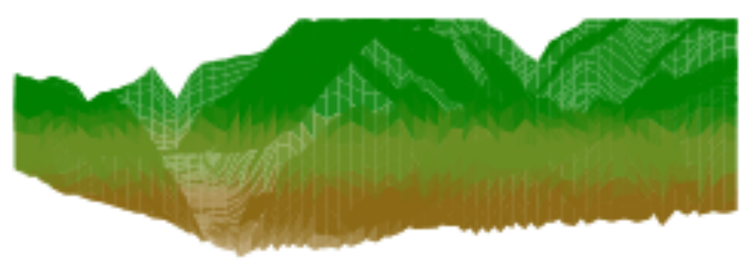
Event rates for several IceCube fluxes: Event rates for several of the best-fit fluxes of IceCube analyses. Pink line is closest to spectrum assumed plot on left

Currently working on simulation with detailed geography of the Colca valley



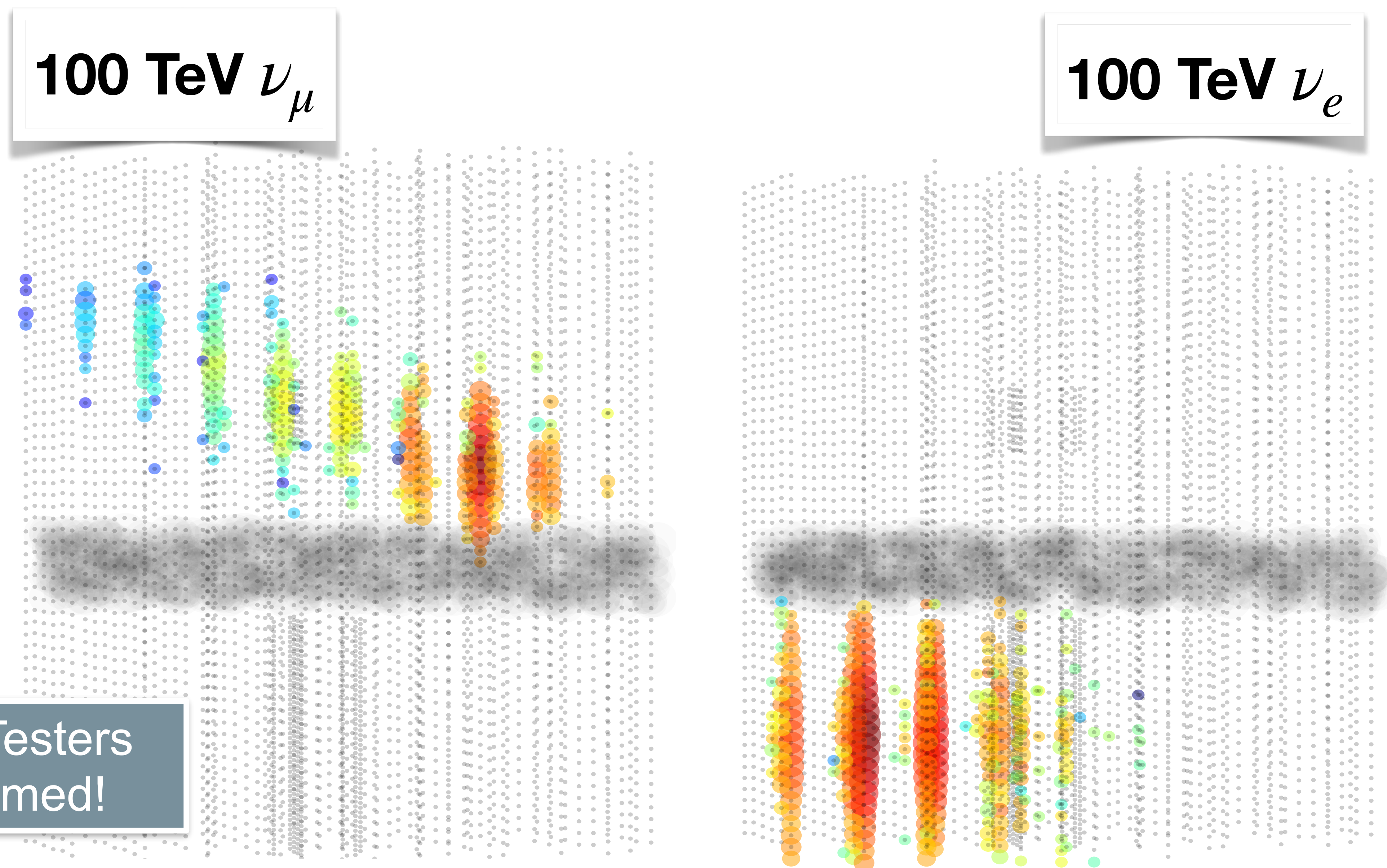
- Initial simulation of ν_τ in Colca valley is complete
- Working on connecting to CORSIKA to simulate air shower
- TauRunner will serve as neutrino injector
- All being written in Julia





PROMETHEUS: Open-Source Neutrino Telescope Simulation

- Open-source simulation of neutrino telescopes from event injection to weighting
- You give it a physics scenario, it gives you times of photons arriving at the given optical modules
- These events can then be weighted to give the rate at the detector
- Can also be used to find effective areas for a given neutrino telescope



Beta Testers Welcomed!

Conclusion

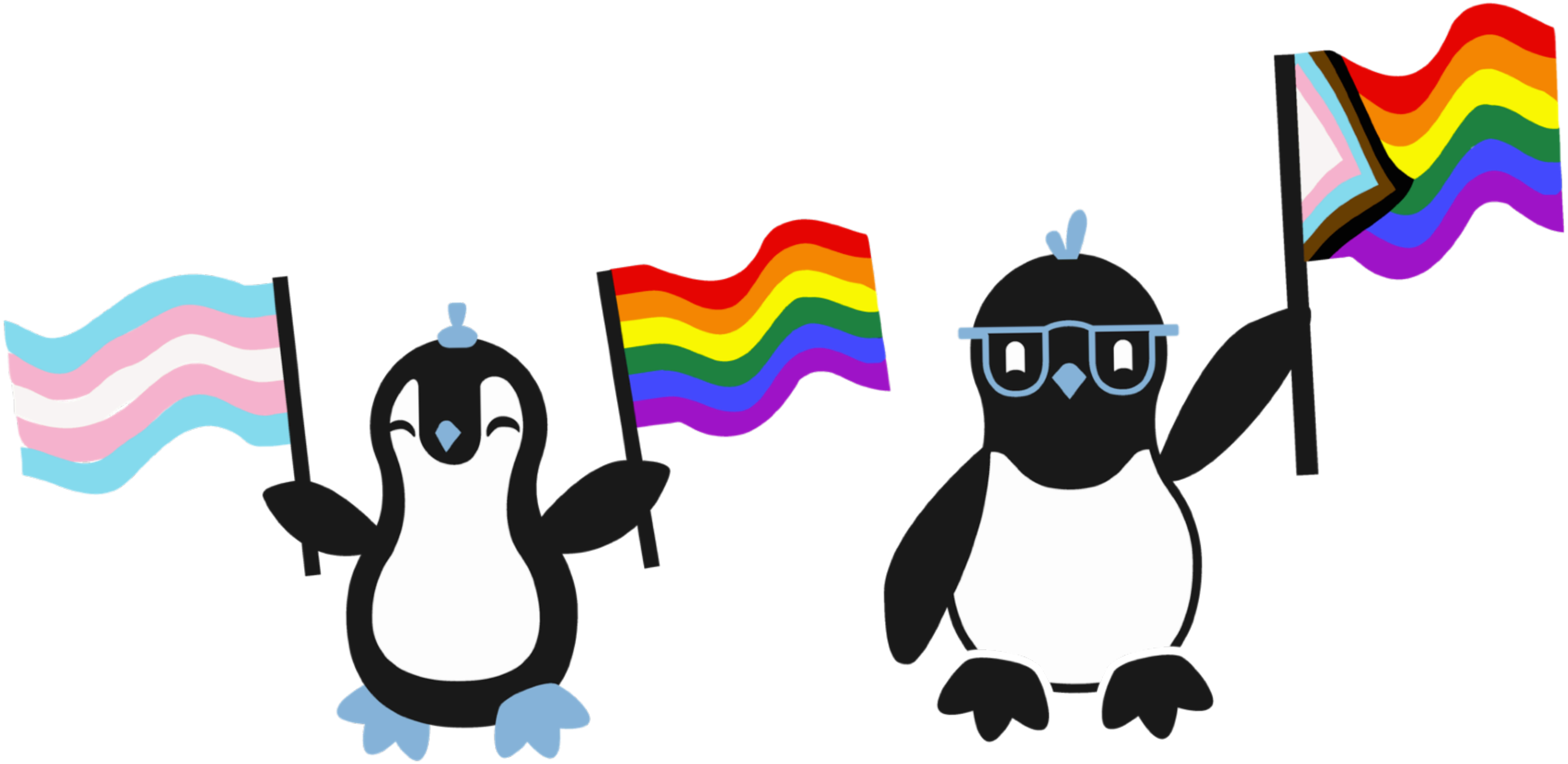
Neutrino Physics is truly in the midst of interesting times:

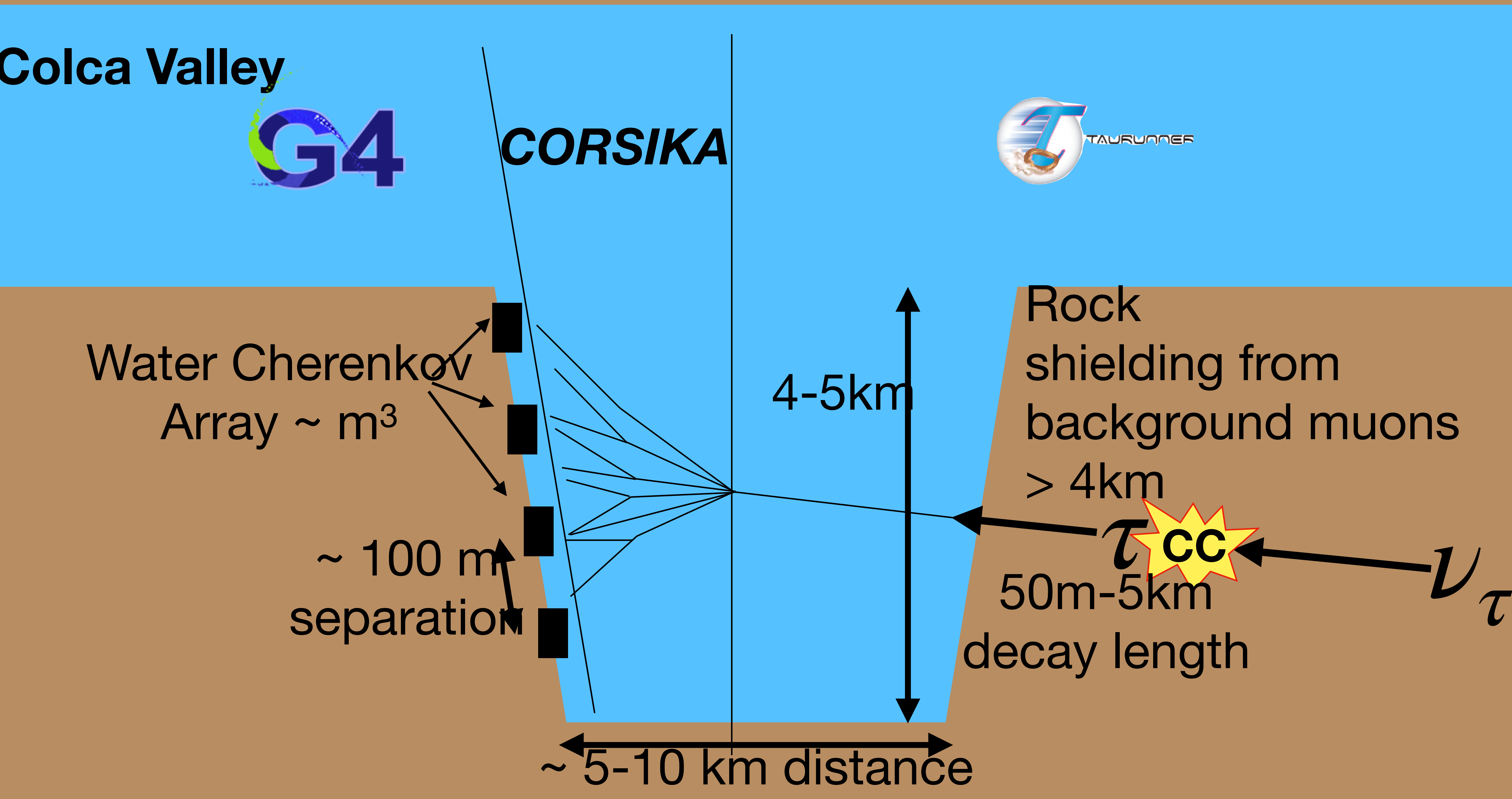
- First candidate astrophysical neutrino sources have been detected.
- Spectral measurements of the high-energy diffuse spectra start to give hint of structure.
- We are studying neutrino properties at PeV energies!
- We have the Dark Matter problem that maybe related to neutrinos.
- We have reached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

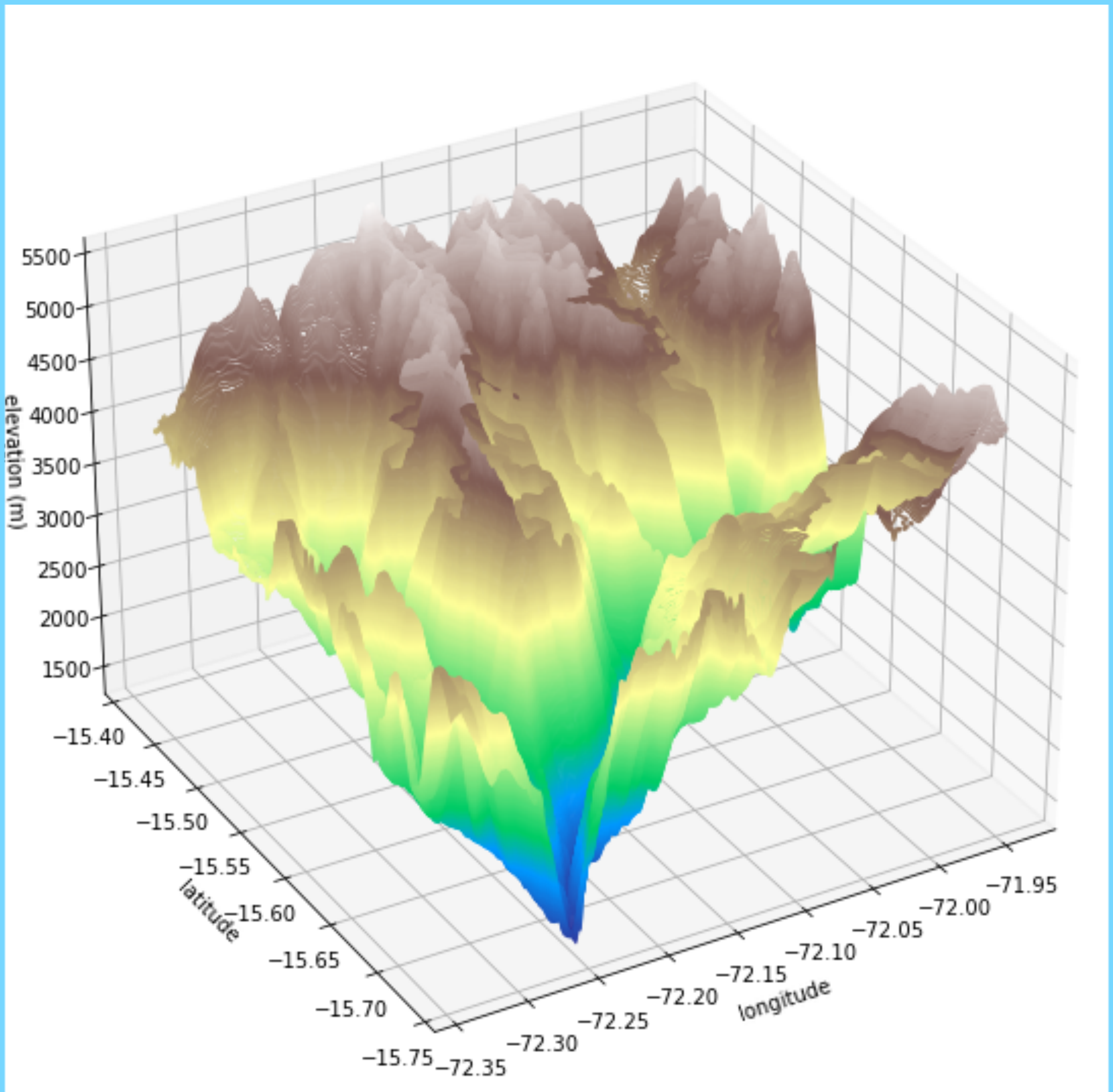
Thanks!





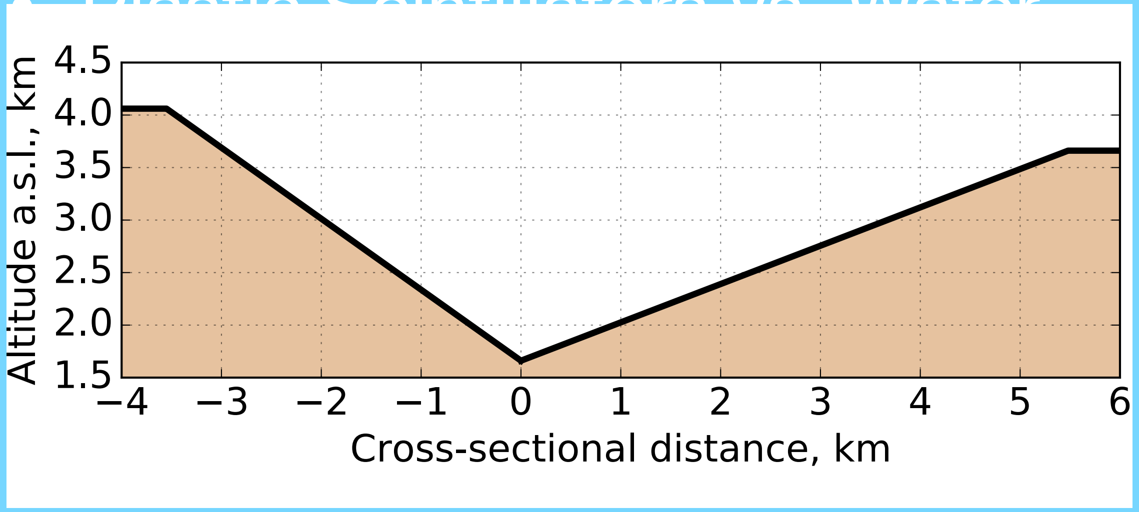
Colca Valley
G4
CORSIKA
TAURUNNER
Water Cherenkov
Array ~ m³
4-5km
Rock
shielding from
background muons
> 4km
τ
CC
ν τ
50m-5km
decay length
~ 100 m
separation
~ 5-10 km distance

First Stage / Current Work



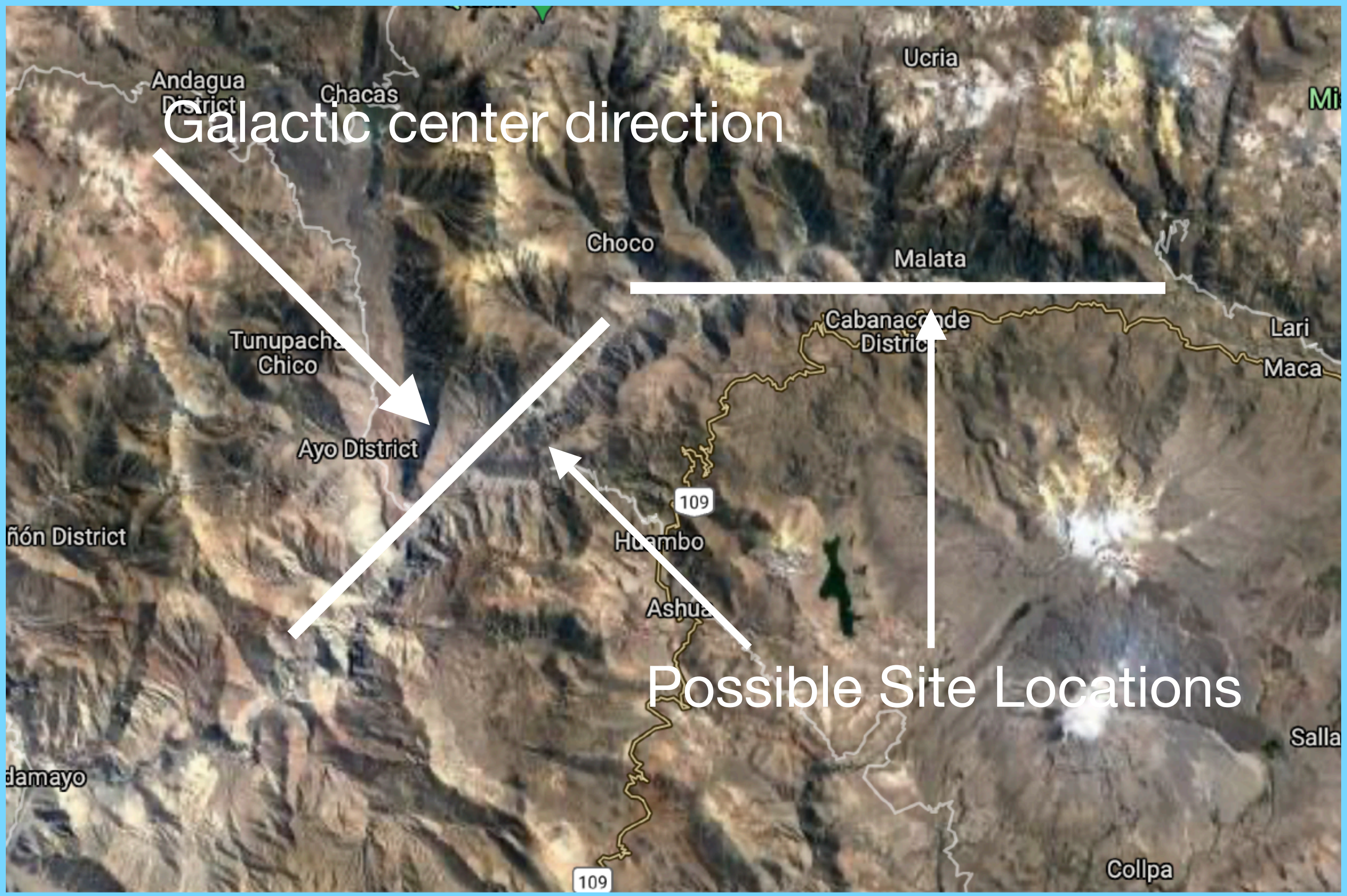
https://www.gpsvisualizer.com/elevation

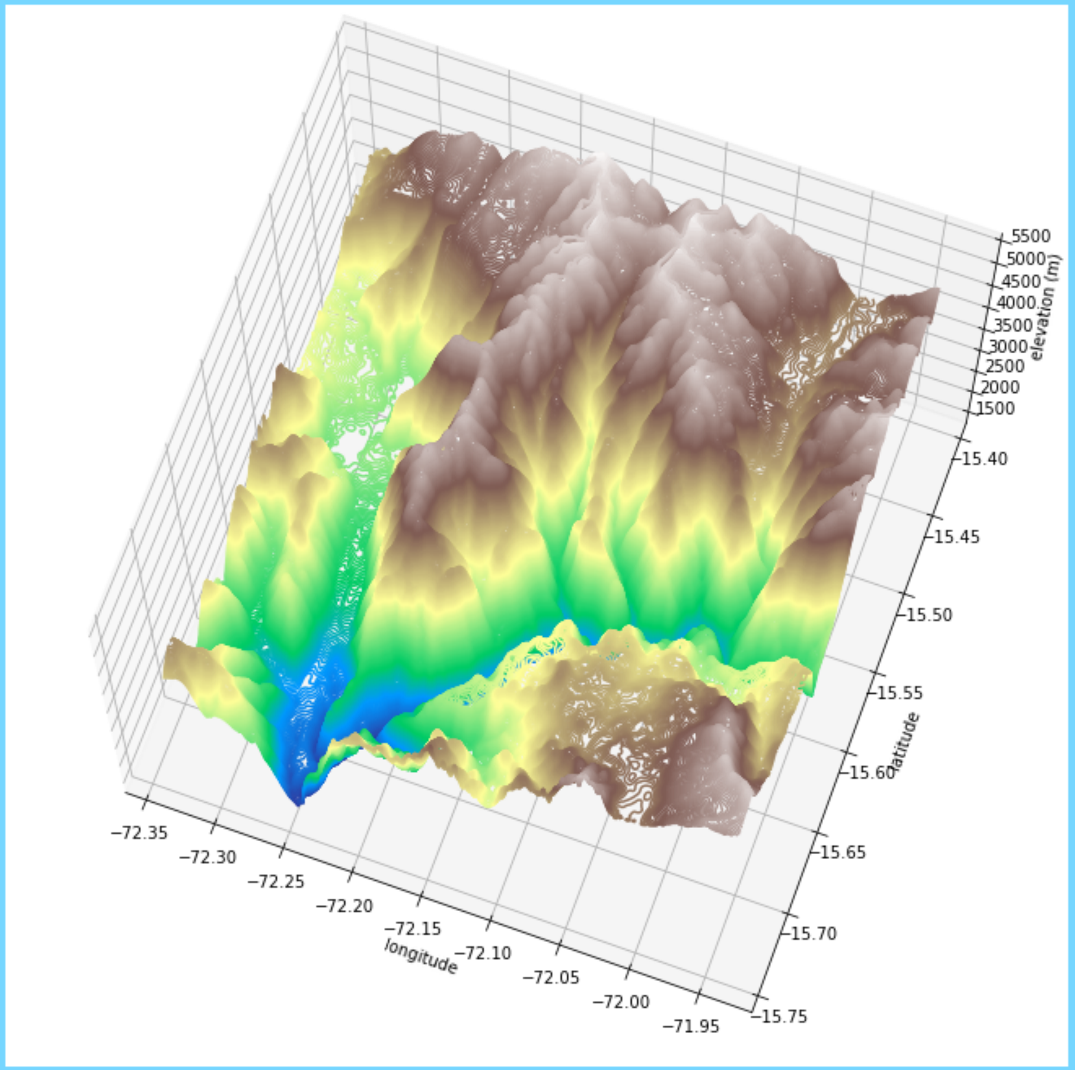
- Updating topographical models
- Previous estimations for prelim figures used simple geography
- Update propagation MC to include more complex geometries
- Plastic Scintillators vs. Water



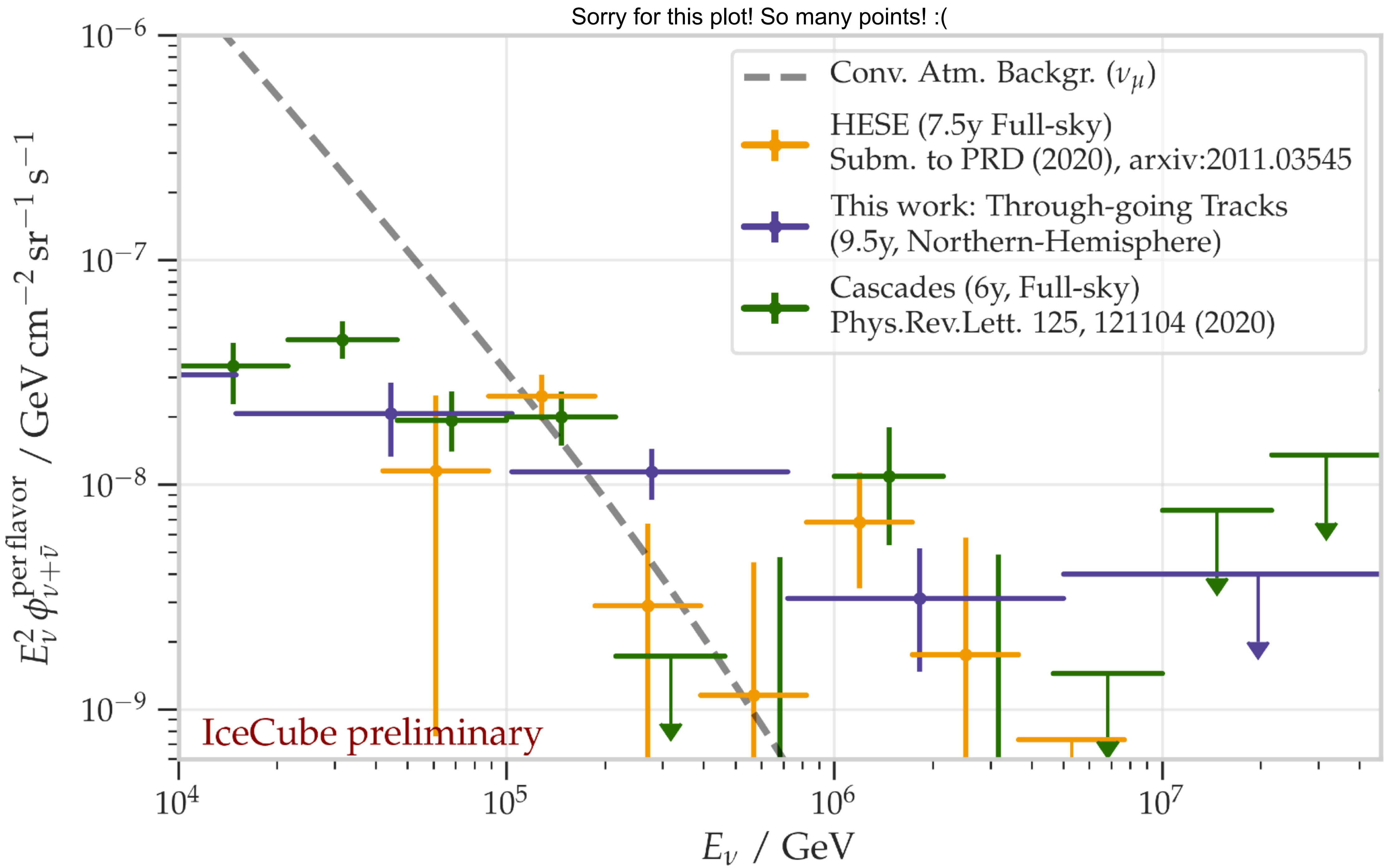
Romero-Wolf et al., arXiv:2002.06475v1

Dark Matter too





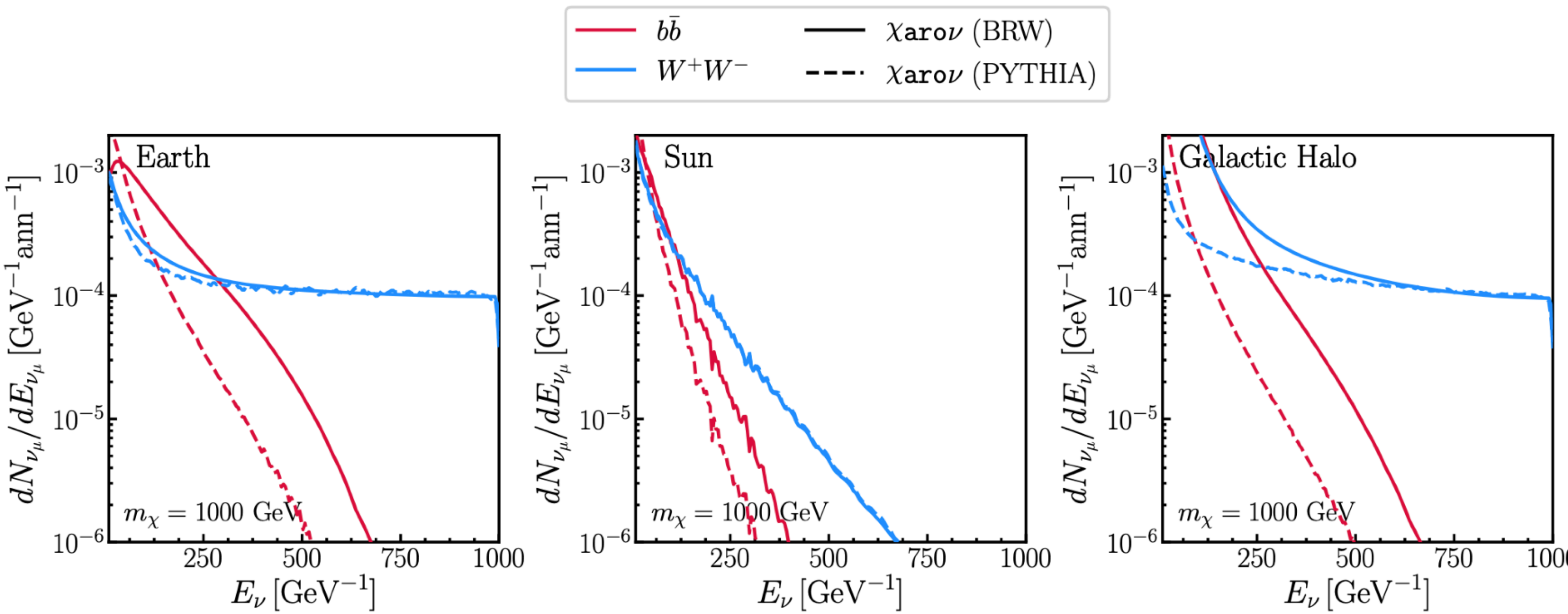
Trying to go beyond a Power Law …



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

For good limits, we need good predictions!

https://github.com/IceCubeOpenSource/charon

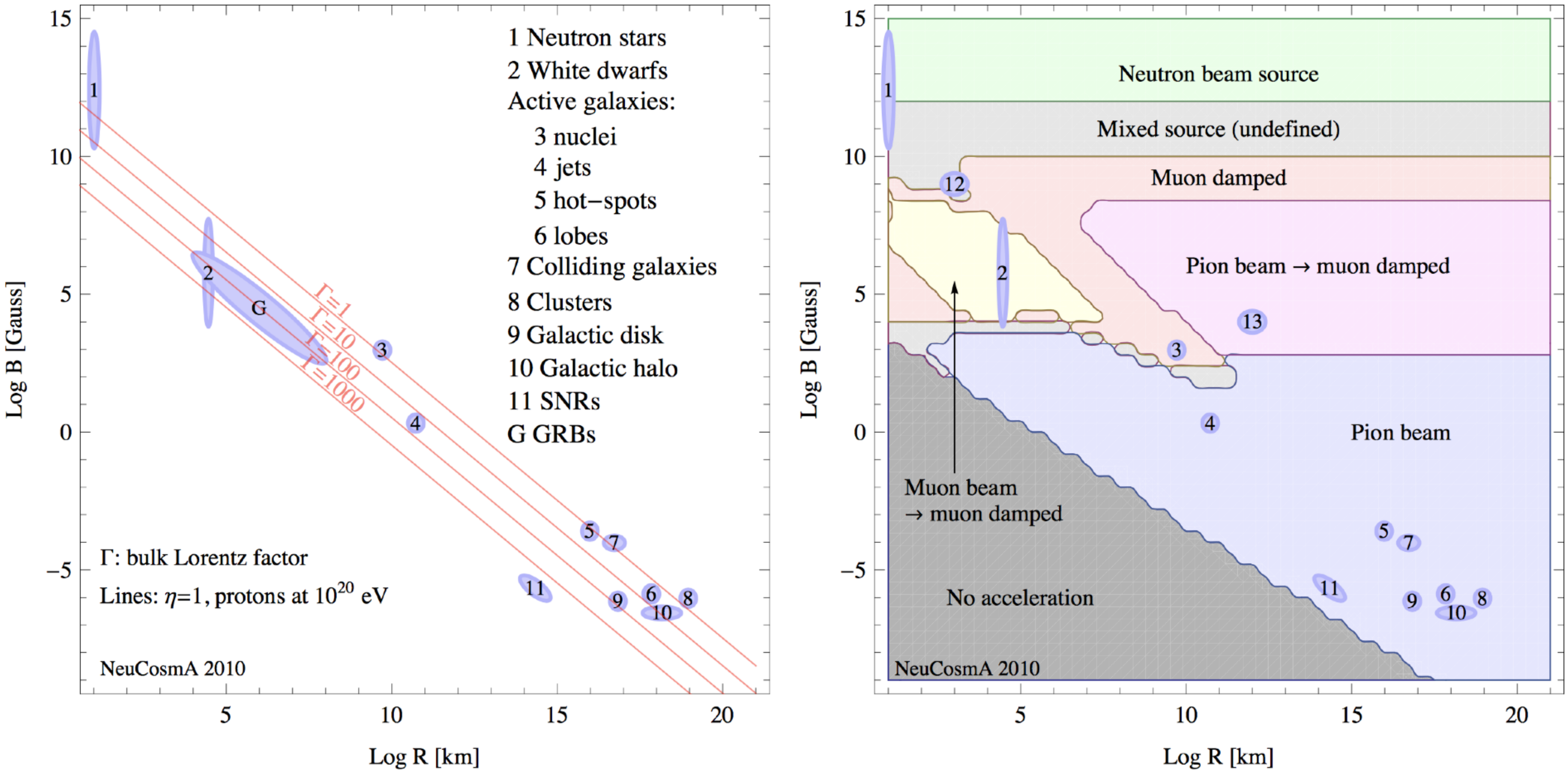


IceCube results with updated calculations to appear soon!

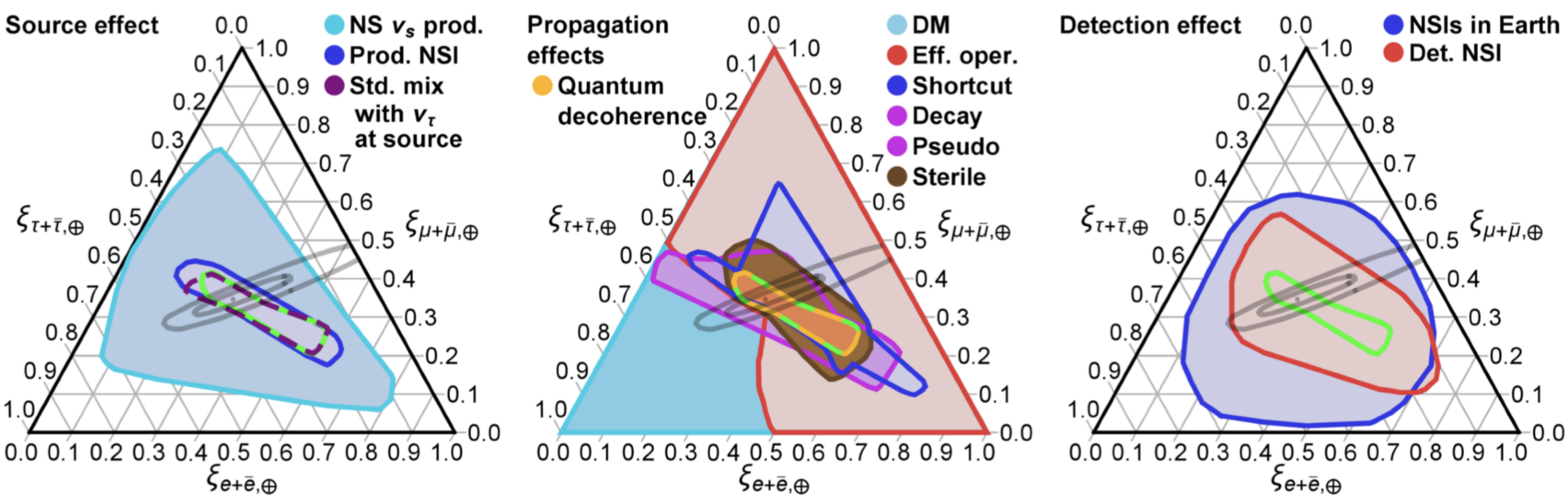
Q. Liu & J. Lazar *et al* 2007.15010

Bauer, Rodd & Webber *et al* 2007.15001

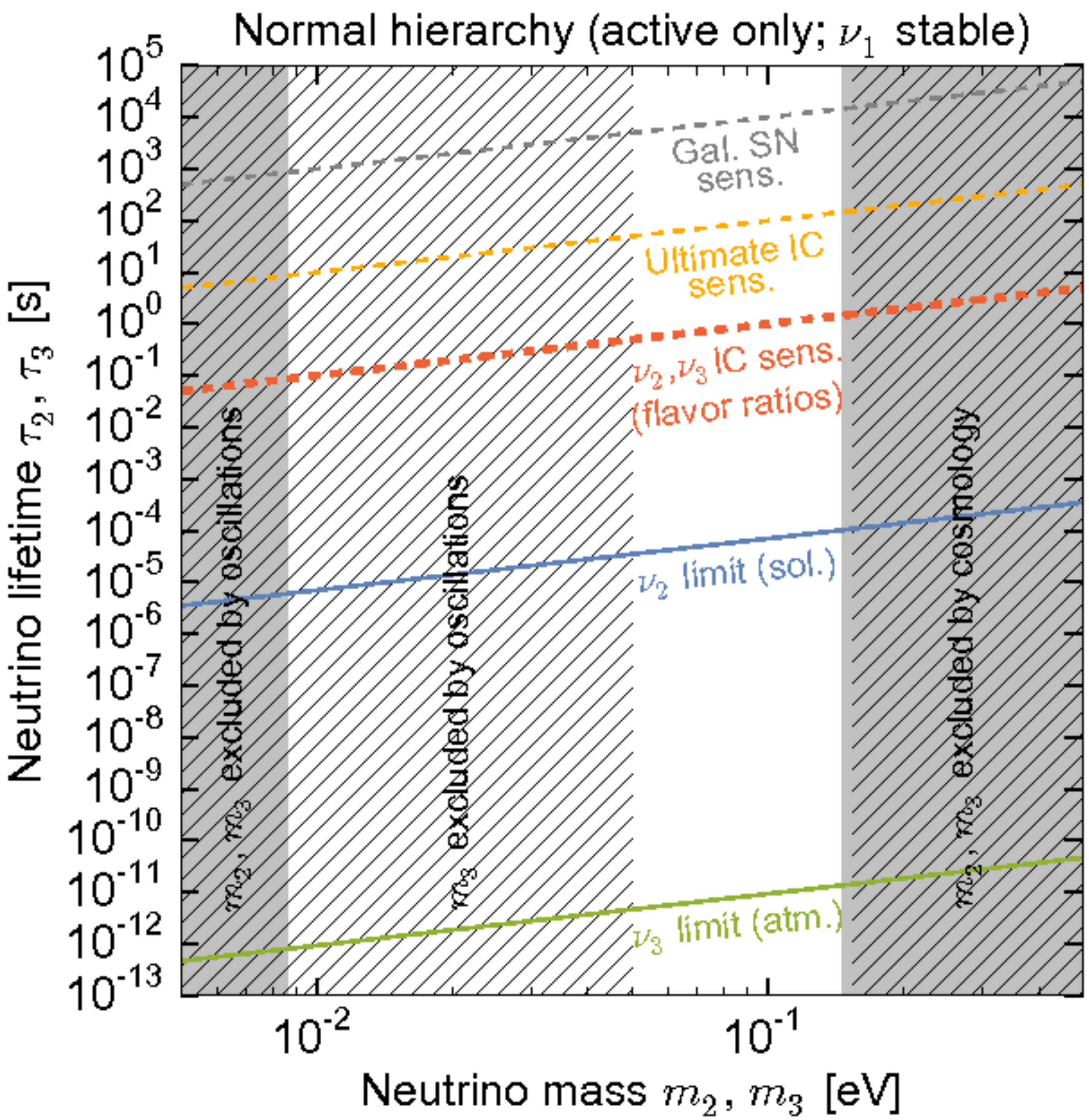
Sources of Astrophysical Neutrinos

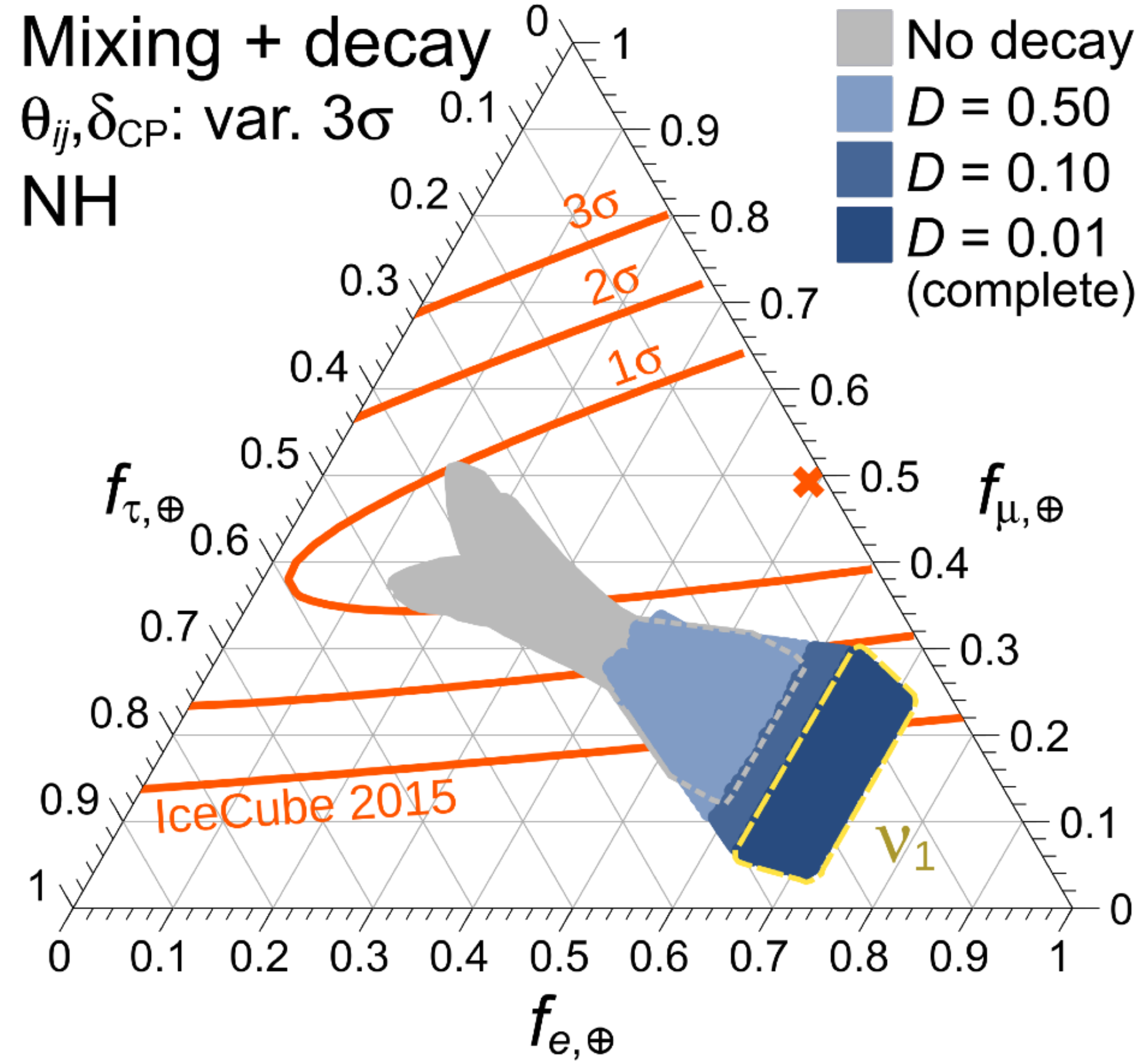


(arXiv:1007:0006)

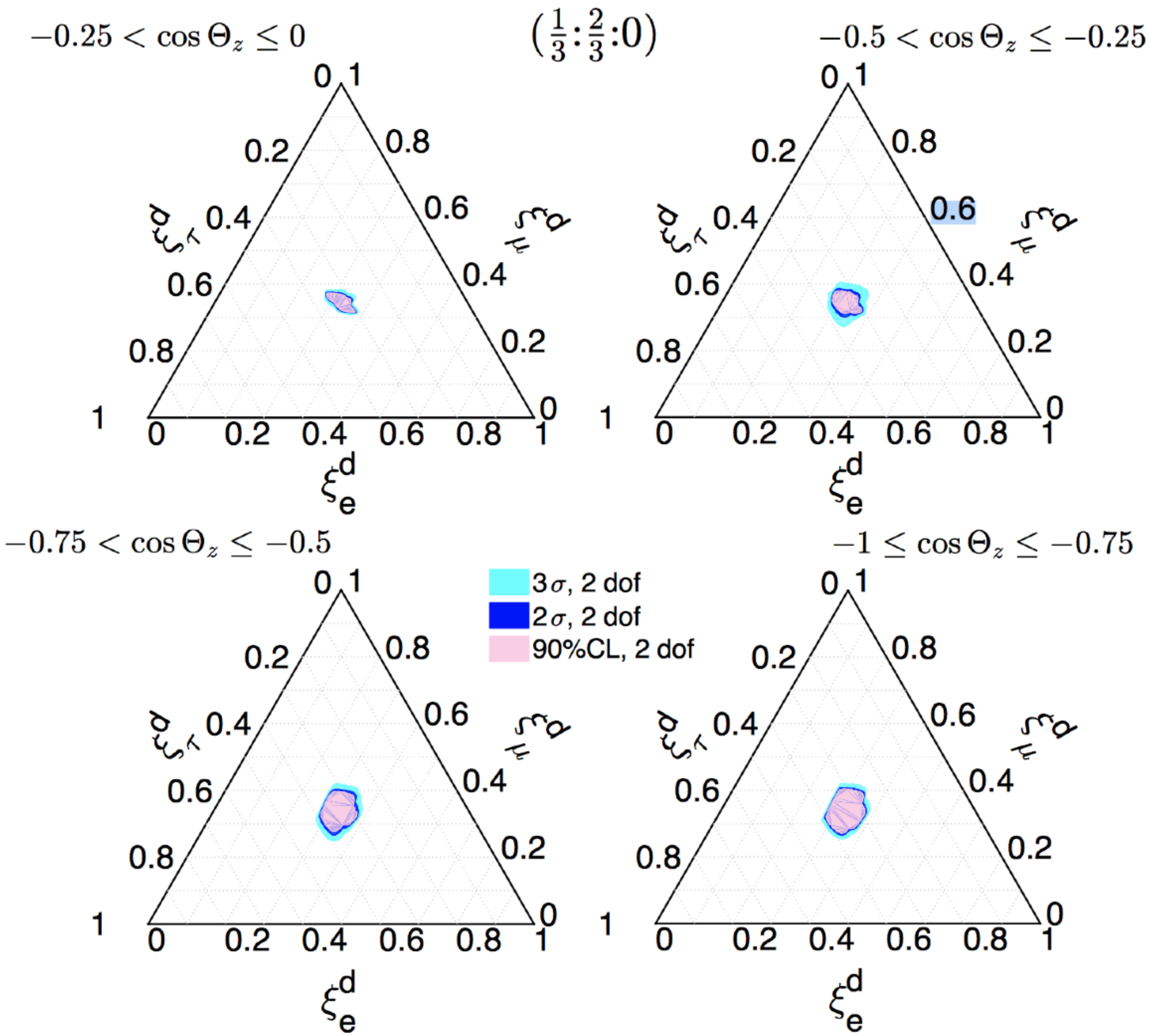


Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684



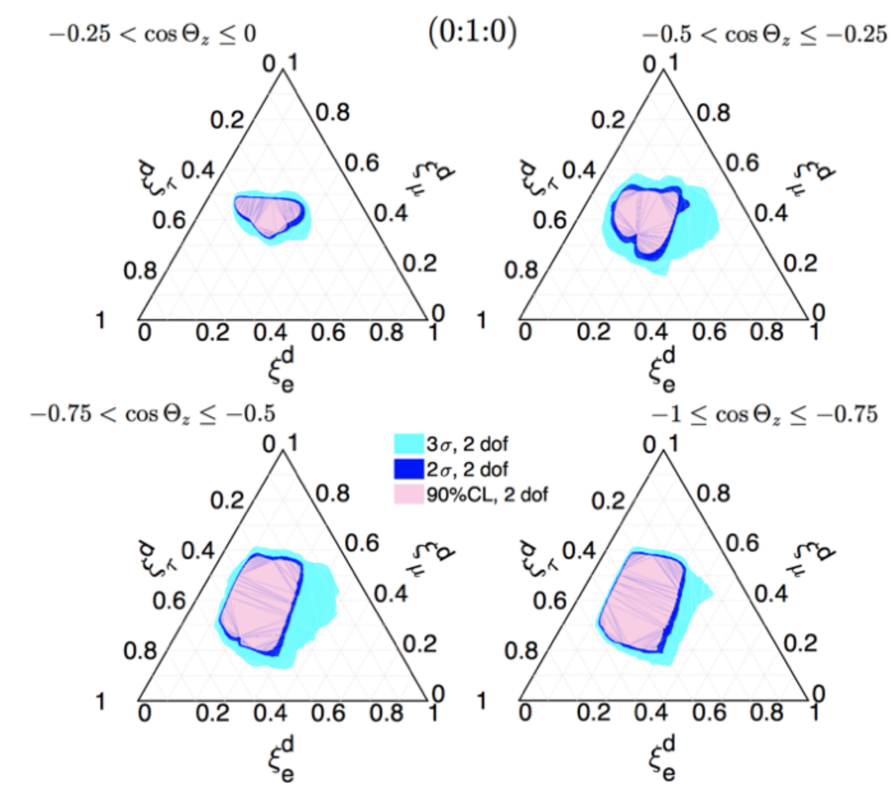


M. Bustamante, J. Beacom, K. Murase (1610.02096)

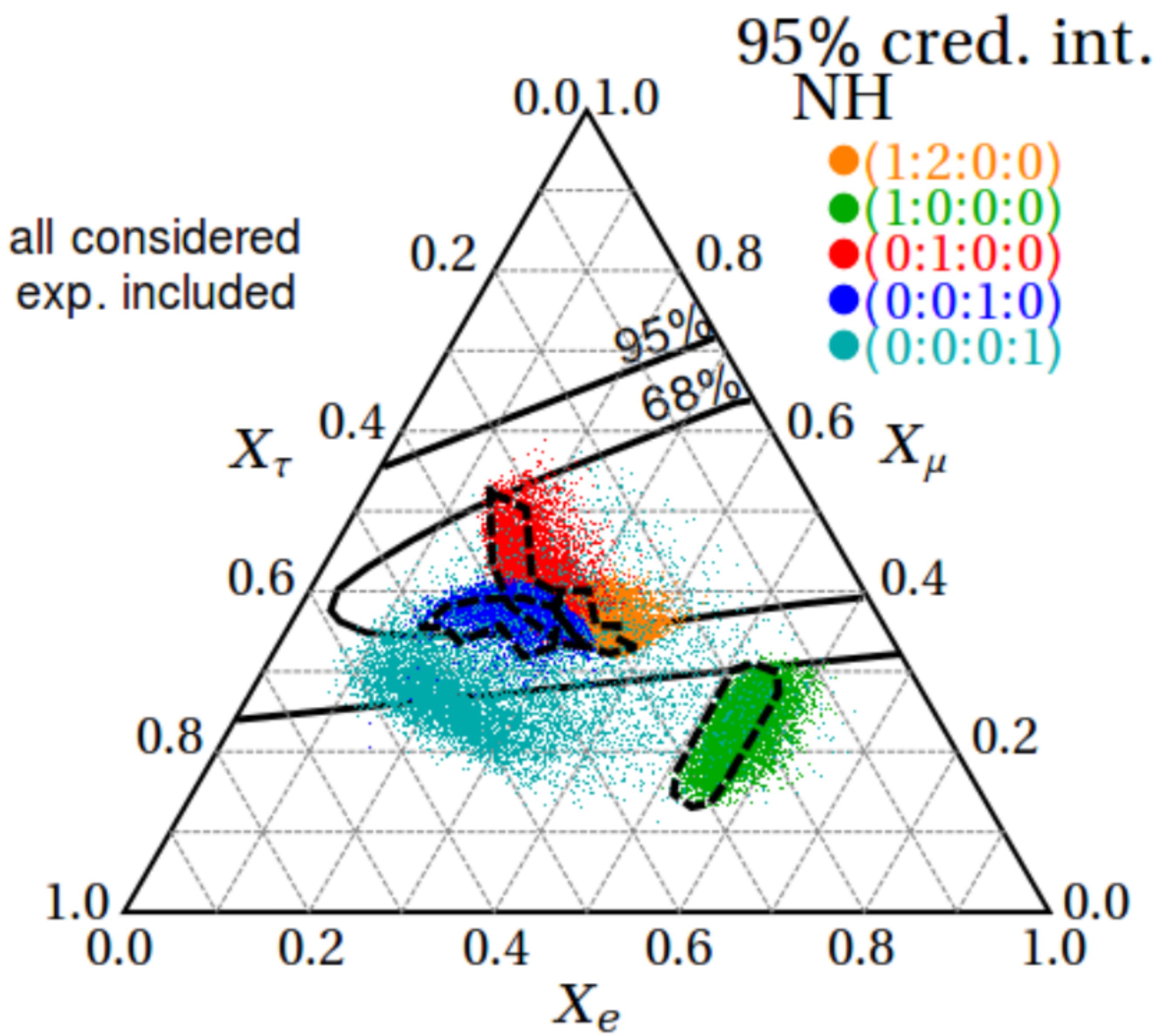


In the pion scenario NSI effects are small.

This is not the case for other initial flavor ratios.



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



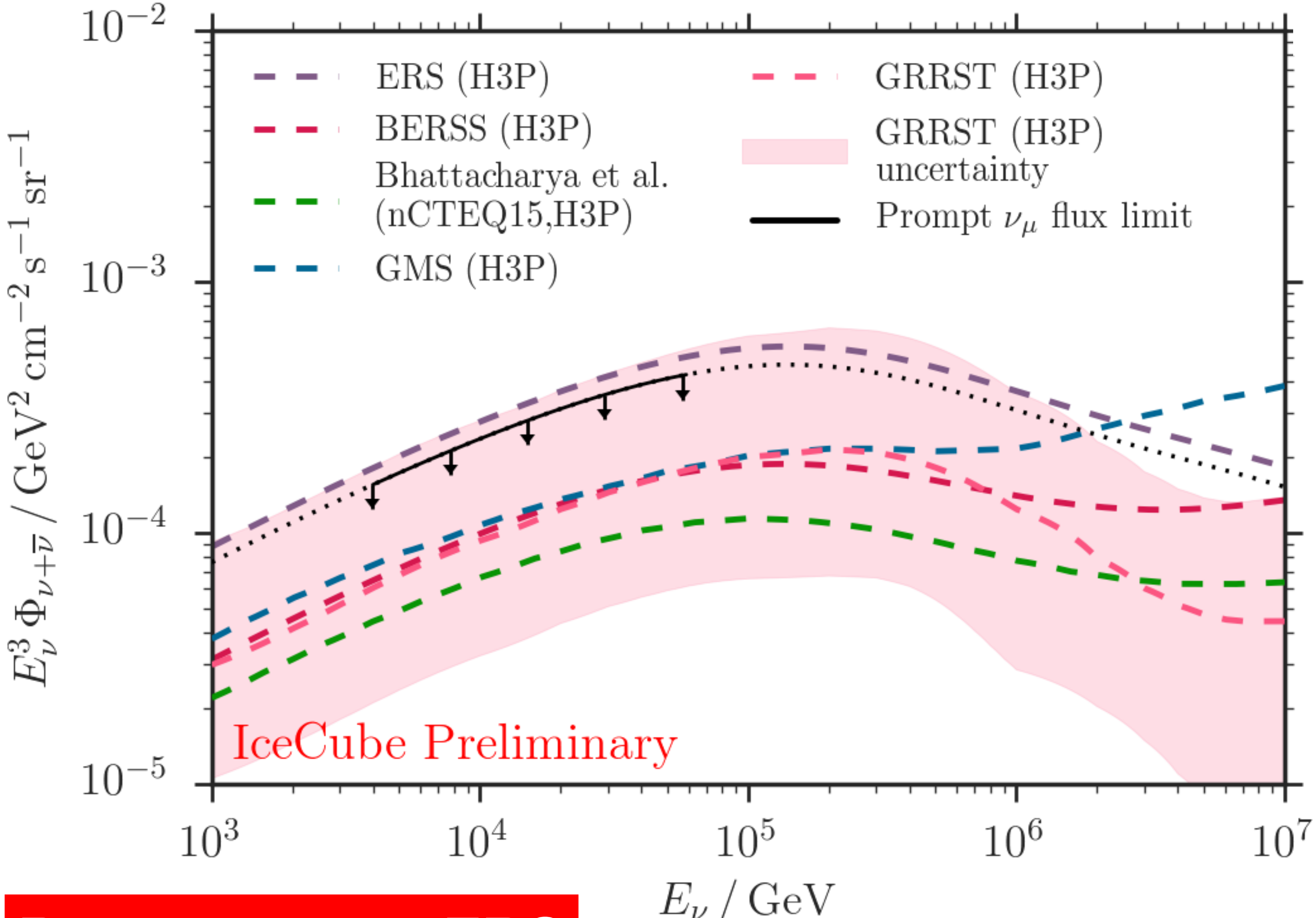
- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

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

Also, constraints from the Northern Sky

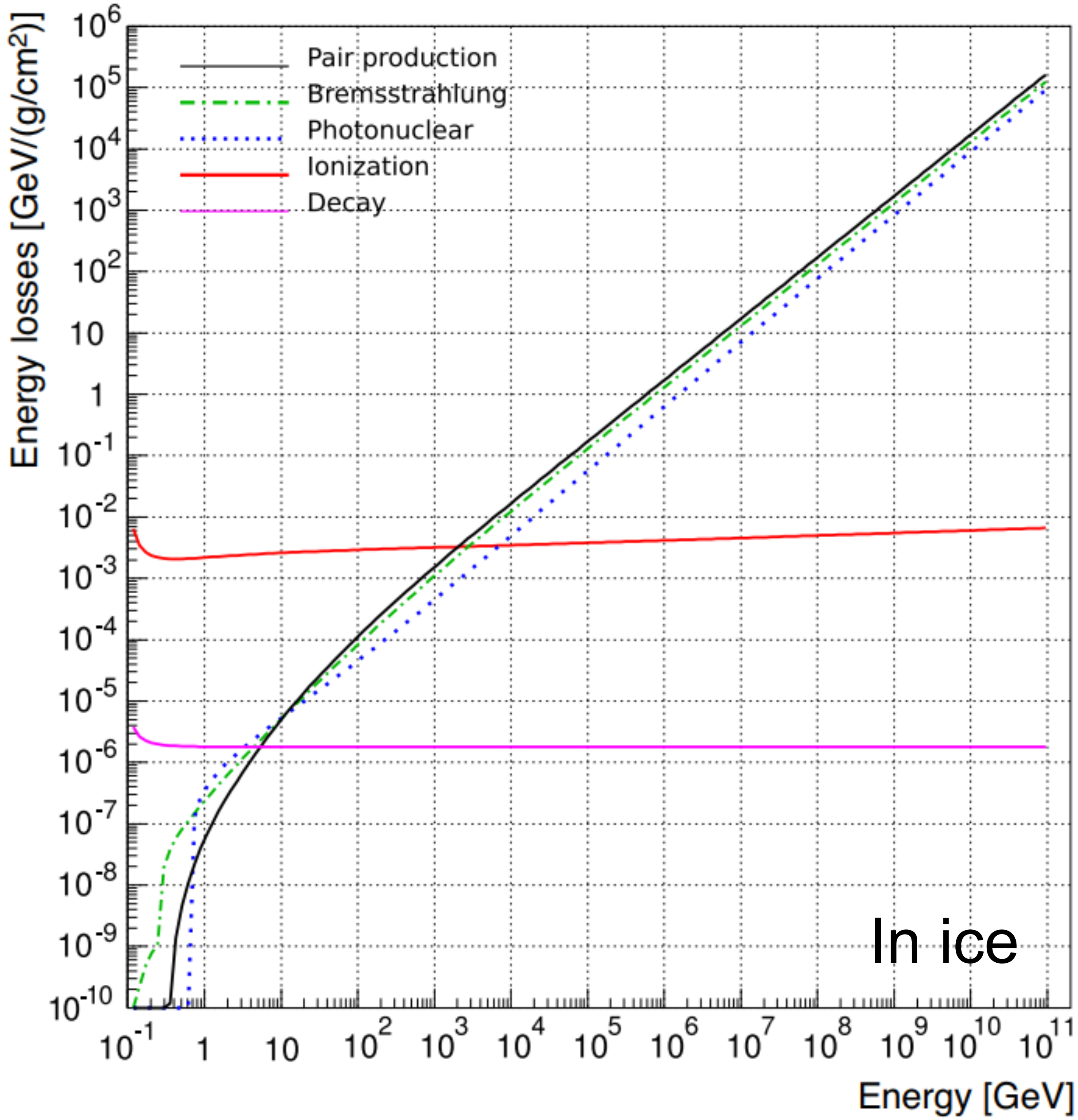
Limits from 8 years of through-going muons

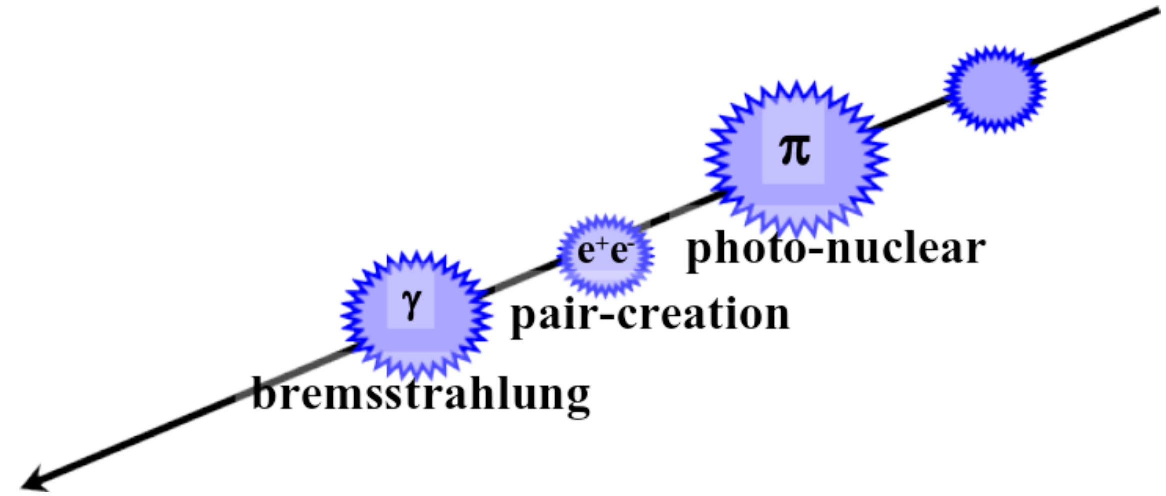
No prompt yet!



Prompt < 0.86 ERS

Muon losses and ranges





Mean energy losses are well described by

$$-\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_I + \left(\frac{dE}{dx}\right)_B + \left(\frac{dE}{dx}\right)_P + \left(\frac{dE}{dx}\right)_N$$

$$-\frac{dE}{dx} = a_I(E) + b(E)\cdot E$$

$$\text{with} \quad b(E) = b_B(E) + b_P(E) + b_N(E)$$

Mean muon range

$$x_f = \log(1 + E_i \cdot b/a)/b$$

medium	$a, \frac{\text{GeV}}{\text{mwe}}$	$b, \frac{10^{-3}}{\text{mwe}}$
ice	0.268	0.470

Muon losses are stochastic processes

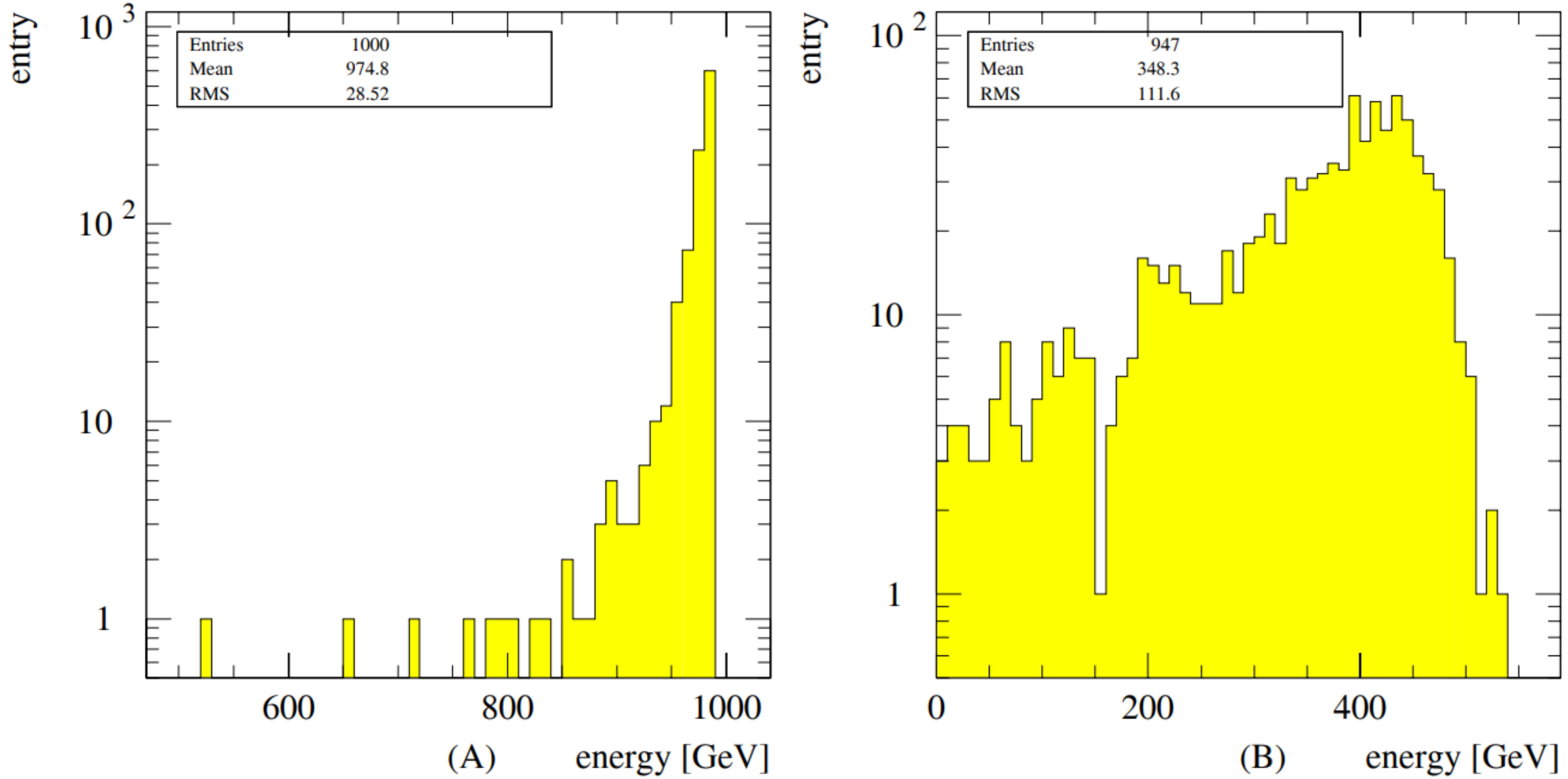


Figure 3.12: Stochastic character of muon energy loss The picture shows distributions of the final energy of 1000 simulated muons (initial energy $1TeV$) after passing (A) $50m$ and (B) $1500m$ of fresh water, simulated with GEANT (section 6.2)

From C. Wiebusch (1995)