Challenging the Standard Model with IceCube

New methods and ideas at the frontiers of particle physics
Aspen Center for Physics Winter Conference
Aspen, Colorado, USA
March 25, 2022

Carlos Argüelles

HARVARD UNIVERSITY

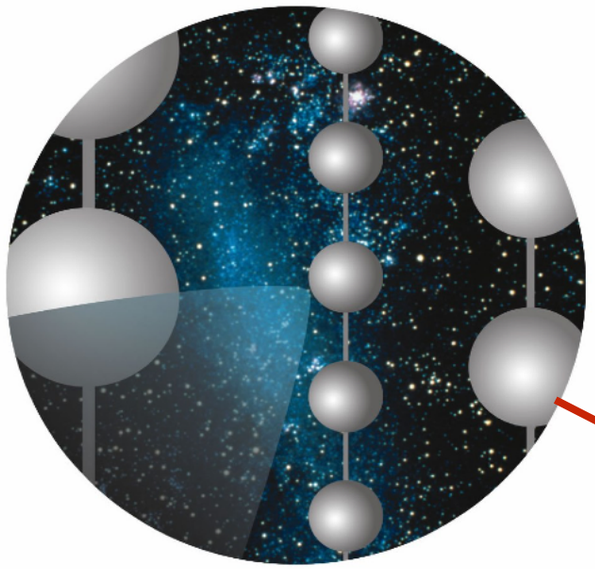
IceCube South Pole Neutrino Observatory

How does the Universe look in neutrinos?

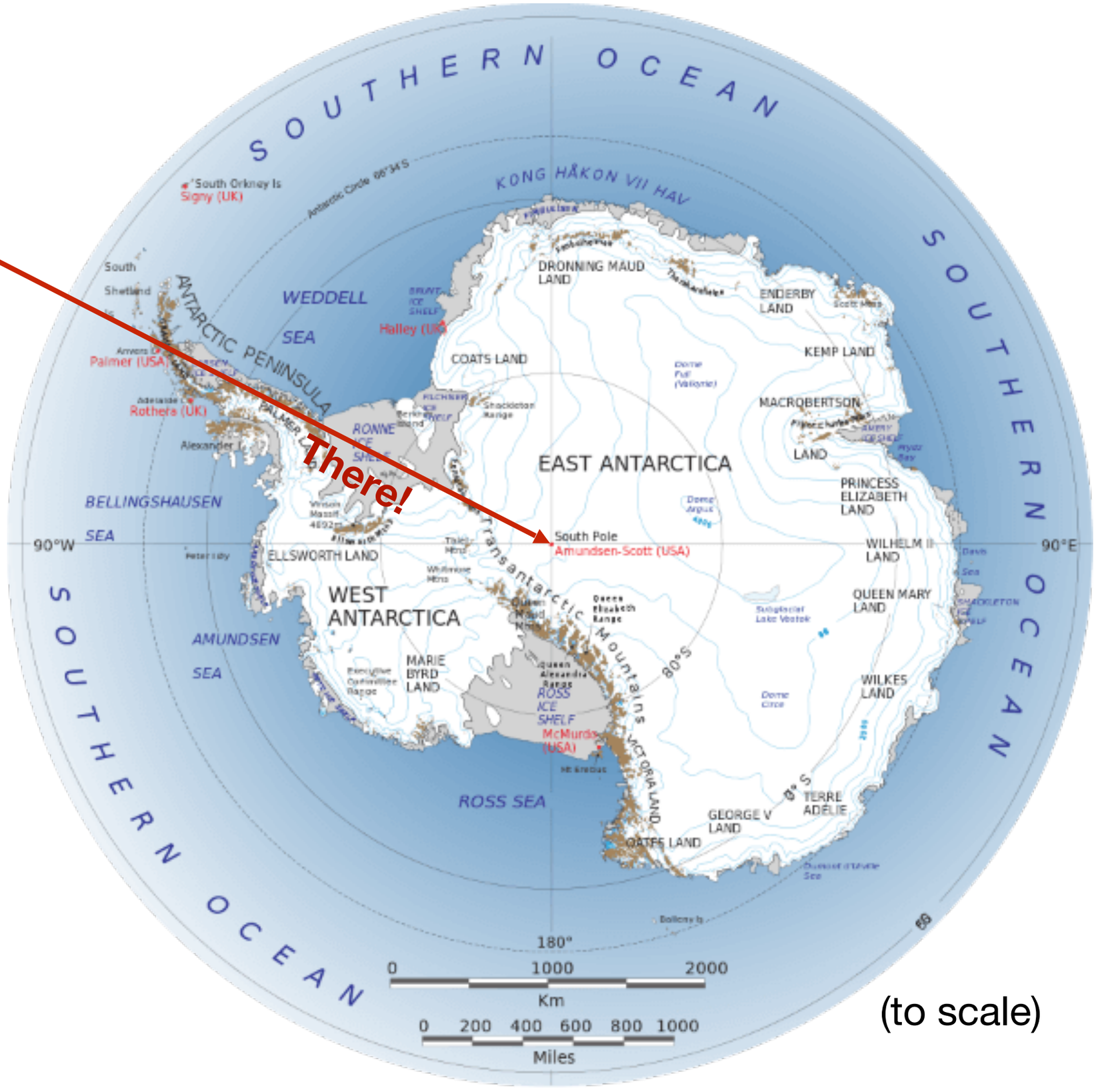
How do high-energy neutrinos behave?

Outline of the rest of this talk:

1. IceCube 101
2. Searching for new forces:
    -Measuring high-energy neutrino cross section
3. Searching for dark matter:
    -Neutrino-Dark Matter Interactions
4. Searching for a new space-time symmetry:
    -Lorentz Violation Effects on Flavor
5. The future

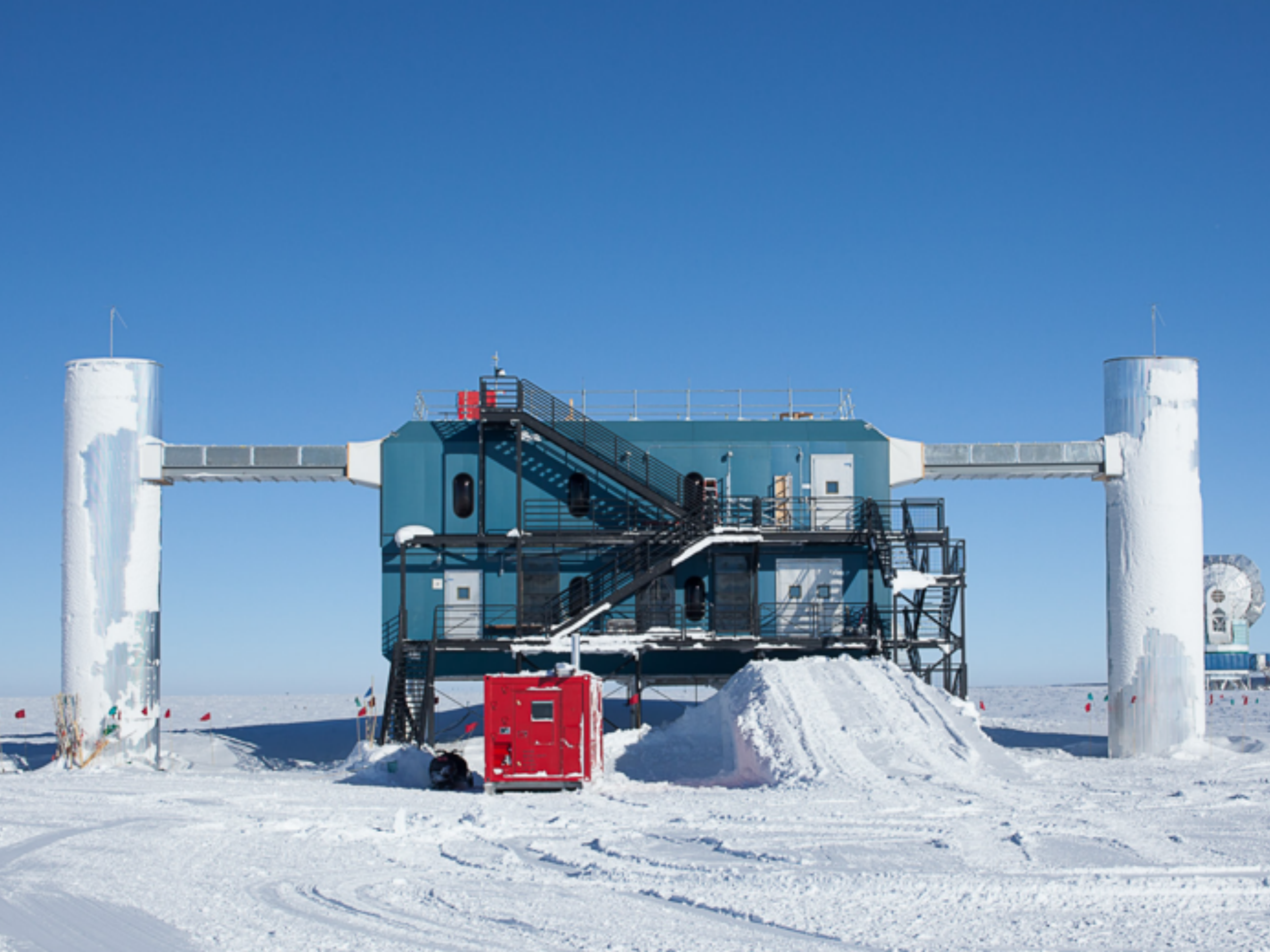


IceCube



(to scale)

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



IceCube

South Pole Neutrino Observatory

IceCube Laboratory

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

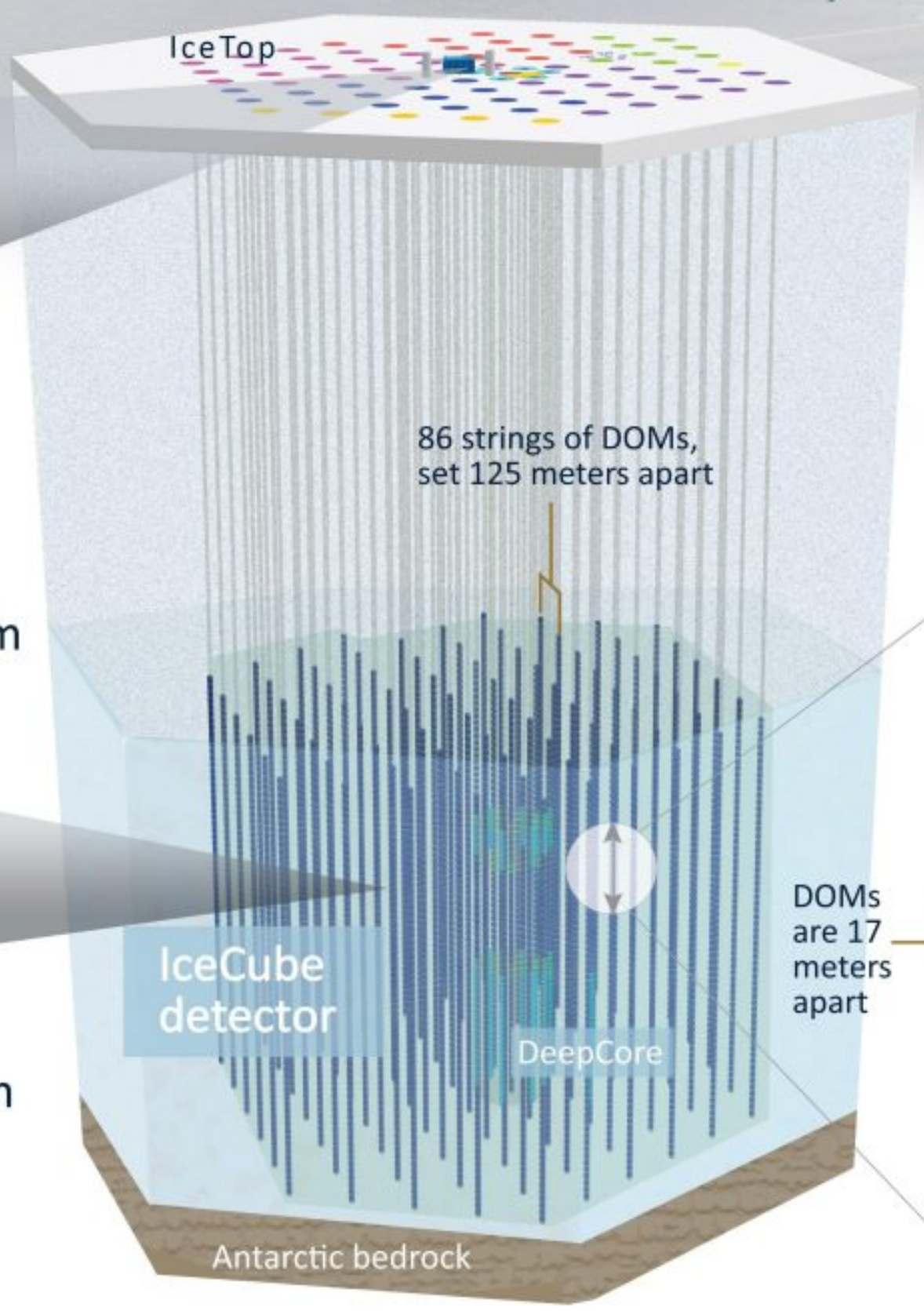
50 m

1450 m

2450 m

Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

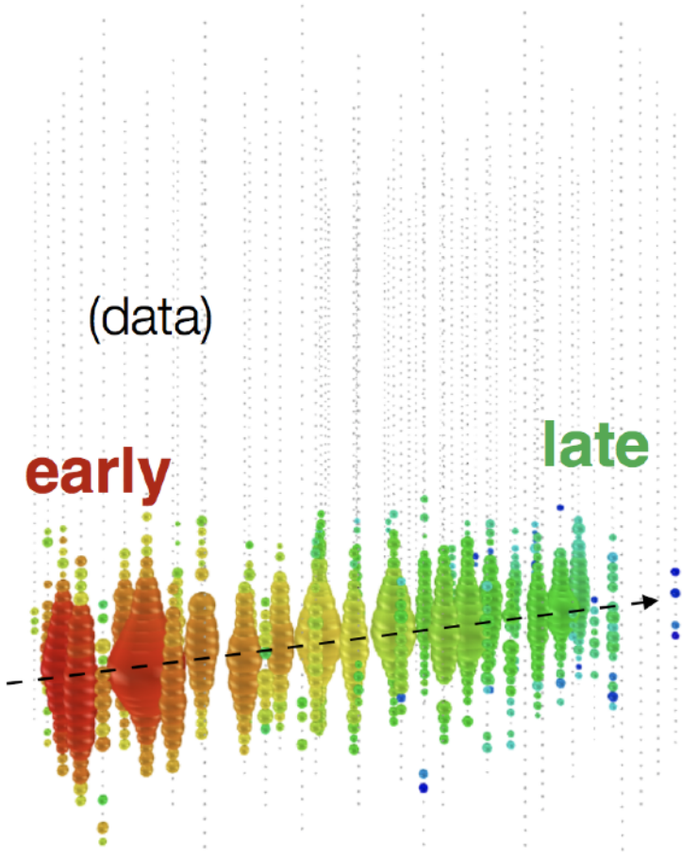


Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

All event morphologies

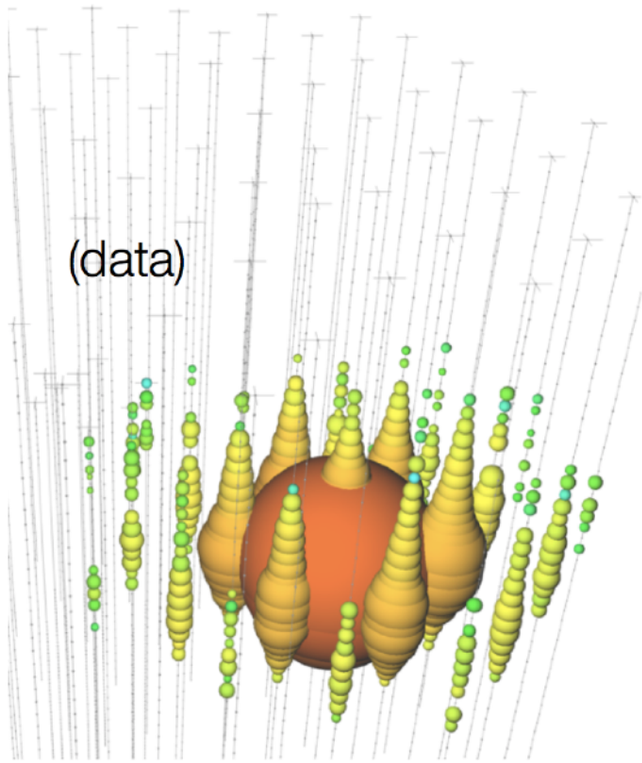
Charged-current ν_μ



Up-going track

Factor of ~ 2 energy resolution
< 1 degree angular resolution

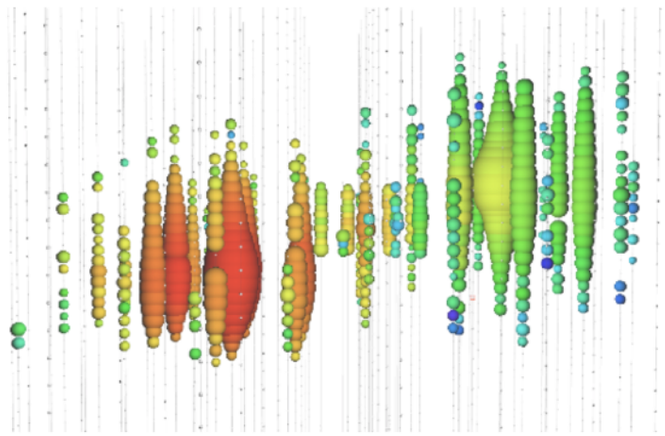
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

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

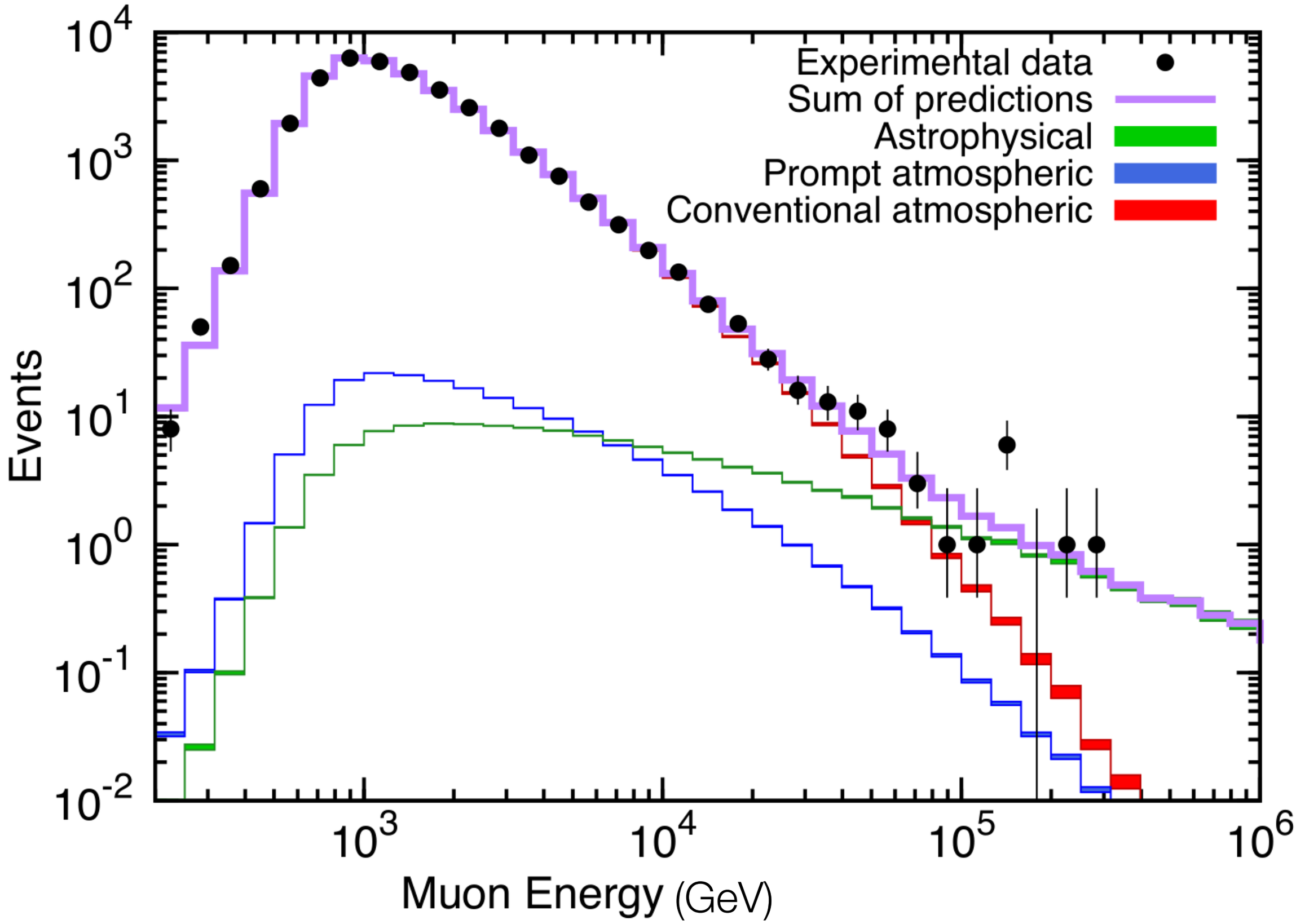
Charged-current ν_τ



Double cascade

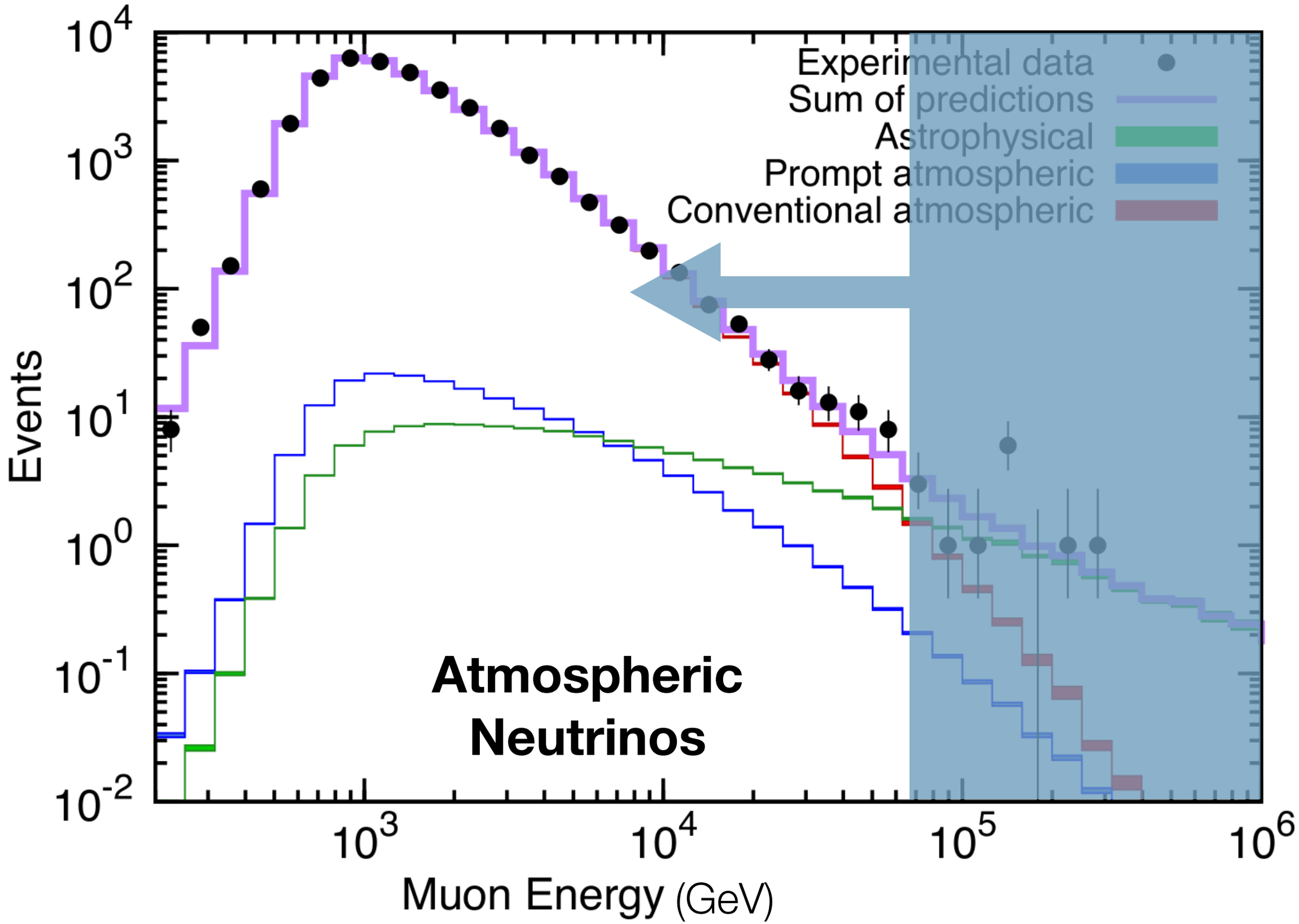
(resolvable above ~ 100 TeV deposited energy)

Distribution of Muons In IceCube



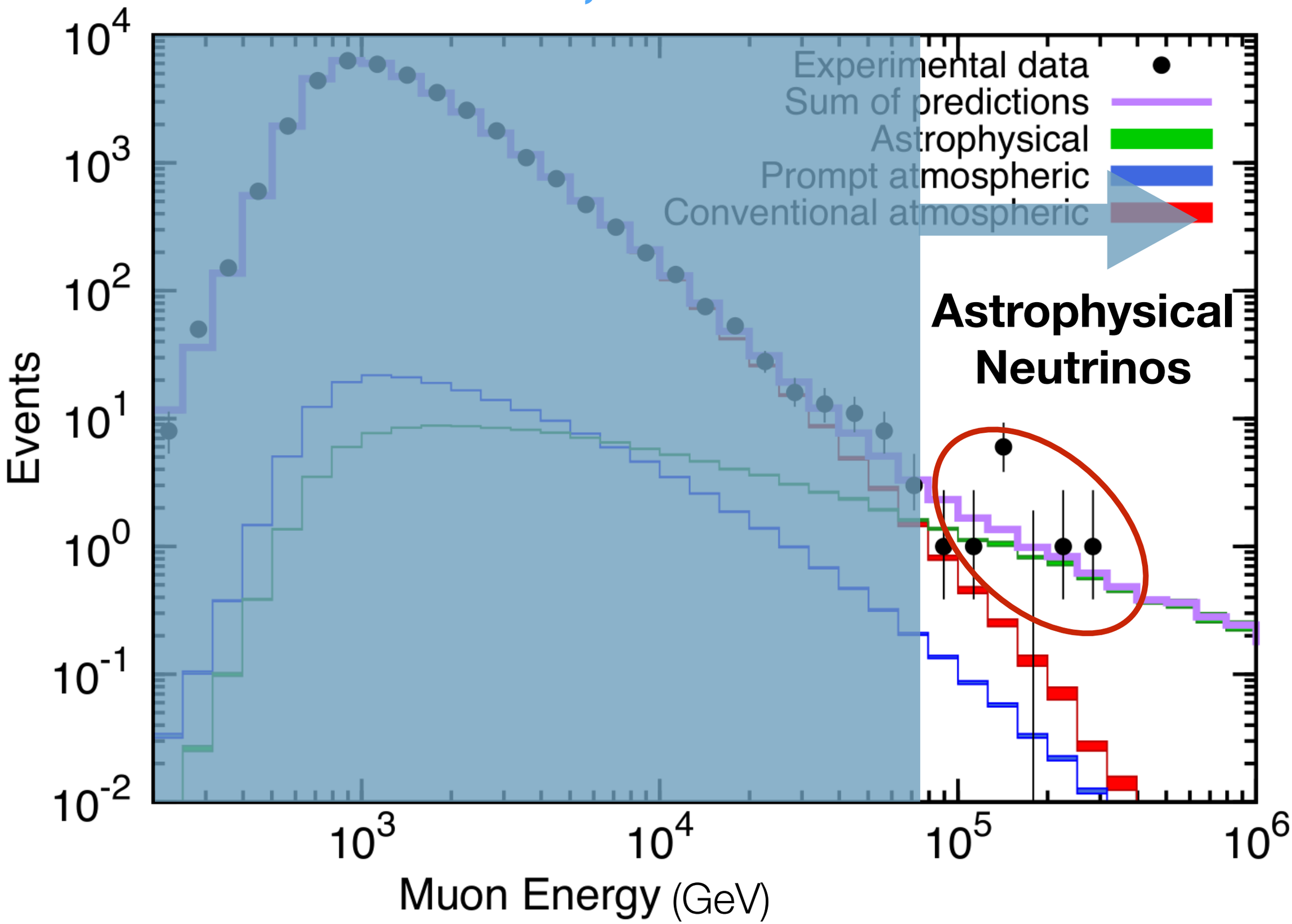
Phys. Rev. Lett. 115, 081102 (2015)

IceCube observes a lot of atmospheric neutrinos!



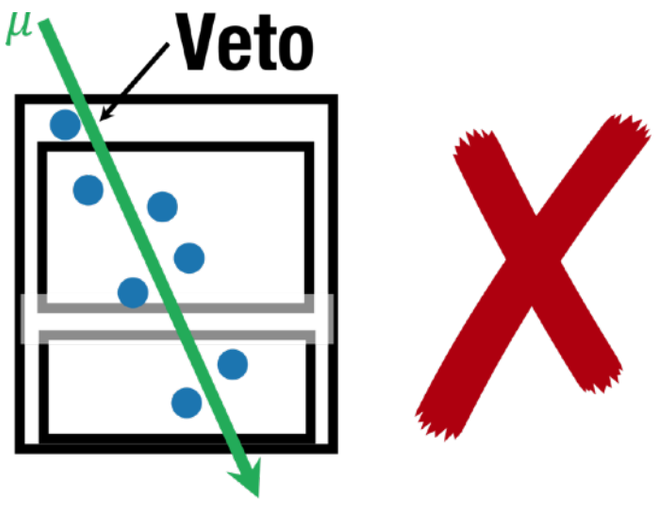
Phys. Rev. Lett. 115, 081102 (2015)

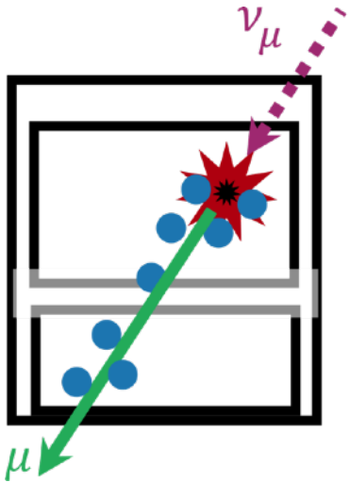
But wait, there's more!

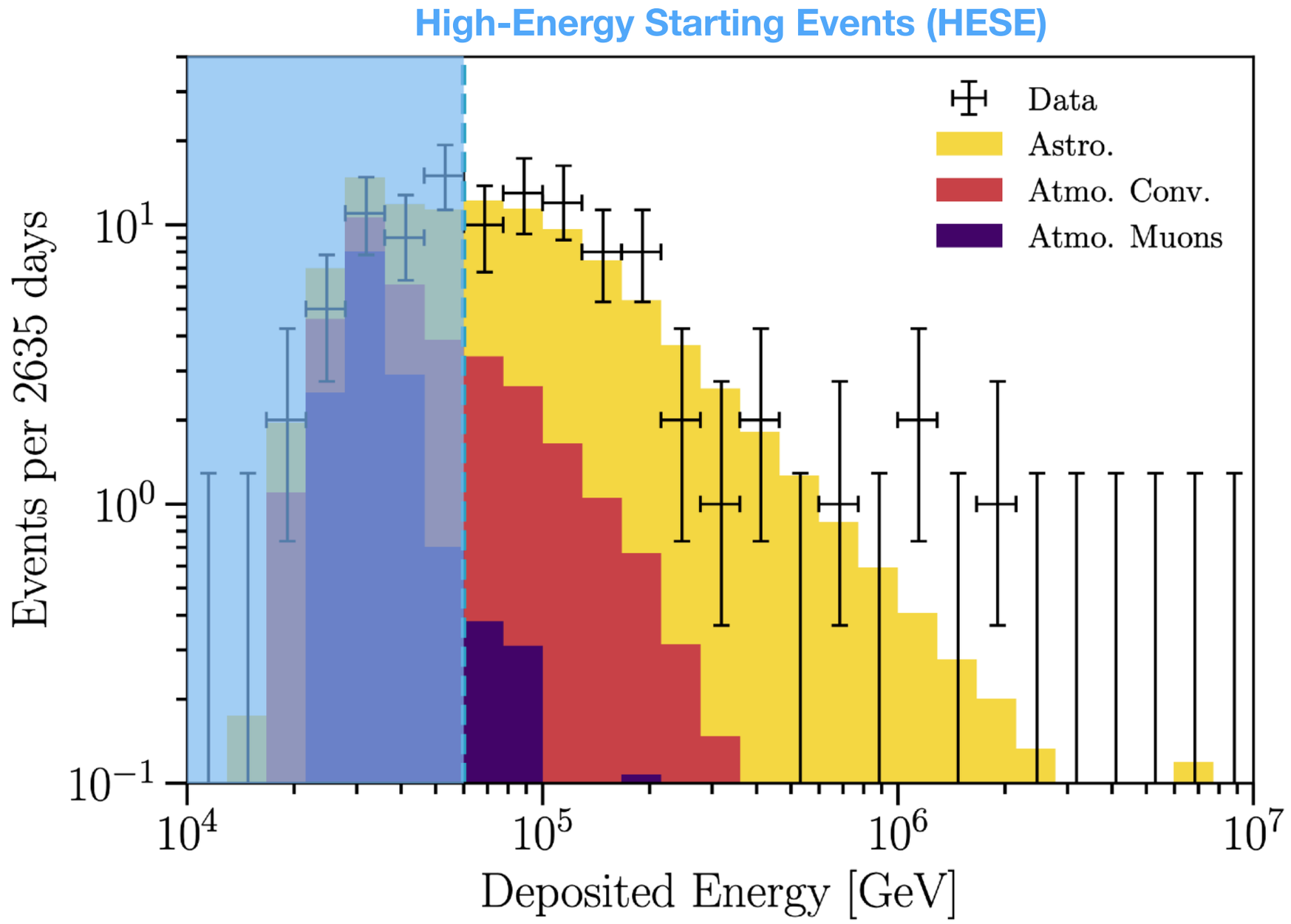


Phys. Rev. Lett. 115, 081102 (2015)

High Energy Is Dominated by Astrophysical Neutrinos



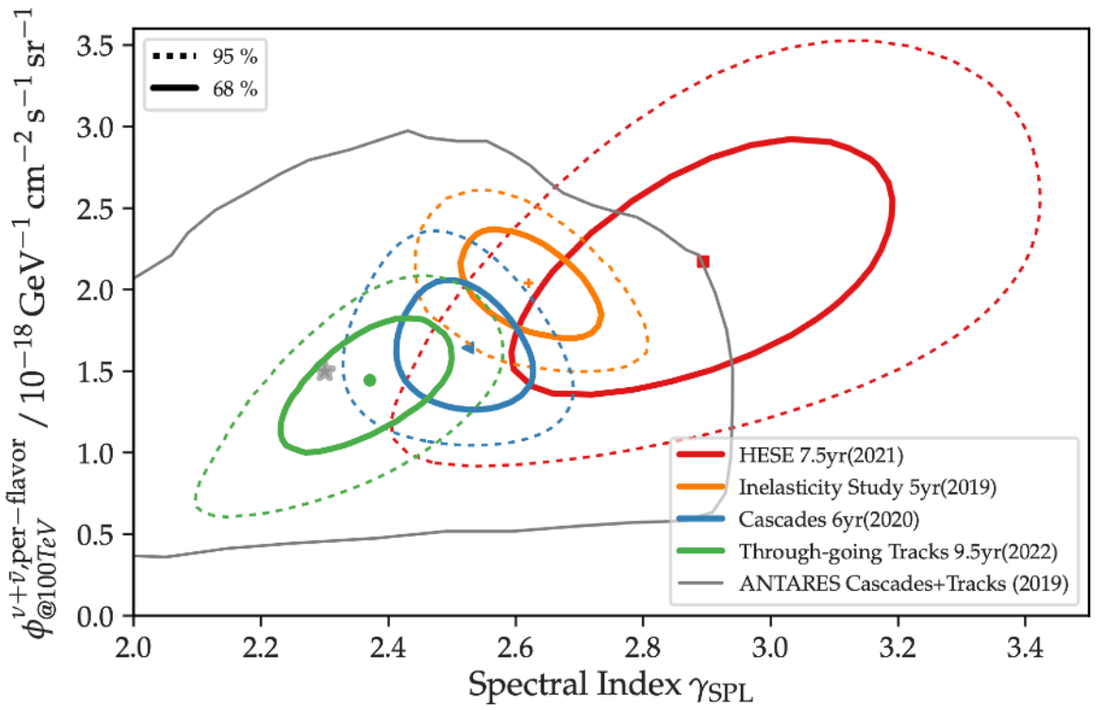


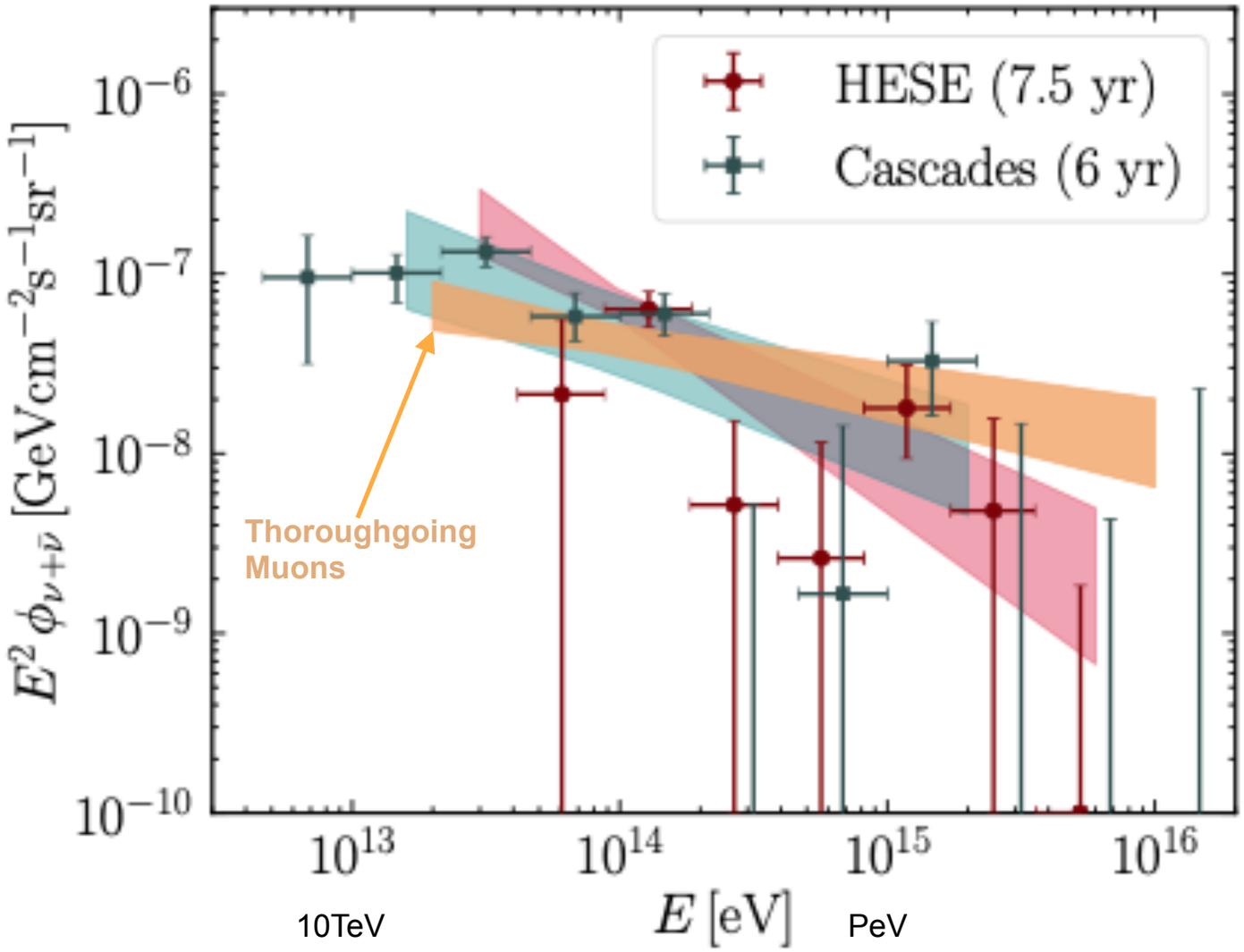


IceCube Coll. 2011.03545

High Energy Is Dominated by Astrophysical Neutrinos

IceCube Coll. 2011.03545, 2111.10299





-Astrophysical neutrinos seeing in all morphological channels in all directions.
-Well-described by a power-law in energy, though hints of structure appearing.
-First neutrino sources detected!

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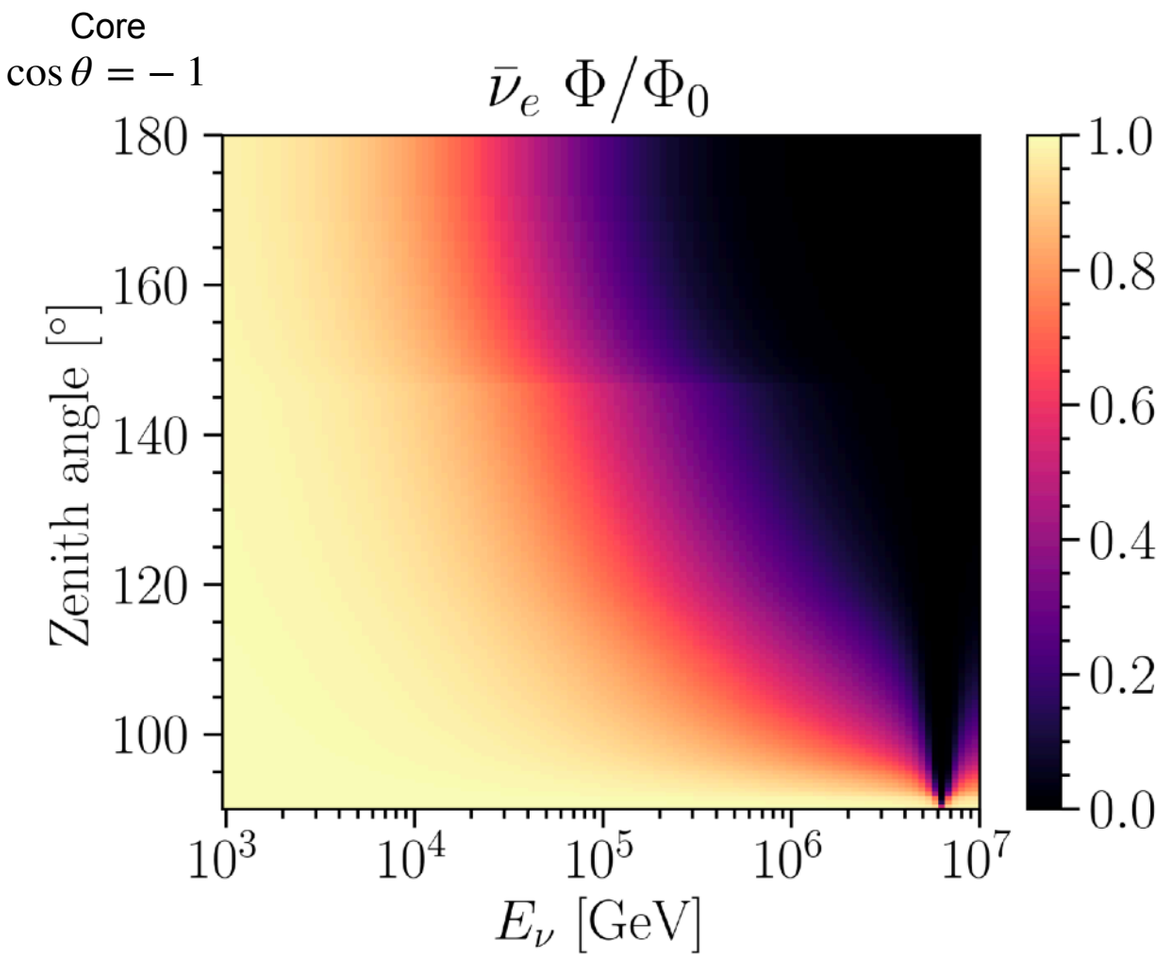
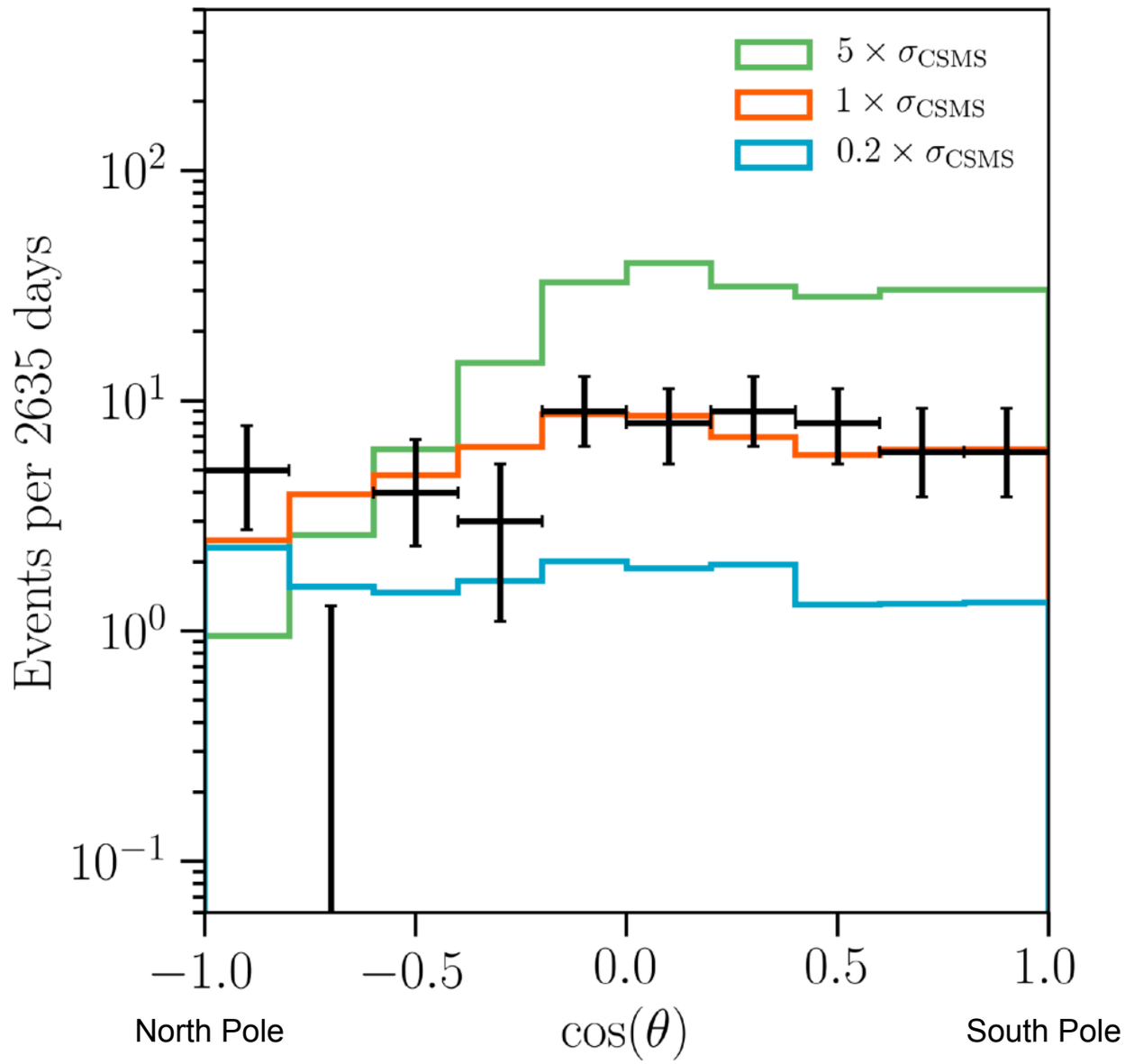
We can use the Earth opacity to infer the neutrino deep-inelastic cross section*

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

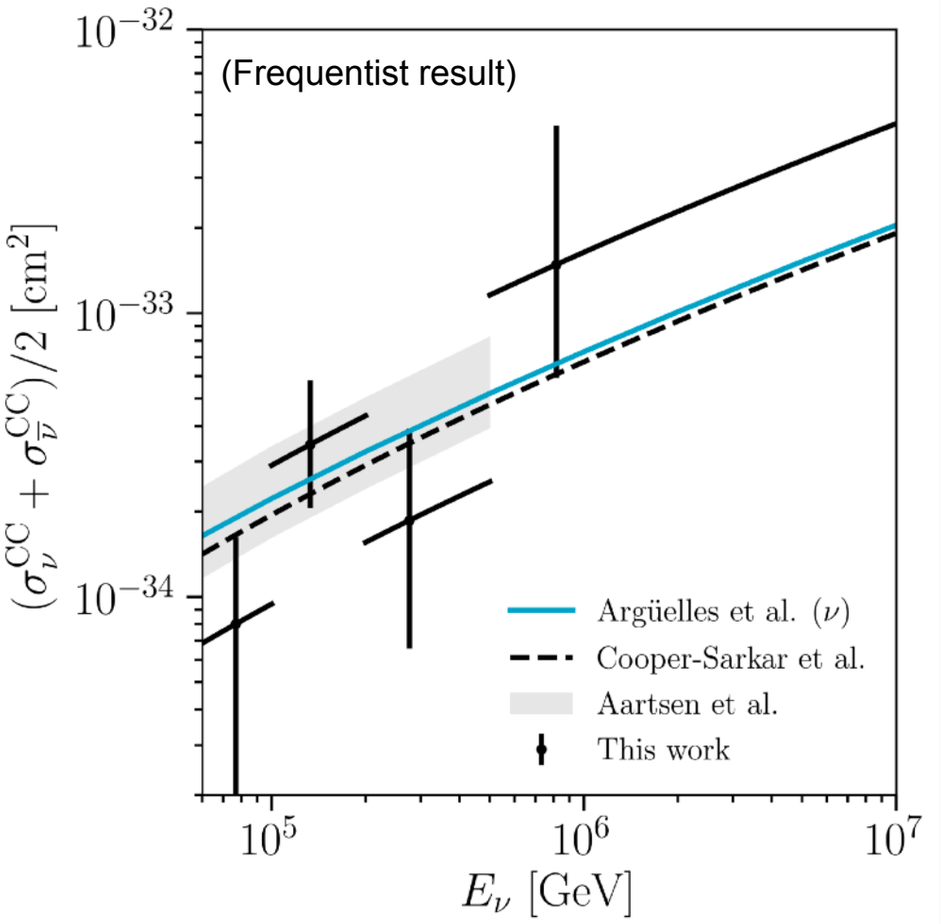


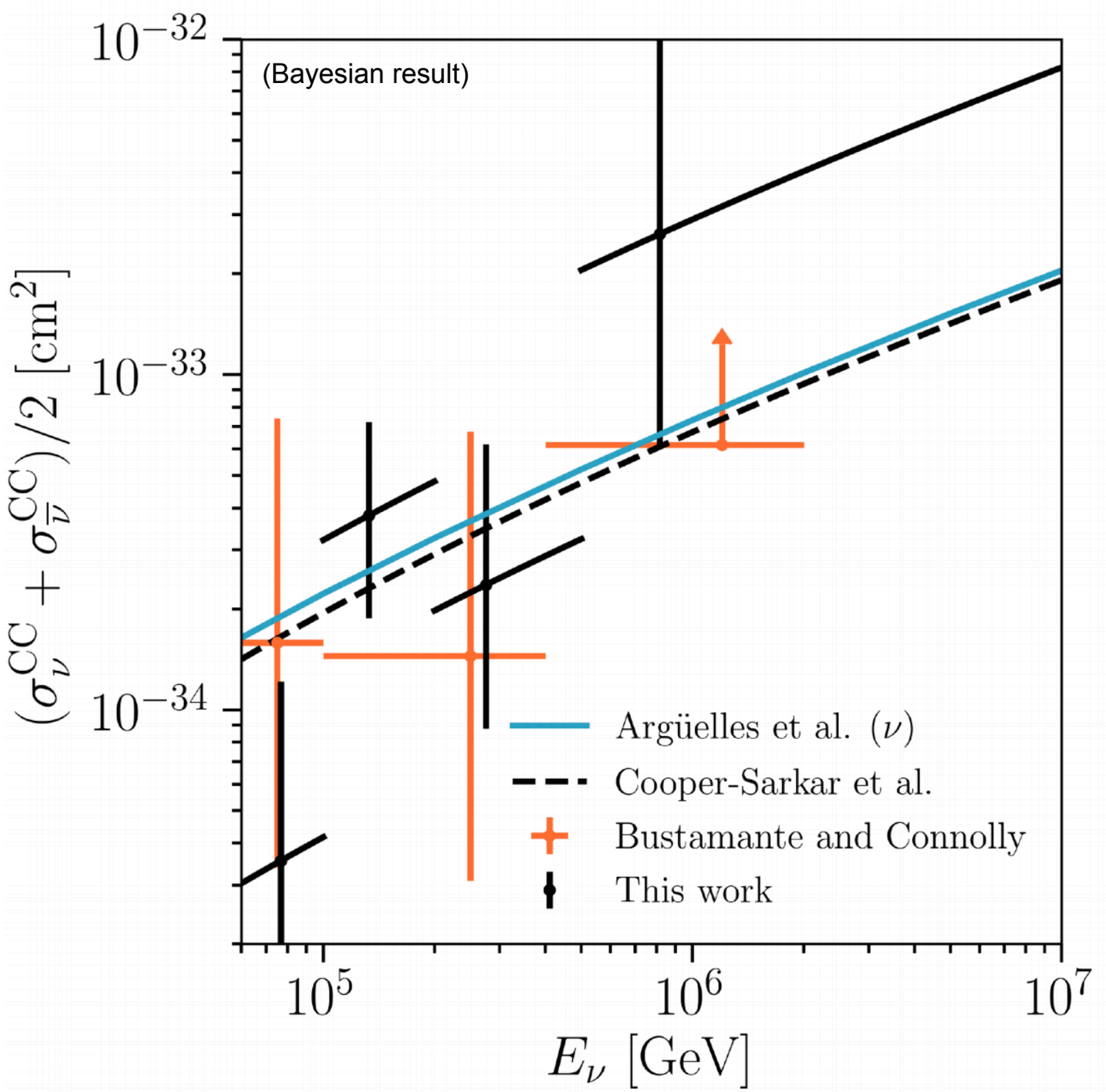


CSMS: is a NLO pQCD reference calculation of the neutrino-nucleon cross section, Cooper-Sarkar et al, JHEP 08 (2011) 042. See also A. Garcia et al JCAP 09 (2020) 025; CA, F. Halzen, L. Wille, M. Kroll, MH Reno, Phys. Rev. D92: 074040 (2015); A. Connolly *et al* Phys. Rev. D83: 113009,2011; R. Gandhi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





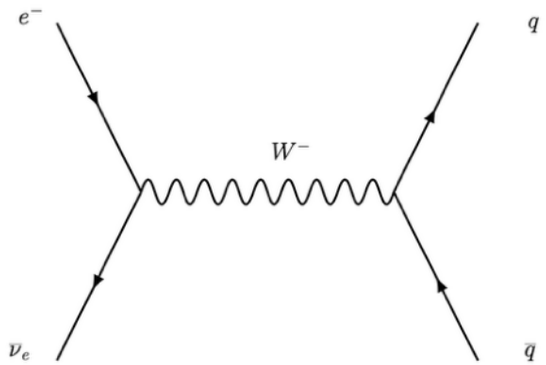
Bustamante & Connolly: PRL 122, 041101 (2019)
Argüelles: Phys. Rev. D92: 074040 (2015)
Cooper-Sarkar: JHEP 08 (2011) 042

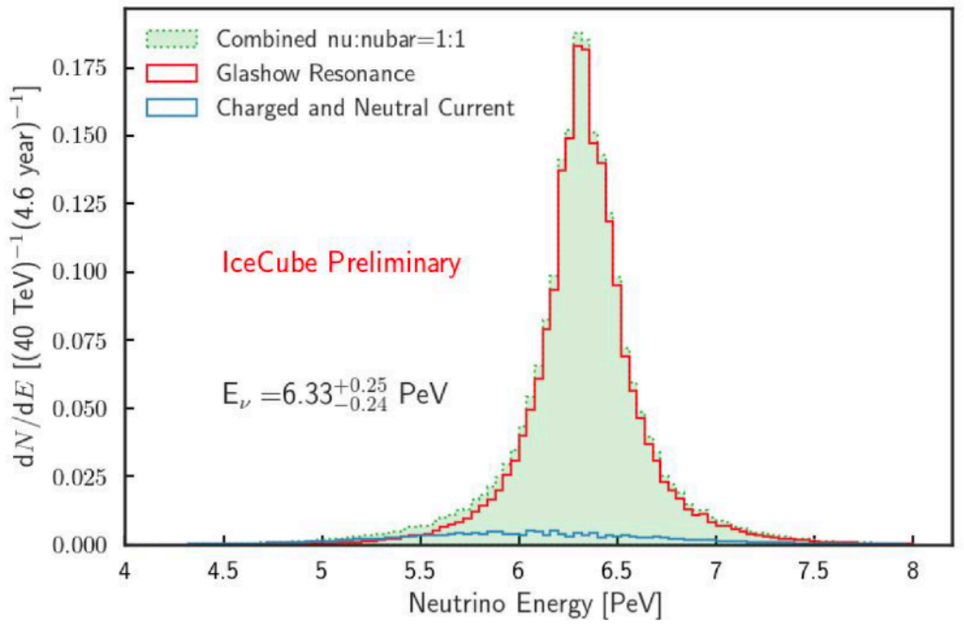
The first Glashow resonance event:

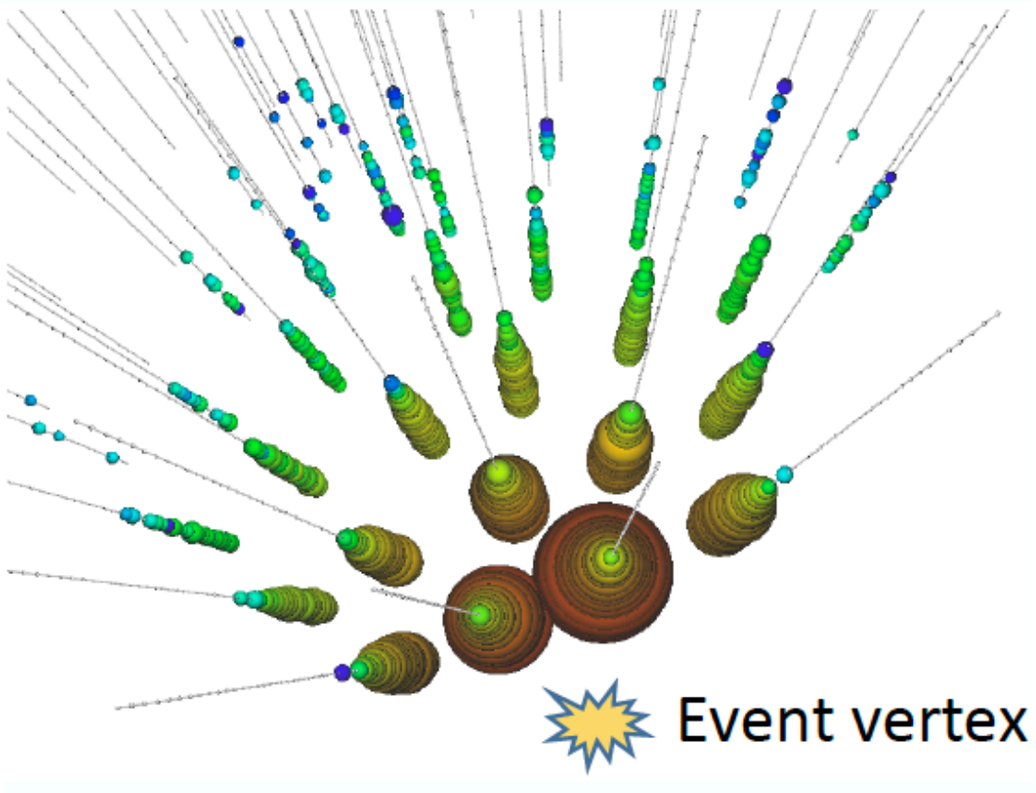
anti-ν_e + atomic electron → real W at 6.3 PeV

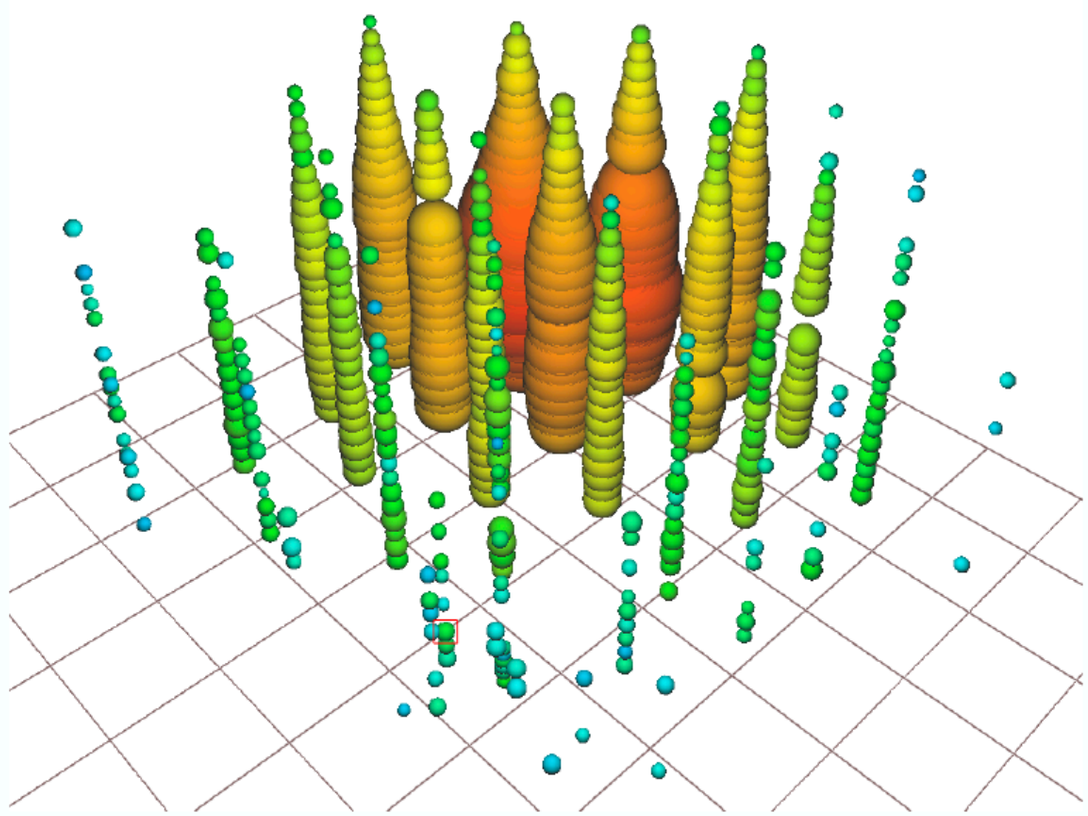
IceCube Coll. Nature Vol. 591 (2021)

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



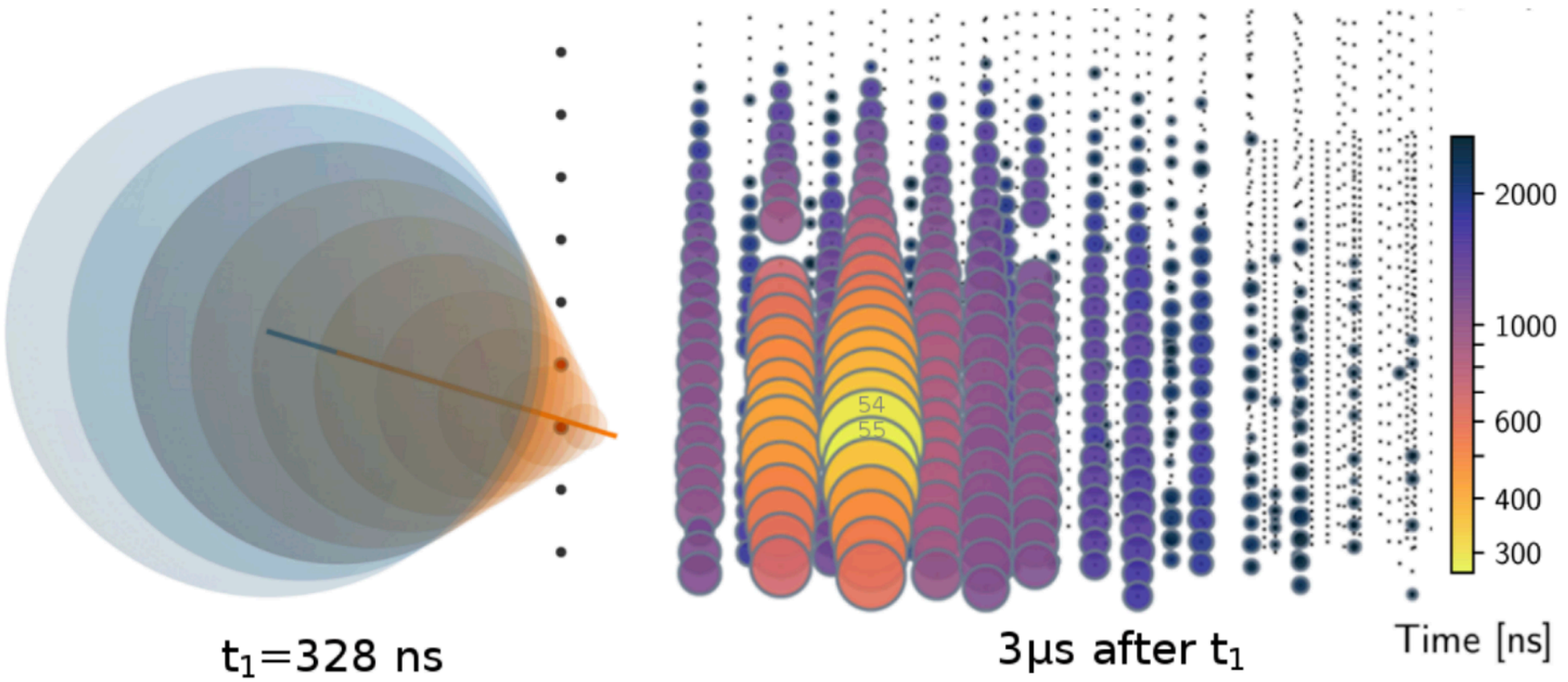


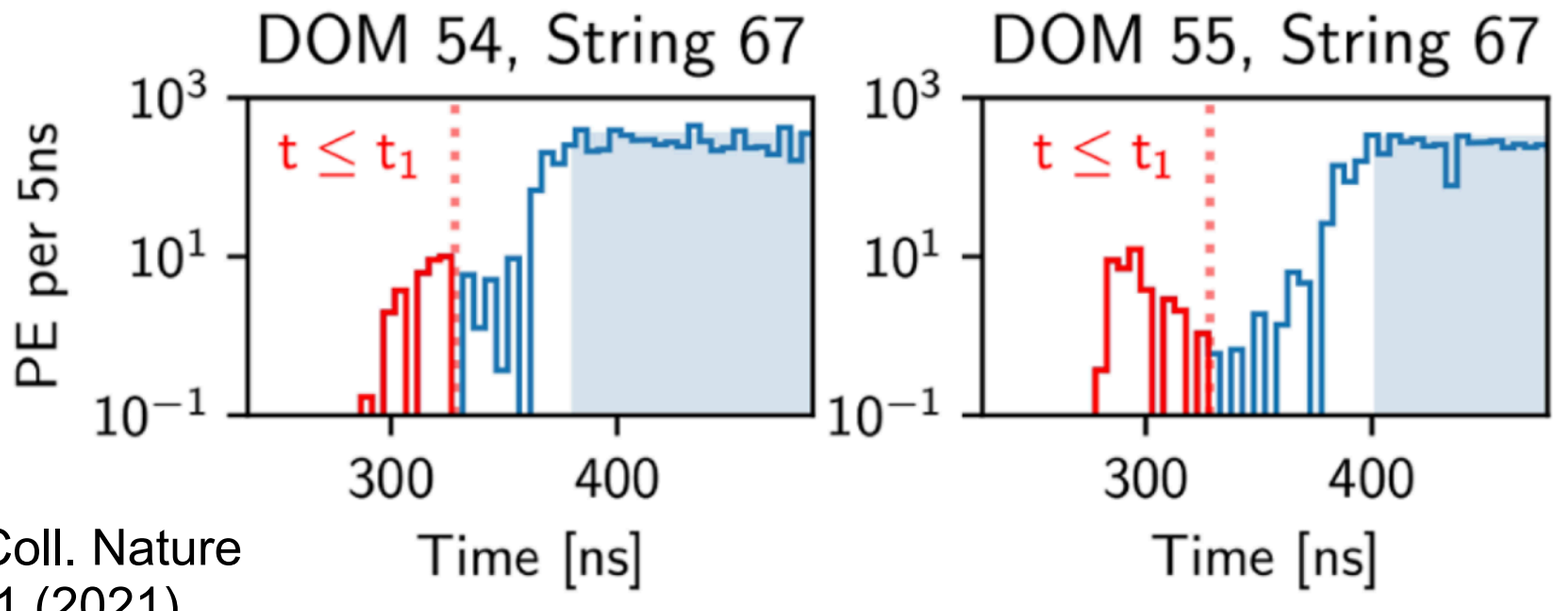




Hadronic shower from W-decay:

Early muons followed by electromagnetic shower





IceCube Coll. Nature Vol. 591 (2021)

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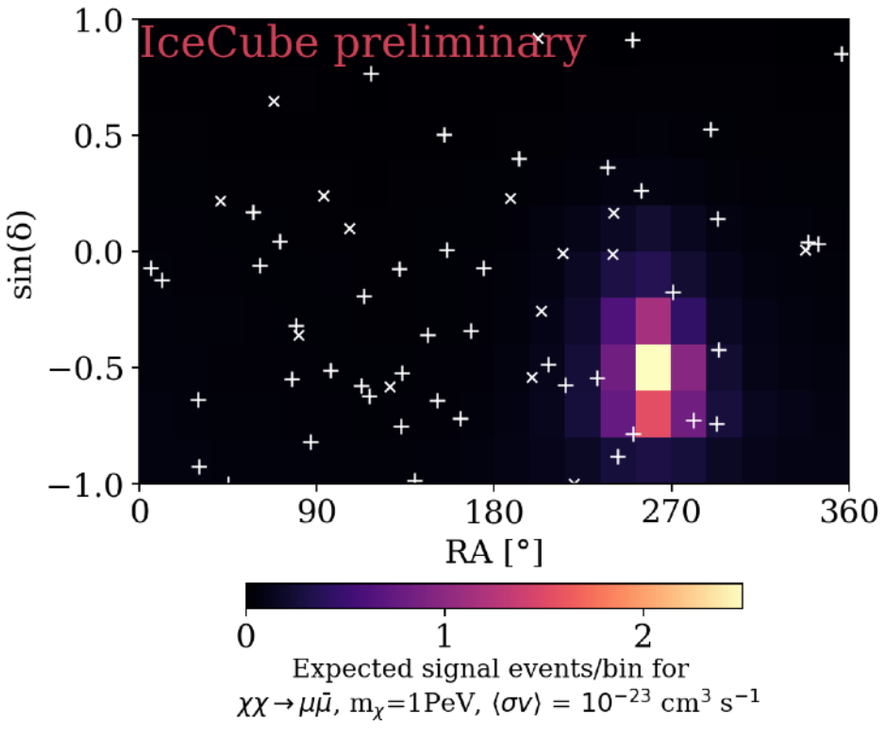
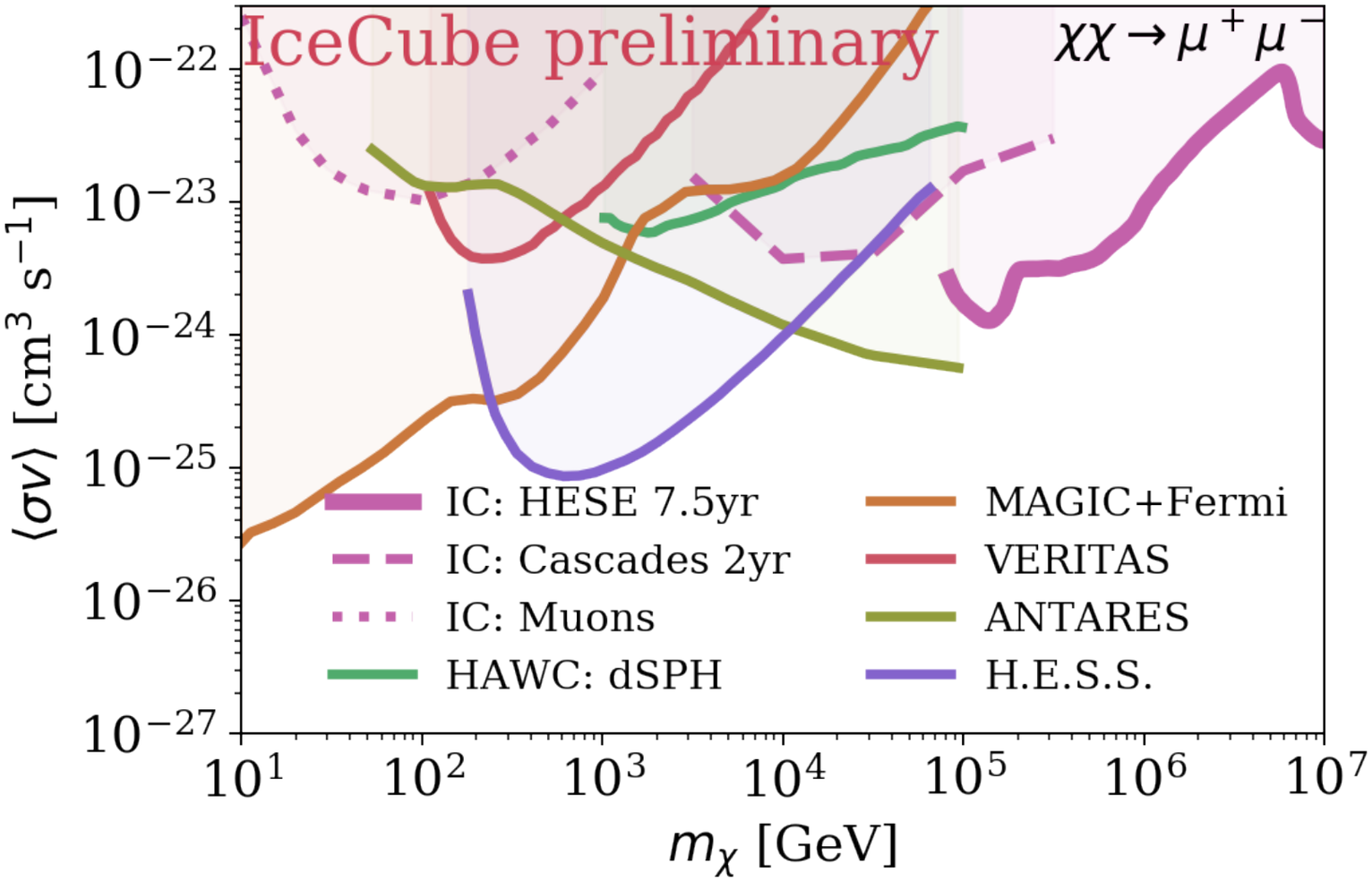
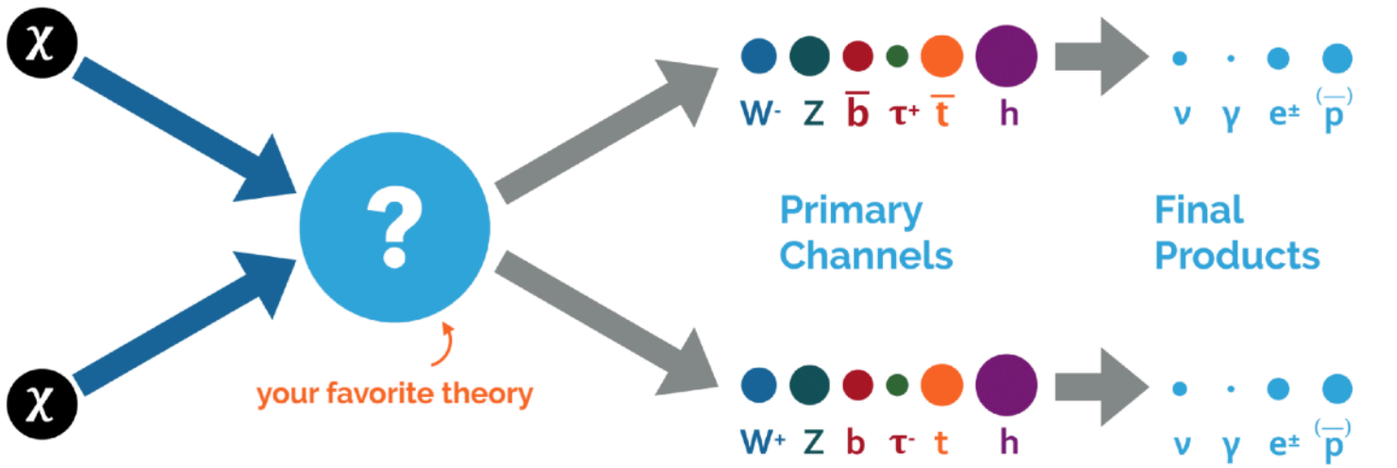
Dark matter annihilation

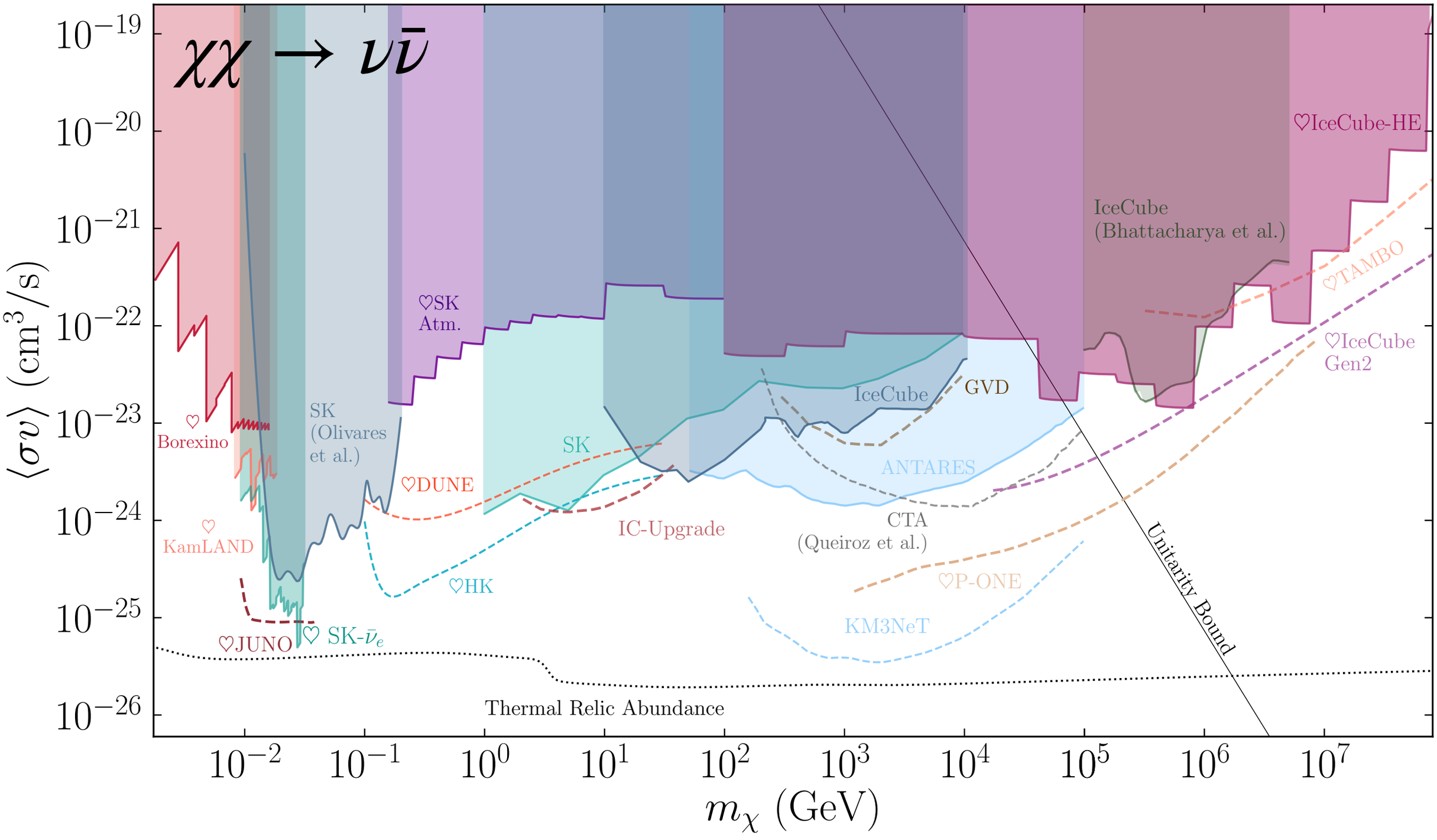






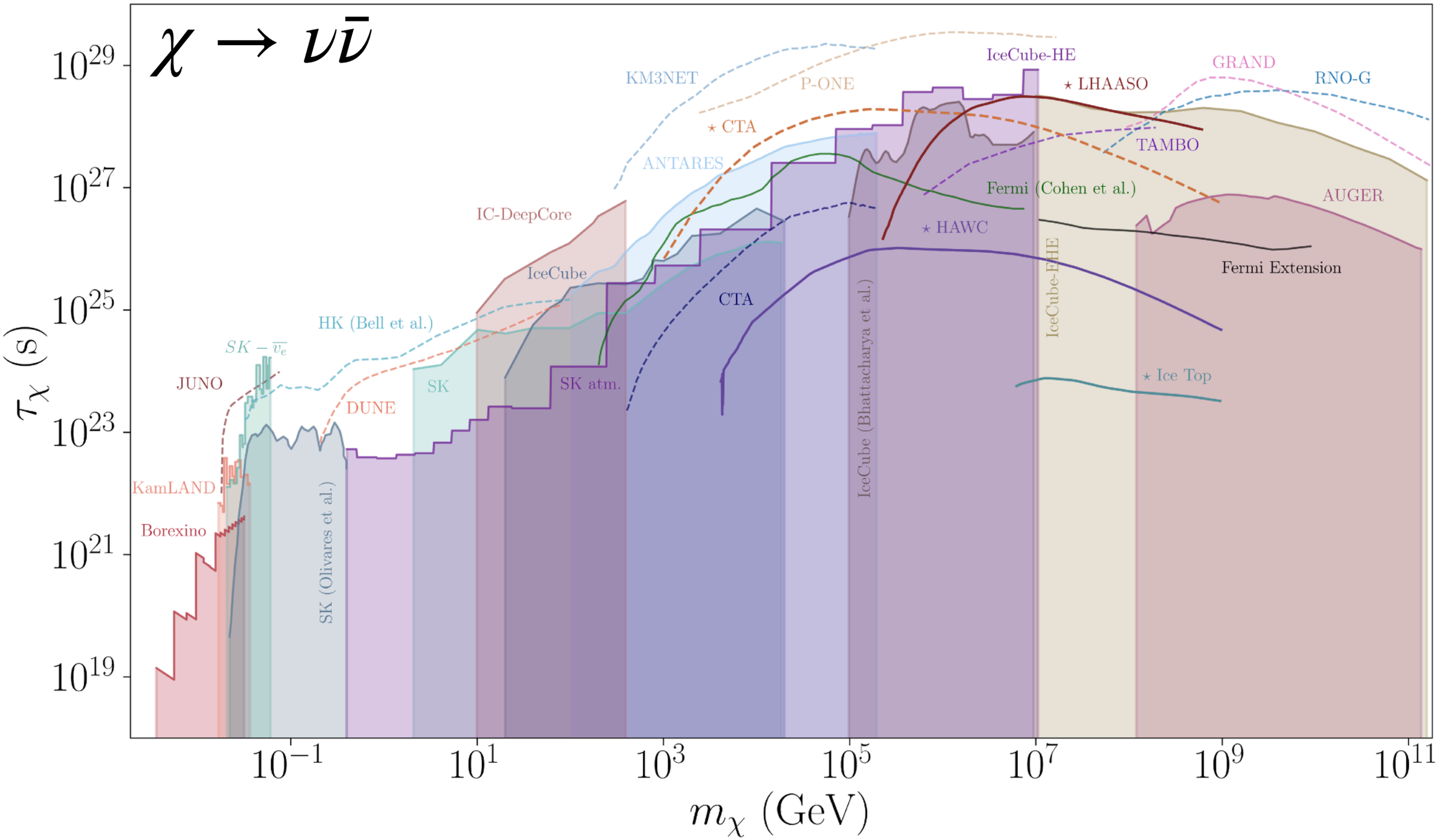
CA, H. Dujmovic arXiv 1907.11193.
See also Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

And many more measurements ...



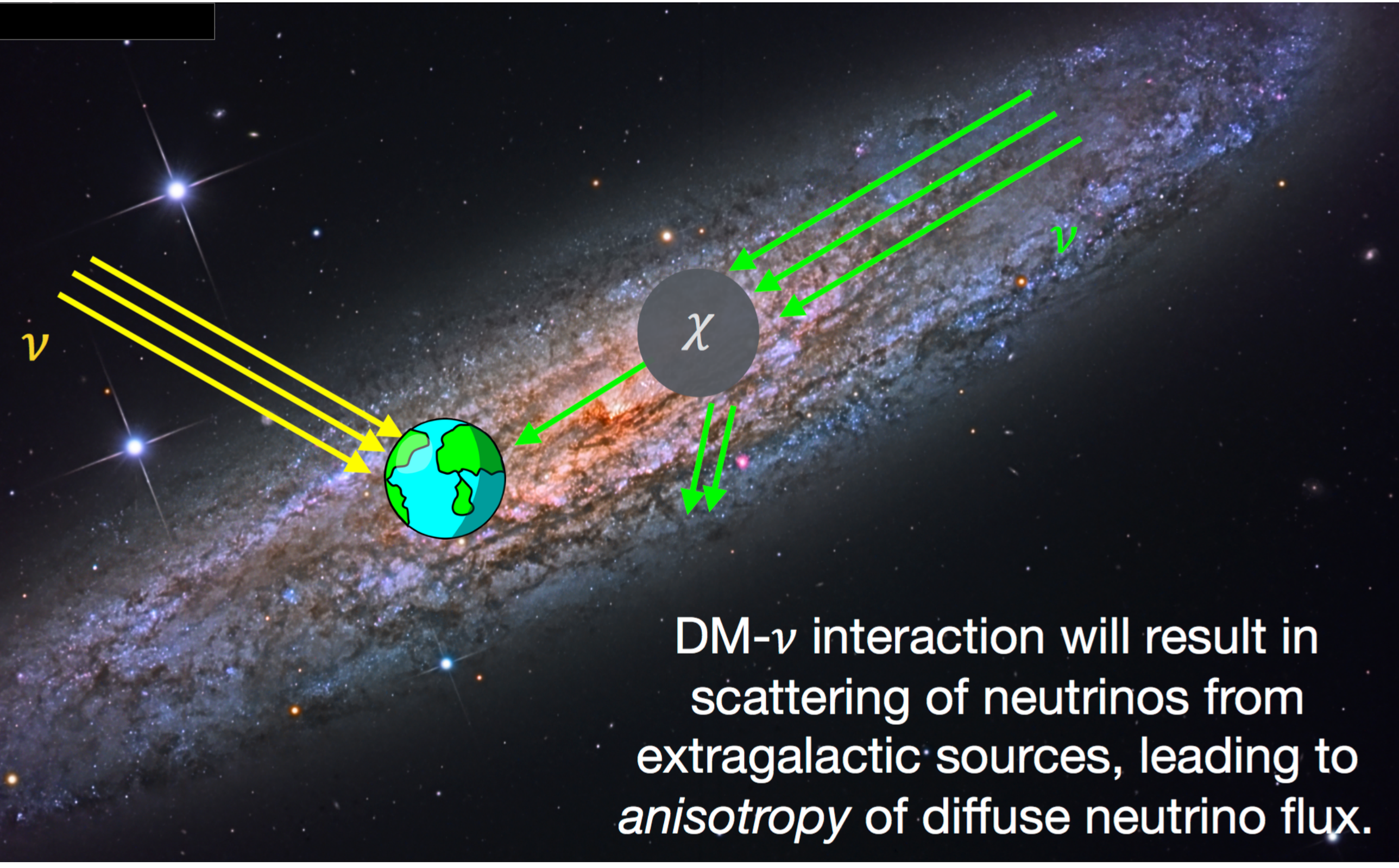
CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.

And many more measurements ...



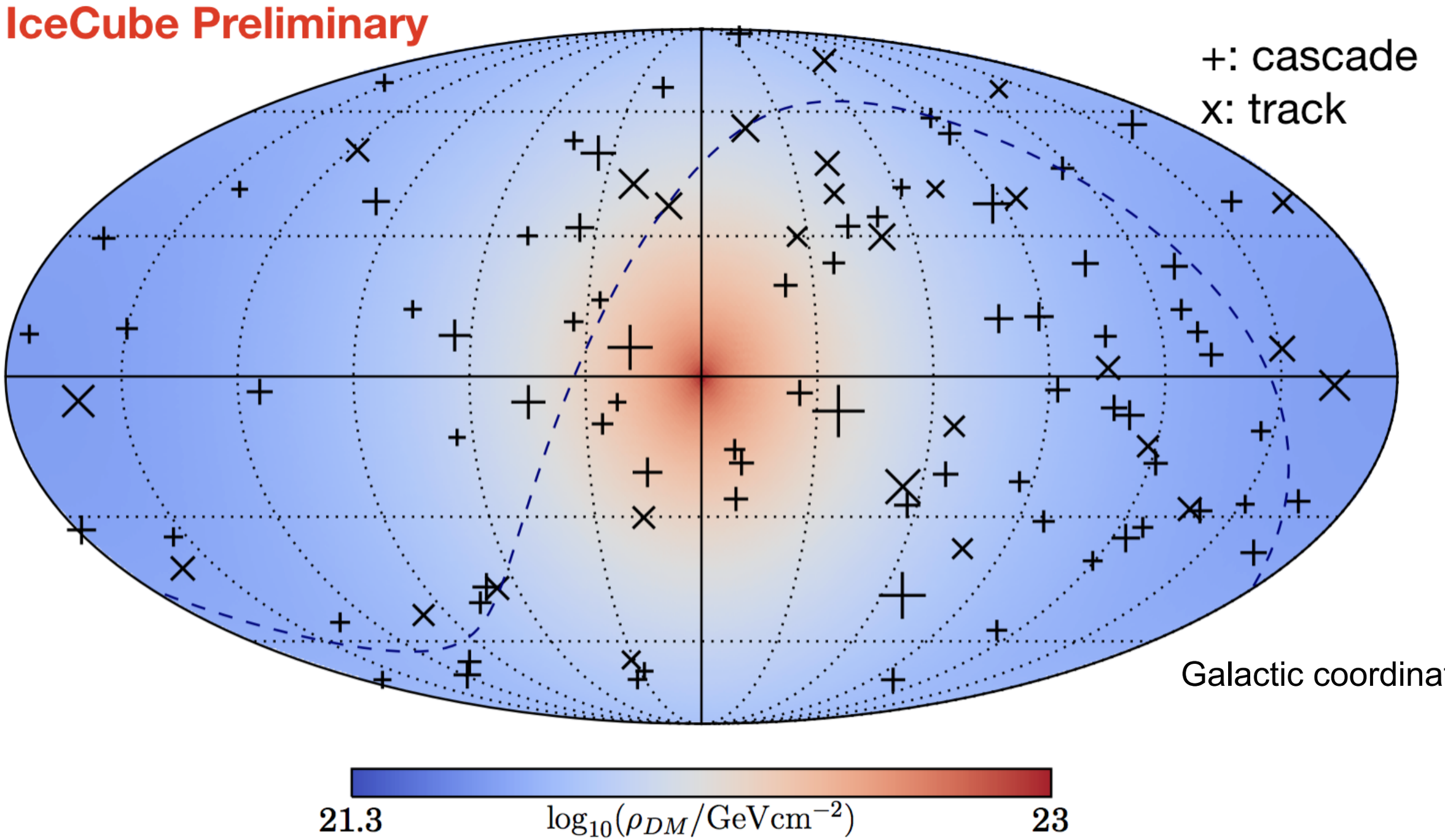
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White
to appear soon…

Dark matter neutrino scattering



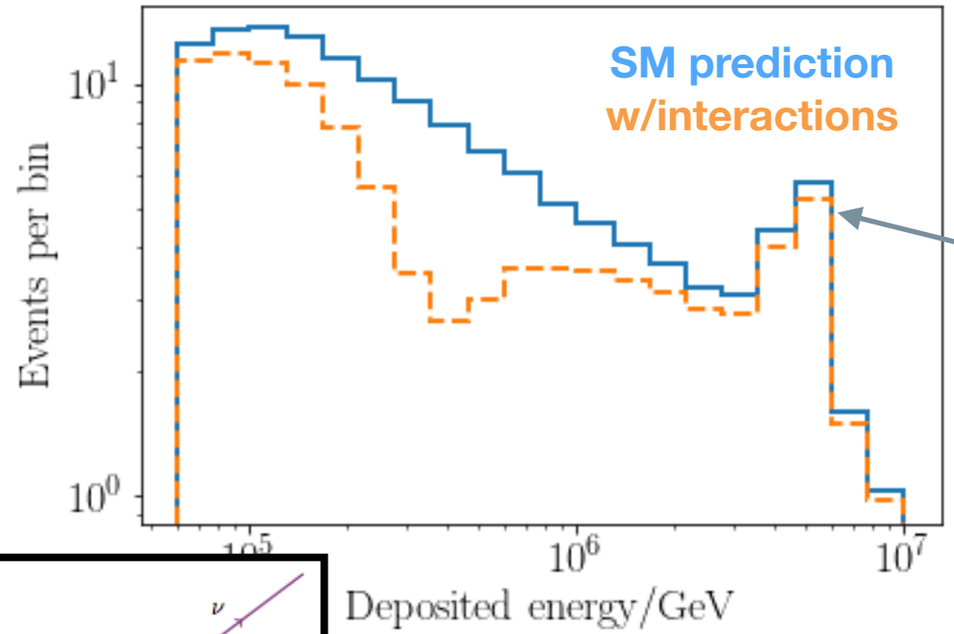
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

HESE Neutrino skymap

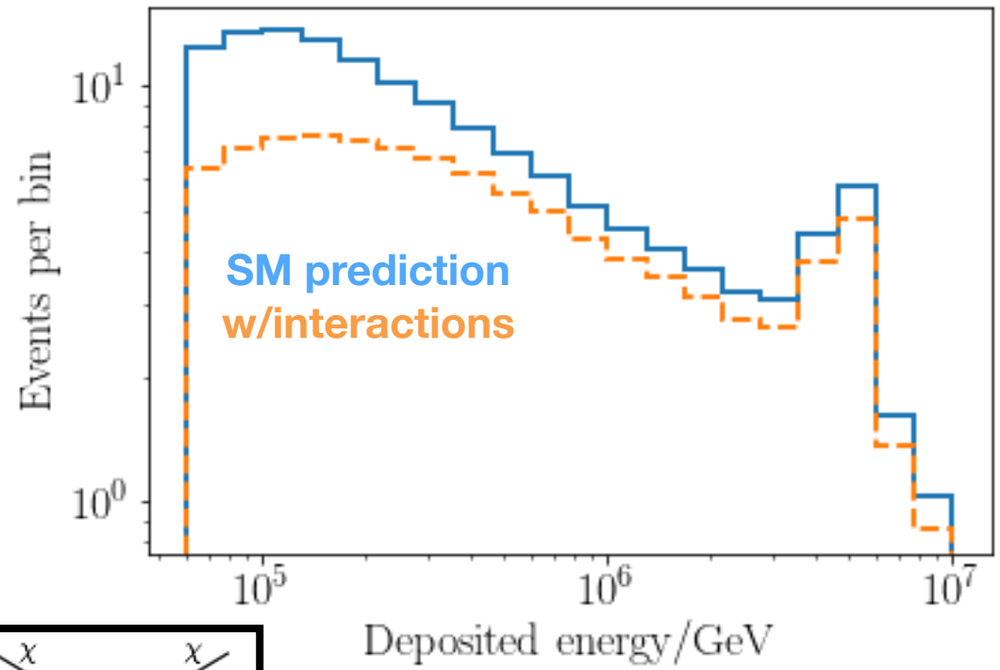


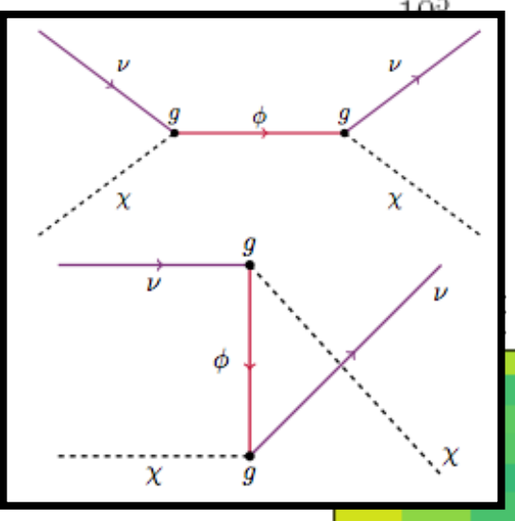
Events are compatible with an isotropic distribution: found no signal!

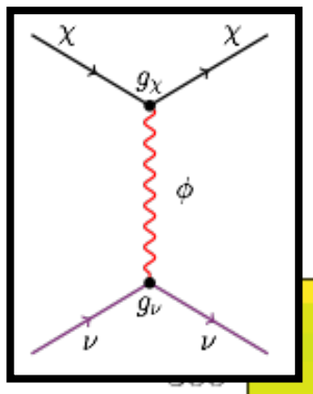
Also include effects in energy and direction



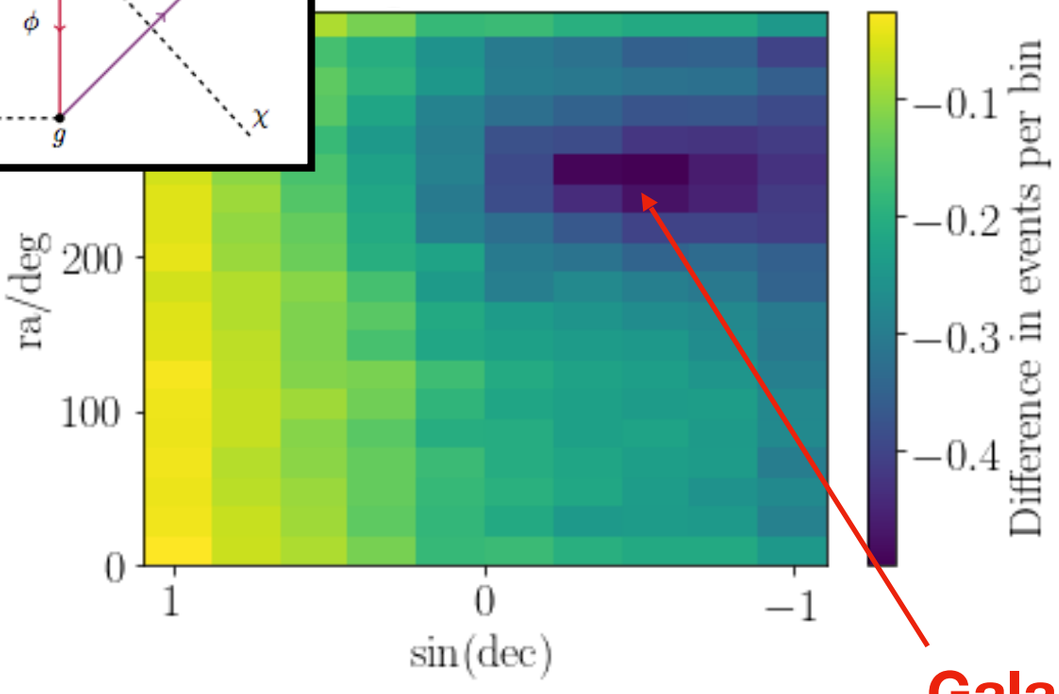
Glashow resonance



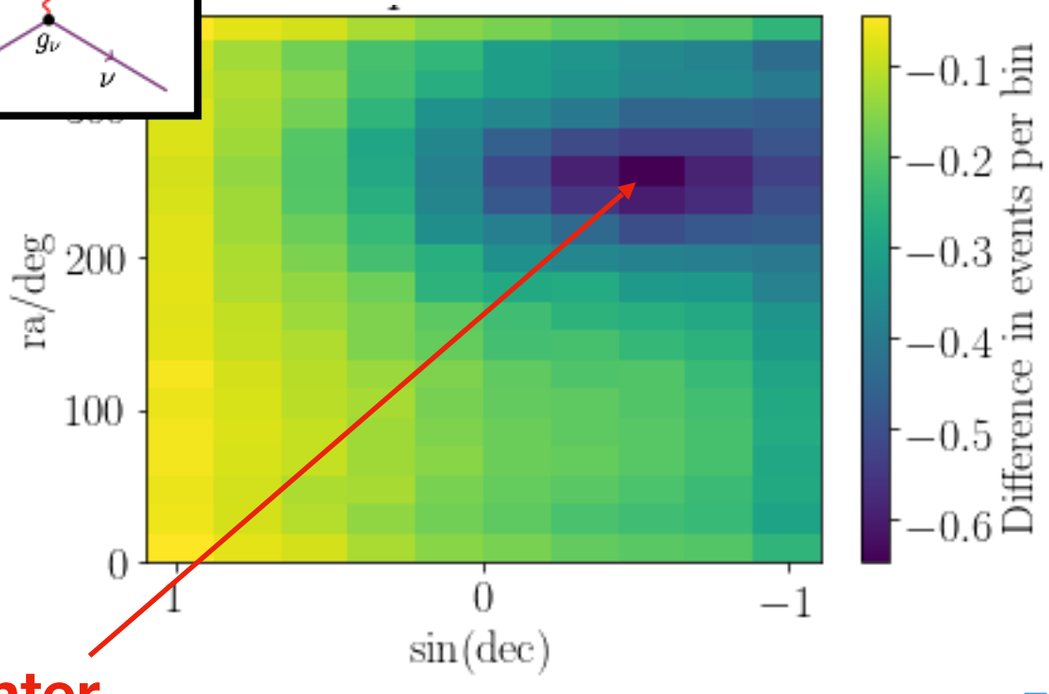




Integrated over energy

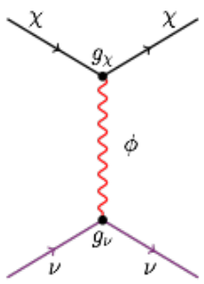


Integrated over energy

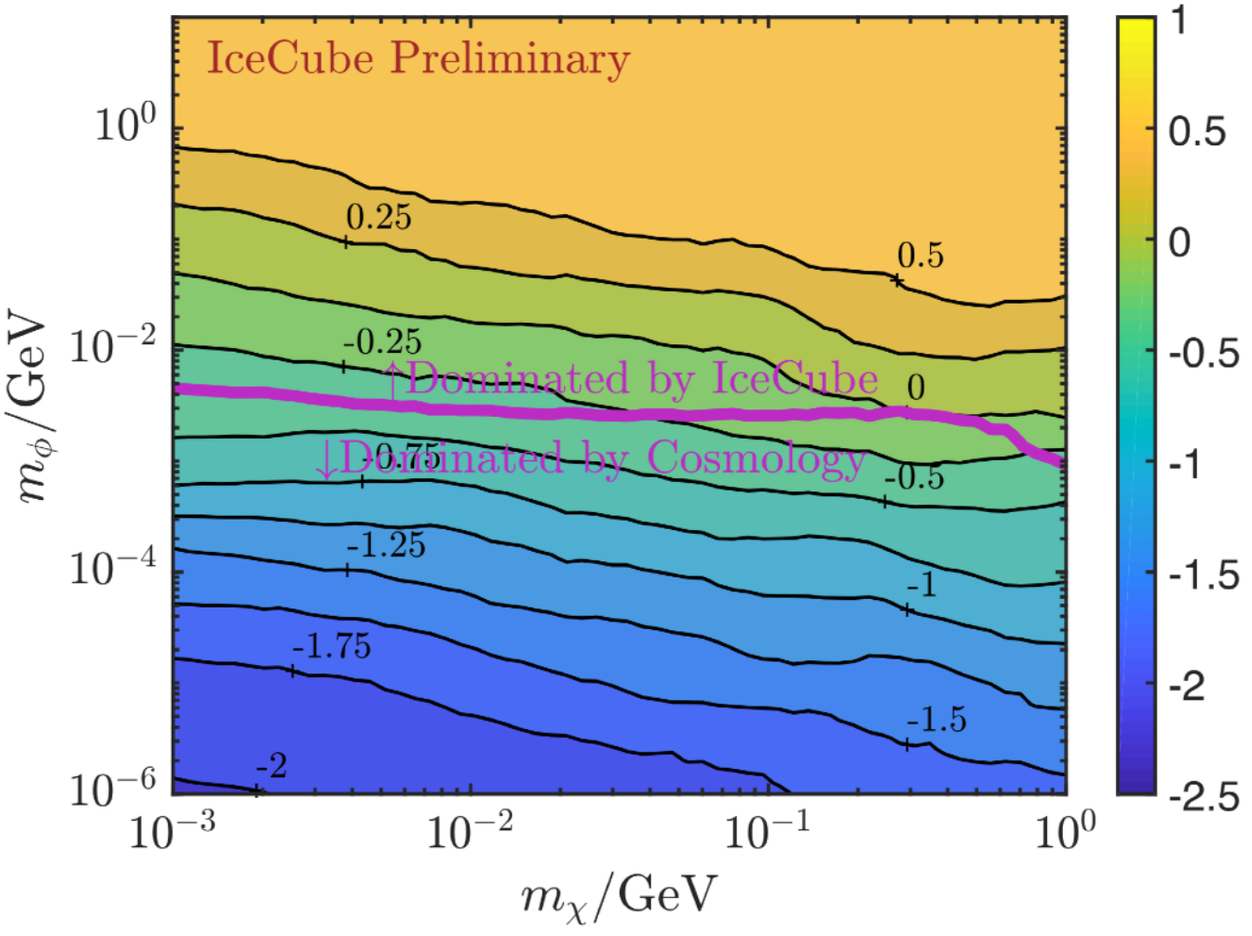


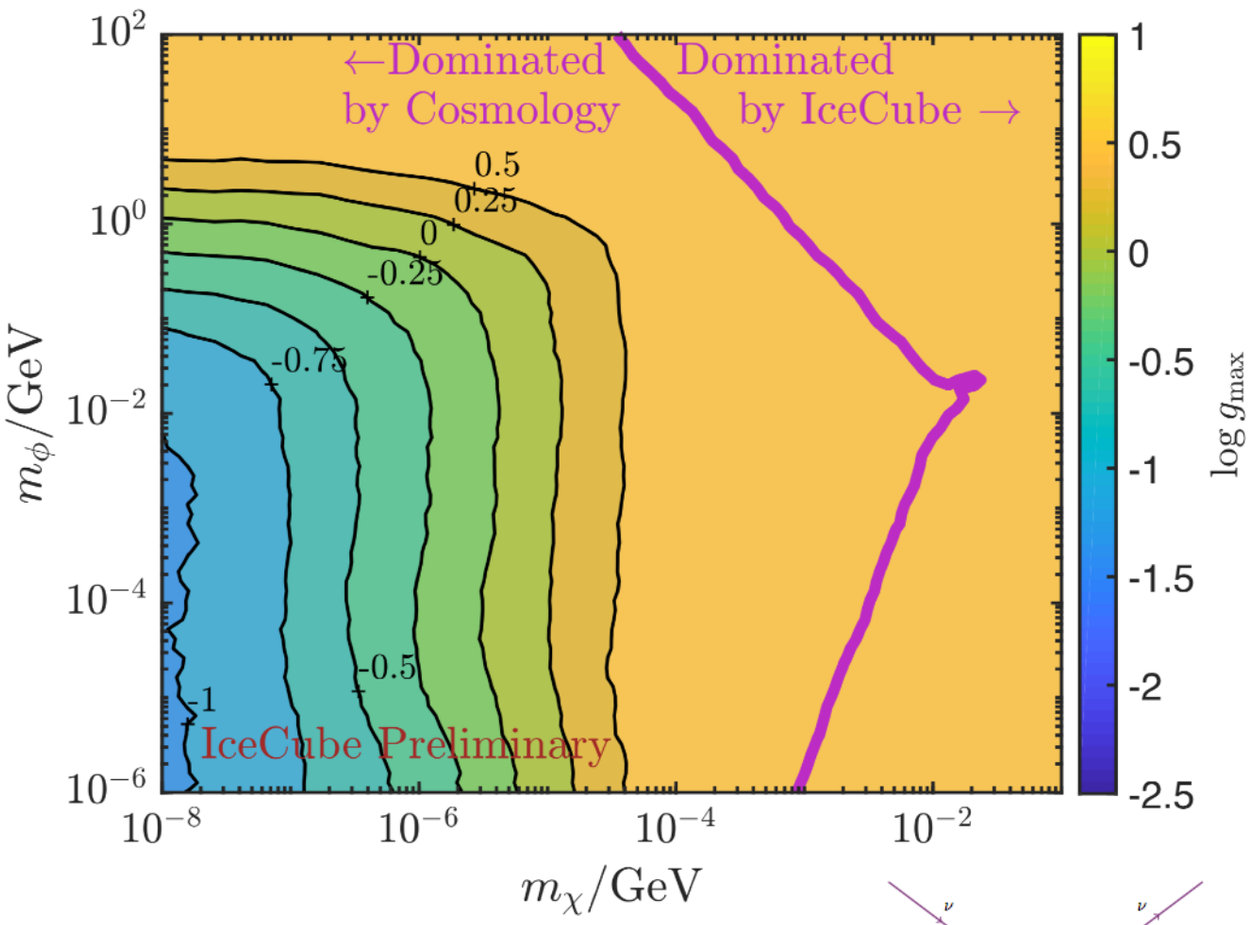
Galactic center

New constraints on neutrino-dark matter interactions



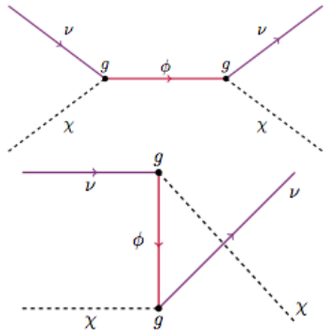
IceCube Work In Progress





Color scale is the maximum allowed coupling.

Cosmological bounds using Large Scale Structure from Escudero et al 2016



dark matter-neutrino couplings
CA et al. arXiv:1703.00451
Kelly et al arXiv:1808.02889
Choi et al. arXiv:1903.03302

neutrino-neutrino couplings
Ng & Beacom arXiv:1404.2288
Kelly et al arXiv:1808.02889
Carpio et al. arXiv:2104.15136

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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.

Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

Flavor composition @ source

(GRBs, AGNs, blazars, pulsars…)

$(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion

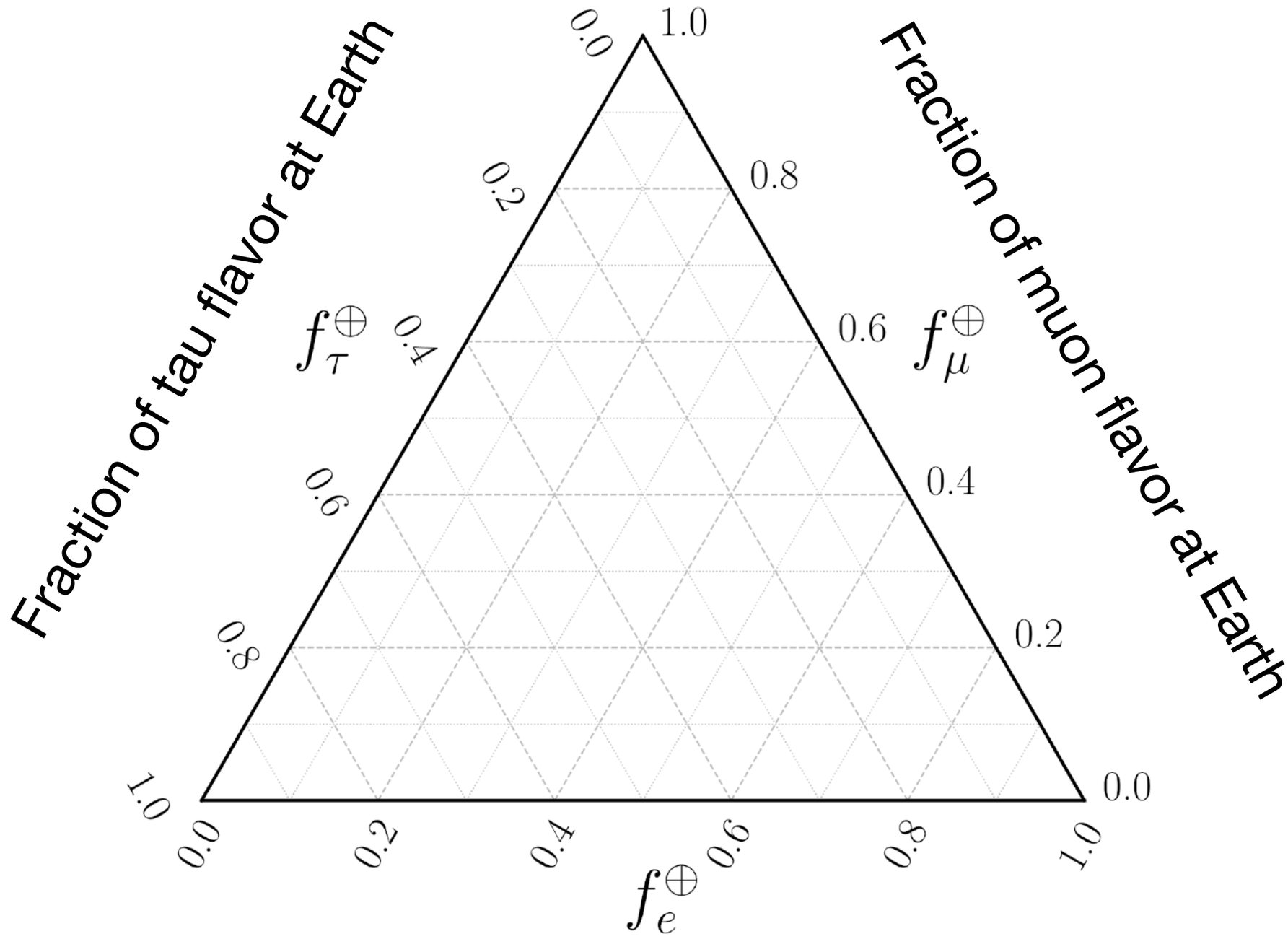
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\downarrow$$
$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

(1:2:0)

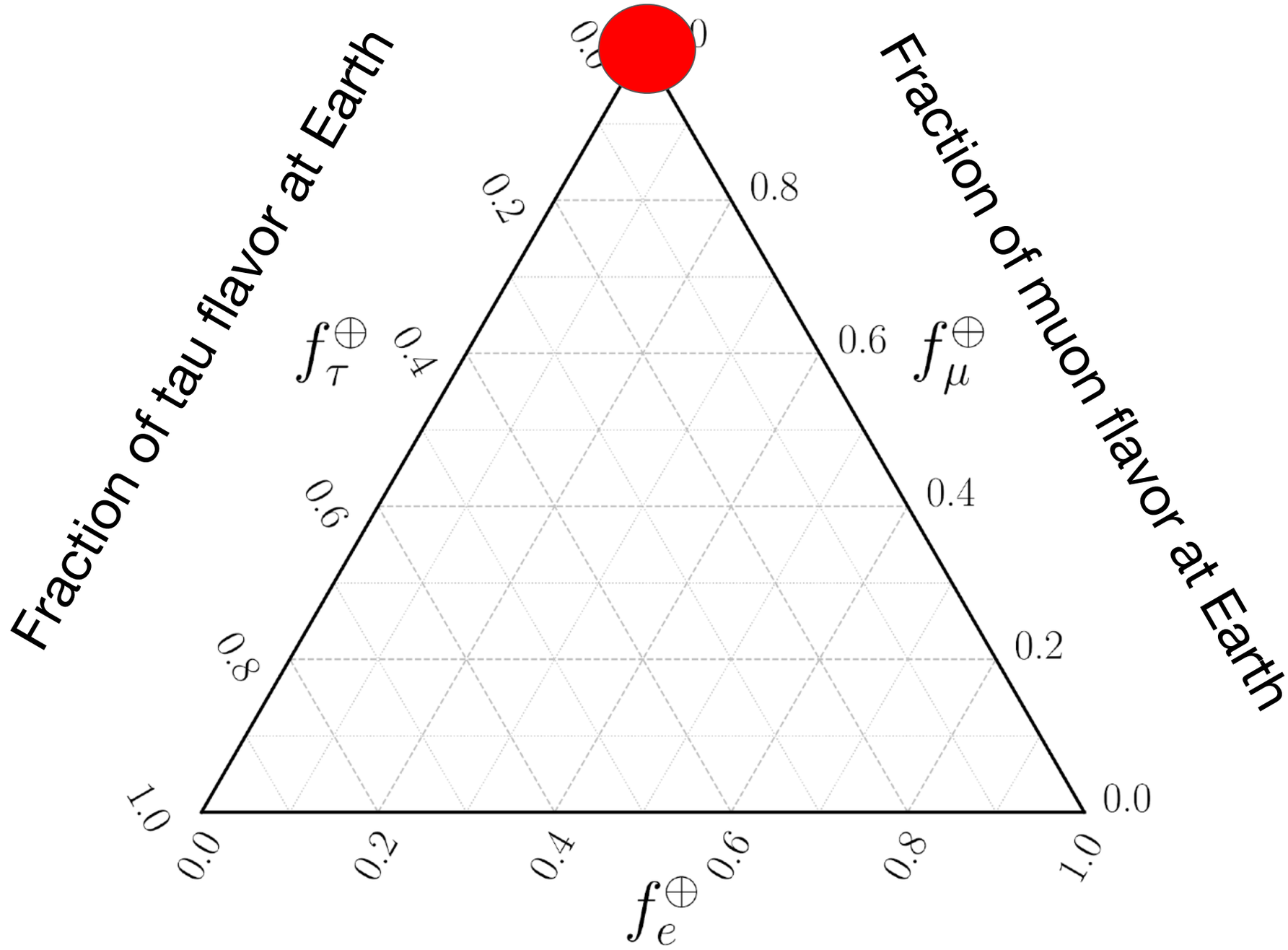
Muon-damped $\pi^+ \to \cancel{\mu^+} + \nu_\mu$ (0:1:0)

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

The flavor triangle



The flavor triangle



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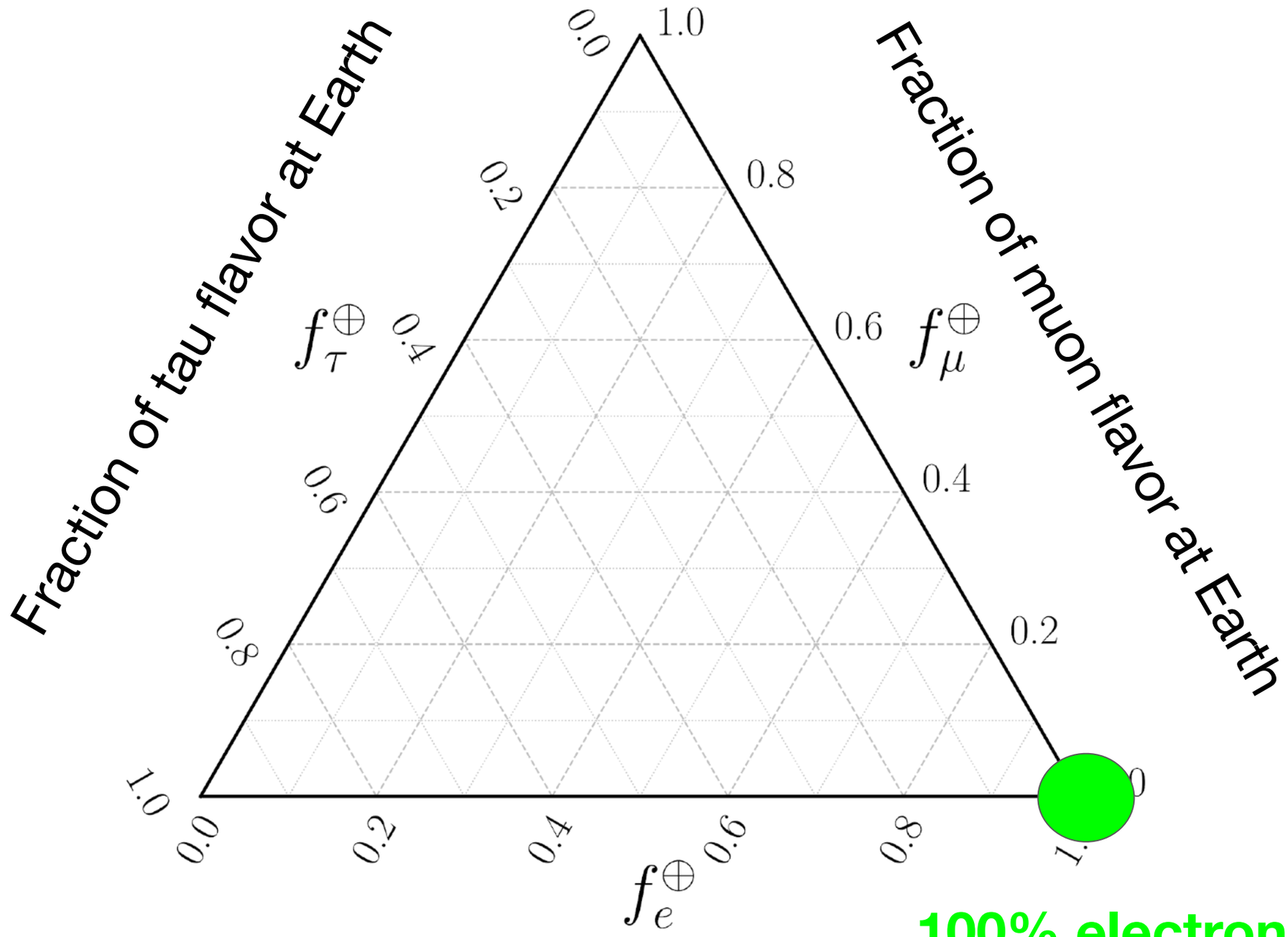
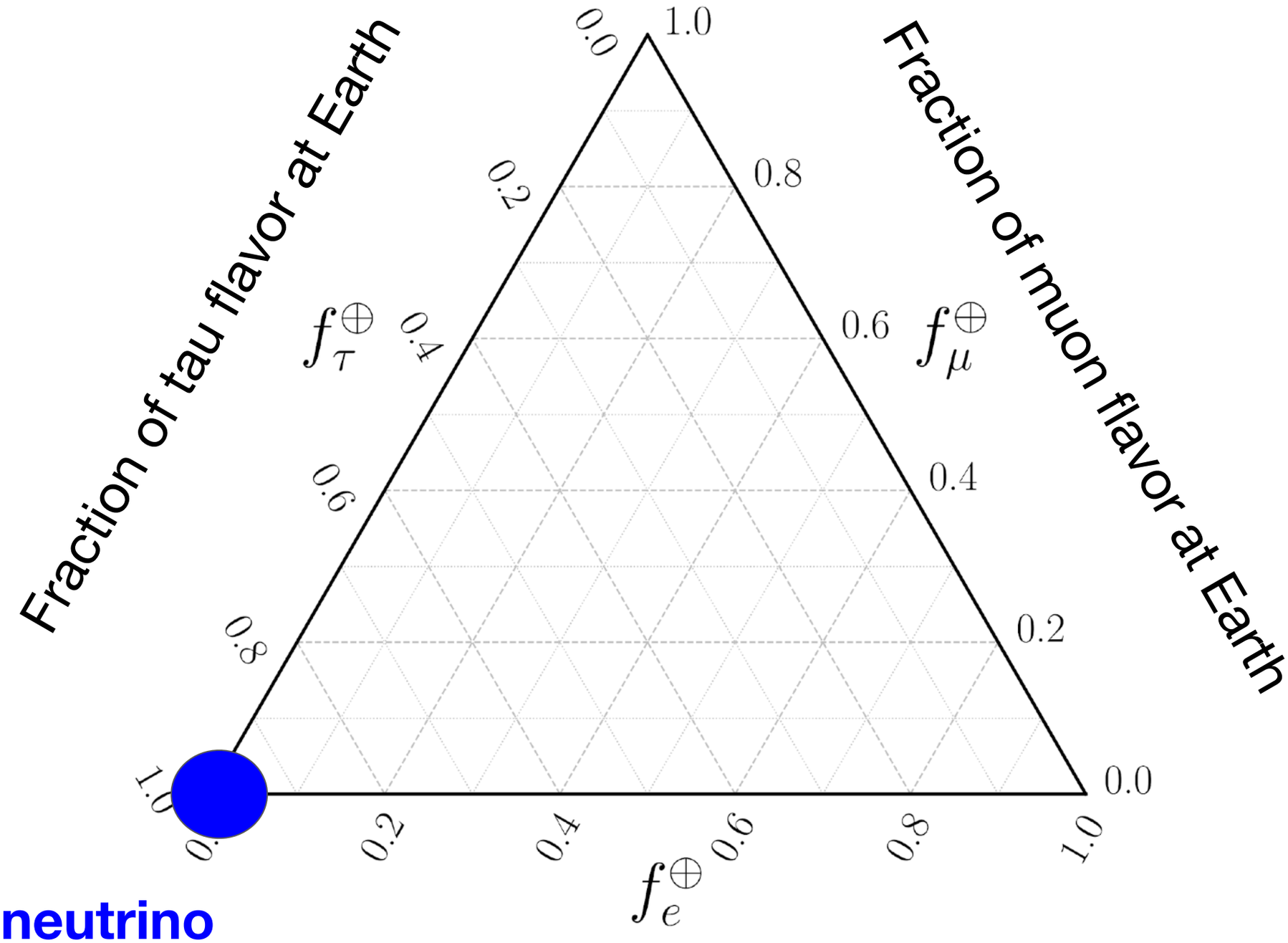


100% electron neutrino

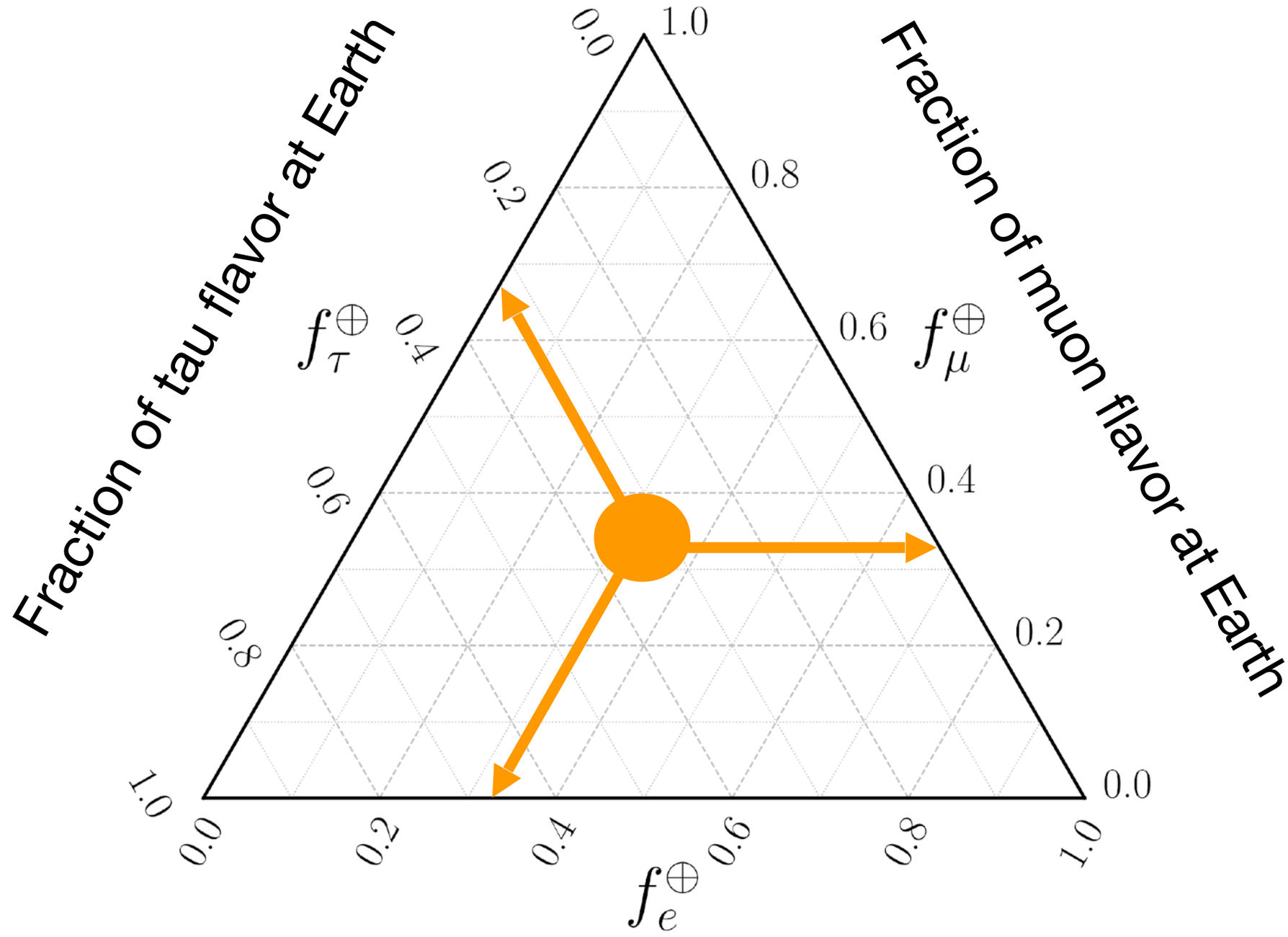
The flavor triangle



100% tau neutrino

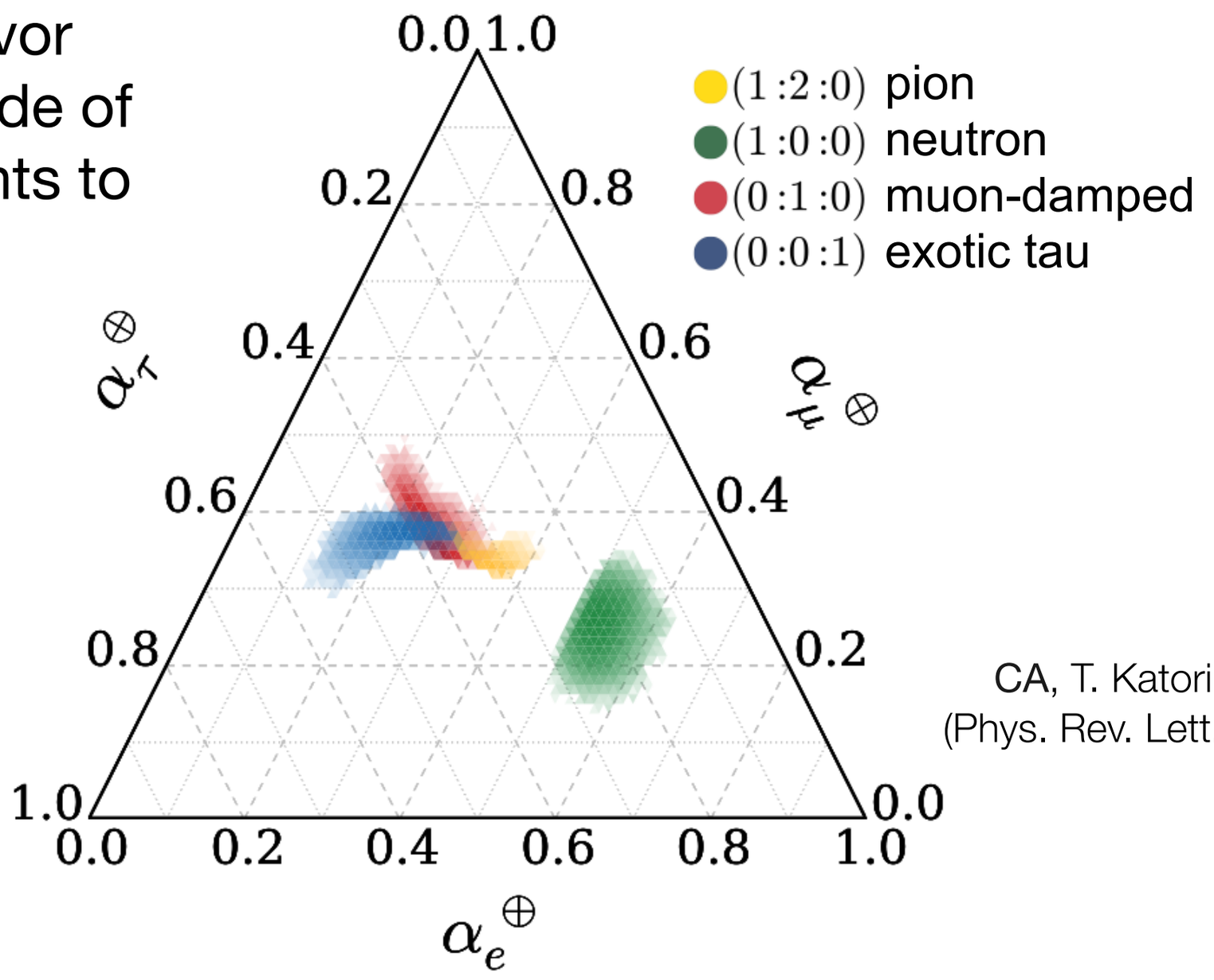
The flavor triangle

⅓ of each flavor



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)

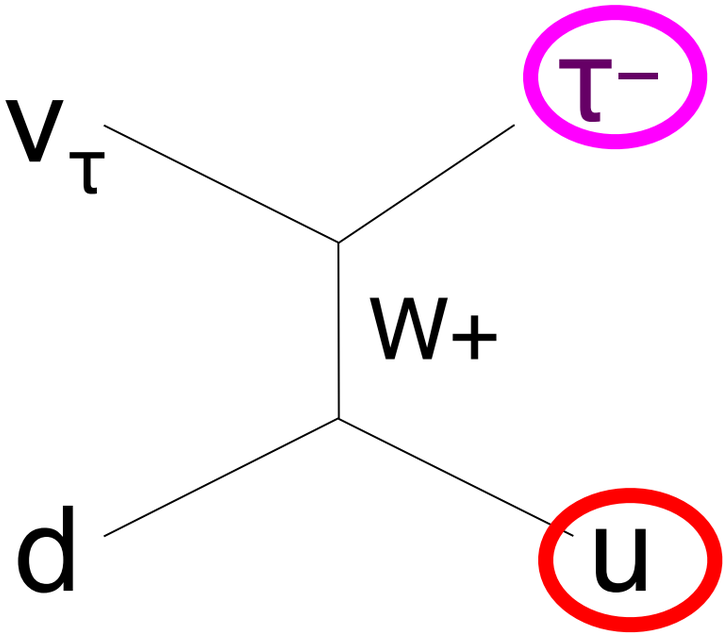
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

First astrophysical ν_τ candidate found!

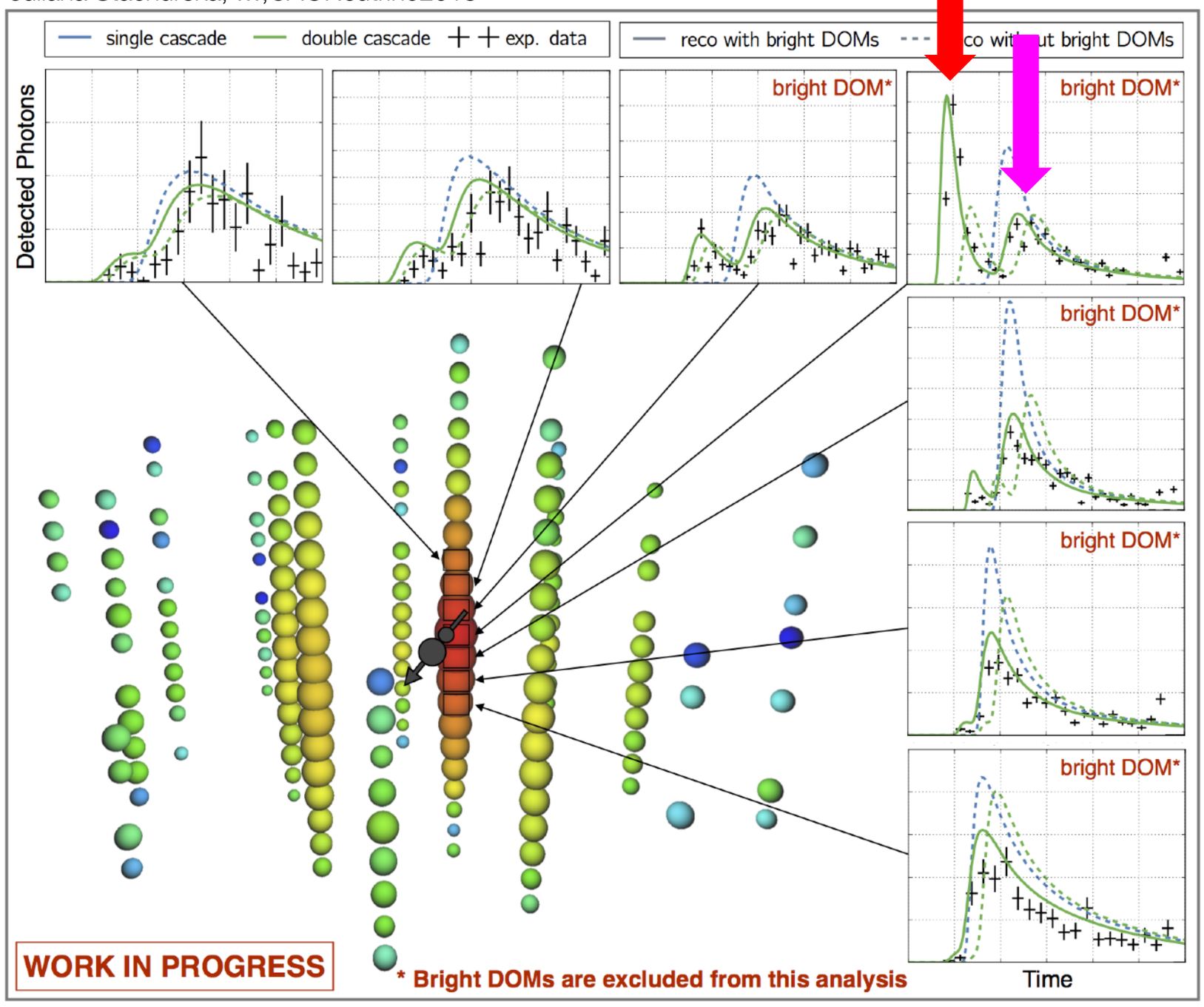
Total deposited energy ~ 90 TeV.

First "bang" in time (shower)

Second "bang" in time (tau decay)

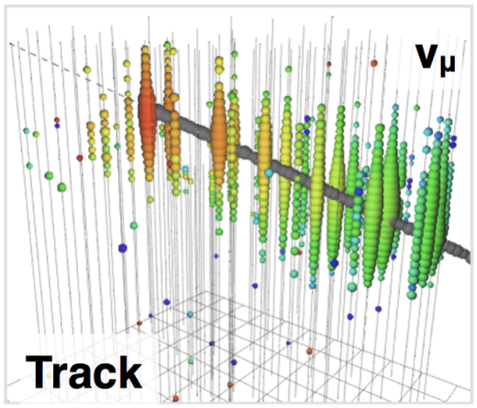


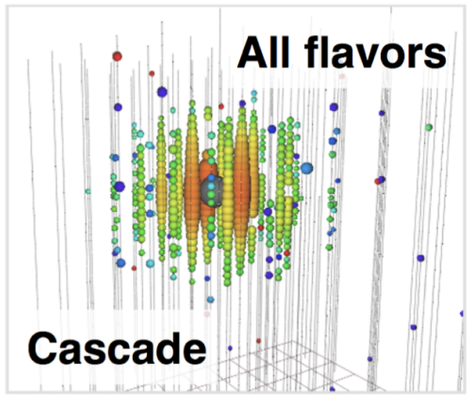
Juliana Stachurska, …,CA@Neutrino2018

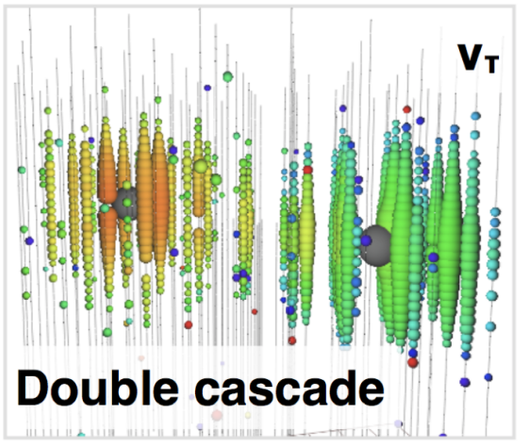


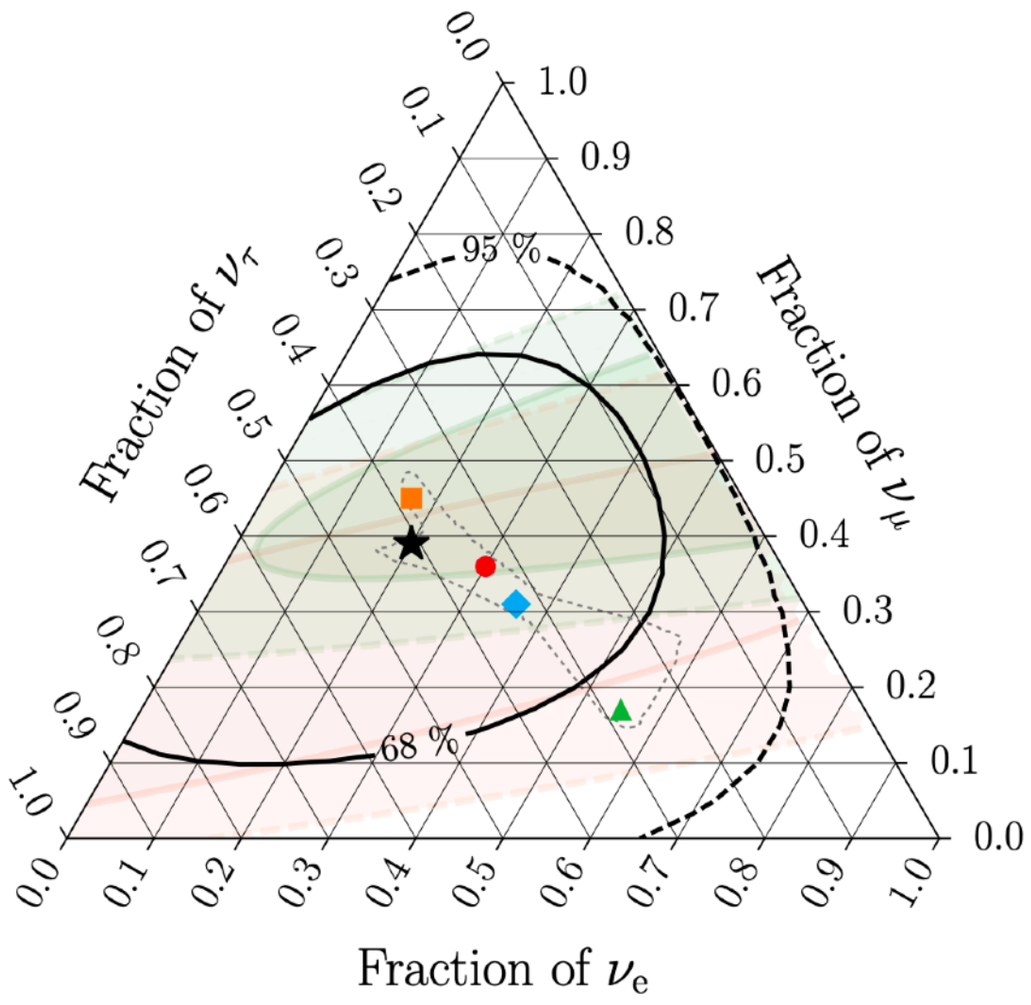
IceCube Collaboration, https://arxiv.org/abs/2011.03561

Astrophysical neutrino flavor measurements with High-Energy Starting Events









HESE with ternary topology ID	$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:
★ Best fit: 0.20 : 0.39 : 0.42	■ 0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
Global Fit (IceCube, APJ 2015)	● 1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
Inelasticity (IceCube, PRD 2019)	▲ 1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
3ν-mixing 3σ allowed region	◆ 1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

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

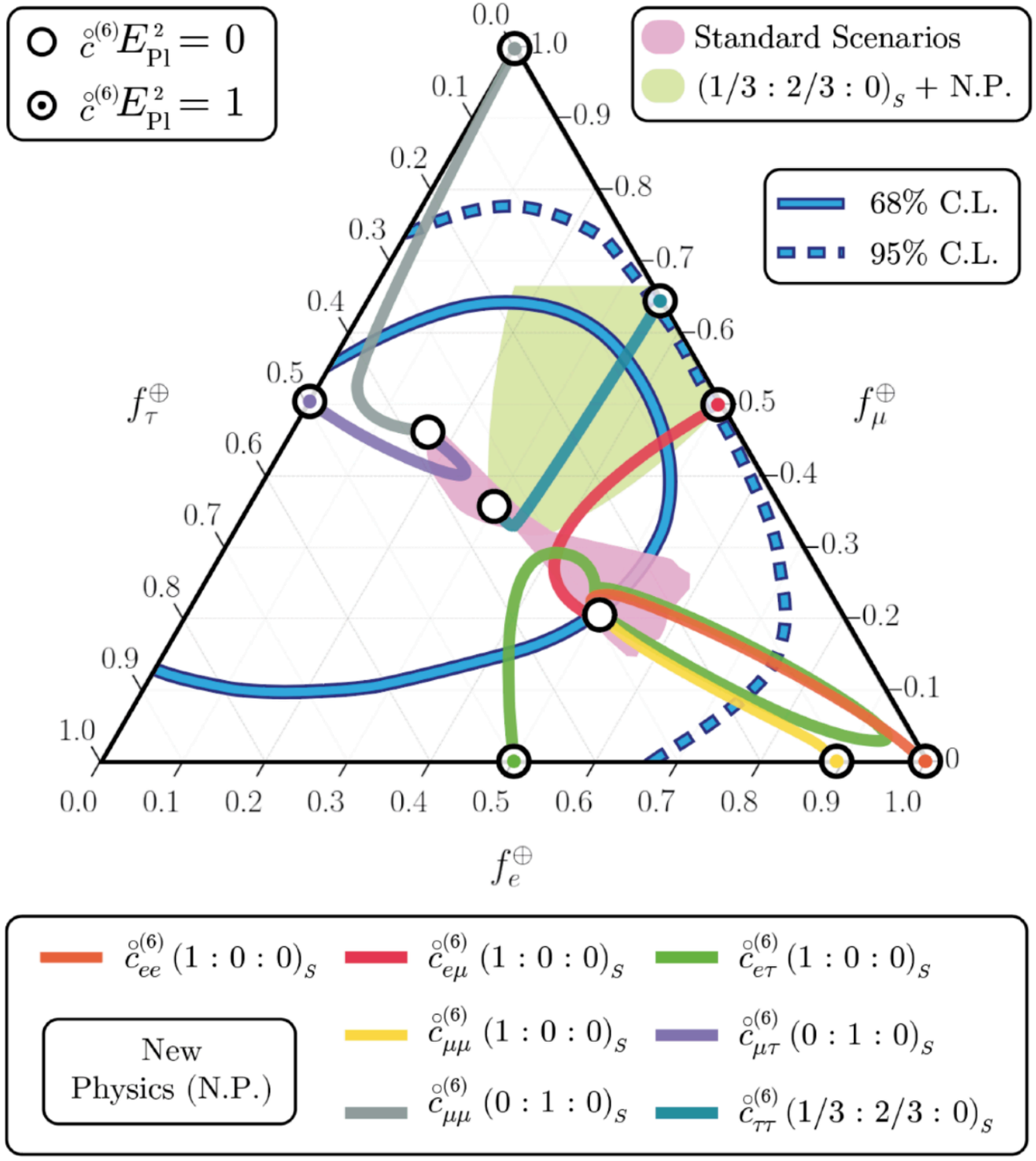
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

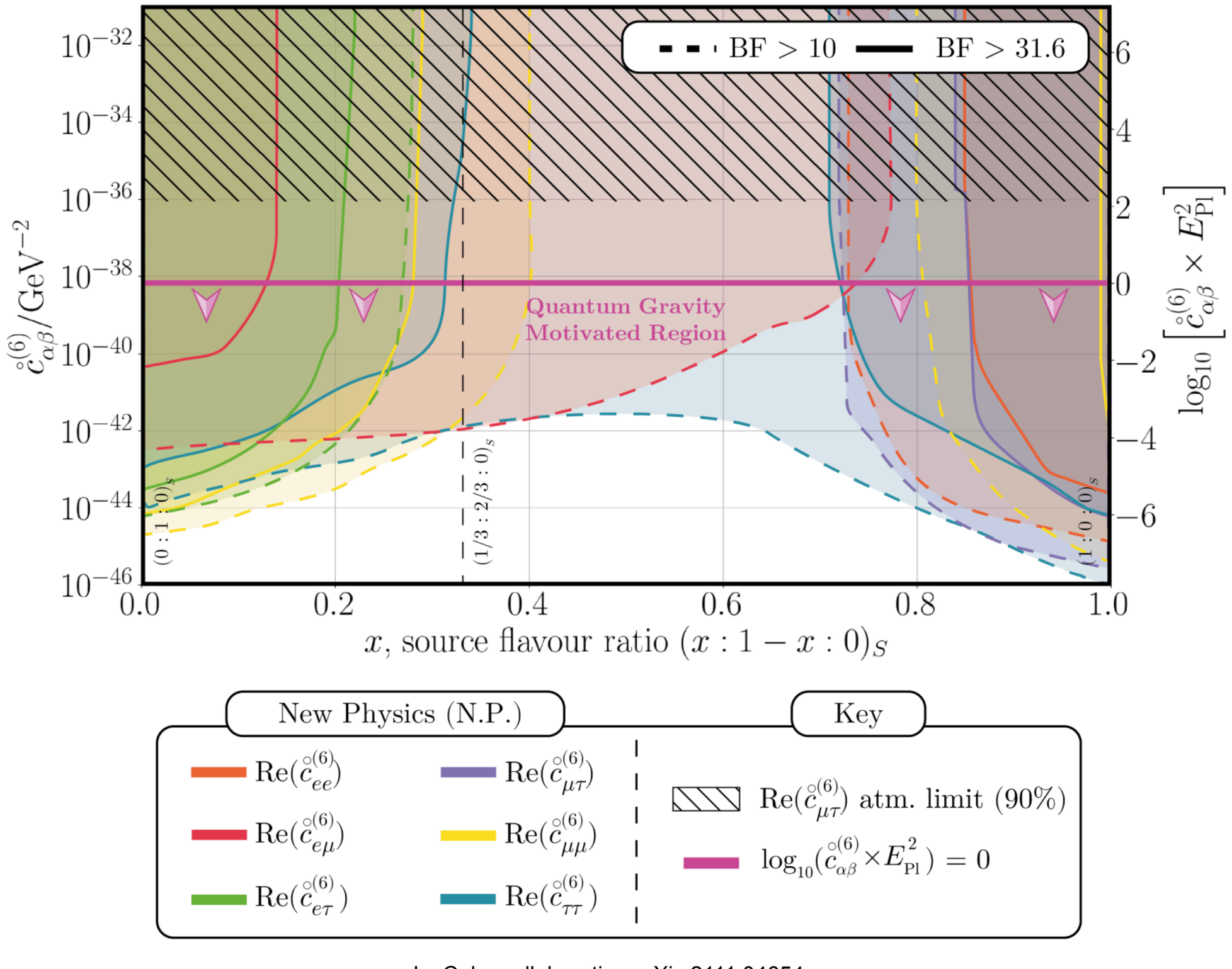
$(0:1:0)$ neutron

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



IceCube collaboration arXiv:2111.04654

Results on high-dimensional LV operators

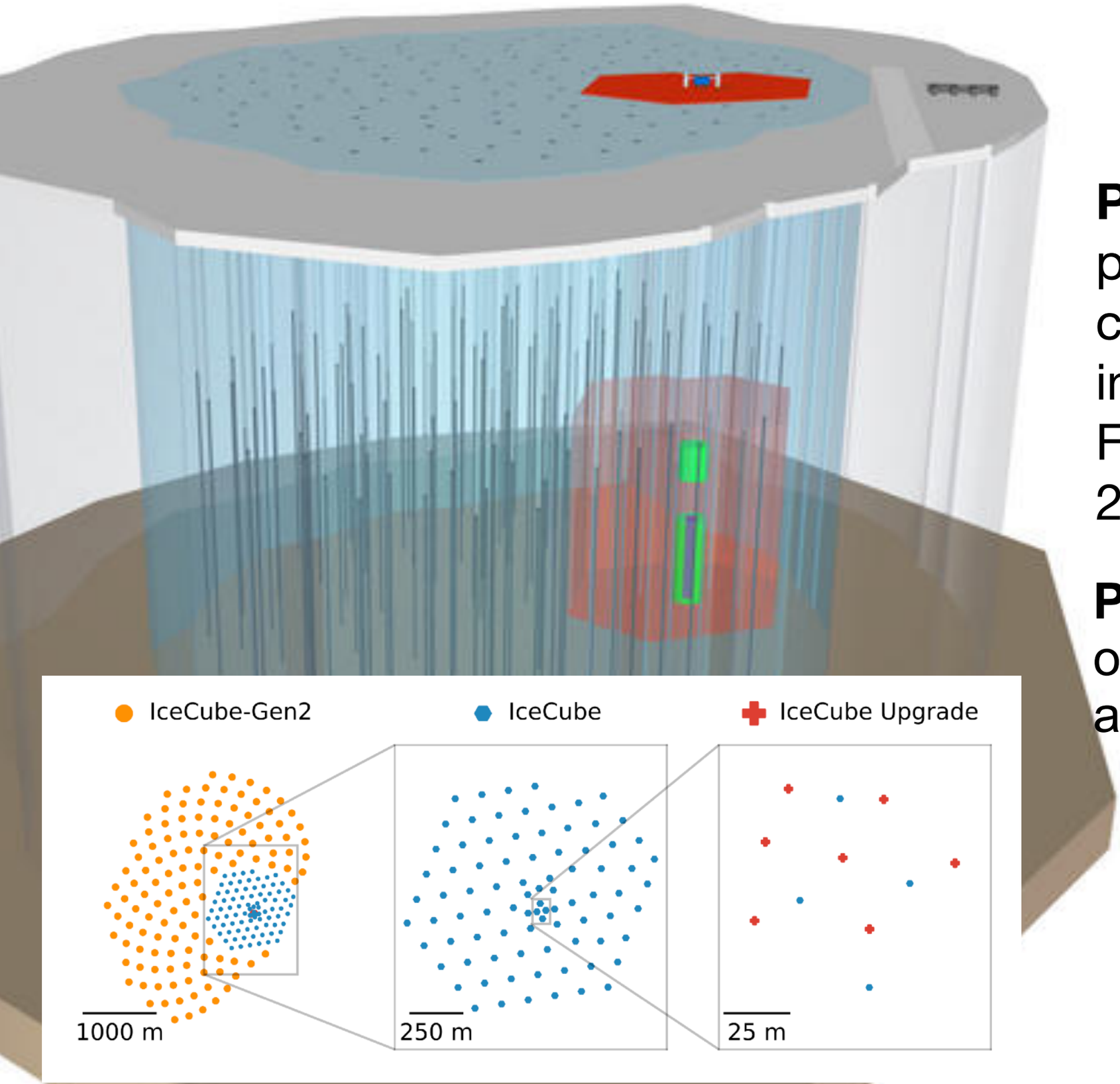


IceCube collaboration arXiv:2111.04654

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

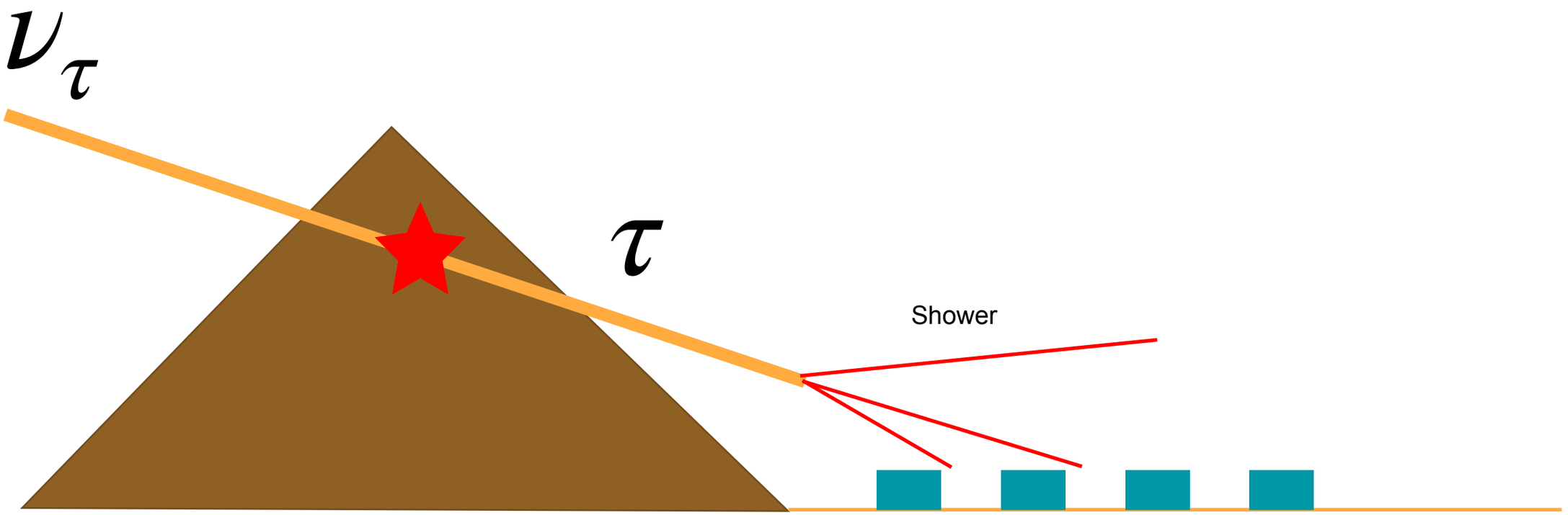
The IceCube Upgrades



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

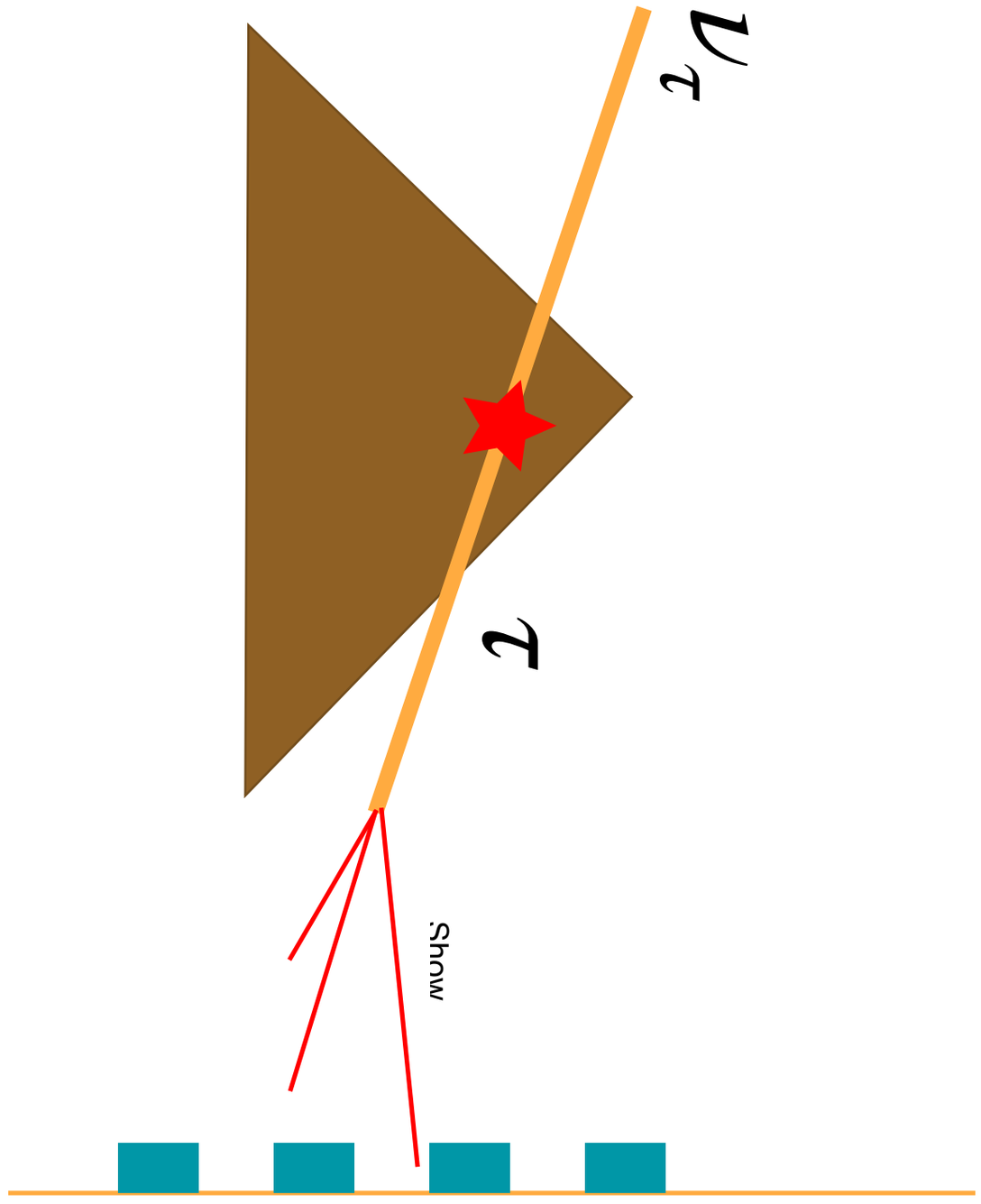
Phase 2: x10 the volume of present IceCube, plus additional detectors.

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

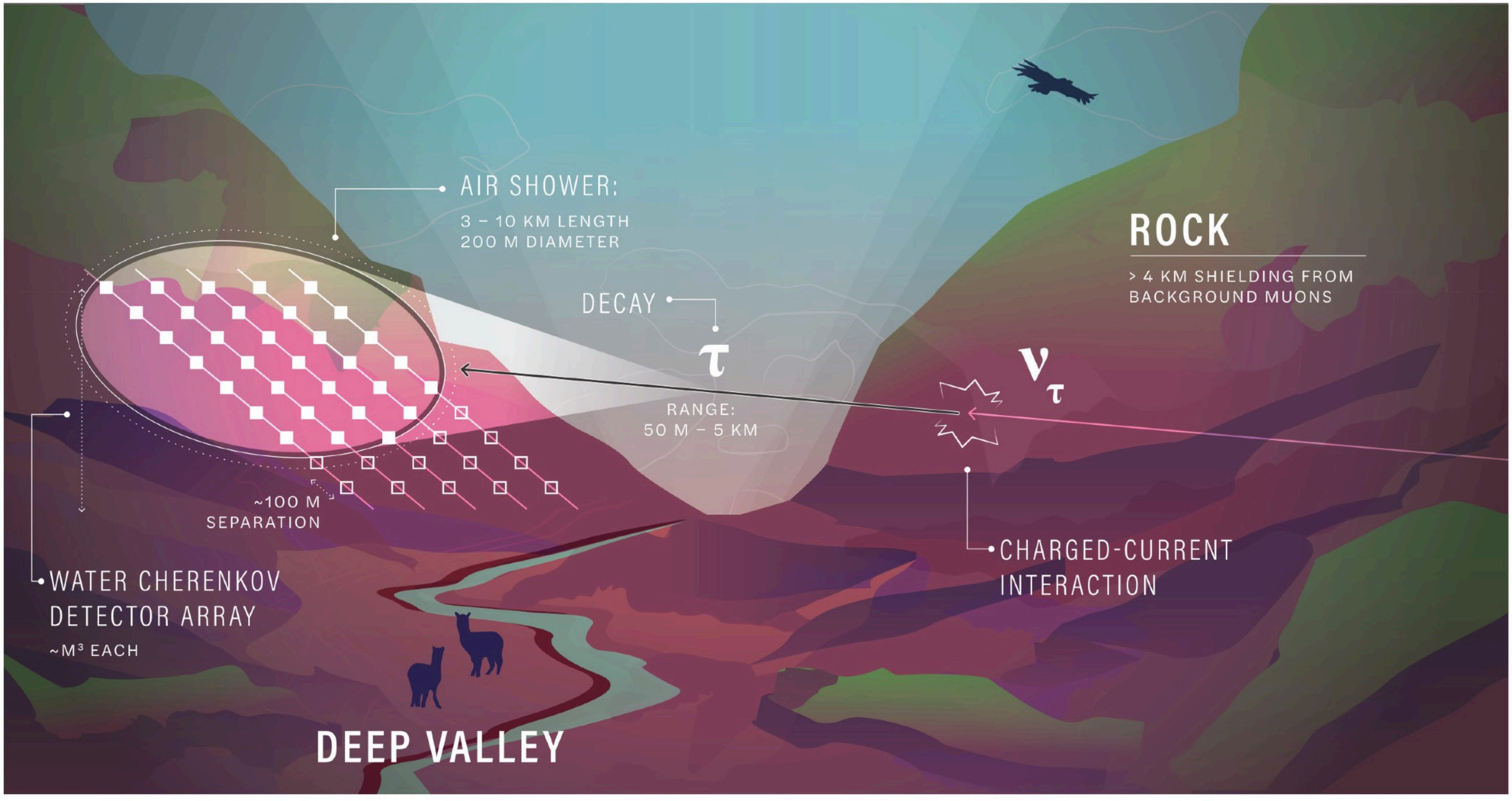
Thinking about Earth-skimming neutrino detectors



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*!

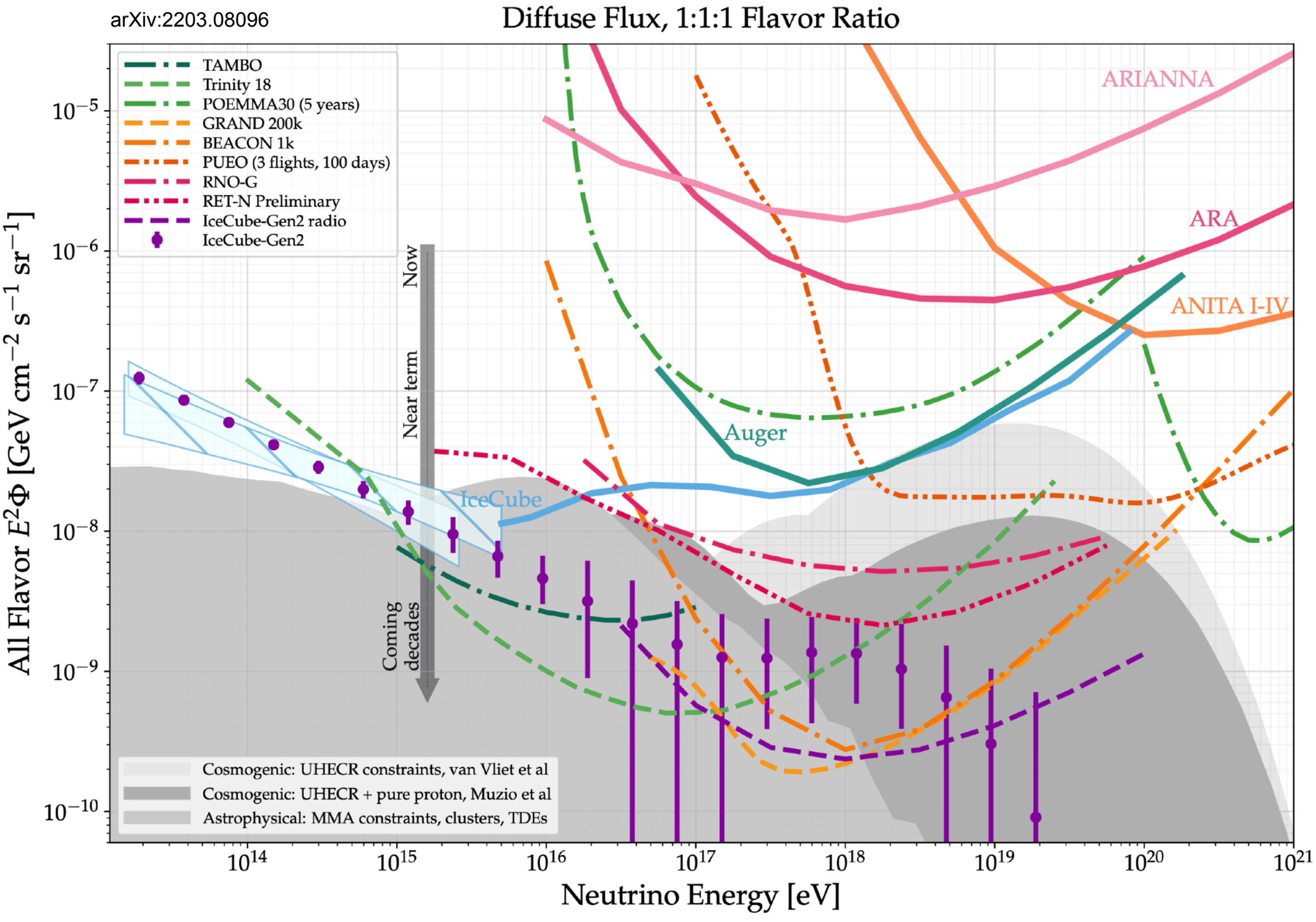


TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

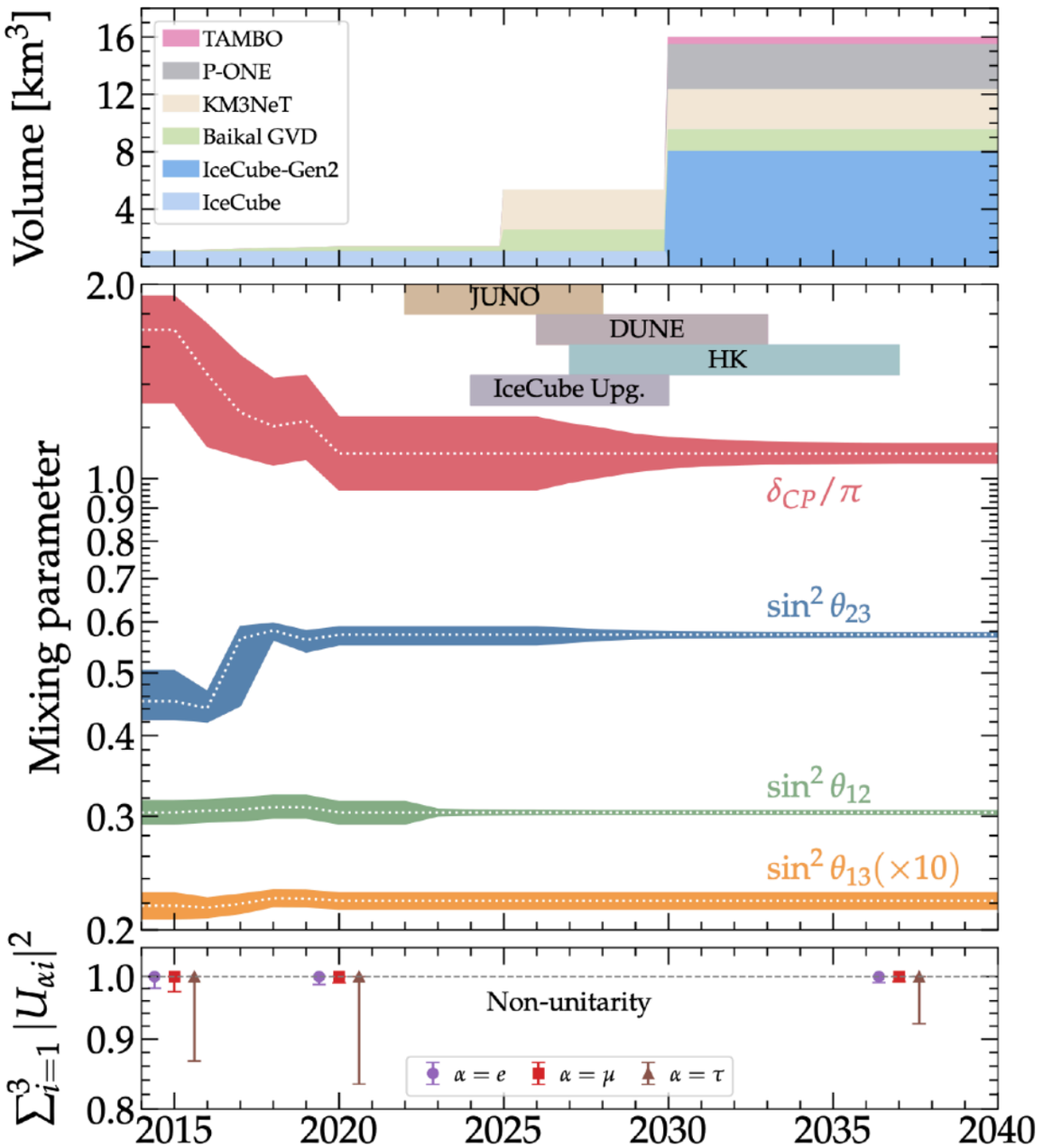
Romero-Wolf *et al* https://arxiv.org/abs/2002.06475

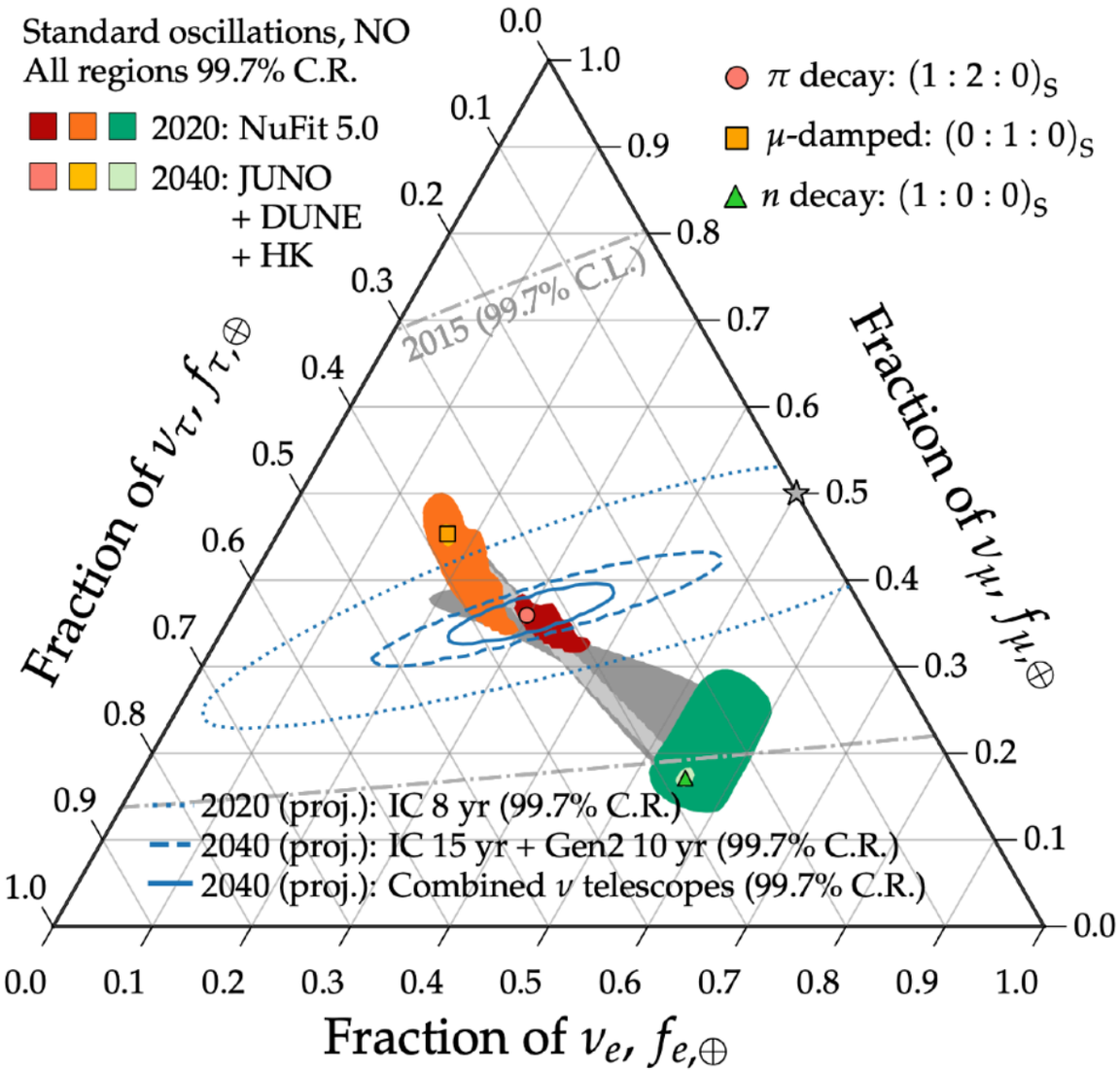
*TAMBO means house or inn in Quechua.

Next Generation Experiments Flux Sensitivity



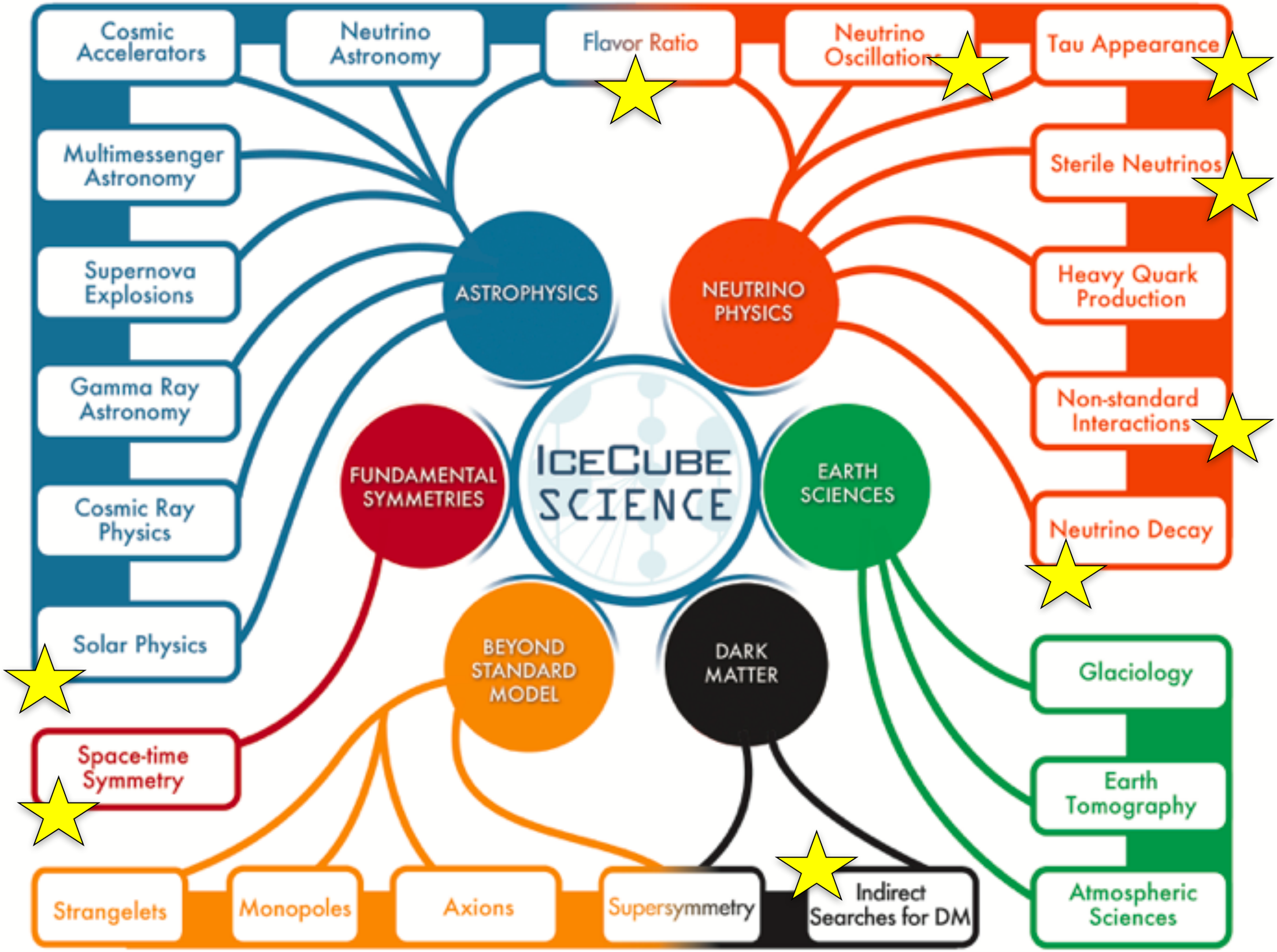
Projected Upgrade Flavor Measurement





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

IceCube is more than just a telescope!



Conclusion

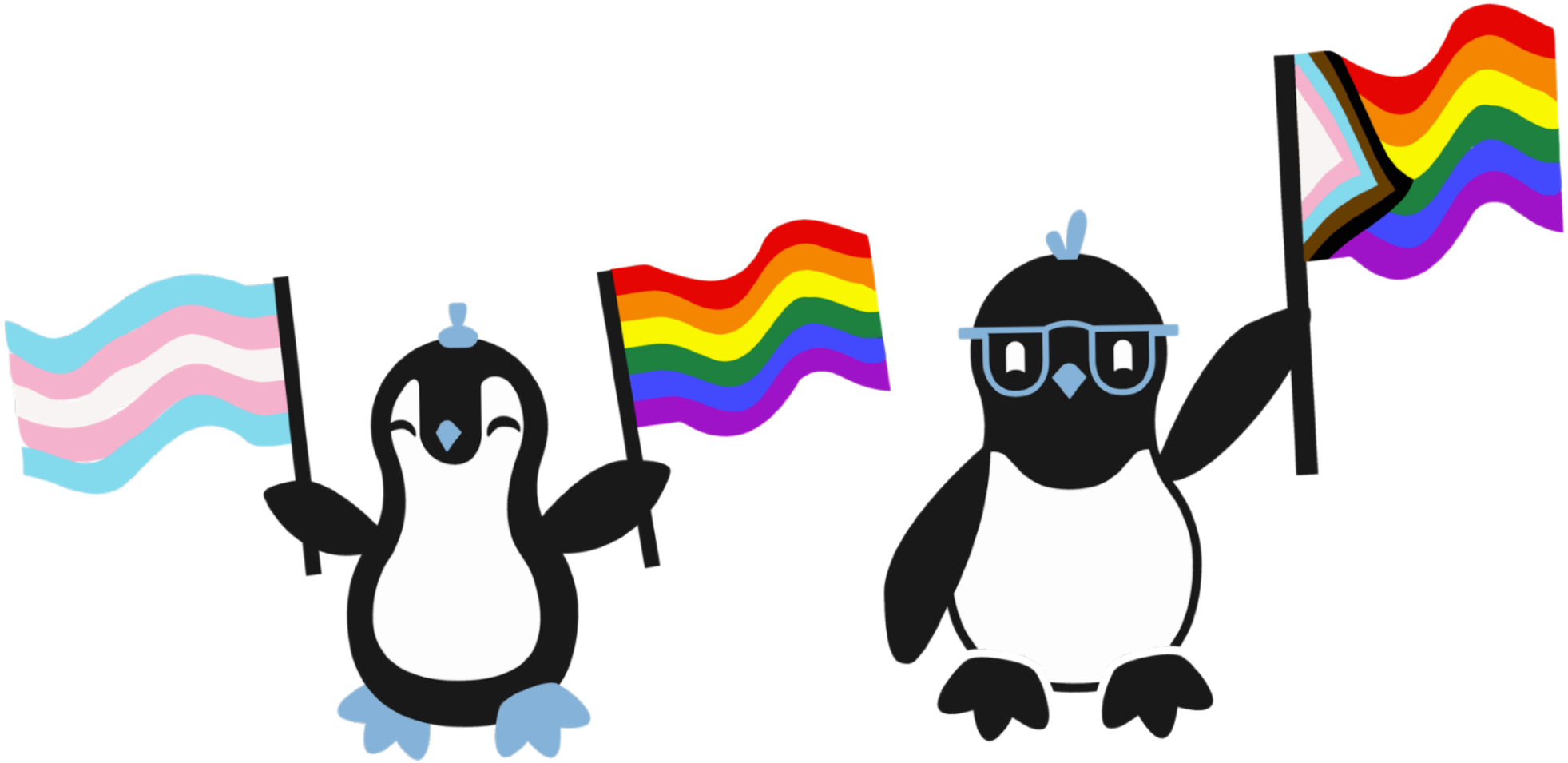
Neutrino Physics is truly in the midst of interesting times:

- 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.

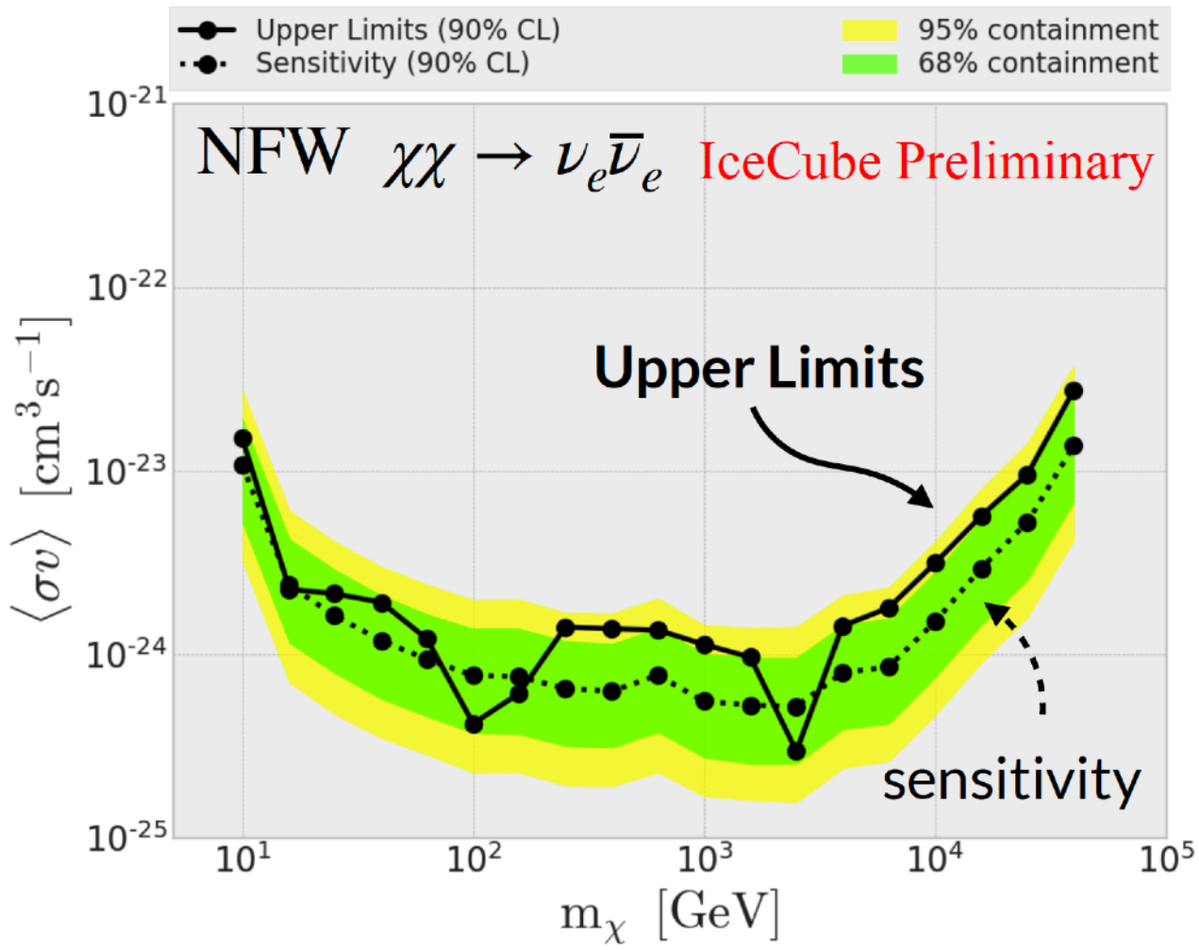
We also have great possibilities for the future:

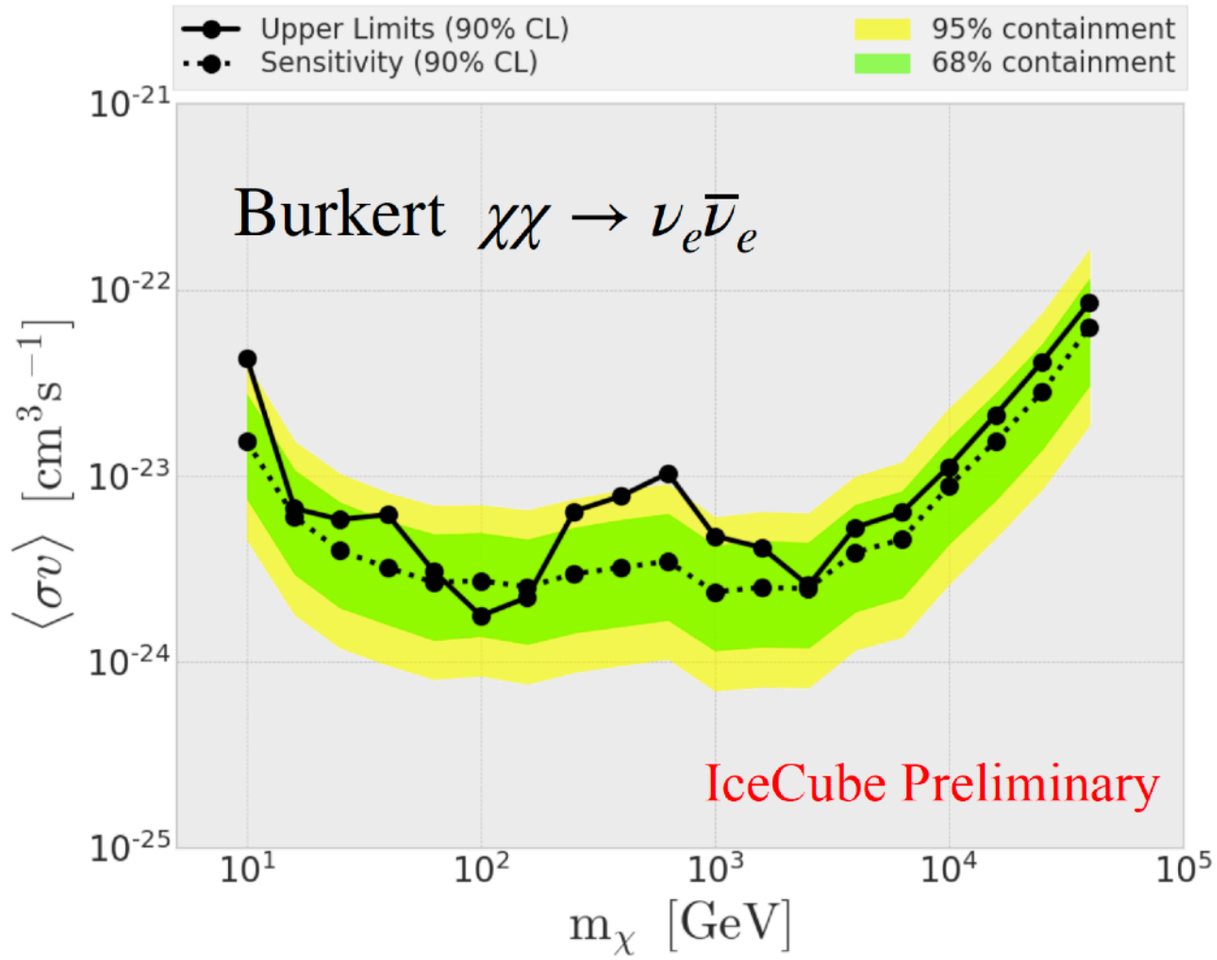
- Combination of IceCube measurements
- New results from Km3NeT and GVD-Baikal
- Next generation neutrino observatories will provide a *nu* picture of the Universe.

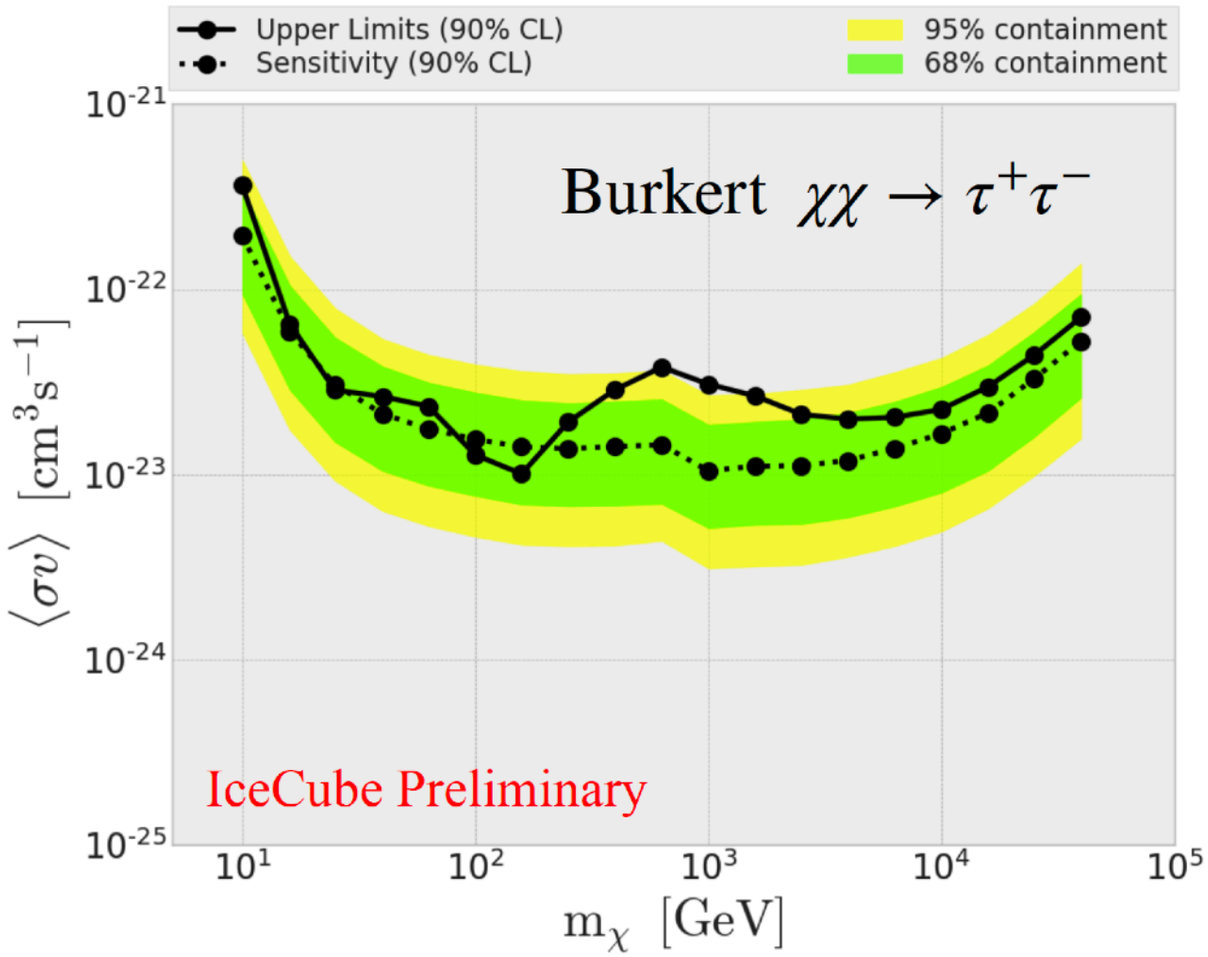
Thanks!

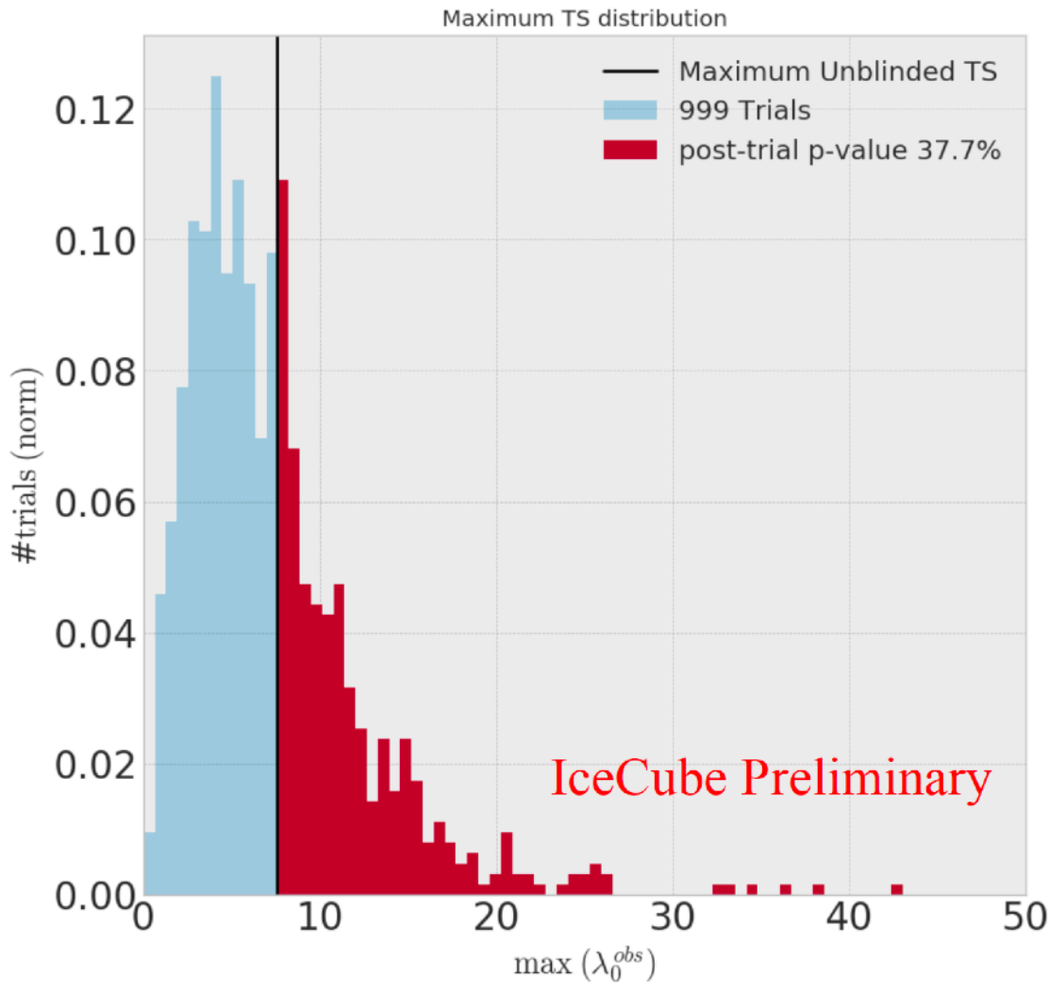


Bonus slides

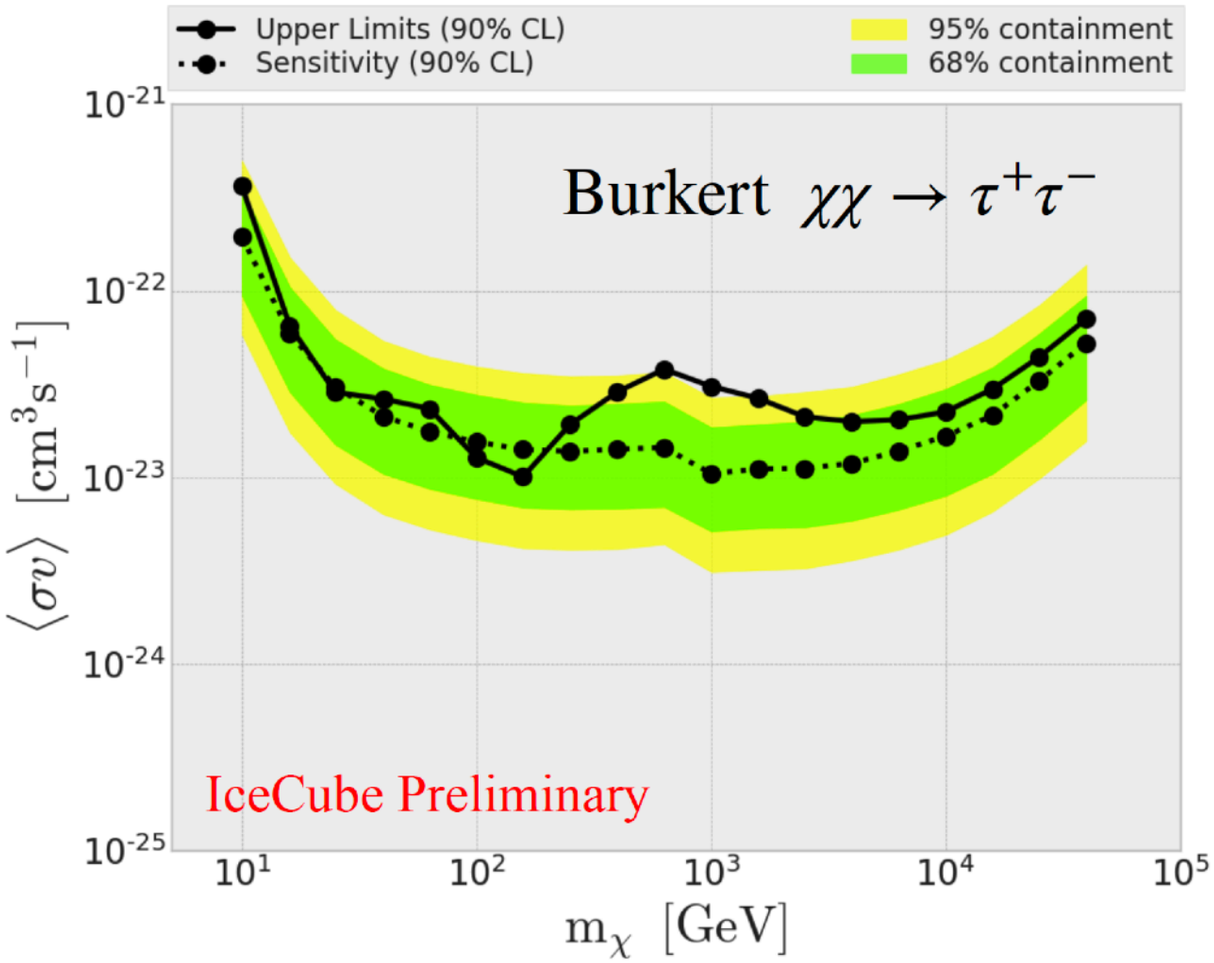

Upper Limits (90% CL)
Sensitivity (90% CL)
95% containment
68% containment
NFW $\chi\chi \rightarrow \nu_e\bar{\nu}_e$ IceCube Preliminary
Upper Limits
sensitivity
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]
m_χ [GeV]

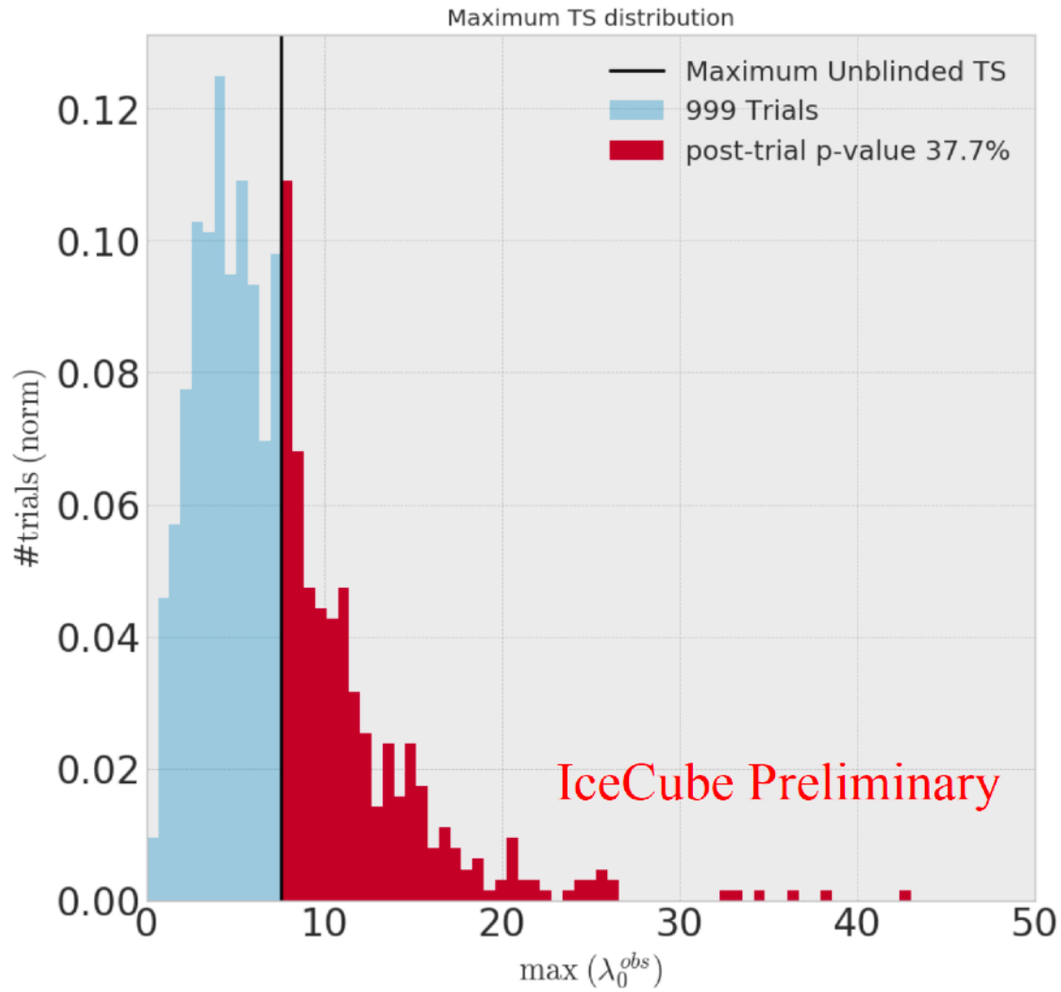

Upper Limits (90% CL)
Sensitivity (90% CL)
95% containment
68% containment
Burkert $\chi\chi \rightarrow \nu_e\bar{\nu}_e$
IceCube Preliminary
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]
m_χ [GeV]





- Most significant results is $m_\chi = 1$ TeV with pre(post)-trial p-value 0.3% (~38%)





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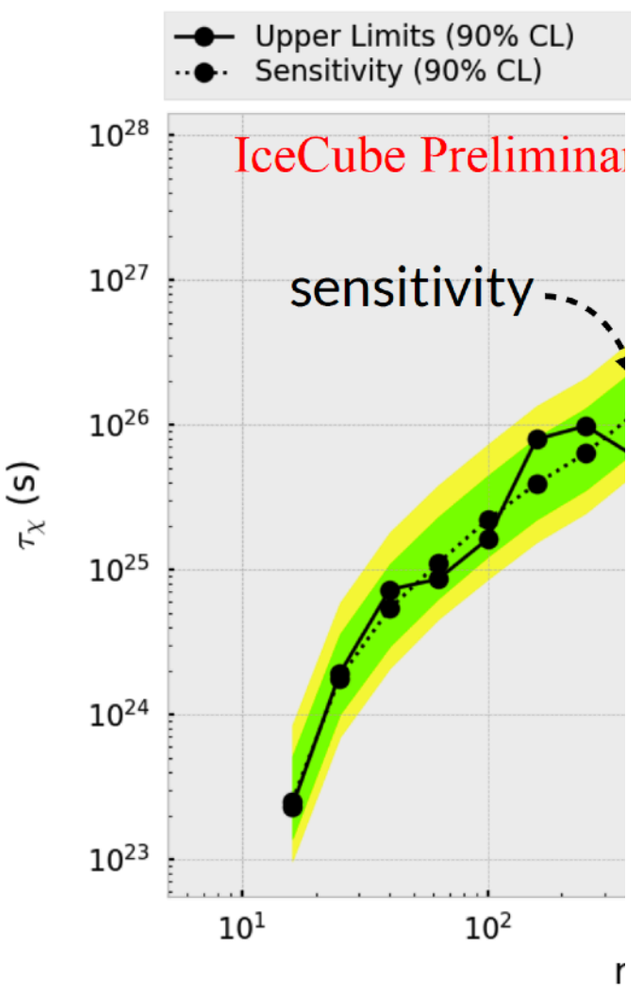
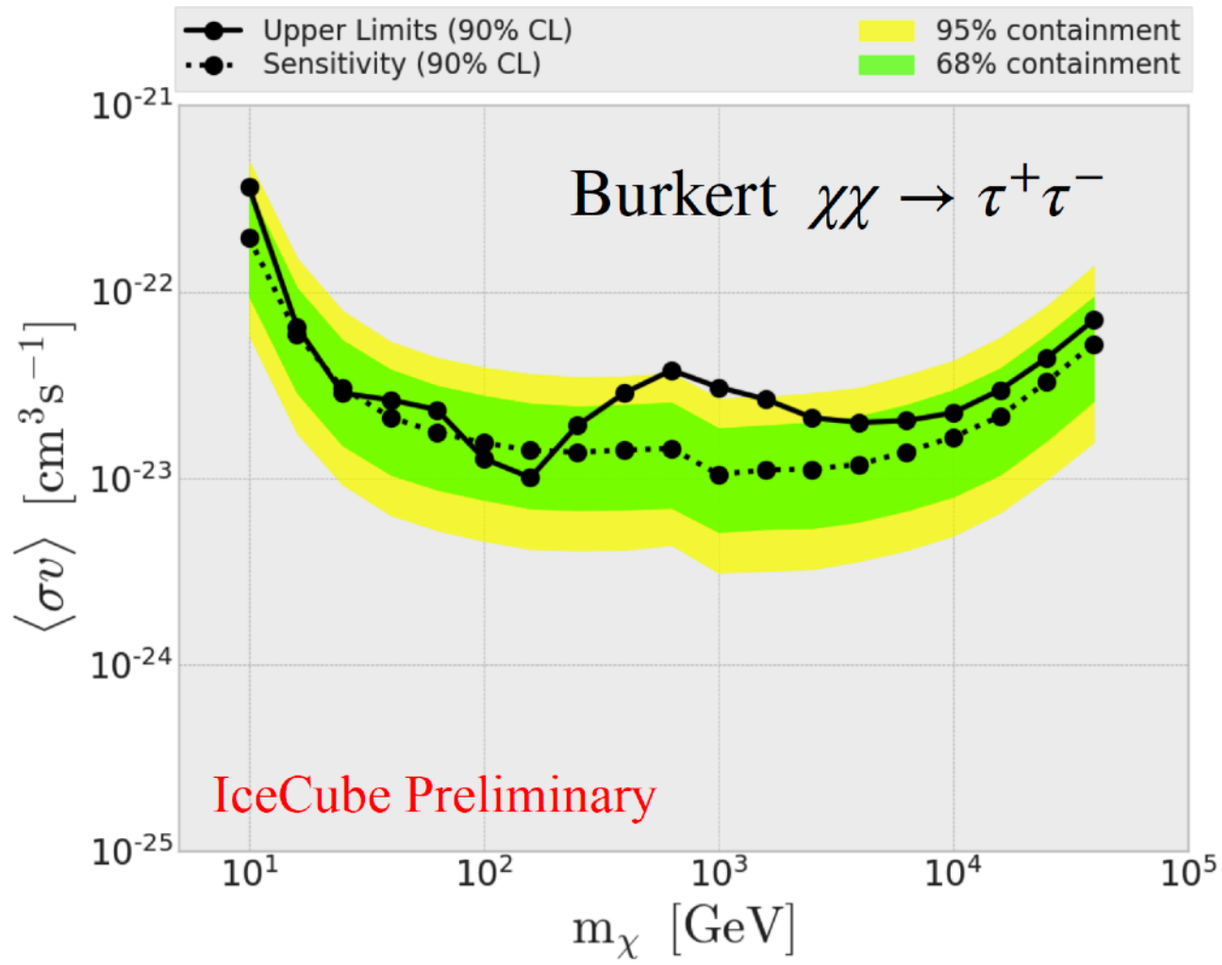
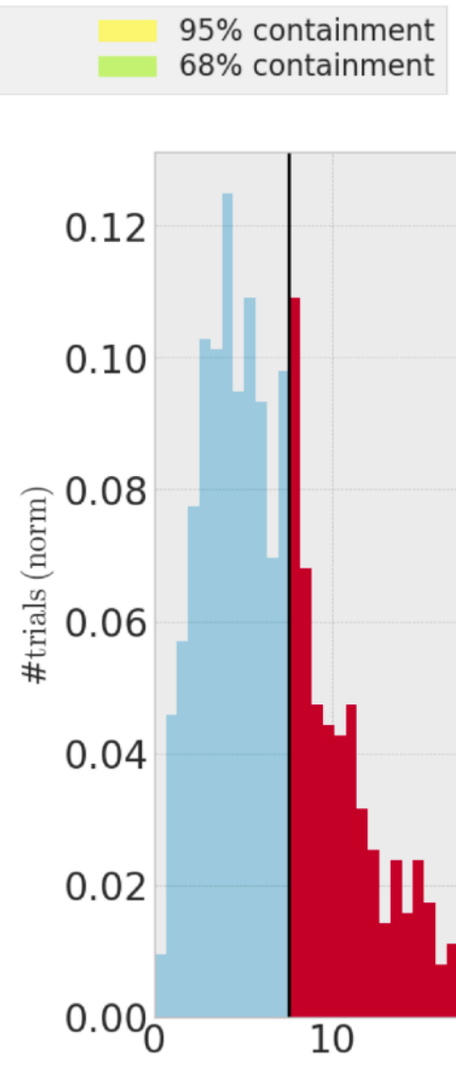
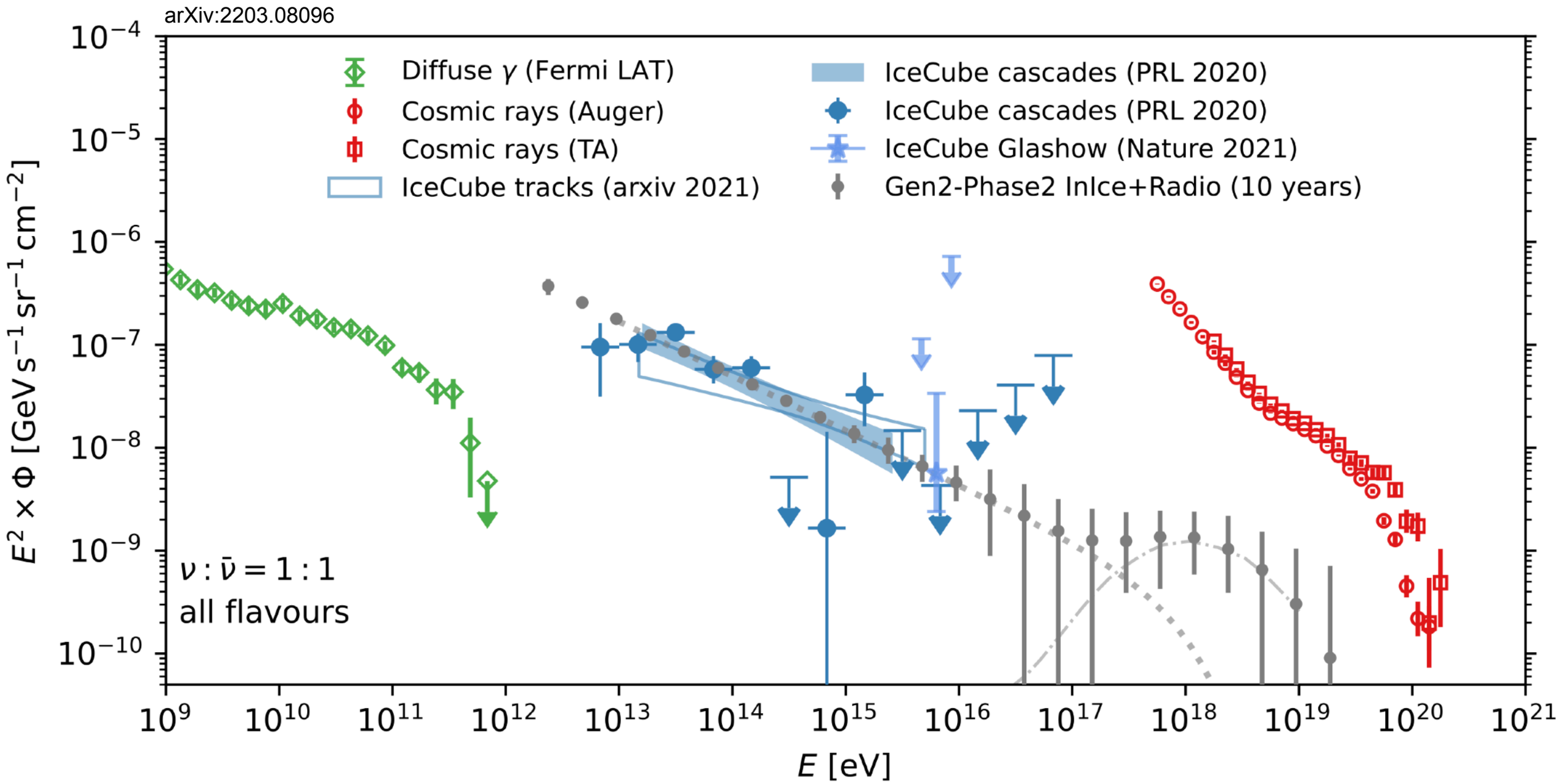




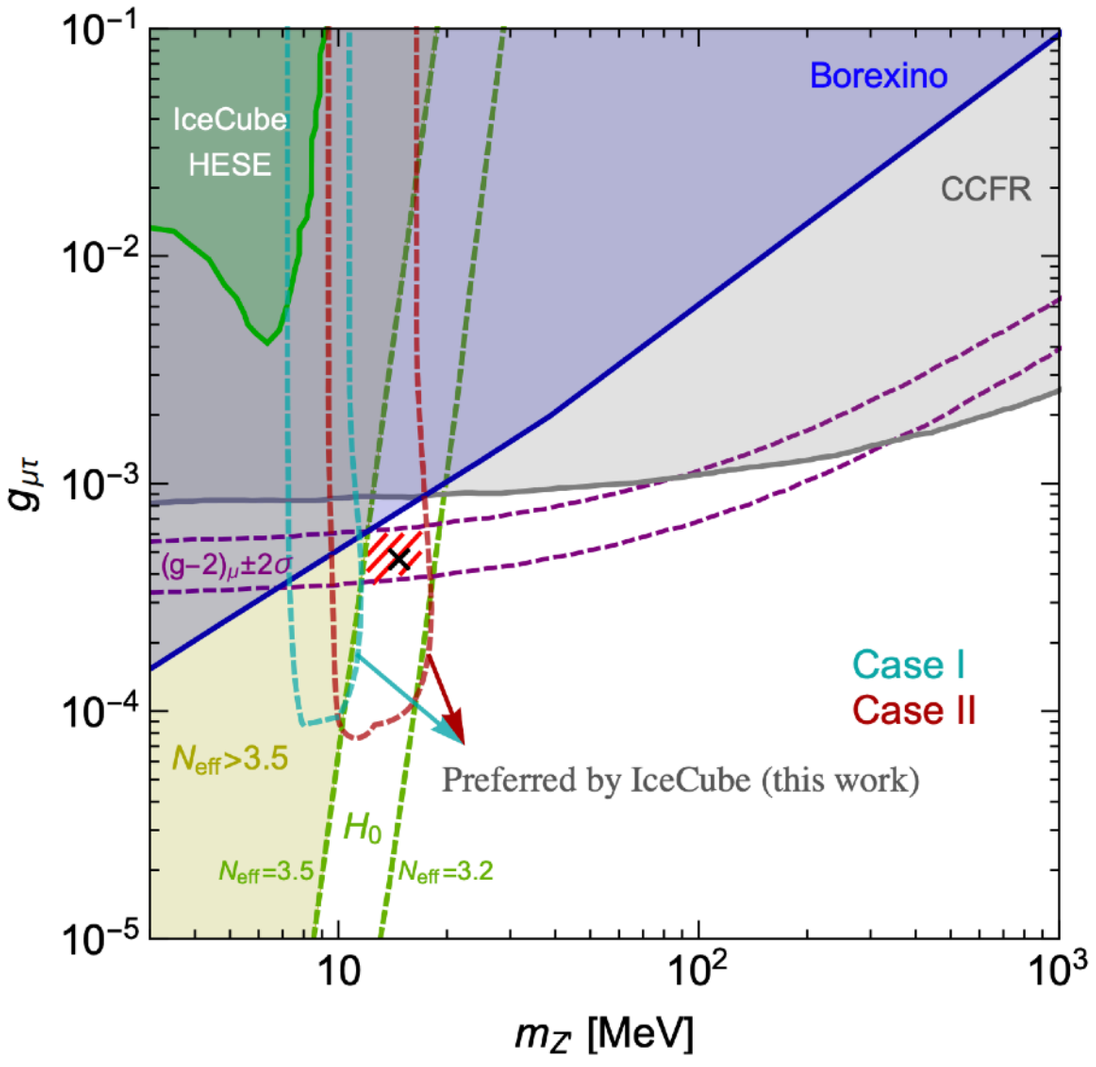


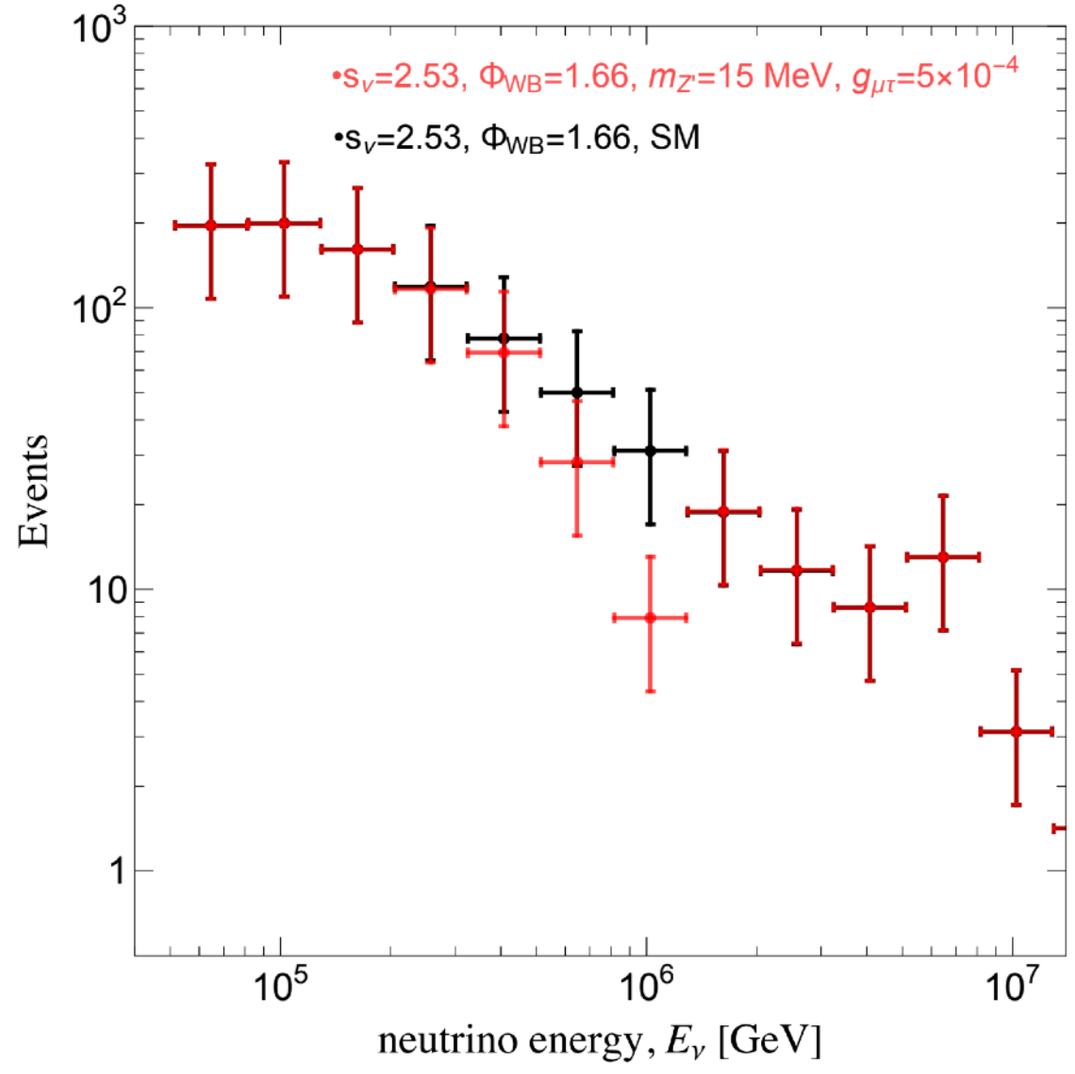
- Most significant results is $m_\chi = 1\ \mathrm{TeV}$ with pre(post)-trial p-va

IceCube-Gen2
Expected Measurement of Astrophysical Flux



Carpio et al. arXiv:2104.15136





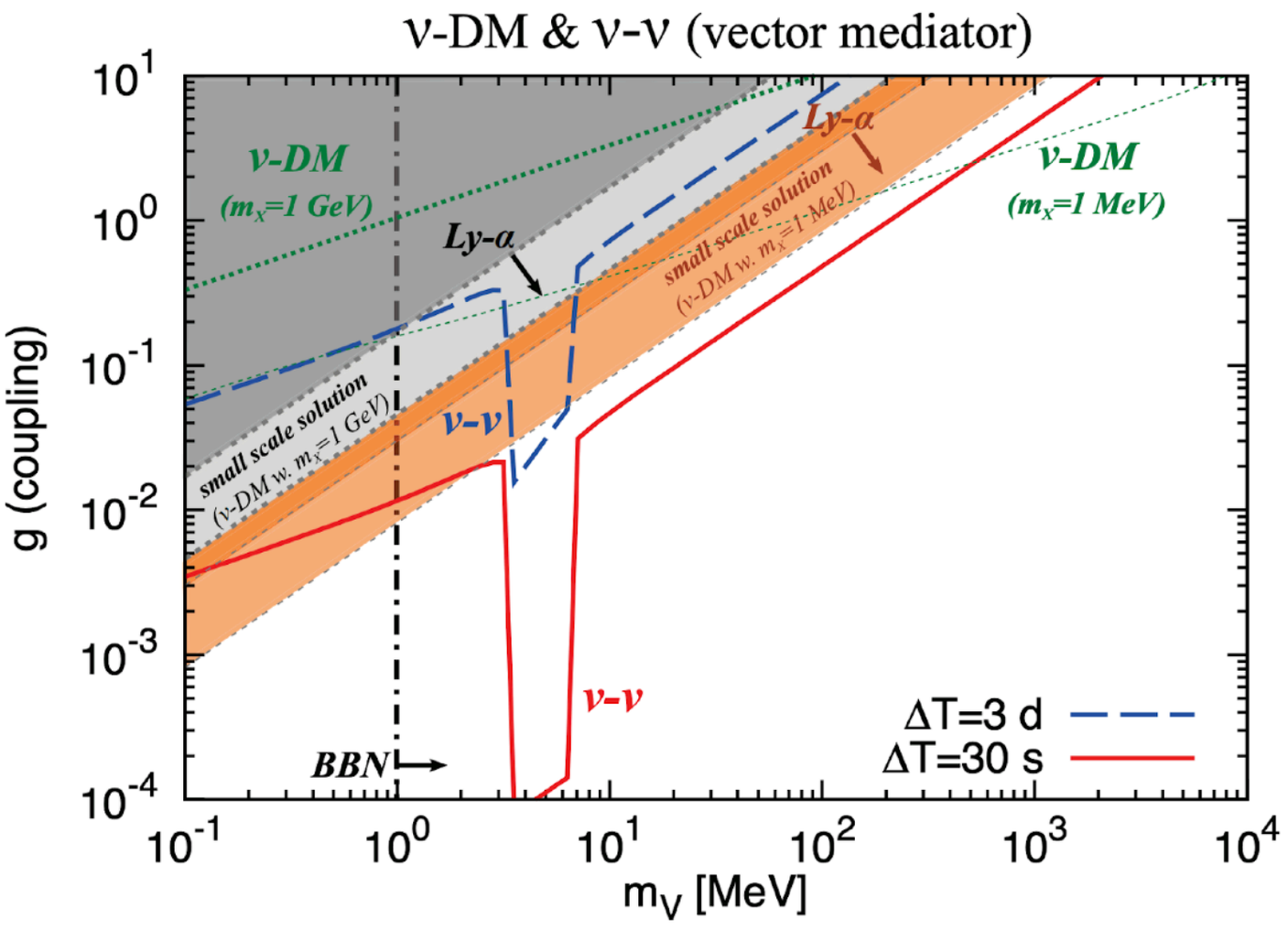
Time of Flight Measurements

$$(\Delta v_{\nu\gamma}/c)_{SN1987A} \sim 3 \cdot 10^{-9}$$

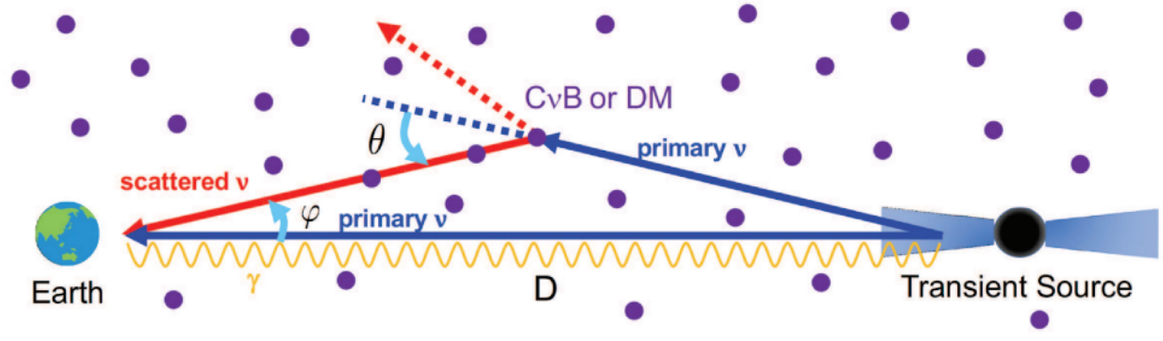
$$(\Delta v_{\nu\gamma}/c)_{TXS} \sim 10^{-11}$$

$$v(E) = c\left[1 - s_n \frac{n+1}{2}\left(\frac{E}{E_{LV,n}}\right)^n\right]$$

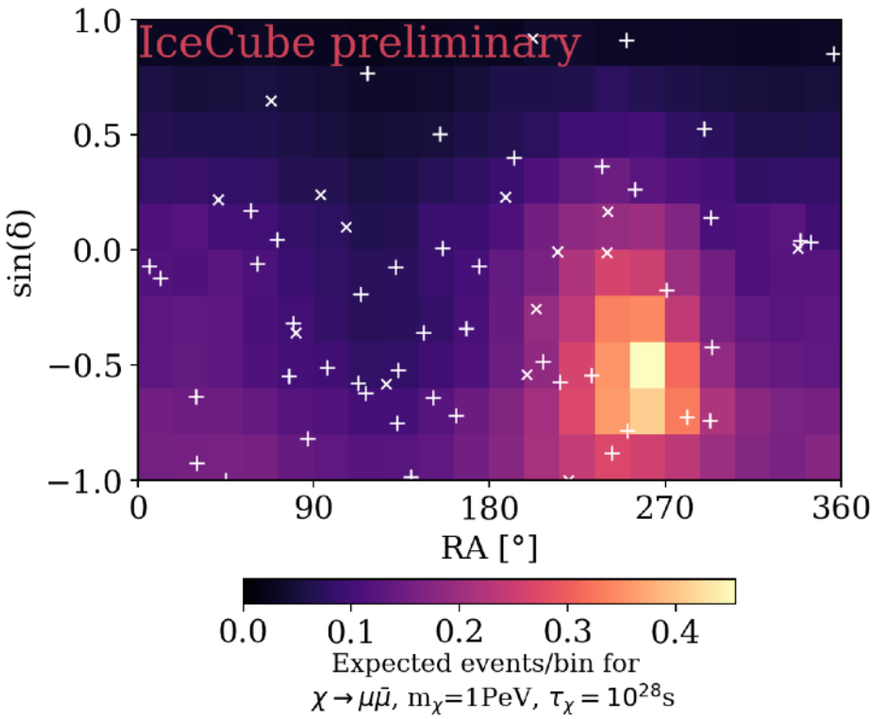
Dark Matter-neutrino interactions
Murase & Shoemaker arXiv:1903.08607

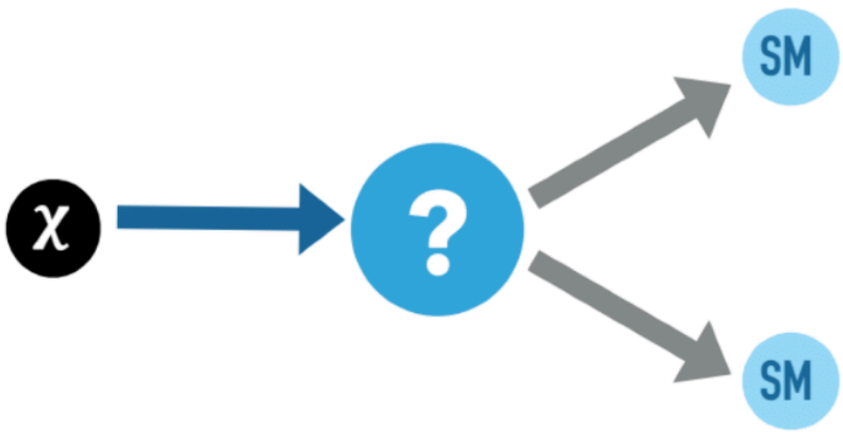


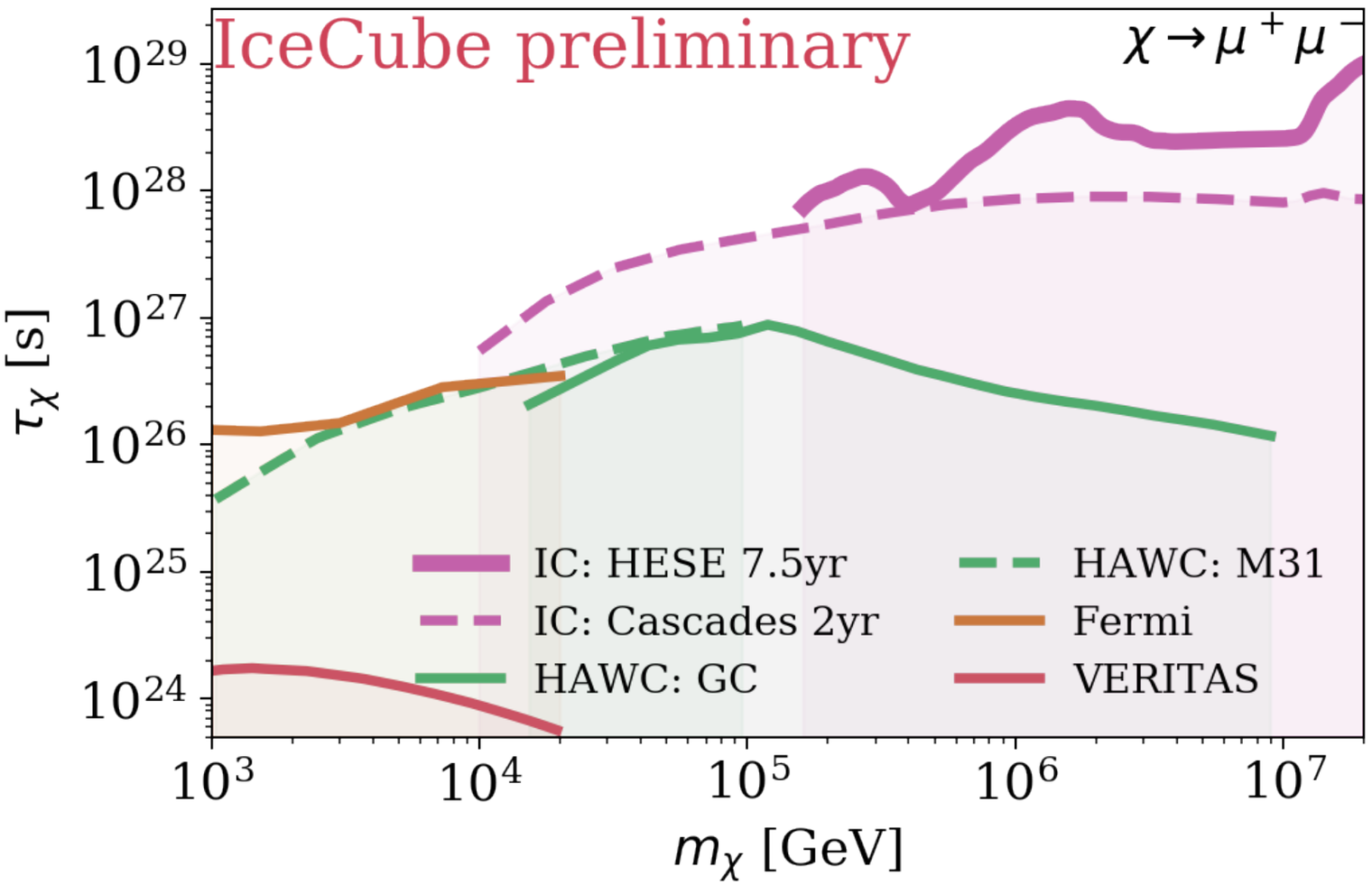
Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568



Dark matter decay

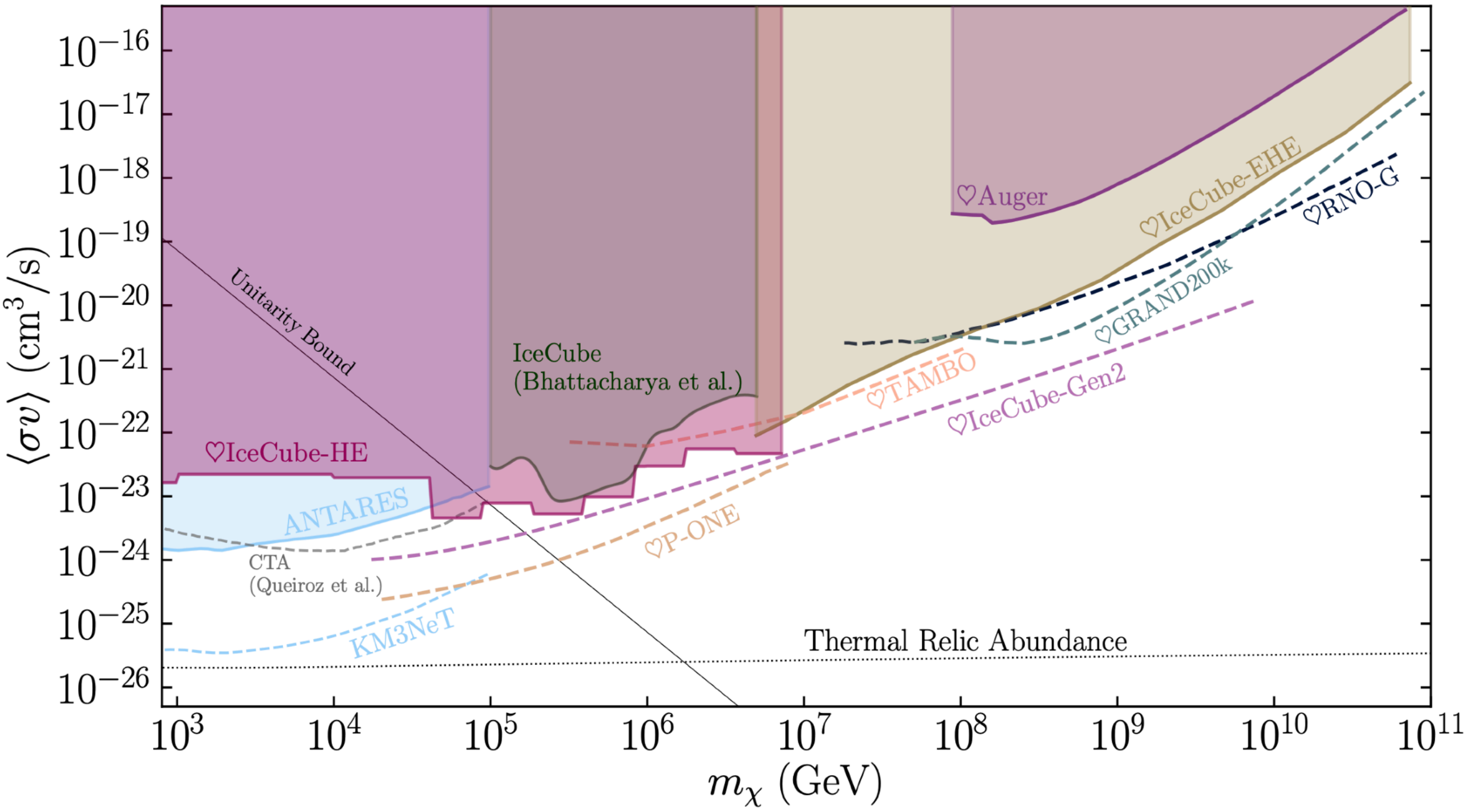






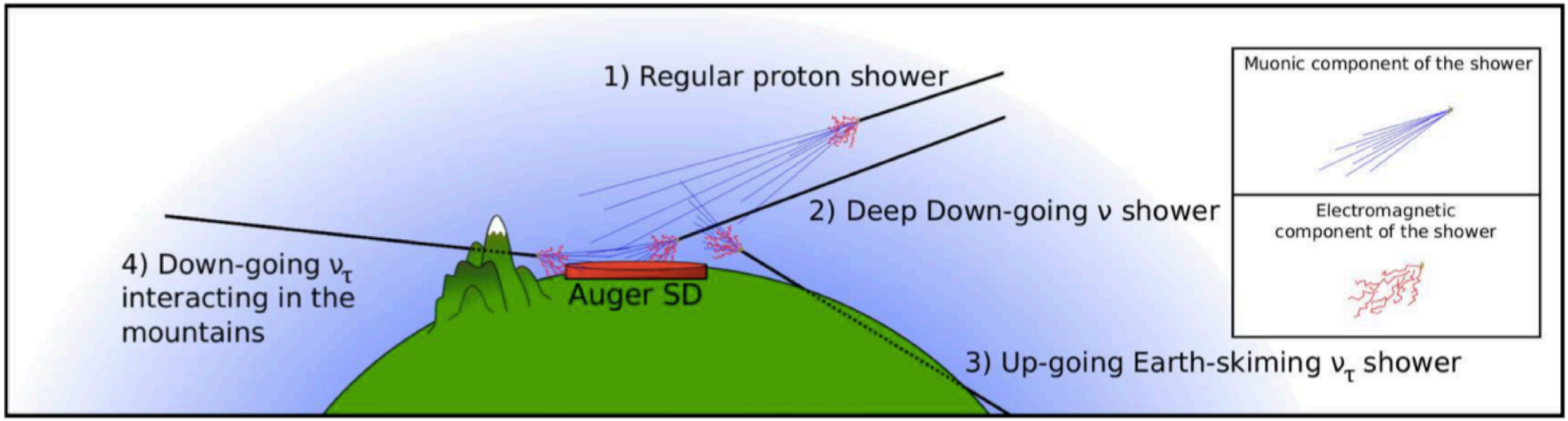
CA, H. Dujmovic arXiv 1907.11193

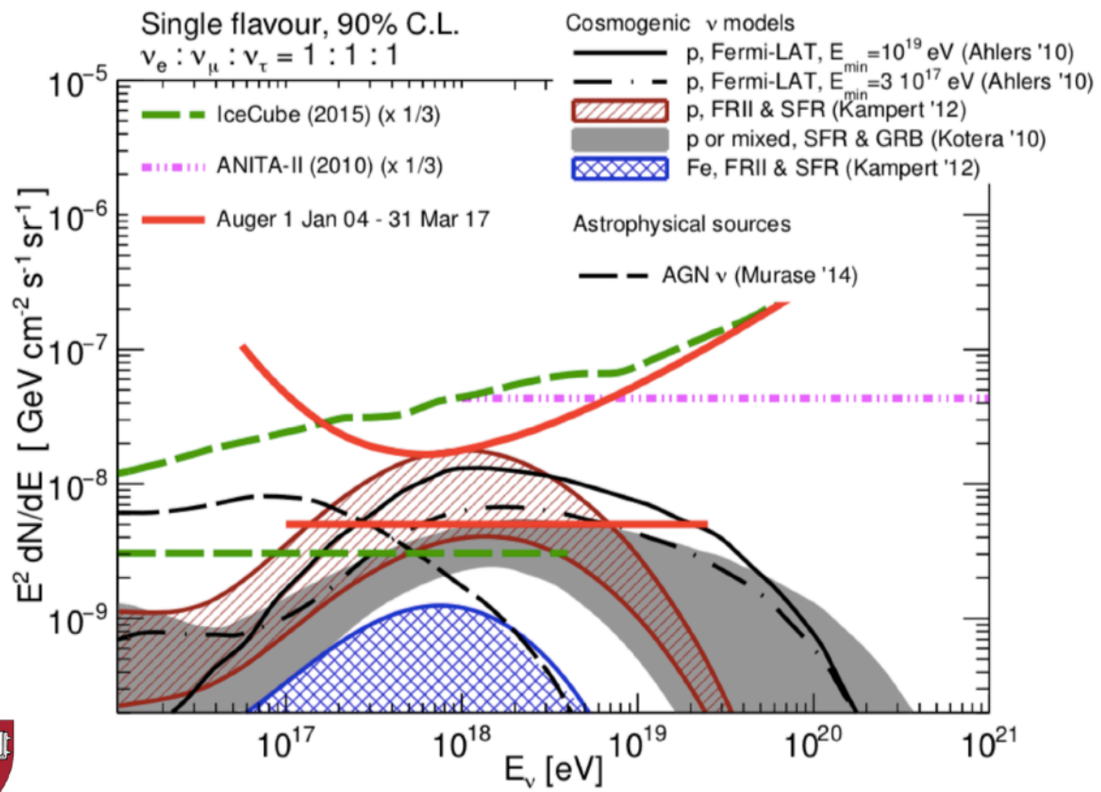
Next Generation Dark Matter Searches



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*.

Earth-skimming neutrino detectors

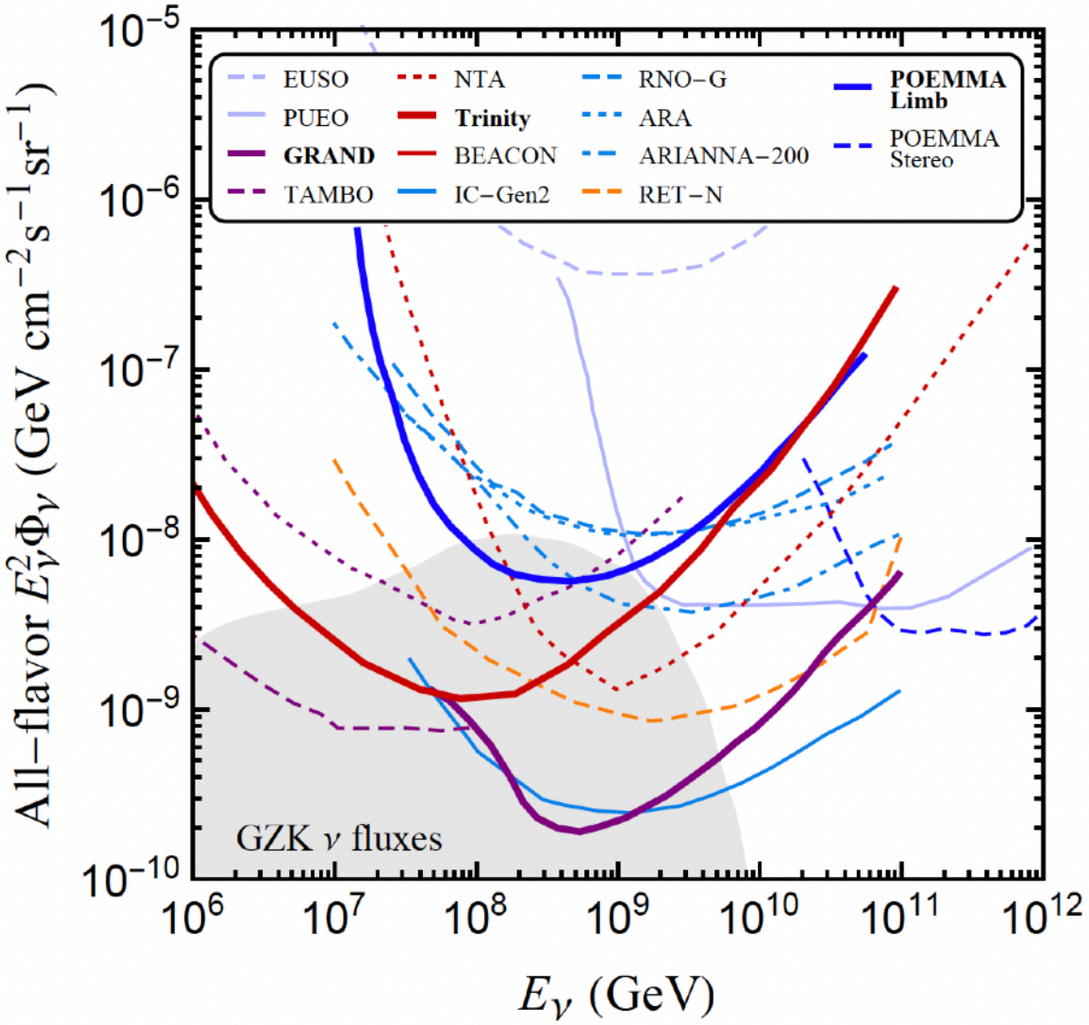




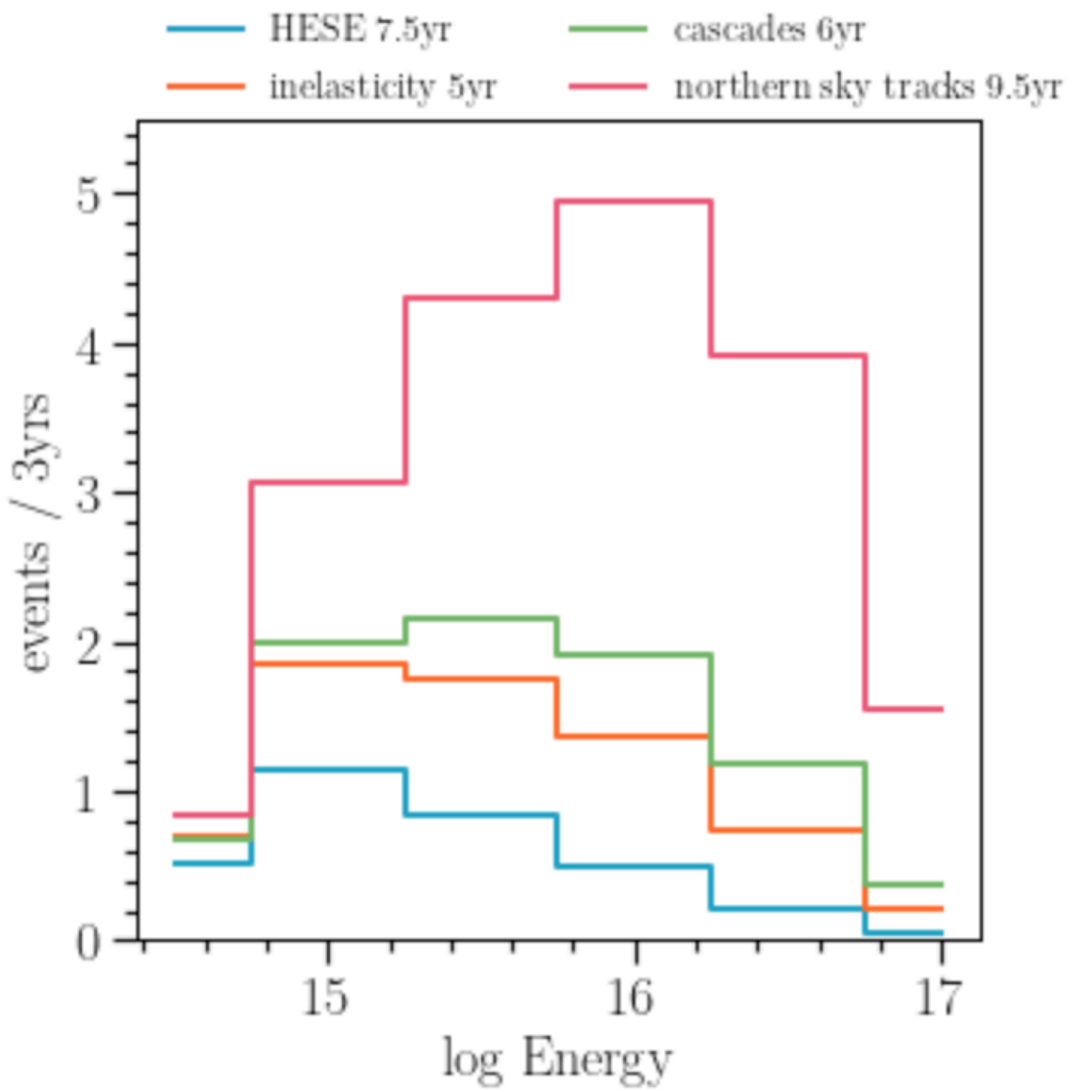
Earth-skimming neutrino detection uses mountains as the neutrino target and then detects the tau shower using Cherenkov detectors (Auger) or radio antennas (GRAND, proposed).

Angular acceptance is limited.

Preliminary Sensitivities

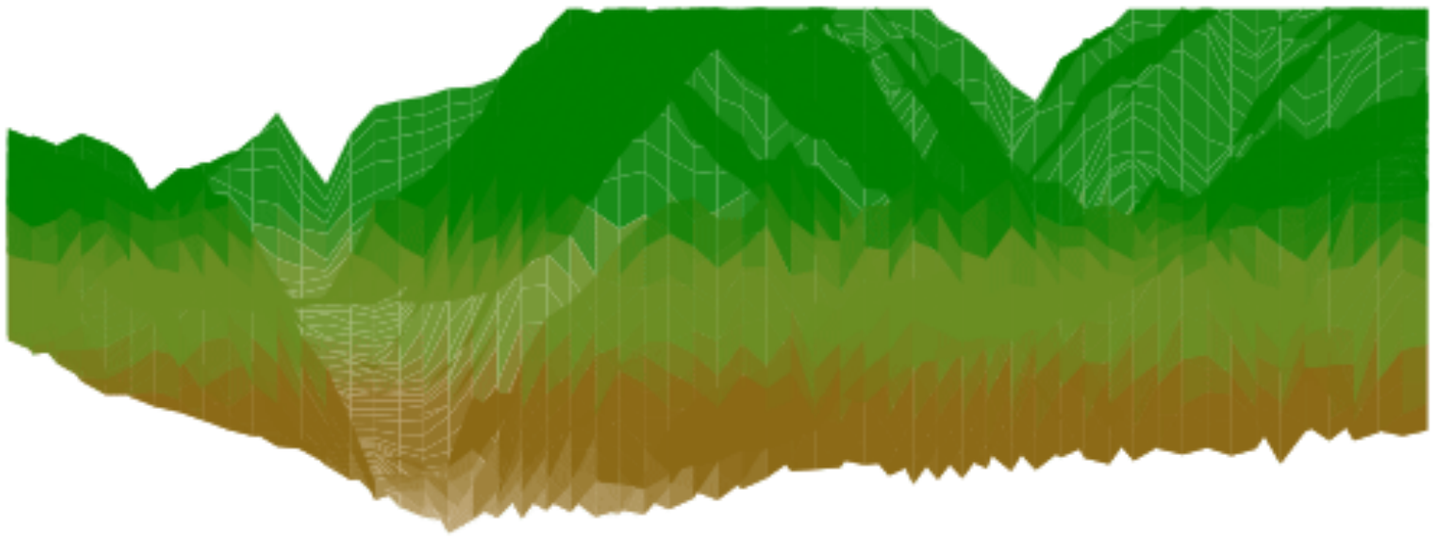


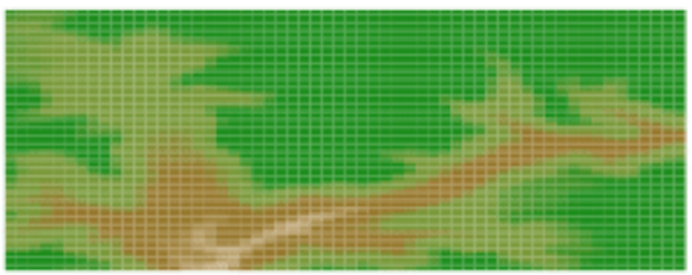
Sensitivities to E_ν^{-2} flux for next generation experiments: Note that almost the entire energy range from 10^6 GeV to 10^{11} GeV can be optimally covered by TAMBO and IceCube-Gen2

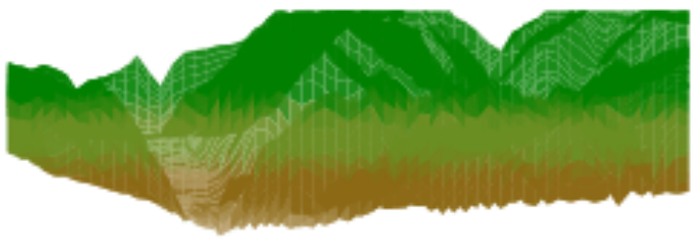


Event rates for several IceCube fluxes: Event rates for several of the best-fit fluxes of IceCube analyses. Pink line is closest to spectrum assumed plot on left

Currently working on simulation with detailed geography of the Colca valley





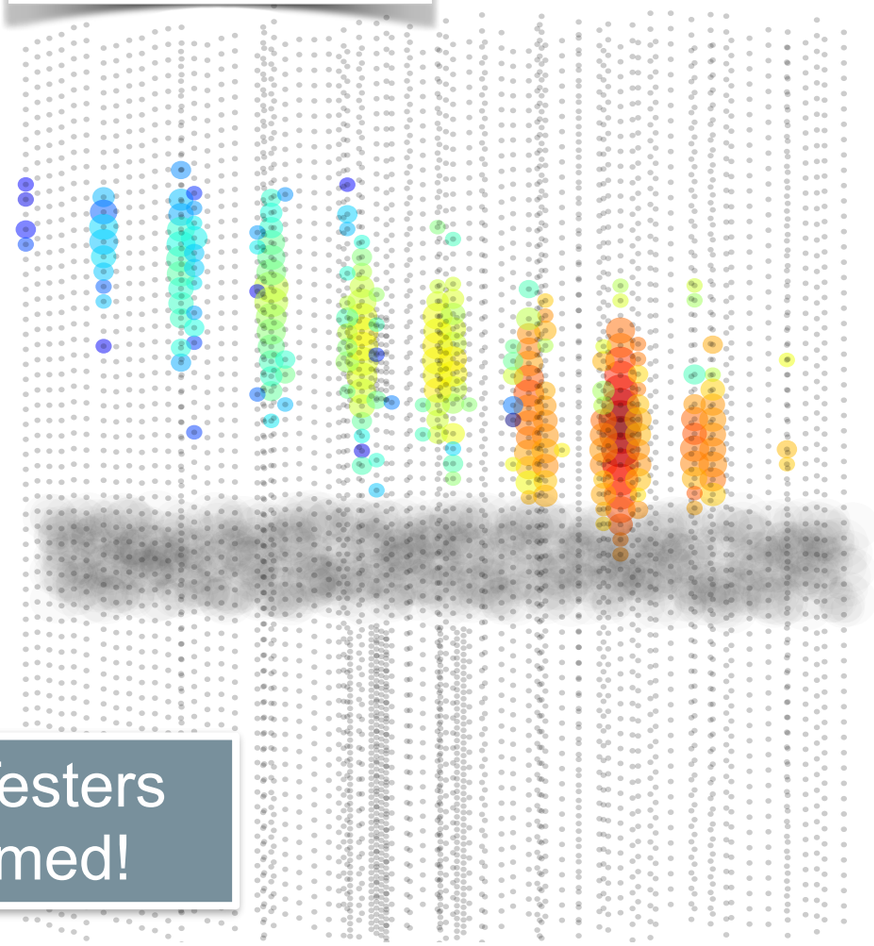


- Initial simulation of ν_τ in Colca valley is complete
- Working on connecting to CORSIKA to simulate air shower
- TauRunner will serve as neutrino injector
- All being written in Julia

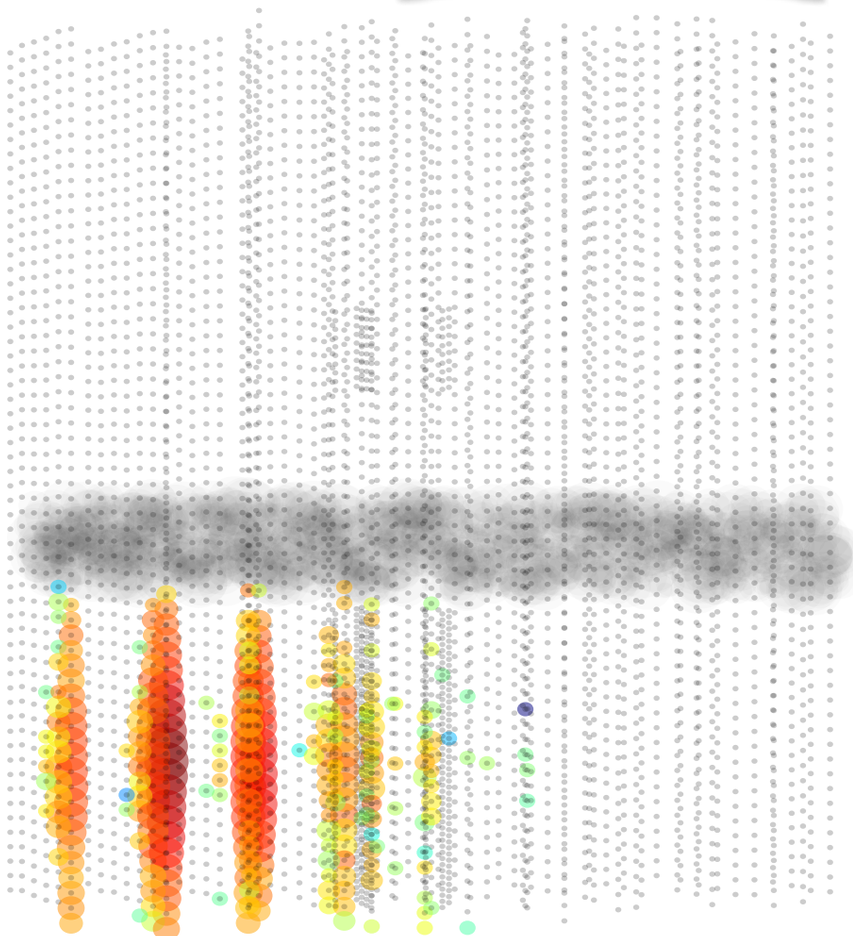
PROMETHEUS: Open-Source Neutrino Telescope Simulation

- 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

100 TeV ν_μ



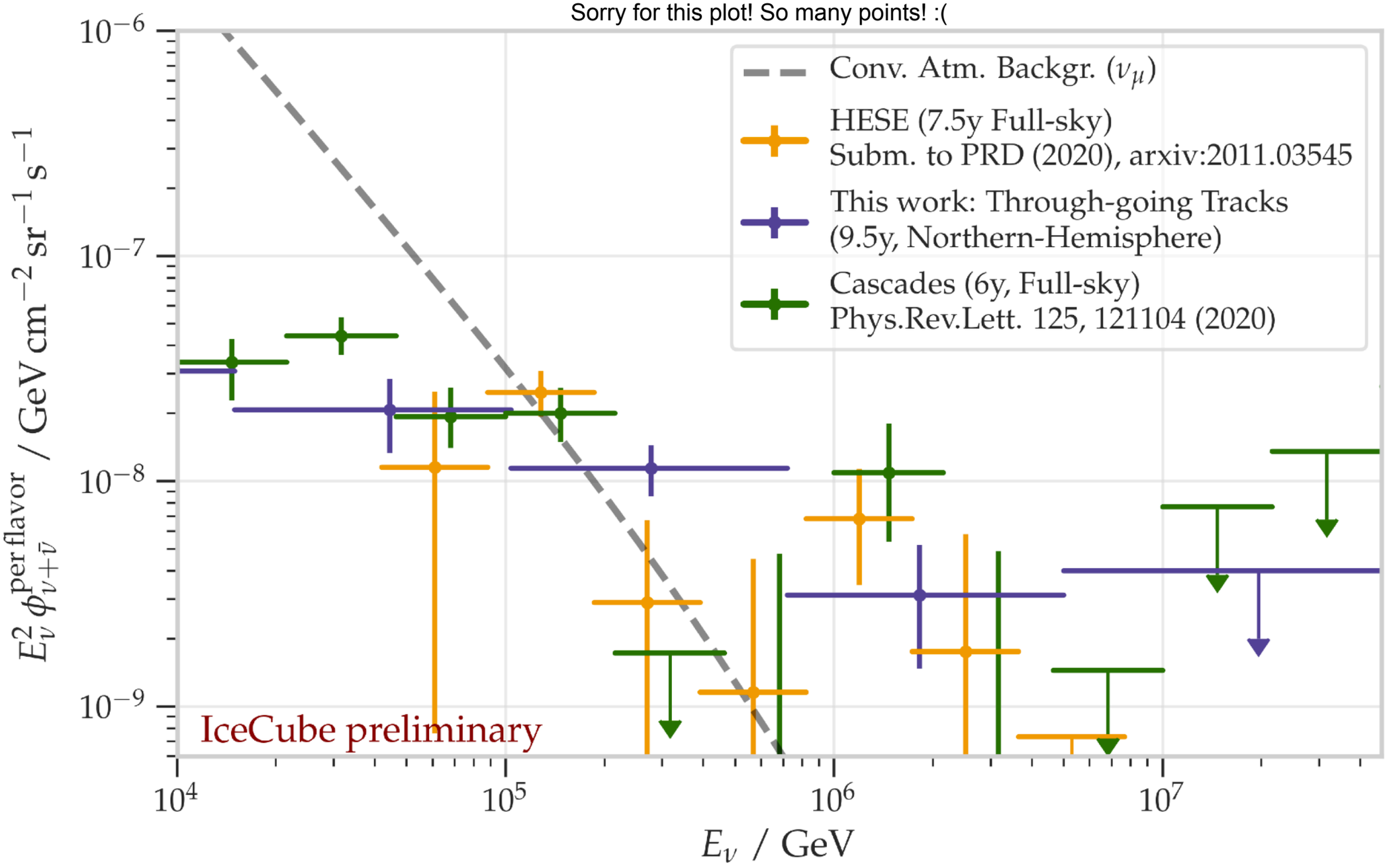
100 TeV ν_e



Beta Testers Welcomed!

Trying to go beyond a Power Law …

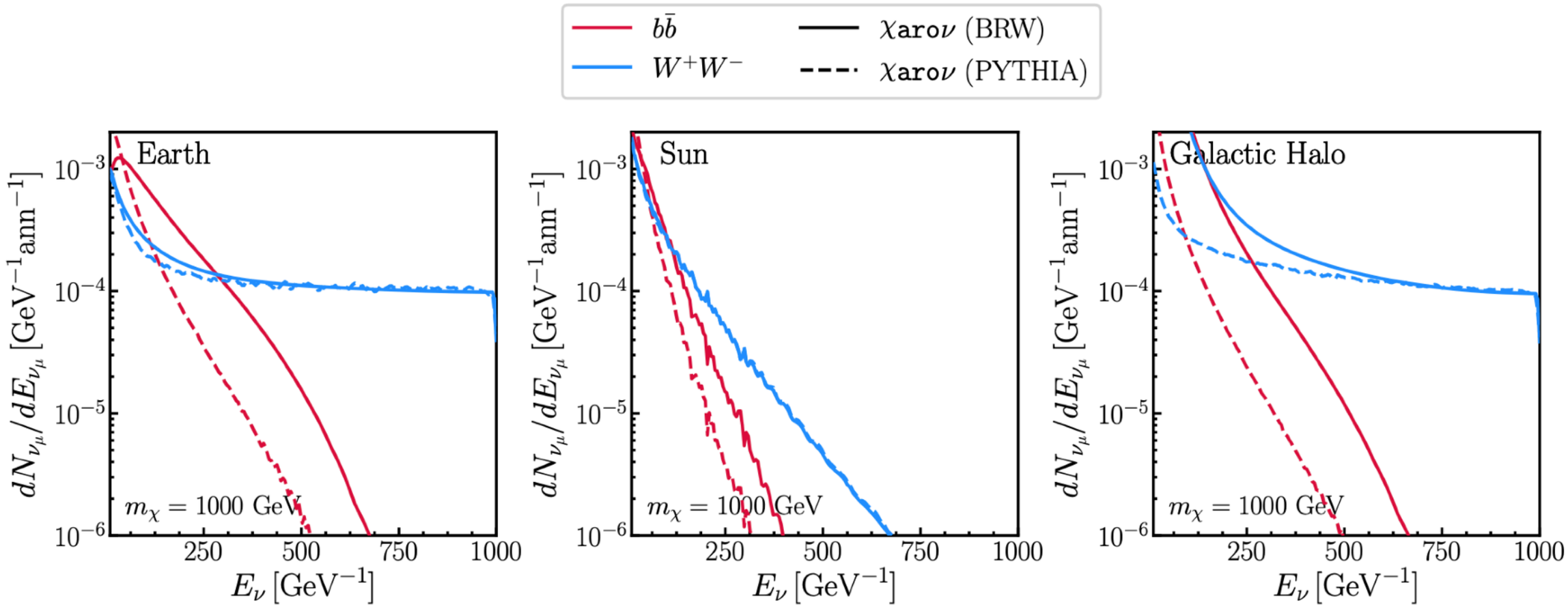
Sorry for this plot! So many points! :(



- 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

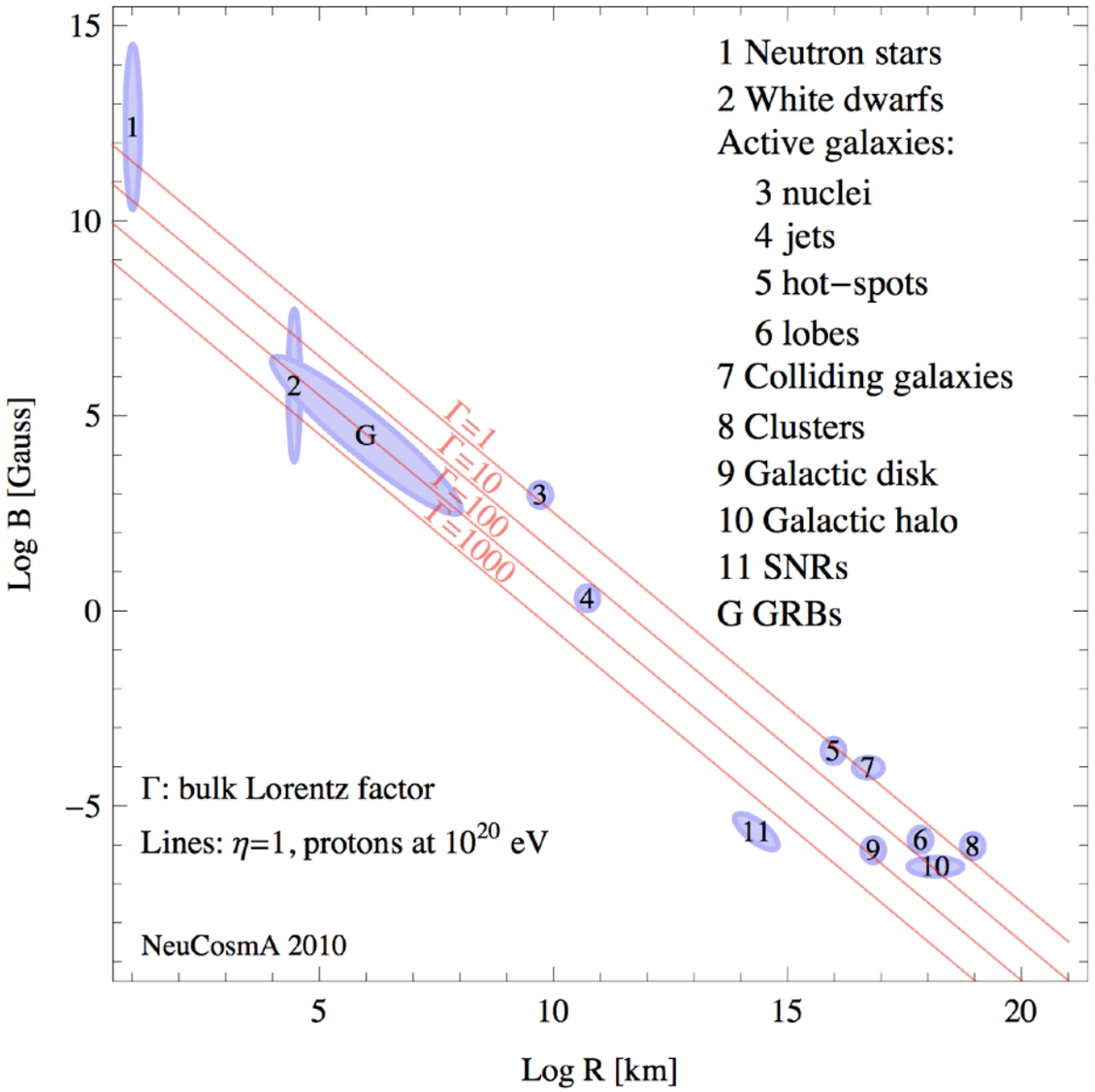


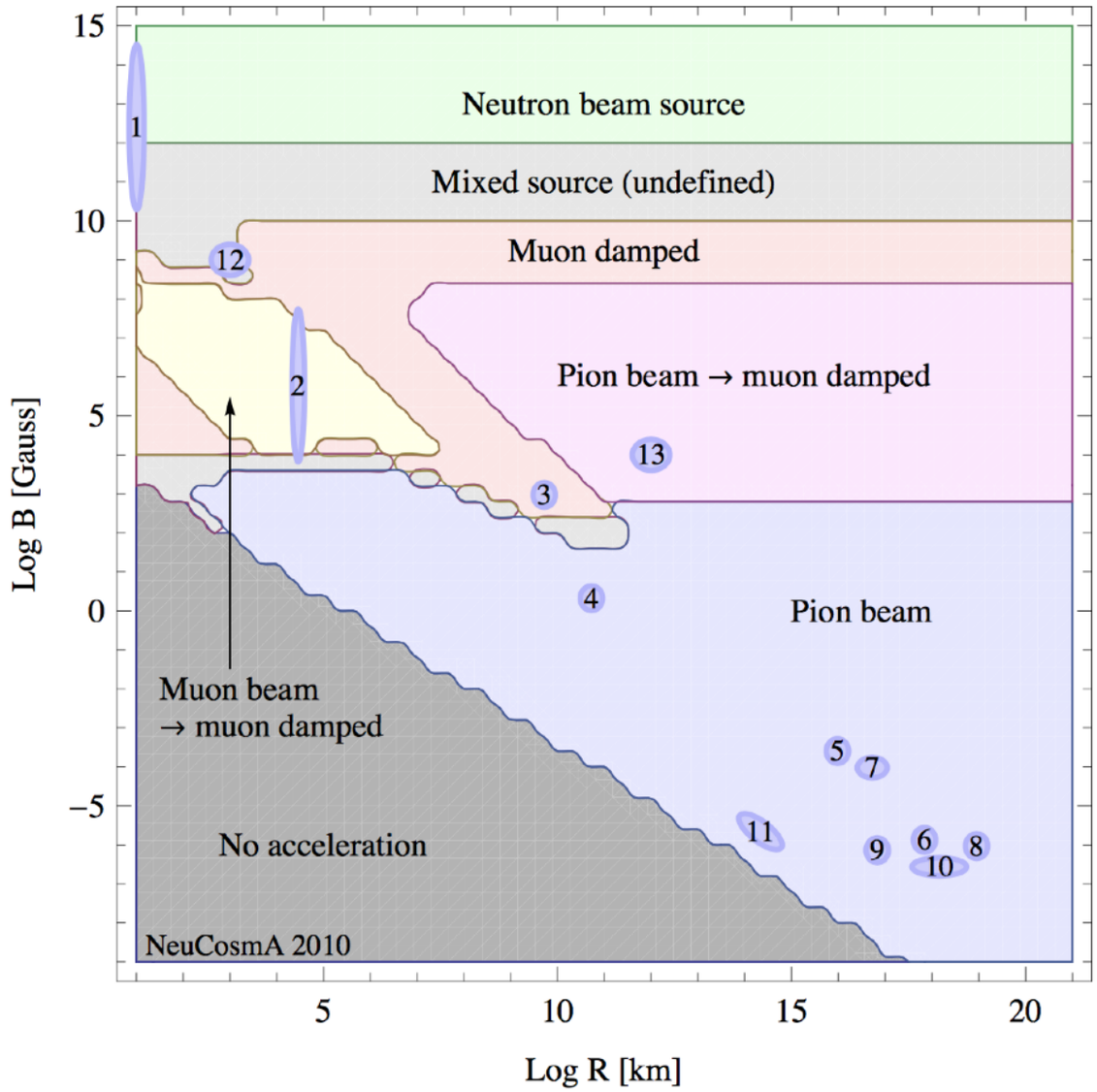
IceCube results with updated calculations to appear soon!

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

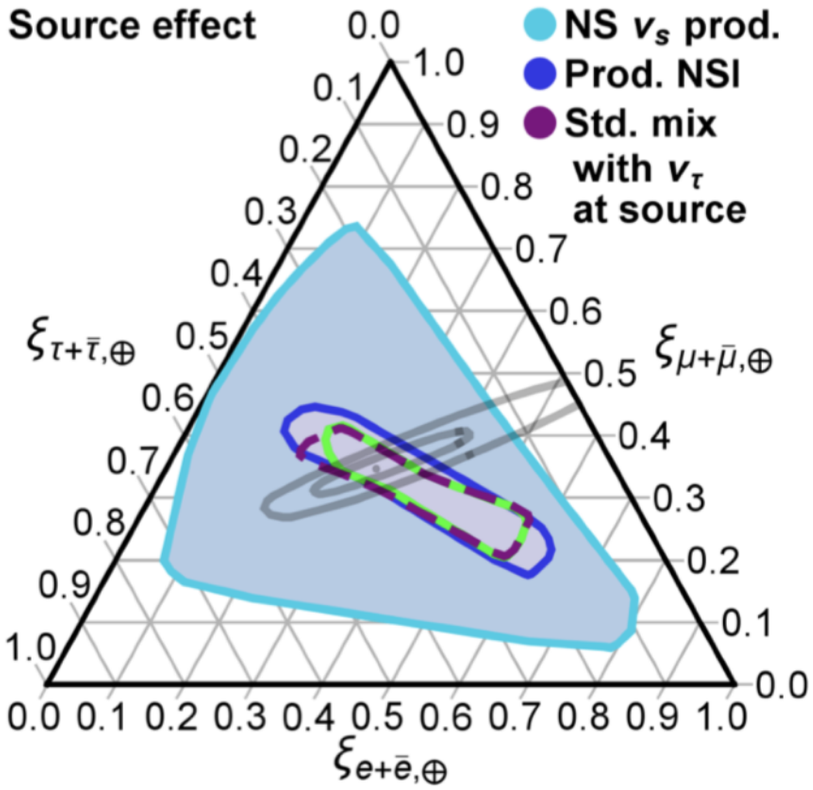
Bauer, Rodd & Webber *et al* 2007.15001

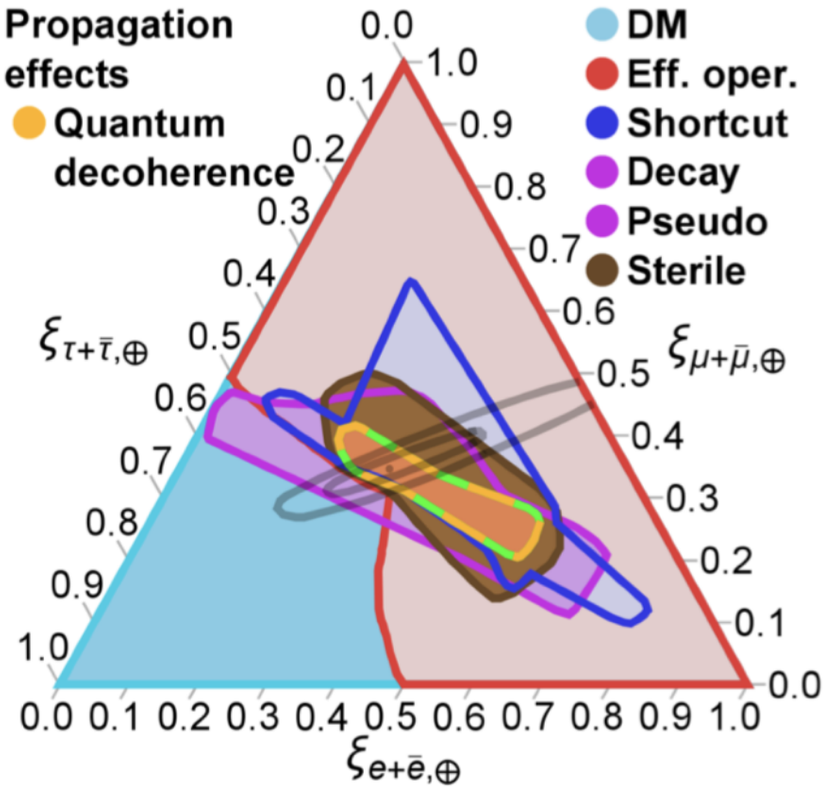
Sources of Astrophysical Neutrinos

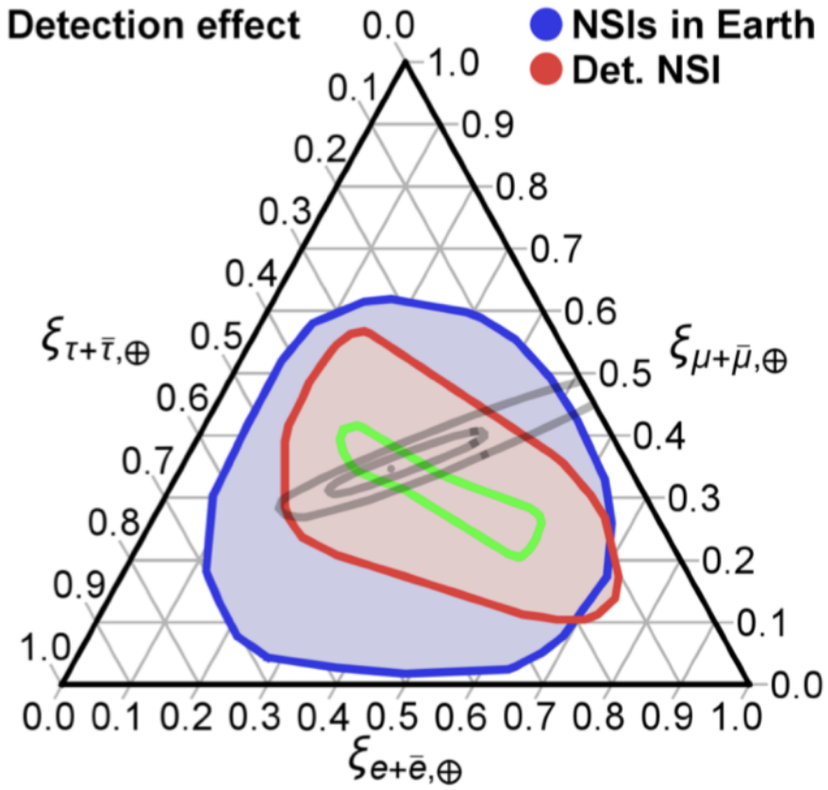




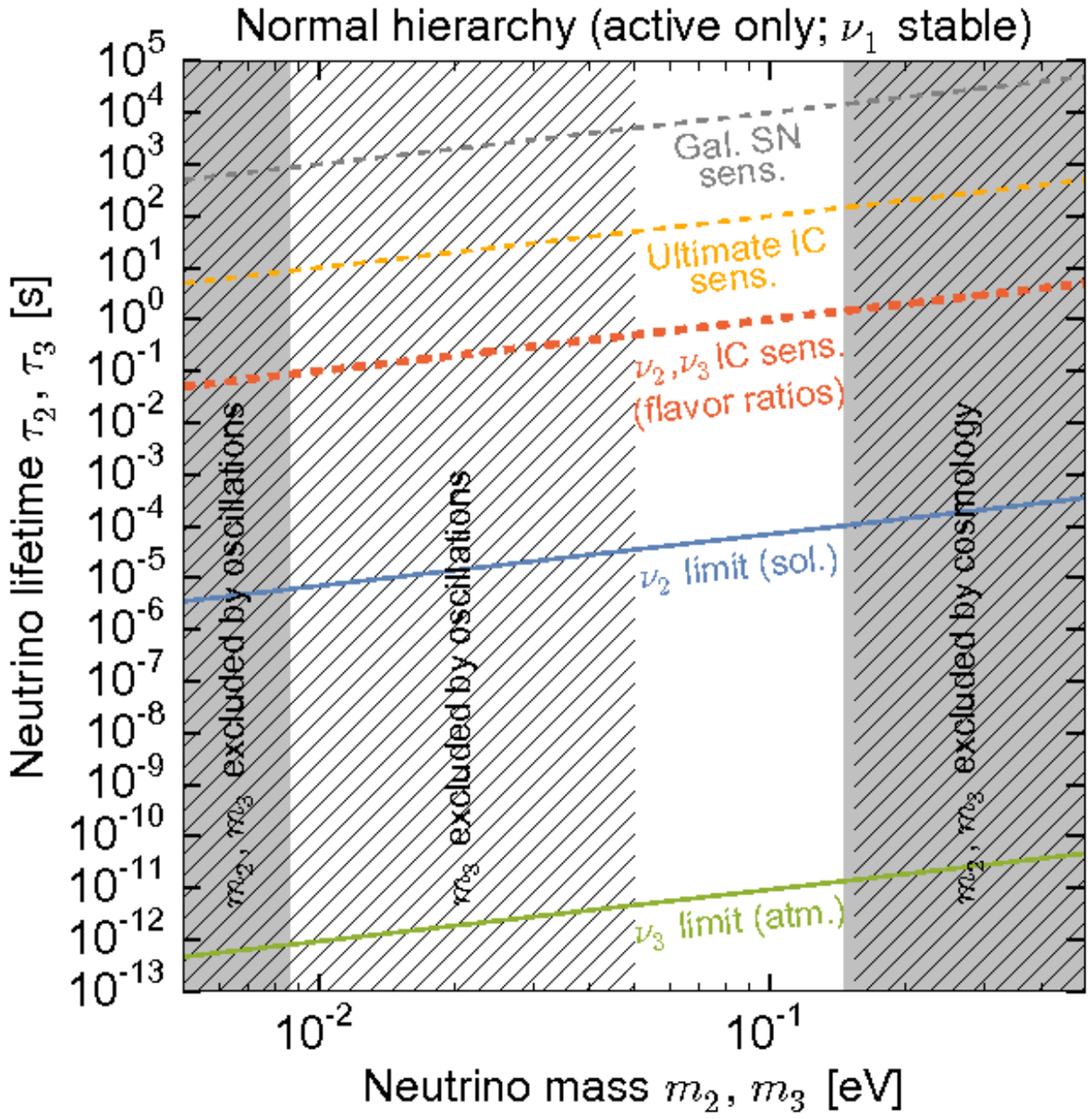
(arXiv:1007:0006)

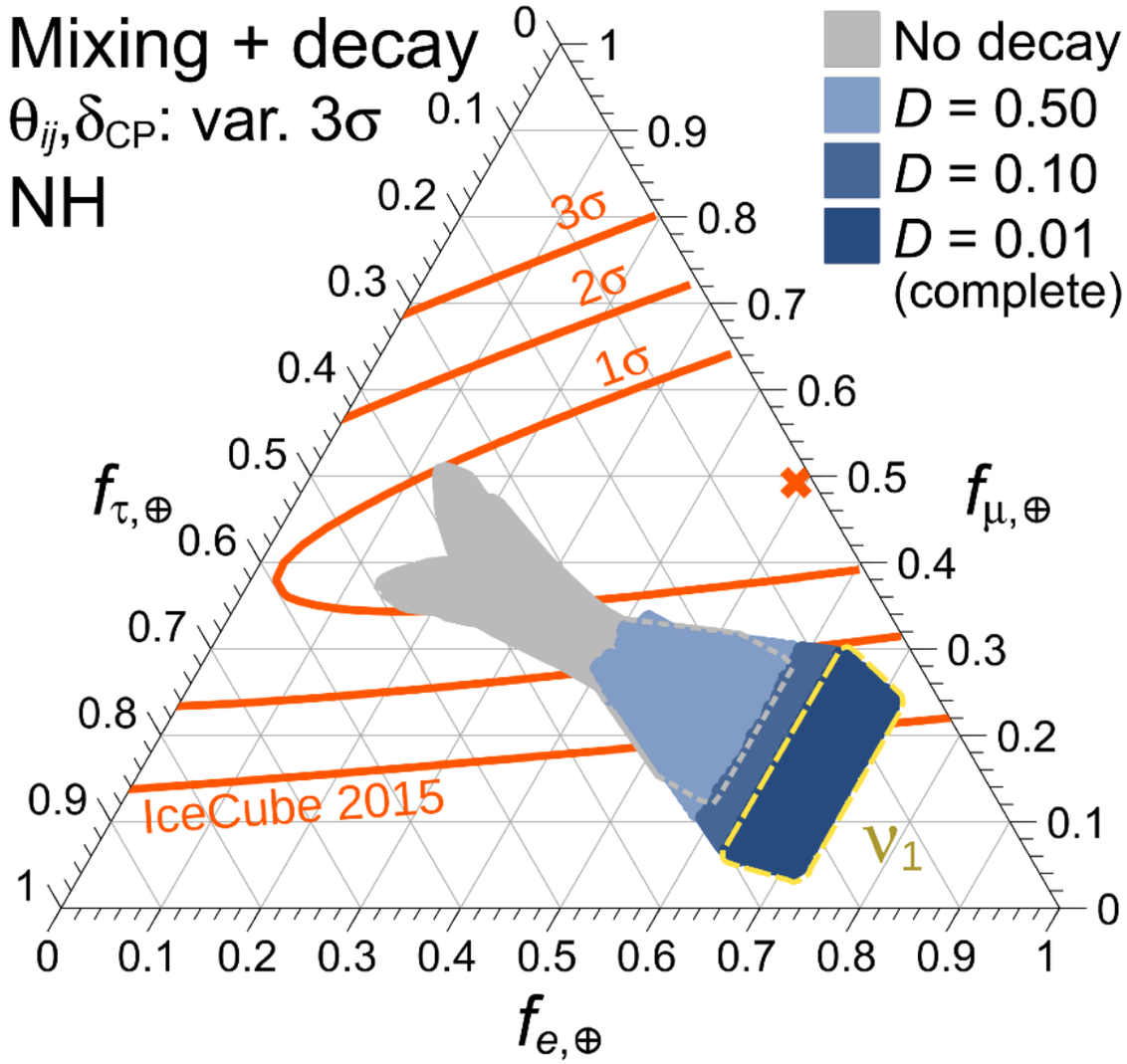




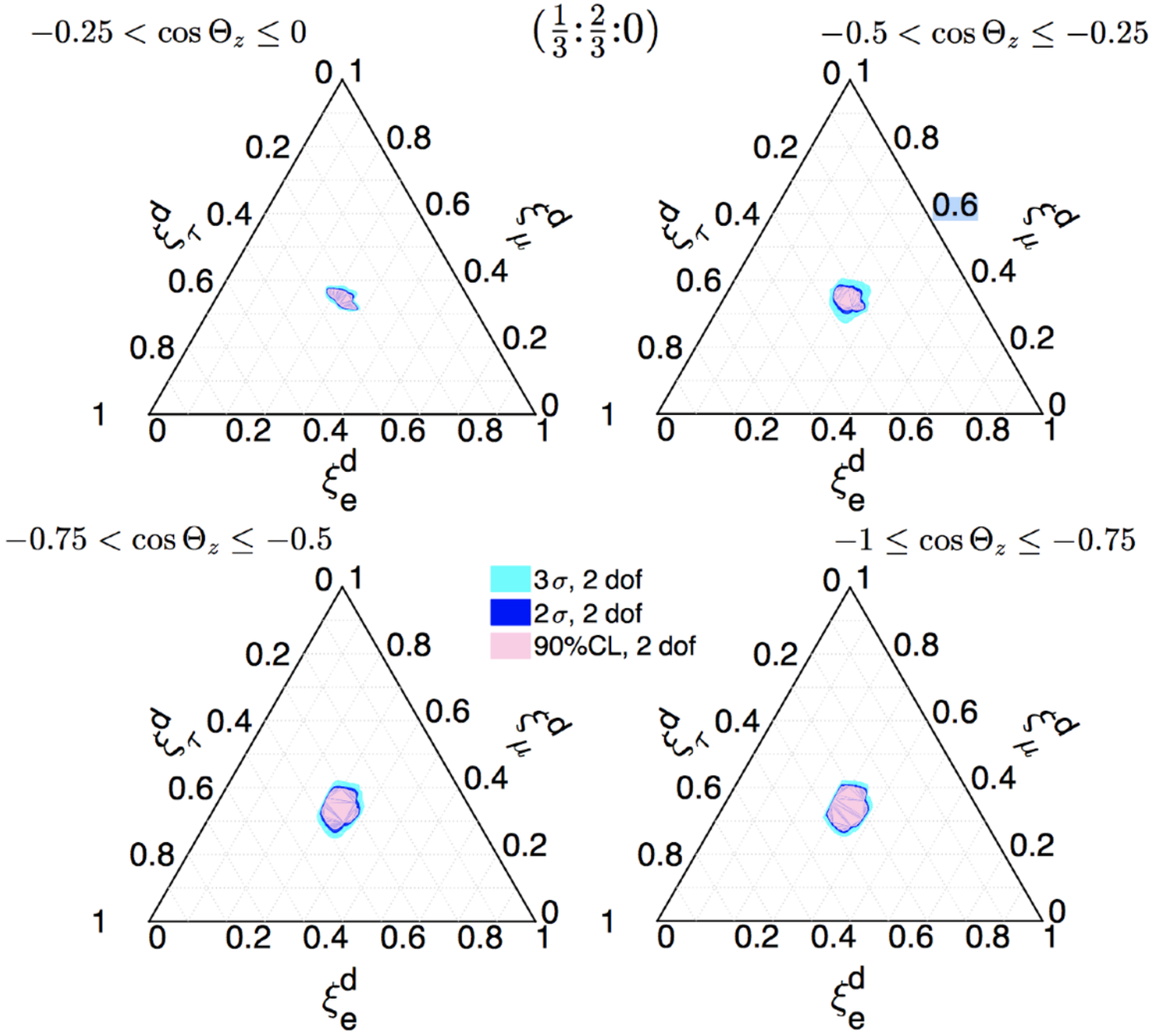


Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684



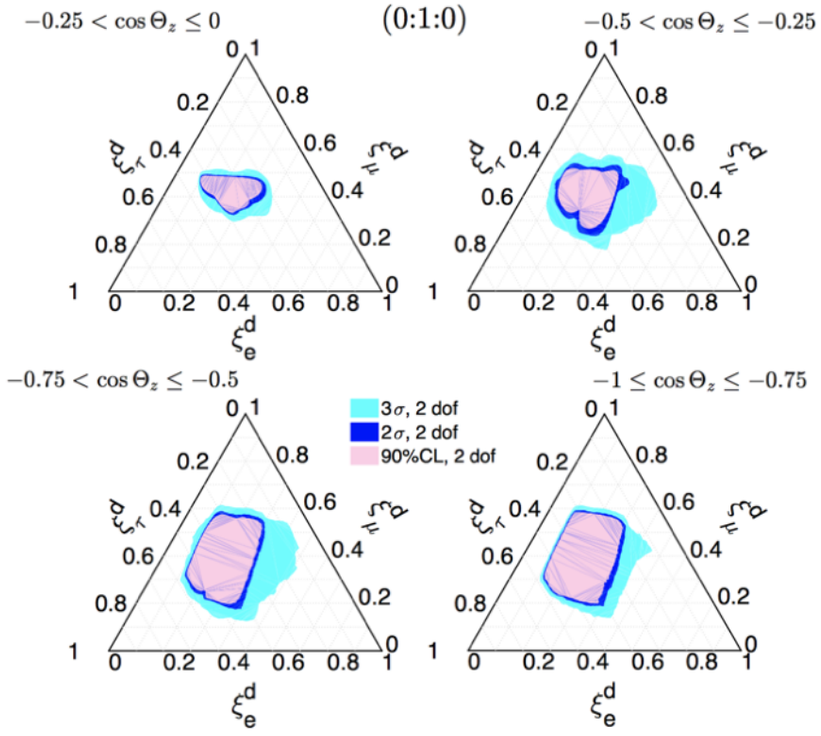


M. Bustamante, J. Beacom, K. Murase (1610.02096)

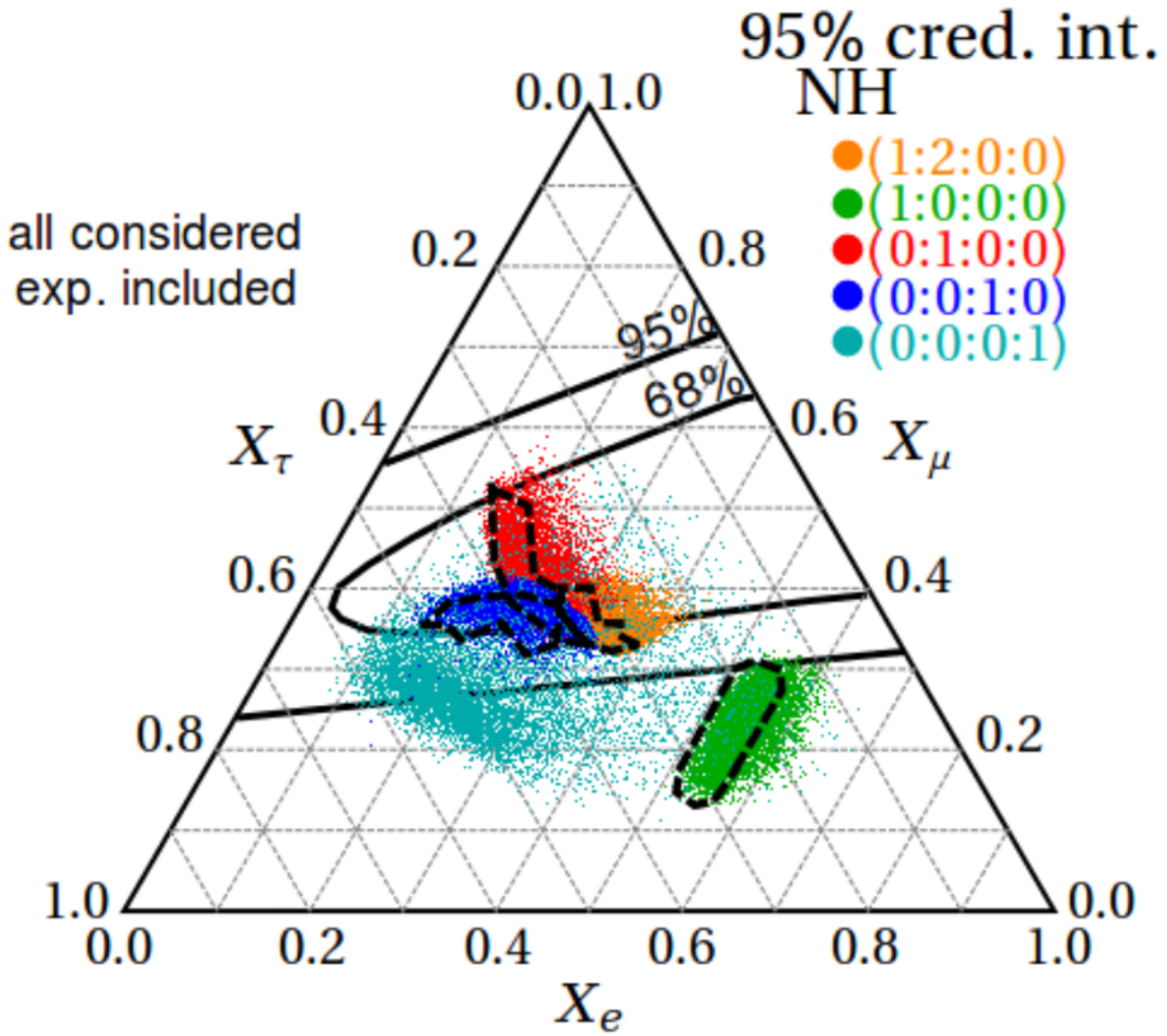


In the pion scenario NSI effects are small.

This is not the case for other initial flavor ratios.



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



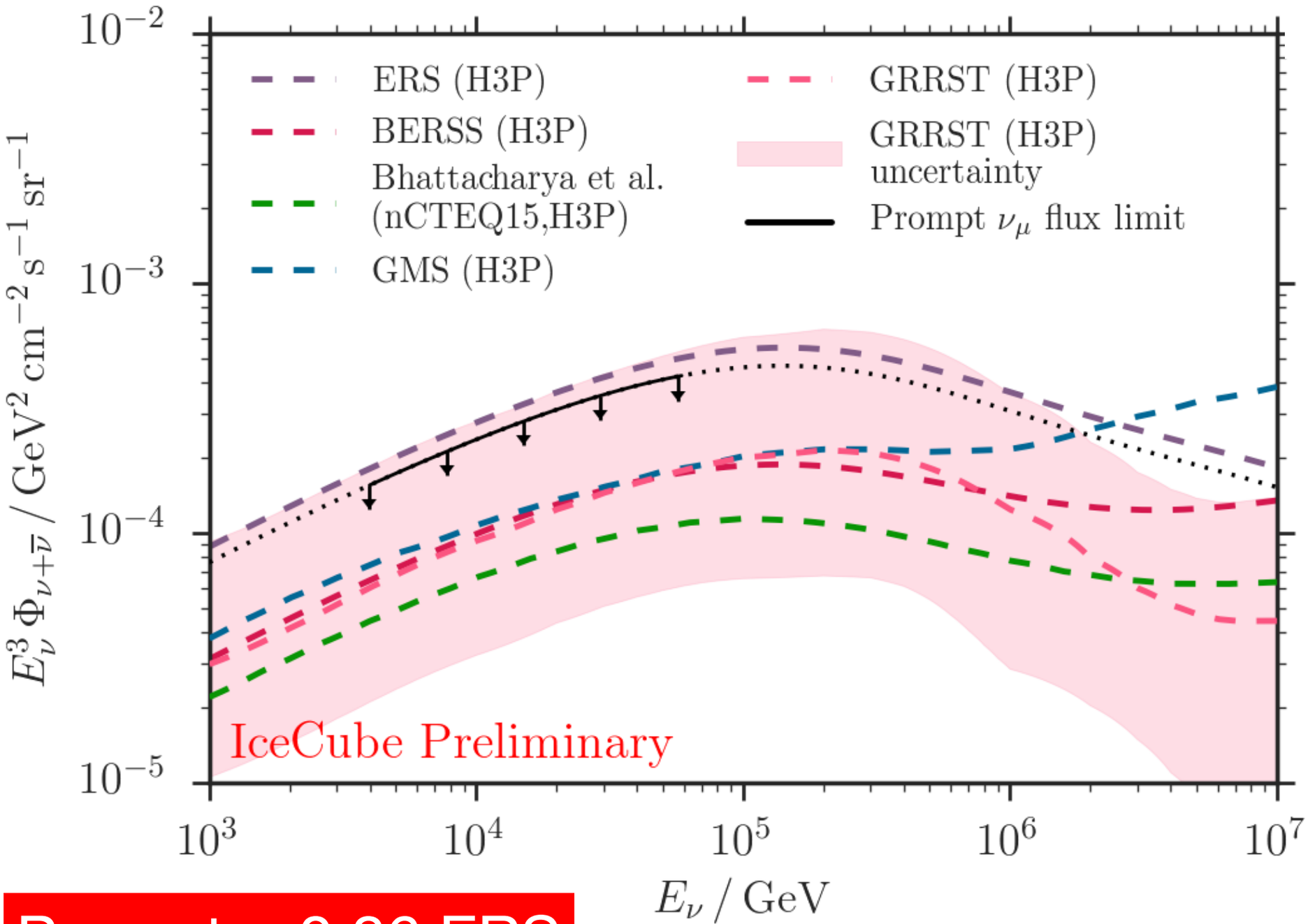
- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

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

Also, constraints from the Northern Sky

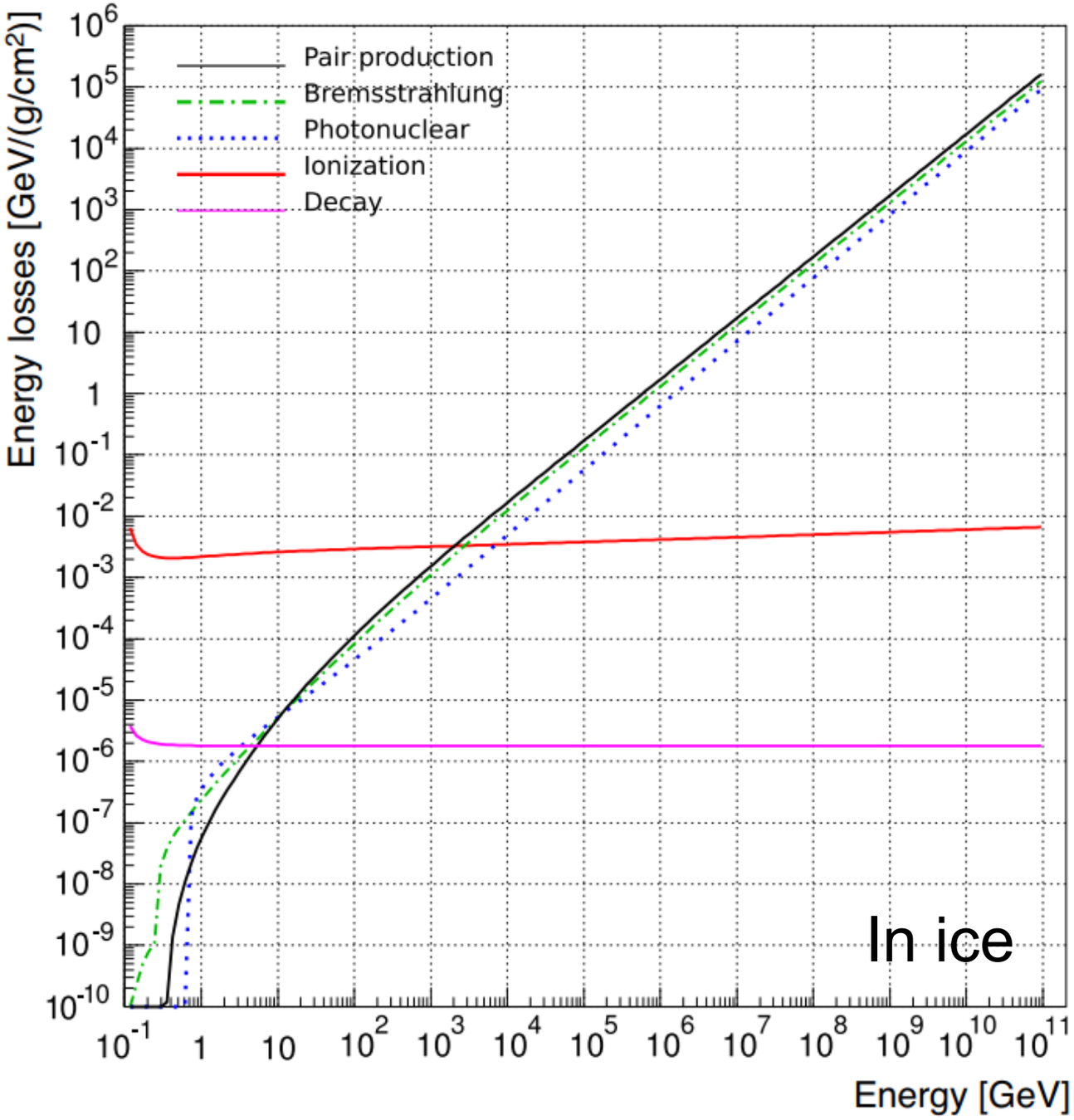
Limits from 8 years of through-going muons

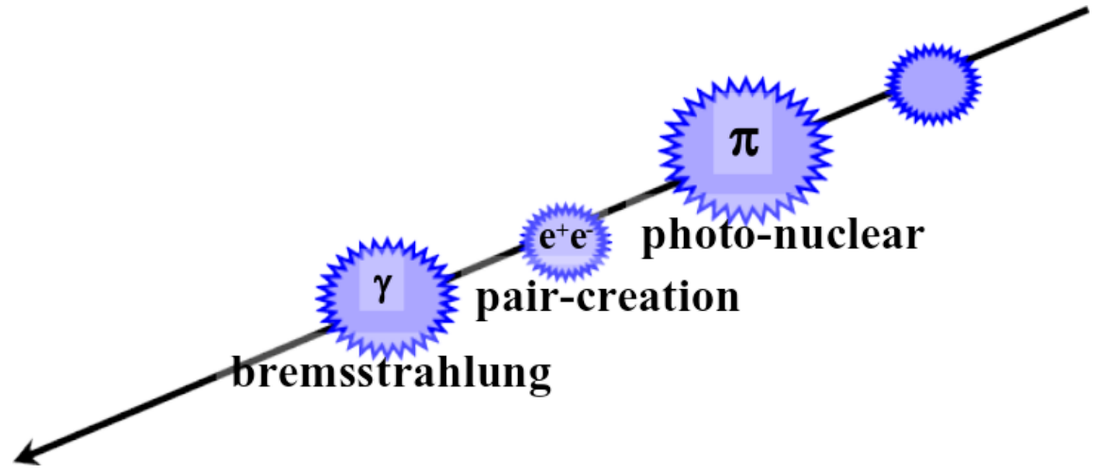
No prompt yet!



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

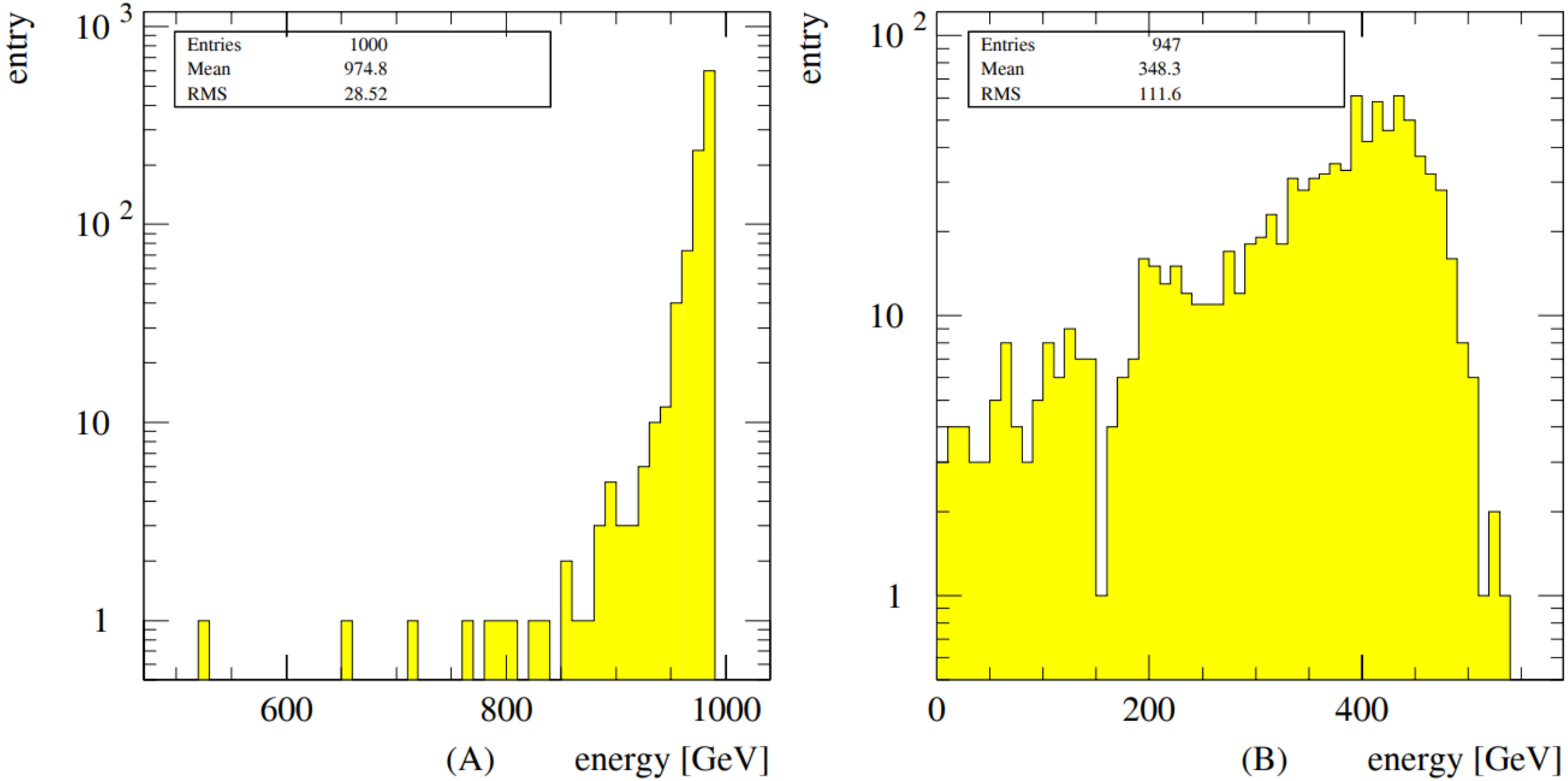


Figure 3.12: Stochastic character of muon energy loss The picture shows distributions of the final energy of 1000 simulated muons (initial energy $1TeV$) after passing (A) $50m$ and (B) $1500m$ of fresh water, simulated with GEANT (section 6.2)

From C. Wiebusch (1995)