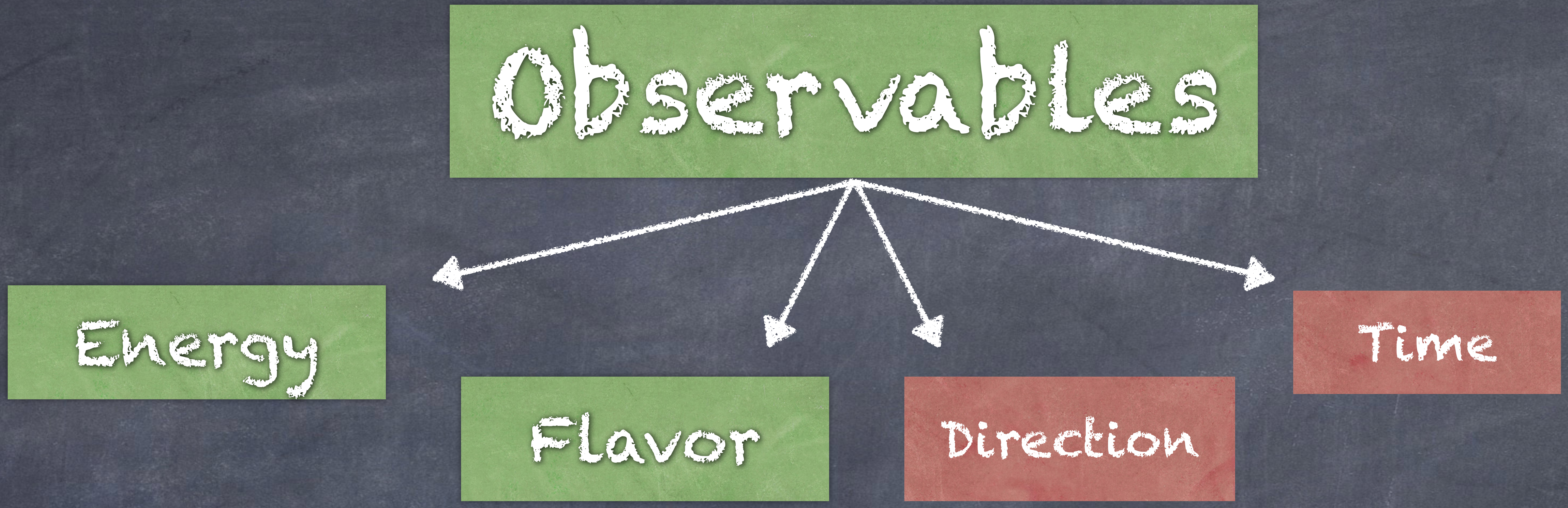
High Energy neutrinos: Backgrounds and measurements

Ibrahim Safa

Interdisciplinary developments in neutrino physics

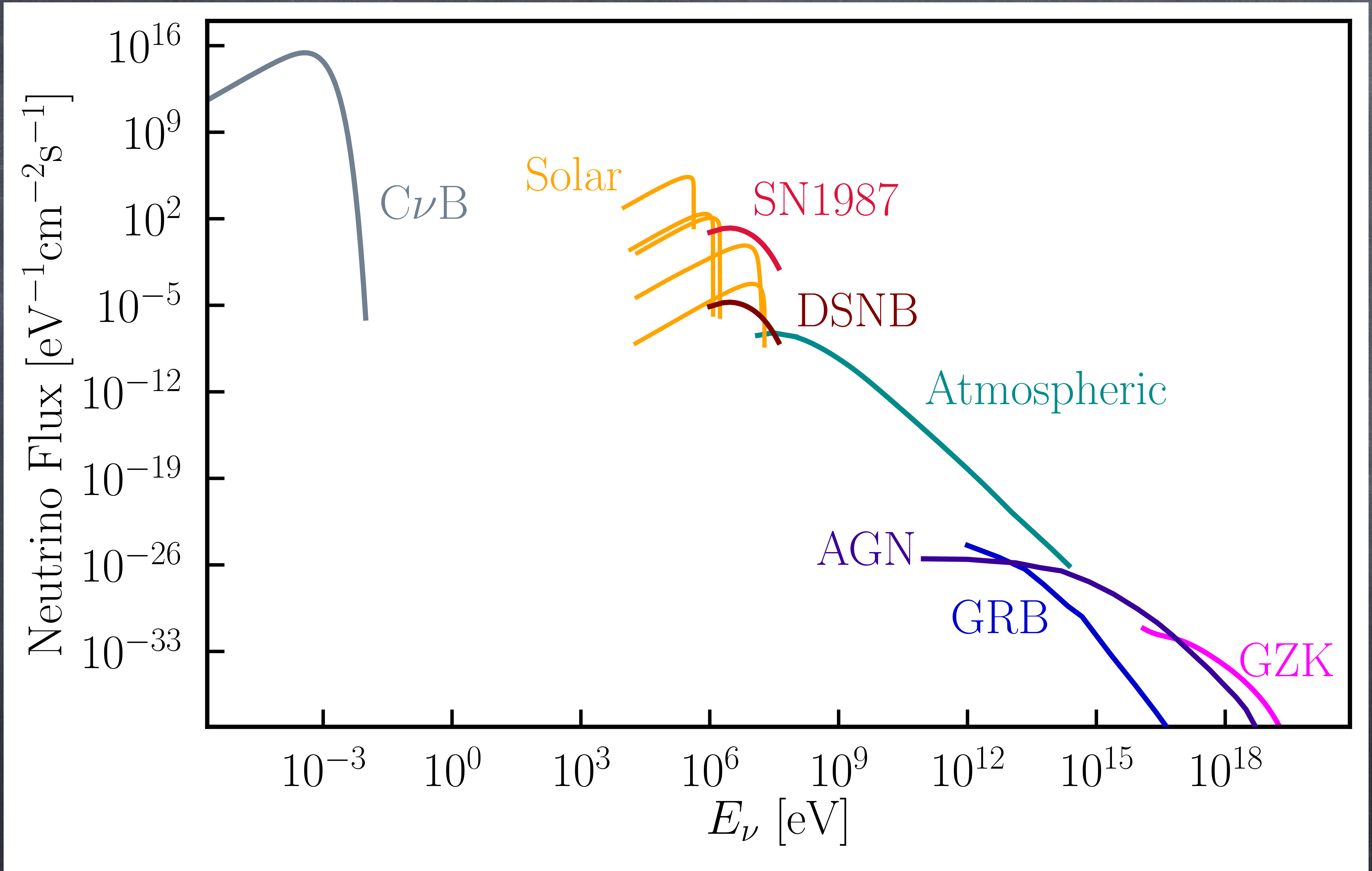
KITP March 31 2022

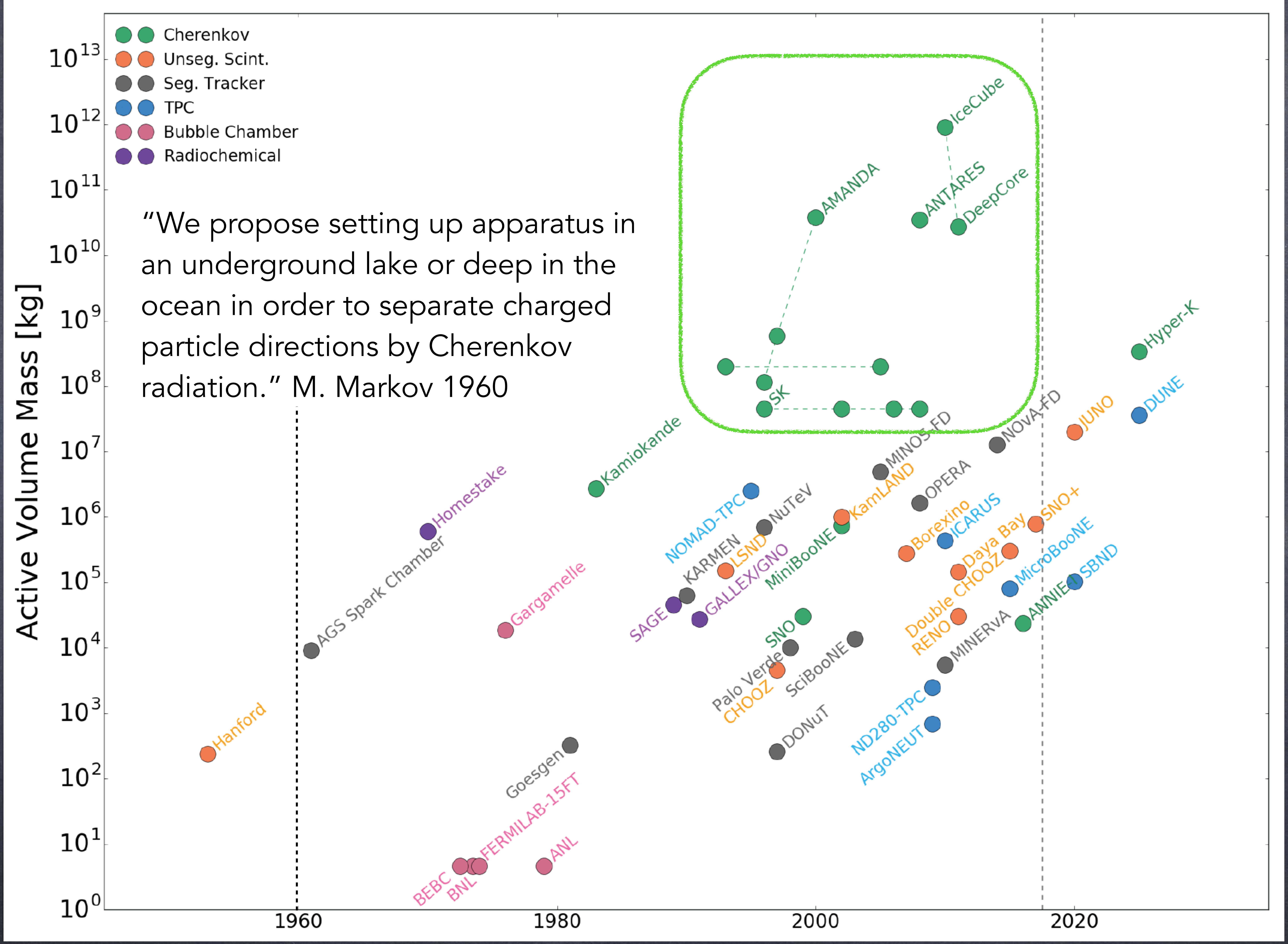


This talk:

- Astrophysical neutrino measurements
- Neutrino Flavor as a unique probe at extreme scales
- Role of tau neutrinos
- Atmospheric neutrinos
- Future Prospects

Neutrinos in nature

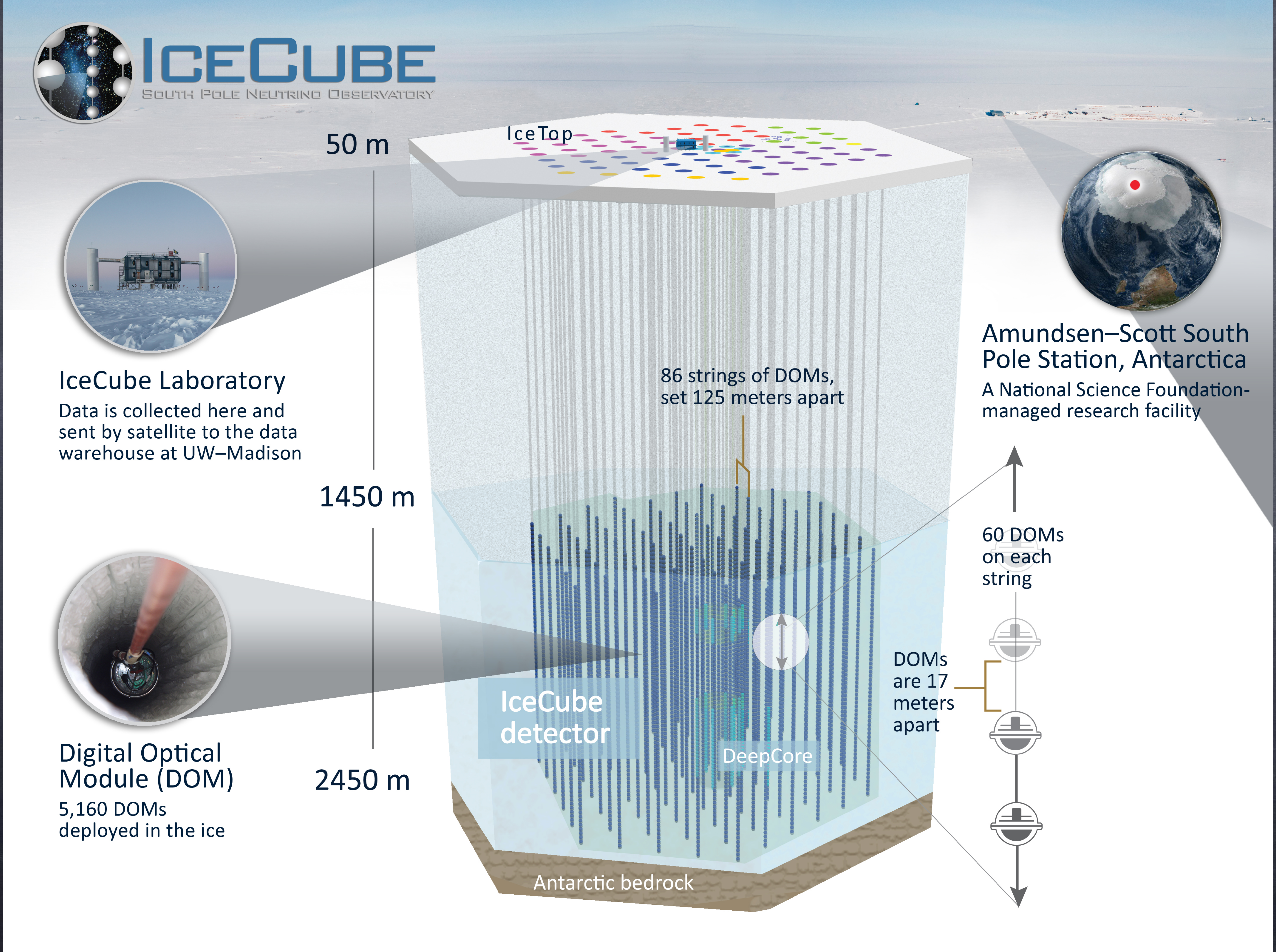




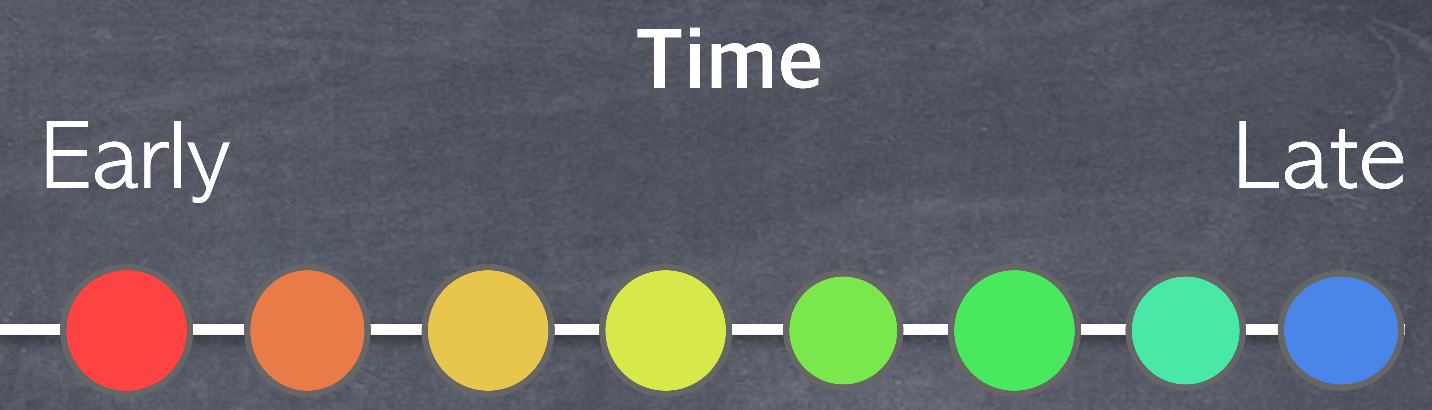
"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation." M. Markov 1960

Credit: C. Argüelles

The IceCube Experiment

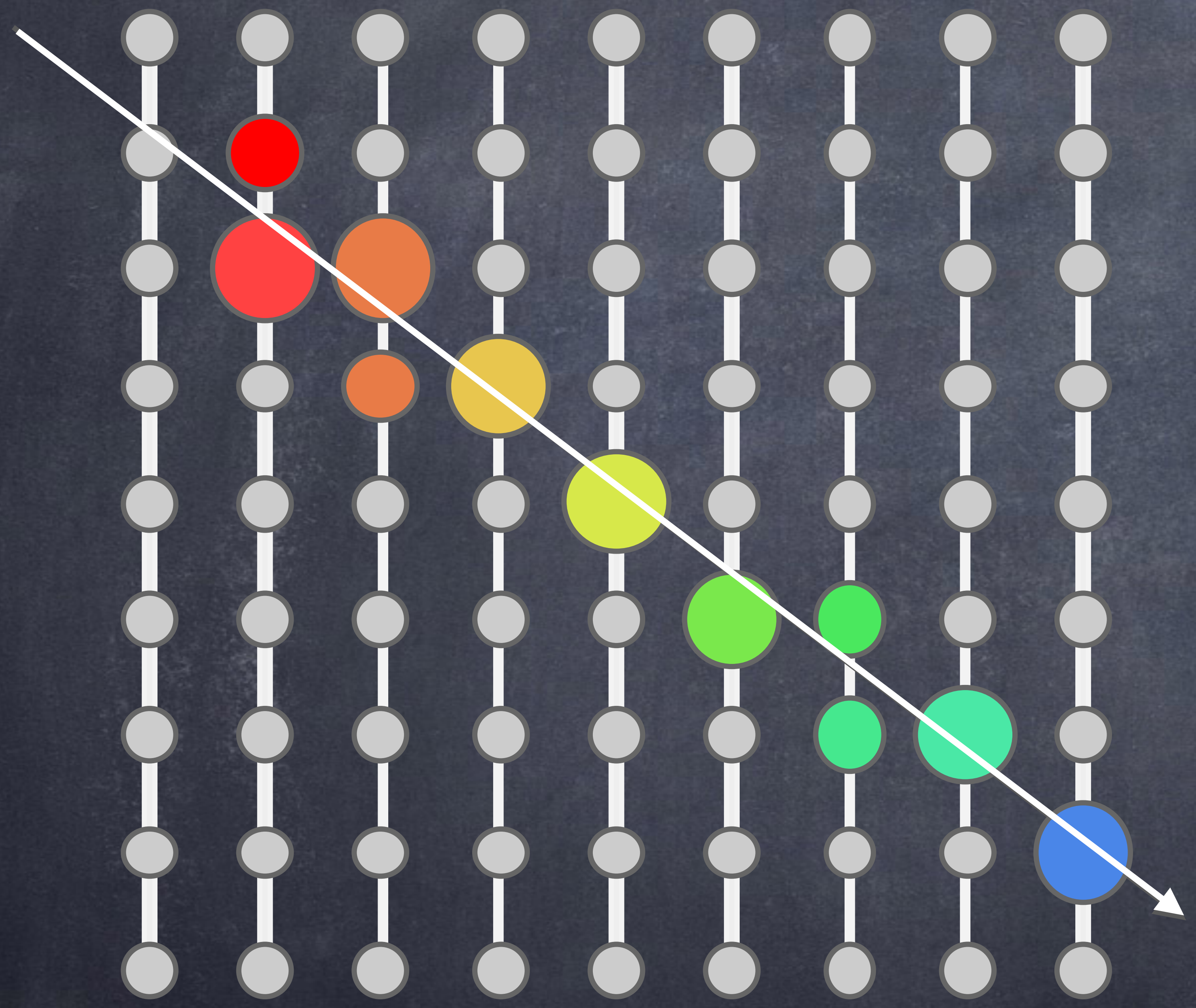

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station,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

Event Topologies



Track

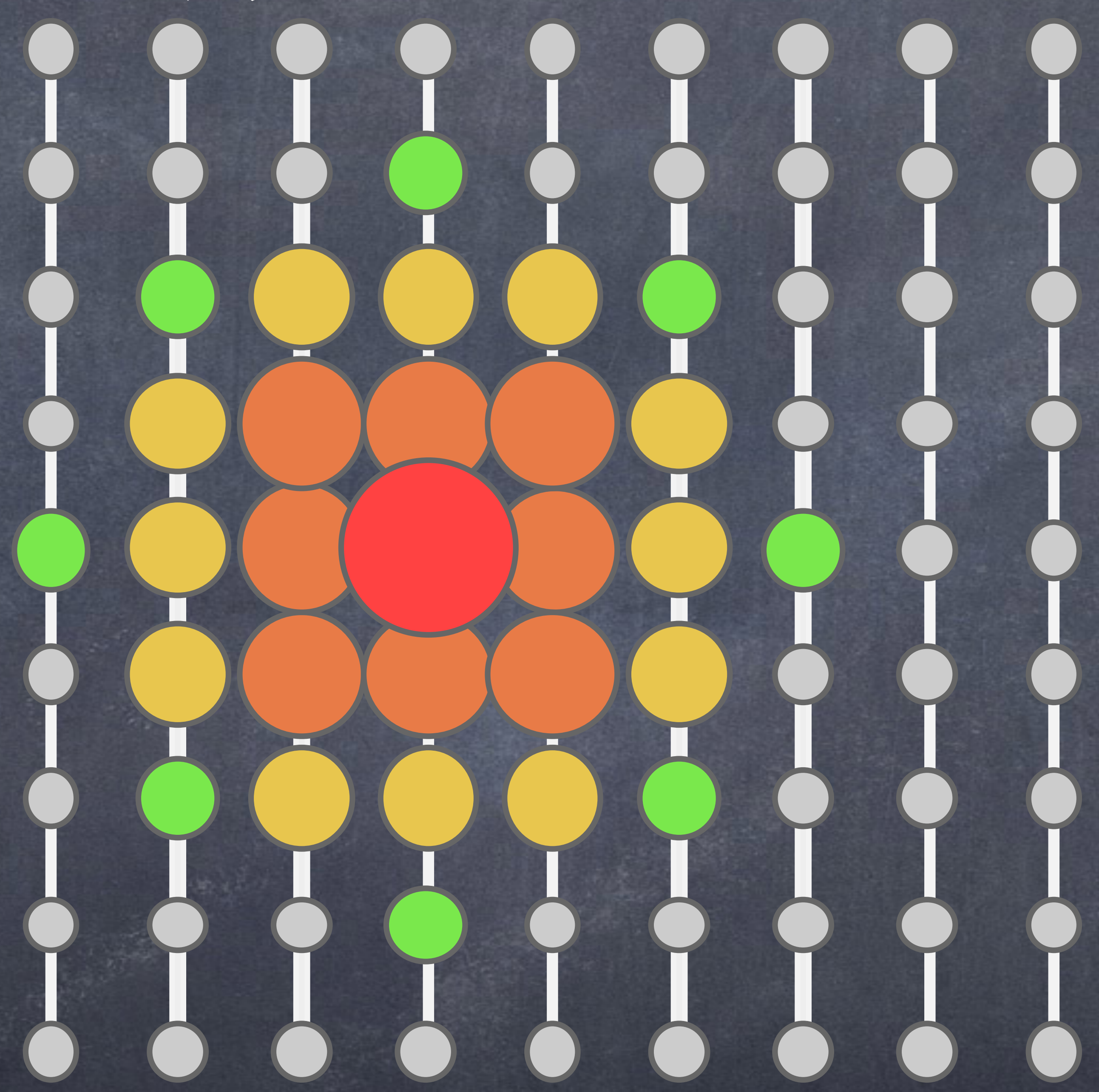
Muon Neutrino CC



Factor of ~2 energy resolution
0.3° angular resolution at
100TeV

Cascade

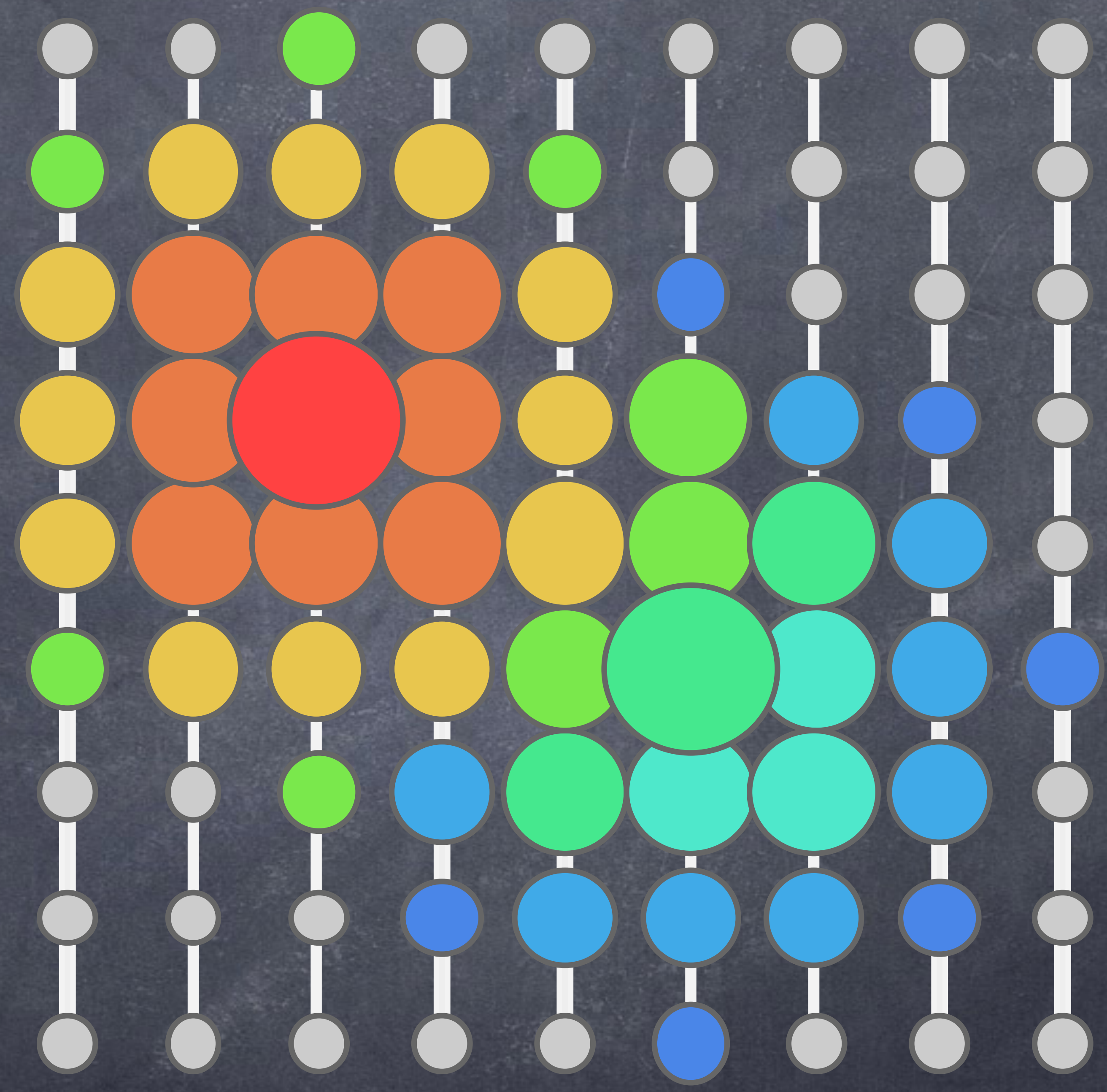
Electron/Tau Neutrino CC
All NC

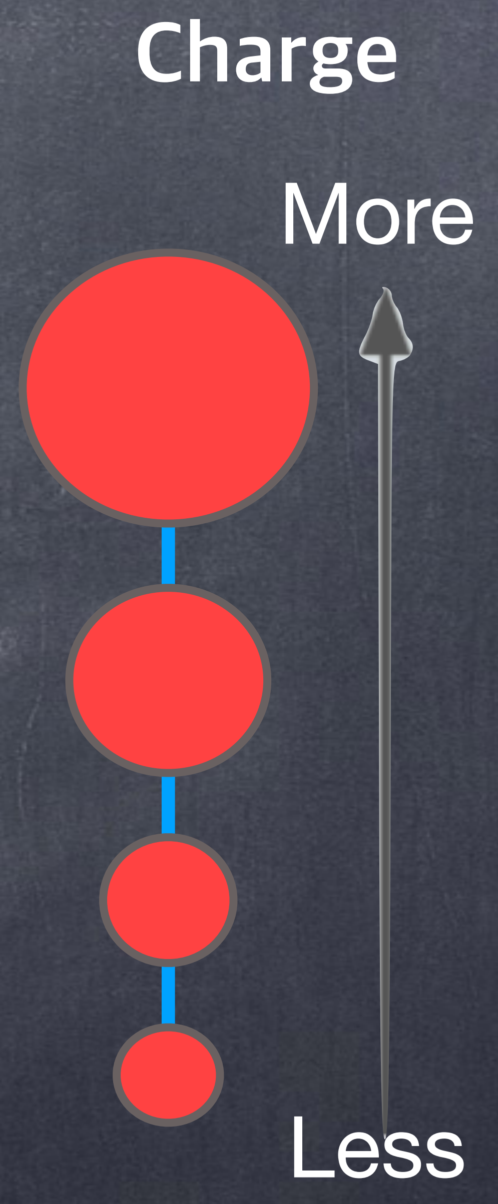


15% deposited energy resolution
8° angular resolution above
100TeV

Double Cascade

High Energy Tau Neutrino CC



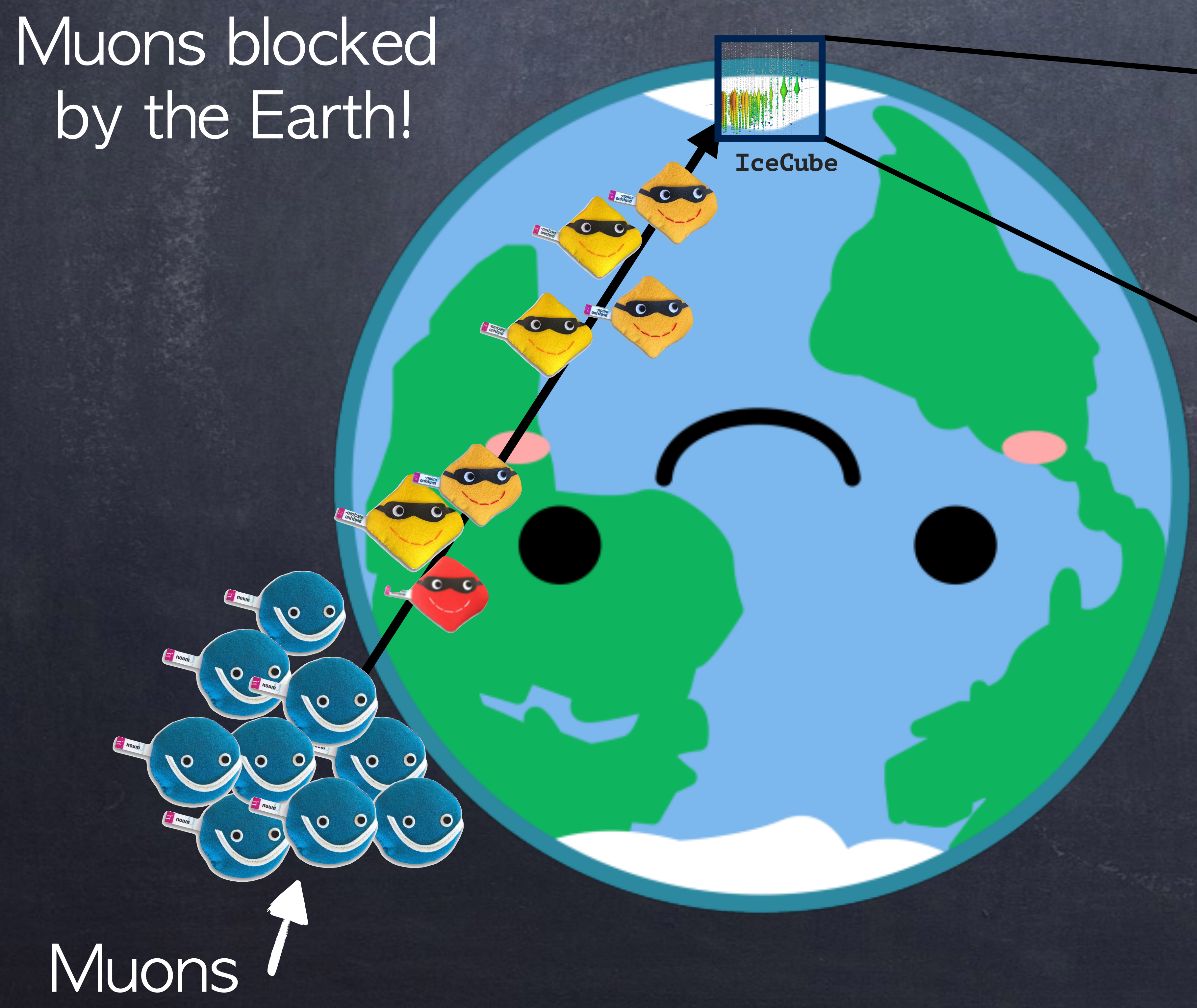


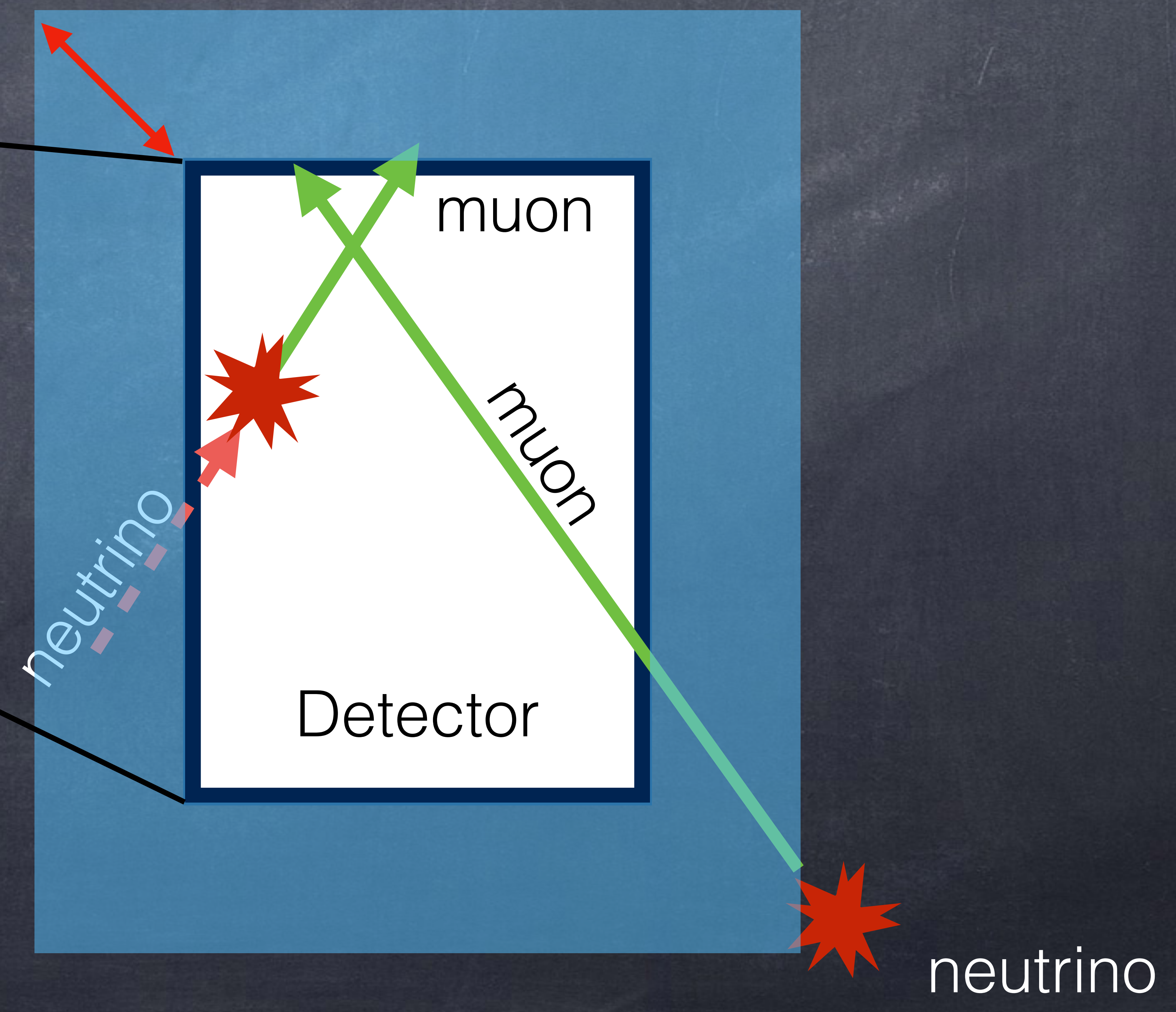
Angular/Energy resolution
comparable to cascades
First candidates observed!

Astrophysical Neutrinos

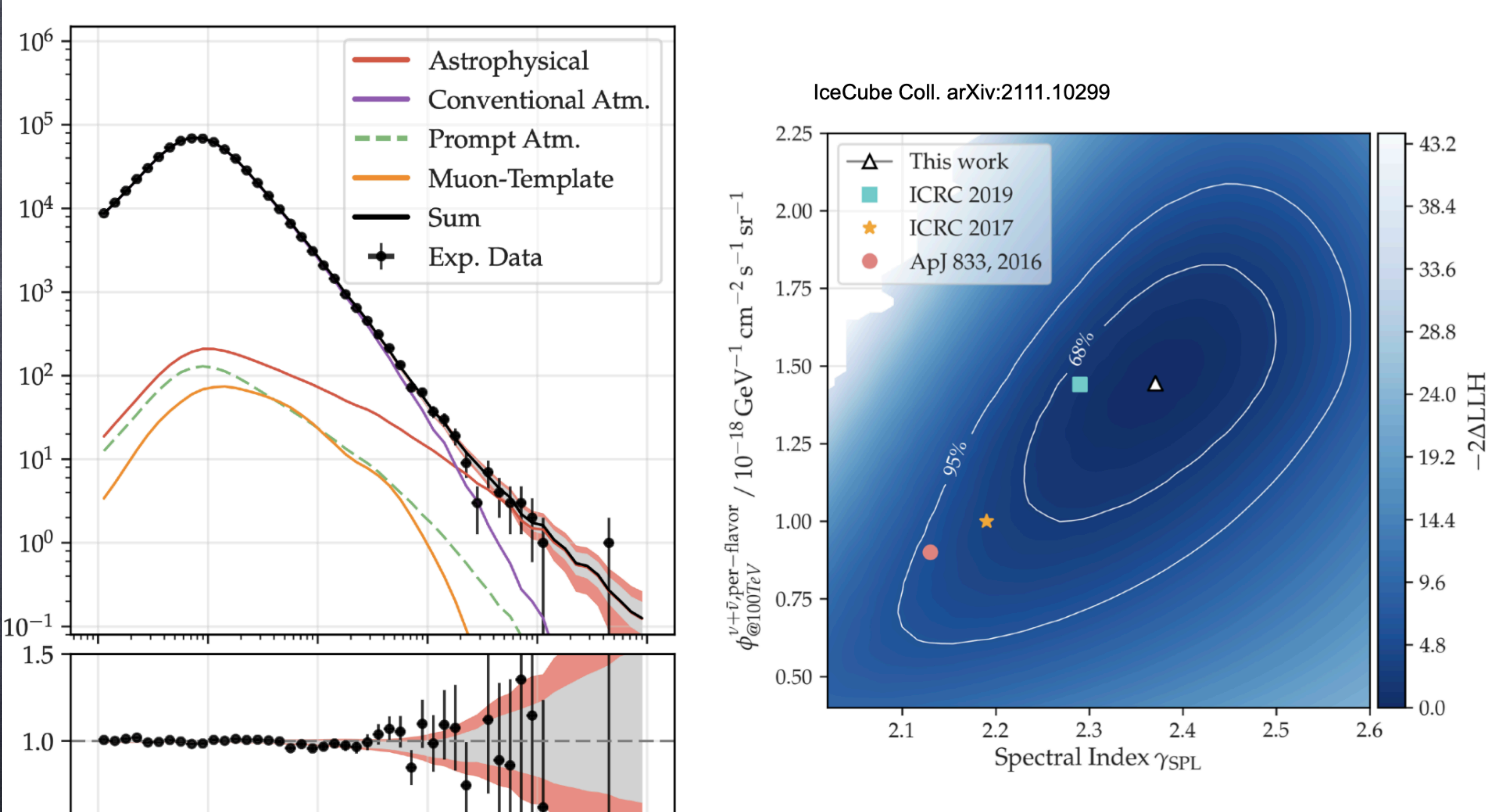
Upgoing muon neutrinos

- Earth is a perfect muon blocker.
- Upgoing muon tracks most likely caused by CC-ν_μ interaction in or around the ice.
- Muons above 1 TeV travel several kilometers in ice.
- Effective volume is increased by the muon range.



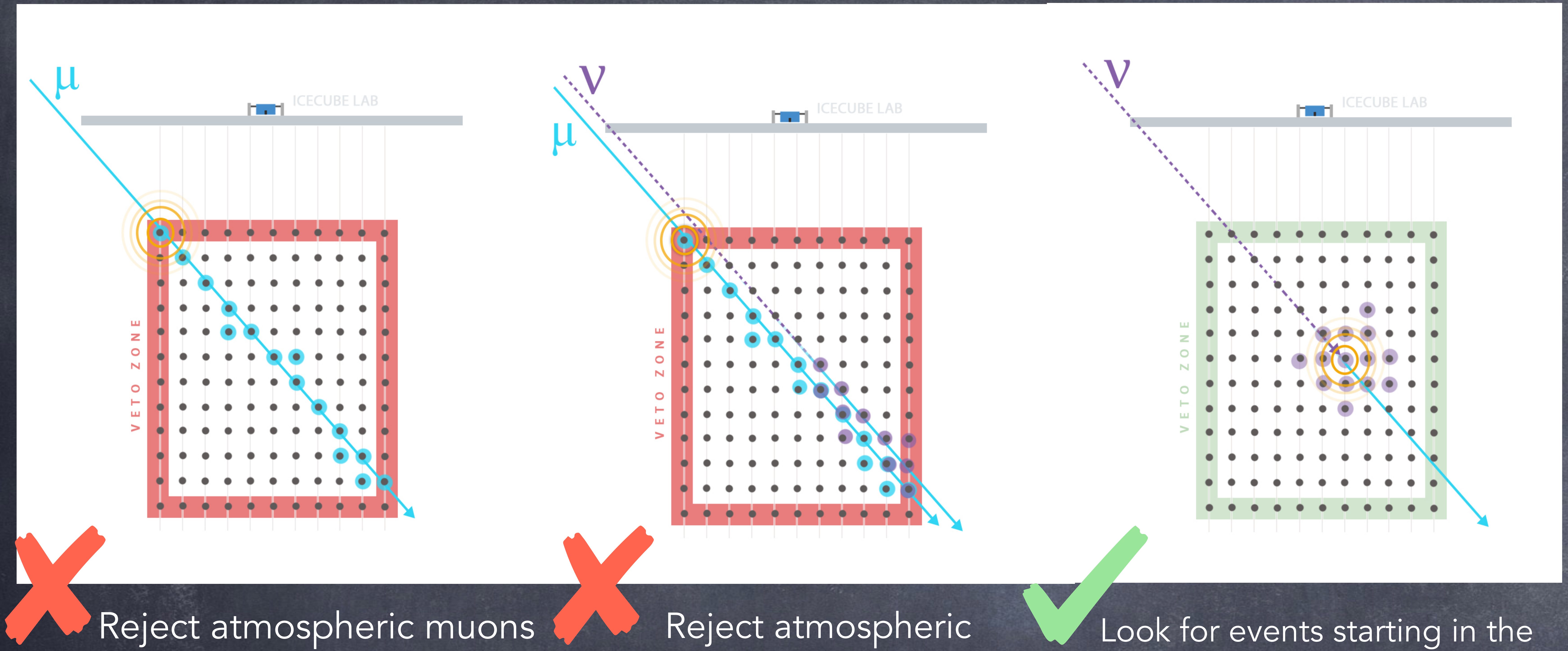


Upgoing muon neutrinos



$$\gamma = 2.37 \pm 0.1$$

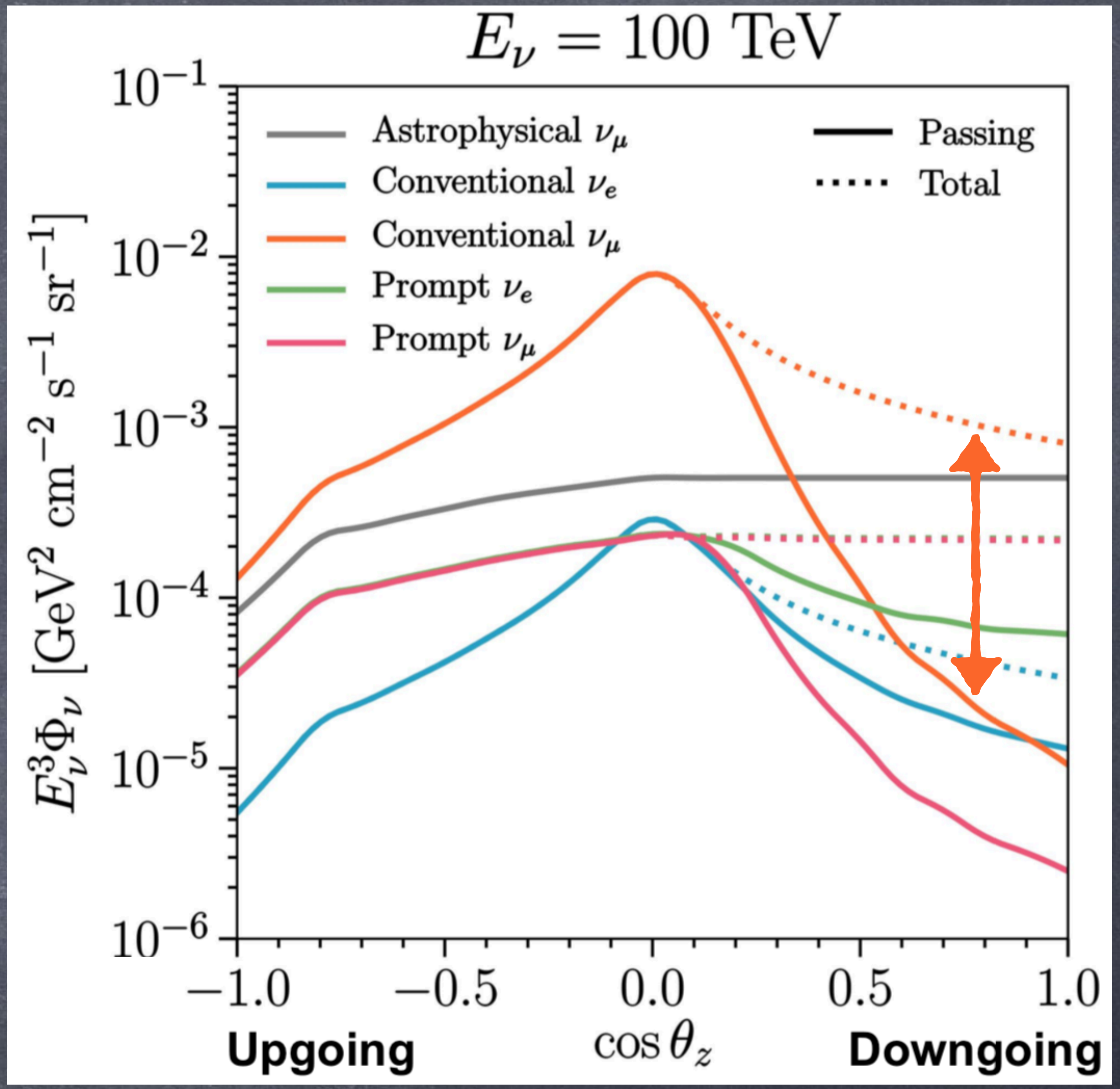
High Energy Starting Events (HESE)



Reject atmospheric muons

Reject atmospheric neutrinos via accompanying muons

Look for events starting in the fiducial volume with no accompanying muon



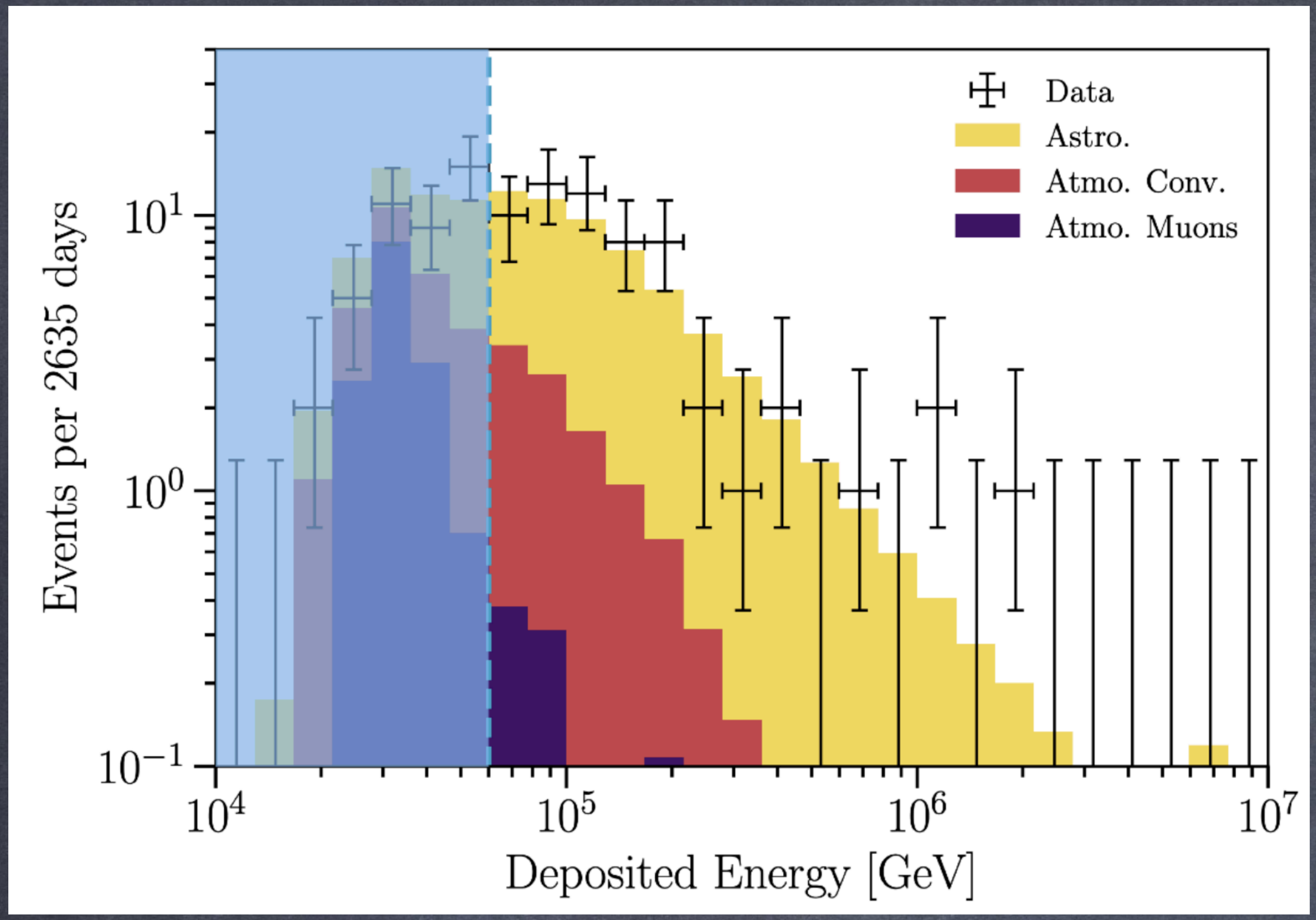
"Conventional" atmospheric neutrino suppression reaches two orders of magnitude in the downgoing region

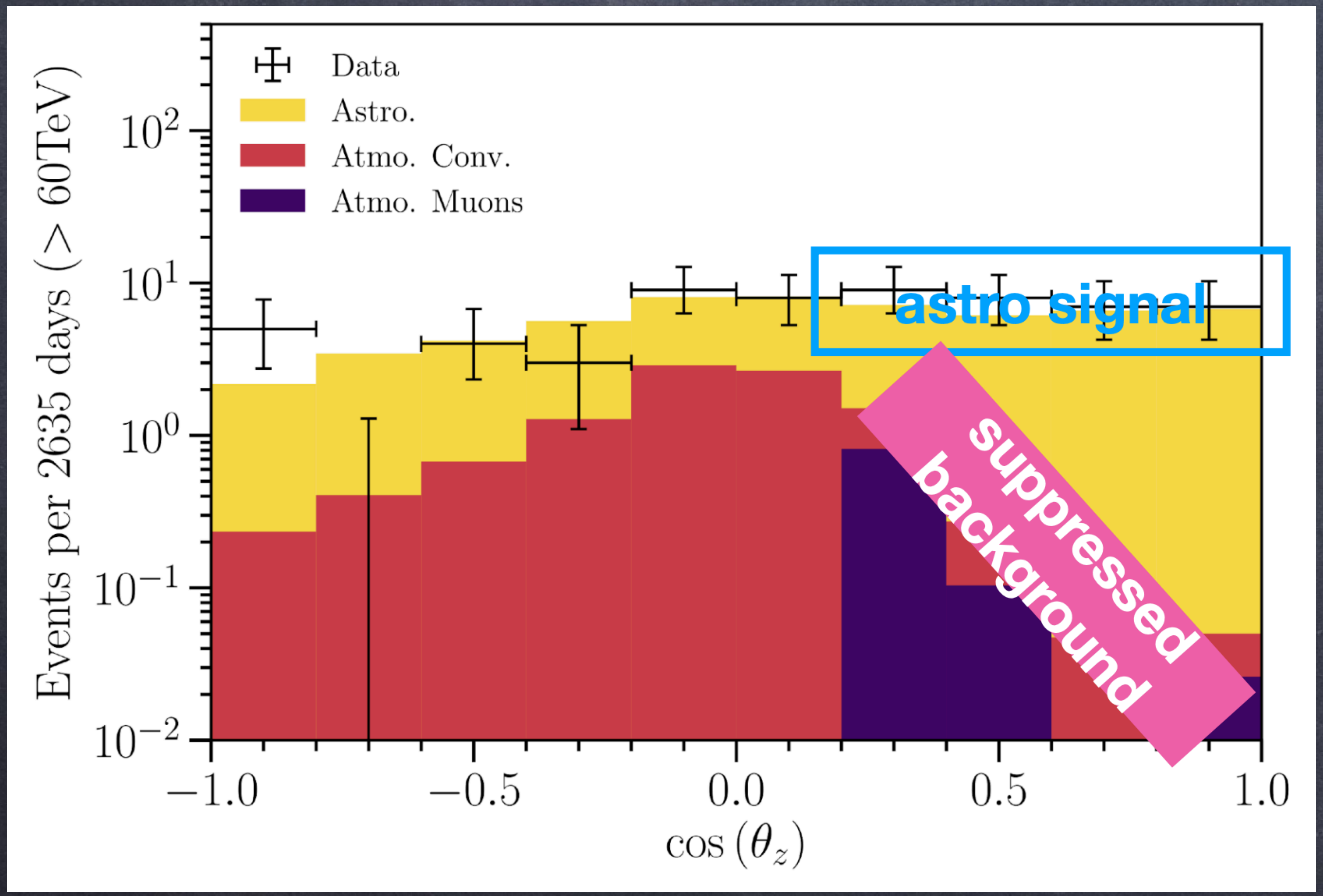
- A high astrophysical neutrino purity sample.
- Excellent rejection of atmospheric background in the downgoing region.
- New results including 7.5 years of data

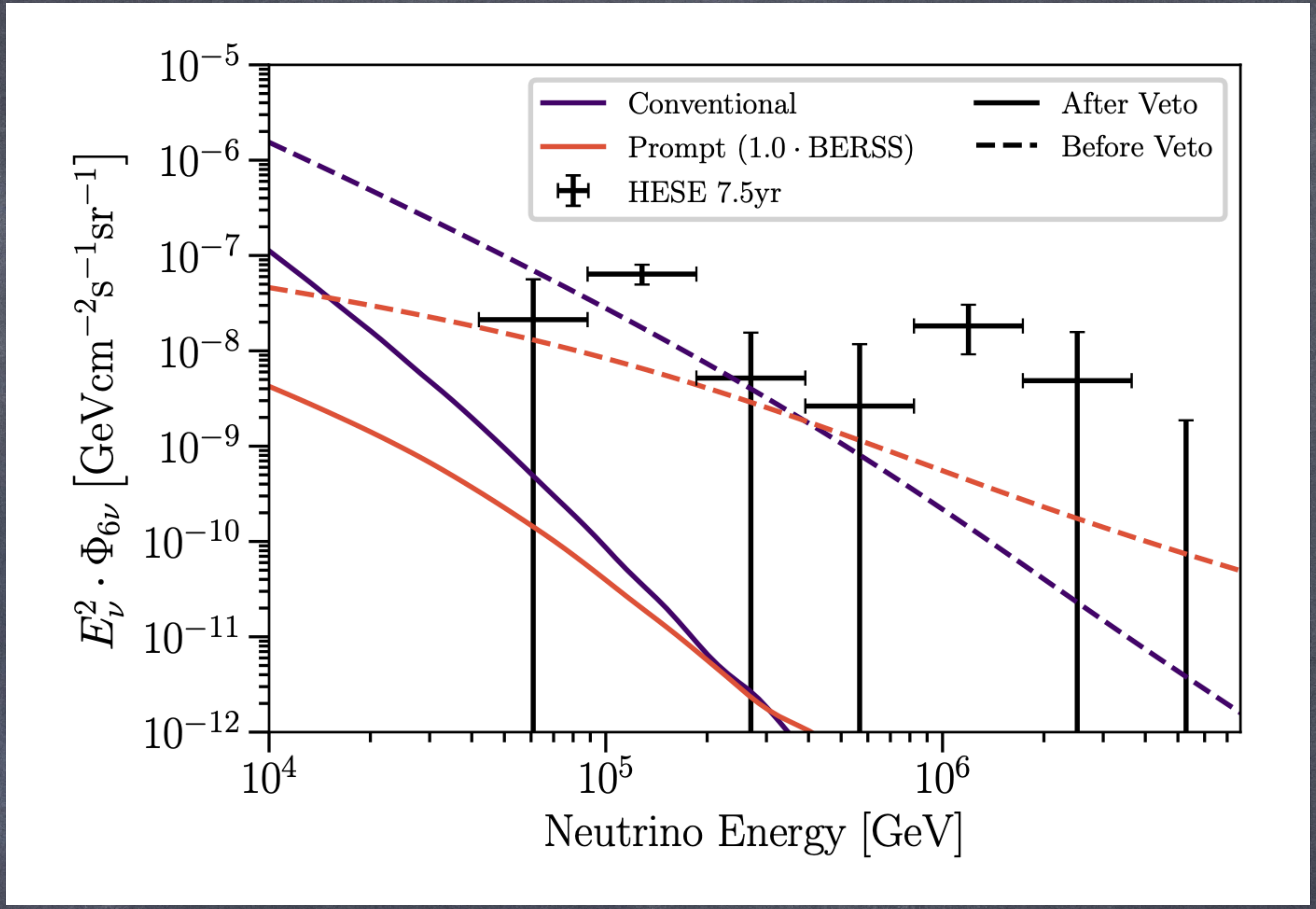
Schönert, Gaisser, Resconi, Schulz Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen Phys. Rev. D 90; 023009(2014)
Argüelles, Palomares-Ruiz, Schneider, Wille, Yuan JCAP 1807 (2018) no.07, 047

$\gamma = 2.9 \pm 0.2$

Phys. Rev. D 104, 022002 (2021)

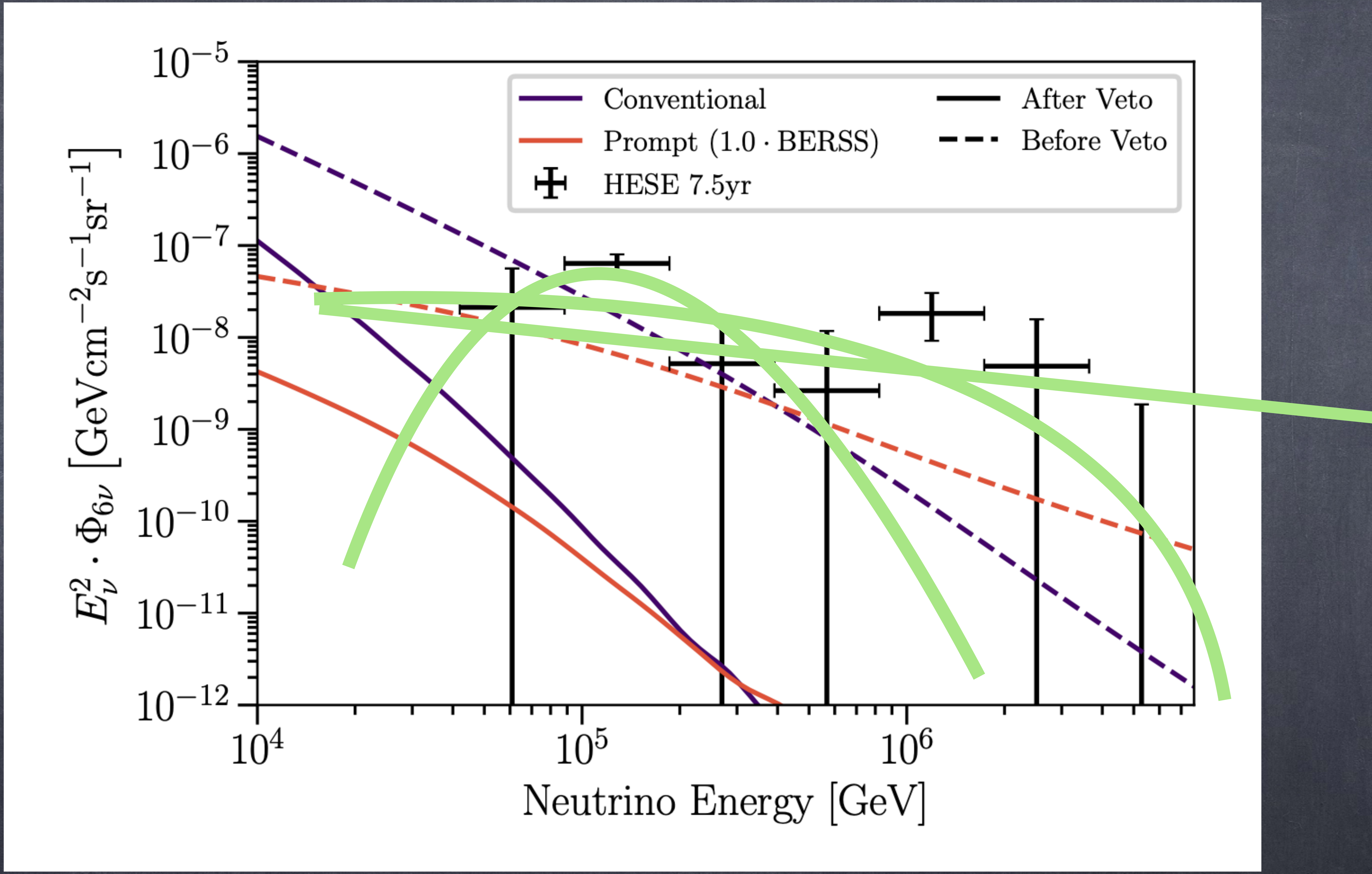






- 102 events in 7.5 years
- Fit region above 60 TeV deposited energy
- Data/MC and fitting code publicly available

◉ Features cannot be teased out yet
◉ Need more statistics.



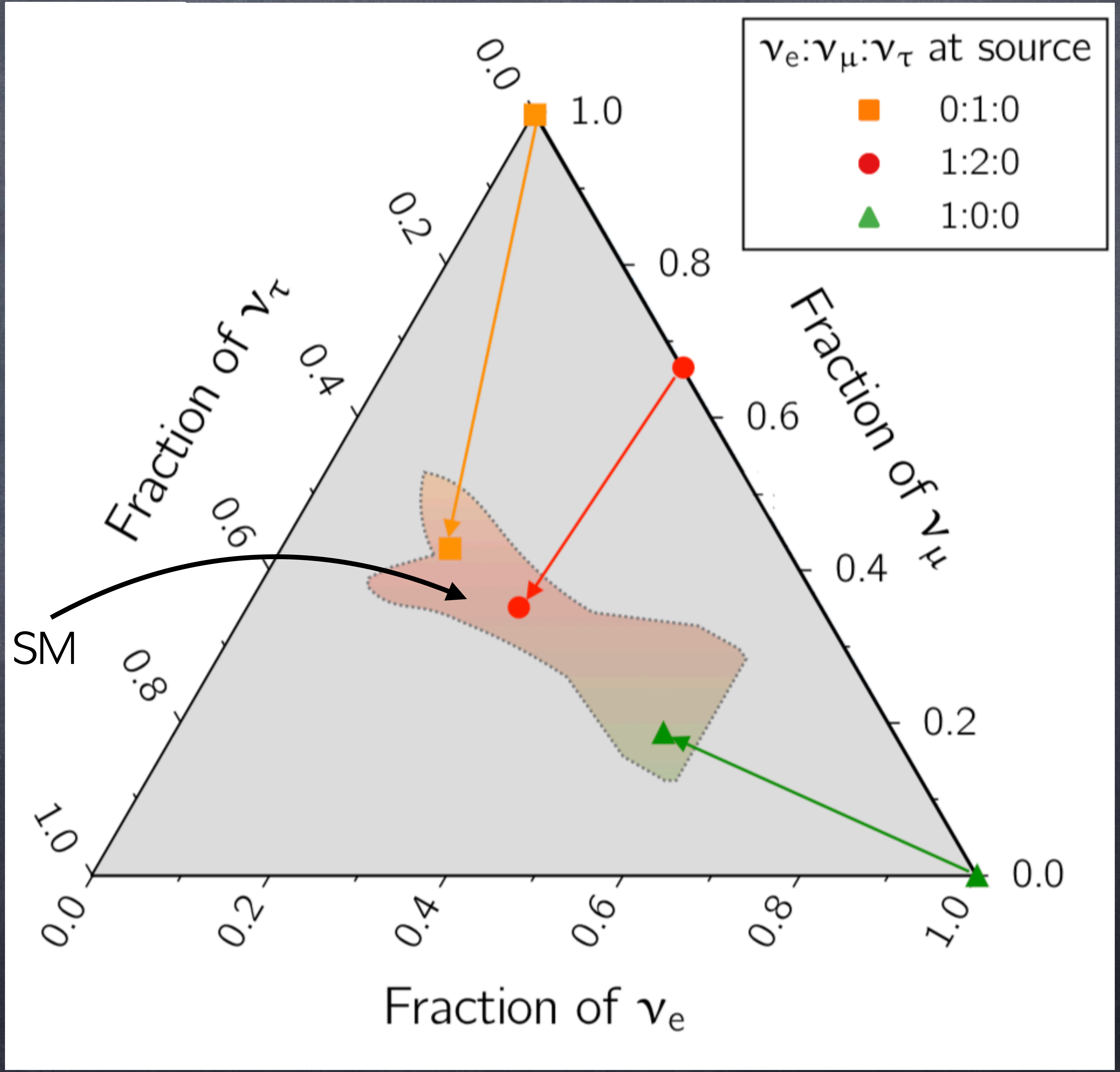
Astrophysical Neutrino Flavor

(1:0:0) neutron decay
(1:2:0) pion production
(0:1:0) muon dumped

→ (1:1:1)

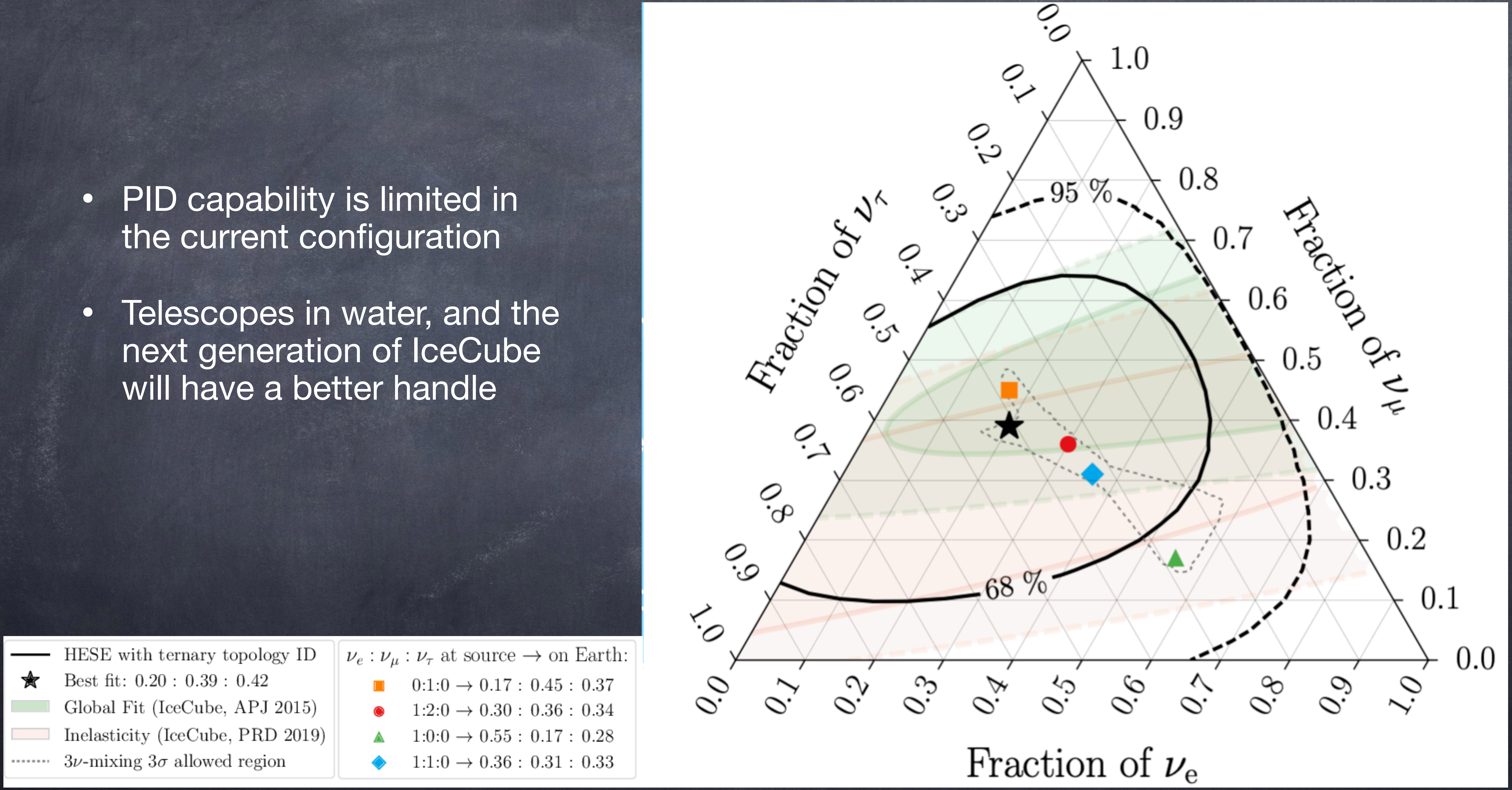
- Measurement of astrophysical neutrino flavor ratio is a probe of oscillations over cosmological baselines and TeV-PeV energies.

- A deviation from standard oscillations in flavor measurements is a smoking gun for new physics.



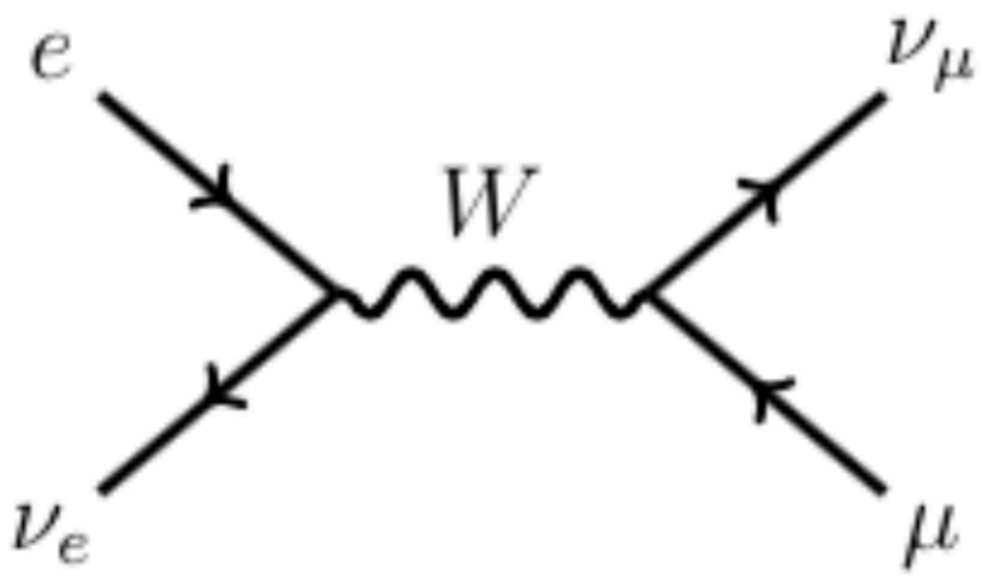
Astrophysical Flavor measurement

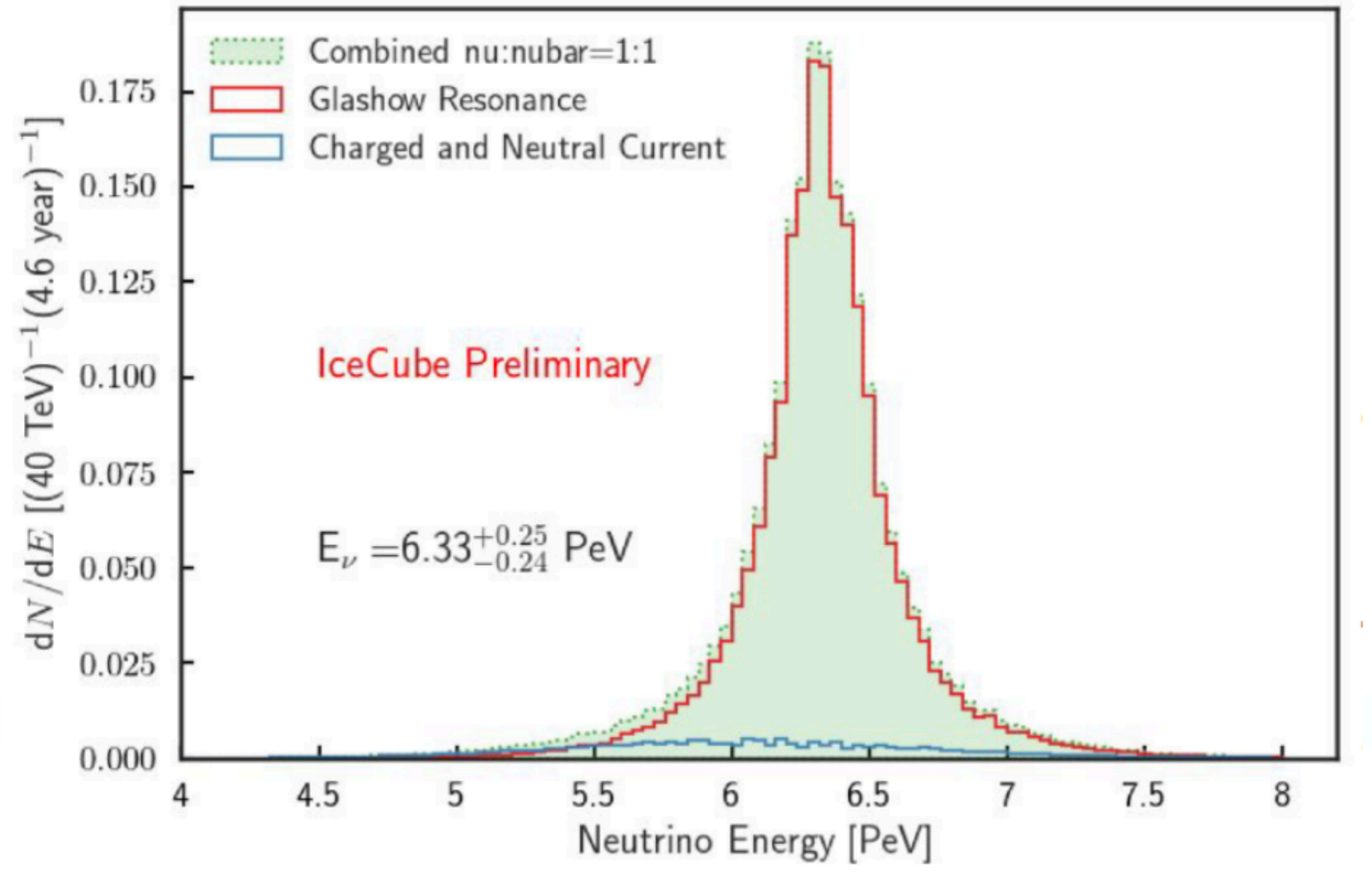
- PID capability is limited in the current configuration
- Telescopes in water, and the next generation of IceCube will have a better handle

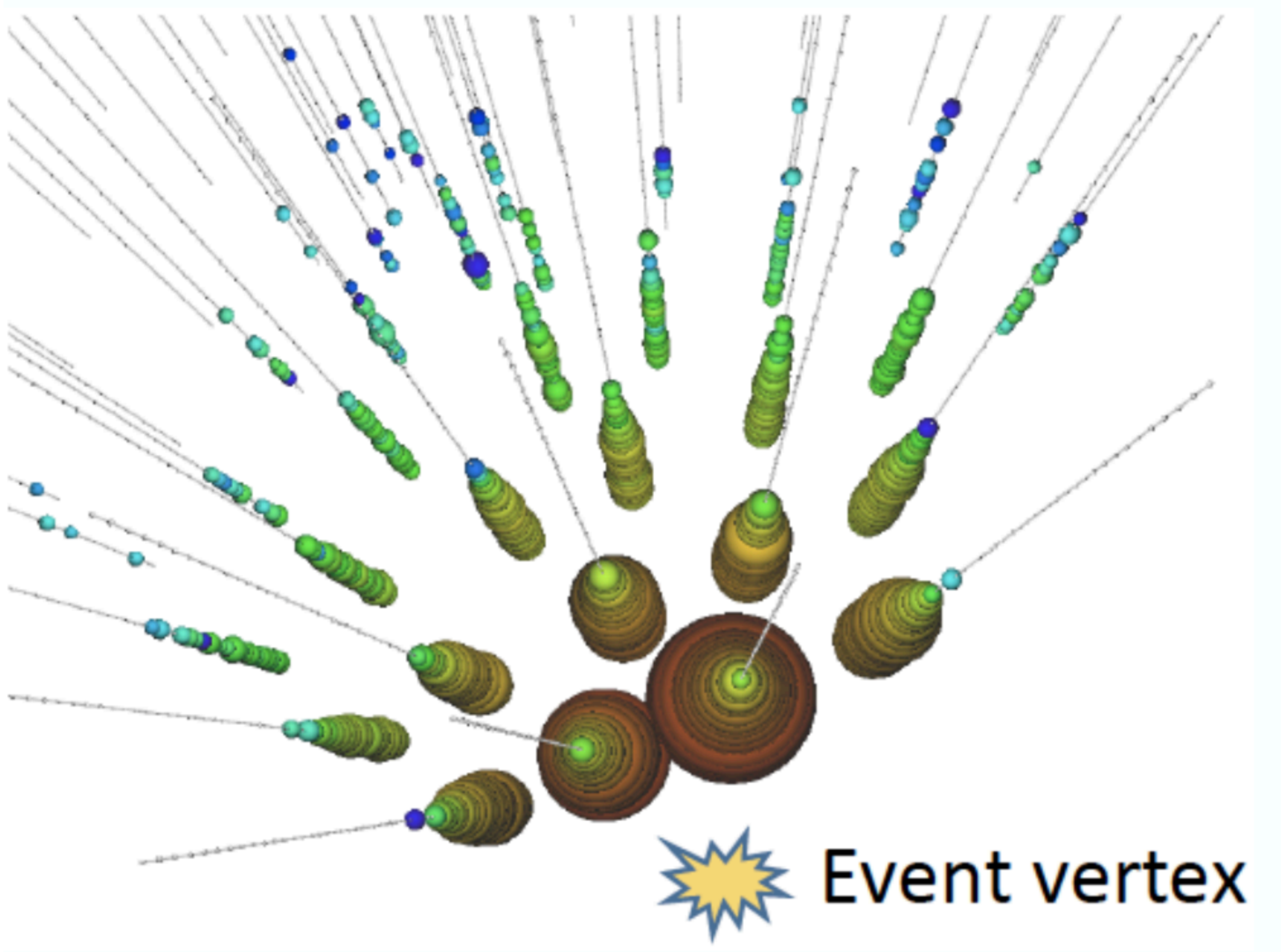


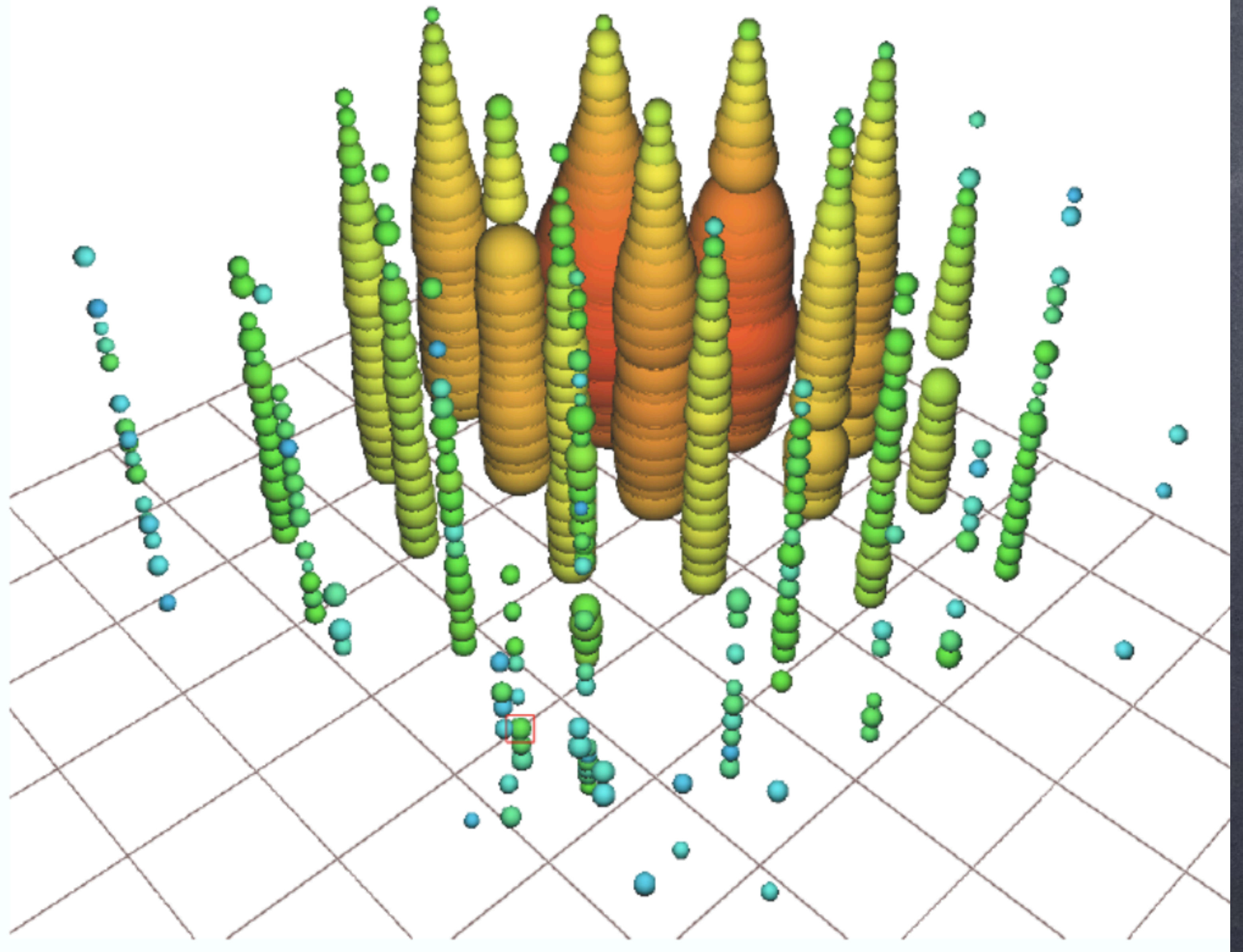
Glashow Resonance

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





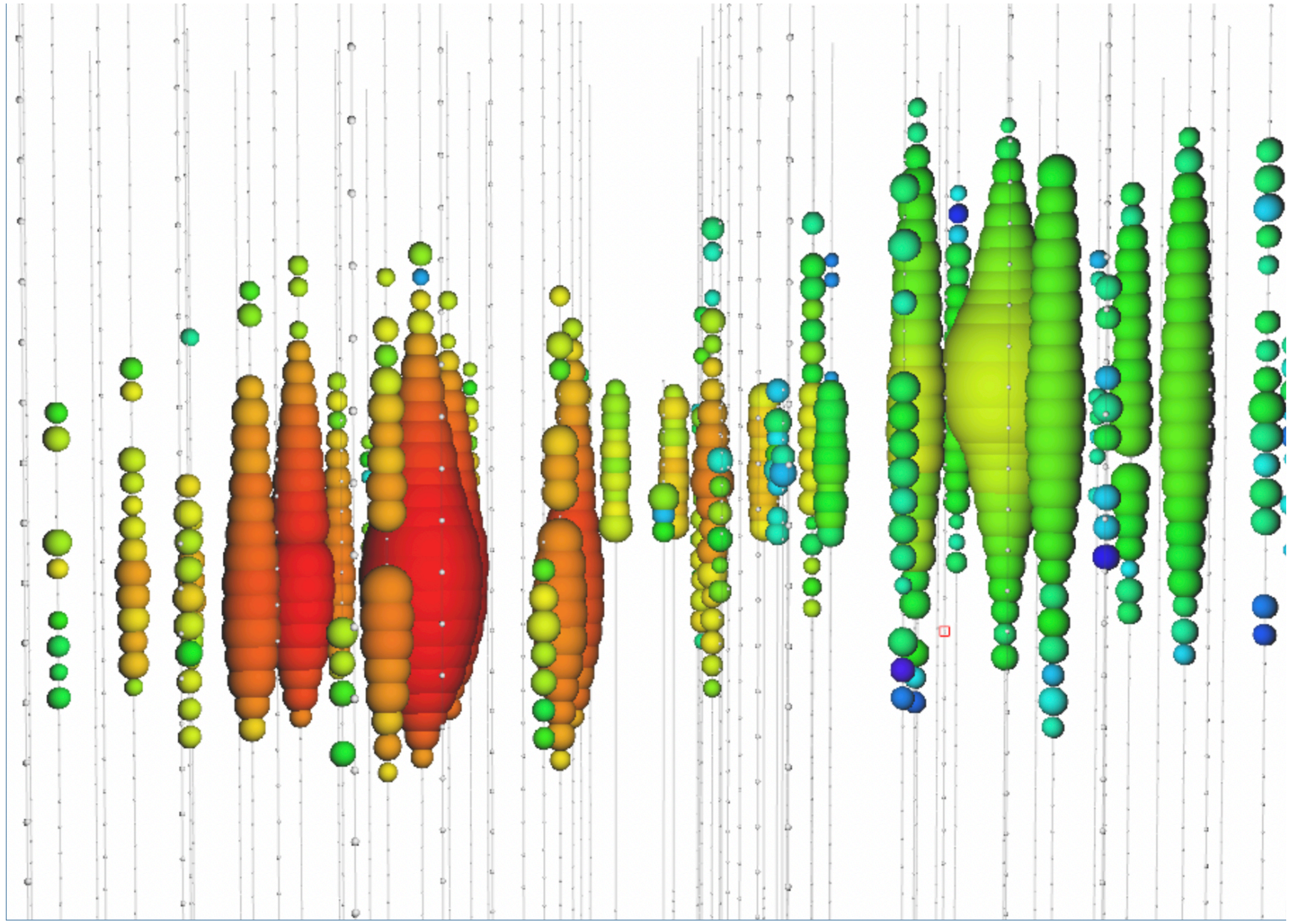




IceCube Coll. Nature volume 591, p. 220–224 (2021)

Tau Neutrinos in IceCube

Expectation

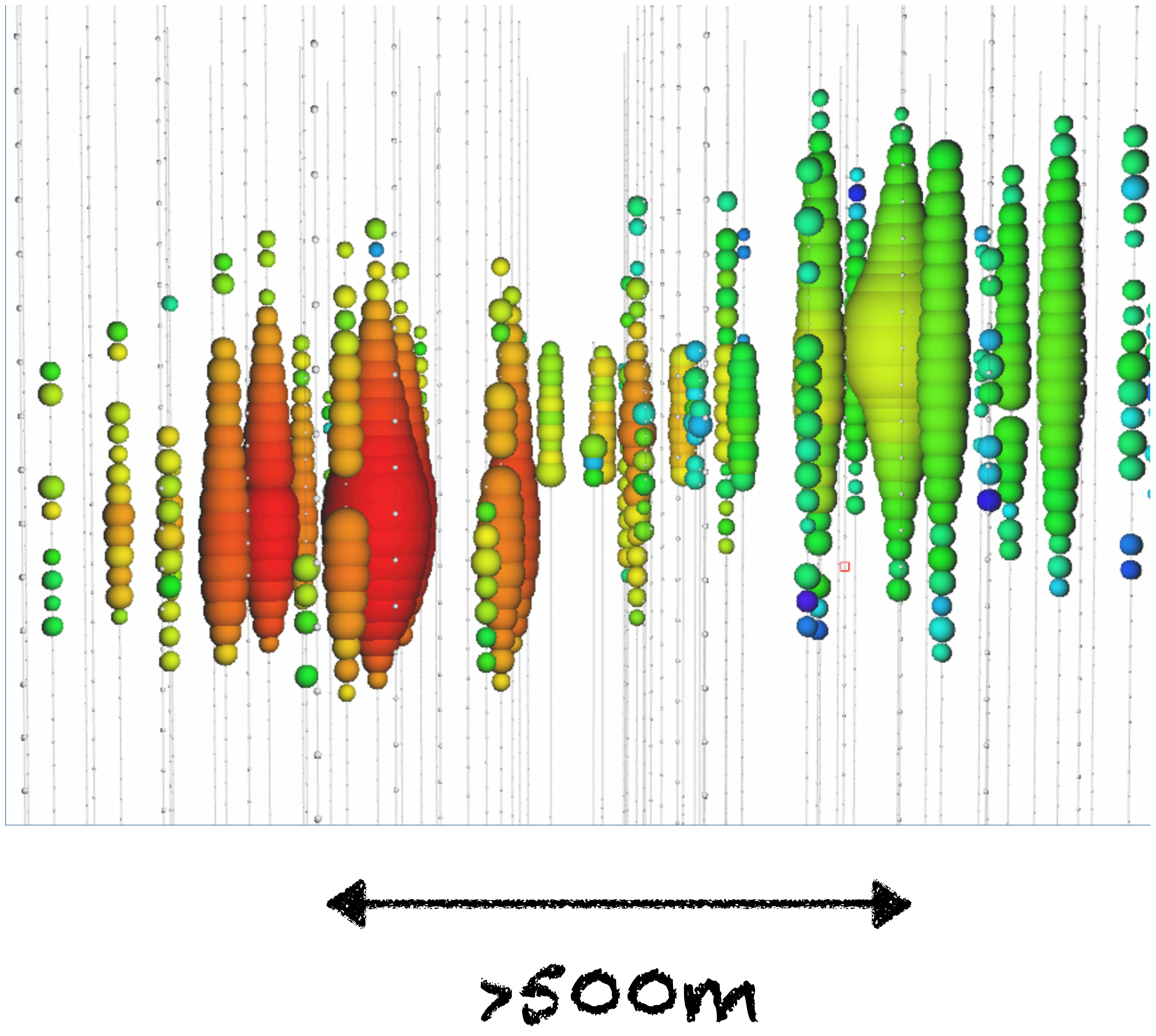


>500m

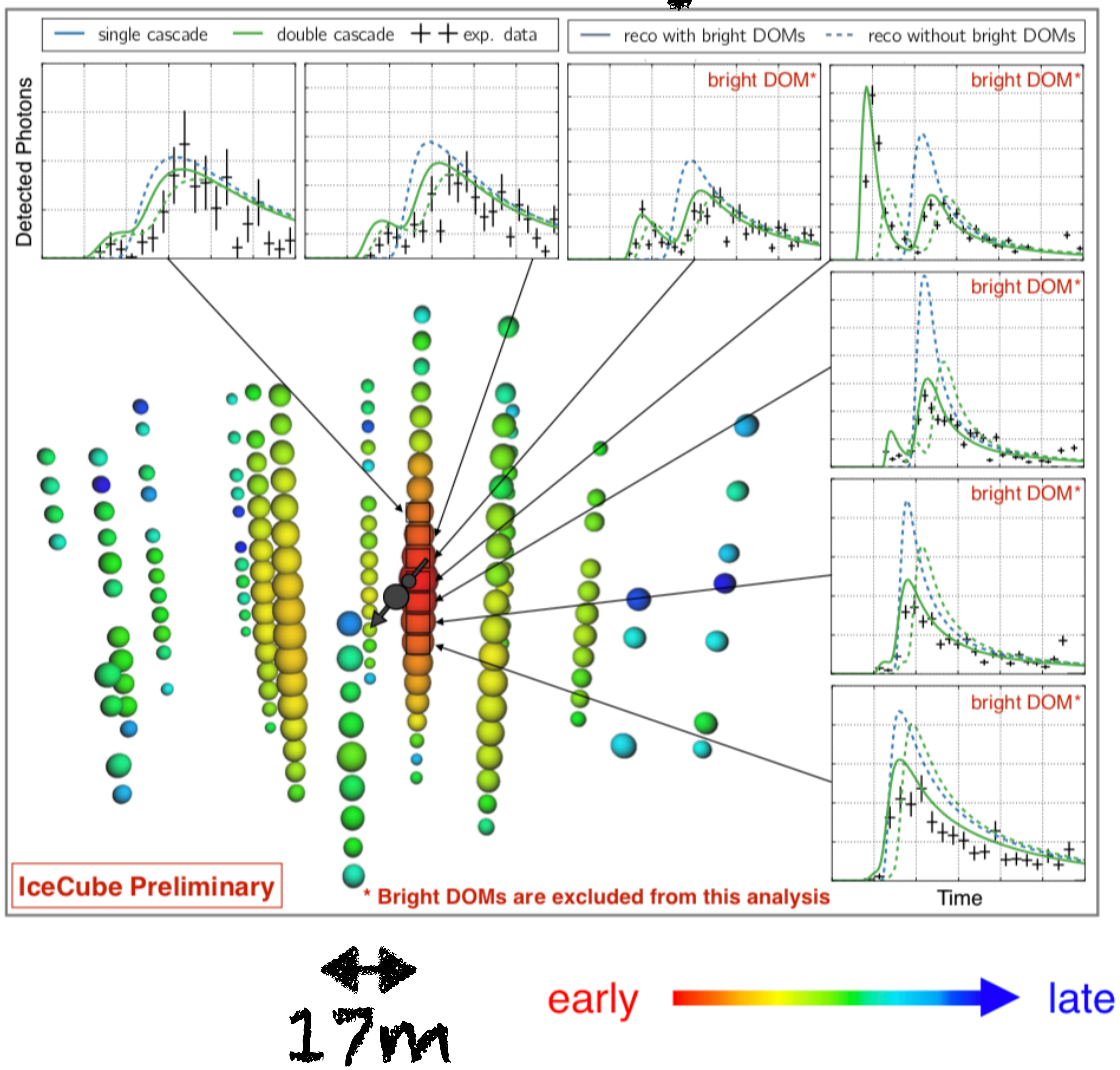
Tau decay length is ~50m/PeV

Tau Neutrinos in IceCube

Expectation

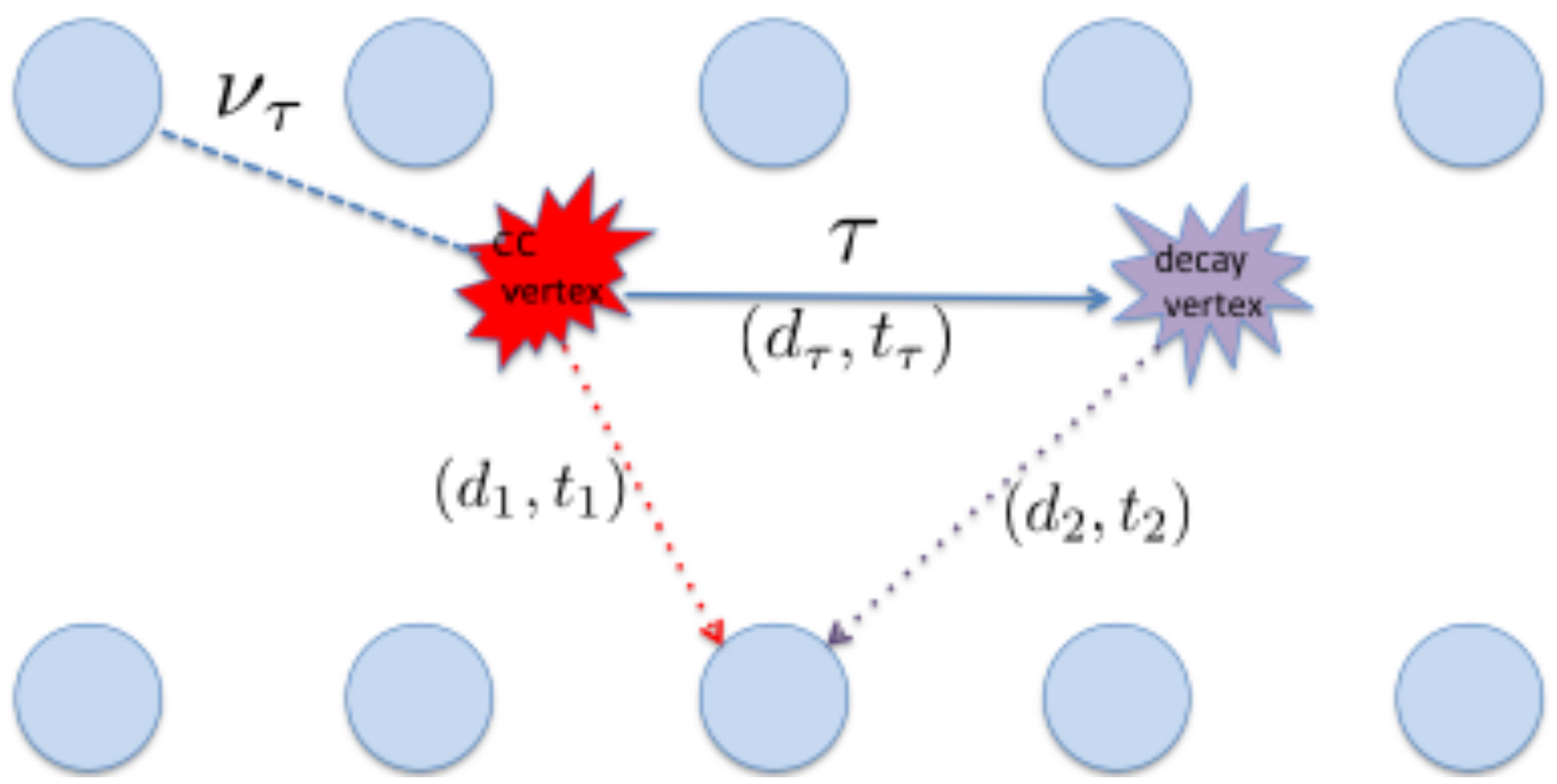


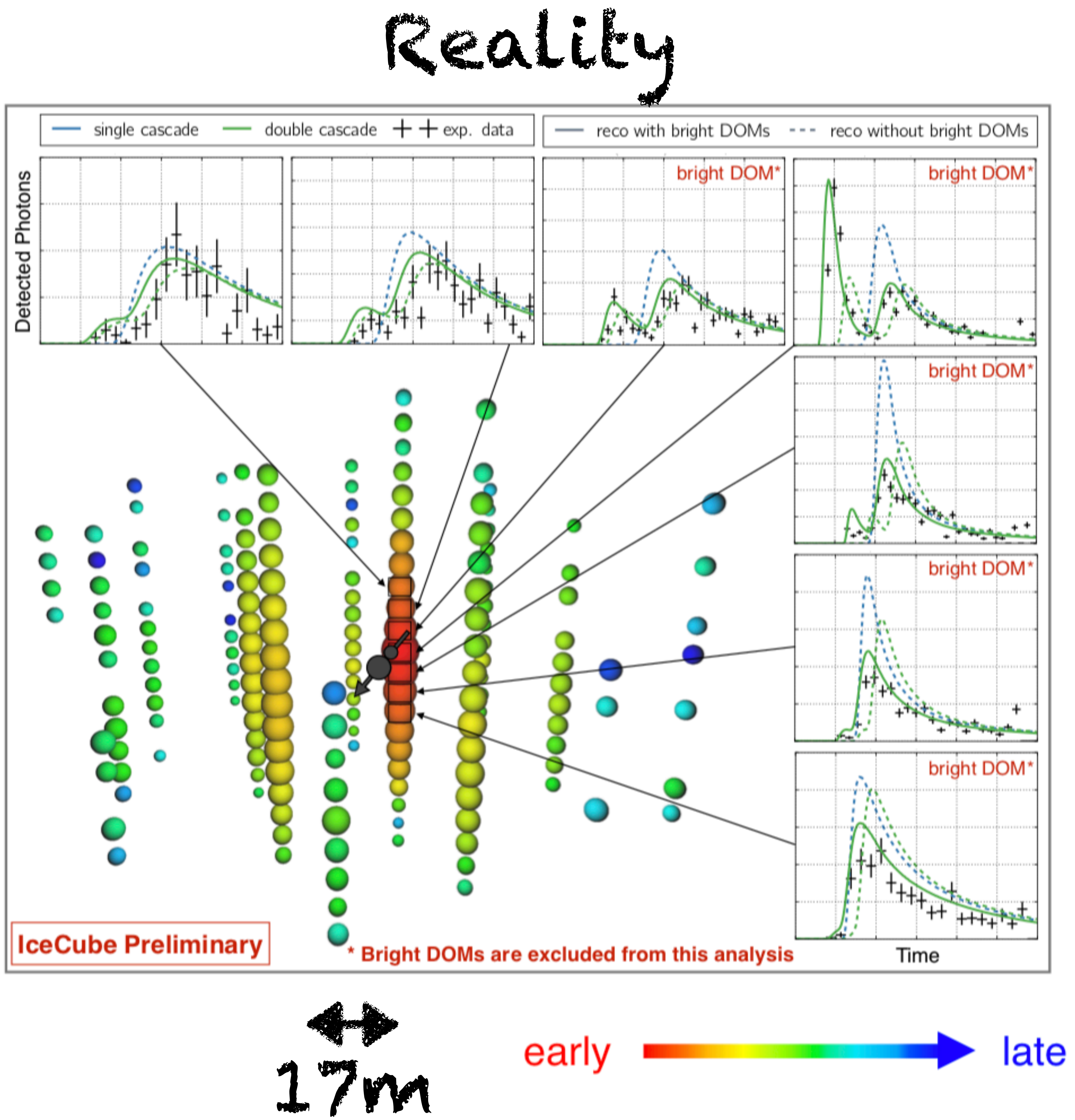
Reality



Tau Neutrinos in IceCube

- Total deposited energy ~90 TeV
- Same event identified in three independent analyses
- Two light deposits temporally separated





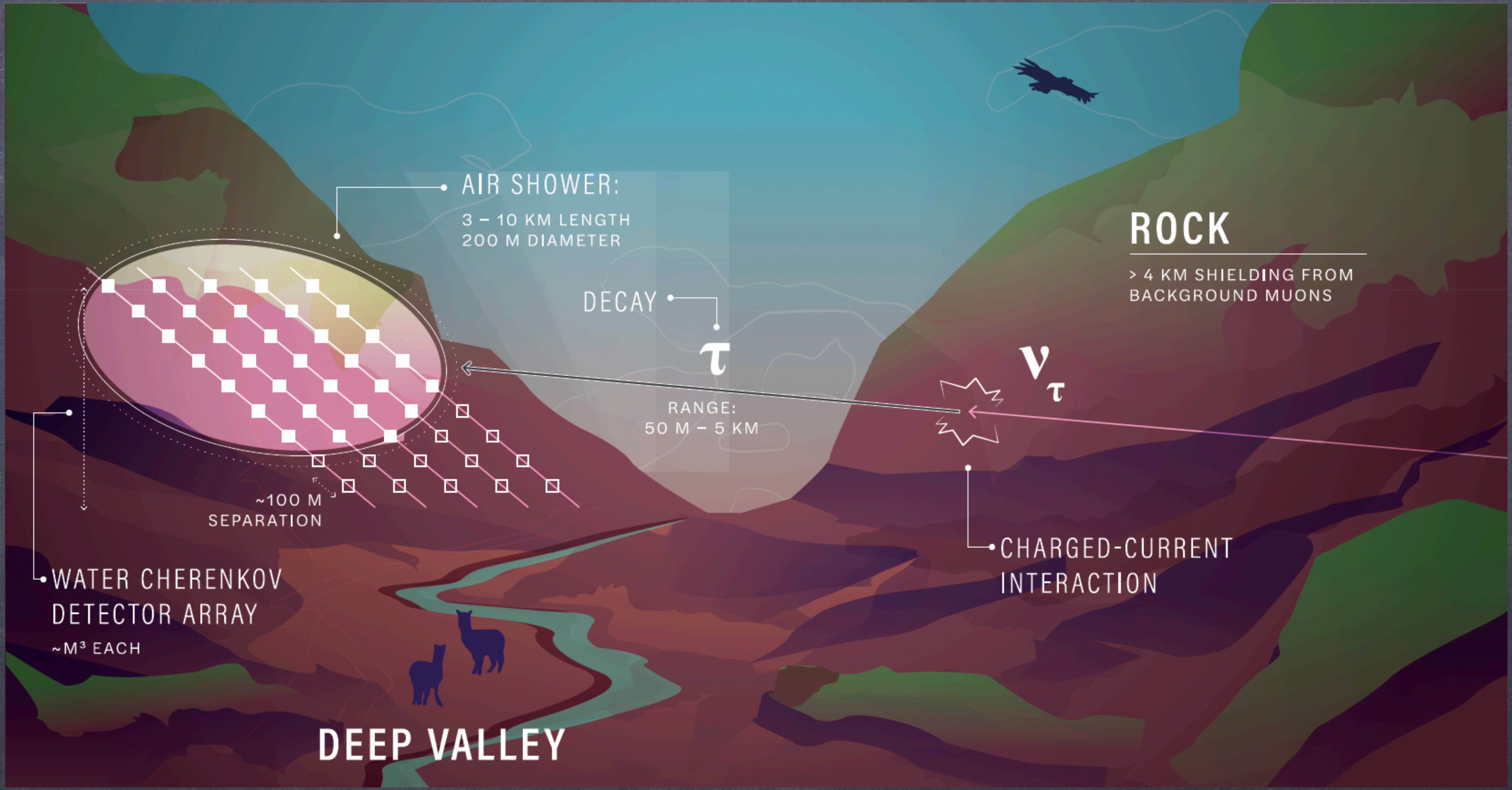
TAMBO: Hunting tau neutrinos in the Colca Valley

- Unique natural geometry: Deep (6km) and narrow (4km)

- Uses well established detection technologies

- Improves tau neutrino effective area by an order of magnitude

- Approximately 21 events in 3 years of operation



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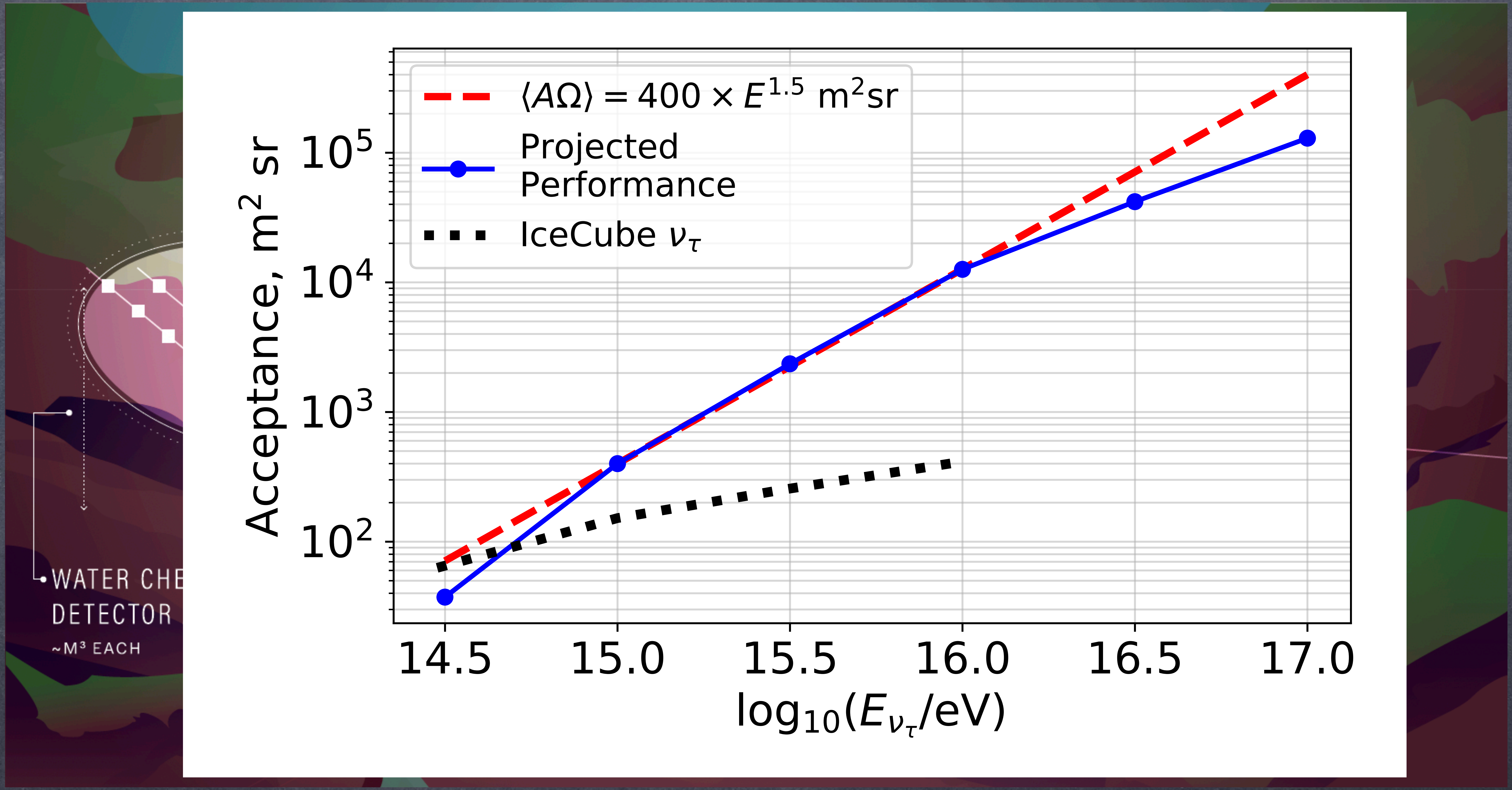
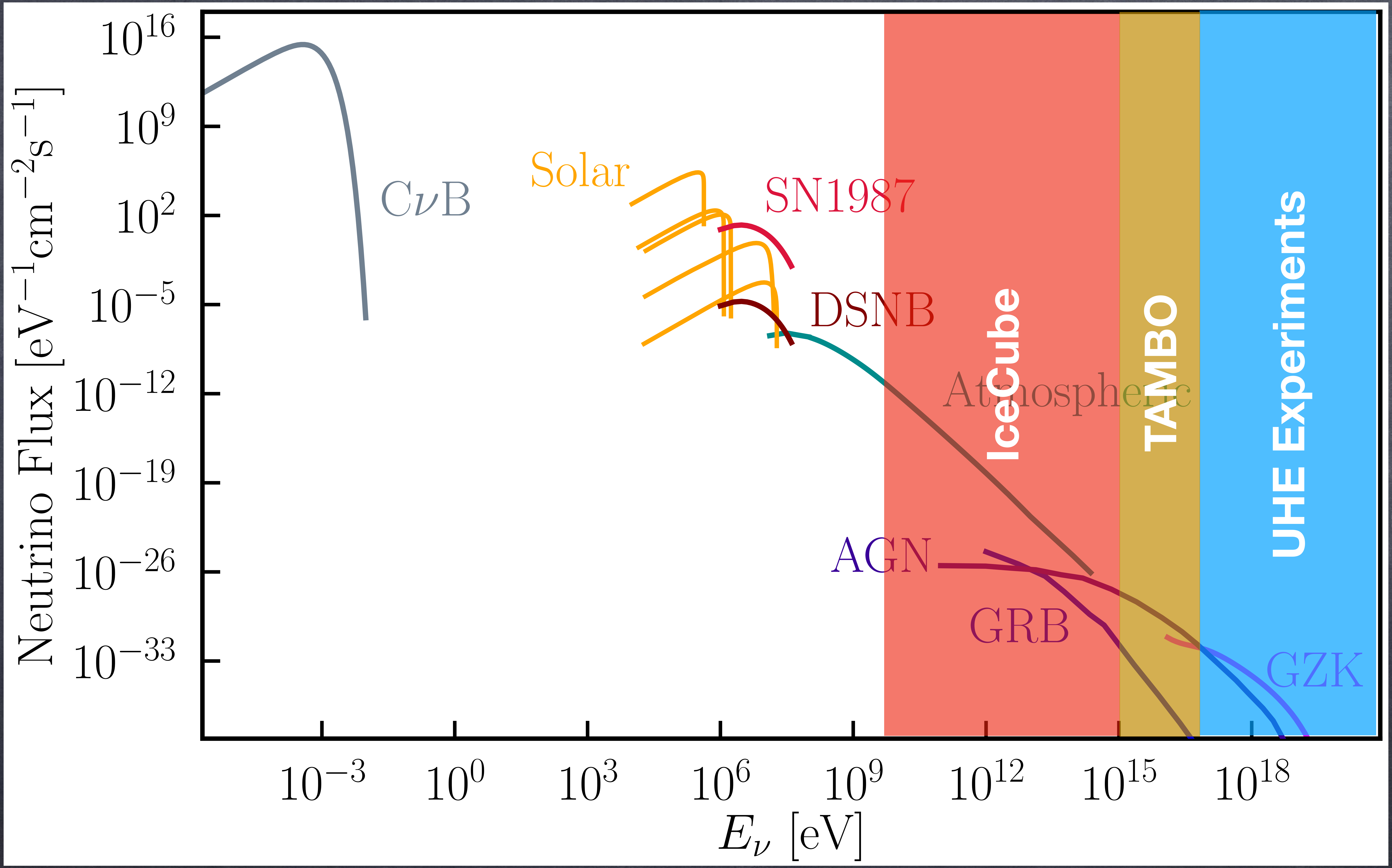


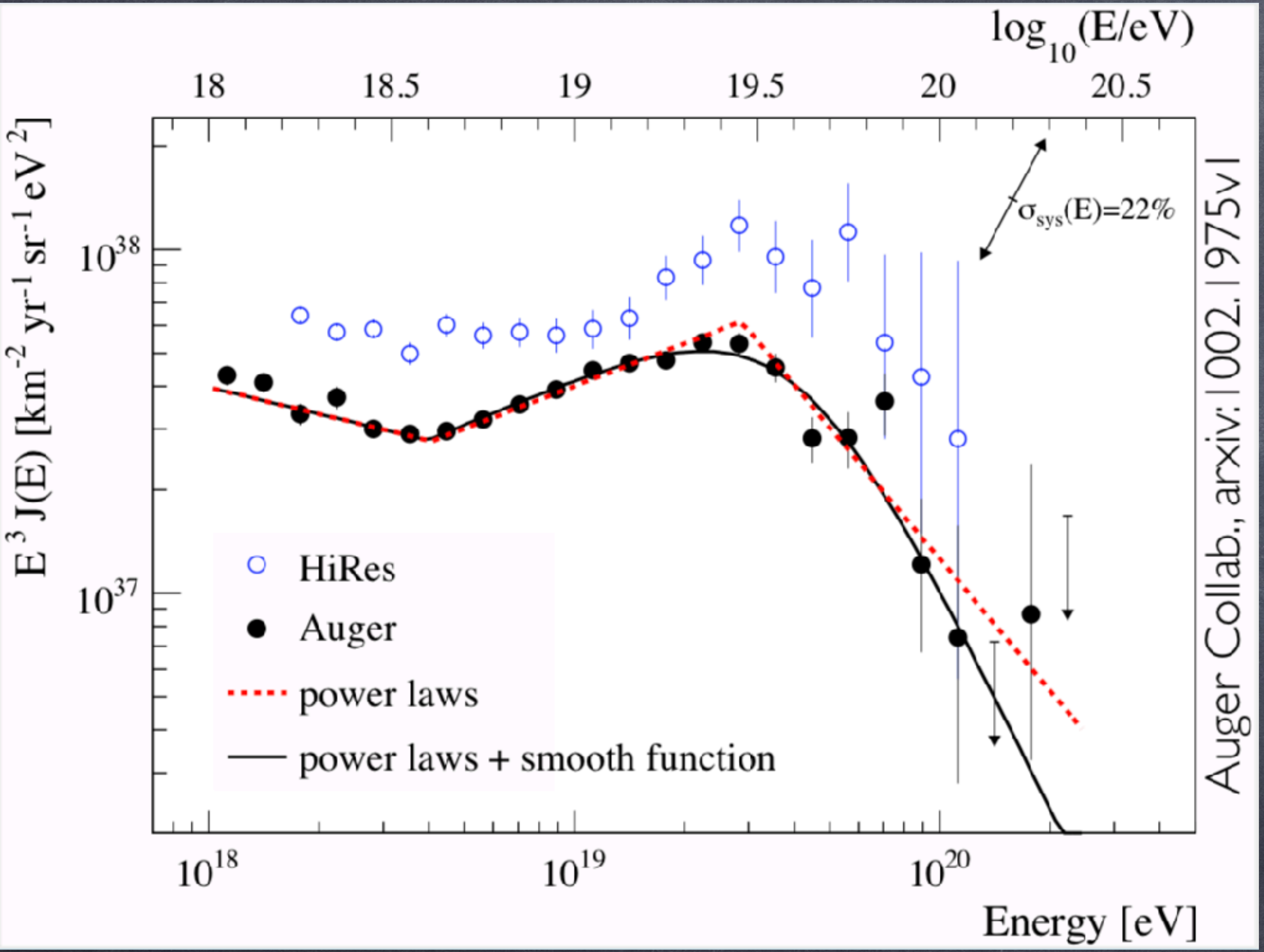
Romero-Wolf et al., arXiv:2002.06475v1



Neutrino Flux [eV^{-1}cm^{-2}s^{-1}]
10^{16}
10^{9}
10^{2}
10^{-5}
10^{-12}
10^{-19}
10^{-26}
10^{-33}
CνB
Solar
SN1987
DSNB
Atmospheric
IceCube
TAMBO
UHE Experiments
AGN
GRB
GZK
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
E_ν [eV]

UHE Neutrinos

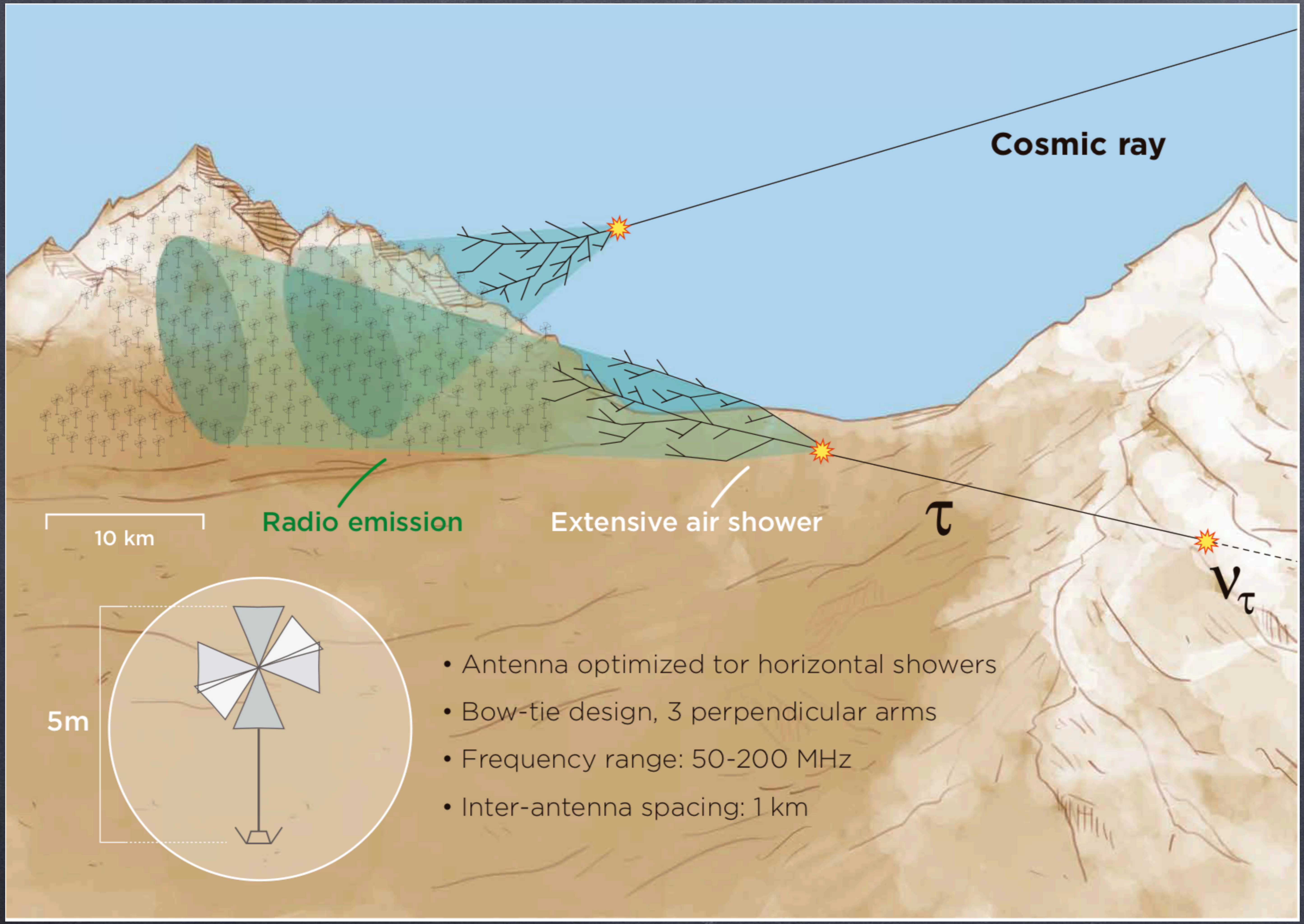
Ultra-High Energy (GZK) Neutrinos (E > 10^{17} eV)



A diffuse flux:

- UHE cosmic rays are attenuated by the CMB
- Cutoff observed decades after original prediction
- Guaranteed flux of UHE neutrinos that has yet to be observed

Direct Detection

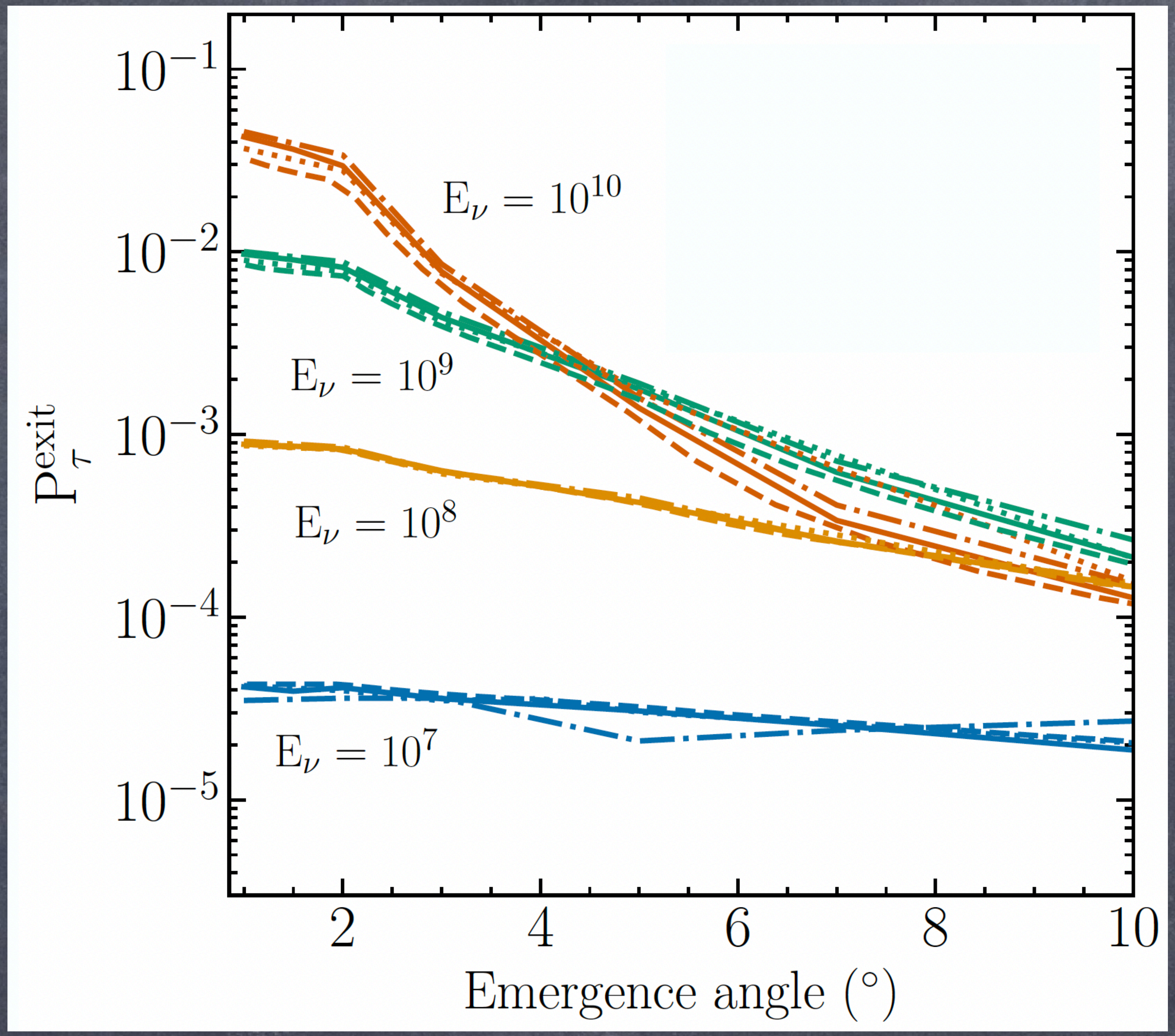


Álvarez-Muñiz et al. Sci. China-Phys. Mech. Astron. 63, 219501 (2020)

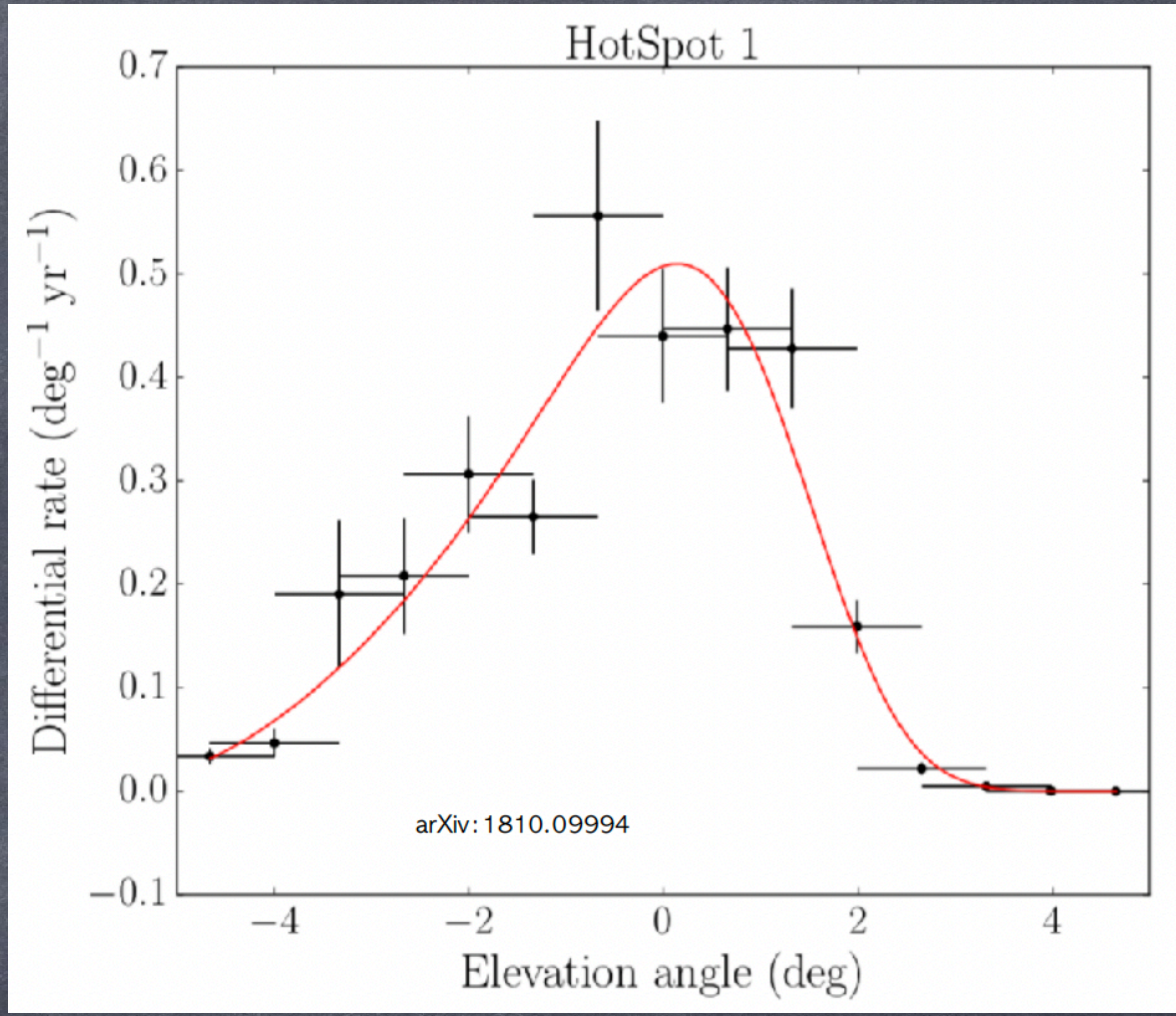
- Use atmosphere, mountains, volcanoes, and a sliver of the Earth as target.
- Detect radio emission from tau decay showers in the ice/atmosphere. (ANITA/GRAND/RNO-G/POEMMA)
- Cherenkov light from taus also detectable (POEMMA)
- Fluorescent light detection possible with precision optical detectors (ASHRA/NTA)

Direct Detection: Limitations

- Earth-skimming searches are limited to a small fraction of the sky
- Primary flux quickly lost as angle steepens
- Taus emerging at steeper angles have energy below radio threshold

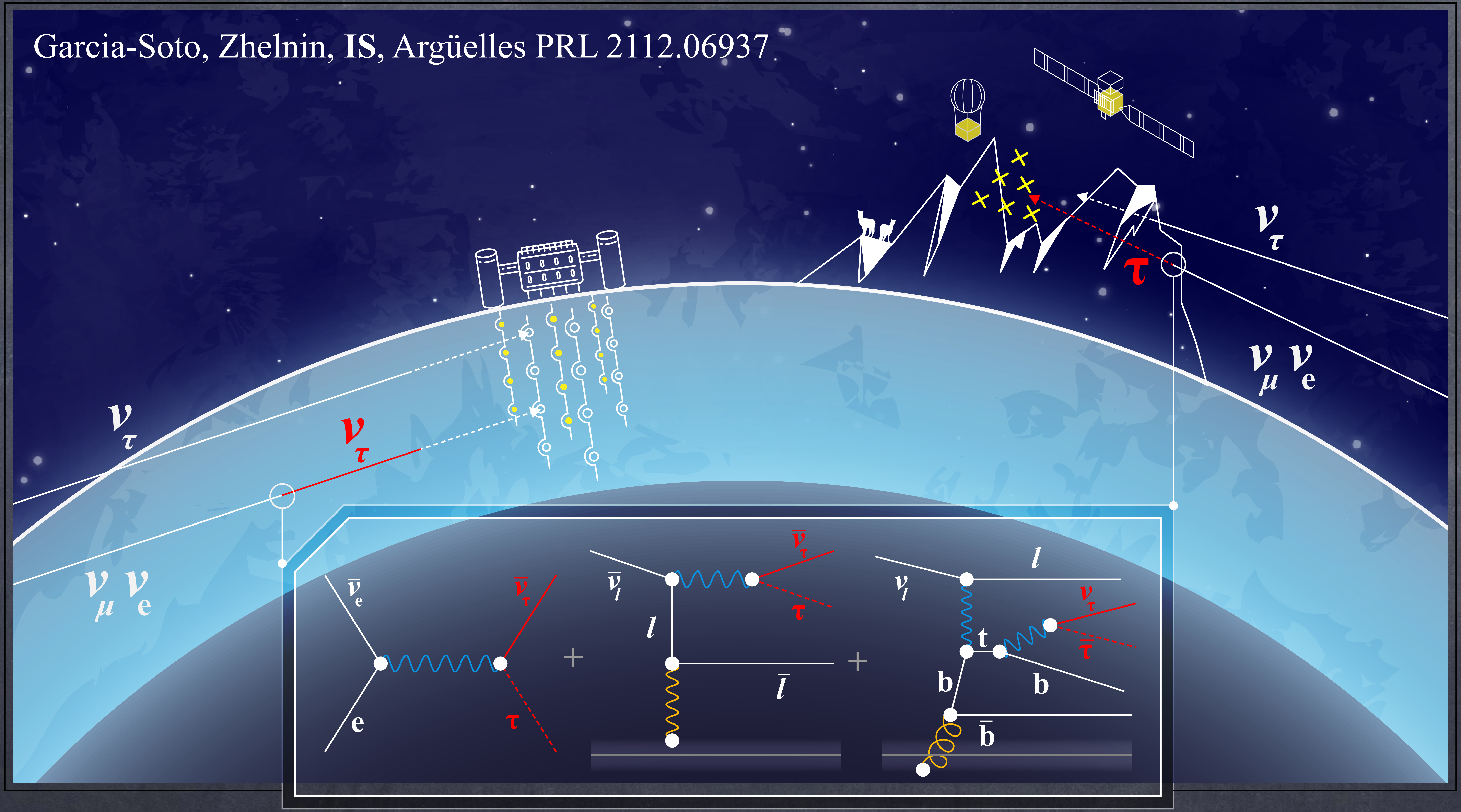


Exit probability as a function of emergence angle. Targeted high-energy flux quickly attenuated as angle increases



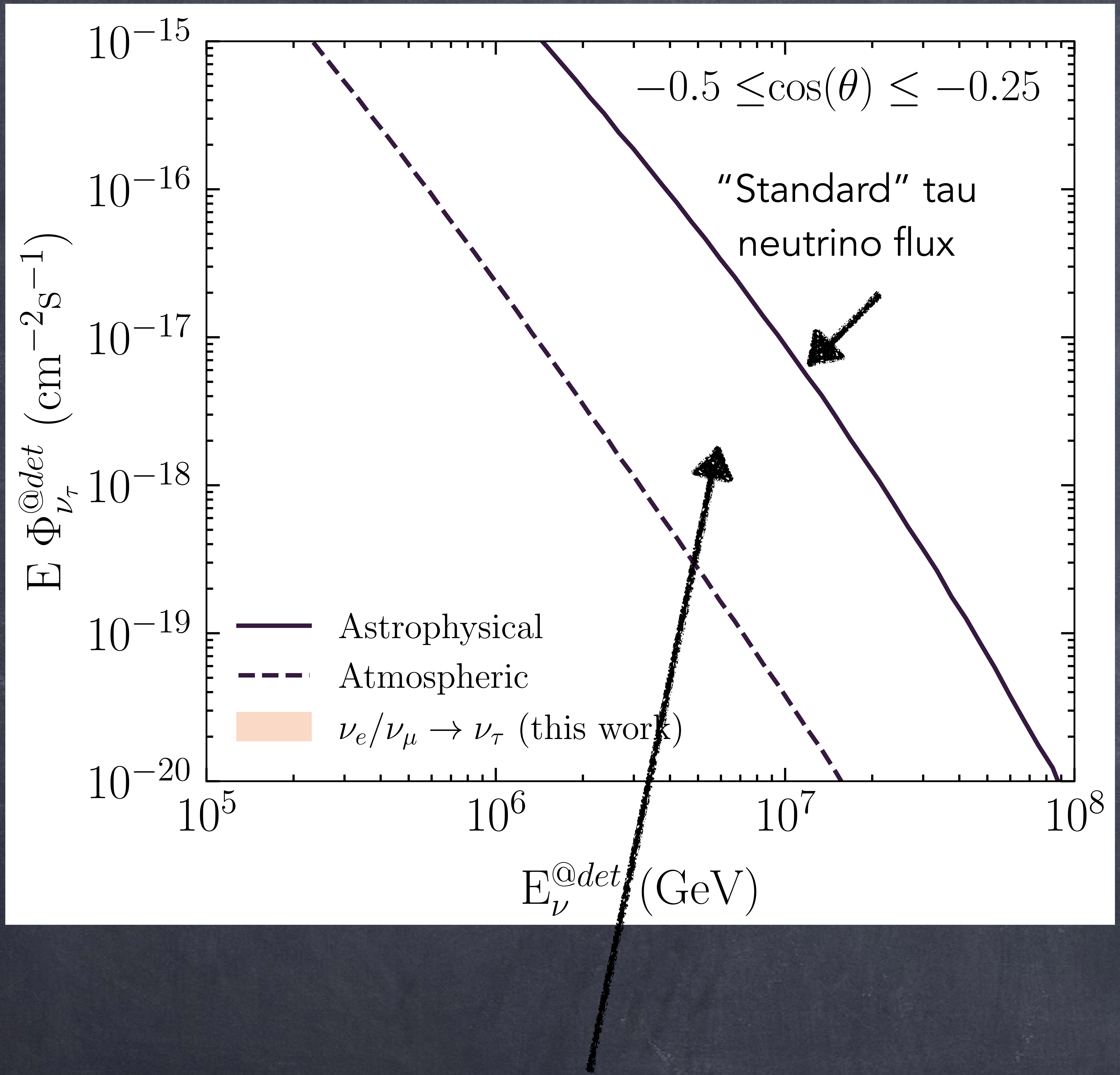
Rate of neutrinos at GRAND as a function of elevation angle. Note the quick drop in rate as you move away from zero degrees

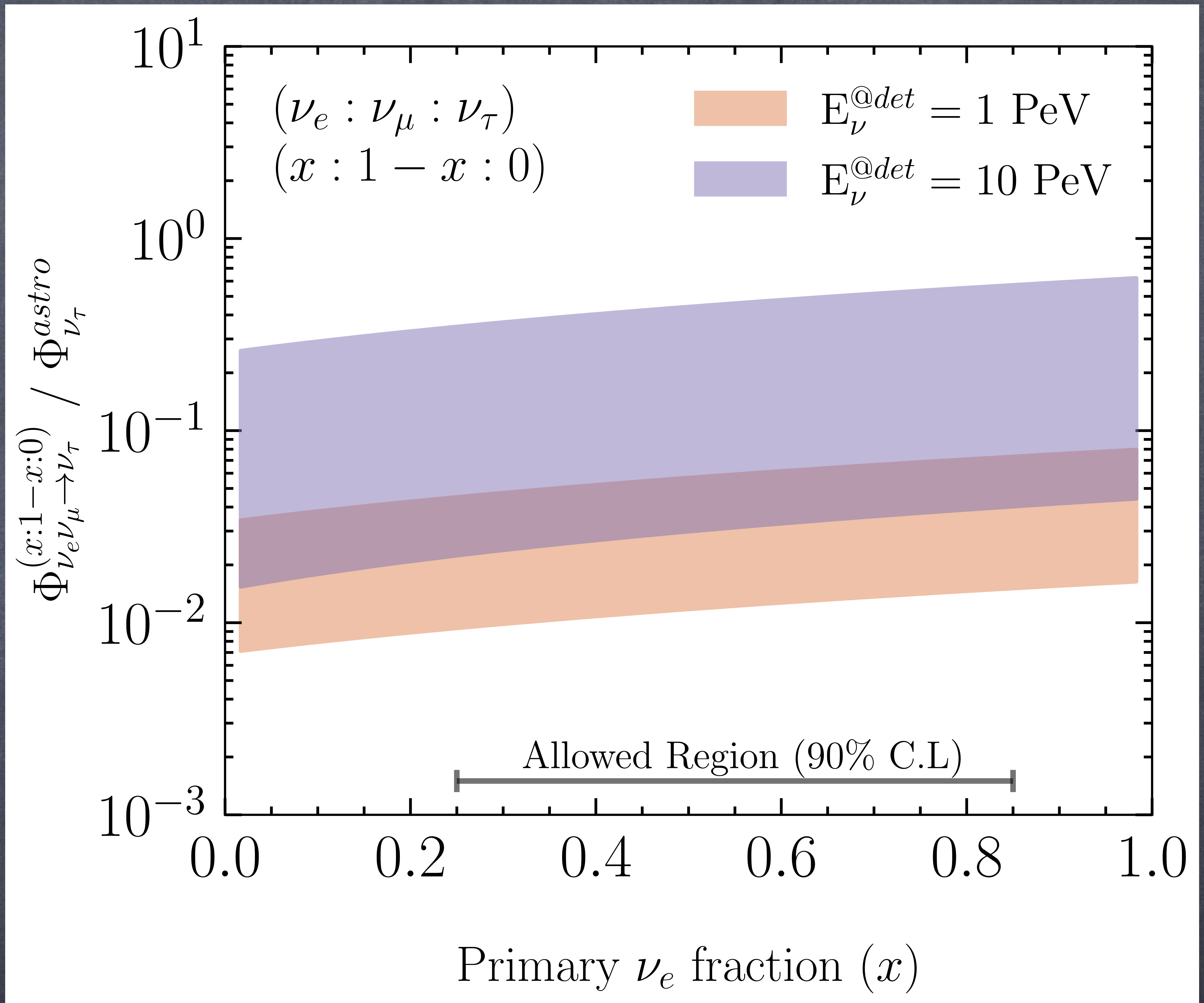
Intrinsic Backgrounds for tau searches



Tau neutrinos can be produced by muon and electron neutrino fluxes

Intrinsic Backgrounds for tau searches

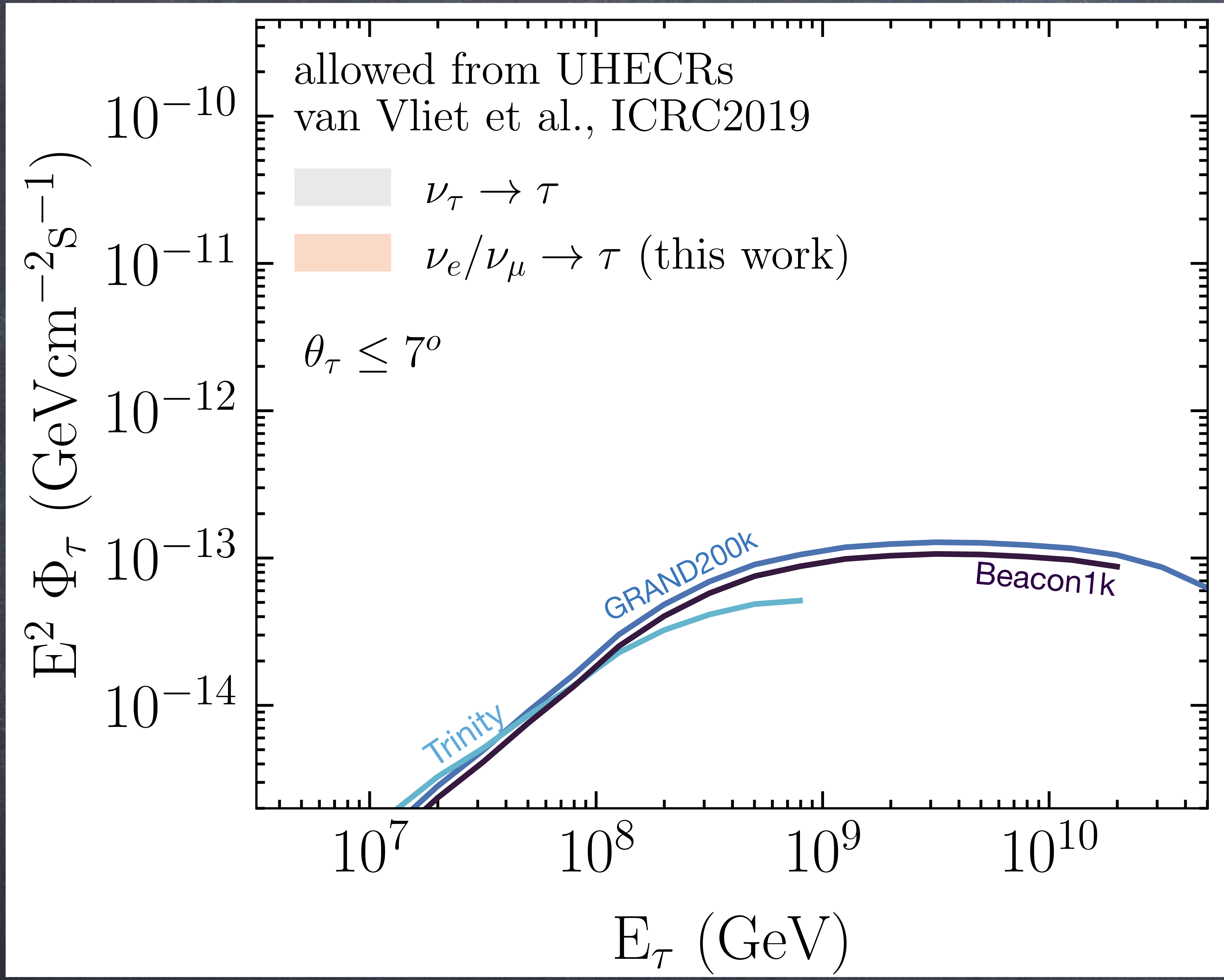




A. Garcia-Soto, P. Zhelnin, **IS**, C. Argüelles PRL 2112.06937

Tau neutrinos produced by muon and electron neutrino primaries

Guaranteed tau neutrinos



- Tau neutrinos at ultra-high energies can be detected, regardless of the production/ oscillation physics involved.
- This also means the primary and secondary fluxes are degenerate.
- We *need* complementary all-flavor detectors in addition to tau neutrino detectors

Tau neutrino regeneration

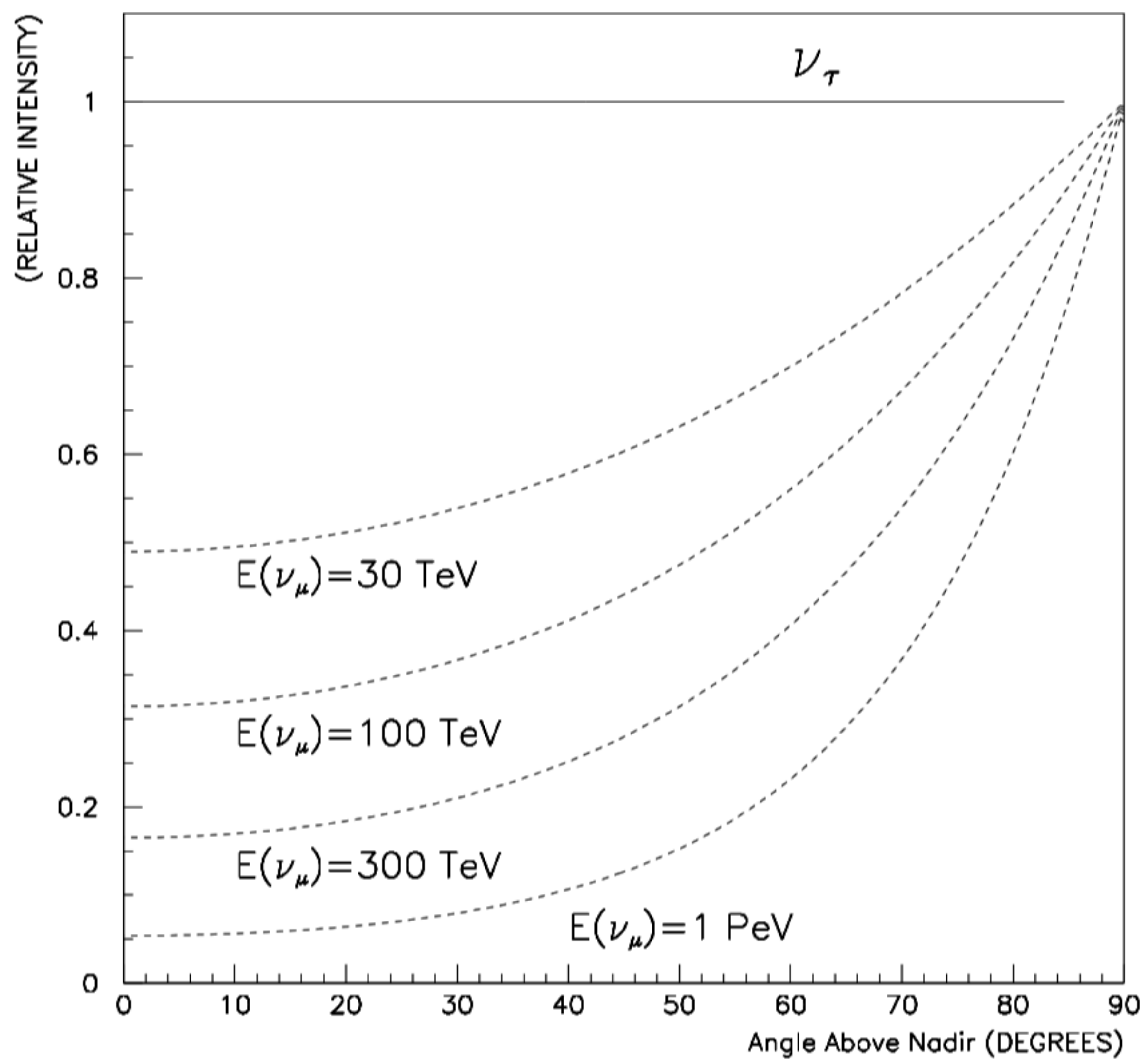
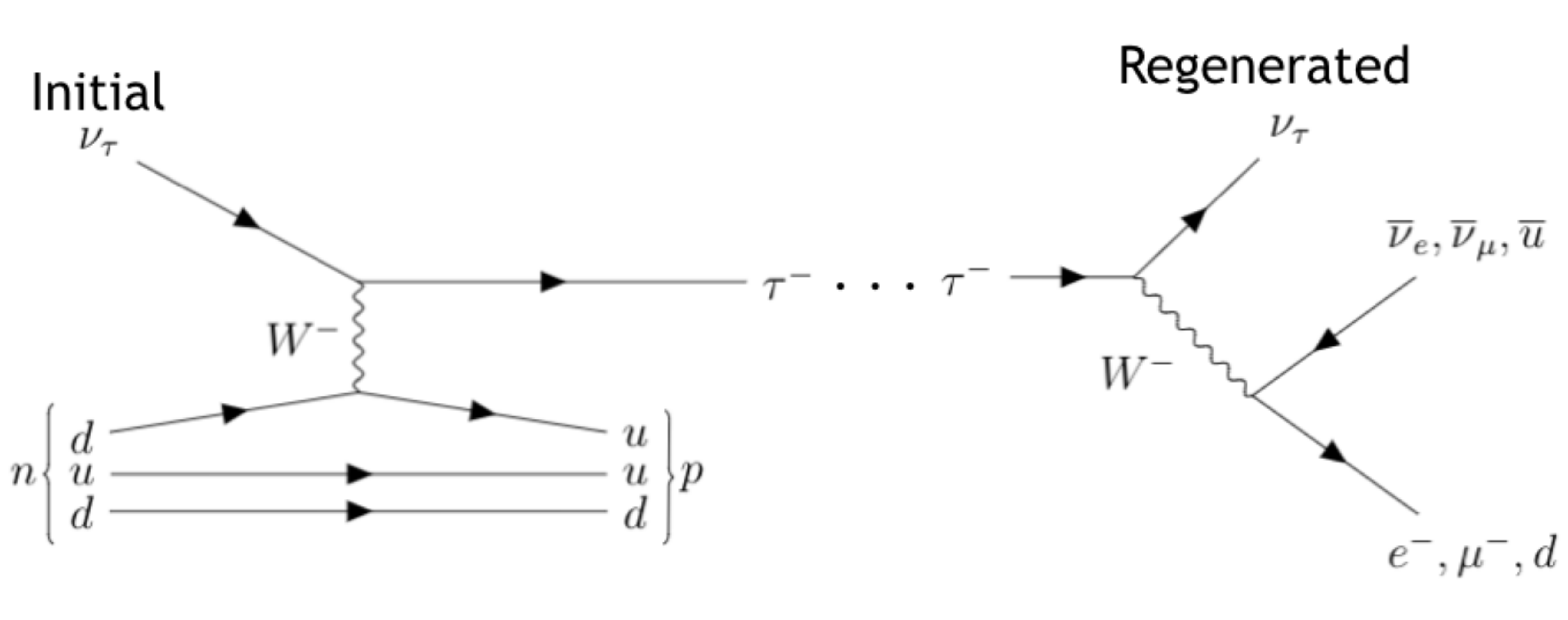


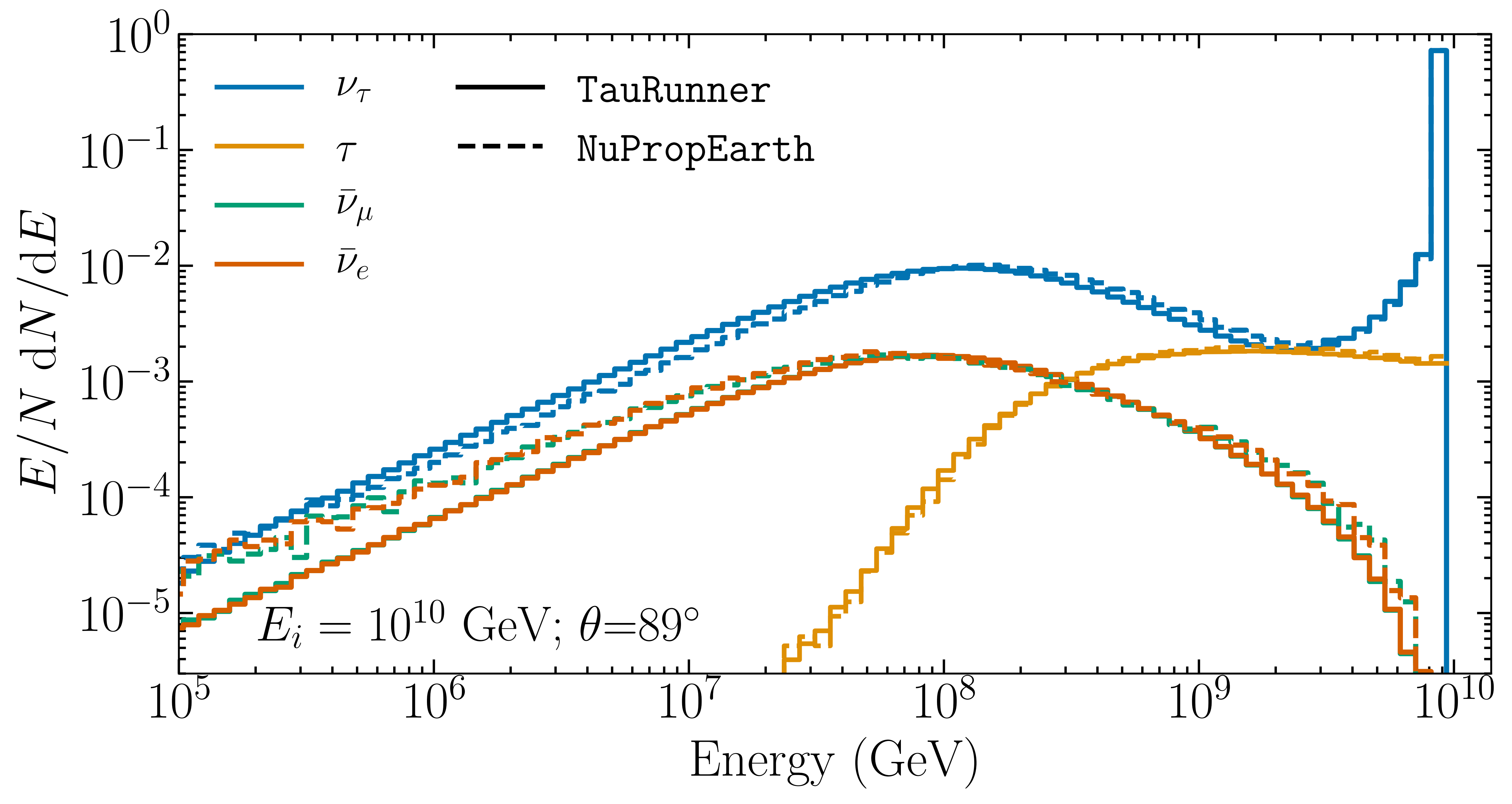
FIG. 2. Plot of the transmission of ν_μ and ν_τ through the Earth's. The transmission of ν_τ is essentially independent of their energy, as described in the text. The event rates are normalized to the maximum.



- Weak decays scale as ~m_ℓ^5. Tau lifetime is ~10^7 times shorter than the muon.
- Critical energy for taus (where decay- and interaction- length are equal) is ~1EeV in rock.
- Unabsorbed secondary flux of tau neutrinos

Ritz & Seckel 1988 Nucl. Phys. B304
Halzen & Saltzberg 1998 PRL 81, 4305
Beacom, Crotty, Kolb 2002 PRD 021302

New energies, new needs



IS, Lazar, Pizzuto et al arXiv 2110.14662

- Comprehensive neutrino MC generator at high-energies.

- Accounts for all relevant effects at this scale, including tau energy losses, polarization, and secondary production of neutrinos.

https://github.com/icecube/TauRunner

ANITA's Anomalous Events

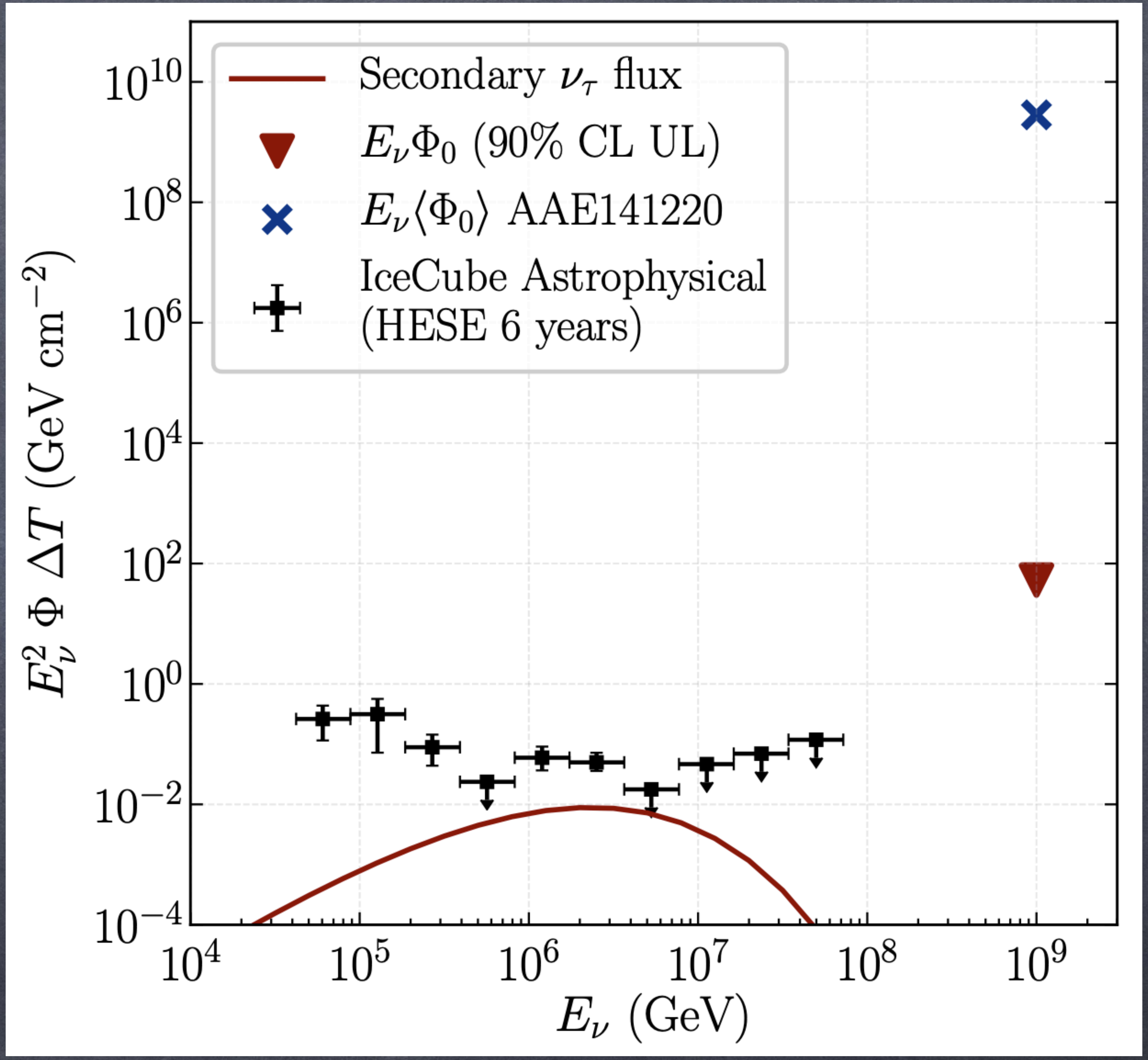
- ANITA reported 2 anomalous events seemingly coming from tau decay showers.

- Reported incoming angle is in tension with diffuse interpretations.

- Secondary tau neutrinos particularly effective for point-source fluxes.

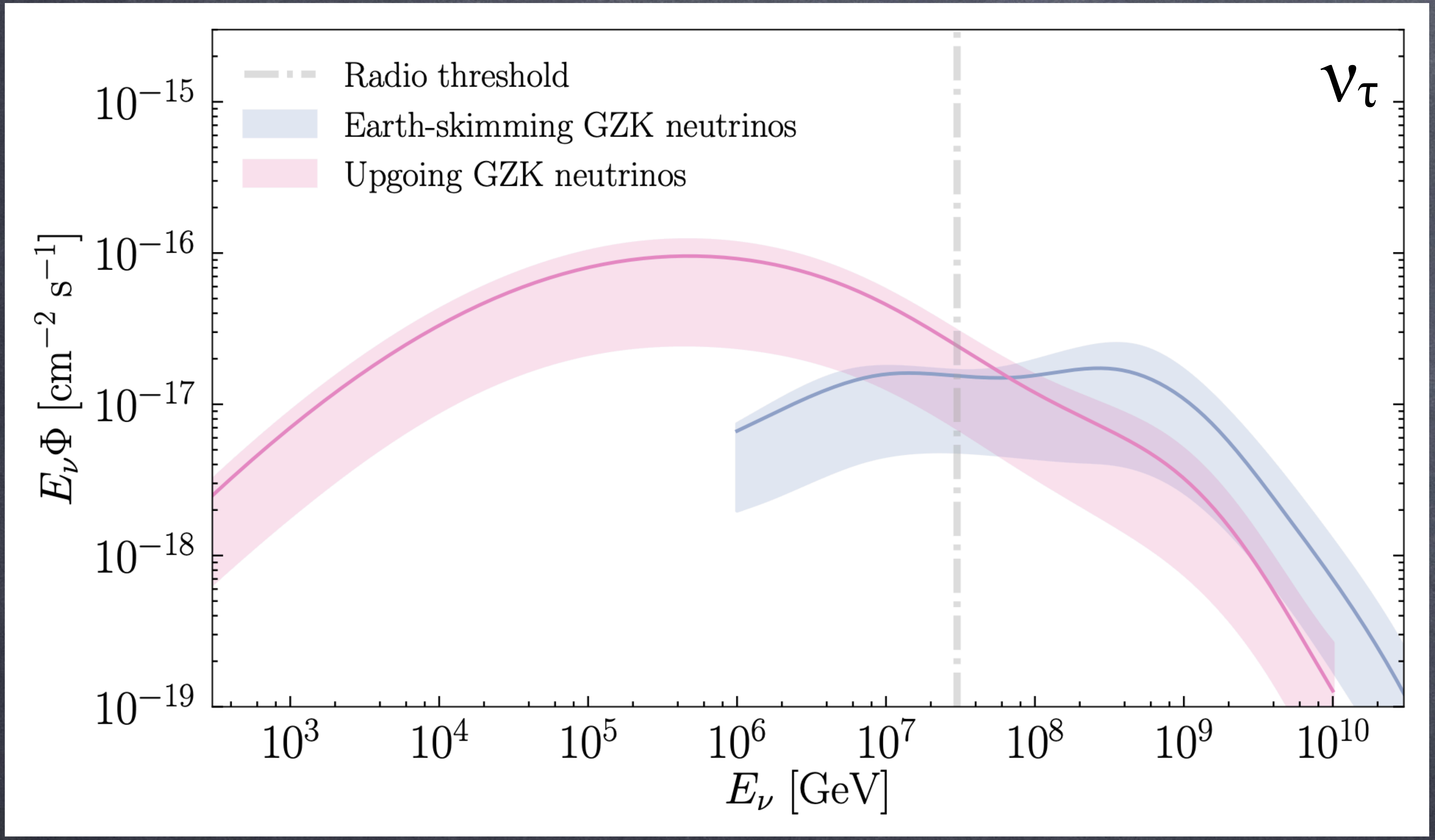
- Above 1 EeV, secondary neutrino distributions are degenerate with respect to primary energy.

- Allowed primary flux (maroon arrow) is orders of magnitude below expected flux to produce one event in ANITA-III (black hexagon)



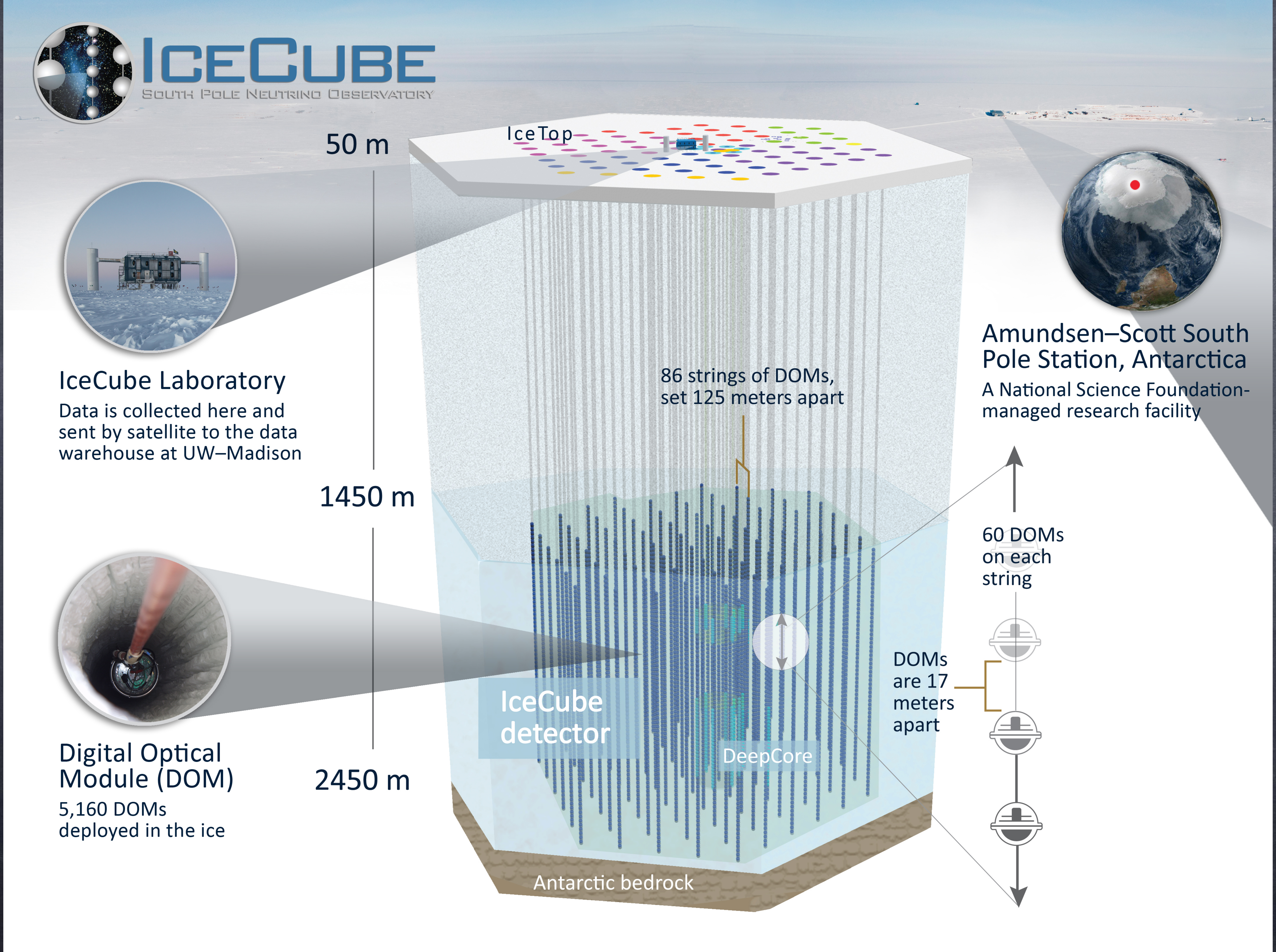
IS *et al* JCAP01(2020)012
IceCube Collaboration, ApJ v892, 01(2020)

Upgoing GZK neutrinos



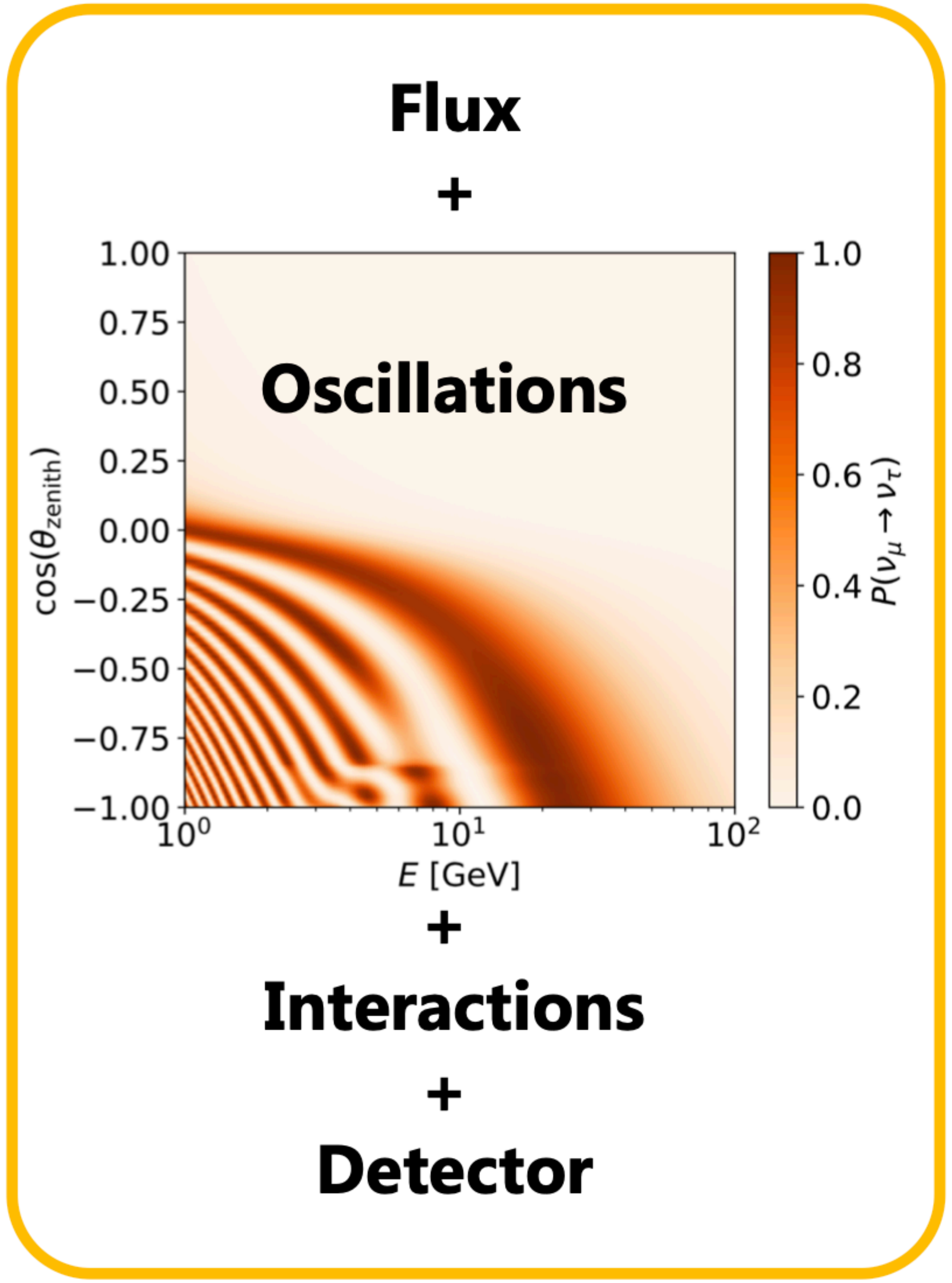
Argüelles, Halzen, Kheirandish, IS. 2203.13827

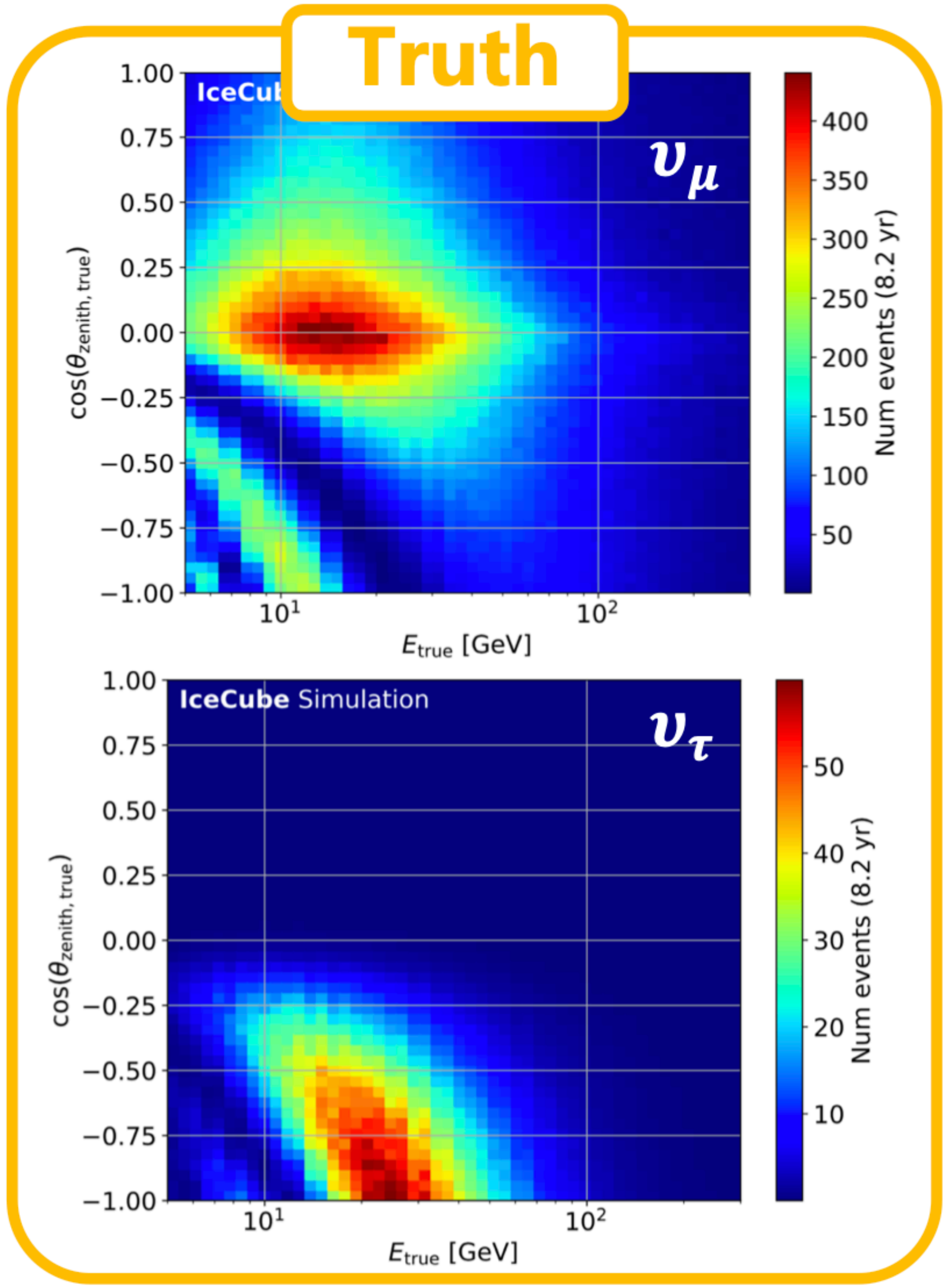
- EeV tau neutrinos emerge from Earth with O(PeV) energies.
- This is below the energy threshold for radio experiments but can be probed by existing detectors
- However, the astrophysical is a background for this measurement.
- Design of future experiments should account for this.

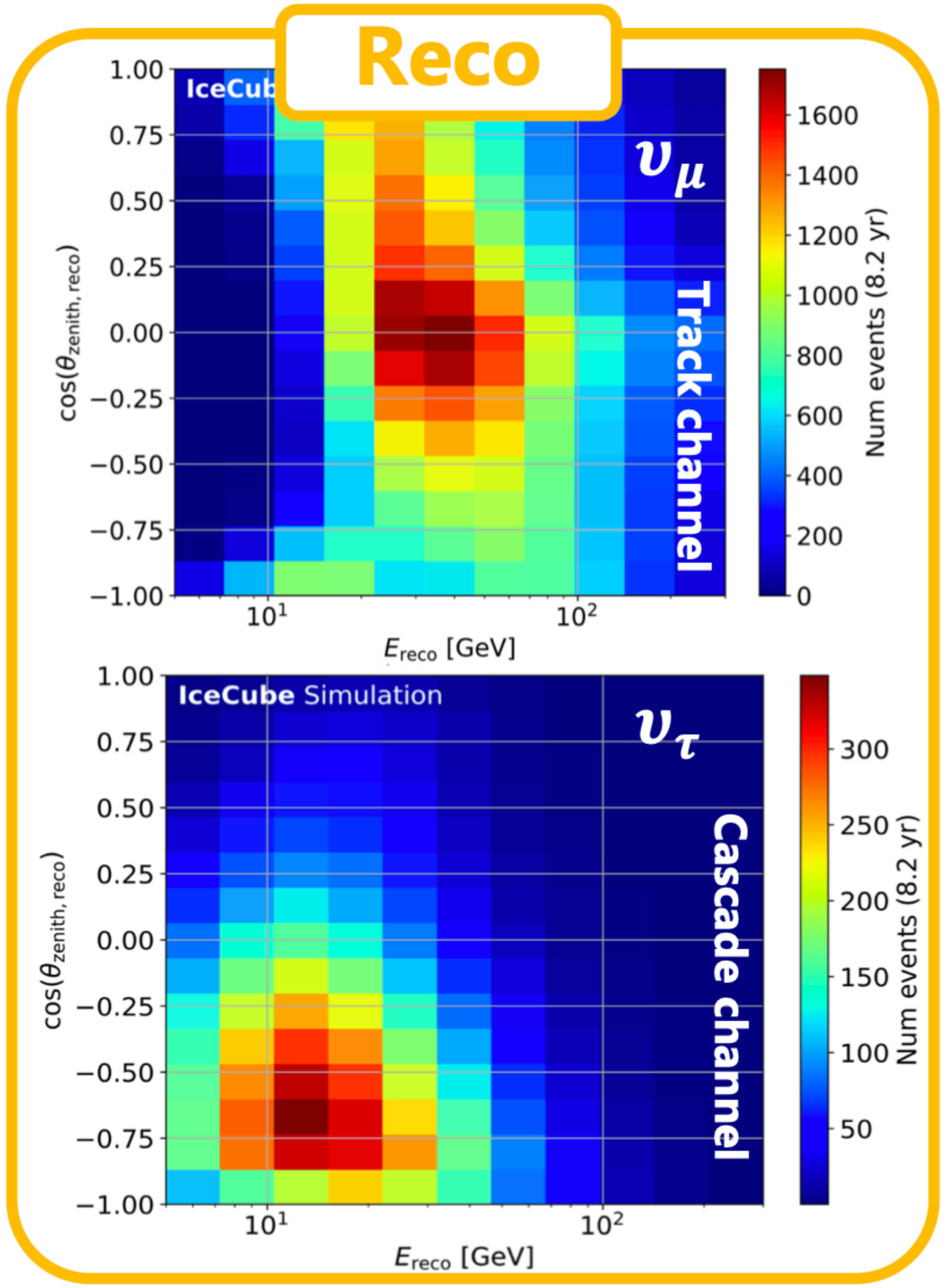

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station,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

Oscillations with DeepCore

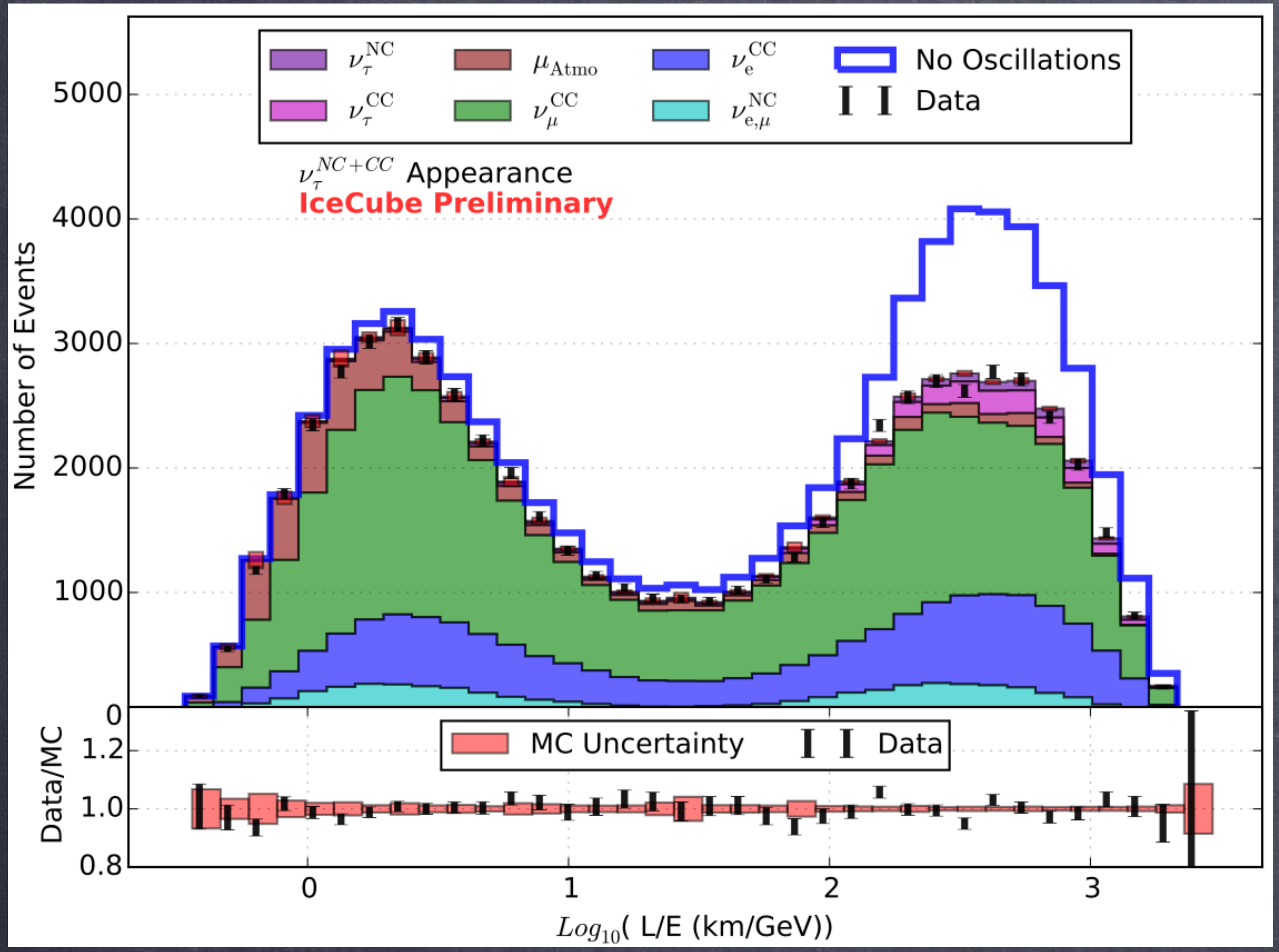
- Simultaneously observe ν_μ **disappearance** and ν_τ **appearance**
  - Operating above ~4 GeV $\nu_{\tau,CC}$ threshold
- Measure 3D distortions in reconstructed [energy, zenith, PID]

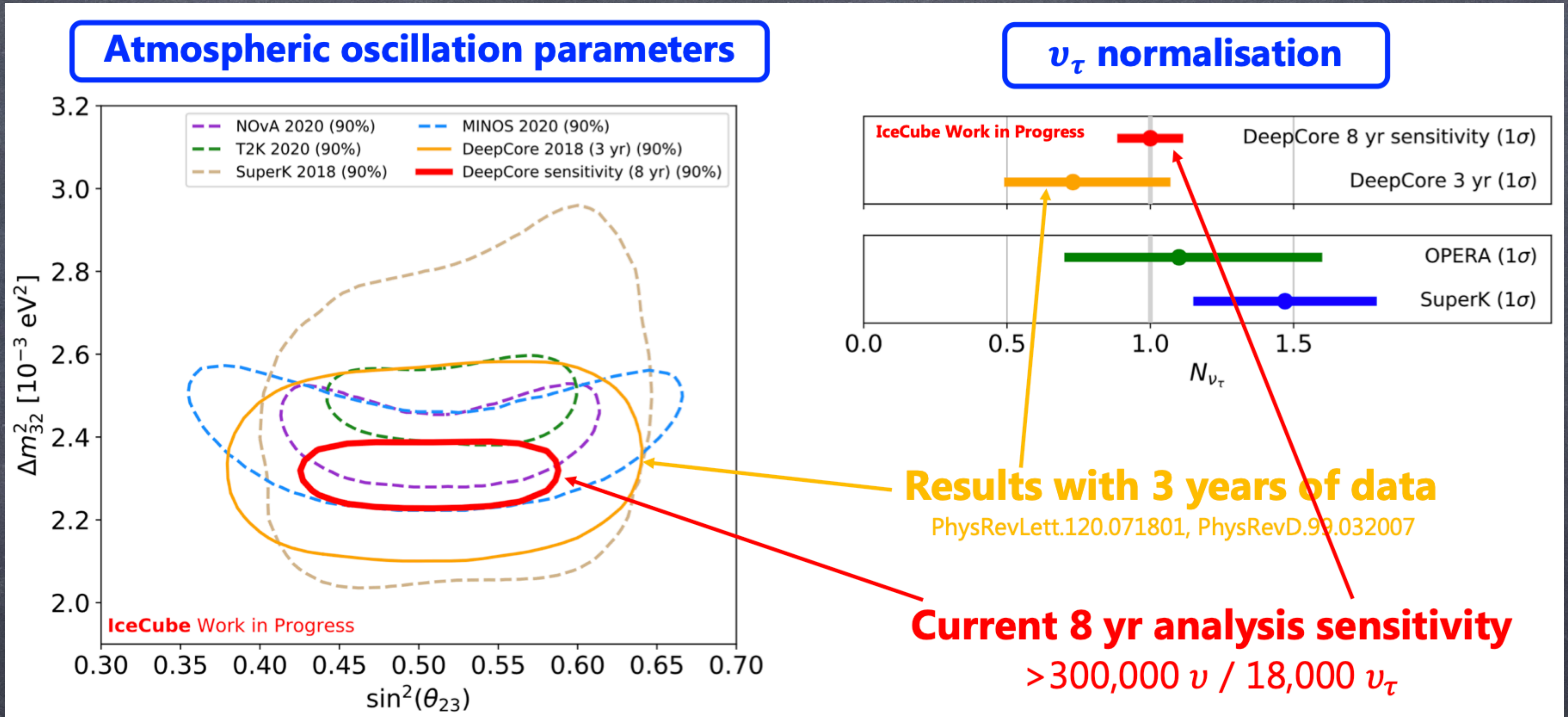






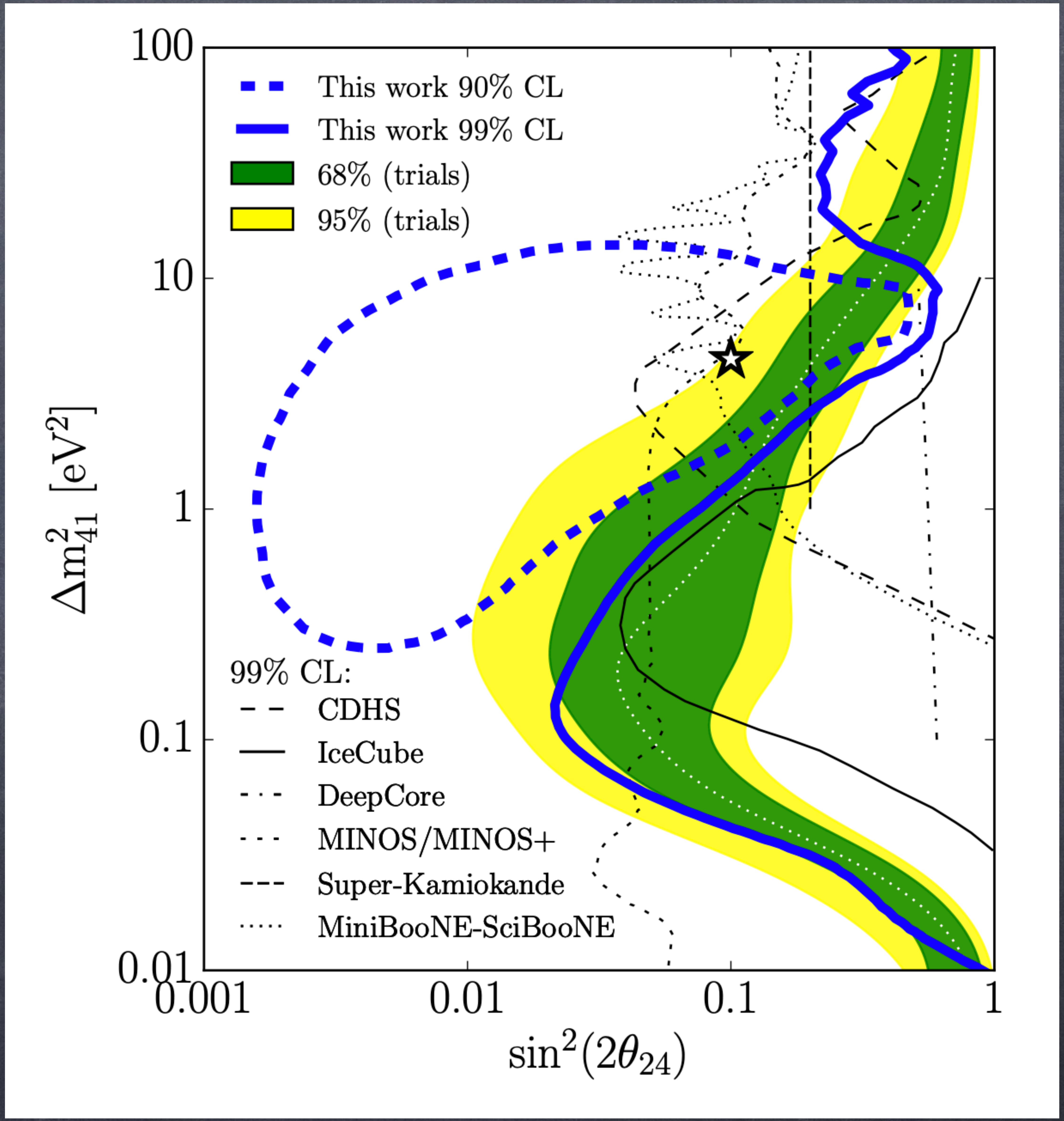
Oscillations with DeepCore





eV-scale steriles in IceCube

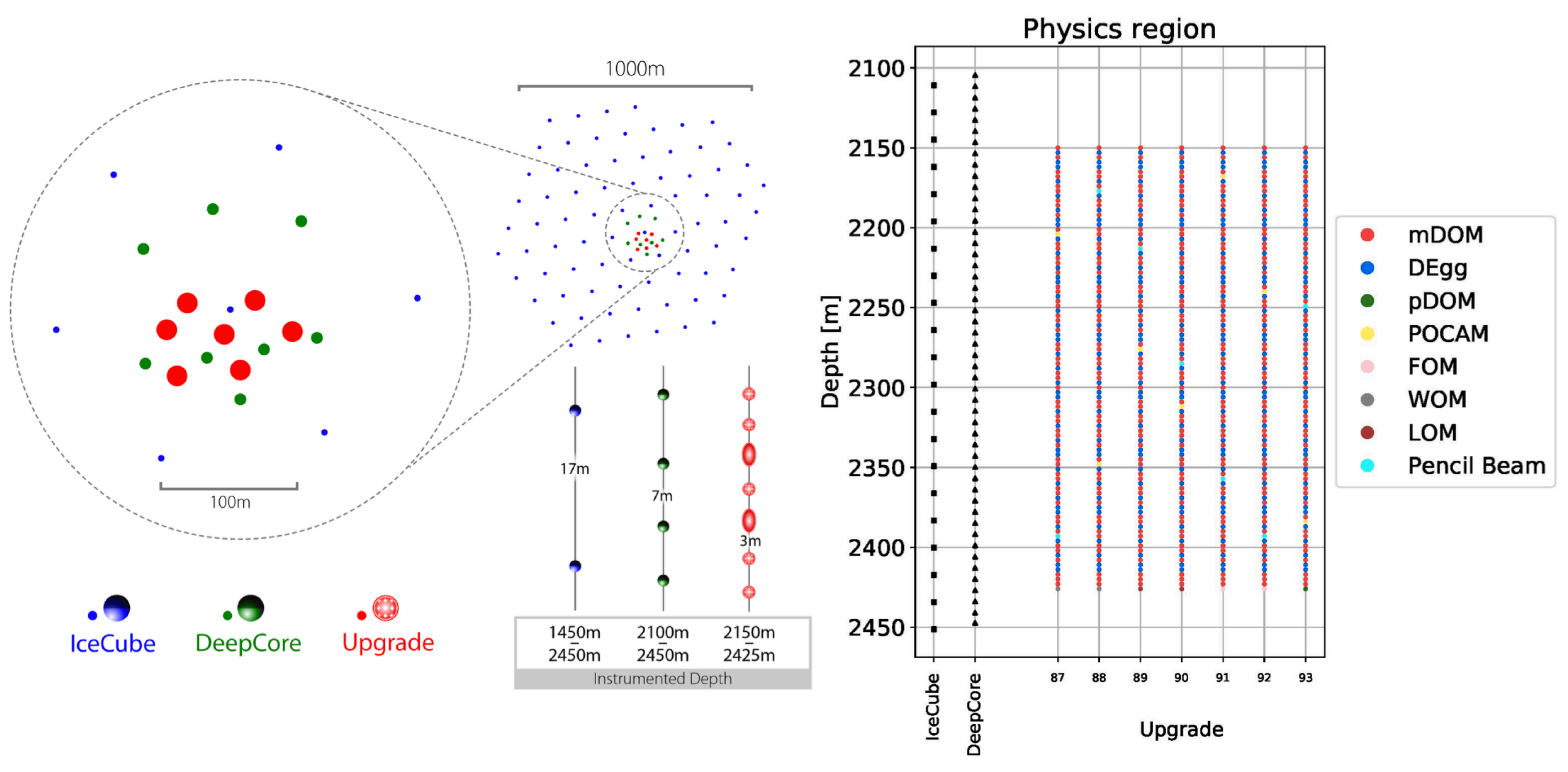
- Updated analysis with 8 years of data.
- ~305,735 muon neutrino events
- Best-fit: Δm^2_{41} = 4.5 eV^2 and $\sin^2(2\theta_{24})$ = 0.1 with a p-value of ~8%



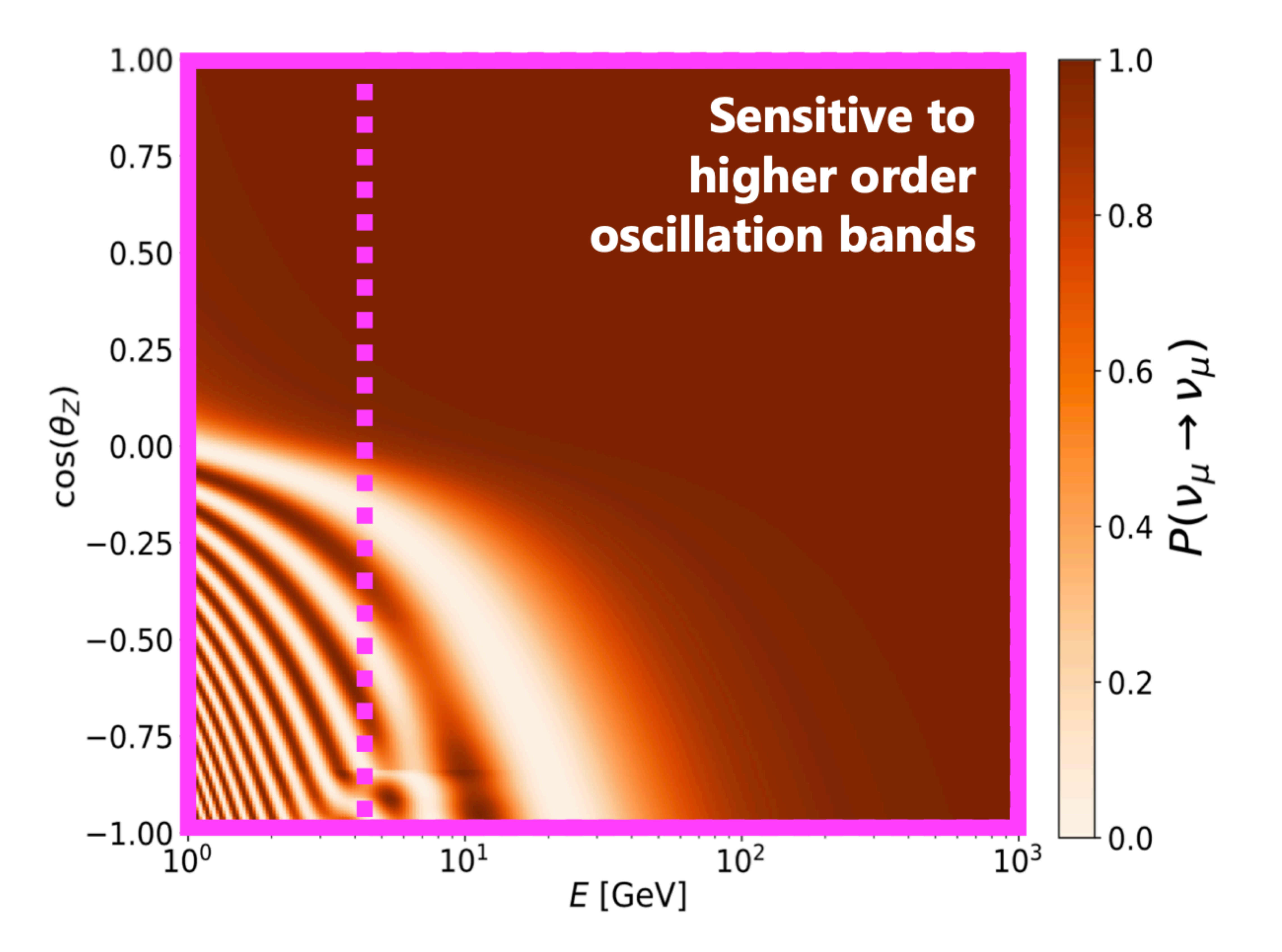
IceCube Collaboration:
Phys. Rev. Lett. 125, 141801 (2020)
Phys. Rev. D 102, 052009 (2020)

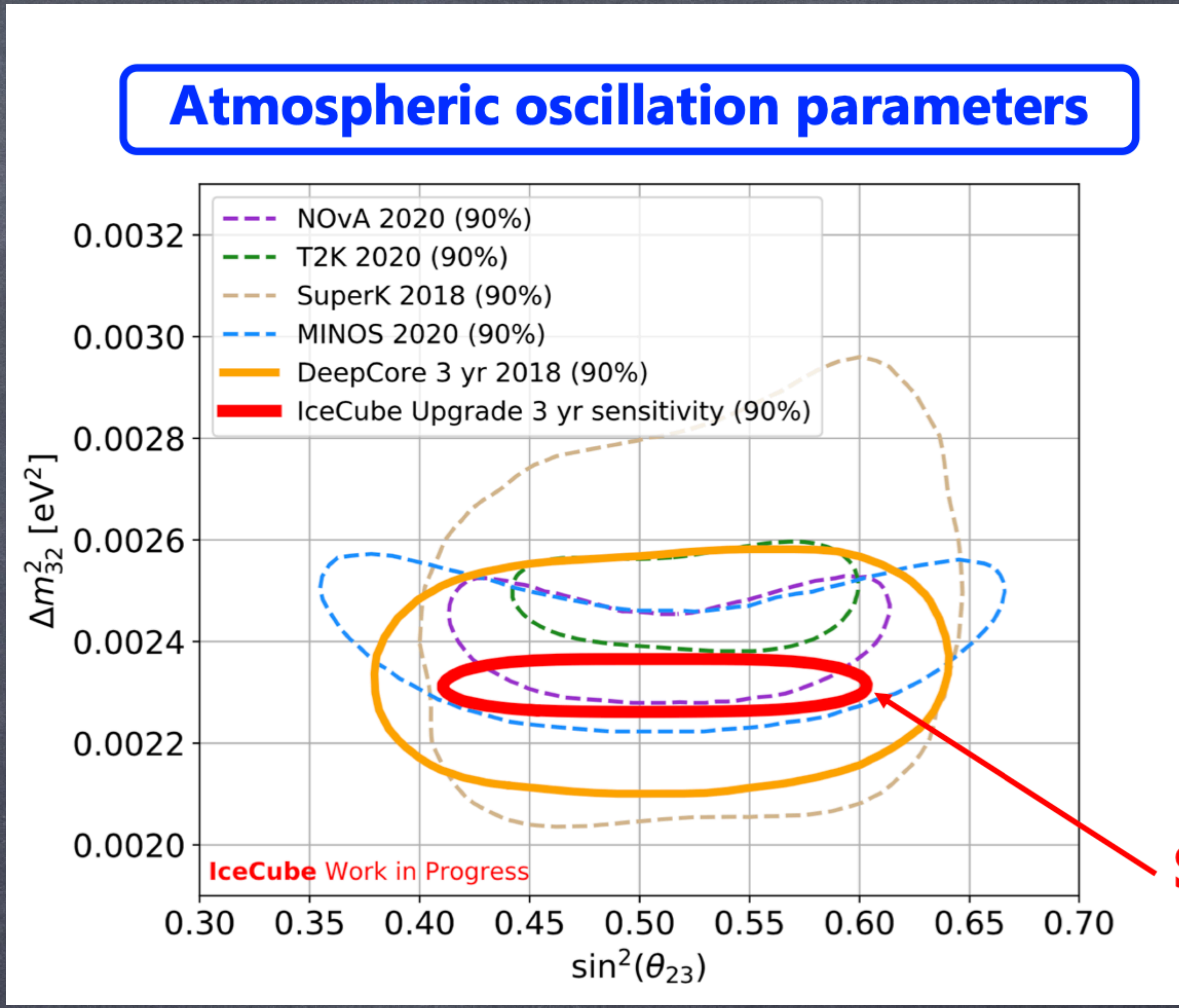
IceCube Upgrade

- 7 strings within the DeepCore volume
- Fully funded. Deployment expected in 2024-2025 season
- Multiple PMT configurations and calibration devices. Will control major systematic uncertainties (ice models)



IceCube Upgrade





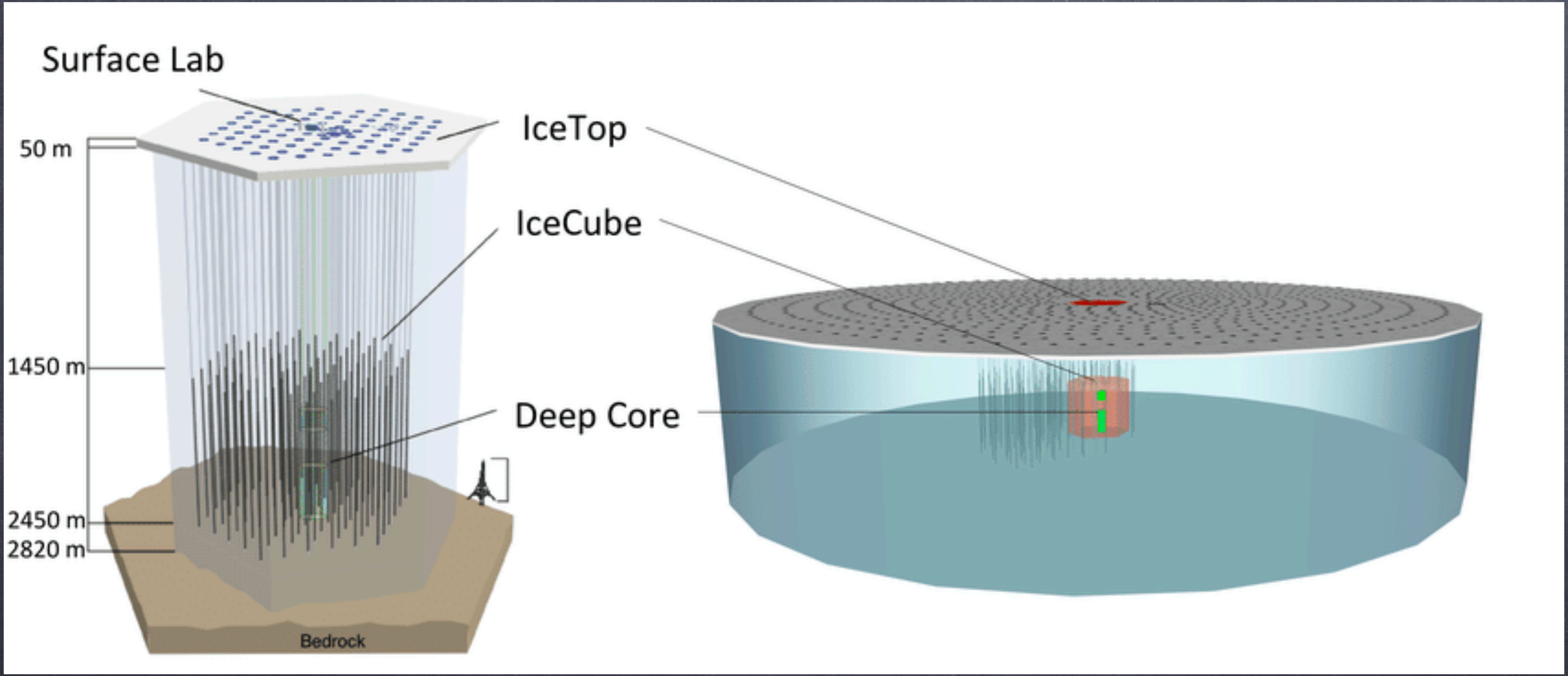
Lower neutrino energy threshold (~1GeV)

Conclusions

- IceCube measured an astrophysical neutrino flux extending up to ~10 PeV and will soon be joined by a network of telescopes.
- Flavor composition is an important tool for the discovery of new physics.
- Precise characterization of this flux requires a new generation of experiments.
- Better simulation of neutrino propagation physics at extreme energies provides new opportunities
- We need: more data, more experiments, more telescopes, better modeling, better simulations in the UHE neutrino sector.

Thank you

IceCube-Gen2



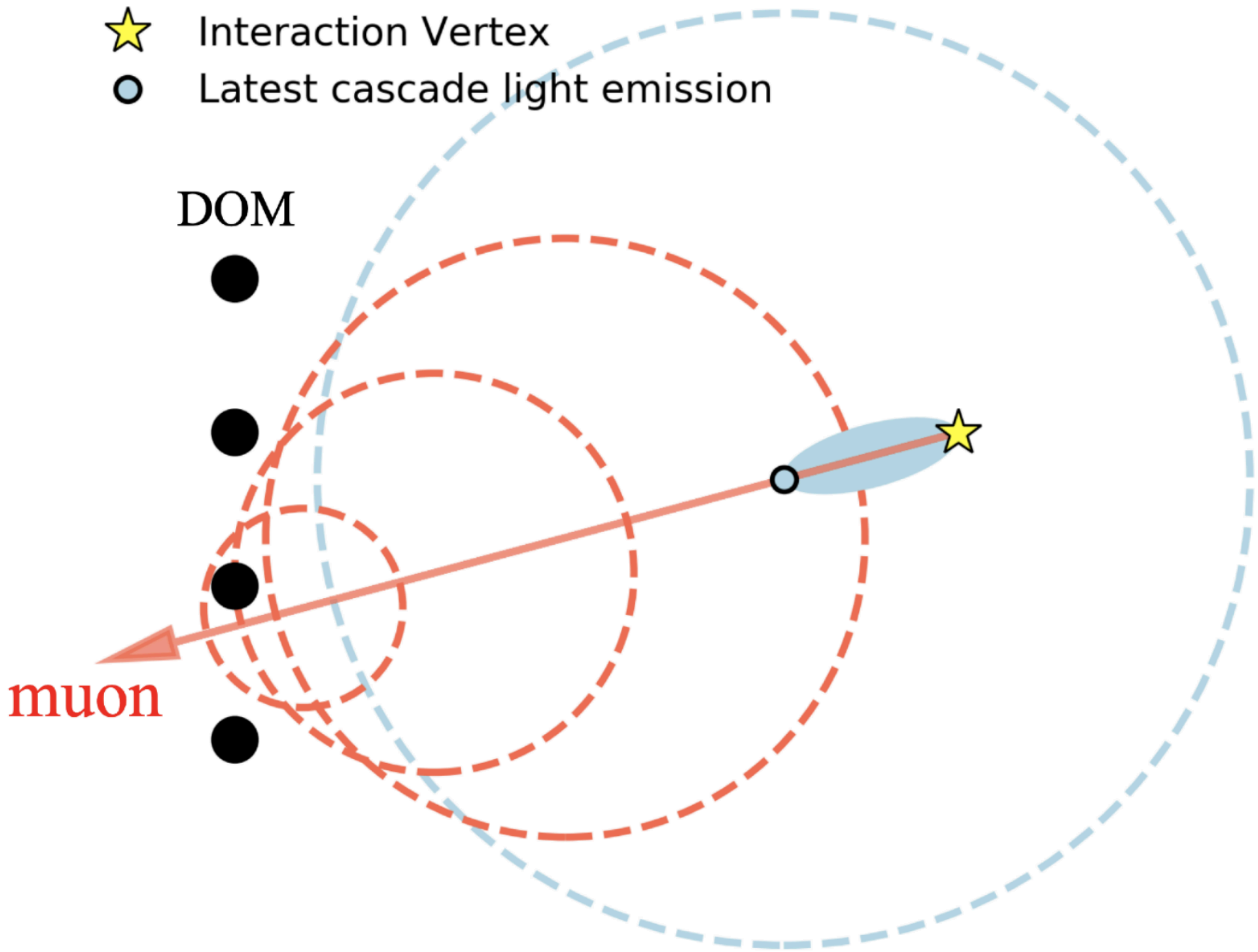
Glashow

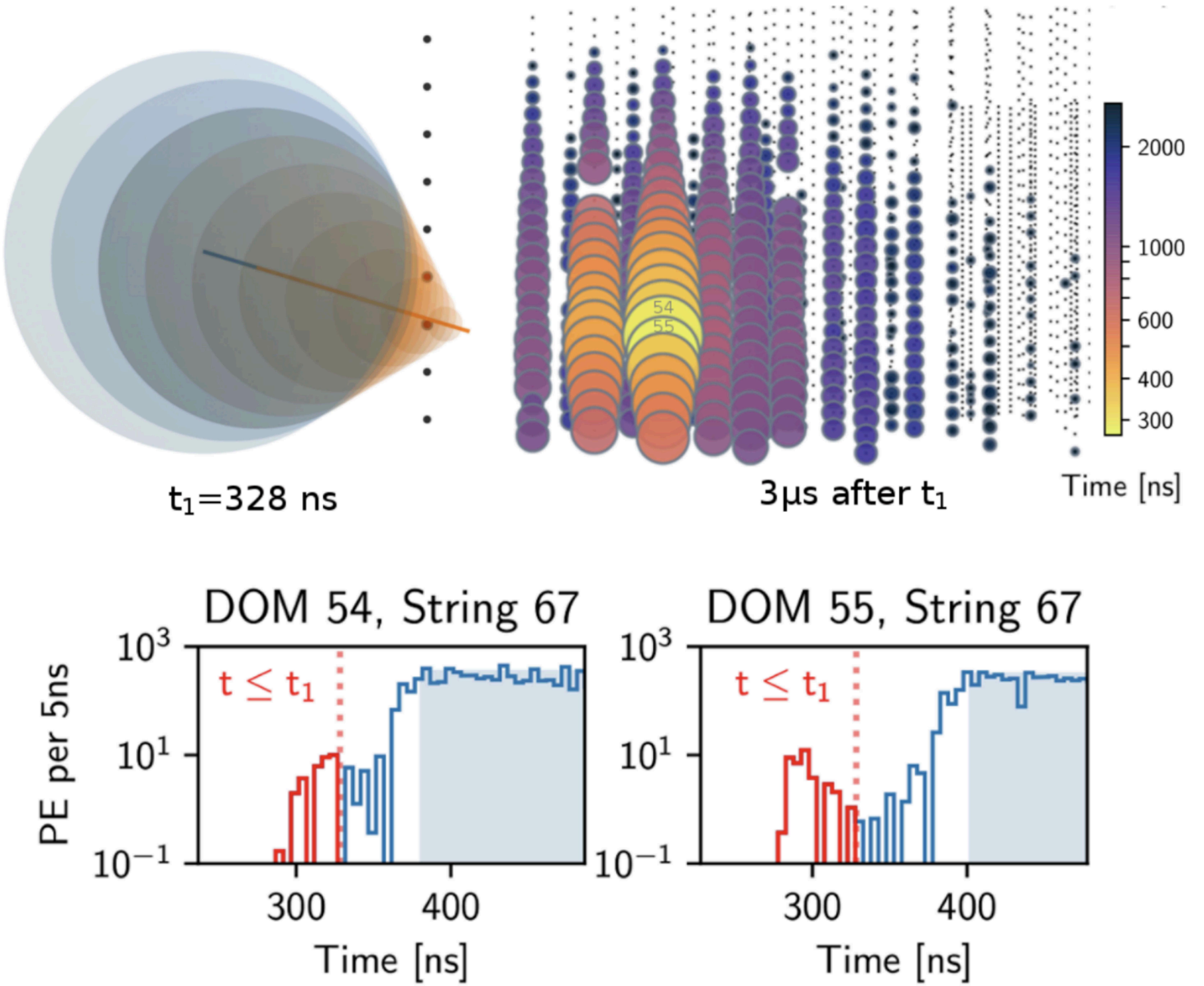
Signal:
hadronic (quark-antiquark decay of the W)

Or

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

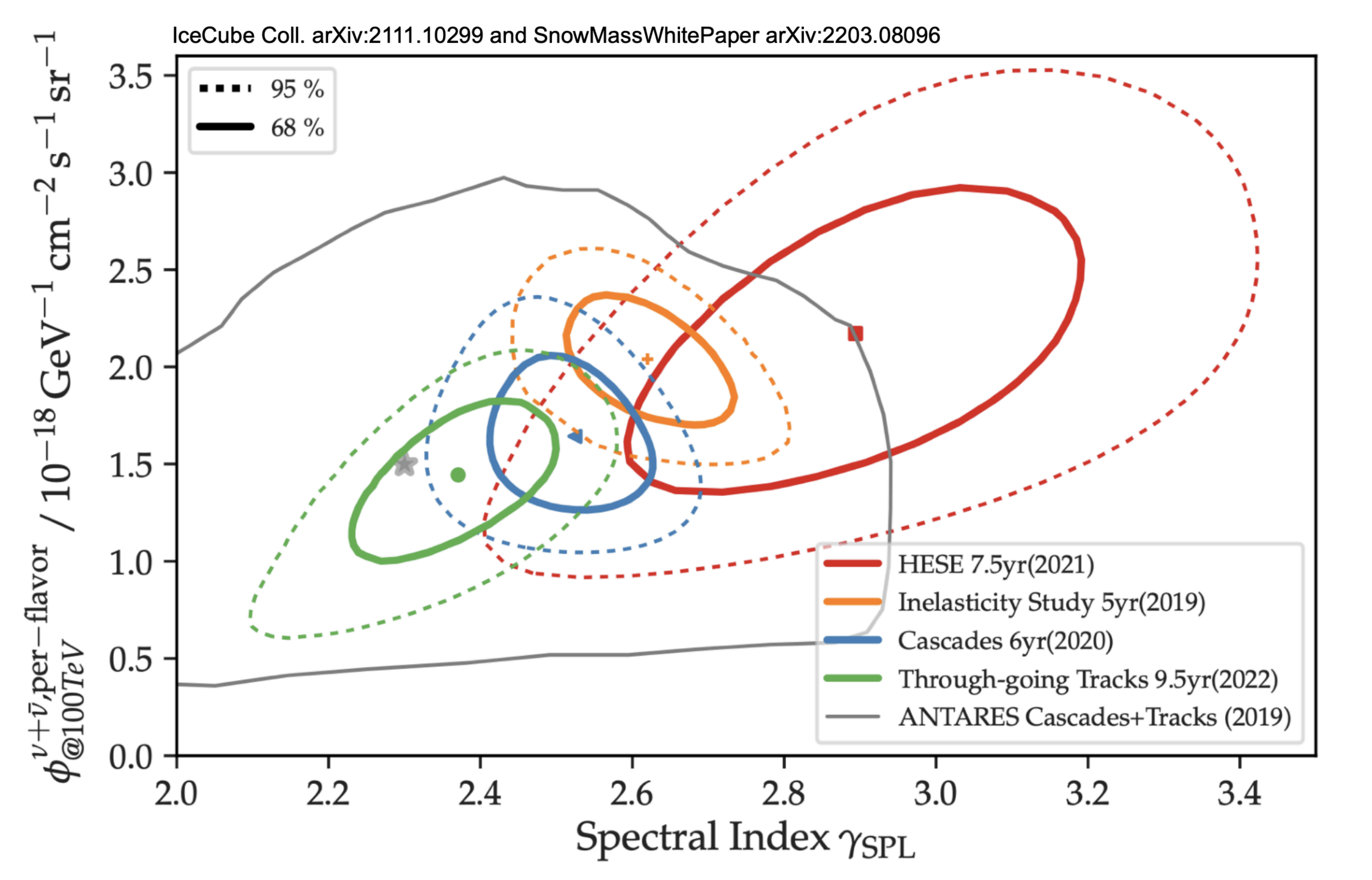
muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)



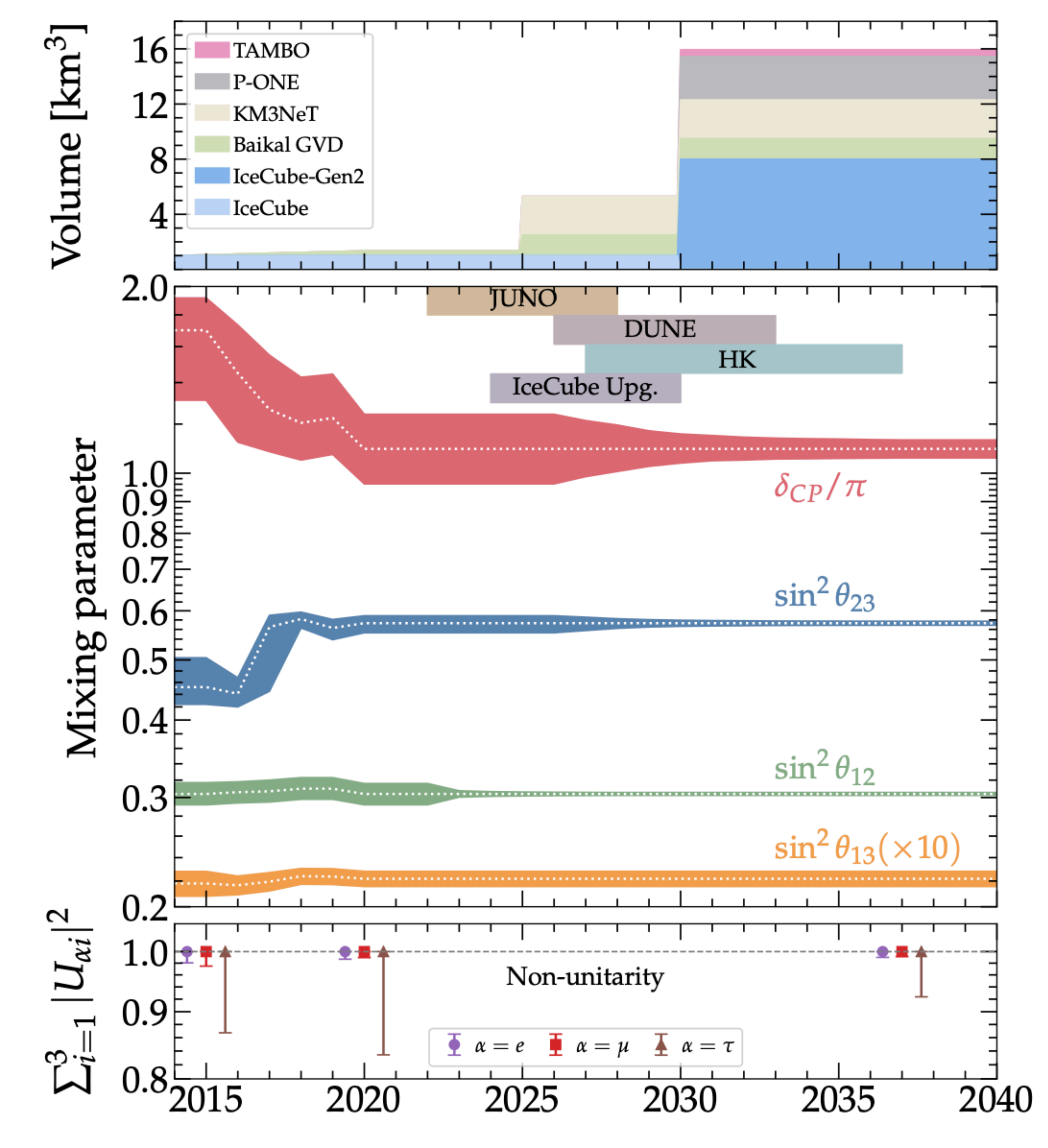


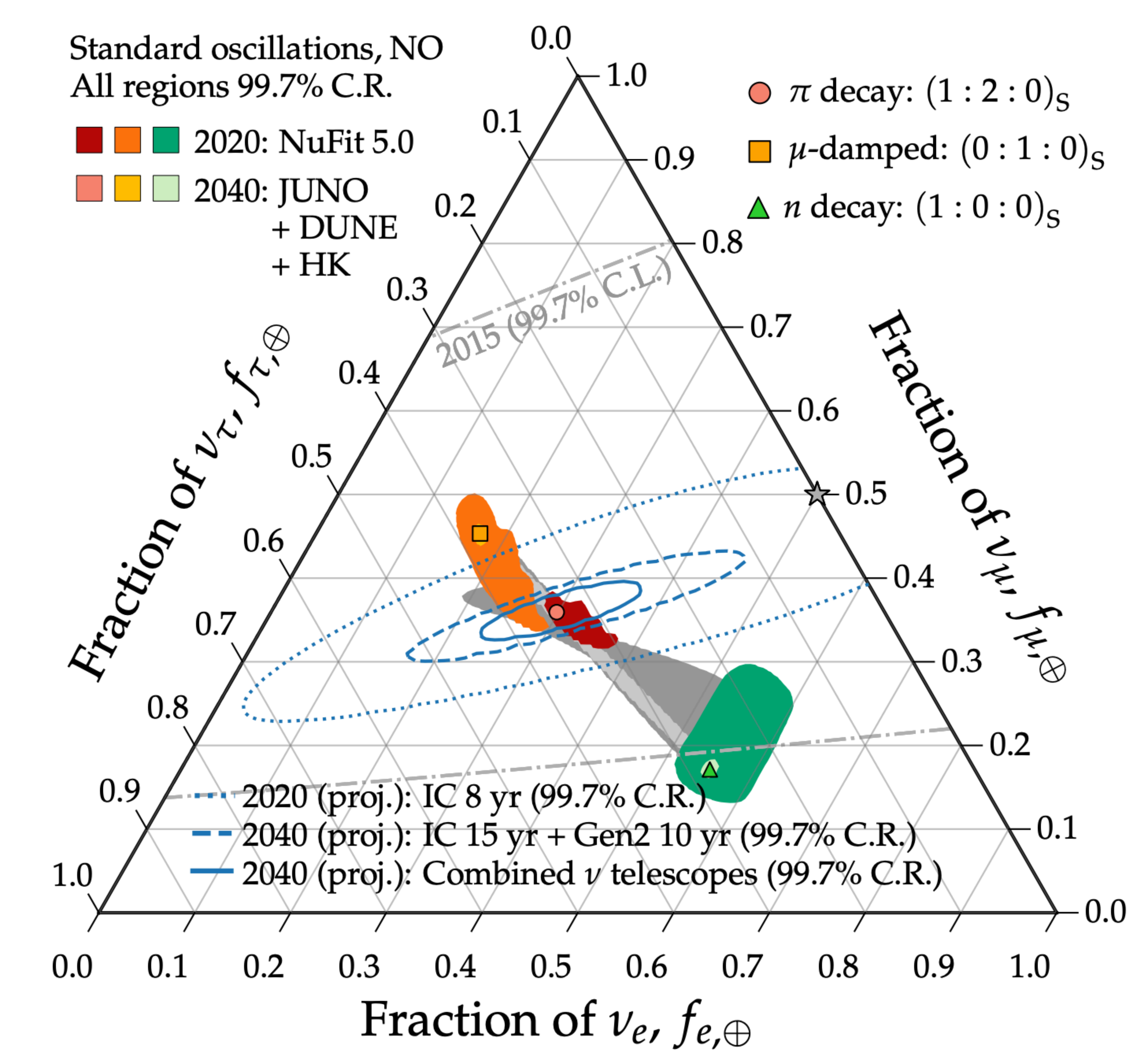
54
55
2000
1000
600
400
300
Time [ns]
t₁=328 ns
3μs after t₁
DOM 54, String 67
DOM 55, String 67
t ≤ t₁
t ≤ t₁
PE per 5ns
10³
10¹
10⁻¹
300
400
Time [ns]
Time [ns]

Astro measurements



Flavors in the future





Song, Li, Argüelles, Bustamante, Vincent 2012.12893

Astrophysical flavor: A probe of Lorentz violating effects

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

Dimension

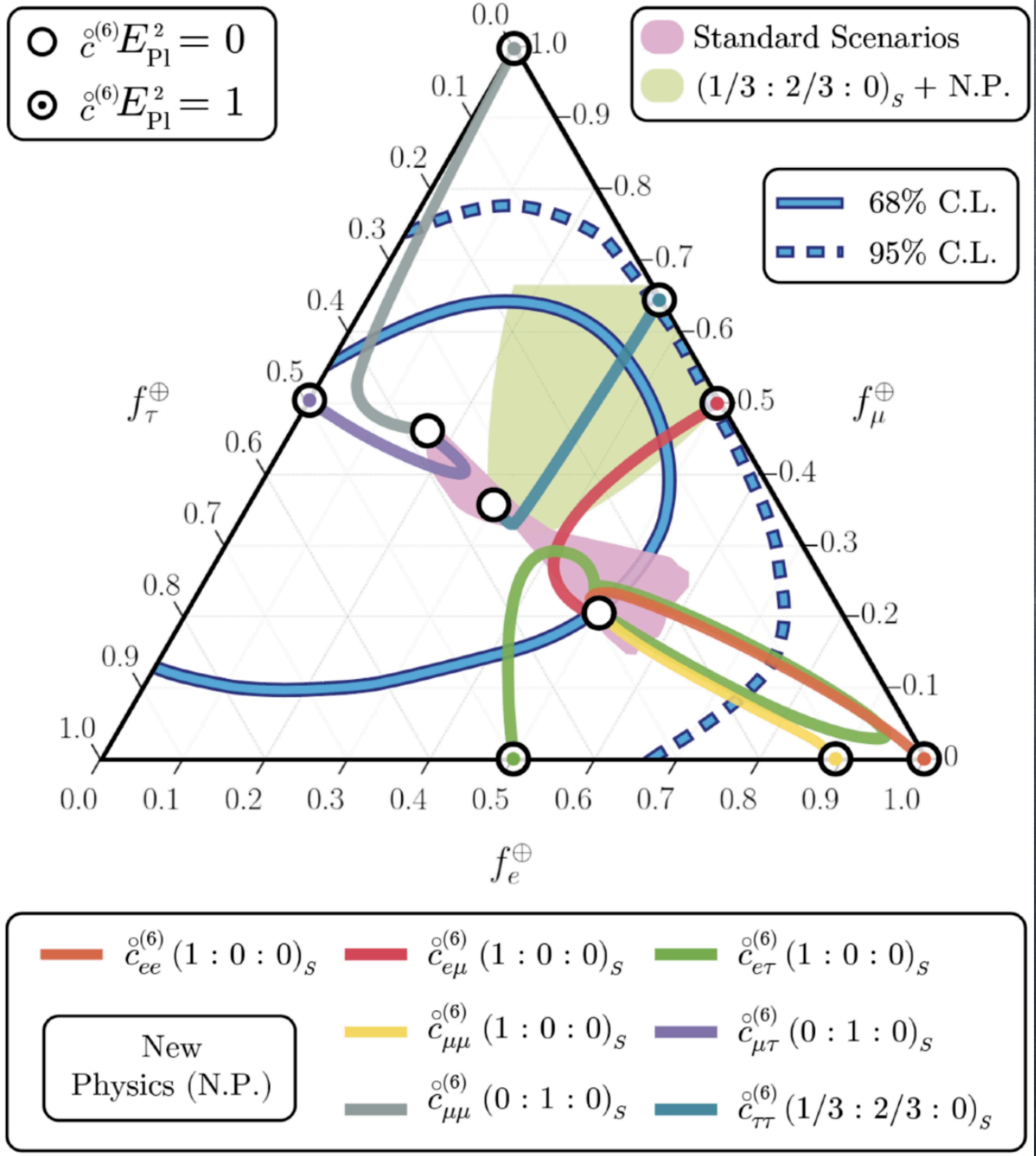
Standard Mixing

New Physics Terms

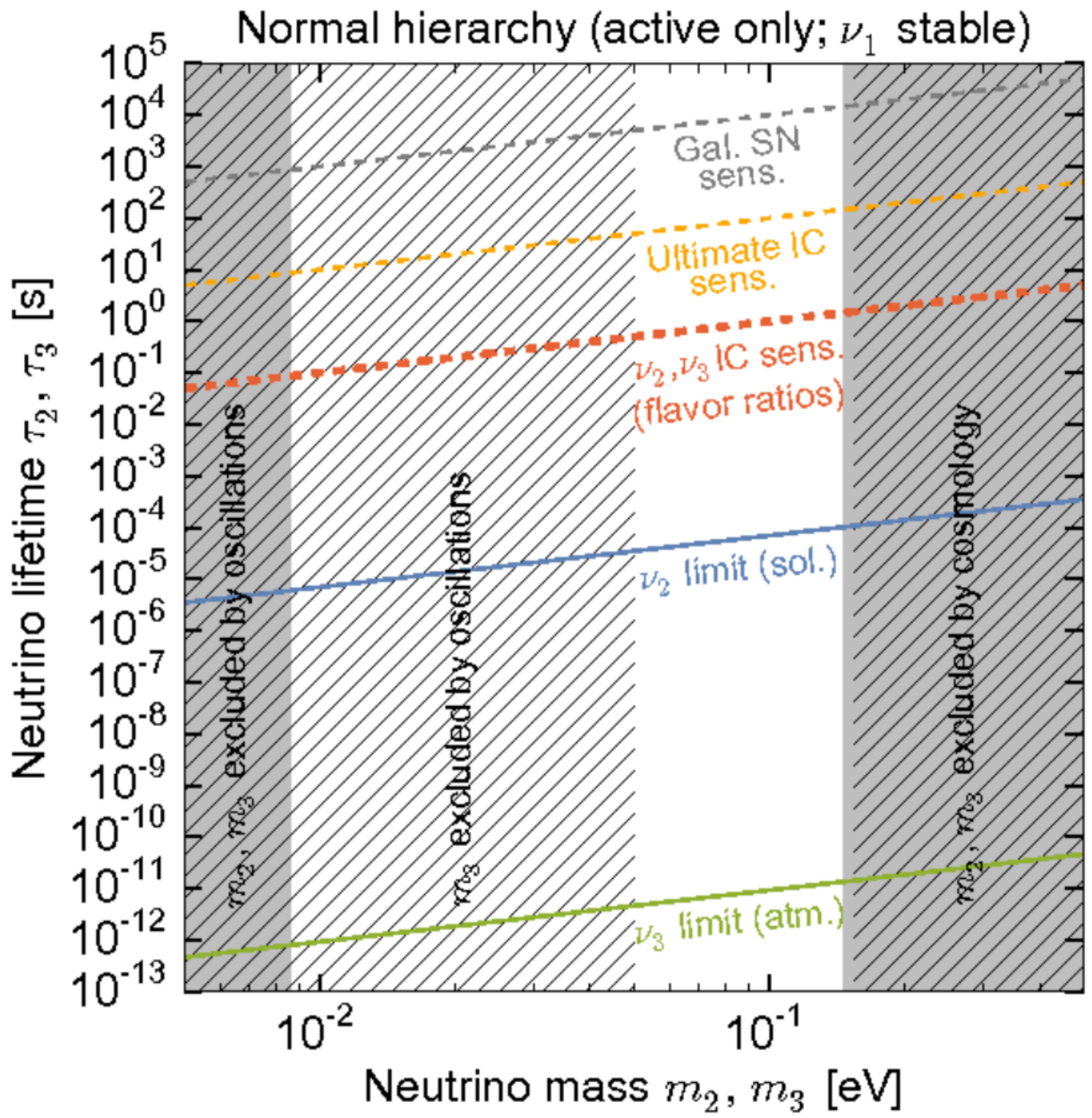
$(1:2:0)$ **pion**

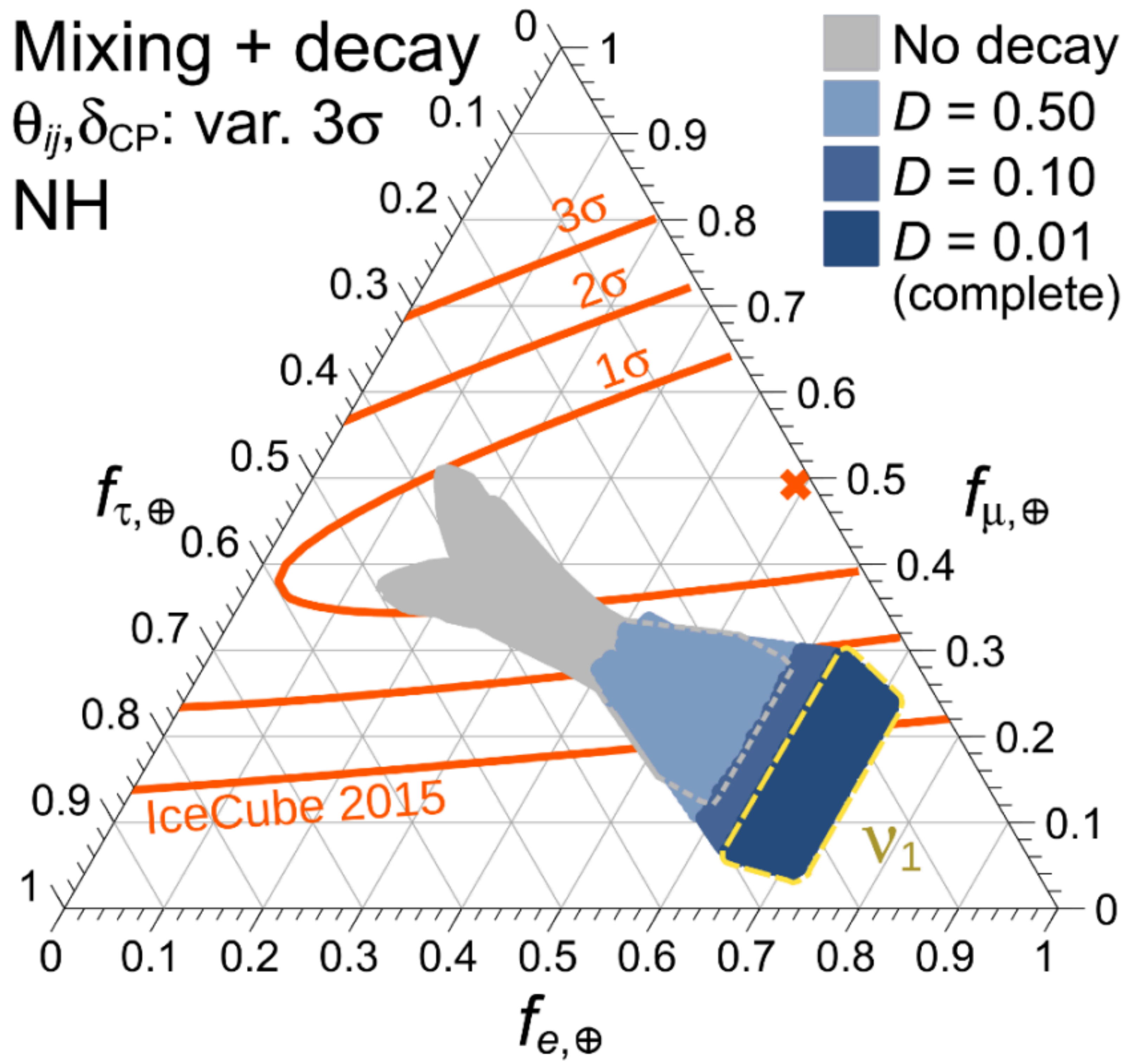
$(0:1:0)$ **neutron**

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



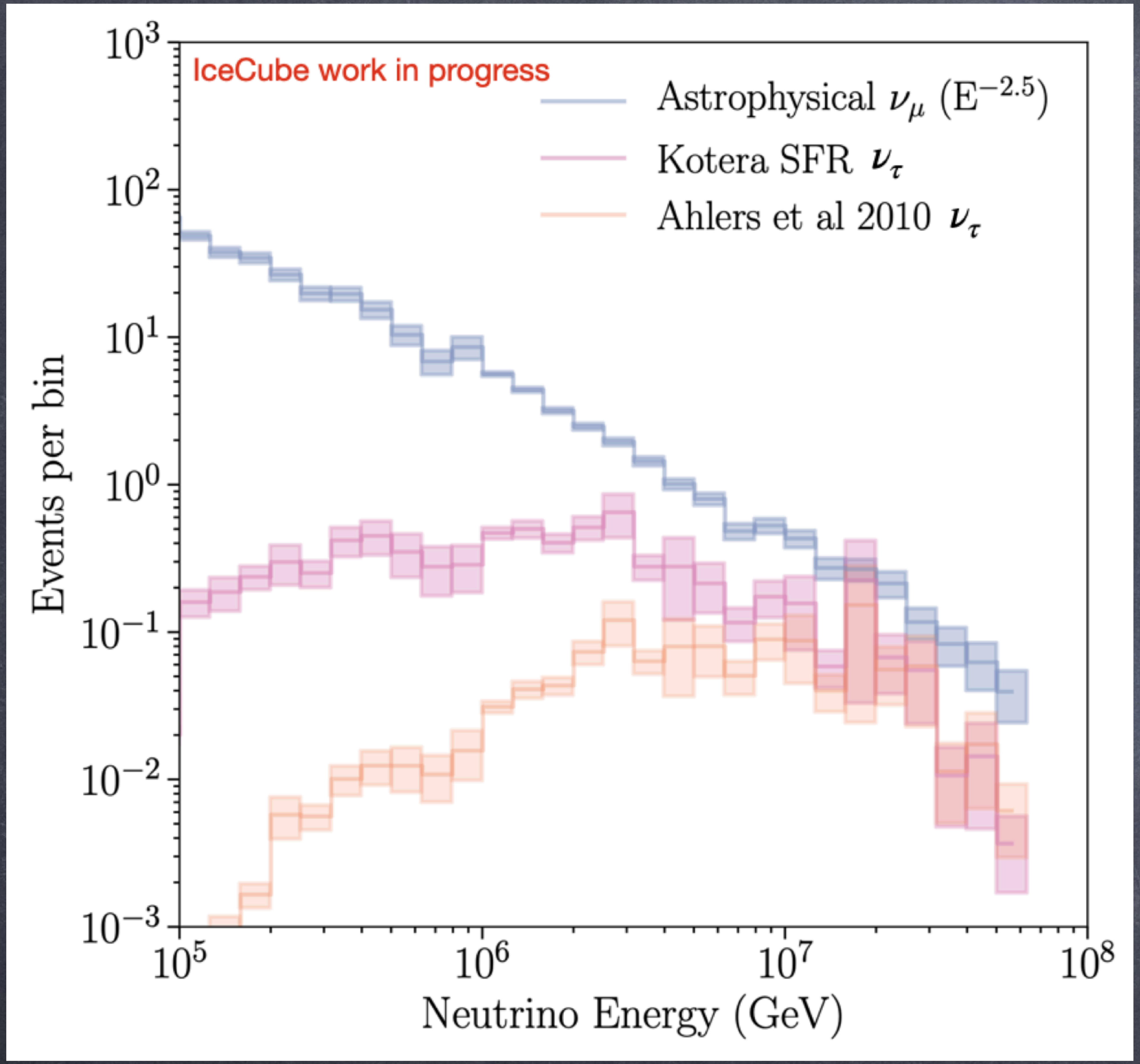
IceCube collaboration arXiv:2111.04654





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

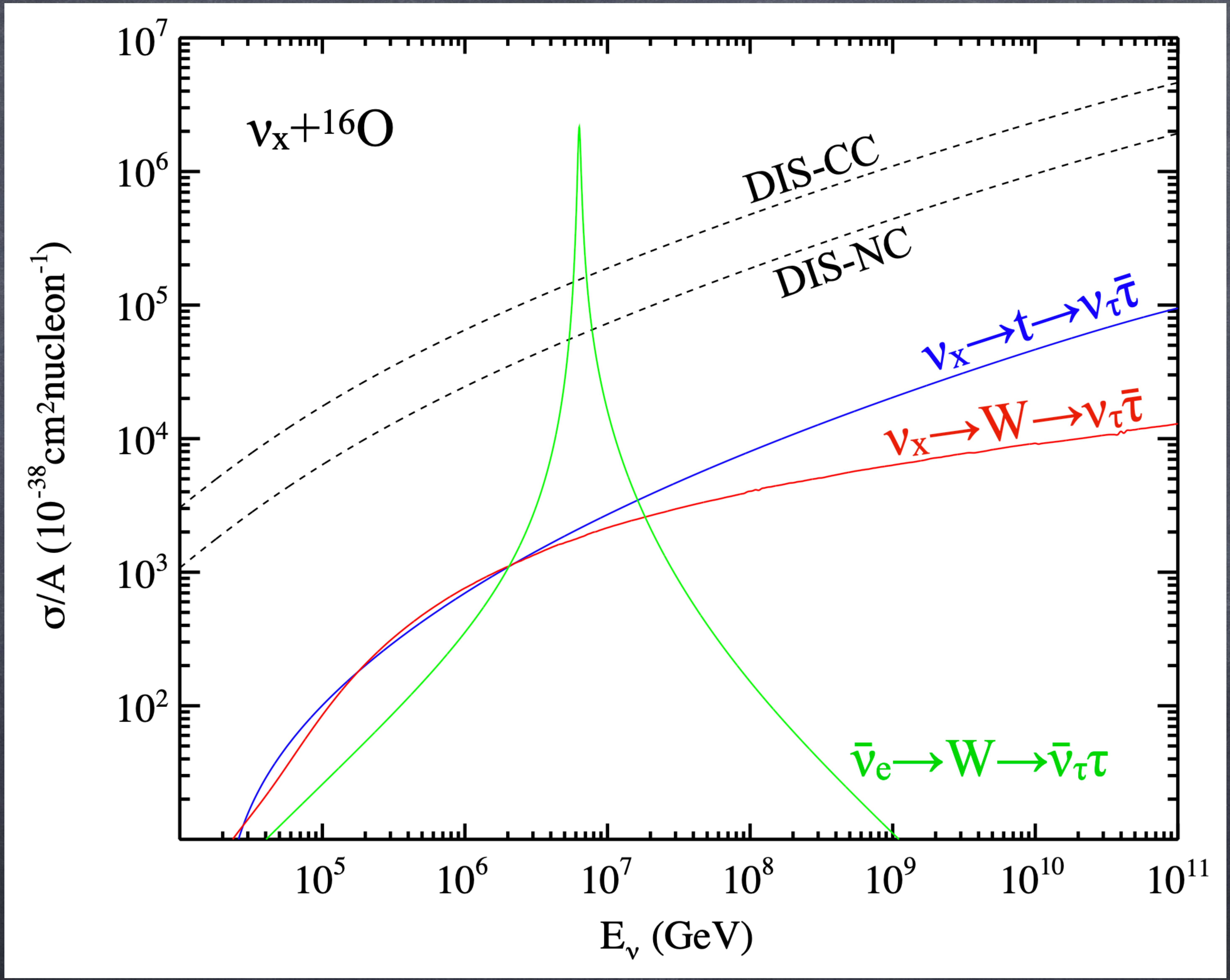
Upgoing GZK neutrinos



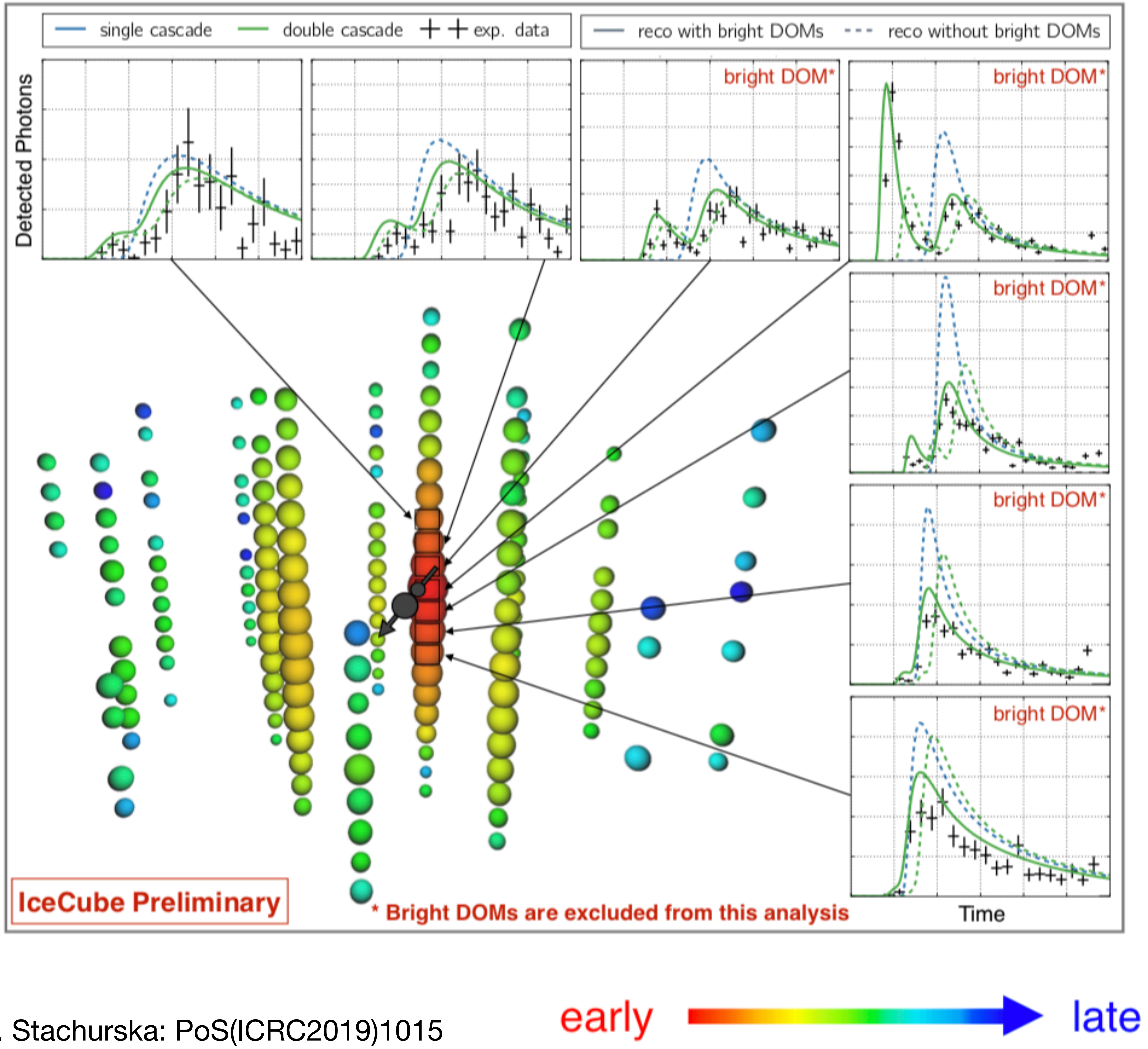
IS for the IceCube Collaboration
(PoS2021) DOI: 10.22323/1.395.1170

- Performing analysis in IceCube to search for this signal.
- Secondary tau neutrino signal contributes equally to rate at detector above ~few PeV

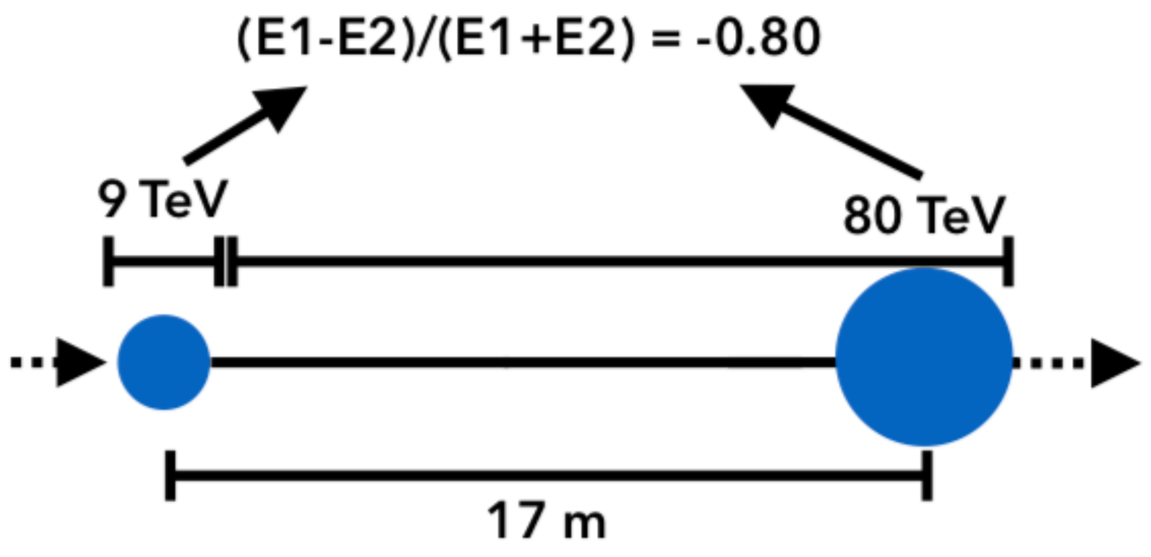
Tau Appearance cross sections



First astrophysical tau-neutrino candidate



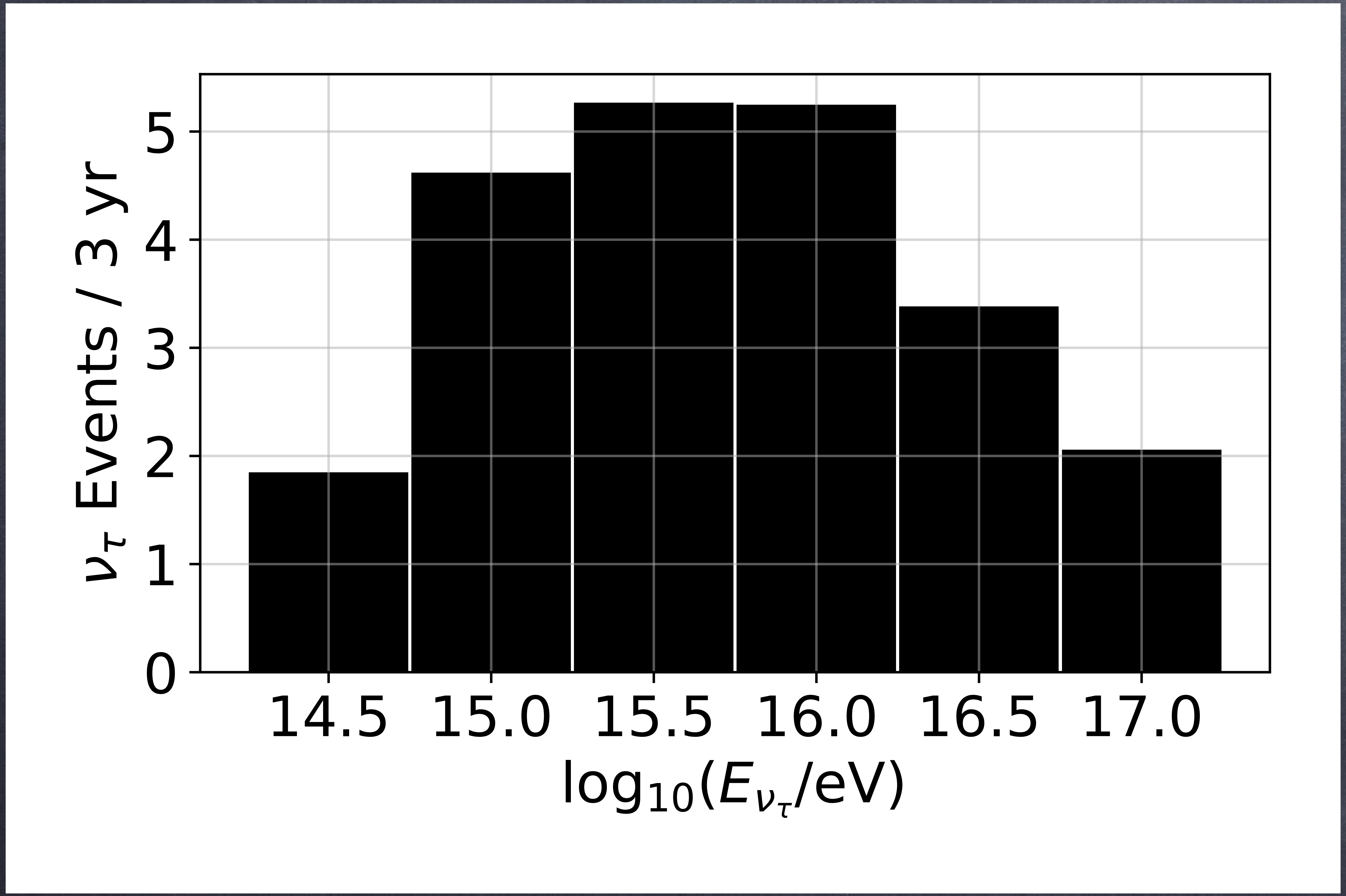
- Event identified in three analyses. Aptly named 'Double Double'.
- Double pulse shape clearly visible.
- Observed light arrival time pattern favors the double cascade hypothesis.



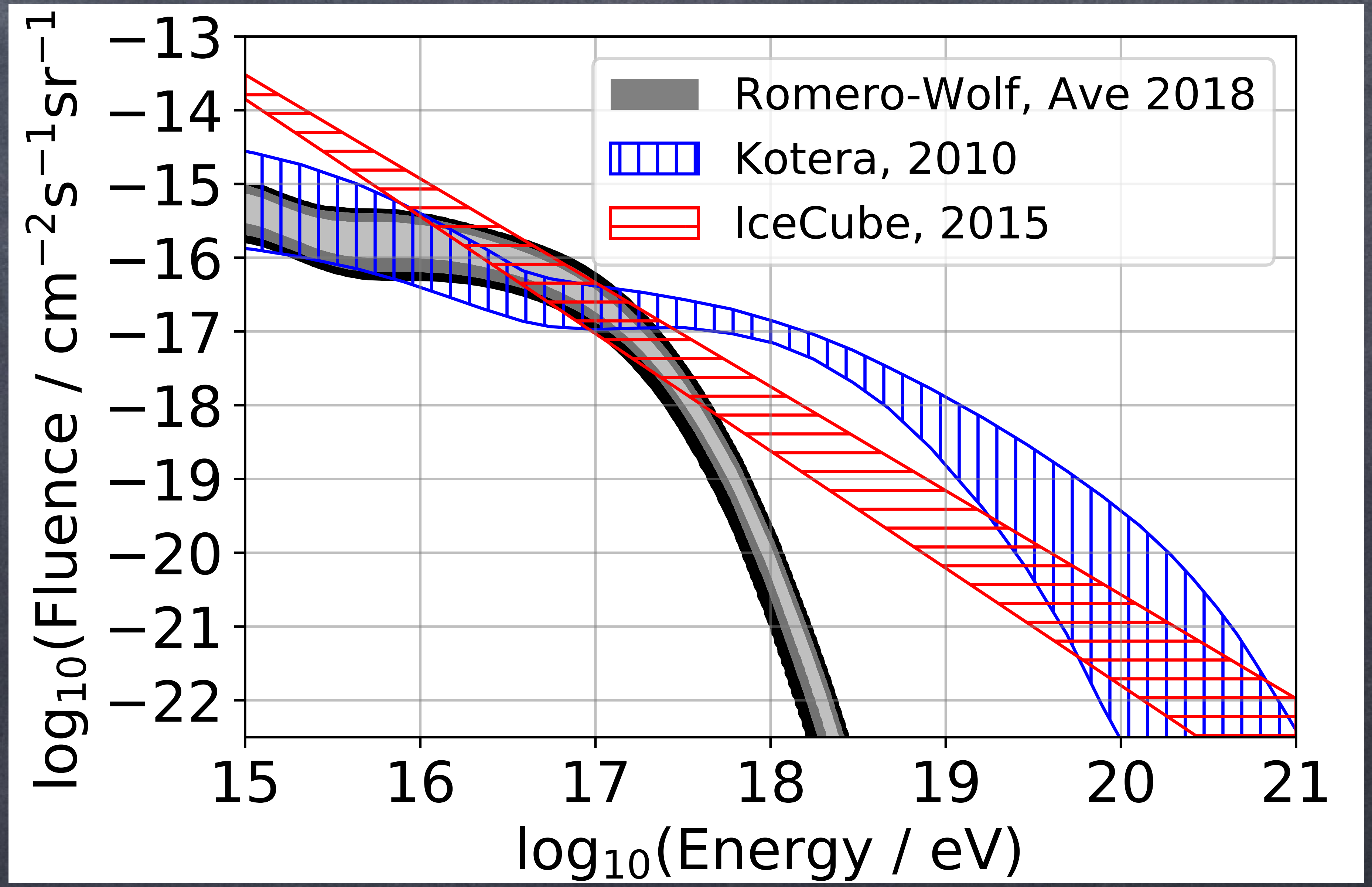
- Dedicated resimulations assuming best-fit HESE spectrum show 97% of Double-Double like events are ν_τ-induced.

J. Stachurska: PoS(ICRC2019)1015

- 21 events in 3 years with a peak at 3 PeV



Romero-Wolfet al., arXiv:2002.06475v1



Romero-Wolf et al., arXiv:2002.06475v1