High Energy Neutrino Astronomy

VSON 2022

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2022.07.19

CHIBA UNIVERSITY

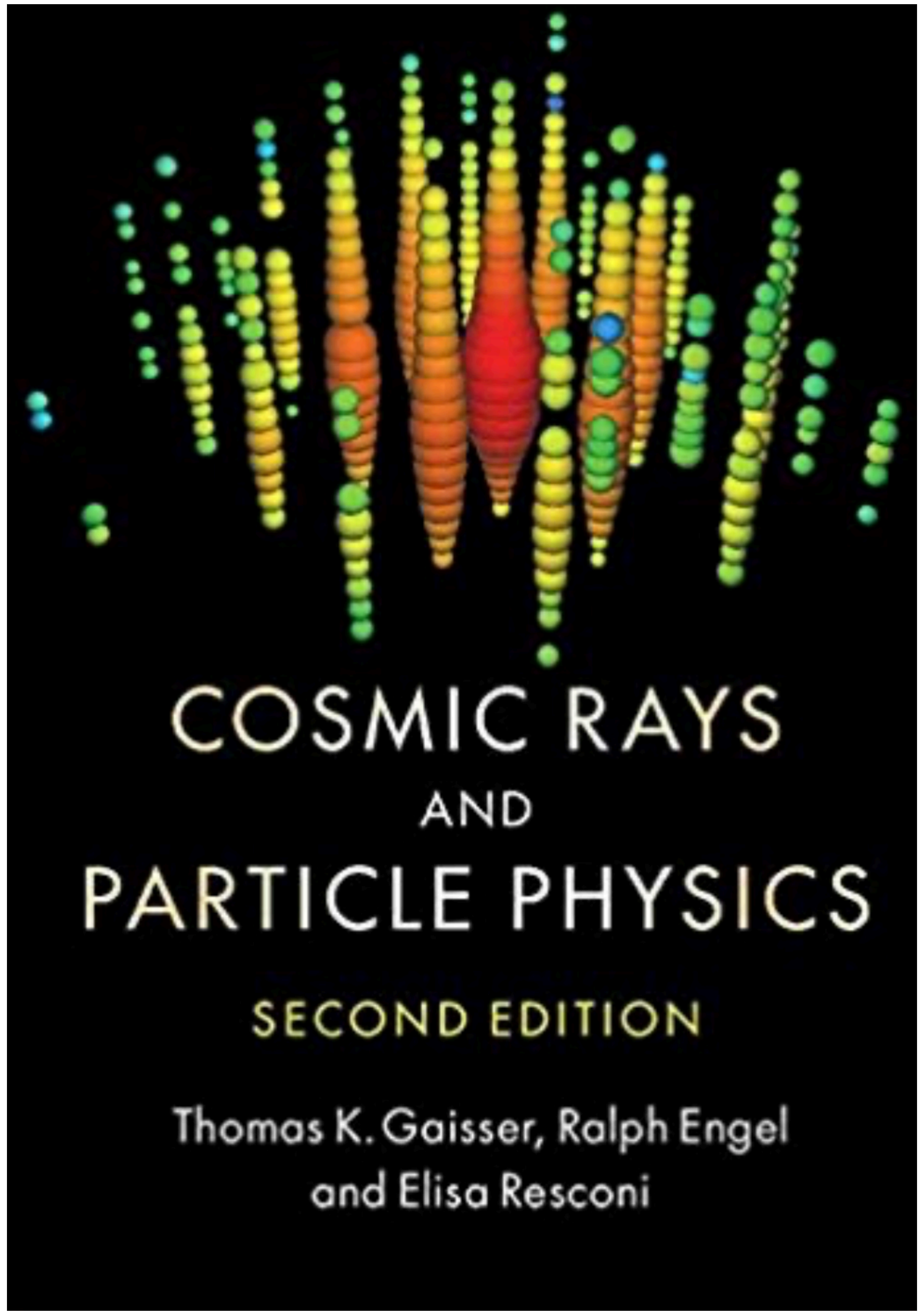
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

ICEHAP

Hi! I’m Max!

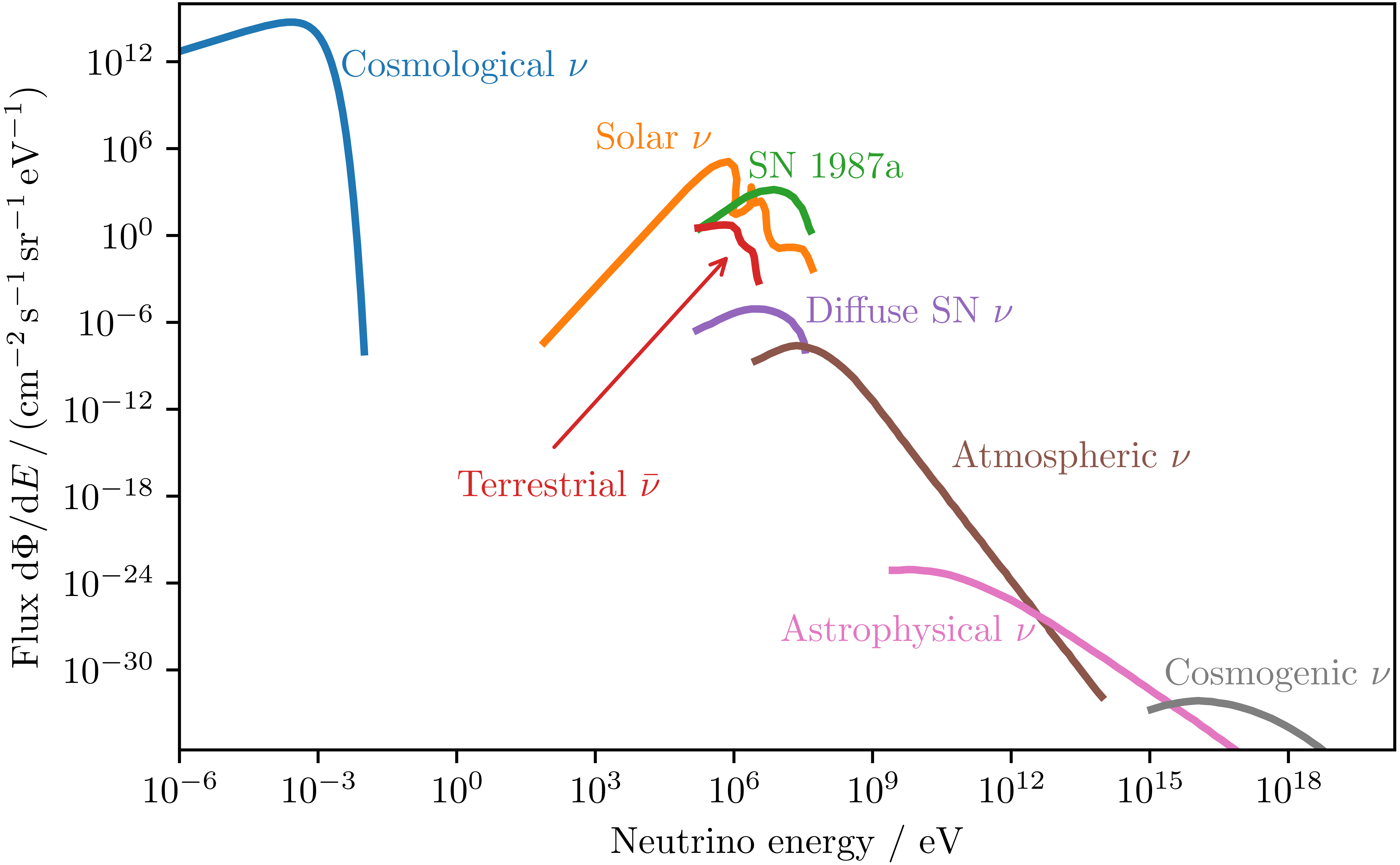
2015-2019 PhD at TU Dortmund
since 2019 Postdoc at Chiba U

Textbook recommendation

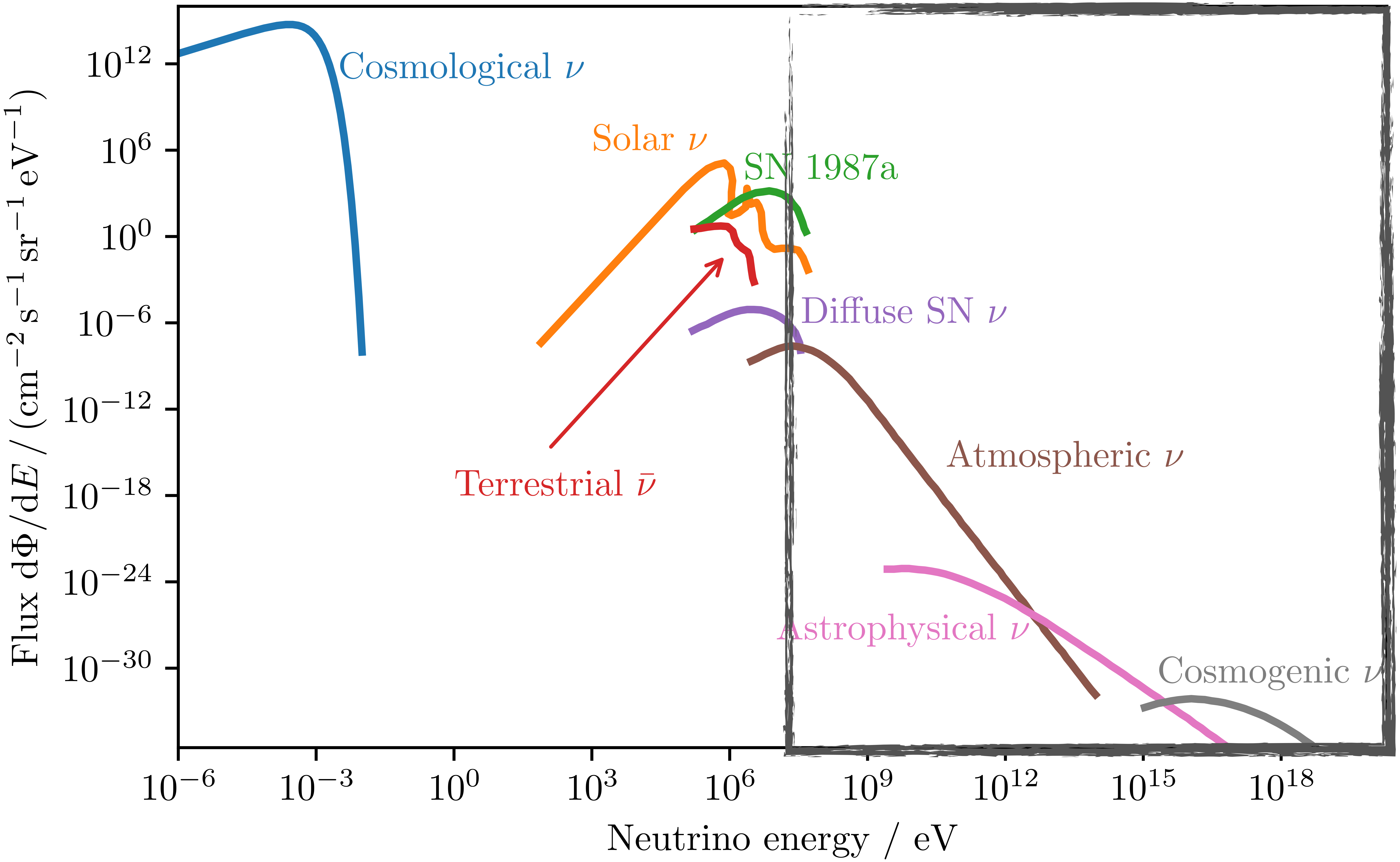


Cosmic Rays and Particle Physics, 2nd edition
(Cambridge university press, ISBN: 9780521016469)

Thomas K. Gaisser, University of Delaware
Ralph Engel, Karlsruhe Institute of Technology, Germany
Elisa Resconi, Technische Universität München



Cosmological ν
Solar ν
SN 1987a
Terrestrial $\bar{\nu}$
Diffuse SN ν
Atmospheric ν
Astrophysical ν
Cosmogenic ν
Flux $d\Phi/dE$ / $(cm^{-2}\,s^{-1}\,sr^{-1}\,eV^{-1})$
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Neutrino energy / eV


Cosmological ν
Solar ν
SN 1987a
Terrestrial ν̄
Diffuse SN ν
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Cosmogenic ν
10^12
10^6
10^0
10^−6
10^−12
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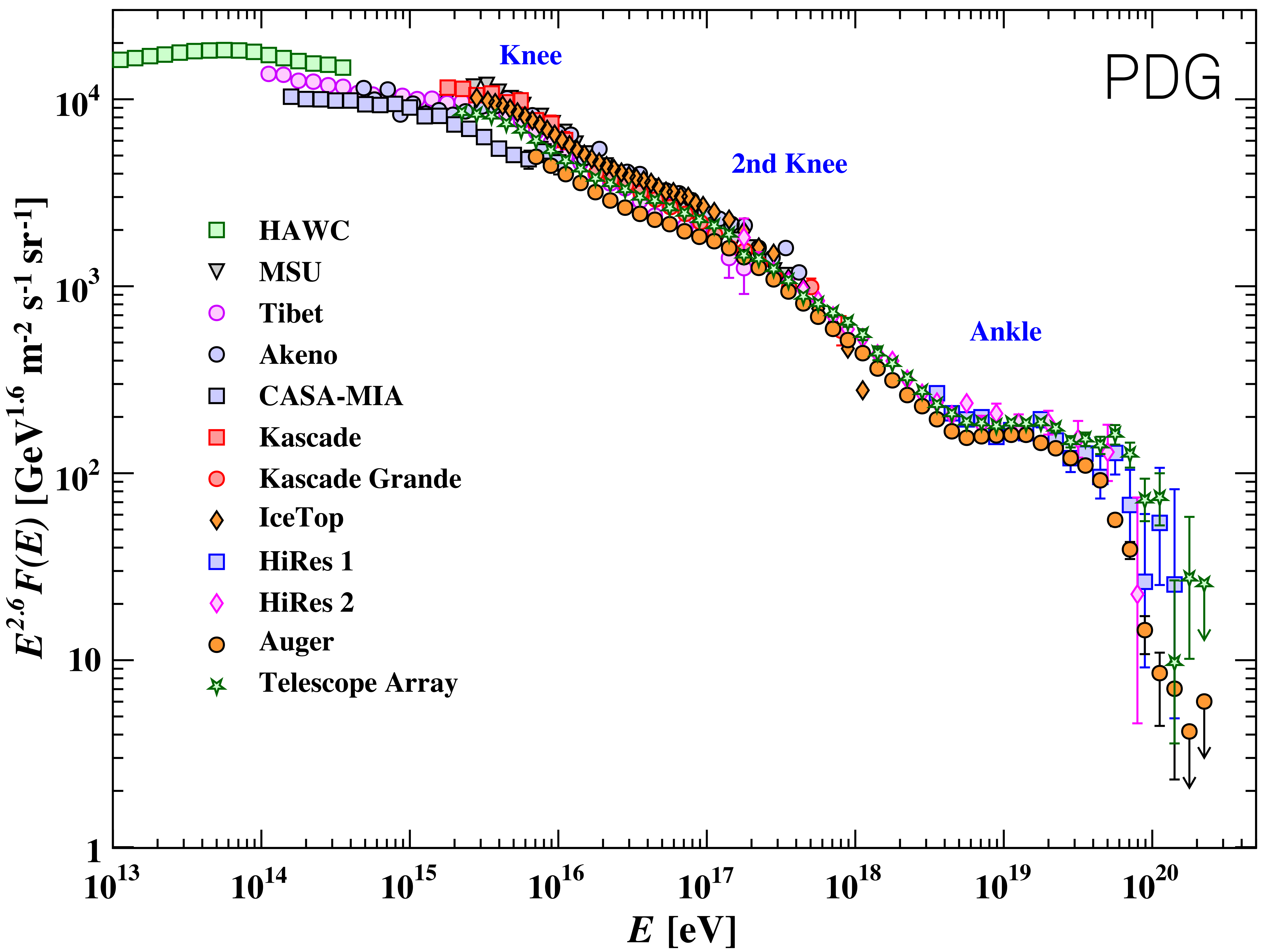
10^−30
Flux dΦ/dE / (cm^−2 s^−1 sr^−1 eV^−1)
10^−6
10^−3
10^0
10^3
10^6
10^9
10^12
10^15
10^18
Neutrino energy / eV

Why study high energy neutrinos?

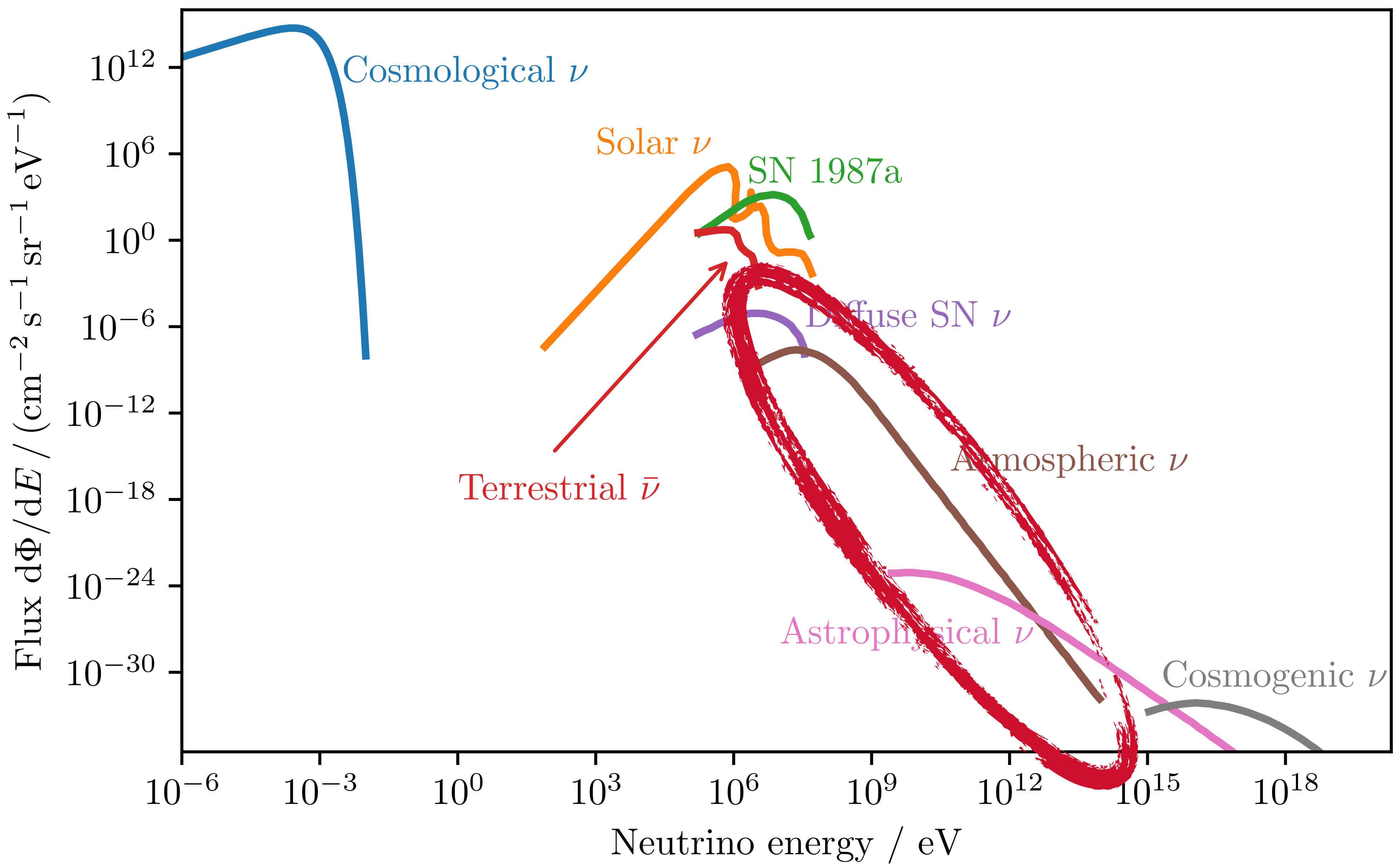
- The universe is accelerating cosmic rays up to enormous energies
  - Where are they accelerated?
  - How do they reach energies up to ~10^{20} eV
- Neutrinos can probe the cosmic ray sources

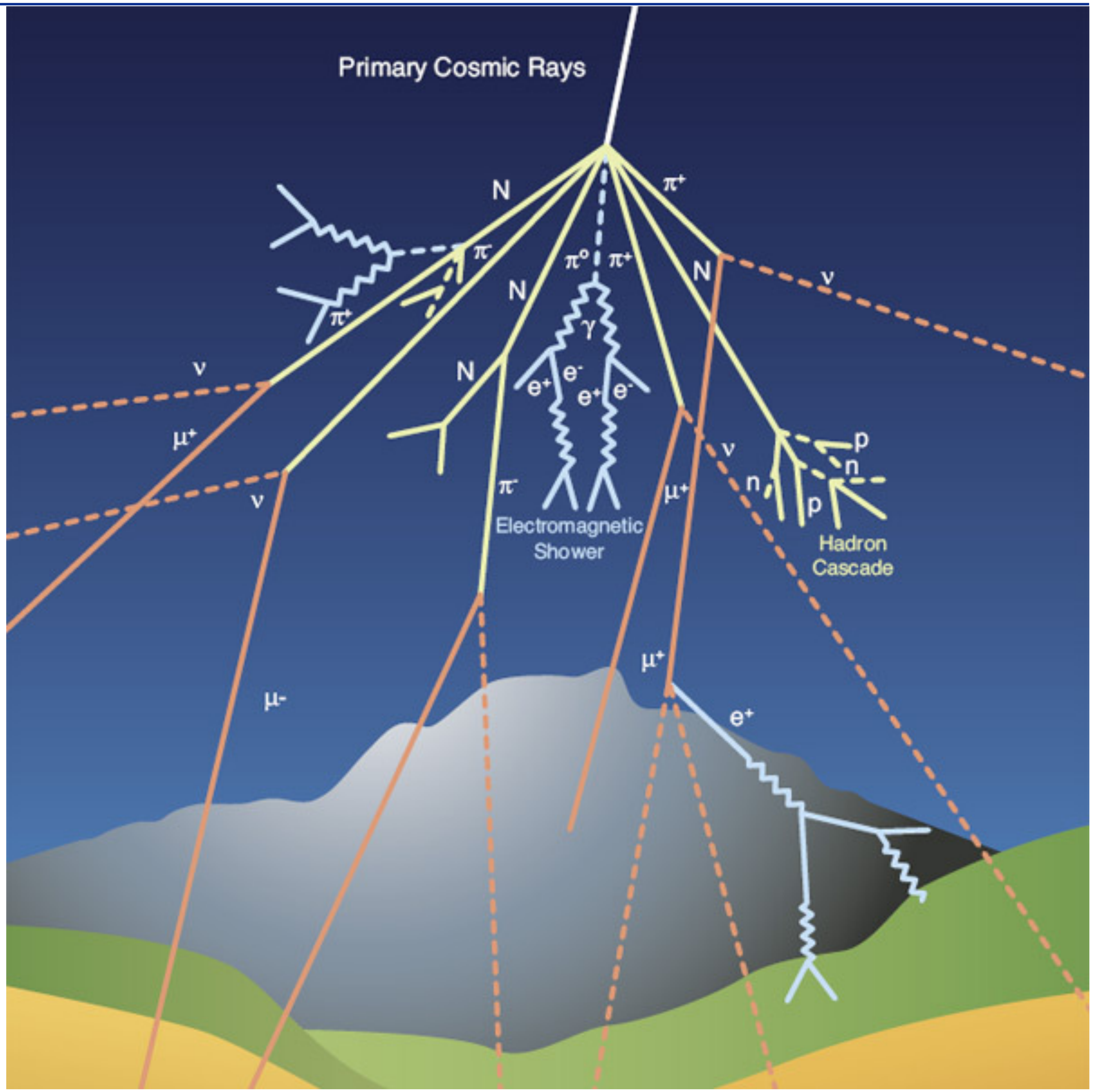
All-particle cosmic ray spectrum



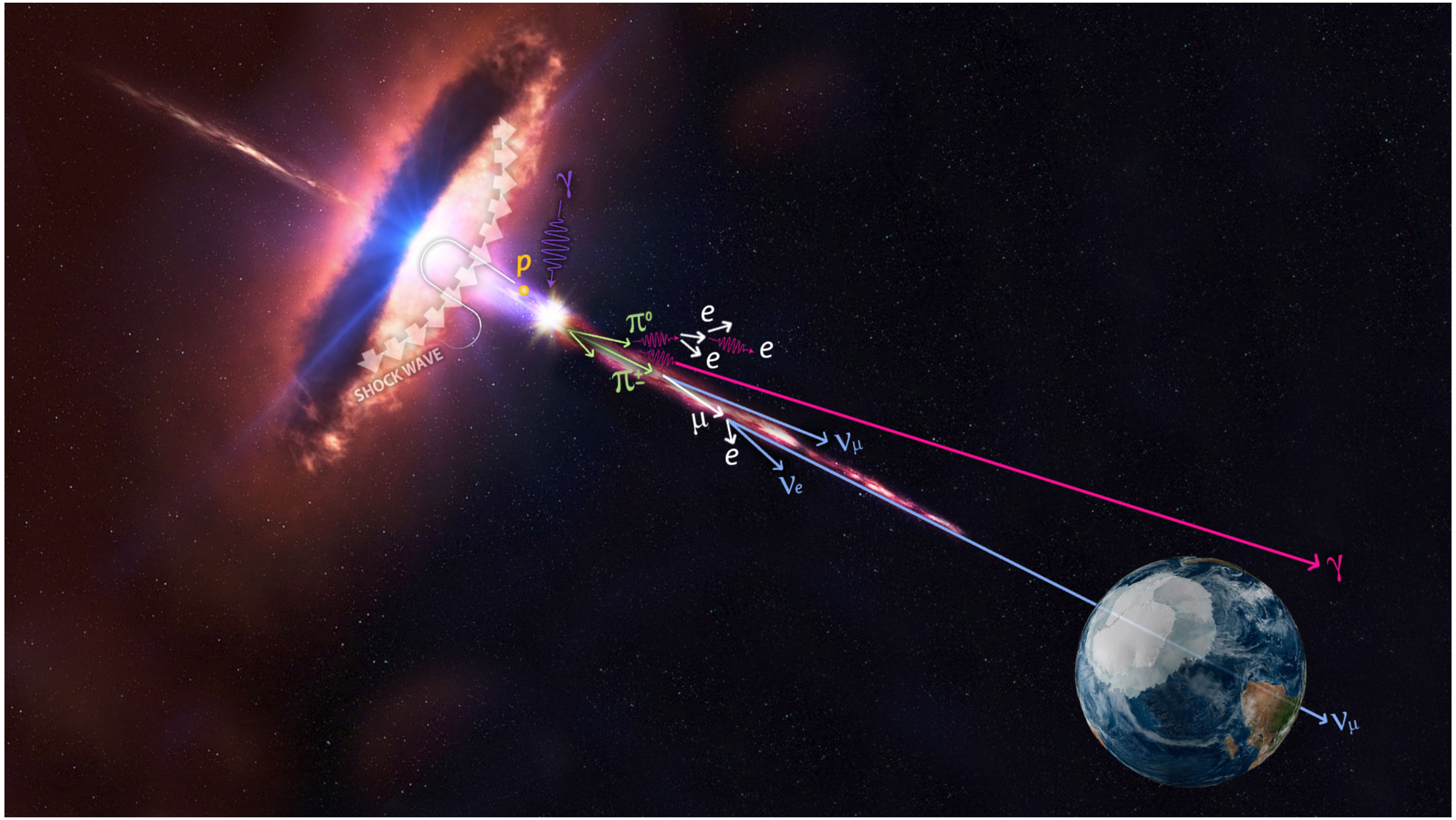
Cosmic ray showers — atmospheric neutrinos

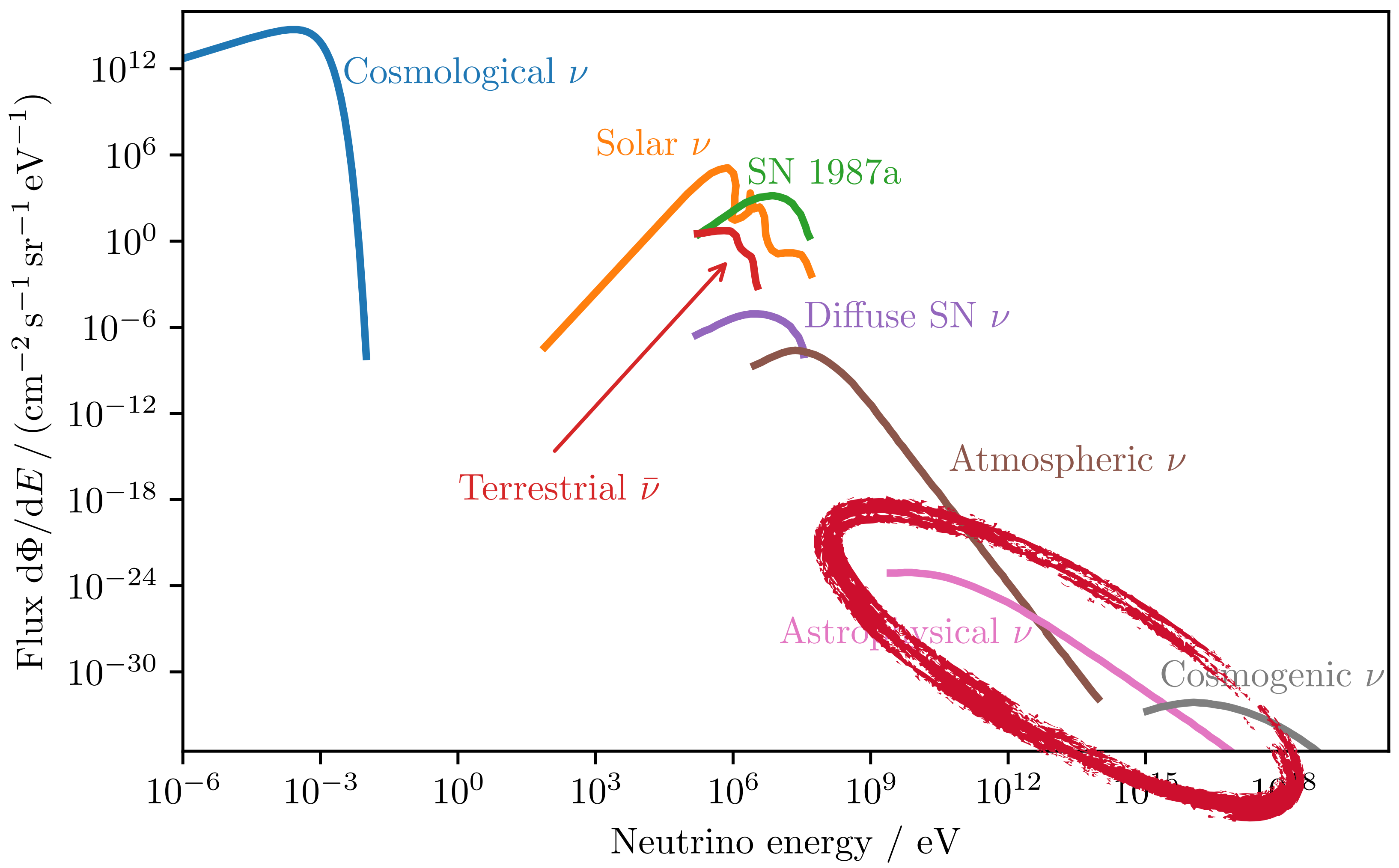
- Secondary particles produced in air showers
- Up to very high energies (~ 100 TeV)
- But with a steeply falling energy spectrum ~$E^{-3.7}$





Cosmic messengers — astrophysical neutrinos

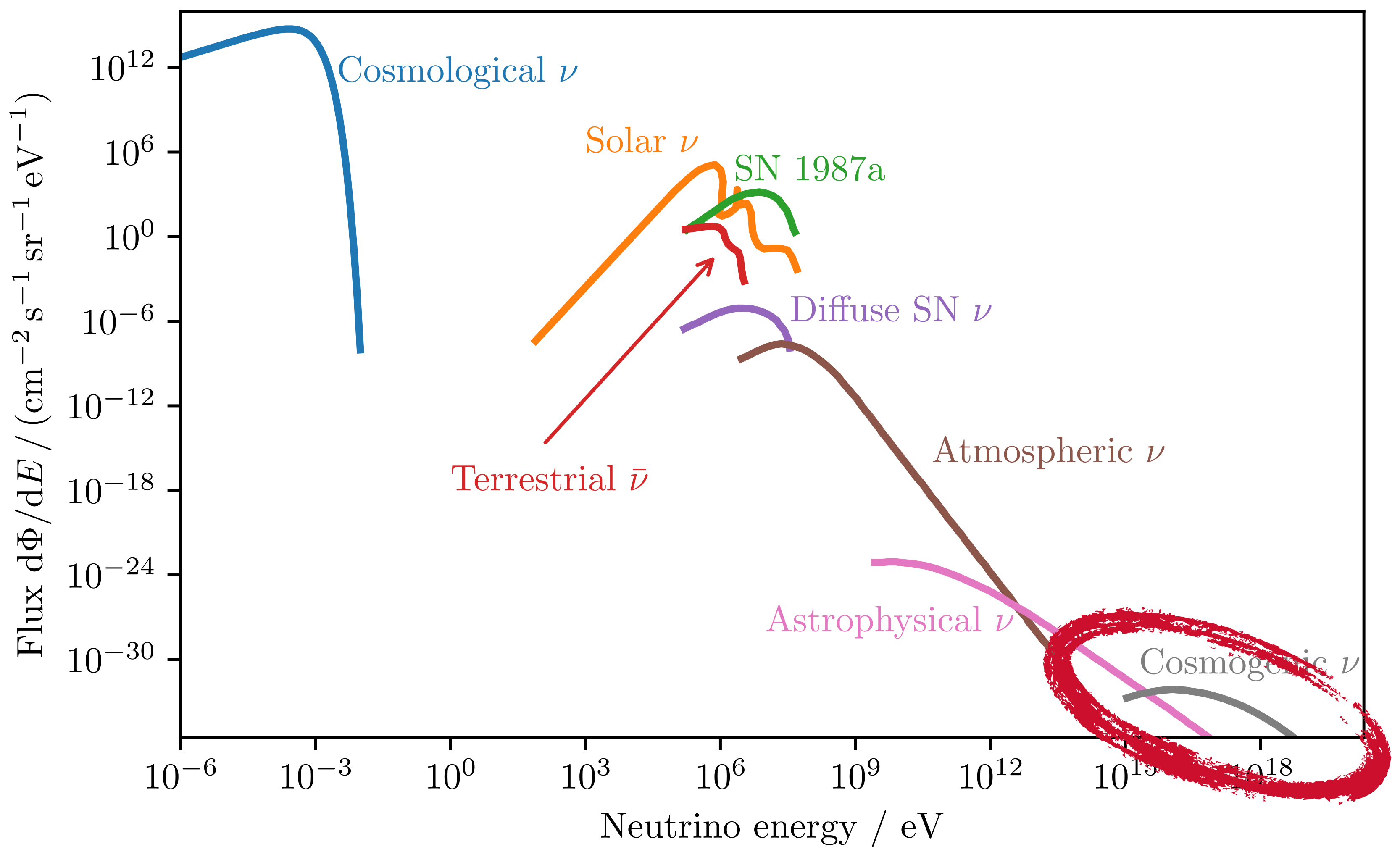


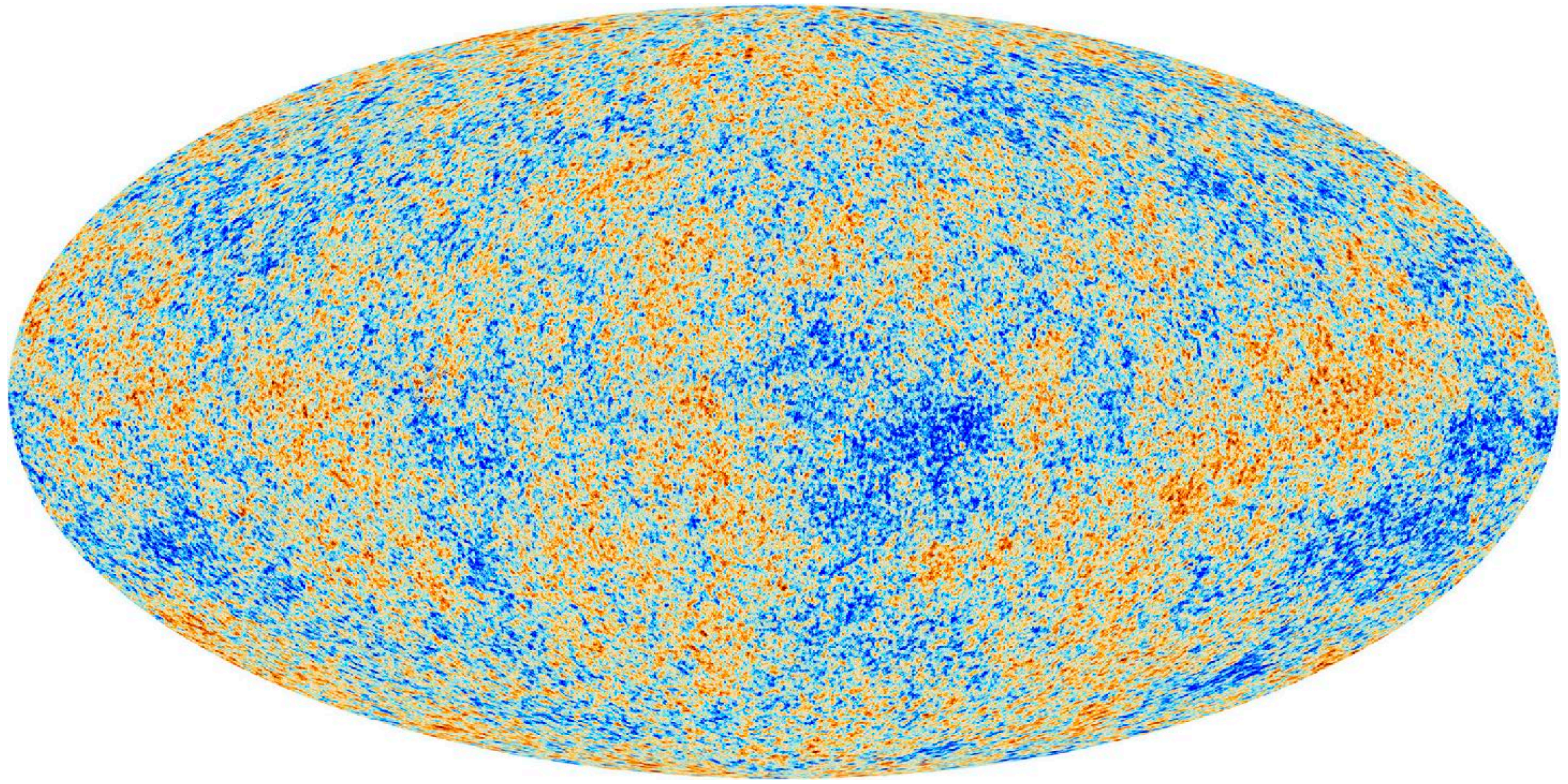


- The acceleration and production of high energy protons, gamma rays and neutrinos is related.
- Expected flavor ratio is (1:2:0)

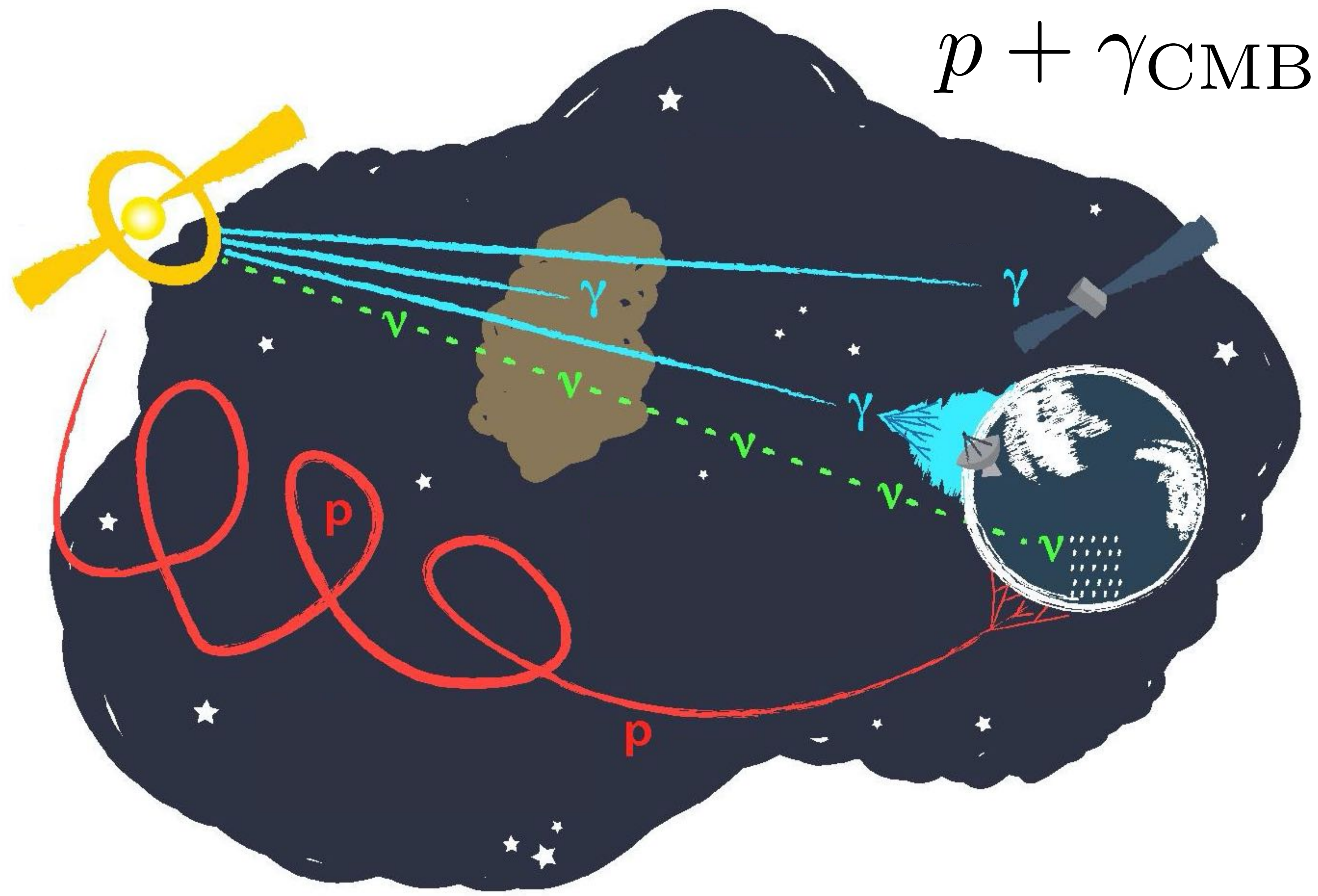
$$\begin{matrix} p+p \\ p+\gamma \end{matrix} \rightarrow X + \pi \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \end{cases}$$

Cosmic messengers — cosmogenic neutrinos (GZK)





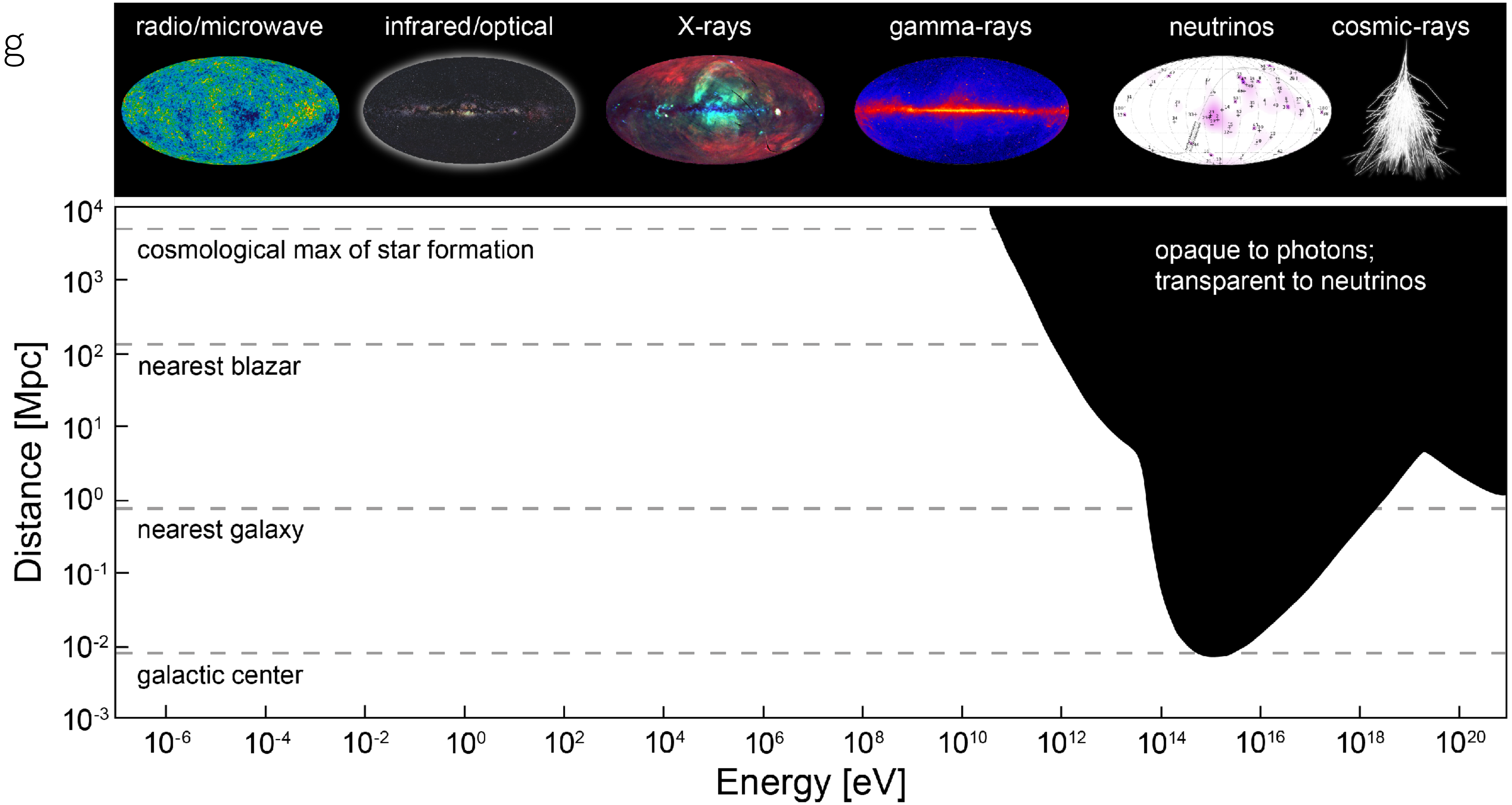
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+}$$



- Ultra high energy protons interact with the cosmic microwave background
- Limits the maximum energy at which cosmic rays reach us to ~ $5*10^{19}$ eV
- GZK cutoff
- The decays of the Δ^{+} produce a flux of ultra high energy neutrinos!

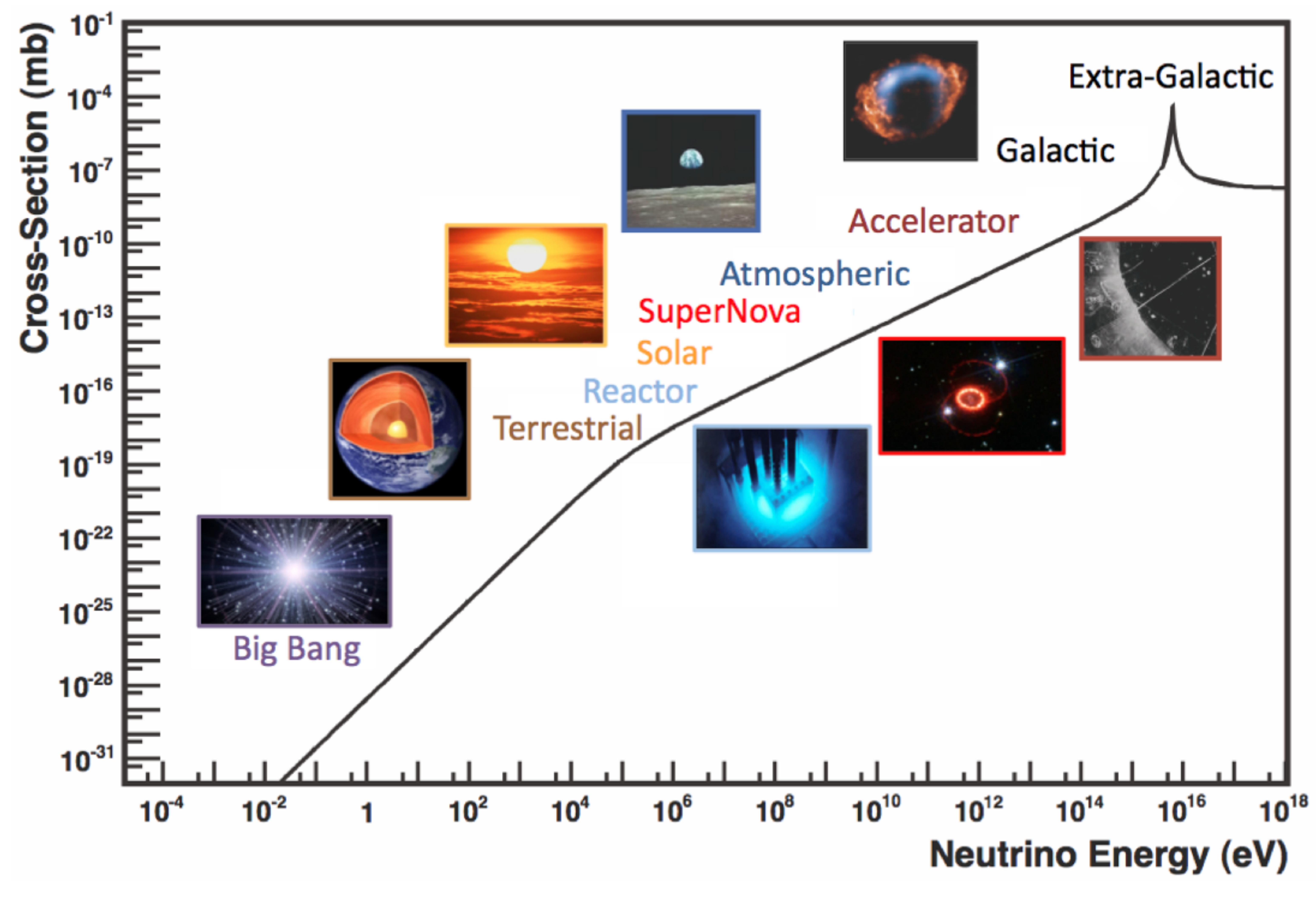
What makes the neutrino a special messenger?

- Neutral and weakly interacting
- Propagate cosmic distances without significant attenuation or deflection



What makes the neutrino a special messenger?

- Neutral and weakly interacting
- Propagate cosmic distances without significant attenuation or deflection
- Attenuation starts becoming a relevant factor at high energies
- The Earth starts to absorb a significant fraction of neutrinos above ~50 TeV



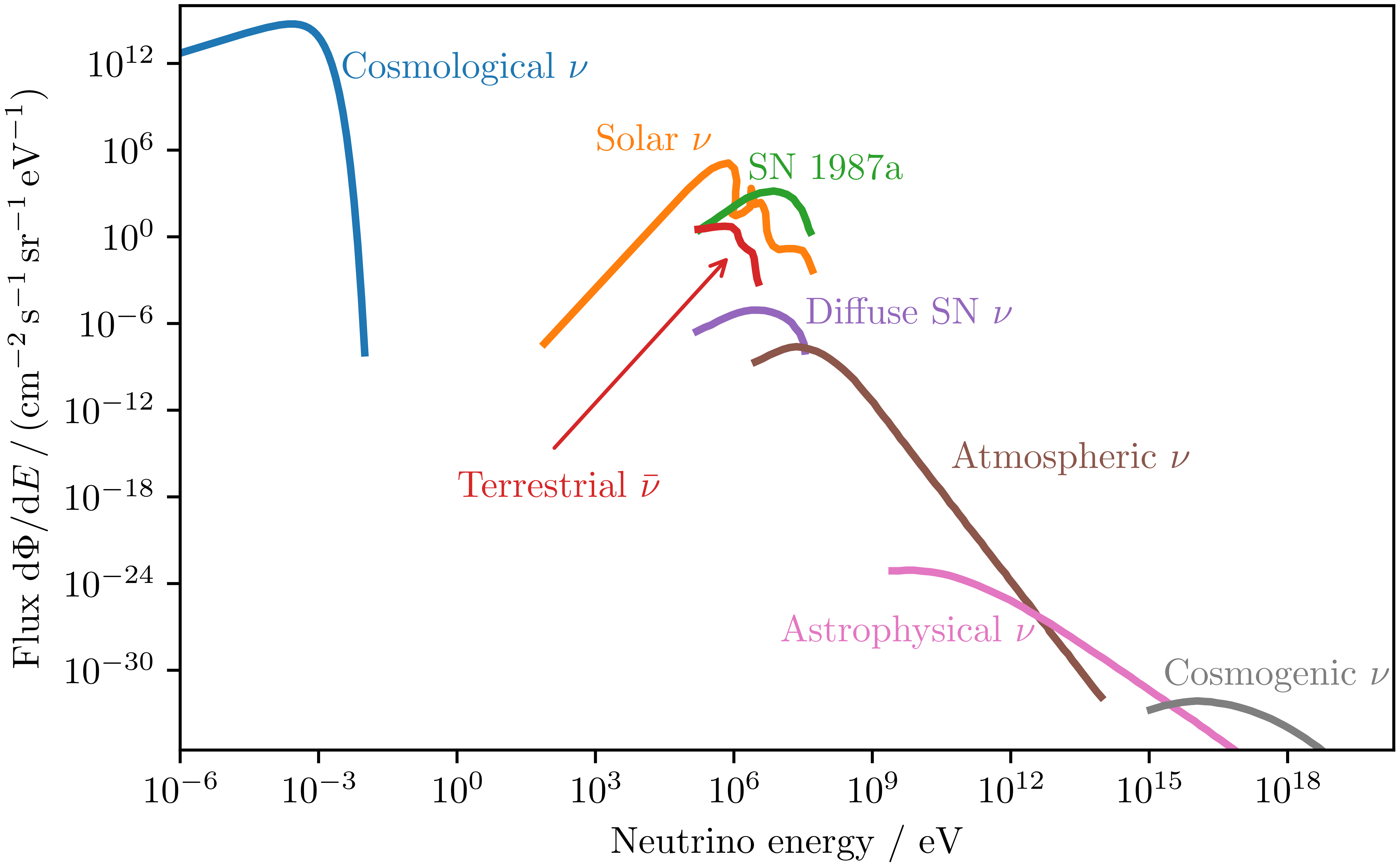
Neutrino fluxes

- High energy neutrino fluxes are steeply falling power laws

$$\Phi_\nu = \Phi_0 \cdot E^{-\gamma}$$

- High energy neutrinos require large detection volumes

- The South Pole offers large amounts of really clear ice



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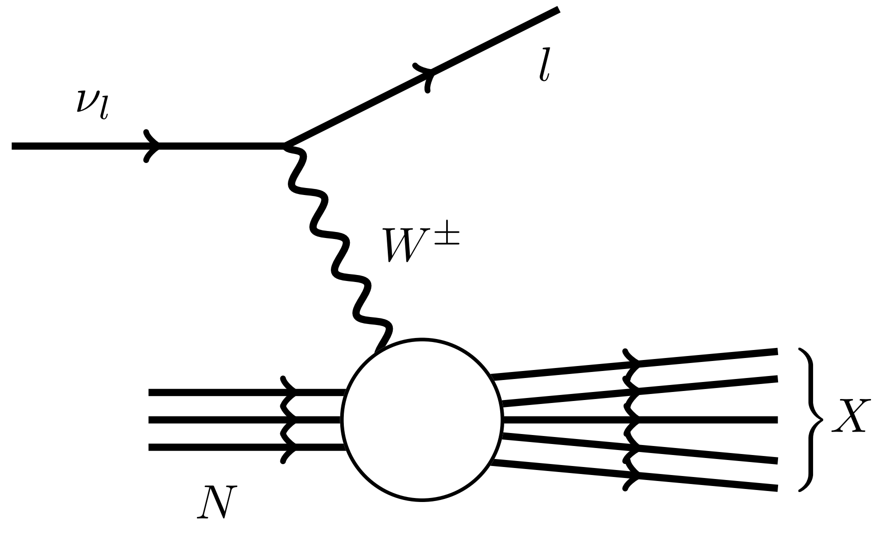
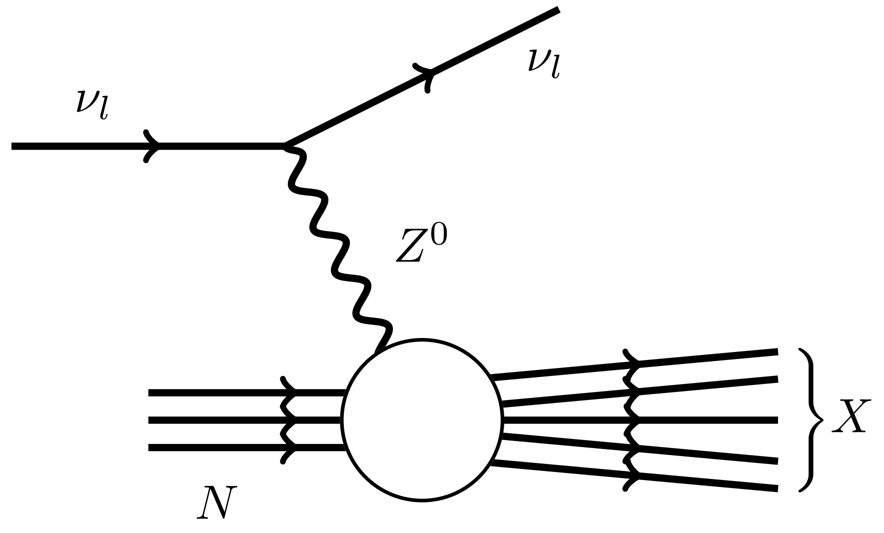
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
ICEHAP
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube detector
DeepCore
DOMs are 17 meters apart
2450 m
Antarctic bedrock
Detector Design
1 gigaton of instrumented ice
5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
1 square kilometer surface array, IceTop, with 324 DOMs
00:00:02
2 nanosecond time resolution
IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily

Events in IceCube

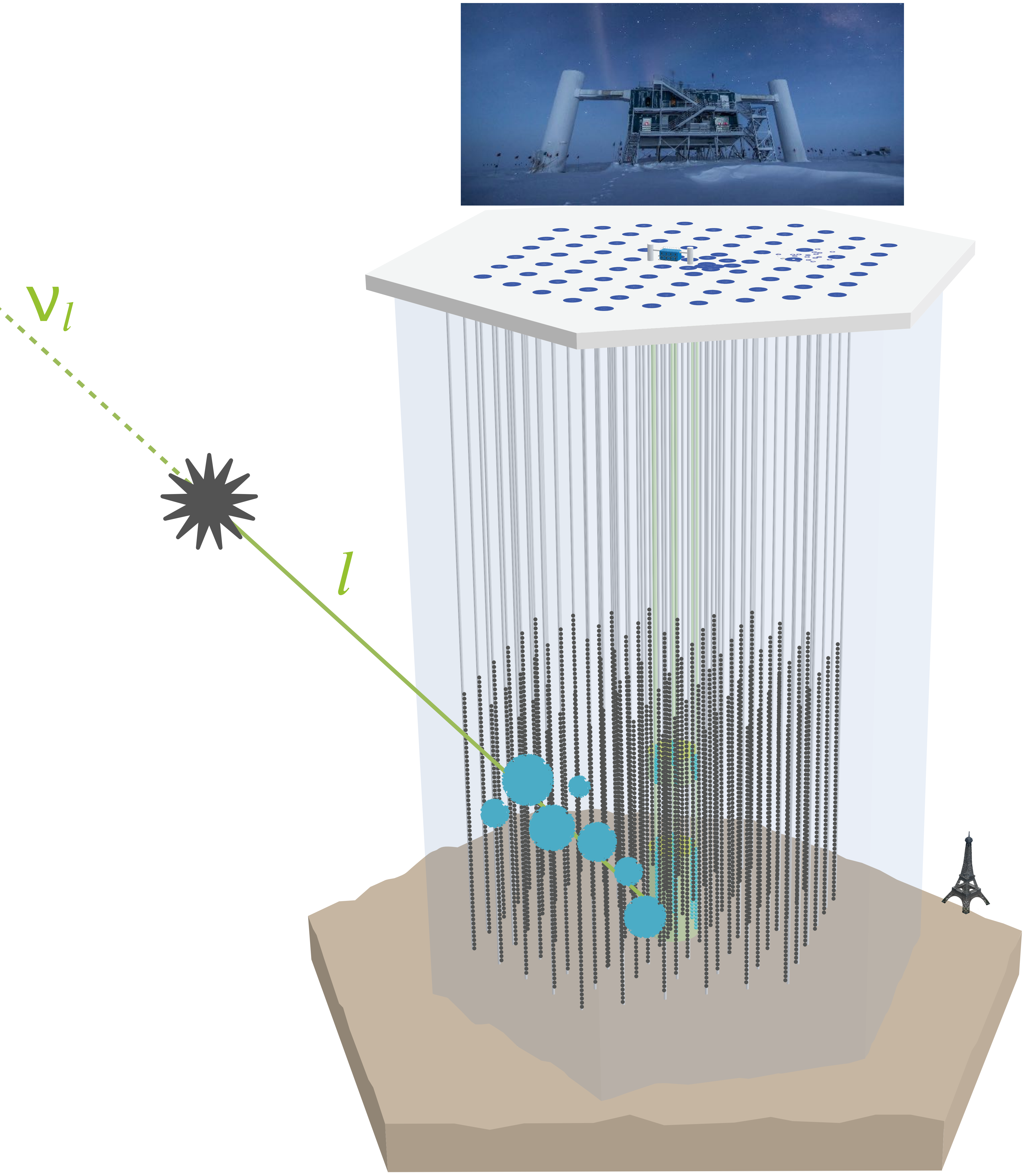
- Neutrinos interact via deep inelastic scattering
- Charged current (CC)



- Neutral current (NC)

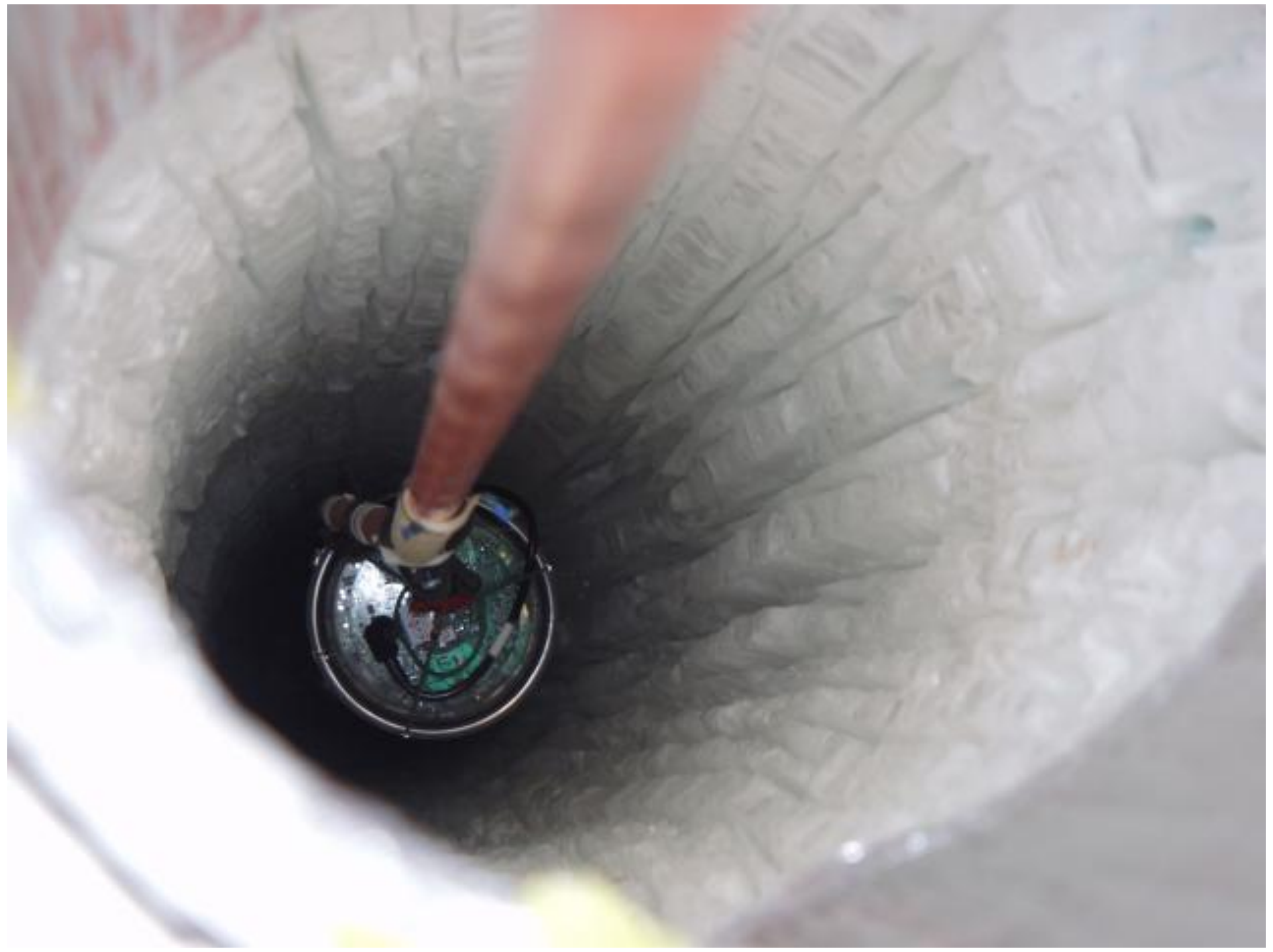


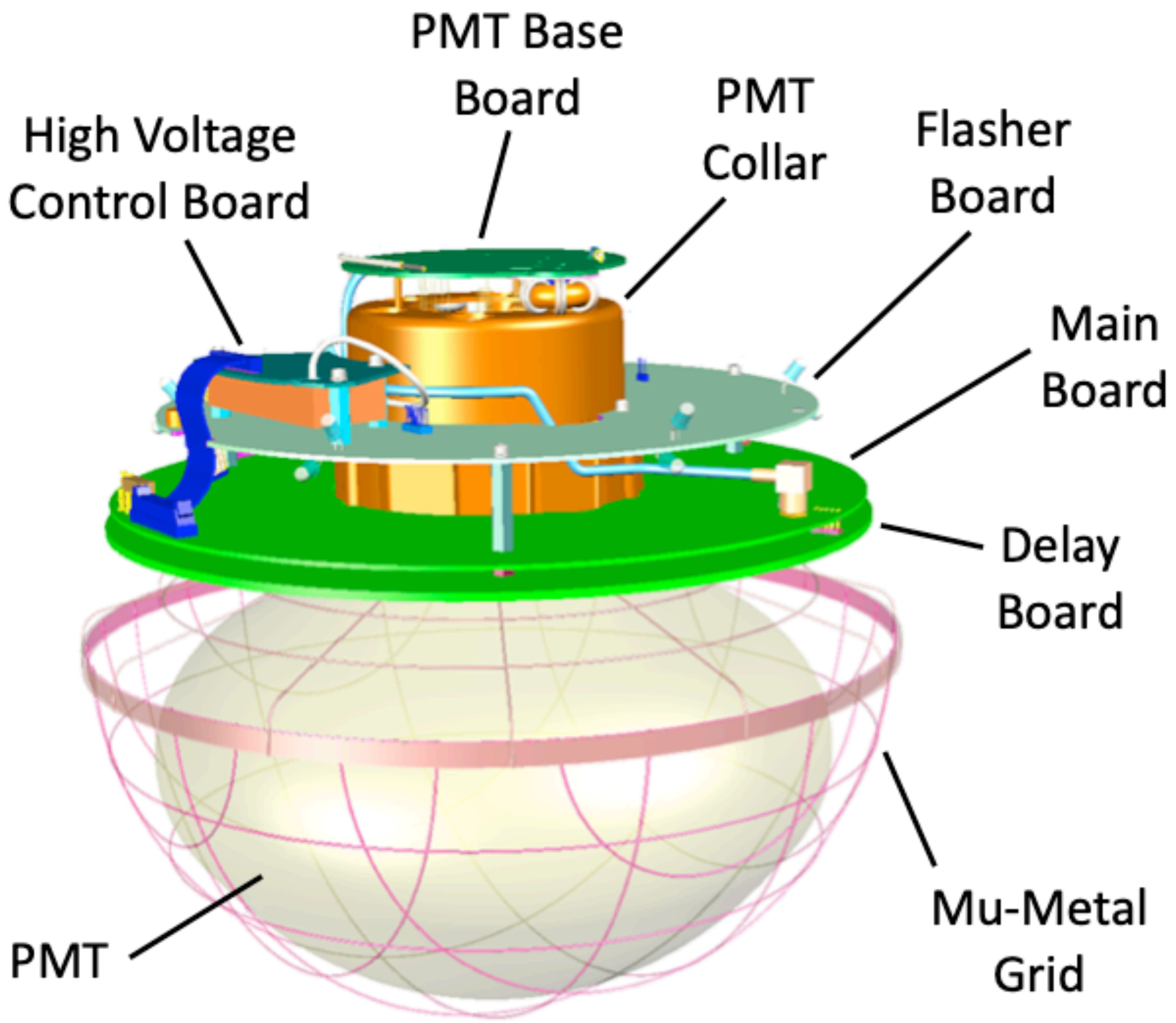
- Charged leptons and hadrons produce Cherenkov radiation

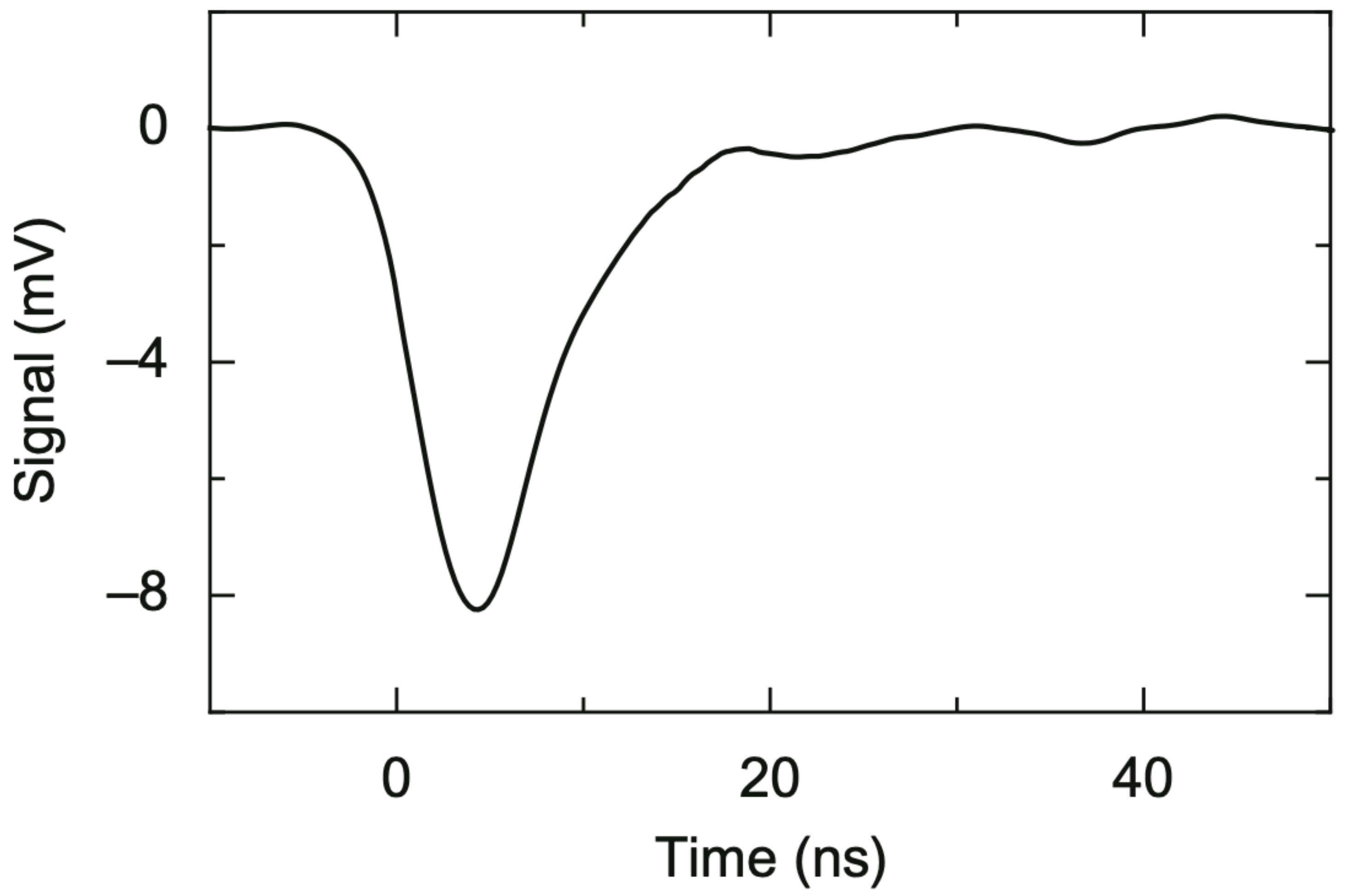


The IceCube DOM

- The first IceCube DOM descending down into its hole



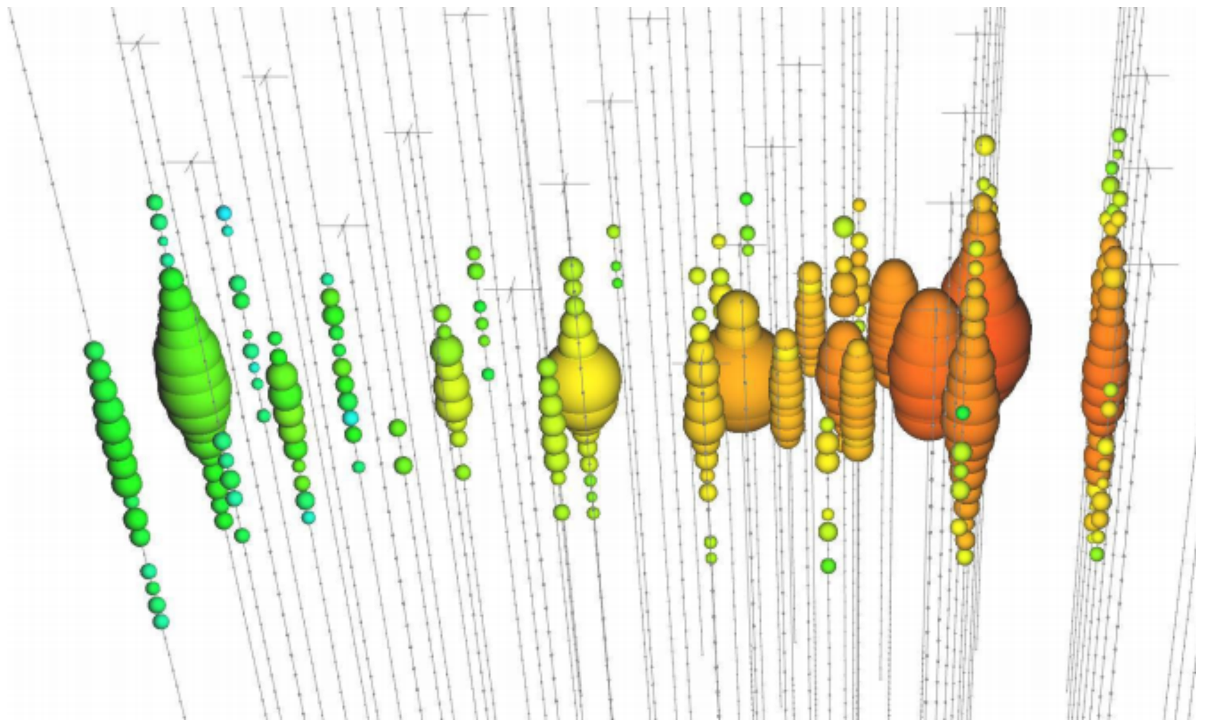


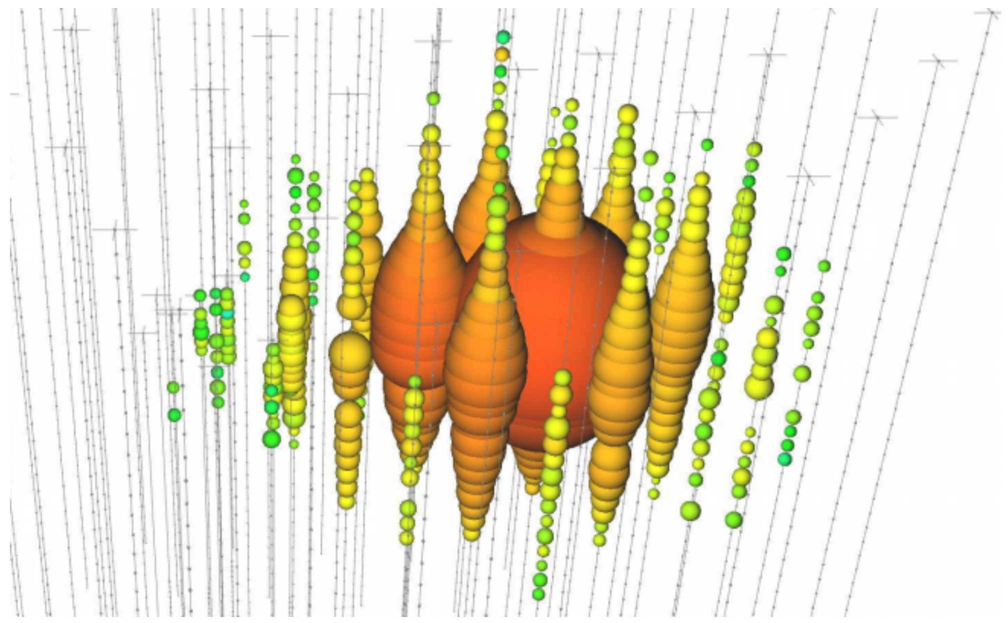


Event topologies

- Tracks:
  - Energy resolution: ~factor of 2
  - Angular resolution: 0.2° - 1°
- Cascades:
  - Energy resolution: ~15% (if contained)
  - Angular resolution: 5° - 15°
- Double Bang/Double Cascade:
  - Resolution in-between values for tracks and cascades depending on tau length
  - Inherently higher probability to be of astrophysical origin

early hits
late hits


Data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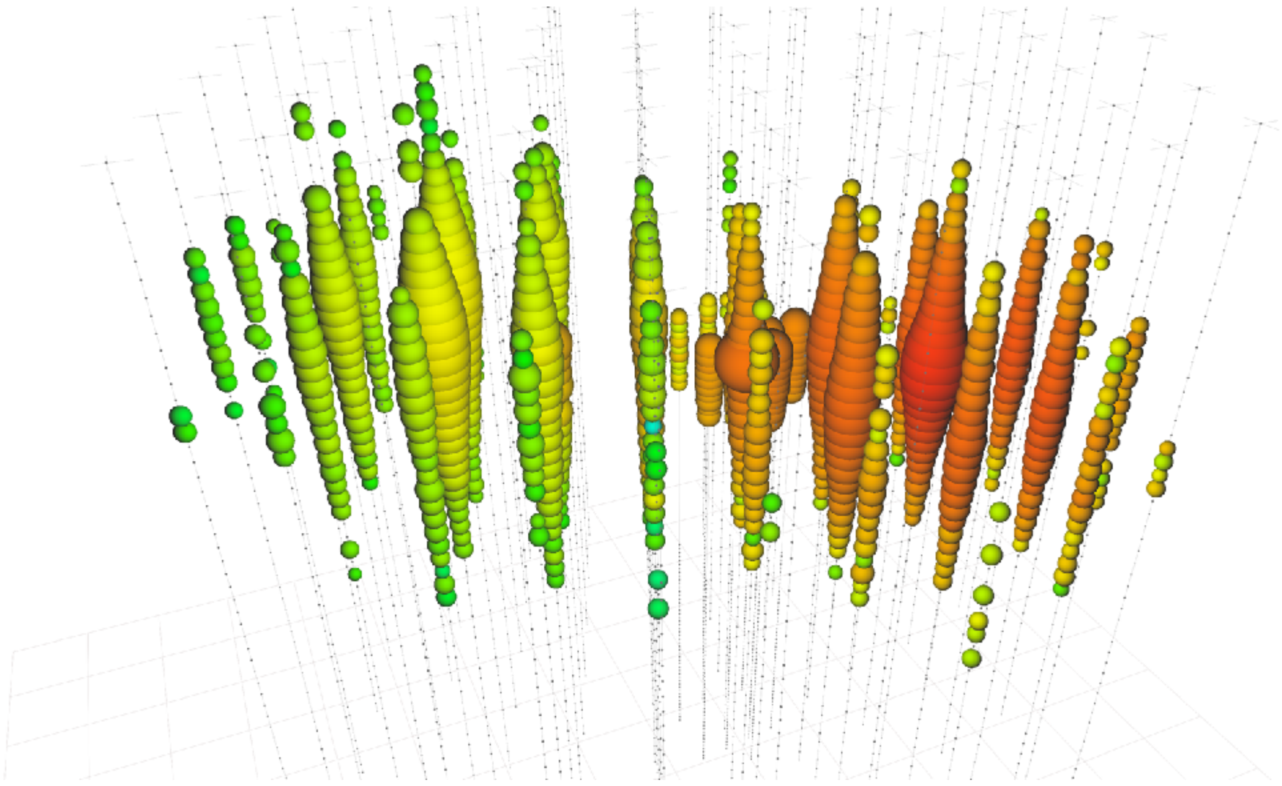
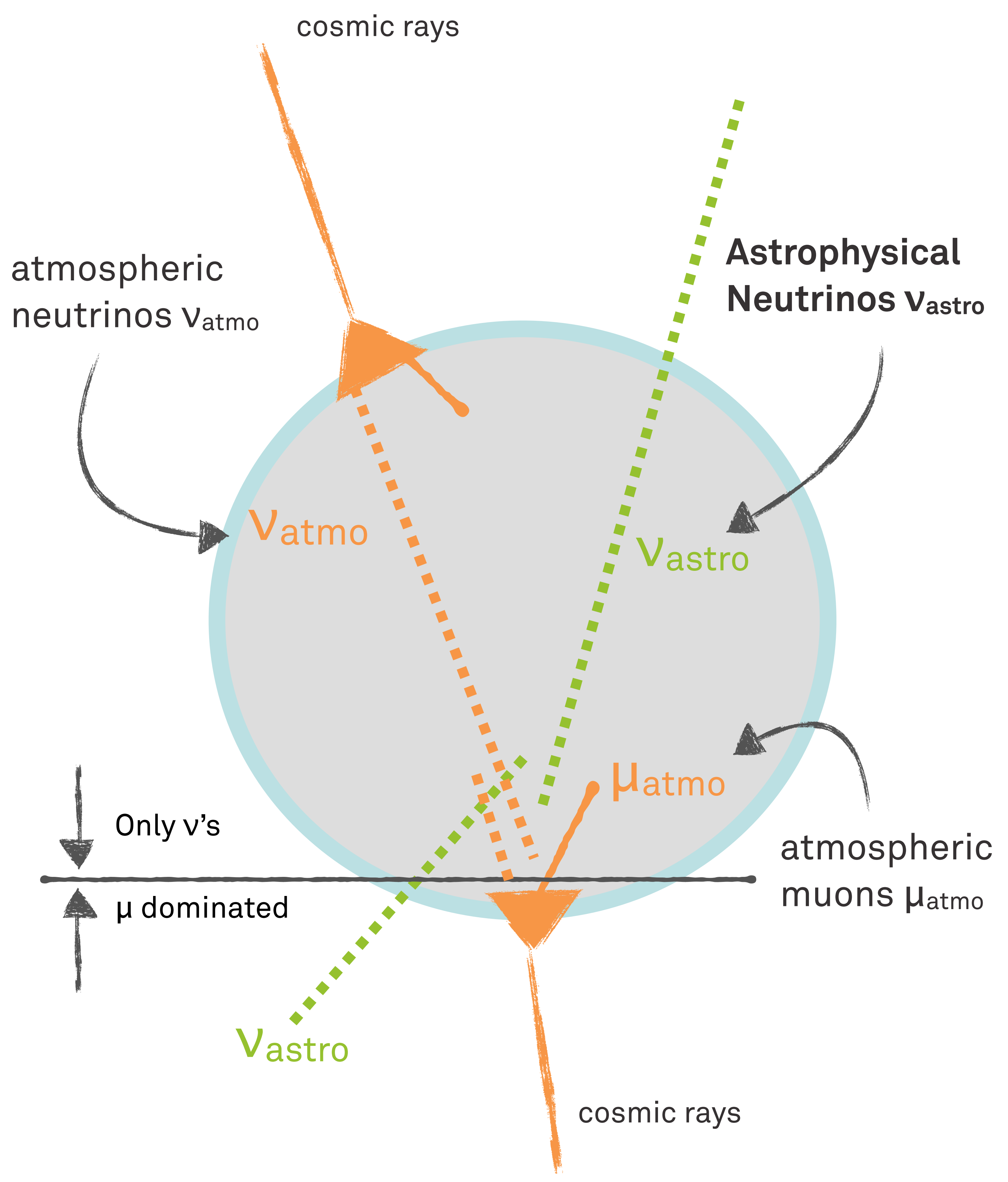
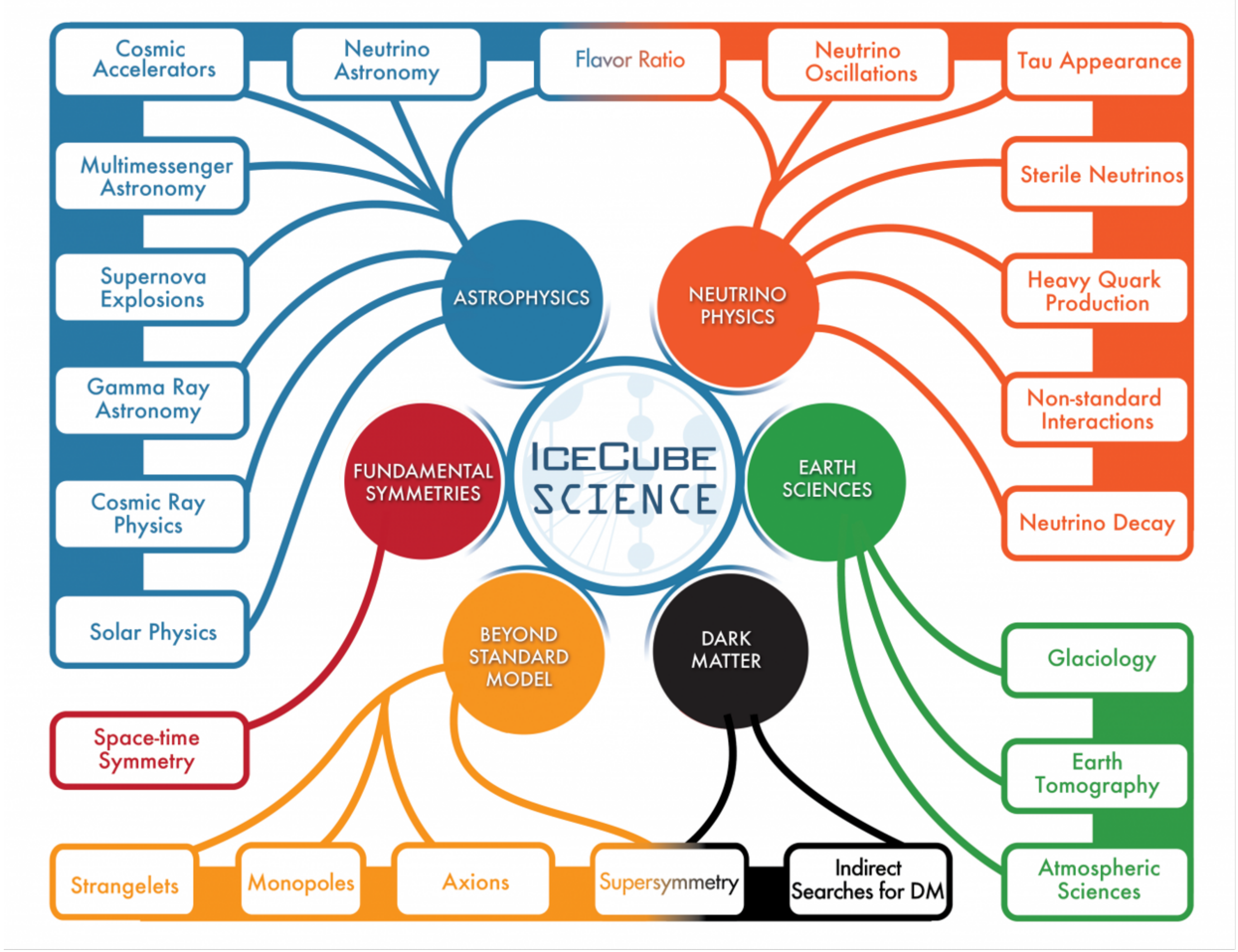

Sim.

Signal and Backgrounds

- Background from Earth's atmosphere:
  - Downgoing muons from cosmic ray air showers (~3000 / s)
  - Atmospheric neutrinos, also produced in CR air showers (~10 / hour)
    - Conventional atmos. neutrinos ($E^{-3.7}$) from π/K
    - Prompt atmos. neutrinos ($E^{-2.7}$) from charmed mesons

- Signal:
  - Astrophysical neutrinos produced in astrophysical objects (~ 10-100 / year)
  - Harder energy spectrum + different angular distribution




Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
ASTROPHYSICS
NEUTRINO PHYSICS
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
Cosmic Ray Physics
Neutrino Decay
Solar Physics
BEYOND STANDARD MODEL
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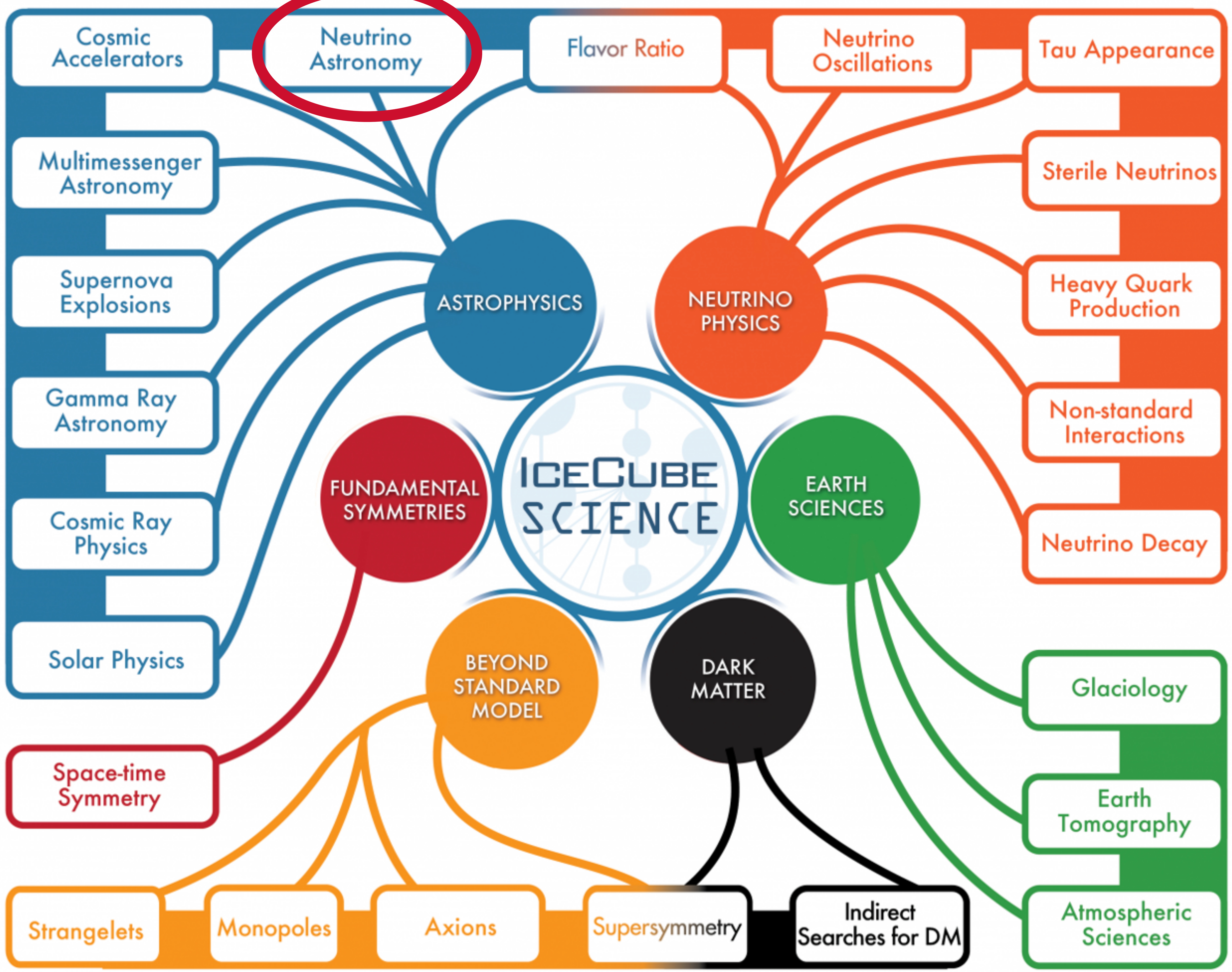
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences



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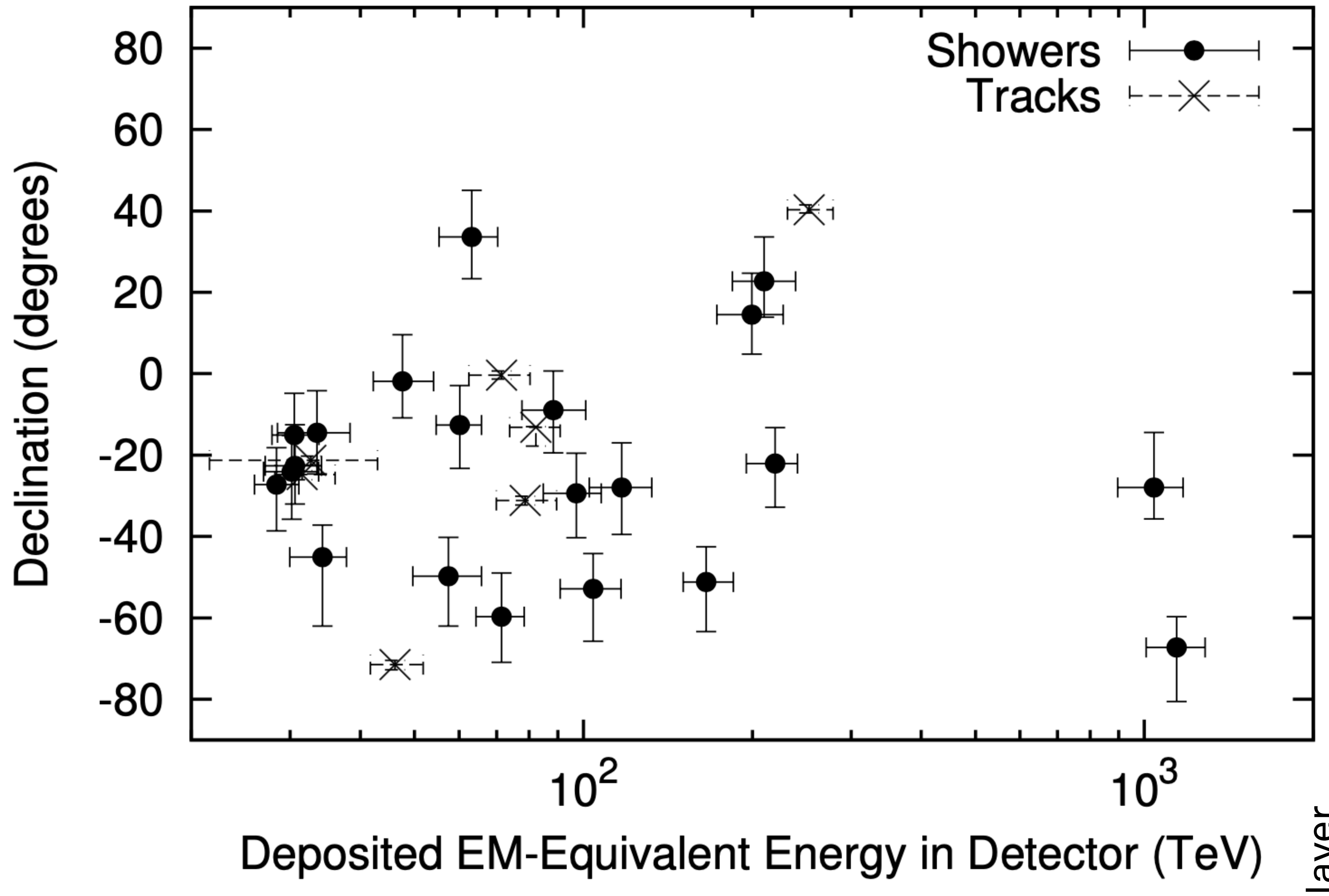
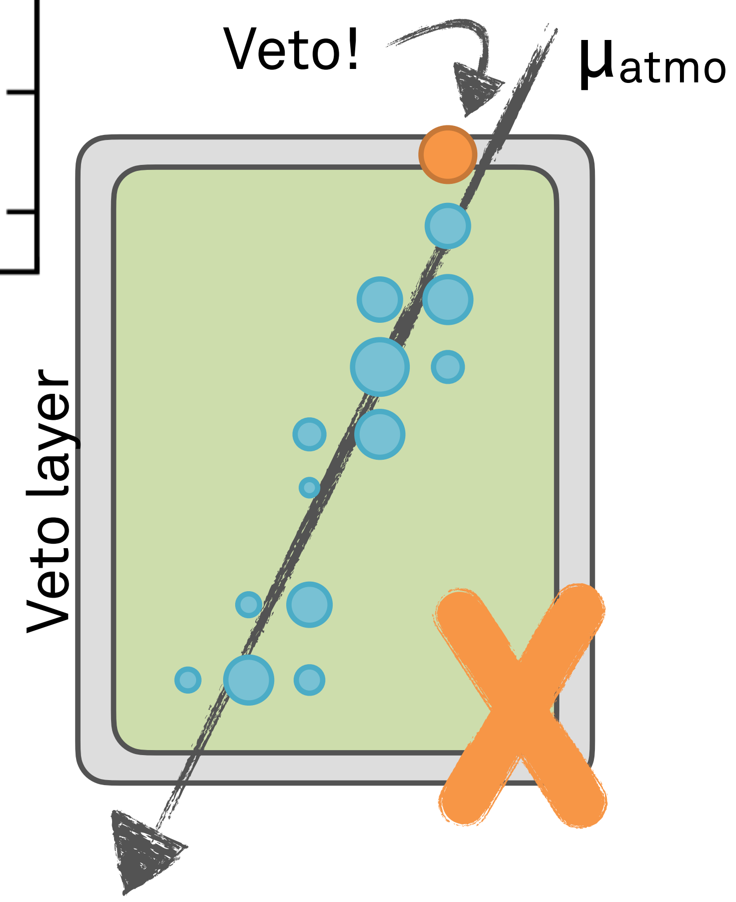
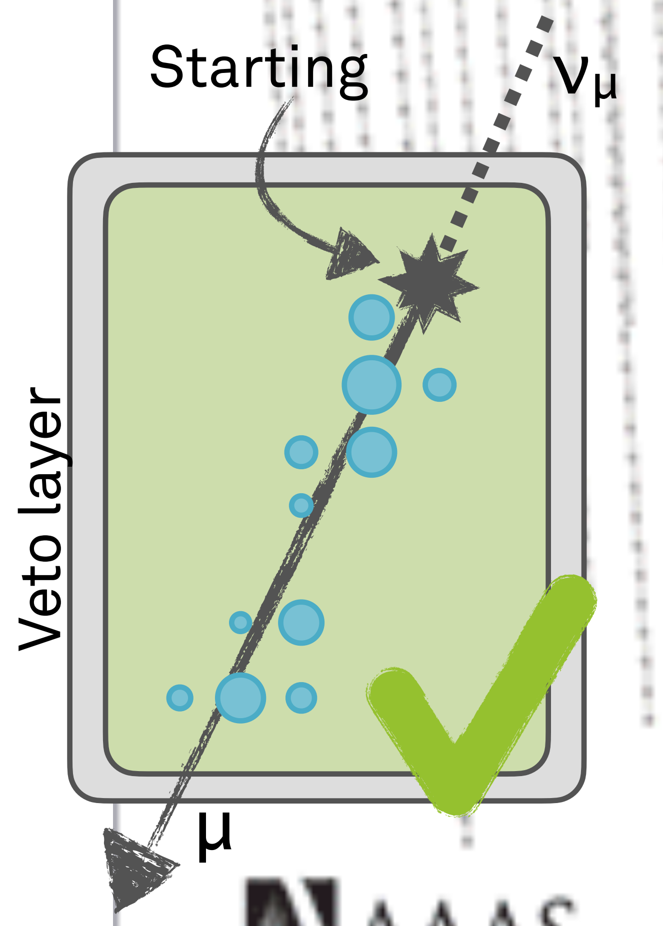
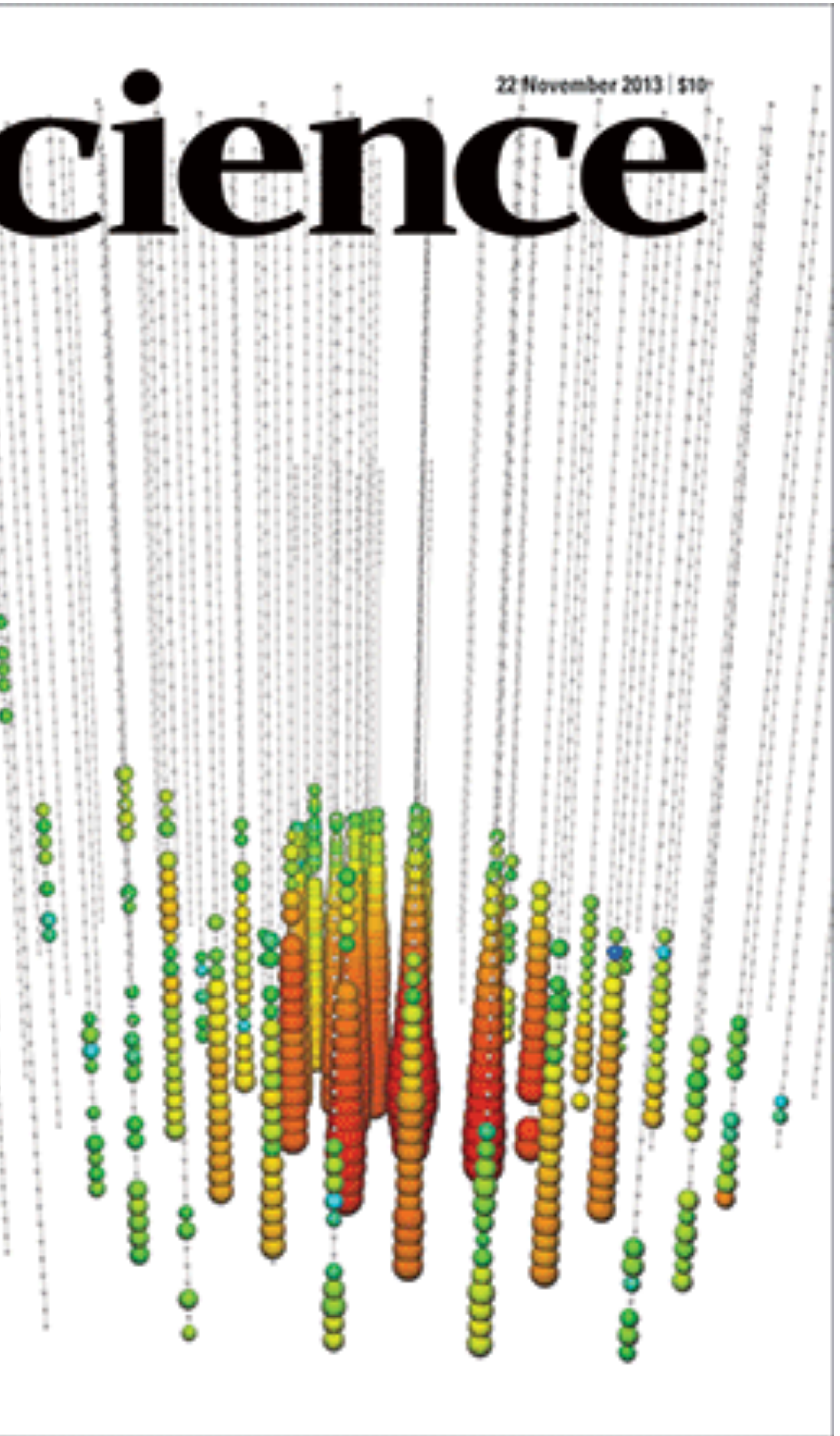
First evidence for astrophysical neutrinos (HESE)

- First observation (2013): 28 neutrino events
- 30 TeV - 1.2 PeV energy



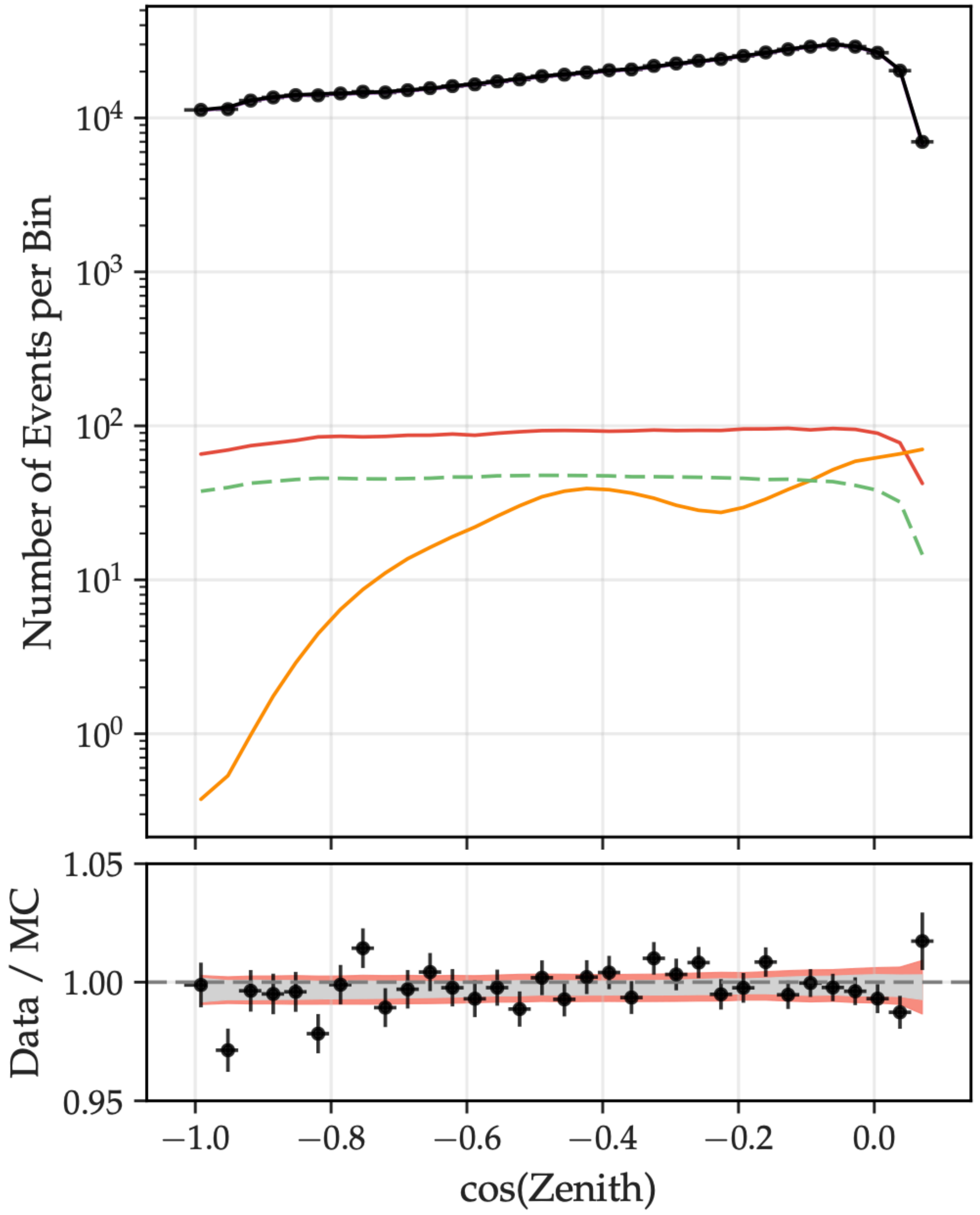


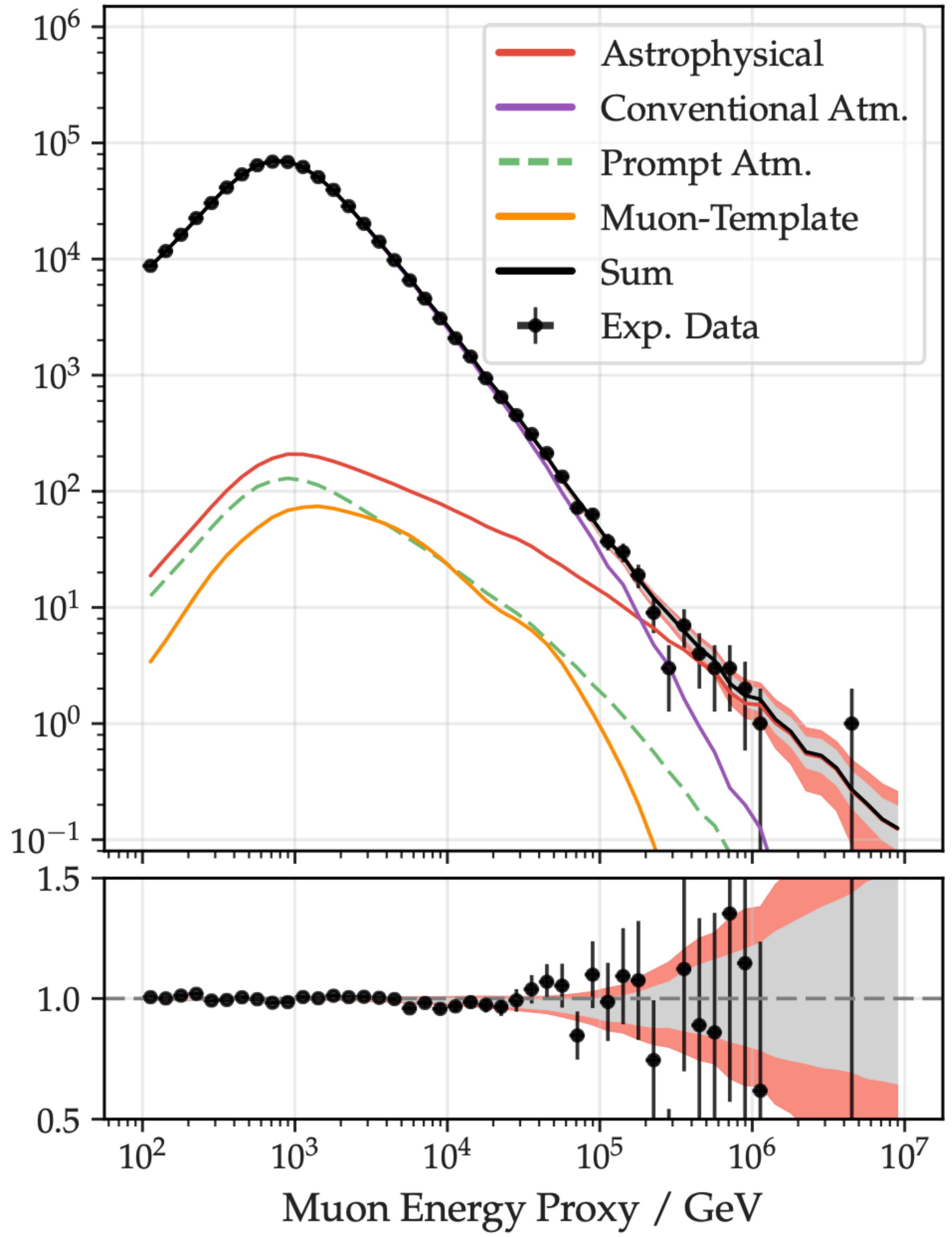


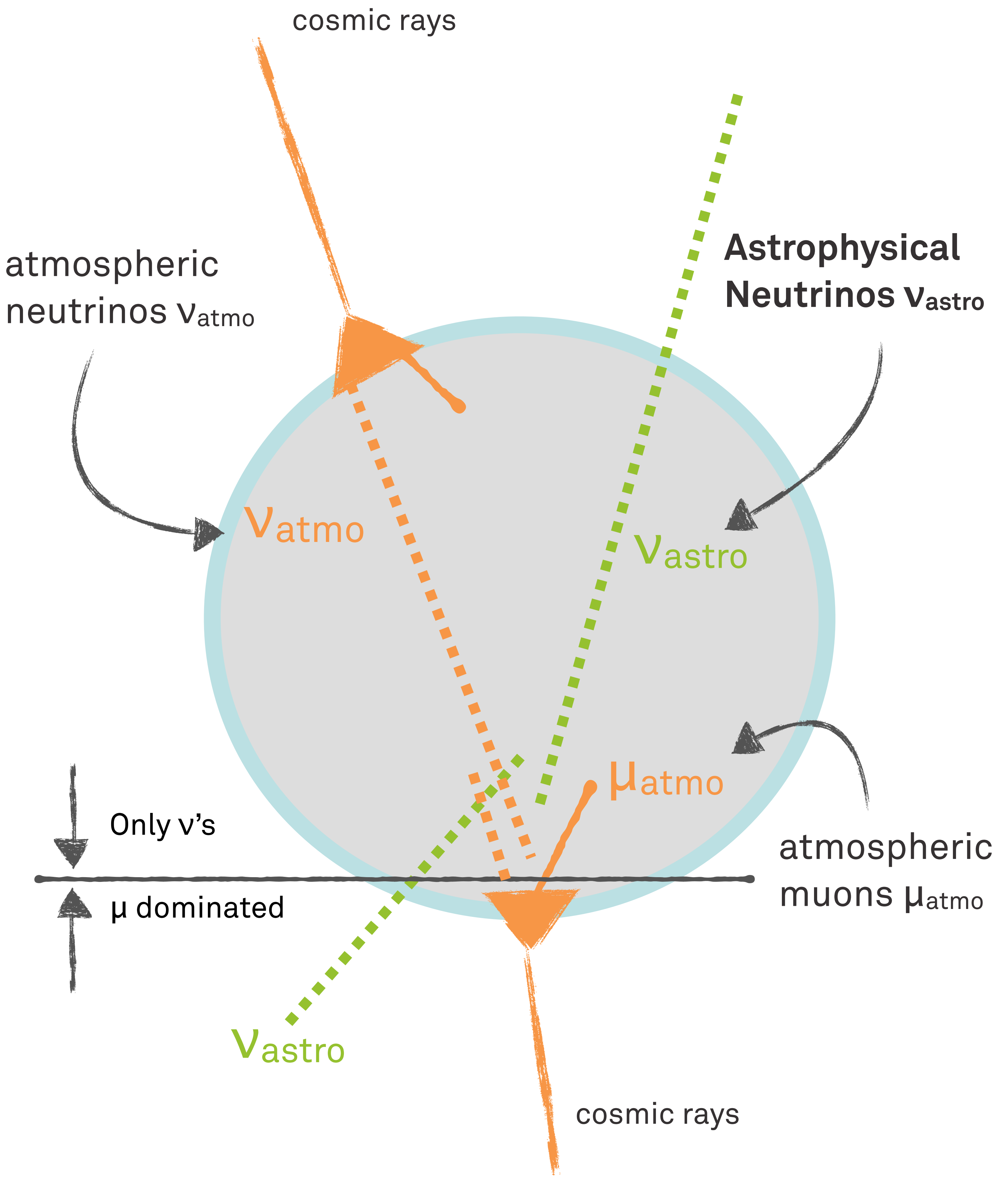


Upgoing track selection

- Event selection of ~650k upgoing track events







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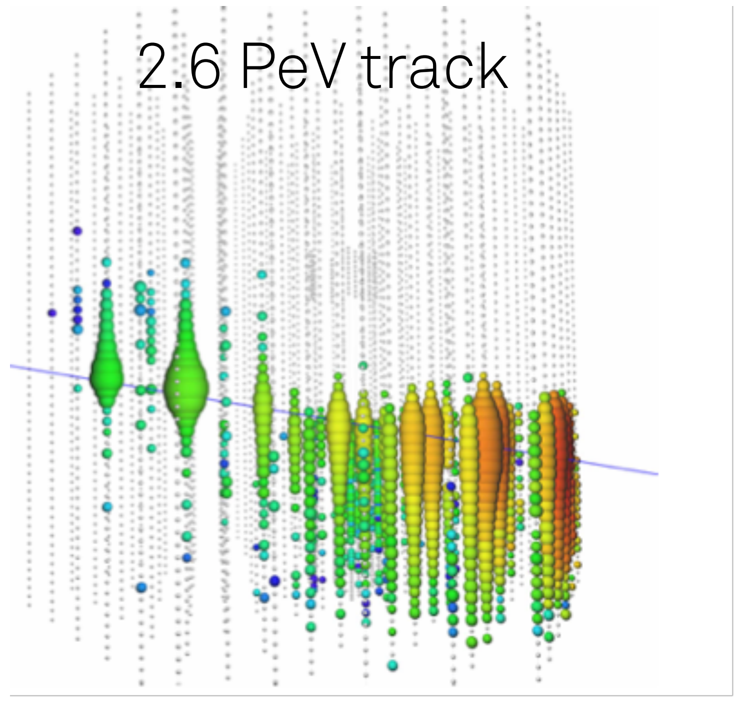
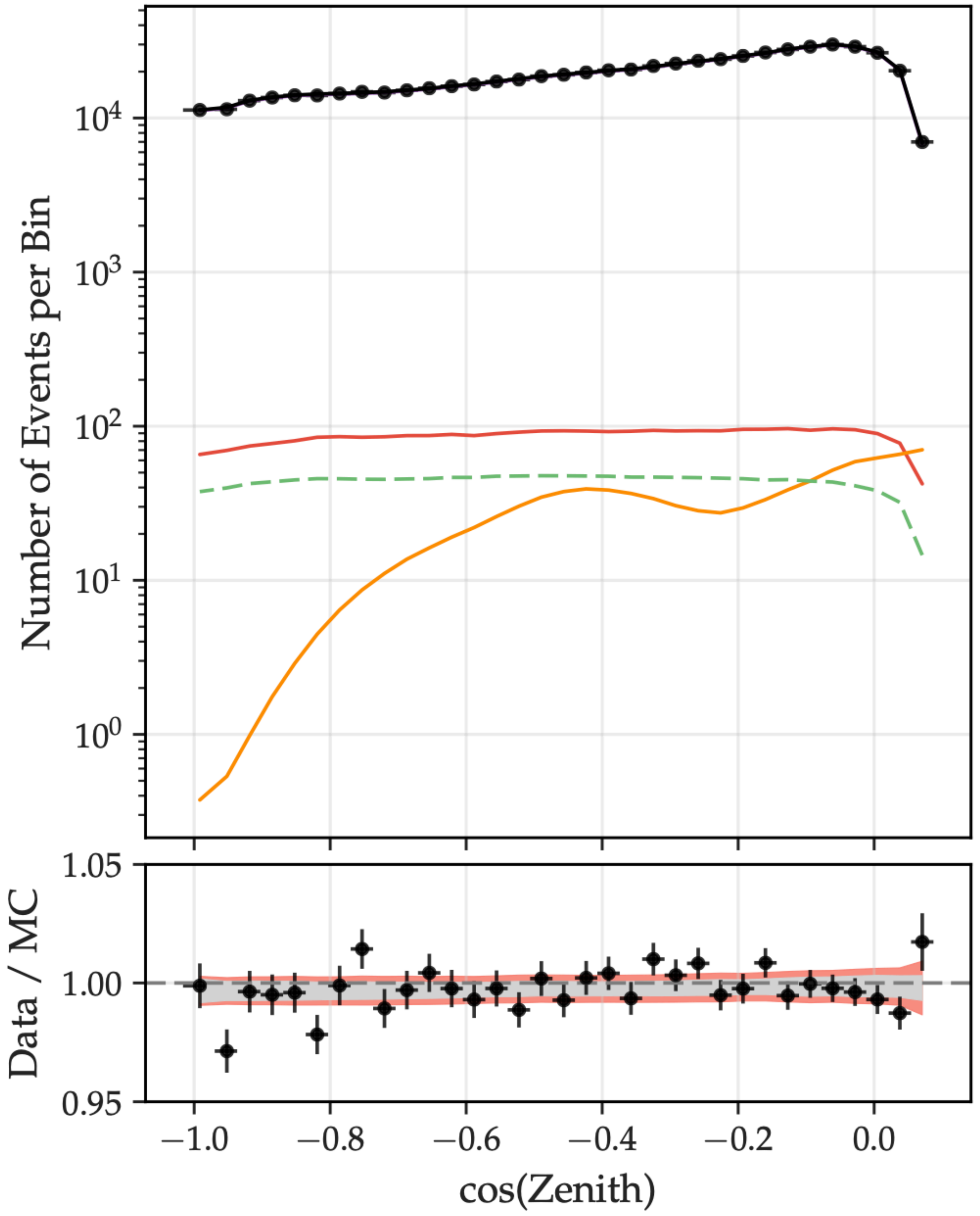
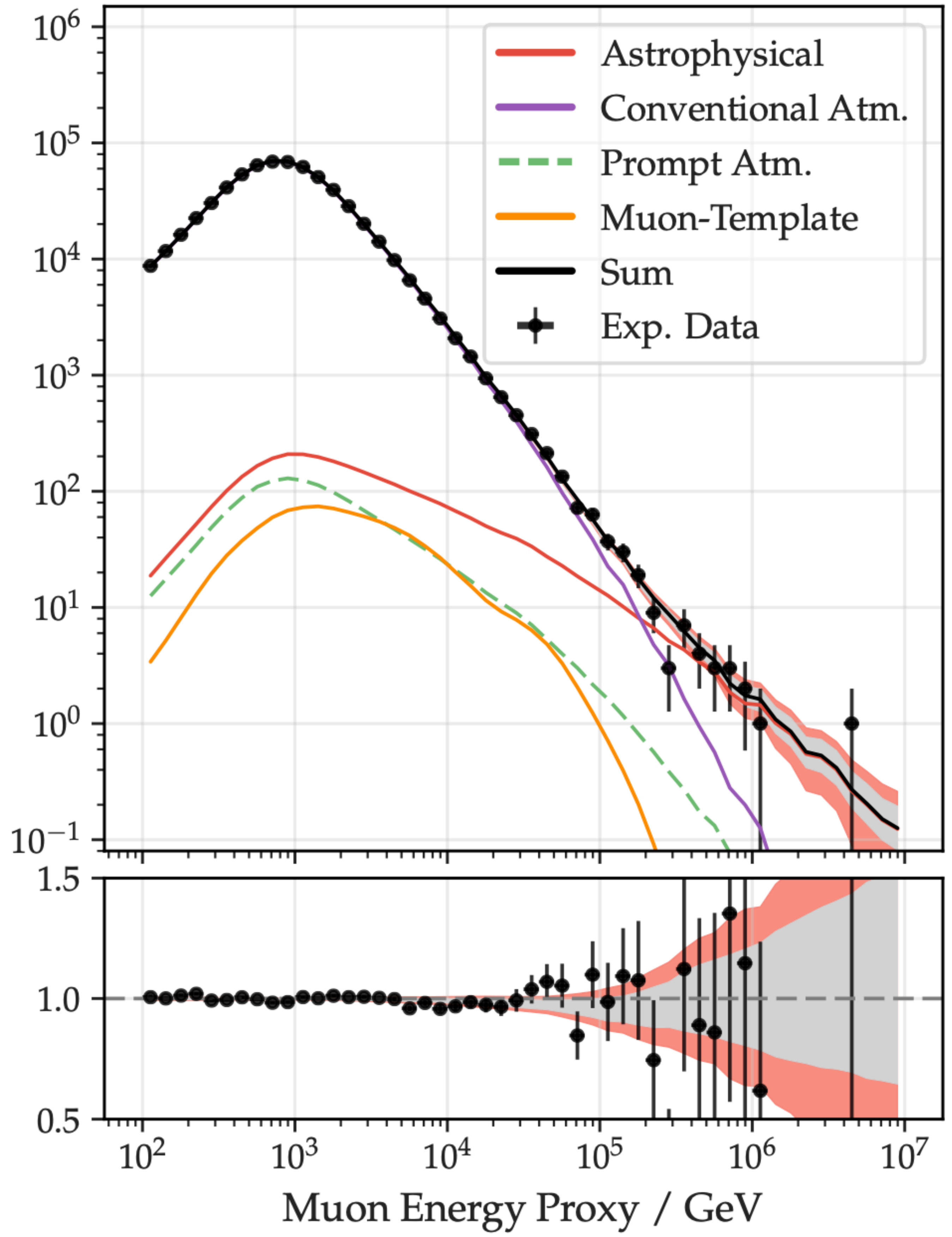
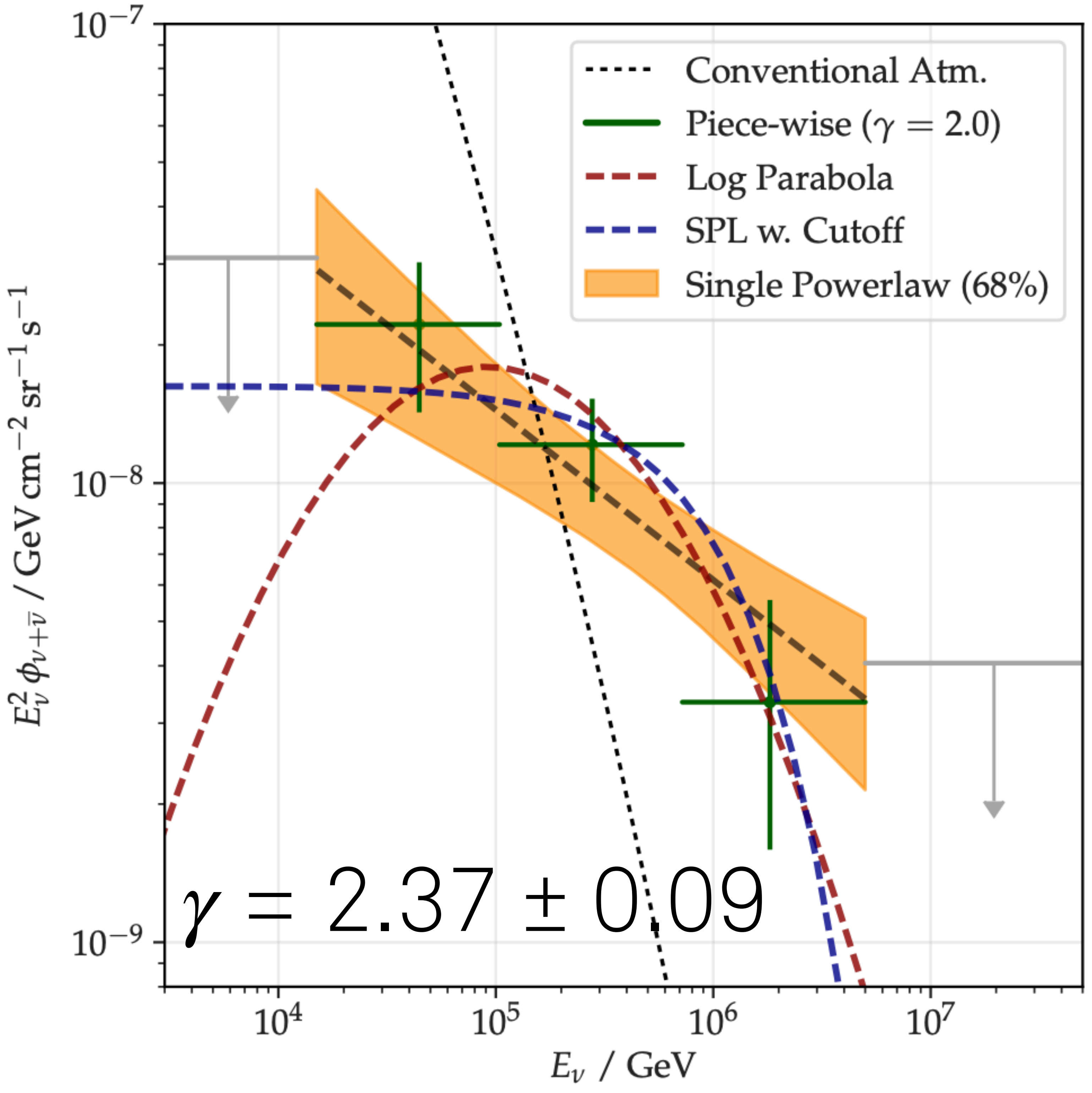


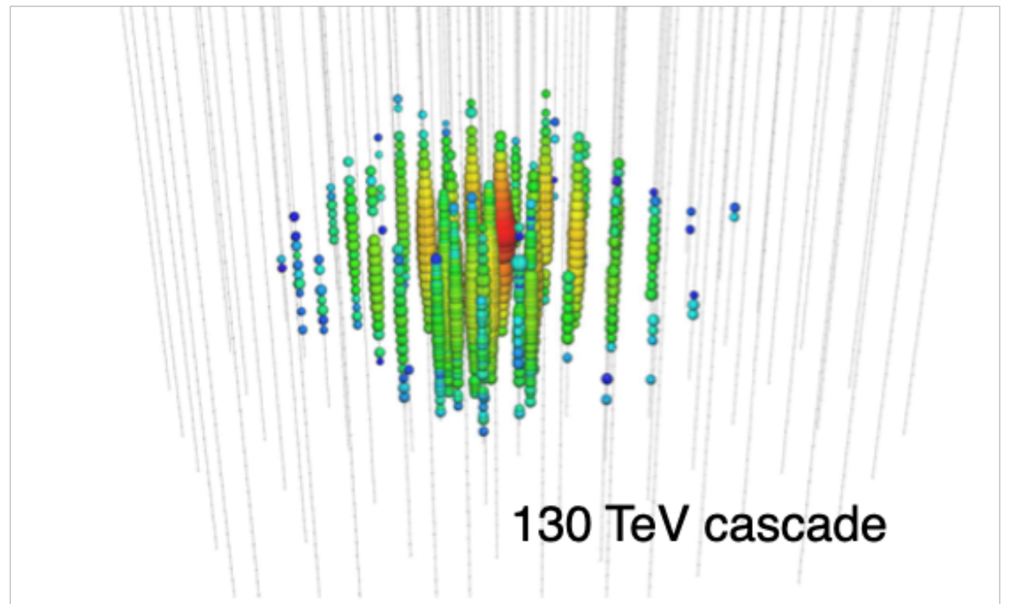


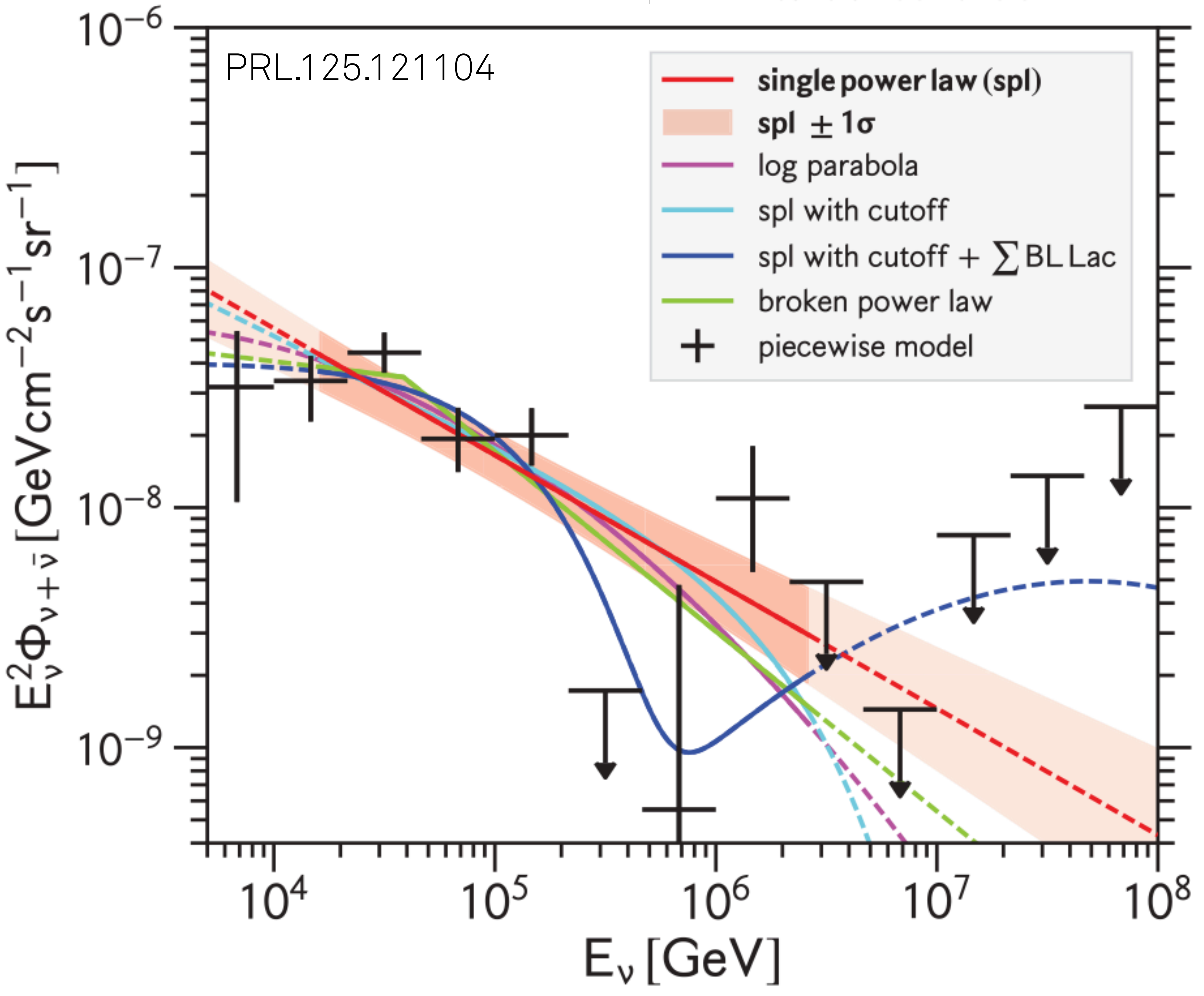




Cascade selection

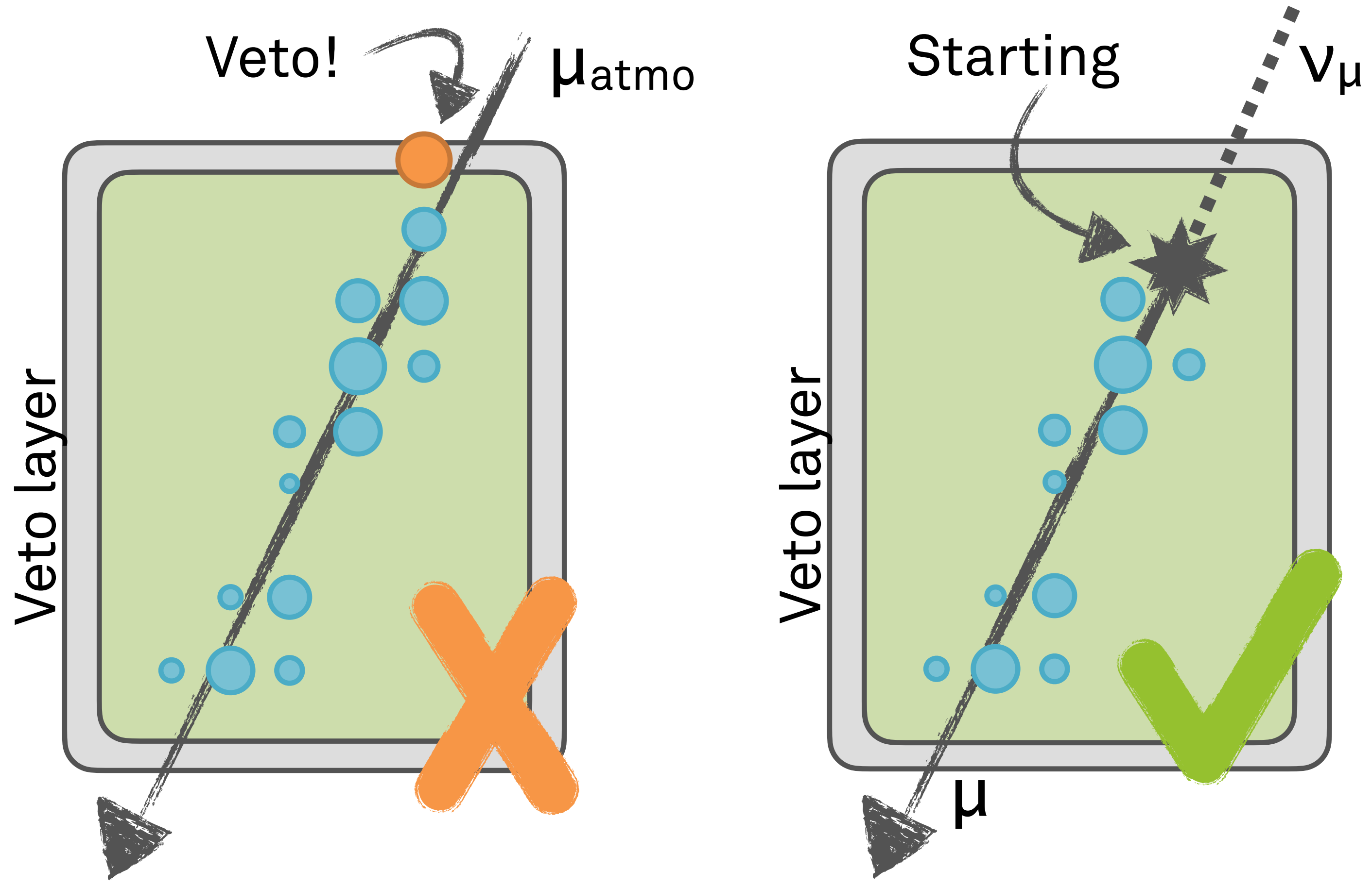
- Selects contained cascades including ~400 astrophysical electron neutrino, tau neutrino and neutrino NC events
- Better energy resolution, but worse angular resolution compared to the track selection
- Rejects atmospheric neutrino events using a self-veto technique
- $\gamma = 2.53 \pm 0.07$



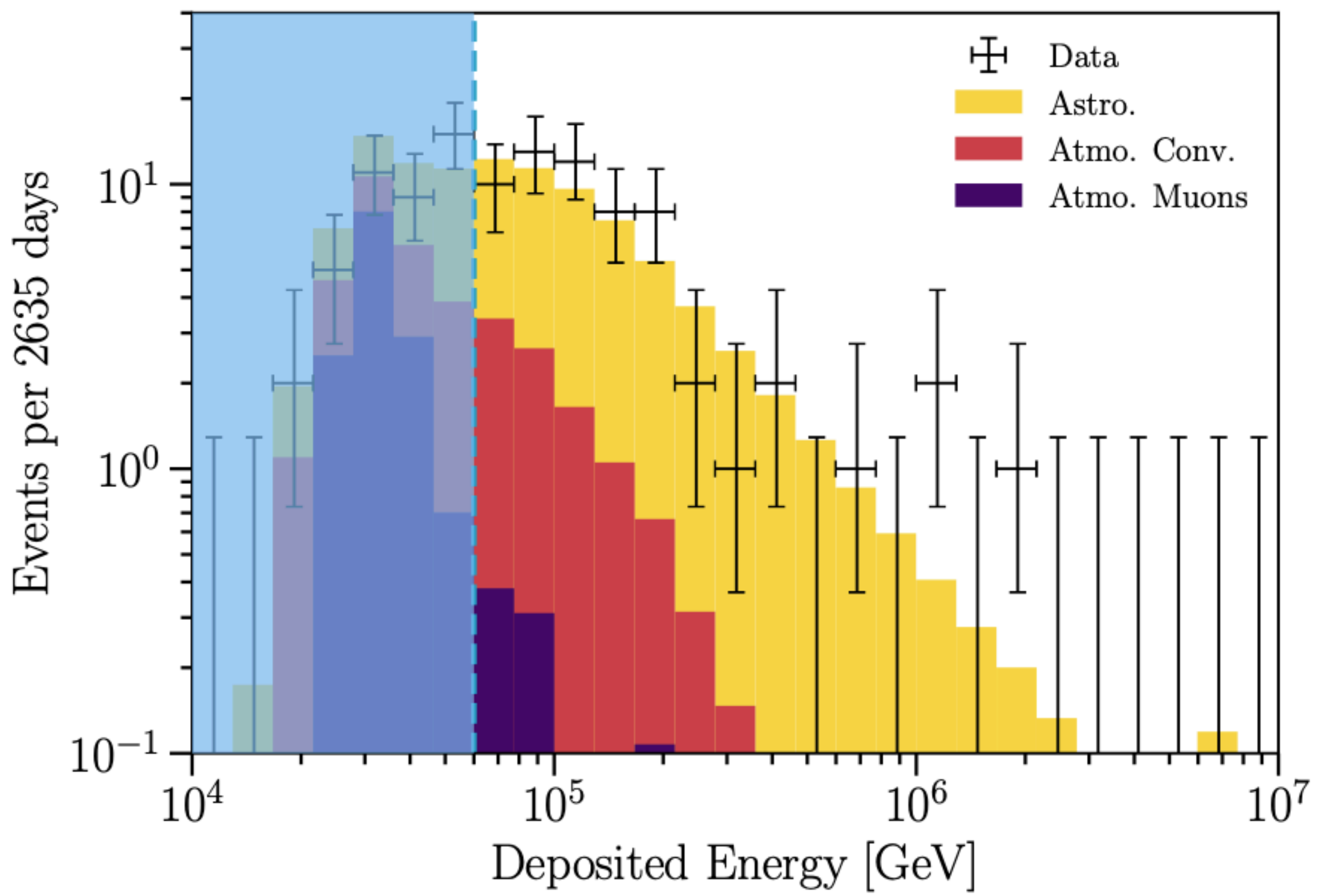


High energy starting events

- Hybrid selection of starting events: Mostly cascades but also tracks
- 60 observed events with reconstructed energies above 60 TeV in 7.5 years of data
- $\gamma = 2.87 \pm 0.2$

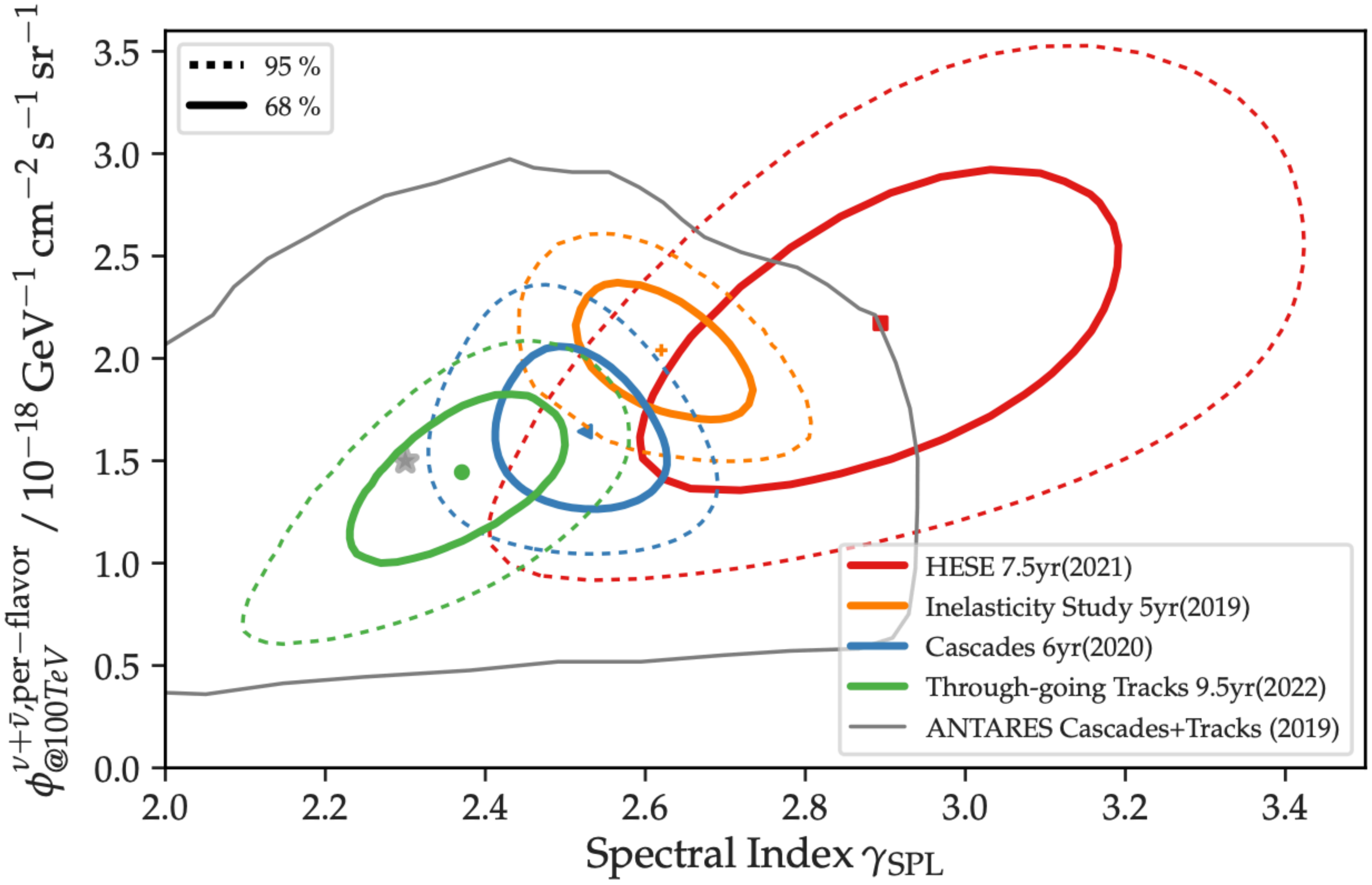


PRD 104, 022002 (2021)



Spectral measurements of astrophysical neutrinos

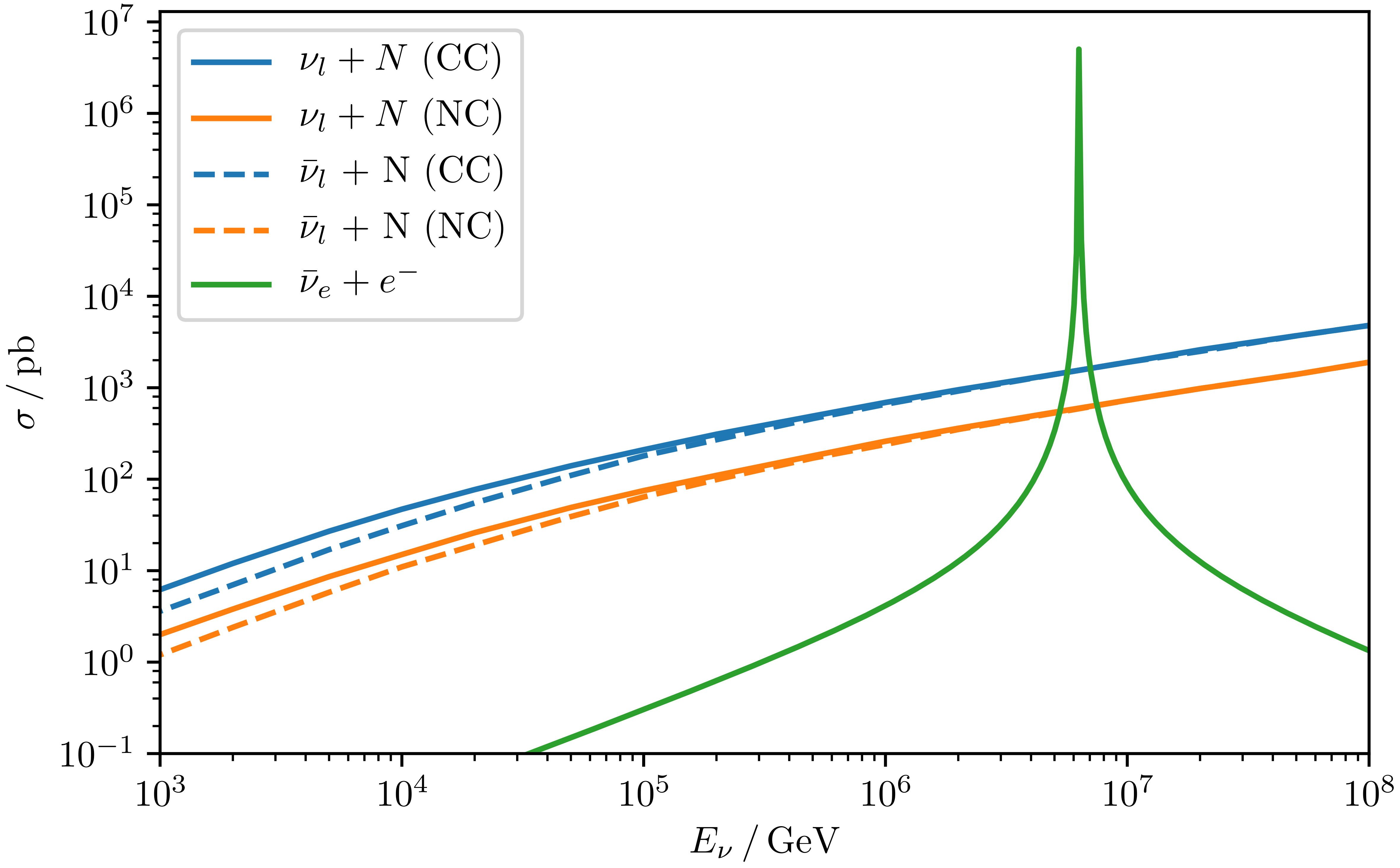
- Several complementary measurements
- All measurements are consistent with a single power law
- Slight tension @ 2σ level
- Working on a global fit to combine multiple event selections and treat their systematics uniformly

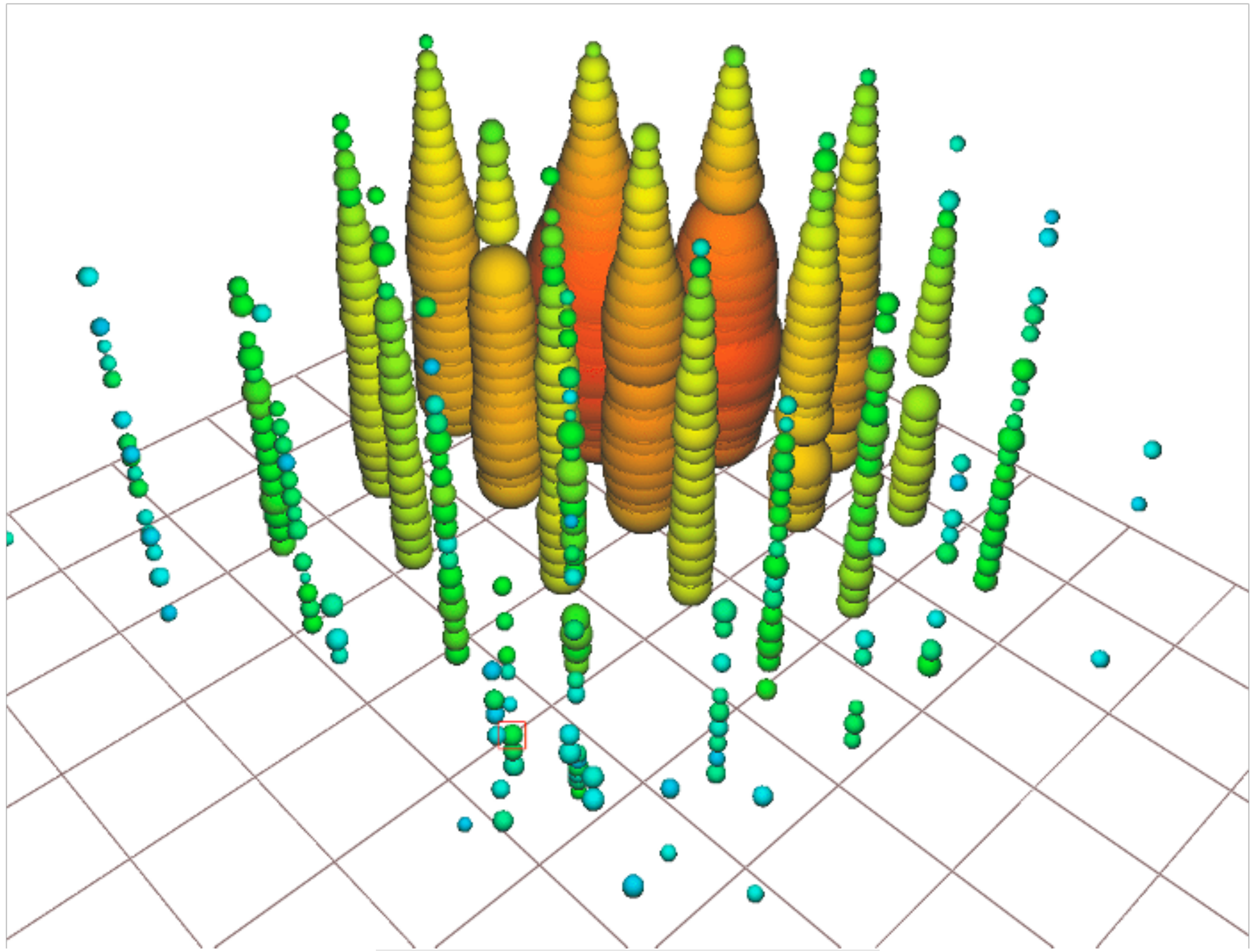


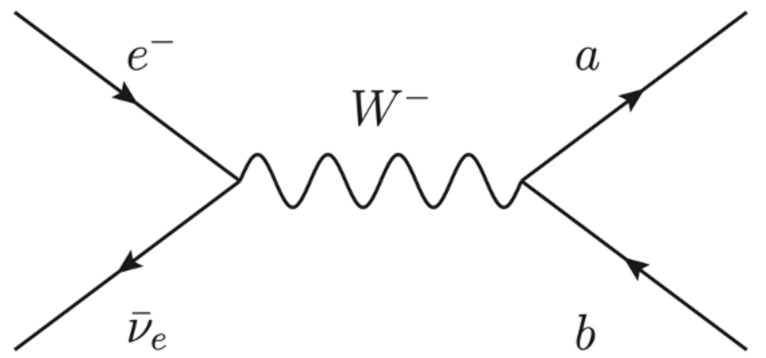
Glashow resonance

Nature 591, 220–224 (2021)

- Partially contained event search found a cascade with a reconstructed energy of ~6 PeV
- Found to be consistent with a Glashow resonance: **on-shell** formation of a W-boson







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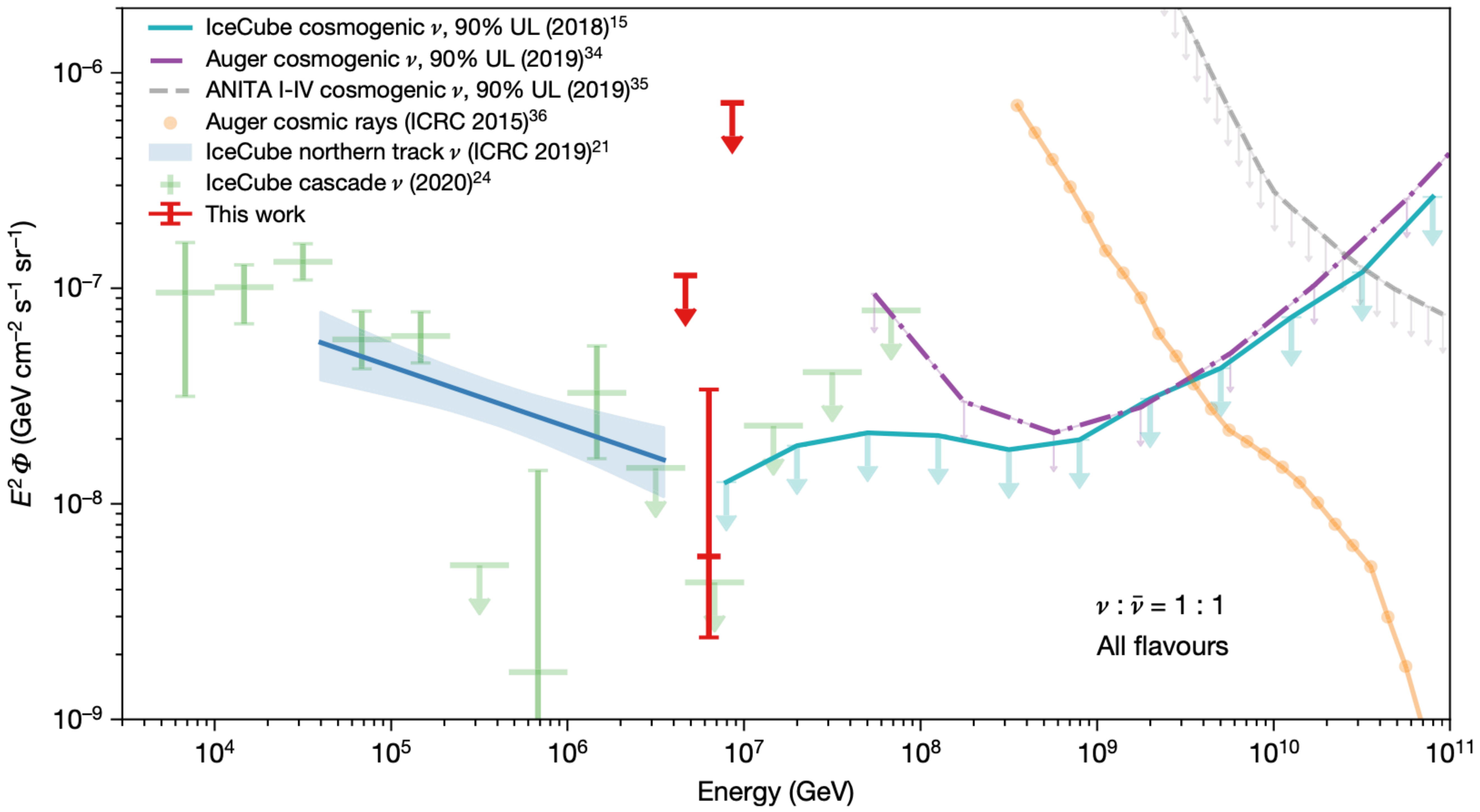
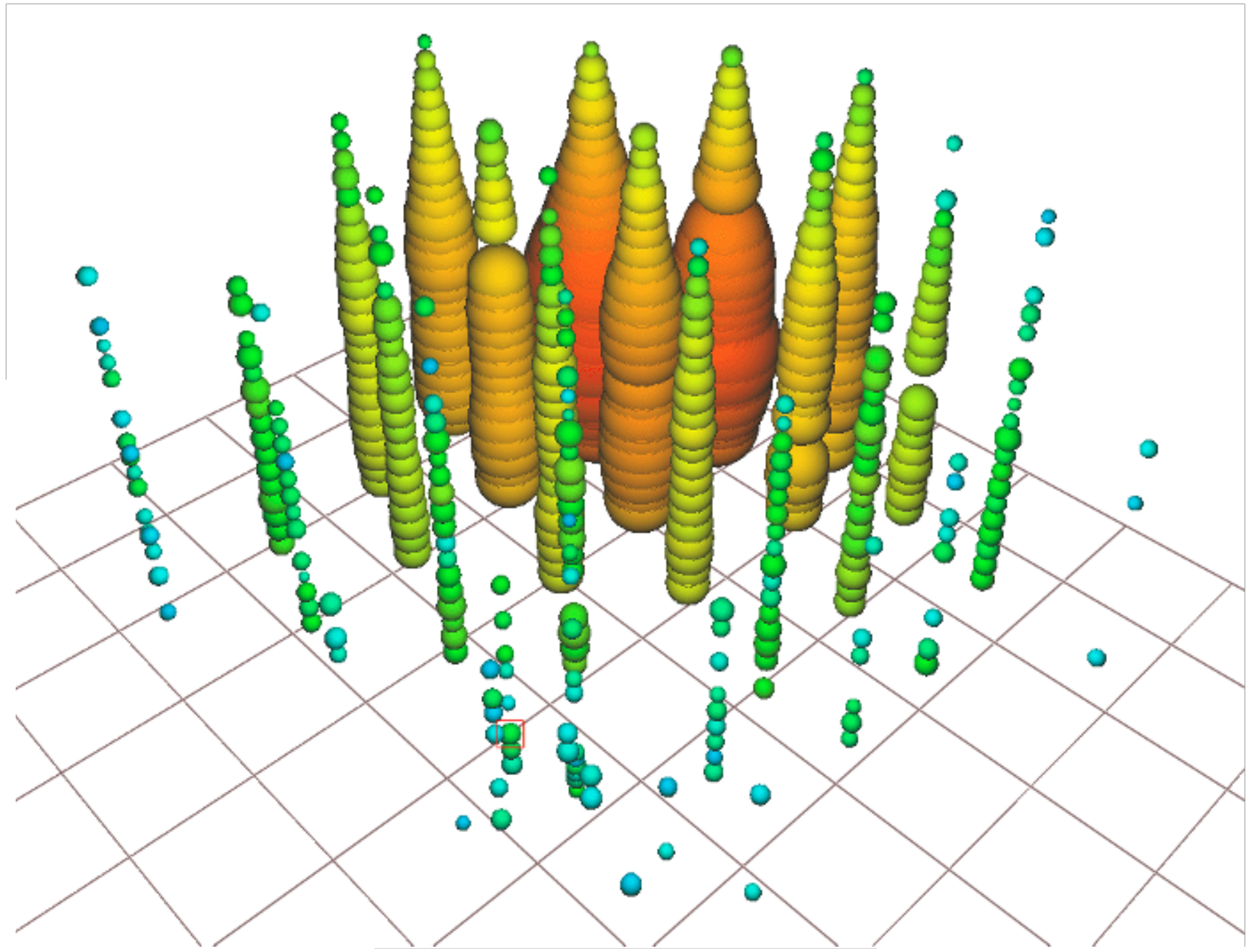
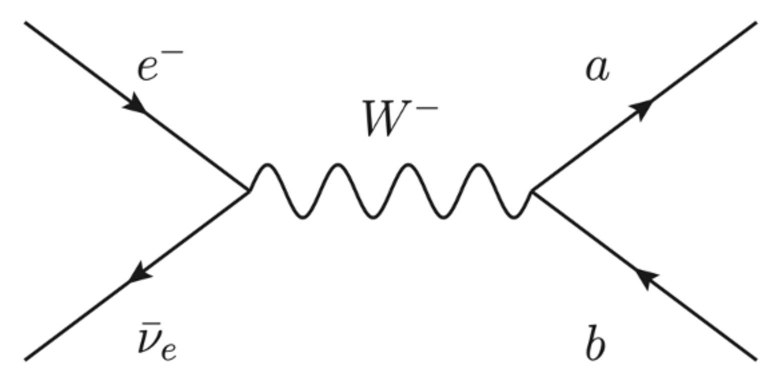
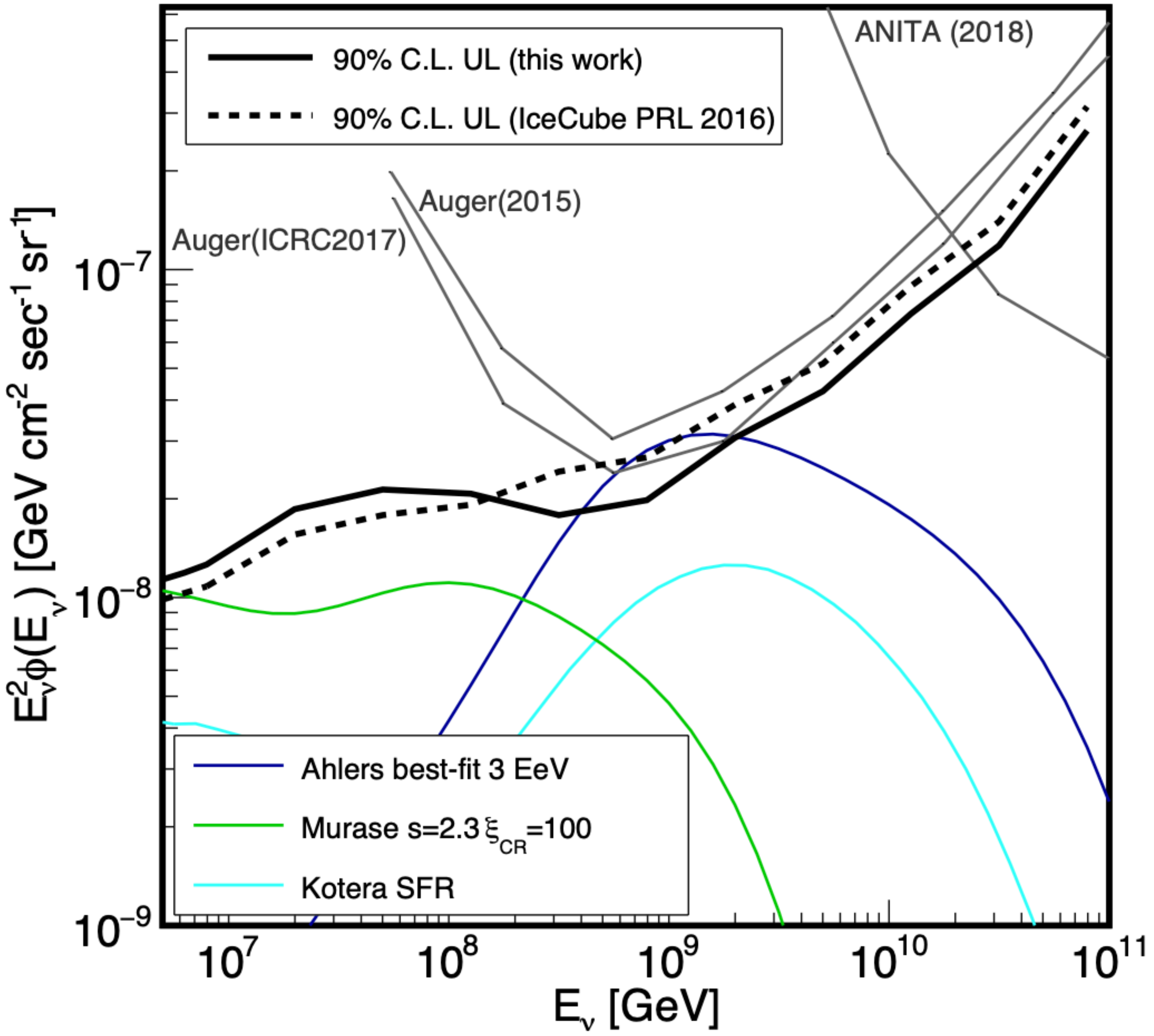




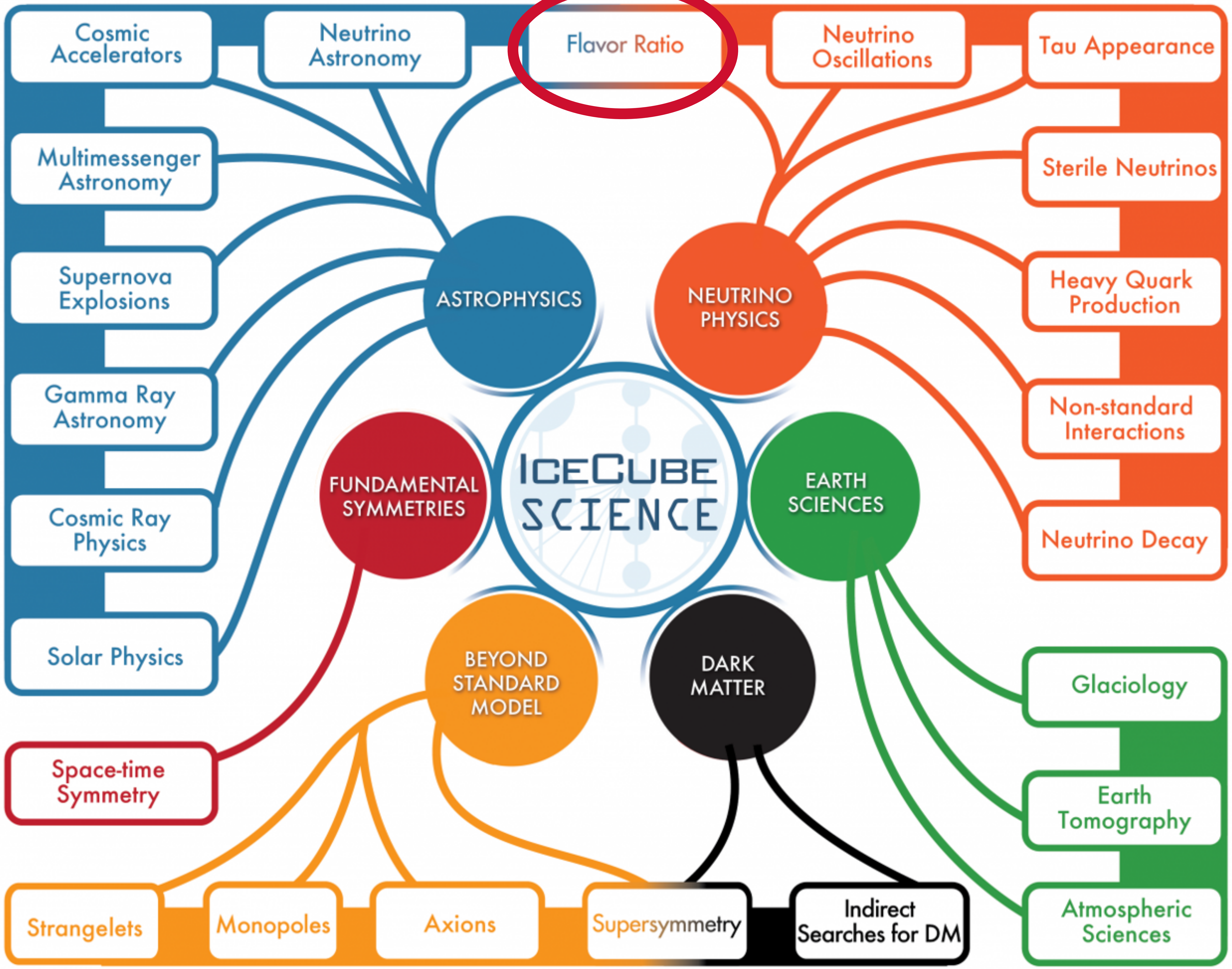


Cosmogenic neutrino search

- Event selection targeting the highest energy events (PeV - 100 EeV energies)
- Found 2 events in 9 years of data
- Consistent with a flux of astrophysical neutrinos
- Differential upper limit on the flux of cosmogenic neutrinos



arxiv.org/abs/1807.01820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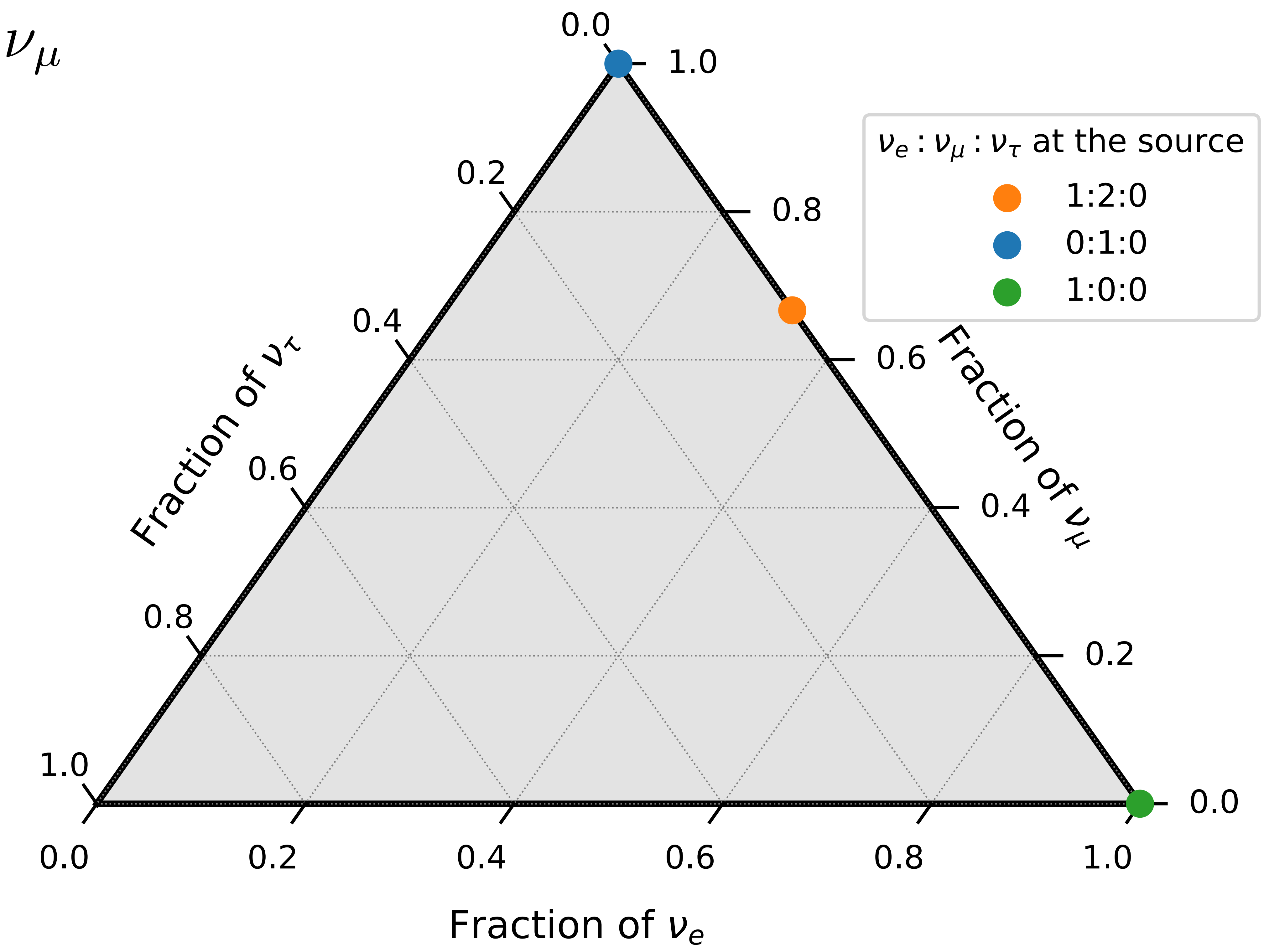
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences

Tau neutrino searches — flavour ratio measurement

- There are 3 different flavour ratio models for neutrinos from astrophysical sources
  - Pion decay (1:2:0): $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$
  - Muon damping (0:1:0): $\pi^+ \to \cancel{\mu^+} + \nu_\mu$
  - Neutron decay (1:0:0): $n \to p + e^- + \bar{\nu}_e$

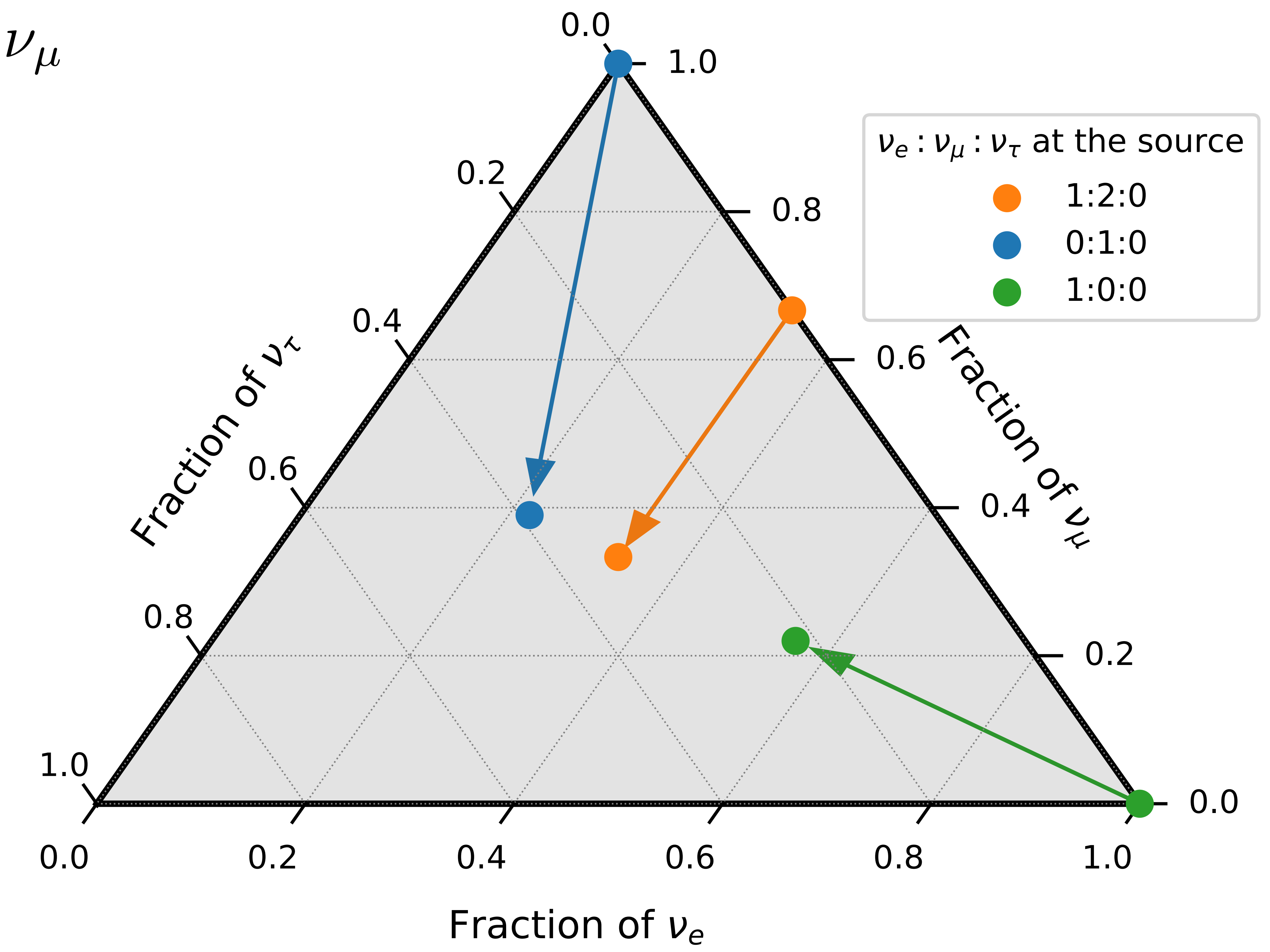


Tau neutrino searches — flavour ratio measurement

- There are 3 different flavour ratio models for neutrinos from astrophysical sources
  - Pion decay (1:2:0): $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$
  - Muon damping (0:1:0): $\pi^+ \rightarrow \cancel{\mu^+} + \nu_\mu$
  - Neutron decay (1:0:0): $n \rightarrow p + e^- + \bar{\nu}_e$

- The initial flavour ratio is modified at the Earth due to neutrino flavour mixing

- Muon damping and neutron decay model are „extreme cases“ and the real ratio should be confined within those two models

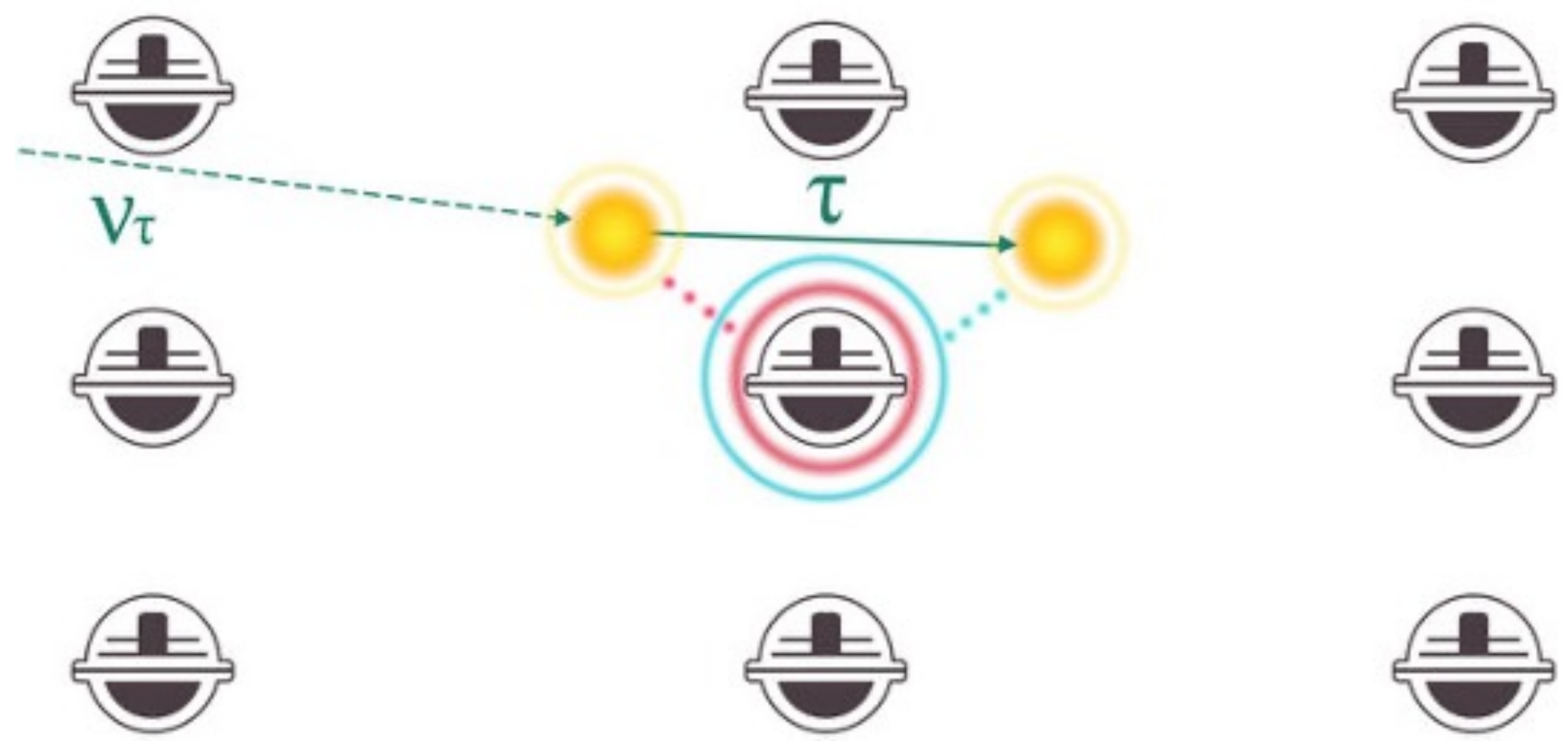


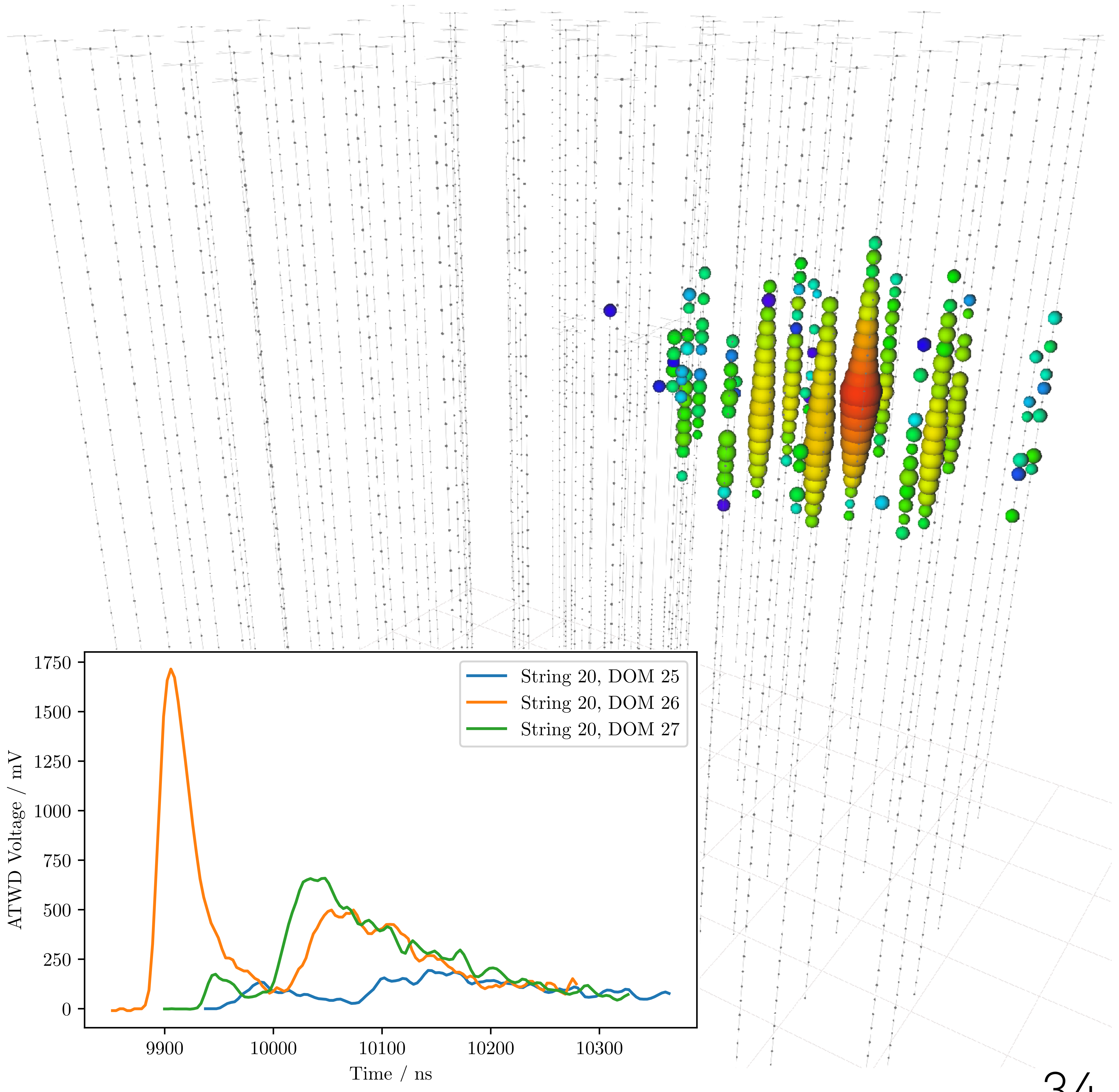
Tau neutrino searches — flavour ratio measurement

arXiv:1909.05127

- Search for a double pulse / double cascade signature from the initial nutau CC interaction and the tau lepton decay

$$L_\tau \simeq 50 \frac{\mathrm{m}}{\mathrm{PeV}}$$





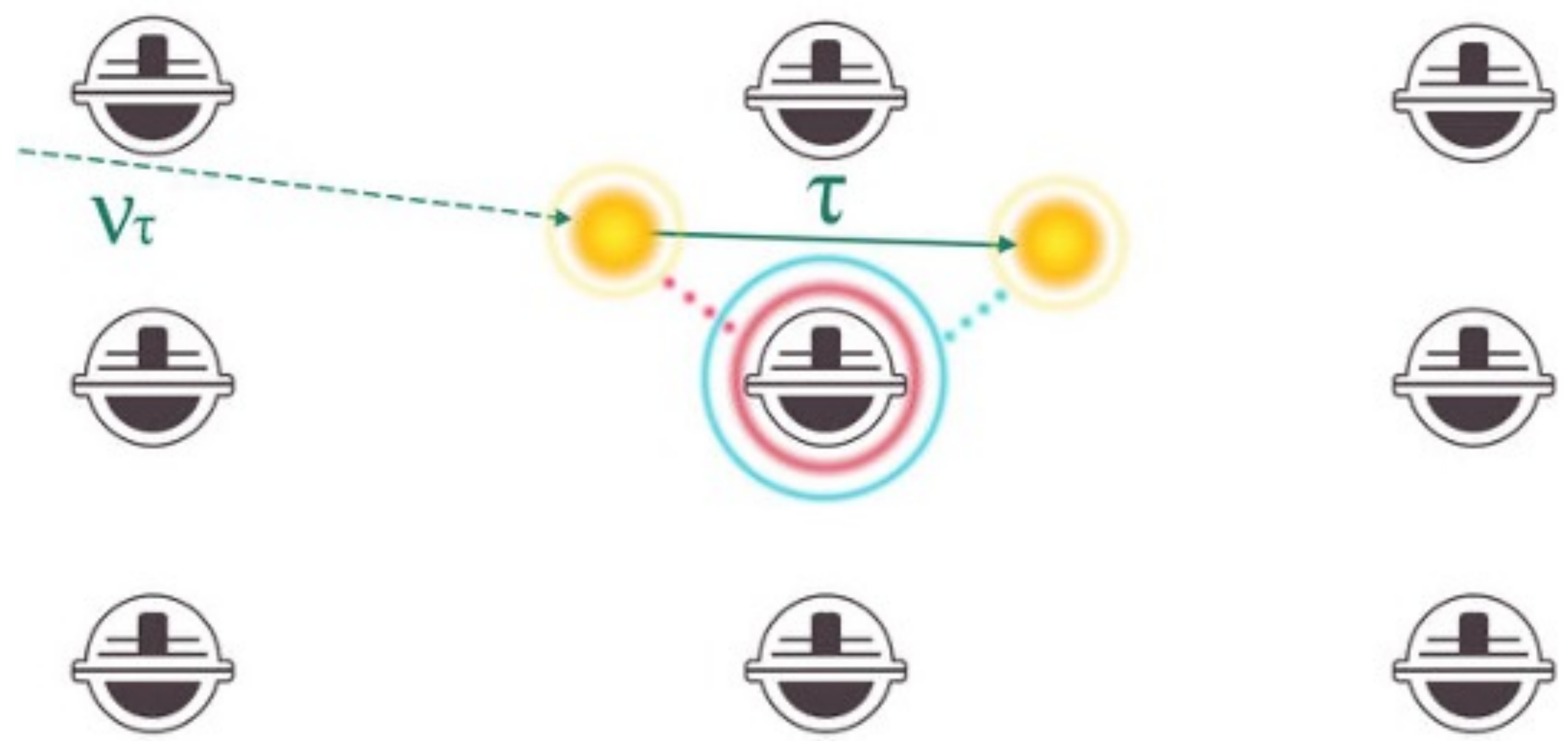
arxiv 2011.03561
(submitted to EPJC)

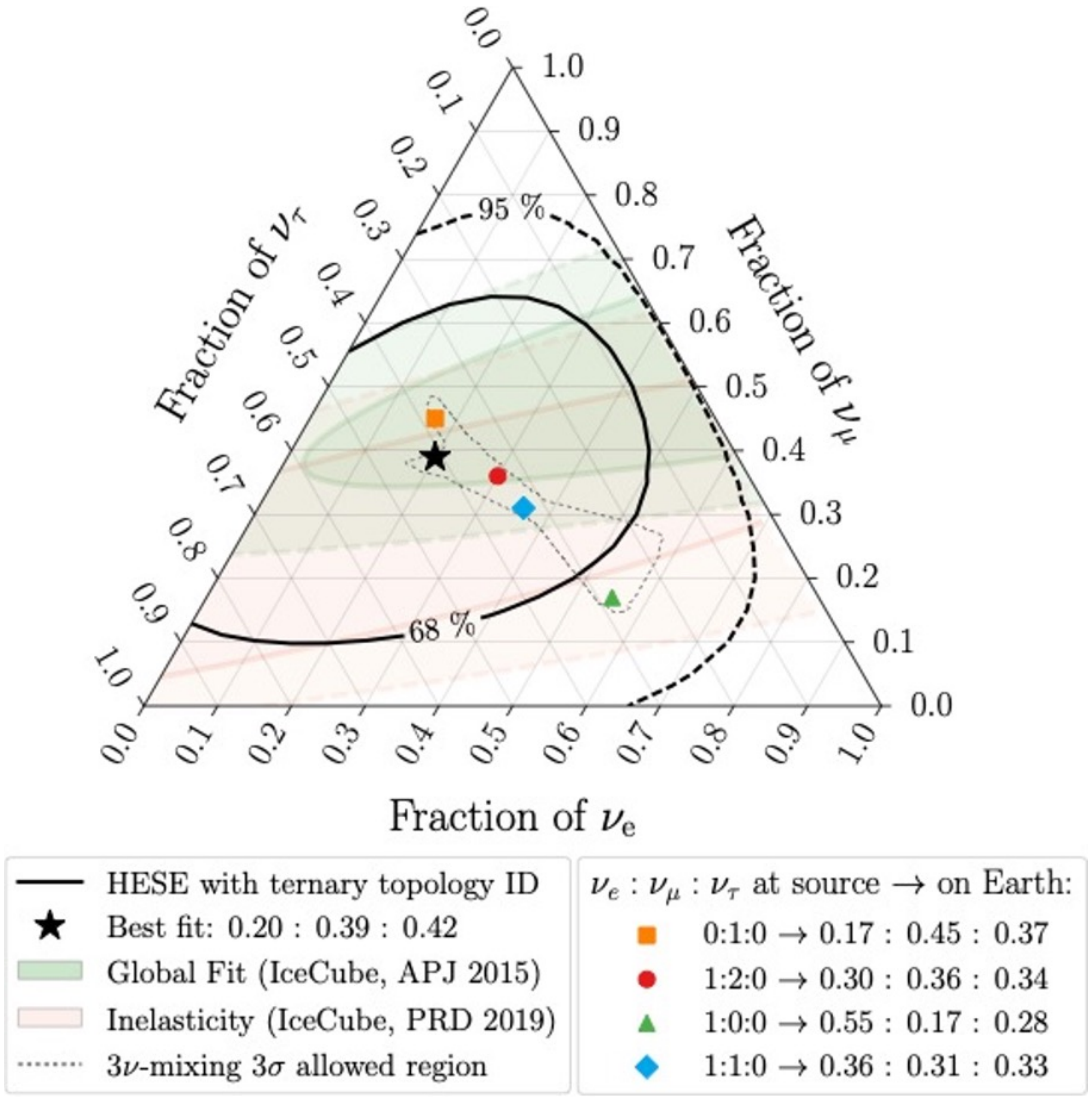
Tau neutrino searches — flavour ratio measurement

- High energy starting event selection reconstructs events using a double cascade hypothesis

- Measuring the astrophysical neutrino flavor ratio rejects no tau neutrinos with 2.8σ confidence level

$$L_\tau \simeq 50 \frac{\mathrm{m}}{\mathrm{PeV}}$$





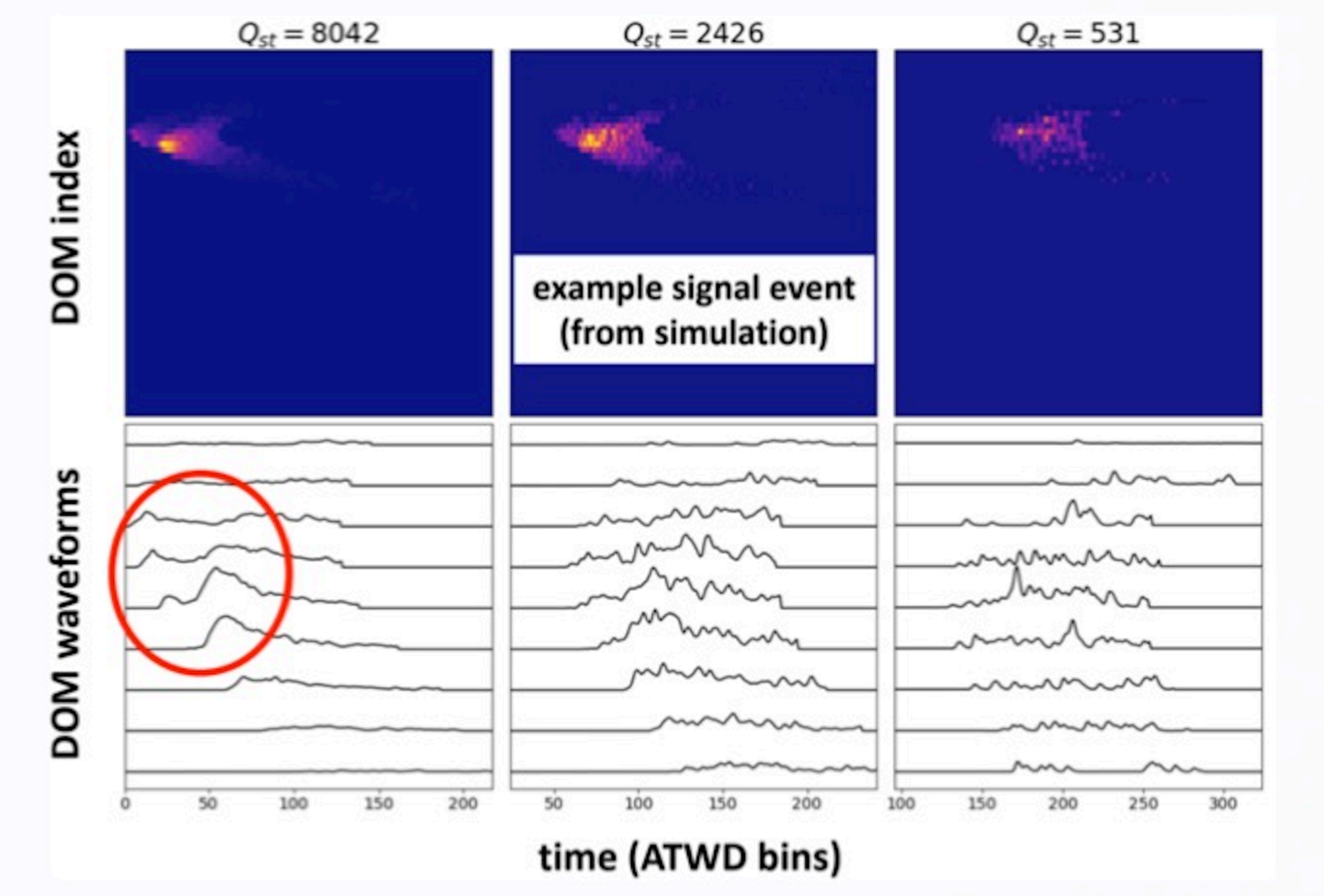
Tau neutrino searches

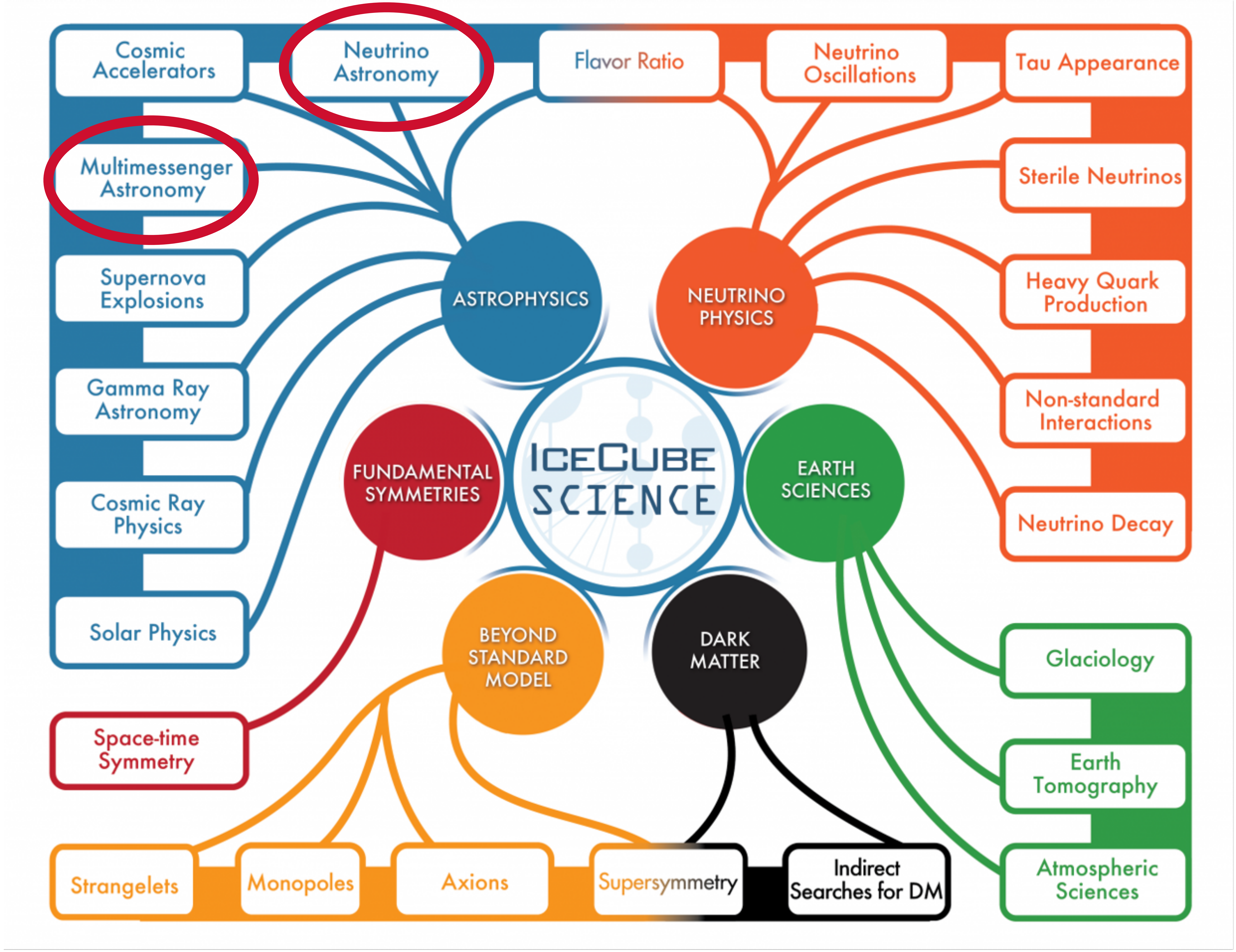
D. Pankova, A. Fienberg, D. Cowen (PSU)

- New search looking at the nutau double pulse channel using convolutional neural networks

- Classify pictures from waveform information on high charge strings

- Expecting 5 ν_τ events over a background of 0.5
- >50% chance to reject no tau neutrinos with more than 5σ after unblinding

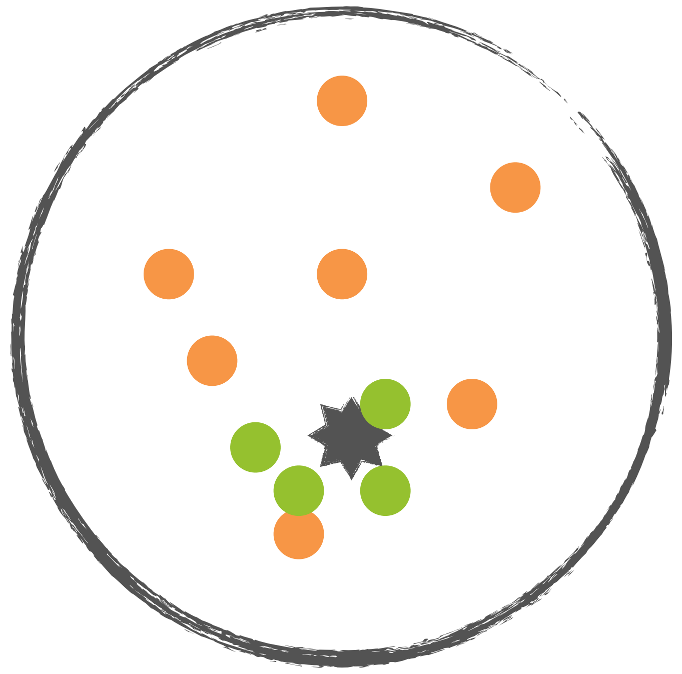



Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
ASTROPHYSICS
NEUTRINO PHYSICS
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
Cosmic Ray Physics
Neutrino Decay
Solar Physics
BEYOND STANDARD MODEL
DARK MATTER
Glaciology
Space-time Symmetry
Earth Tomography
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM
Atmospheric Sciences

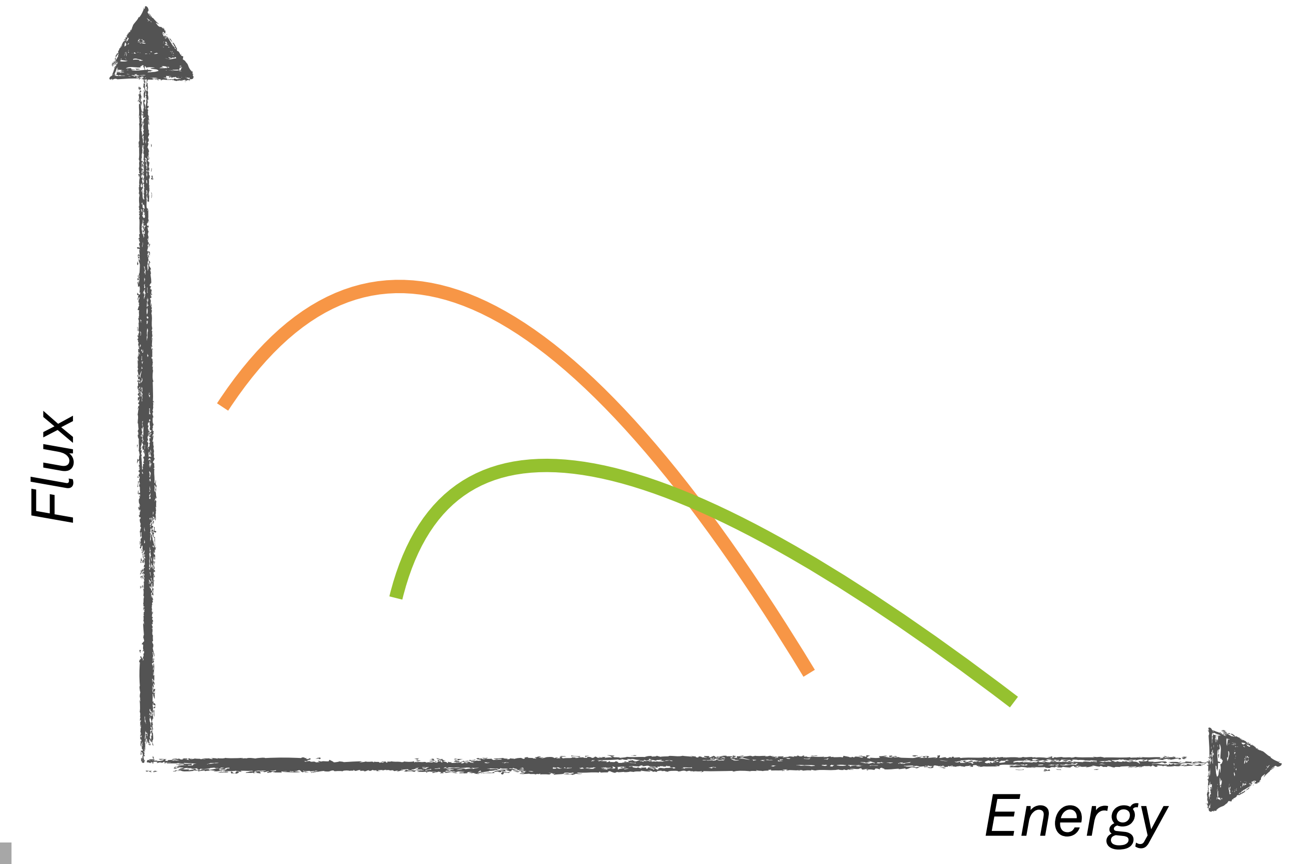
Point source analyses in IceCube

- Study the clustering of neutrinos over the atmospheric expectation

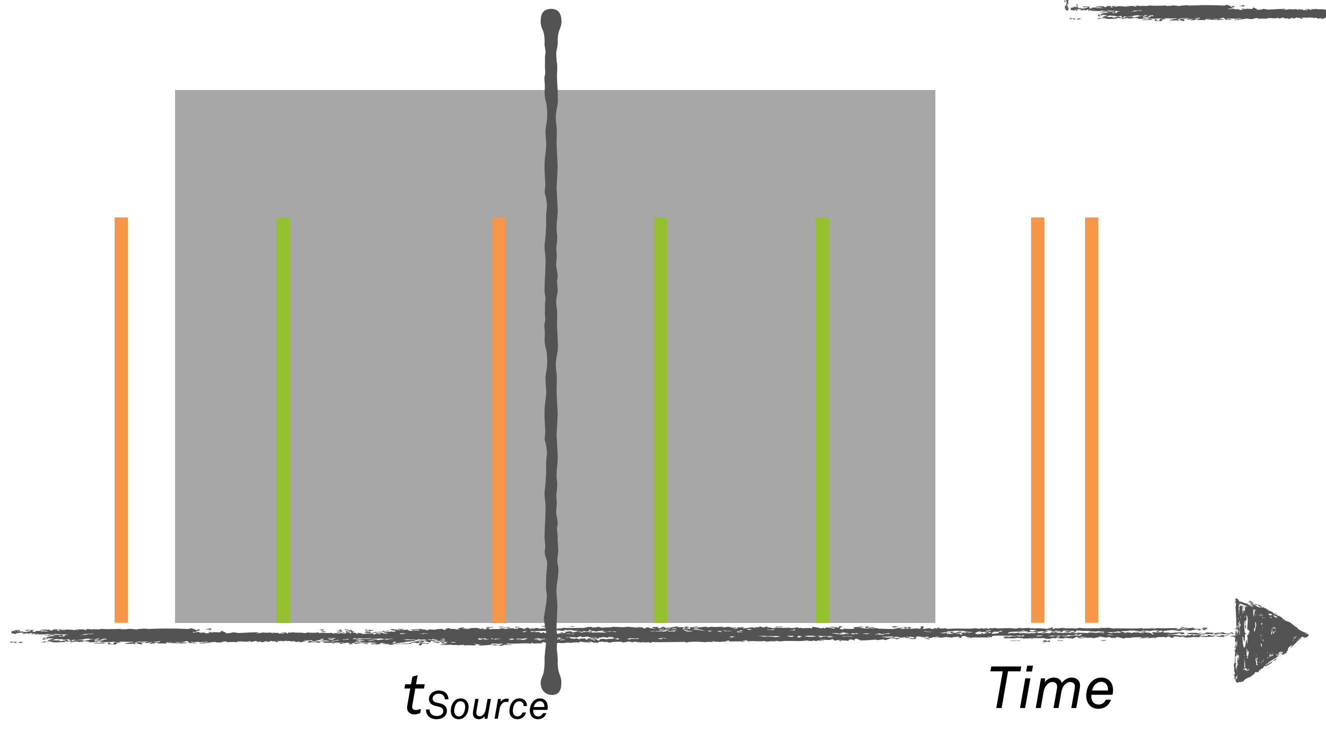
- Spatial clustering
  - Bivariate Gaussian



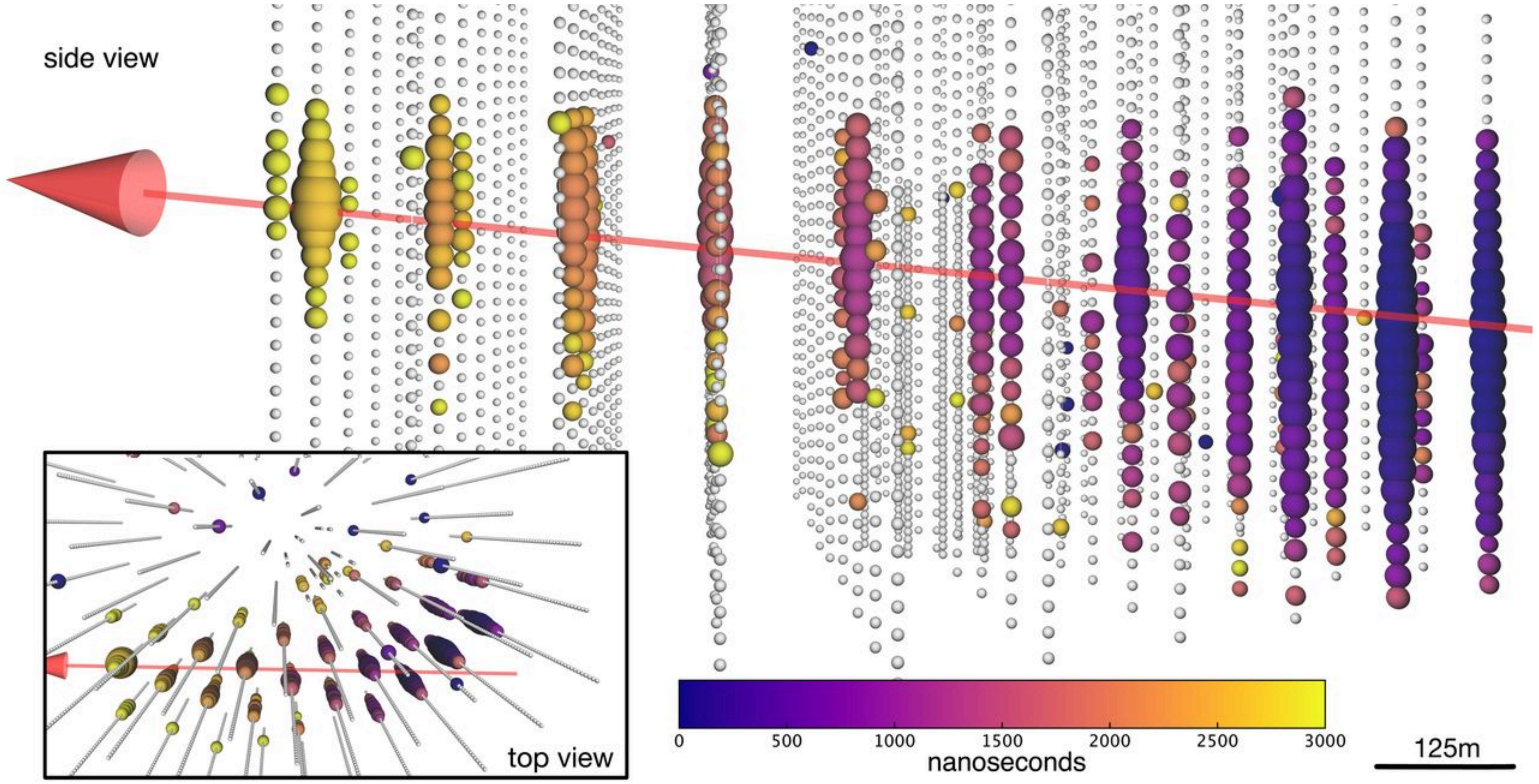
- Energy spectra
  - Signal has a hard spectrum

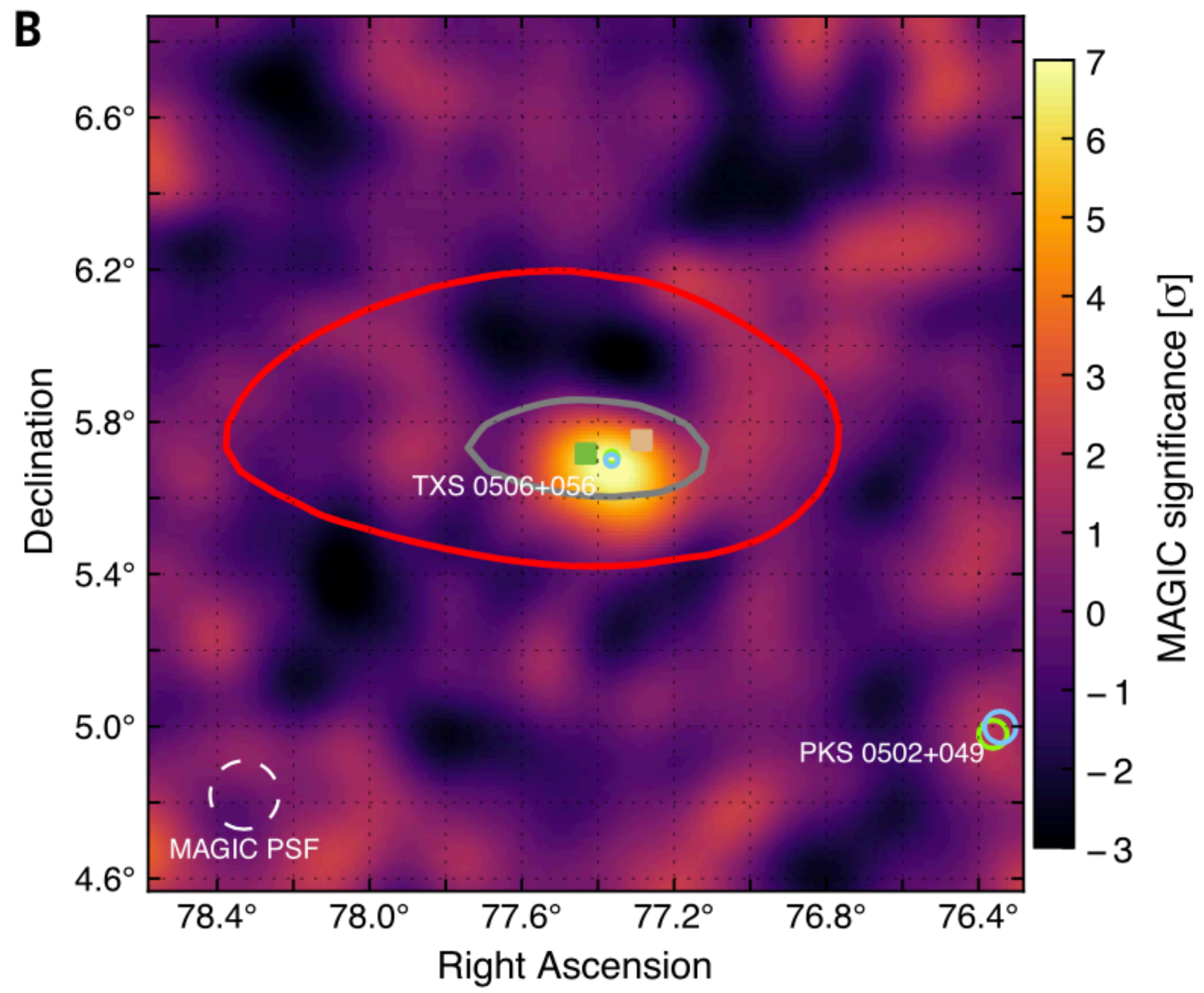


- Clustering in time
  - Box or gaussian profiles used frequently



IC170922A — TXS0506+056





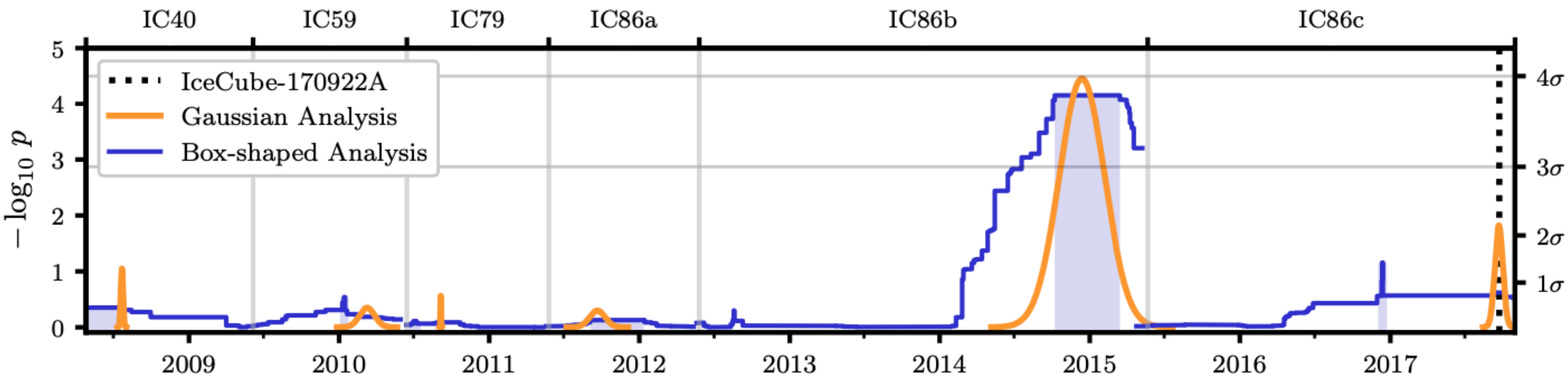
- Deposited energy: 23.7 ± 2.8 TeV
- Estimated neutrino energy: 290 TeV (> 183 TeV @ 90% CL)
- Signalness: 56.5%
- Reconstructed direction: RA $77.36^{\circ}{}^{+0.95^{\circ}}_{-0.65^{\circ}}$
  DEC $+5.72^{\circ}{}^{+0.50^{\circ}}_{-0.30^{\circ}}$

- Reported location consistent with known γ-ray source in state of enhanced emission
- Observed by Fermi LAT and MAGIC telescopes
- Chance coincidence disfavoured at 3σ level

Archival analysis of neutrino emission from TXS0506+056

- Analysis of 9.5 years of archival data with two generic time window shapes
  - No significant access of neutrinos around the alert event seen in 2017
  - Independent neutrino flare in 2014-2015 (post-trial significance of 3.5σ)

- First evidence for a very high energy astrophysical neutrino source.

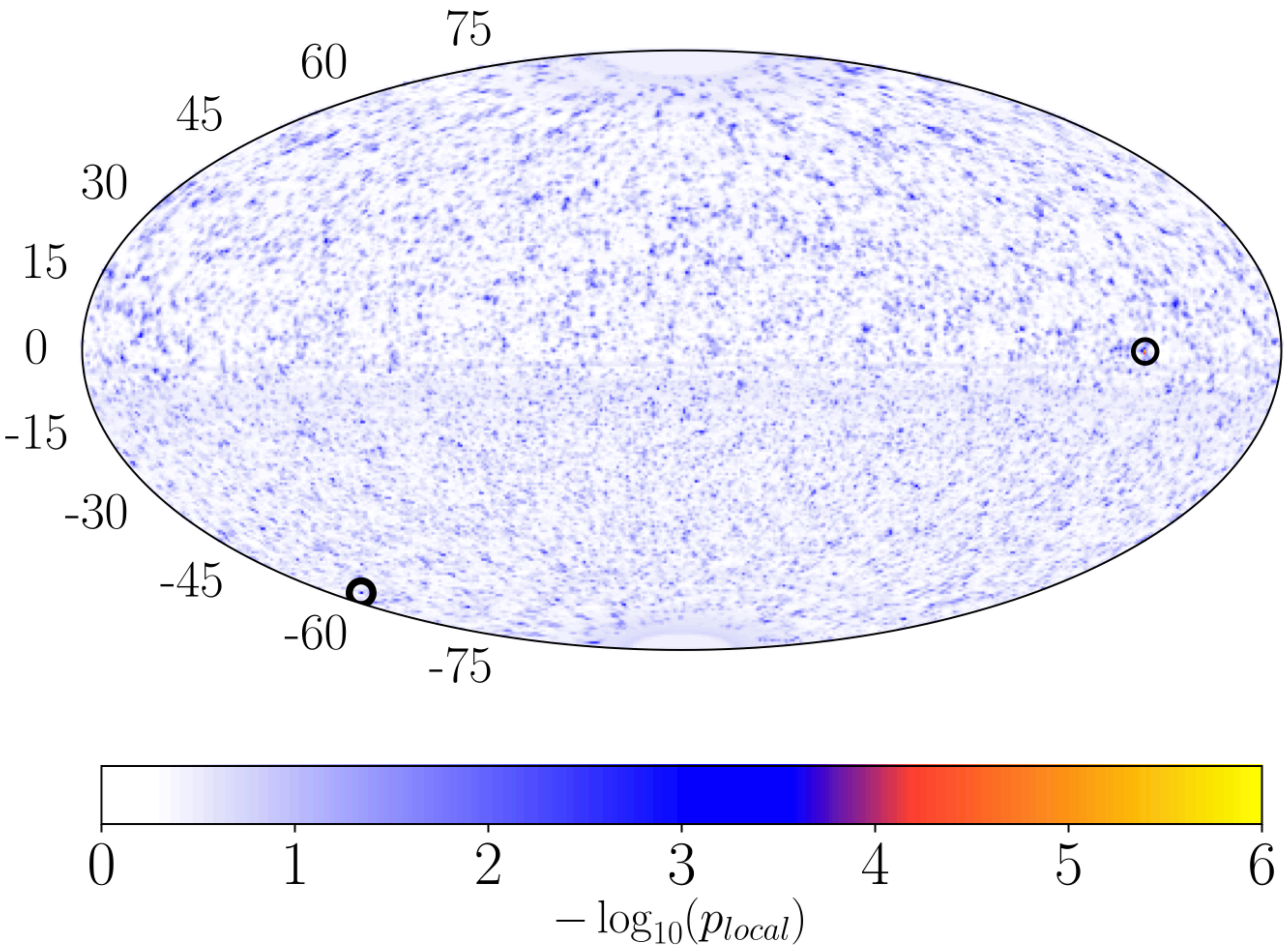


Aartsen et al., Science 2018

Neutrino Skymap

- Analysis of muon tracks from the northern and southern hemisphere in 10 years of IceCube data
- Most significant points on both hemispheres are marked with a circle

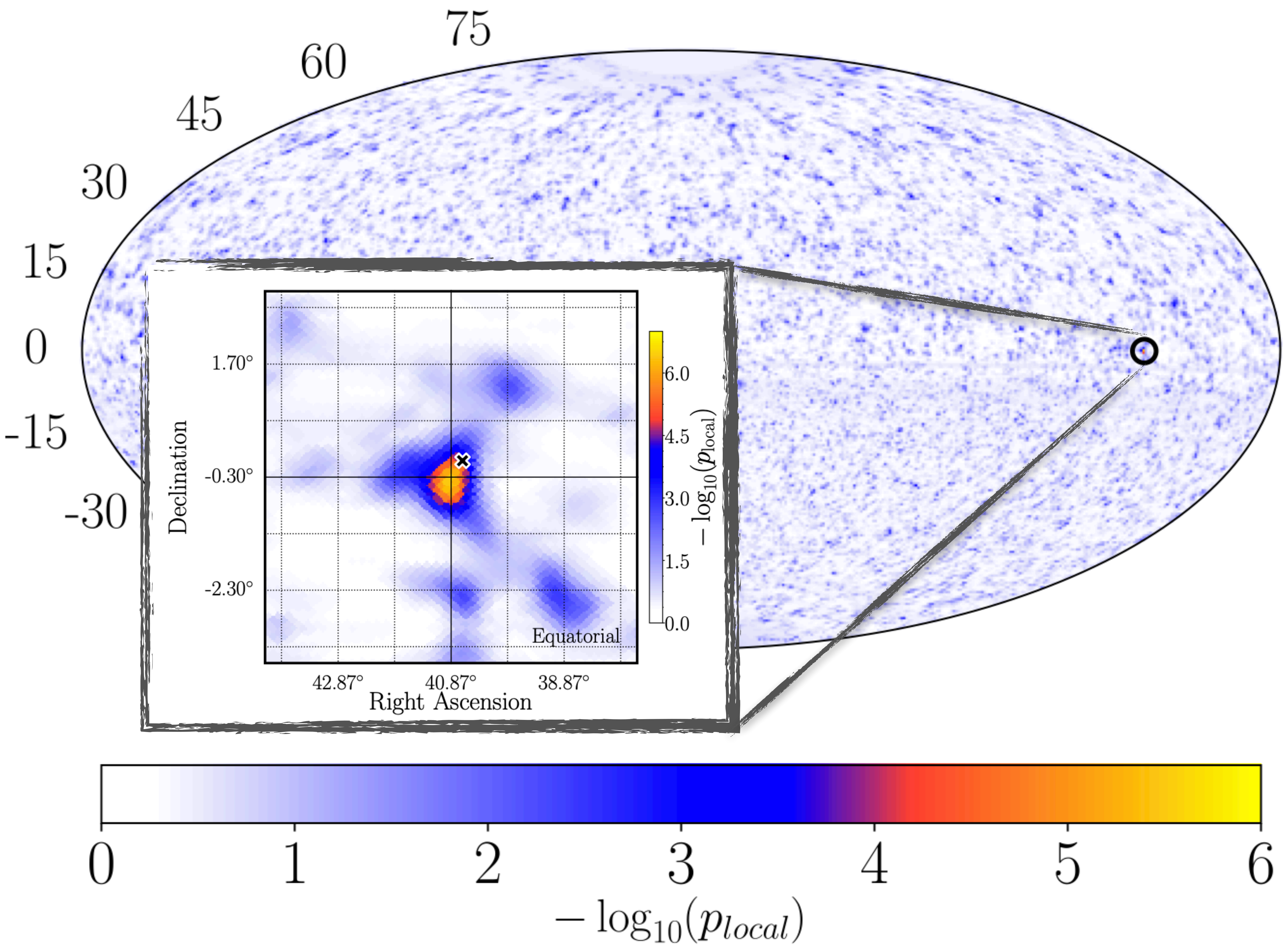
Aartsen et al., PRL124, 051103



Neutrino Skymap

- Analysis of muon tracks from the northern and southern hemisphere in 10 years of IceCube data
- Most significant points on both hemispheres are marked with a circle
- Most significant point in northern hemisphere is 0.35° away from NGC 1068
- Post trial p-value: 0.75

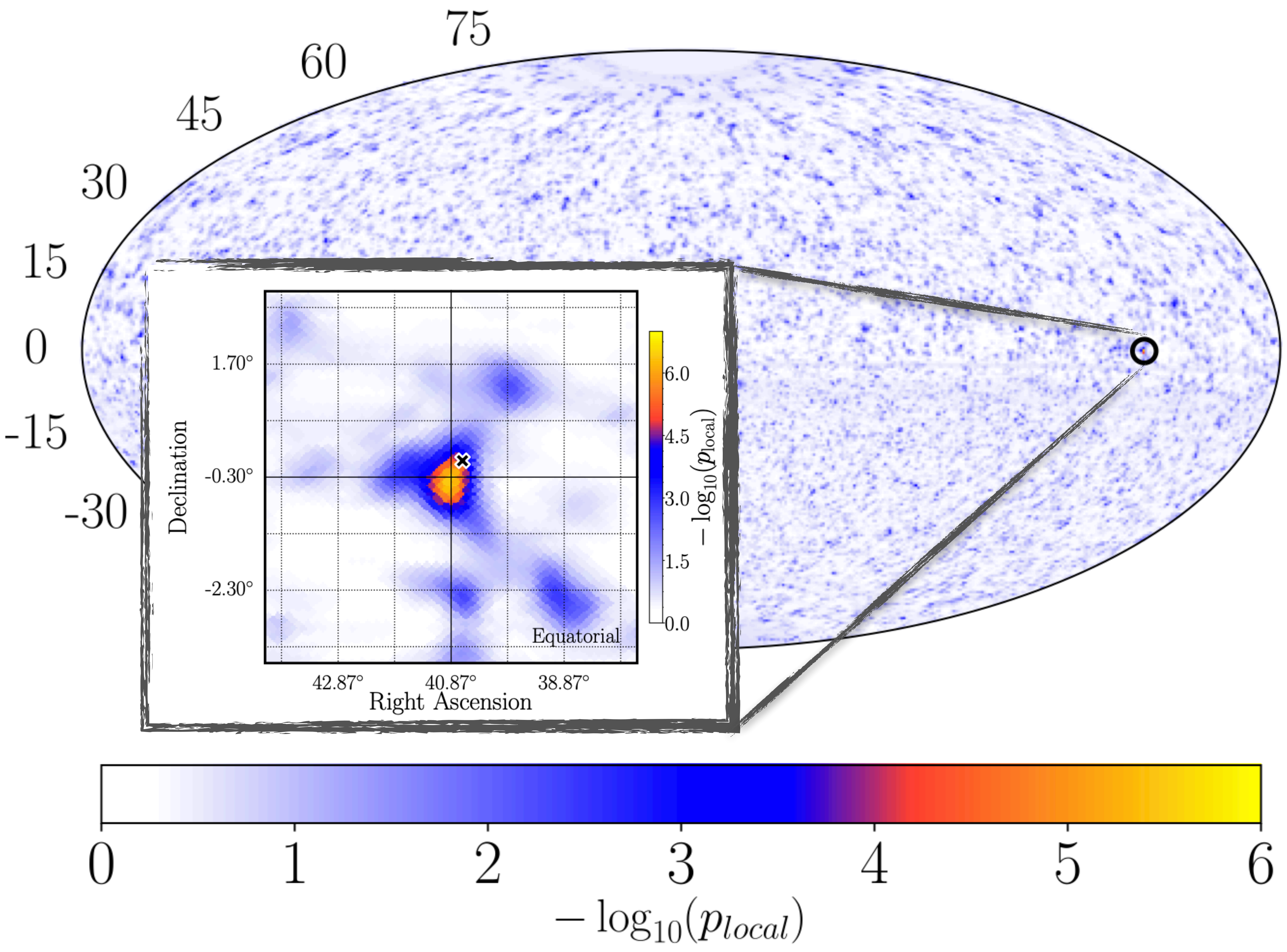
Aartsen et al., PRL124, 051103



Neutrino Skymap — Source catalog searches

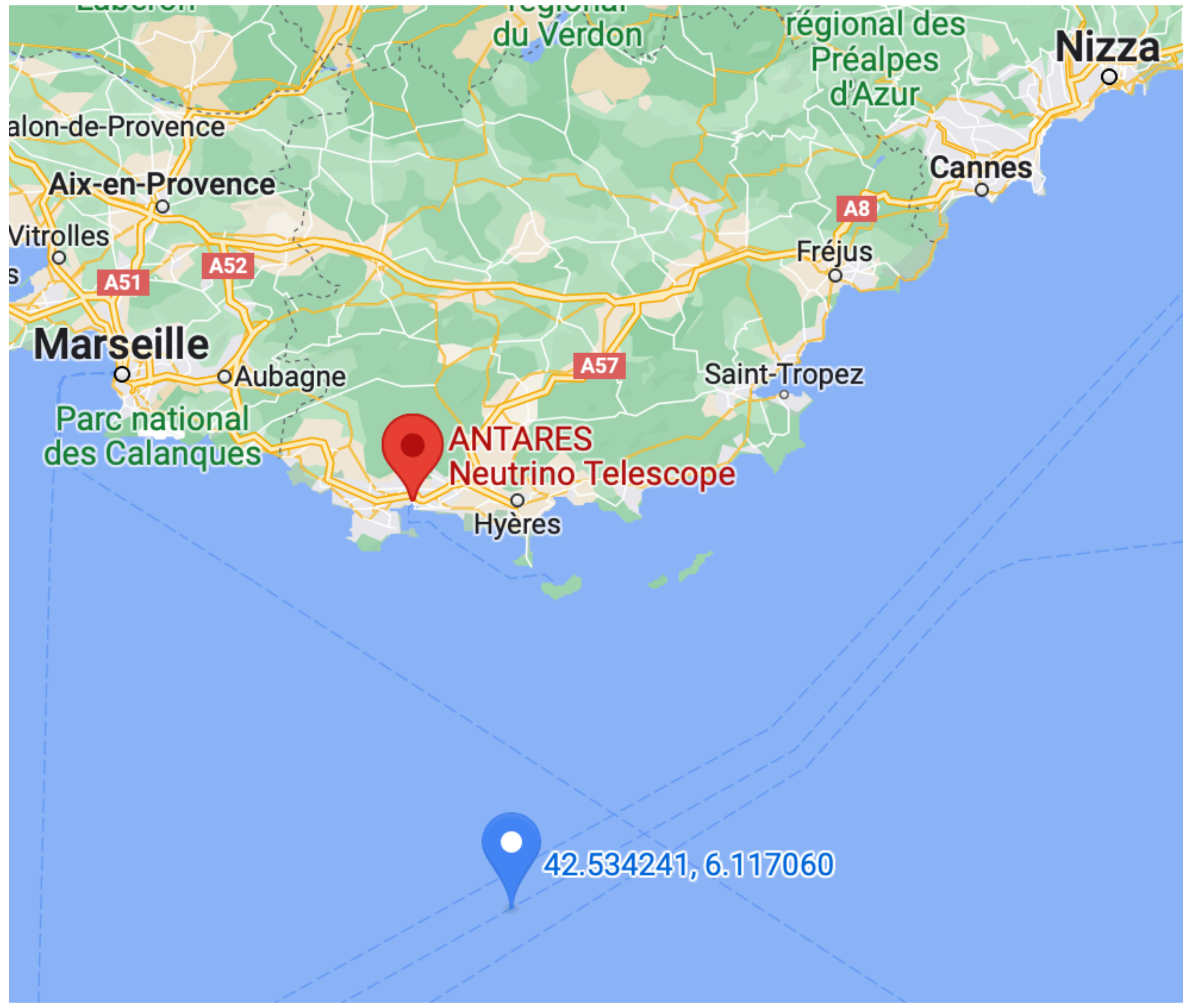
Aartsen et al., PRL124, 051103

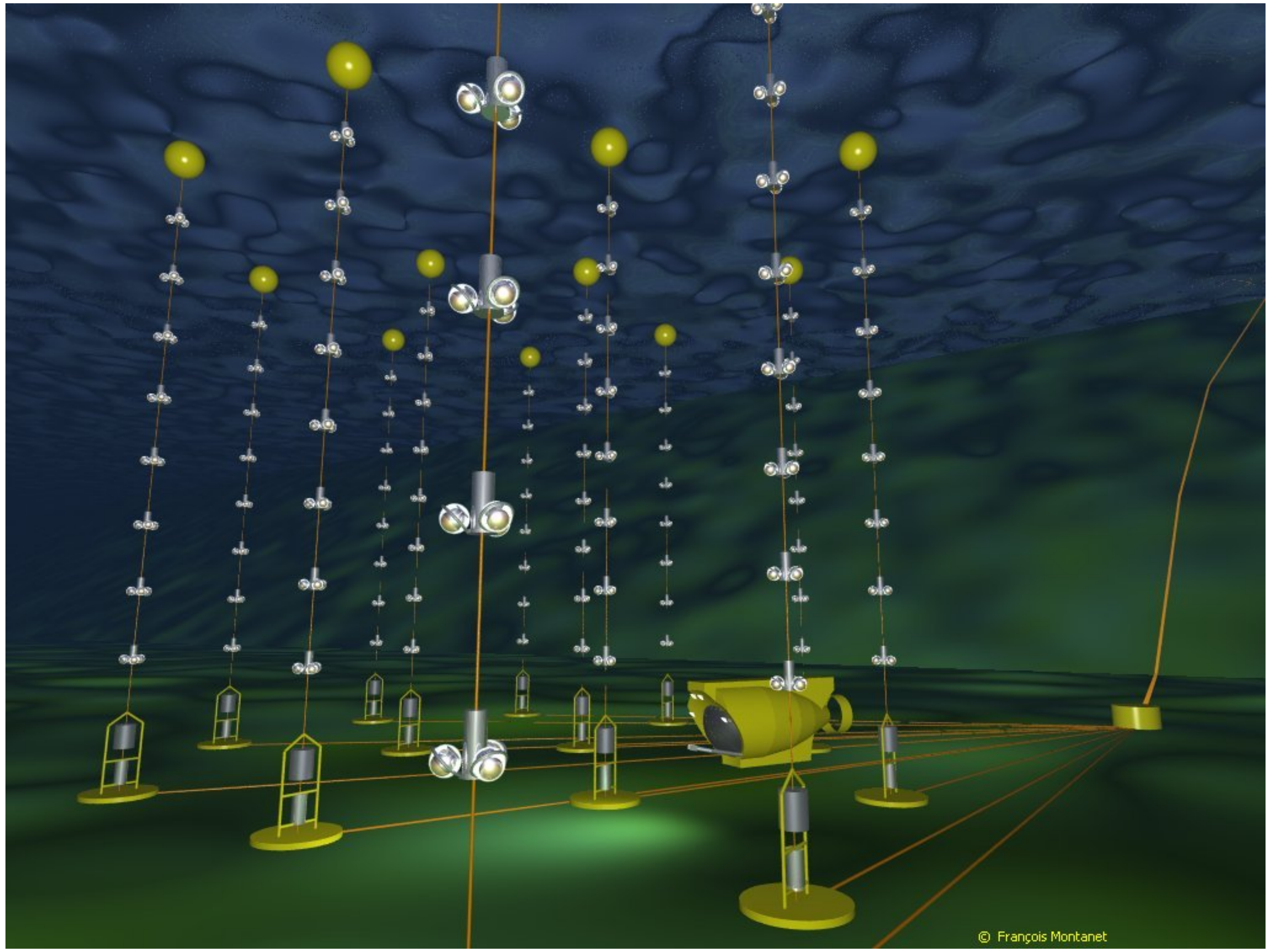
- Goal: Improve sensitivity to possible neutrino source already observed in γ-rays
- Small collection of sources from 4FGL, TeVCat, and gammaCat chosen (110 γ-ray sources selected)
- Highest significance obtained for NGC1068 (post-trial): 2.9σ
  Seyfert-II-galaxy



ANTARES

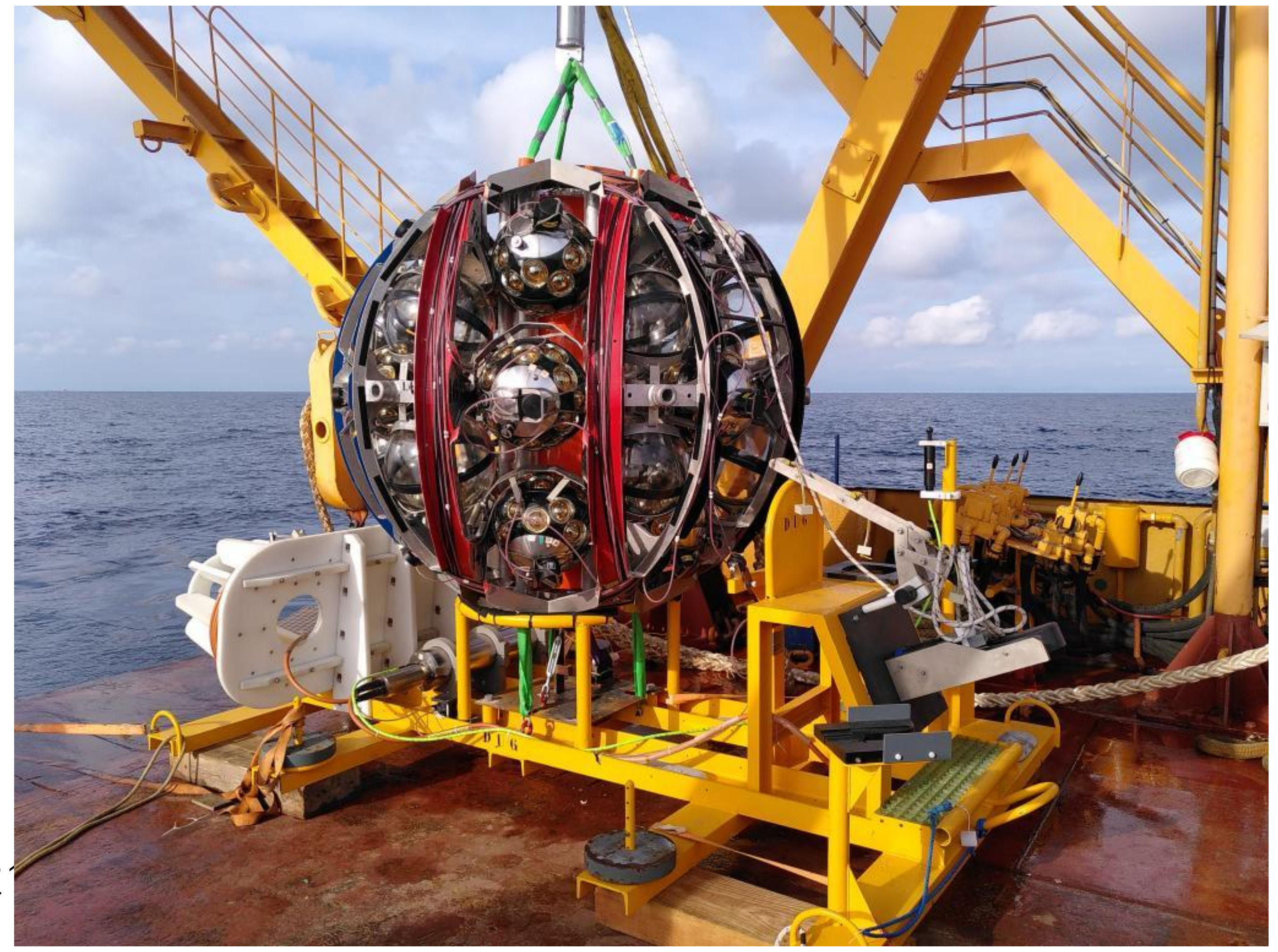
- At a depth of 2.5 km in the mediterranean sea
- 12 strings, 70m spacing, 75 PMTs per string (10“)
- ANTARES has been fully dismantled ~3 weeks ago

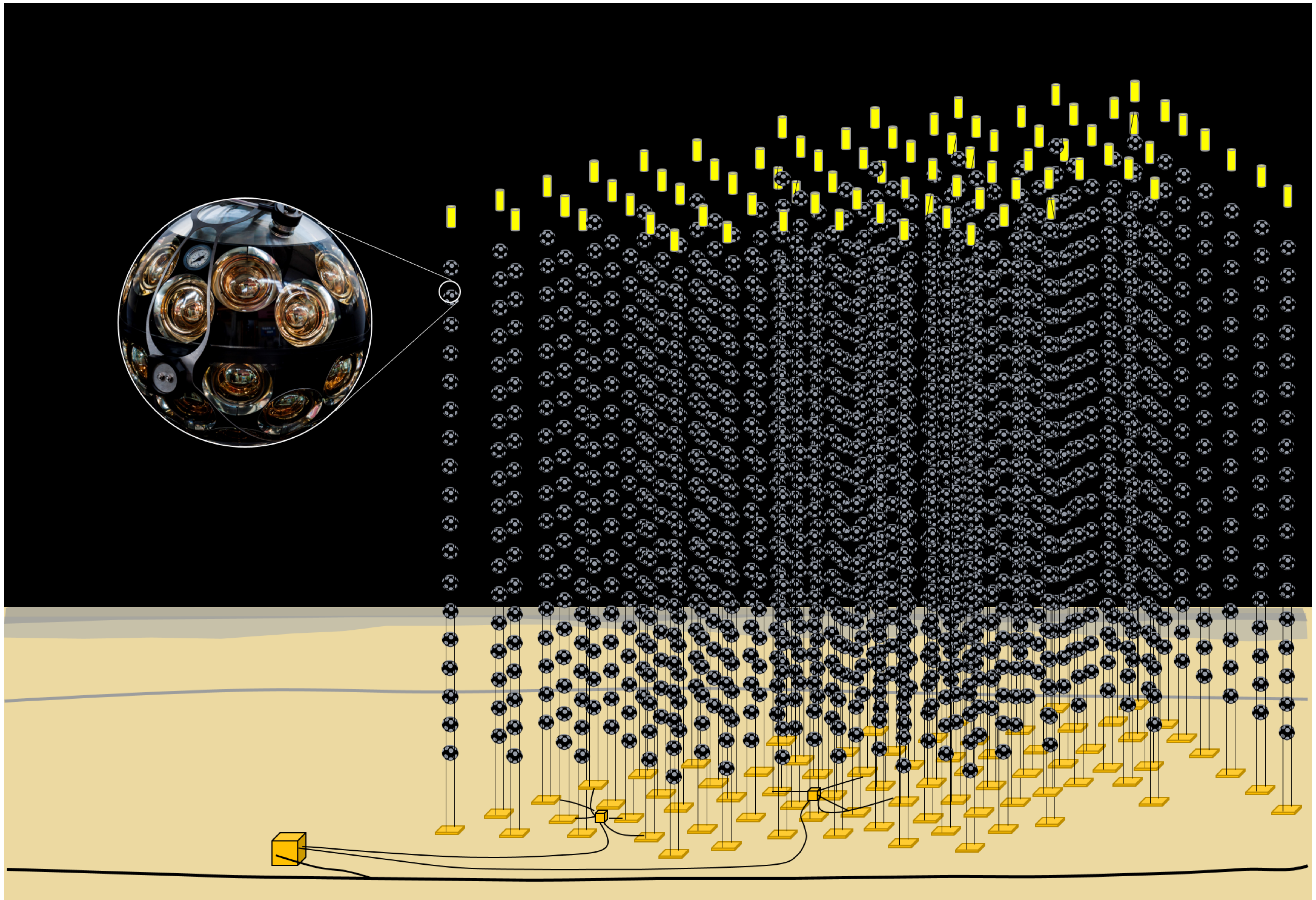




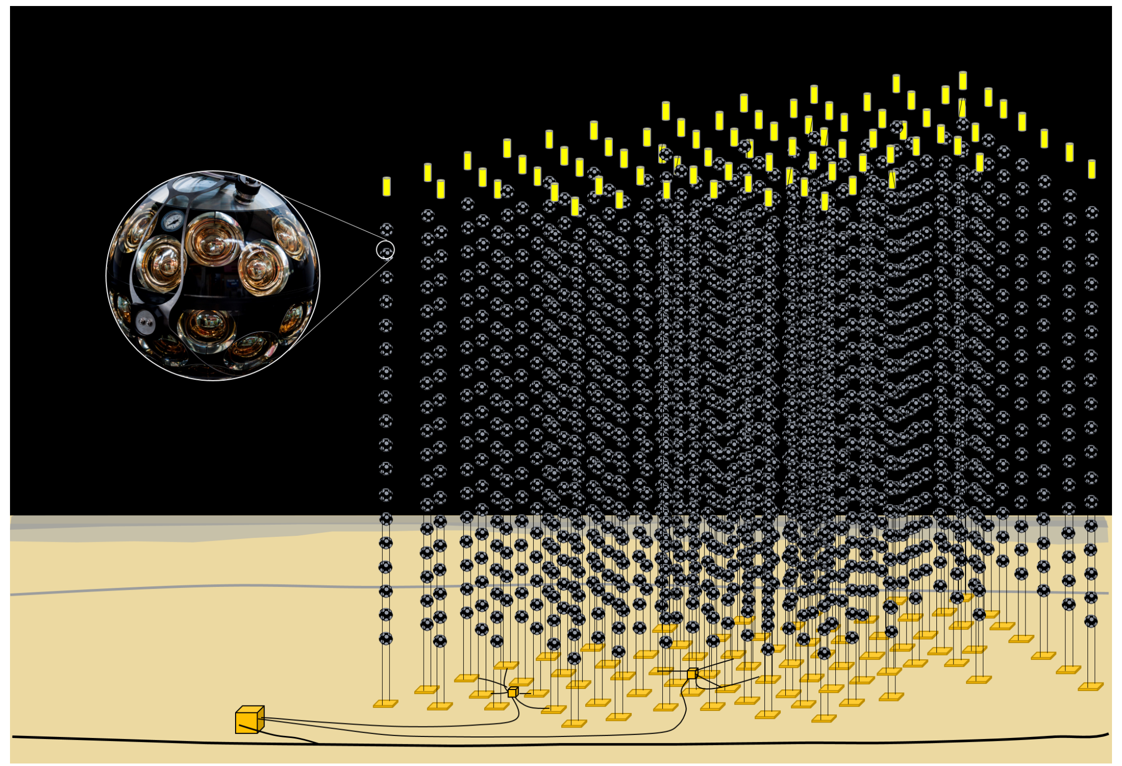
KM3NeT

- 12000 optical modules on 600 strings
- 31 3-inch PMTs in each mDOM (43cm diameter)
- ARCA (astroparticle focus) and ORCA (oscillation physics focus)
- Installation ongoing

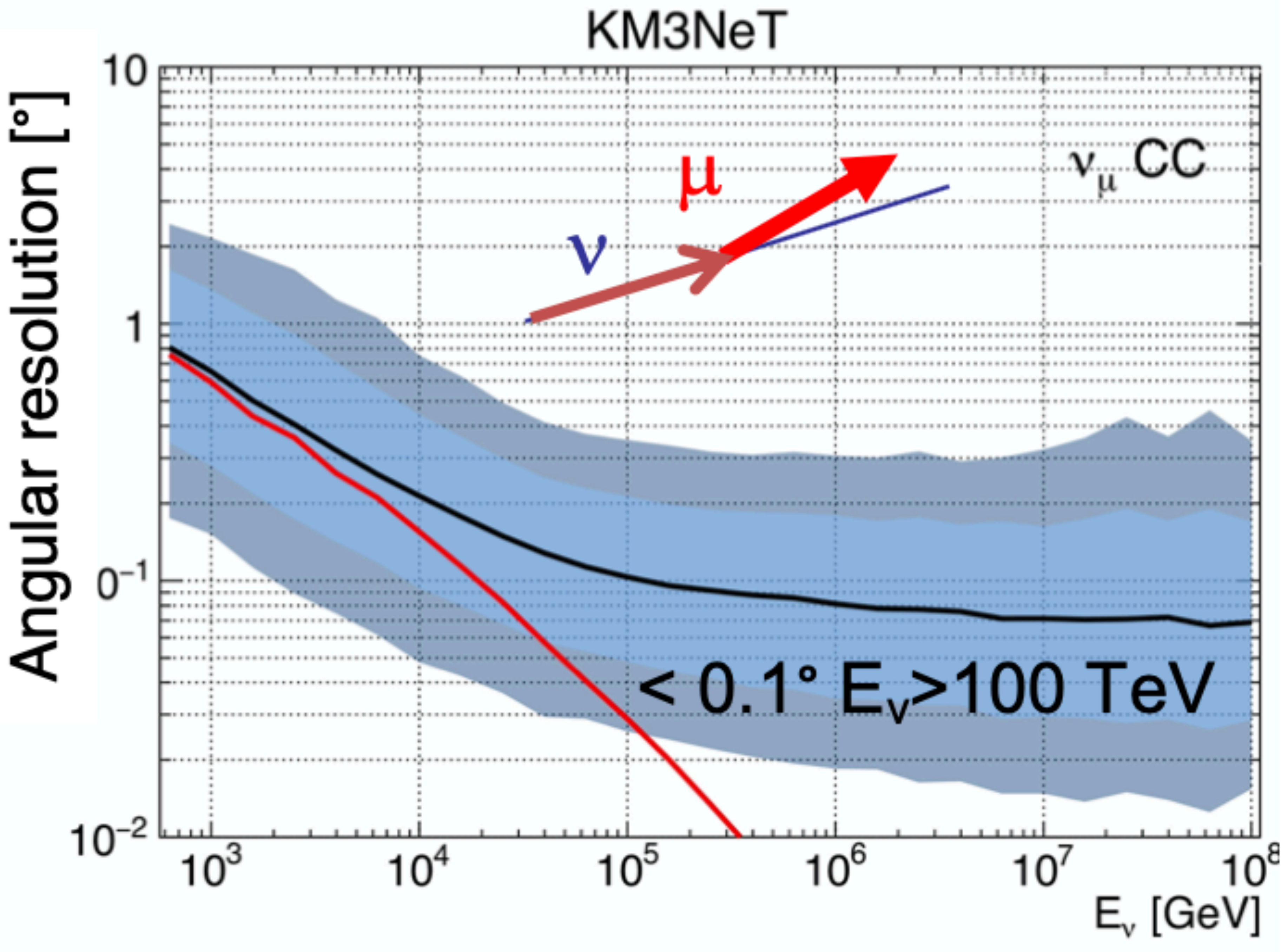


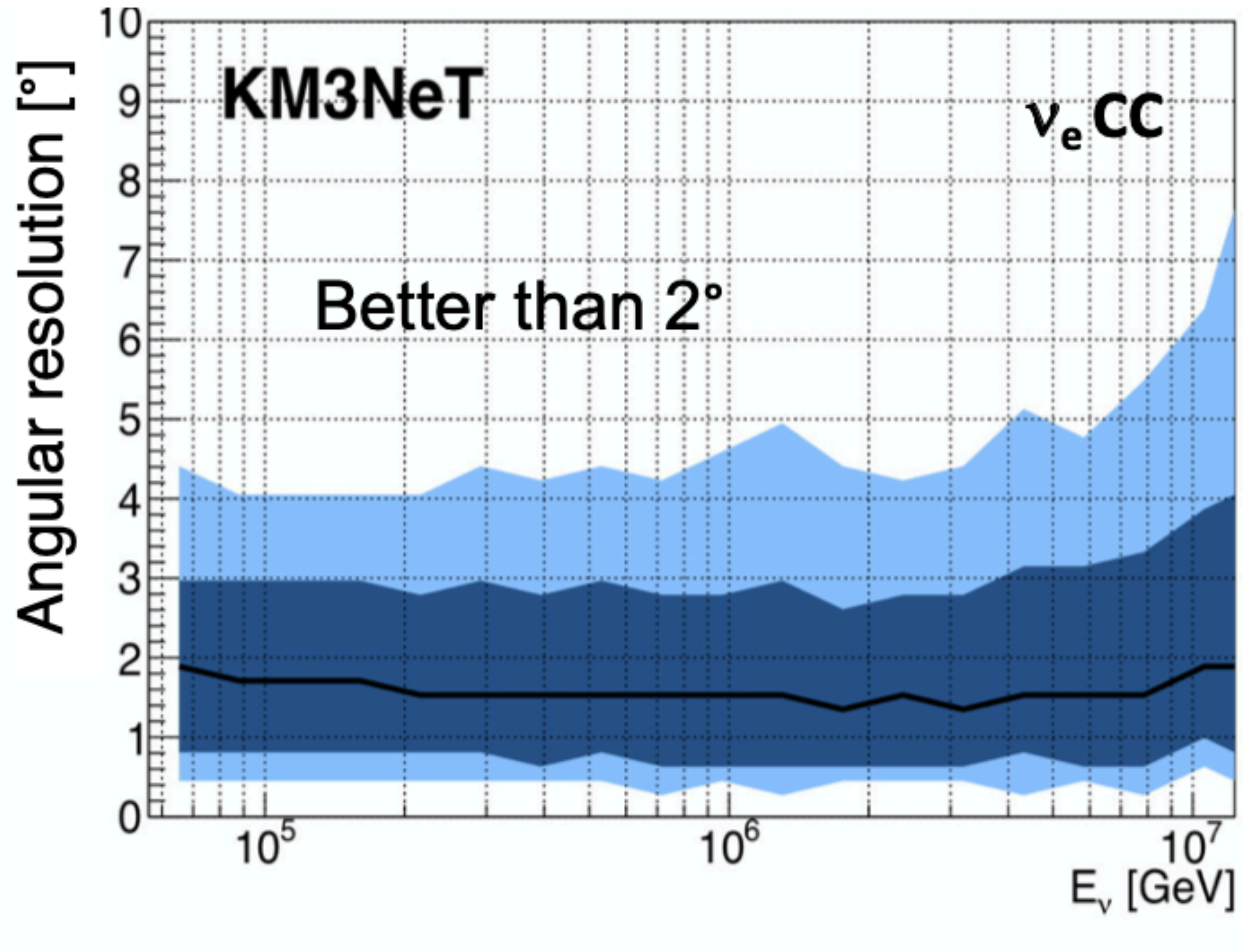


KM3NeT



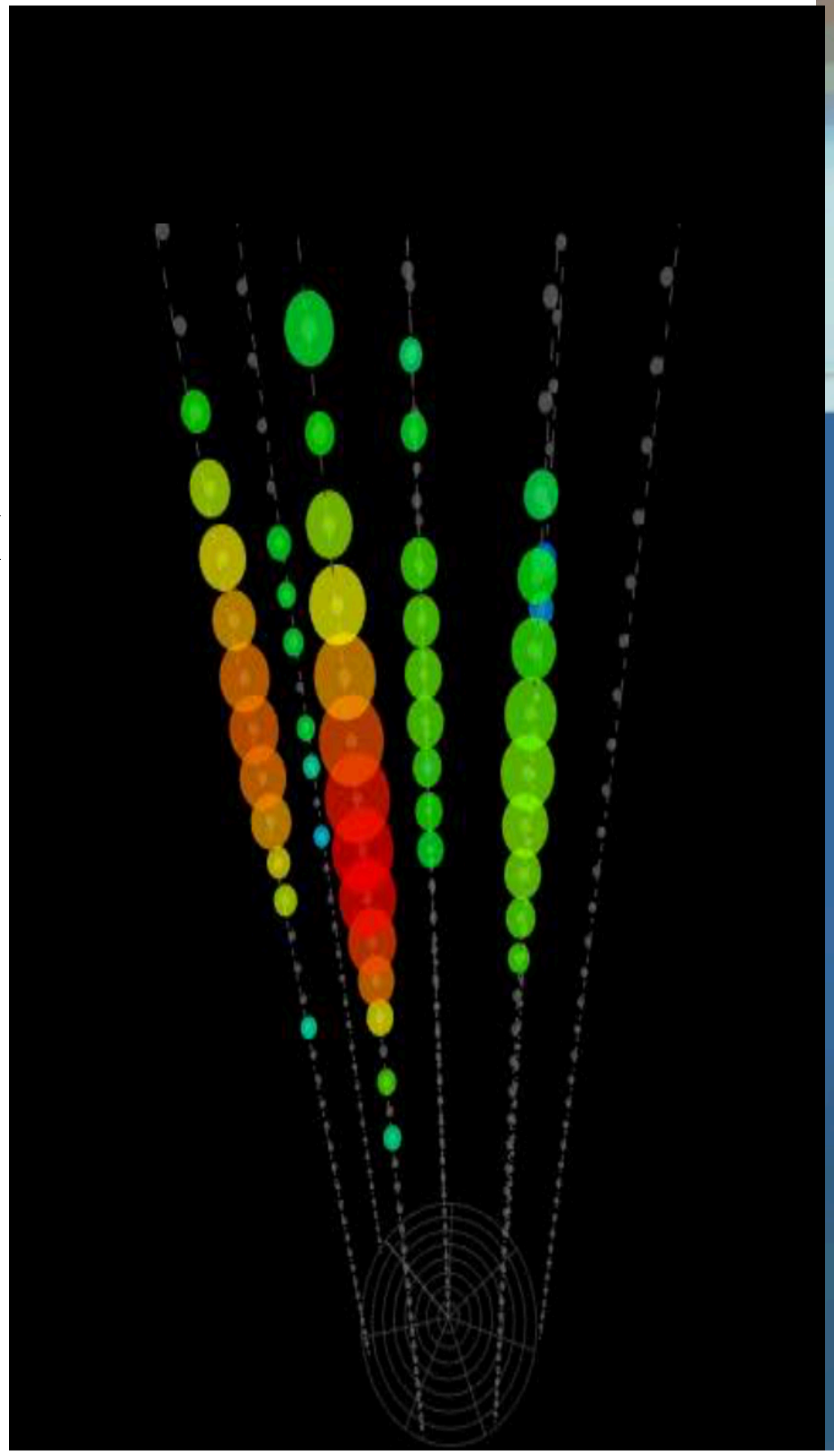
- Angular resolution
  - Scattering length of water~100m (ice ~20m)
  - Significantly better angular resolution compared to IceCube
  - Good to detect point sources

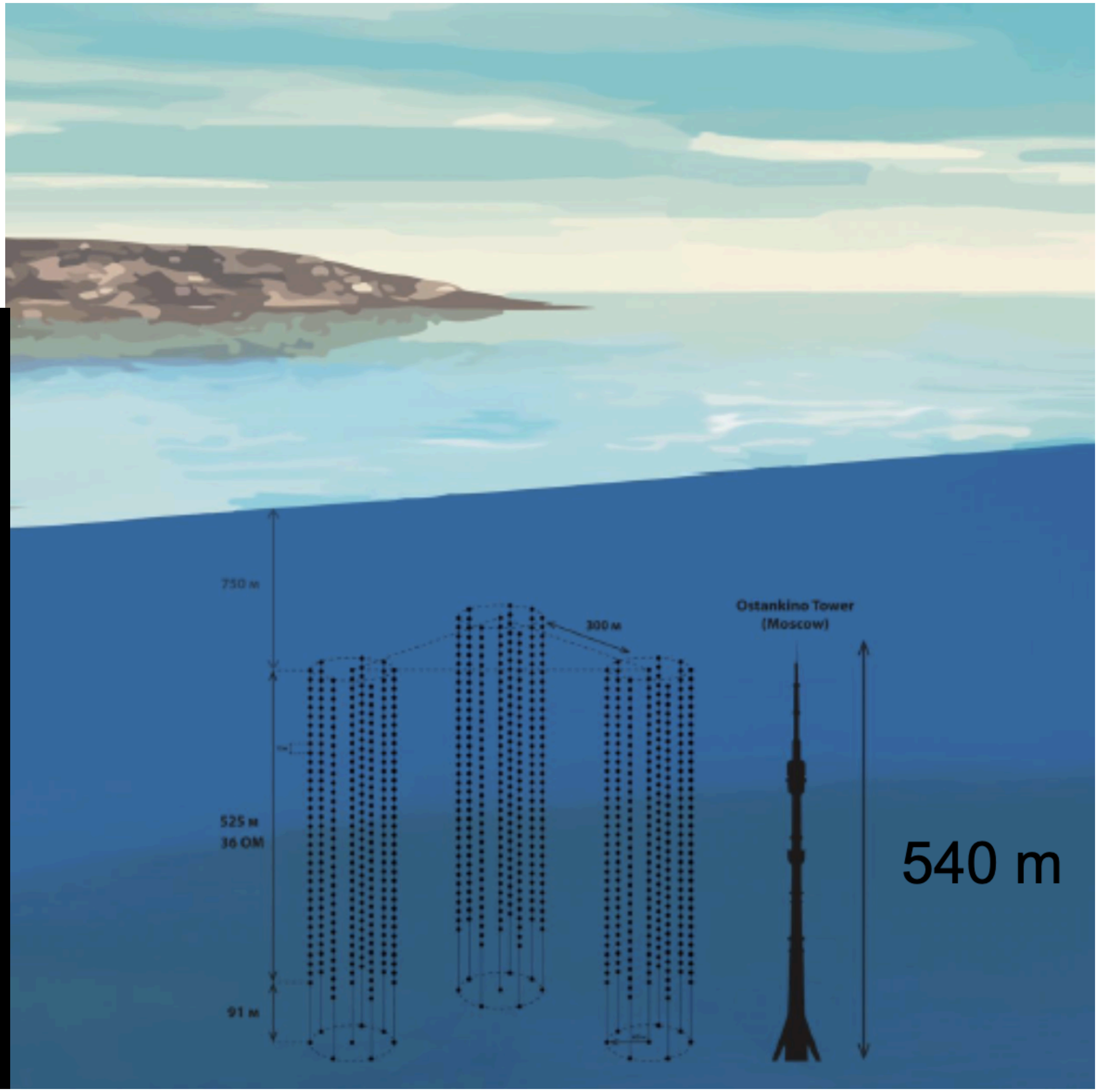




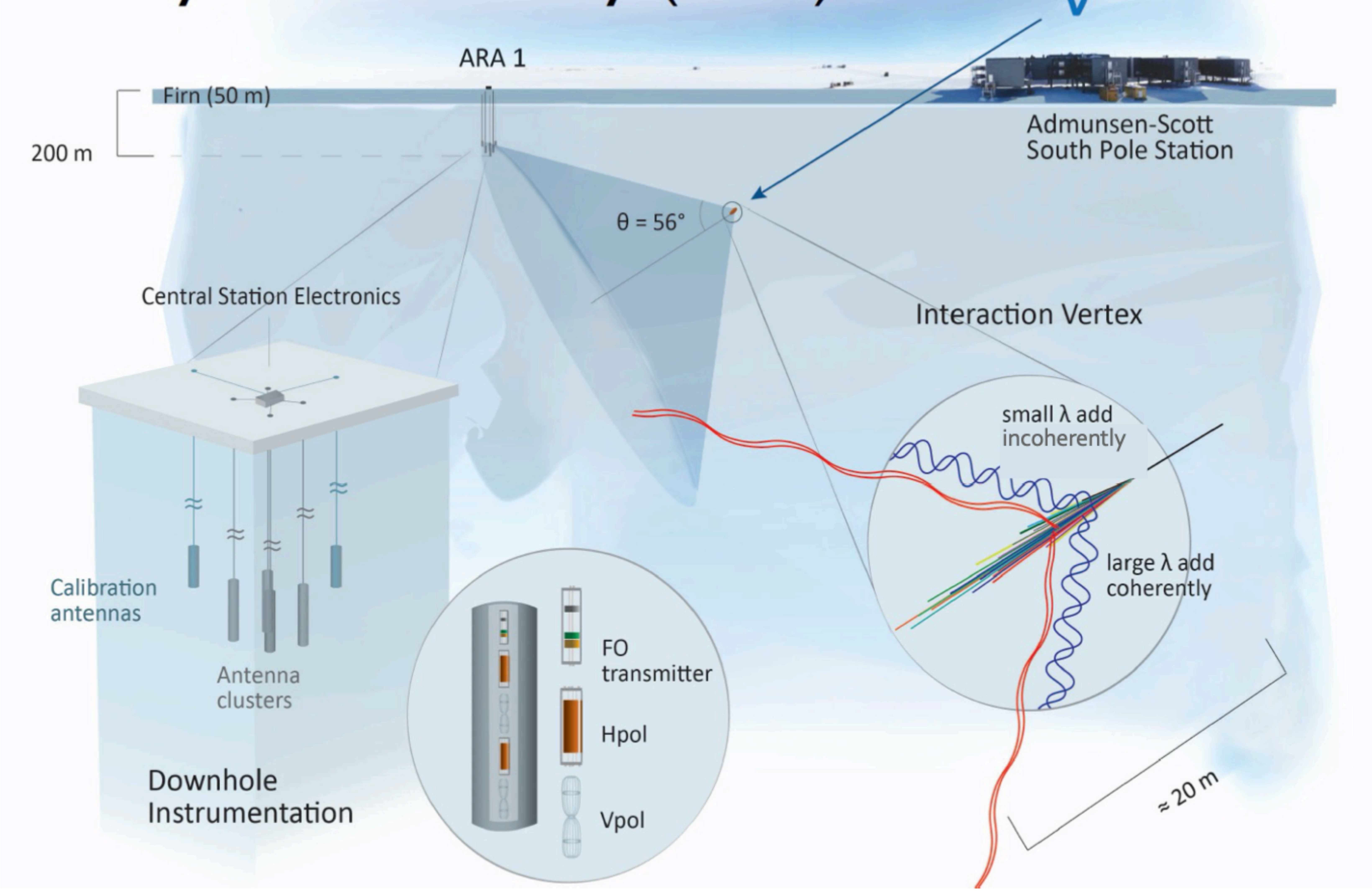
Baikal-GVD

- Under construction since 2016
- First stage completed: GVD-I
  - 8 clusters of 288 DOMs each
- Recently observed astrophysical flux at 3σ level with $E^{-2.46}$ spectrum
- Event display for the highest energy event with reco. energy of 1.2 PeV





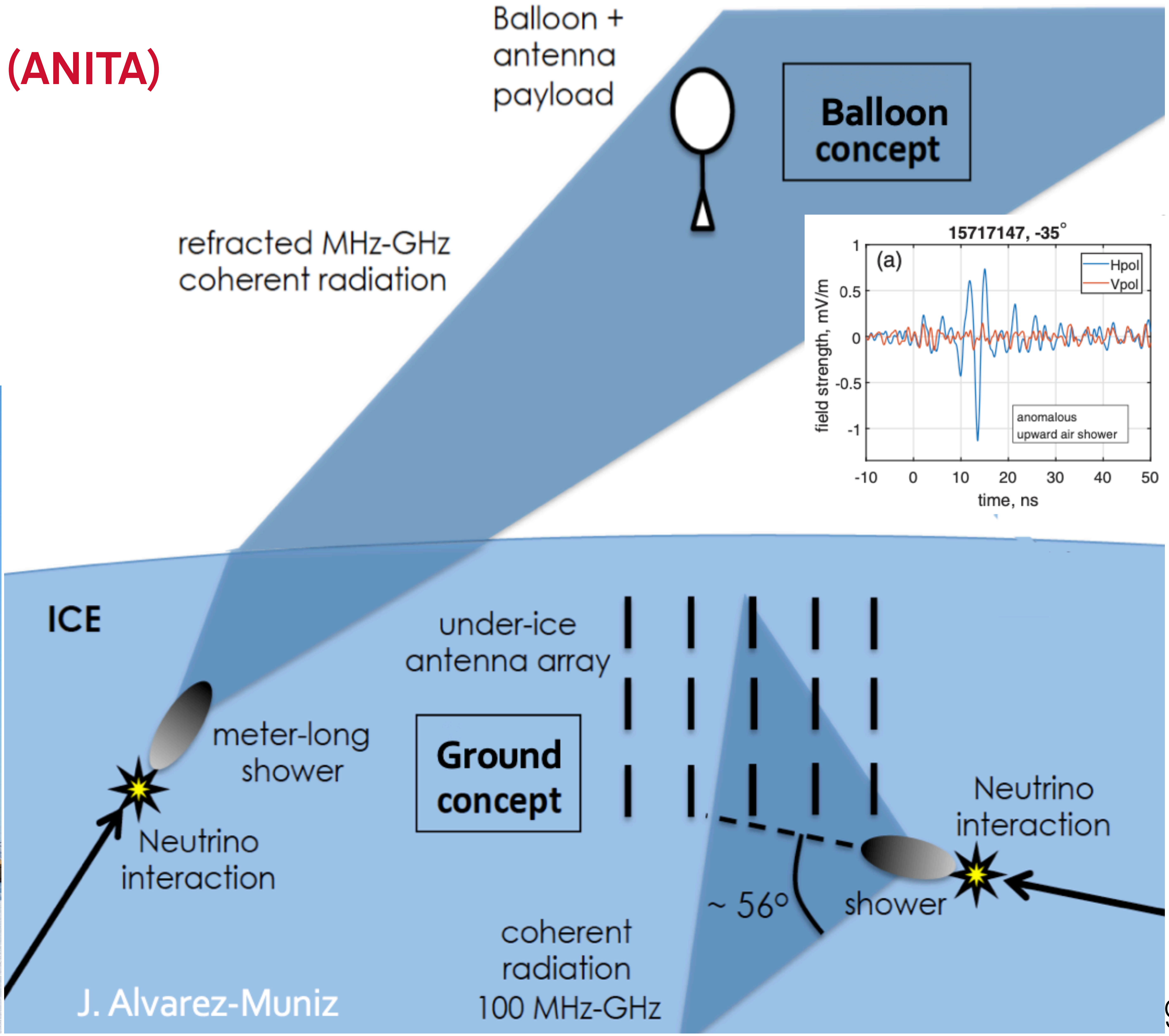
Askaryan Radio Array (ARA)



- GZK neutrinos:
  0.01 neutrinos/km3/yr
- Need a huge detection volume to detect a seizable amount of GZK neutrinos
- Attenuation length for radio frequencies O(1km)

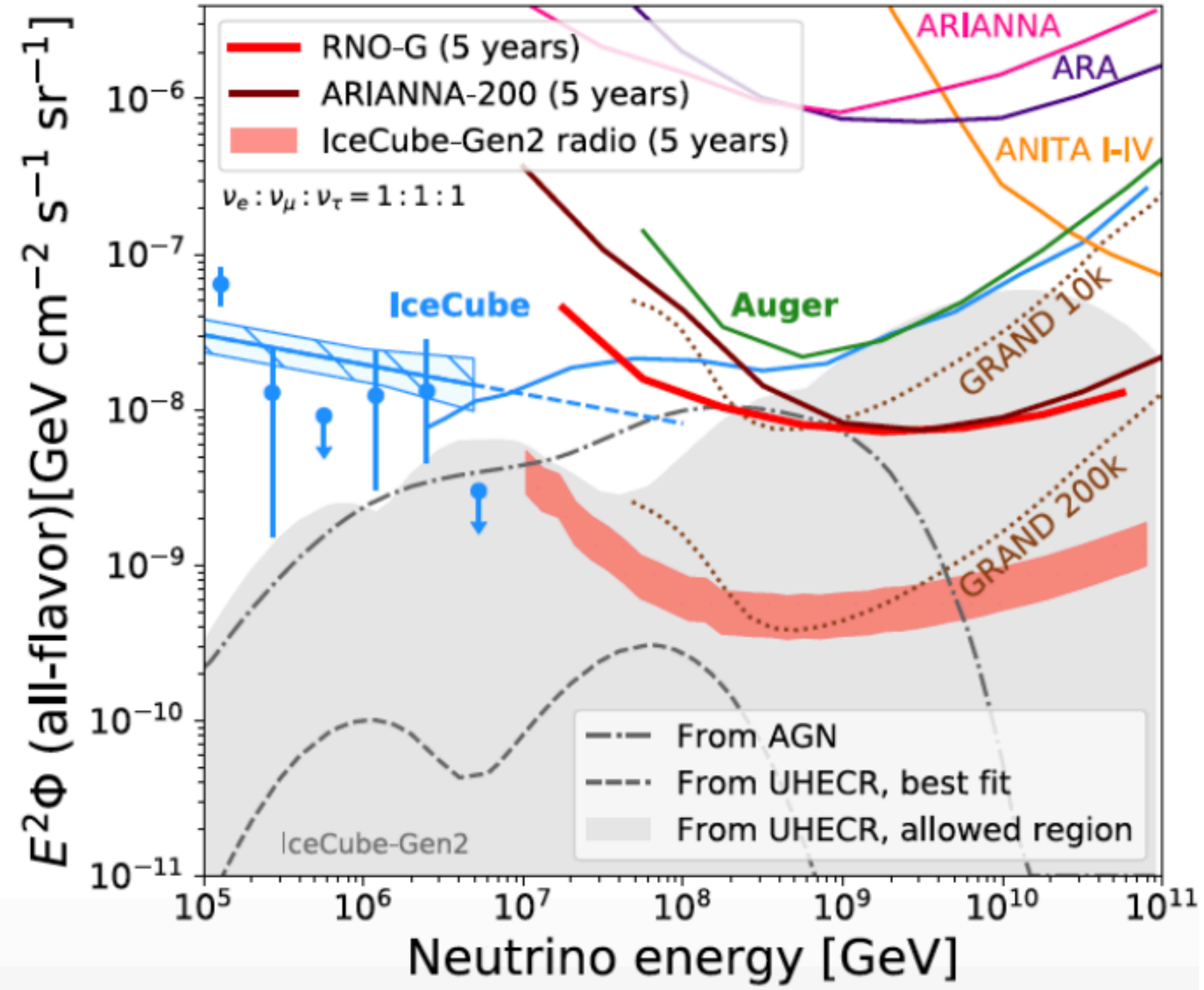
ANtarctic Impulsive Transient Antenna (ANITA)

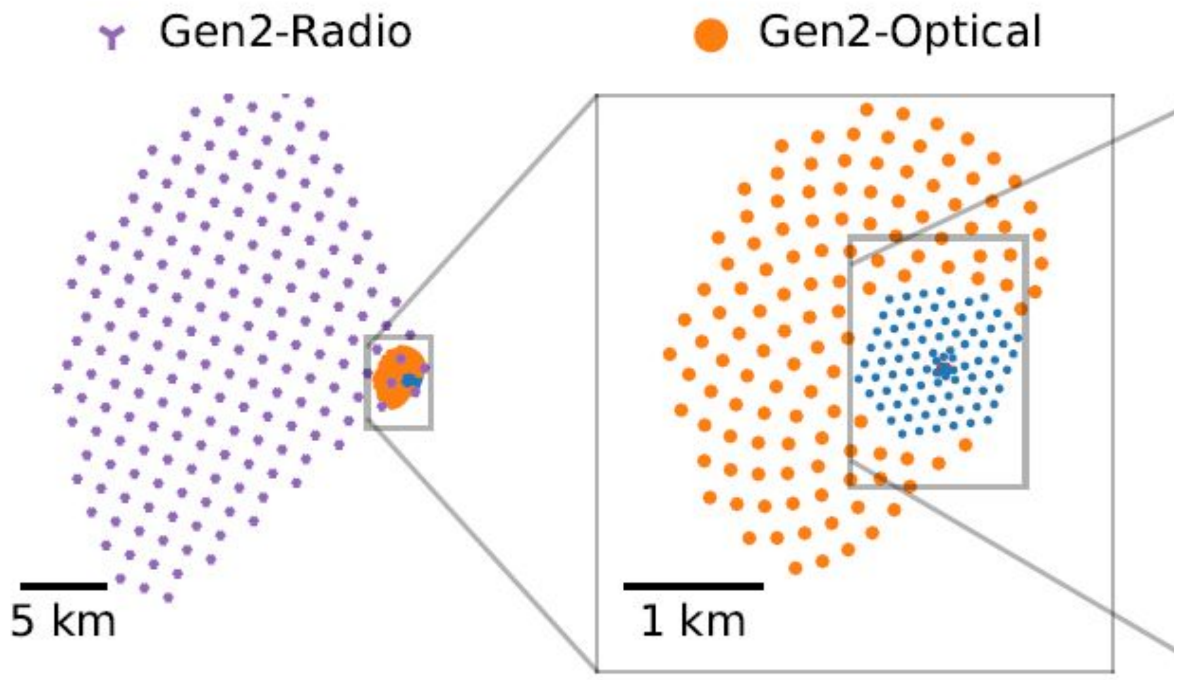
- 4 balloon flights launched from Antarctica
- 40 horn antennas (200 - 1200 MHz)
- No discovery of UHE neutrinos
- ~100 UHE cosmic ray events (> 10^9 GeV)

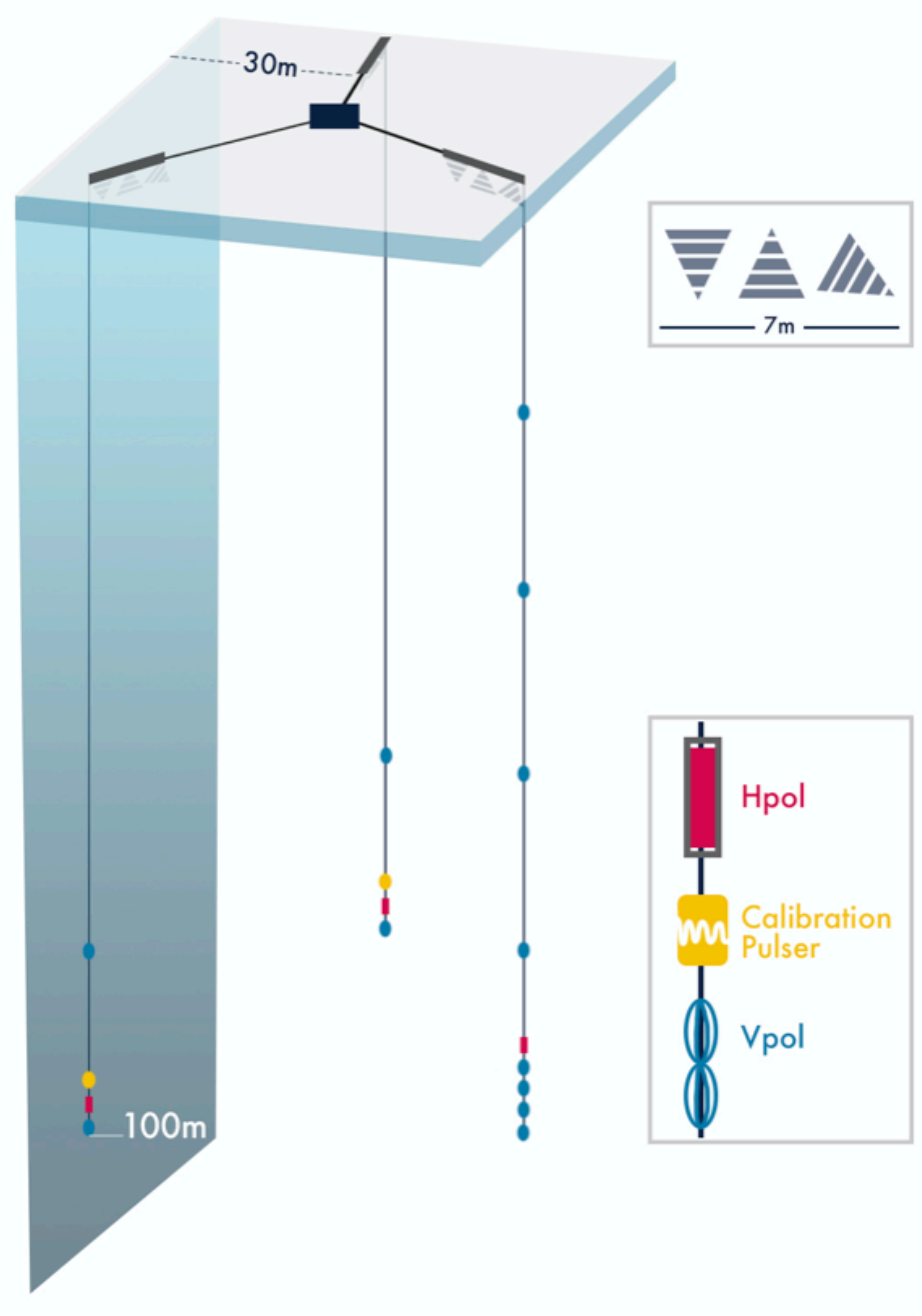


IceCube Gen2 Radio (and RNO-G)

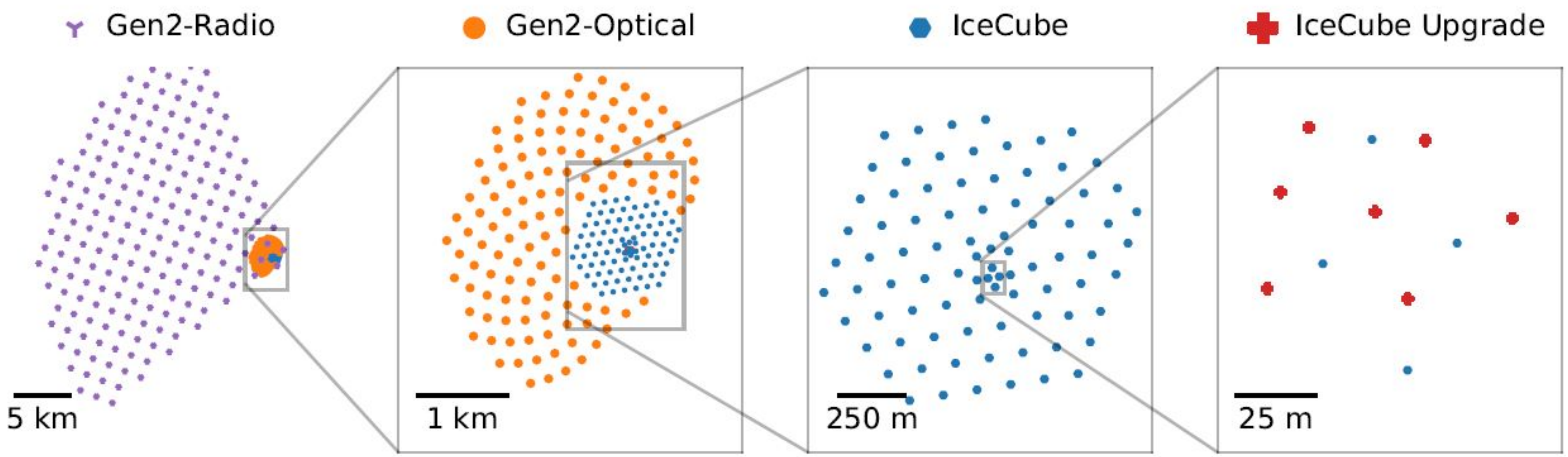
- Radio component is required to reach the science goals of IceCube Gen2 at the highest energies
  - Detecting a flux of cosmogenic neutrinos







What's next? IceCube Gen2



- IceCube Gen2 (design phase):
  - Optical array ~8 times larger than Gen1
  - Increase statistics around the PeV region
  - Reveal neutrino sources
  - Extend IceCubes multi messenger campaign to even higher energies
- IceCube Upgrade:
  - Sensors are already in production
  - Testbed for new sensor types (D-Egg, mDOM)
  - Improved detector calibration/ice model characterization

IceCube Gen2 Facilities — Pixelated sensors

IceCube Upgrade | IceCube Gen2

D-Egg

mDOM

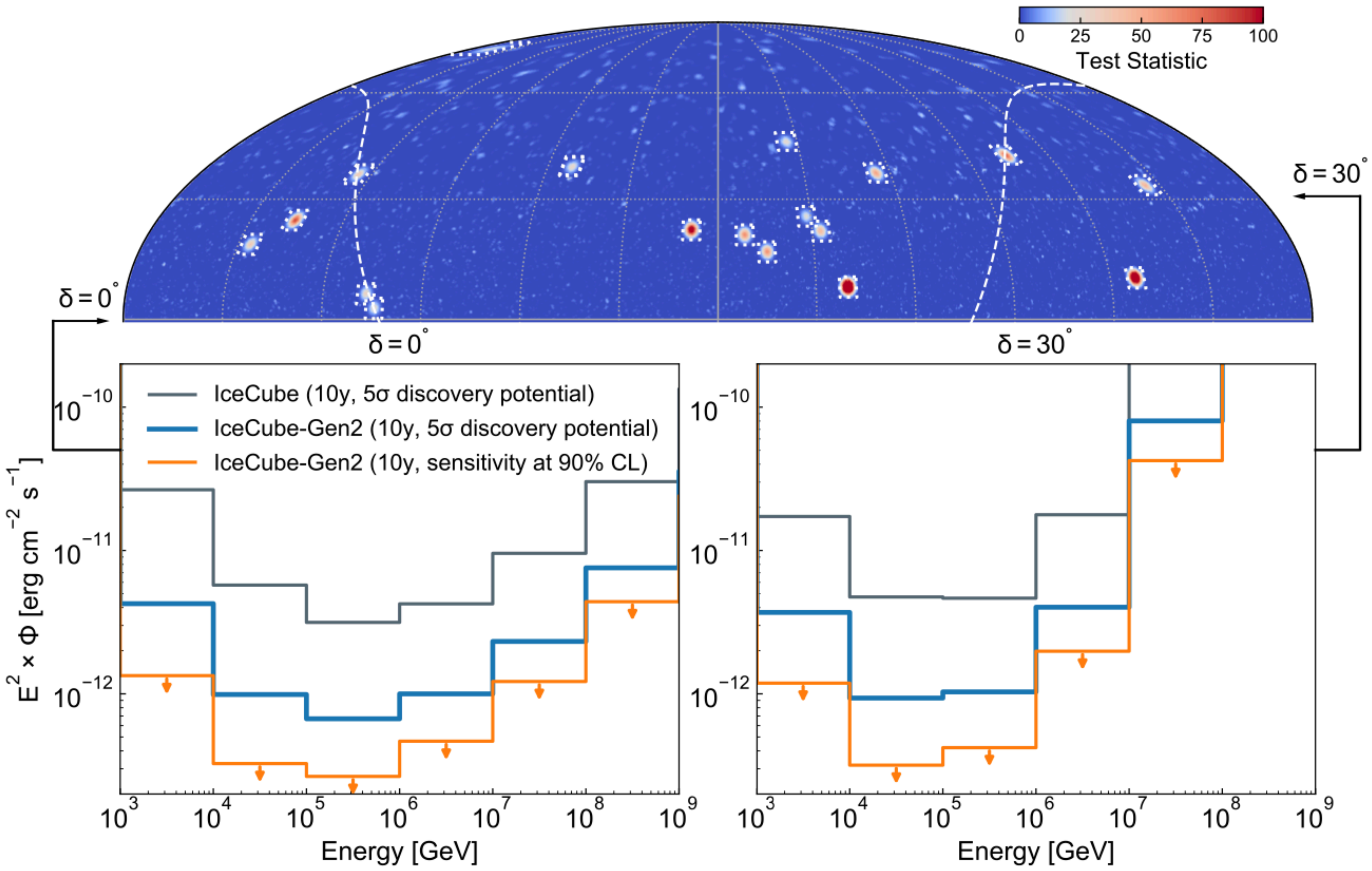
Gen2 LOM

- Two 8“ high QE PMTs
- Clearer glass
- Reduced diameter

- Good sensitivity to photon directions
- Experience from KM3NeT

- Maximize sensitivity gains made by D-Egg and mDOM
- Minimize costs for assembly and deployment

Factor 5 improved sensitivity compared to IceCube



Thank you!

THE ICECUBE COLLABORATION

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UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
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University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

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Fonds de la Recherche Scientifique (FRS-FNRS)
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Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

IceCube Realtime Alerts v2

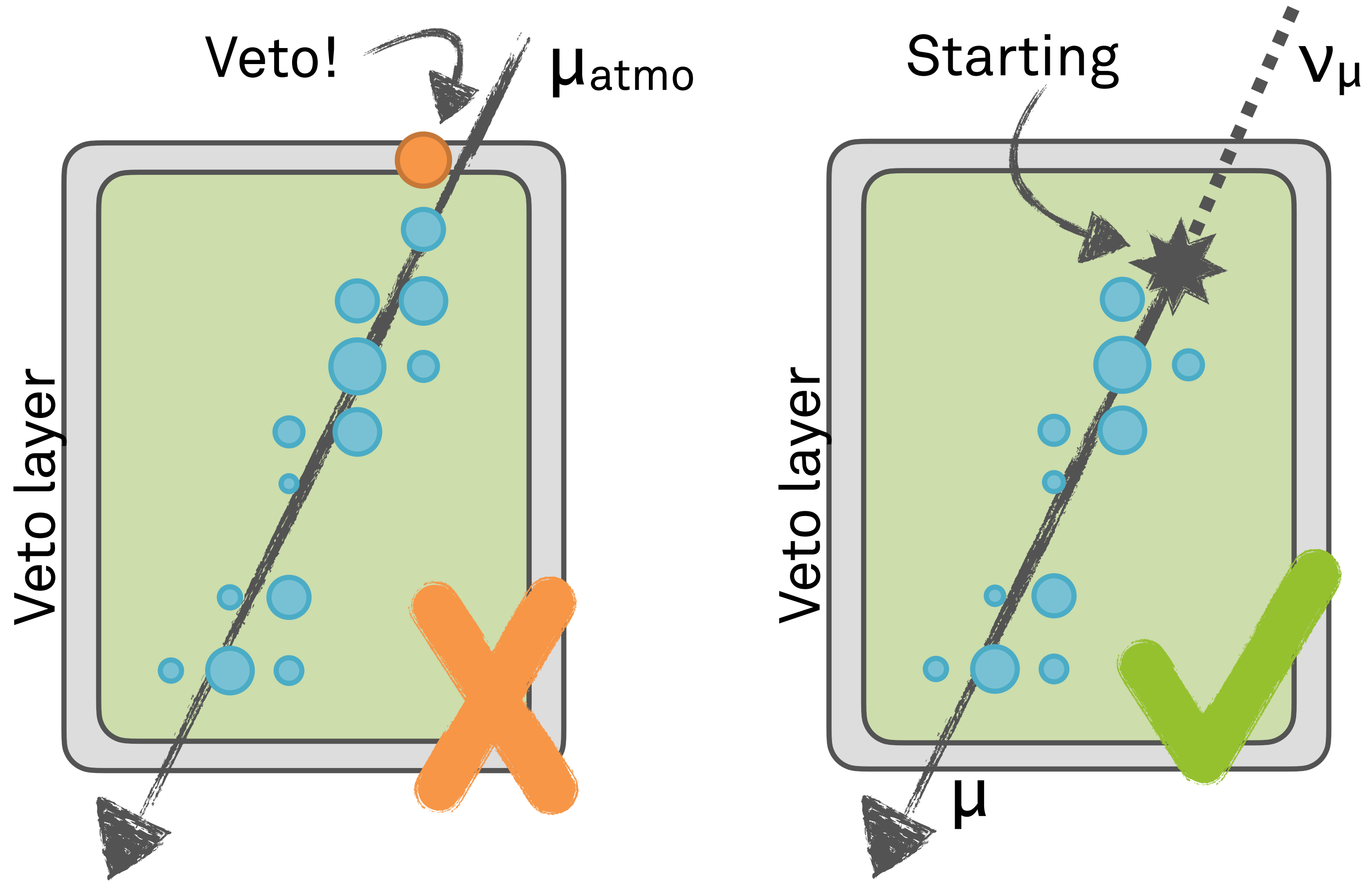
- Two types of alerts: Gold (50% signal purity) and Bronze (30% signal purity)
- Combination of multiple event selections:
  - GFU (Gamma-ray Follow Up) (~24 / year)
  - EHE (~5 / year)
  - HESE (~2 / year)
  - HESE Cascades (new addition) (~8 / year)
- Distributed as GCN/AMON notices
- Time delay between event and alert < 3min

Example alert

```
TITLE:           GCN/AMON NOTICE
NOTICE_DATE:     Fri 20 Nov 20 14:12:28 UT
NOTICE_TYPE:     ICECUBE Astrotrack Bronze
STREAM:          25
RUN_NUM:         134715
EVENT_NUM:       65785778
SRC_RA:          307.5299d {+20h 30m 07s} (J2000),
                 307.7180d {+20h 30m 52s} (current),
                 307.0798d {+20h 28m 19s} (1950)
SRC_DEC:         +40.7700d {+40d 46' 12"} (J2000),
                 +40.8410d {+40d 50' 28"} (current),
                 +40.6013d {+40d 36' 05"} (1950)
SRC_ERROR:       280.79 [arcmin radius, stat-only, 90% containment]
SRC_ERROR50:     158.40 [arcmin radius, stat-only, 50% containment]
DISCOVERY_DATE:  19173 TJD;   325 DOY;   20/11/20 (yy/mm/dd)
DISCOVERY_TIME:  35080 SOD {09:44:40.55} UT
REVISION:        1
ENERGY:          1.5396e+02 [TeV]
SIGNALNESS:      5.0338e-01 [dn]
FAR:             0.2947 [yr^-1]
SUN_POSTN:       236.49d {+15h 45m 58s}  -19.87d {-19d 52' 19"}
SUN_DIST:        89.62 [deg]   Sun_angle= -4.7 [hr] (East of Sun)
MOON_POSTN:      313.45d {+20h 53m 47s}  -21.60d {-21d 36' 09"}
MOON_DIST:       62.67 [deg]
GAL_COORDS:      79.44,  0.94 [deg] galactic lon,lat of the event
ECL_COORDS:      327.73, 56.93 [deg] ecliptic lon,lat of the event
COMMENTS:        IceCube Bronze event.
COMMENTS:        The position error is statistical only, there is no systematic added.
```

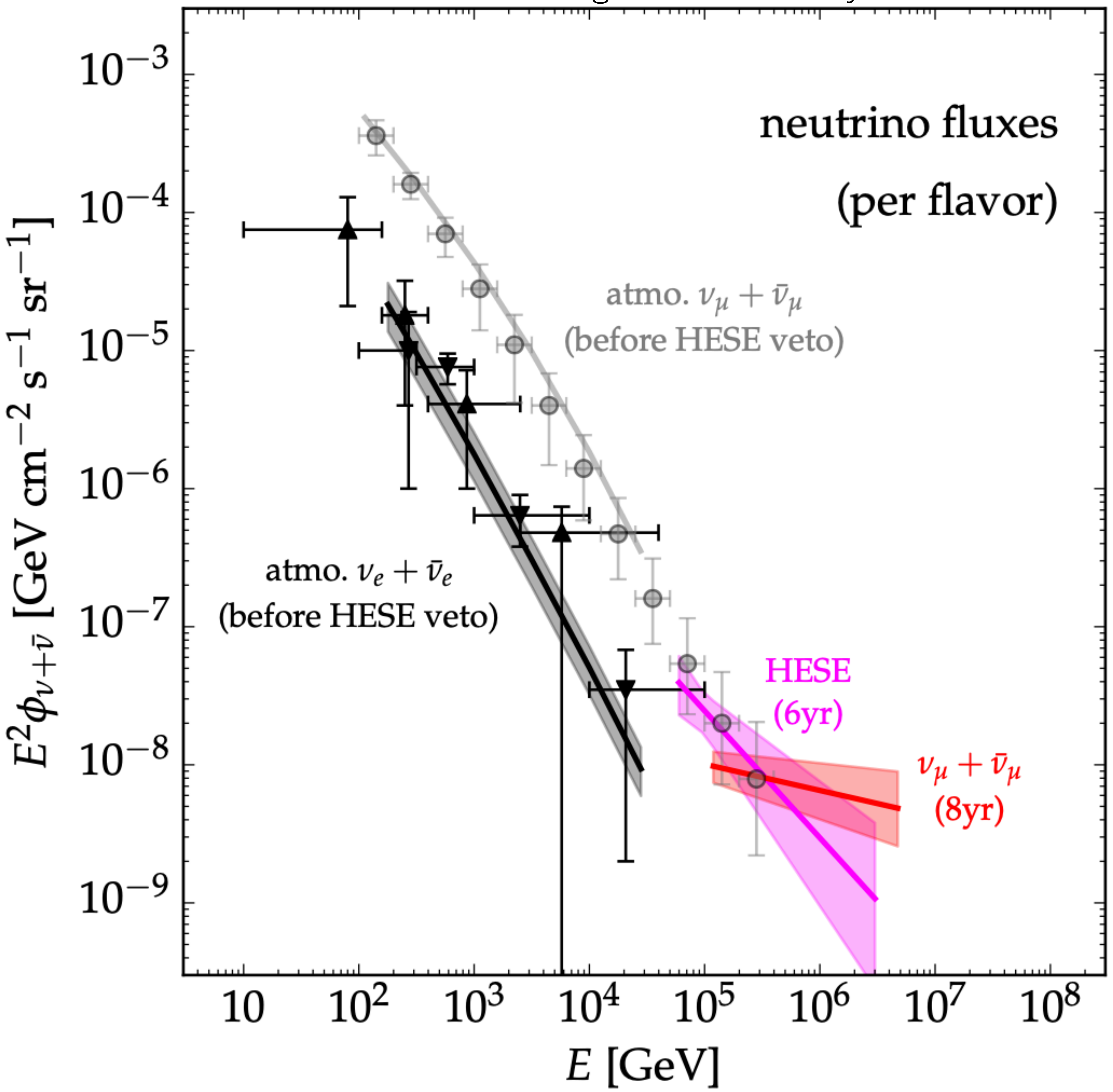
Astrophysical neutrinos

- Astrophysical neutrinos can be identified via very different event selection strategies
  - Up-going, through-going tracks using the Earth as a shield from atmospheric muons (red)
  - Selecting starting tracks and cascades to reject atmospheric muons (pink)



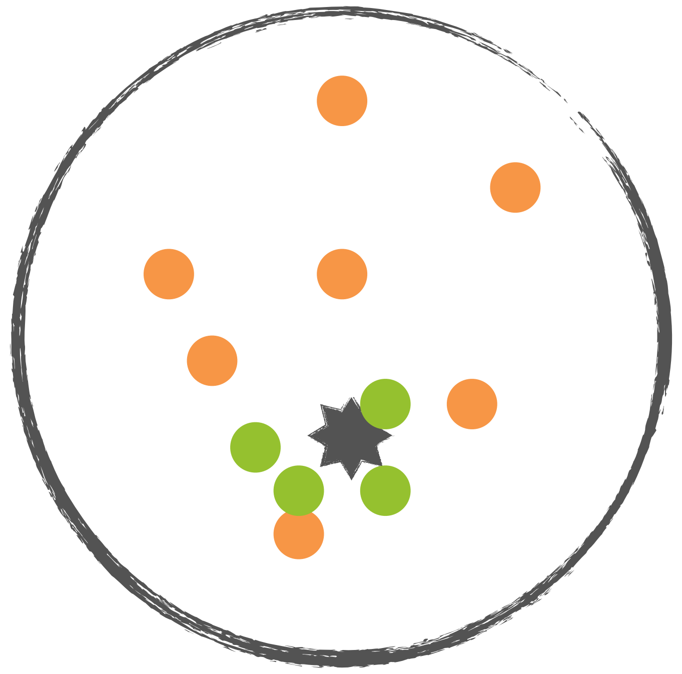
- Clear observation of a diffuse neutrino flux

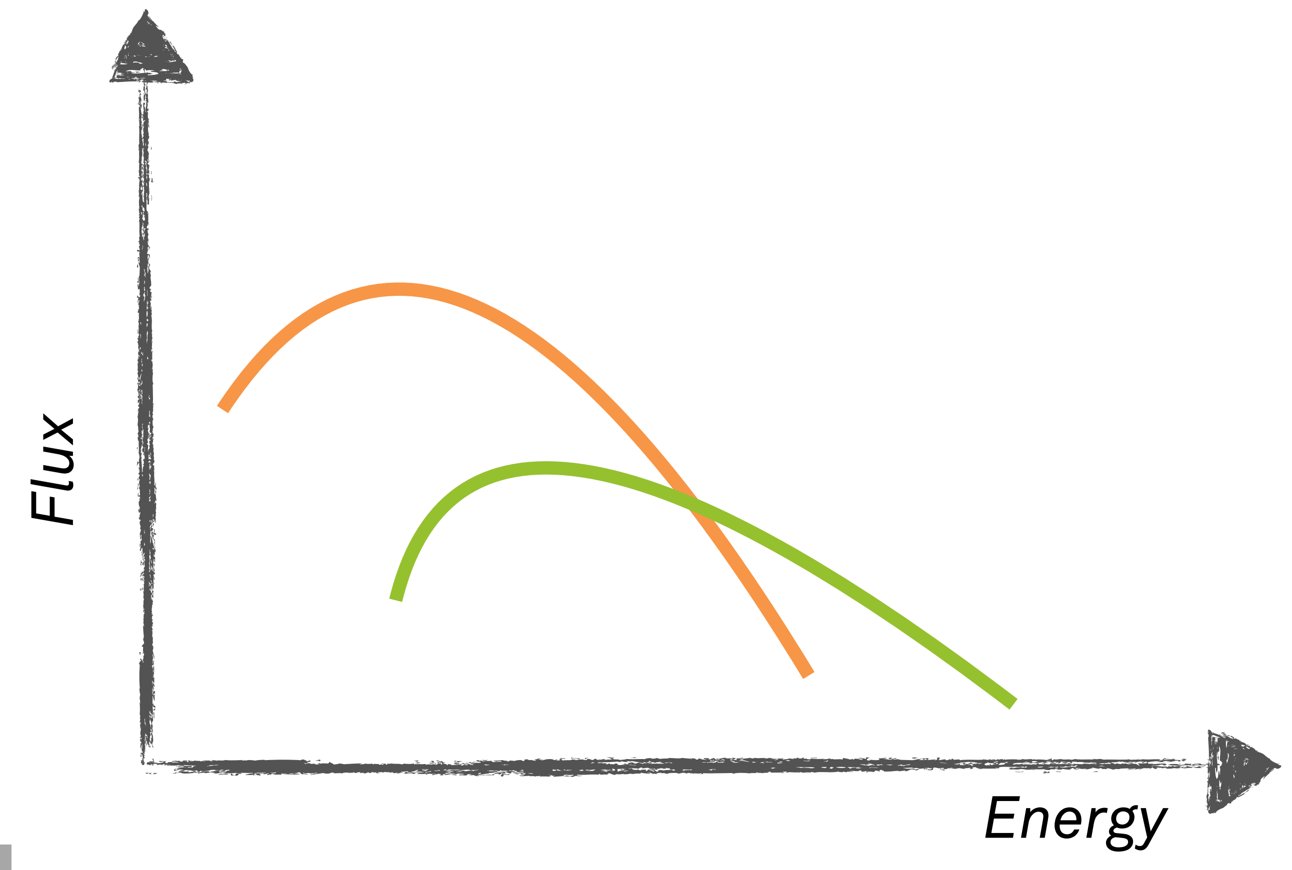
Ahlers et al., Prog. Part. Nucl. Phys. 2018



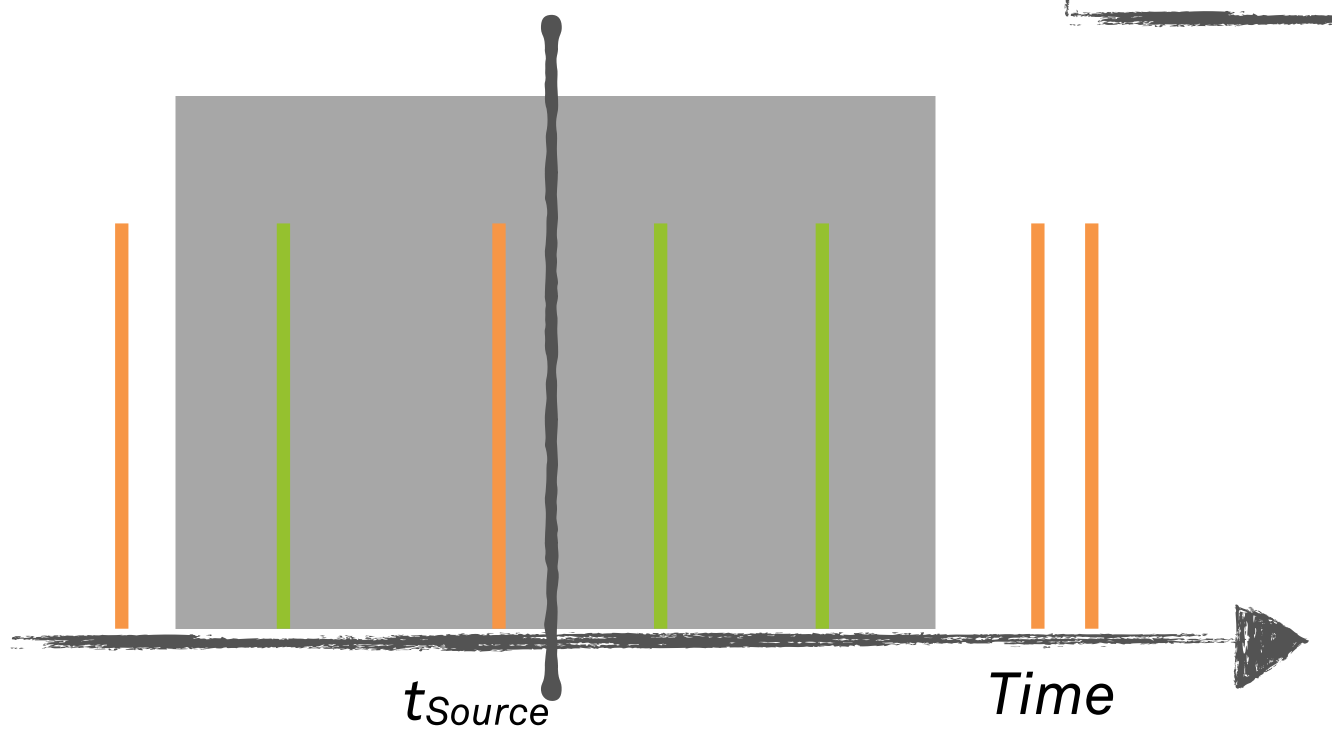
Point source analyses in IceCube

- Study the clustering of neutrinos over the atmospheric expectation

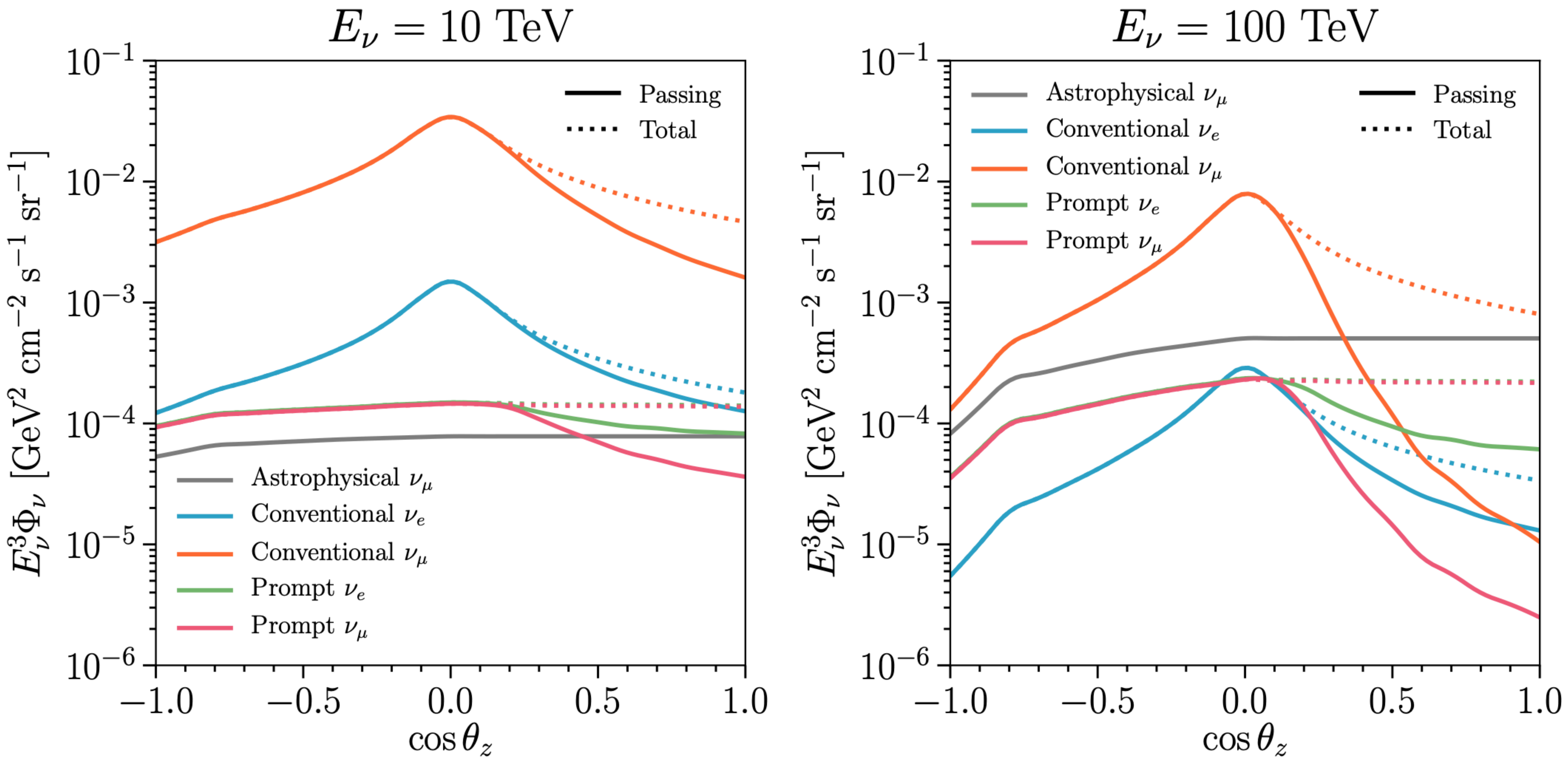




- Spatial clustering
  - Bivariate Gaussian
- Energy spectra
  - Signal has a hard spectrum
- Clustering in time
  - Box or gaussian profiles used frequently



Angular distributions and atmospheric self veto effect



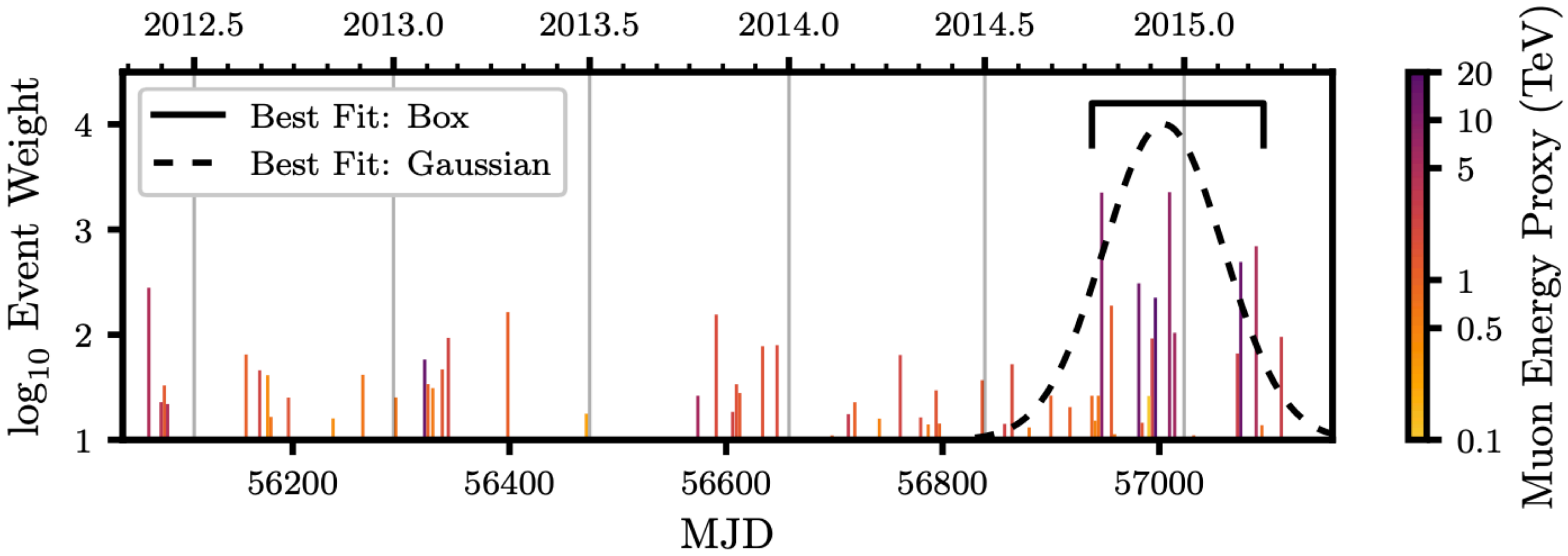
Arguelles et al., JCAP 2018

CHIBA UNIVERSITY

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

ICEHAP

Archival analysis of neutrino emission from TXS0506+056

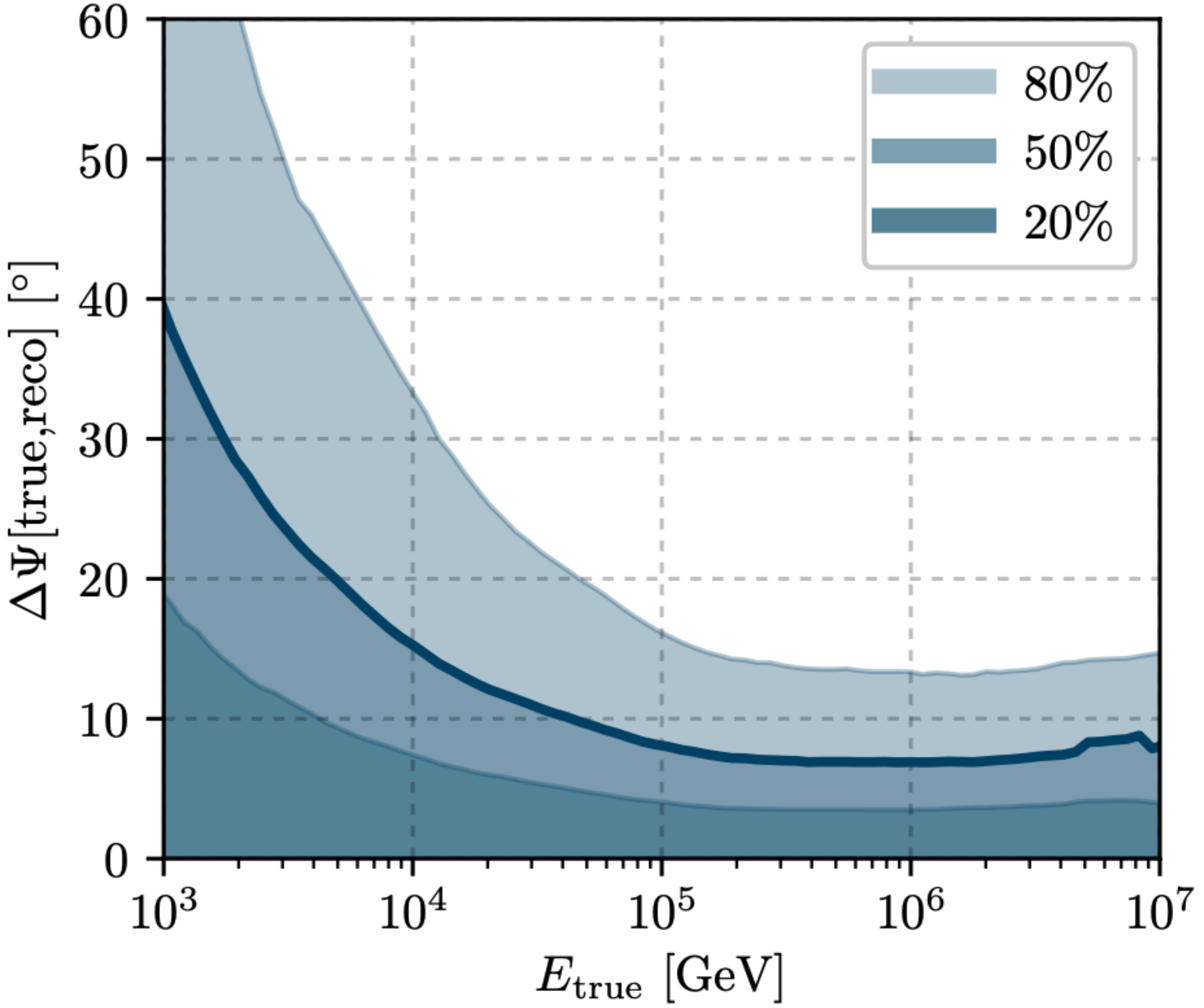


Aartsen et al., Science 2018

Point source searches with cascades

- New neural network based reconstruction
- Improved angular resolution for cascade events

Aartsen et al., ApJ 886 2019



IceCube Gen2 — 10 year discovery potential

- Orange band is the region compatible with the total diffuse astrophysical neutrino flux
- Shaded regions highlight where IC / IC-Gen2 are able to discover one or more sources of the population (in the northern hemisphere, optical only)