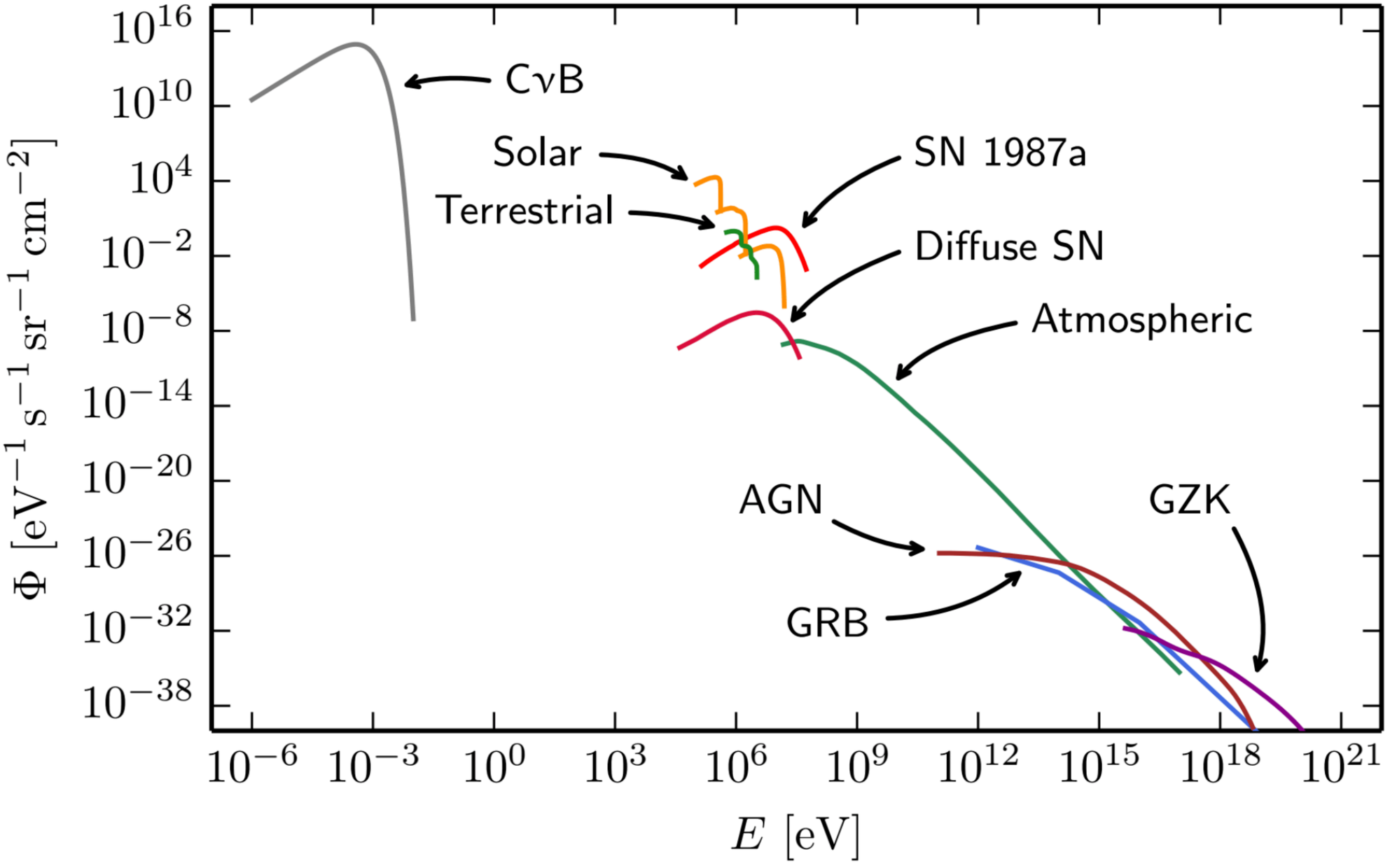
Recent Results from IceCube

Ibrahim Safa
for the IceCube Collaboration

ISMD 2019 - Santa Fe, NM


CνB
Solar
Terrestrial
SN 1987a
Diffuse SN
Atmospheric
AGN
GRB
GZK
$\Phi\ [\mathrm{eV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{cm}^{-2}]$
$E\ [\mathrm{eV}]$
10^{16}
10^{10}
10^{4}
10^{-2}
10^{-8}
10^{-14}
10^{-20}
10^{-26}
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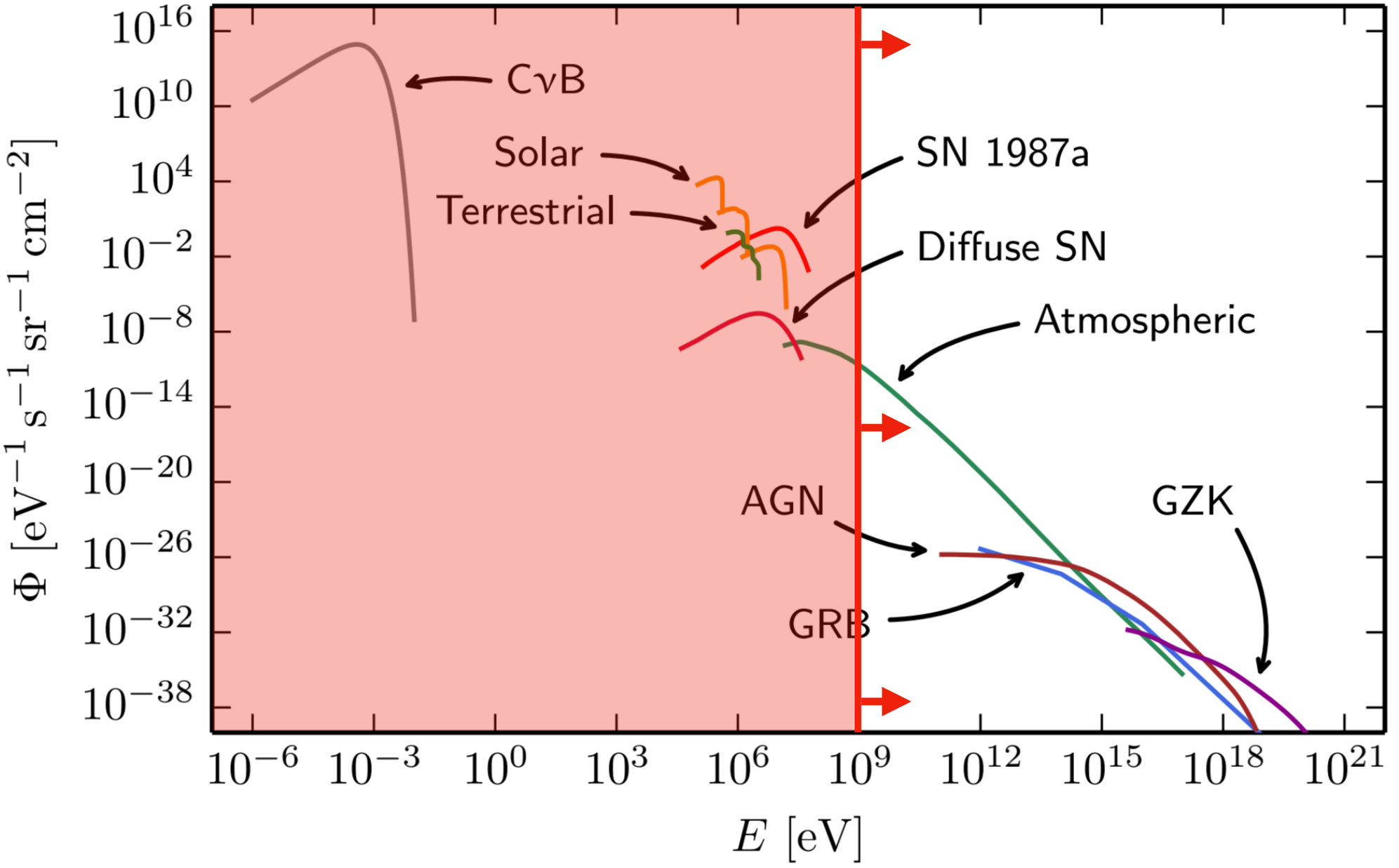
10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21}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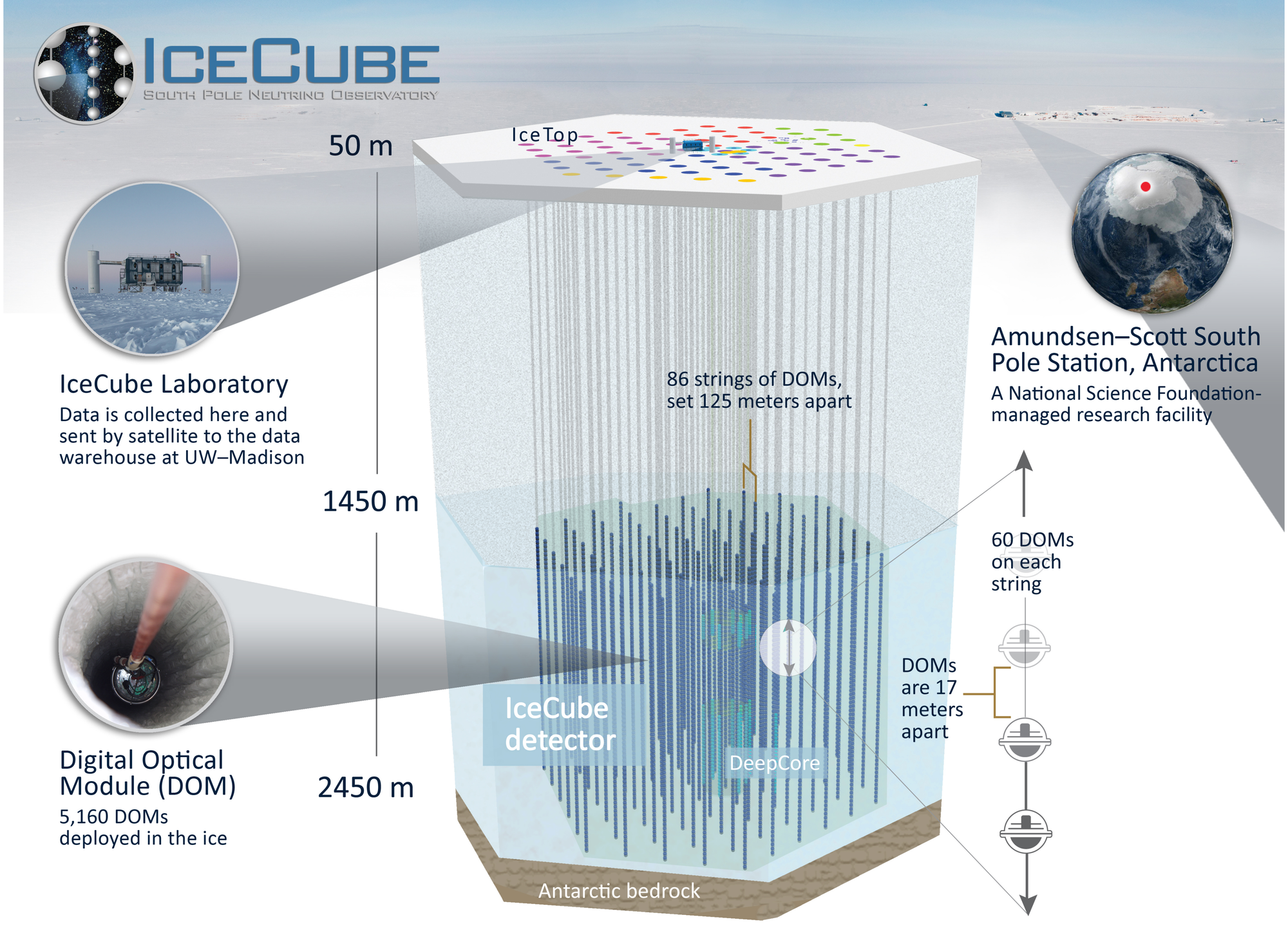
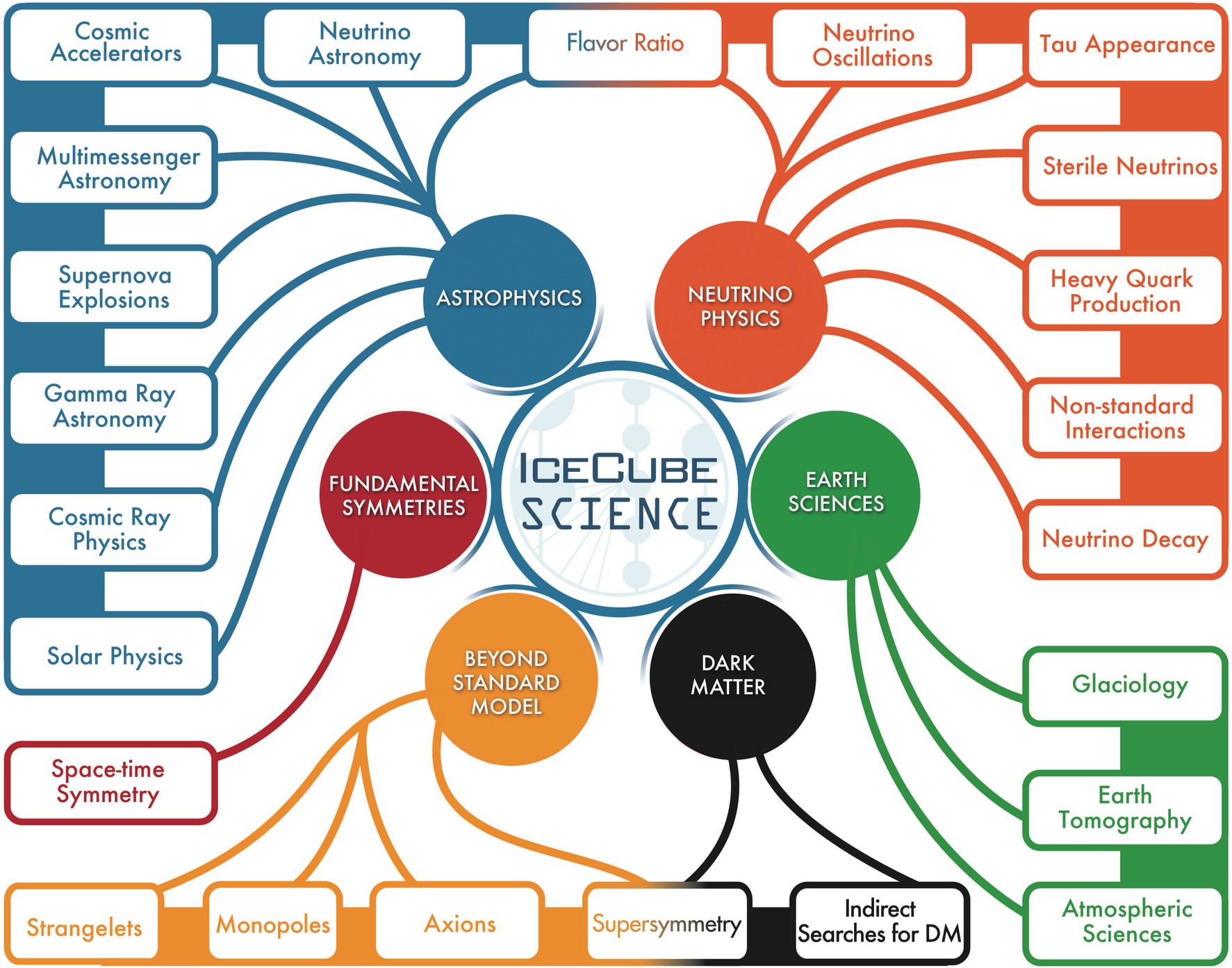
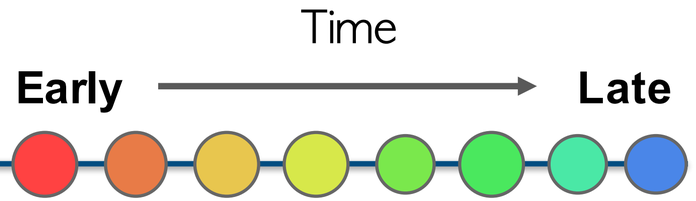
The IceCube Experiment

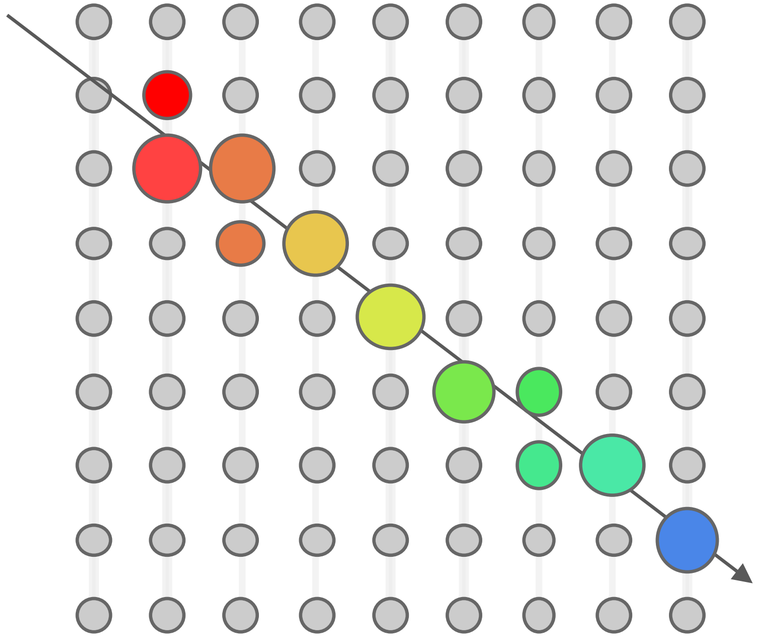

IceCube
South Pole Neutrino Observatory
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic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


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

Event Topologies

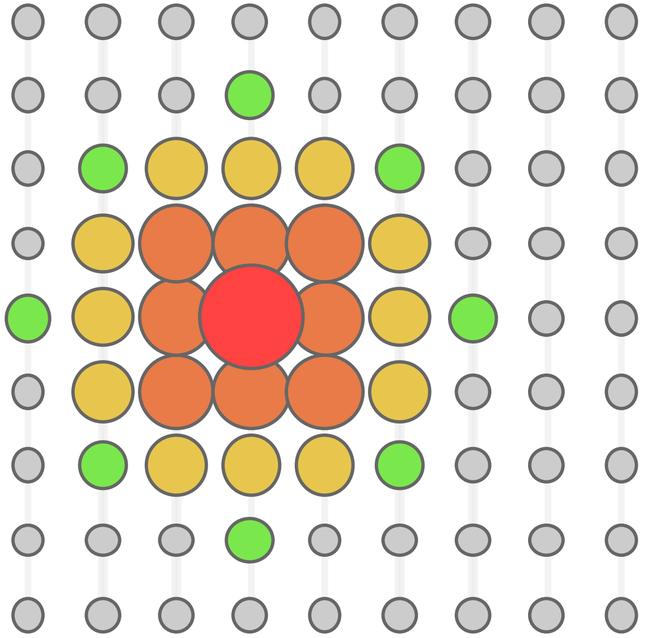


Track
Muon Neutrino CC



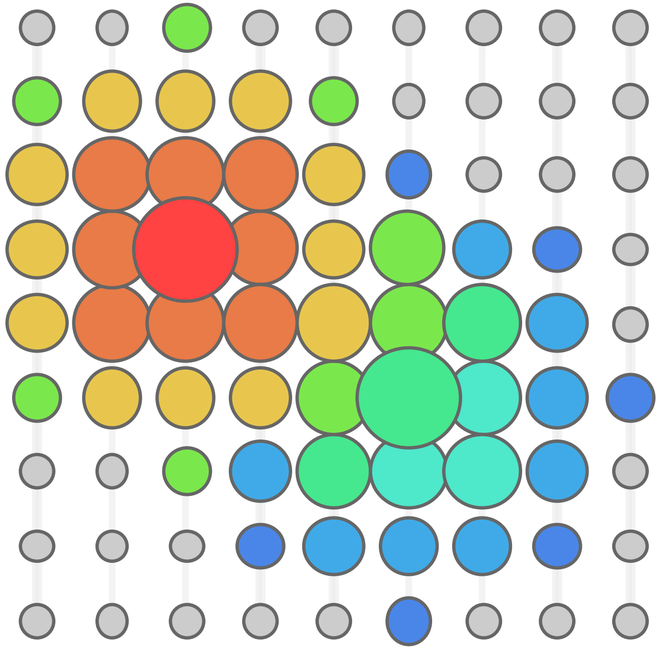
Factor of ~2 energy resolution
0.3° angular resolution at 100TeV

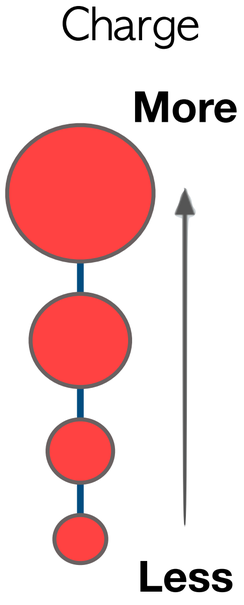
Cascade
Electron Neutrino CC
Tau Neutrino CC
Neutrino NC



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

Double Cascade
High Energy Tau Neutrino CC





Angular and energy resolution comparable to cascades
First candidates observed!

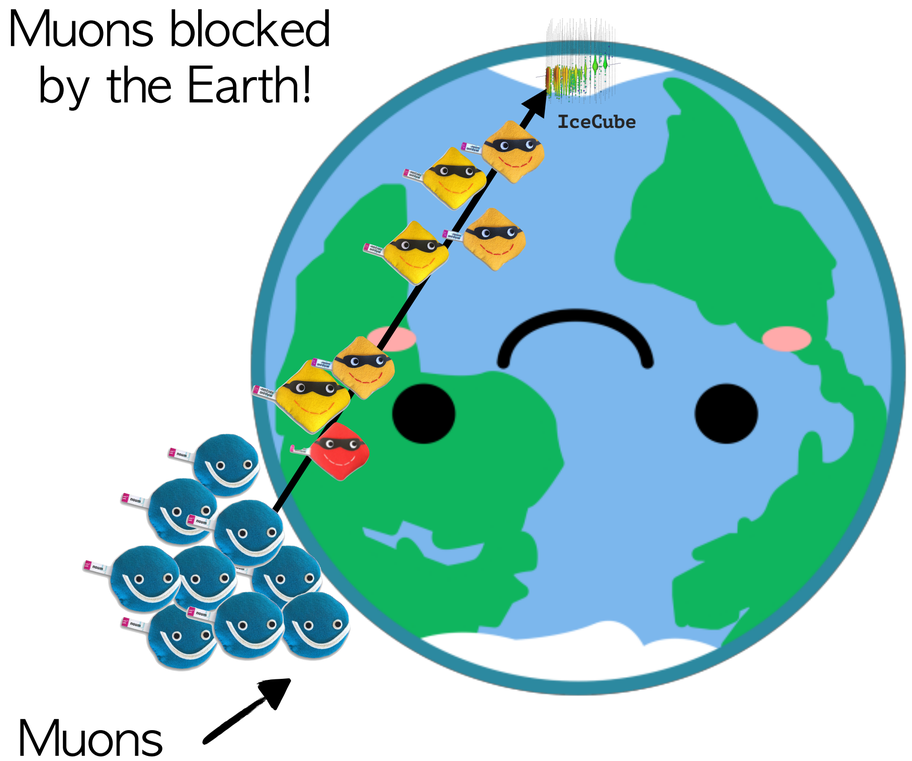
Graphic: A.Schneider

Astrophysical Neutrinos

Through-going muon neutrinos

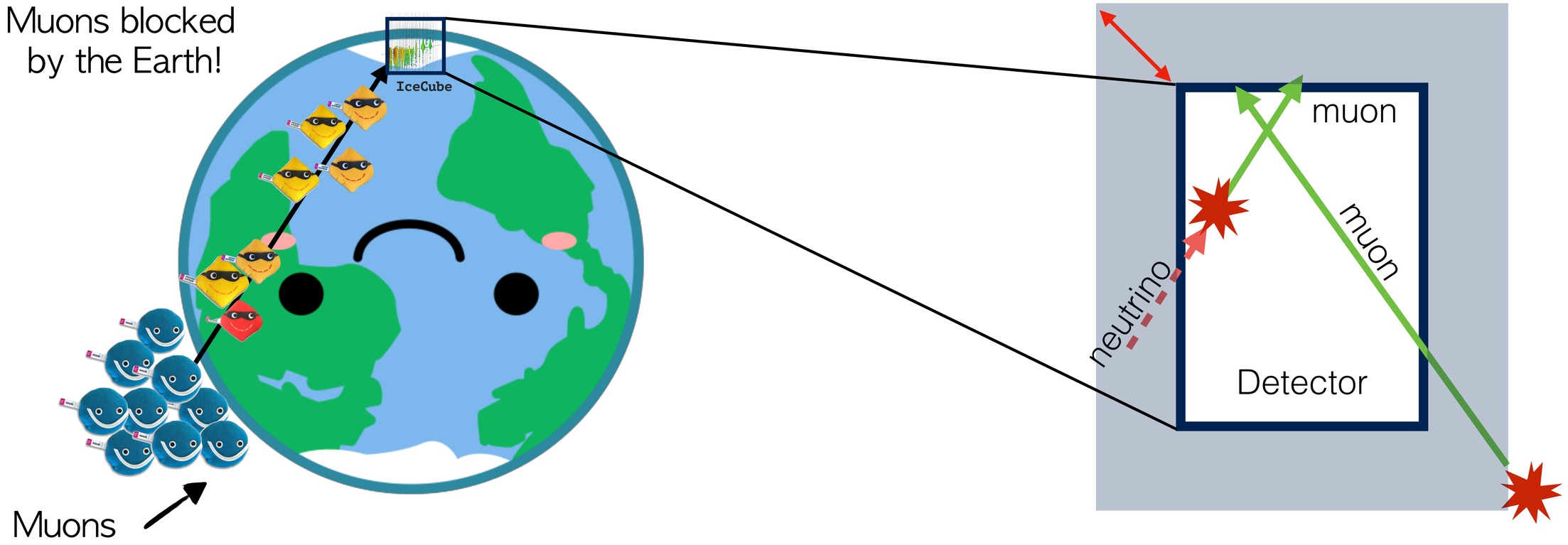
Through-going muon neutrinos

- Earth is a perfect muon blocker.
- Observed upgoing muon tracks are most likely caused by a CC-ν_μ interaction in or around the ice.

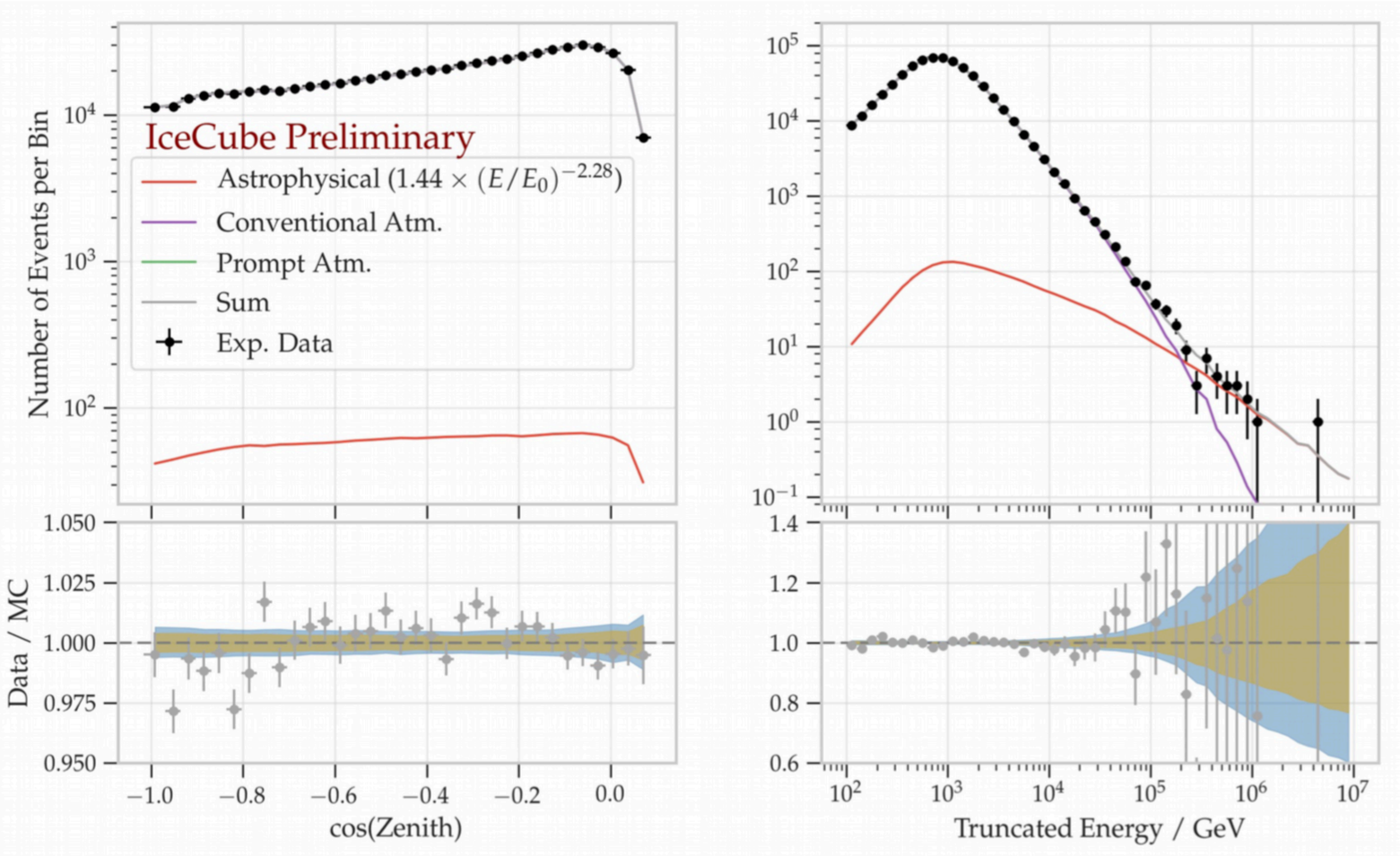


Through-going muon neutrinos

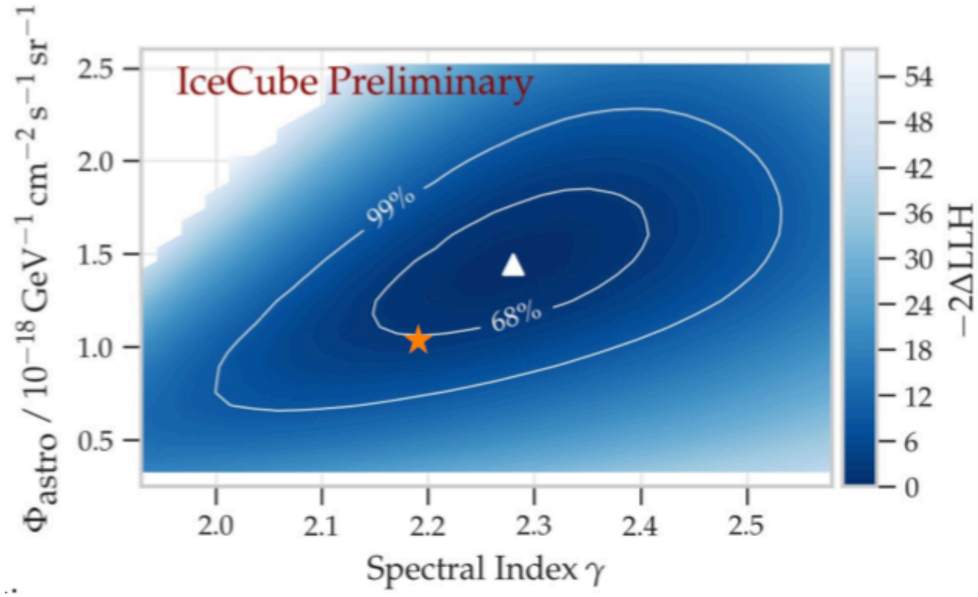
- Earth is a perfect muon blocker.
- Observed upgoing muon tracks are most likely caused by a CC-ν_μ interaction in or around the ice.
- Muons above a TeV travel several kilometers in the ice.
- Effective volume is increased by the muon range.



Through-going muon neutrinos

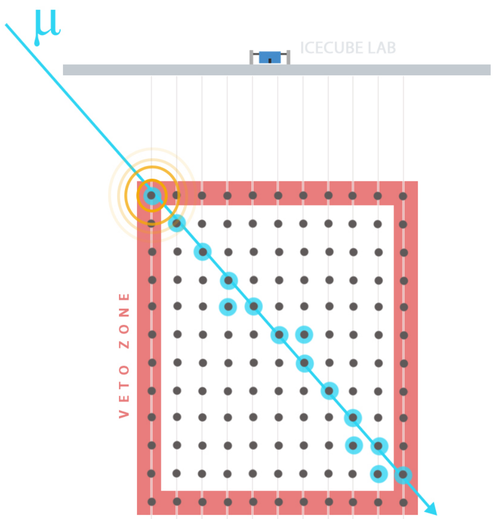


- New results with 9.5 years of data.
- Excess of high-energy component is clearly visible.
- Best-fit Astrophysical spectral index is 2.28 ± 0.09

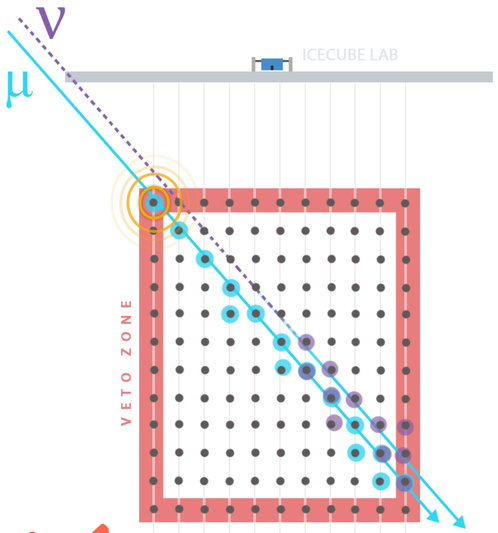


J. Stettner PoS(ICRC2019)1017

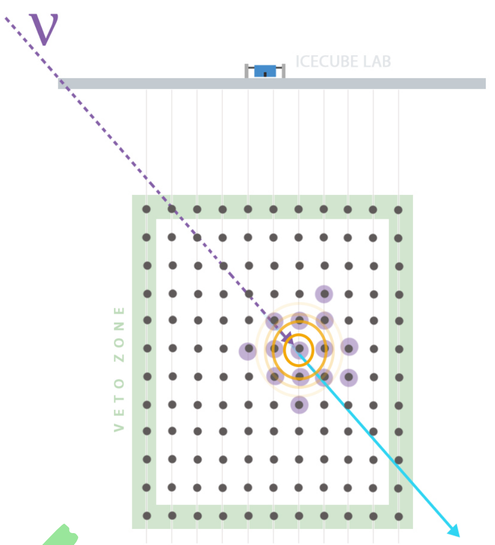
High Energy Starting Events (HESE)



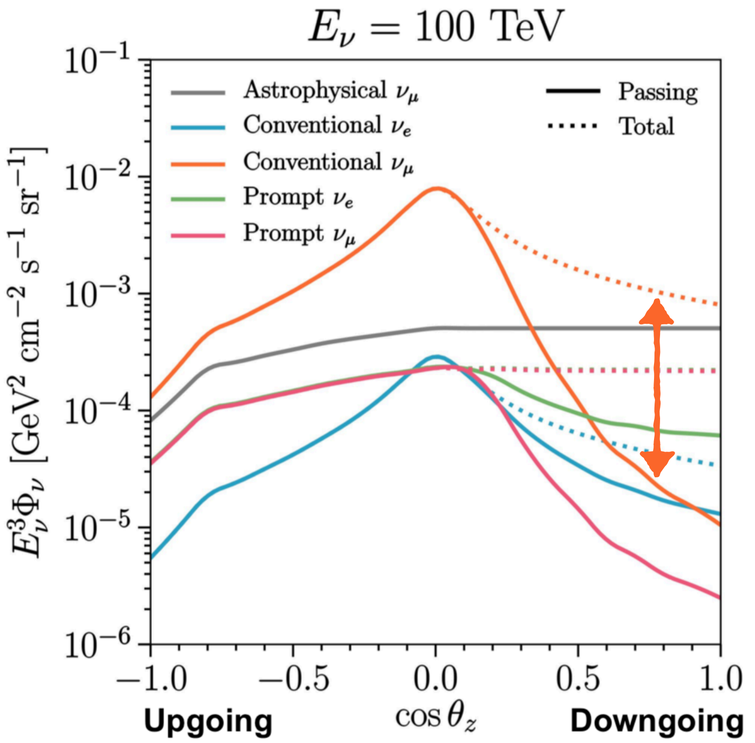
Reject atmospheric muons



Reject atmospheric neutrinos via accompanying muons



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

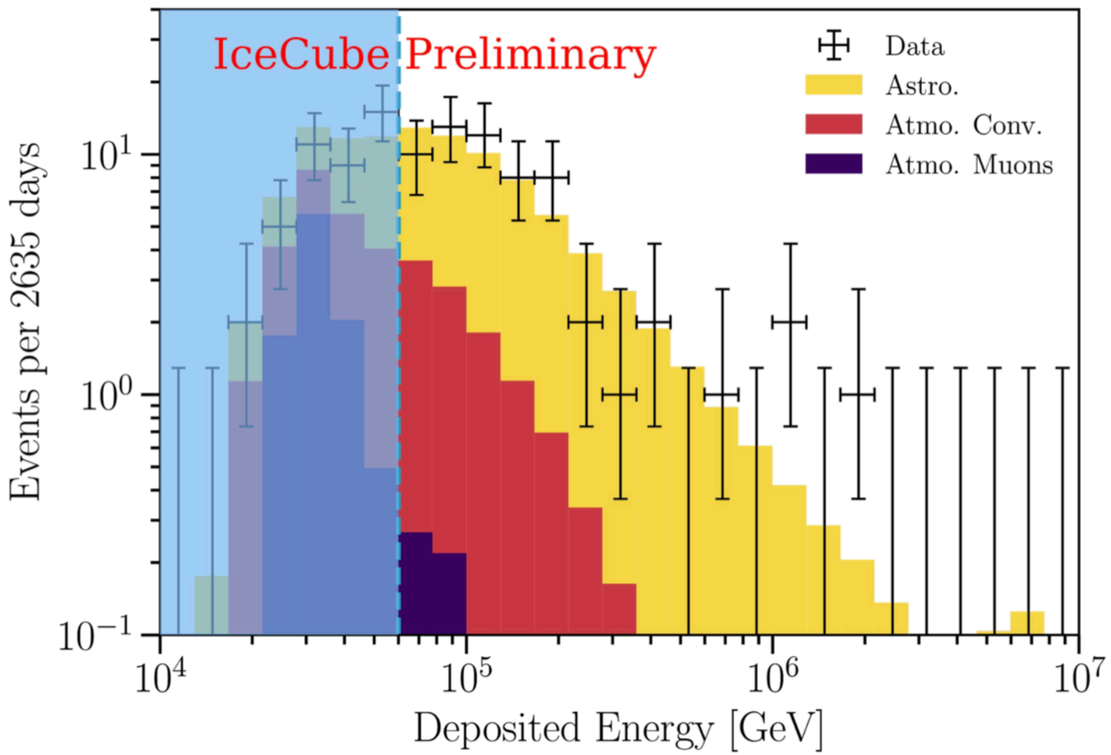


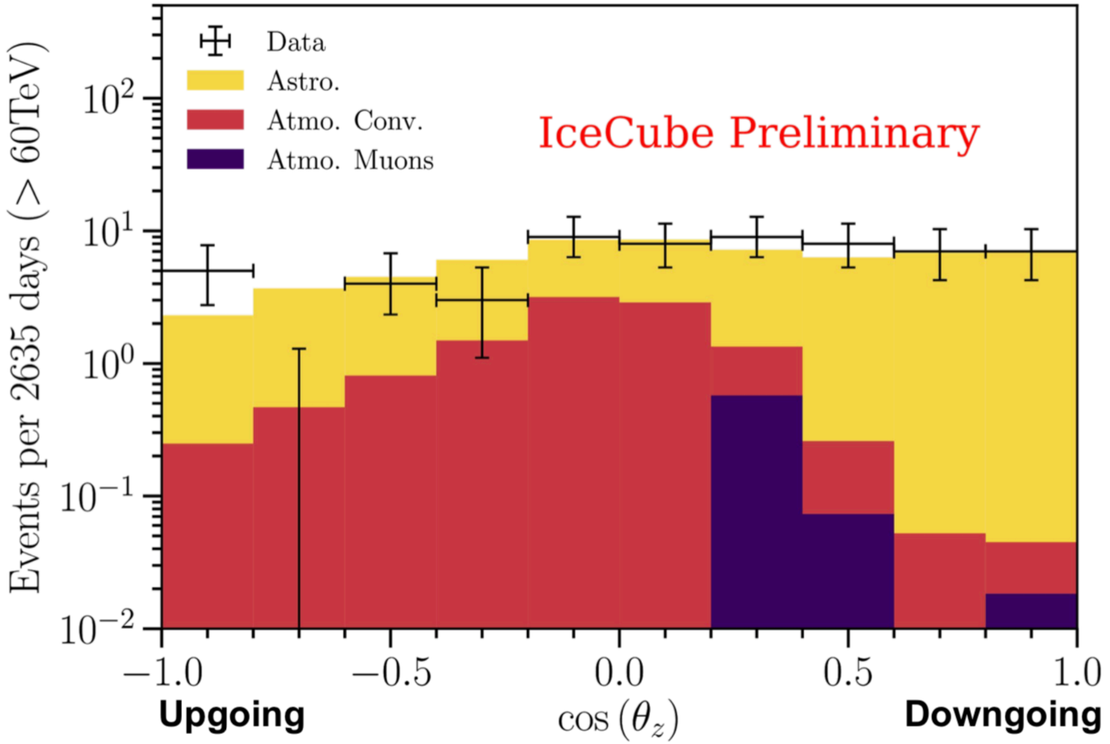
- A high neutrino signal purity sample.
- Excellent rejection of atmospheric background in the downgoing region.
- New results including 7.5 years of data

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

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

High Energy Starting Events (HESE)

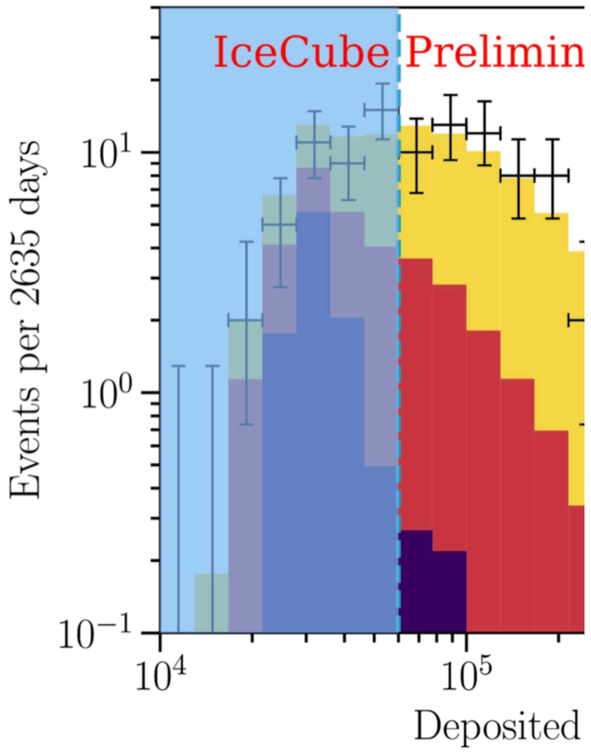


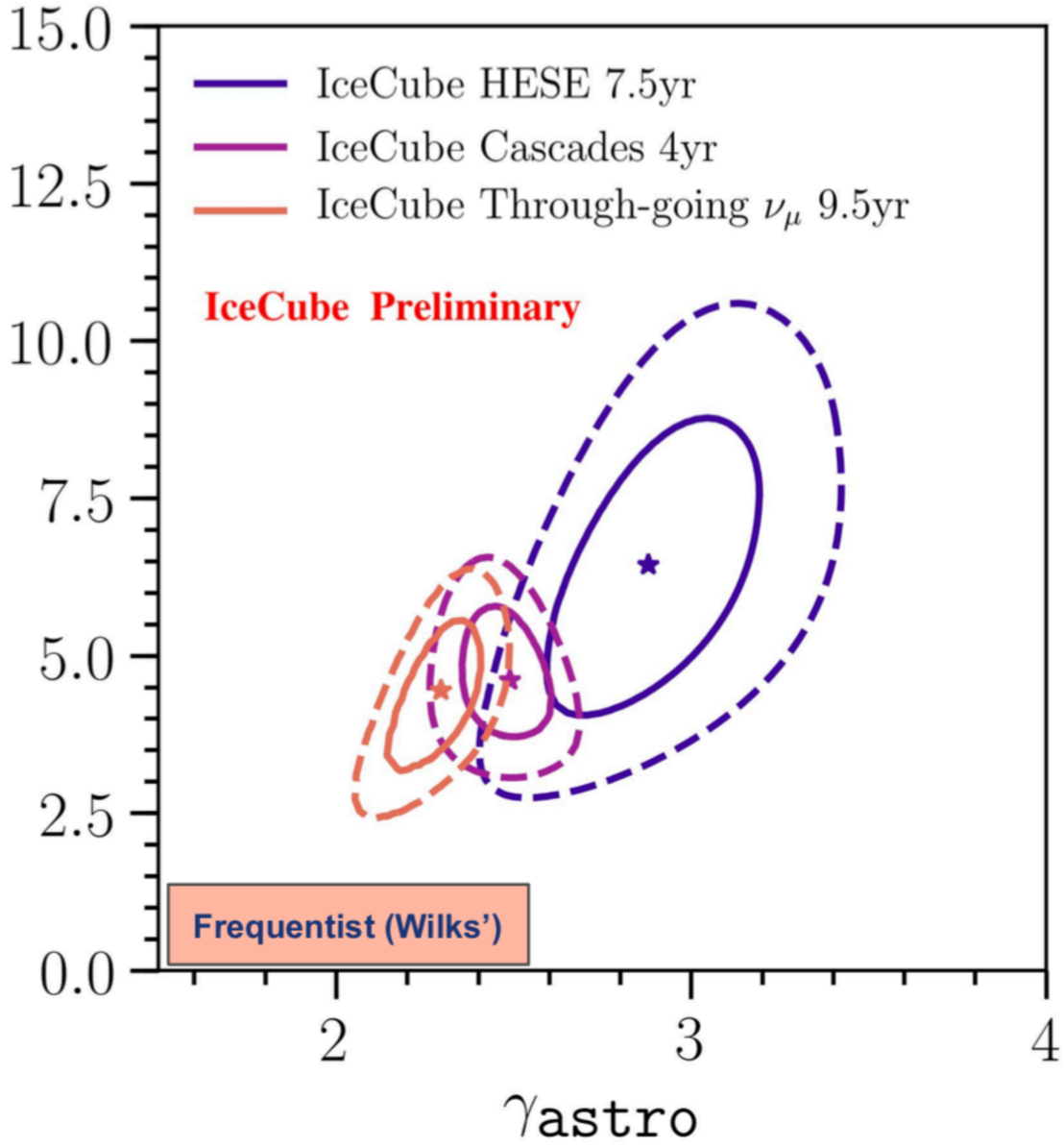


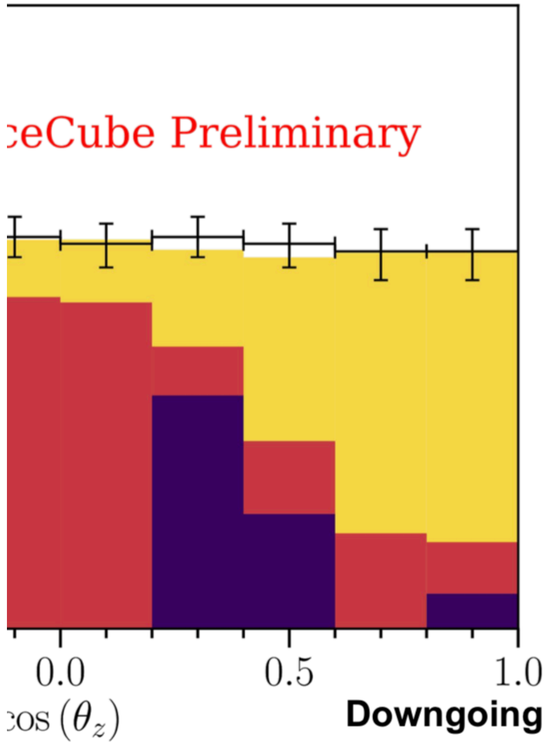
- 22 new events in 2016.
- 9 new events in 2017.
- 102 events in full sample. 60 of them above 60 TeV.

- Best-fit spectral index: 2.89 ± 0.2
- Fit performed for events above 60 TeV

High Energy Starting Events (HESE)





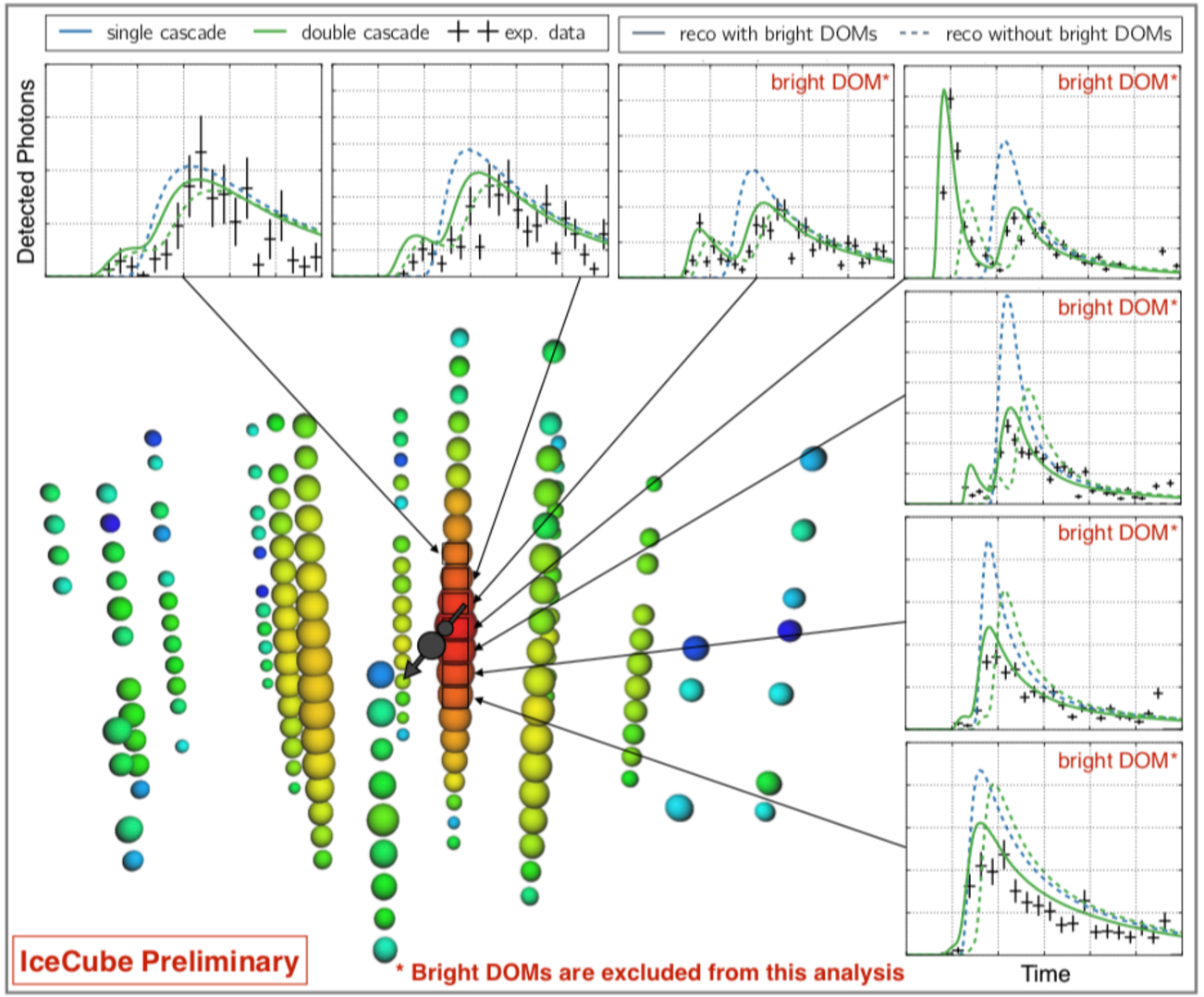


- 22 new events
- 9 new events in
- 102 events in fu above 60 TeV.

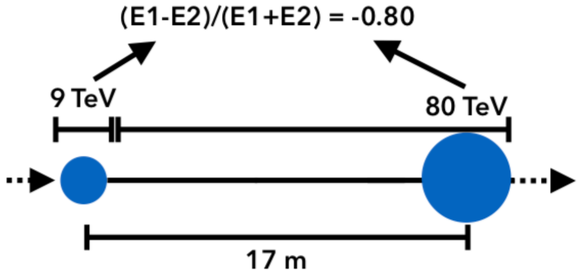
ndex: 2.89 ± 0.2

events above 60 TeV

First astrophysical tau-neutrino candidate

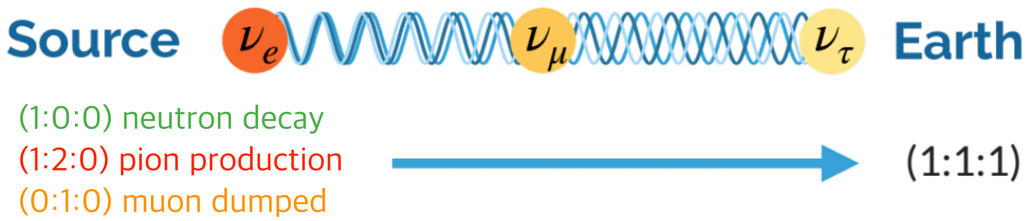


- Event identified in three analyses. Aptly named 'Double Double'.
- Double pulse shape clearly visible.
- Observed light arrival time pattern favors the double cascade hypothesis.



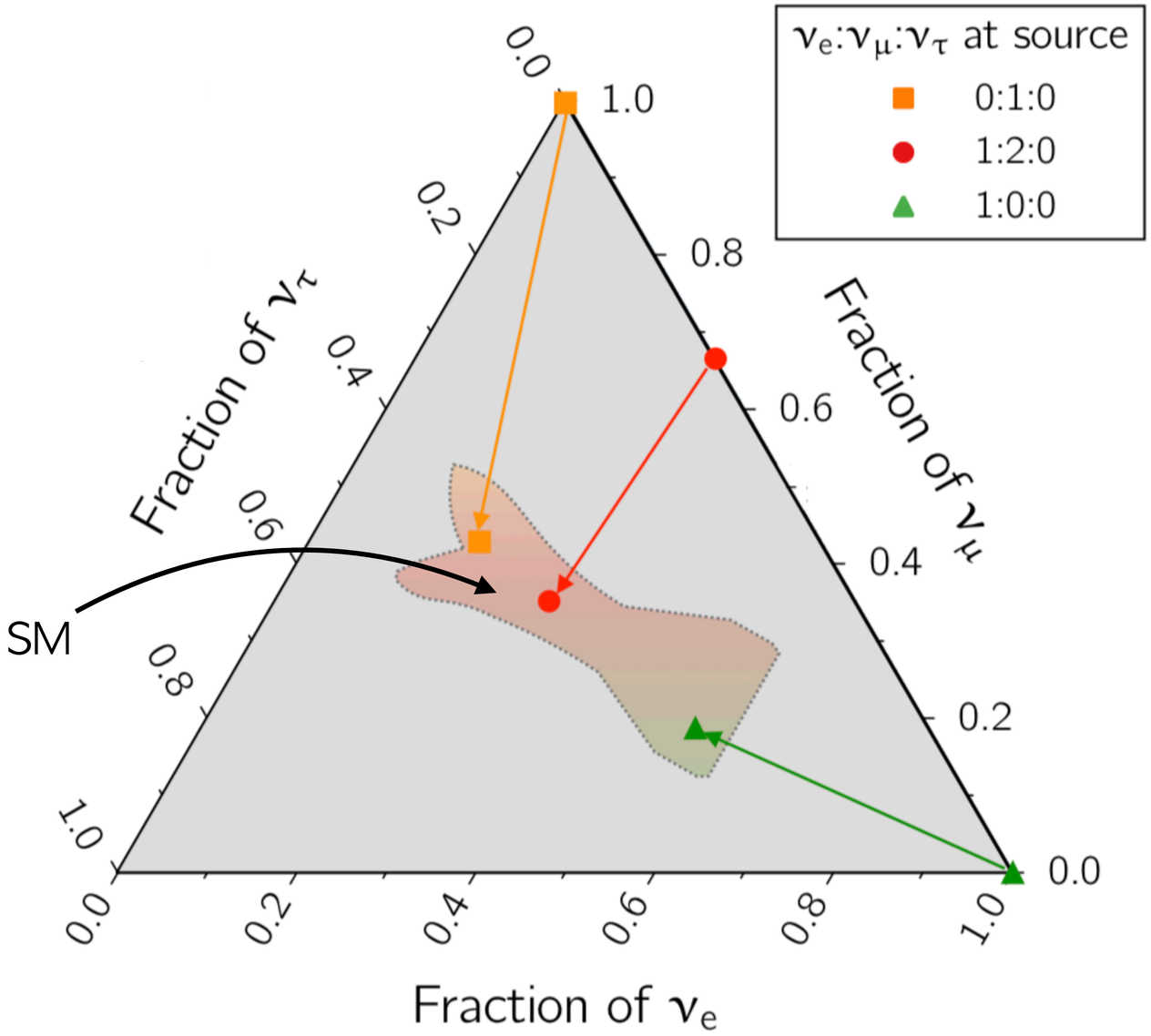
- Dedicated resimulations assuming best-fit HESE spectrum show 97% of Double-Double like events are ν_τ-induced.

Astrophysical Neutrino Flavor

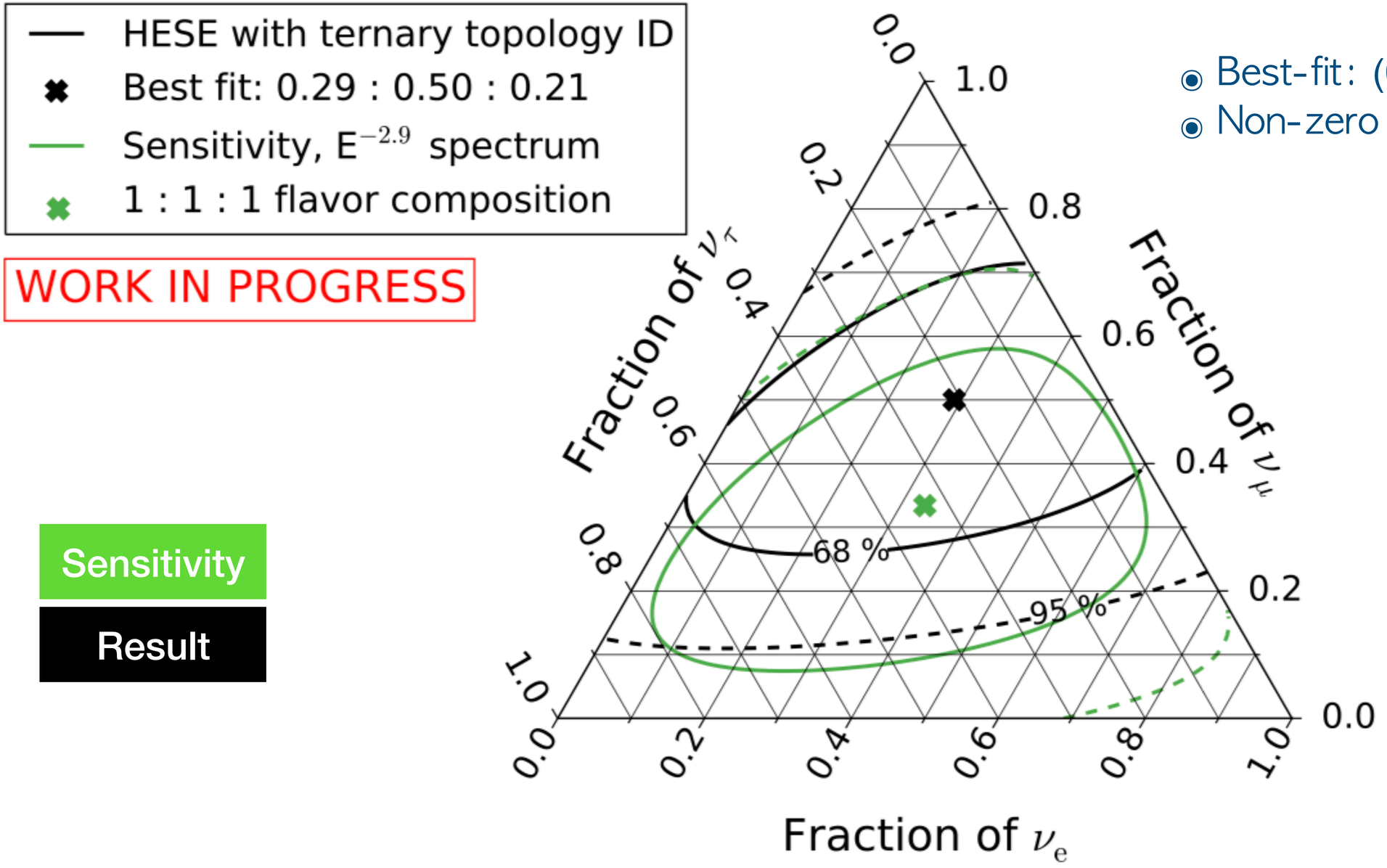


- Measurement of astrophysical neutrino flavor ratio is a probe of oscillations over cosmological baselines and TeV-PeV energies.

- A deviation from standard oscillations in flavor measurements is a probe for new neutrino physics.



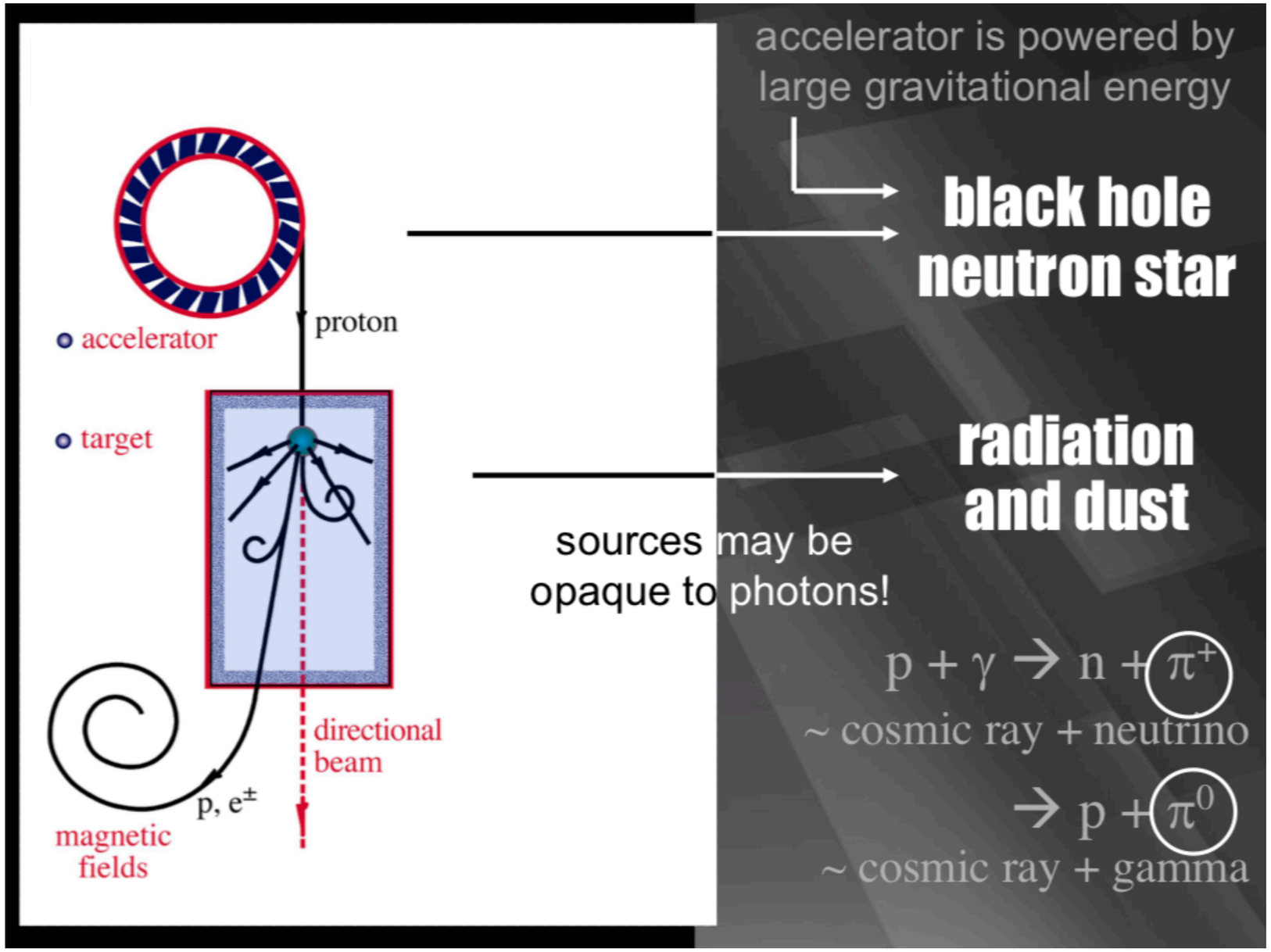
HESE Flavor ratio measurement consistent with (1 : 1 : 1)



- Best-fit: (0.29:0.5:0.21)
- Non-zero ν_τ component!

Where are they all coming from?

A Particle Physicist's guide to PeV neutrino beams

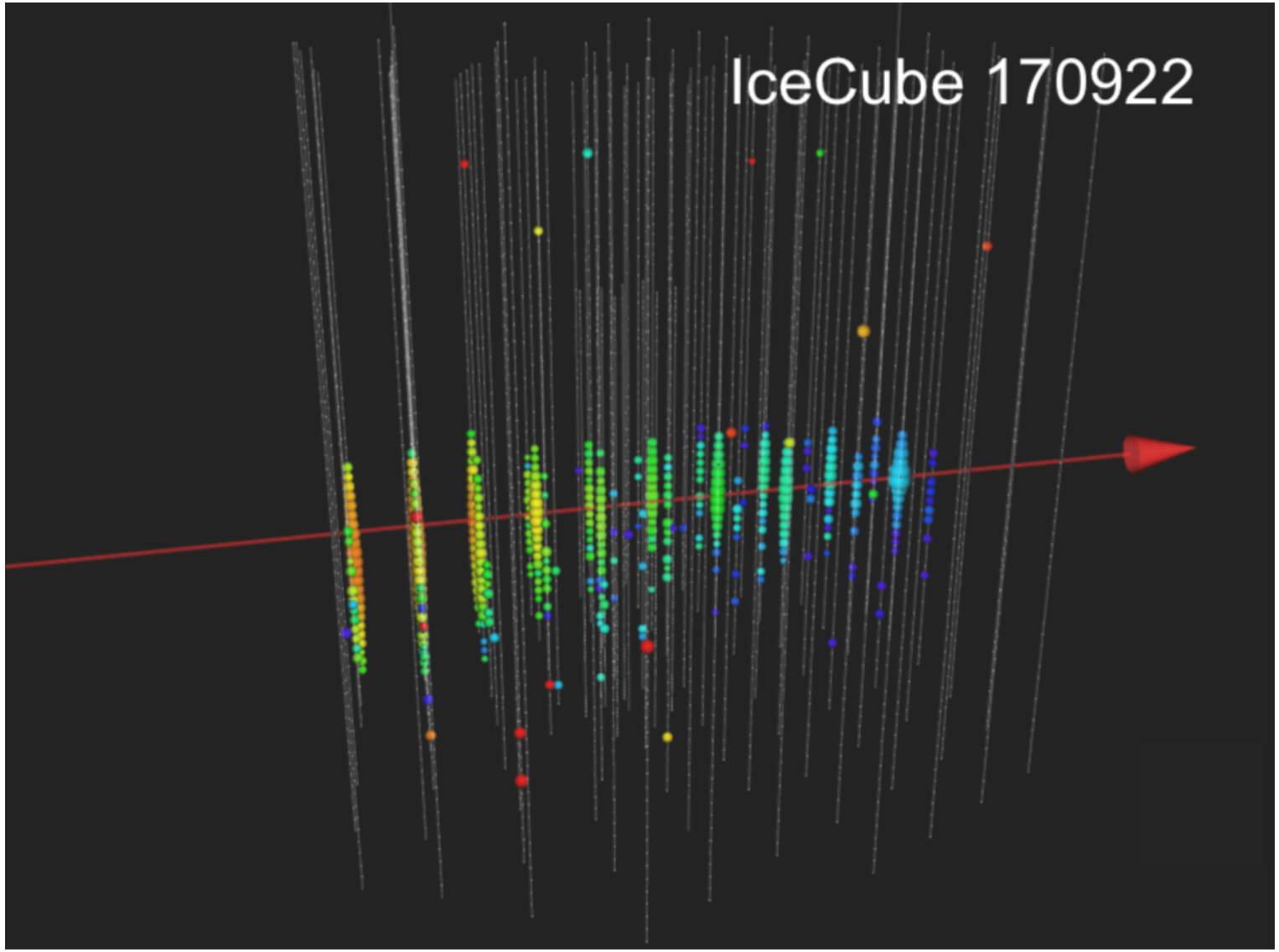


- Extreme gravitational well provides acceleration.
- Jetted protons collide with radiation and dust (beam dump)
- Neutrinos produced via pion decay.
- Extremely dense region implies efficient neutrino production and gamma-ray absorption at the source.

Catching Wind

Catching Wind

- IceCube detected a high-energy upgoing muon track 5.7 degrees below the horizon (IC170922A). Best-fit neutrino energy is 290 TeV assuming E^{-2} spectrum.



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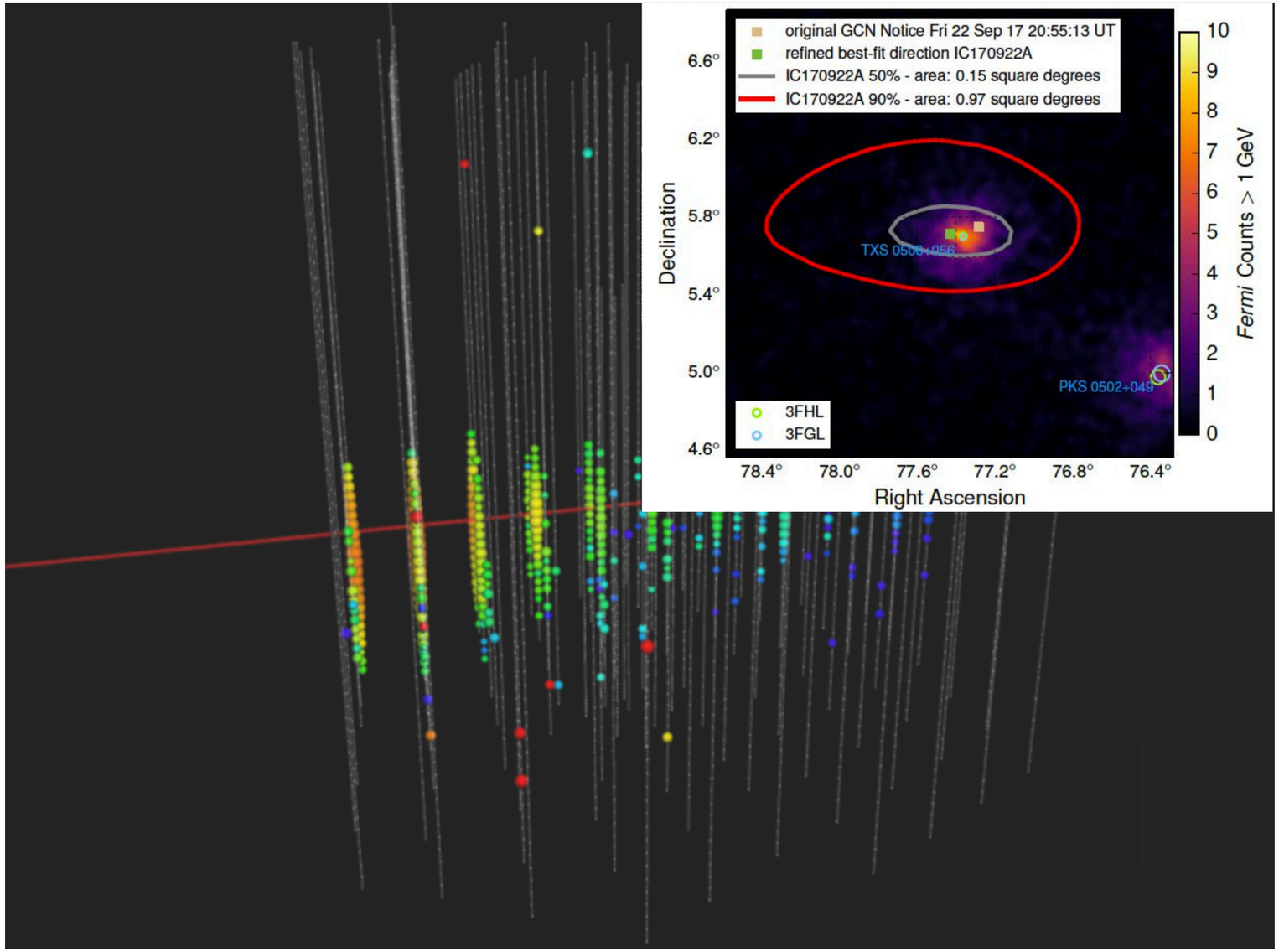
- Fermi gamma-ray satellite, in a followup to the IceCube alert, reported a flaring blazar within ~0.1 degrees of IceCube event (TXS 0506+056).



Catching Wind

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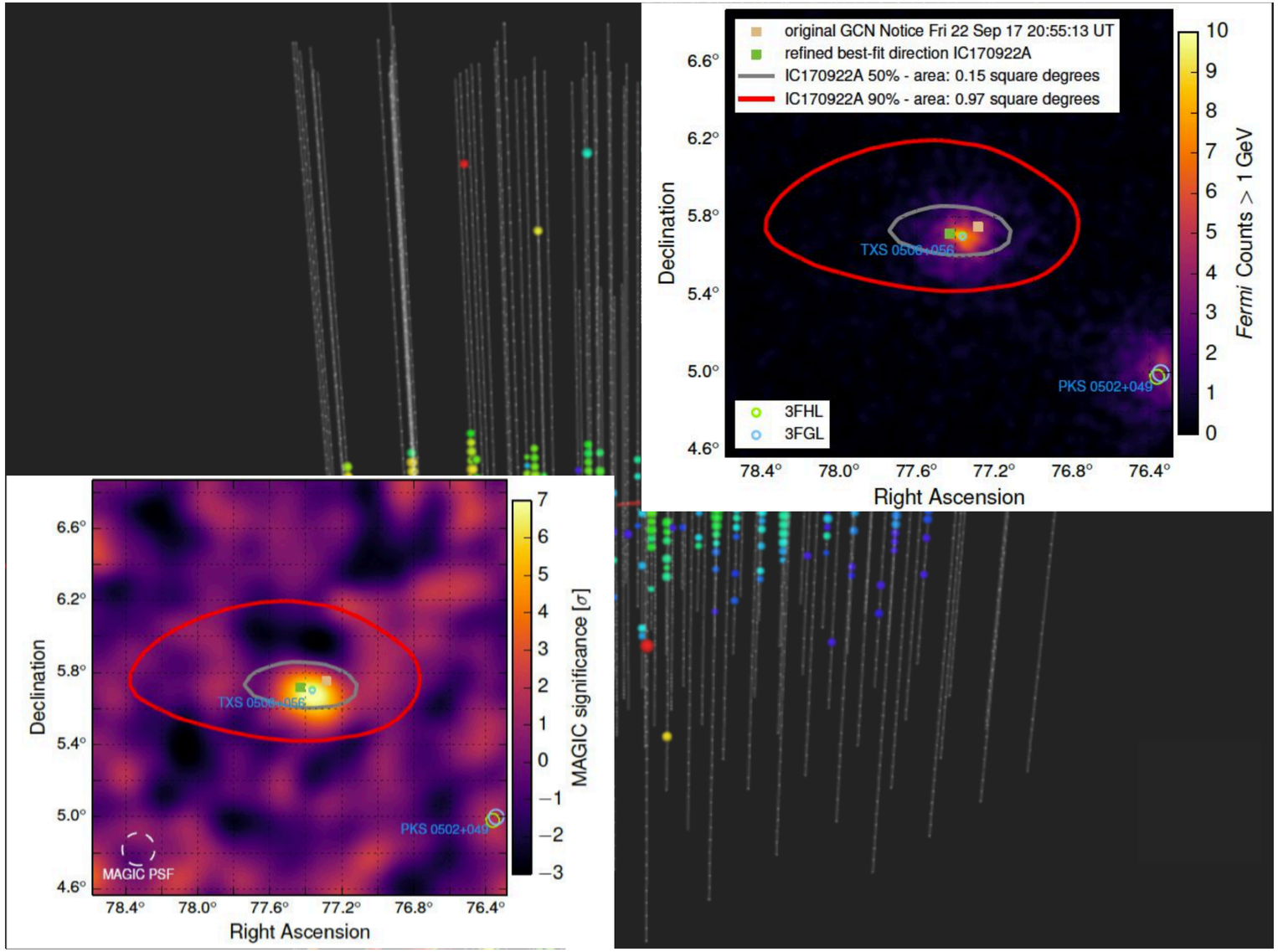
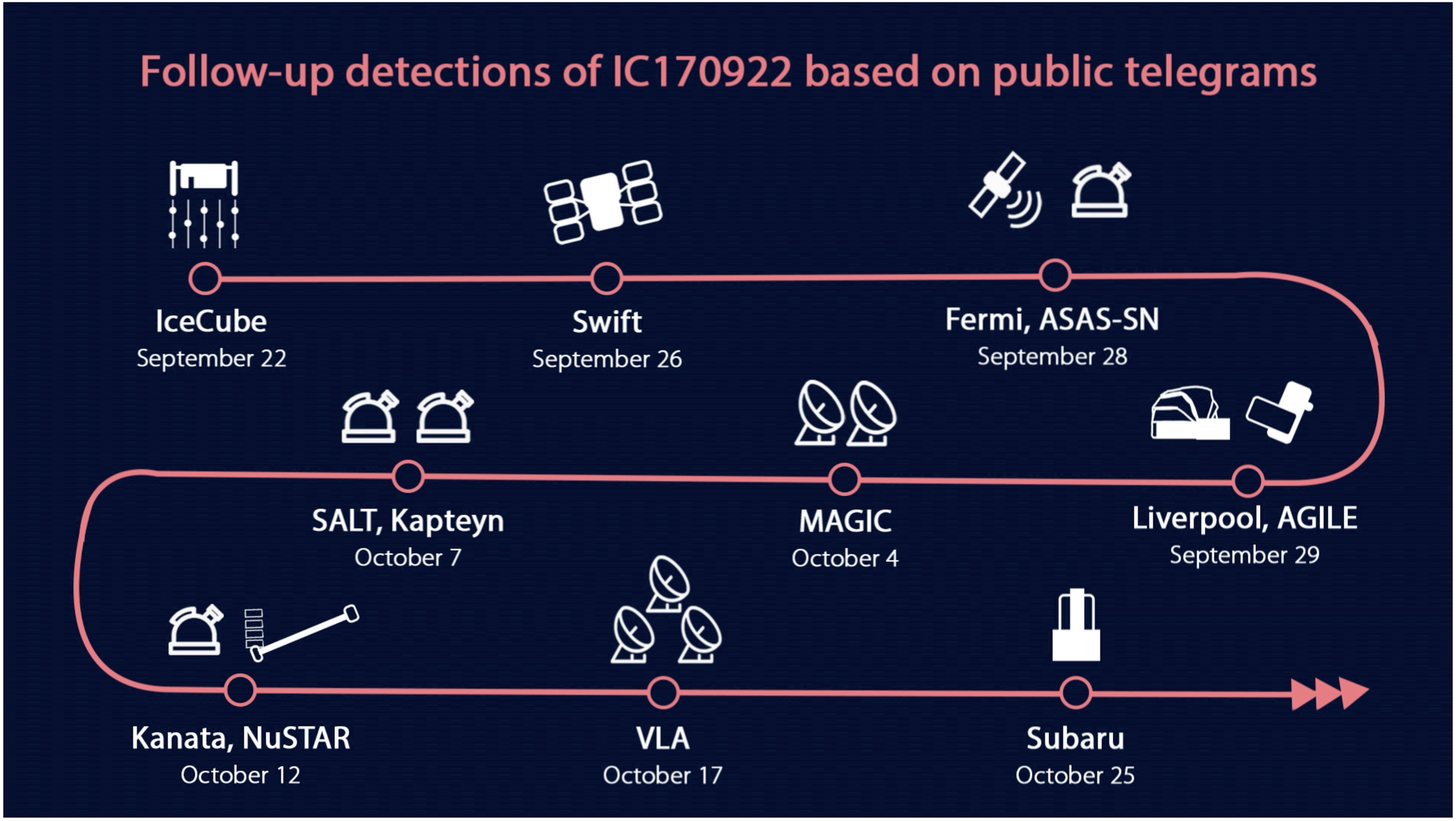
- Fermi gamma-ray satellite, in a followup to the IceCube alert, reported a flaring blazar within ~0.1 degrees of IceCube event (TXS 0506+056).
- MAGIC reported >100 GeV gamma rays in that direction.
- Chance correlation with enhanced gamma-ray activity rejected at more than 3σ level.

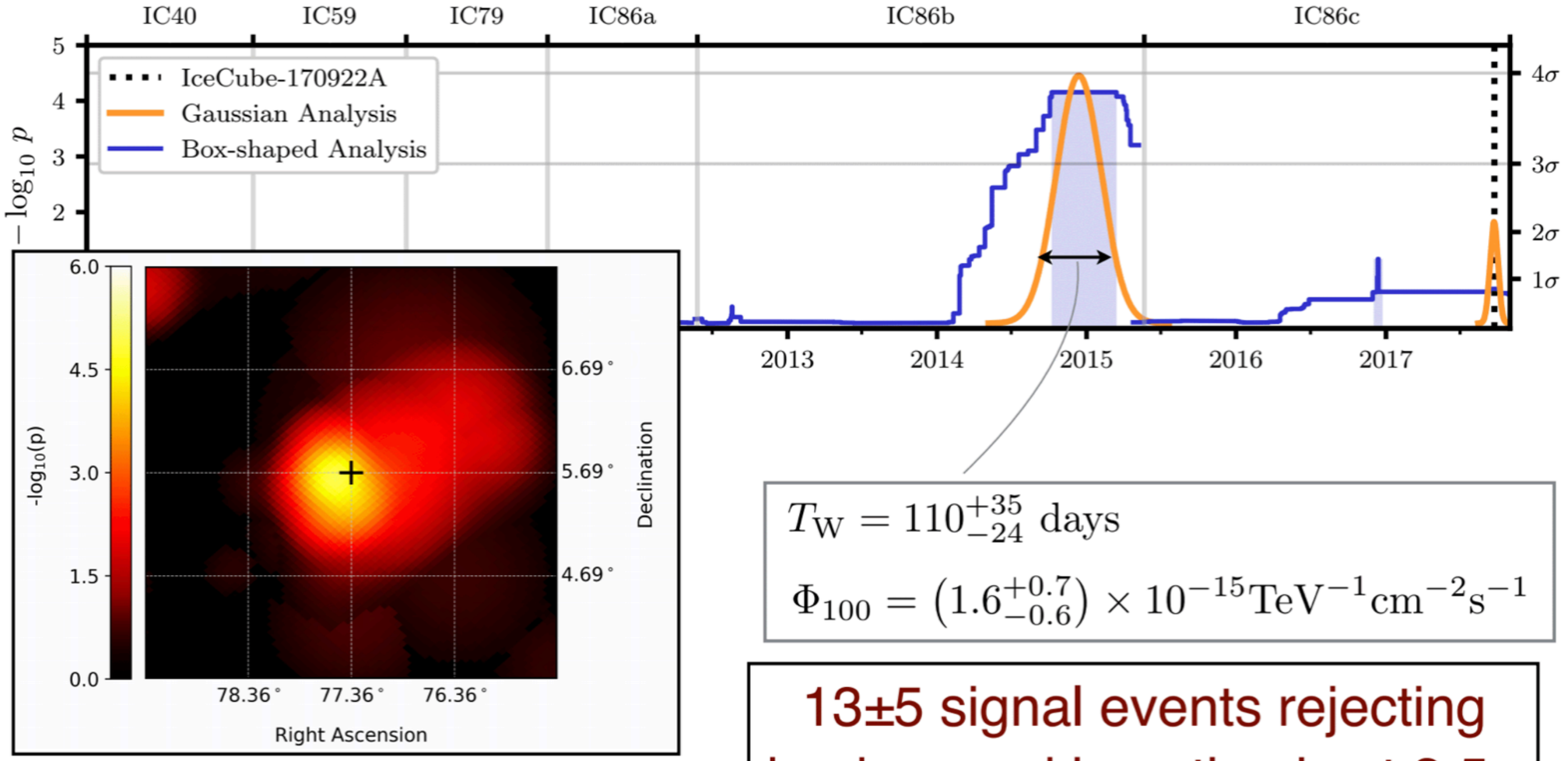


Follow-up detections of IC170922 based on public telegrams



Following the thread

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



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

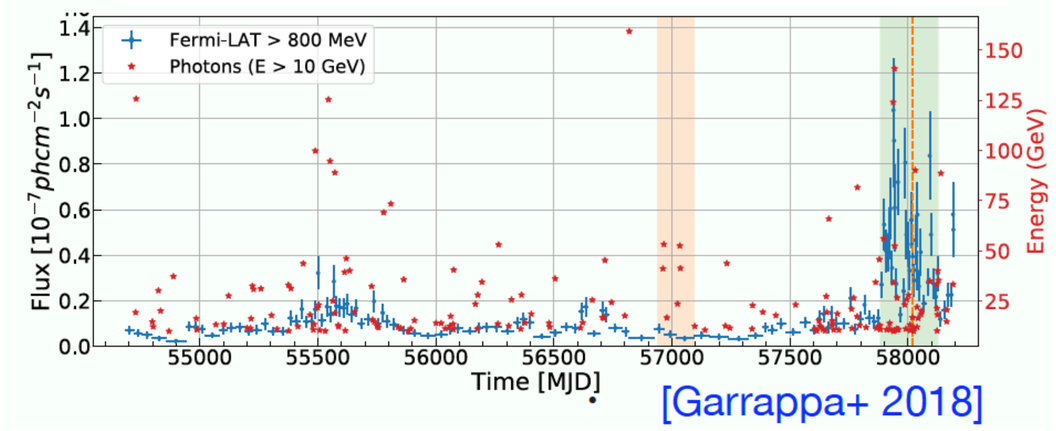
$$\Phi_{100} = \left(1.6^{+0.7}_{-0.6}\right) \times 10^{-15}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

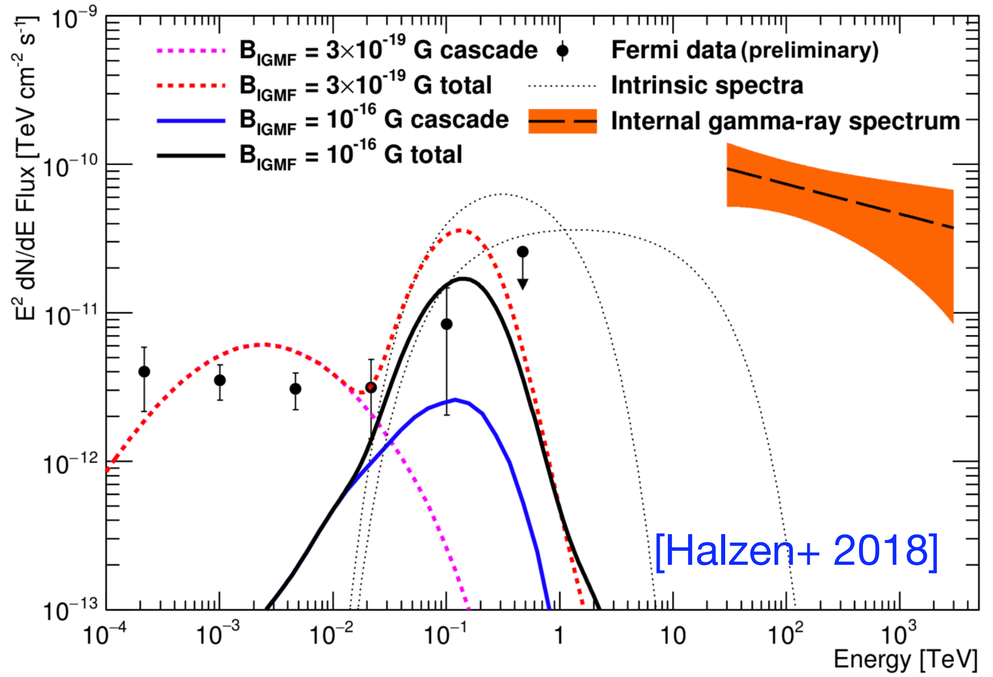
[IceCube, Science 2018]

13±5 signal events rejecting background hypothesis at 3.5σ

Connecting the dots

- The ten-year averaged flux of TXS is dominated by the flare in 2014.
- No gamma-ray enhancement detected in 2014, but hints of a hardening spectrum (Padovani+ 2018, Garrappa+2018)
- Halzen+ 2018 showed that efficient neutrino emitters with high radiation density are opaque to high-energy gamma-rays.
- Major accretion event needed to explain the target density required for the 2014 flare. Vanilla Blazars are not the answer.

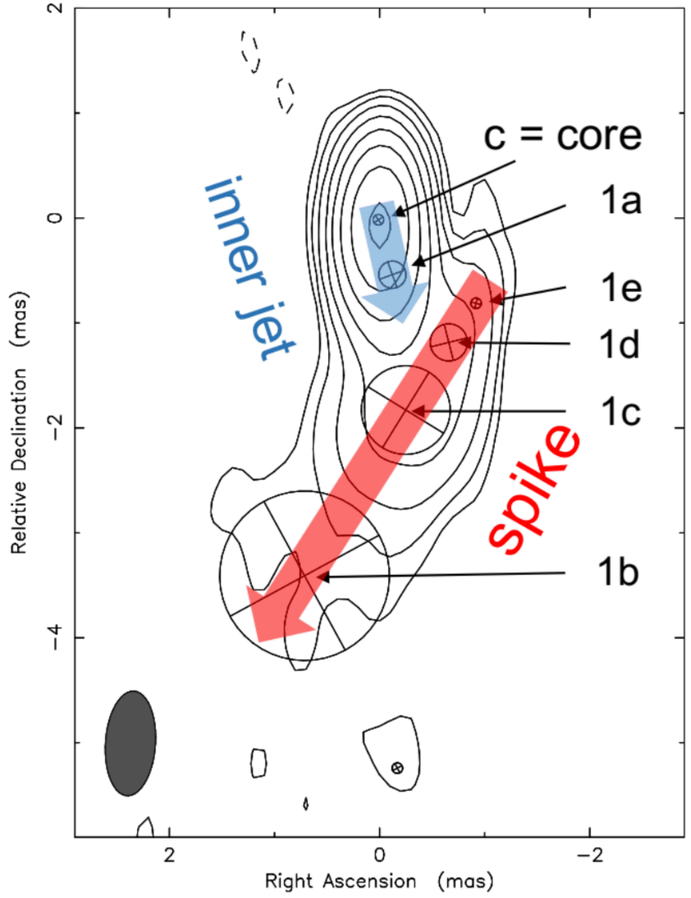




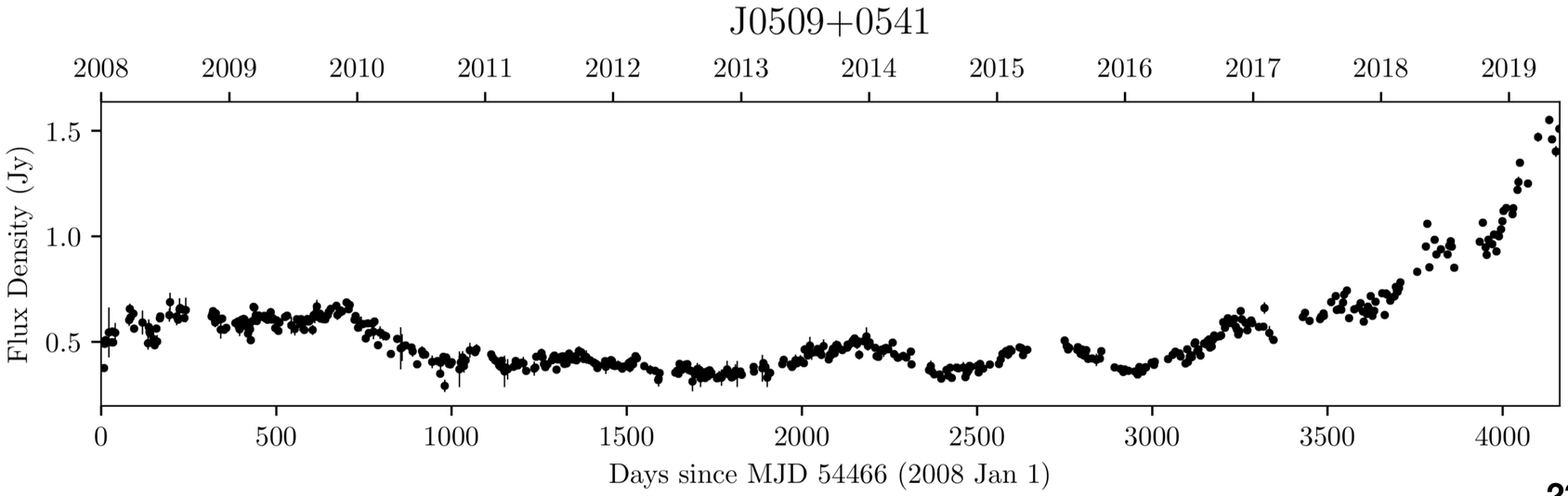
Galaxy Mergers

A Cosmic Collider: IceCube neutrino generated in a precessing jet-jet interaction in TXS 0506+056?

S. Britzen[1], C. Fendt[2], M. Böttcher[3], M. Zajaček[1,4,5], F. Jaron[1,6], I.N. Pashchenko[7], A. Araudo[8,9], V. Karas[8], and O. Kurtanidze[10]



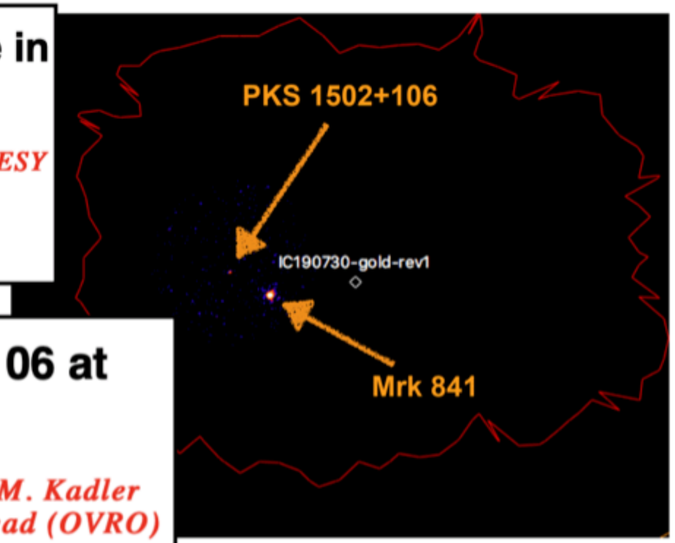
- TXS 0506+056: Not a typical Blazar.
- A closer look in the radio band suggests 2-jet structure.
- Colliding jets implies merging galaxies.
- This provides the necessary target density for efficient neutrino production.



Galaxy Mergers

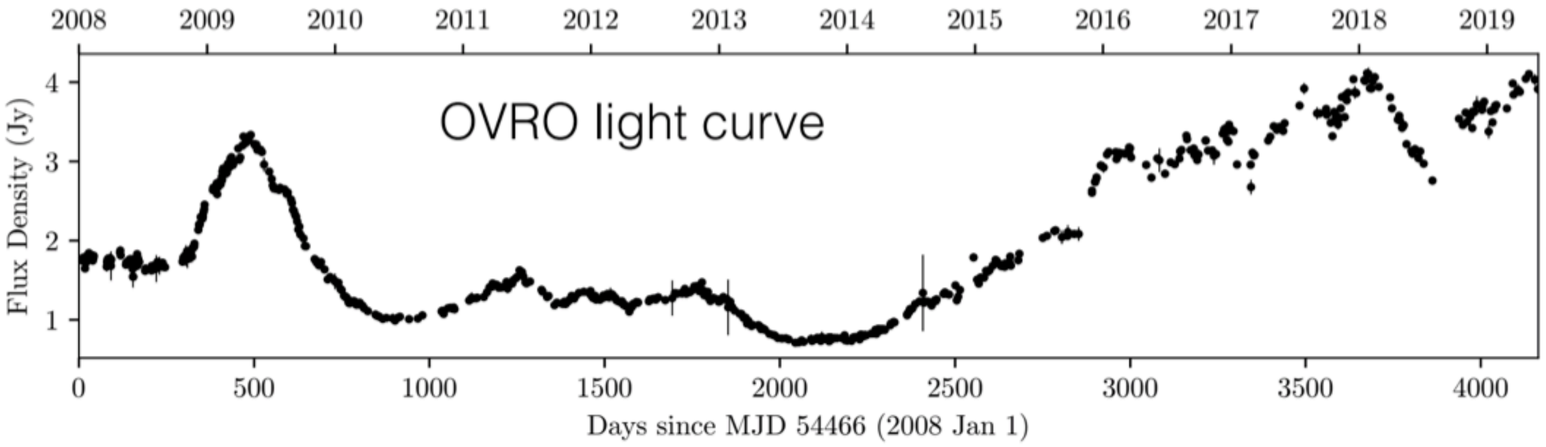
IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106

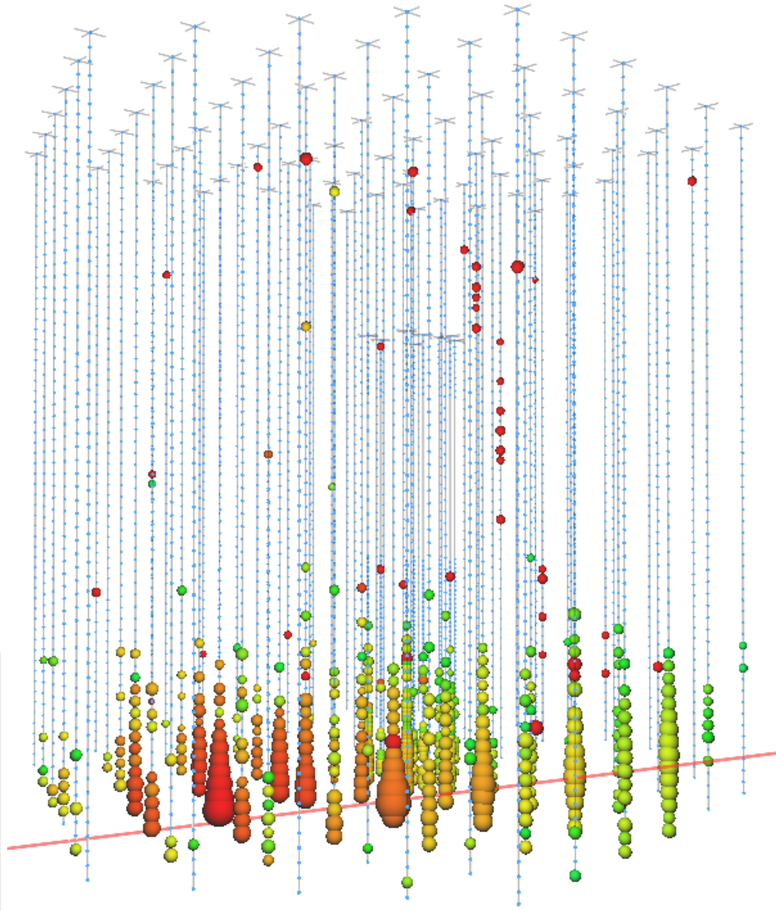
ATel #12967; *Ignacio Taboada (Georgia Institute of Technology), Robert Stein (DESY Zeuthen)*
on 30 Jul 2019; 23:58 UT
Credential Certification: Ignacio Taboada (itaboada@gatech.edu)



Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

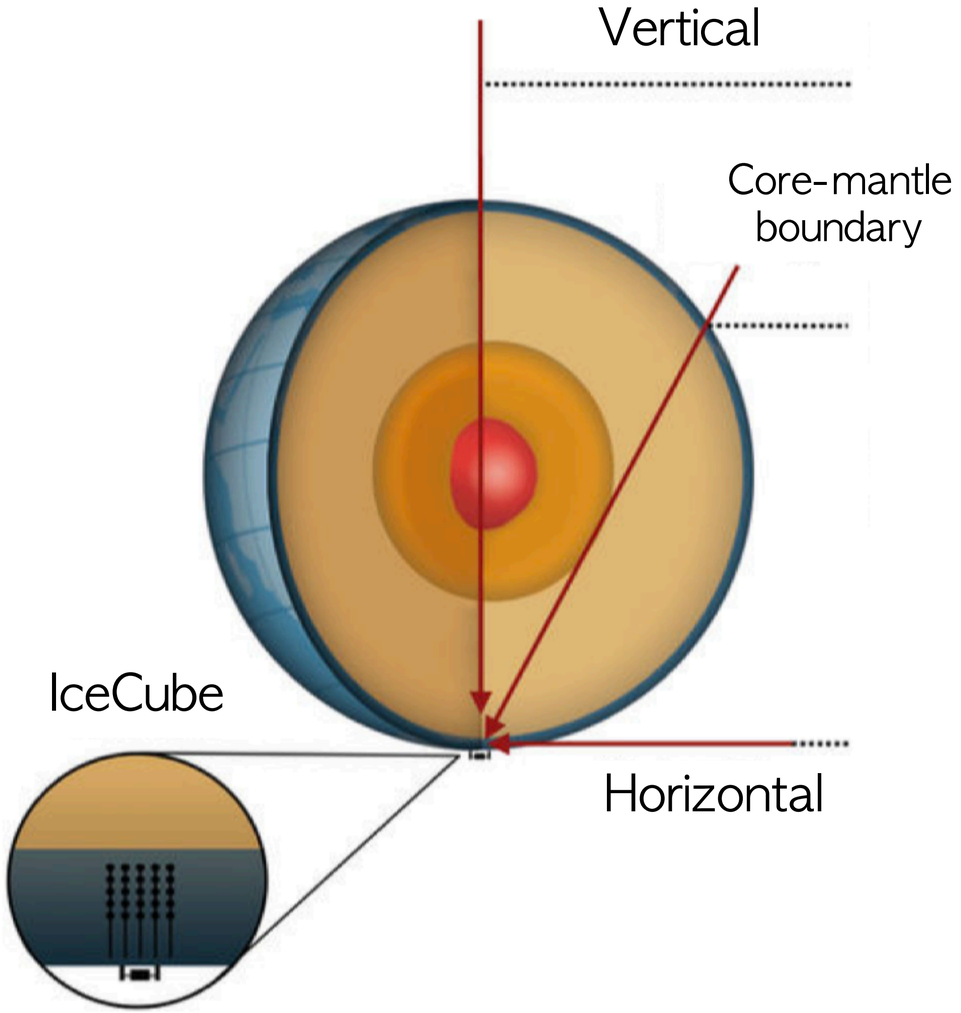


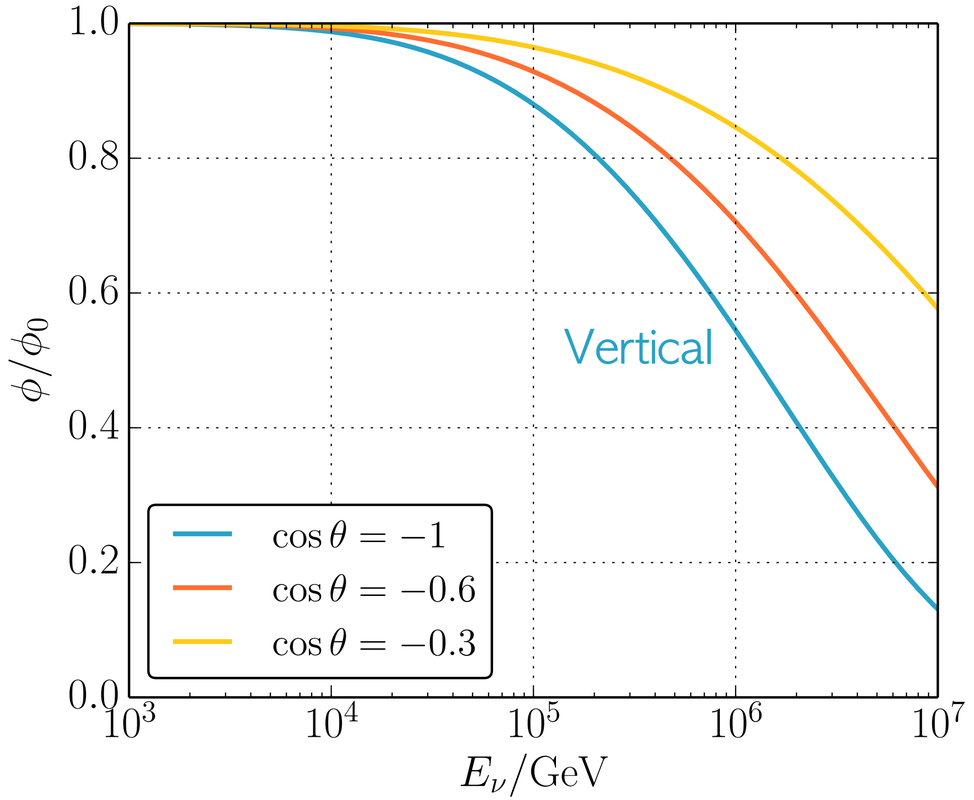


Neutrino Cross Sections at TeV+

High Energy neutrino flux attenuation depends on energy and zenith angle.

- Total neutrino cross-section can be measured with IceCube using Cascades (good energy resolution) or tracks (good angular resolution), or a combination of both.

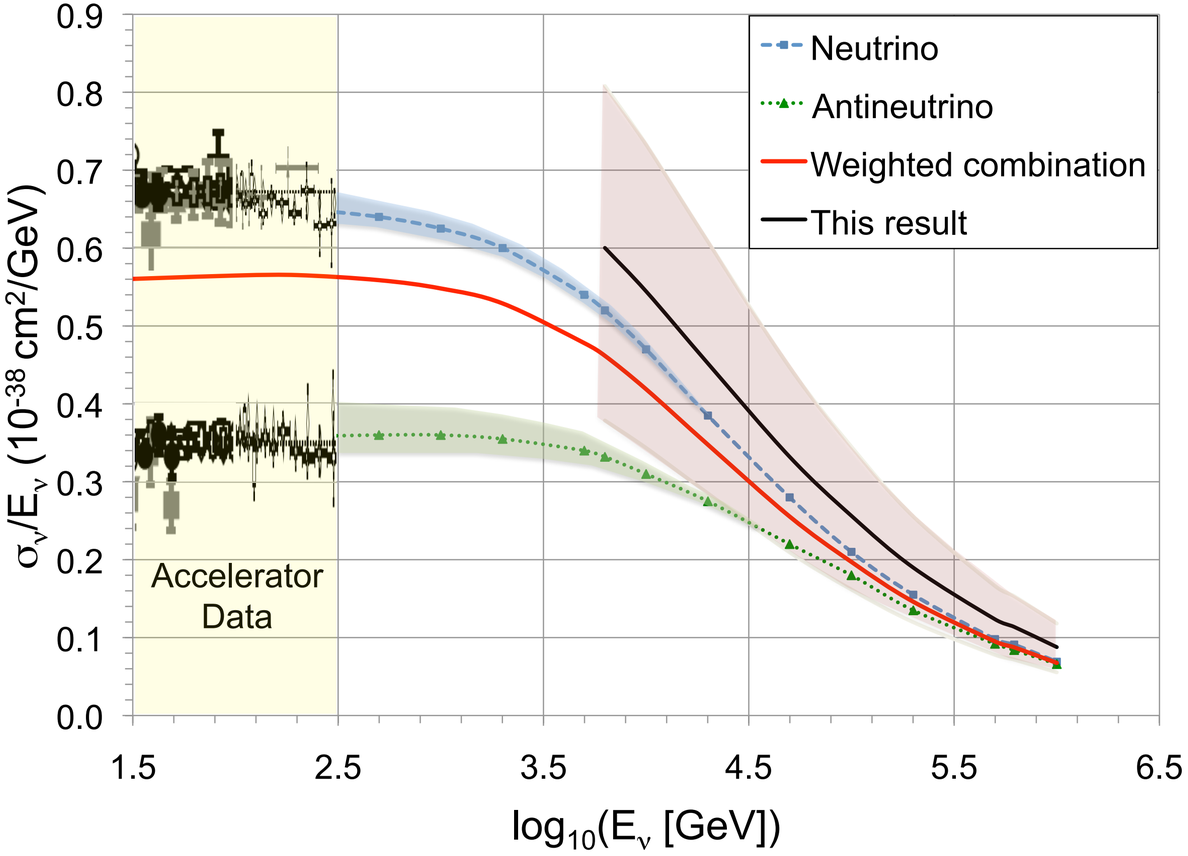




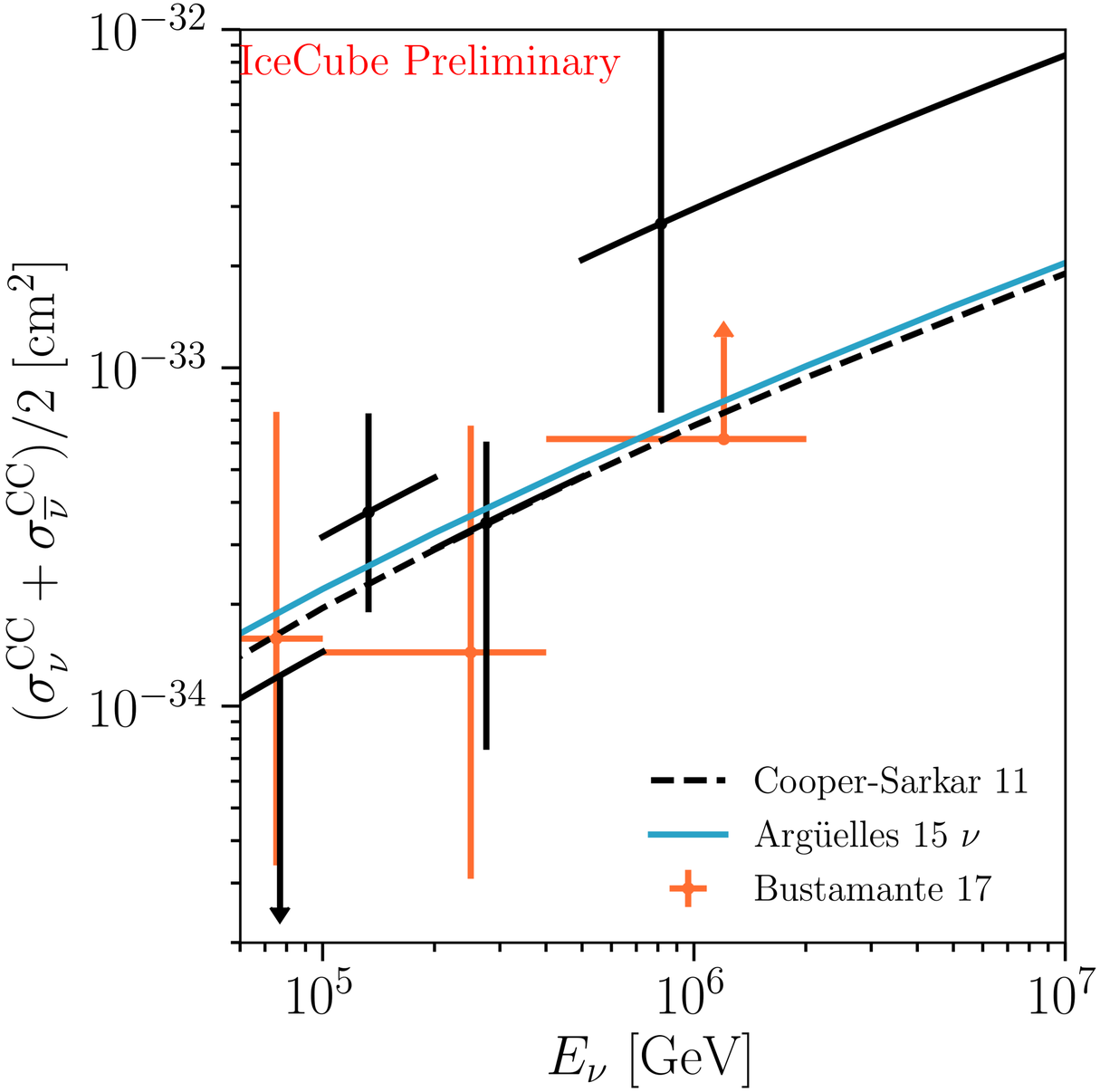
Ghandi et al. Astropart.Phys.5:81-110,1996
Connolly et al. Phys.Rev. D83 (2011) 113009

Vincent et al. JCAP 1711 (2017) 012
Bertone et al. arXiv:1808.02034

Upgoing Muon-neutrinos

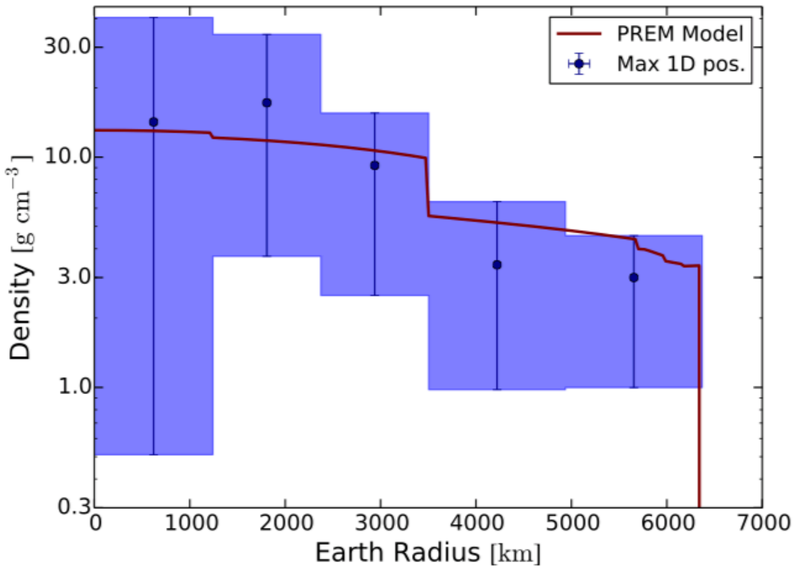


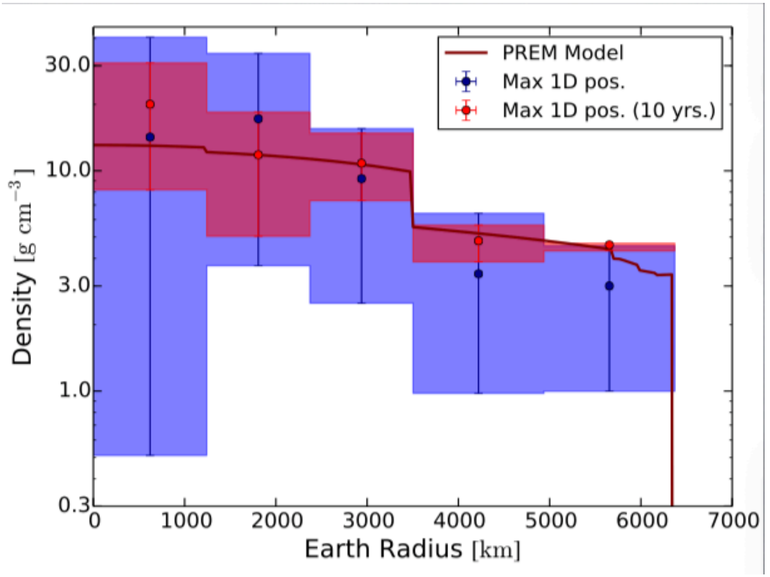
New Results using HESE

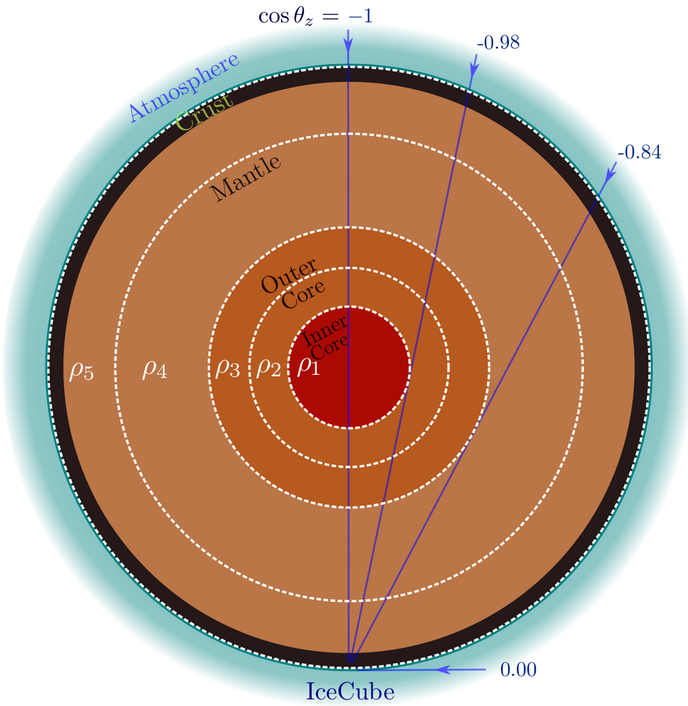


Earth Tomography with High Energy neutrinos

- Idea proposed since the 70's. In theory can be done with oscillations or absorption using man-made, atmospheric, or astrophysical neutrino beams.





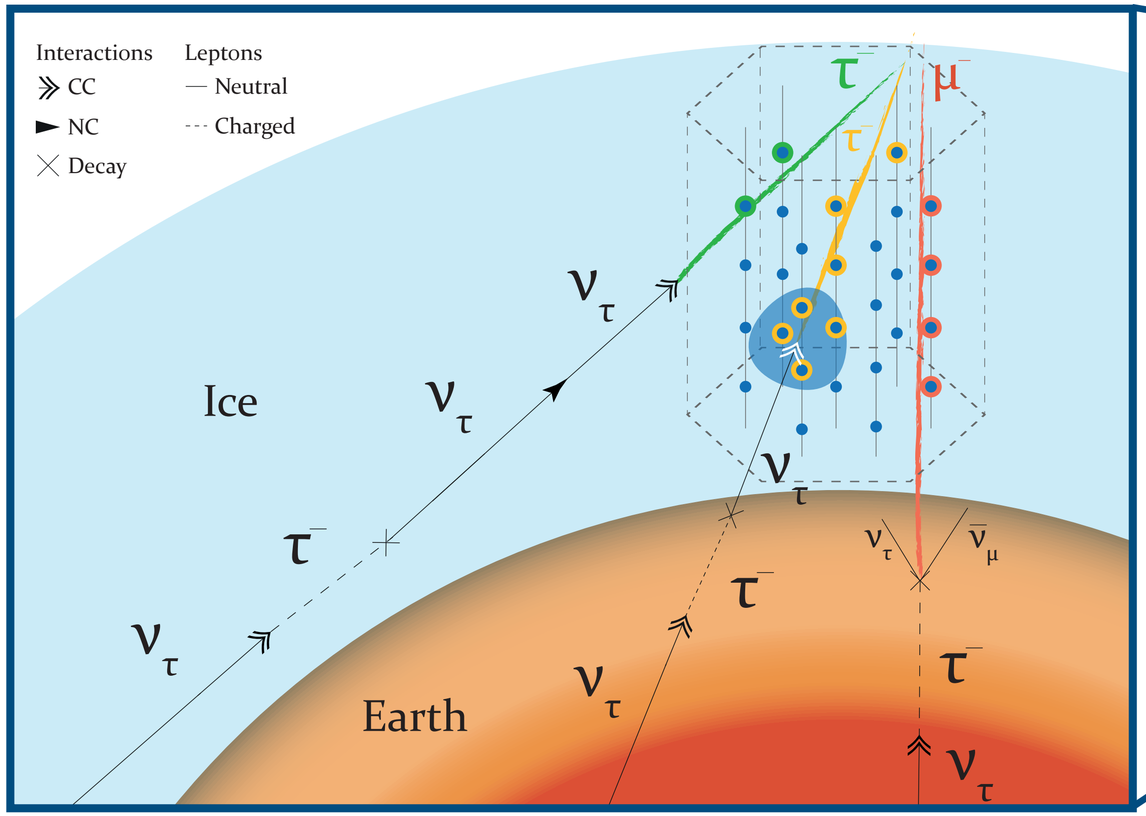


- Authors chose to fit for a 5-layer Earth model (1 inner core, 2 outer core, and 2 mantle)

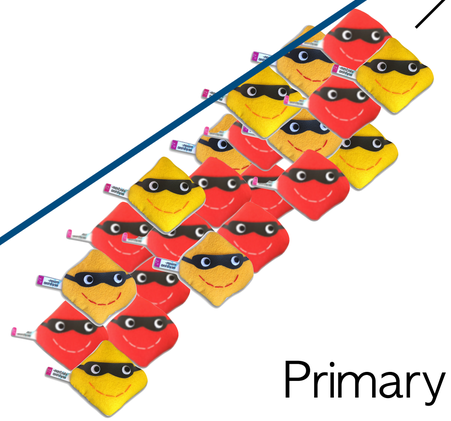
- First measurement of earth's density profile with 1 year of IceCube data! (A.Donini+ Nature Physics 15:37, 2019)
- Dedicated IceCube analysis with 10 years of data is ongoing (the 10 year projection is shown in red).

Followup to anomalous ANITA detections

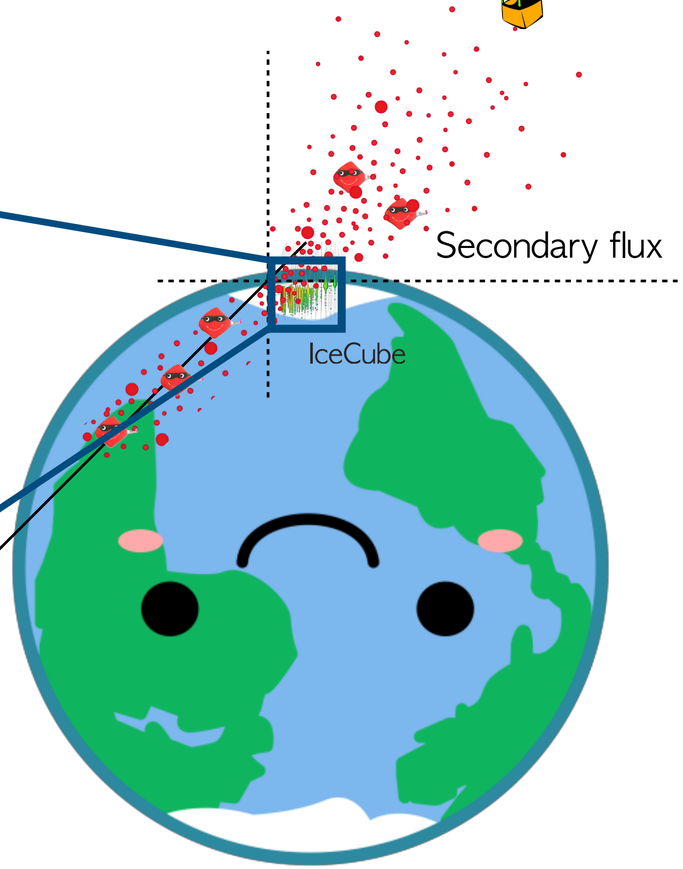
- EeV neutrinos have a mean interaction length of $\mathcal{O}(100)$ kilometers in Earth.
- ν_τ CC produces τ —〉 Short τ lifetime —〉 τ decays before losing too much energy, producing a flux of secondary tau neutrinos.
- Any flux that caused the ANITA event can be tested via its secondaries in IceCube.



IS et. al PoS(ICRC2019)995



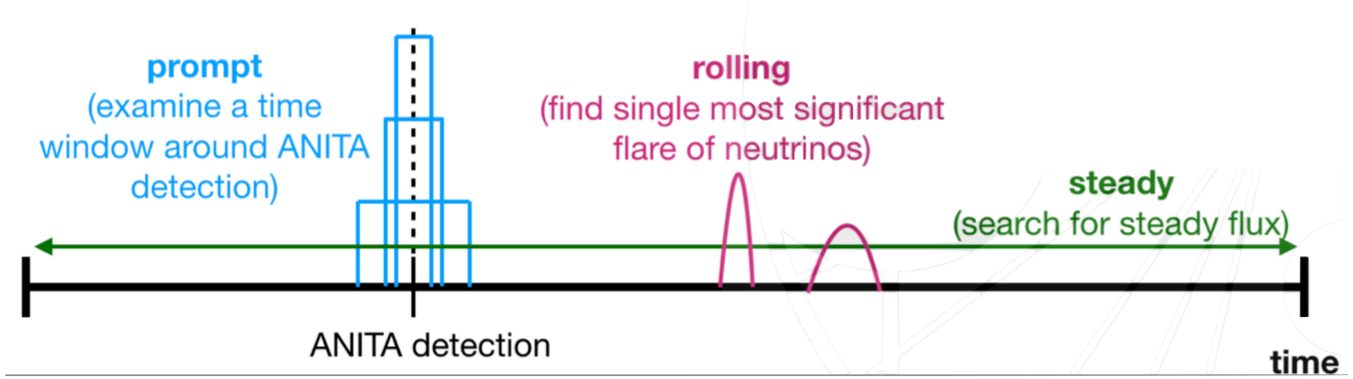
Primary Incident neutrinos

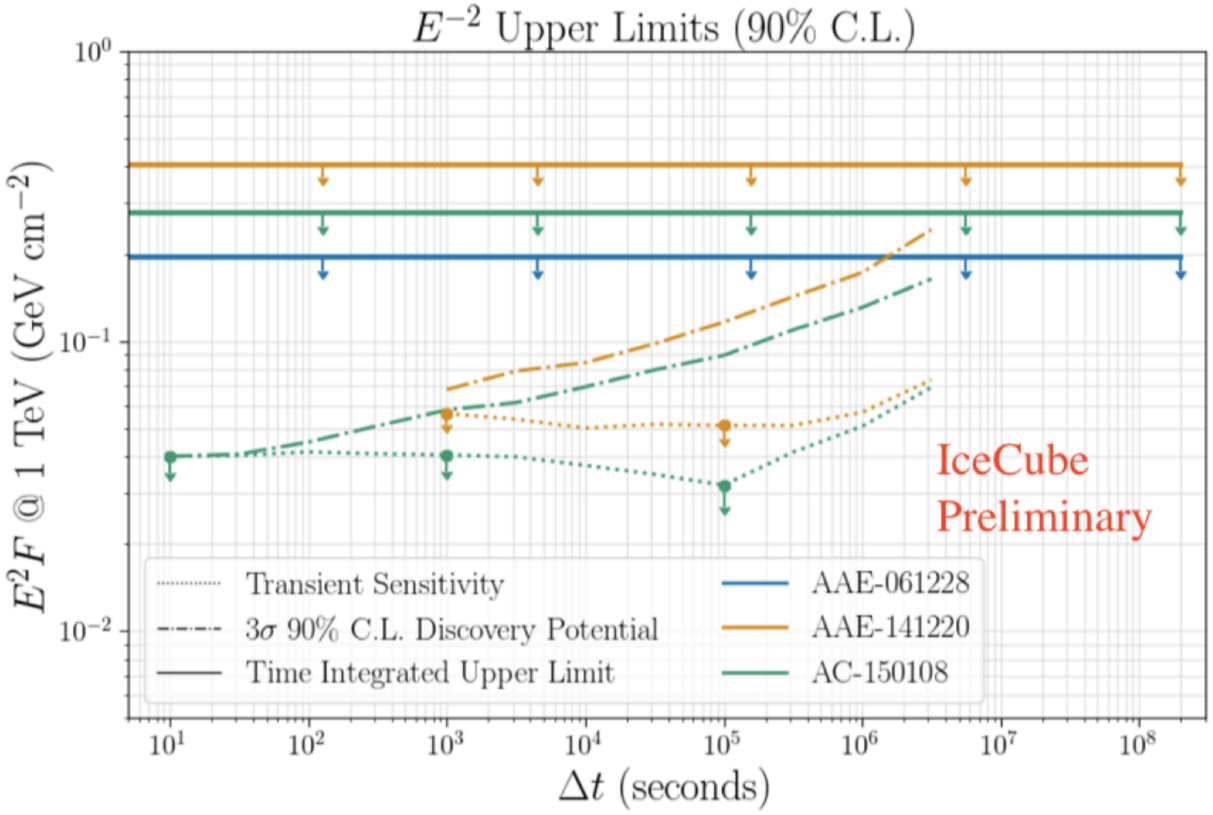


- ANITA reported two anomalous events during their 2006 and 2014 flight.

- Three point source searches for neutrinos in the direction of the anomalous event reported in 2014.
  - Prompt: Time window around ANITA detection.
  - Rolling: Varying time window, looking for flares in same direction.
  - Steady: Search for steady flux.

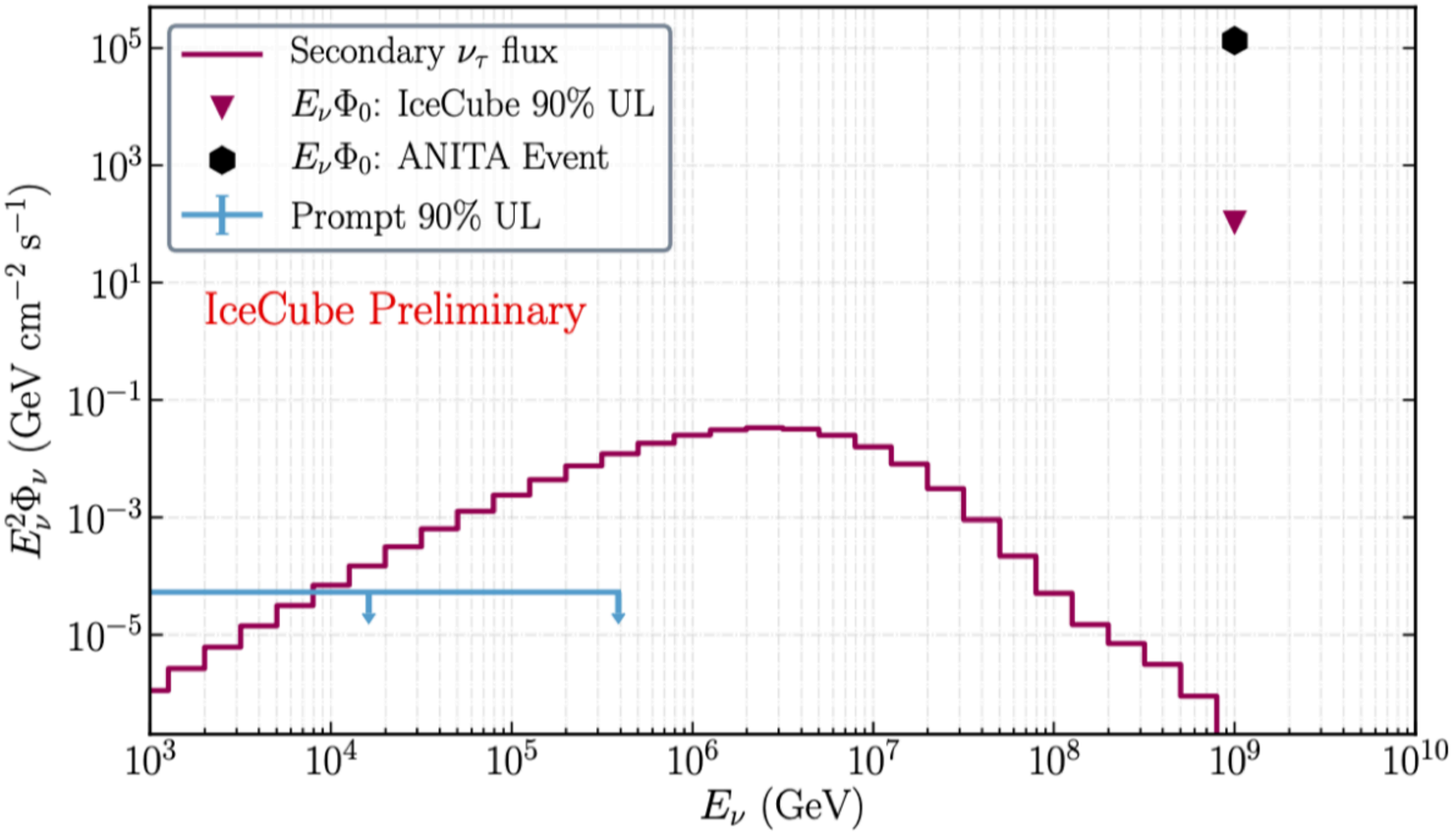
No correlation was found. Upper limits placed on TeV muon-neutrino flux.





ANITA detections highly unlikely to be caused by SM astrophysical neutrinos, regardless of spectral assumptions or emission time profile.

- Based on ANITA acceptance, calculate best-fit normalization on the incoming flux (Black hexagon)
- Calculate upper limit on the normalization based on the non-observation of secondaries at IceCube (maroon triangle)
- Upper limits require an overfluctuation at the 10^3 level for AAE141220 to accommodate a point-source interpretation.



Summary

- Updated measurements of the Astrophysical spectrum:
  - HESE: spectral index 2.89 , favors single-power law.
  - Through-going numu: spectral index 2.28, also favors single power law.
- Updated Flavor ratio measurement, compatible with (1:1:1).
- First Astrophysical tau-neutrino candidates!
- First potential source of PeV cosmic-rays identified.
- New measurement of Neutrino cross section at TeV+
- First measurement of Earth density profile with weak interactions.
- IceCube followup confirms ANITA anomalous events are unlikely to be caused by SM astrophysical neutrinos, regardless of source spectrum and time-profile.

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IceCube
South Pole Neutrino Observatory

icecube.wisc.edu

More on Double Double

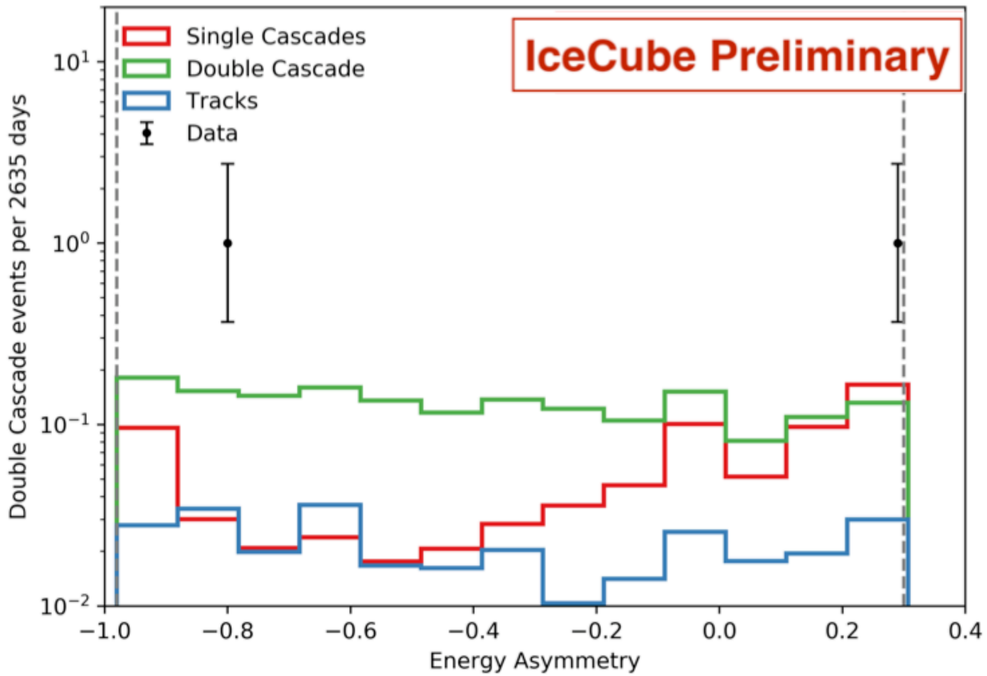

Table 3: Observables of the two Double Cascades

	Event#1 (Big Bird)	Event#2 (Double Double)
Energy of 1st cascade	1.2 PeV	9 TeV
Energy of 2nd cascade	0.6 PeV	80 TeV
Energy Asymmetry	0.29	-0.80
Length	16 m	17 m

IceCube-Gen2: Science Case