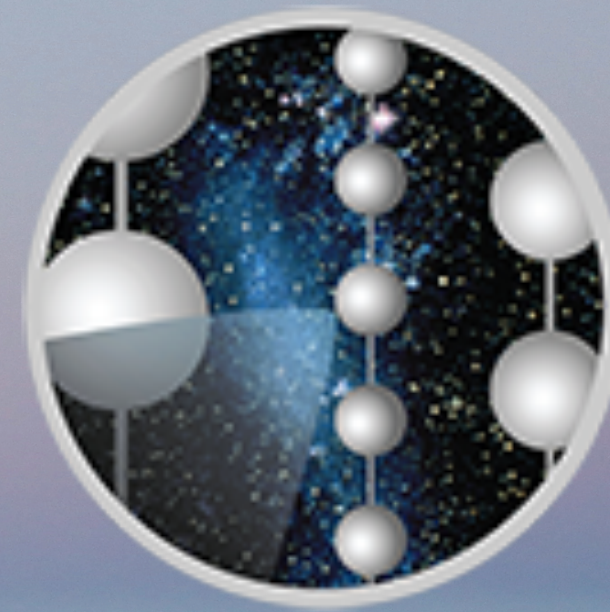


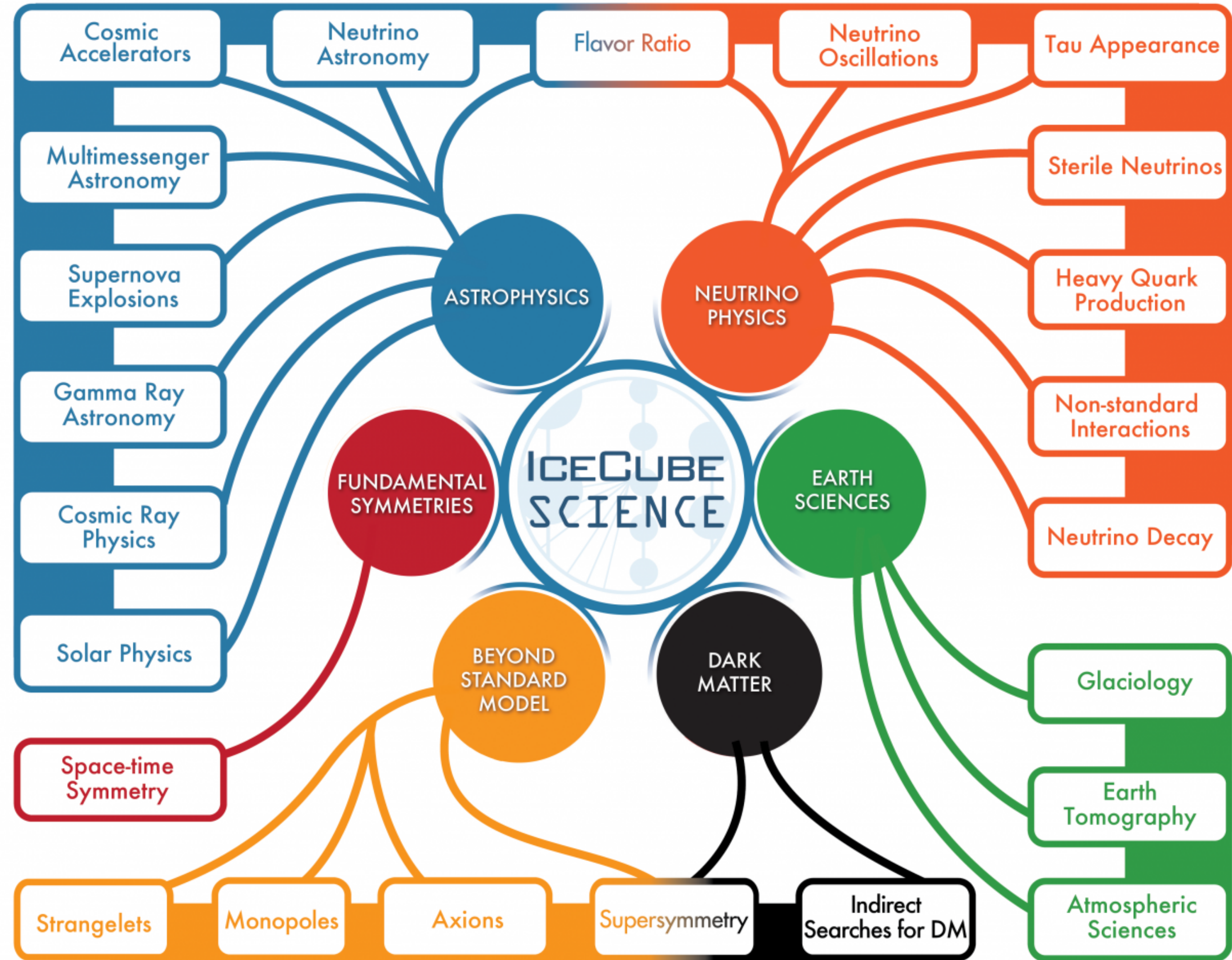
HIGH-ENERGY NEUTRINOS OF COSMIC ORIGIN



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

S. Toscano on behalf of IceCube

- ▶ The IceCube Neutrino Telescope
- ▶ Results from IceCube: **Astrophysical Neutrinos**
- ▶ Conclusions



Admunsen-Scott South Pole Station

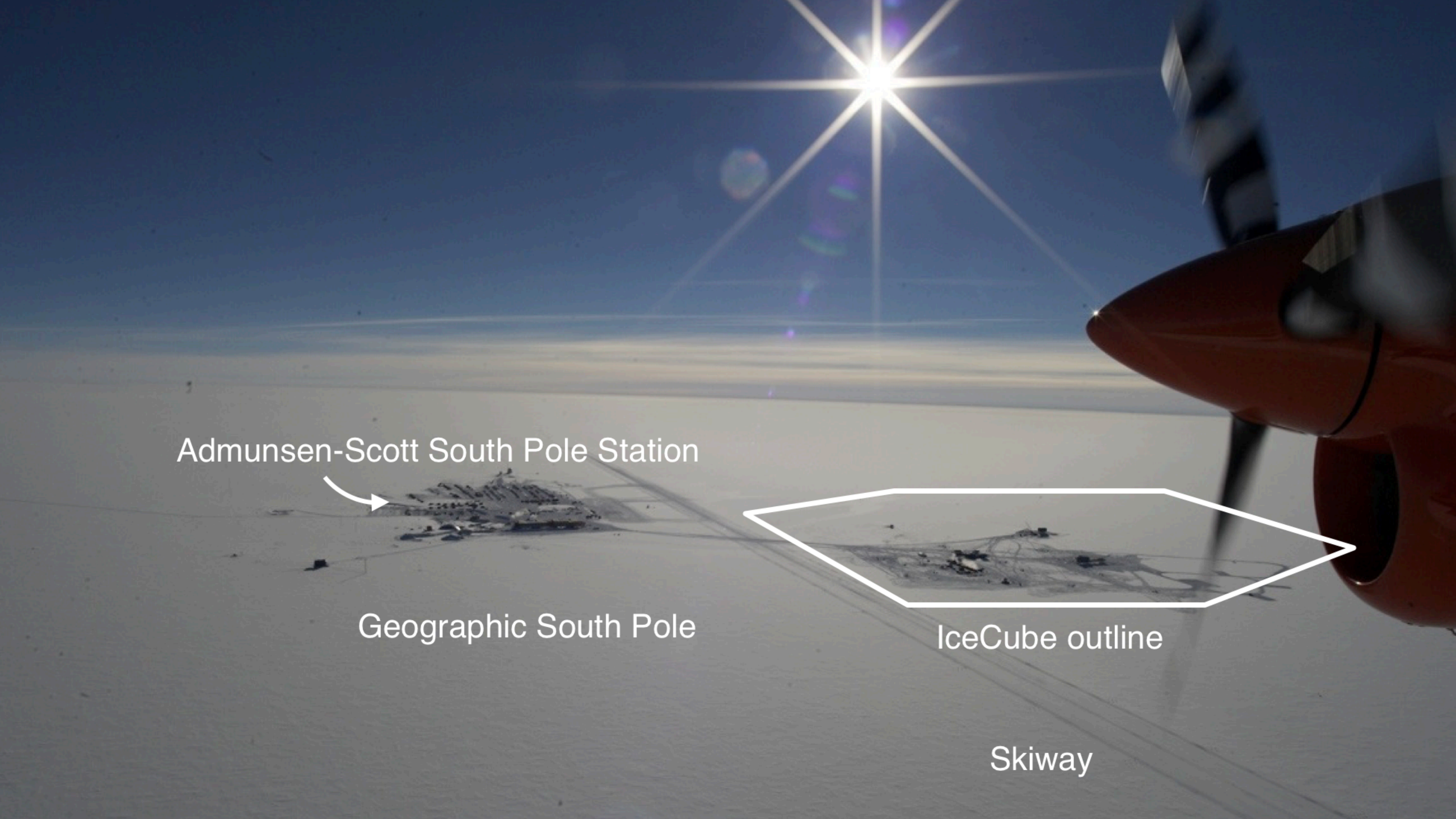


Geographic South Pole

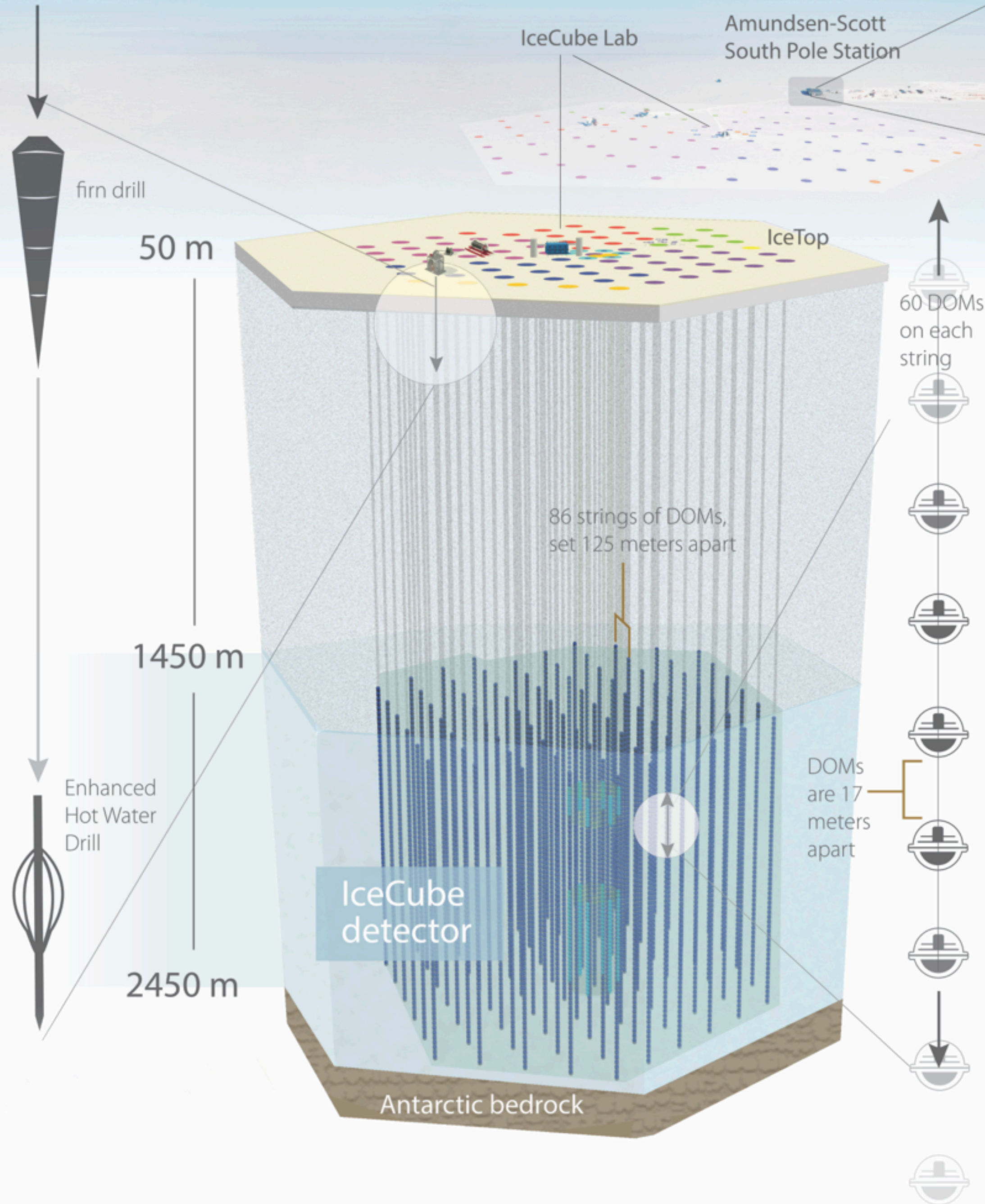


IceCube outline

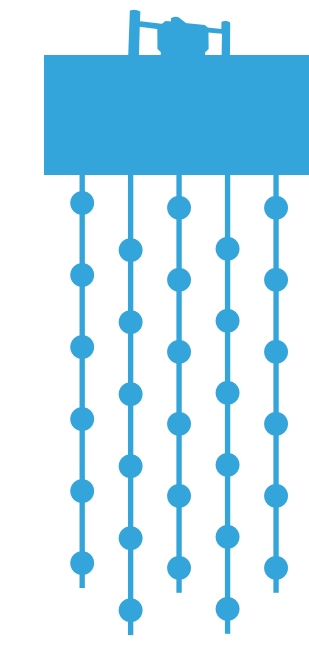
Skiway



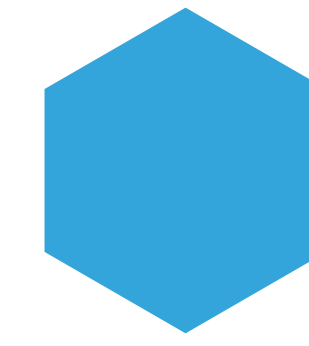
IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each
6 denser strings called DeepCore



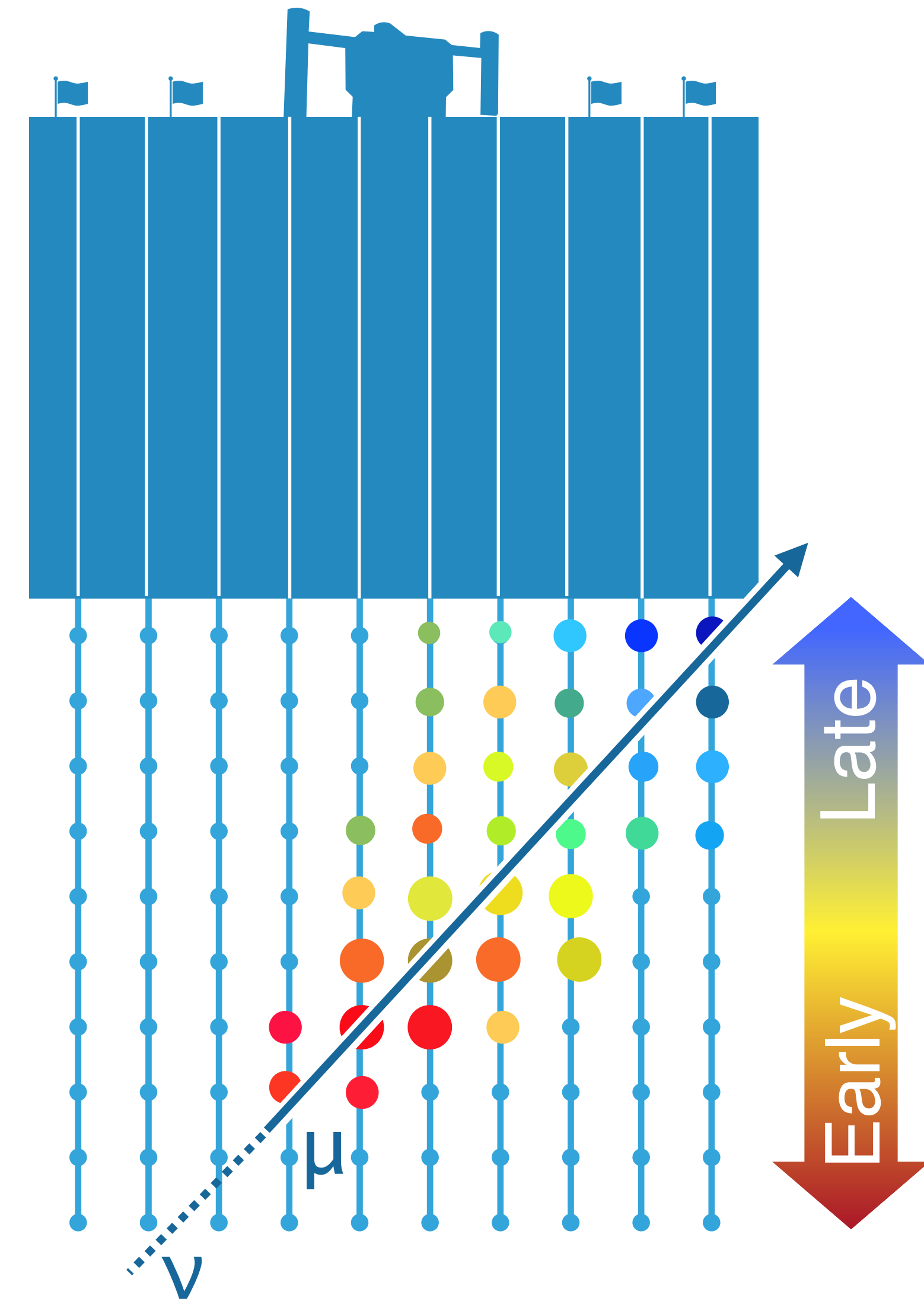
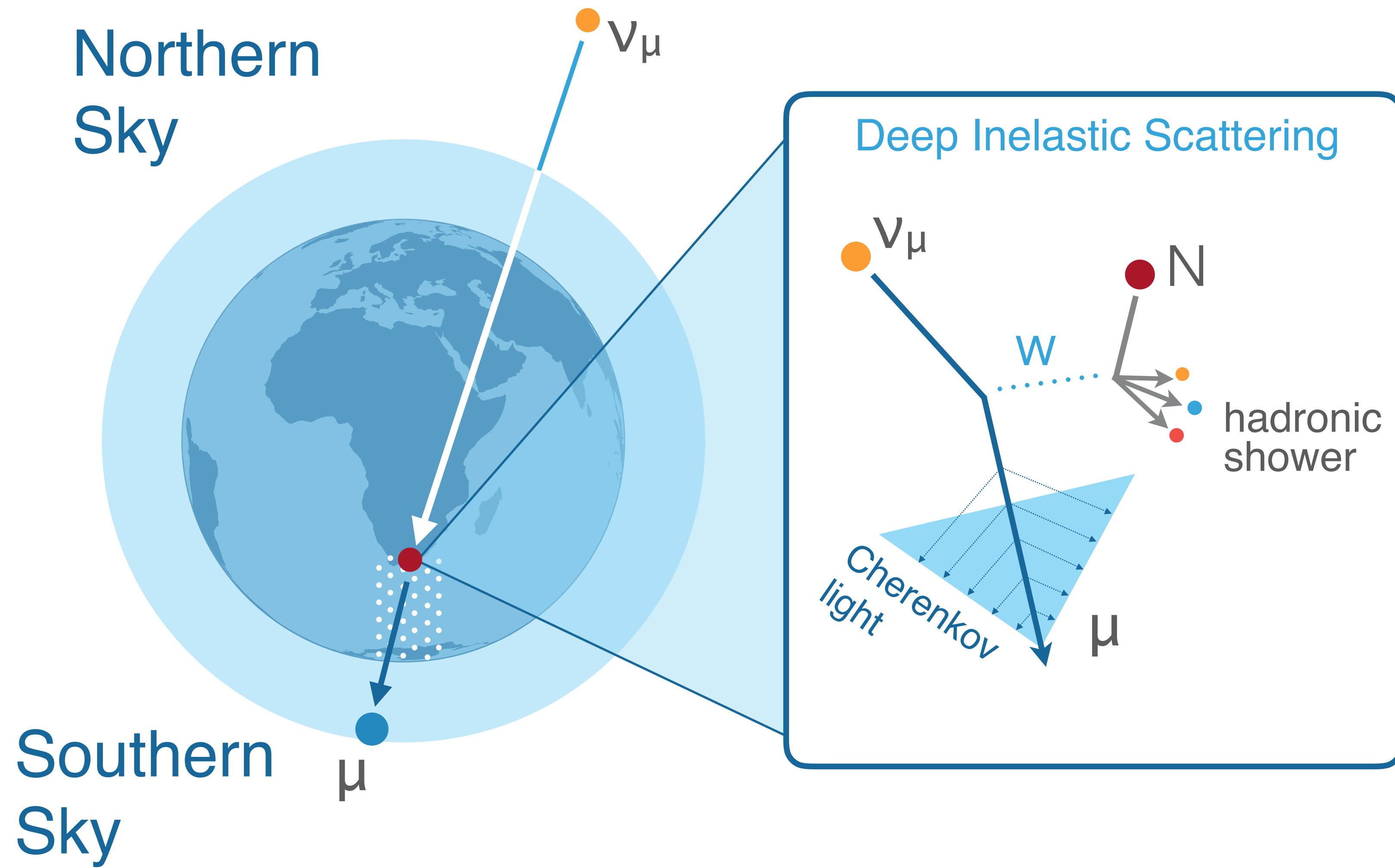
1 km² surface array with 324 DOMs: IceTop



Completion in December 2010



Detection principle

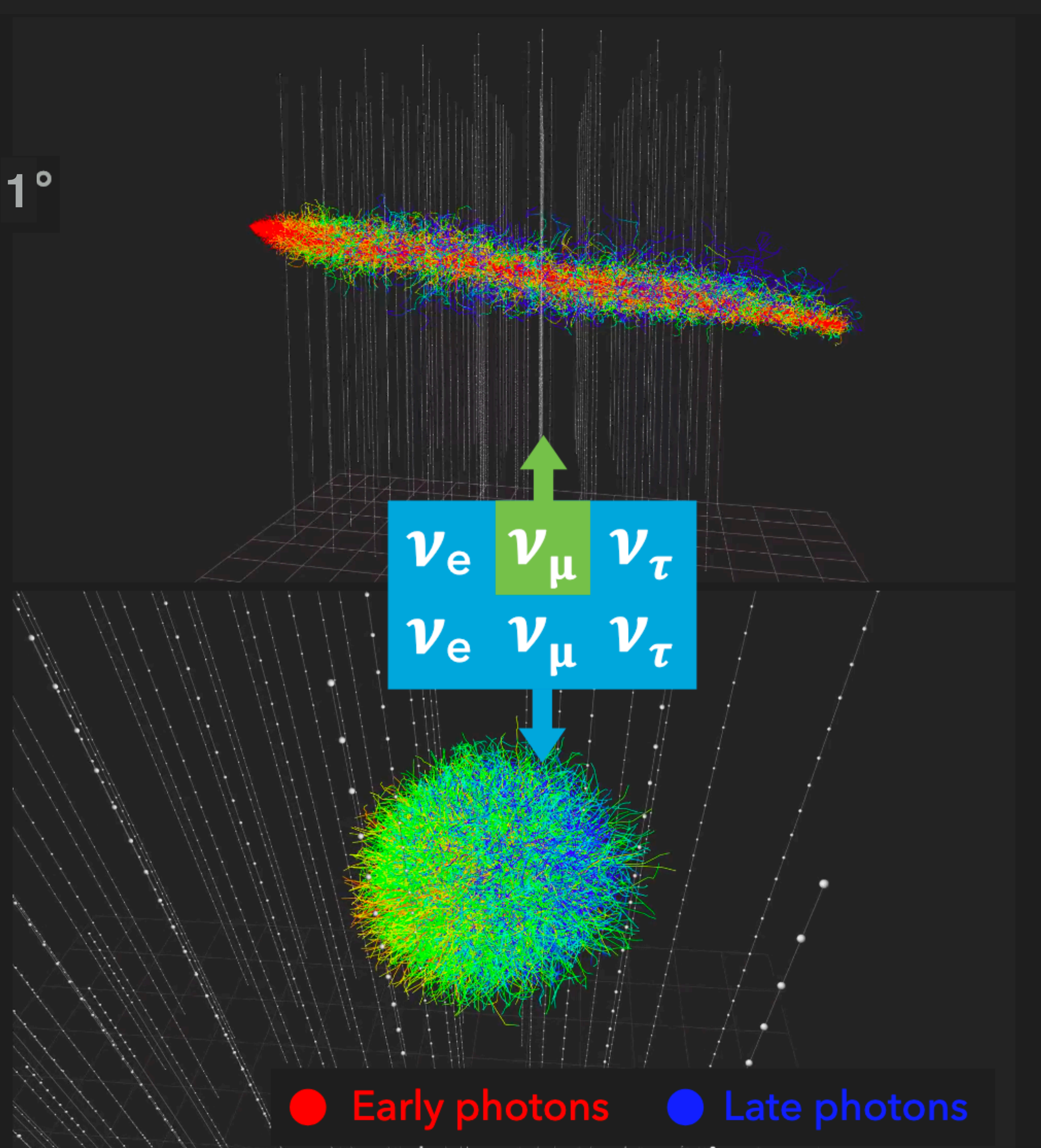


Track topology

- ▶ Good angular resolution $0.2^\circ - 1^\circ$
→ Neutrino Astronomy
- ▶ Vertex can be outside the detector → Increased effective volume

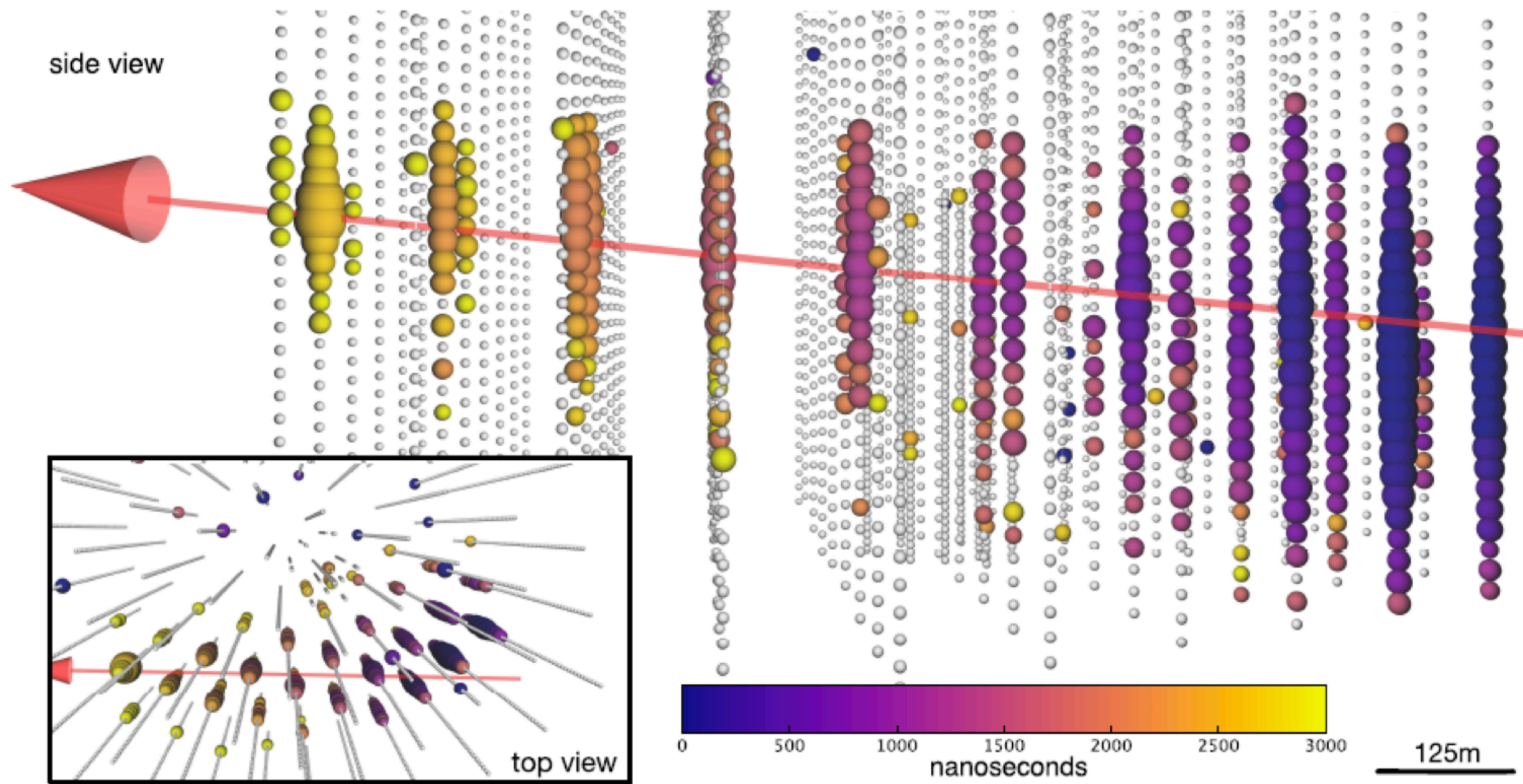
Cascade topology

- ▶ All flavors
- ▶ Fully active calorimeter → Good energy resolution $\pm 15\%$ deposited energy
- ▶ Angular reconstruction possible → $\sim 10^\circ > 100 \text{ TeV}$

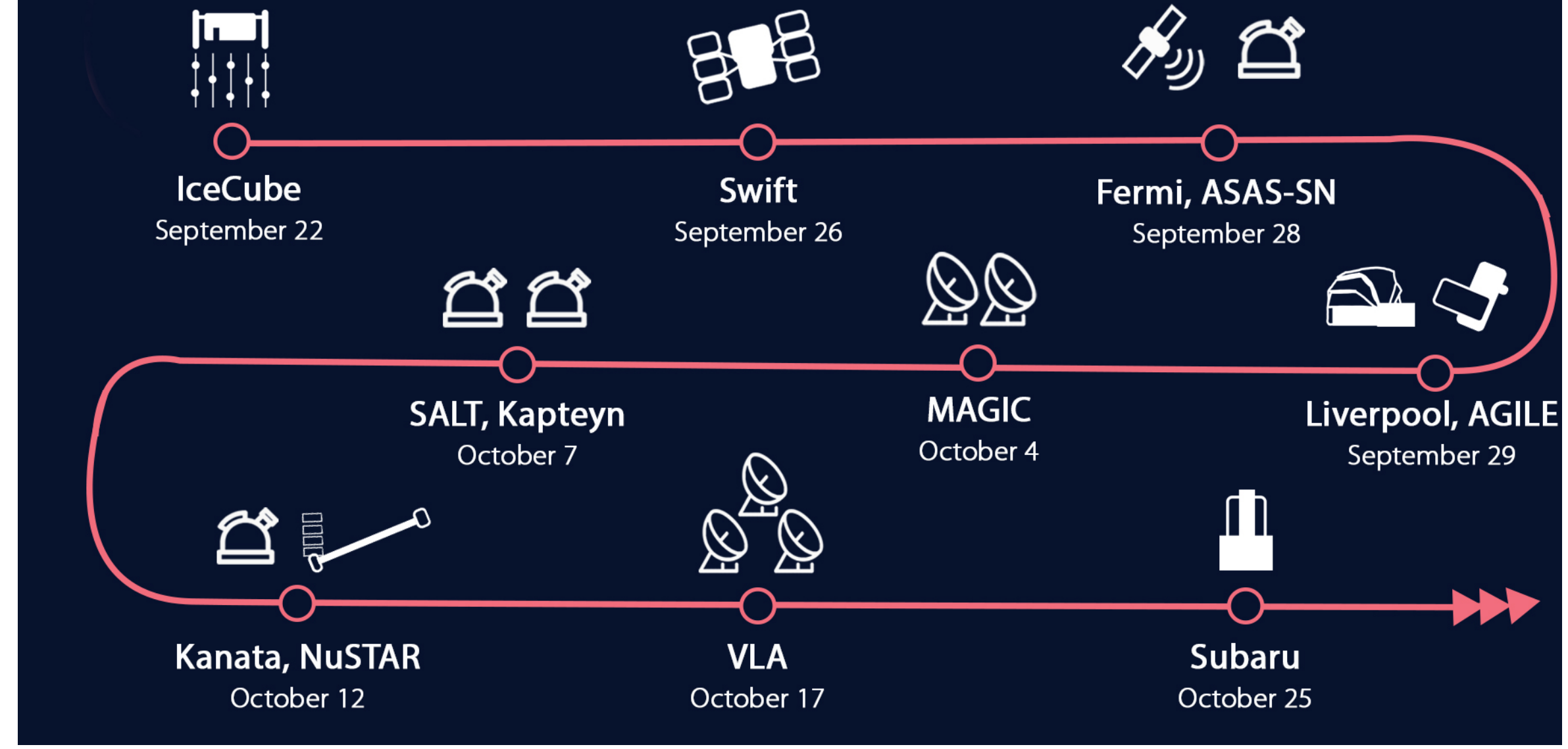


IceCube-170922A

$E = 290 \text{ TeV}$



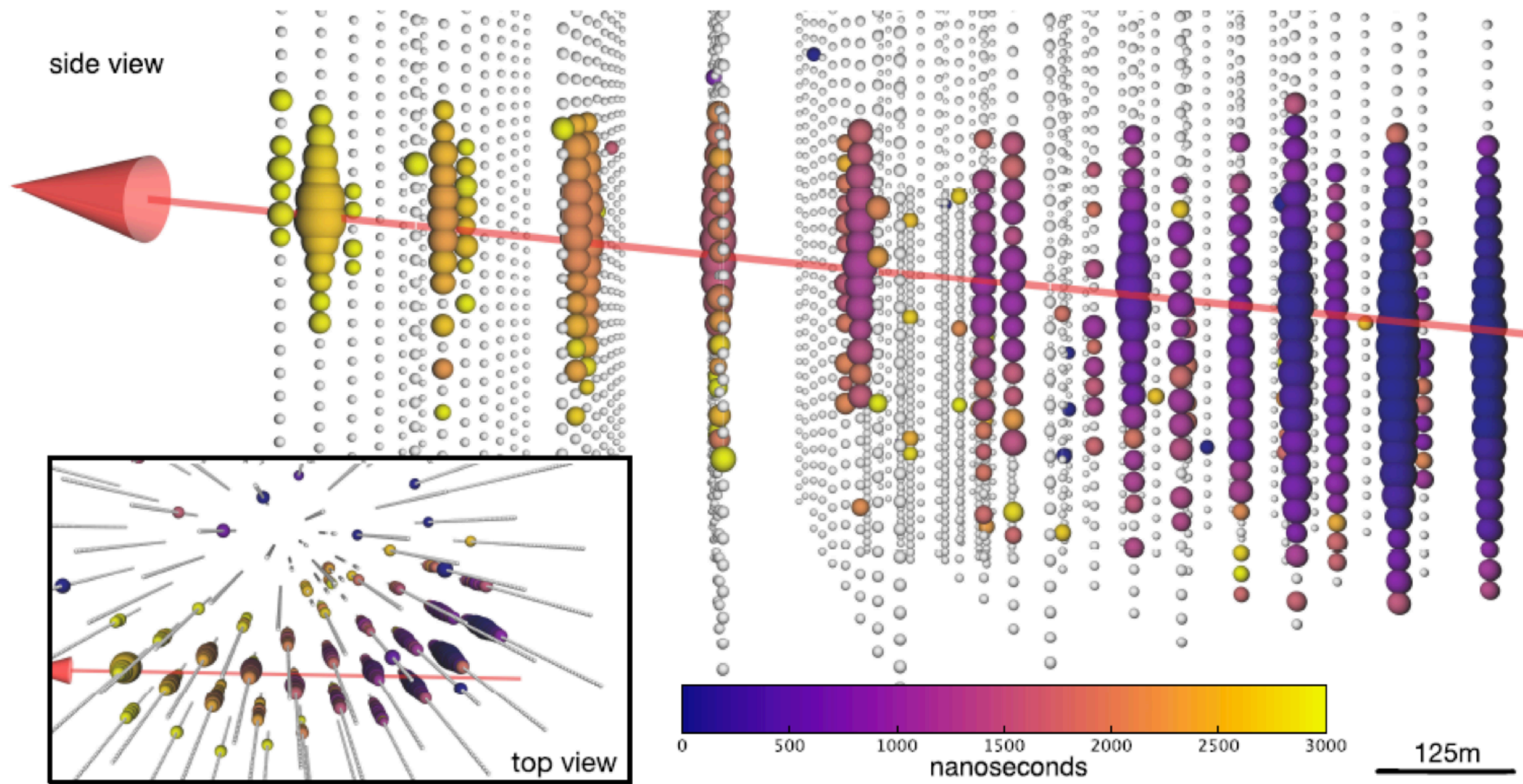
Follow-up detections of IC170922 based on public telegrams



Science 13 Jul 2018: Vol. 361, Issue 6398

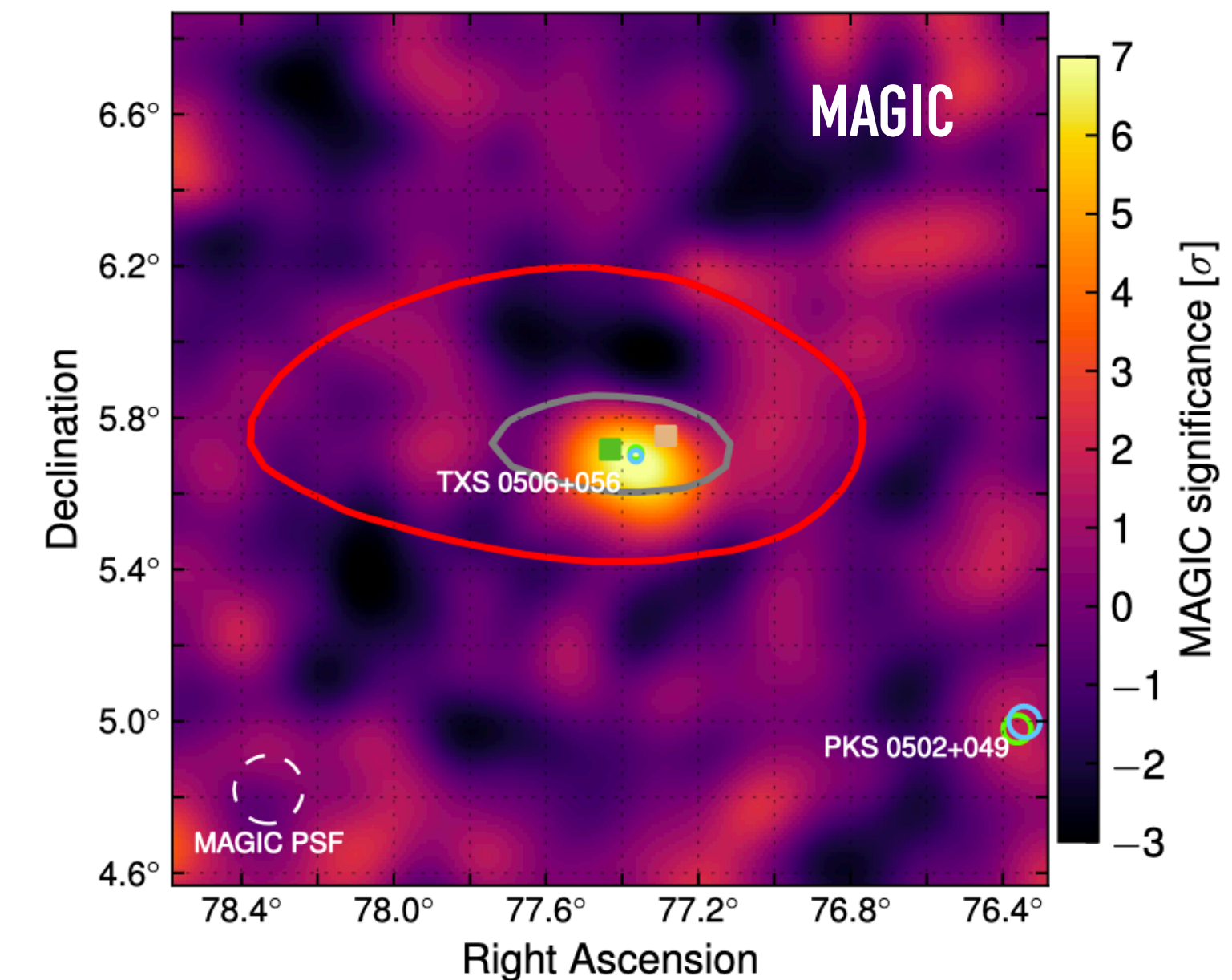
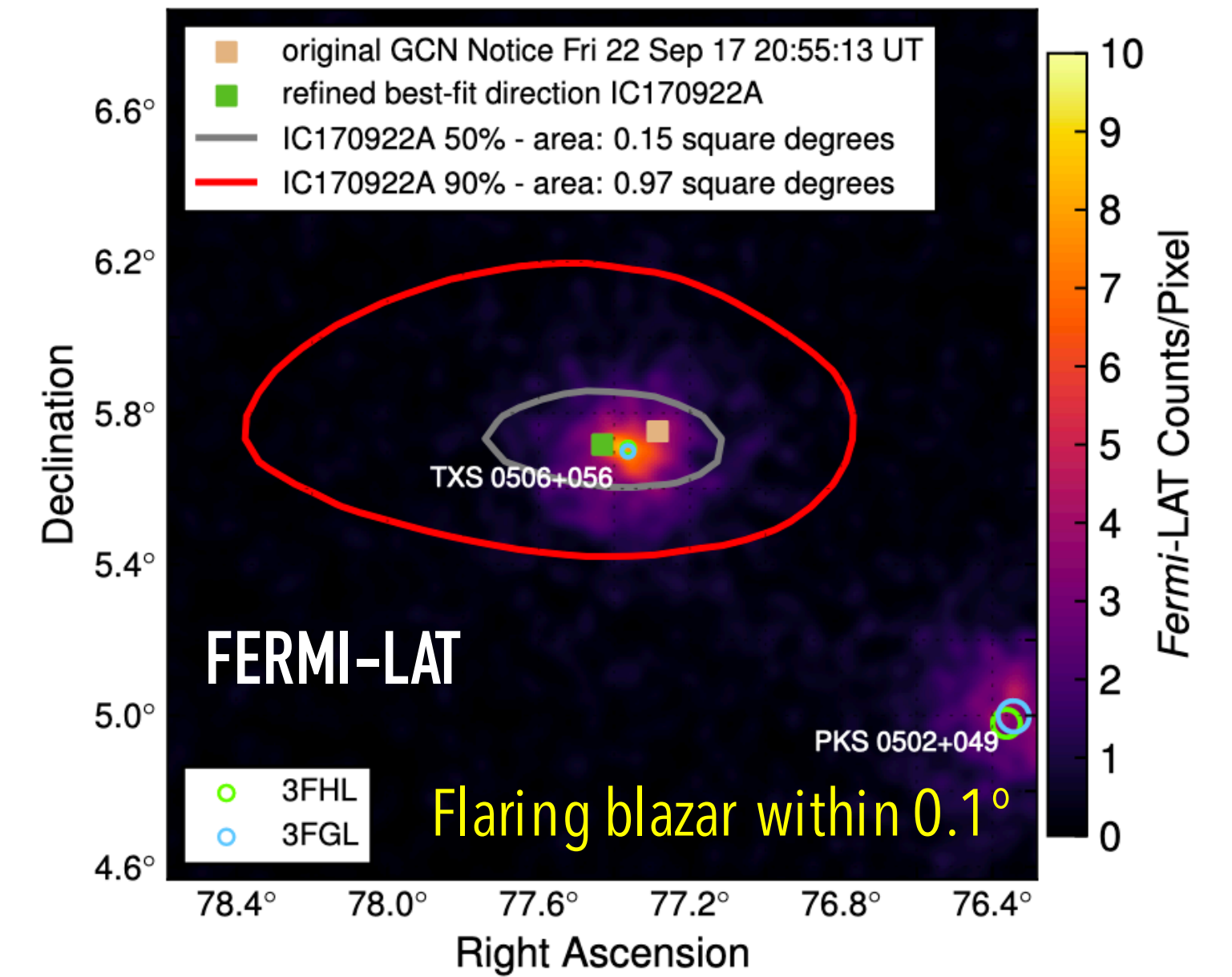
IceCube-170922A

$E = 290 \text{ TeV}$



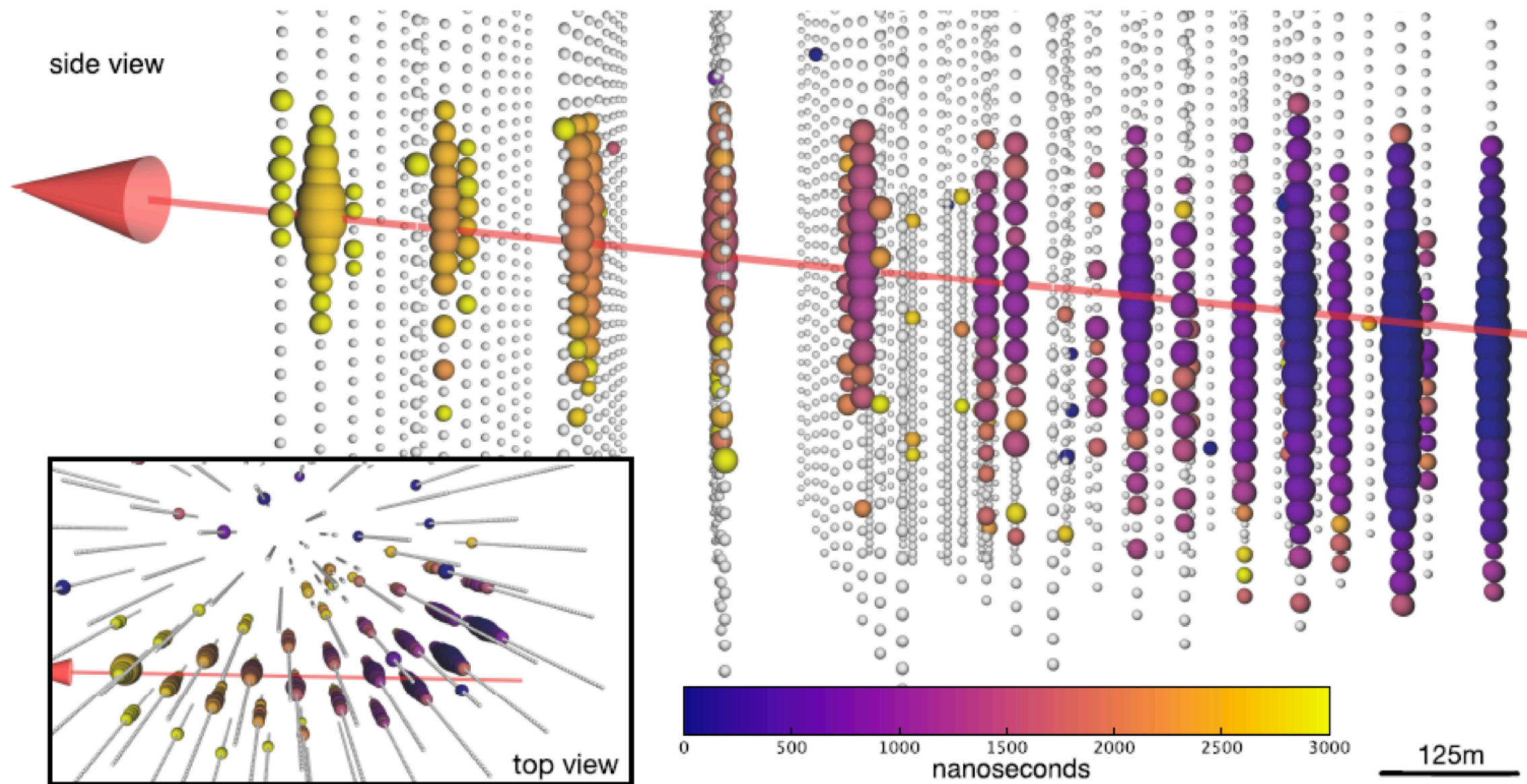
Science 13 Jul 2018: Vol. 361, Issue 6398

Follow-up observation of the alert IceCube-170922A reveals correlation with the flaring blazar TXS 0506+056, preferred to chance at 3σ .



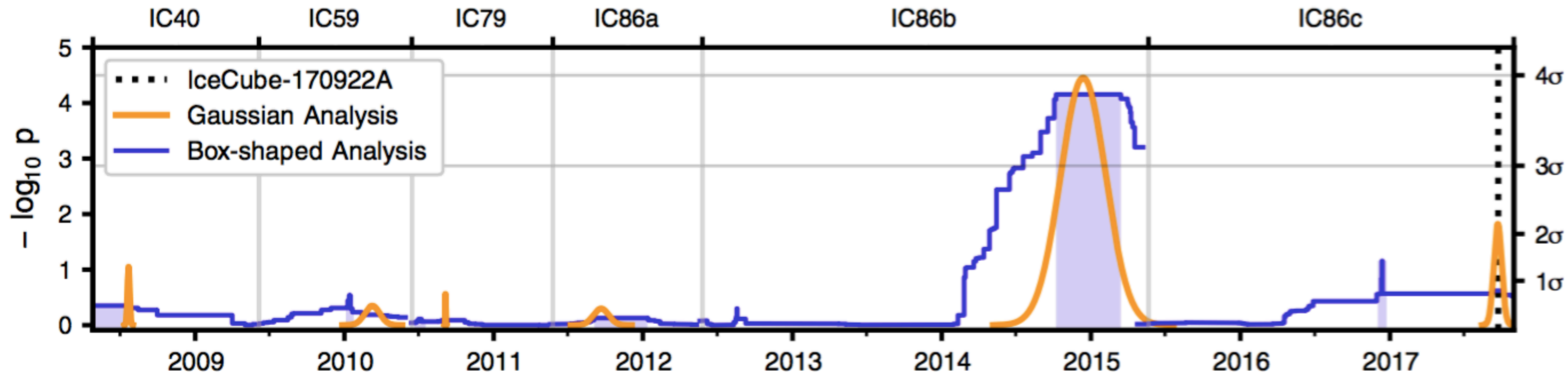
IceCube-170922A

$E = 290 \text{ TeV}$

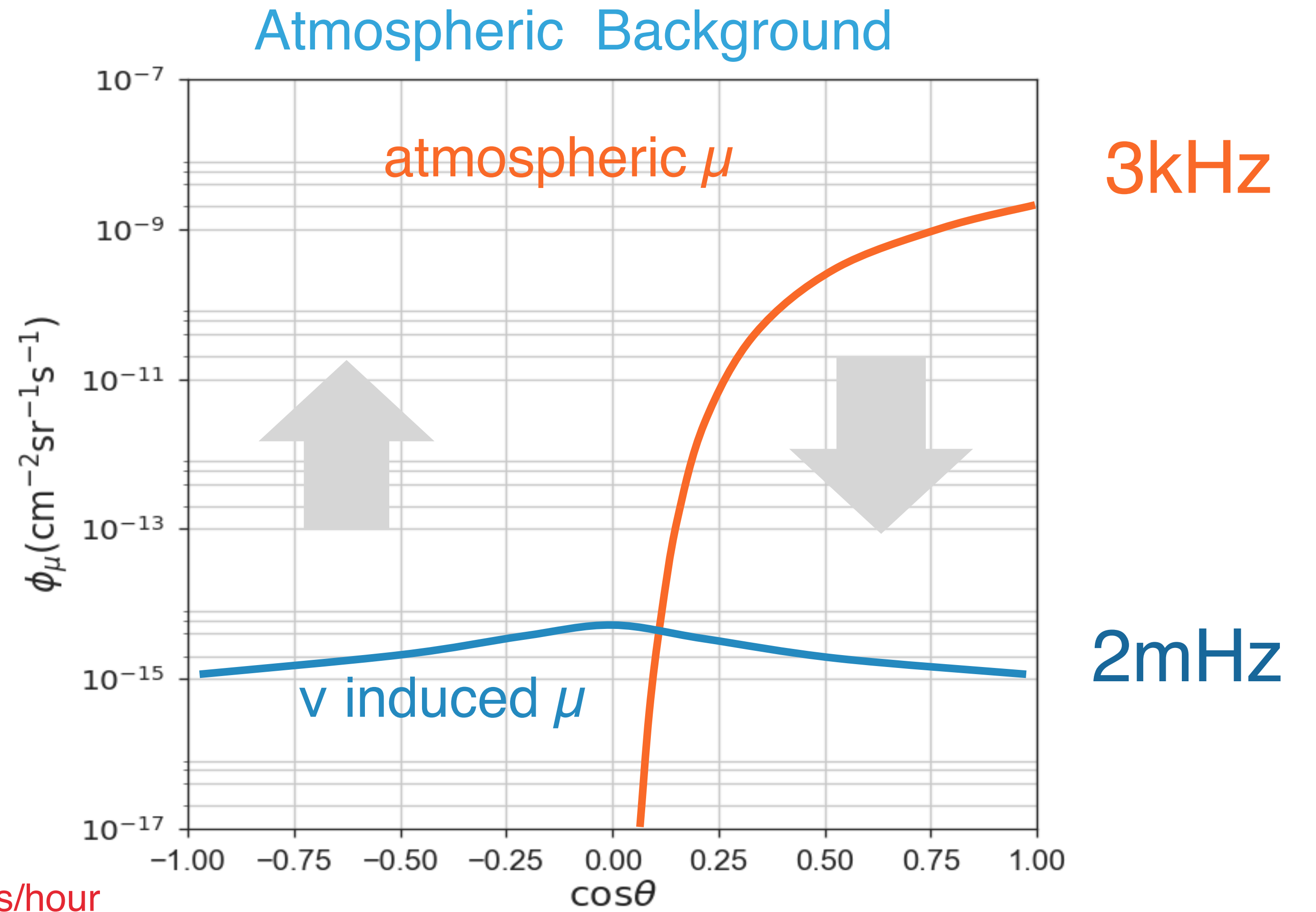
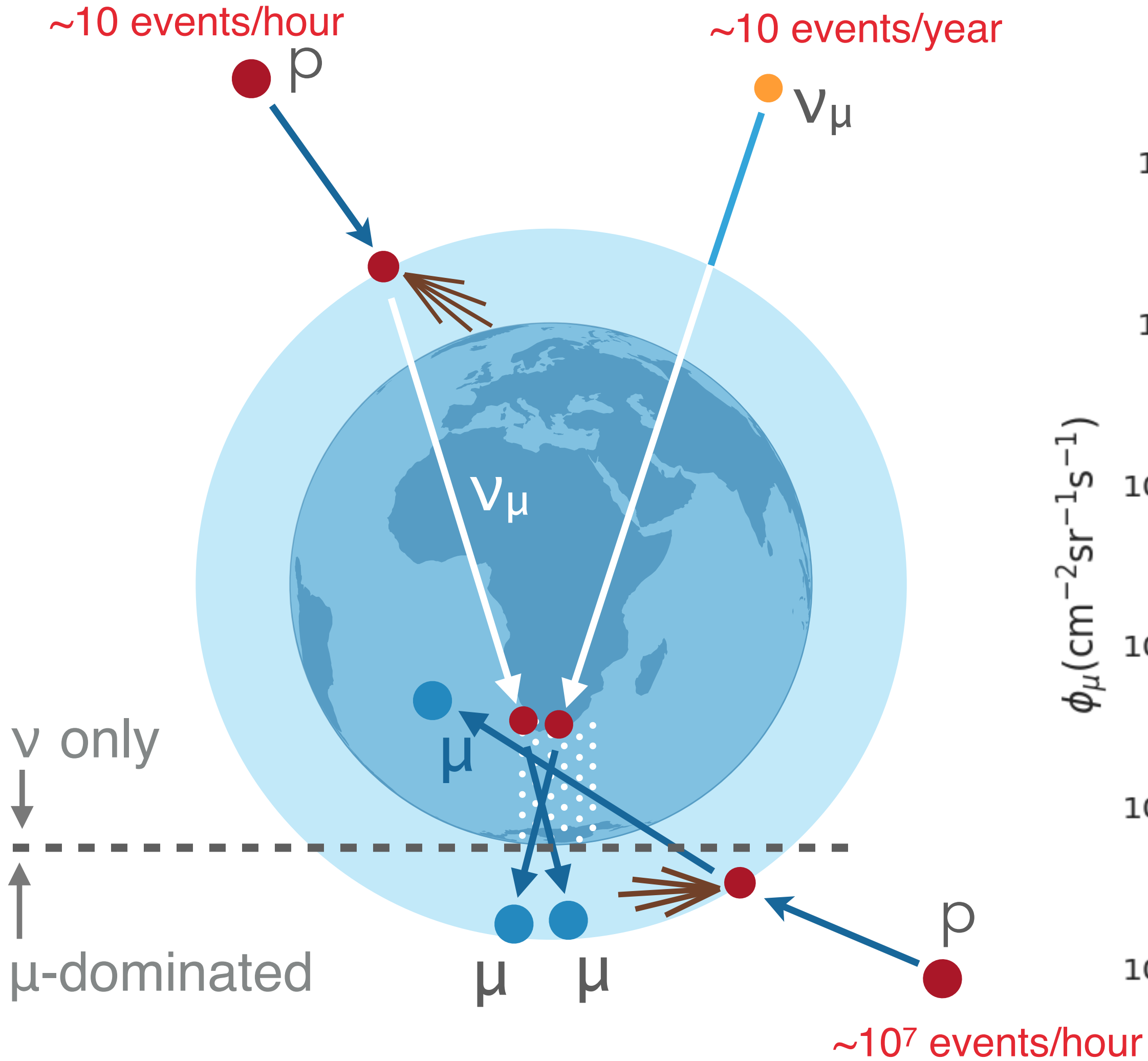


**Excess of neutrinos observed between September 2014 and March 2015.
Background only hypothesis rejected at 3.5σ**

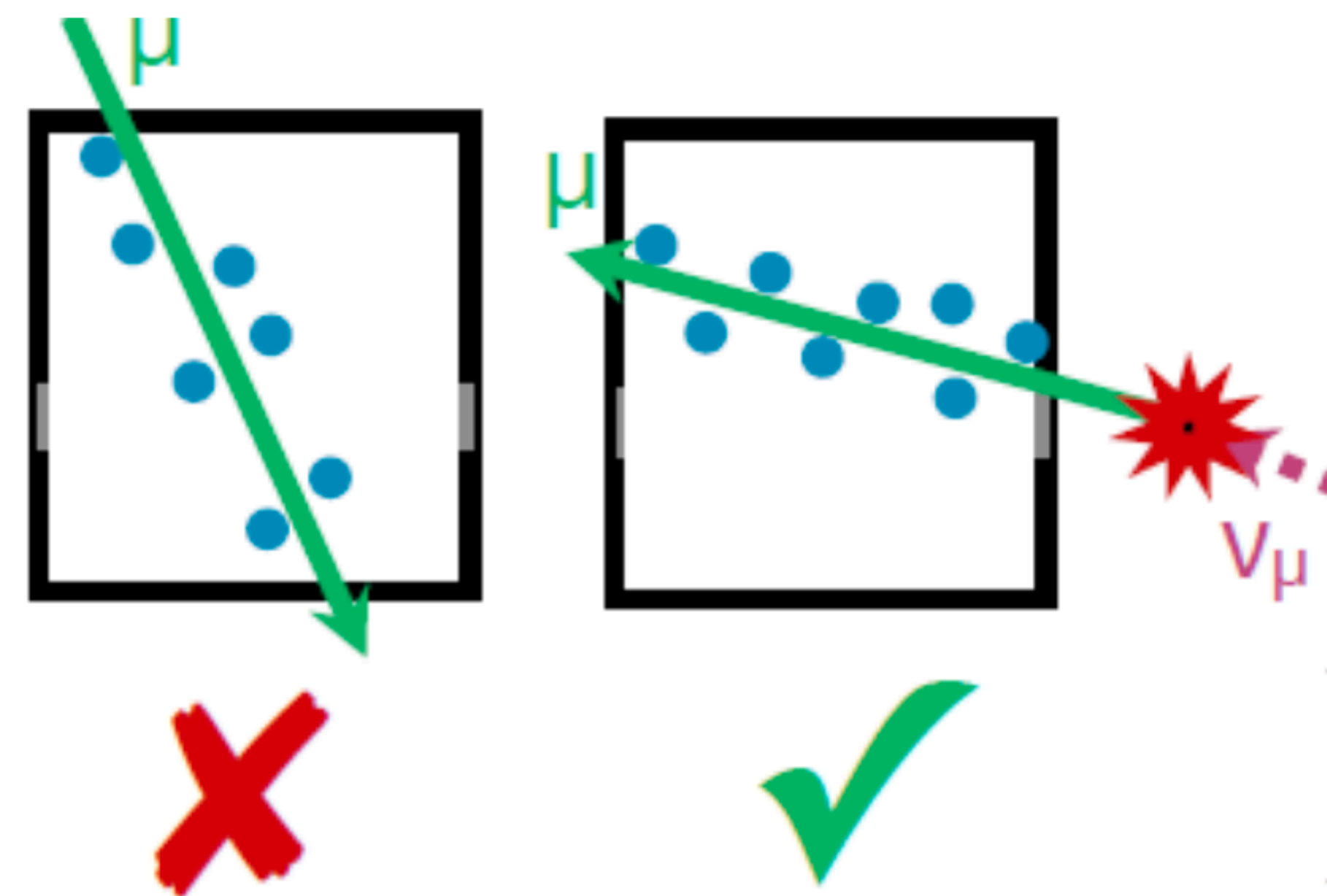
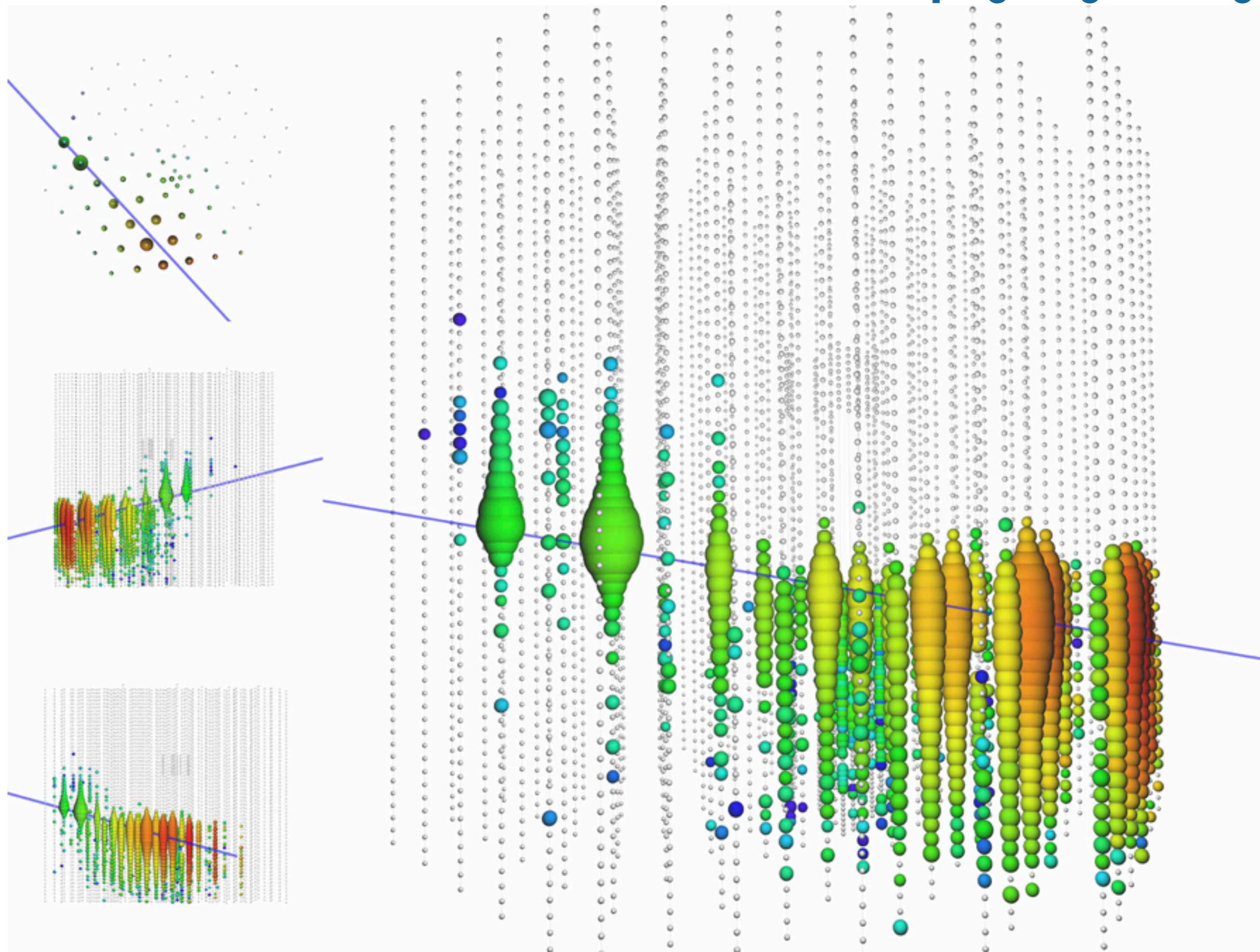
Science 13 Jul 2018: Vol. 361, Issue 6398



The atmospheric background



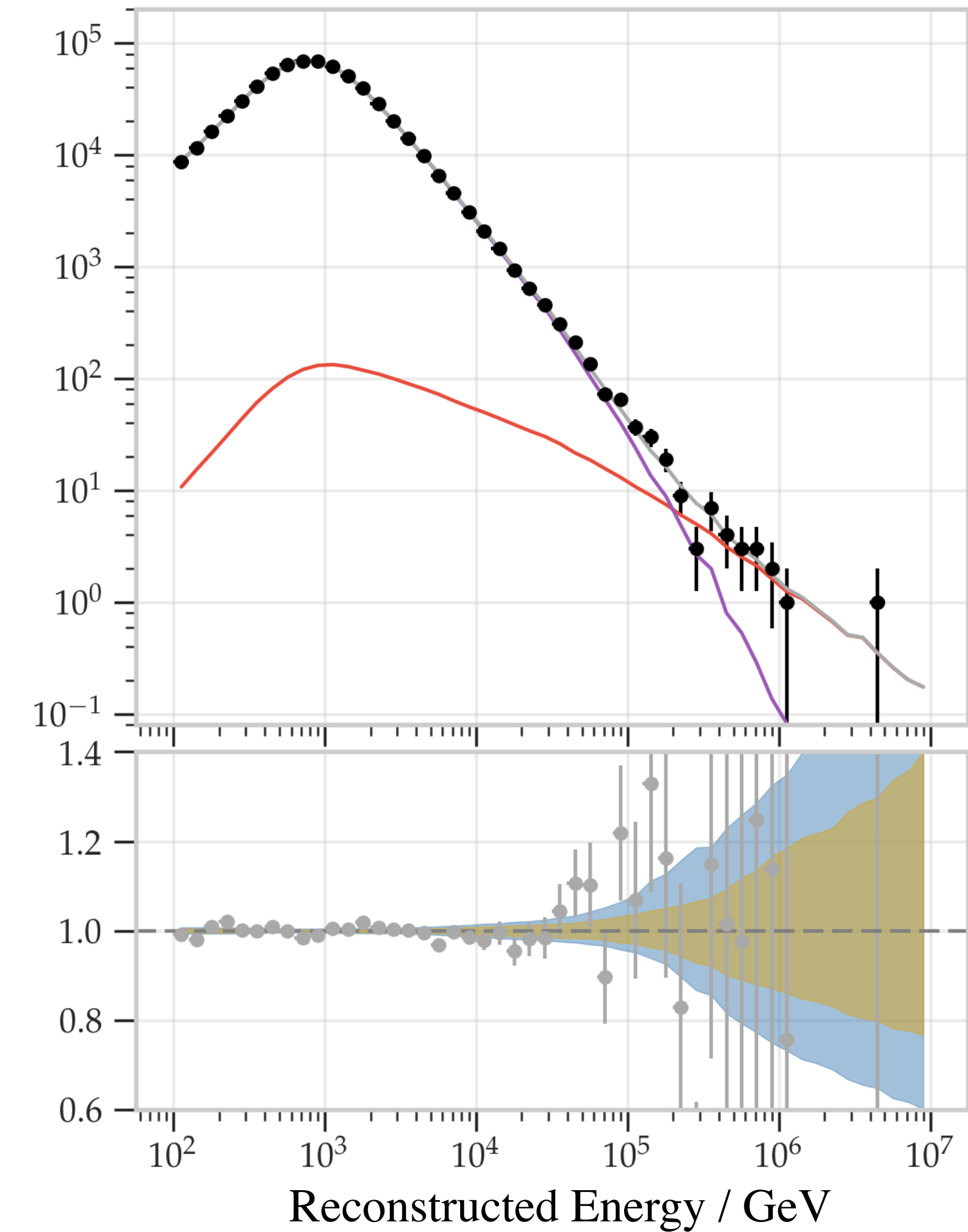
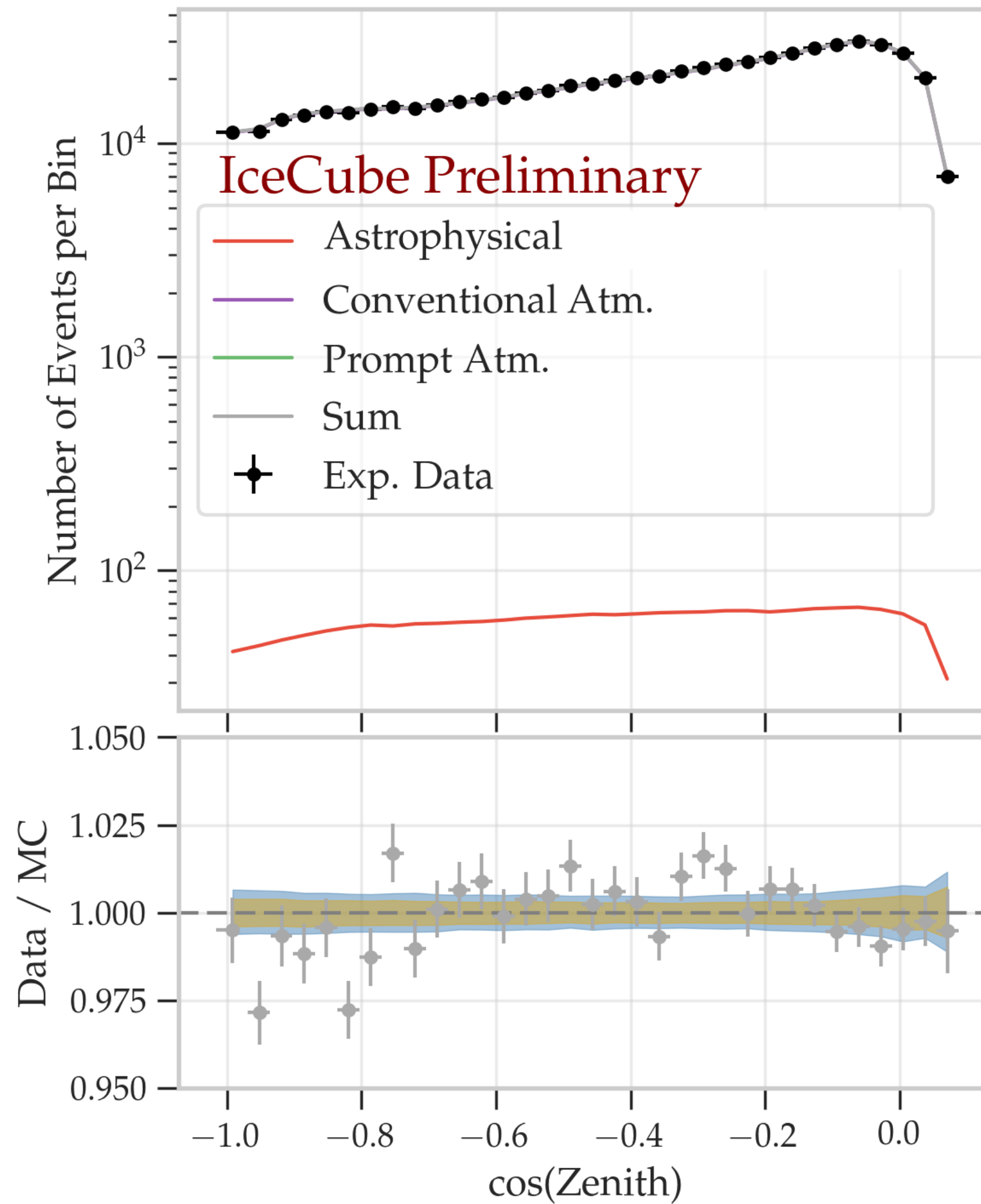
Up-going through-going muons travelled through the Earth



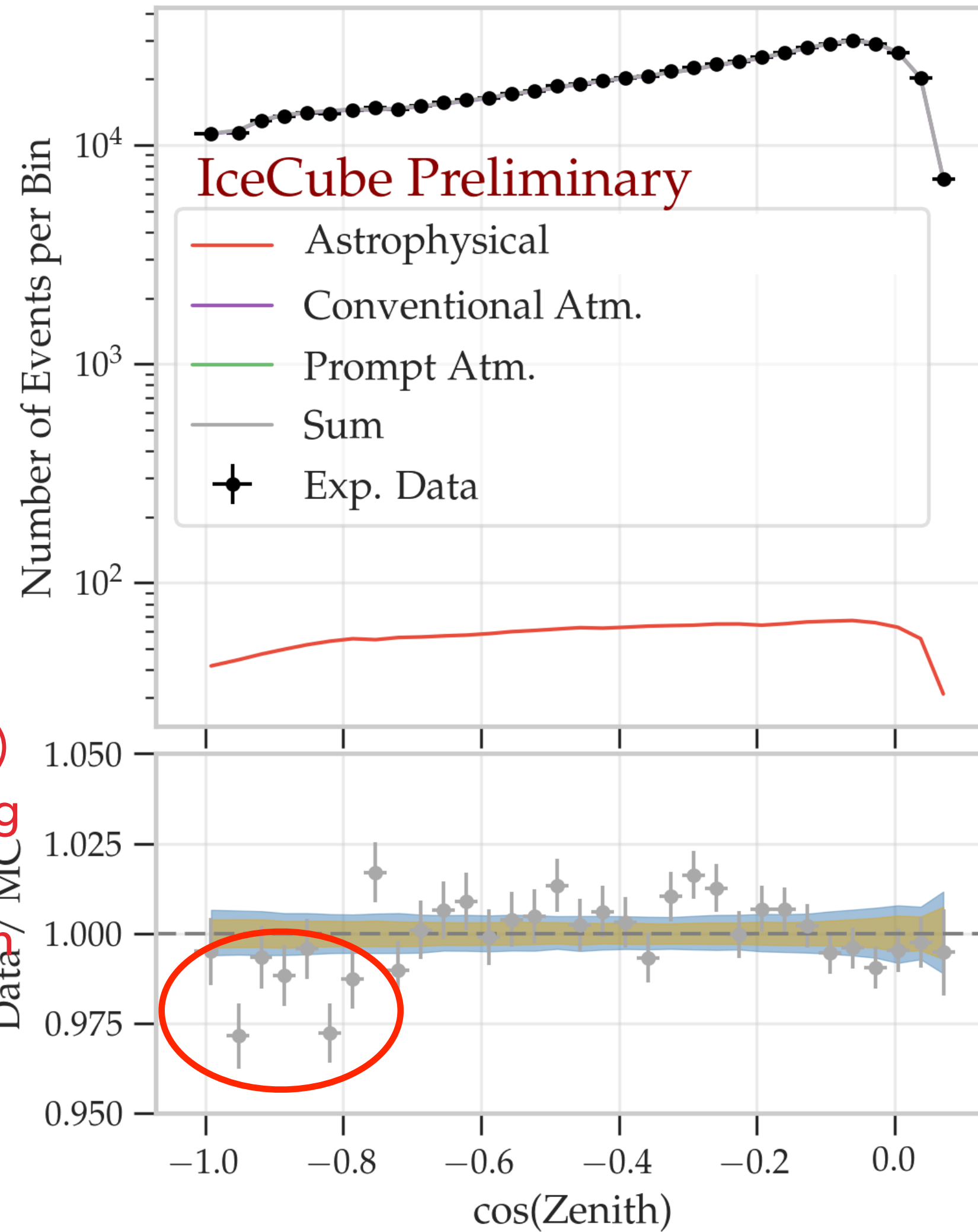
Diffuse- ν_μ sample (Northern Sky)

Updated calibration, updated background modeling and systematics.

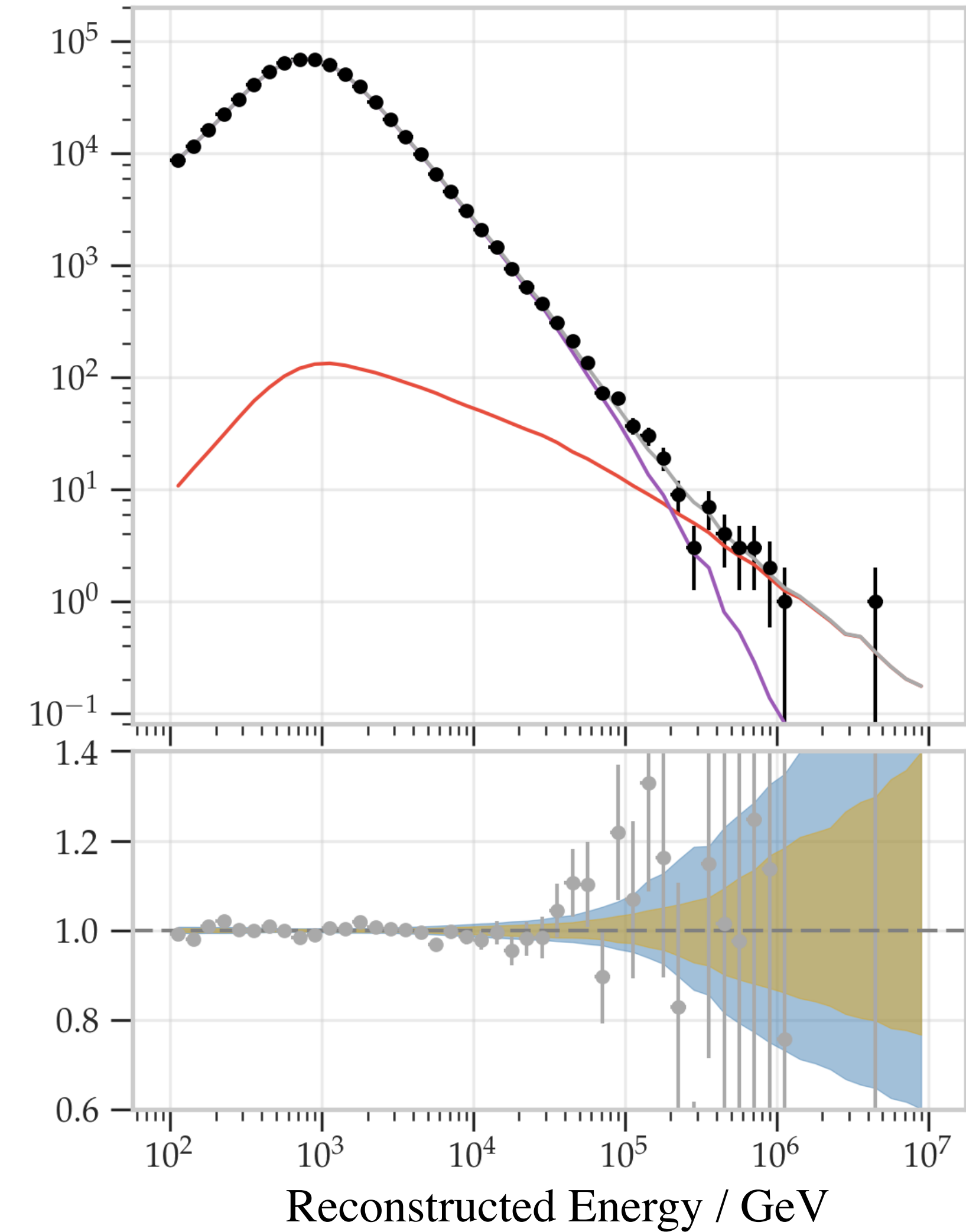
[IceCube Collaboration, PoS (ICRC2019) 1017]



CLEAR EXCESS > 100 TEV (57 EVENTS)
HIGH STAT. $\sim 650,000$ EVENTS (~ 1000 – 2000 ASTROPHYSICAL)
HARD SPECTRUM ($\gamma \sim 2.28$), SLIGHTLY SOFTER THAN PREVIOUS 8YR RESULTS ($\gamma \sim 2.19$) MOSTLY CAUSED BY A BETTER TREATMENT OF THE PRIMARY COSMIC-RAY FLUX

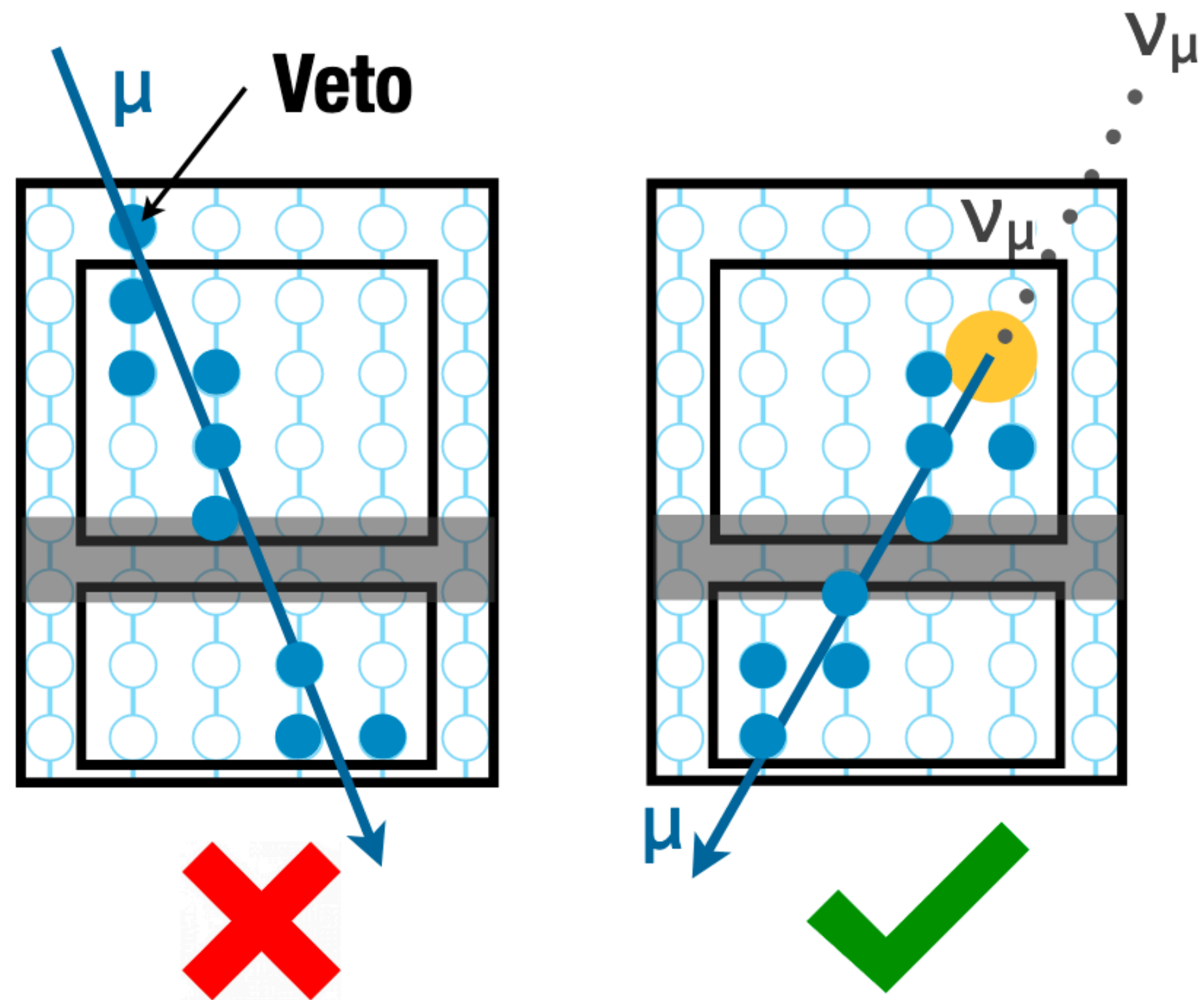


Small deficit (1- 2%)
for straight up-going
events under
investigation (driven
by $E < 5$ TeV)

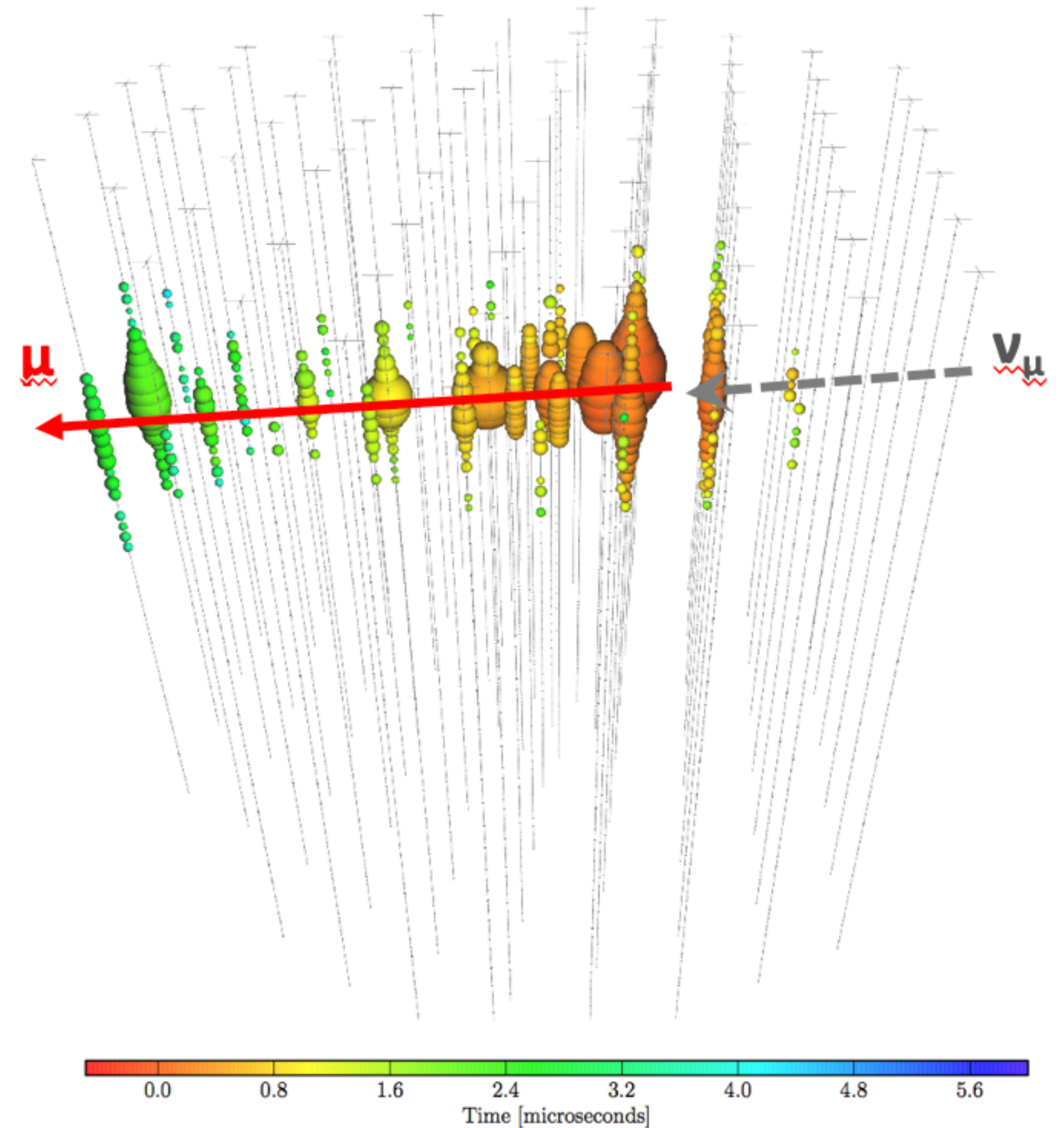


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High Energy Starting Events (HESE)

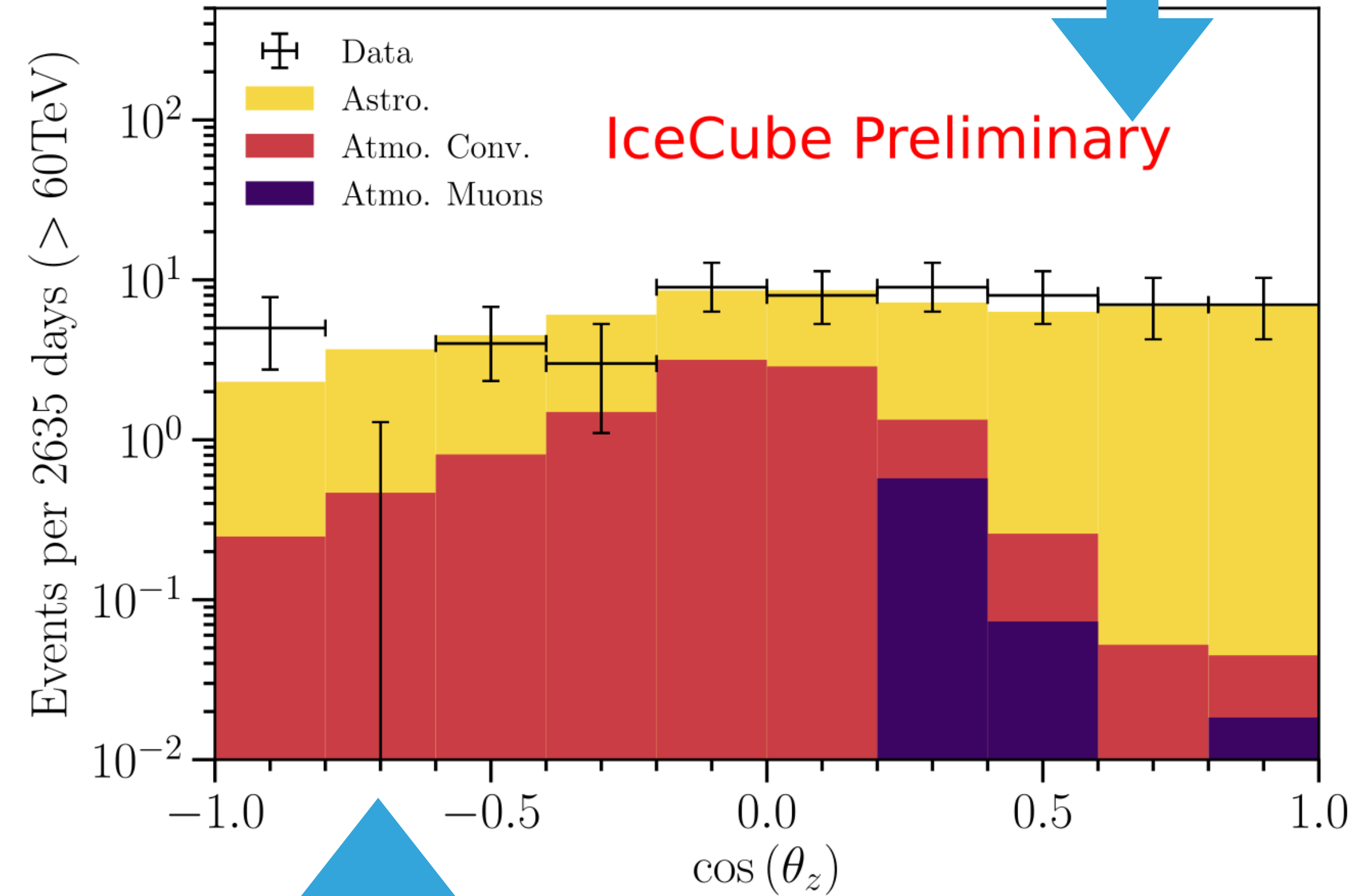
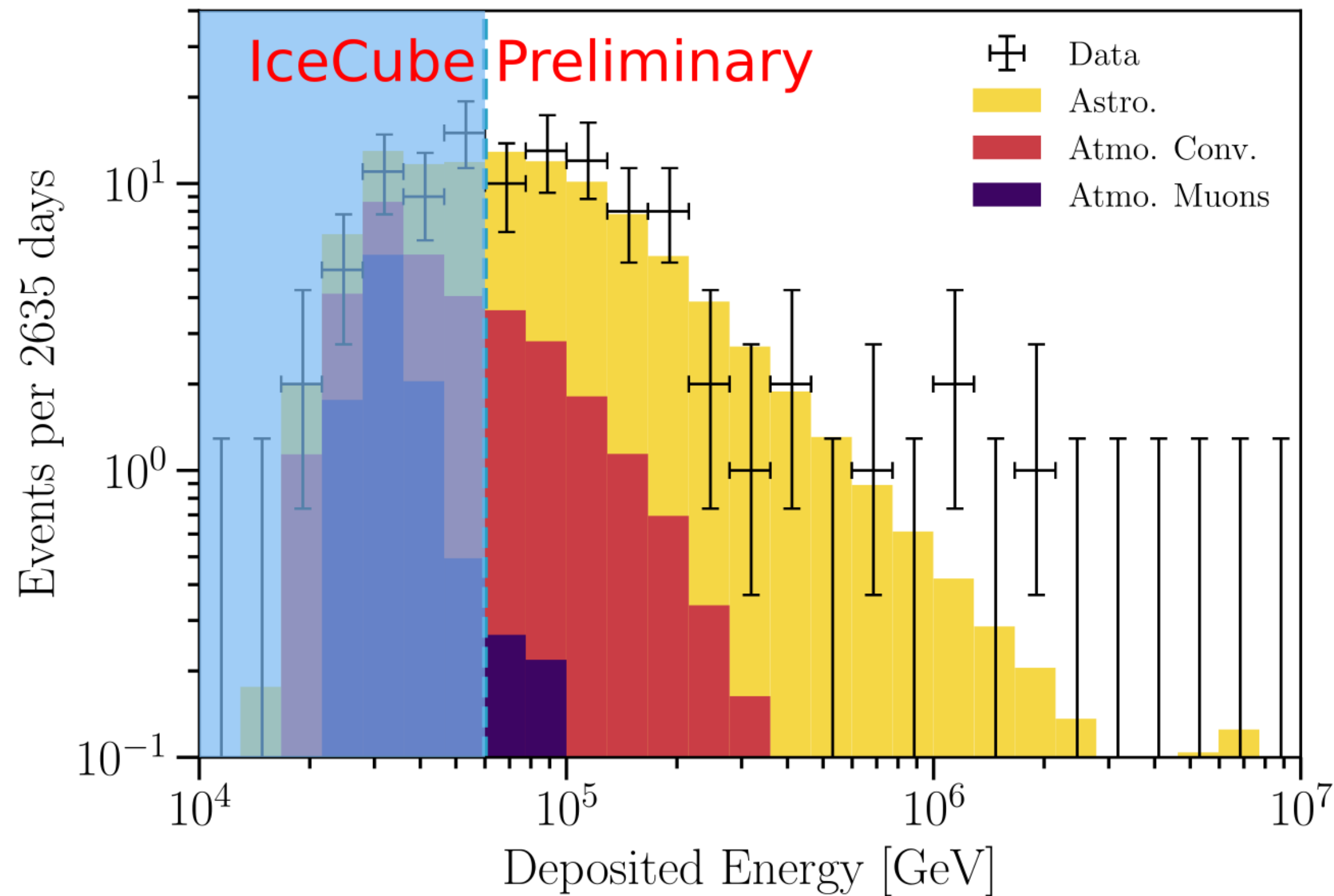


Hybrid (tracks and cascades) - 4π



Updated calibration, updated background modeling and systematics, new double cascade identifier.

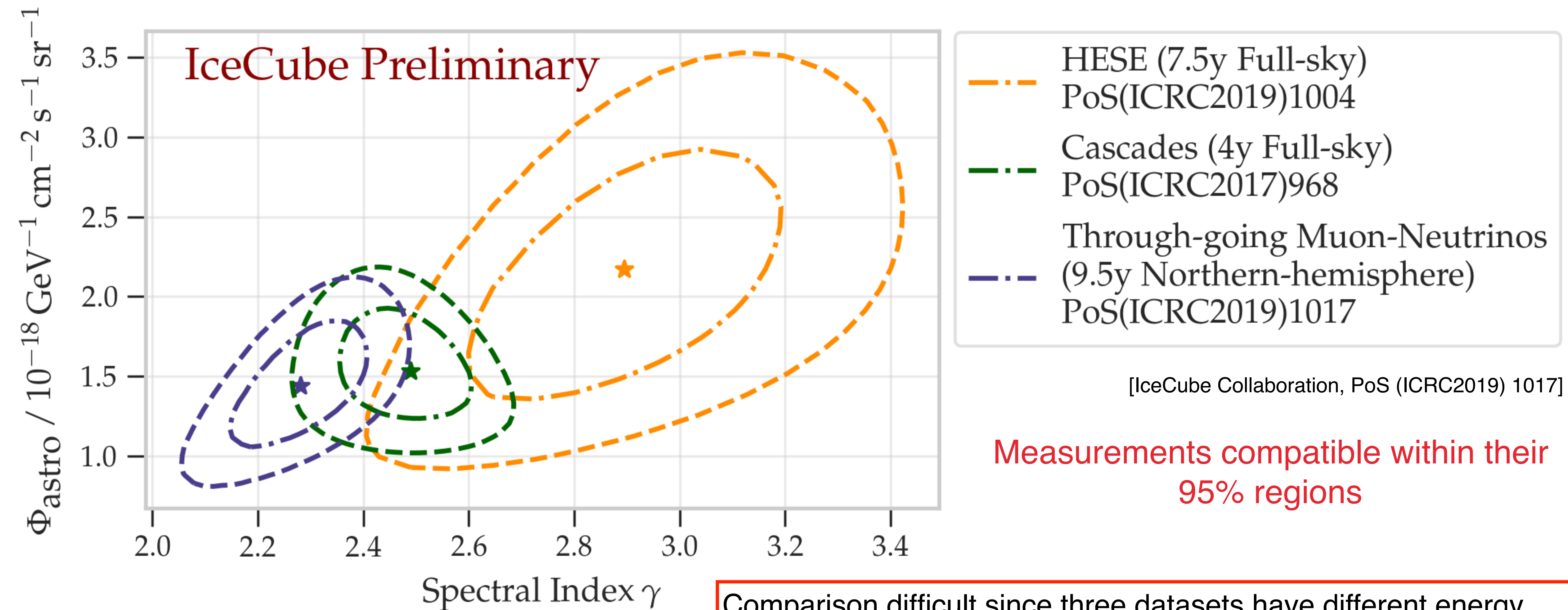
Southern Sky



Northern Sky

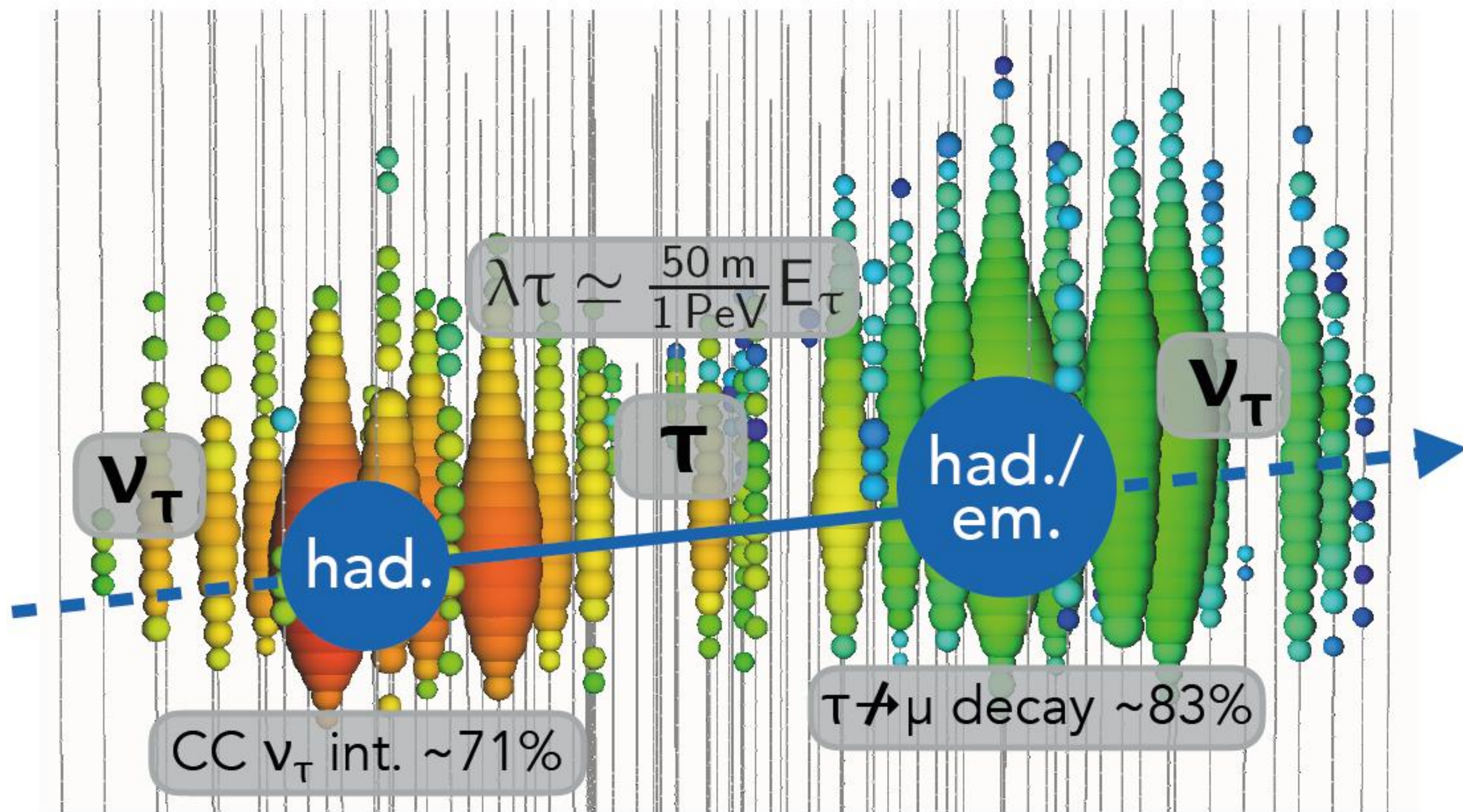
CLEAR EXCESS ABOVE ATMOSPHERIC BACKGROUND $> 60\text{ TeV}$
 SOFT SPECTRUM ($\gamma \sim 2.9$)
 NO PeV EVENTS OBSERVED SINCE 2013

Single power law astrophysical neutrino spectrum (no break preferred)

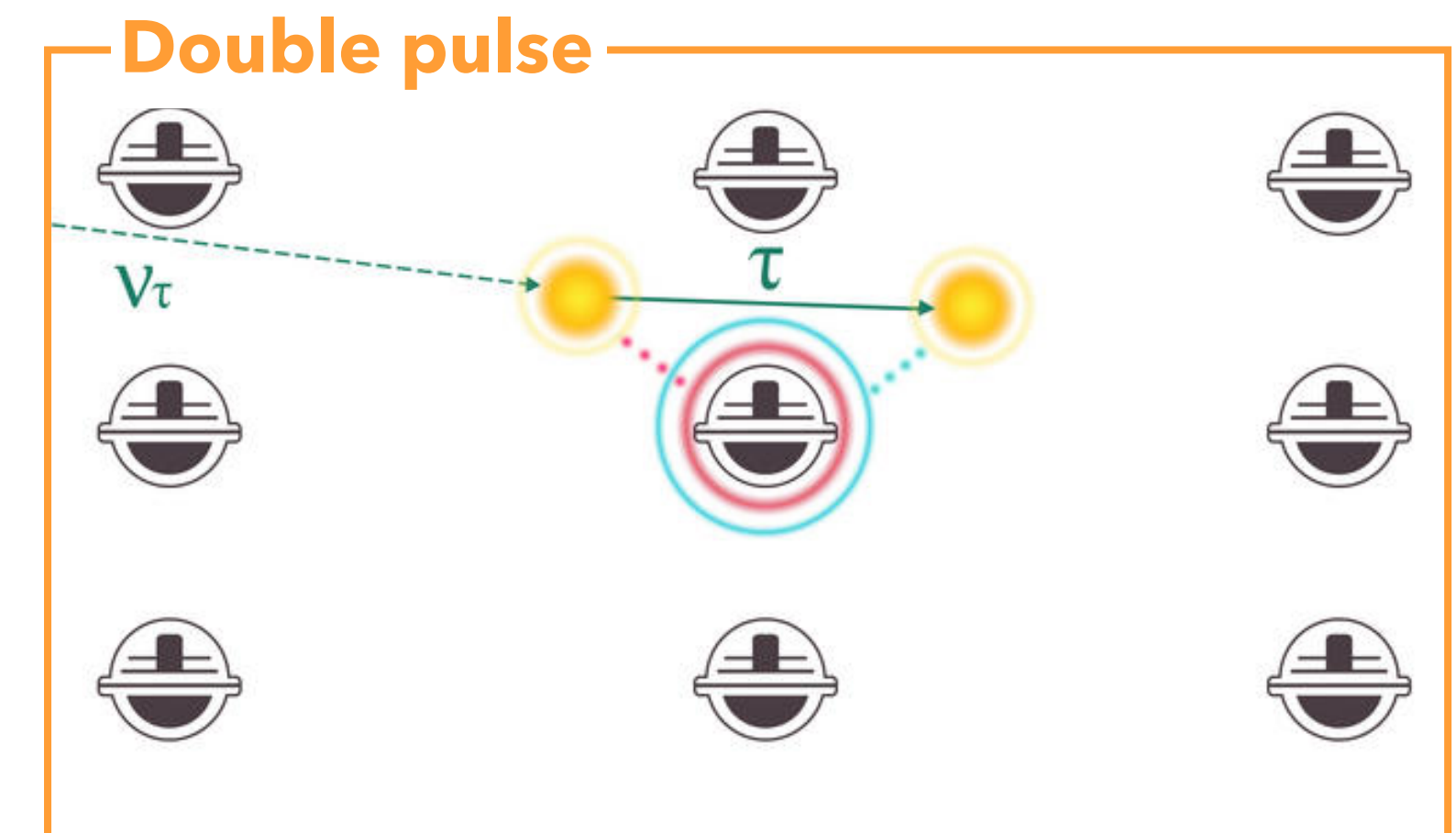
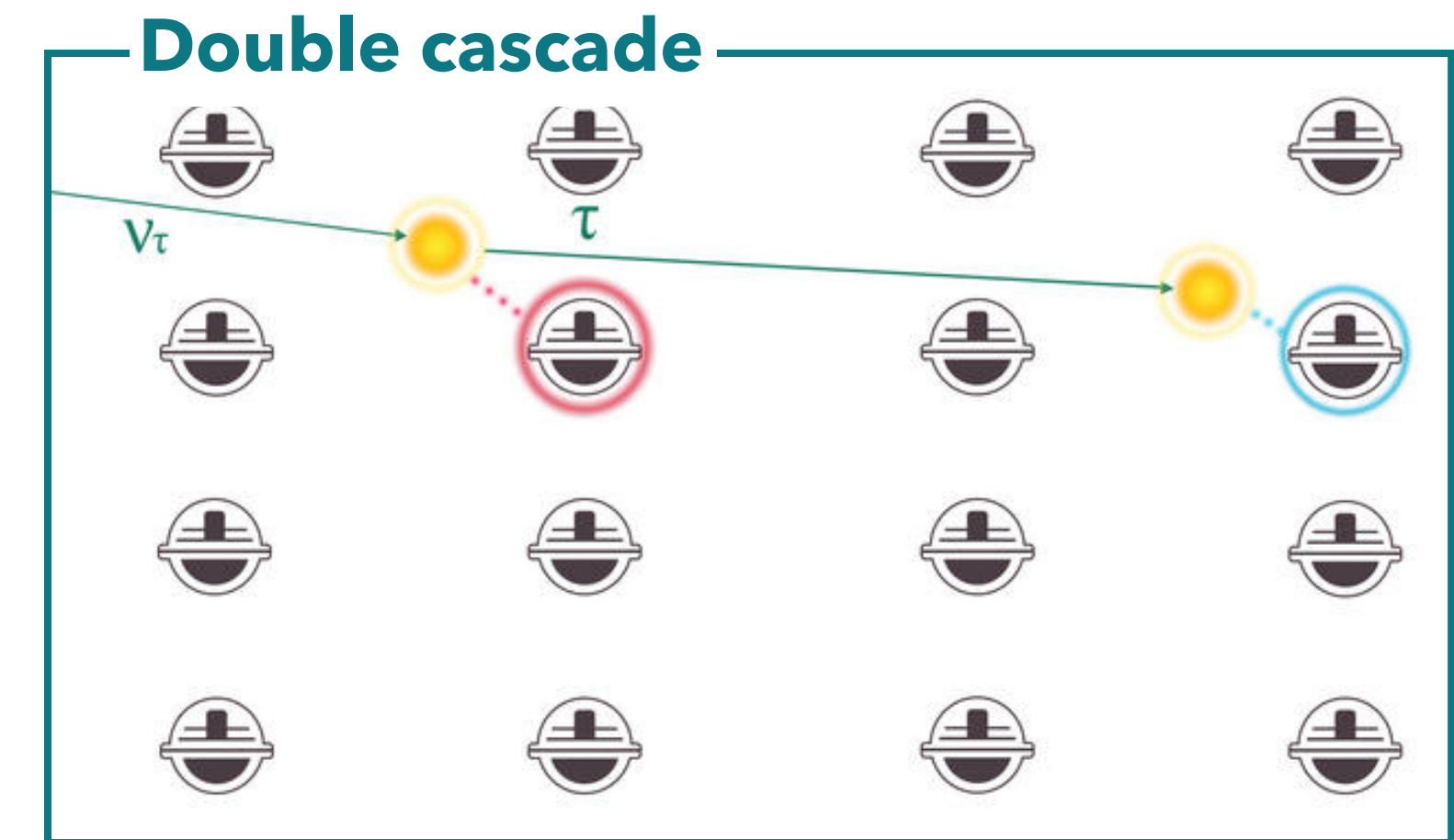


Comparison difficult since three datasets have different energy cuts and select different morphologies -> Working on a global fit

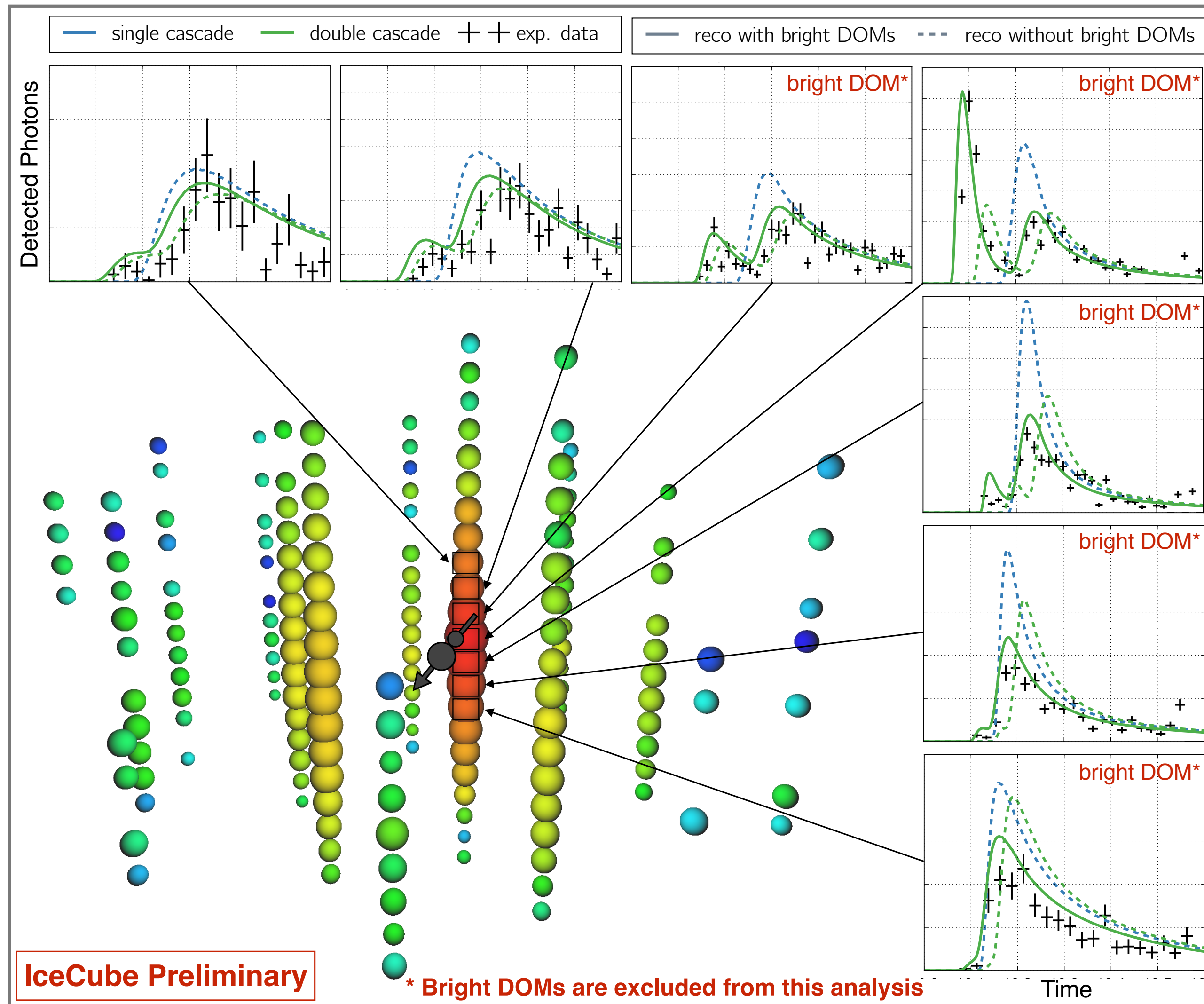
Standard neutrino oscillation predicts full mixing at Earth: $\sim 1/3$ of astrophysical neutrinos should be ν_τ



simulated double bang event with ~ 10 PeV neutrino energy

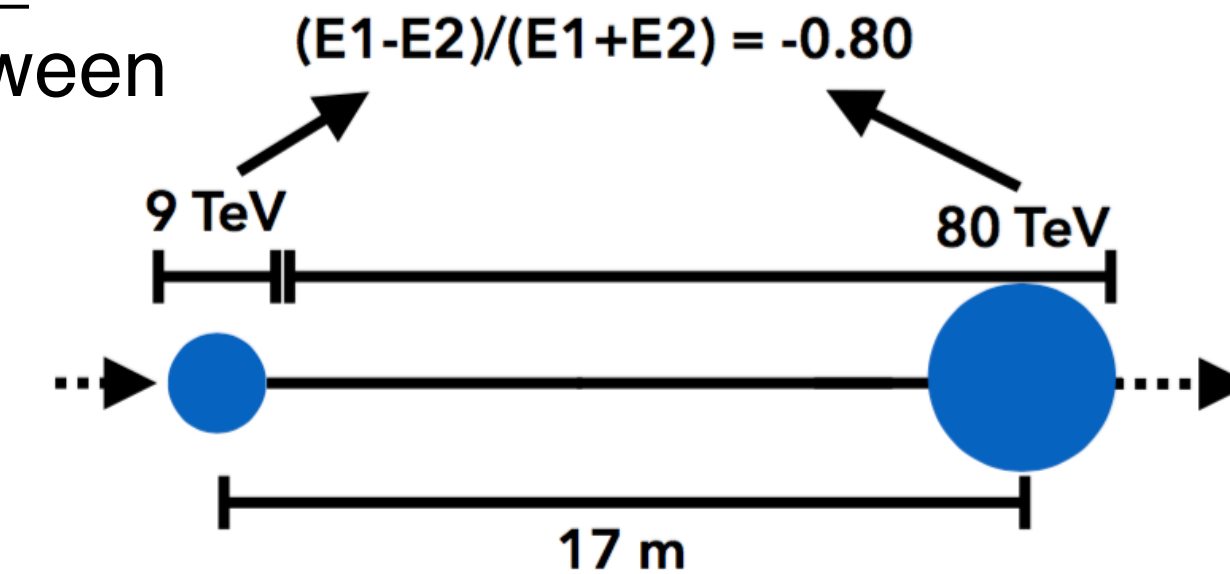


- ▶ (Almost) no atmospheric background
- ▶ Good energy resolution
- ▶ Good angular resolution



New double cascade identifier:

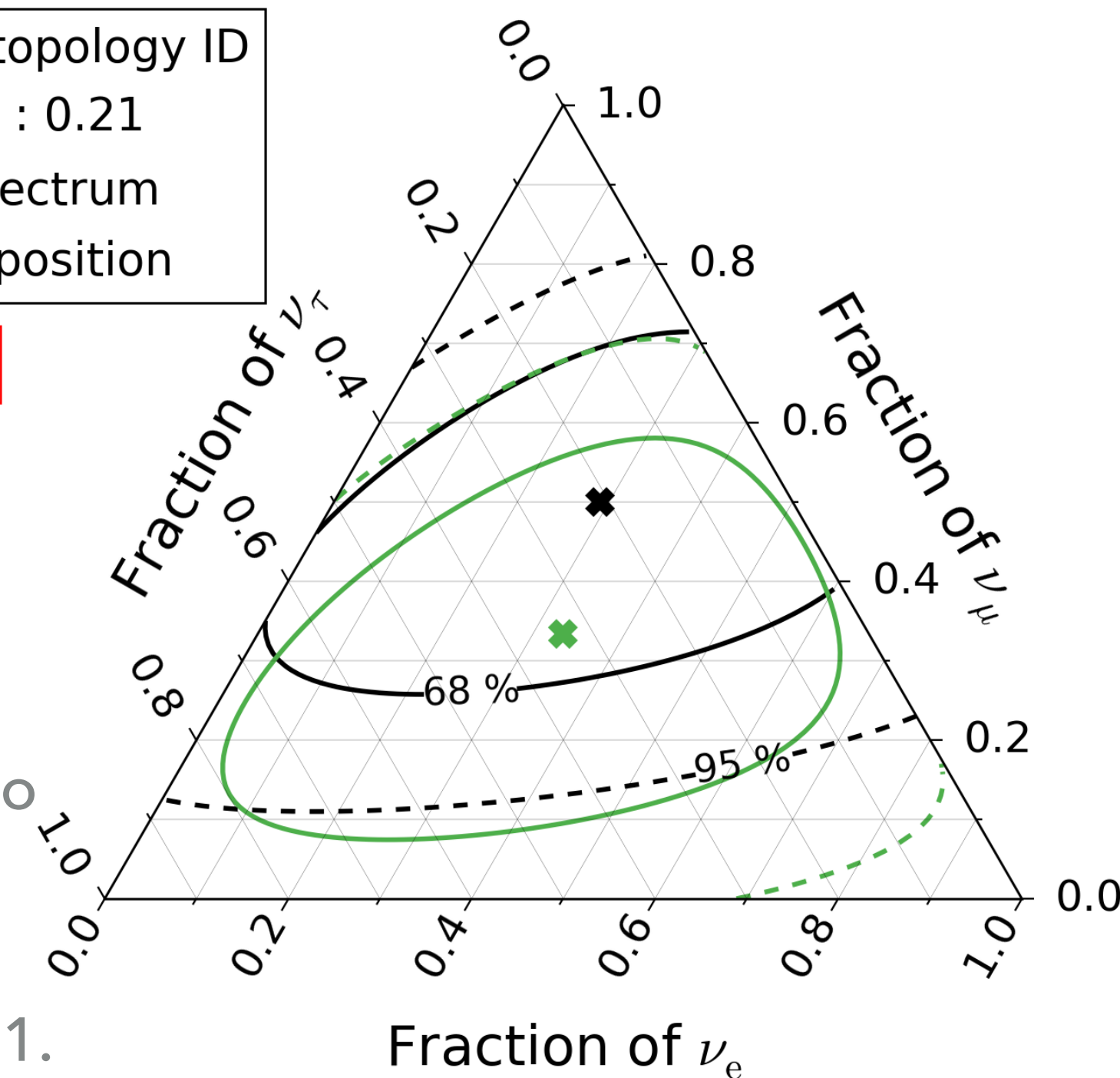
- Event length (distance between the two cascades)
- Energy asymmetry
- Fraction of total energy deposited close to vertices

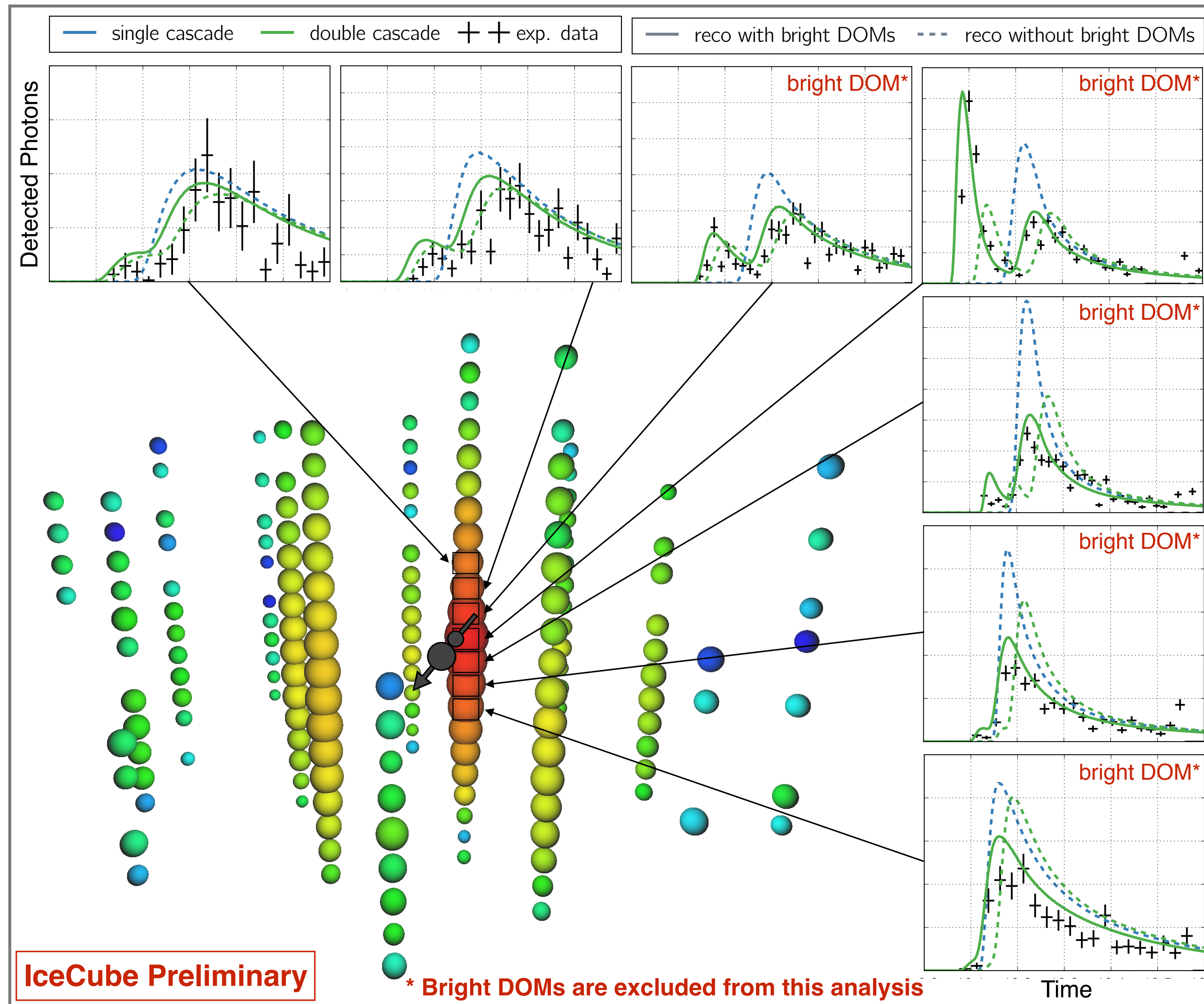


- HESE with ternary topology ID
- ✱ Best fit: 0.29 : 0.50 : 0.21
- Sensitivity, $E^{-2.9}$ spectrum
- ✱ 1 : 1 : 1 flavor composition

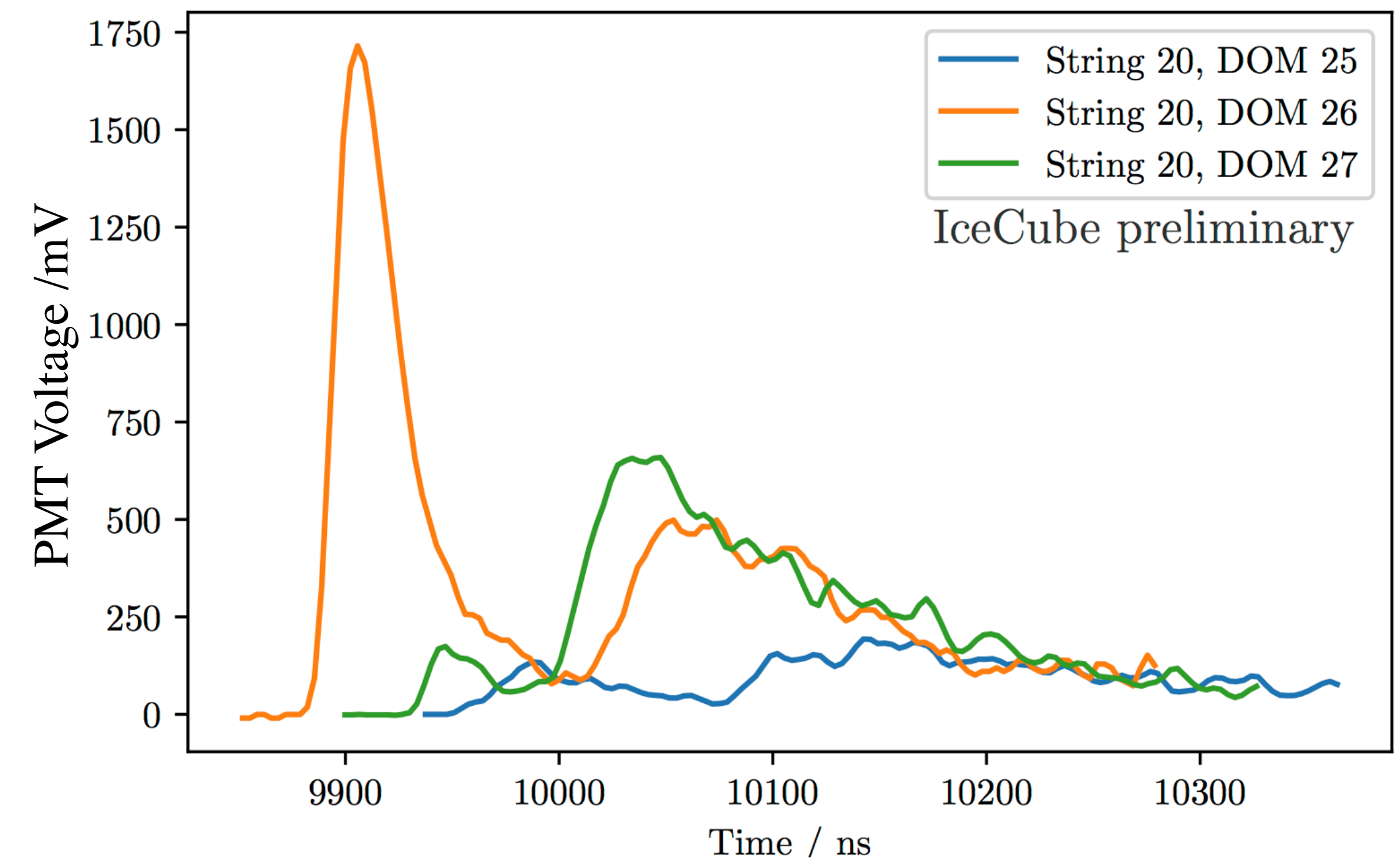
WORK IN PROGRESS

Instead of equipartition fit of the three flavors individual contribution to the astrophysical normalization constraining the sum to 1.





It is the only event passing both the double cascade search and double pulse waveform criteria from two independent searches.

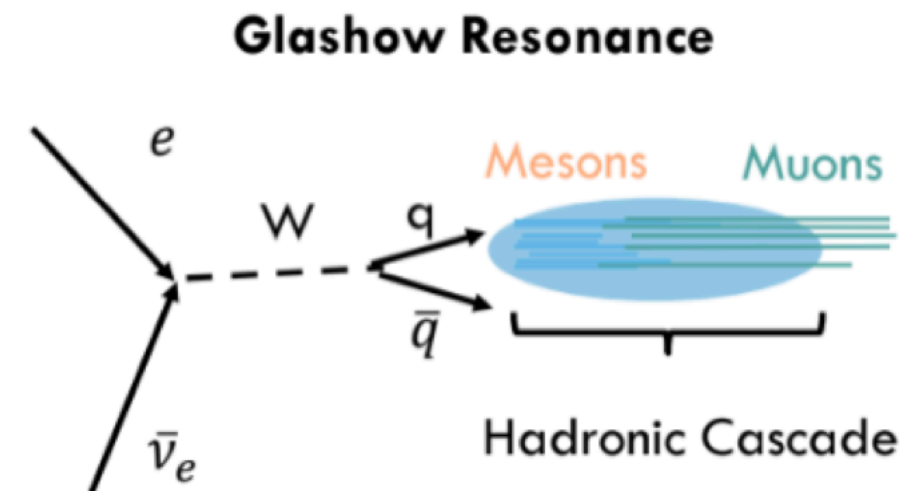
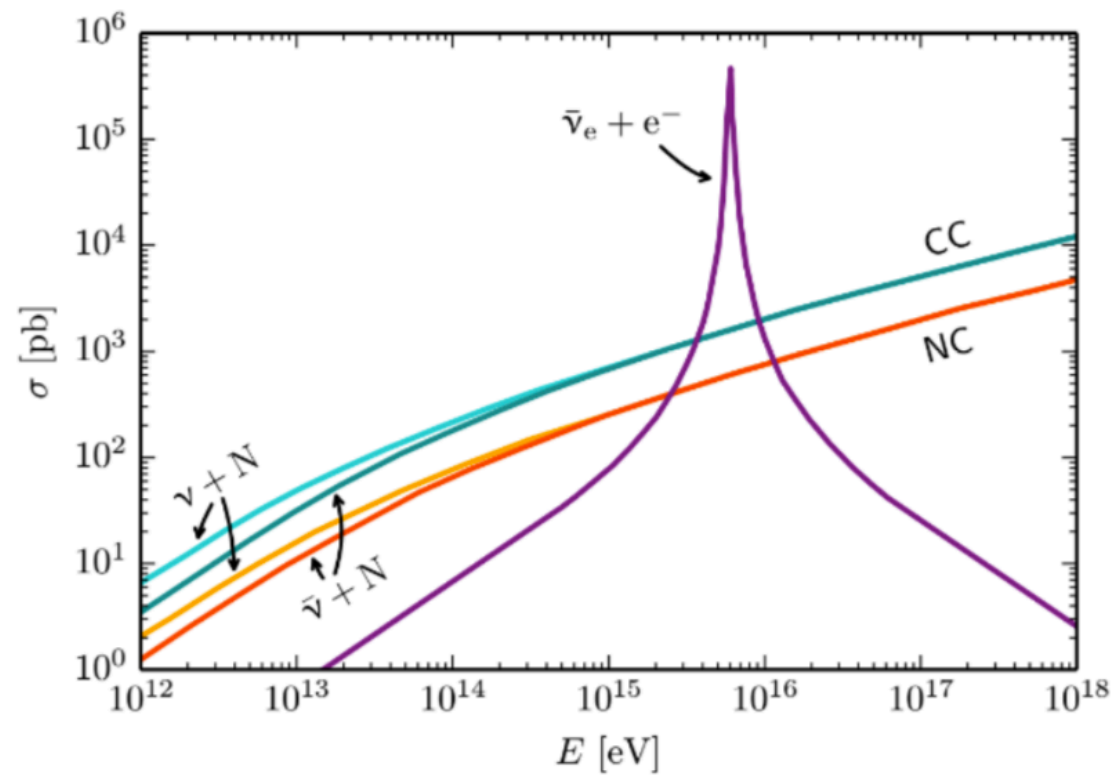


[IceCube Collaboration, PoS (ICRC2019) 1036]

[IceCube Collaboration, PoS (ICRC2019) 960]

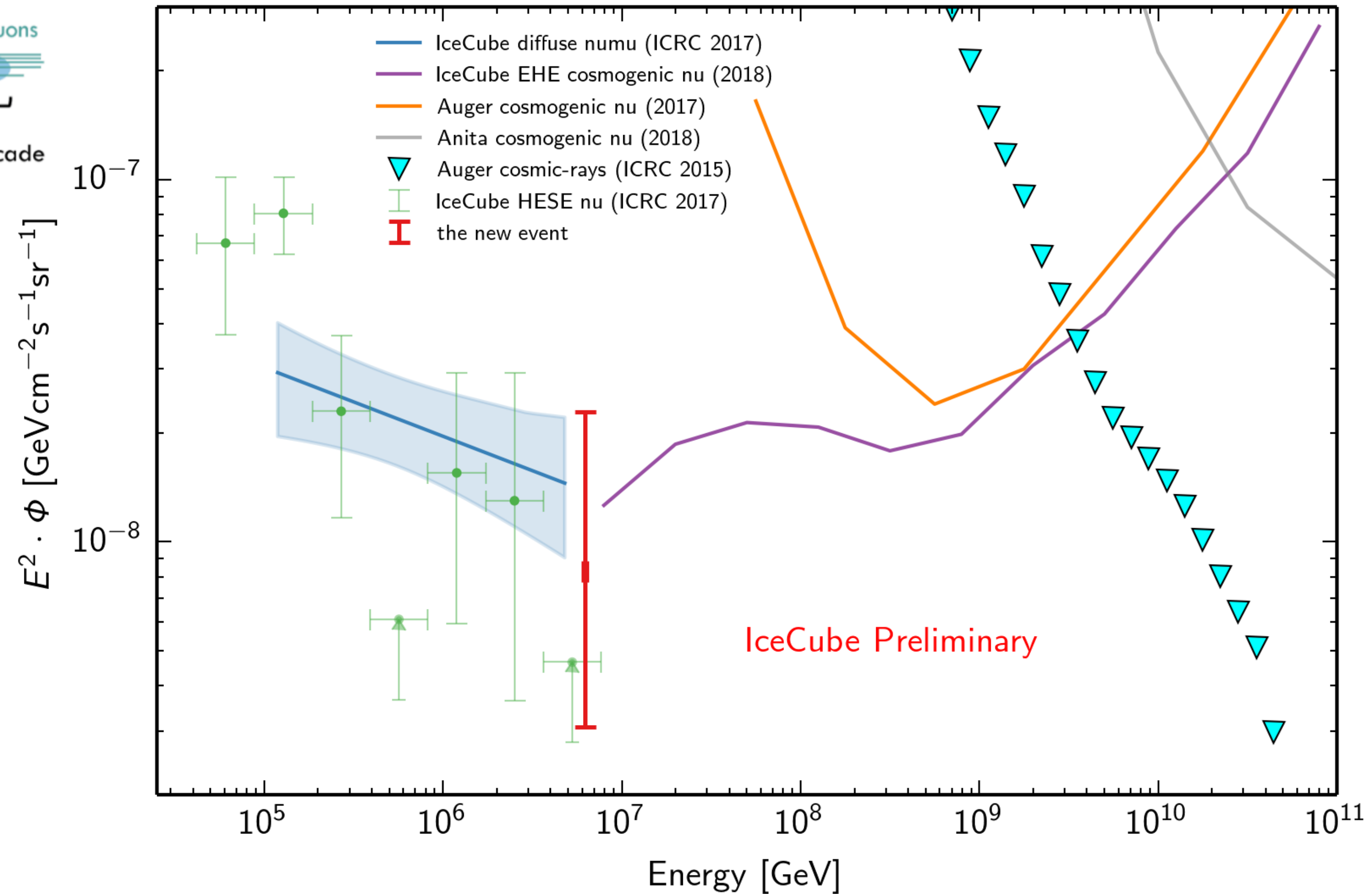
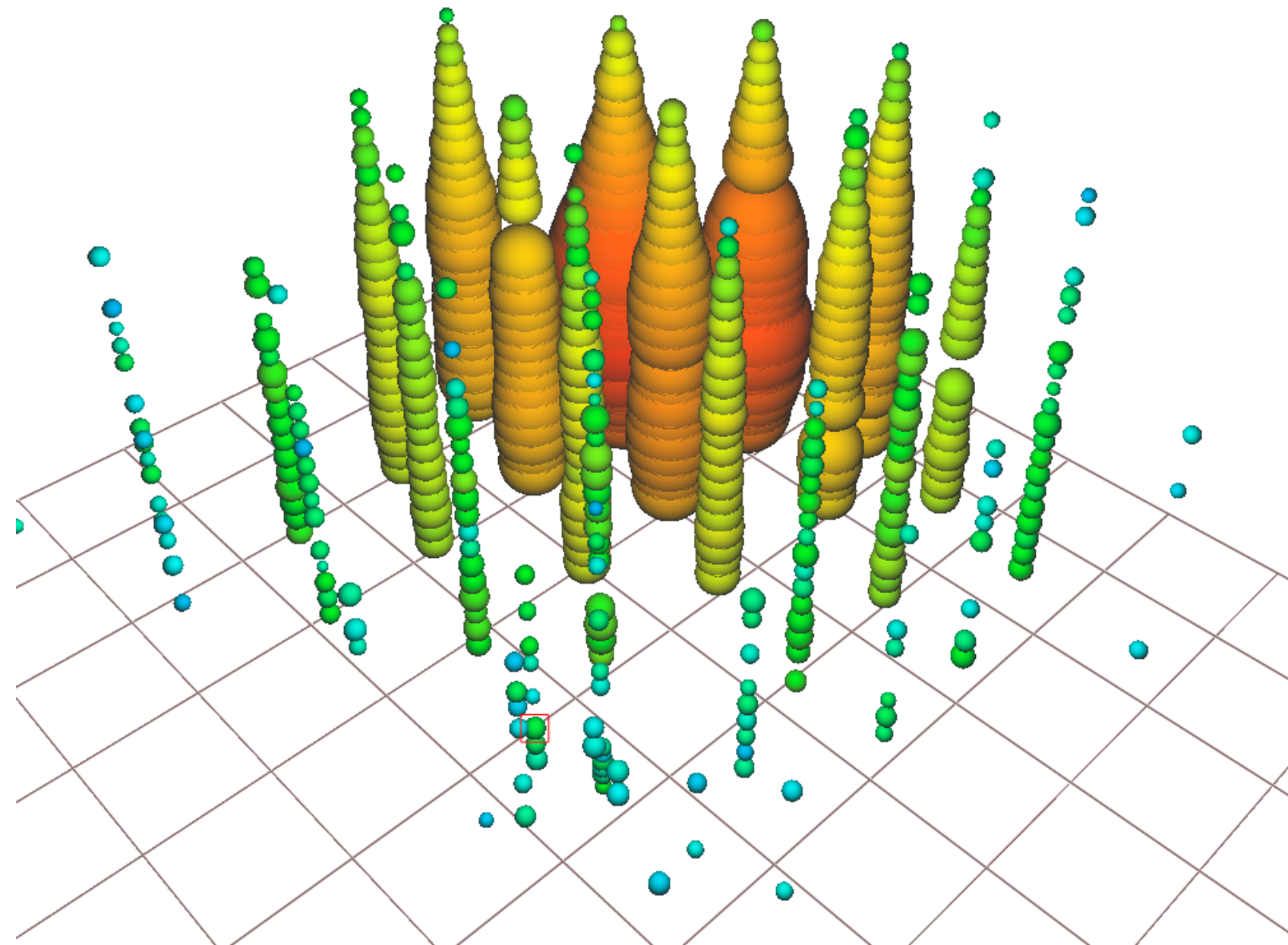
Partially contained cascades: the first Glashow event candidate

S. L. Glashow, Phys. Rev. 118 (1960) 316-317.



[Lu Lu (IceCube coll.), UHECR 2018, pub. in prep.]

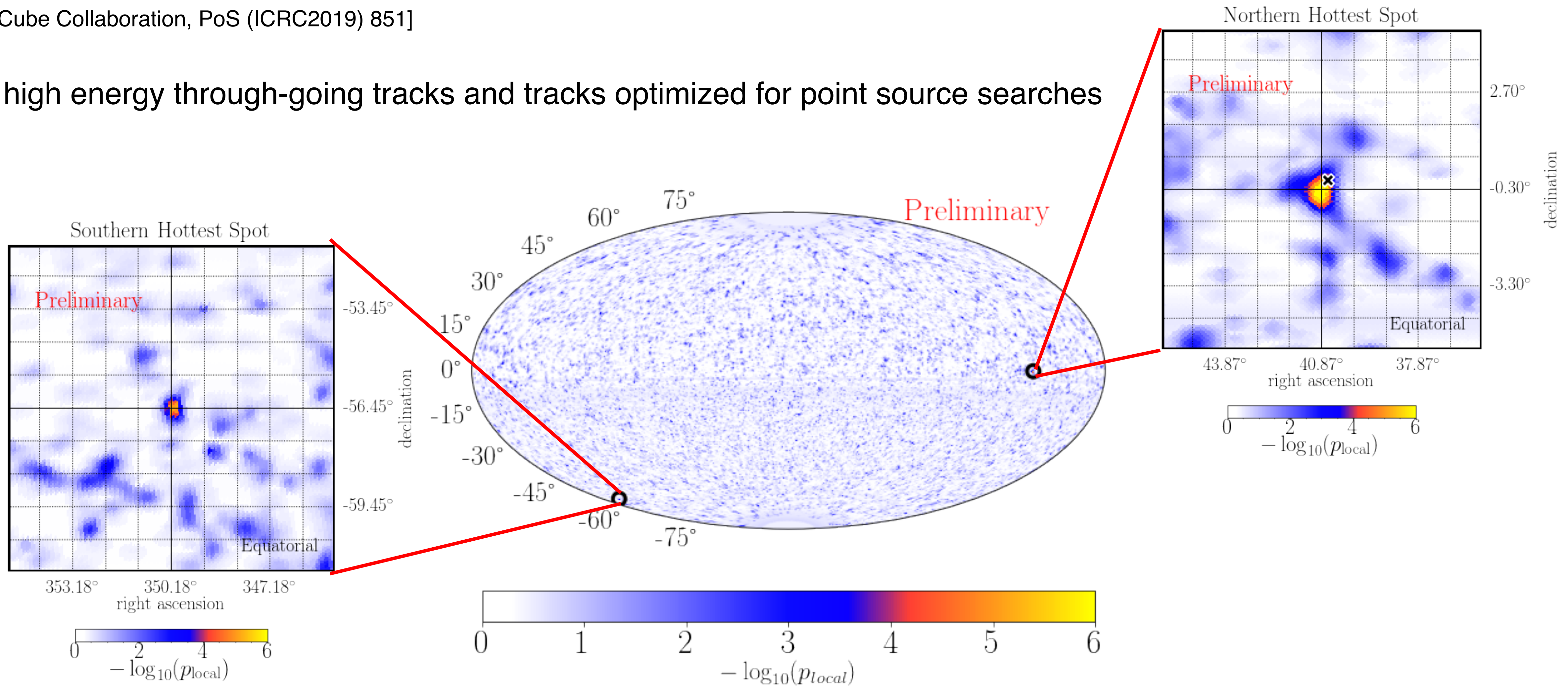
Resonance: $E_\nu = 6.3$ PeV
 Typical visible energy is 93%



Astrophysical neutrinos: 10 years all sky point sources

[IceCube Collaboration, PoS (ICRC2019) 851]

Using high energy through-going tracks and tracks optimized for point source searches



**NEW SOURCE LIST OF 110 GALACTIC (TeVcat) AND EXTRAGALACTIC (LAT-4FGL) OBJECTS.
HOTTEST SPOT IN THE NORTHERN HEMISPHERE IS A 2.9σ EXCESS AT THE POSITION OF THE SEYFERT GALAXY NGC 1068 (M77)
SOURCE LIST SEARCH IS INCOMPATIBLE WITH BACKGROUND AT 3.3σ (2.25σ WITHOUT TXS 0506)**

- ▶ **Searches from neutrinos from the Galactic plane** [Aartsen et al. 2017, *Astrophys. J.*, 849, 67, arXiv:1707.03416; Albert, A., et al. 2018, *Astrophys. J.*, 868, L20, arXiv:1808.03531; Aartsen et al 2019, arXiv:1907.06714.]
- ▶ **Joint point source searches with ANTARES**
- ▶ **Follow-up observations of external triggers** [IceCube Collaboration PoS (ICRC2019) 1026]
- ▶ **Follow-up observations of GW events** [IceCube Collaboration PoS (ICRC2019) 918, IceCube Collaboration PoS (ICRC2019) 930]
- ▶ **Joint coincident analysis with HAWC (Galactic plane and subthreshold transients through AMON)** [HAWC, IceCube Collaboration, PoS (ICRC2019) 932, HAWC, IceCube Collaboration, PoS (ICRC2019) 841]
- ▶ **Search for correlations with UHECRs (Auger, TA and ANTARES)** [ANTARES, IceCube, Pierre Auger, Telescope Array Collaboration PoS (ICRC2019) 842]



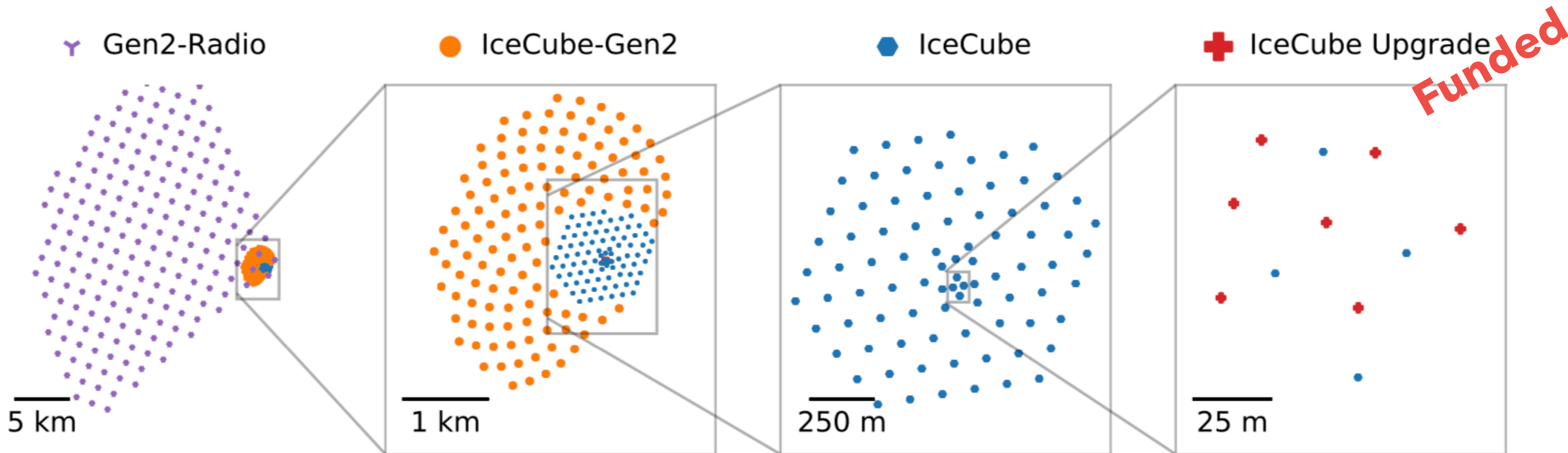
ICECUBE GEN2

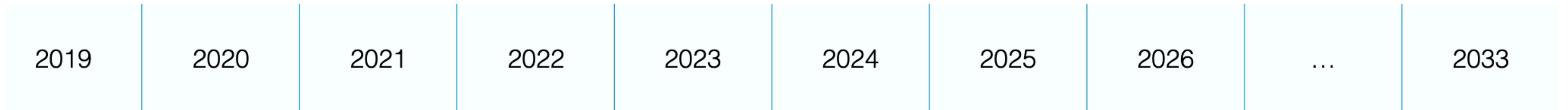


ICECUBE UPGRADE

- OPTICAL DETECTOR: 5-10 KM³
- RADIO DETECTOR: ~500 KM²
- STUDY OF THE ASTROPHYSICAL FLUX > 10 PEV
- DISCOVERY OF GZK NEUTRINOS (~EEV)

- DEEP CORE INFILL (7 NEW STRINGS) IN 2022-2023
- NEUTRINO OSCILLATION
- R&D FOR GEN2: DRILLING, NEW SENSORS
- IMPROVED CALIBRATION OF ARCHIVAL DATA





IceCube Upgrade
Design Production **Deployment**


IceCube-Gen2
R&D Design & Approval Production **Deployment**


A 3D cutaway diagram of the IceCube-Gen2 detector. It shows a large cylindrical cavern with a green floor. A central detector structure is visible, consisting of a blue cylindrical core with a red component. The cavern floor is labeled 'Bedrock'.

Thank you!

THE ICECUBE COLLABORATION

 **AUSTRALIA**
University of Adelaide

 **BELGIUM**
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

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University of Alberta–Edmonton


 **DENMARK**
University of Copenhagen

 **GERMANY**
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität
Münster

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and A&M College
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University of Kansas
University of Maryland
University of Rochester

University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

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Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

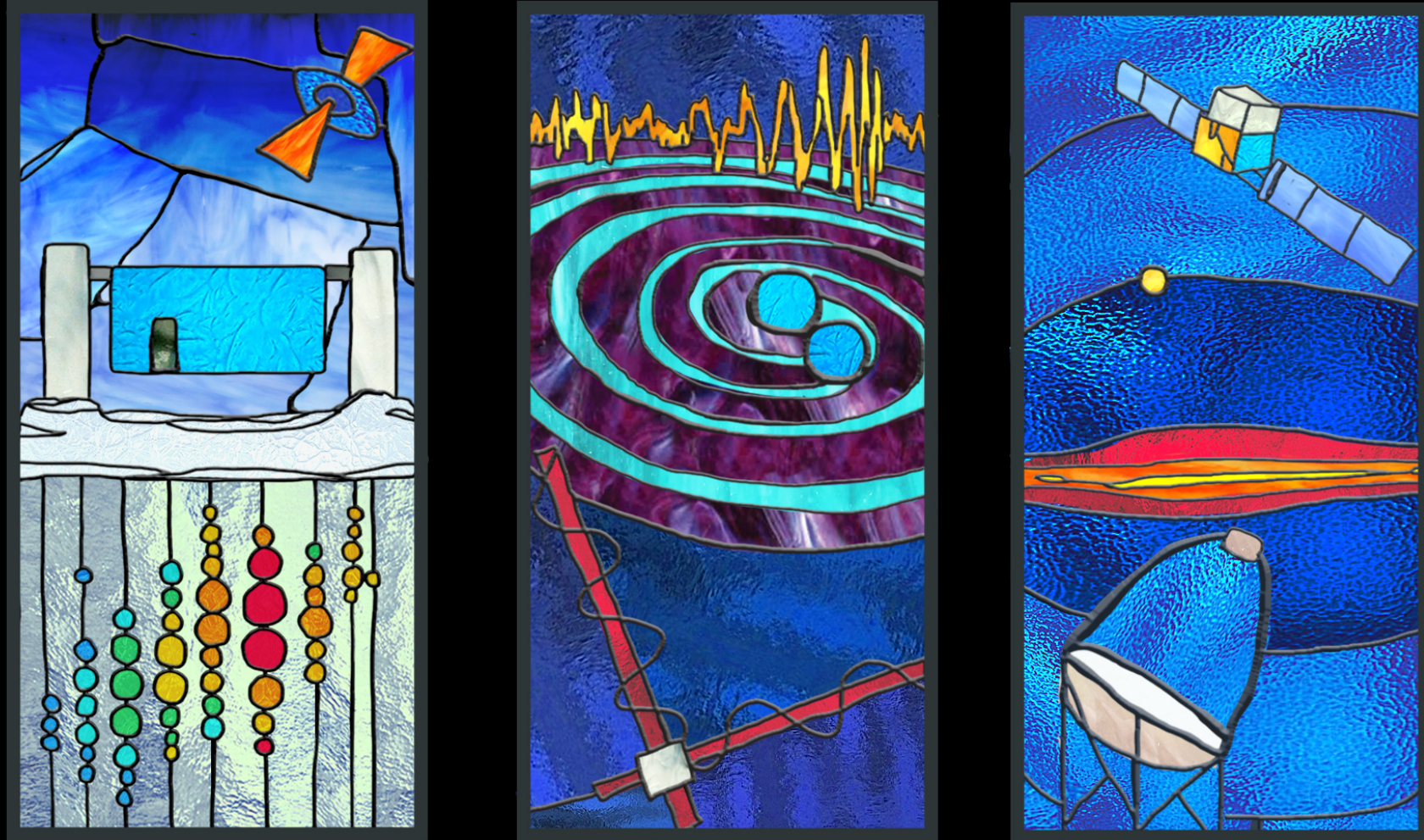
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

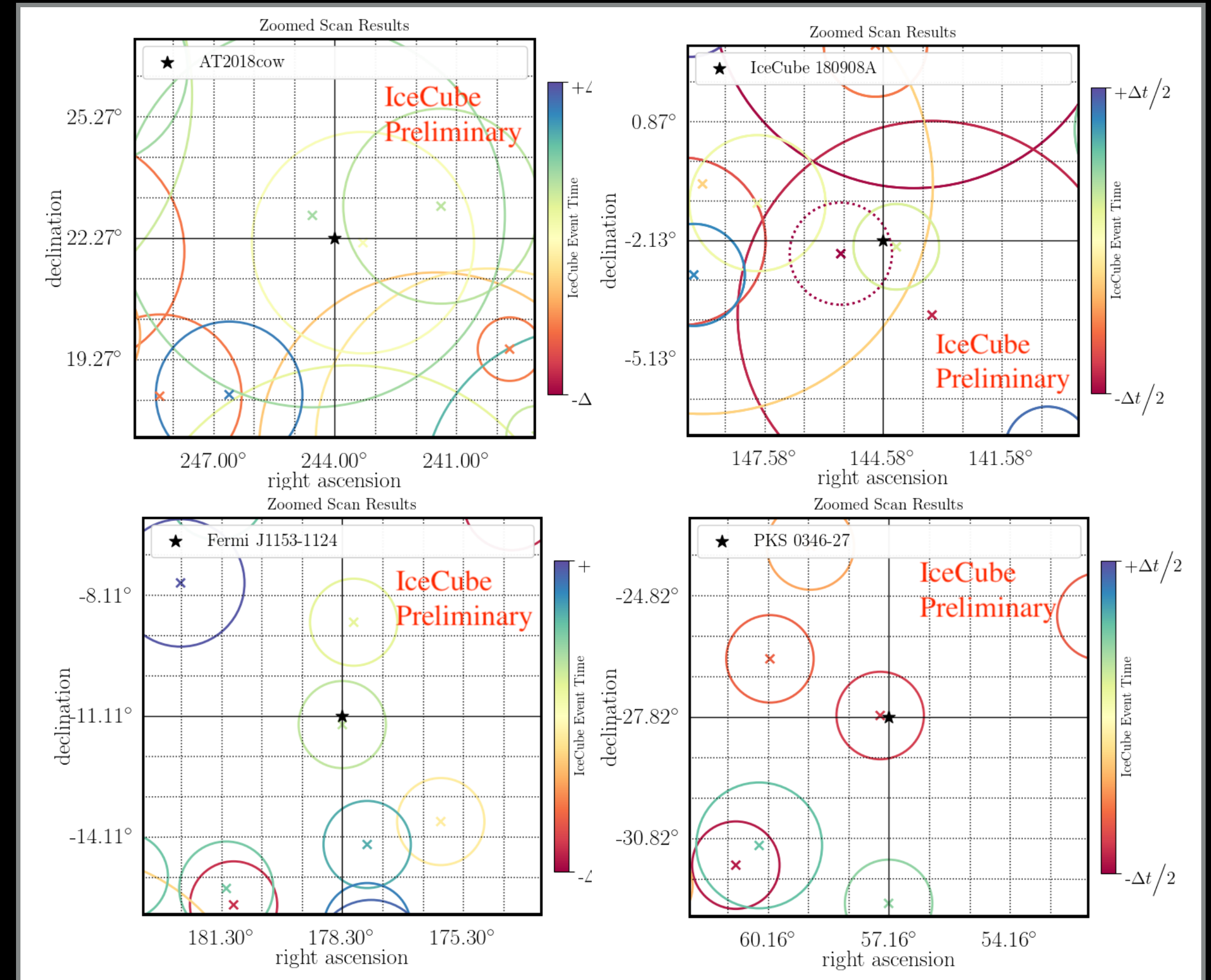
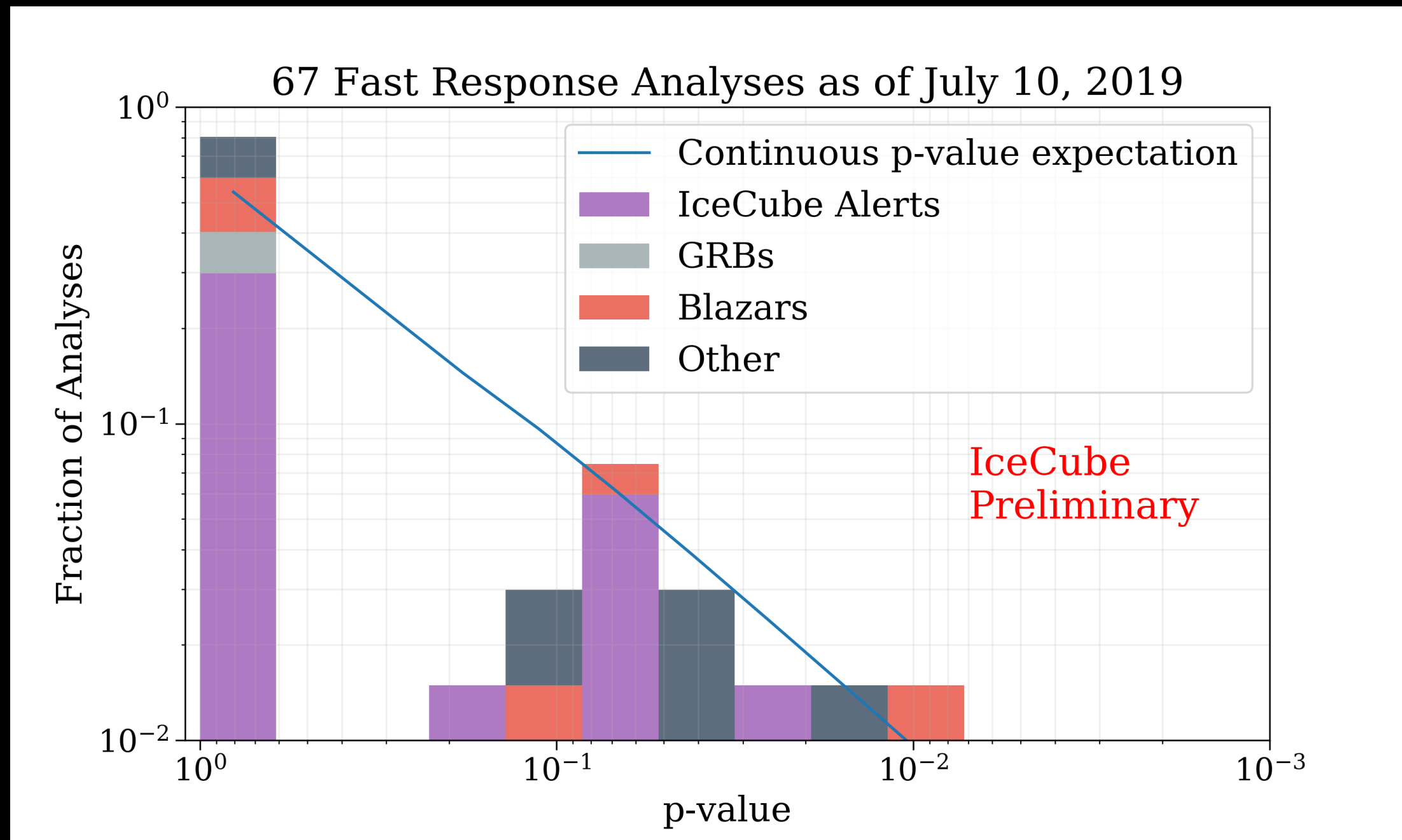


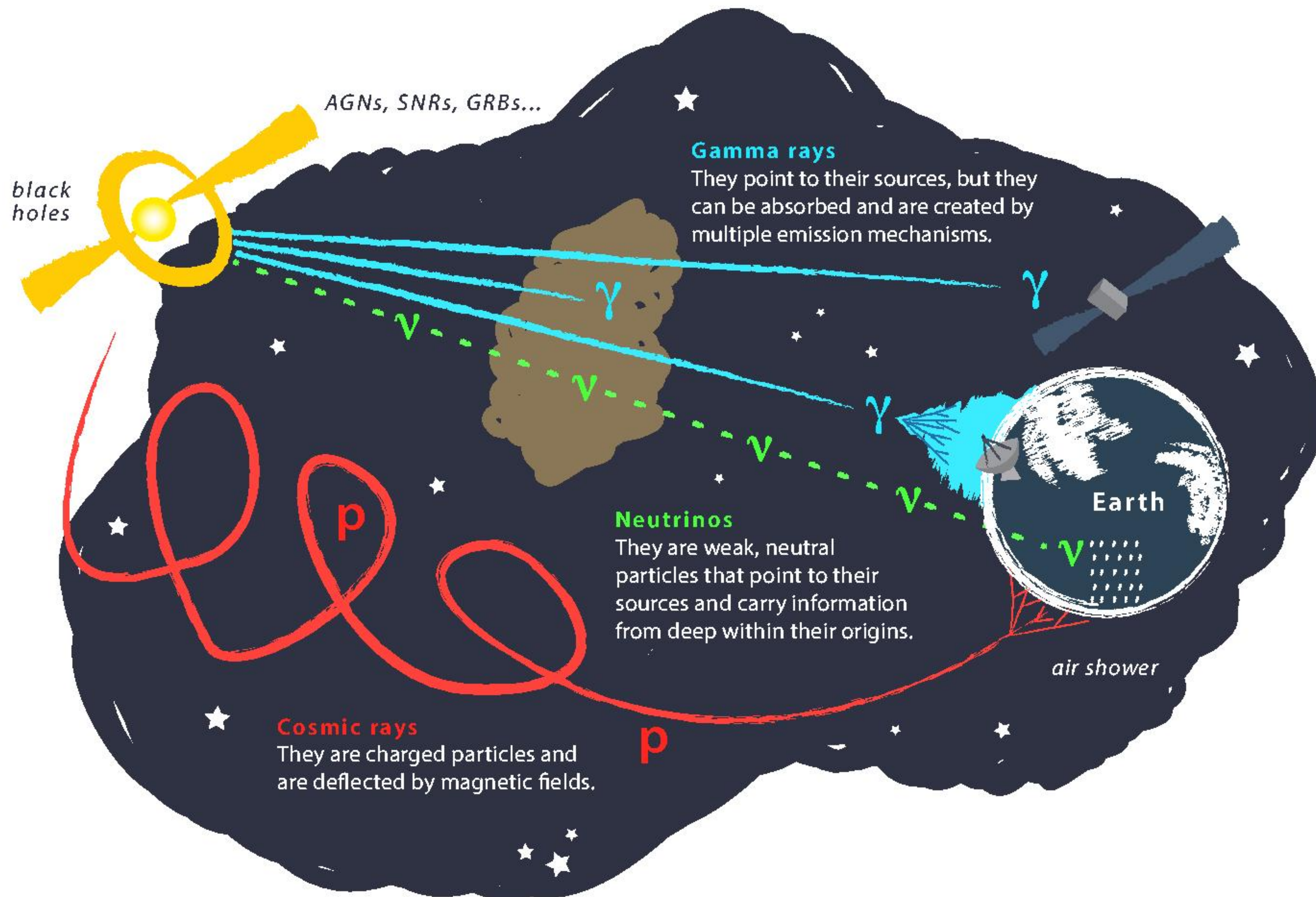
icecube.wisc.edu

FAST RESPONSE ANALYSIS FOR TRANSIENTS



- Perfect sky coverage (all sky) and high duty cycle (99%)
- Follow up on internal and external triggers
- 67 analyses performed as of July 10, 2019
- No statistically significant results





Conventional atmospheric neutrinos

Pions and kaons decay in the atmosphere

Steep energy spectrum: $E^{-3.7}$

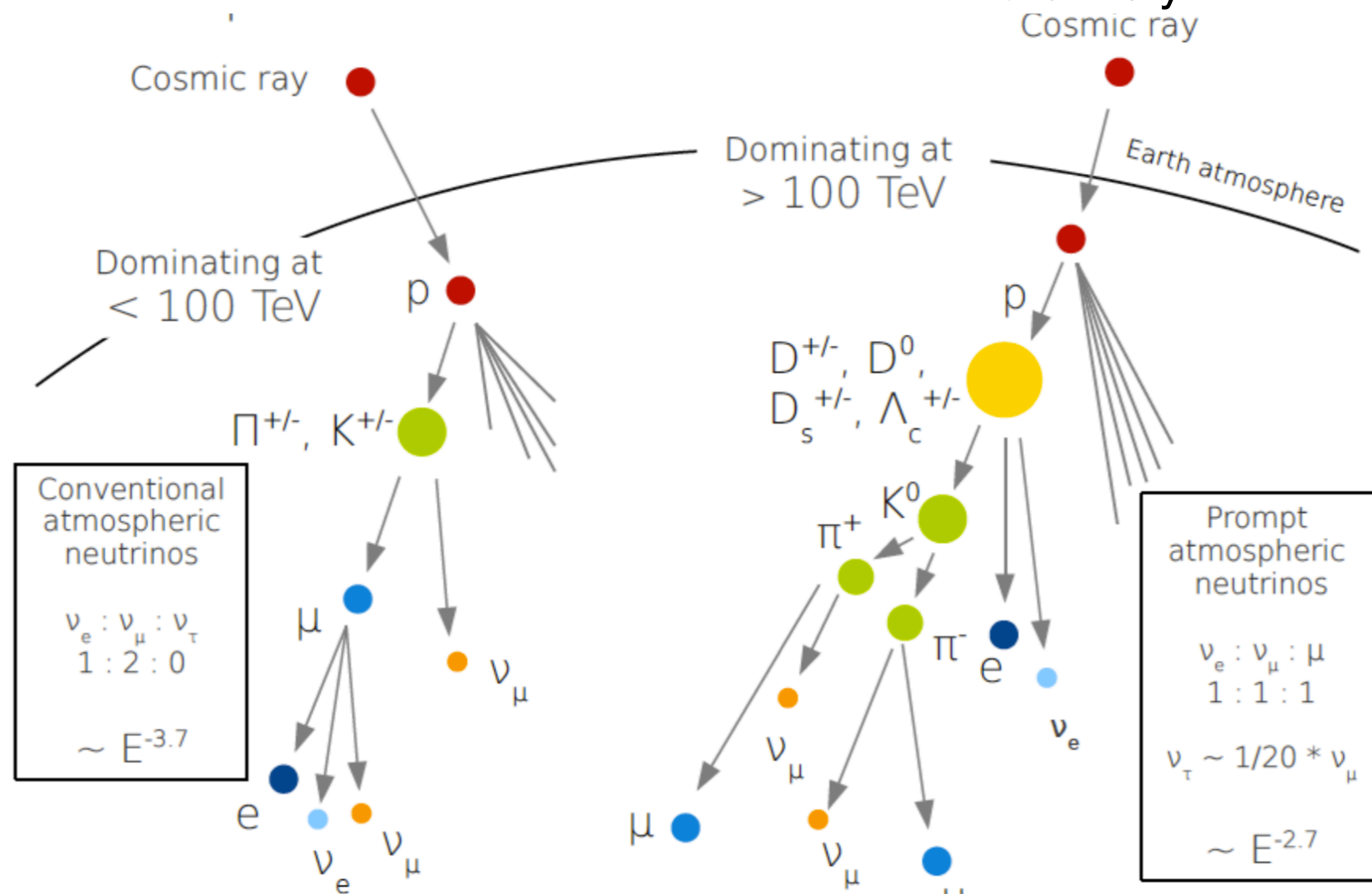
Rate: 100,000/yr

Prompt atmospheric neutrinos

Heavy mesons decay in the atmosphere

Harder energy spectrum: E^{-3}

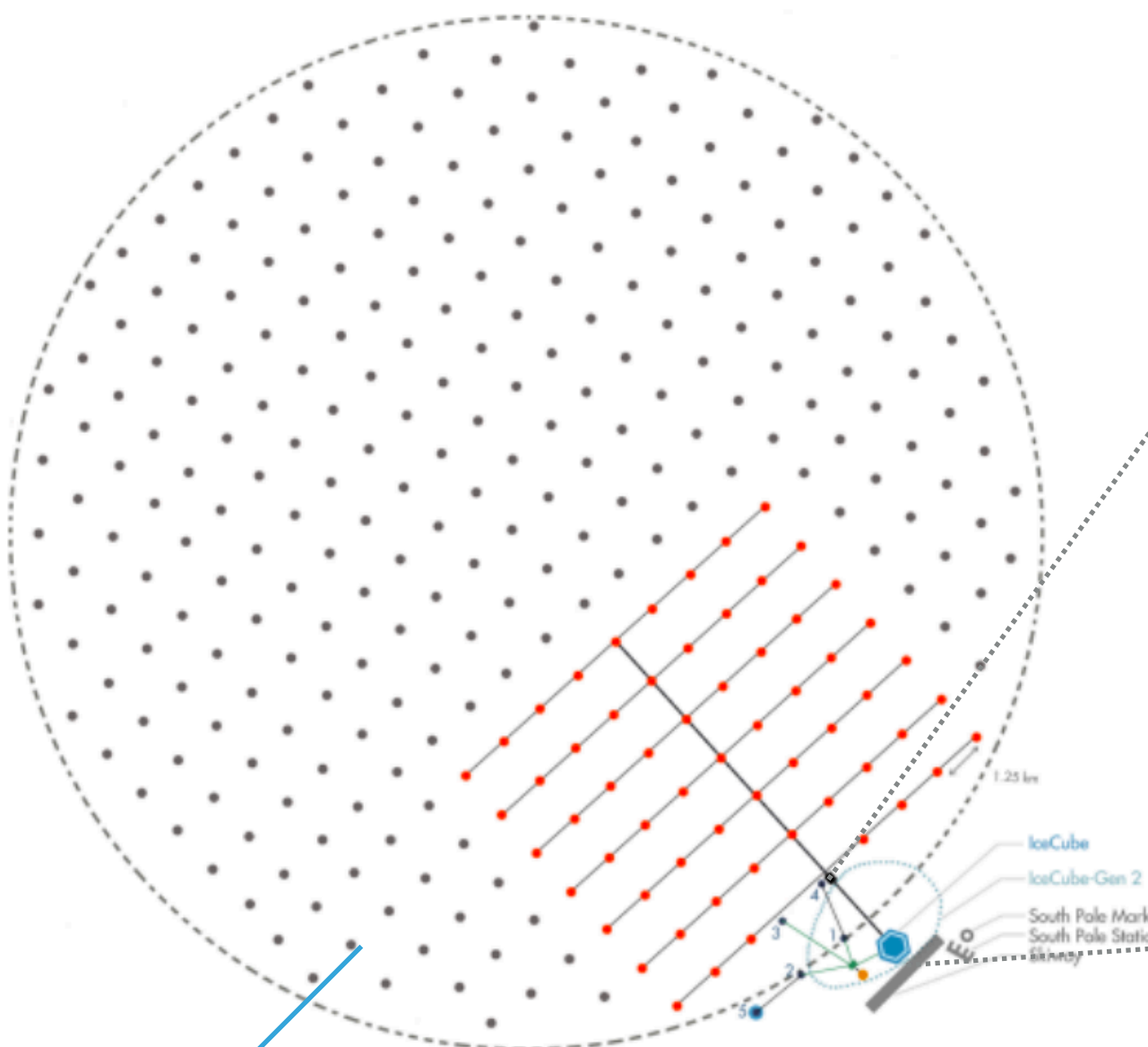
Rate: 20/yr



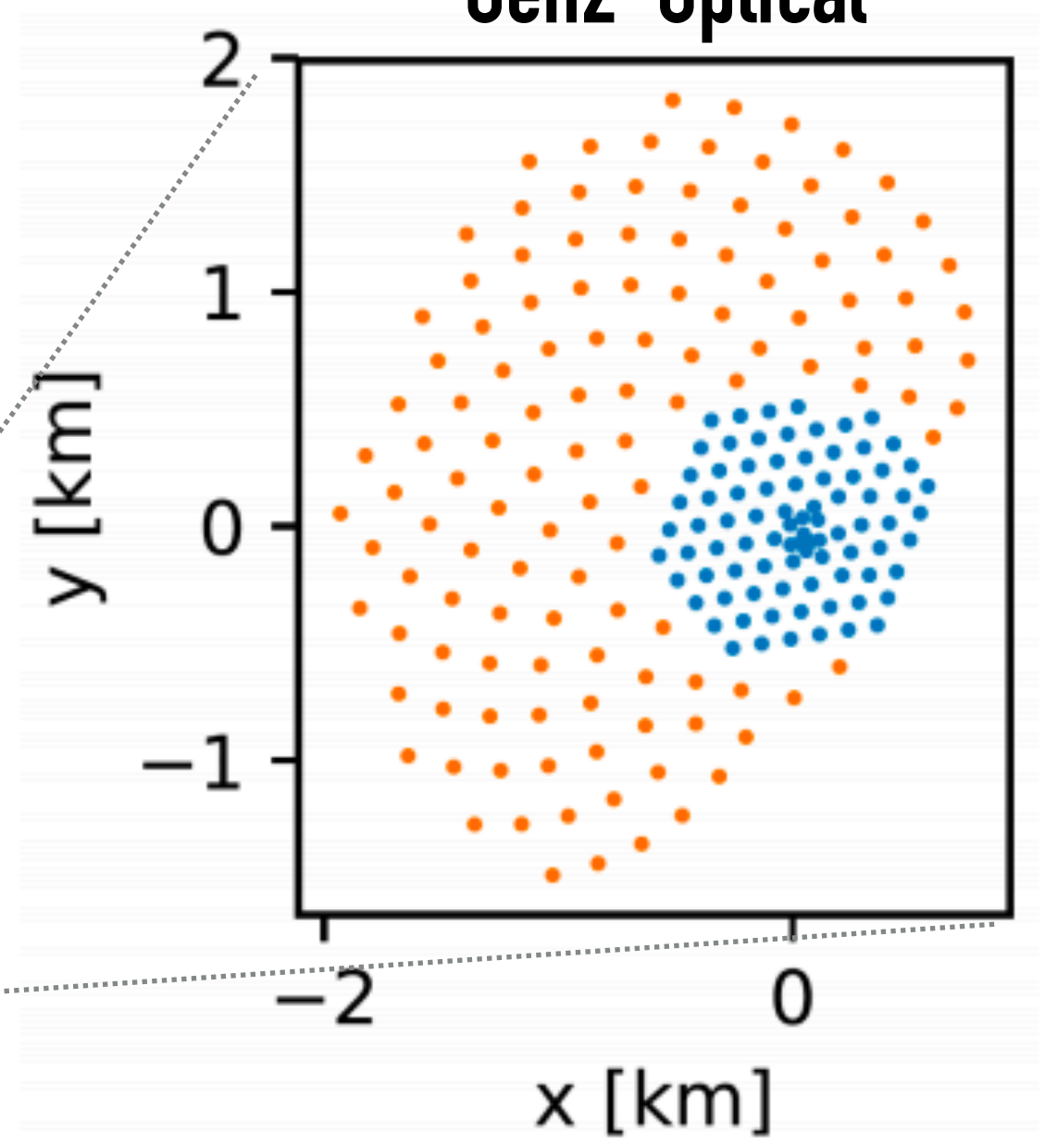


ICECUBE GEN2

Gen2-Radio



Gen2-Optical

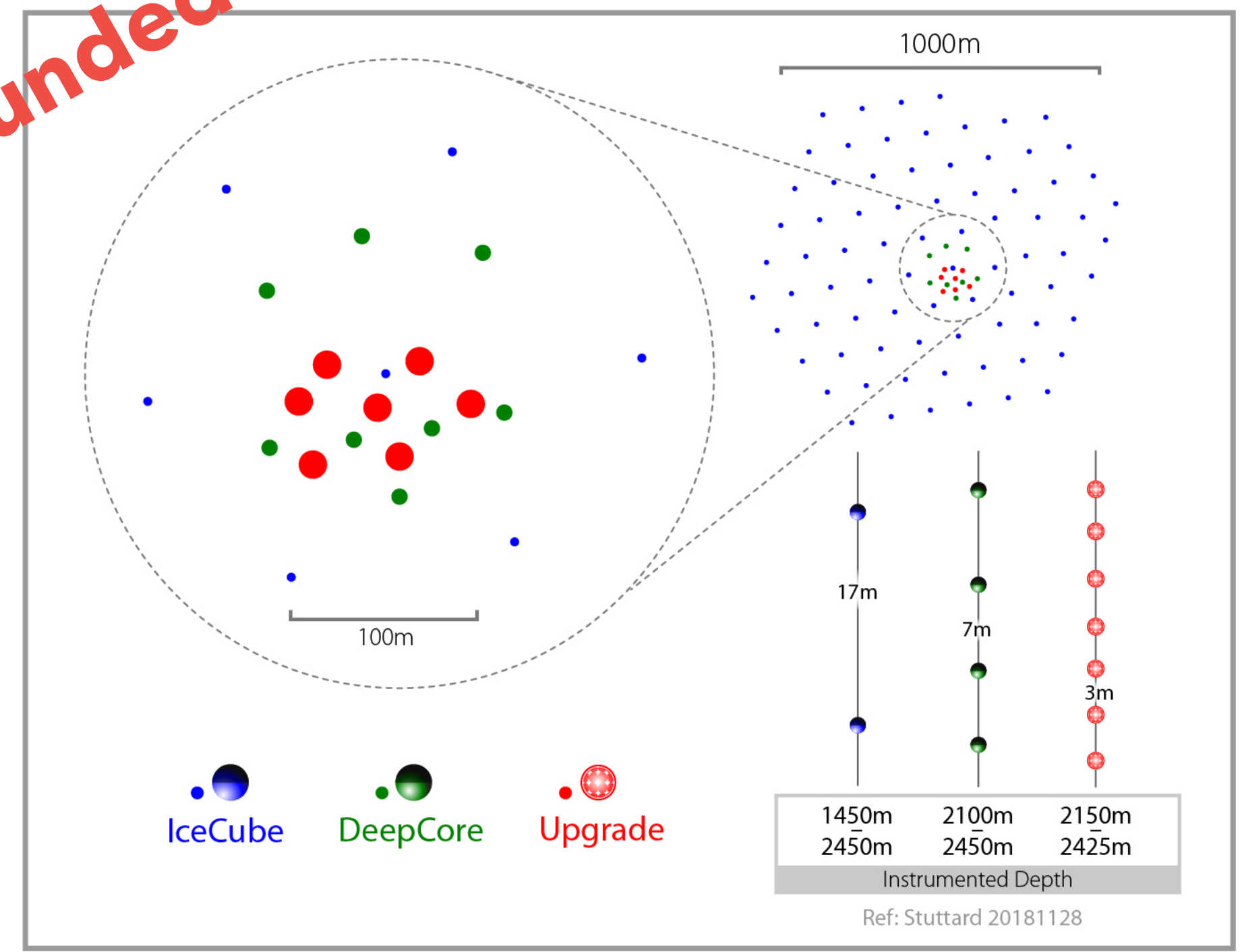


- OPTICAL DETECTOR: 5-10 KM³
- RADIO DETECTOR: ~ 200 STATIONS (~ 20 KM FOOTPRINT)
- STUDY OF THE ASTROPHYSICAL FLUX > 10 PEV
- DISCOVERY OF GZK NEUTRINOS (~ EEV)



ICECUBE UPGRADE

Funded



- DEEP CORE INFILL (7 NEW STRINGS) IN 2022-2023
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