

IceCube Neutrino Observatory



430 people from 59 institutions
in 14 countries

THE ICECUBE COLLABORATION

 **AUSTRALIA**
University of Adelaide

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

 **CANADA**
Queen's University
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
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität
Münster

 **ITALY**
University of Padova

 **JAPAN**
Chiba University

 **NEW ZEALAND**
University of Canterbury

 **REPUBLIC OF KOREA**
Chung-Ang University
Sungkyunkwan University

 **SWEDEN**
Stockholms universitet
Uppsala universitet

 **SWITZERLAND**
Université de Genève

 **TAIWAN**
Academia Sinica

 **UNITED KINGDOM**
University of Oxford

 **UNITED STATES**
Clark Atlanta University
Columbia University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University

Massachusetts Institute
of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines
and Technology
Southern University
and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas

University of Maryland
University of Nevada, Las Vegas
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)

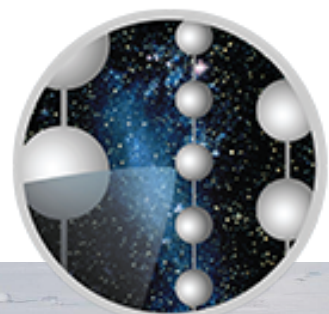
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

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

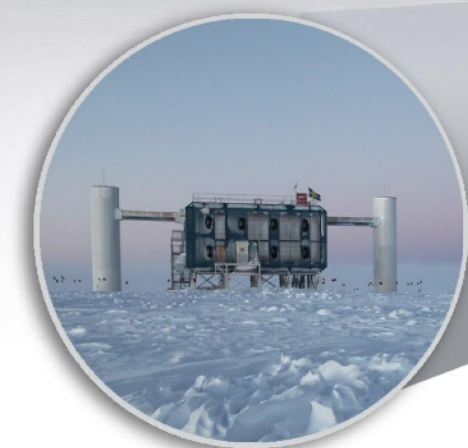
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)



icecube.wisc.edu



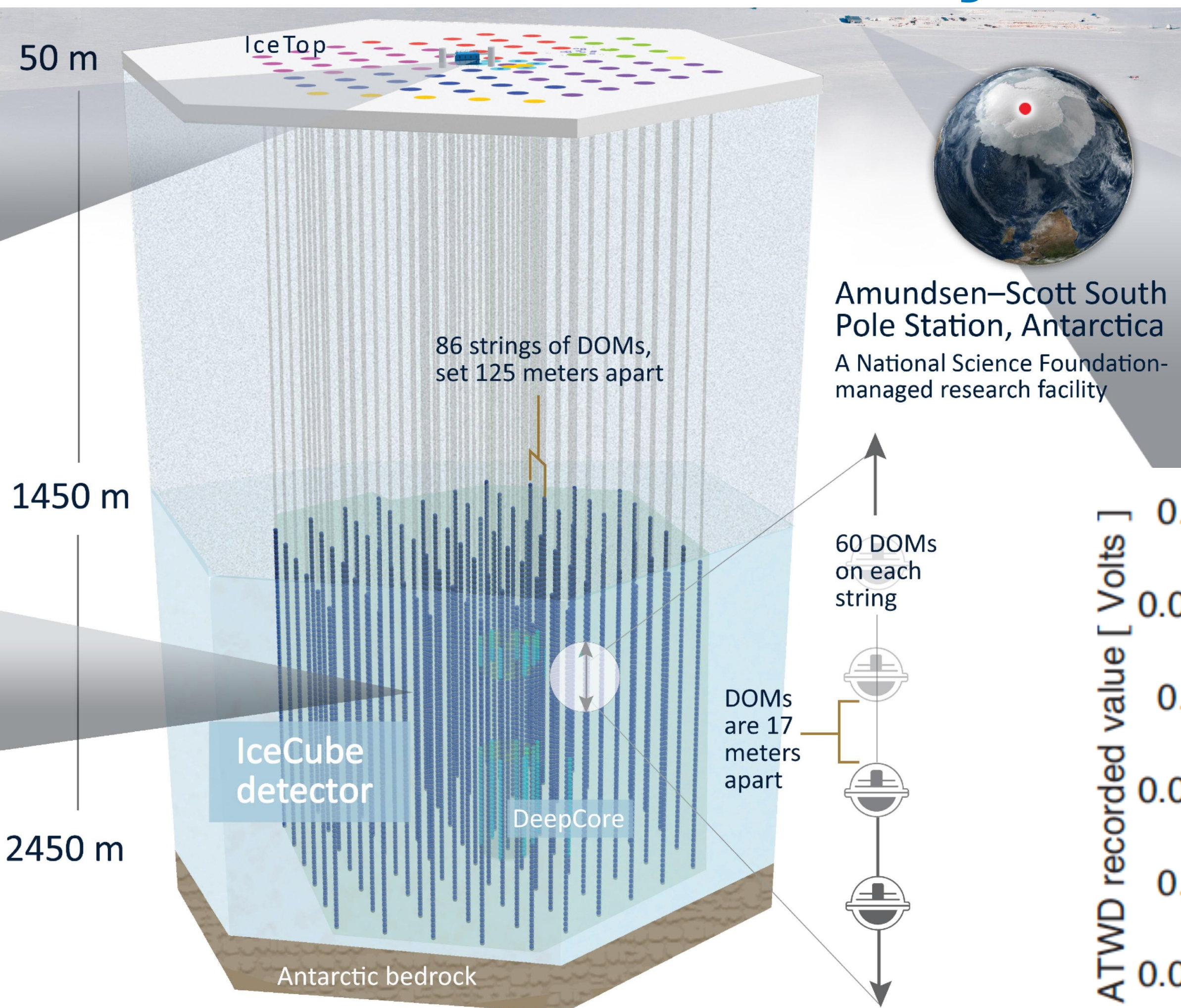
IceCube Neutrino Observatory



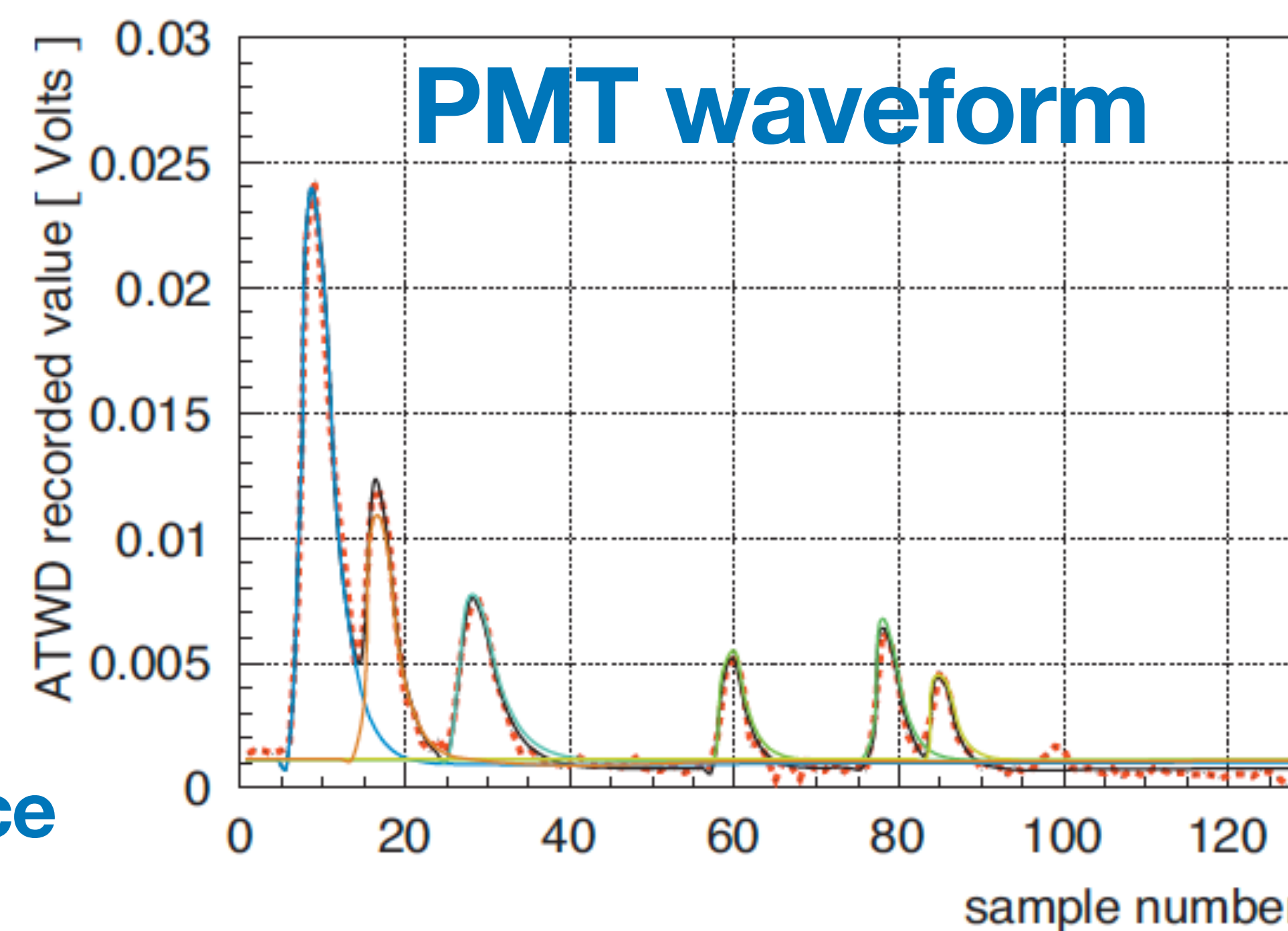
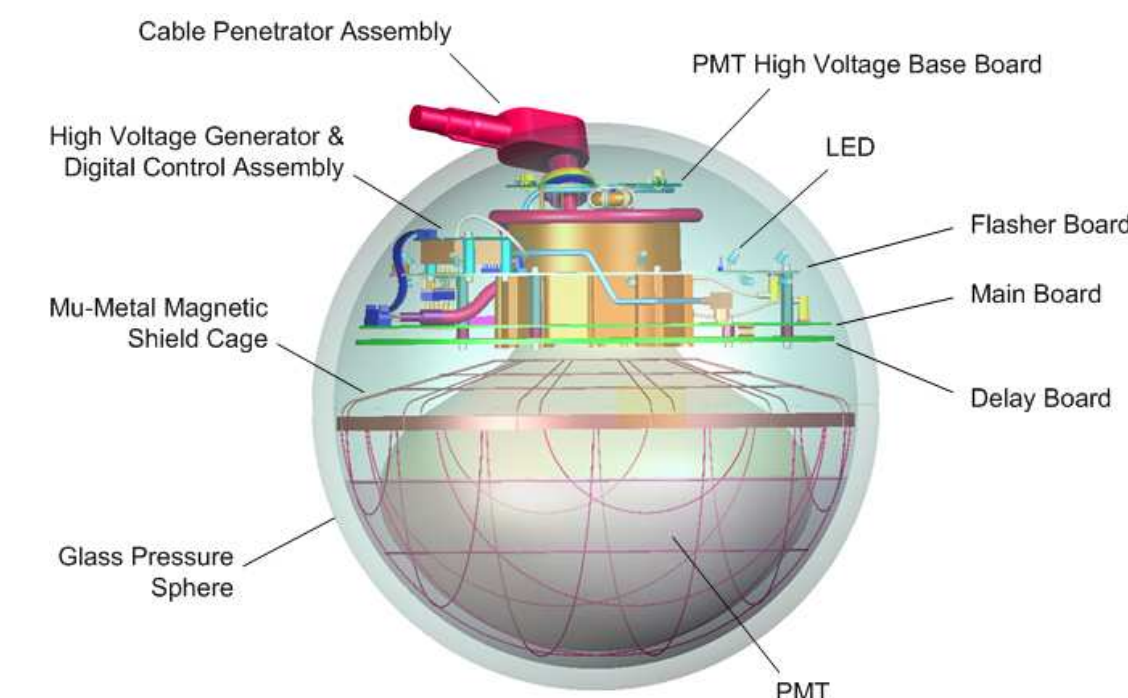
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison



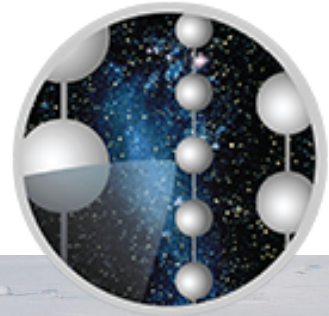
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice



Digital Optical Module (DOM)



Cherenkov Detector using 1 km³ South Pole ice



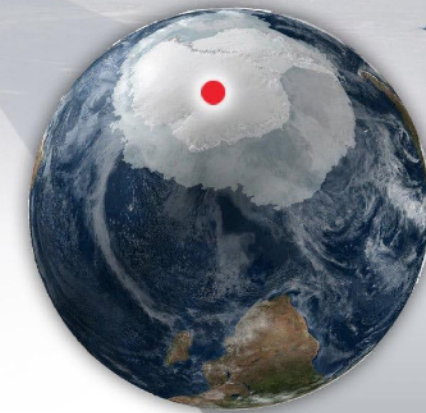
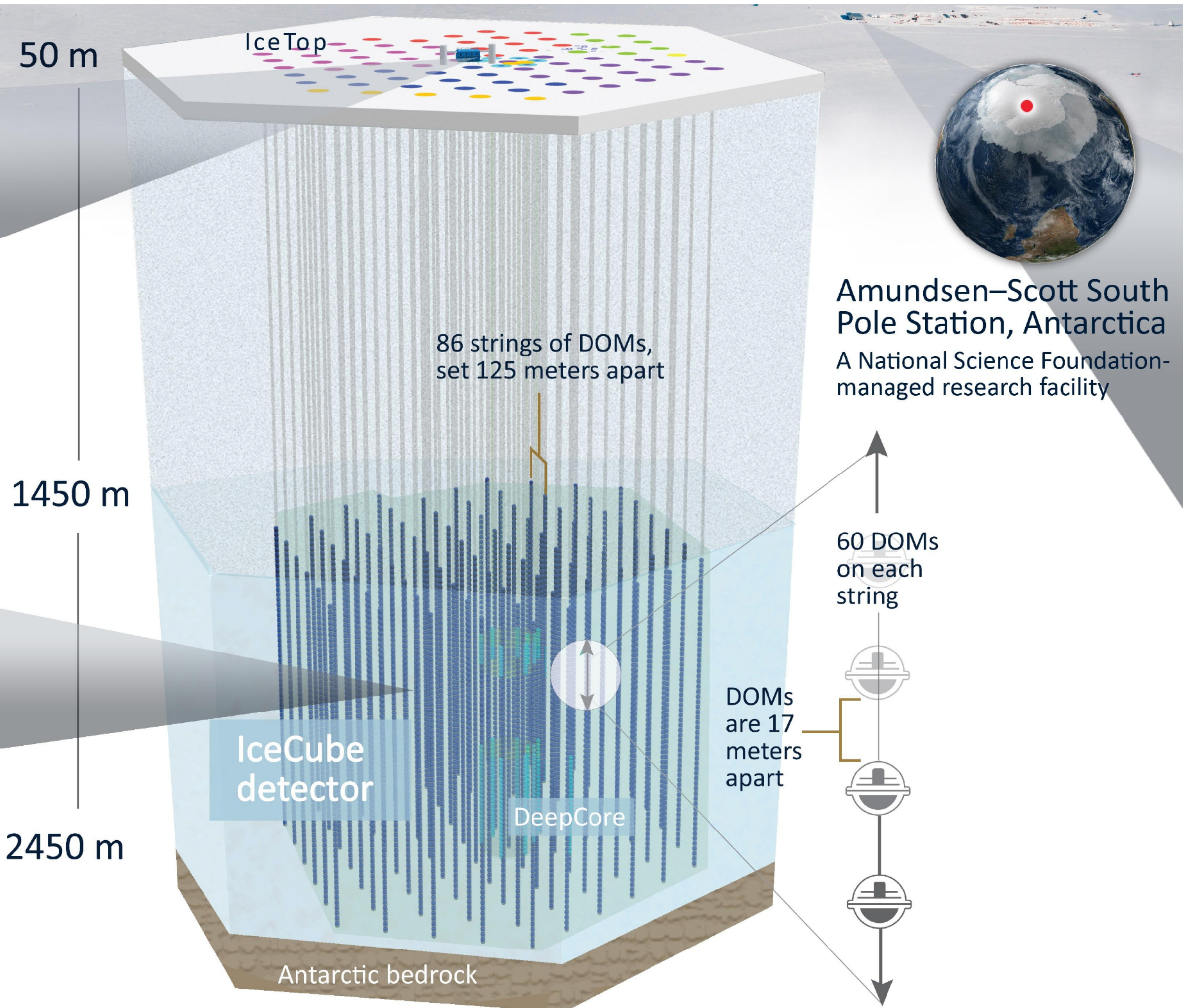
IceCube Neutrino Observatory



IceCube Laboratory
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Digital Optical Module (DOM)
5,160 DOMs deployed in the ice



IceCube Science

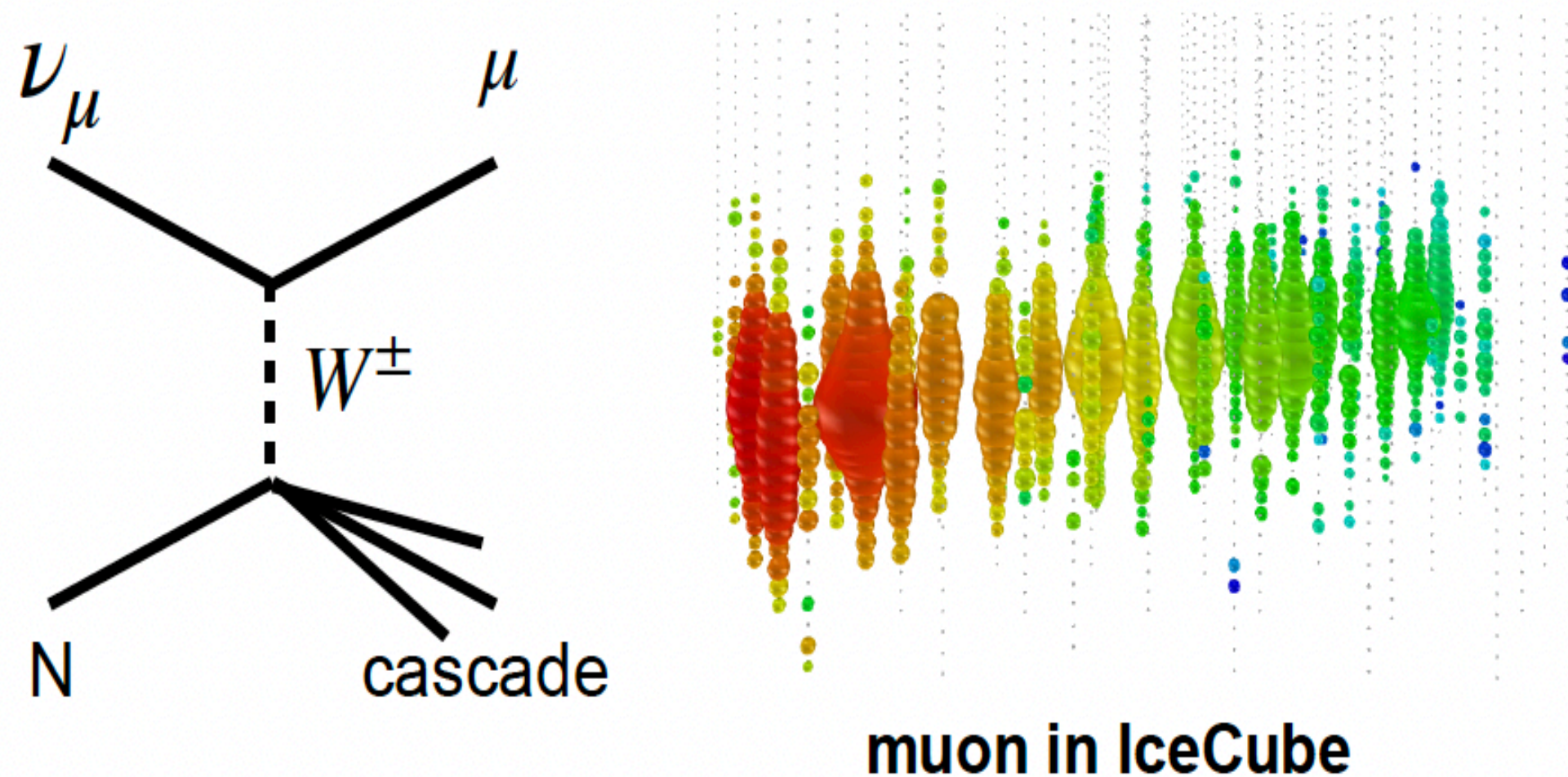
- **Neutrino Astrophysics**
 - Diffuse Neutrinos
 - Search for Neutrino source
 - Multi-messenger astrophysics
- **Neutrino particle physics**
 - Neutrino oscillations
 - Sterile neutrinos & NSI search
- **Cosmic Ray physics**
 - Cosmic ray anisotropy
 - Components of Cosmic ray
 - Cosmic ray spectrum
- **Dark matter & BSM physics**
 - Dark matter indirect detection
 - Axion, Magnetic monopole, SUSY.

Cherenkov Detector using 1 km³ South Pole ice

Event Topology (Track vs. Cascade)

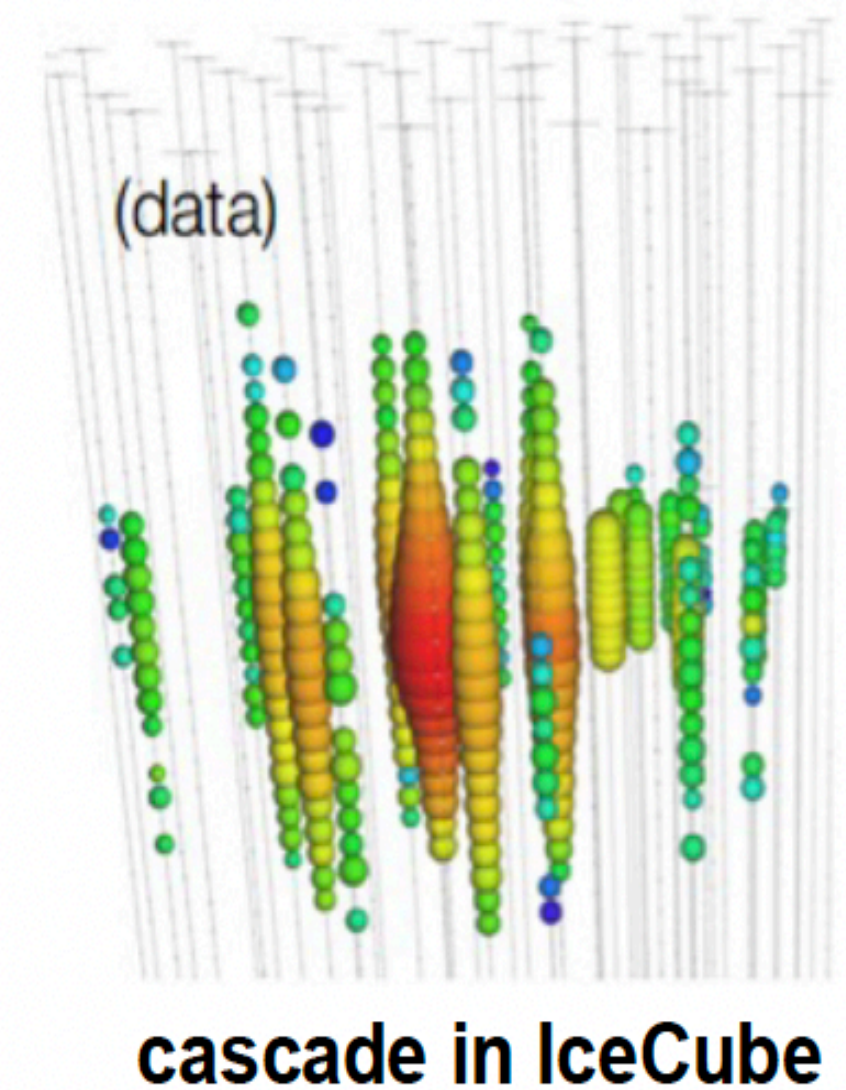
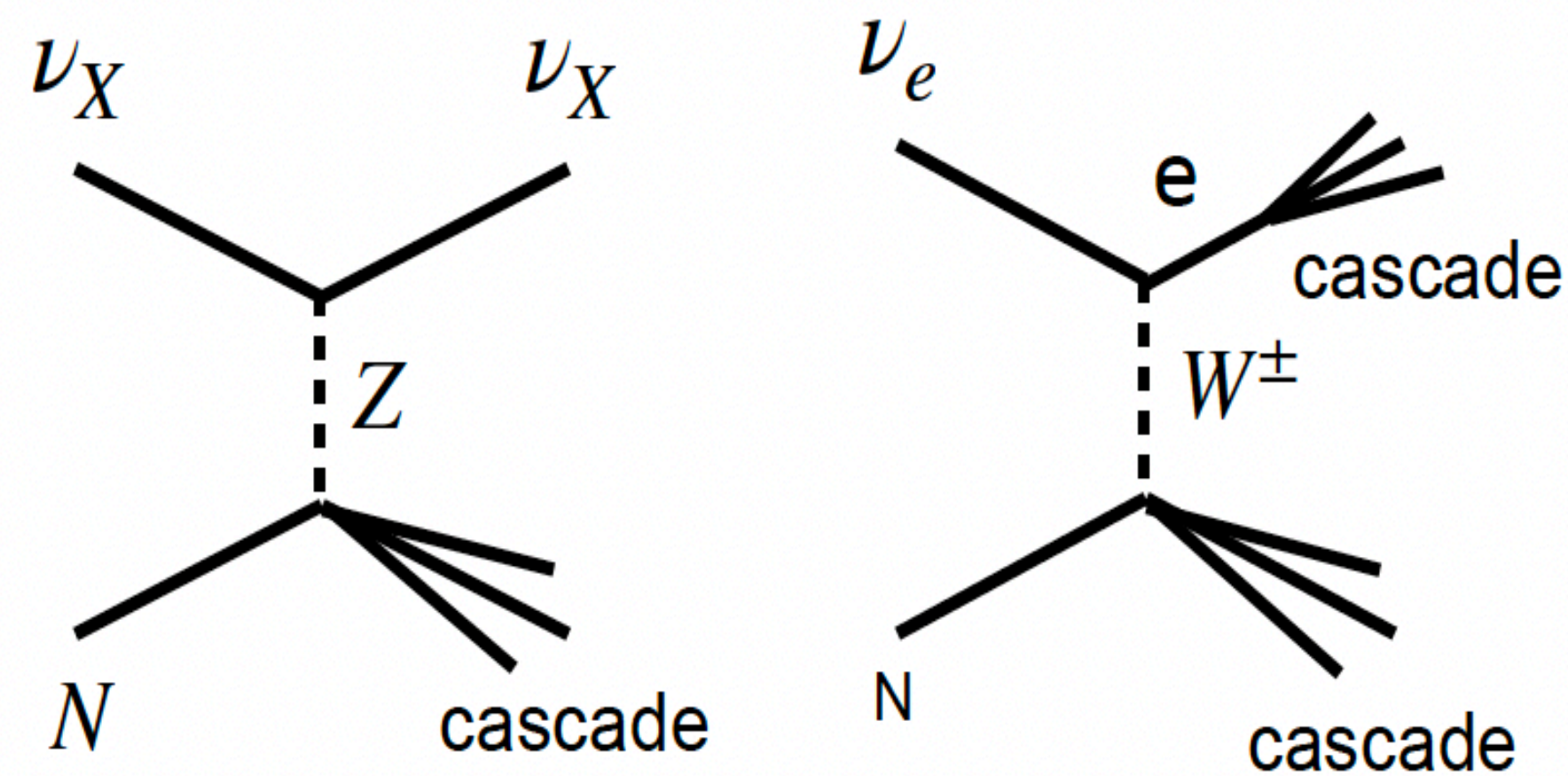
Track-like

- Good angular resolution: 0.5° for $E > 10$ TeV
→ prime channel for point sources
- Energy resolution factor ~ 2

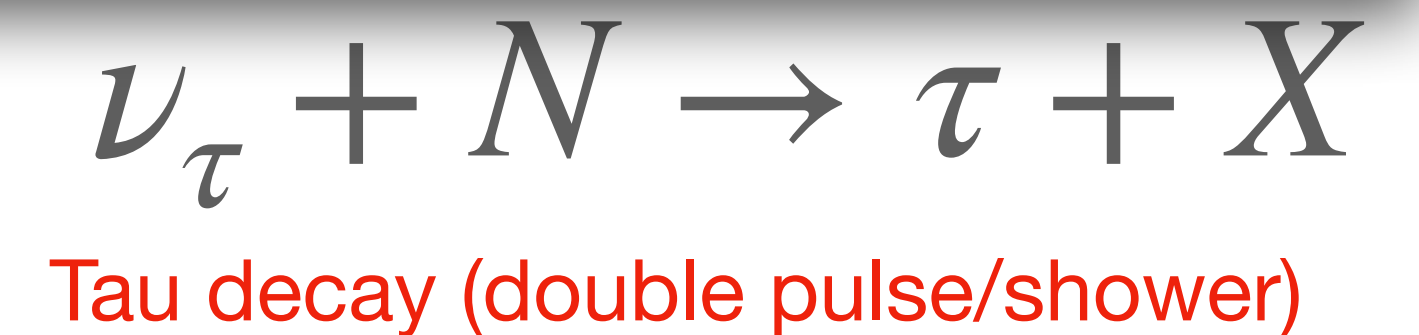
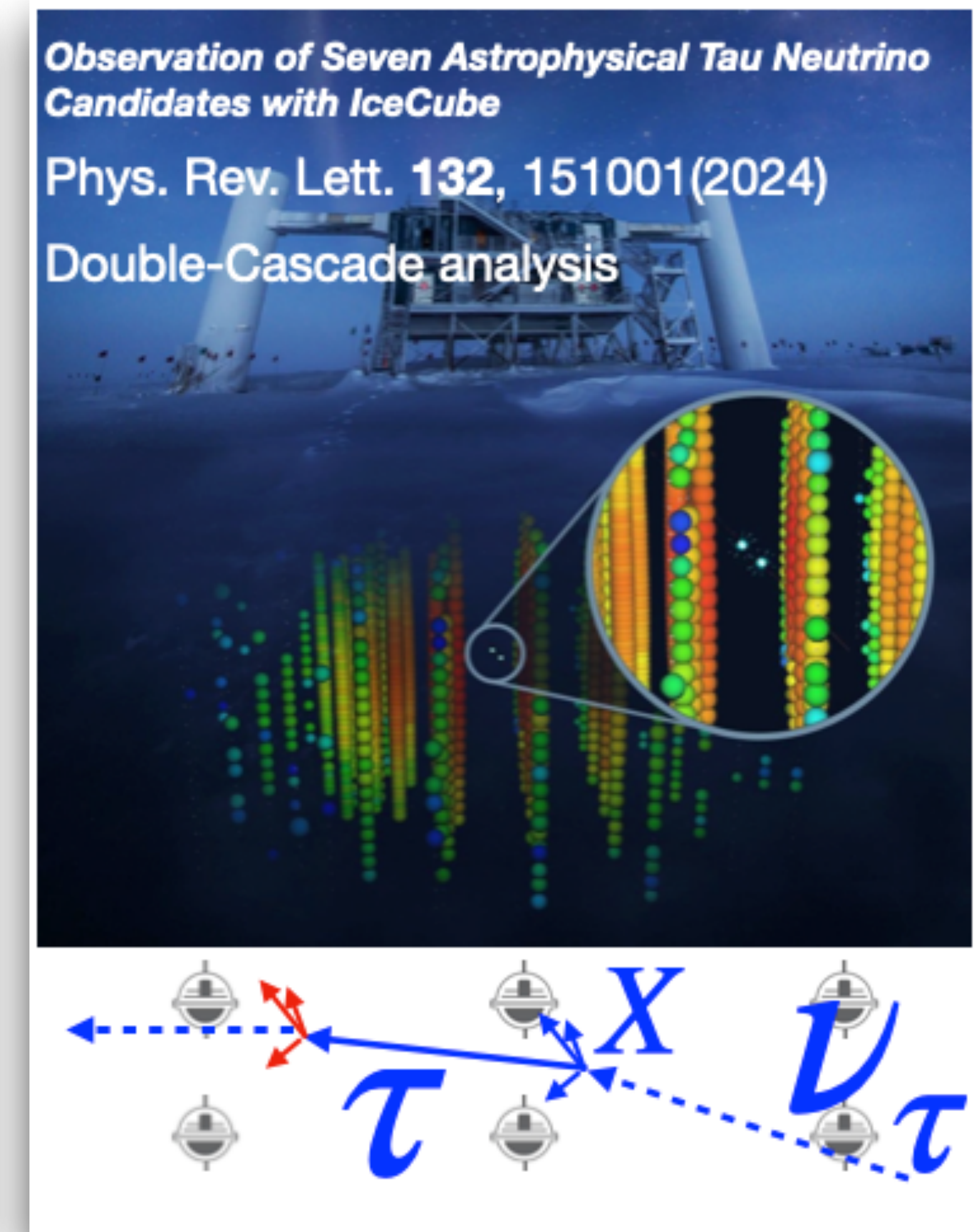
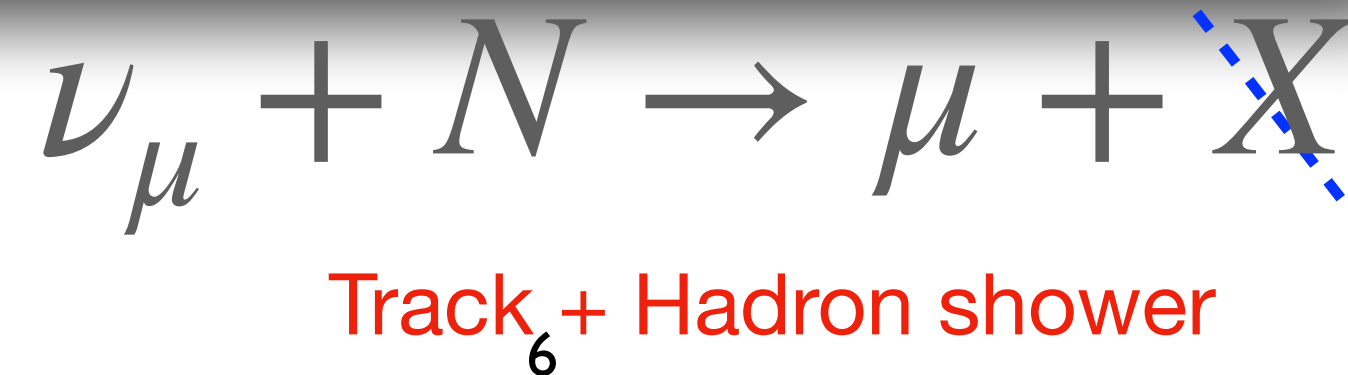
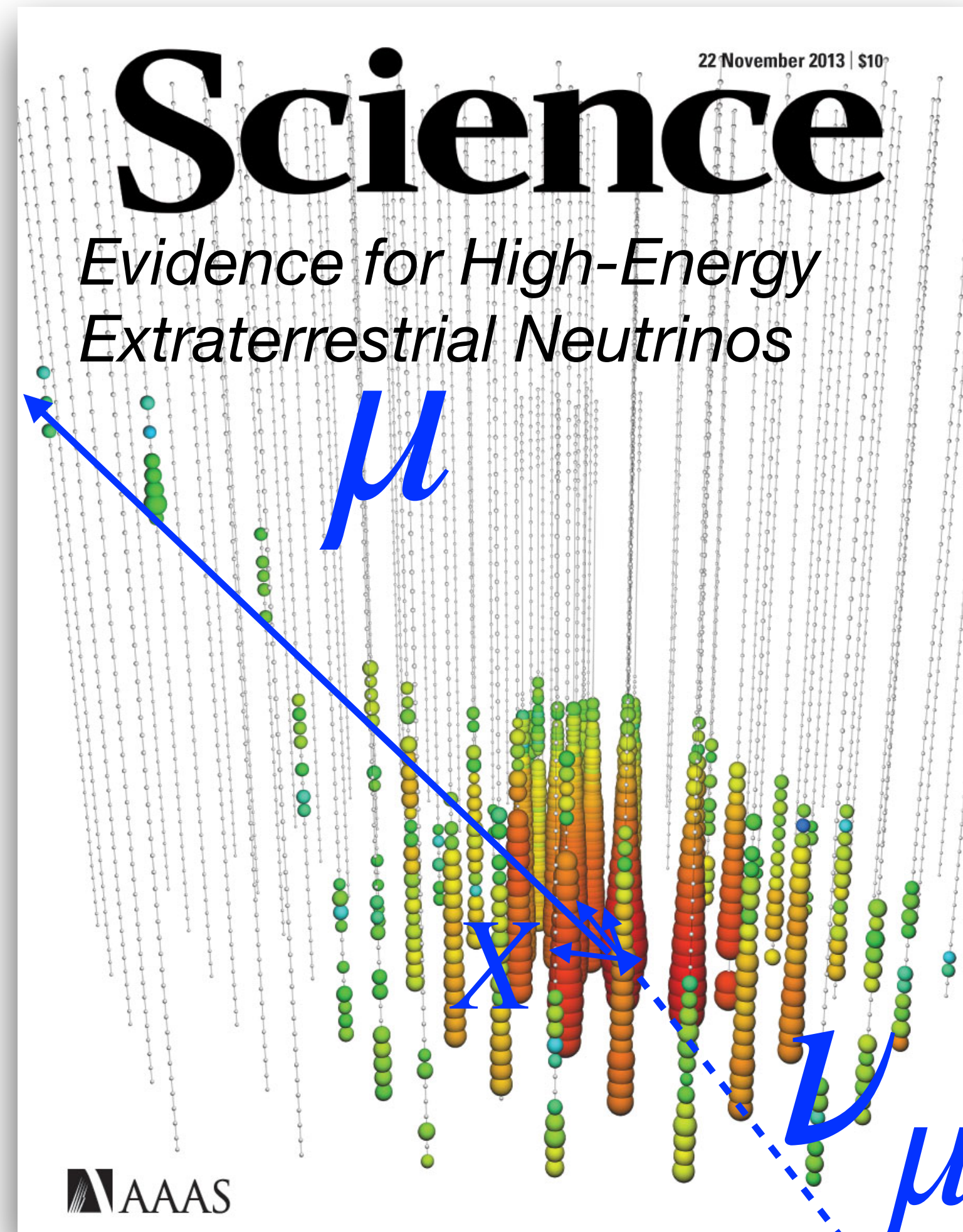
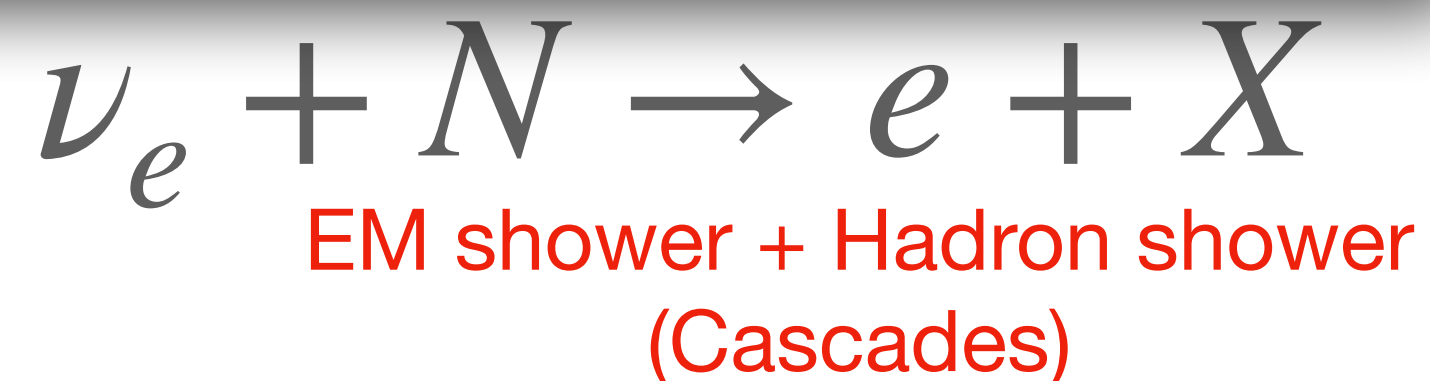
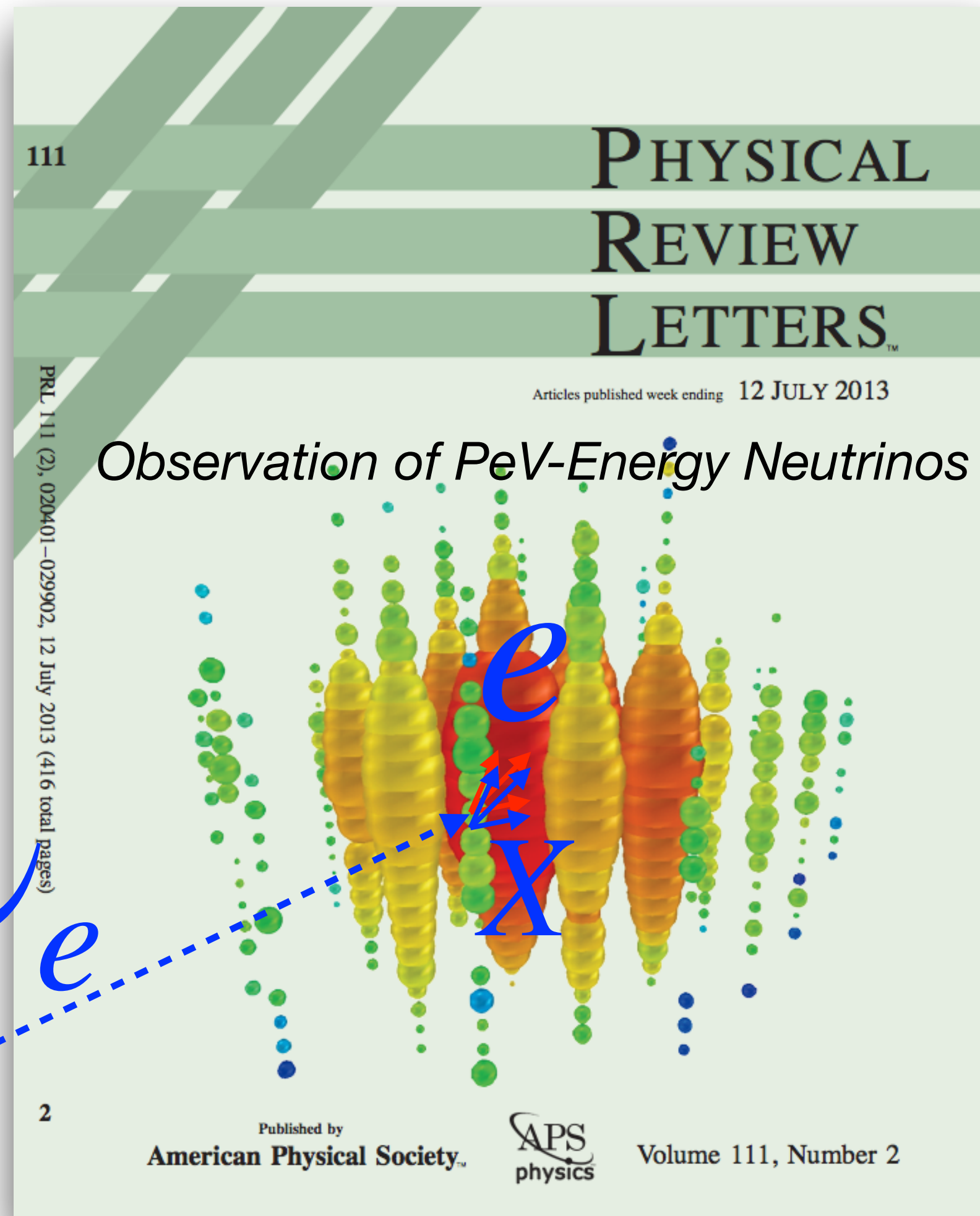


Cascade-like

- Good energy resolution $< 10\%$ for $E > 10$ TeV
- Angular resolution $\lesssim 5^\circ$ for $E > 50$ TeV
(contained events)



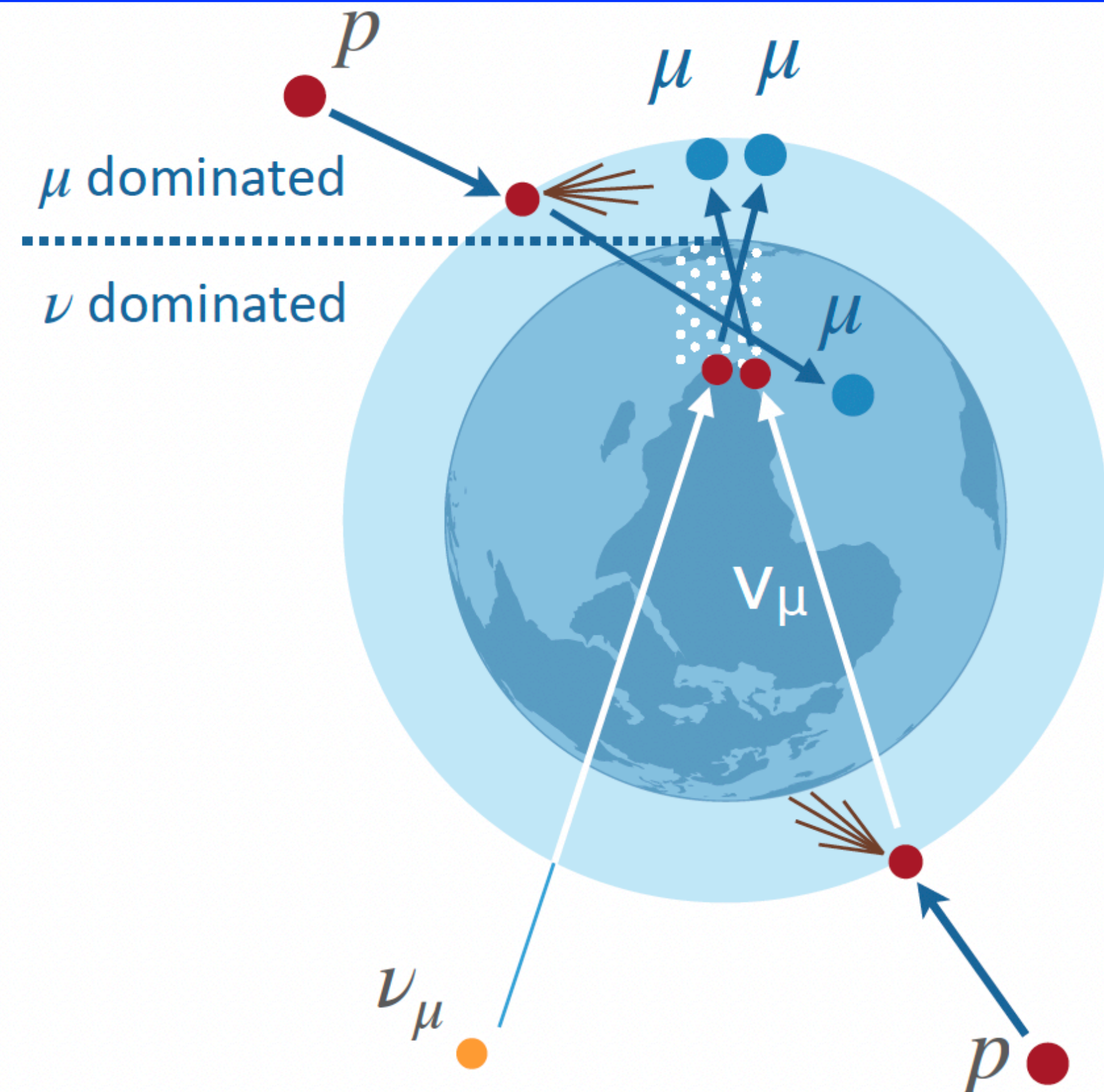
Event Topology (Track vs. Cascade)



Event Selections

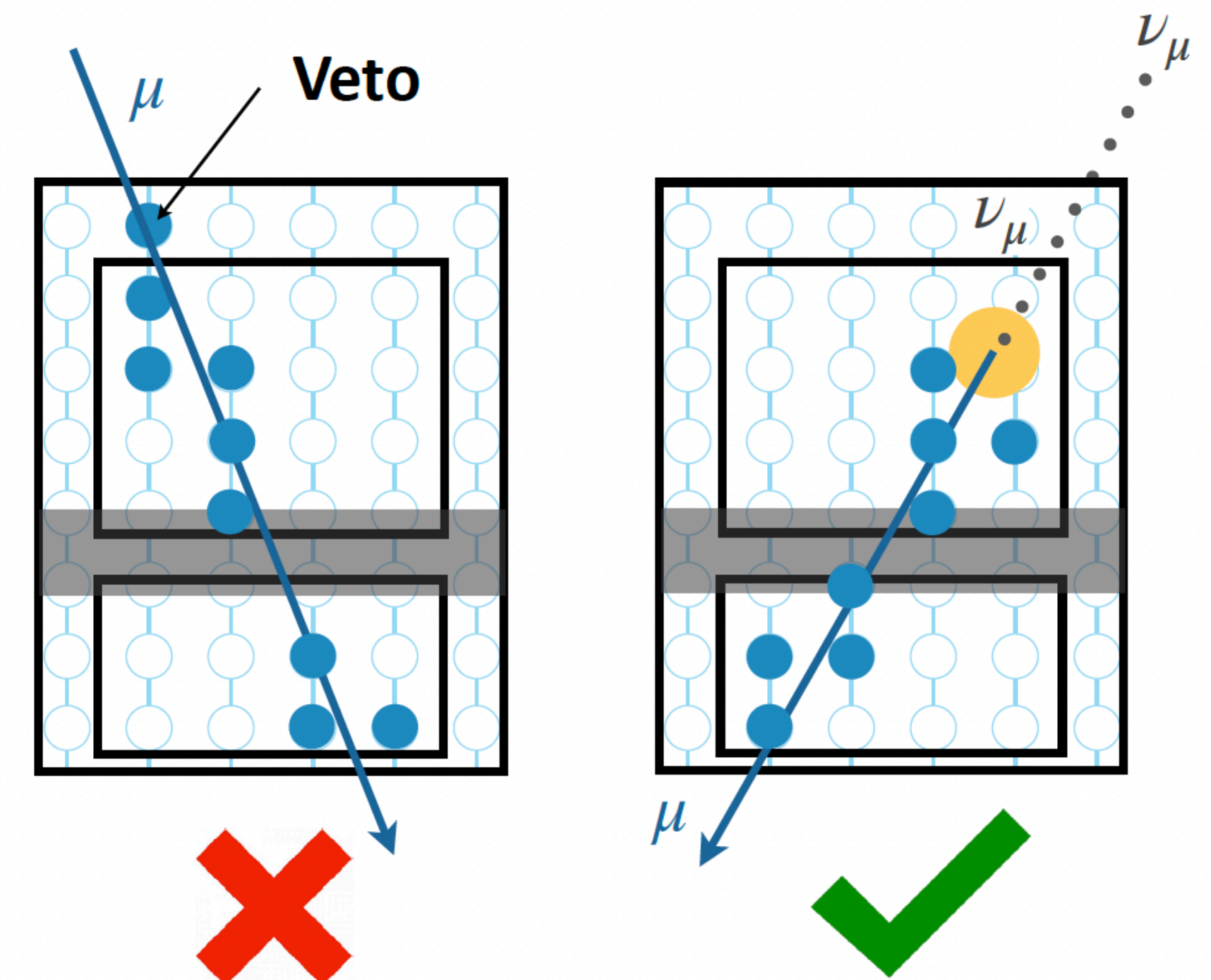
Northern sky through-going Track analysis

- Effective Volume is large (more events)
- Neutrino Search only northern sky (2π)
- Energy measurement in a sampling way

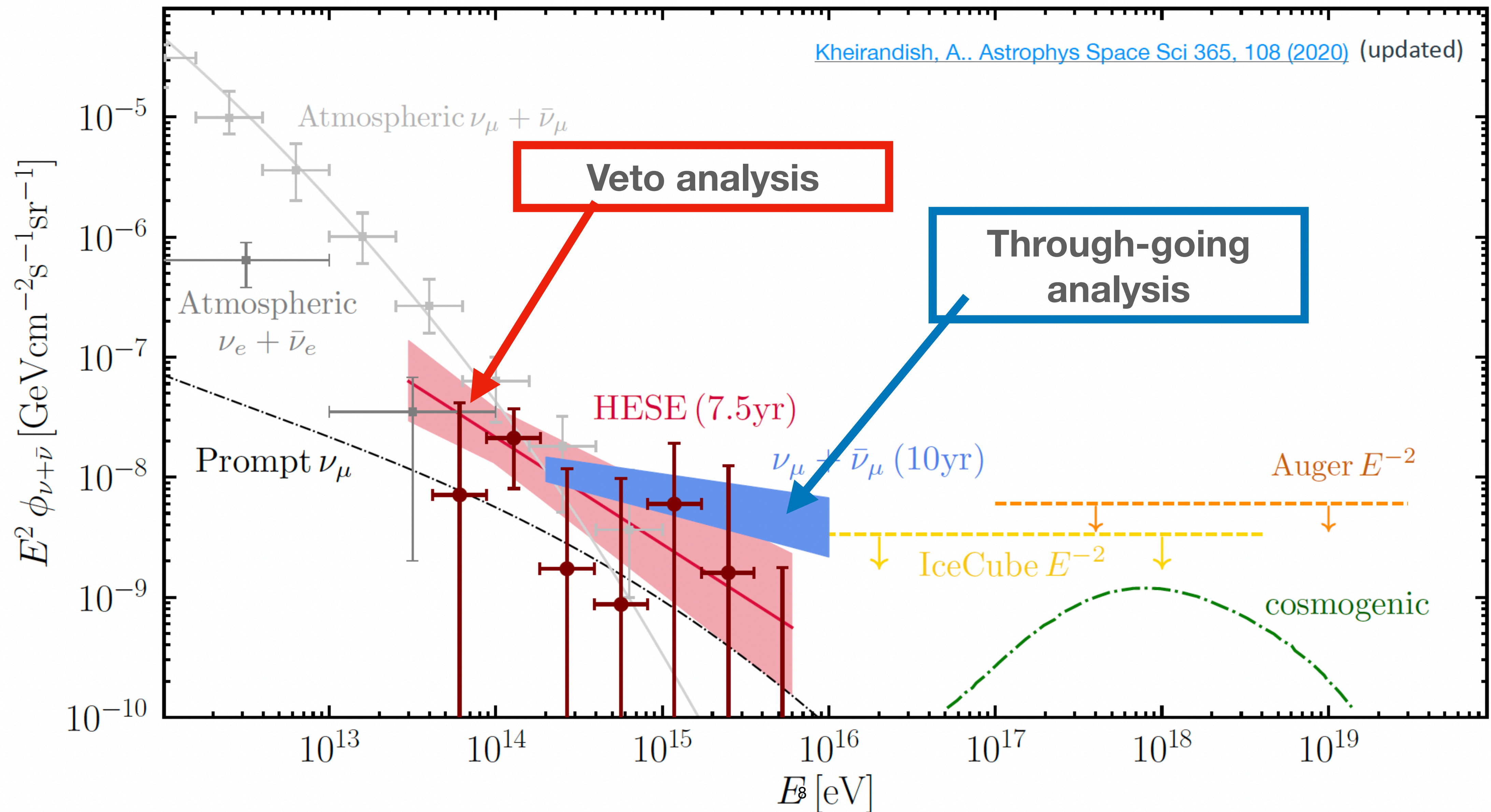


Veto-based analysis

- Veto-Fiducial volume division
- Effective Volume is small (less events)
- All sky Neutrino Search (4π)
- Events can contain cascades.
- Calorimetric energy measurement

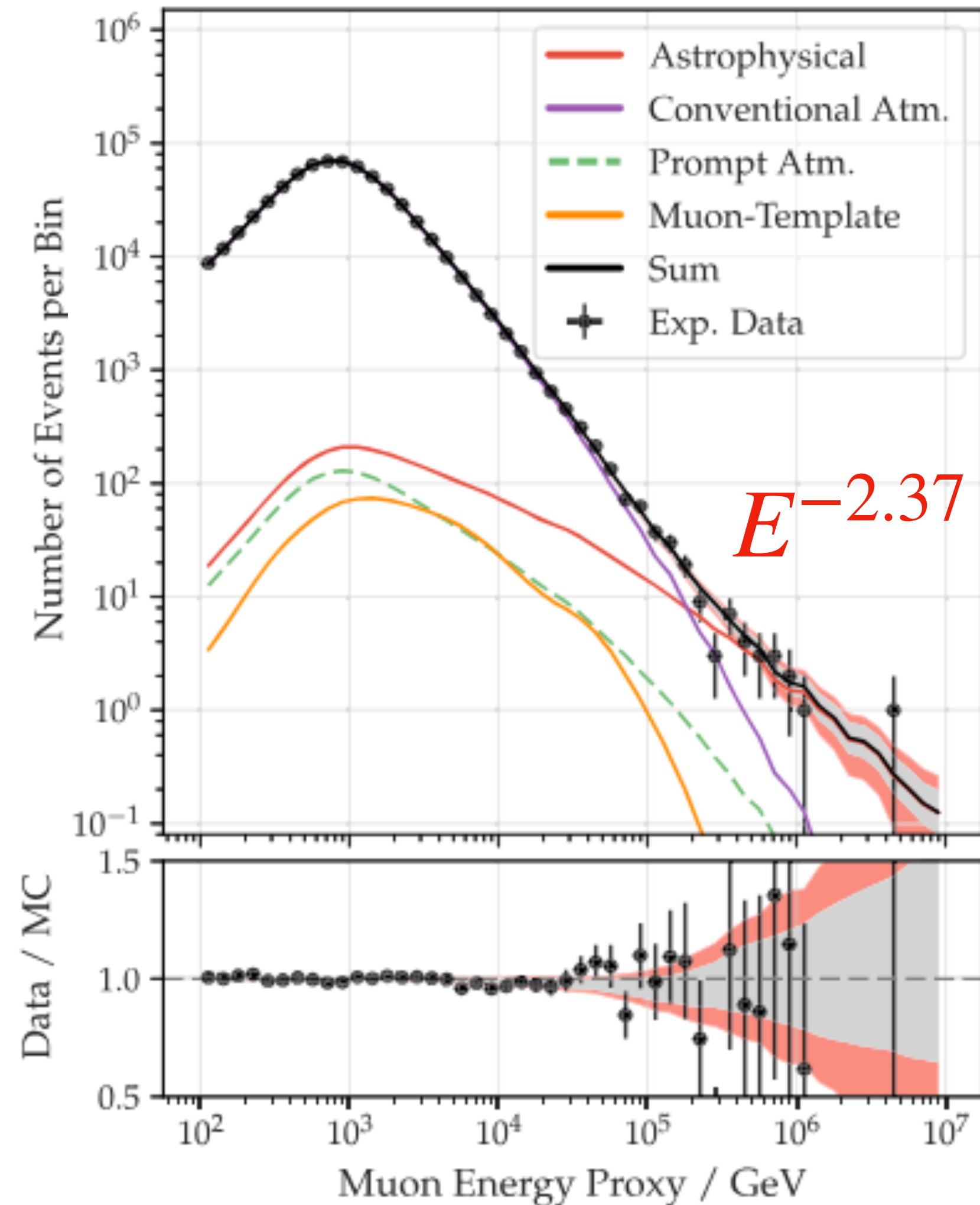


Neutrino Flux (Astrophysical diffuse neutrino)



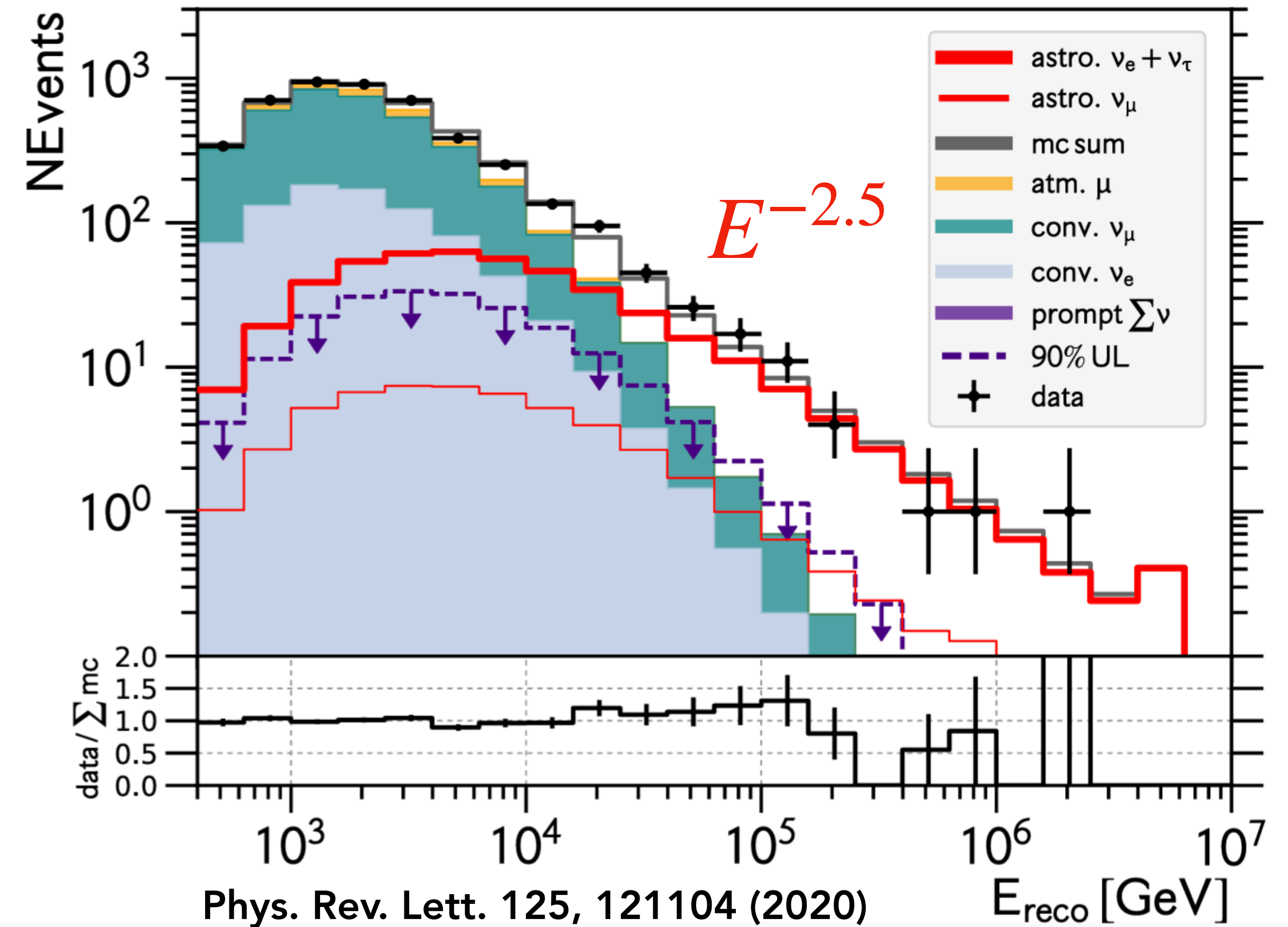
Astrophysical Neutrino Flux

Northern sky through-going Track analysis

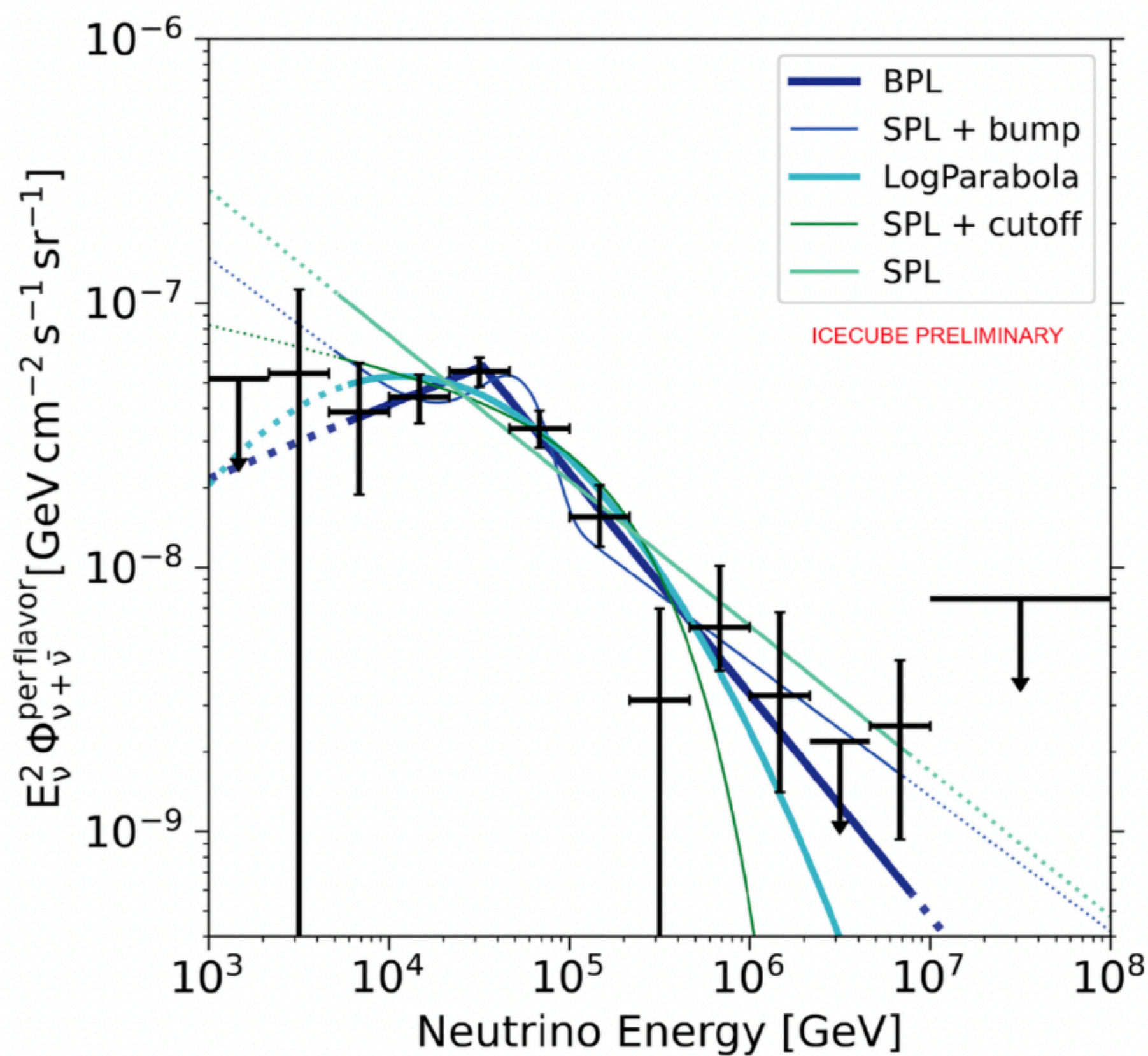
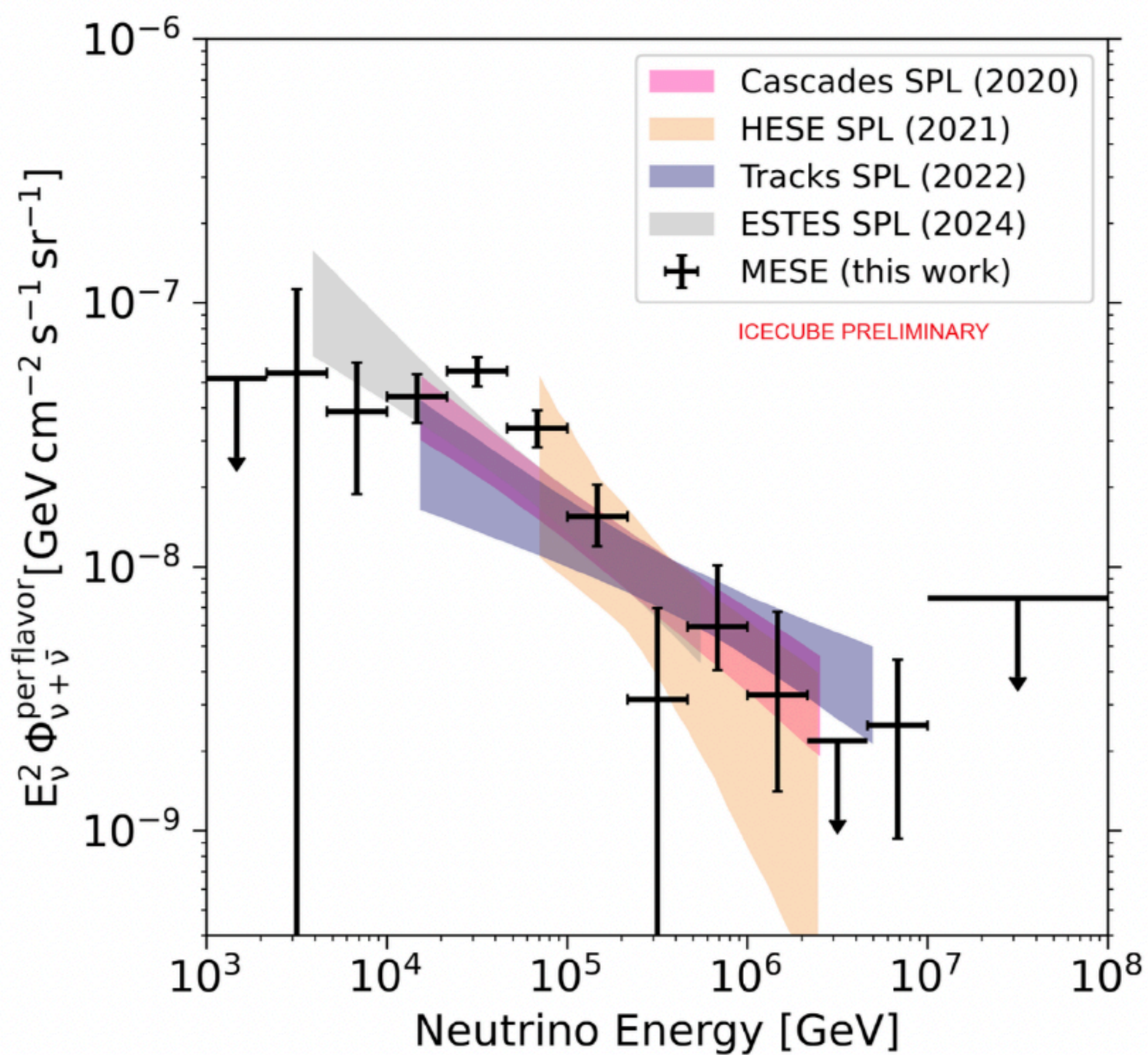


Astrophys. J. 928 , 50 (2022)

All sky Cascades analysis



Astrophysical Neutrino Flux

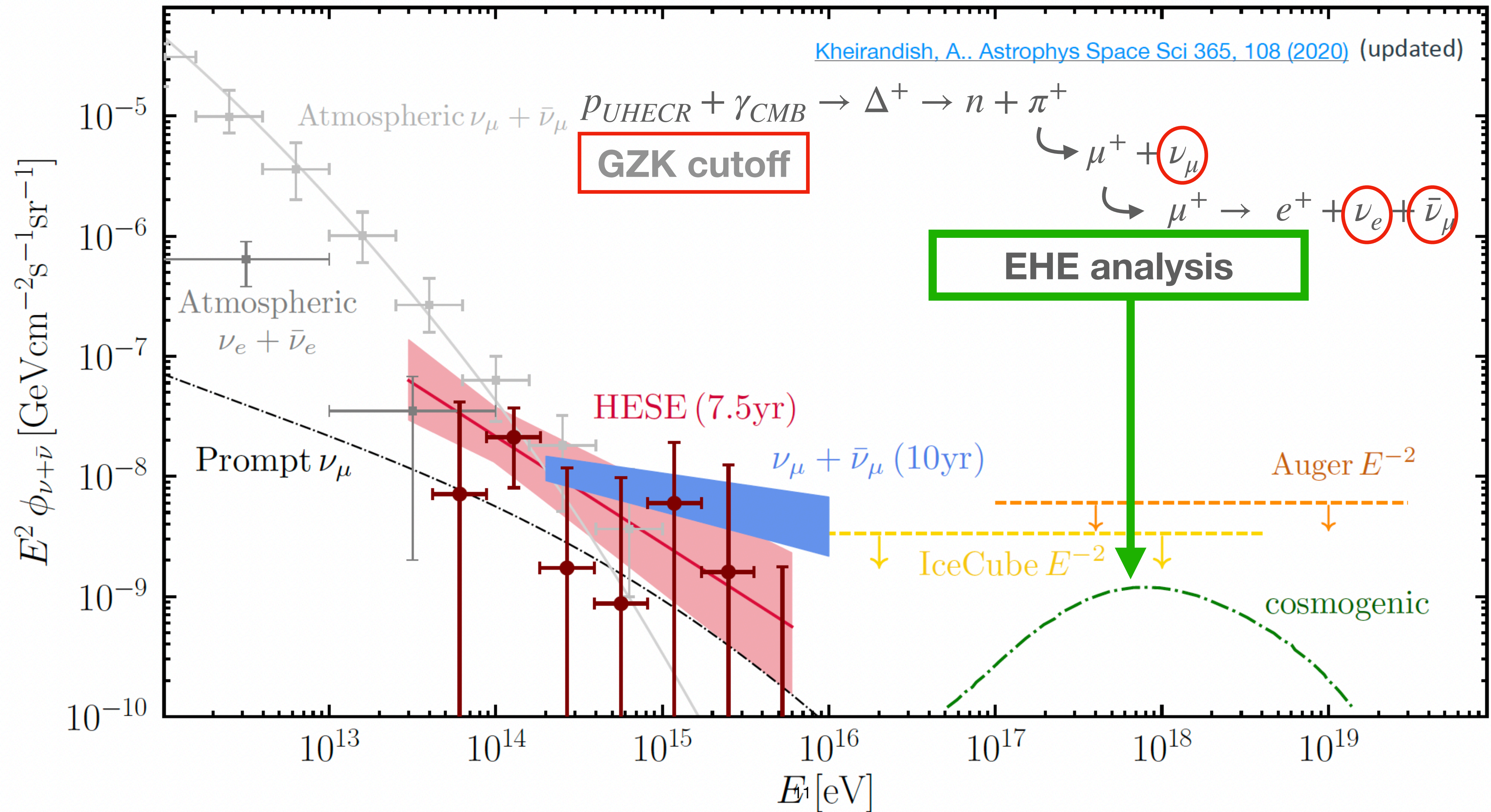


	$-2\Delta\ln\mathcal{L}$ compared to SPL
Single PL	0
SPL + Cutoff	1.8 (0.9 σ)
Log Parabola	19.8 (4.2 σ)
SPL + Bump	22.3 (3.9 σ)
Broken PL	27.3 (4.7 σ)

Astrophysical Neutrino Flux is not a single mechanism!

Single Power model is rejected at 4.7 σ from Broken Power model (hard at low-E and soft at high-E)

Neutrino Flux (GZK neutrinos, Extremely High Energy)



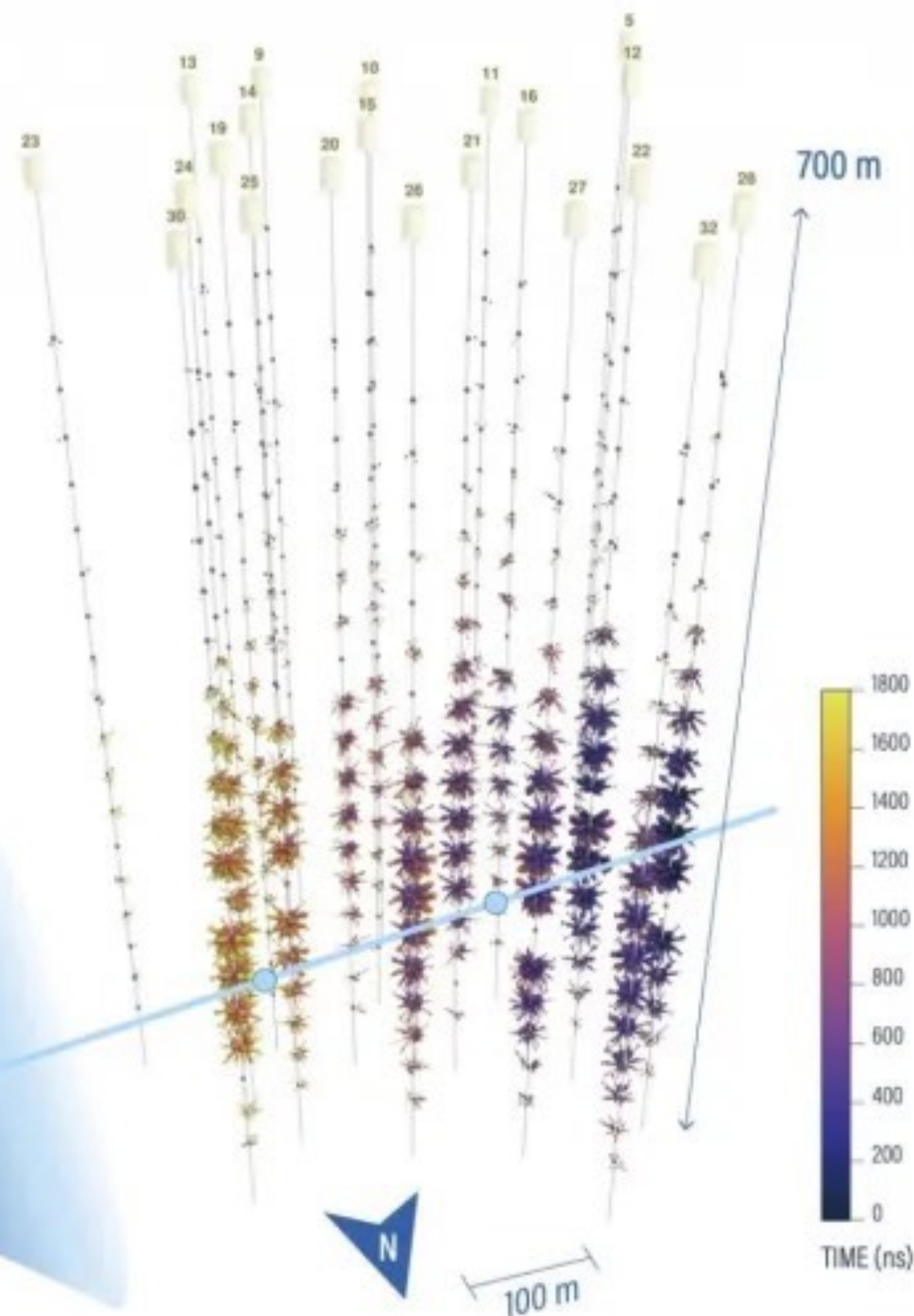
NEUTRINOS



With no electric charge, being extremely light and travelling almost at the speed of light, these elementary particles interact only weakly, and therefore very rarely, with matter. Their elusiveness makes them valuable cosmic messengers, able to bring us unique information about the distant universe.

THE EVENT DISPLAY

A view of the KM3-230213A signal detected by KM3NeT. The spheres are coloured according to the detection time and the reconstructed track of the particle is shown. The size of the blue cone gives an indication on the amplitude of the signal.



THE SOURCES



The origin of the ultra-high energy neutrino could have been one of the cataclysmic events that animate our universe, such as an active galactic nucleus or a gamma-ray burst. Or it could be a neutrino generated by the interaction of an ultra-high energy cosmic-ray particle with the cosmic background radiation that permeates the universe.

THE RECORD NEUTRINO

On 13 February 2023, at a depth of 3450 metres off the coast of Sicily, in Italy, the ARCA detector of the KM3NeT submarine neutrino telescope recorded an extraordinary signal: produced by a neutrino with a record energy of about 220 PeV, corresponding to 220 million billion electronvolts. This signal, named KM3-230213A, provides the first evidence that neutrinos with such extreme energies exist in the universe.

KM3-230213A IDENTIKIT

The cosmic neutrino plunged into the Mediterranean Sea and crossed the Malta continental shelf with an inclination of 0.6° above the horizon. During this journey, it travelled almost at the speed of light and interacted with an atomic nucleus, generating an ultra-relativistic muon, which crossed the whole detector.



KM3NeT Coll, Nature 638 (2025) 8050

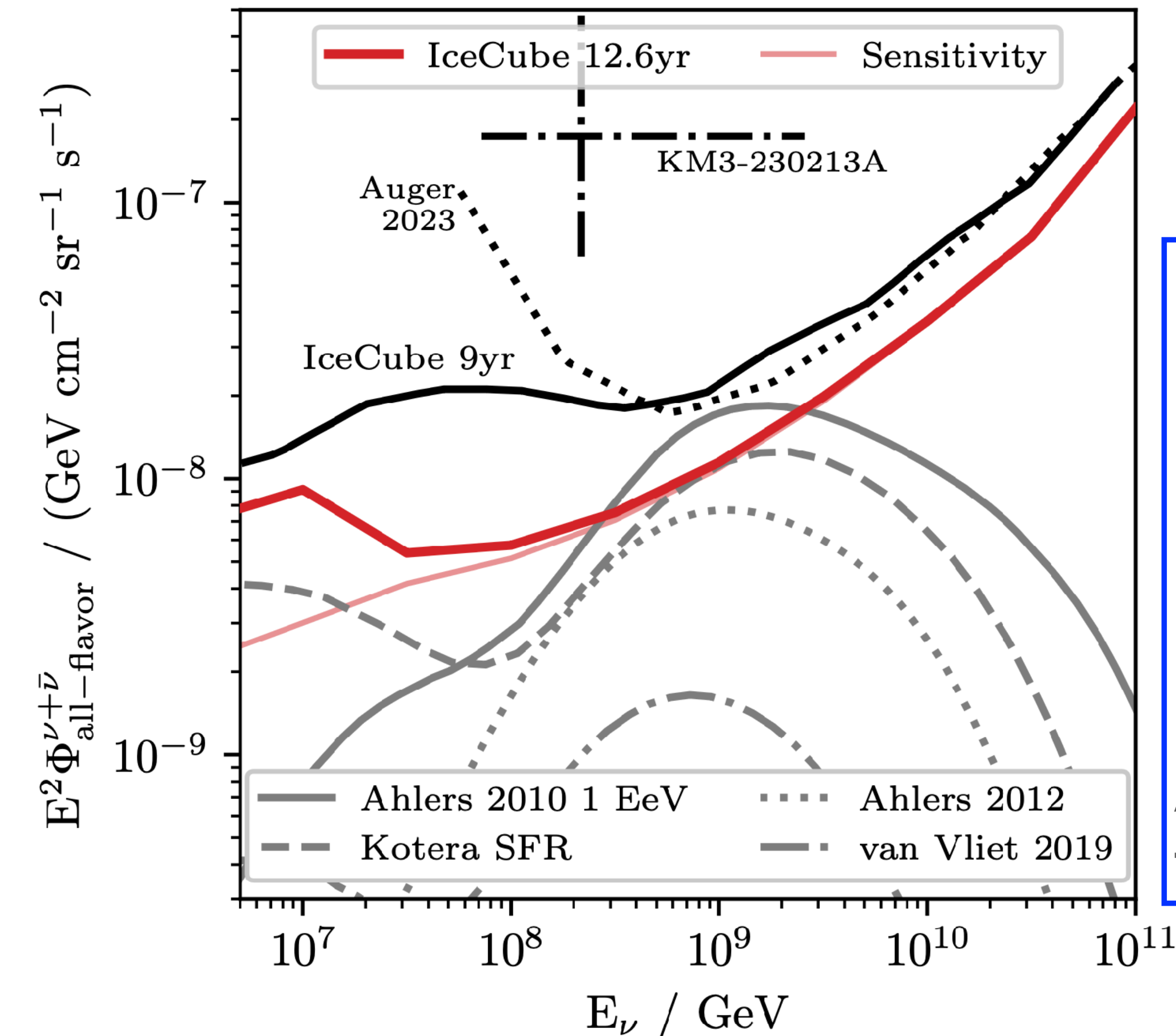


IceCube EHE neutrino search & KM3-230213A

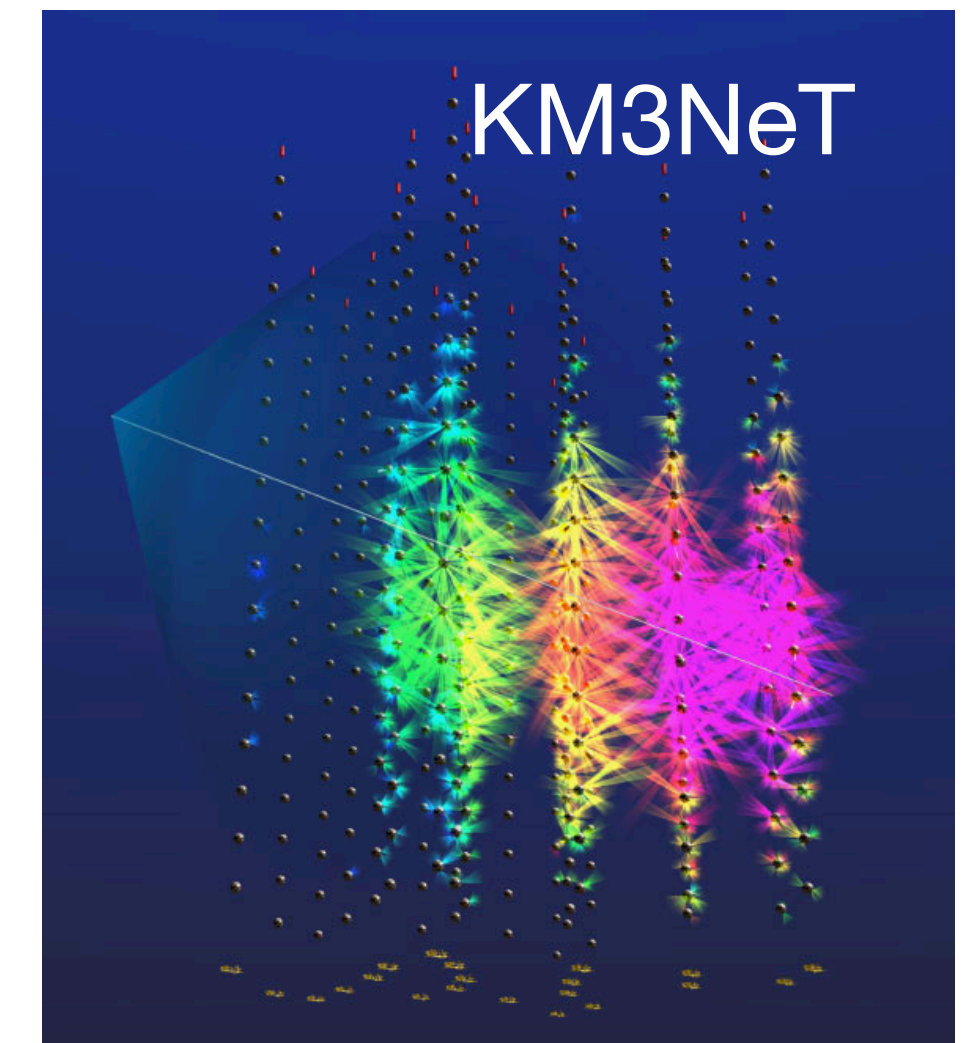
$$p_{UHECR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$\rightarrow \mu^+ + \nu_\mu$$

$$\rightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



- KM3NeT saw EHE candidate at 220 PeV (E^{-2})
- The same flux would require IceCube to have 70 events but none seen. ($>10\sigma$)
- Flux uncertainty can give reconciliation among KM3NeT, Auger, IceCube at most 3σ tension



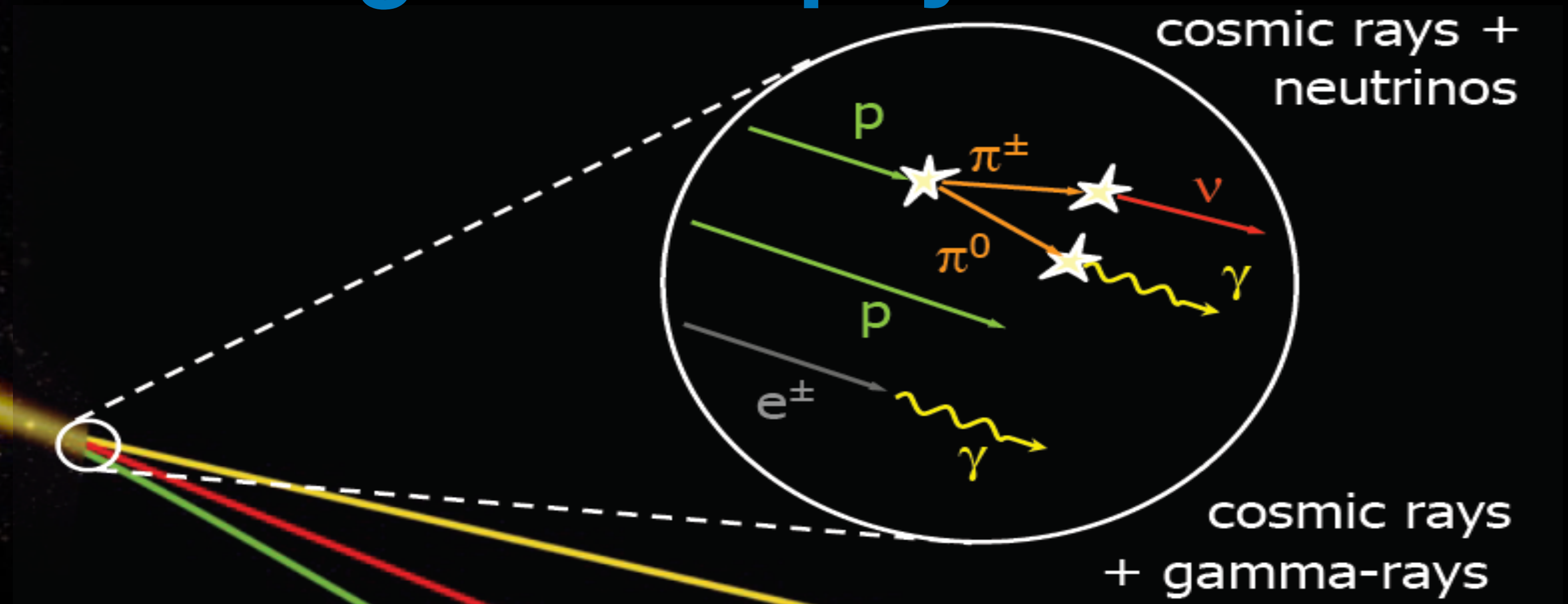
KM3NeT Coll, Nature 638 (2025) 8050

(Personal) Source Questions

Once in a lifetime (1/70 years)

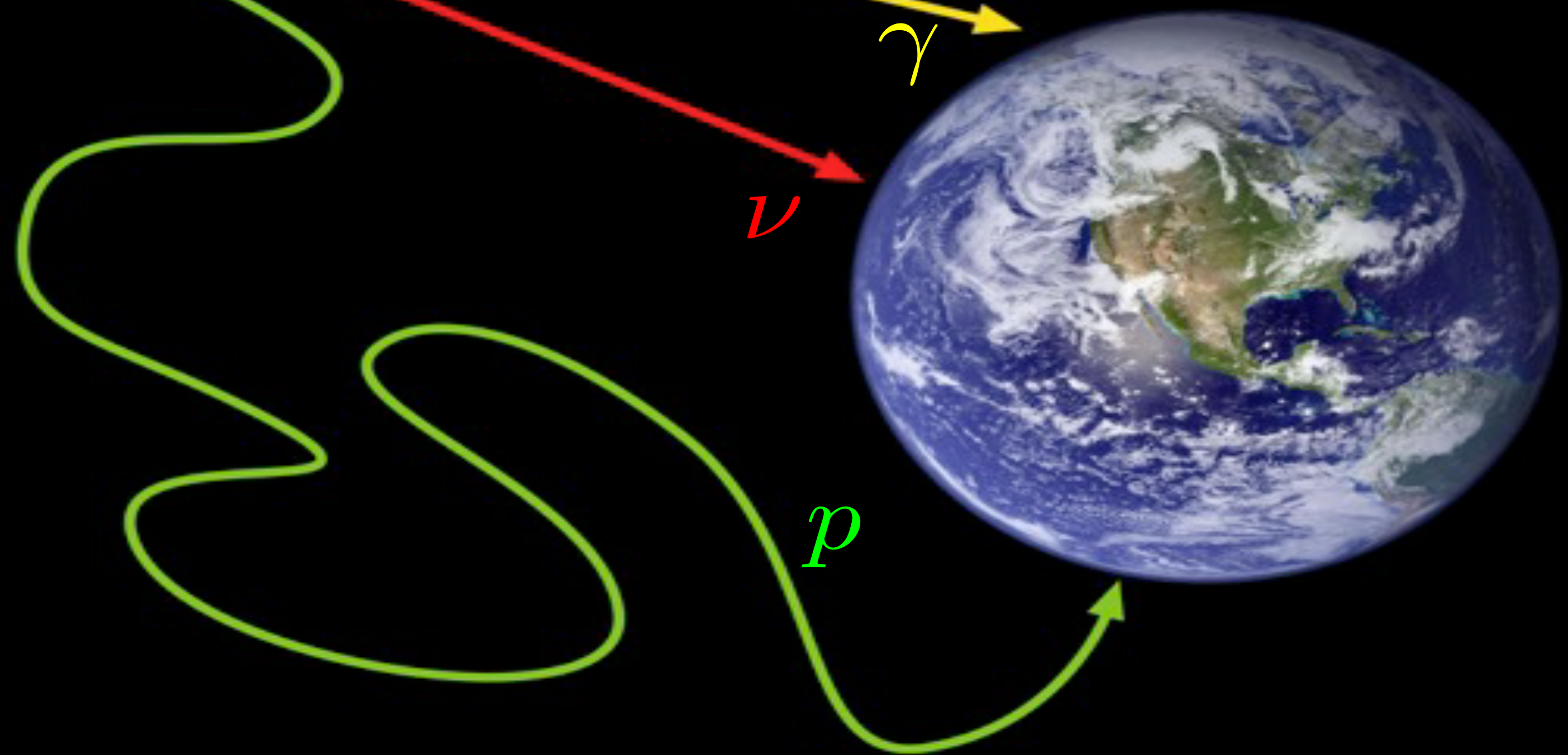
- IceCube (complete, 1 km^3) 14 years VS ARCA (partial, 0.15 km^3) 1 year
- IceCube + AMANDA + Baikal + Antares + Auger + TA + RADIOs VS ARCA
- If this is a GZK neutrino, why only the highest energy? Lower energies?
- Is it possible to have an astrophysical object with ultra-high-energy neutrino emission only without gamma or EM counter parts?
- If it is a once-in-a-lifetime event, why do we build a new detector?

Multi-messenger Astrophysics



Protons or electrons can
produce the observed
gamma rays

Neutrinos only
produced by protons

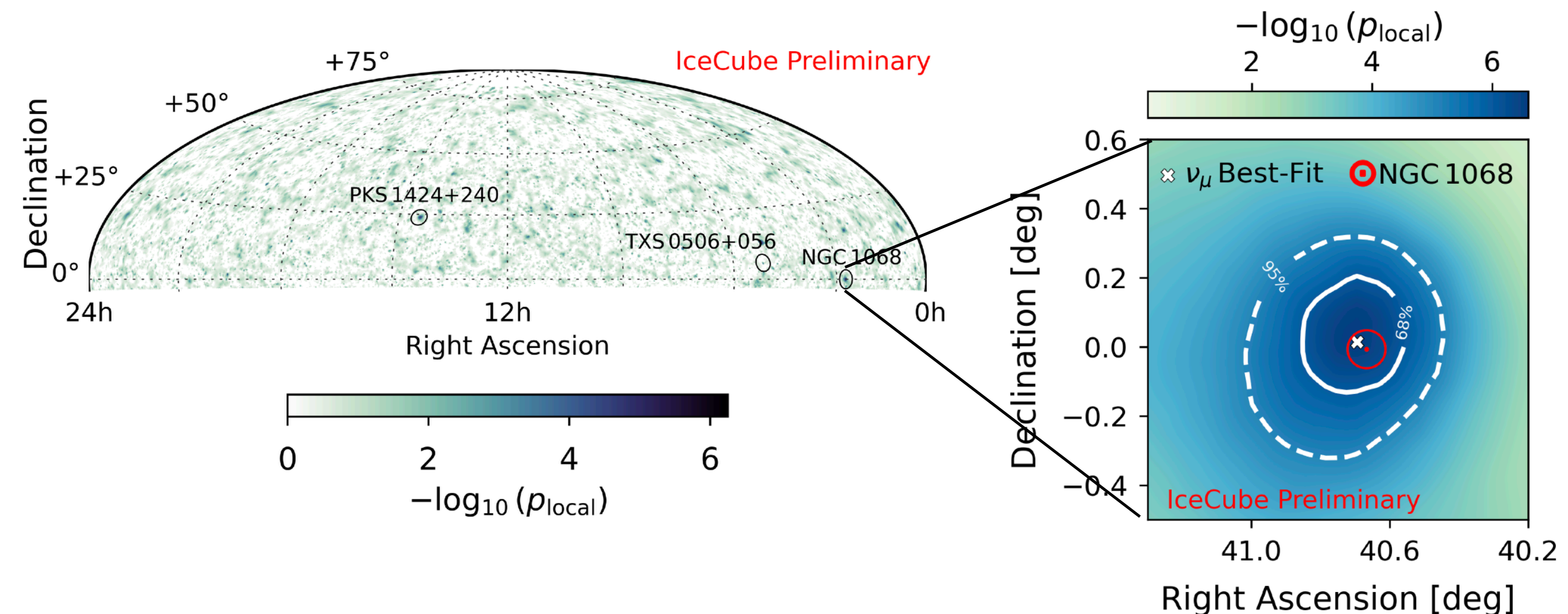


NGC 1068



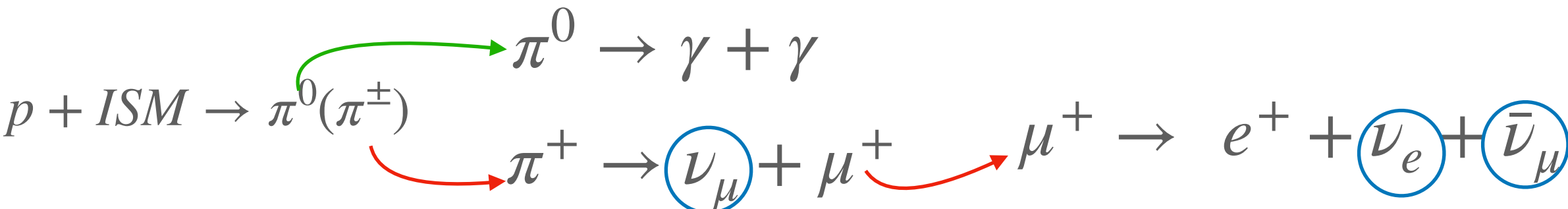
- Barred Spiral Galaxy
- 47 million light year away
- Supermassive Black Hole hidden by a cloud of dust.

*Cosmic-ray interactions occur in a cloud.
Neutrinos are generated in the surrounding medium
where photons attenuate.*

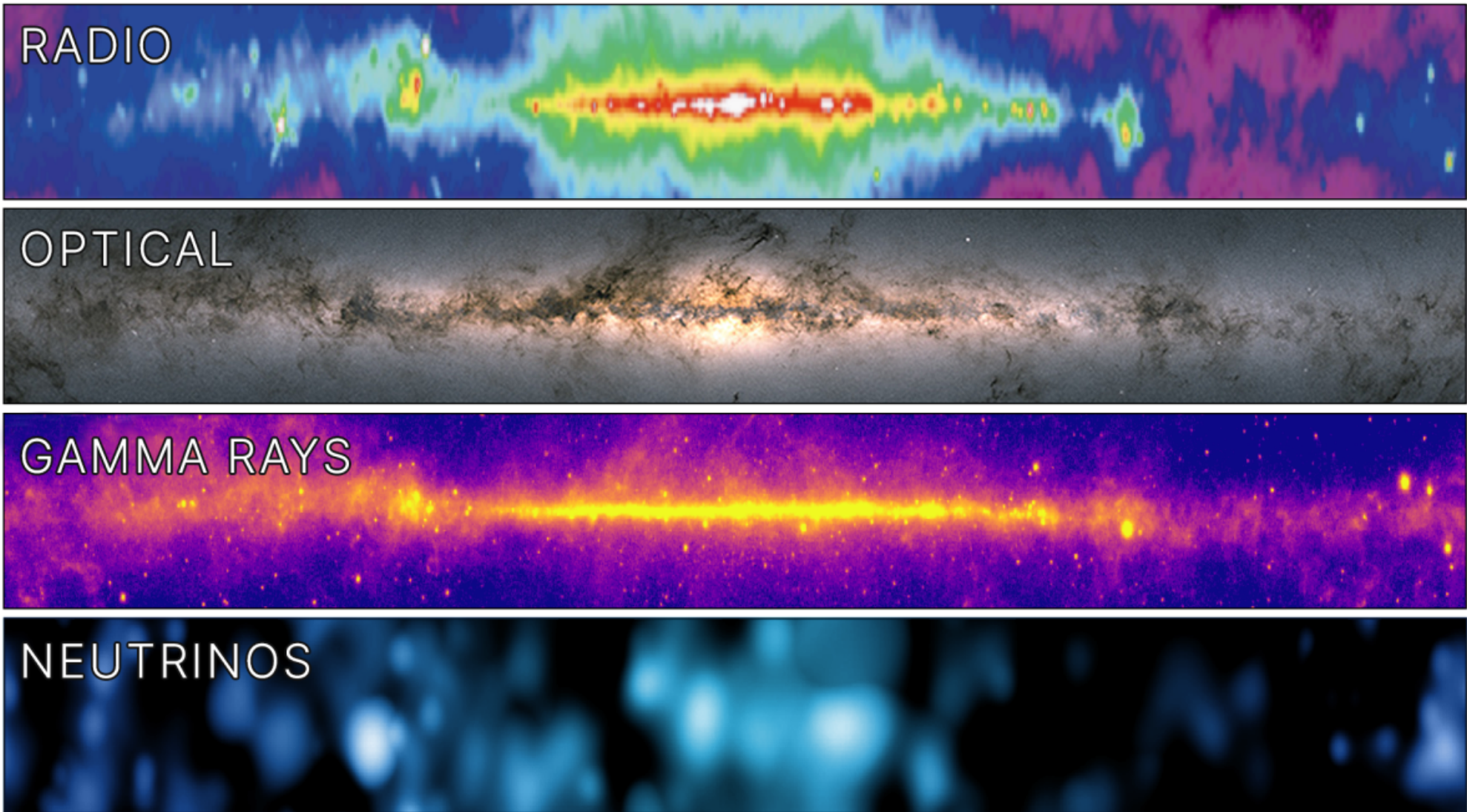
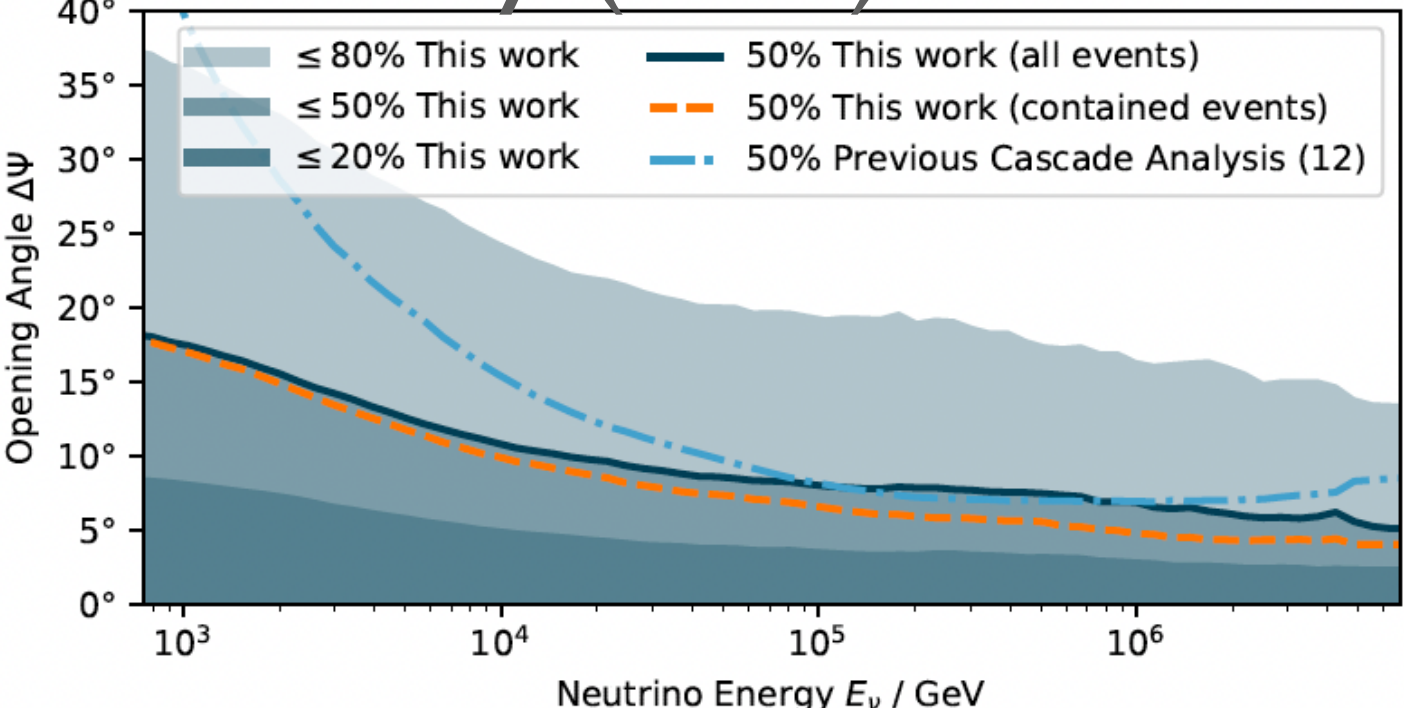
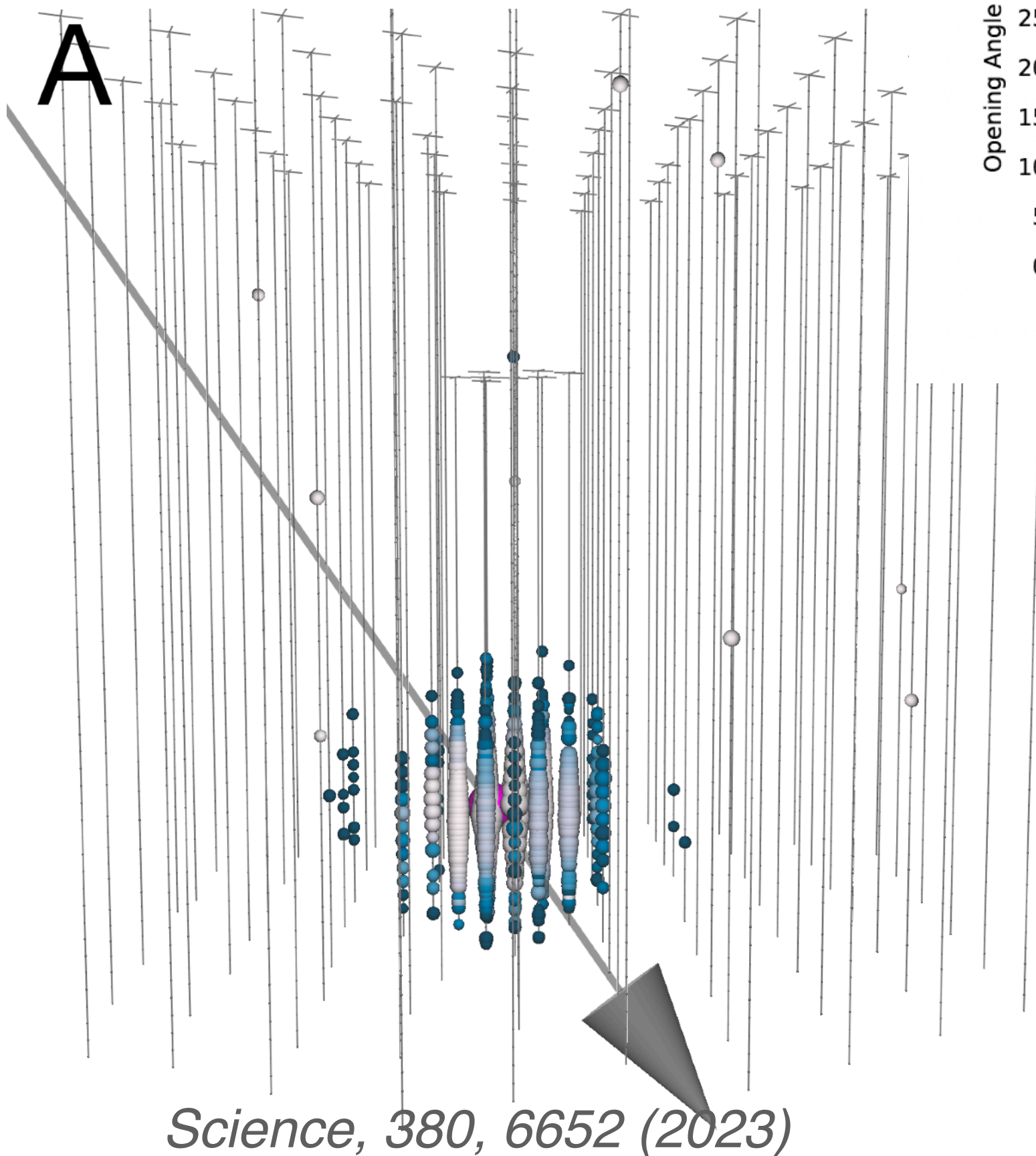


- New analysis with 13 years of data.
- The hottest spot is closer to NGC 1068.
- Significance : 5.0σ local, 4.0σ global
- Prefers softer spectrum ($\sim E^{-3.4}$), indication of a more complex power law.

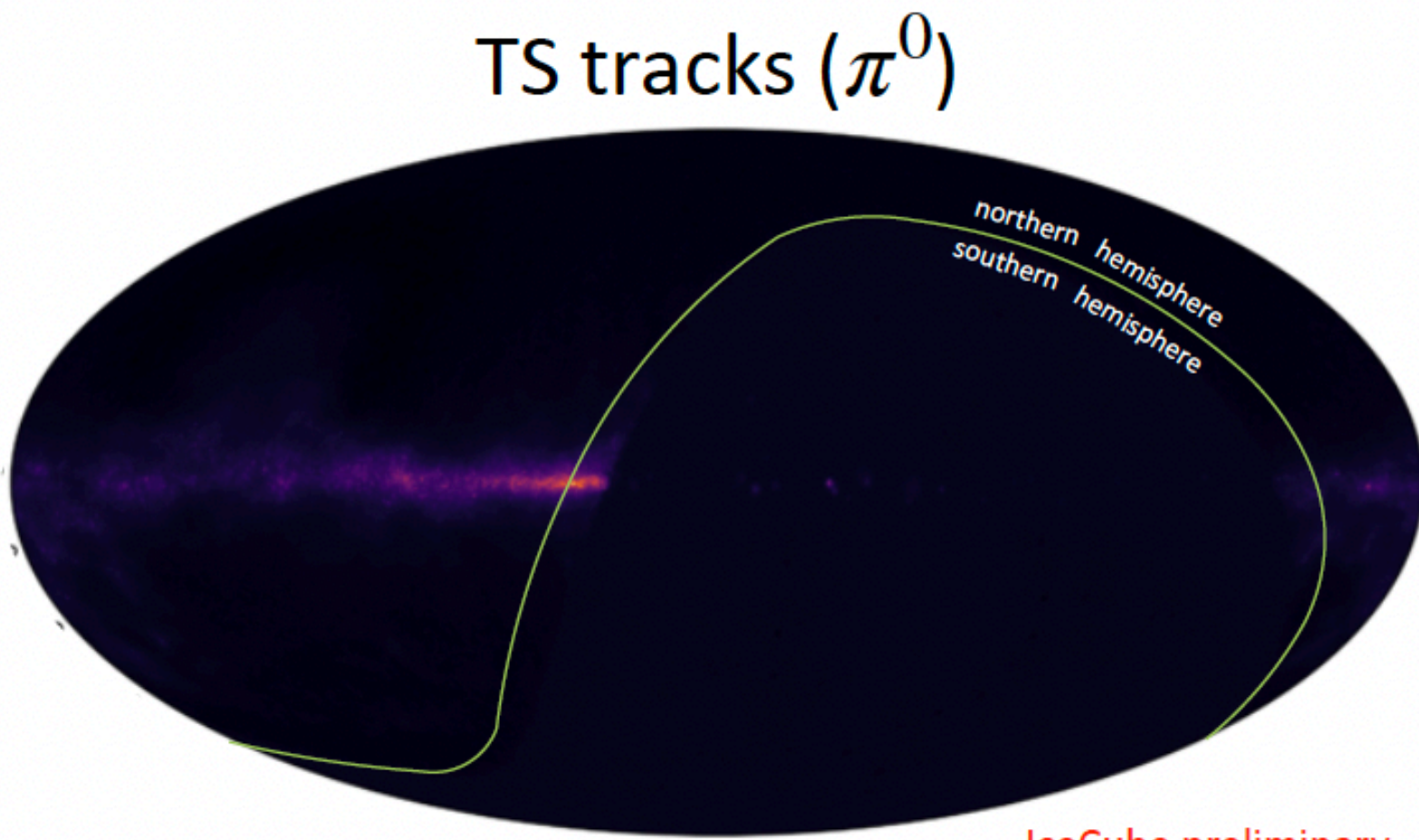
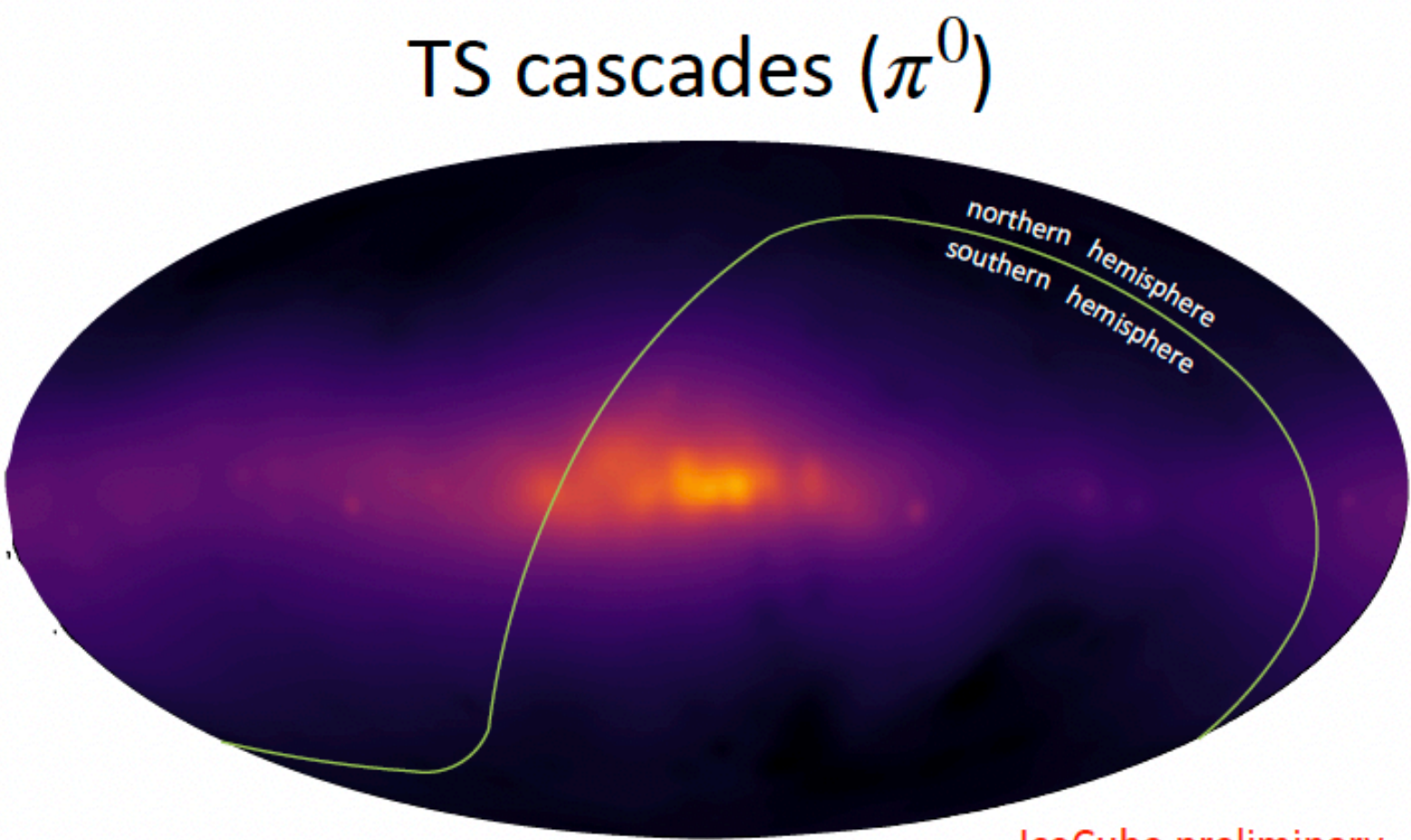
Observation of high-energy neutrinos from the Galactic plane



Improved bkg. rejection and direction reconstruction with new ML open up the Southern Sky (4.5σ)



Science, 380, 6652 (2023)



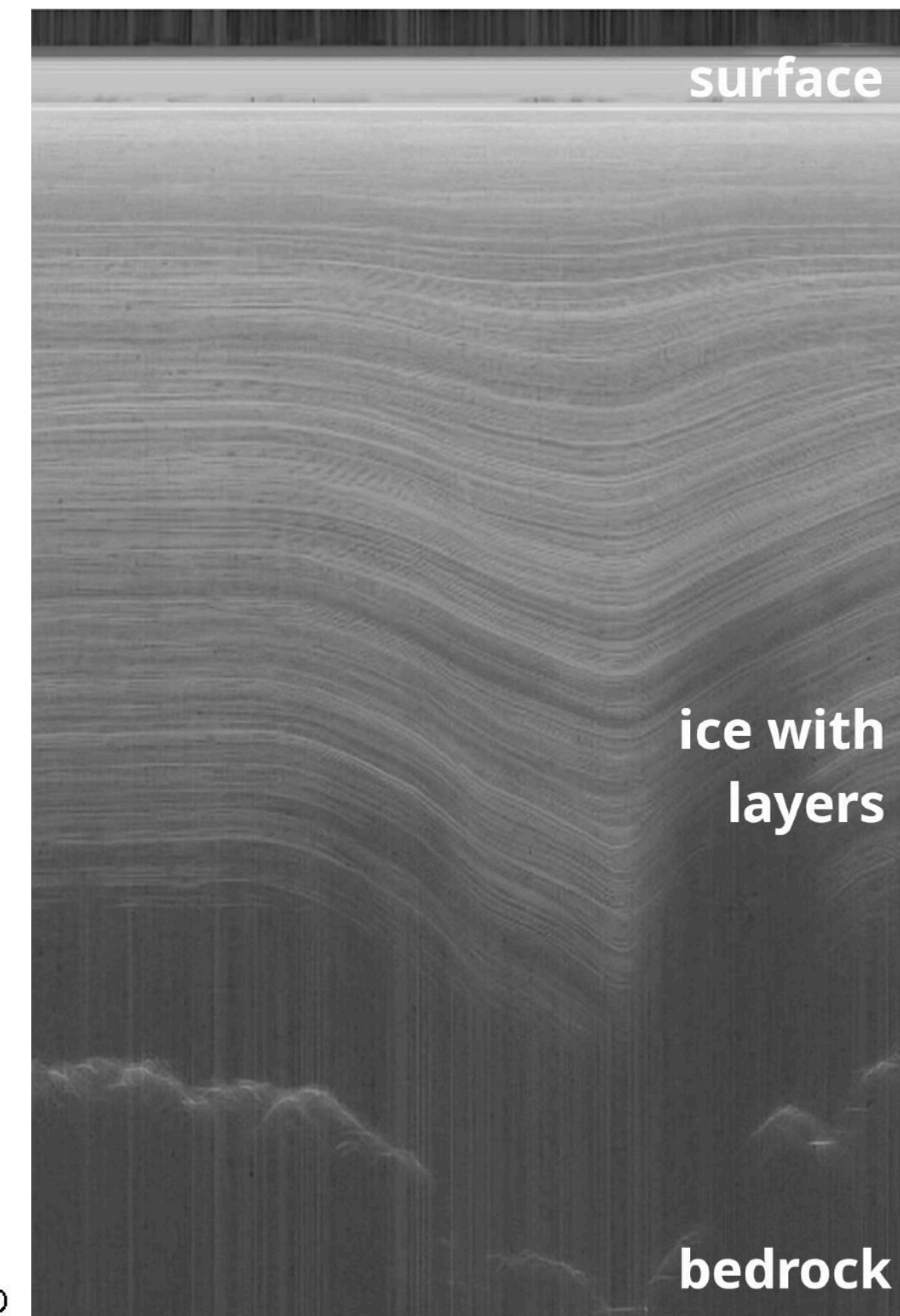
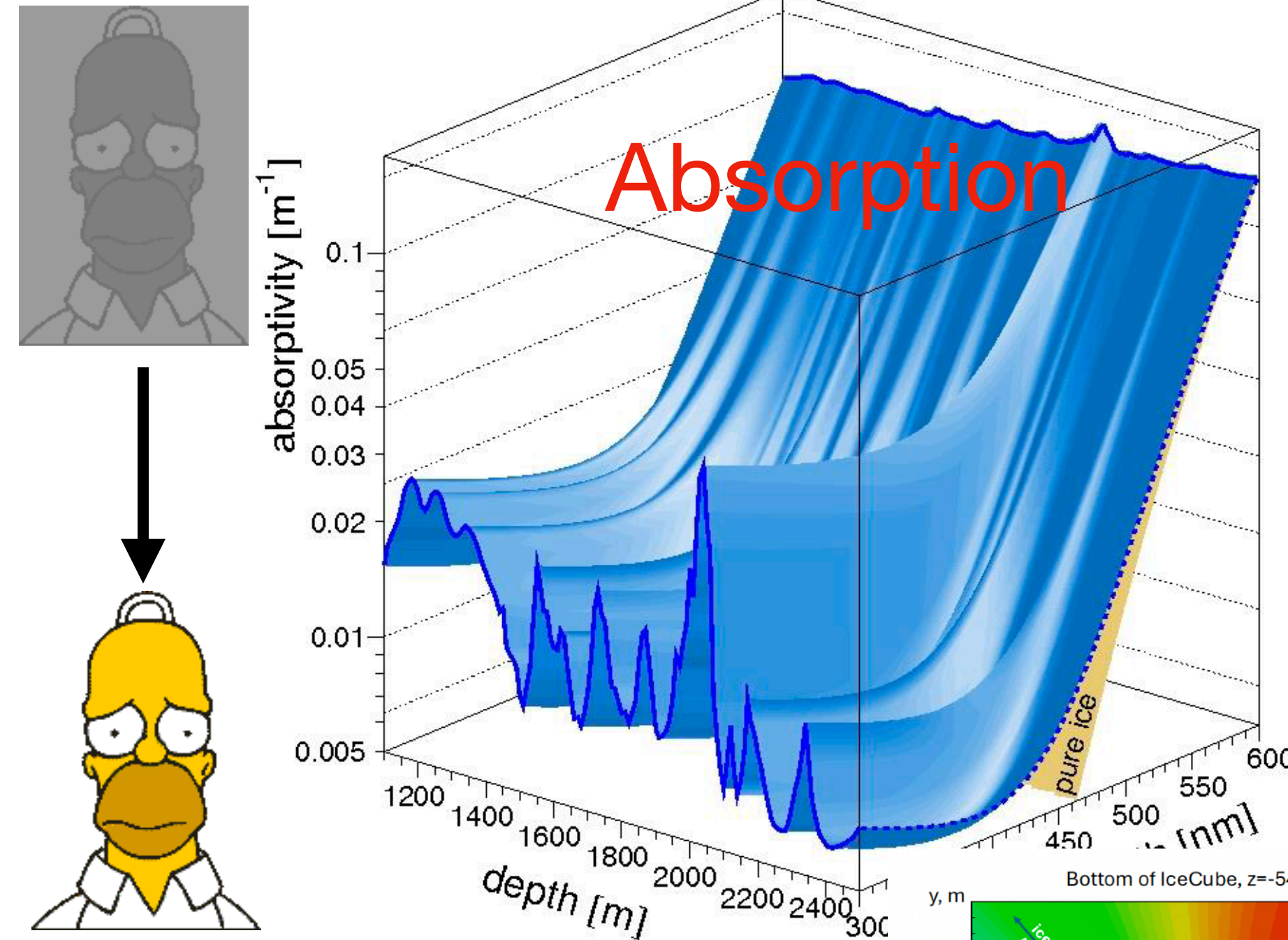
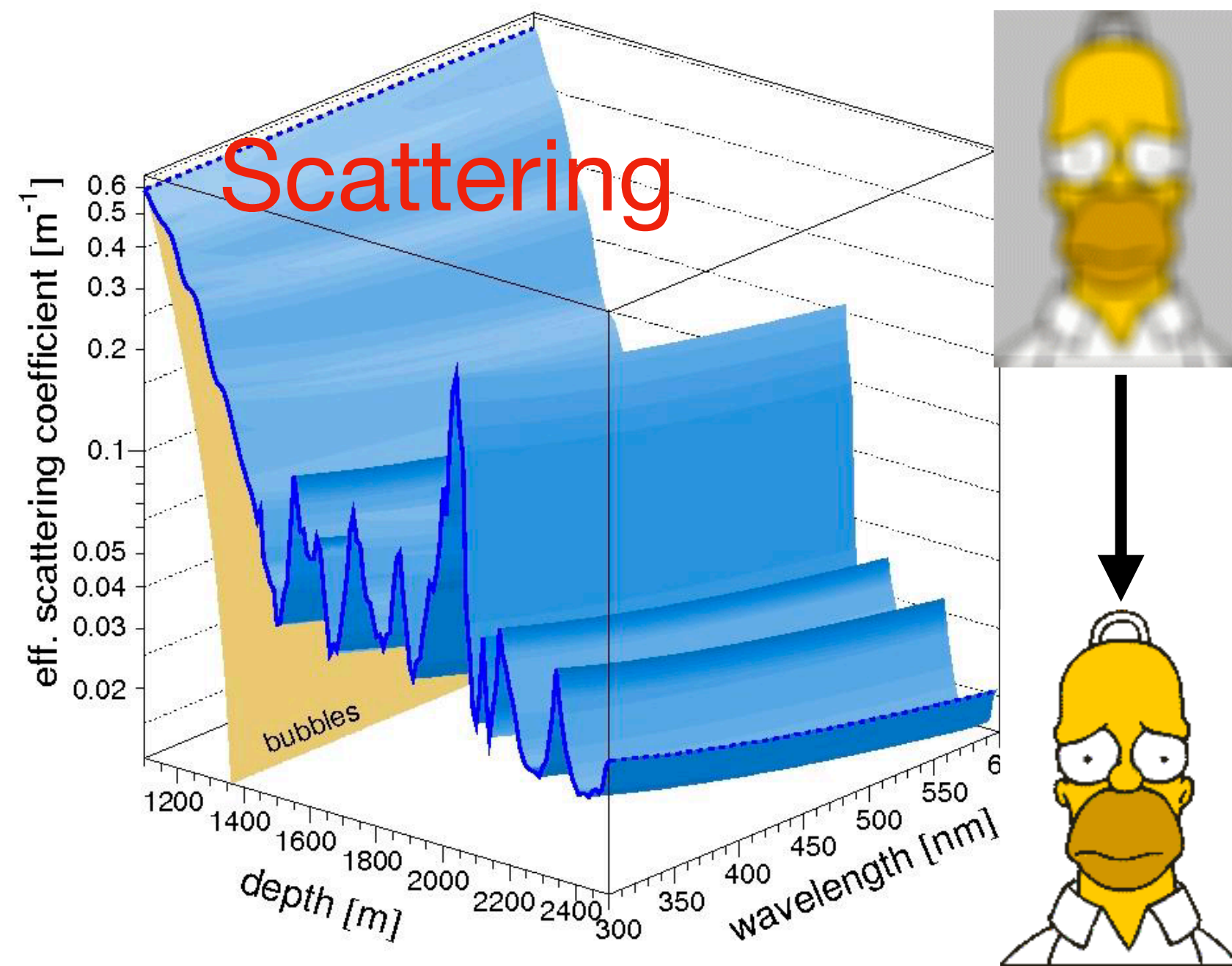
IceCube preliminary

IceCube preliminary

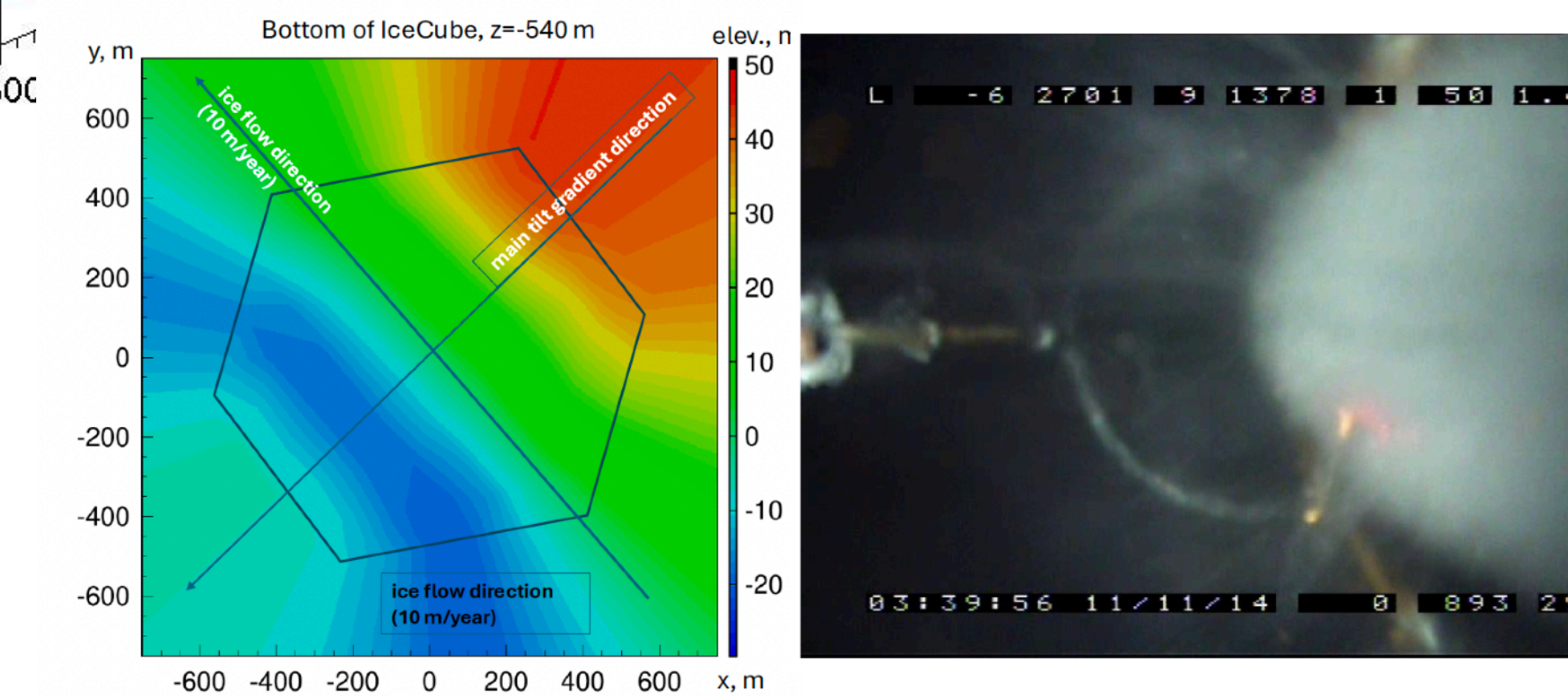
New results show that addition of tracks improves the significance more than 5σ

Ice, Ice, South Pole Ice is very complicated Cherenkov medium

Most of IceCube analysis systematics comes from optical properties of Ice



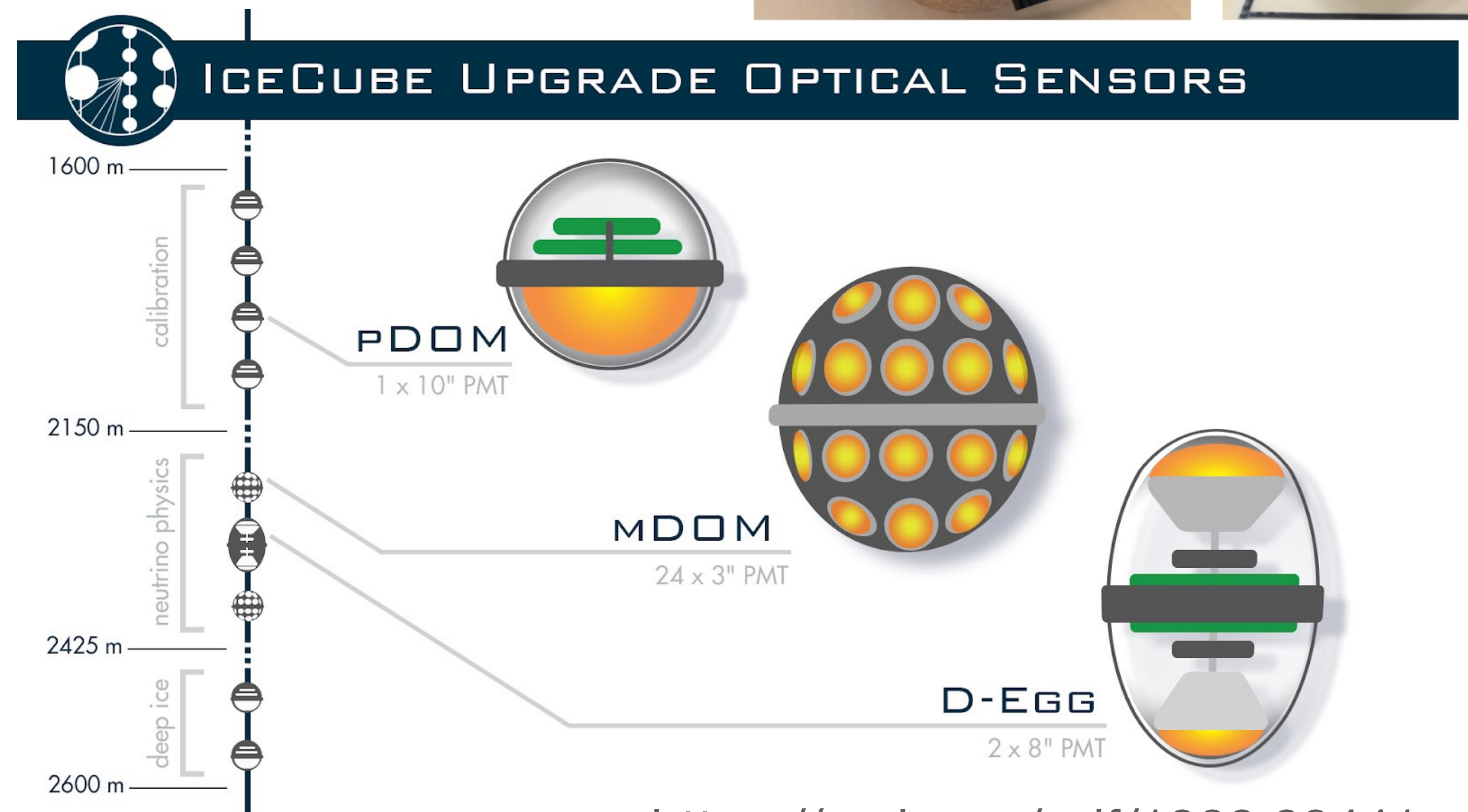
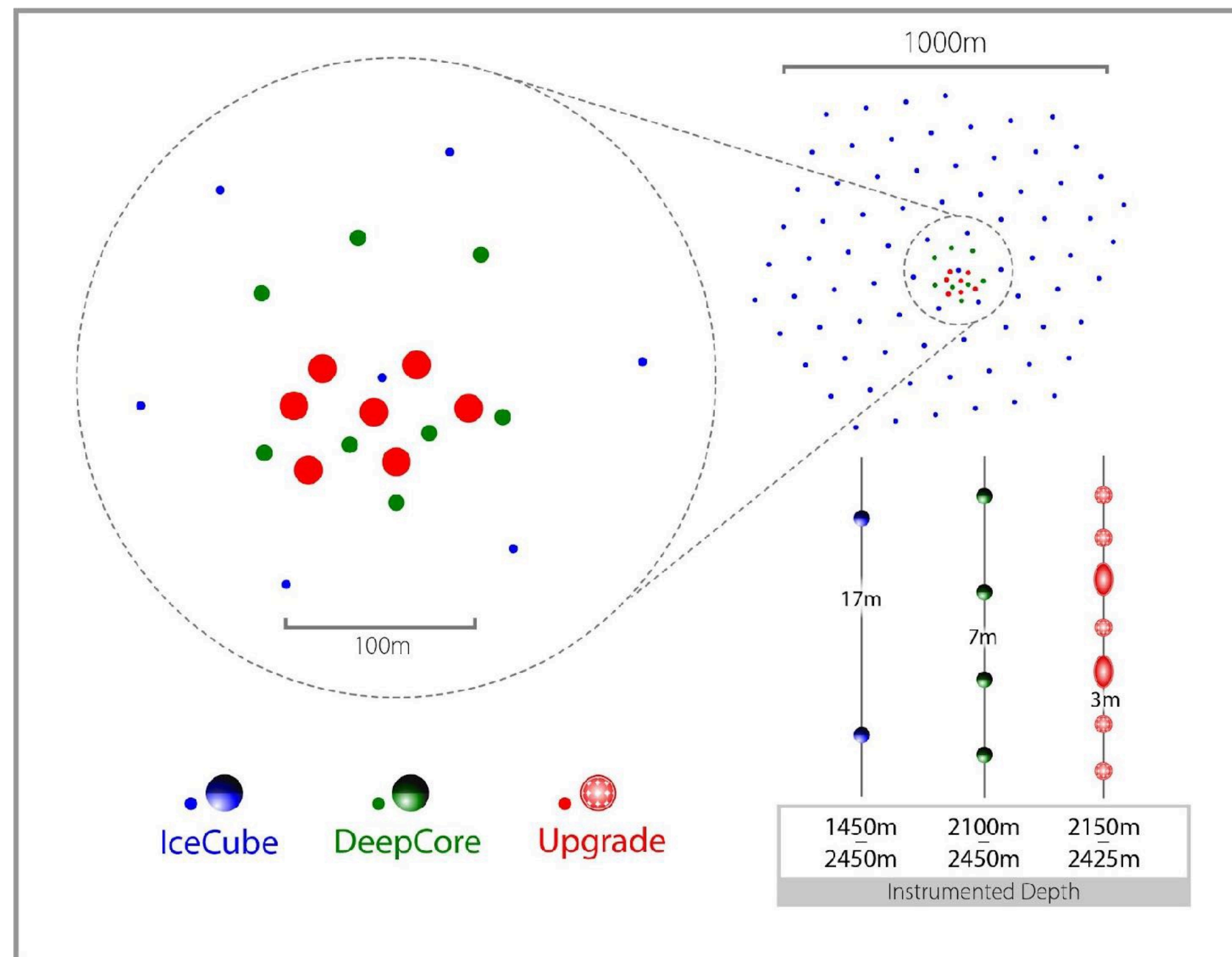
- South Pole Ice is very clear. However, it has a layered structure which shows different optical characteristics (scattering and absorption).
- Ice flows and light travel in birefringent way (along the flow direction; SE- $\rightarrow$ NW).
- Refrozen (Hole) Ice is different from the bulk ice.



The IceCube Upgrade

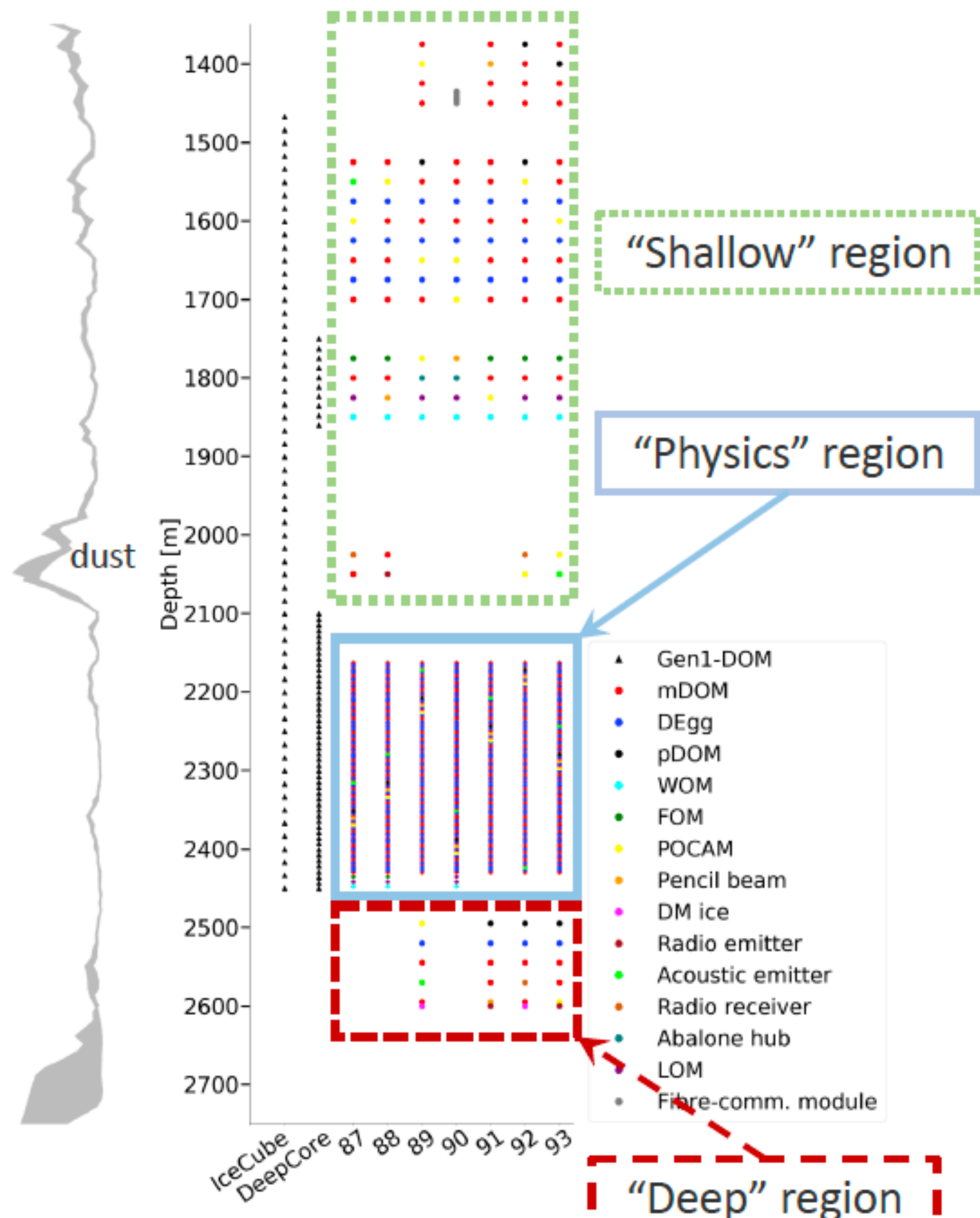
- Instrument additional 7 strings
 - 60-100 DOMs in each string
- Detect neutrinos below 10 GeV
- Construction began and full deployment in 2025/2026
- Testbed for IceCube-Gen2

- Neutrino Oscillations study,
- Neutrino Mass Hierarchy measurement with the Upgrade.
- Neutrinos with Earth matter and density effect in varying baseline
 - Understanding the systematics is the key to the measurement
 - Additional calibration devices is going to be added



<https://arxiv.org/pdf/1908.09441.pdf>

The IceCube Upgrade Contributions

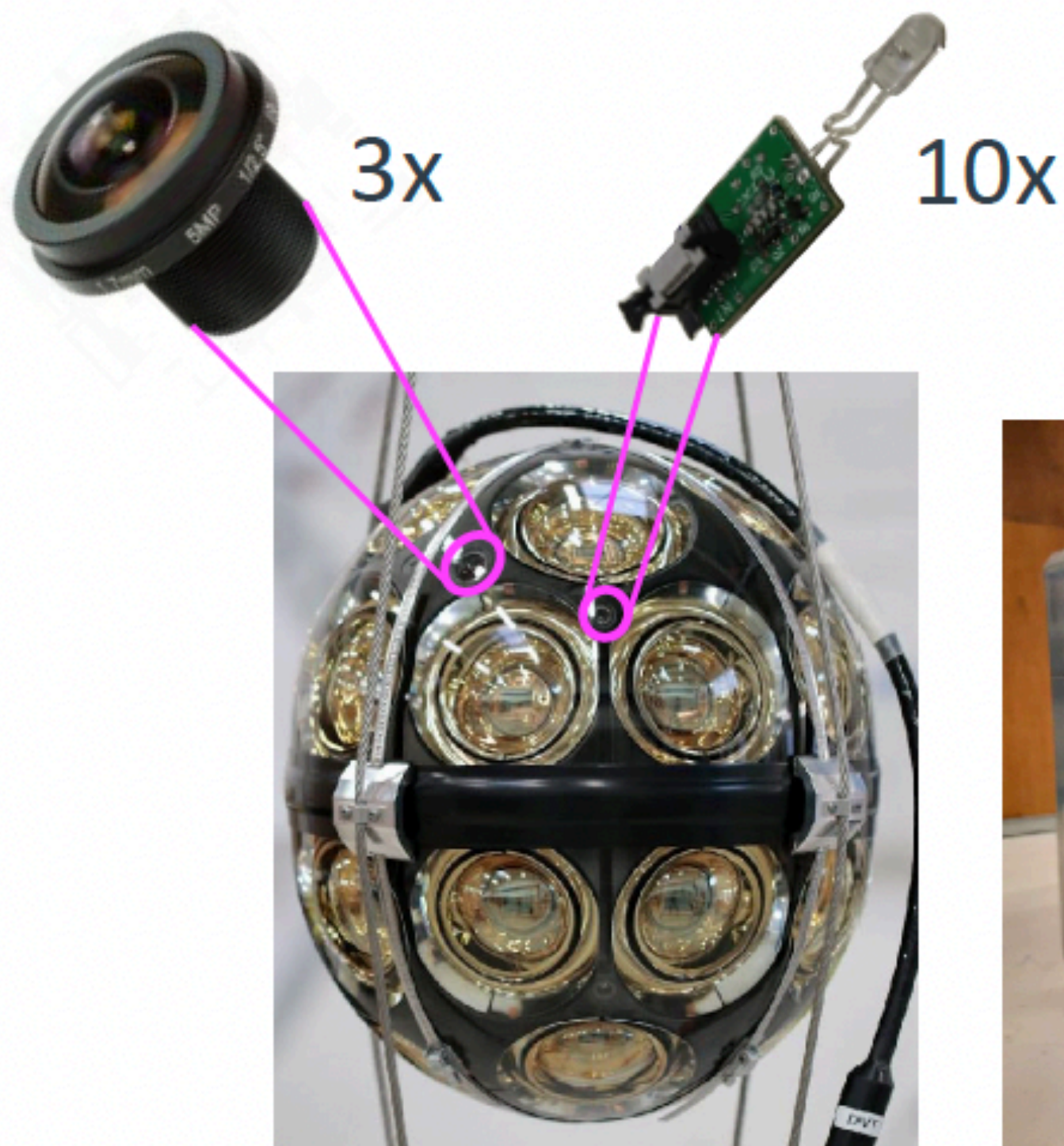


Upgrade Scope (10 km view)

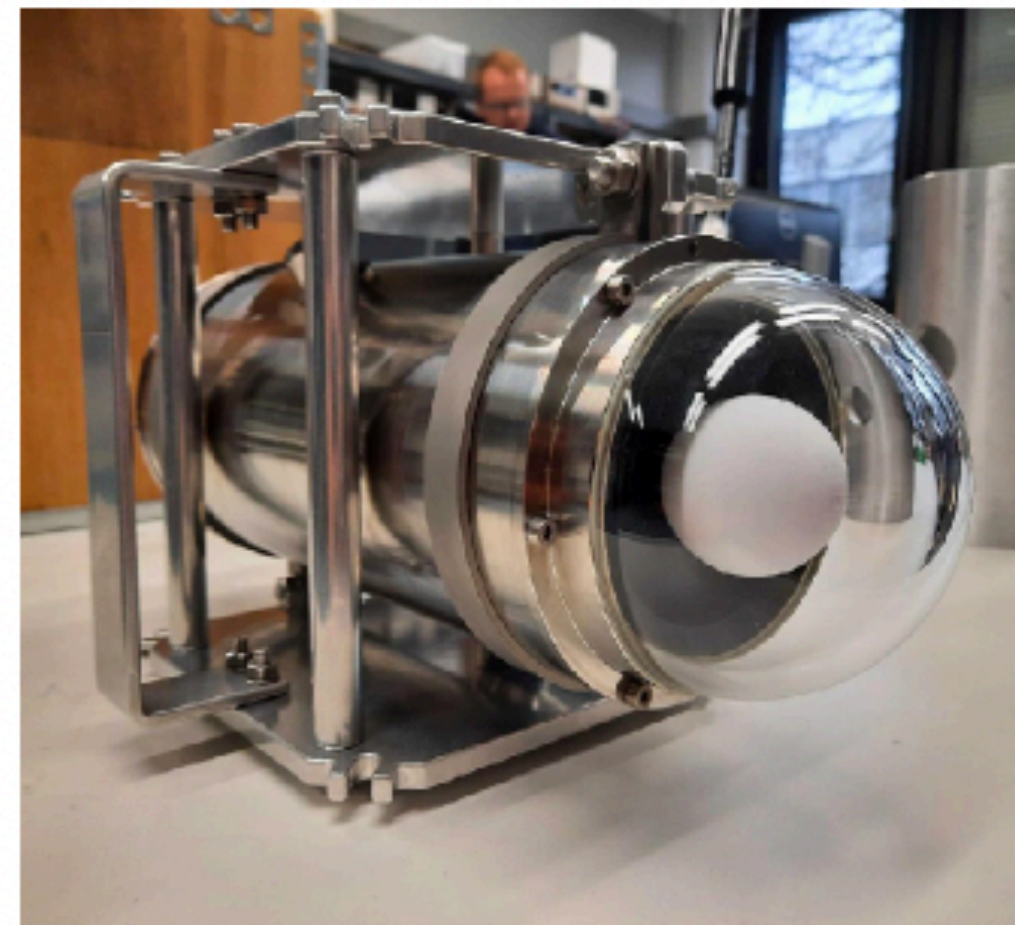
- Major Parts of Detector Instrumentation Instrumentation (***largely in-kind contributions***)
 - 277 D-Eggs (+ spares) (***Chiba University***)
 - 402 mDoms (+ spares) (***Germany; 50% built at DESY-Zeuthen, 50% built at Michigan State University***)
 - 7 Main Cable assemblies (***Michigan State University***) / Surface cables (***Sweden***)
 - In optical module camera systems (***SKKU***)
 - Calibraton Devices / Special Devices (***Various in-kind contributors***)
- Drill and deploy 7 strings of detector elements
 - Drill (University of Wisconsin, Physical Sciences Laboratory)
 - Logistics (NSF Office of Polar Programs)

The IceCube Upgrade Contributions

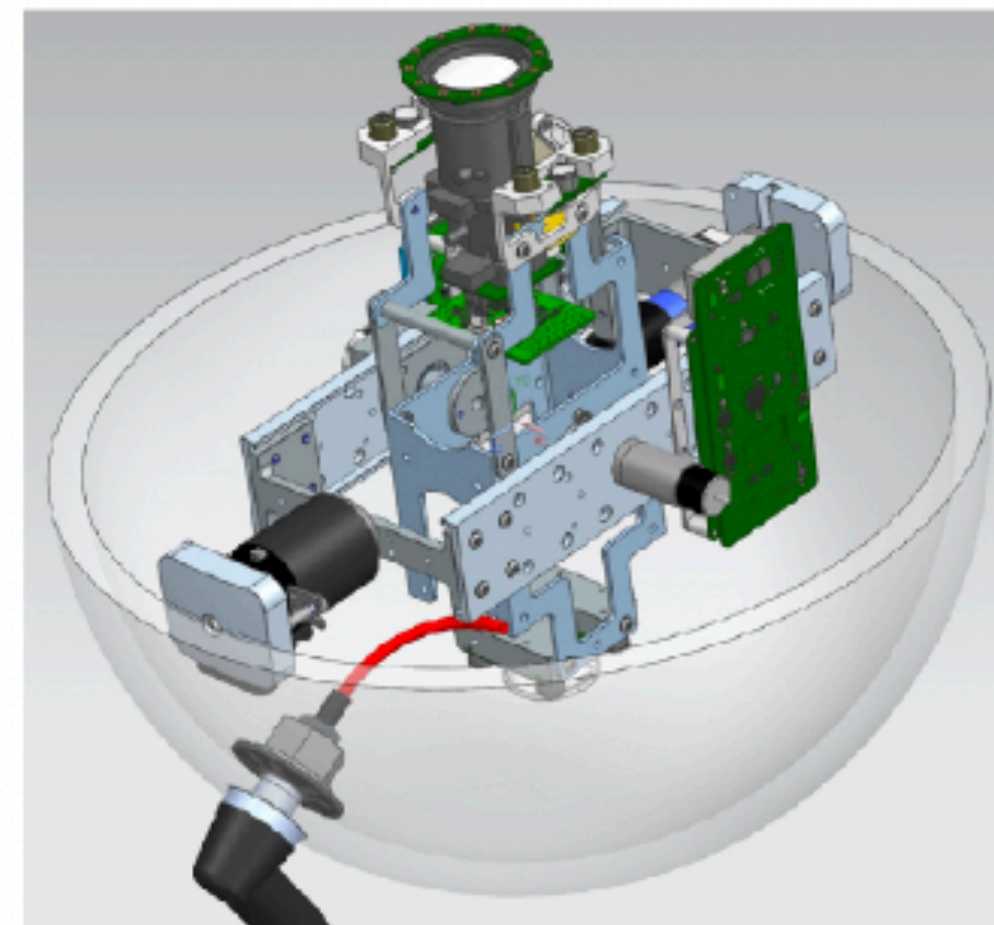
Upgrade Scope (10 km view)



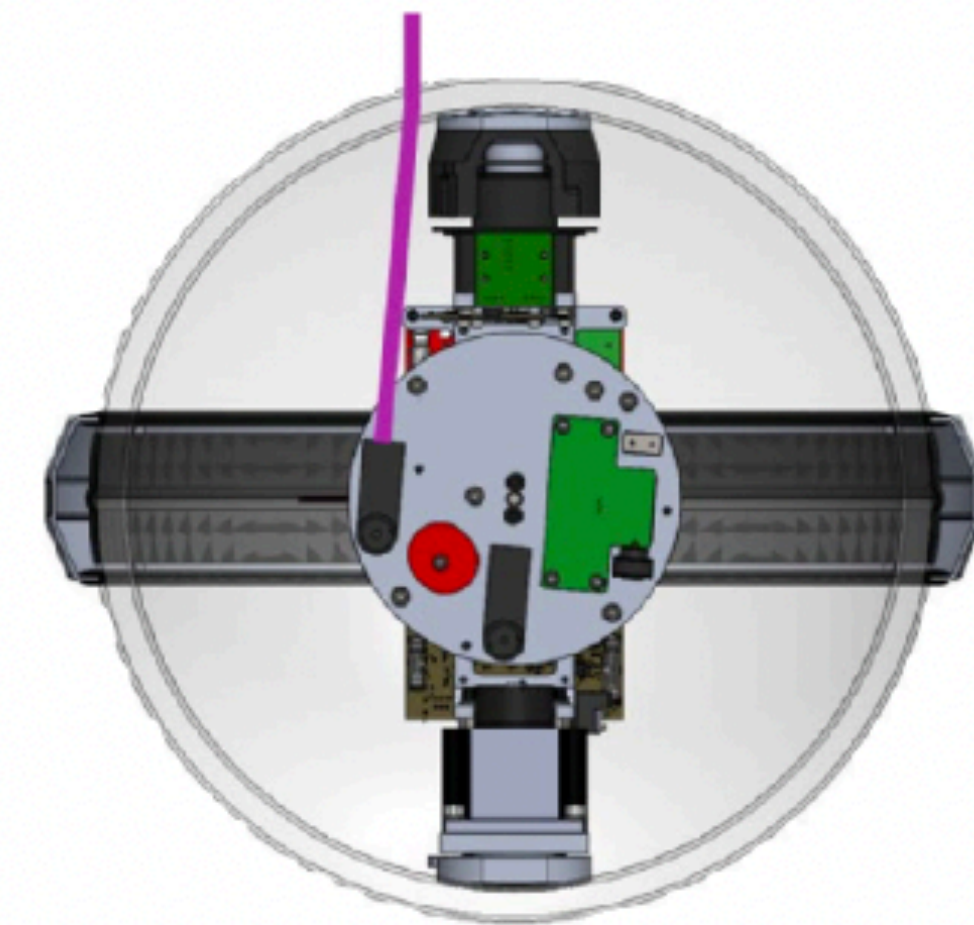
all mDOM/D-Egg



POCAM (22)



Sweden Camera (7)



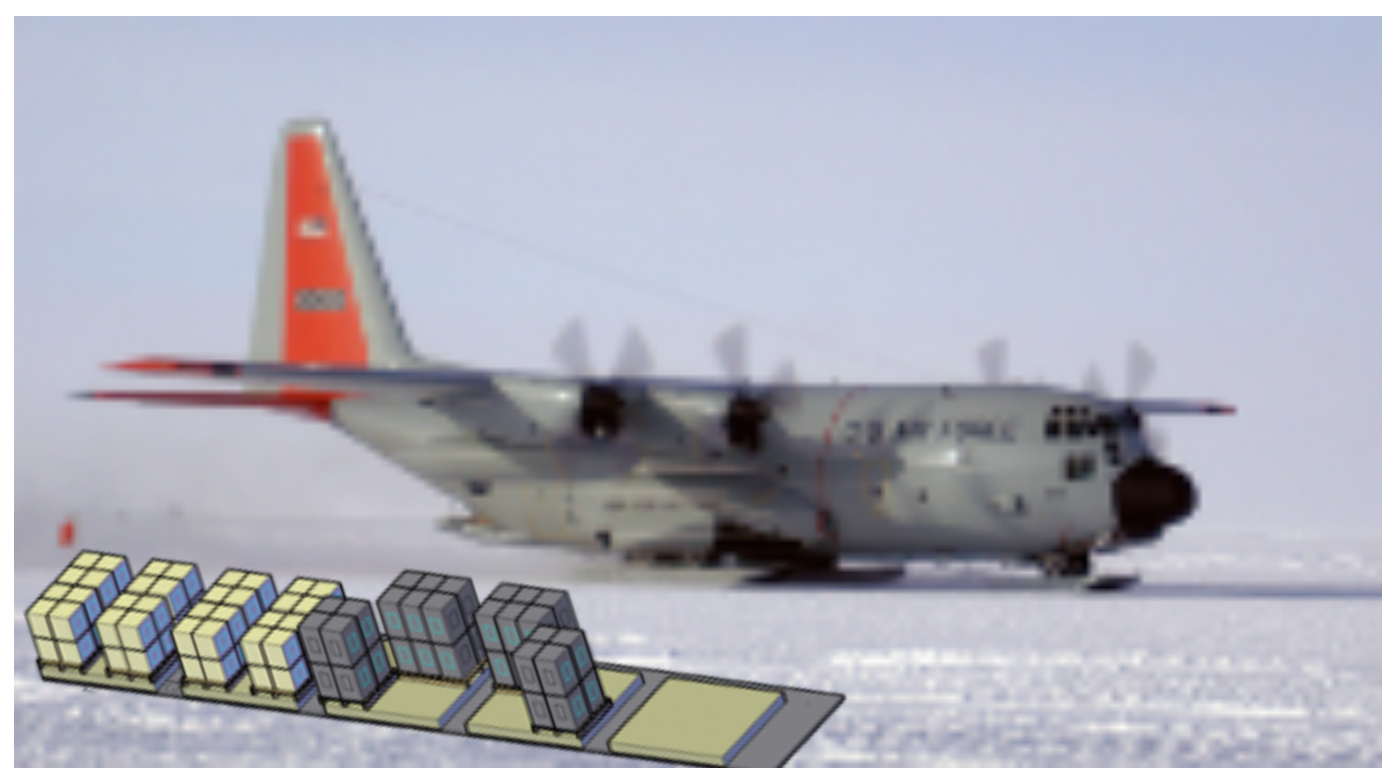
Pencil Beam (11)



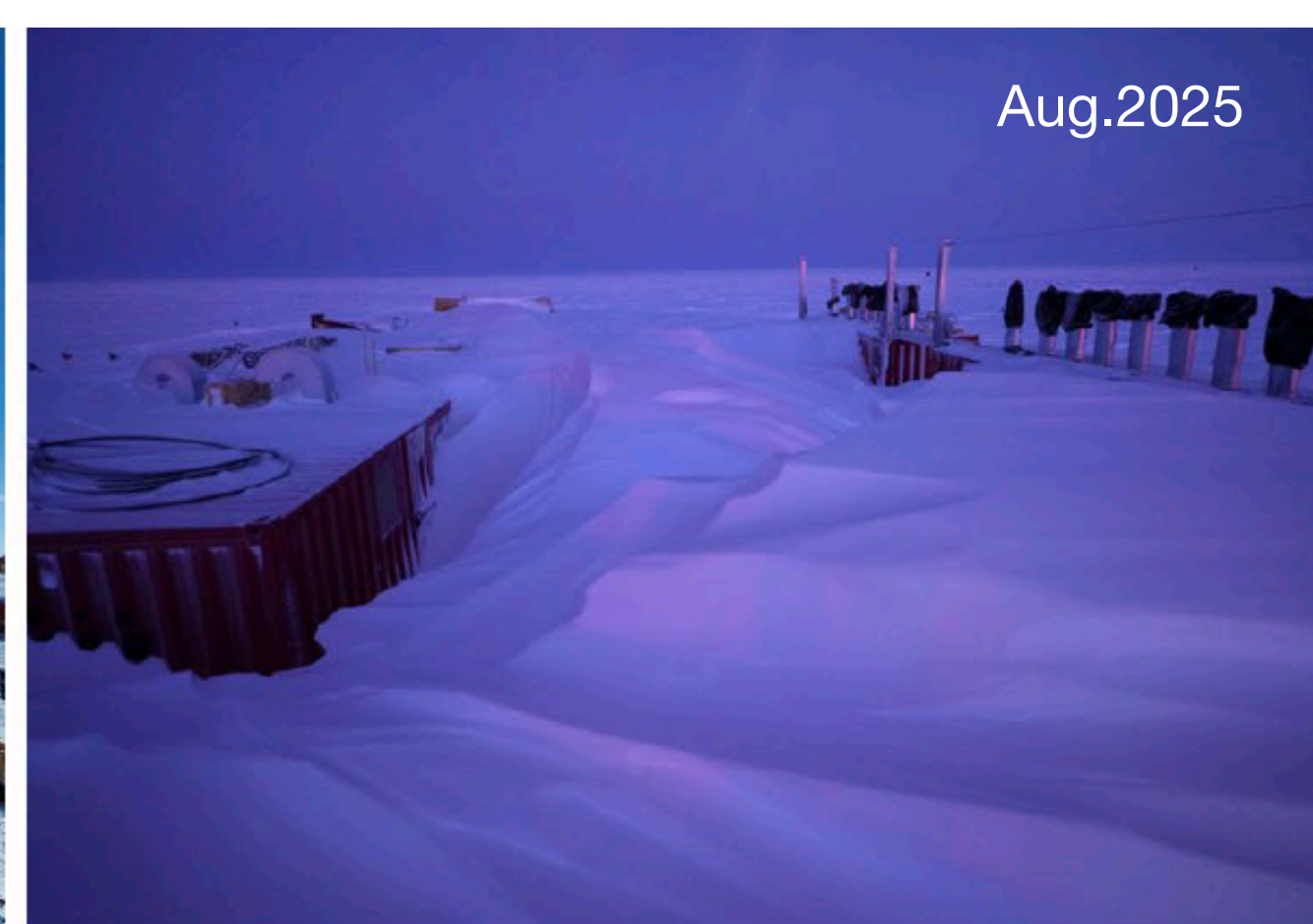
Dust Logge

- Logistics (NSF Office of Polar Programs)





Feb.2025



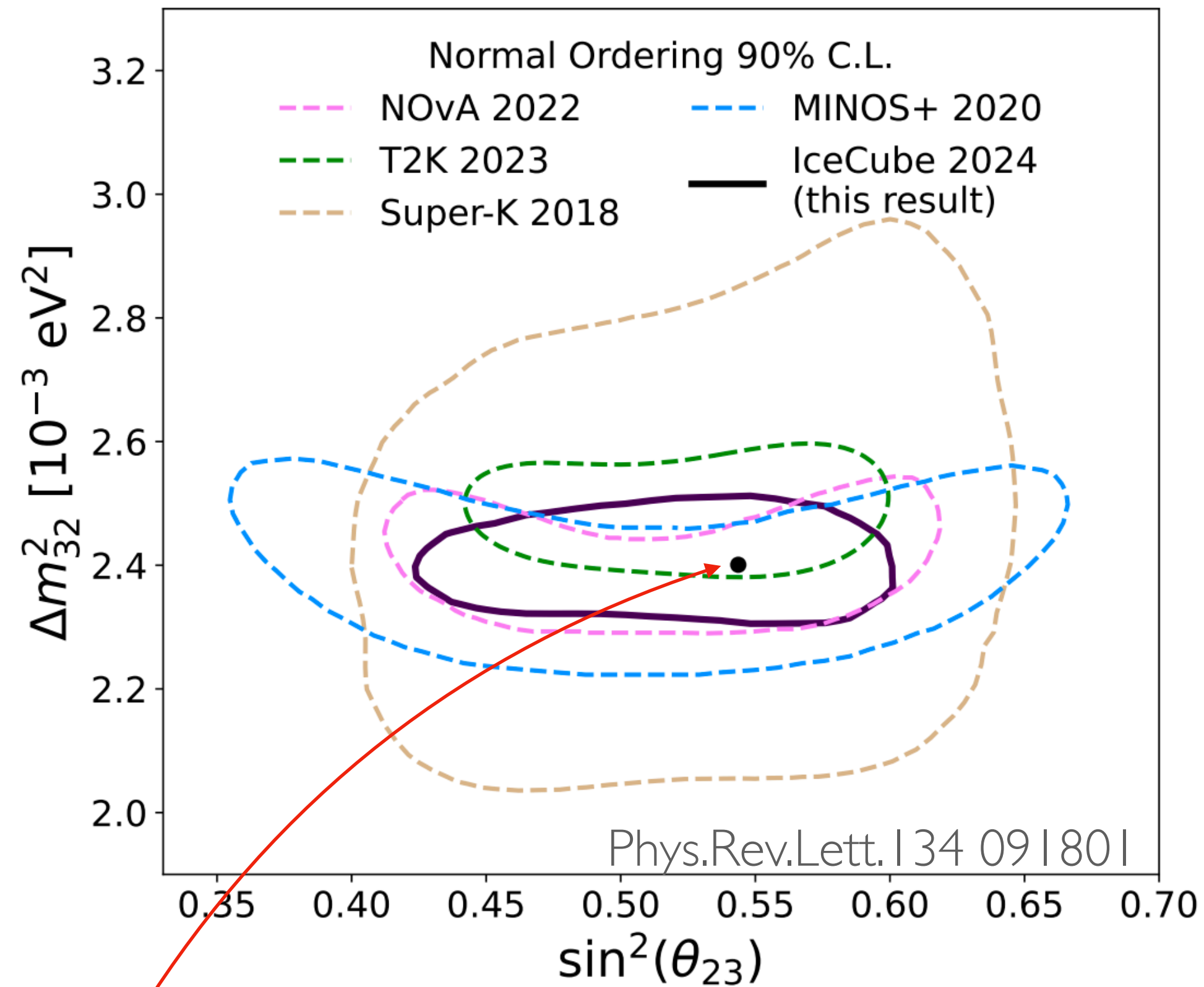
Aug.2025



Nov.2025

Atmospheric Neutrino Oscillation Physics Sensitivity

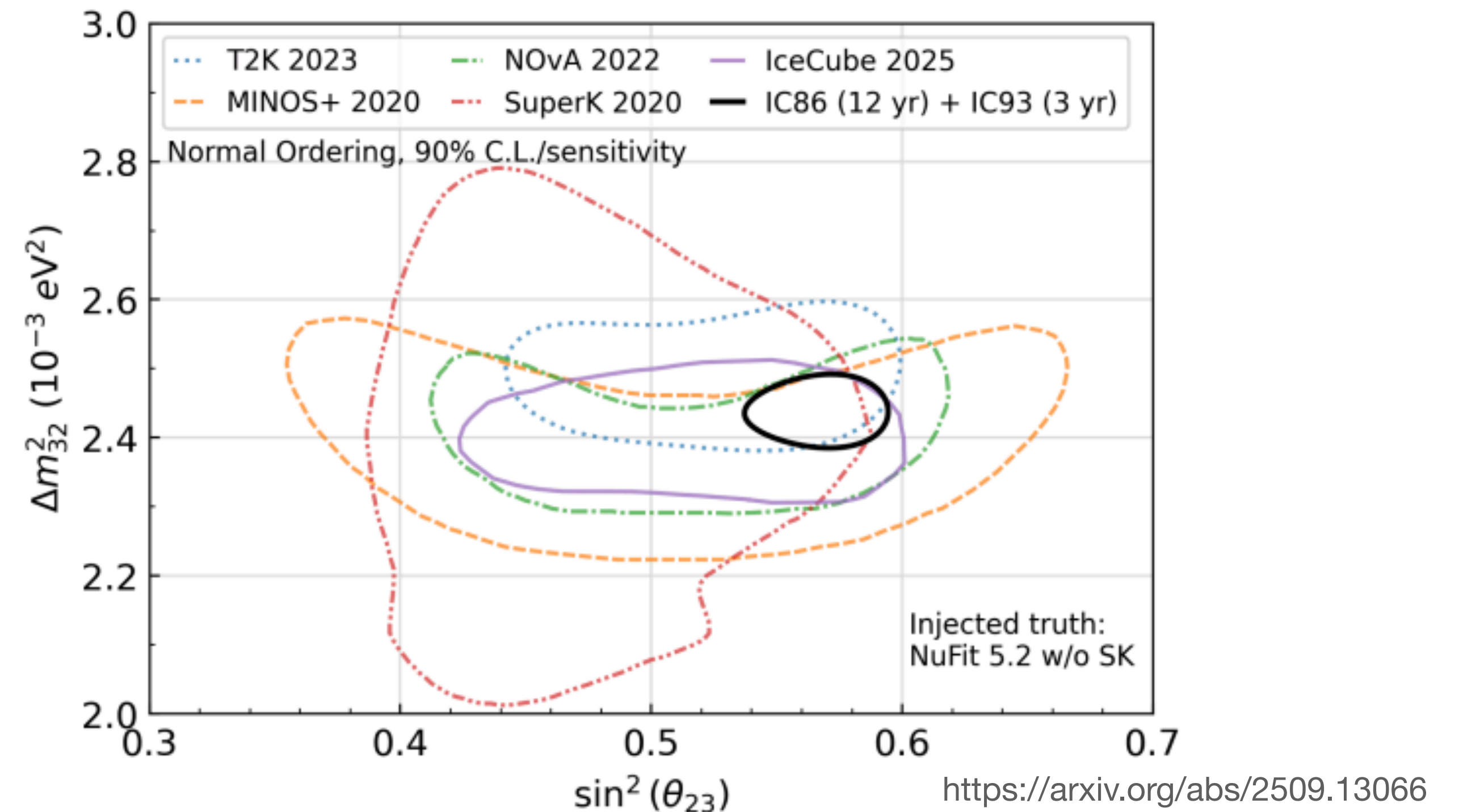
The latest atmospheric neutrino oscillation result (DeepCore)



Best Fit :

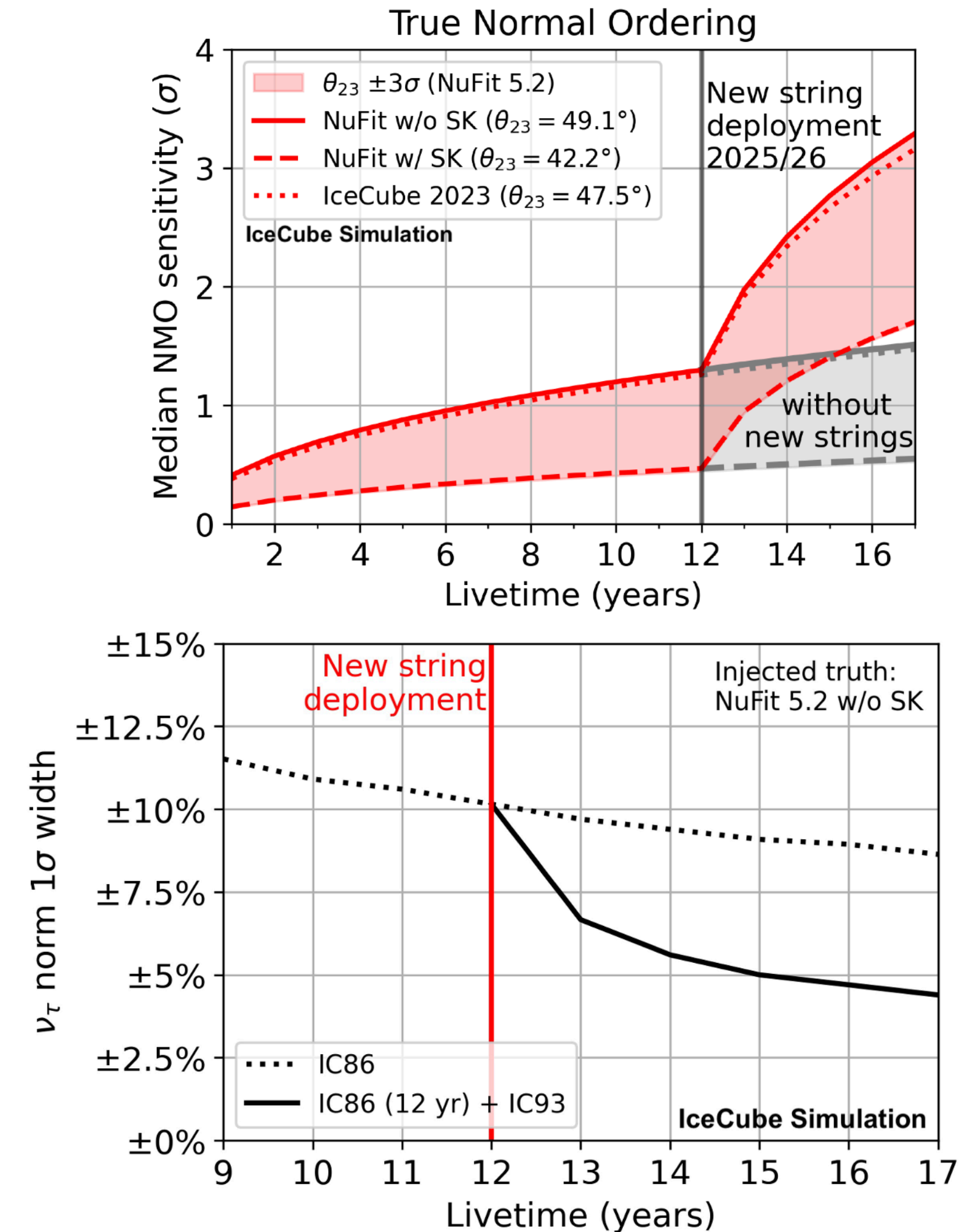
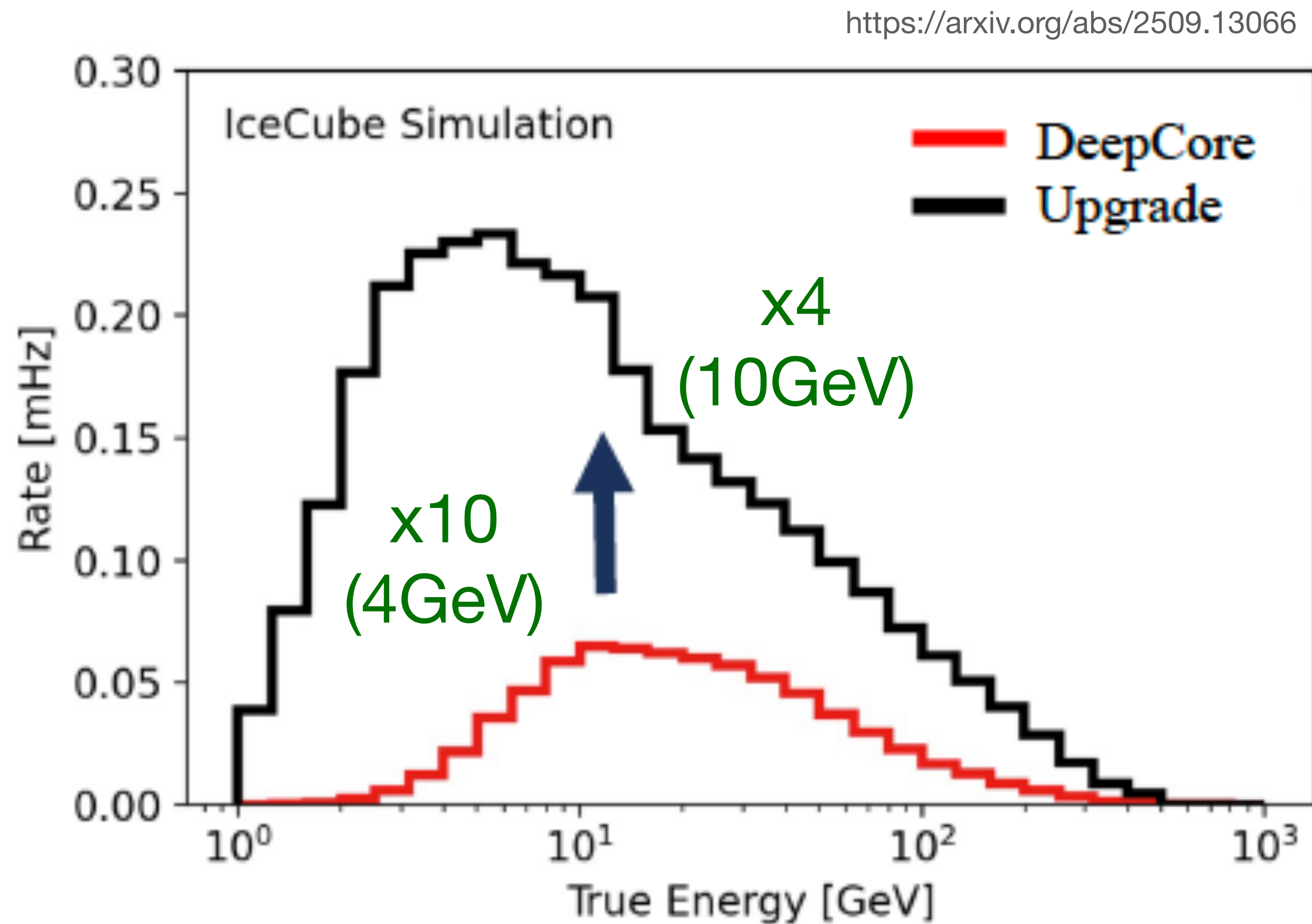
$$\sin^2 \theta_{23} = 0.54^{+0.04}_{-0.03}, \Delta m_{32}^2 = 2.40^{+0.05}_{-0.04} \times 10^{-3} eV^2$$

The DeepCore+Upgrade Sensitivity



The Upgrade will enhance oscillations sensitivity significantly (i.e. $\sin^2 \theta_{23} \sim 4\%$)

Atmospheric Neutrino Oscillation Physics Sensitivity



The Upgrade will enhance oscillations sensitivity significantly with increased statistics and improved systematics

Korea IceCube Activities

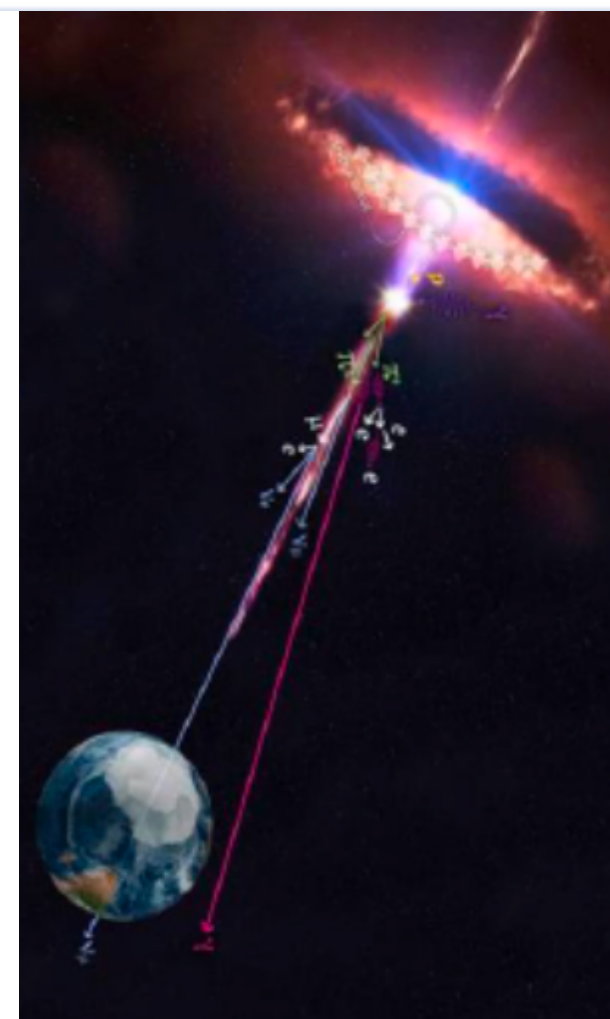
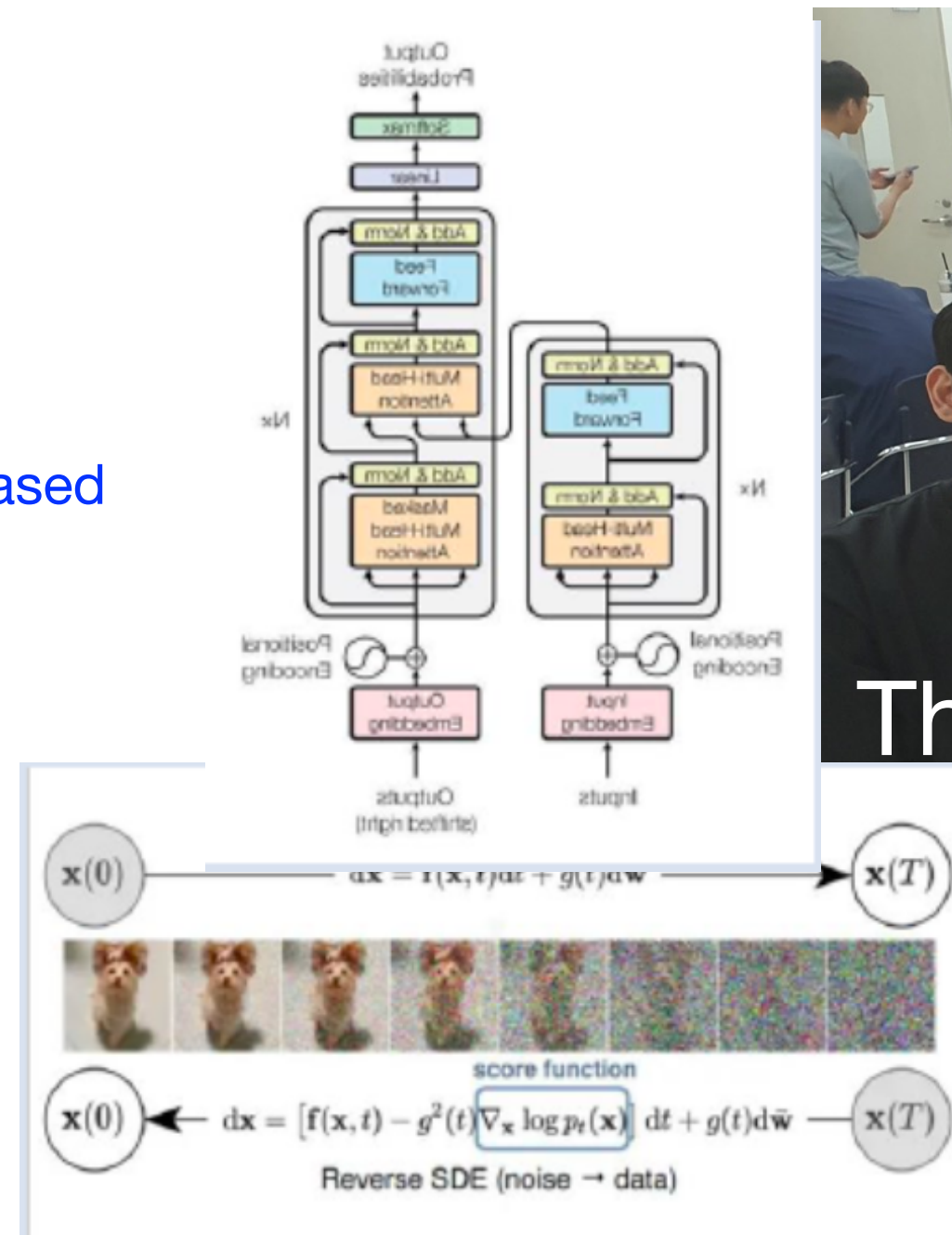
IceCube @ Chung-Ang University

- Study atmospheric neutrinos. Especially electron neutrinos
- Participation in the IceCube-Upgrade simulations. i.e. Photon Propagation & mDOM response.
- Develop a low-energy reconstruction tools using Transformer-based neural network



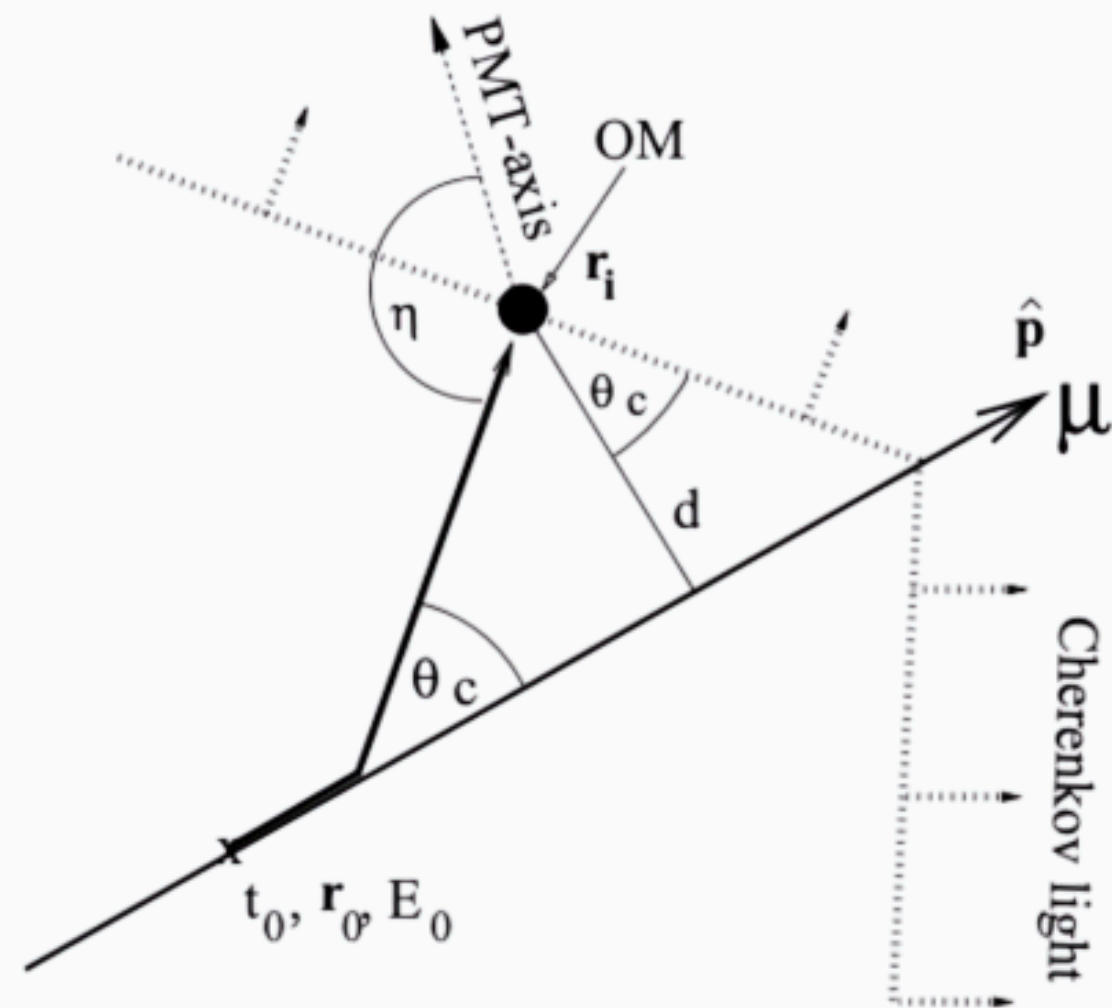
IceCube @ Sungkyunkwan University

- Muon-track reconstruction using a neural network that fits Gupta-Kundu-based arrival-time PDFs
- Generative model for IceCube neutrino event simulation and end-to-end reconstruction using flow and diffusion model
- Optimize pulse cleaning and upgrade PMT noise model based on its timing and charge characteristics



Track Reconstruction (Gupta-Kundu-based time PDF) at SKKU

- For a given track $\vec{\theta}$, the geometric arrival time t_{res} of a Cherenkov photon is as follows:



$$t_{\text{geo}} = t_0 + \frac{\hat{\mathbf{p}} \cdot (\mathbf{r}_i - \mathbf{r}_0) + d \tan \theta_c}{c_{\text{vac}}}$$

- Due to the optical properties of the detector medium, the arrival time of a Cherenkov photon is stochastically delayed. The delay, t_{res} , is modeled by the **Pandel function**.

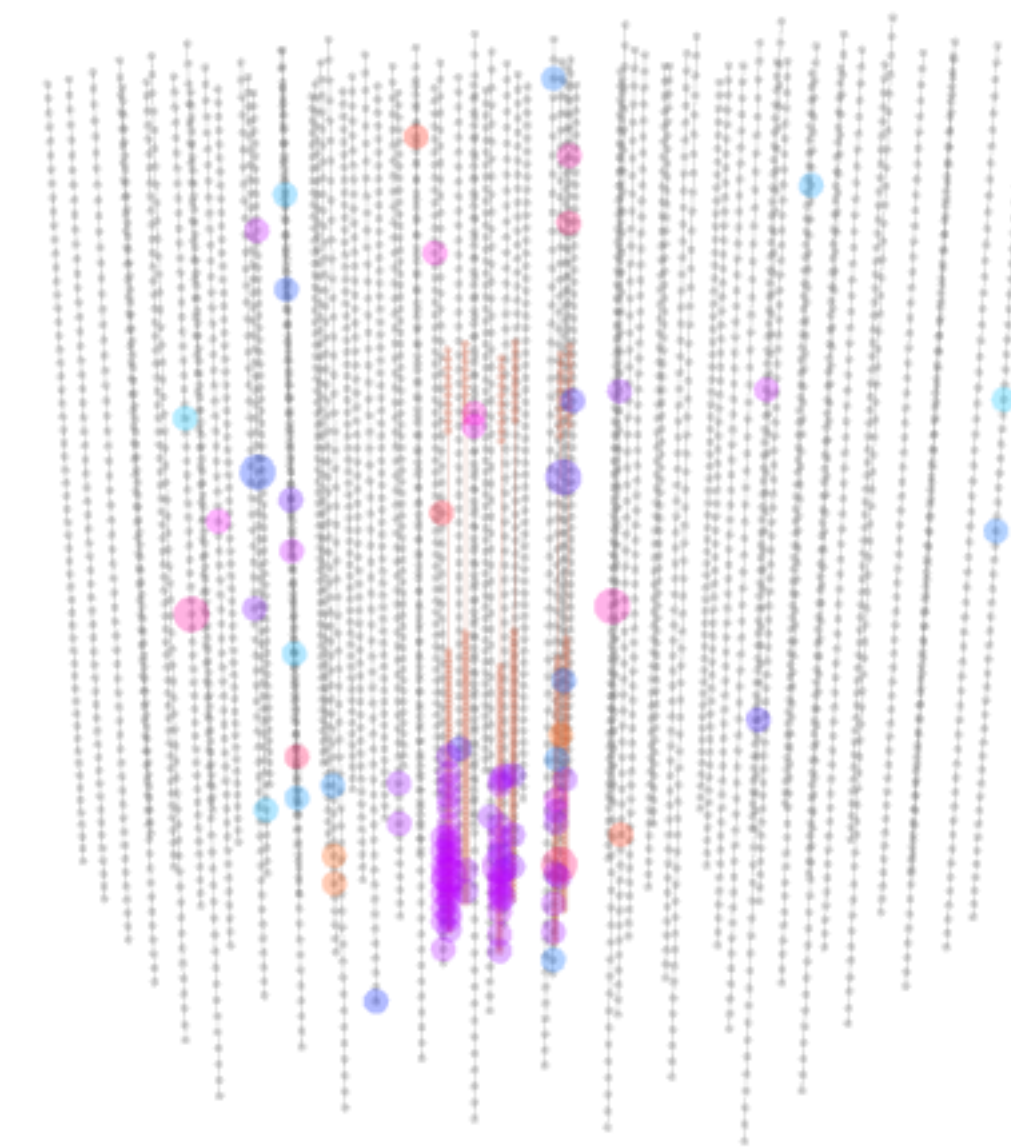
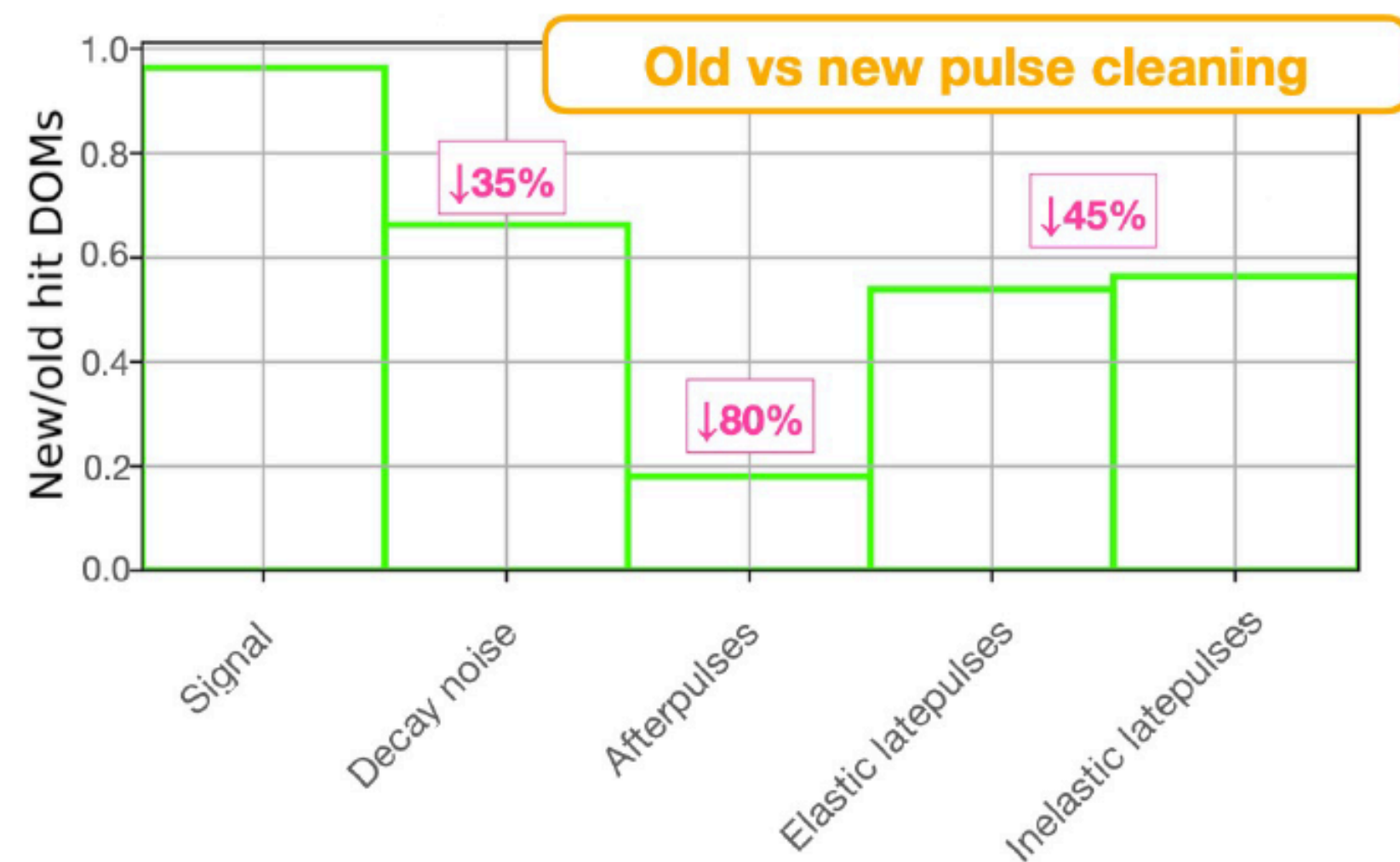
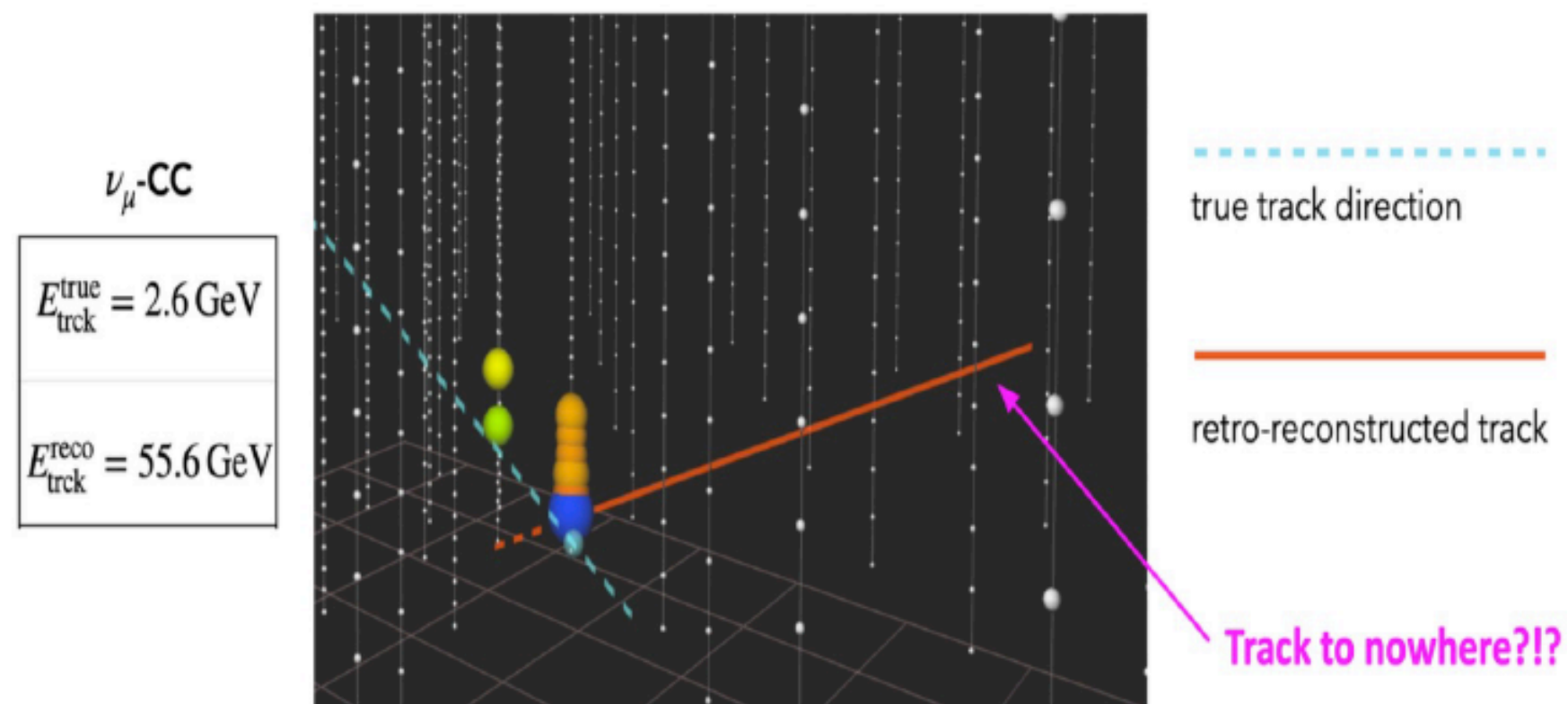
$$p(t_{\text{res}}, |d, \vec{\theta}) = \frac{\beta^\alpha}{\Gamma(\alpha)} t_{\text{res}}^{\alpha-1} \exp(-\beta t_{\text{tes}})$$

- The track is obtained by maximizing the following - form known as the MPE likelihood

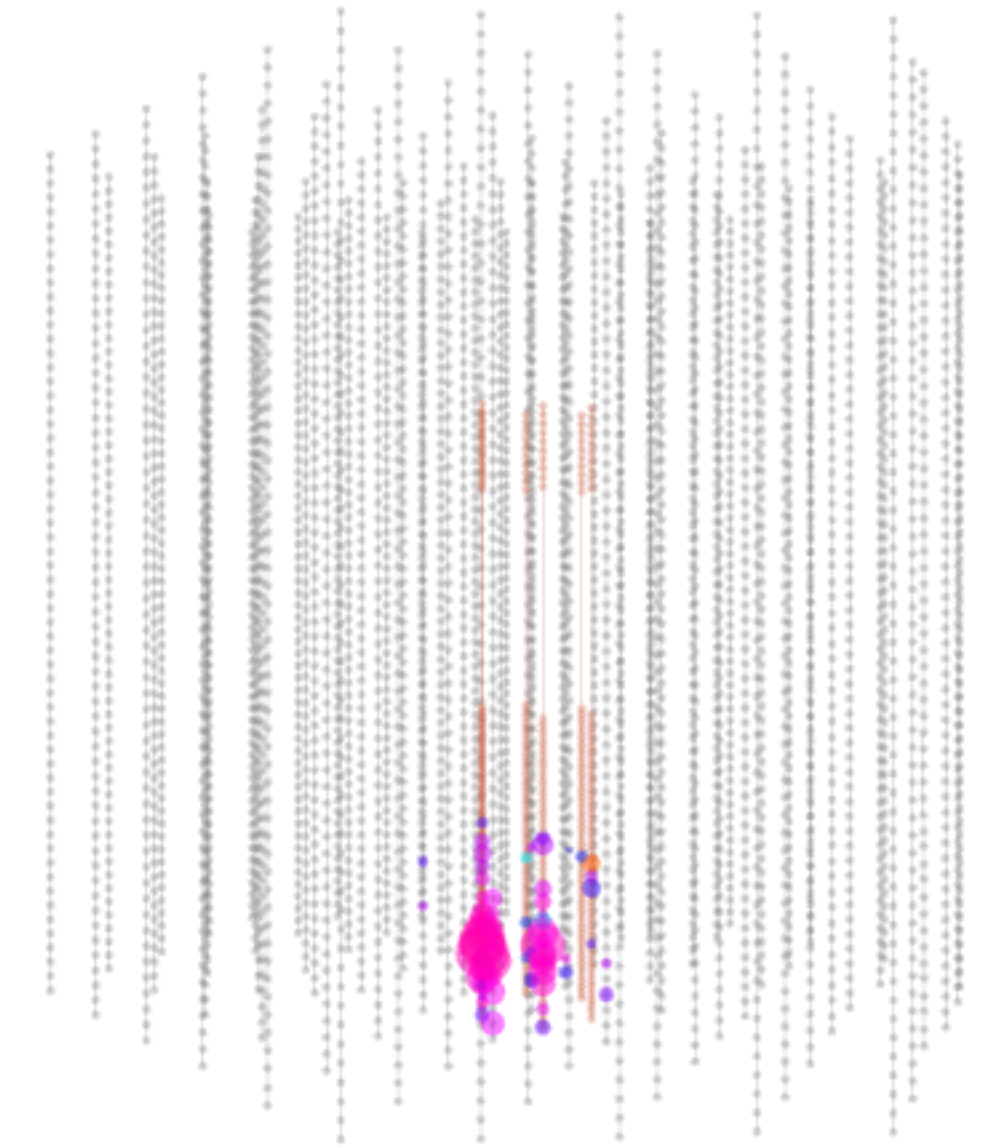
$$\mathcal{L}_{\text{MPE}}(\vec{\theta}) = \prod_i^{\text{1st hits}} n_i \cdot p(t_{\text{res},i} | d, \vec{\theta}) \cdot \left(\int_{t_{\text{res},i}}^{\infty} p(t | d, \vec{\theta}) dt \right)^{n_i-1}$$

Replace the Pandel Function with Gupta-Kundu Generalized Exponential function using neural network training.

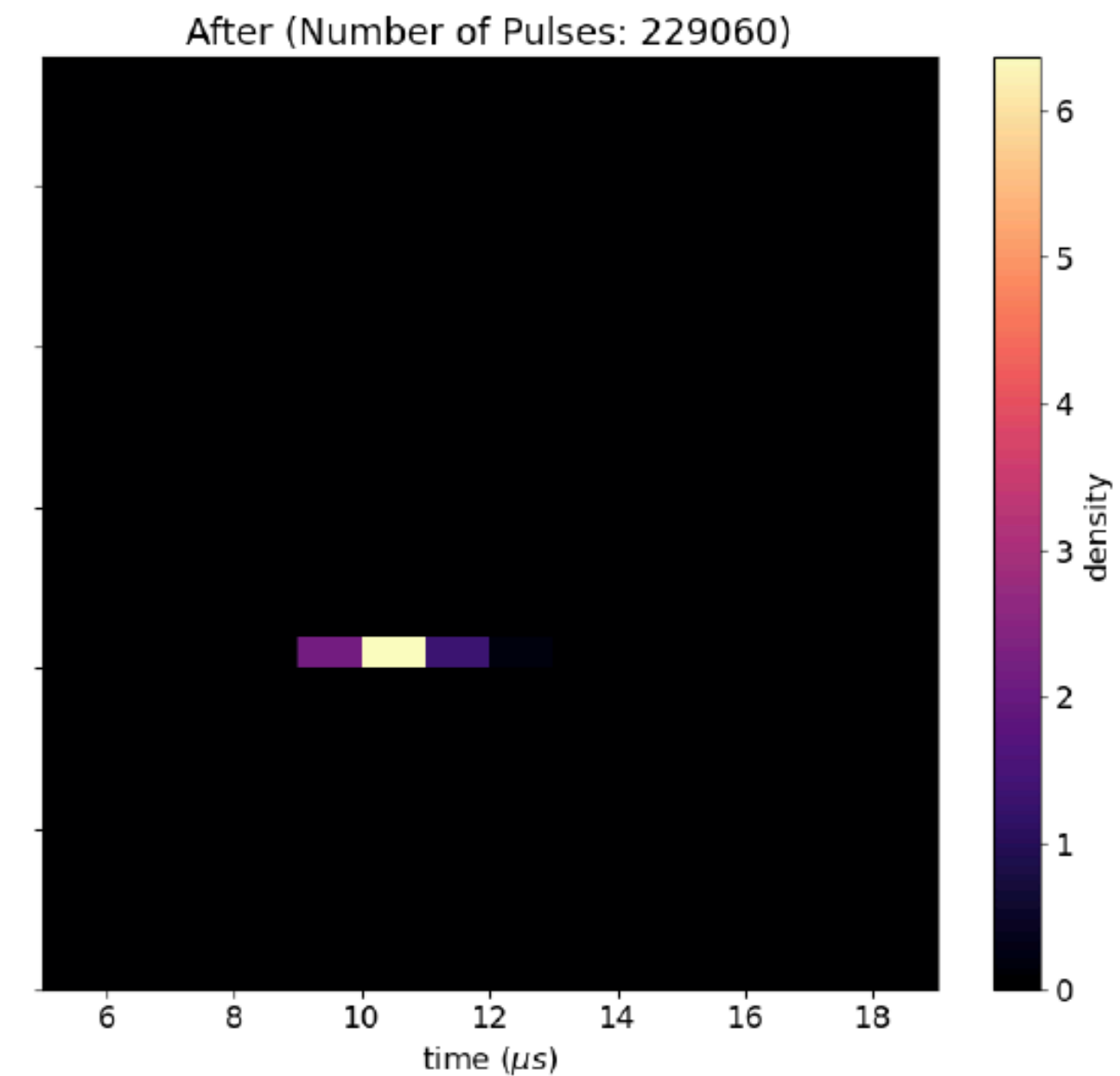
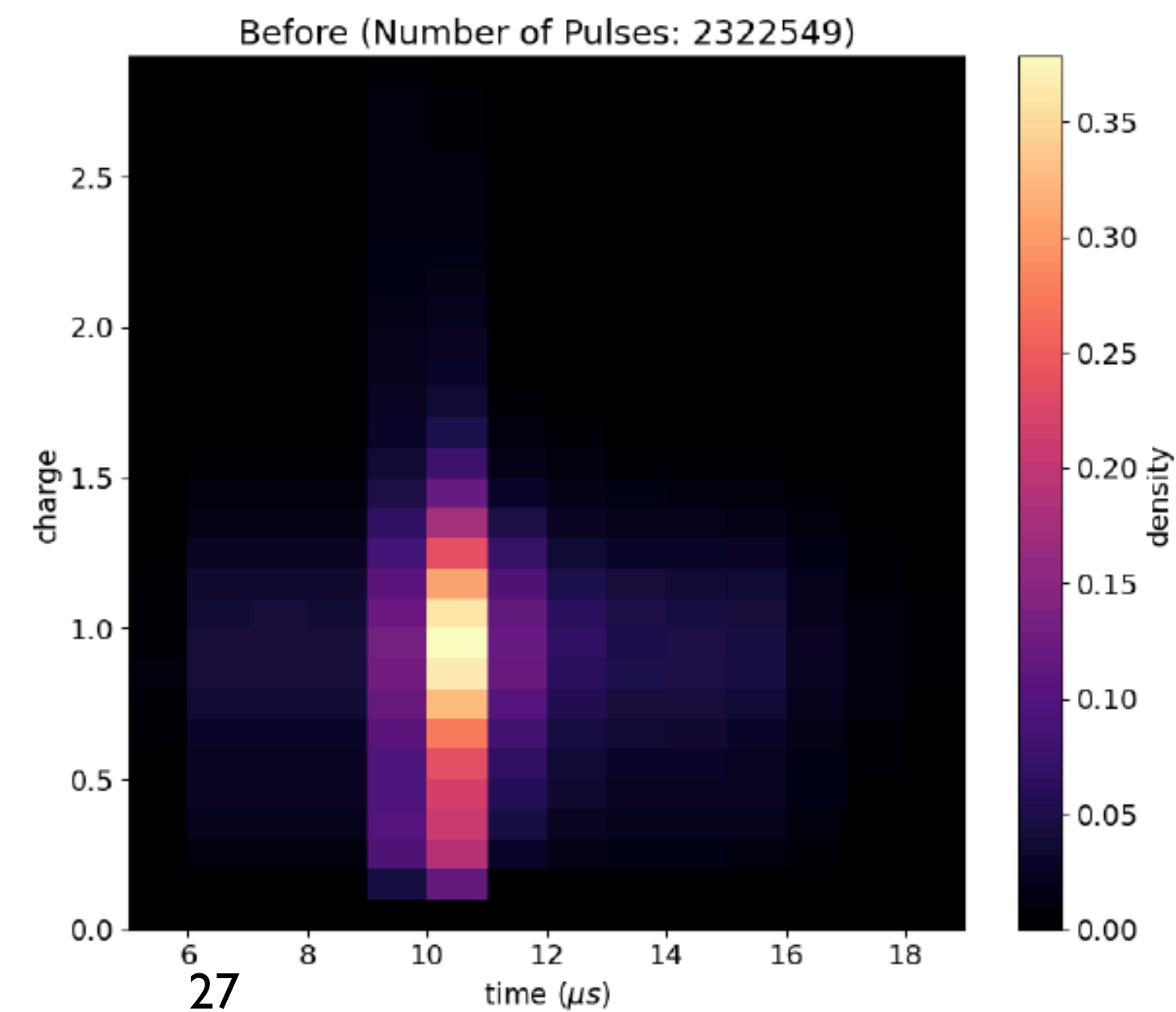
Pulse Cleaning : Modularization and Optimization (SKKU)



Before Cleaning

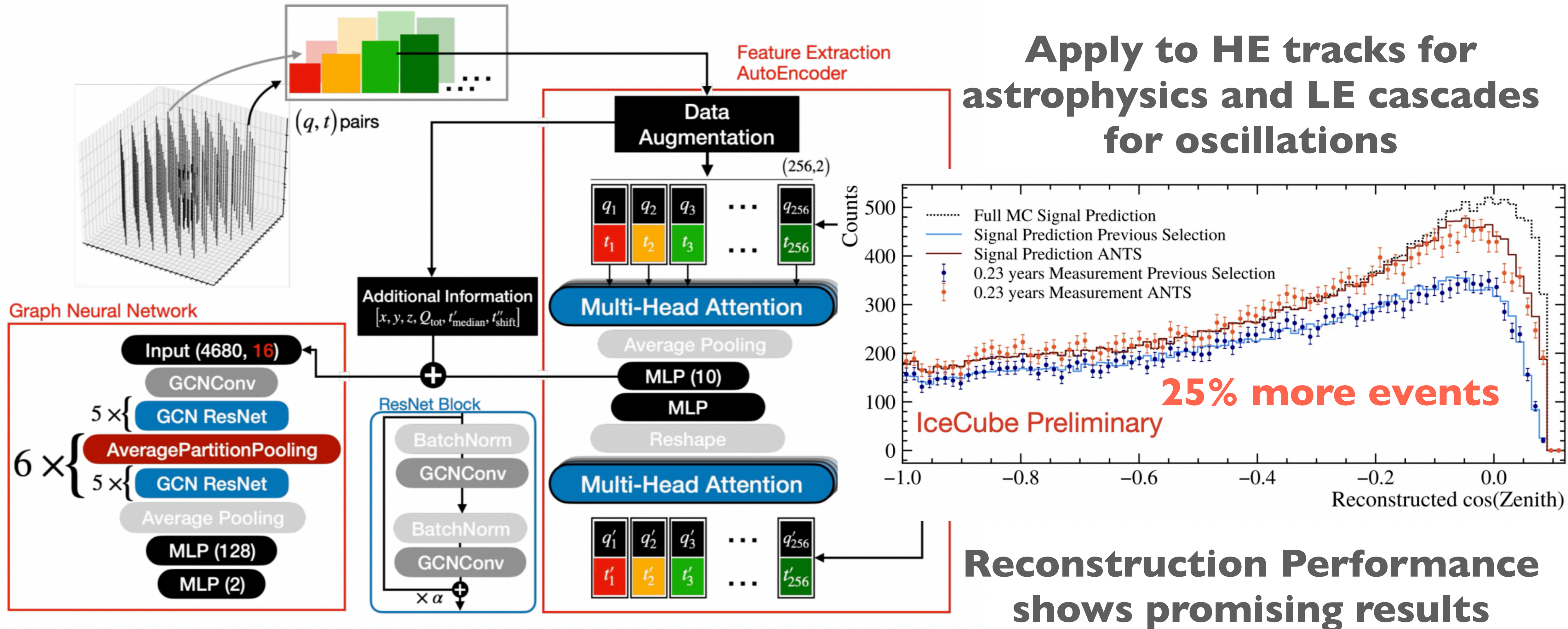


New cleaning segment

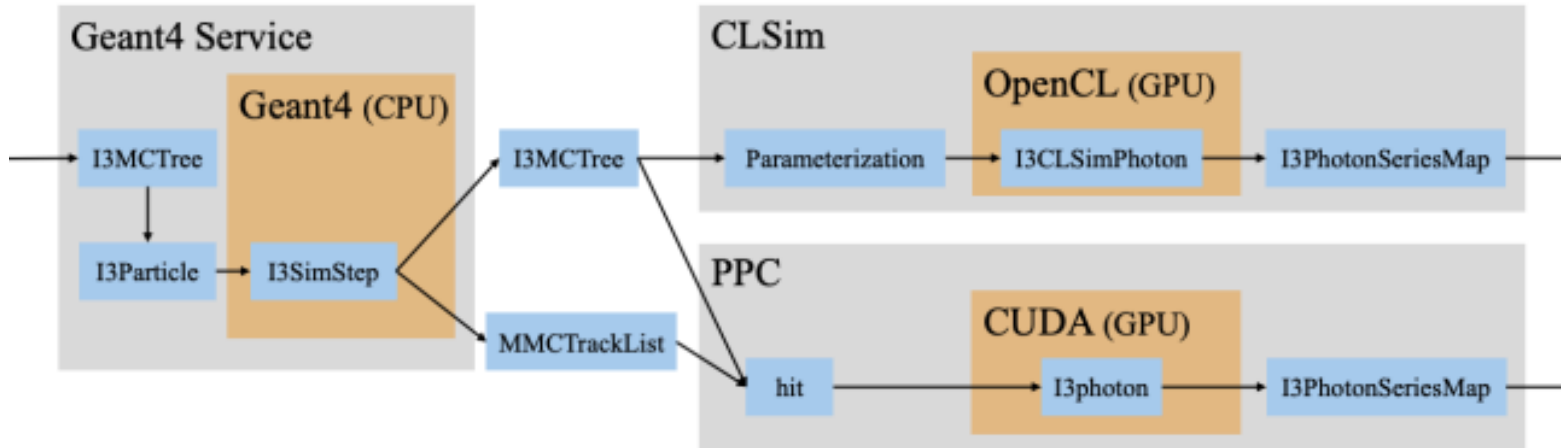


IceCube Upgrade event reconstruction

Transformer-based neutrino event reconstructions (Aachen-CAU)



IceCube Upgrade Simulation development at CAU



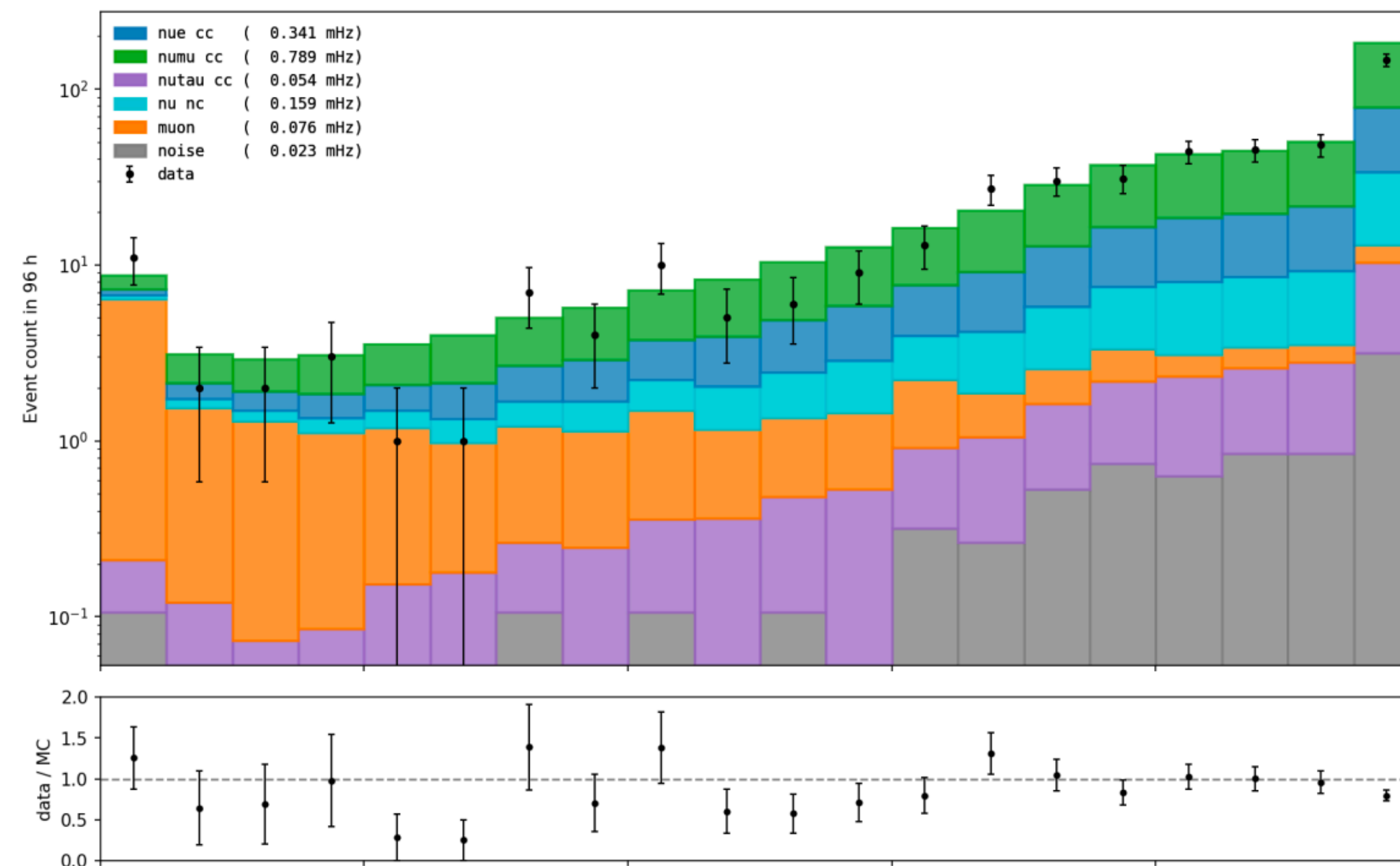
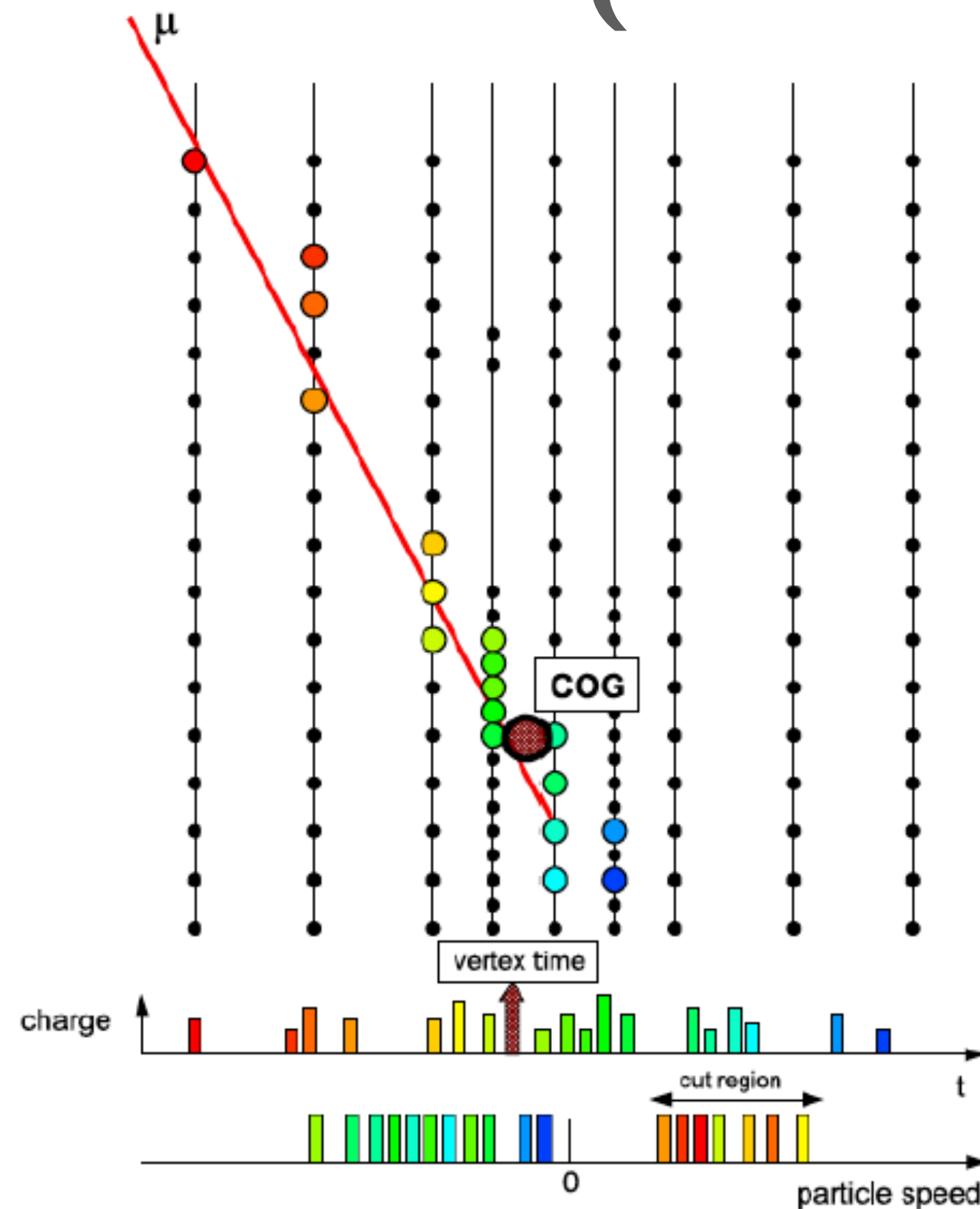
Separation of a code for GPU photon propagation in ice from Geant4 neutrino production makes Upgrade simulation chain more flexible and accessible.

Atmospheric Neutrino Oscillation Physics at CAU

New Veto Algorithms (VICH) by CAU

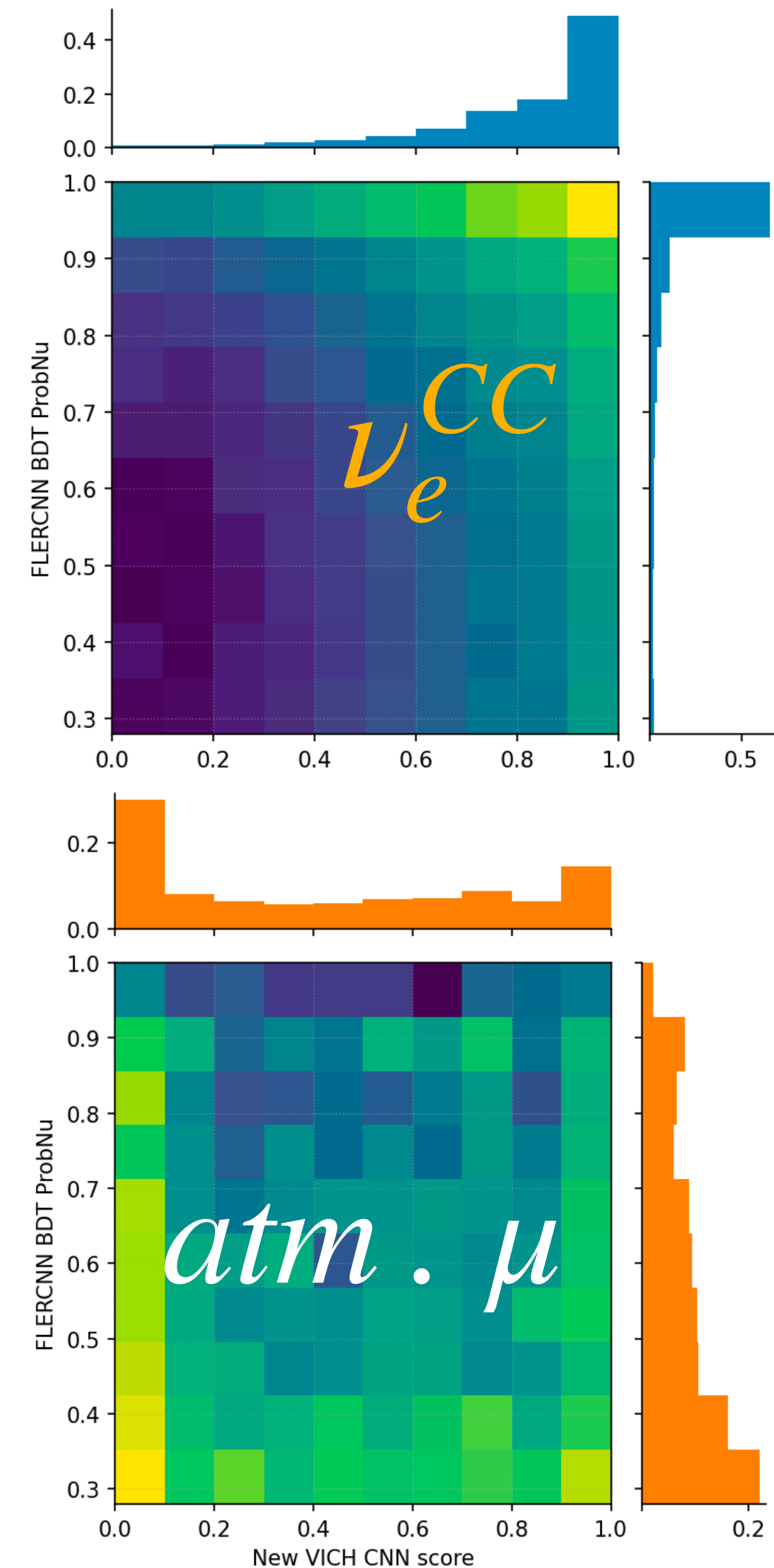
Towards the Upgrade ν_e appearance analysis

($4 \text{ GeV} < \text{Energy} < 15.8 \text{ GeV}$ & $120^\circ < \theta_{\text{zen}} < 180^\circ$)

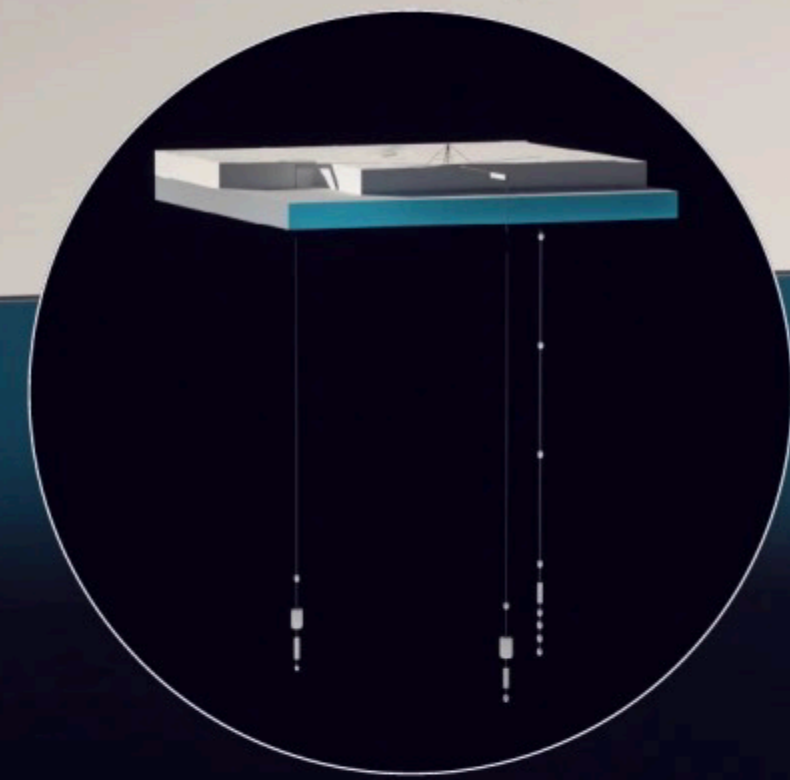


VICH CNN Scores

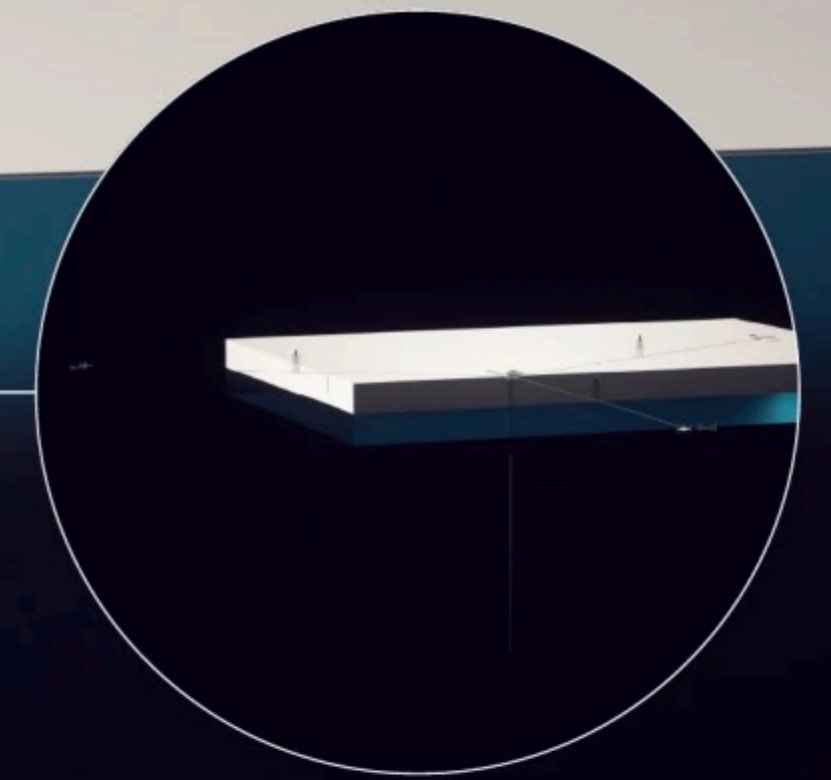
It is clear that reconstruction and PID will be two challenges in the Upgrade. CAU will work on those in $\nu_\mu \rightarrow \nu_e$ analysis



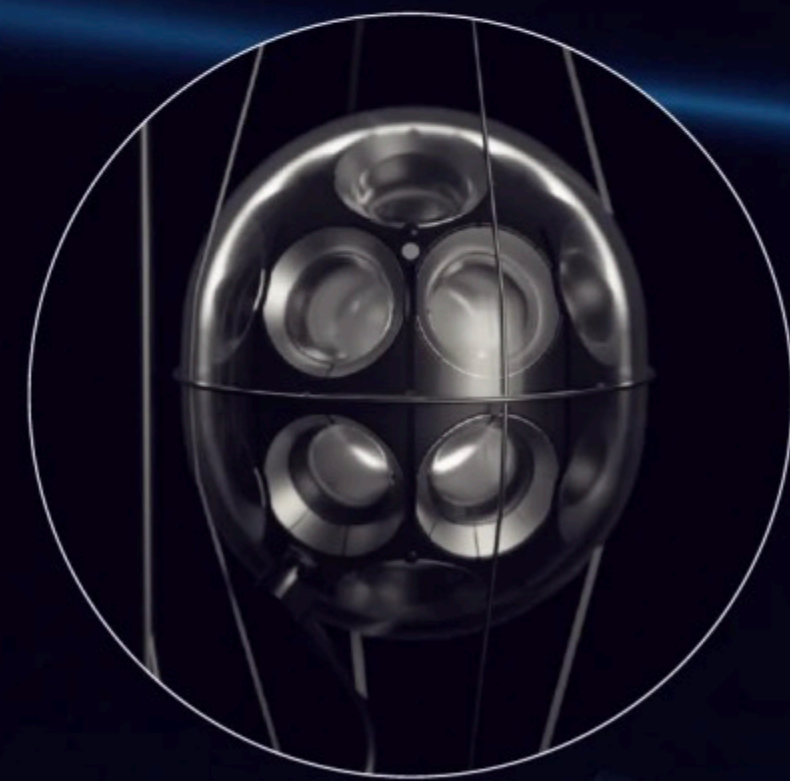
IceCube-Gen2



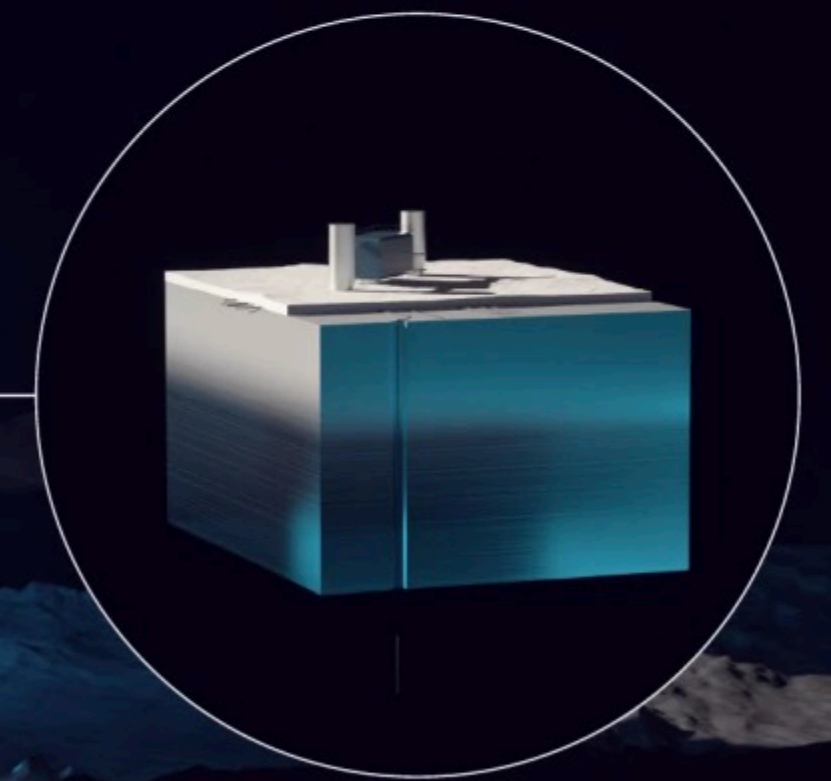
Radio Array | Station



Surface Array | Station



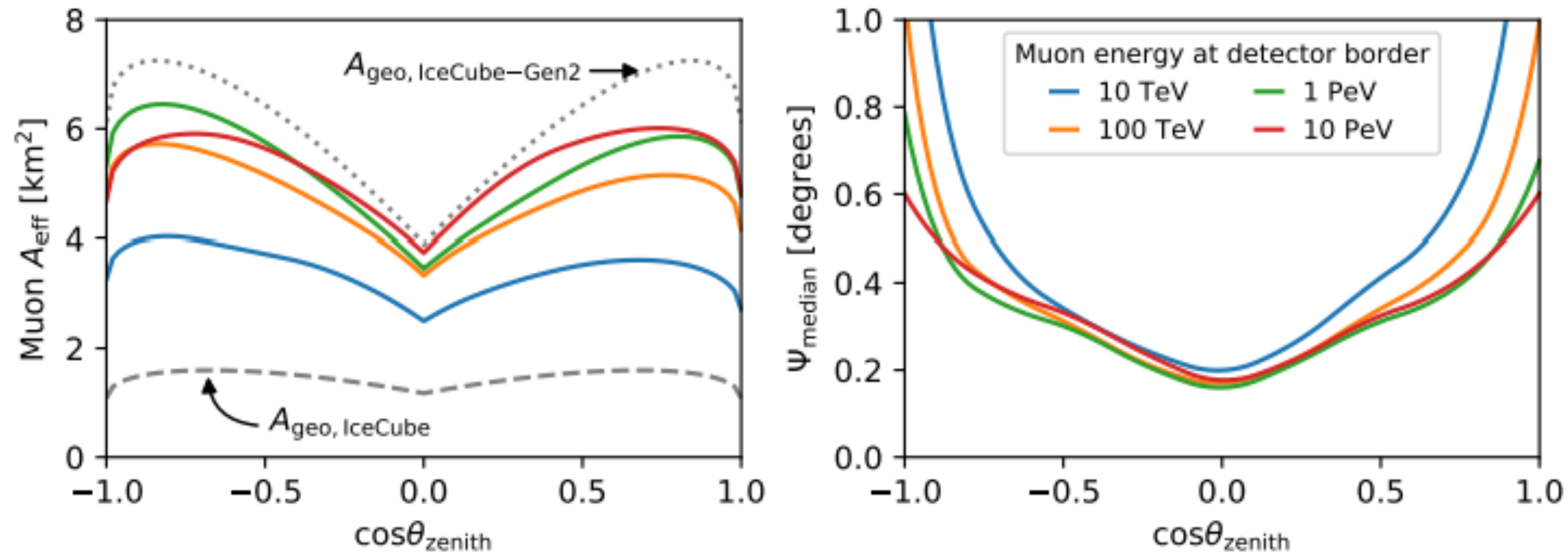
Optical Array | Sensor



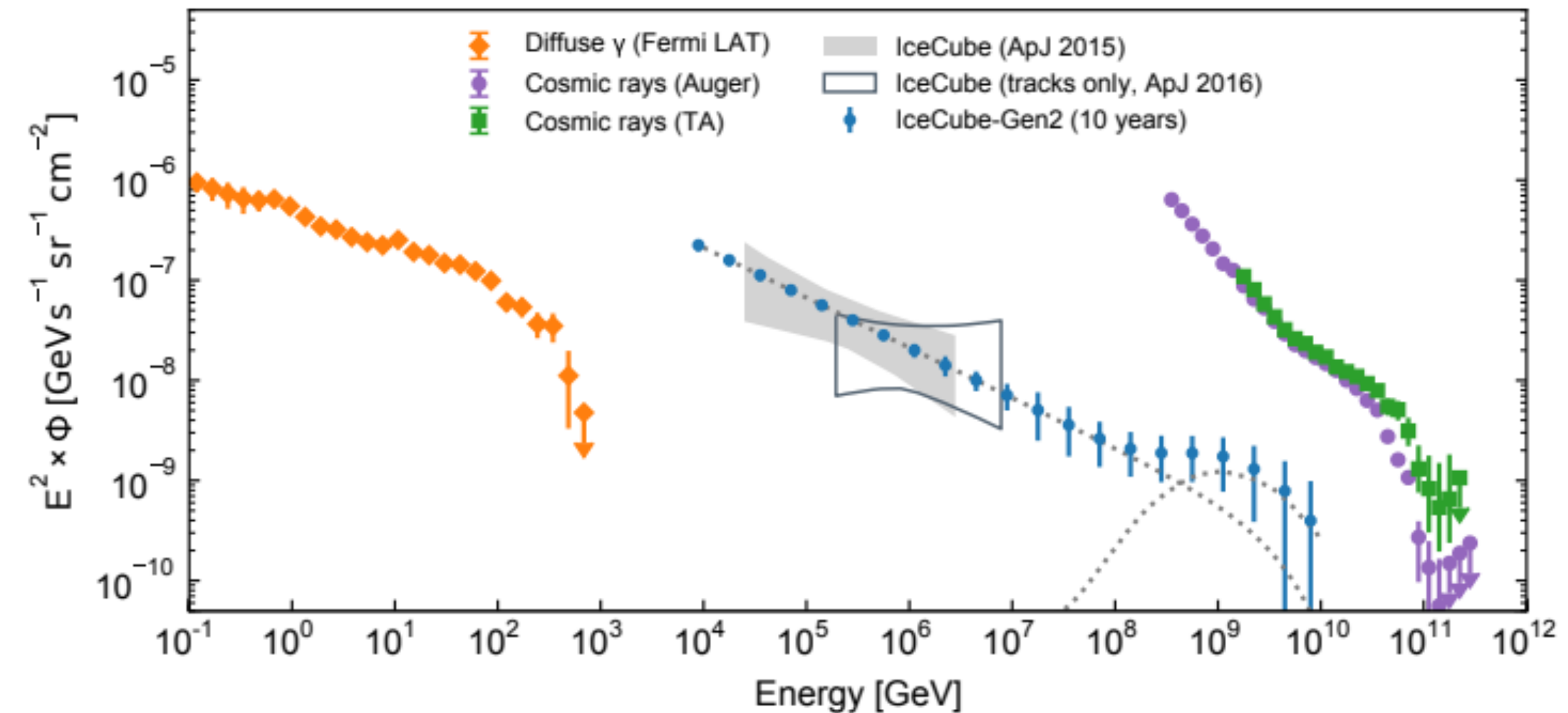
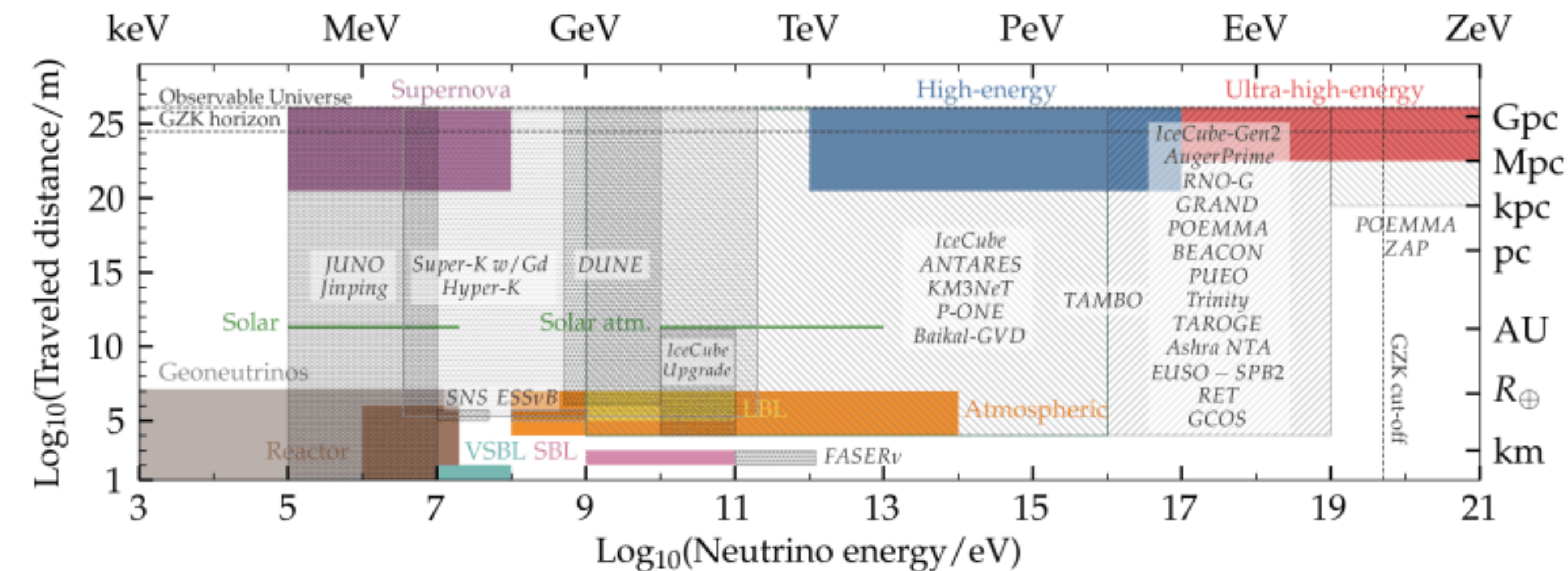
IceCube | Laboratory

IceCube-Gen2: Eyes to the Violent Cosmos

J. Phys. G: Nucl. Part. Phys. **48** 060501 (2021)



Neutrinos from TeV to EeV
Cosmic particle acceleration
Sources and propagation of HE particles
Fundamental physics with HE neutrinos



Summary and Outlook

The IceCube Upgrade is starting now

- Korean IceCube members (~8) are growing. CAU & SKKU
- We are interested in Physics analyses in the Upgrade.
- Participate in detector response simulations and event reconstructions.
- The Upgrade will happen starting now.
- Korean IceCubers will participate in the Upgrade activities.
- 아이스큐브는 활동성 은하핵 과 같은 천체에서 나오는 중성미자 입자를 탐색하는 실험입니다. 국내에서 이제 출발하지만 SKKU-노창동, CAU-하창현 그룹이 새로운 미래를 열것으로 기대하고 있습니다. 많은 관심과 지원 부탁드립니다.

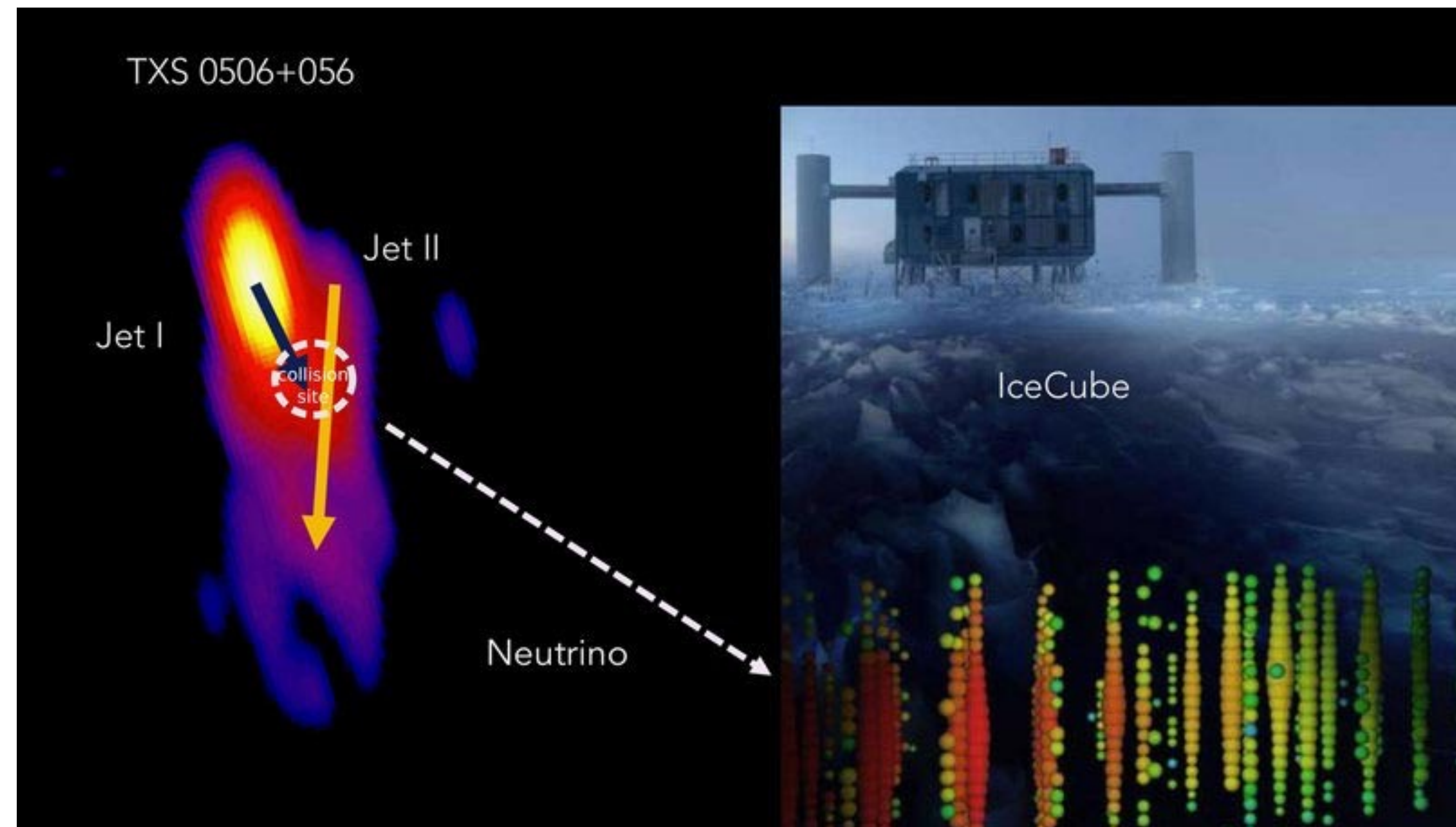
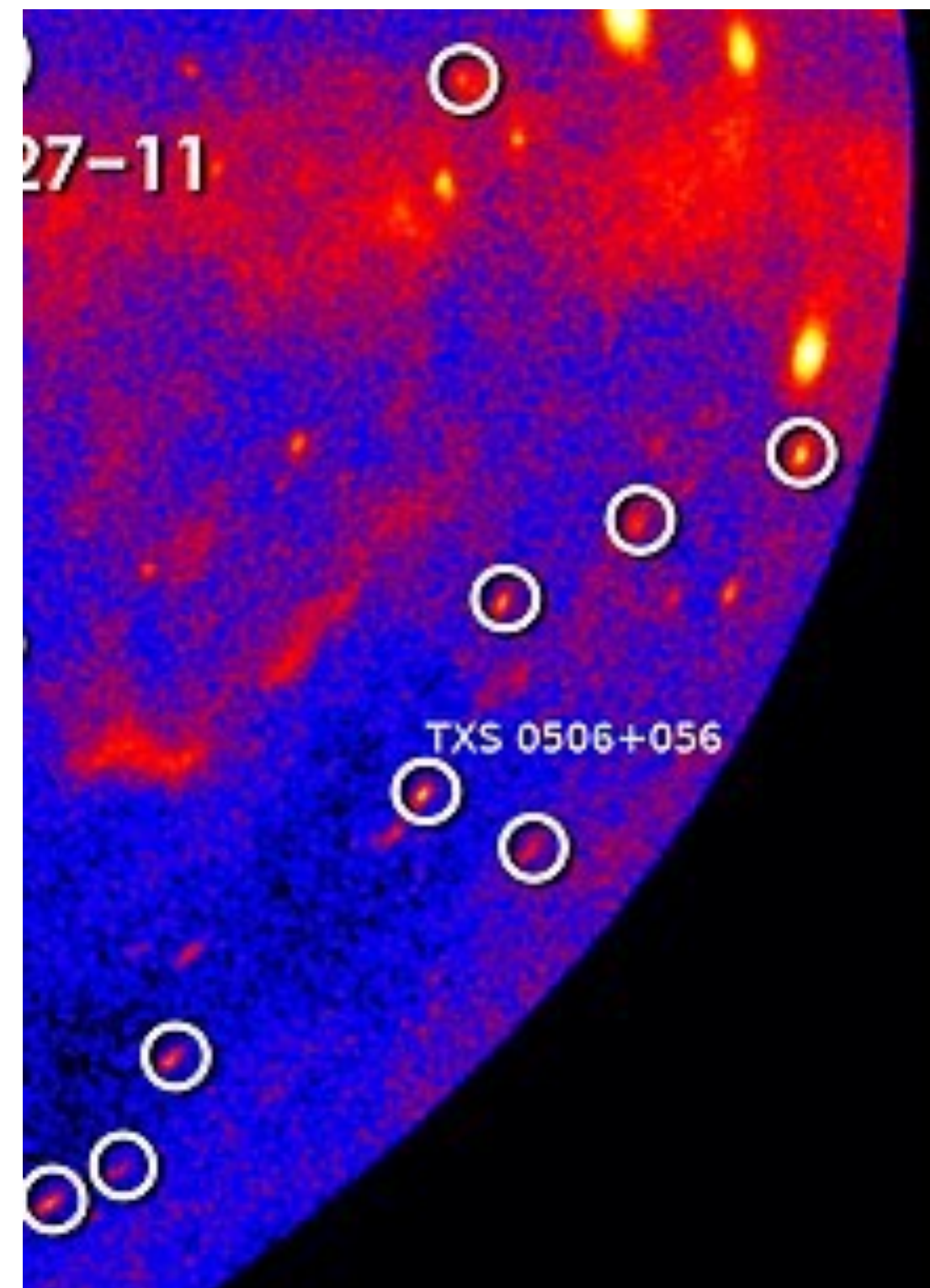
Thank you!



IceCube Collaboration Meeting at Salt Lake City (2025.10)

Back-up

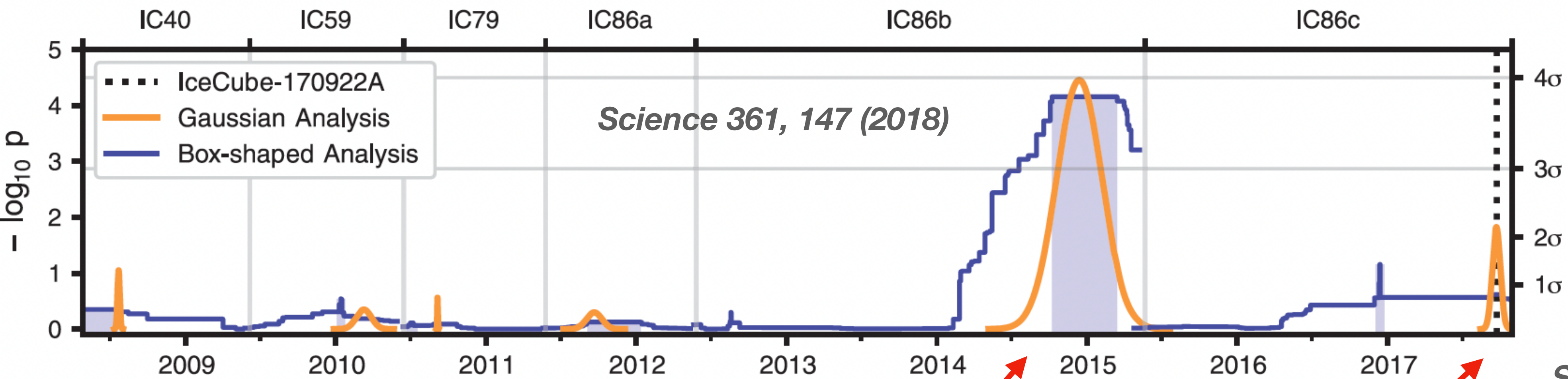
Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A



Science 361, eaat1378 (2018)

IceCube neutrino alert prompted γ -ray follow-up searches by e.g. FermiLAT & MAGIC, resulting in flaring blazar TXS 0506+056, 0.1 deg. from the neutrino.

Neutrino emission from the direction of the blazar TXS 0506+056 in association with the IceCube-170922A

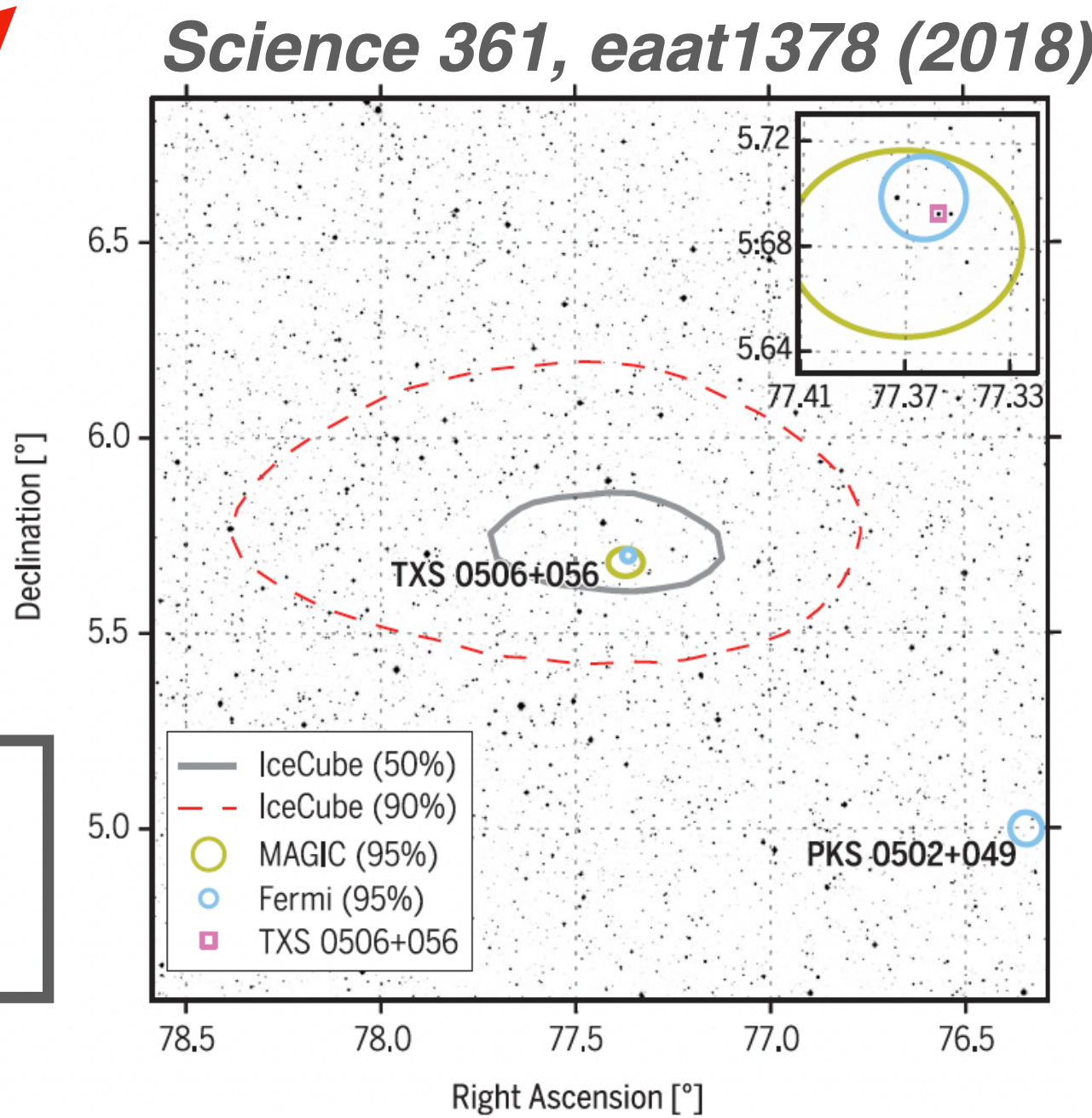


9.5 years of data prior to the Alert.
Archival search for the neutrino emission at
the same position of the blazar

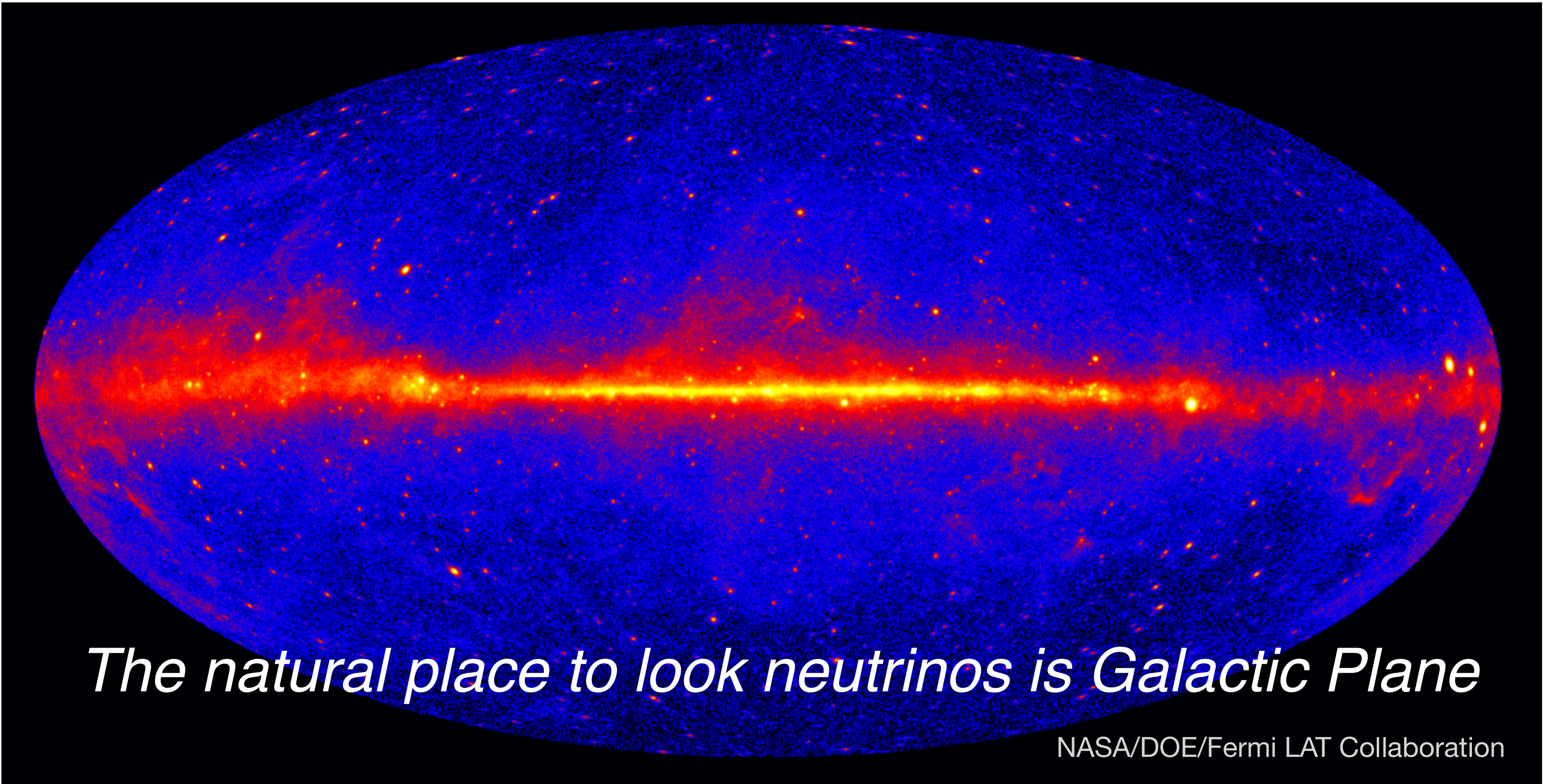
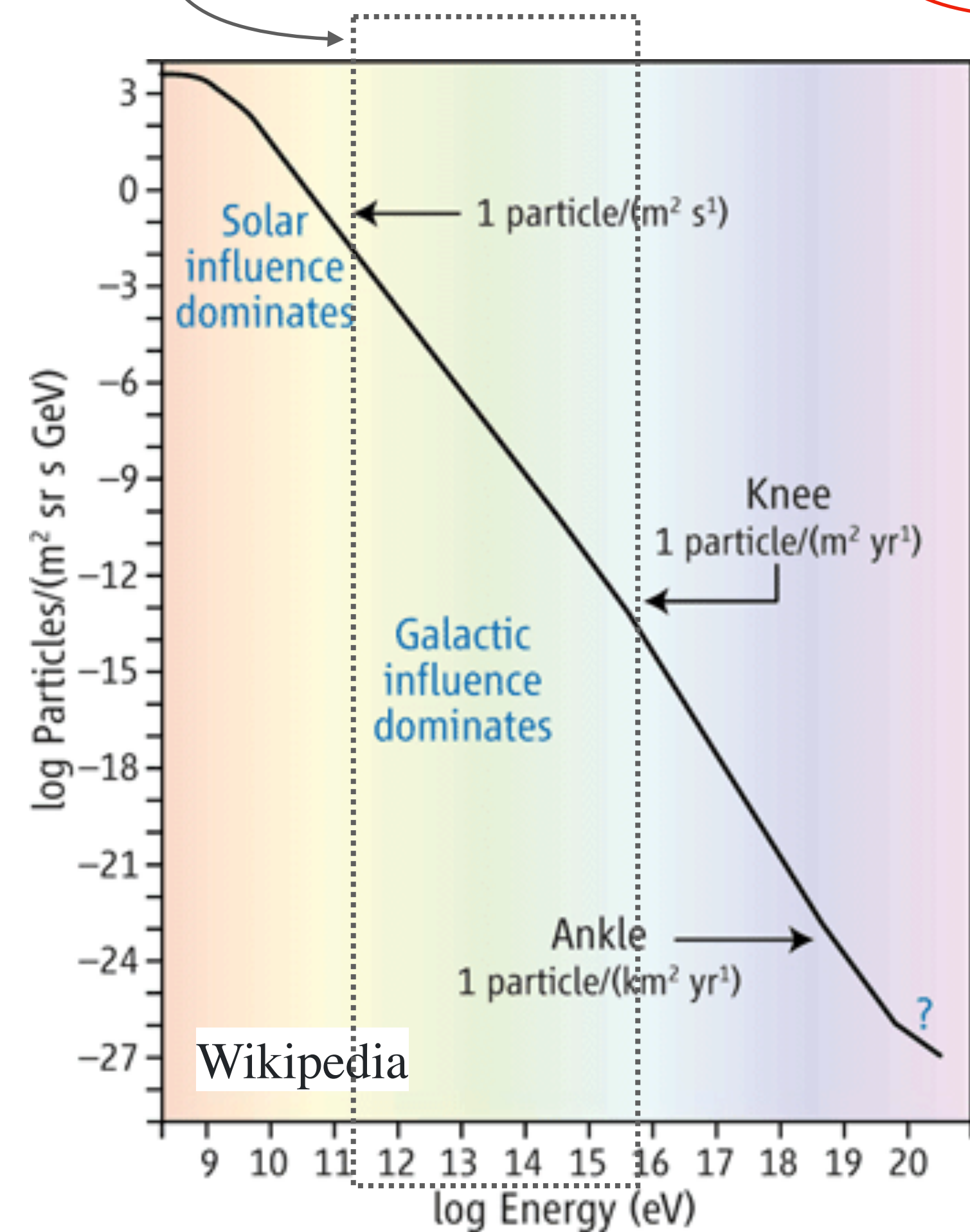
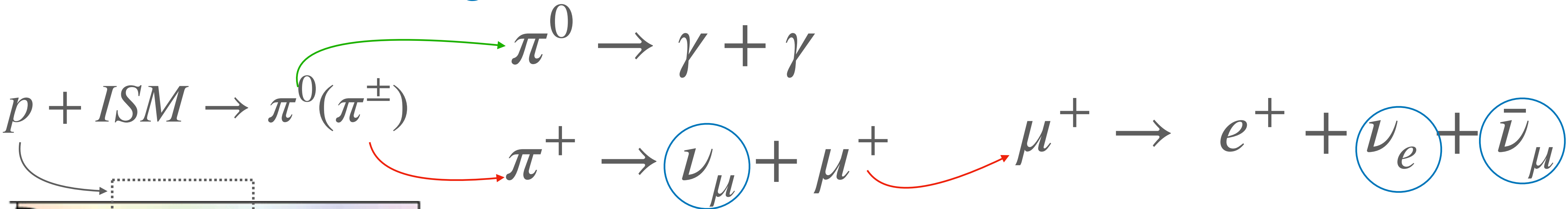
Between Sept. 2014 and Mar. 2015,
independent 3.5σ excess is found at the site.

290TeV neutrino Alert
(IceCube-170922A)
Coincident with γ -ray flare
from blazar TXS 0506+056

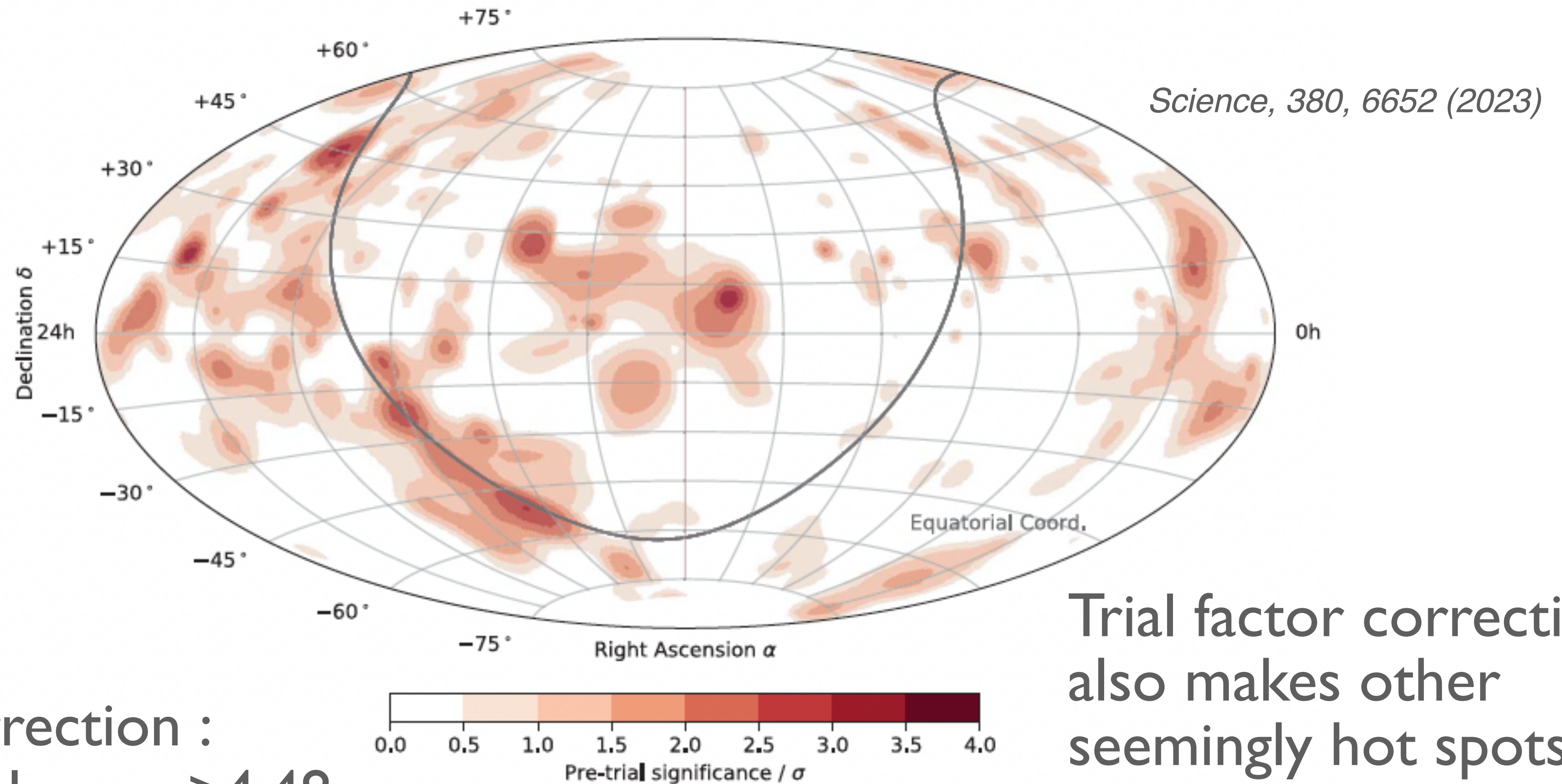
**Blazars are sources of the high-energy astrophysical neutrino flux
and probable sources of the very high energy cosmic rays.**



Galactic Plane : Charged Pions must exist ; Neutrinos should be there



Excess over the Galactic Plane : 4.71σ , 4.37σ , and 3.96σ depending on models, rejecting the background-only hypothesis.

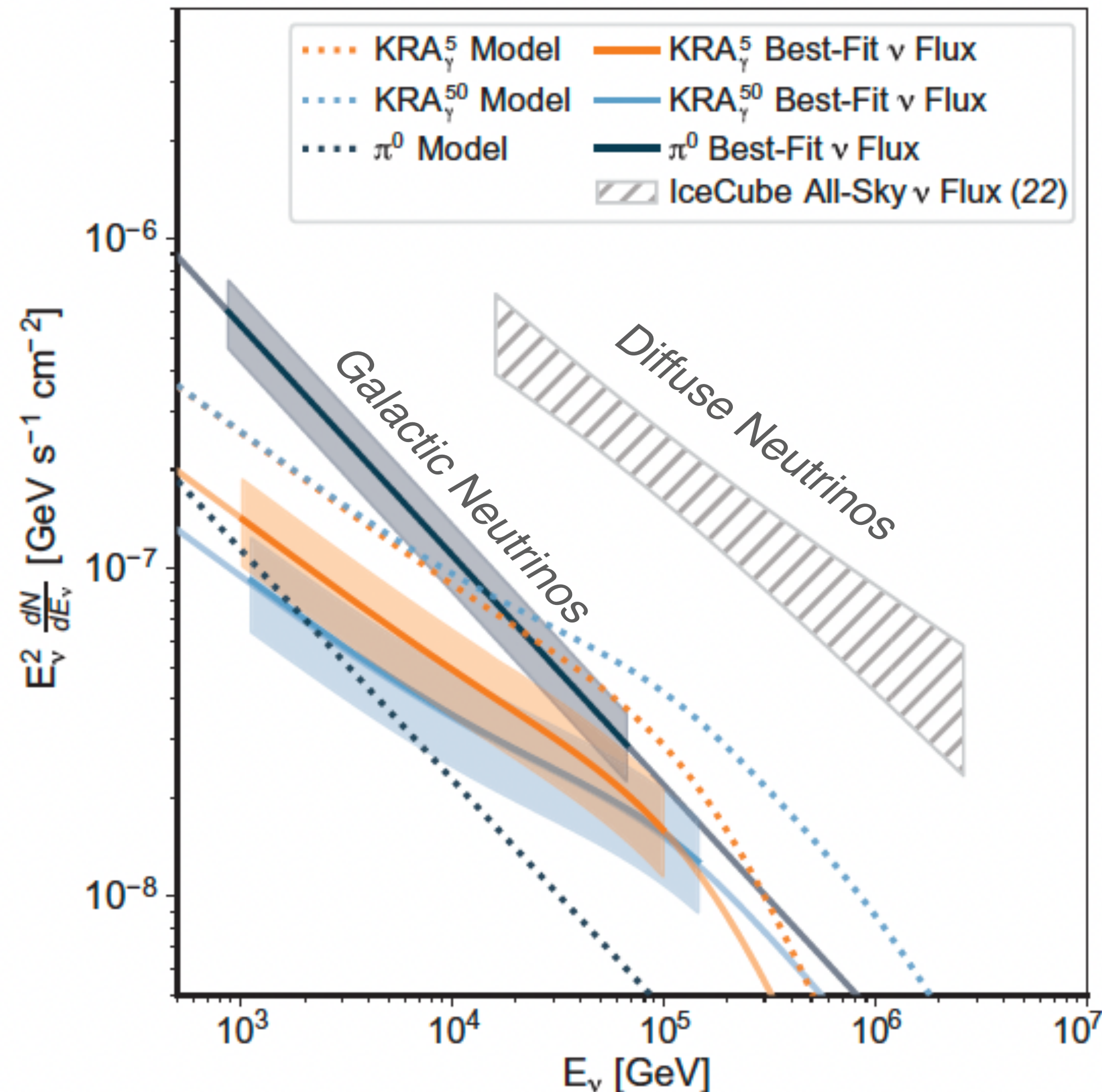


Trial factor correction :
penalty on p-values $\rightarrow 4.48\sigma$

Trial factor correction
also makes other
seemingly hot spots to
be fluctuations

Implications :

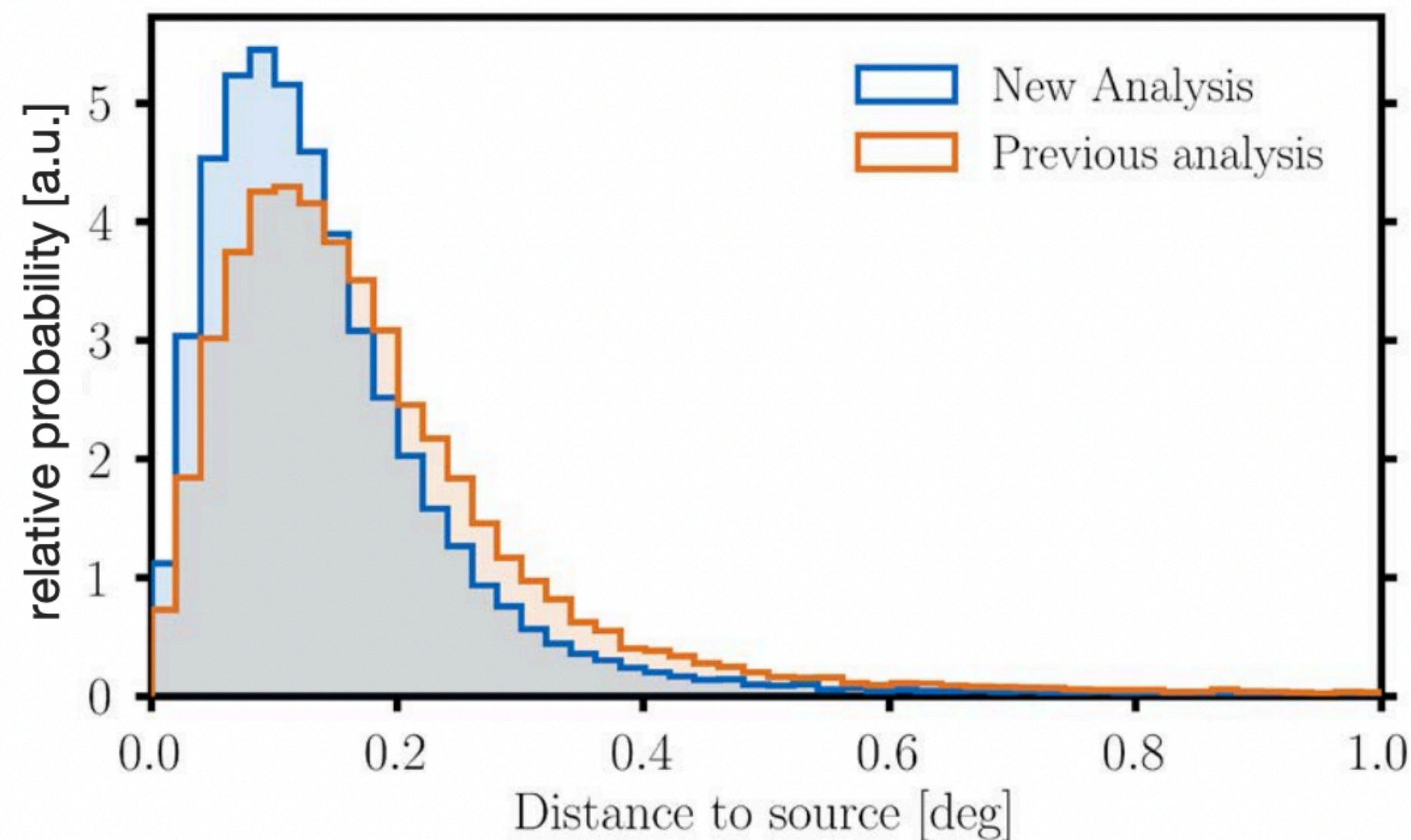
Science, 380, 6652 (2023)



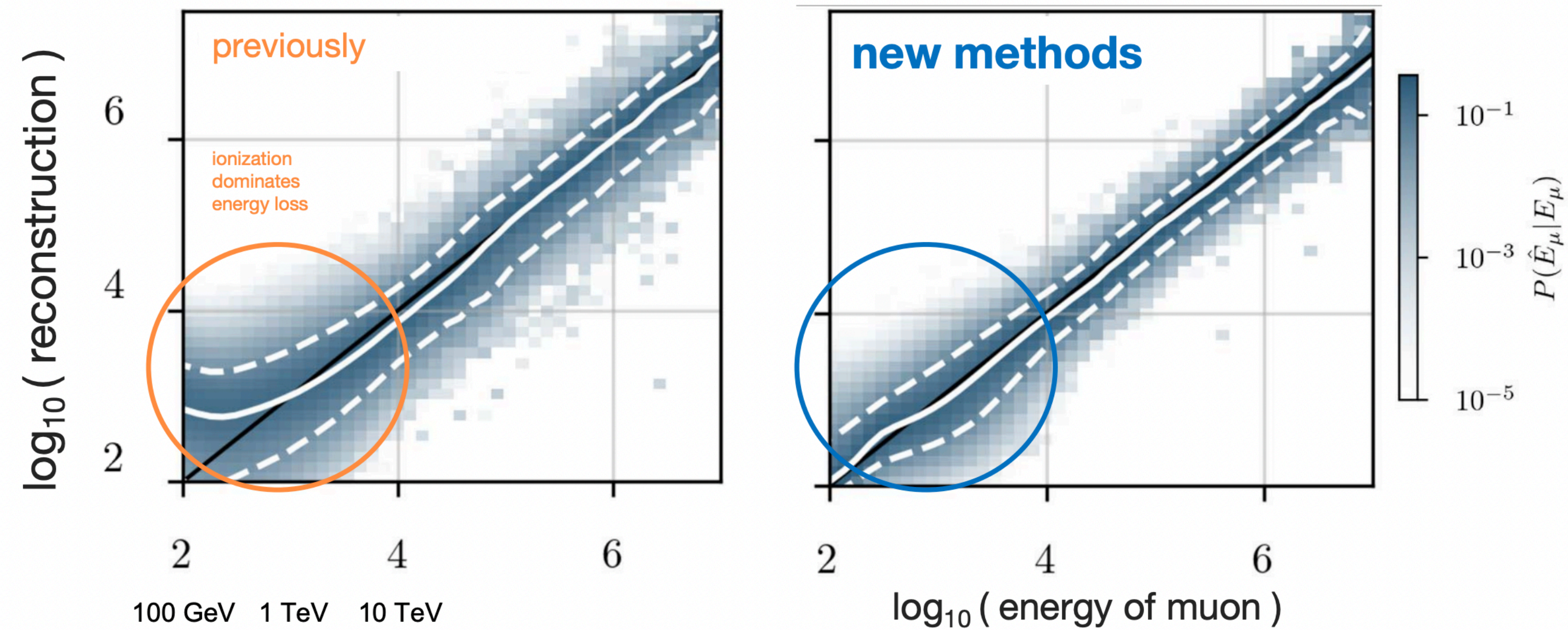
- KRA models and best fits are consistent, except very high energies.
- π^0 model differs by a factor 5, suspicious of CR propagation or spectral index from GC. Best fit agrees with Tibet gamma ray measurements.
- Neutrinos from the Galactic Plane contribute 6~13% to the astrophysical flux at 30 TeV.

Improved data analysis

Reprocessing of the previous data uniformly with new event reconstruction algorithms and new calibrations.

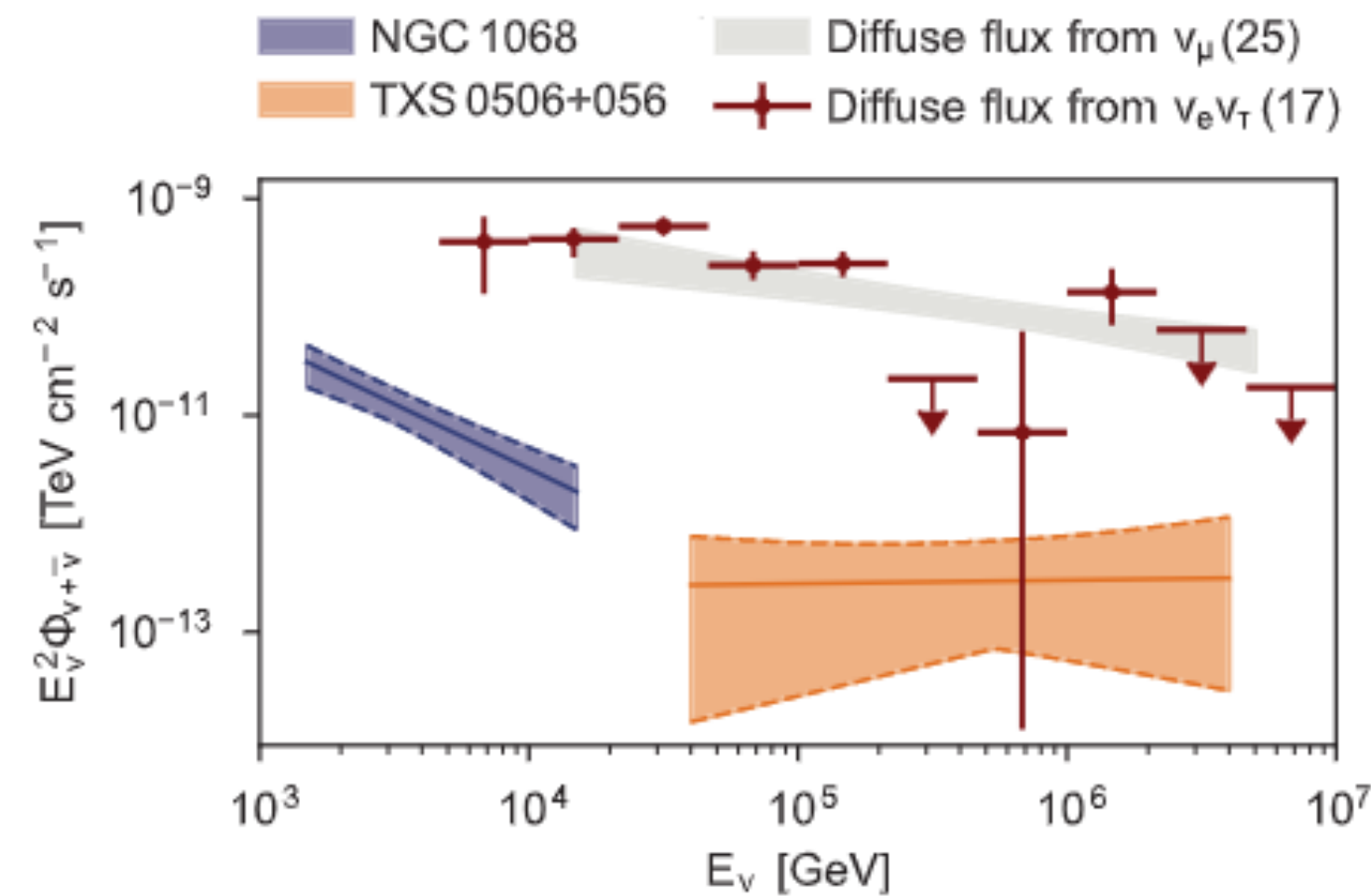
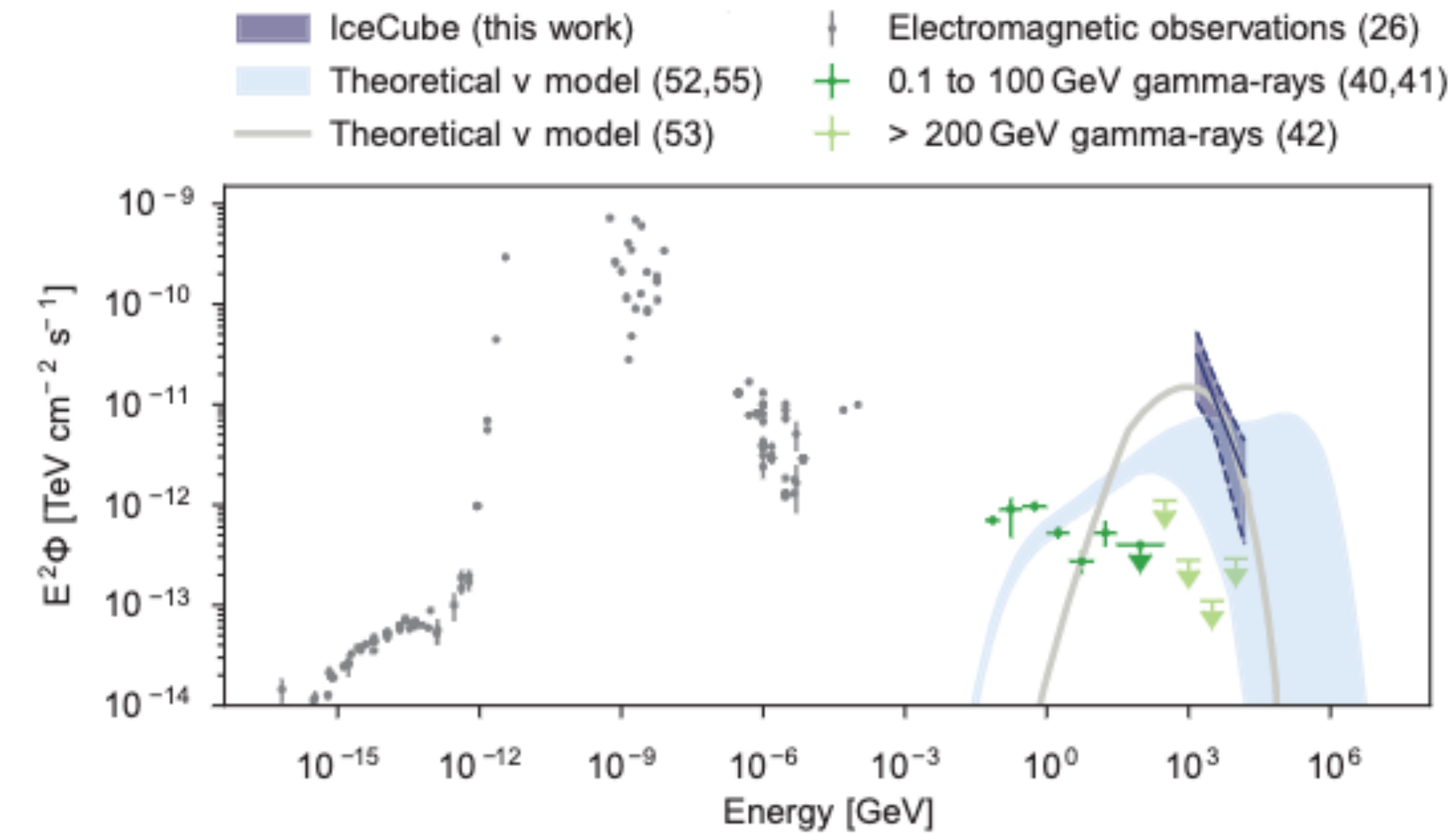
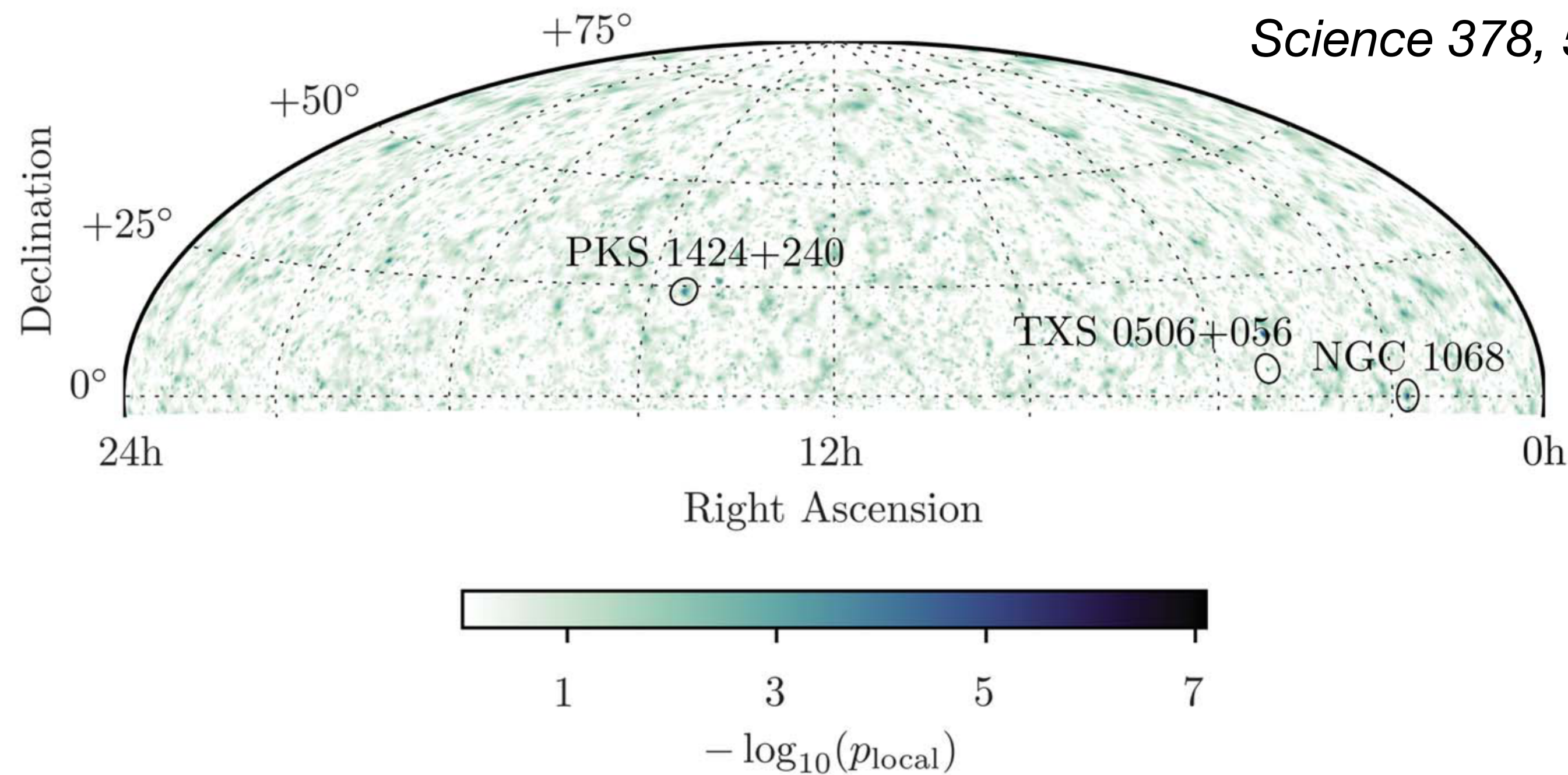


The application of the latest directional reconstruction



Better energy reconstruction by extracting more accurate DOM charge and using Machine Learning.

Evidence for neutrino emission from the nearby active galaxy NGC 1068



An excess of 79^{+22}_{-20} neutrinos at TeV energies (9 year data)

Significance : 5.2σ local, 4.2σ global

The flux of high-energy neutrinos is higher than the upper limit on emissions of TeV gamma rays by an order of magnitude.