중앙대학교
CHUNG-ANG UNIVERSITY

SUNGKYUNKWAN UNIVERSITY 1398 성균관대학교

IceCube Overview

2025 K-Neutrino Symposium
하창현

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

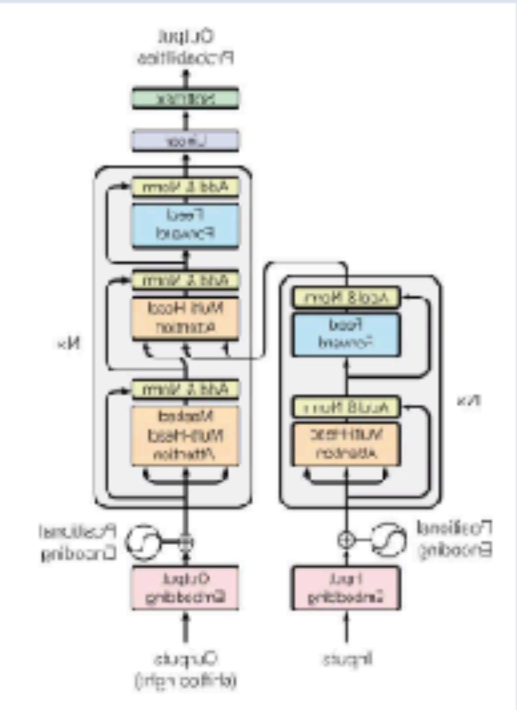

400 people from 59 institutions
in 14 countries
THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
Queen's University
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches 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
NEUTRINO OBSERVATORY
icecube.wisc.edu

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.

IceCube @ Chung-Ang University

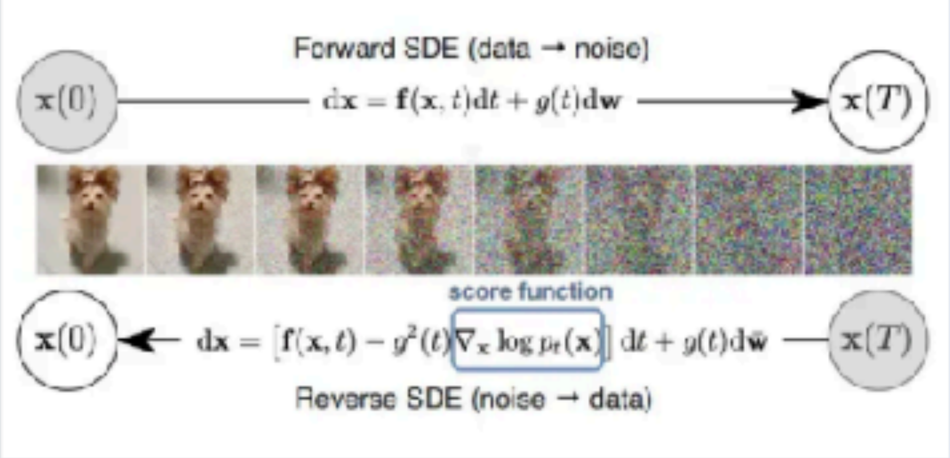
- **CAU wants to study atmospheric neutrinos,**
  - **Especially electron neutrinos.**
- **CAU participates in the simulation for the Upgrade**
  - **Photon Propagation, mDOM response**
- **Develop a low-energy reconstruction algorithm**
  - **Transformer-based neural network.**



Chang Hyon Ha

Hani Kimku

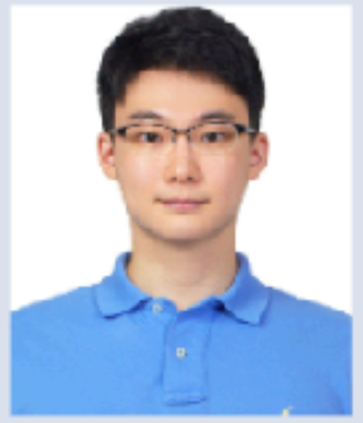
Sooa Kim



IceCube @ Sungkyunkwan University

- **Muon track reconstruction algorithm using mixture density network**
- **Generative model for IceCube neutrino event simulation and end-to-end reconstruction using flow and diffusion model**
- **Optimize gaussian convolution scheme to improve multi-photoelectron likelihood reconstruction**

Chang Dong Rho

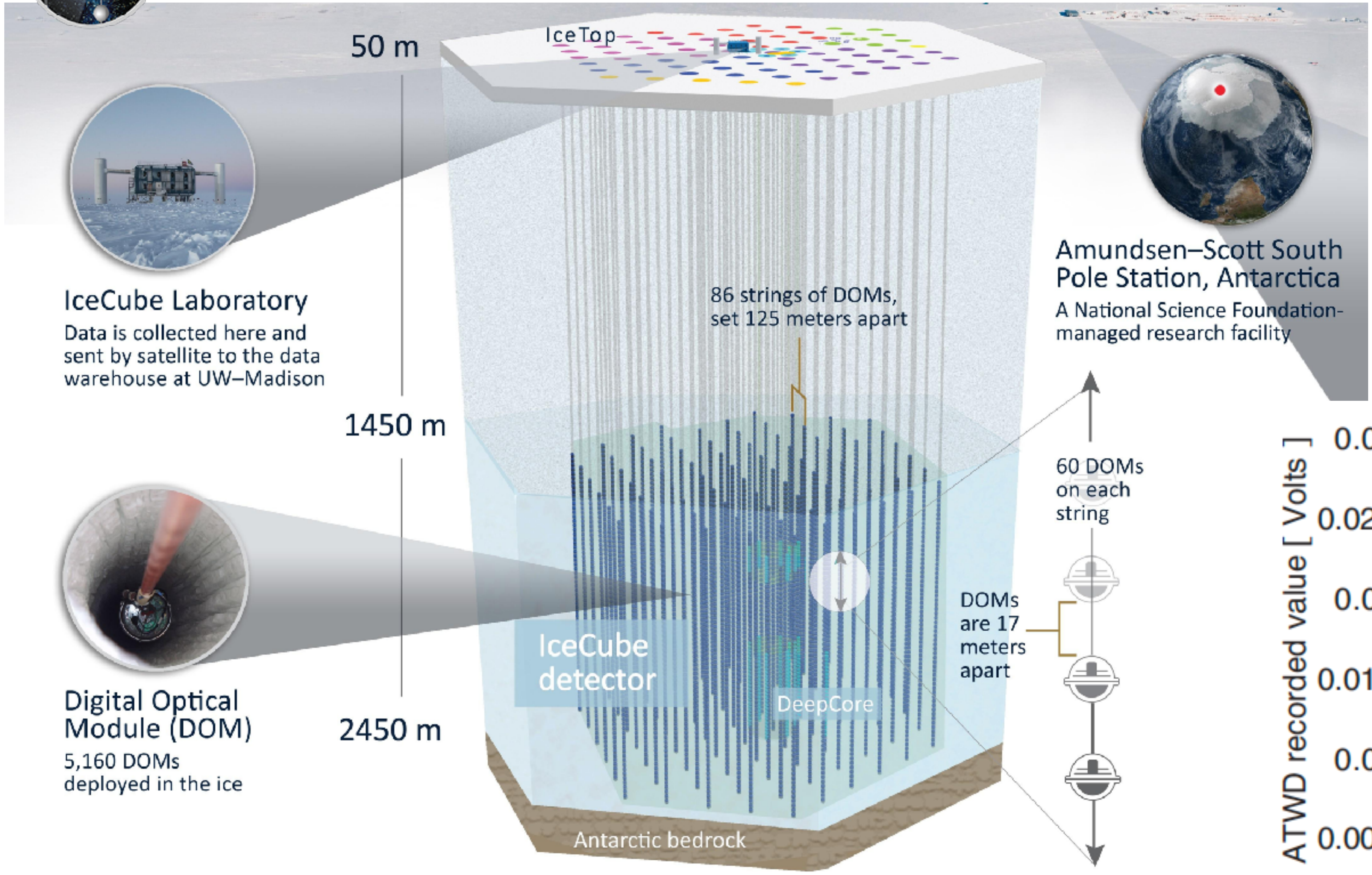


Taeyun Kim

Minje Park

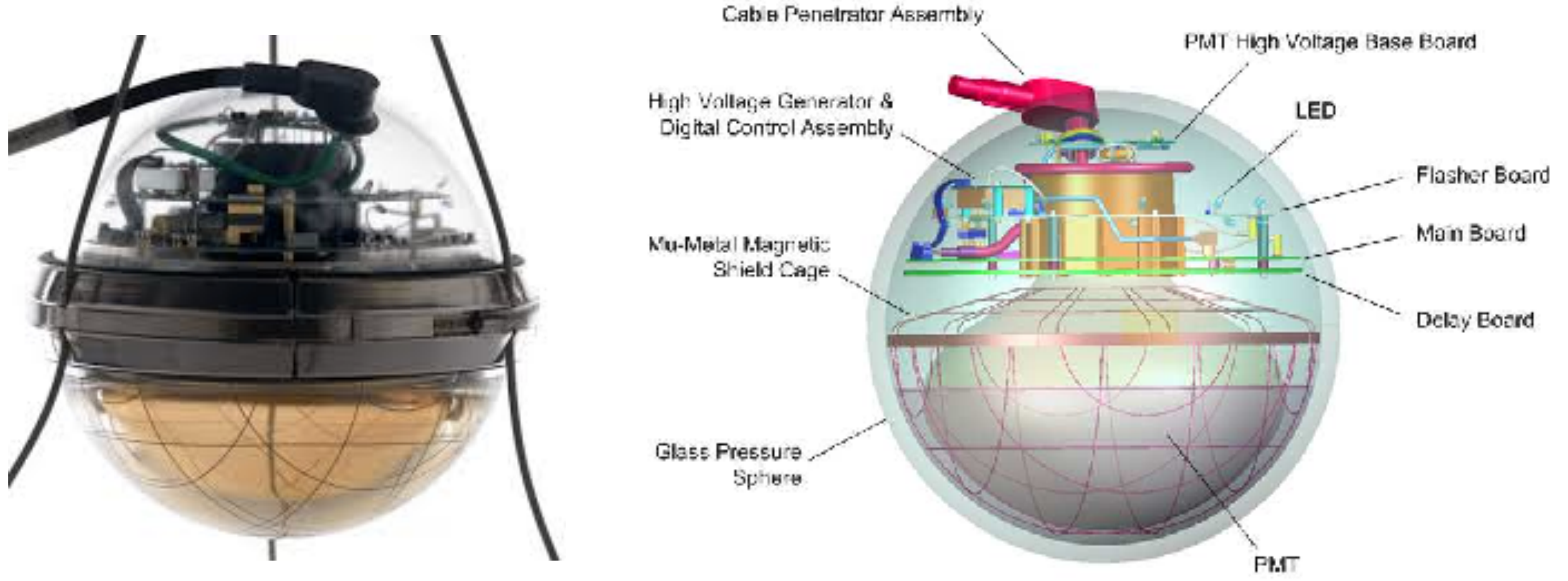
Jiyeong Son

IceCube Neutrino Observatory

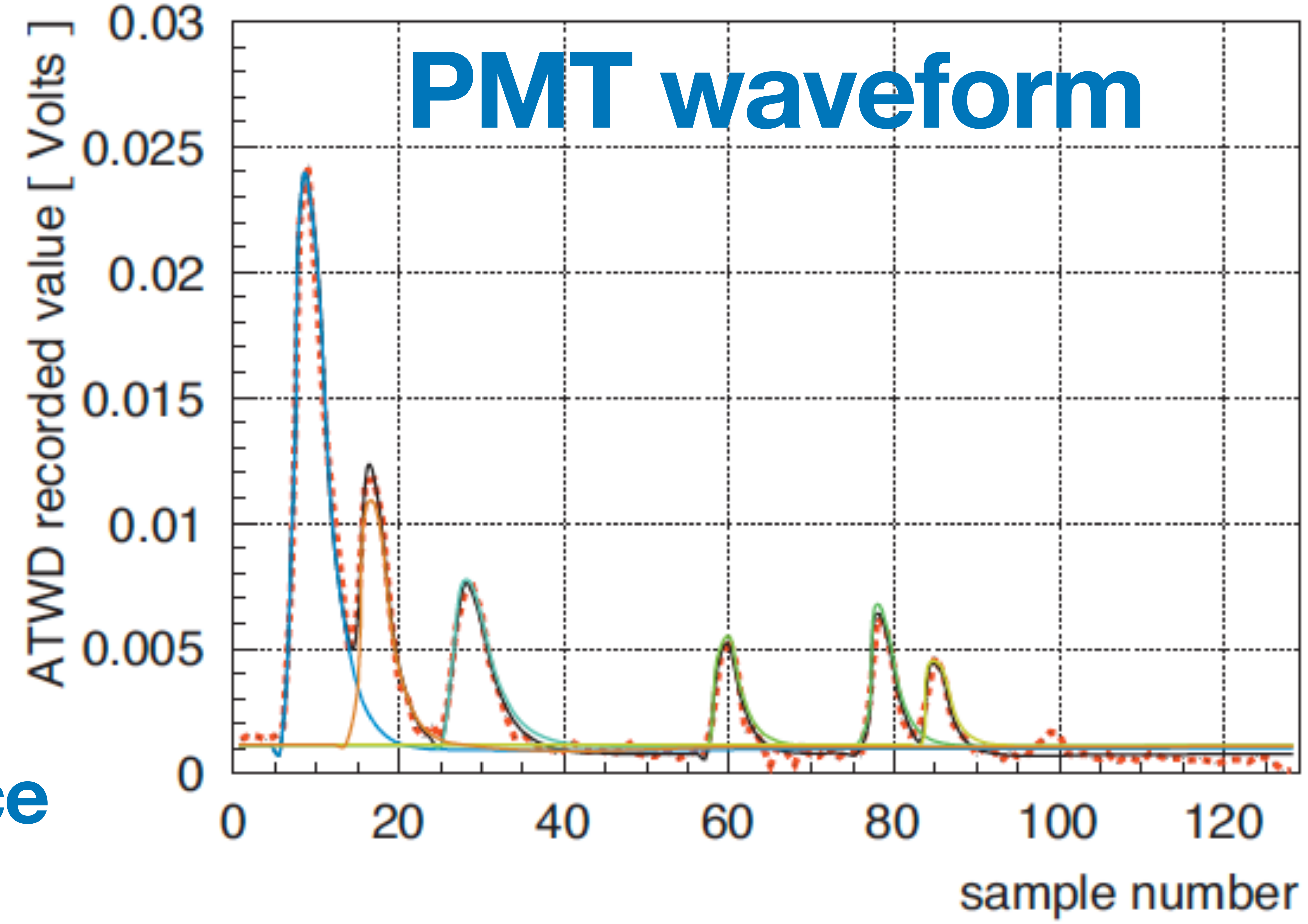


Cherenkov Detector using 1 km³ South Pole ice

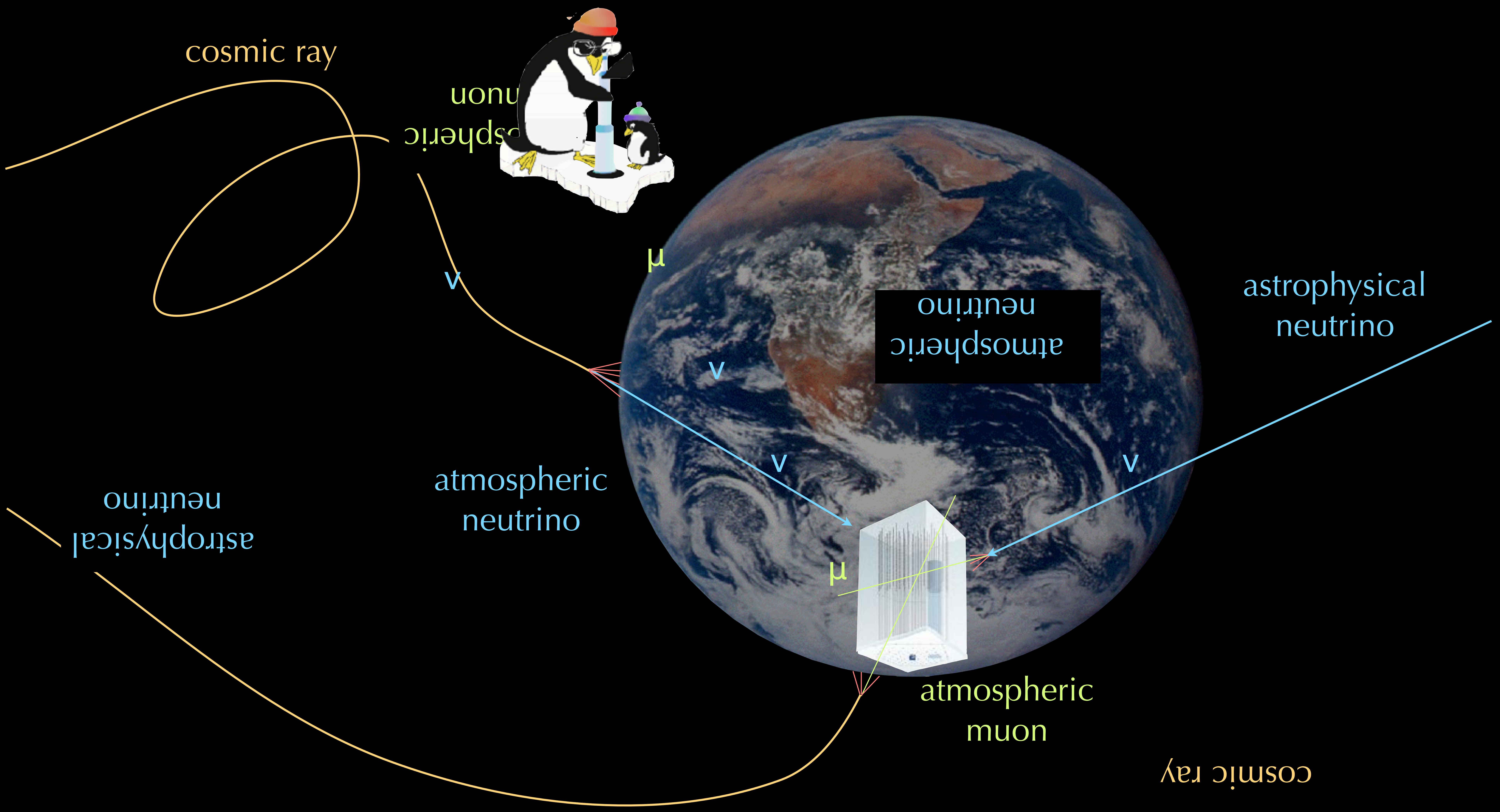
Digital Optical Module (DOM)



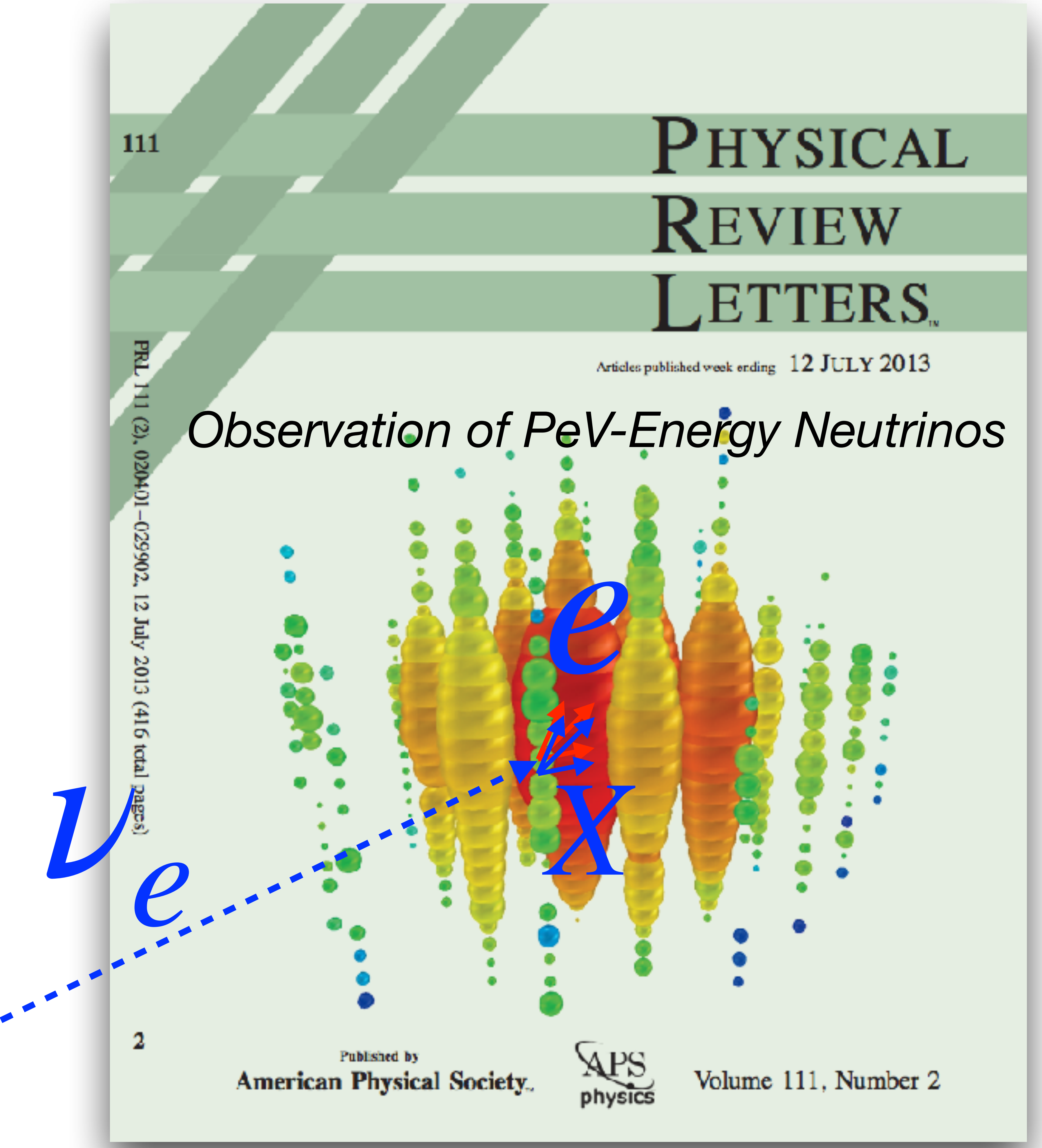
PMT waveform



Neutrinos and Cosmic Rays



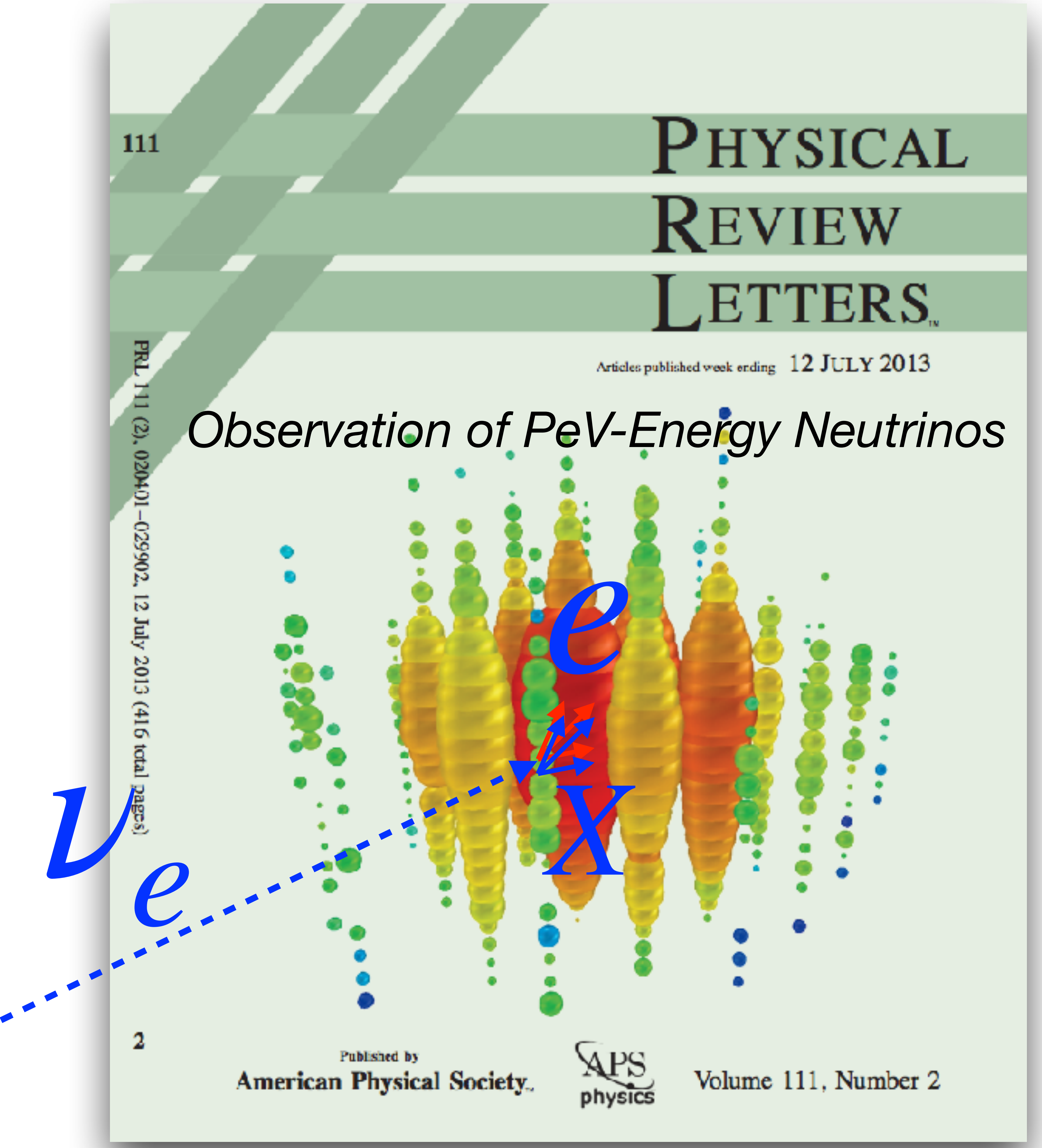
Event Topology (Track vs. Cascade)



$$\nu_e + N \rightarrow e + X$$

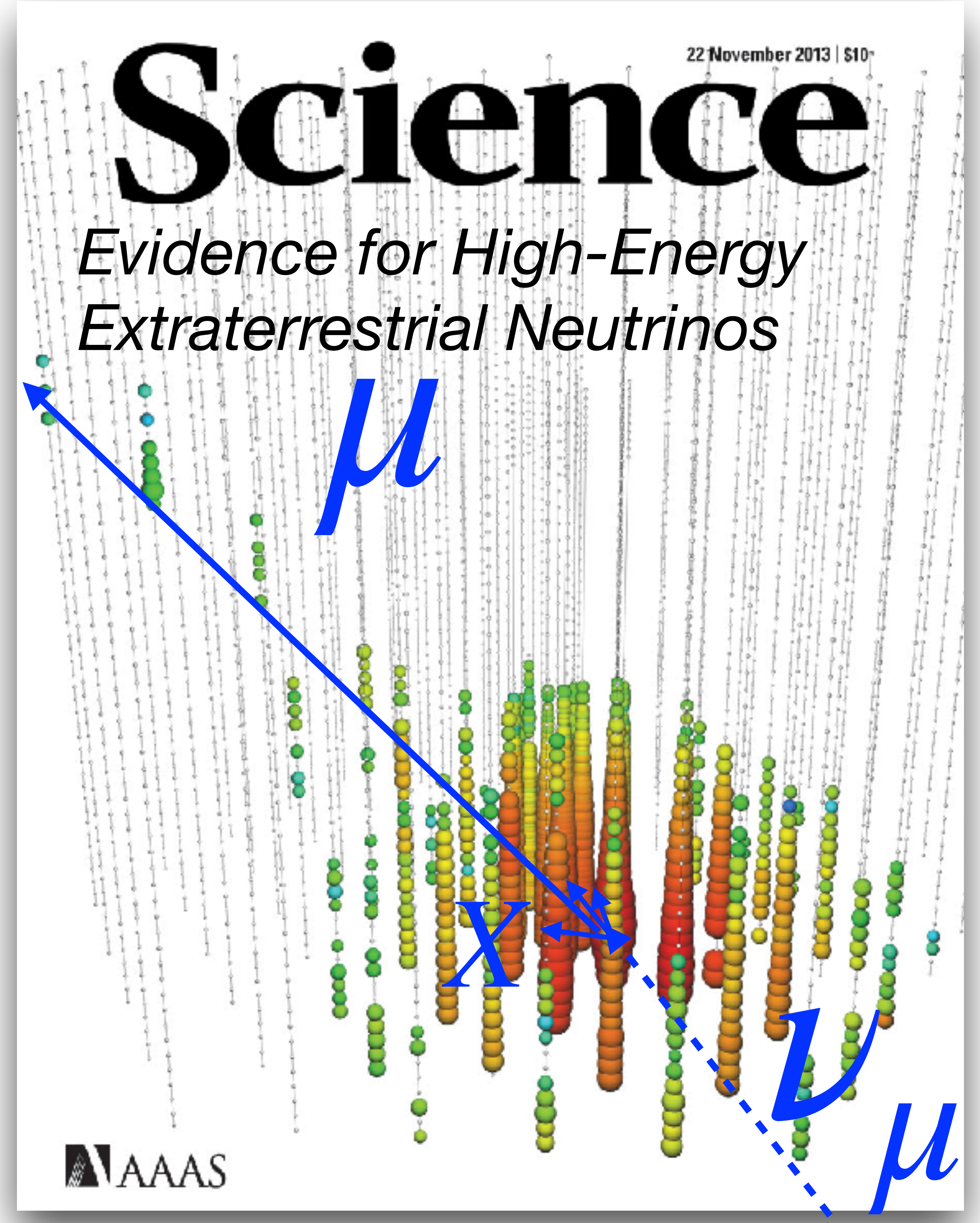
EM shower + Hadron shower
(Cascades)

Event Topology (Track vs. Cascade)



$$\nu_e + N \rightarrow e + X$$

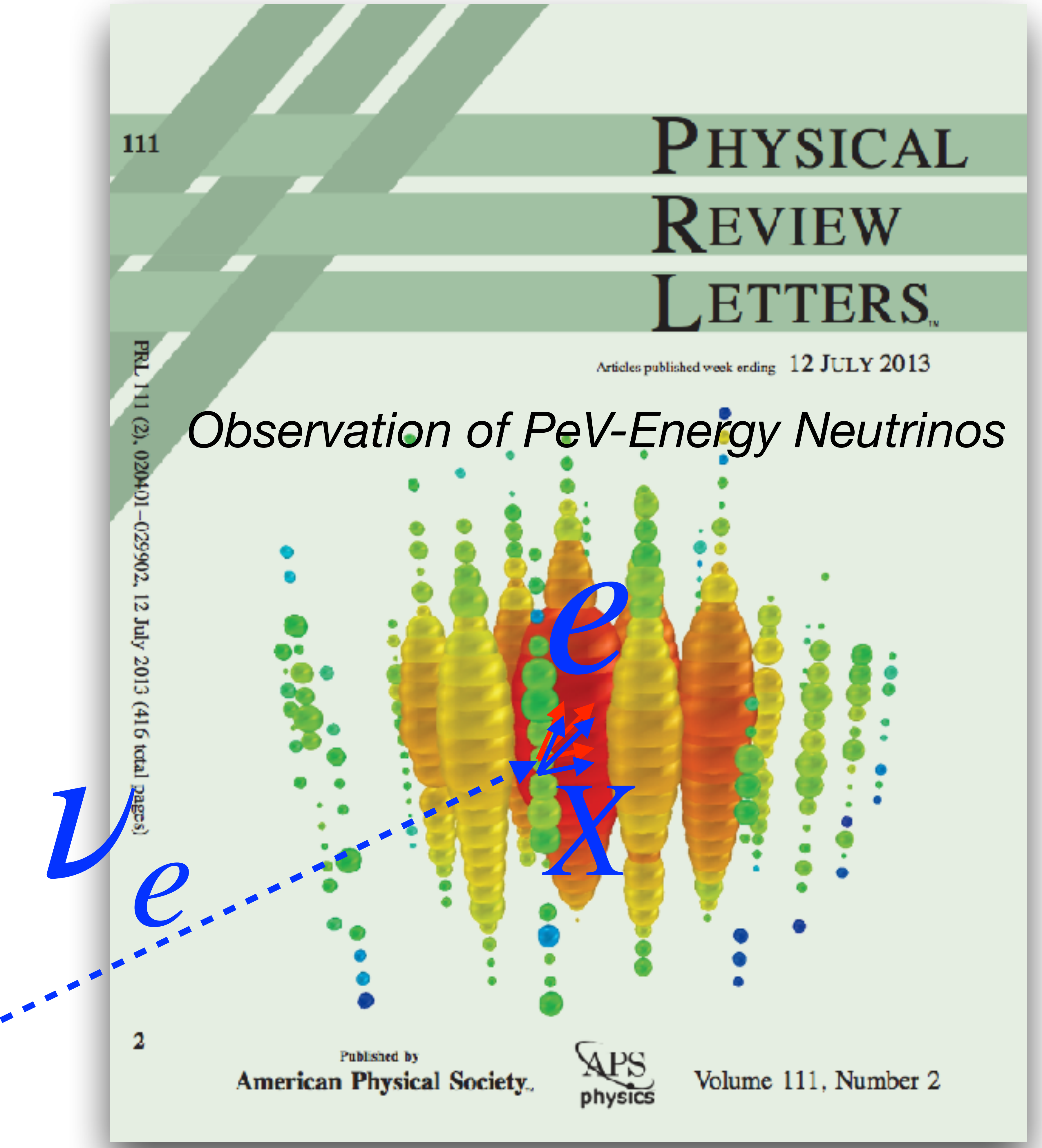
EM shower + Hadron shower
(Cascades)

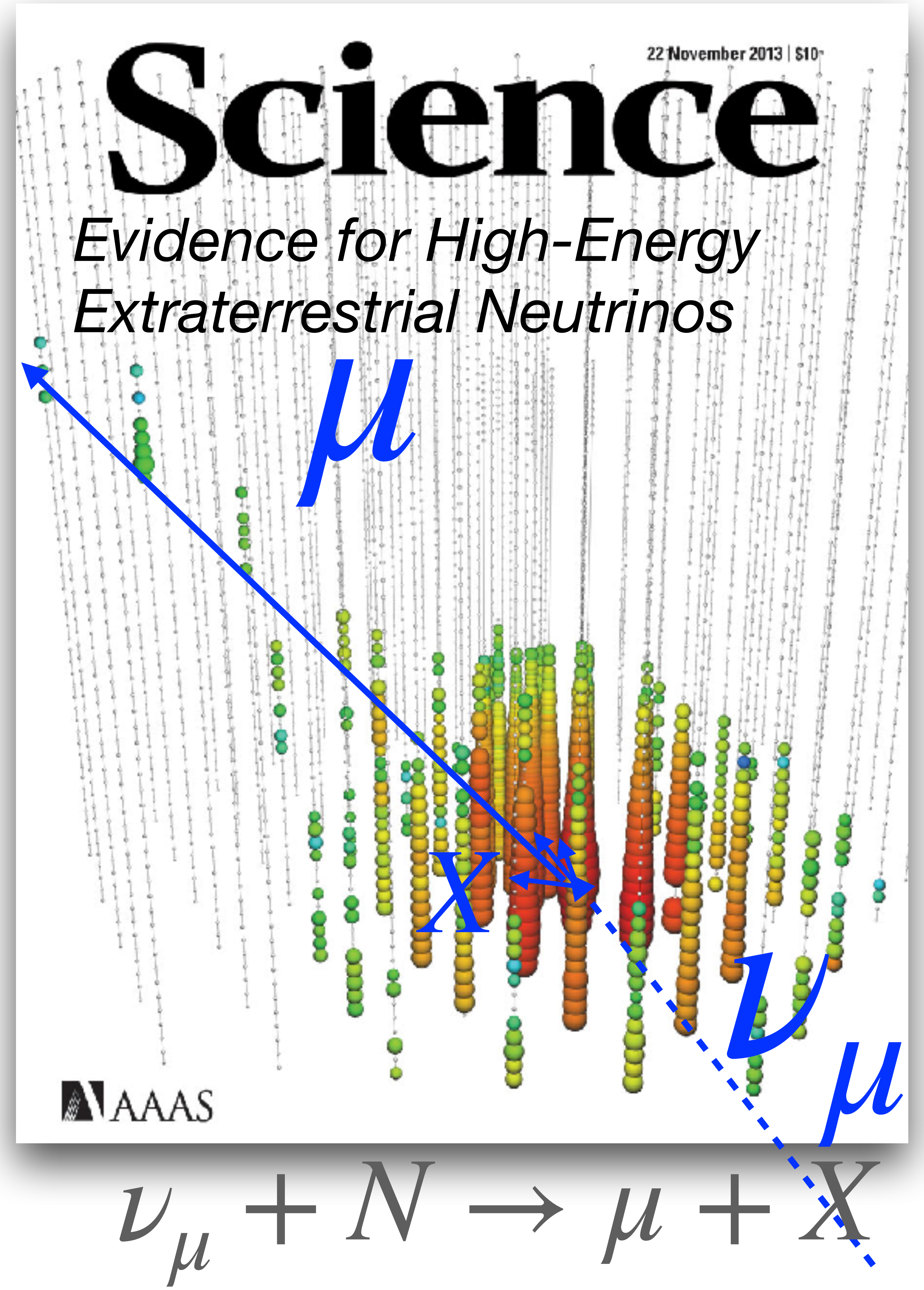


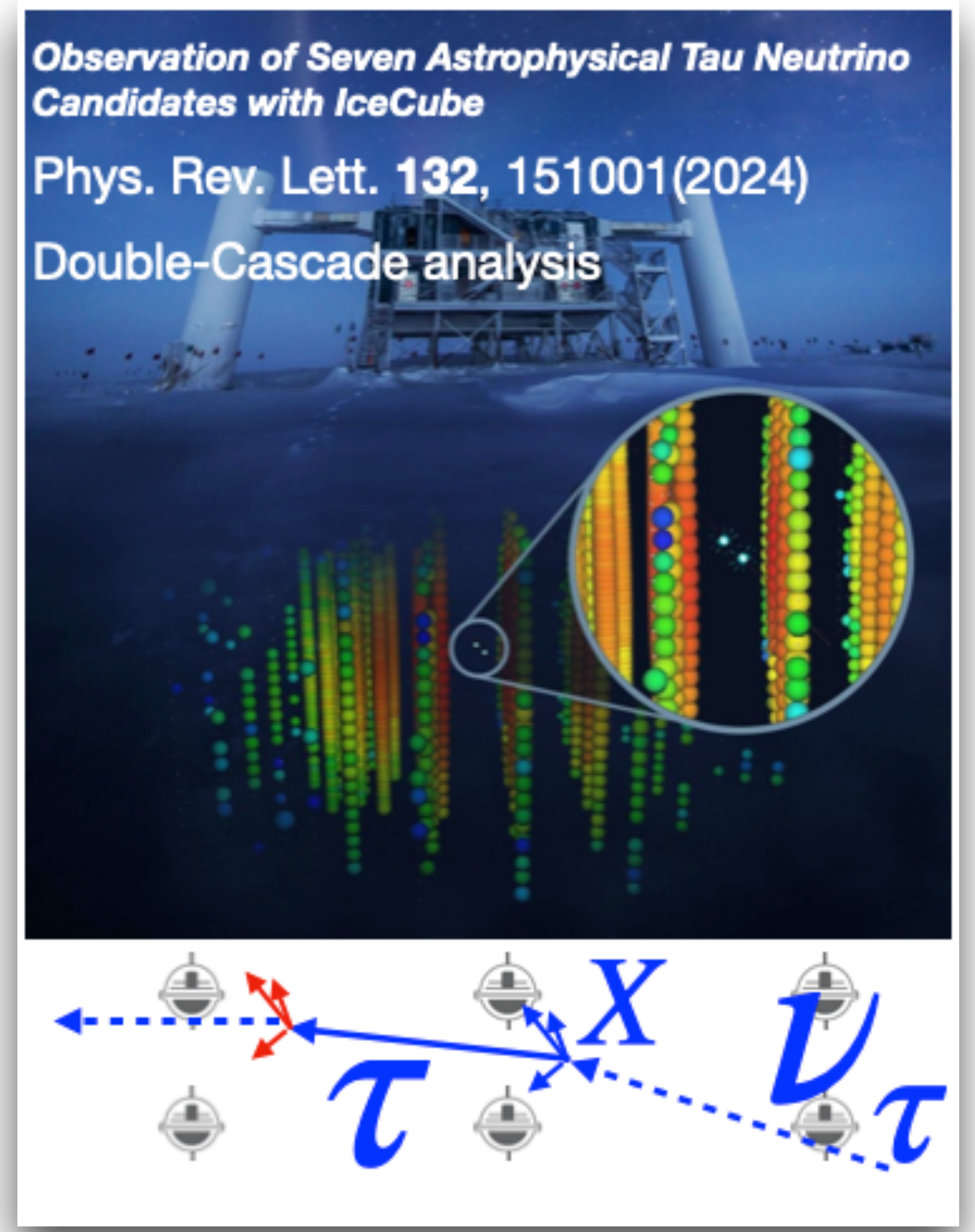
$$\nu_\mu + N \rightarrow \mu + X$$

Track + Hadron shower

Event Topology (Track vs. Cascade)







$$\nu_e + N \rightarrow e + X$$

EM shower + Hadron shower (Cascades)

$$\nu_\mu + N \rightarrow \mu + X$$

Track + Hadron shower

$$\nu_\tau + N \rightarrow \tau + X$$

Tau decay (double pulse/shower)

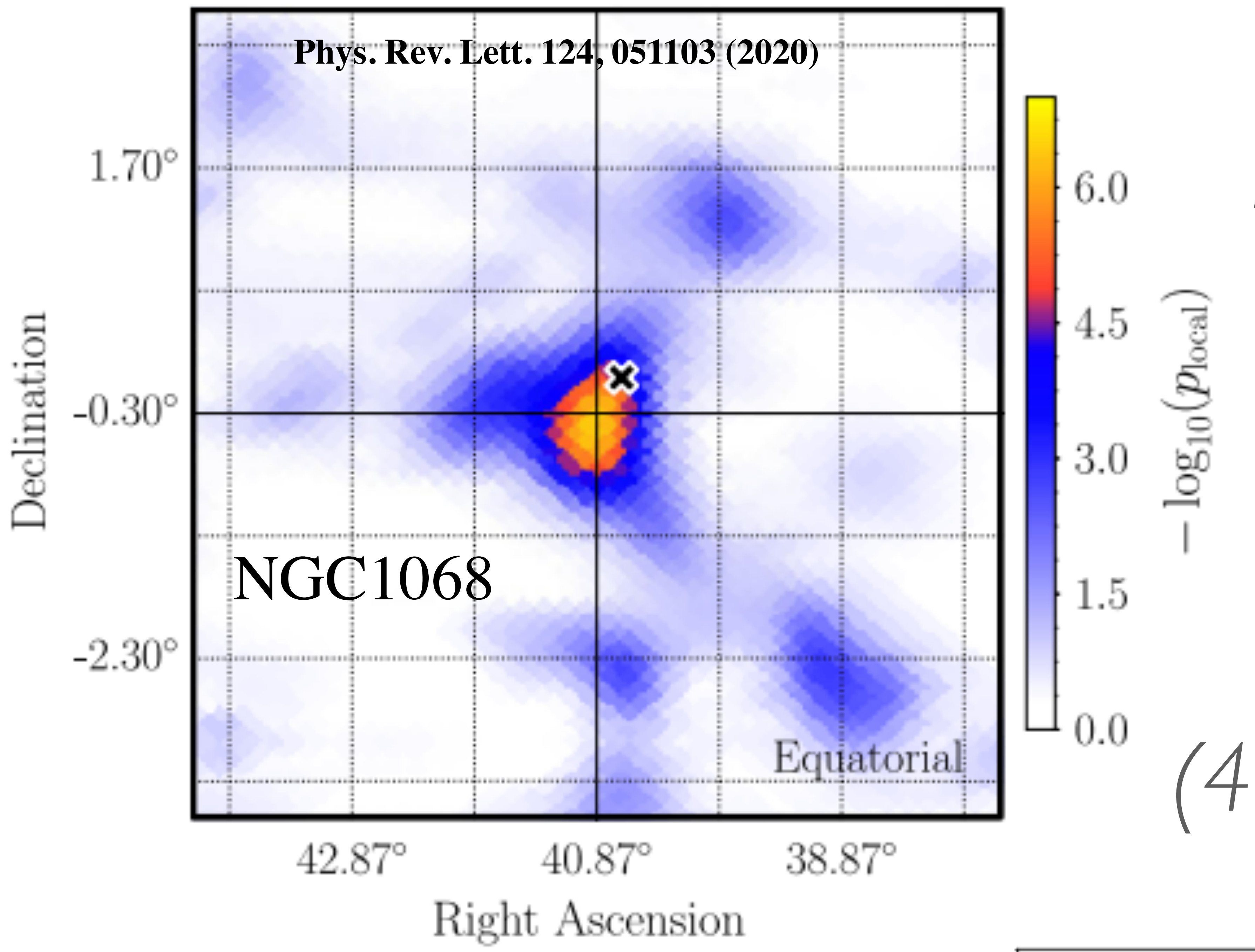
Multi-messenger Astrophysics

Protons *or* electrons can produce the observed gamma rays

Neutrinos only produced by protons

NGC 1068

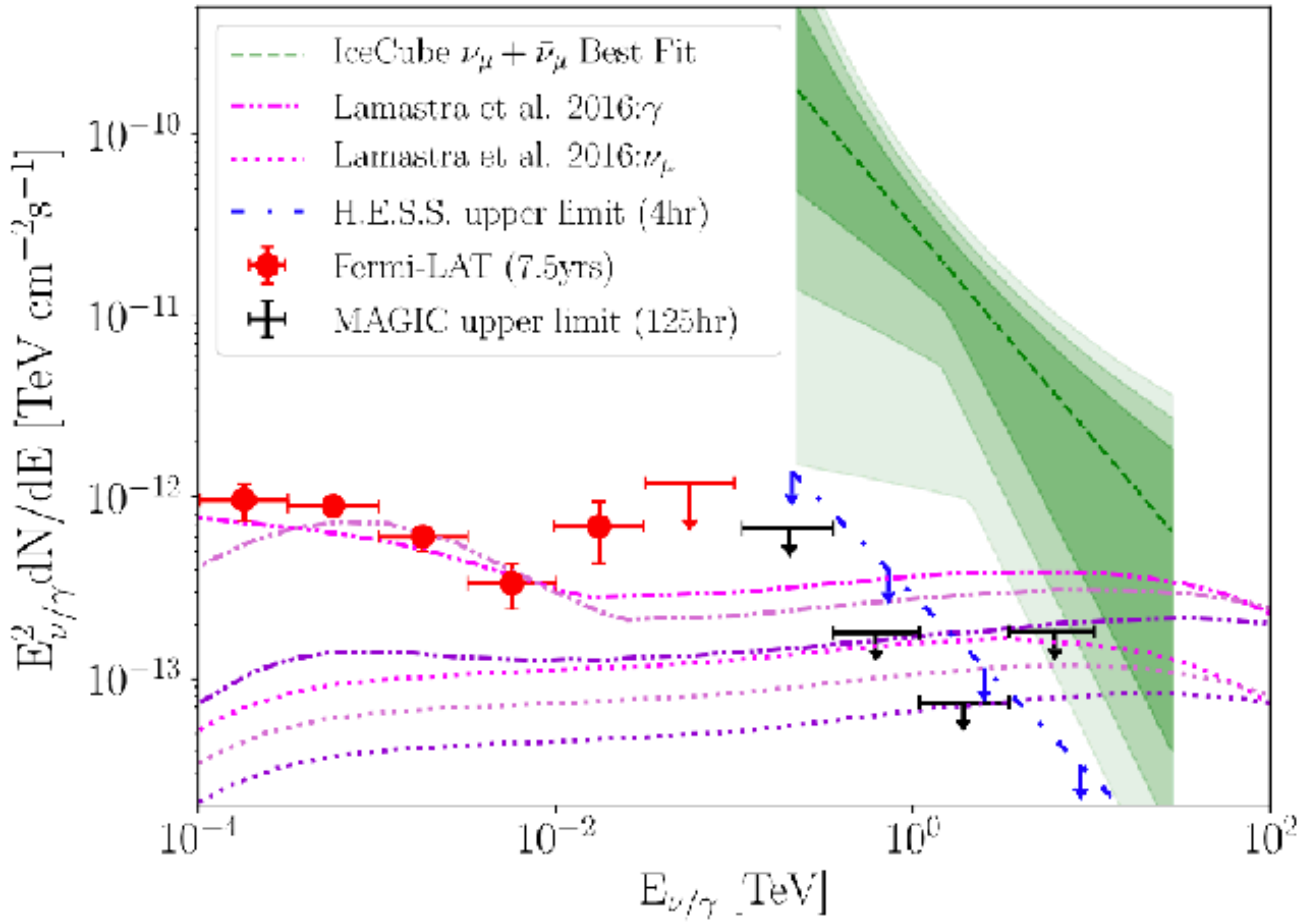
- Barred Spiral Galaxy
- 47 million light year away
- Supermassive Black Hole hidden by a cloud of dust.



Point Source Search with 10 yr data

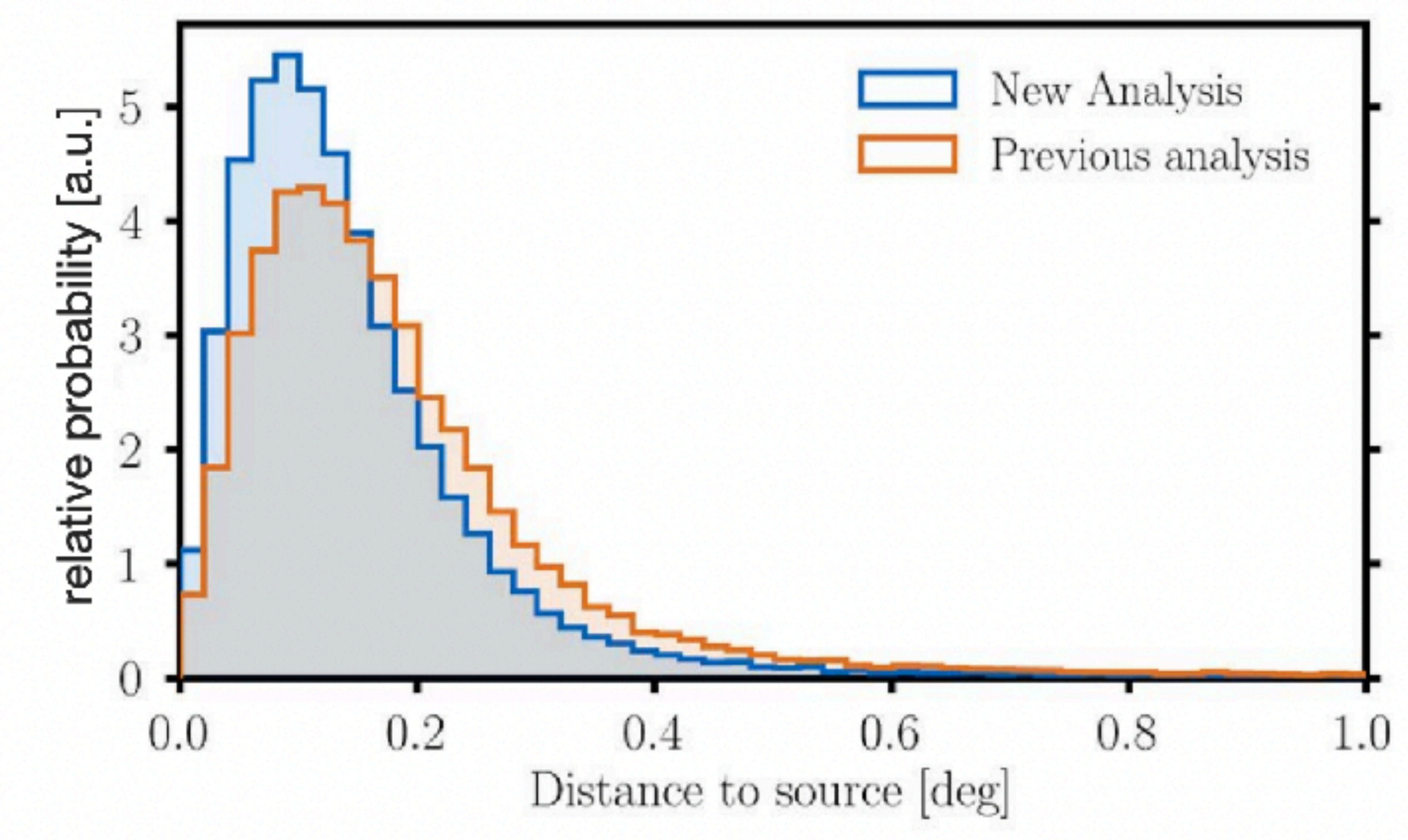
Hottest spot near NGC1068 (4.7σ local, 2.9σ global)

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

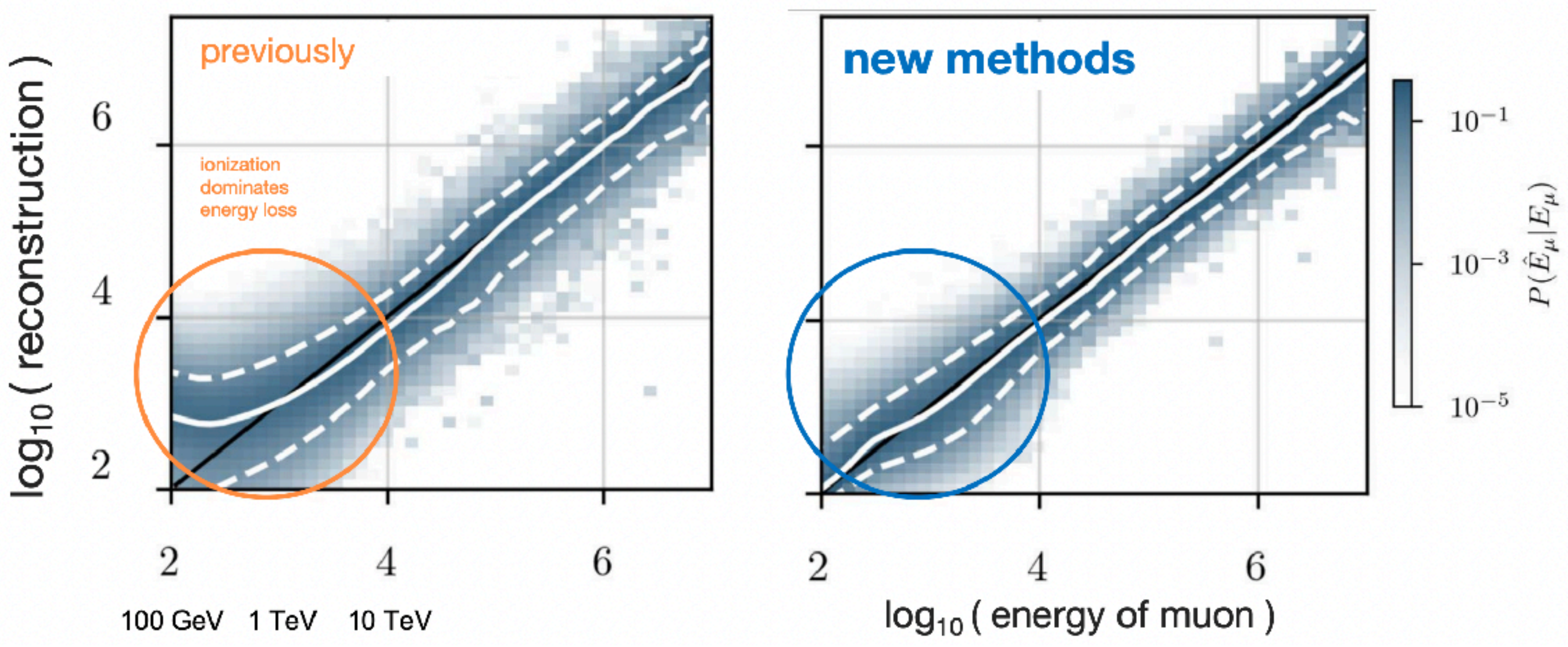


Improved data analysis

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

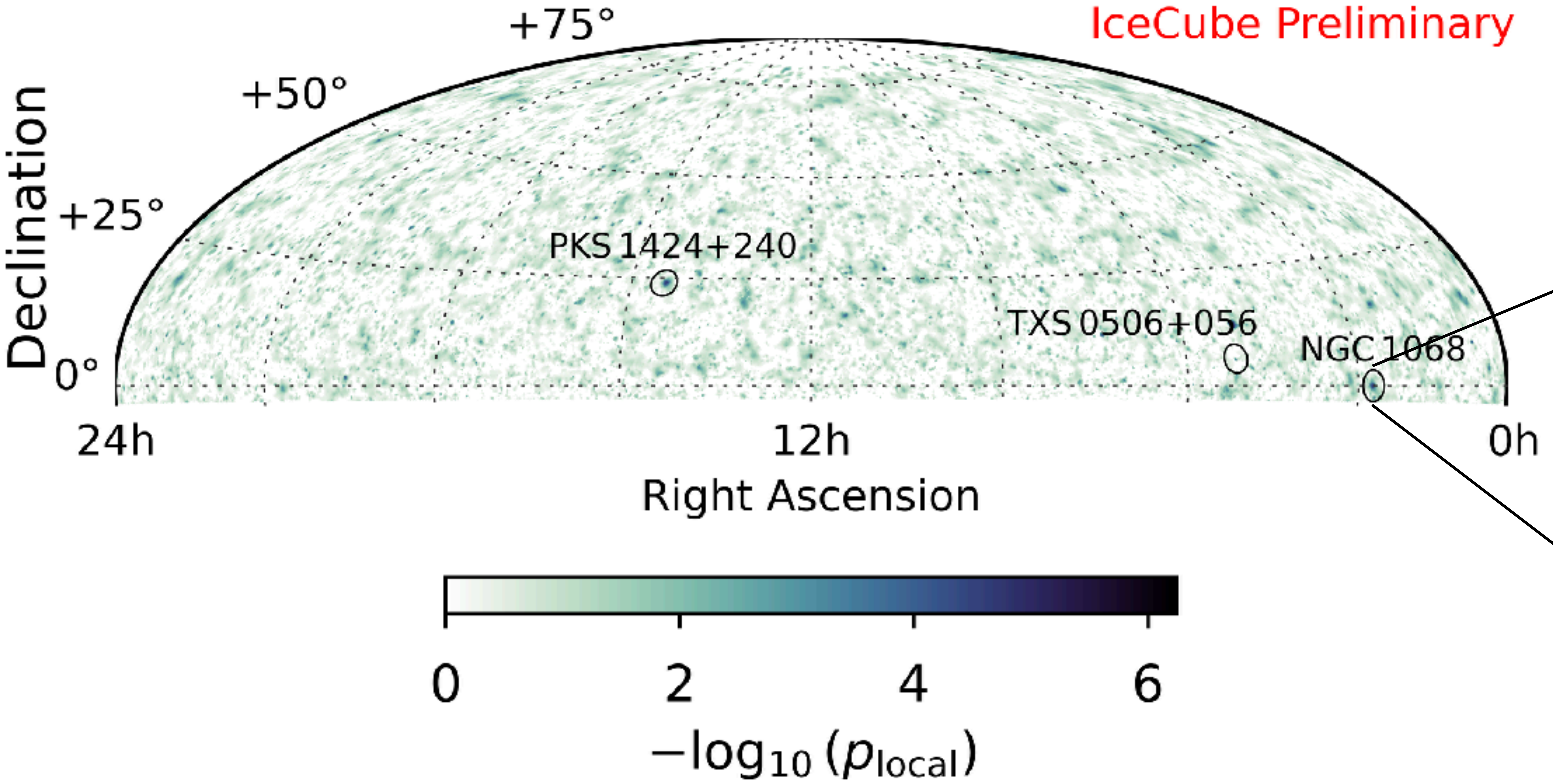


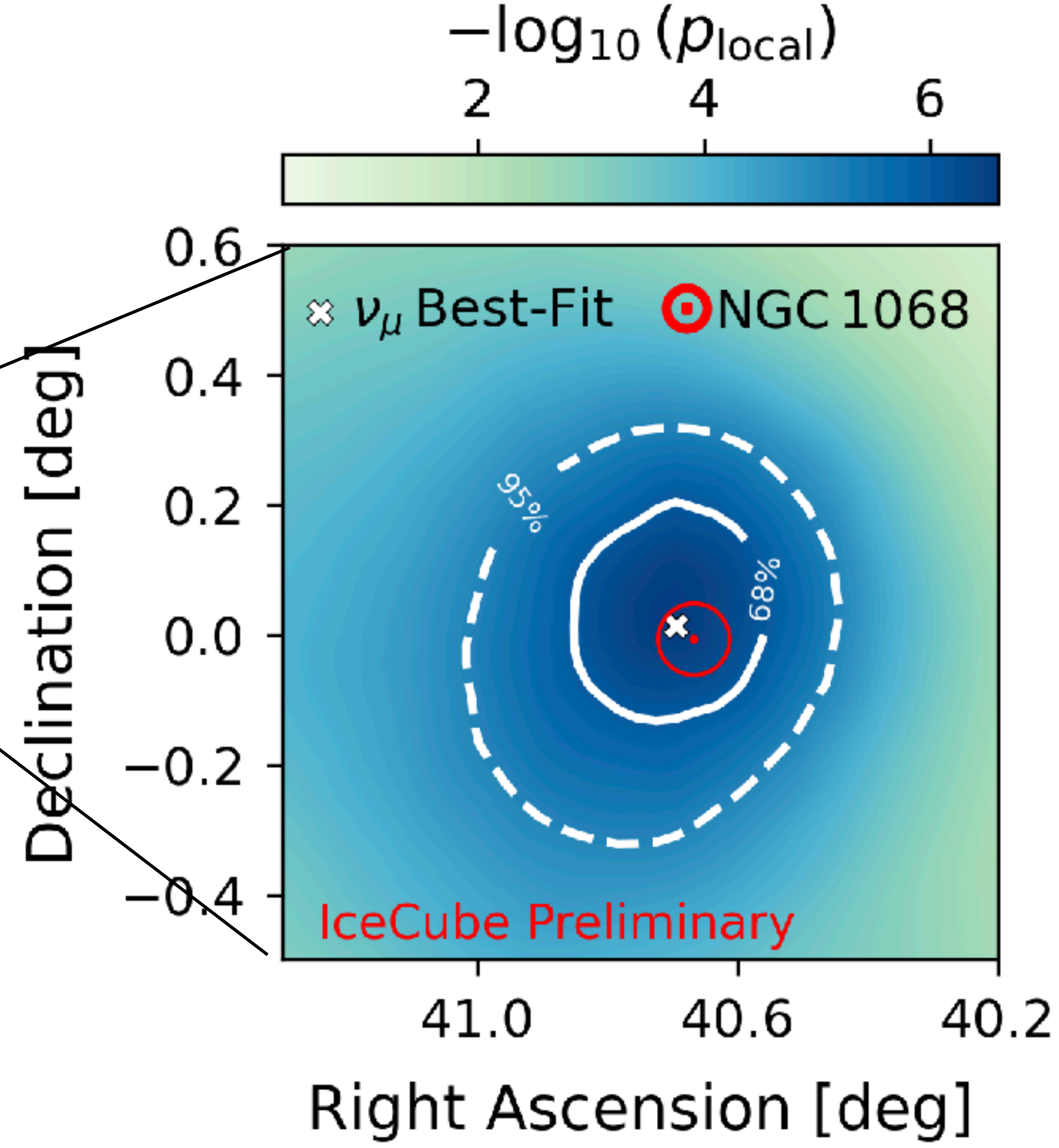
The application of the latest directional reconstruction



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

The latest result for NGC 1068





New analysis with 13 years of data.

The hottest spot is closer to NGC 1068.

Significance : 5.0σ local, 4.0σ global

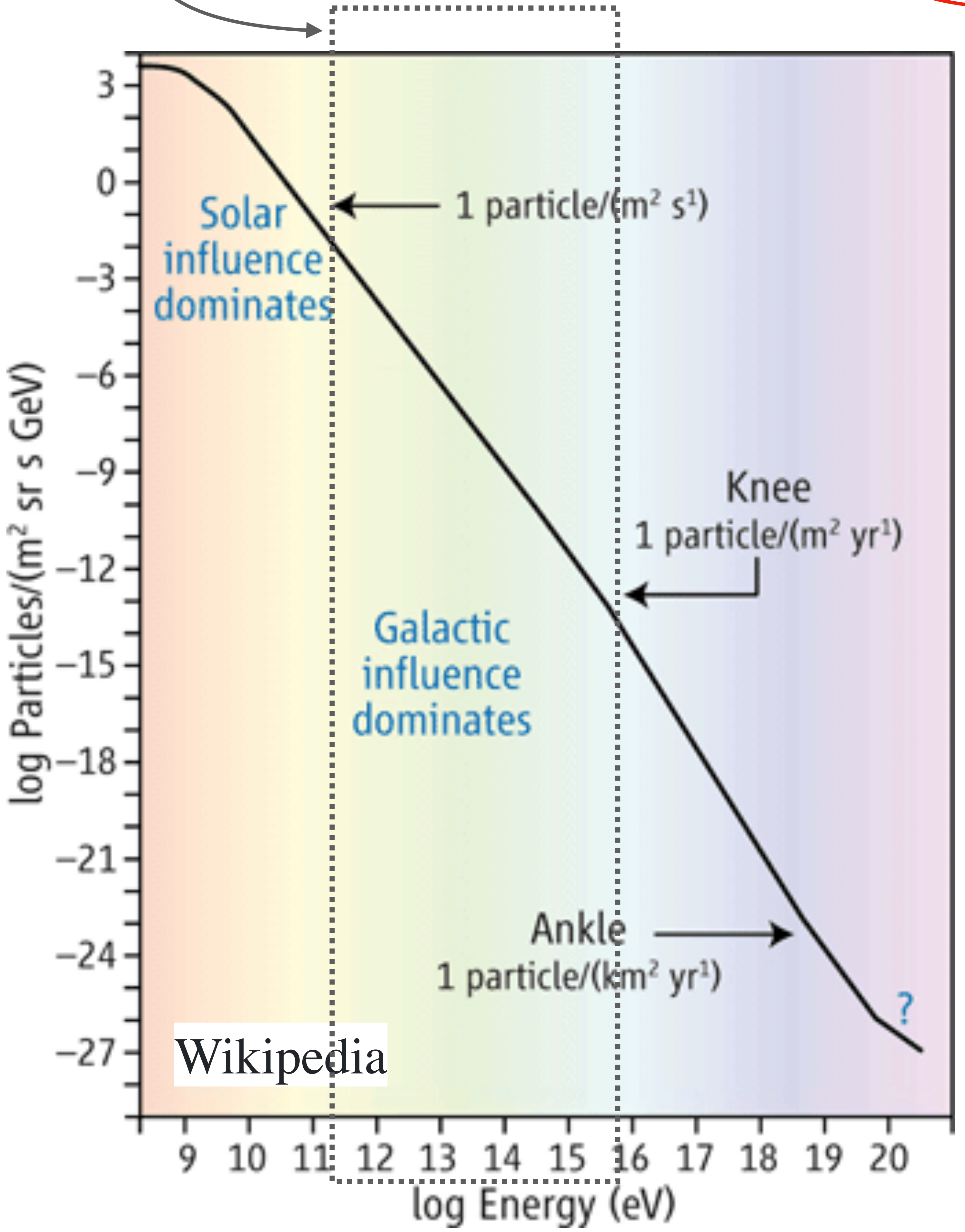
Prefers softer spectrum (~$E^{-3.4}$), indication of a more complex power law.

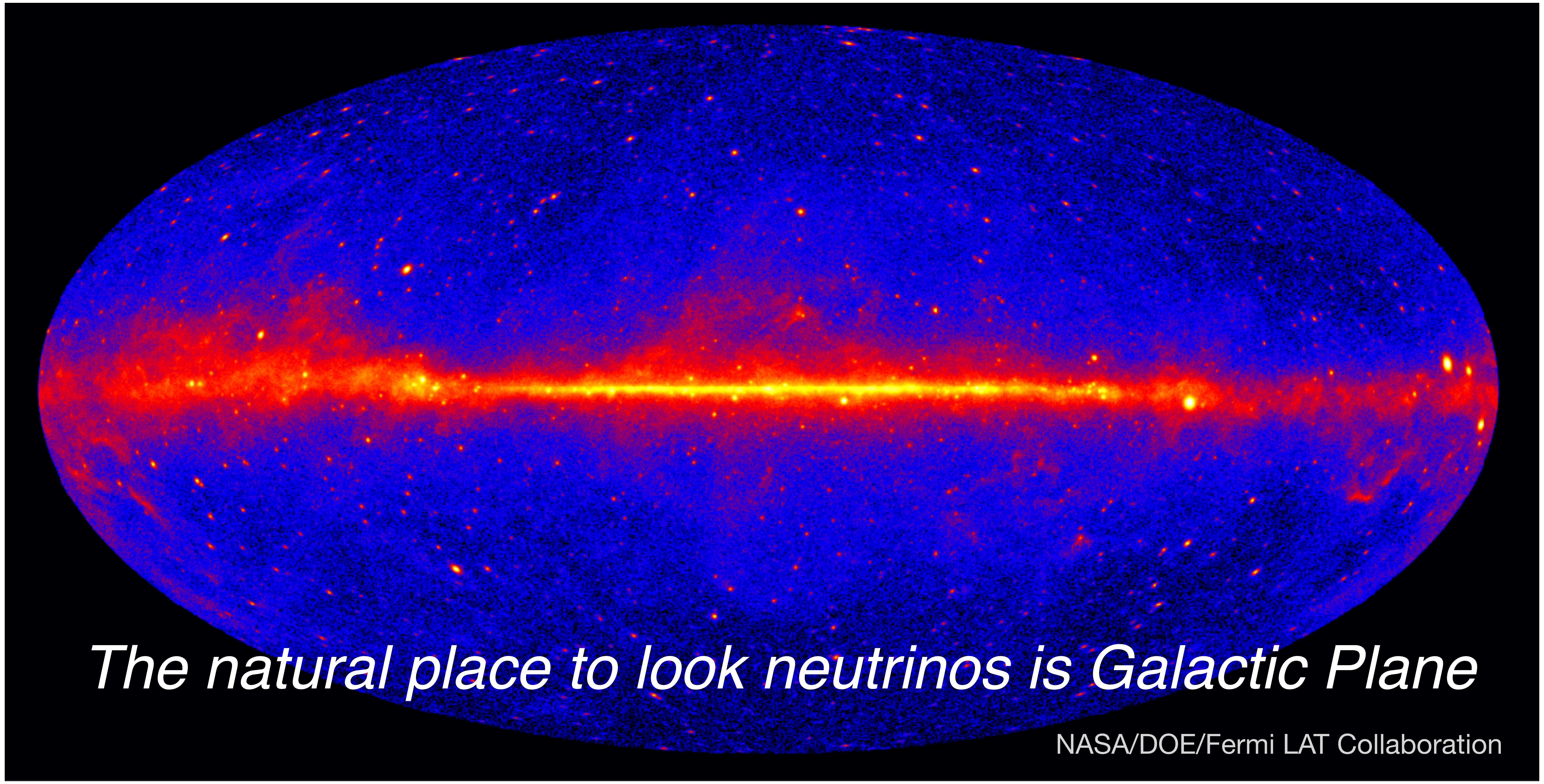
Galactic Plane : Charged Pions must exist ; Neutrinos should be there

$$\pi^0 \rightarrow \gamma + \gamma$$

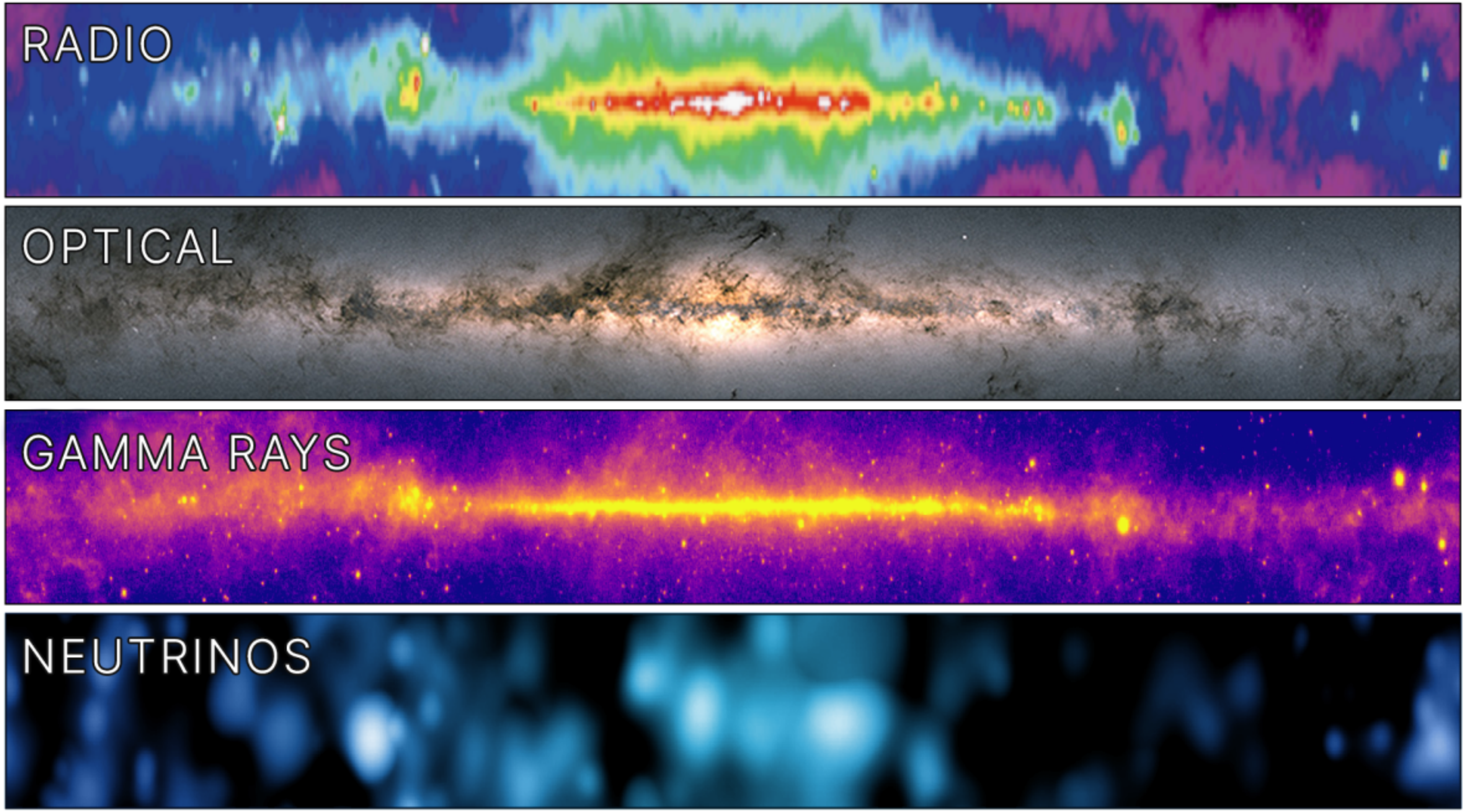
$$p + ISM \rightarrow \pi^0(\pi^\pm)$$

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





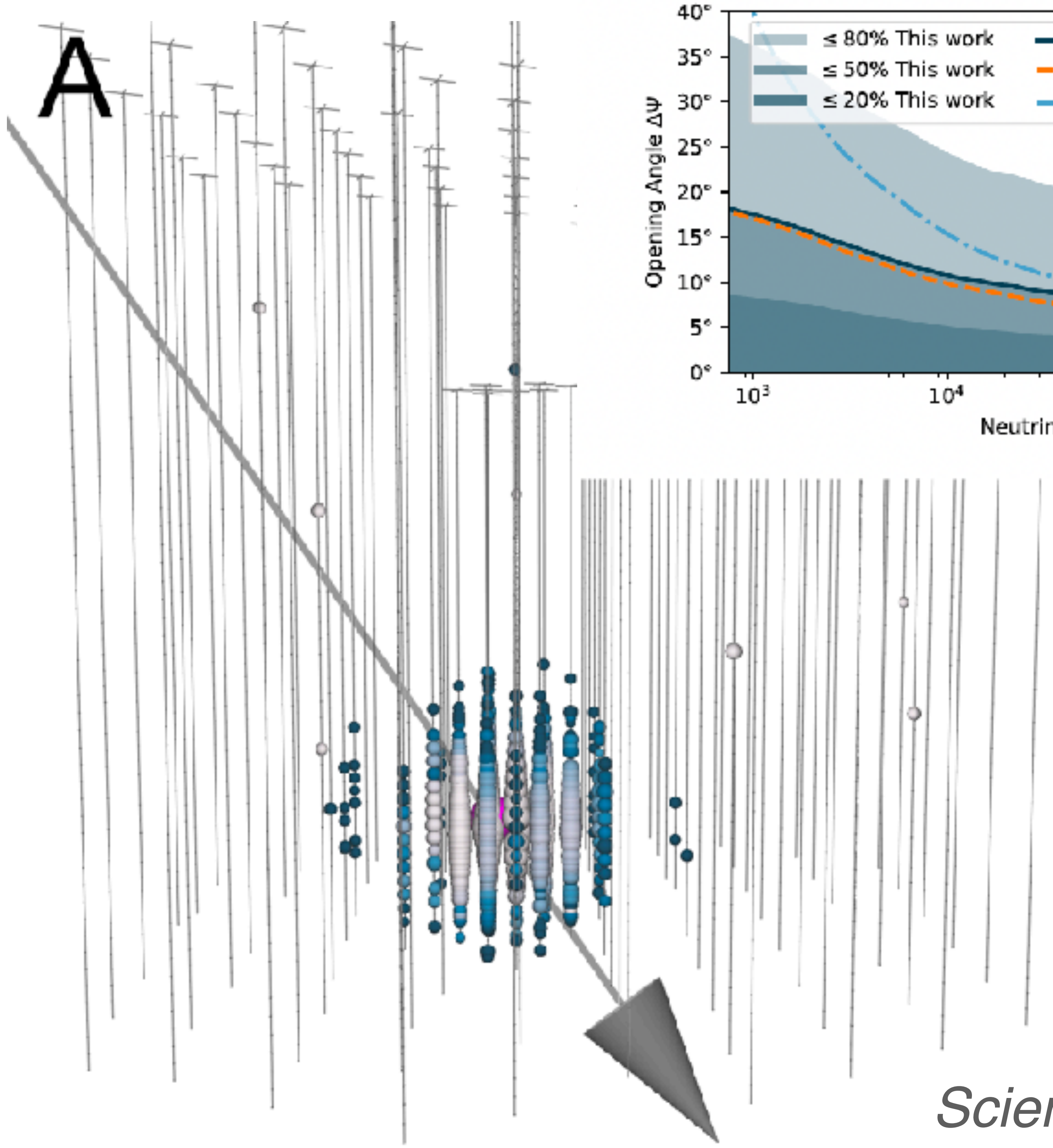
Observation of high-energy neutrinos from the Galactic plane

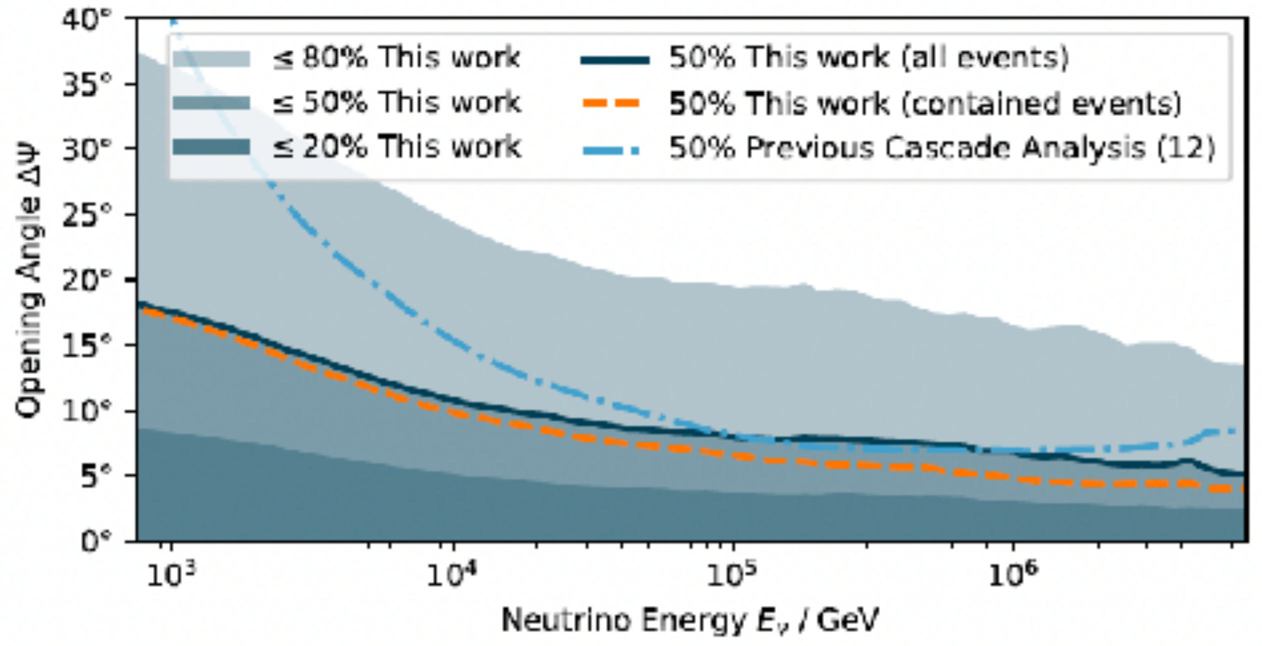


Science, 380, 6652 (2023)

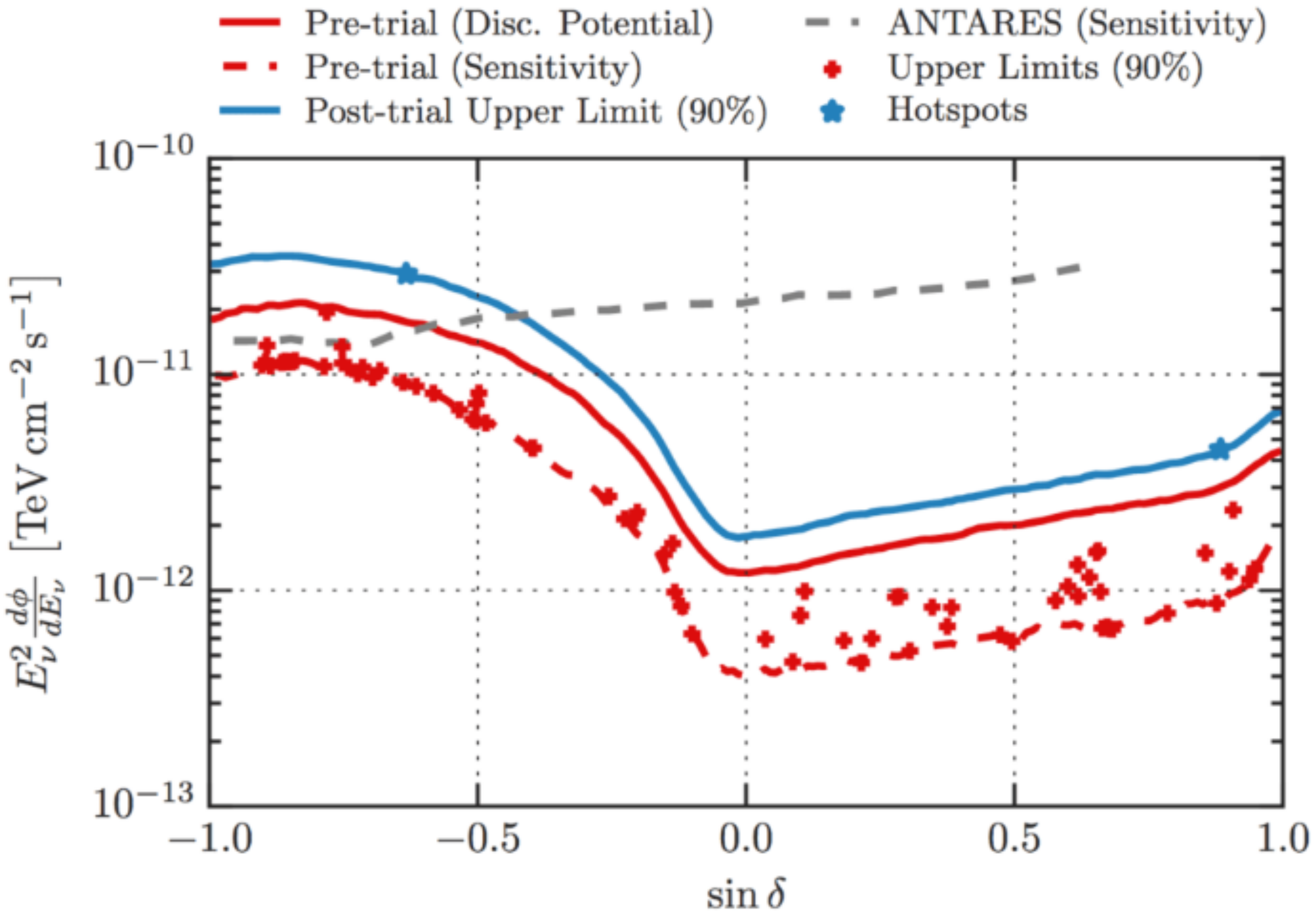
Cascade analysis : Topology (easier atmo. bkg rejection), Energy (full containment), Direction (Machine Learning)

Improve bkg. rejection and direction reconstruction with new ML and open up the Southern Sky.





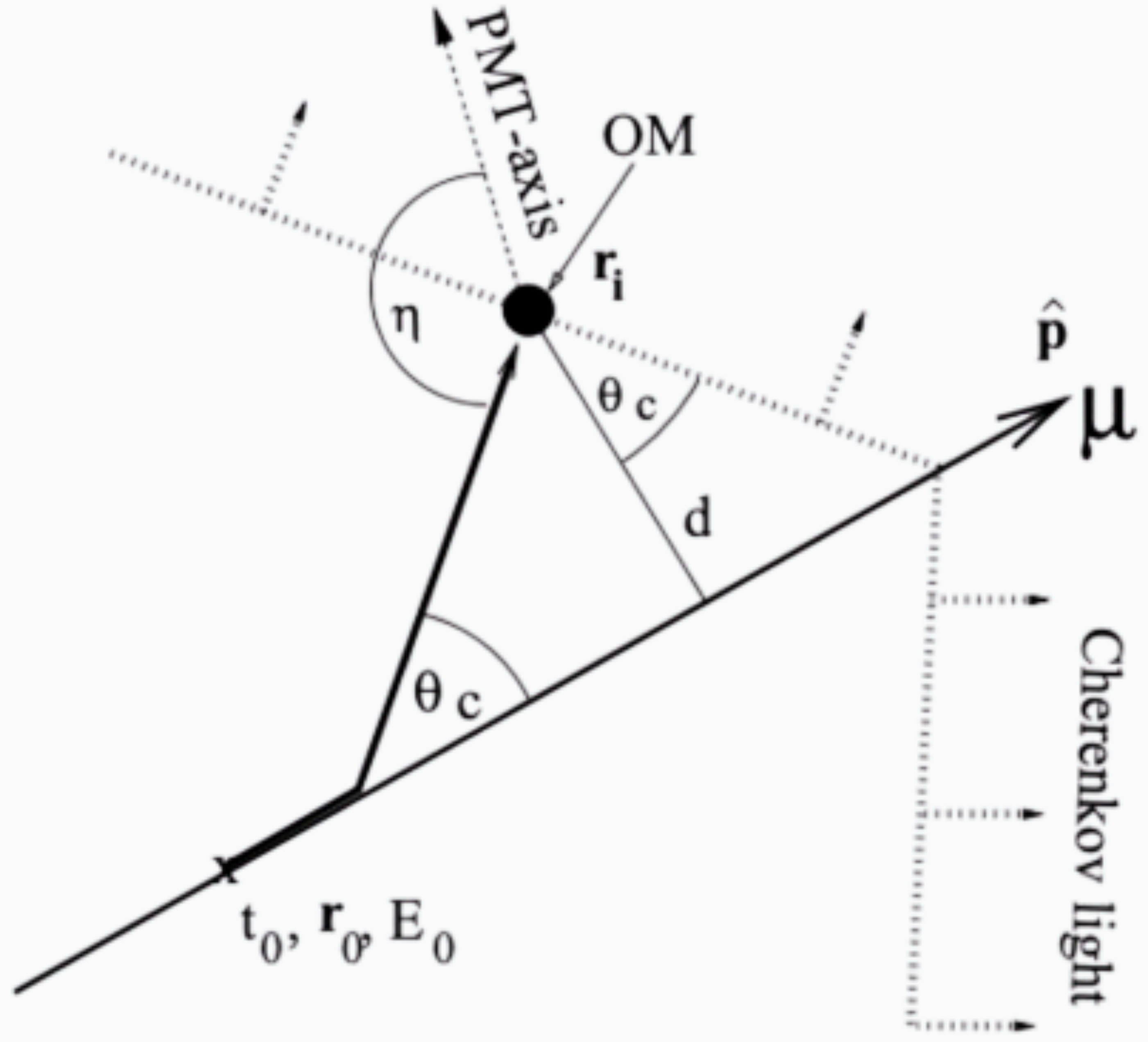
Science, 380, 6652 (2023)



Conventional Through-going Track Analysis : More sensitive to the Northern Sky

Muon-Track Reconstruction

- 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**.

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

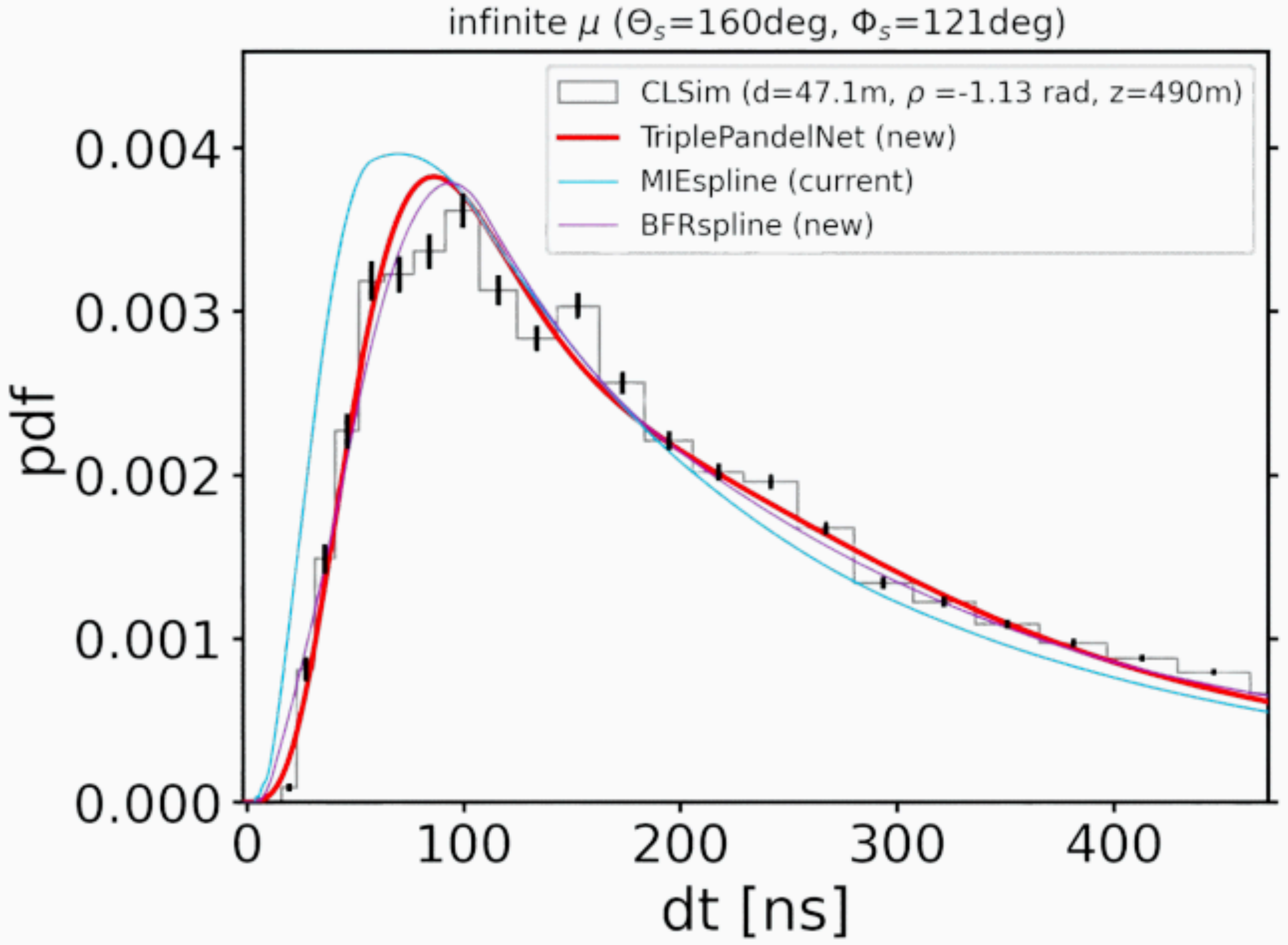
- The track is obtained by maximizing the following - form known as the MPE likelihood

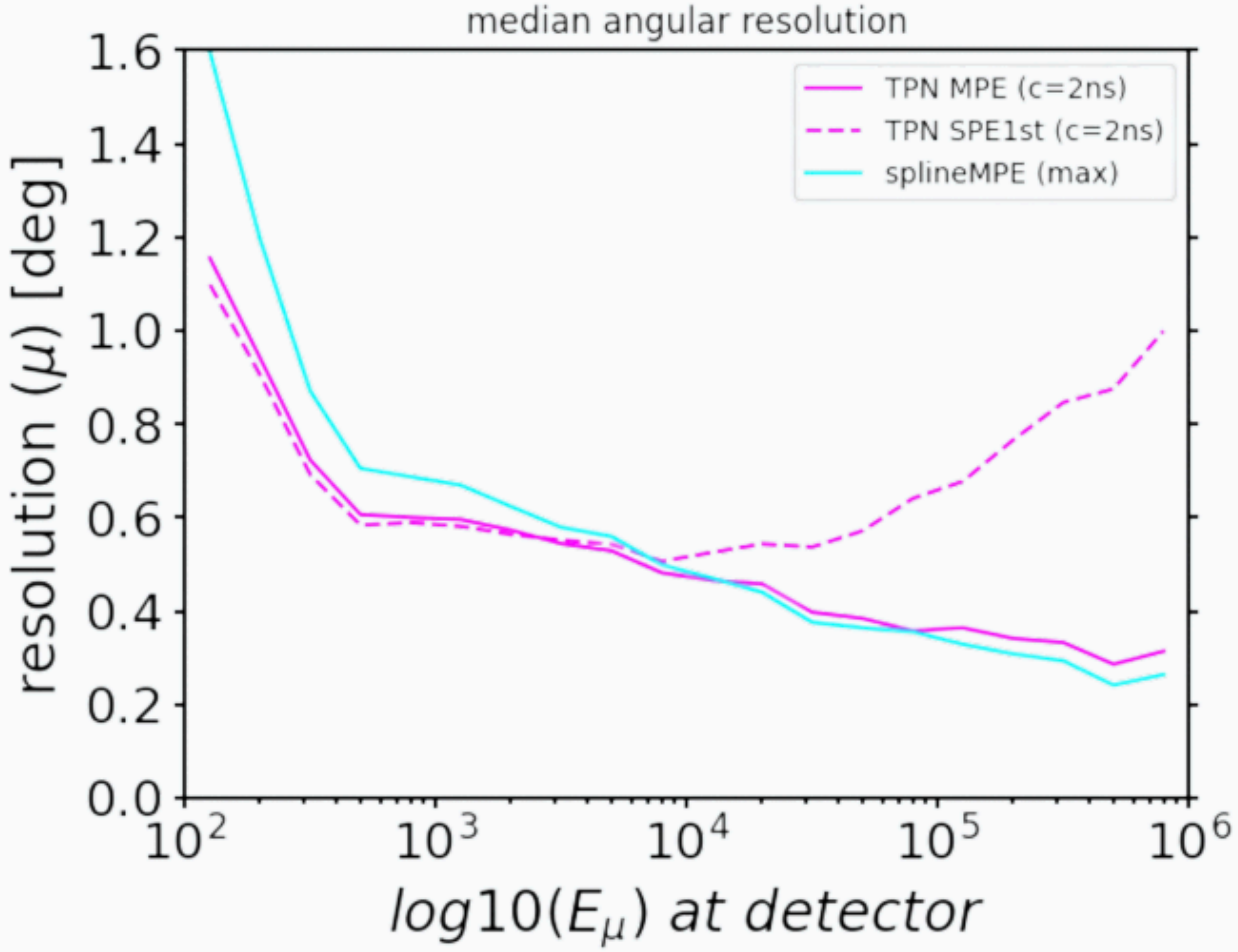
$$\mathscr{L}_{\text{MPE}}(\vec{\theta}) = \prod_{i}^{\text{1st hits}} n_i \cdot p(t_{\text{res},i} \mid d, \vec{\theta}) \cdot \left(\int_{t_{\text{res},i}}^{\infty} p(t \mid d, \vec{\theta}) dt \right)^{n_i - 1}$$

Triple Pandel Network and Reconstruction

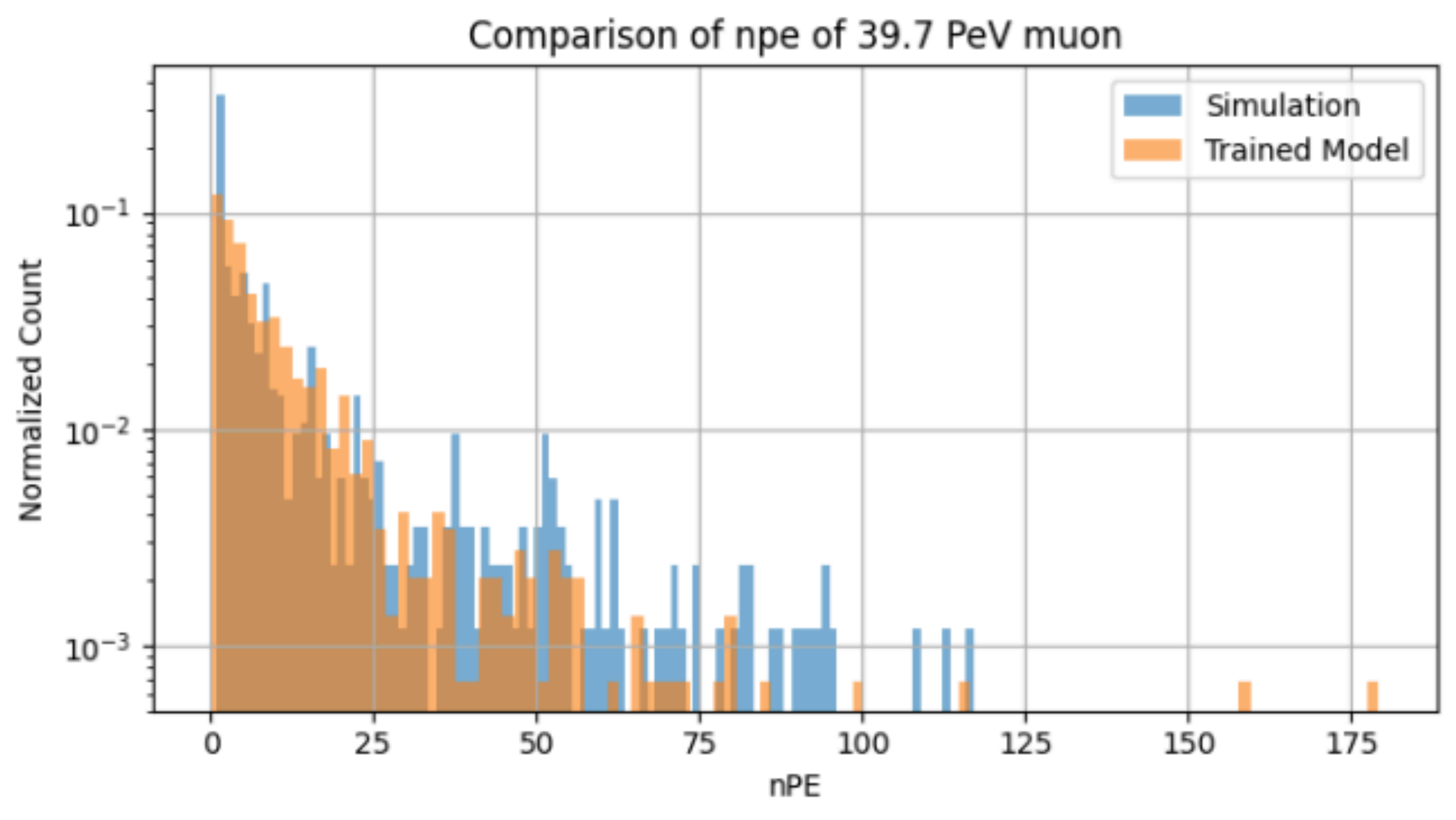
- Due to the non-homogeneous and anisotropic optical properties of the South Pole ice, accurately determining the probability density function $p(t_{\text{res}} \mid d, \vec{\theta})$ is challenging.
- To address this, we designed a deep learning model, the **Triple Pandel Network**, that maps track and DOM geometry, $d, \vec{\theta}$, to photon arrival distribution $p(t_{res}|d, \vec{\theta})$.

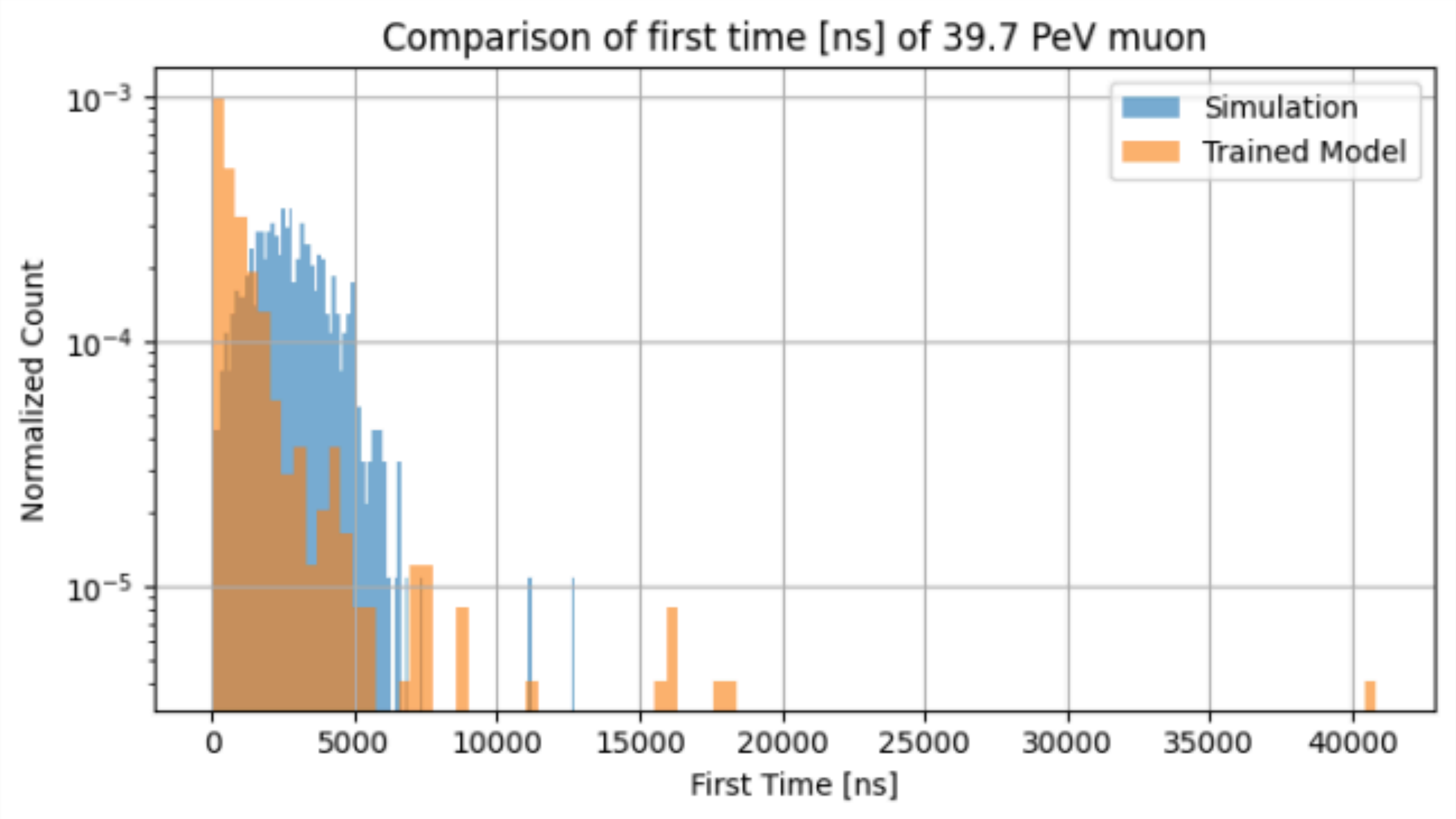
$$p(t_{\text{res}}|d,\vec{\theta}) = \sum_{i=0}^{3} w_i \times \left[\frac{\beta_i^{\alpha_i}}{\Gamma(\alpha_i)} t^{\alpha_i - 1} \exp(-\beta_i t)\right]$$





- **Then How We Use Generative Models for Muon Reconstruction**:
  We first train a model that can produce realistic muon simulation events. As discussed earlier, such models are capable of learning the manifold of the data distribution. So once trained, the model allows us to compute the likelihood of observed data, which can then be used for reconstruction.





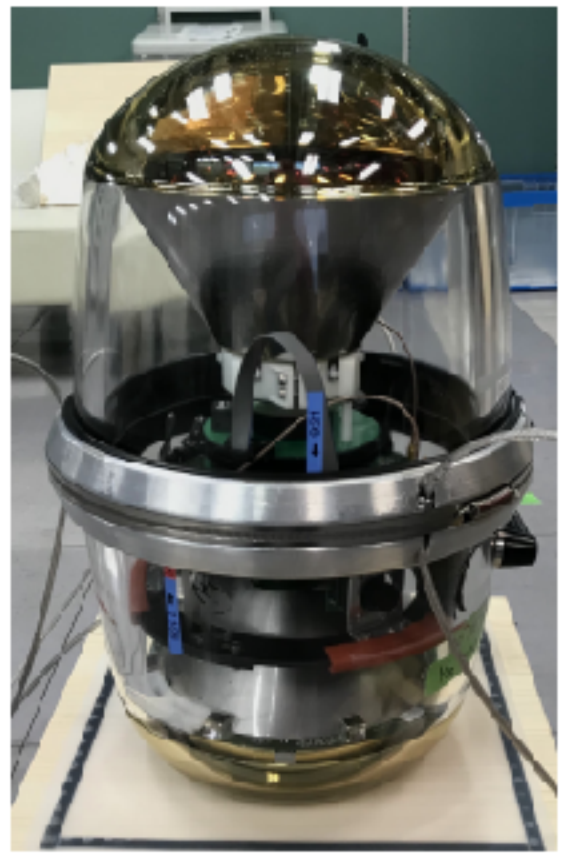
Calibration WG

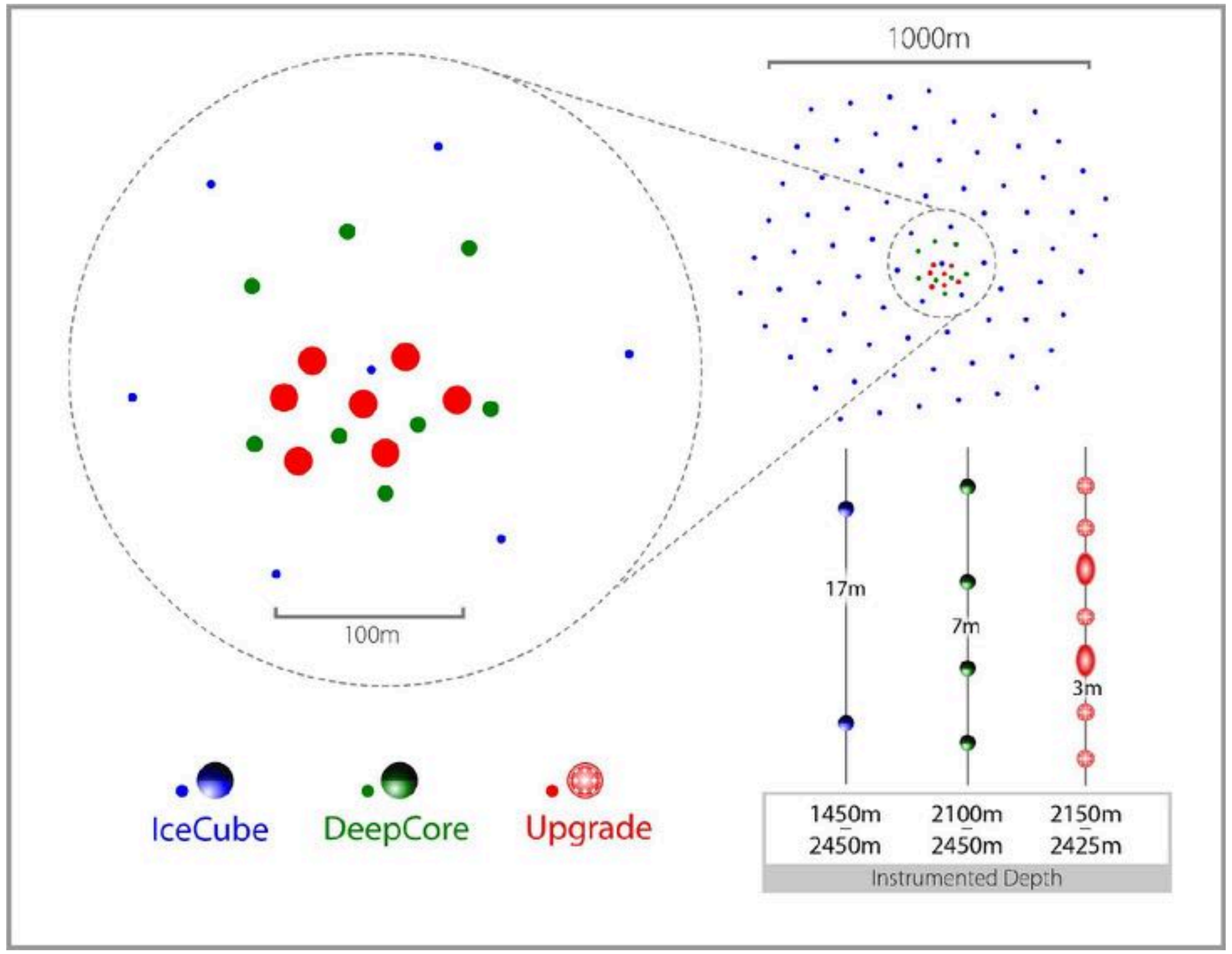
One Slide at IceCube Collaboration Meeting
Uppsala,Sweden a few weeks ago

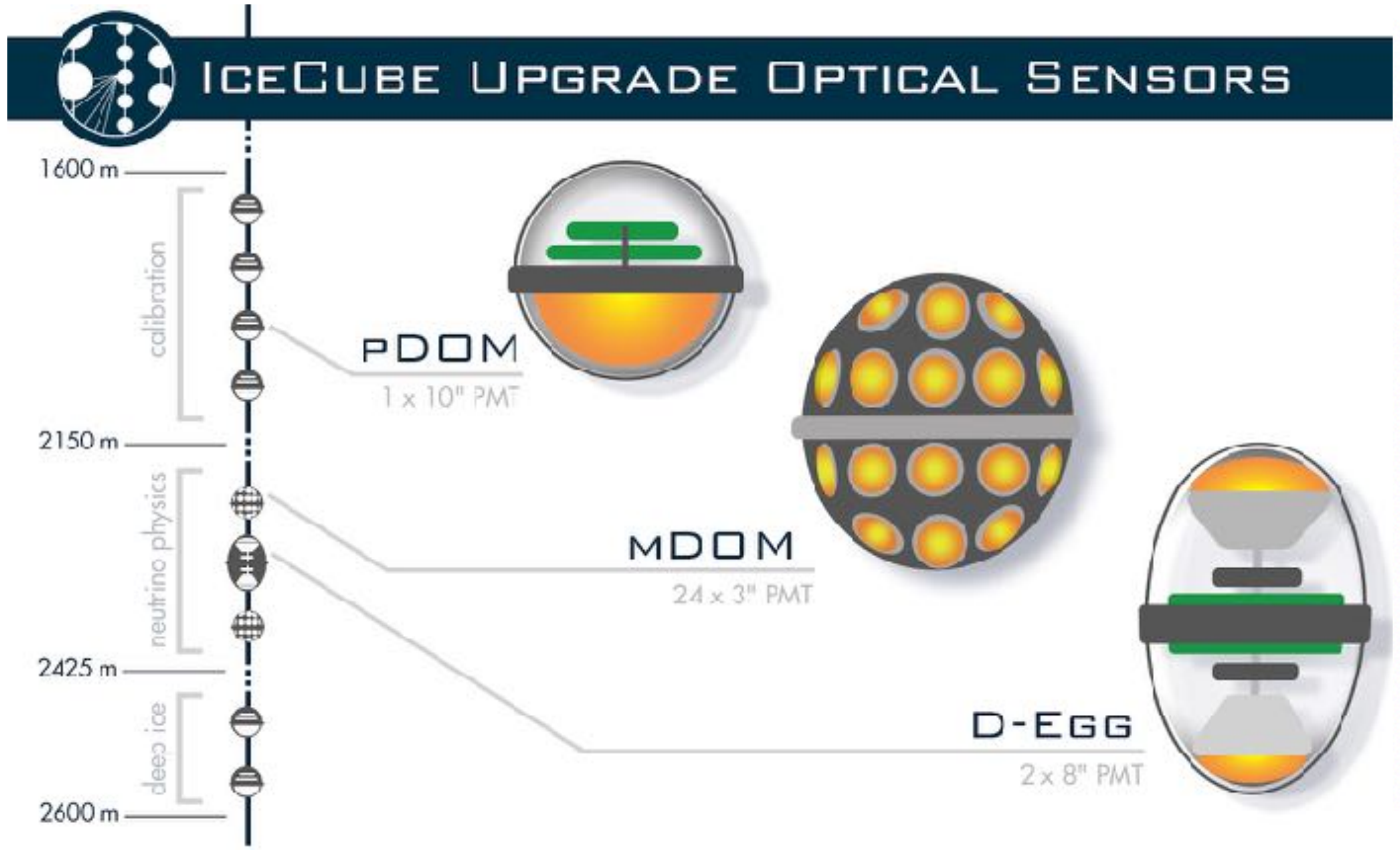
The IceCube Upgrade

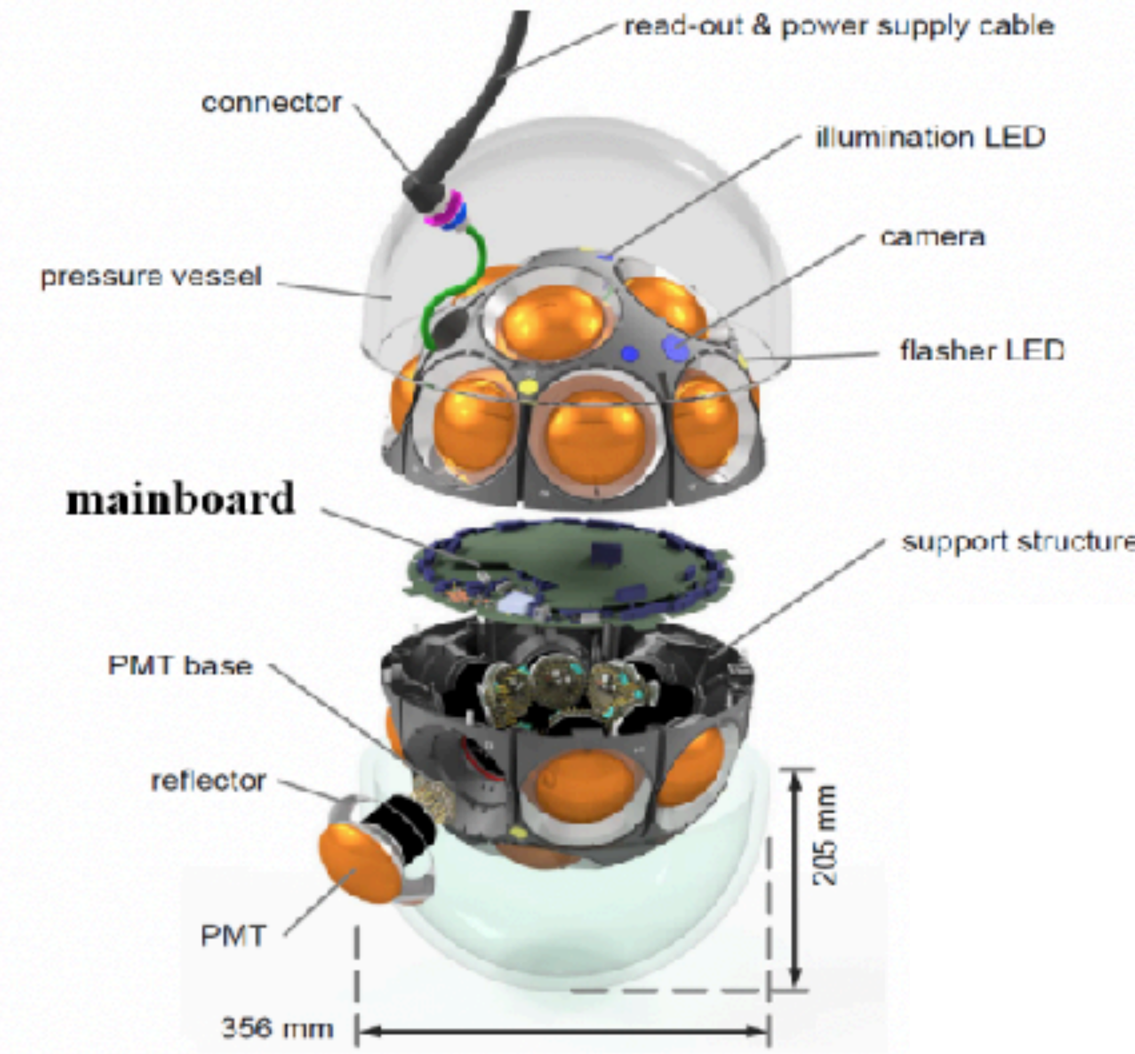
- Instrument additional 7 strings
  - 60-100 DOMs in each string
- Detect neutrinos below 10 GeV
- Construction began and full deployment in 2025/2026
- Testbed for IceCube-Gen2

- 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





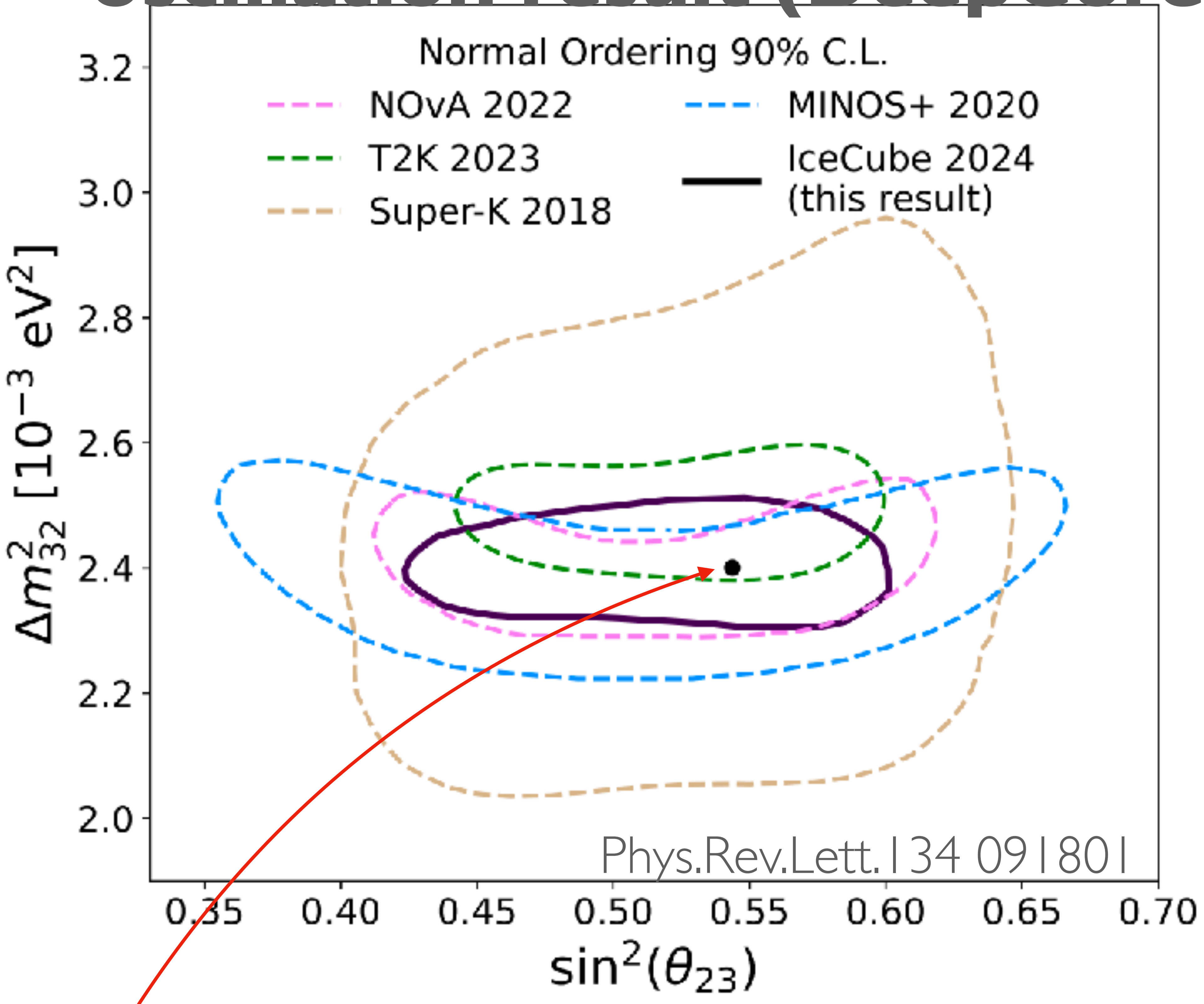




https://arxiv.org/pdf/1908.09441.pdf

Atmospheric Neutrino Oscillation Physics Sensitivity

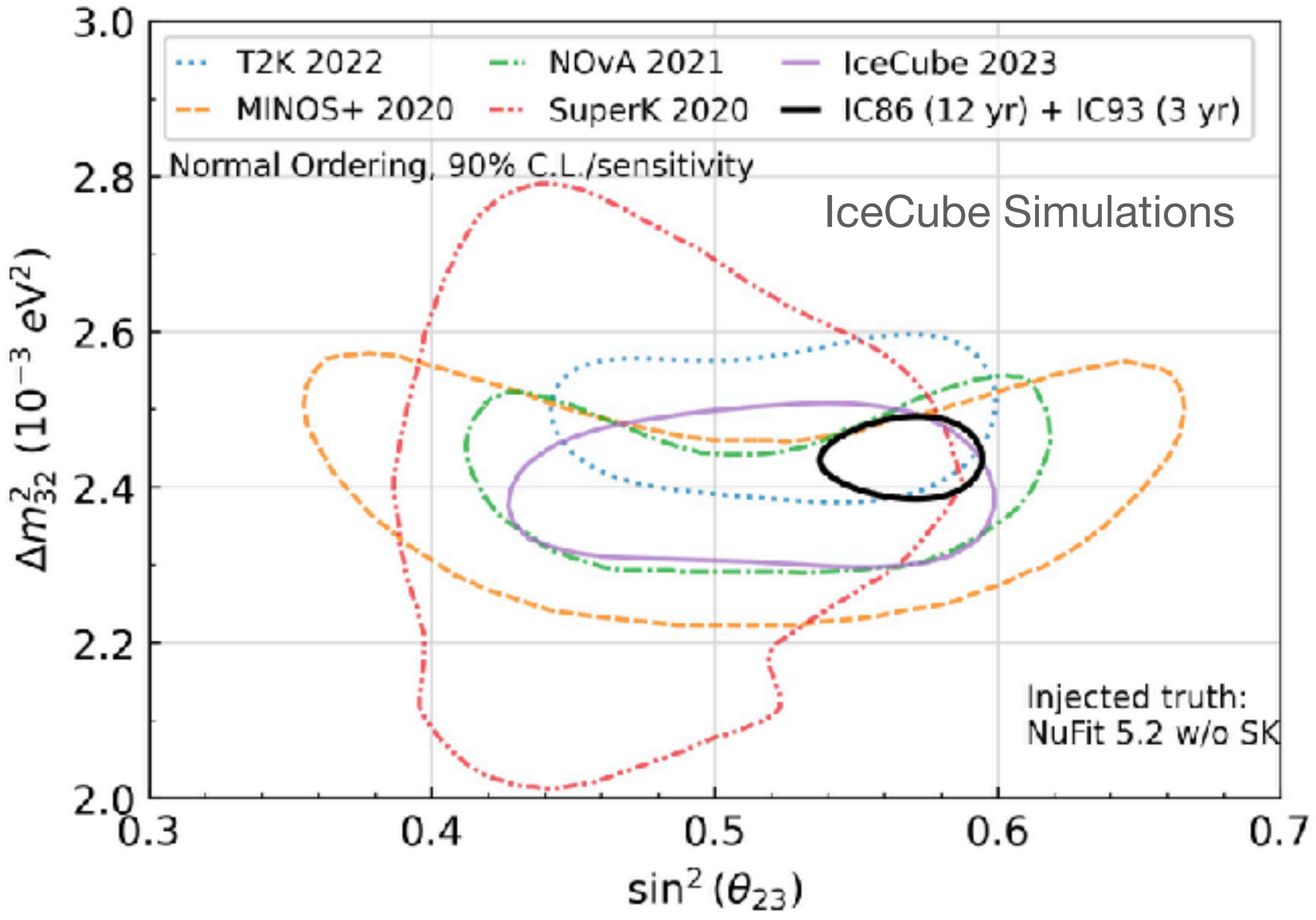
The latest atmospheric neutrino oscillation result (DeepCore)



Best Fit :

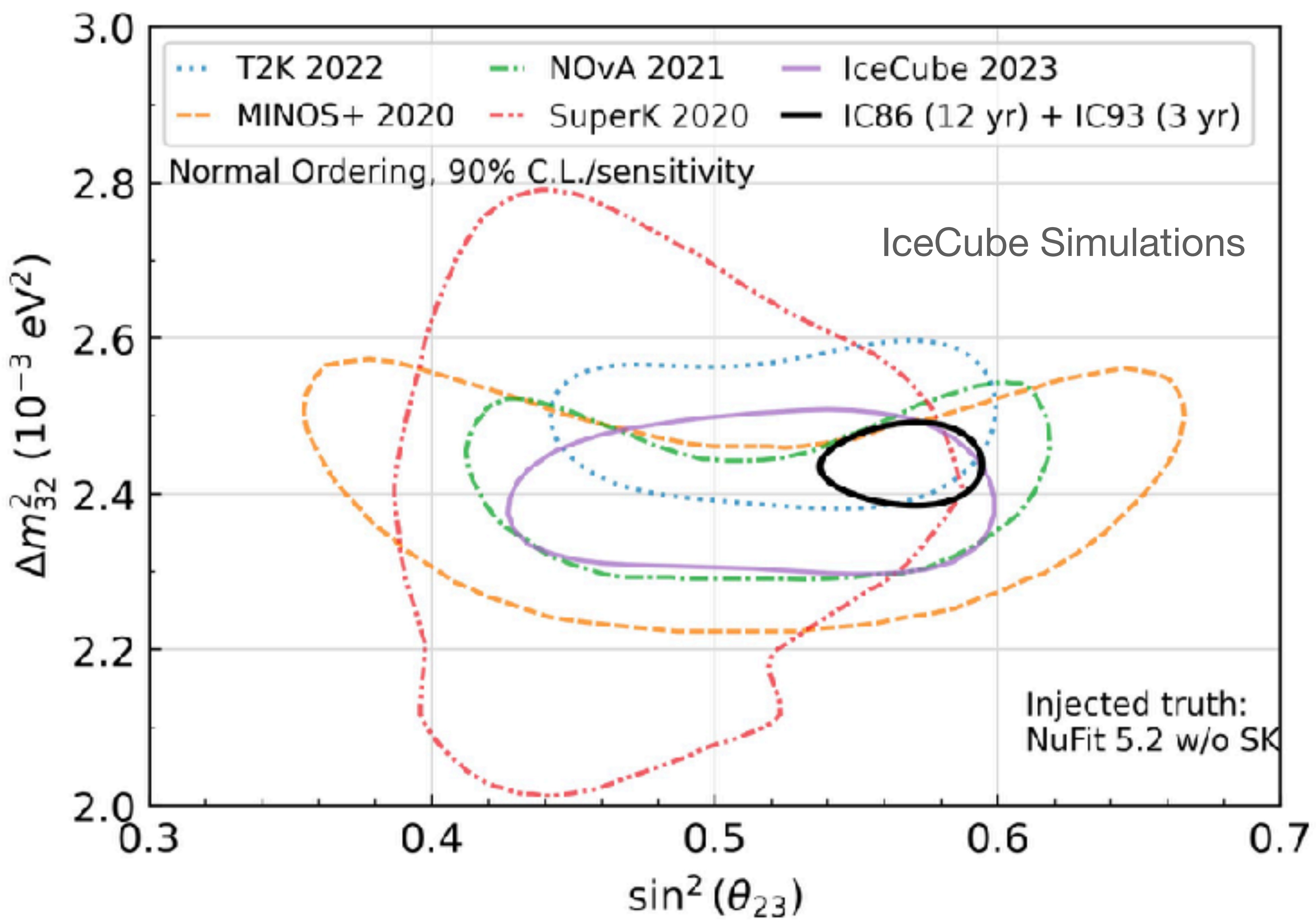
$$\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}\ ,\ \Delta m^2_{32} = 2.40^{+0.05}_{-0.04} \times 10^{-3} eV^2$$

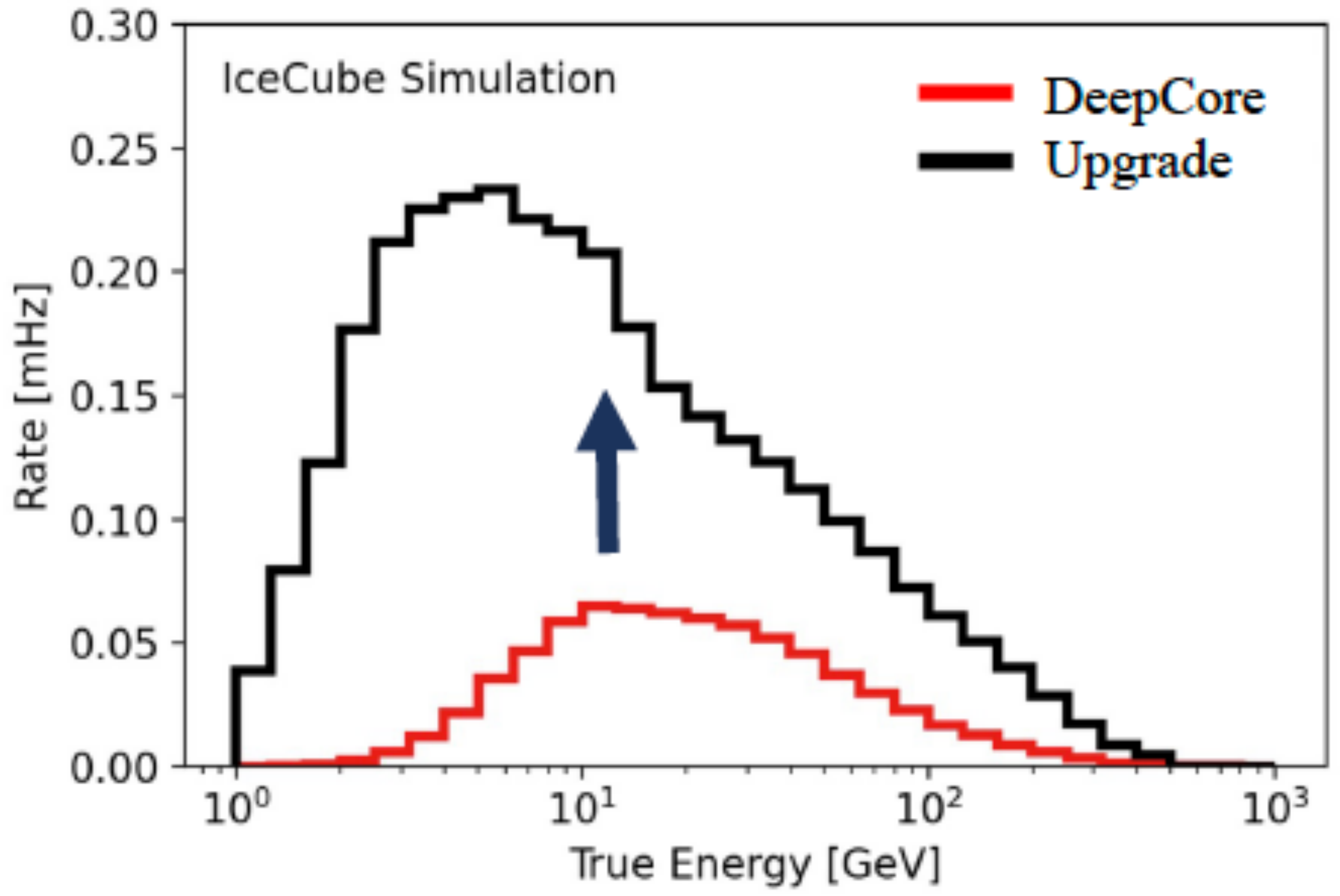
The DeepCore+Upgrade Sensitivity



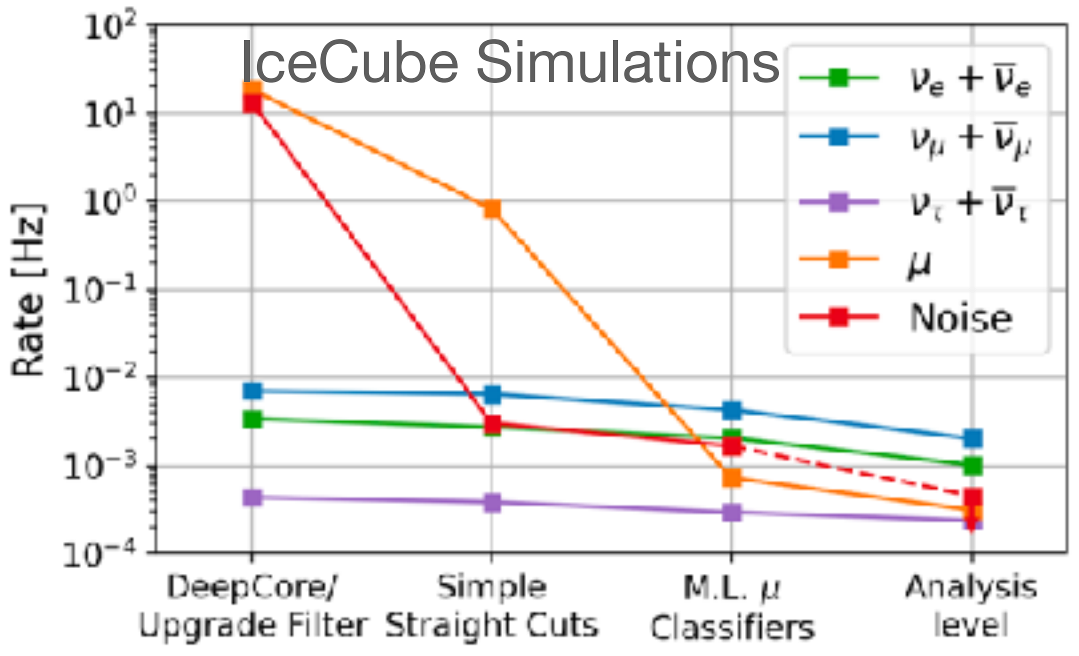
The Upgrade will enhance oscillations sensitivity significantly

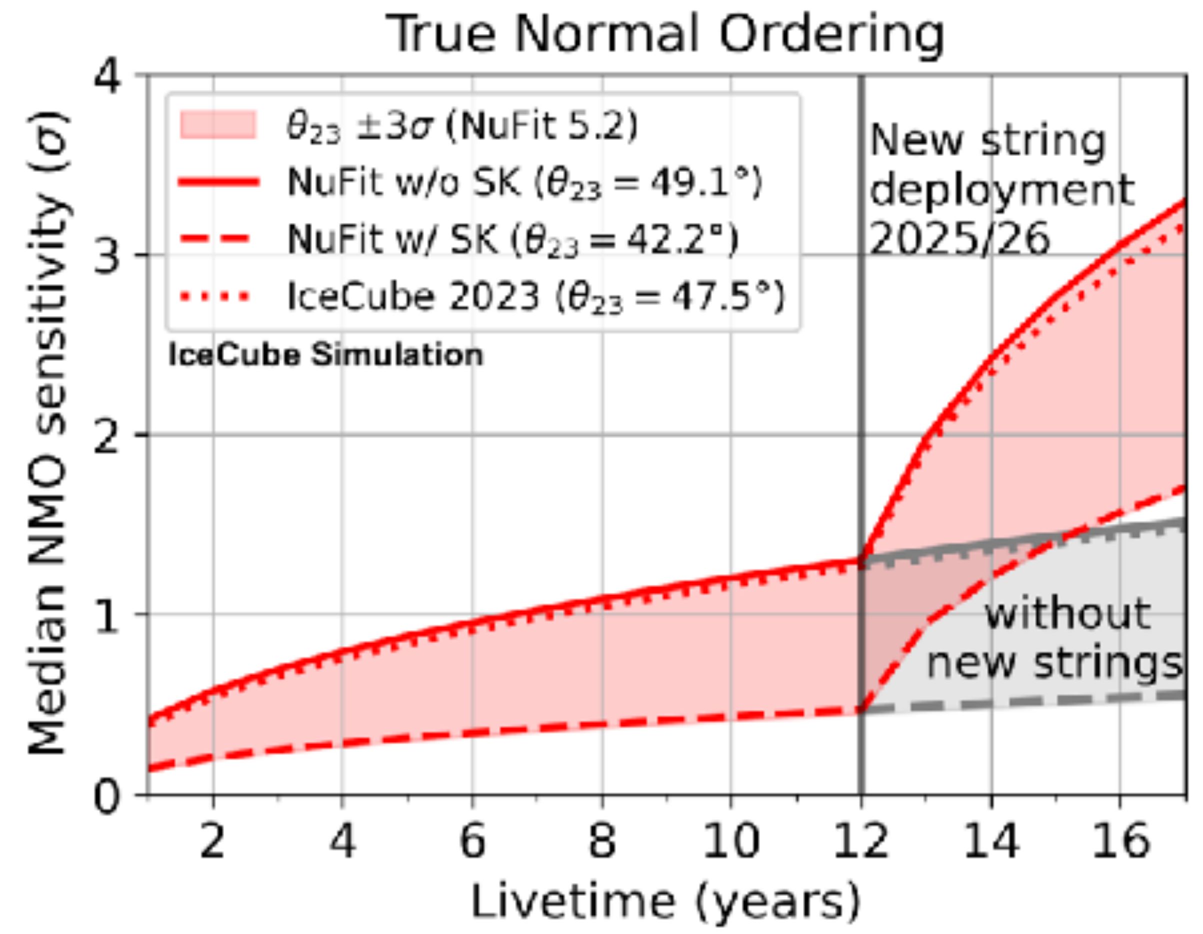
Atmospheric Neutrino Oscillation Physics Sensitivity

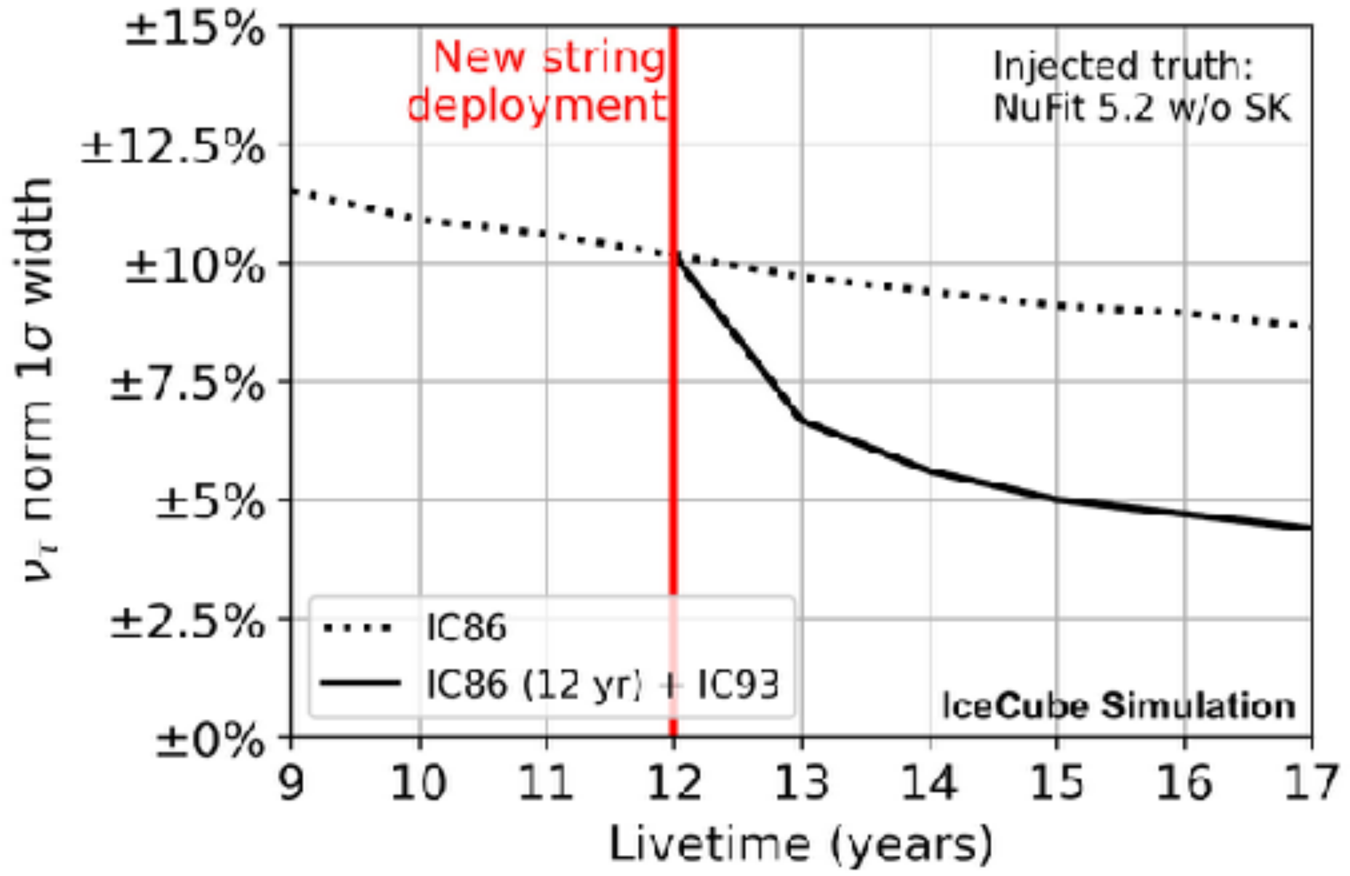




Flavor	IC86	IC93
$\nu_e + \bar{\nu}_e$	0.25 mHz	2.0 mHz
$\nu_\mu + \bar{\nu}_\mu$	0.76 mHz	4.3 mHz
$\nu_\tau + \bar{\nu}_\tau$	0.05 mHz	0.3 mHz





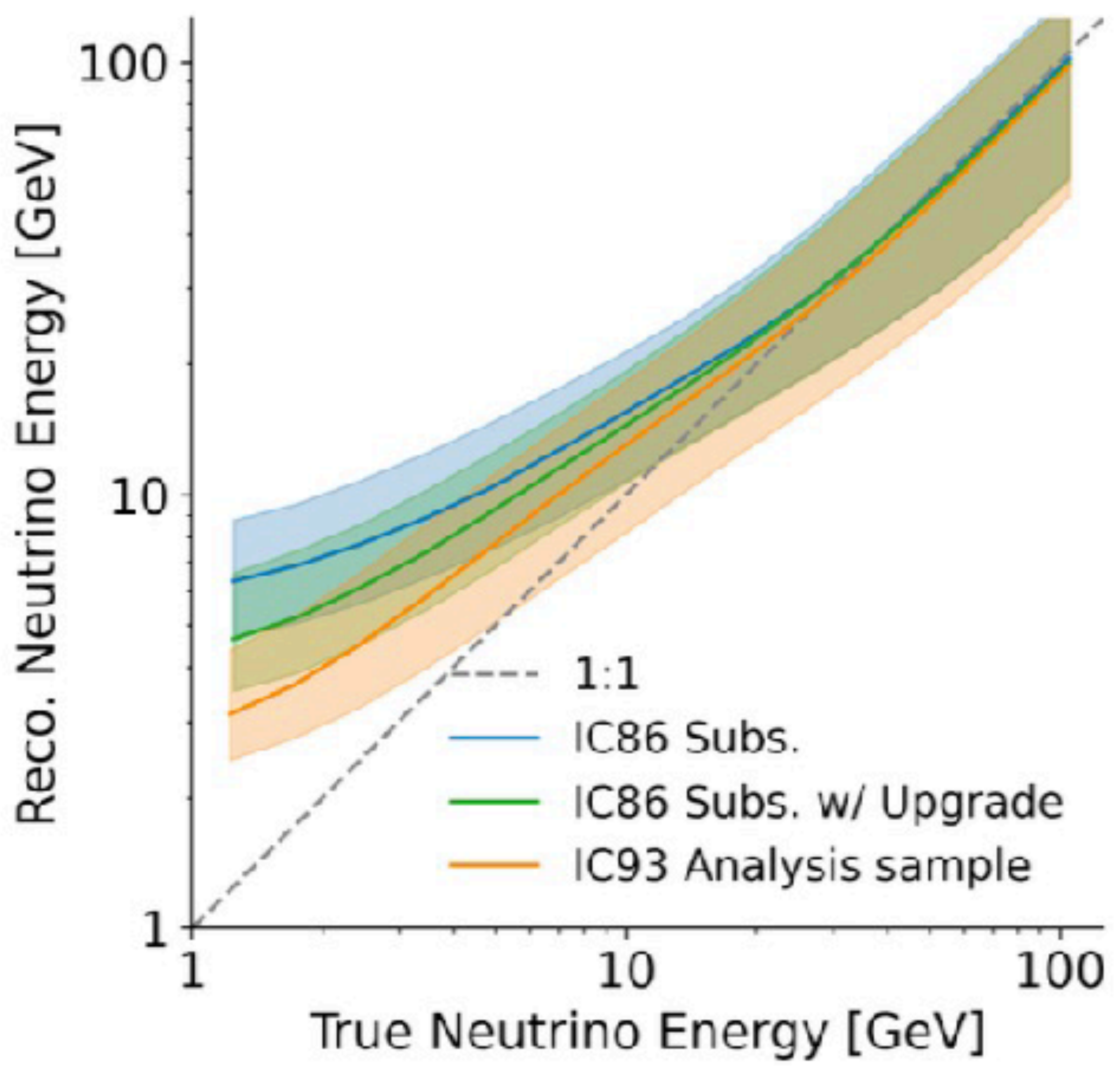


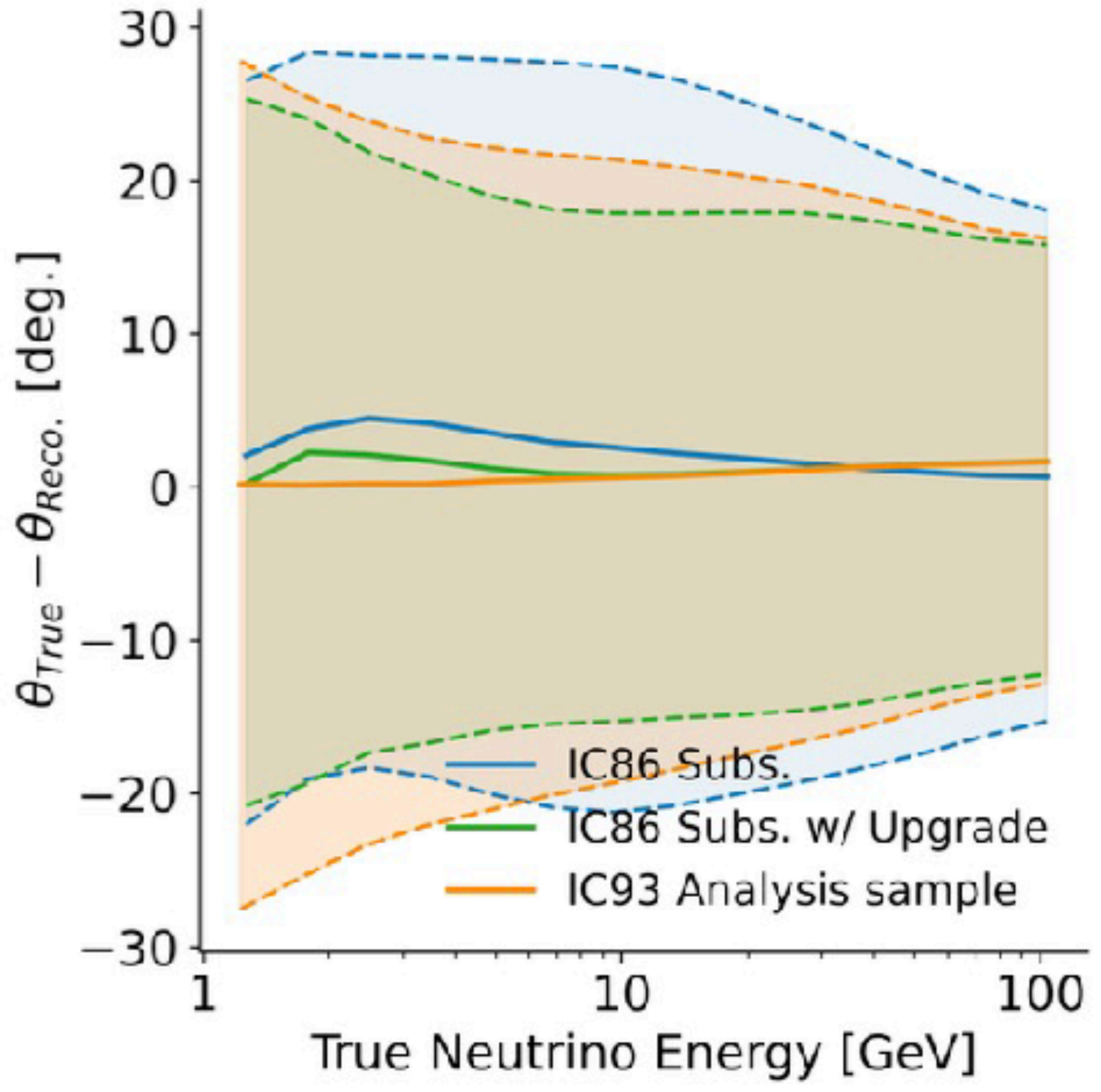
The Upgrade will enhance oscillations sensitivity significantly

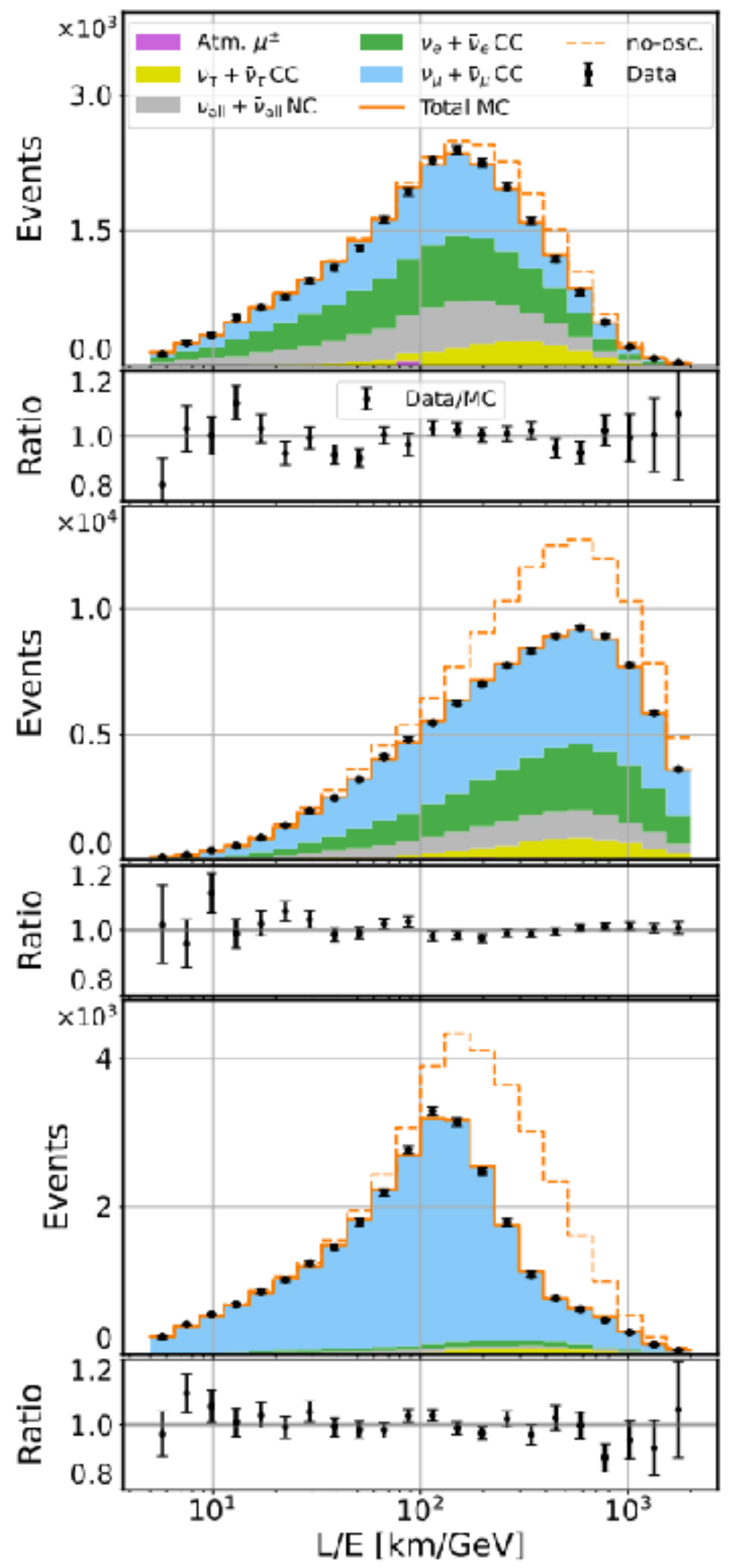
Atmospheric Neutrino Oscillation Physics Sensitivity

Towards the Upgrade ν_e appearance analysis

4 GeV < Energy < 15.8 GeV & 120º < θ_{zen} < 180º







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

Upgrade Plan (Starting Nov. 2025 and deploying all 7 strings in ~3 months)

Summary and Outlook

The IceCube Upgrade is coming

- Korean IceCube members 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 in this winter.


The 3rd K-IceCube workshop
The 3rd
K-IceCube
Workshop
Chung-Ang University
Wed, 26th Feb
NATIONAL
GEOGRAPHIC

Thank you!