

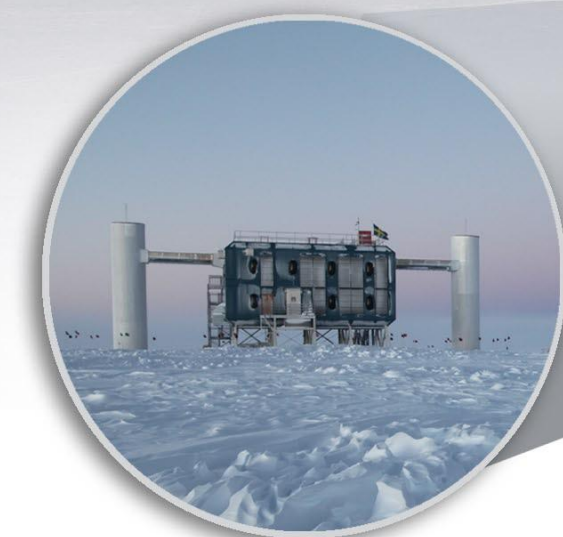


credit: Yuya Makino

Results from the IceCube Experiment using Machine Learning

15 year IceCube Symposium

Maximilian Meier
2026.09.10

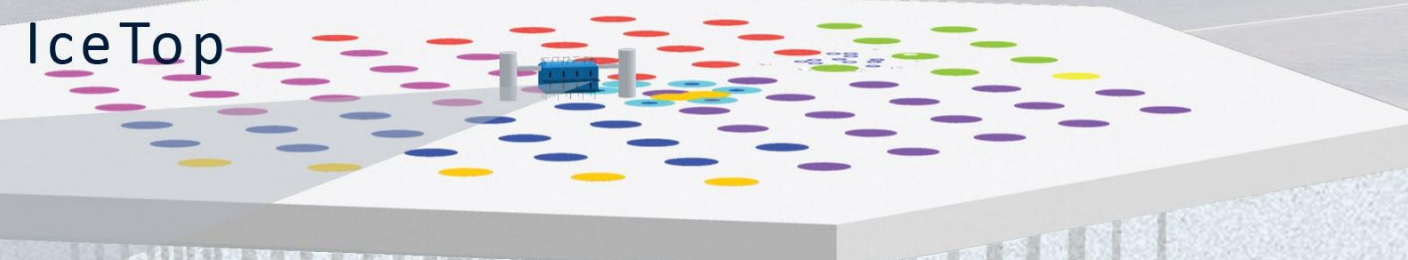


IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison



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

50 m



1450 m

86 strings of DOMs, set 125 meters apart

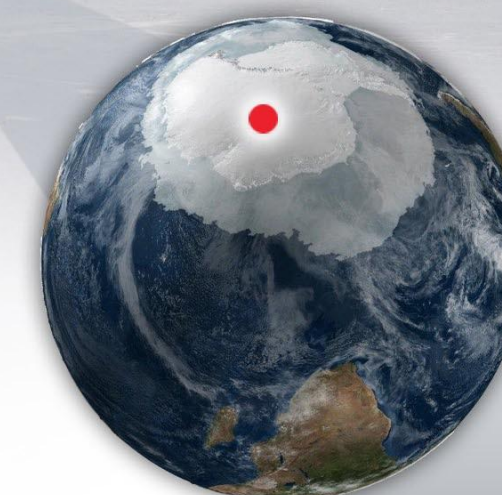
2450 m

IceCube detector

DeepCore

Antarctic bedrock

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

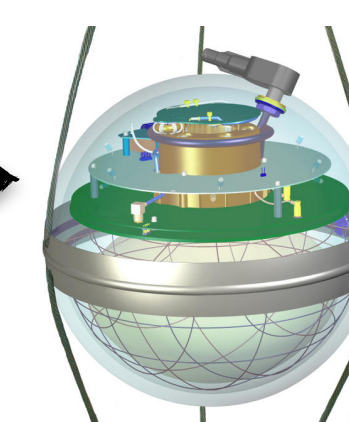


60 DOMs on each string

DOMs are 17 meters apart



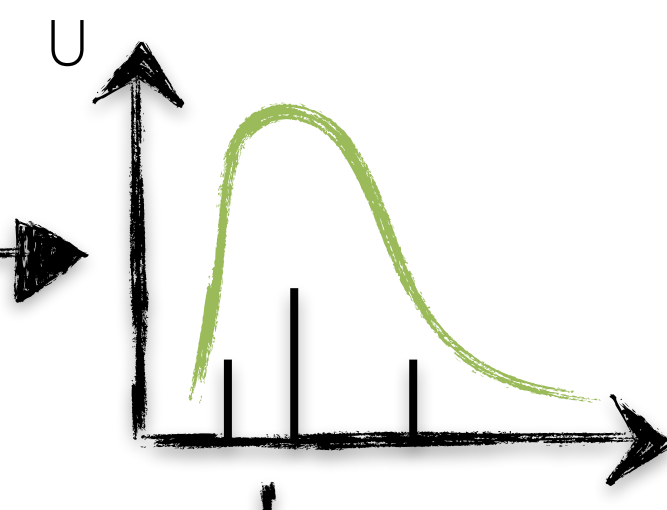
DOM



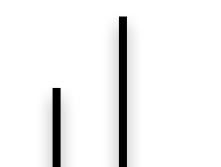
Detector Design

-  1 gigaton of instrumented ice
-  5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
-  1 square kilometer surface array, IceTop, with 324 DOMs
-  2 nanosecond time resolution
-  IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily

Waveform

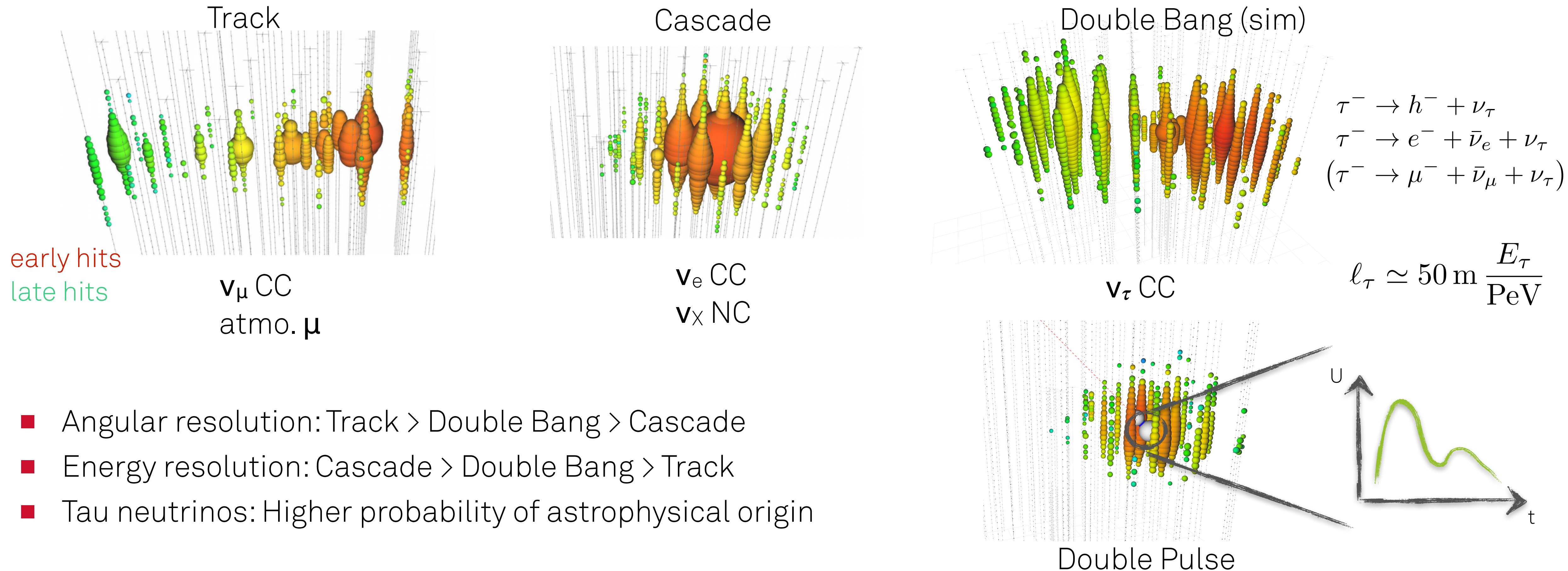


Pulse series: (t_i, q_i)



Event Signatures in IceCube

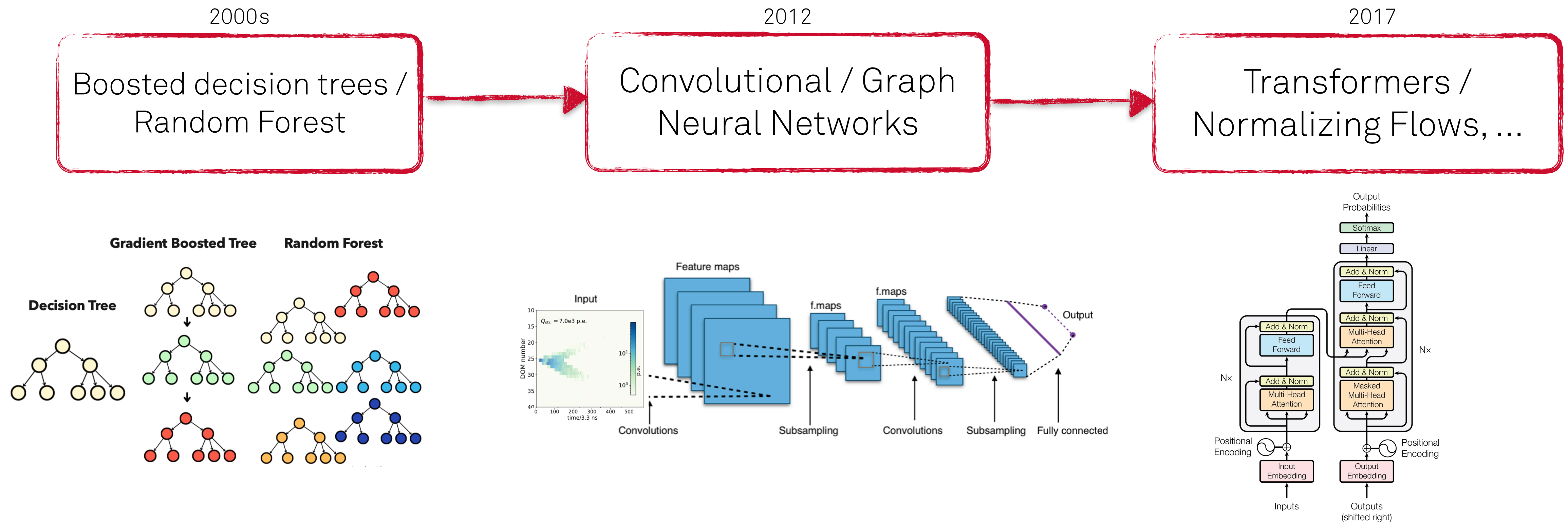
- Neutrinos detected by IceCube interact mostly via deep inelastic scattering



- Angular resolution: Track > Double Bang > Cascade
- Energy resolution: Cascade > Double Bang > Track
- Tau neutrinos: Higher probability of astrophysical origin

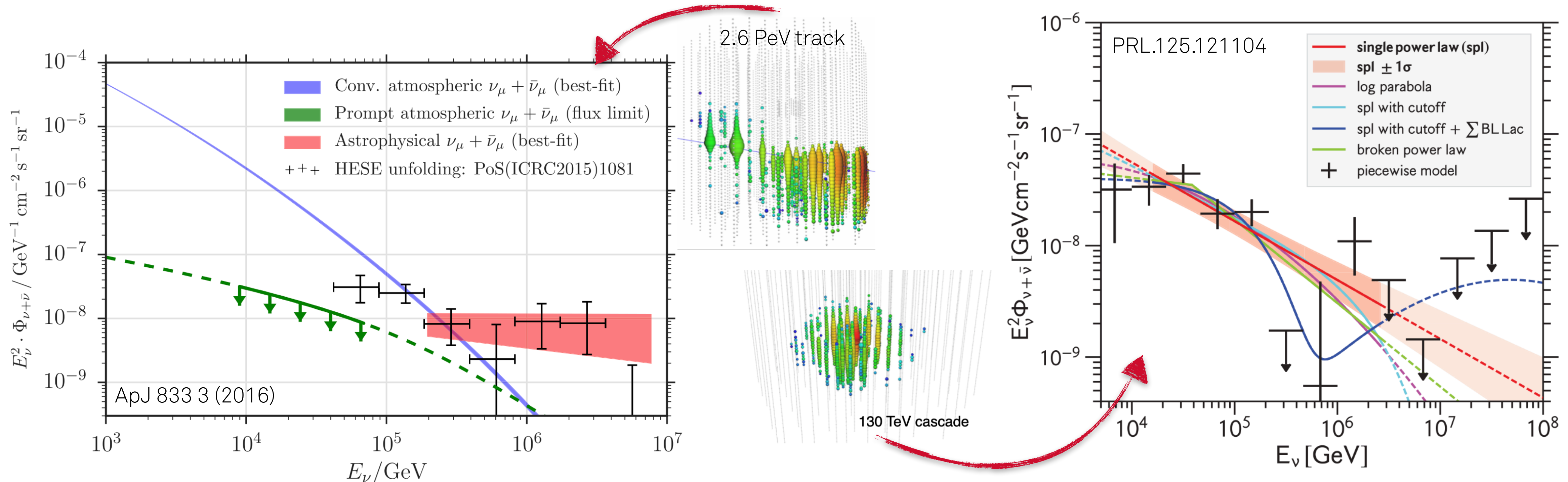
Overview

- Historical overview of popular methods used IceCube
- Recent examples and the impact of AI/ML-methods on IceCube physics



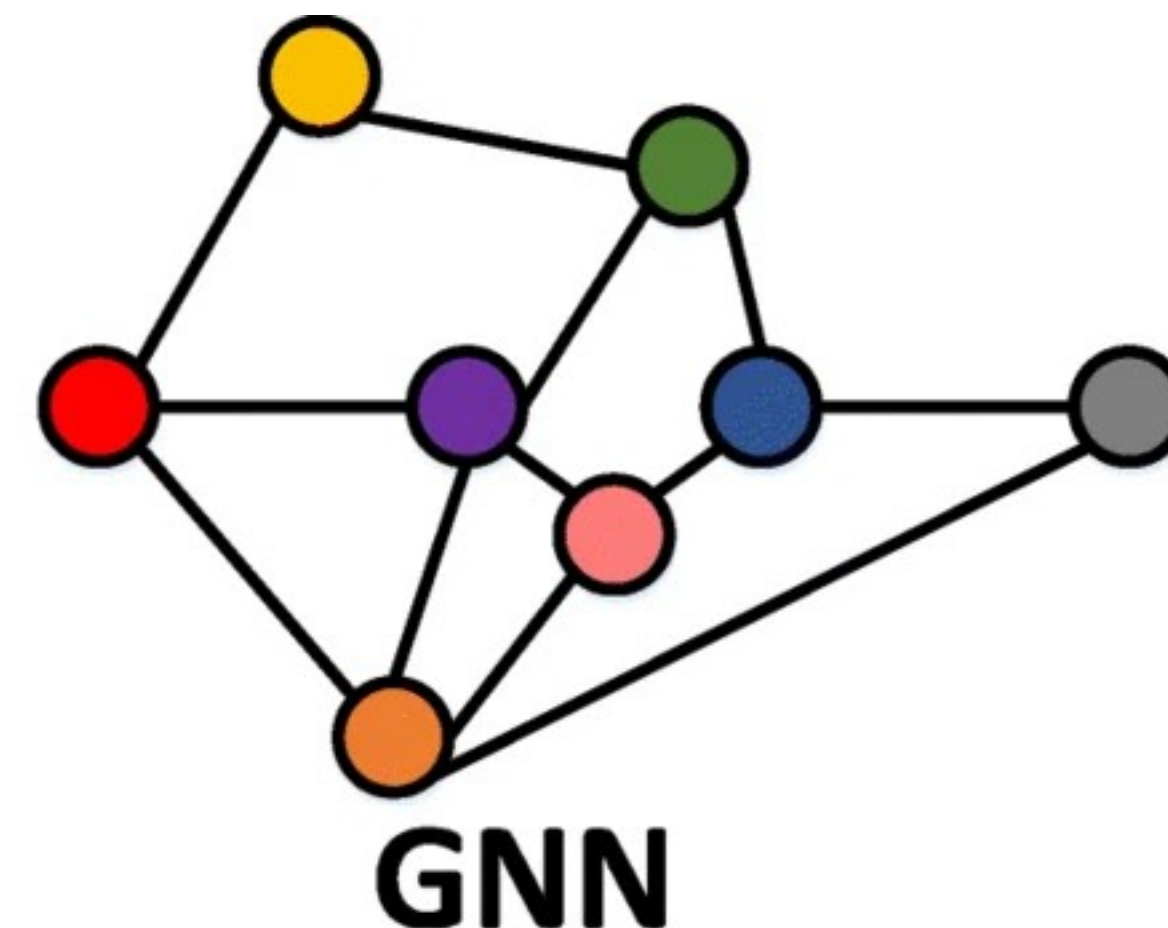
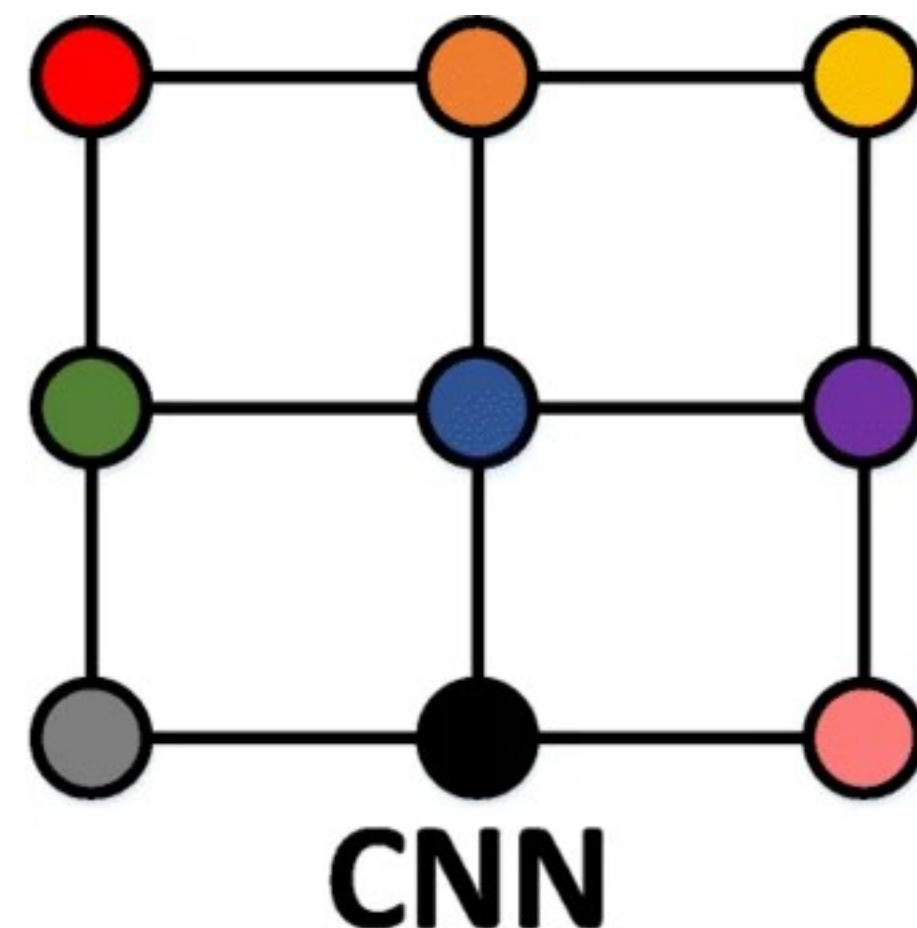
Overview — Tree-based algorithms (BDT, Random Forest)

- BDTs/Random Forests were introduced around 2000 within a few years of each other
- First used in 2010 (IC-40 analysis) before data from full IceCube detector available
- Still actively used now in many analyses today
- Used as robust algorithms for first significant detection of astrophysical neutrinos on large data-samples



Overview — Convolutional neural networks (CNNs) / Graph neural networks (GNN)

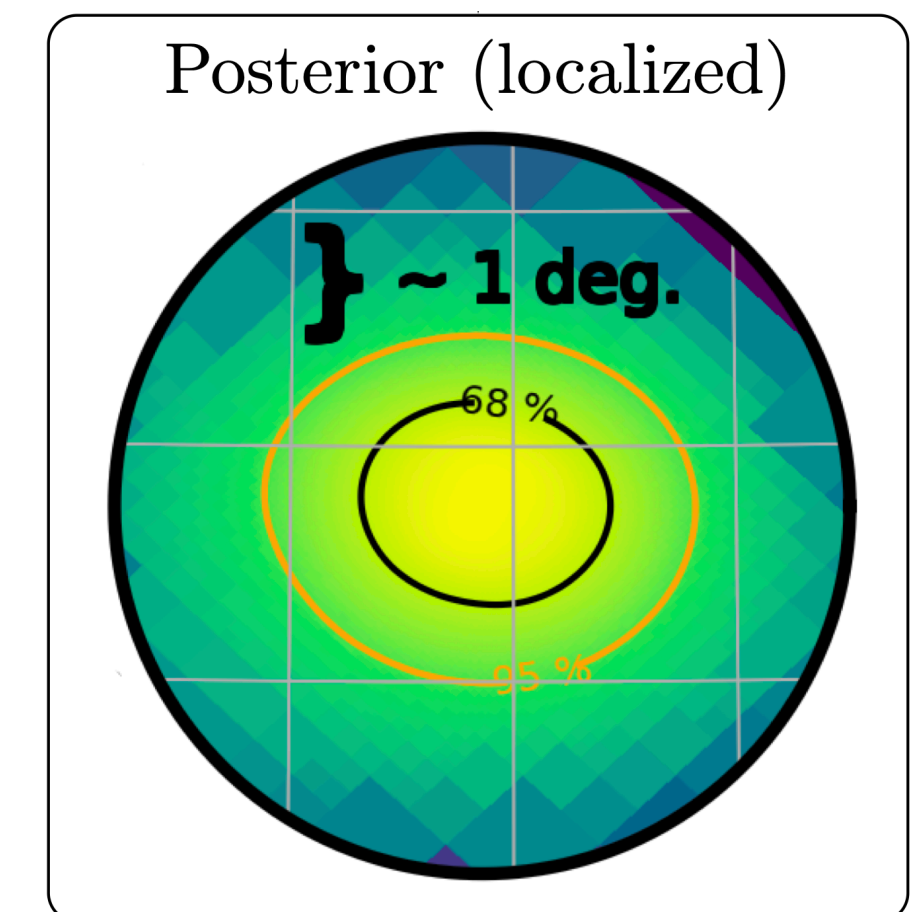
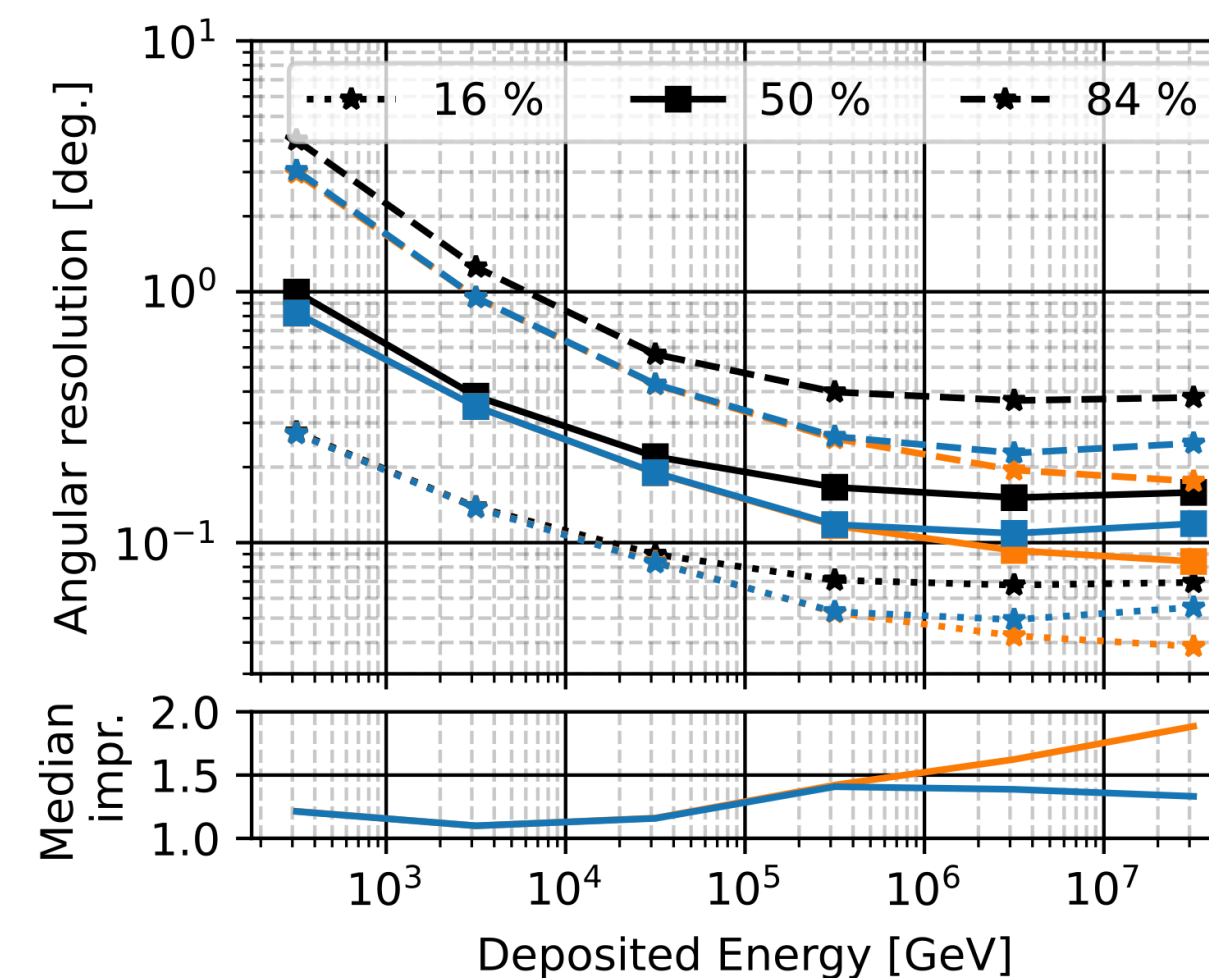
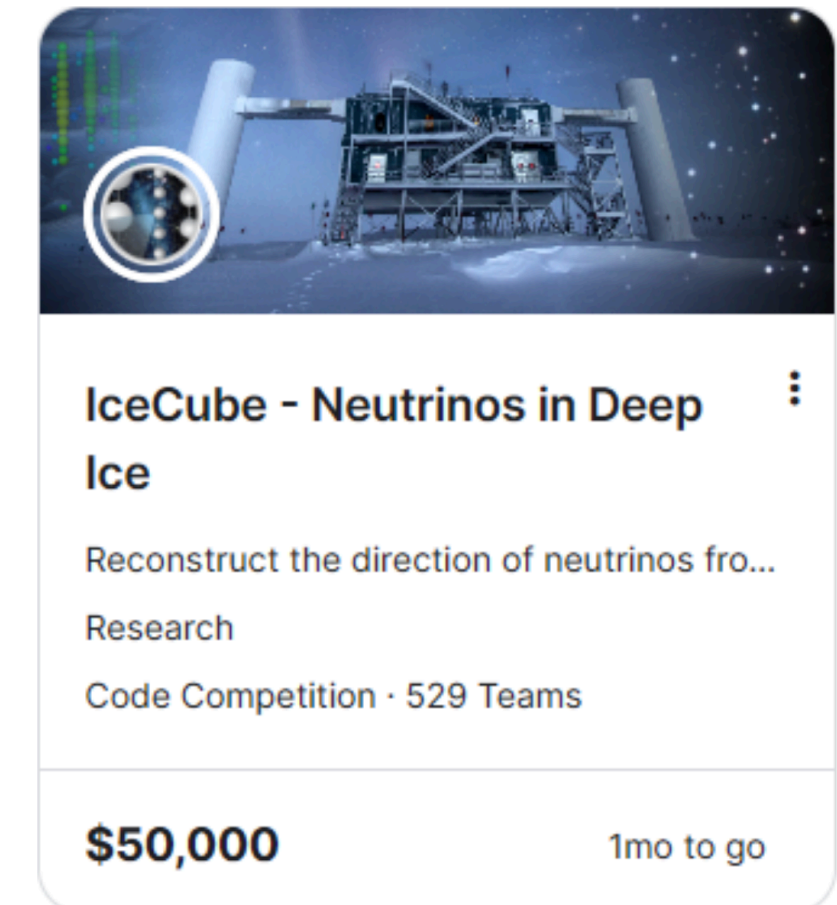
- Became popular after huge success at the image classification competition ImageNet 2012
- From the group of Geoffrey Hinton (2024 physics nobel prize laureate)
- Big impact → Backbone of current AI/Large Language Model boom starting in the 2020s
- First adopted in an IceCube publication in 2021
- Used in many different applications since then
- GNNs can generalize CNNs to irregular inputs → lossless representation of IceCube geometry



Overview — Transformers and Normalizing Flows

- Transformers
 - „Attention is all you need“ — 2017 (Google Research)
 - Big impact on Large Language Models (LLMs)
 - Initially adopted in IceCube’s public Kaggle competition (2023)
 - Now, included in some upcoming IceCube analyses (e.g. PoS(ICRC2025) 1127)
- Normalizing Flows
 - Popularized in 2015
 - First discussed at ICRC 2023
 - First time strictly improving likelihood-based reconstruction for tracks (2026)
 - Also implementing the Transformer architecture

kaggle



Neutrinos from the Galactic Plane

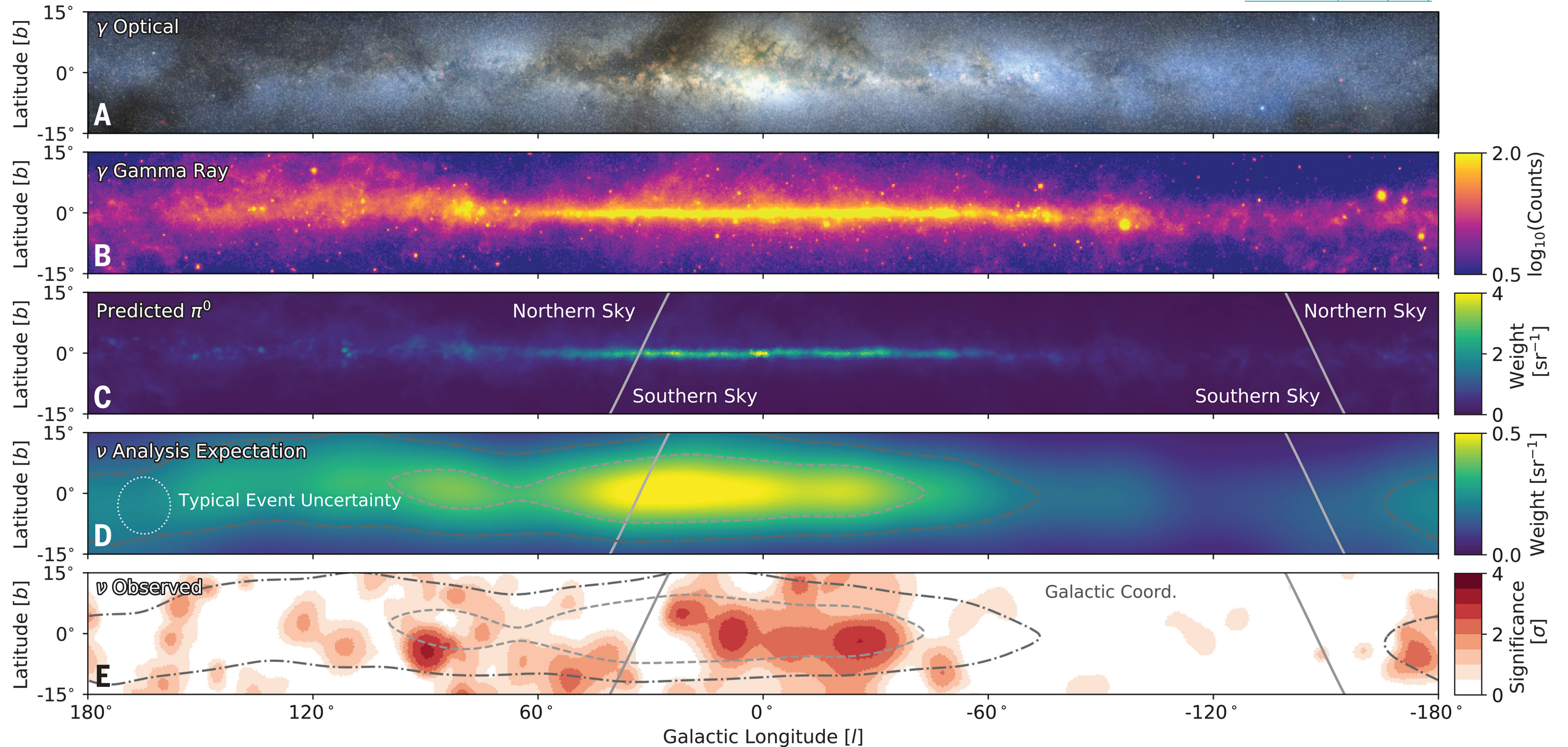
Astrophysical tau neutrinos

Neutrino Oscillation measurement

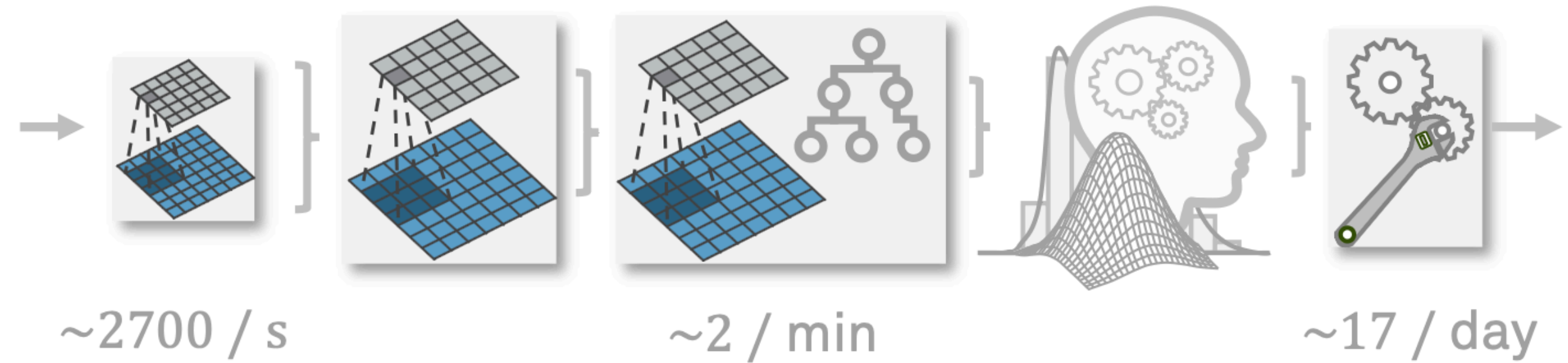
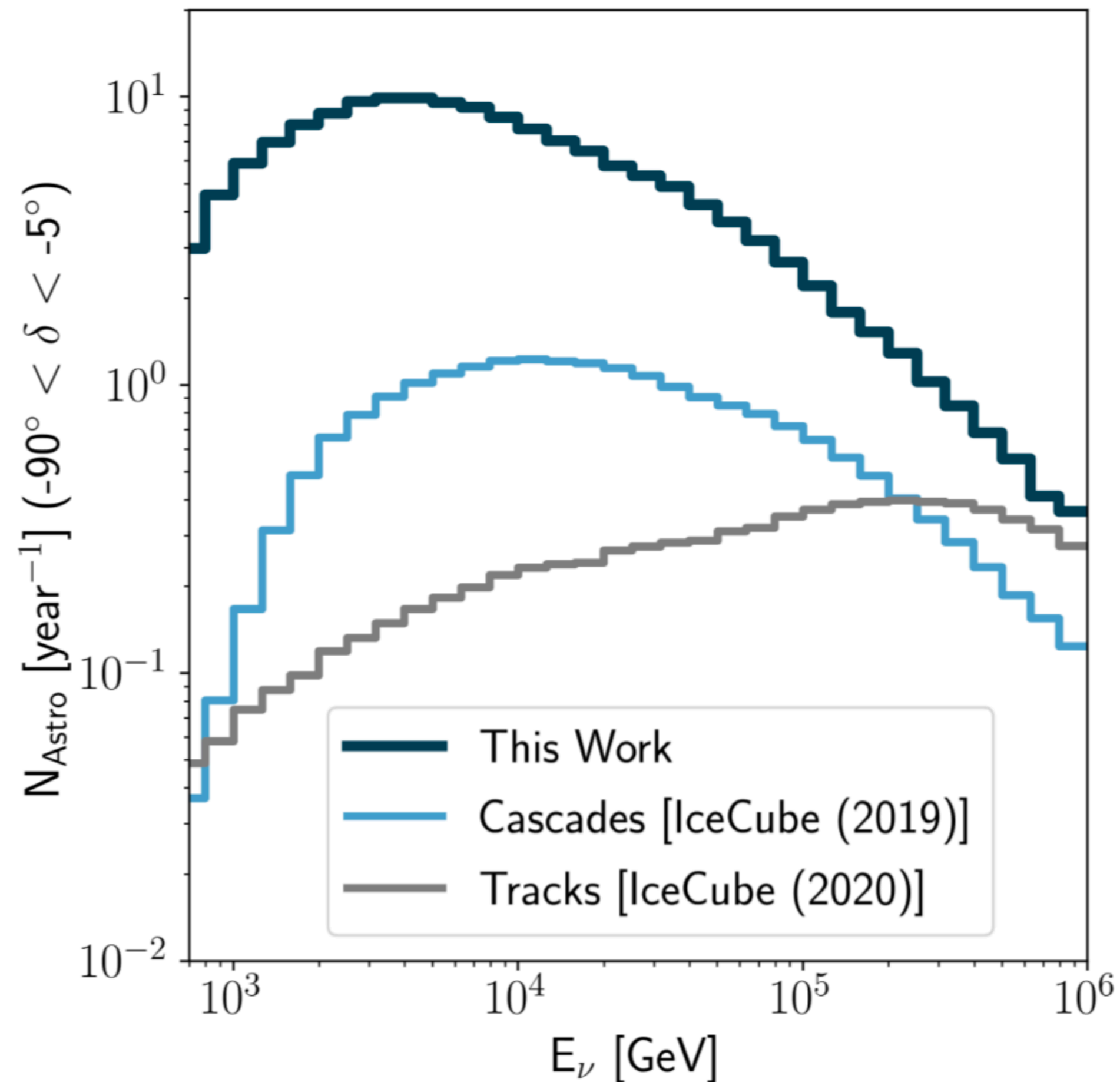
Neutrino Alerts

Neutrinos from the Galactic plane

[Science 380, 6652 \(2023\)](#)



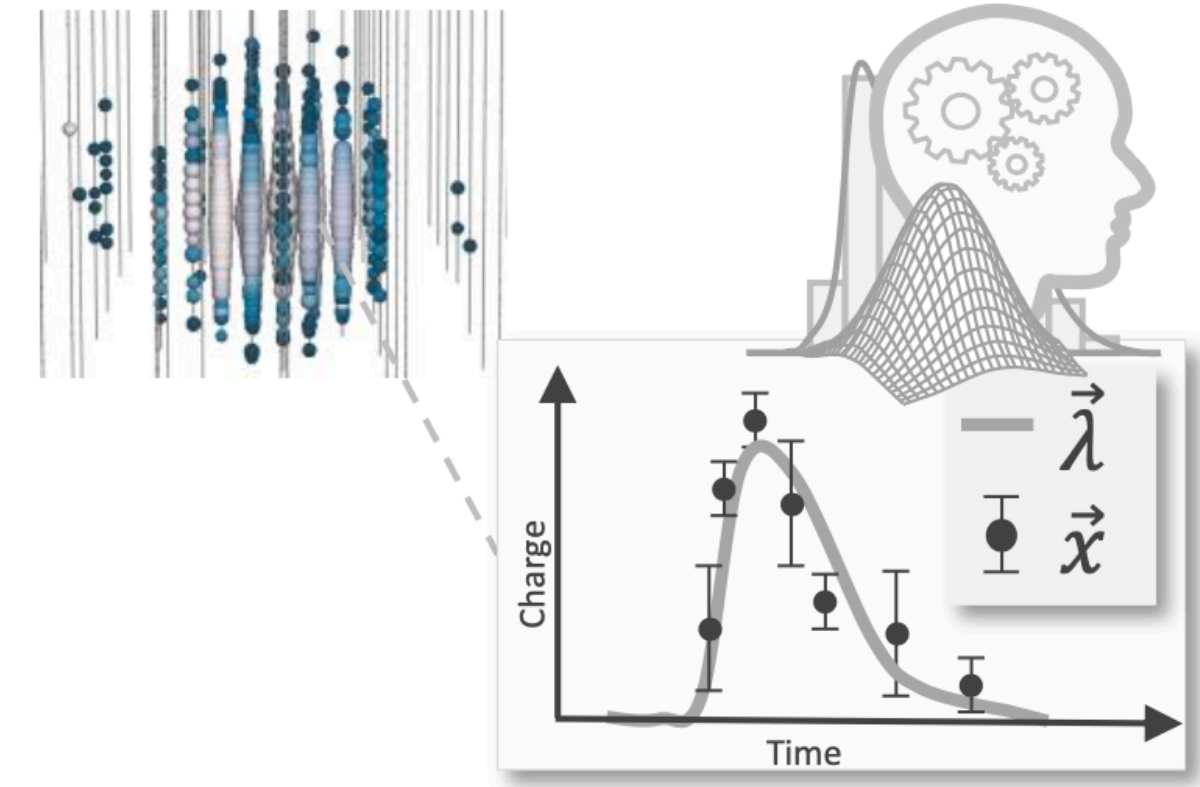
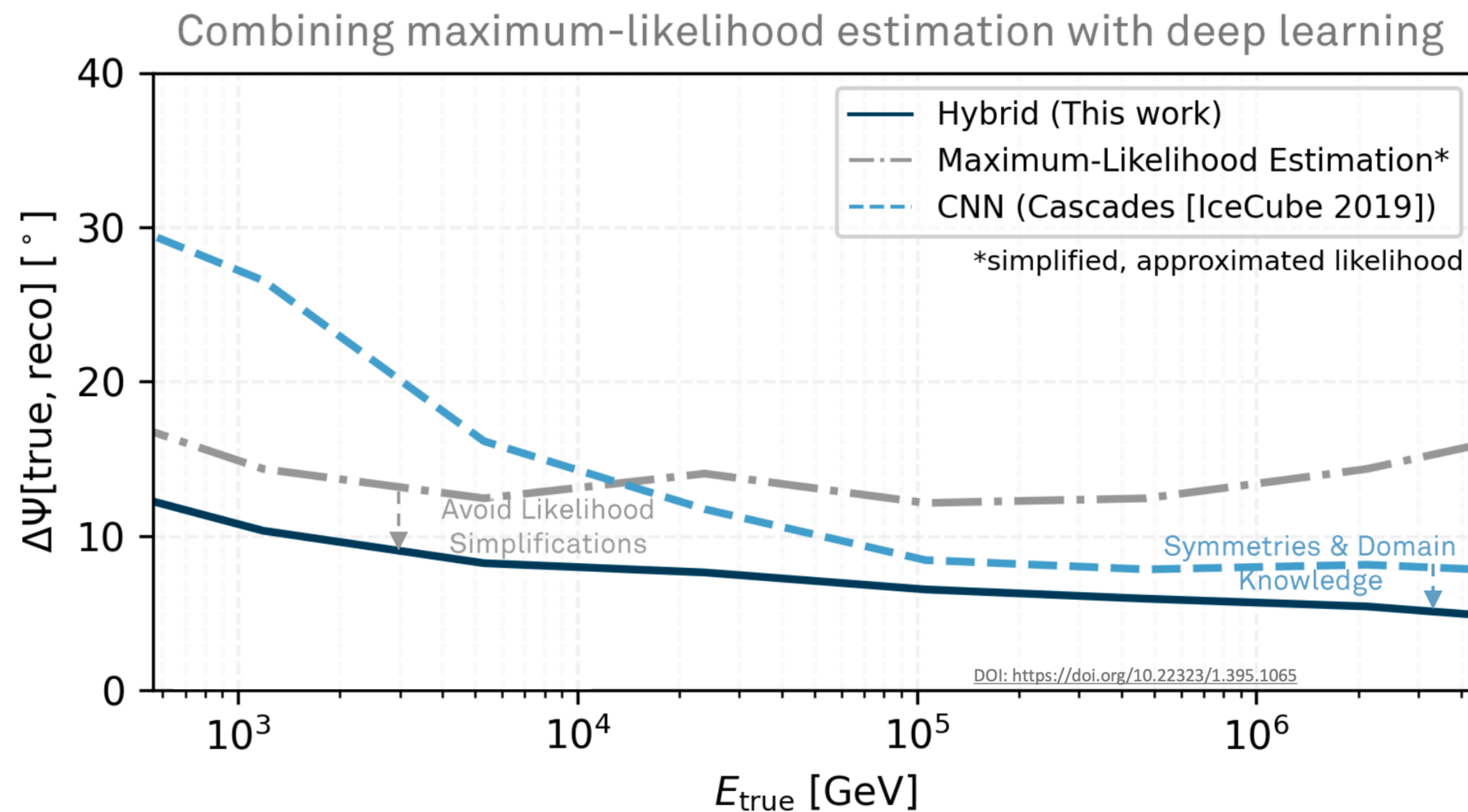
Neutrinos from the Galactic plane



Event Selection:

- Employs a series of convolutional neural networks (CNNs) and boosted decision trees (BDTs)
- 30 times as many events as precursor analysis
- More sensitive than tracks in the Southern sky (most important for neutrinos from Galactic center)

Neutrinos from the Galactic plane



Improvements due to novel ML-based methods

- Improved angular resolution over entire energy range
- Analysis sensitivity improved by a factor of 3
- Equivalent to 75 years of detector livetime using the previous analysis

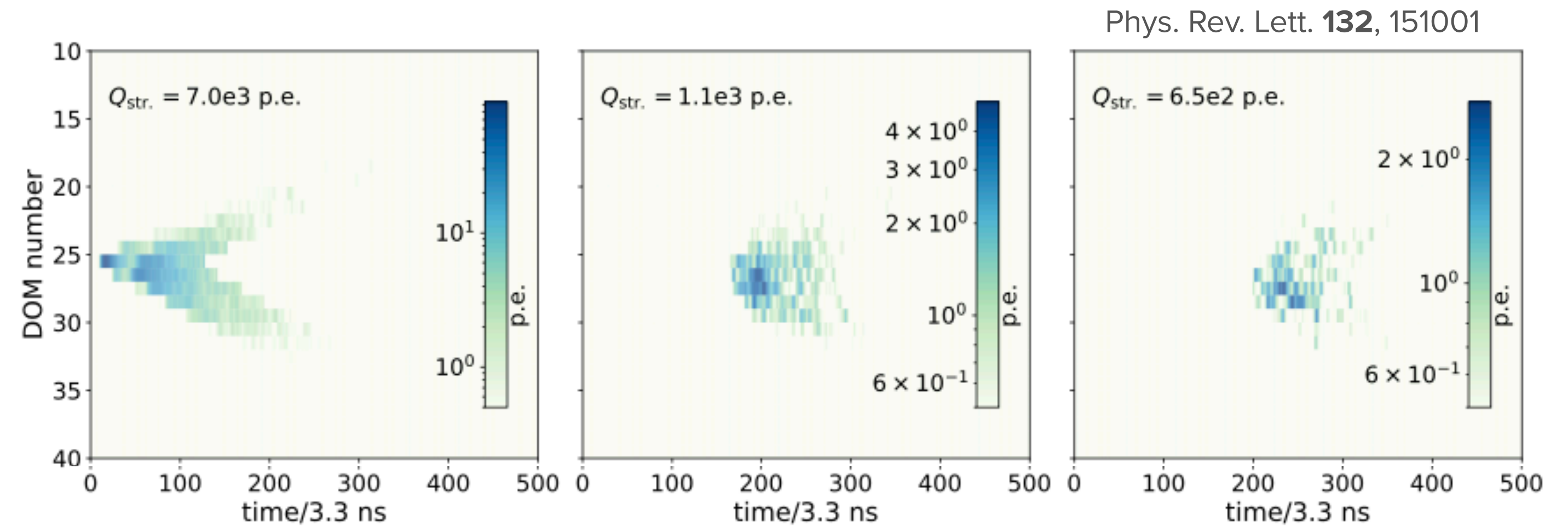
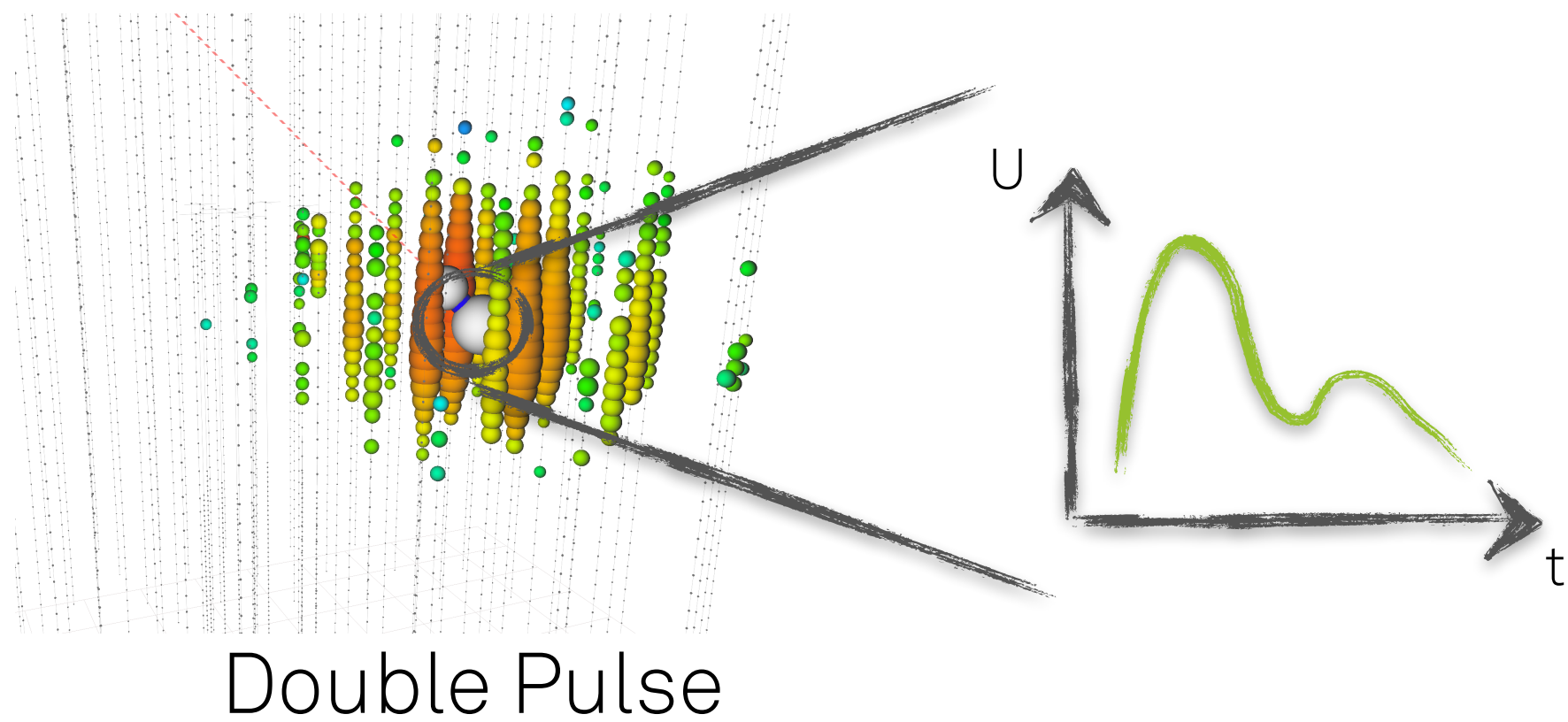
Neutrinos from the Galactic Plane

Astrophysical tau neutrinos

Neutrino Oscillation measurement

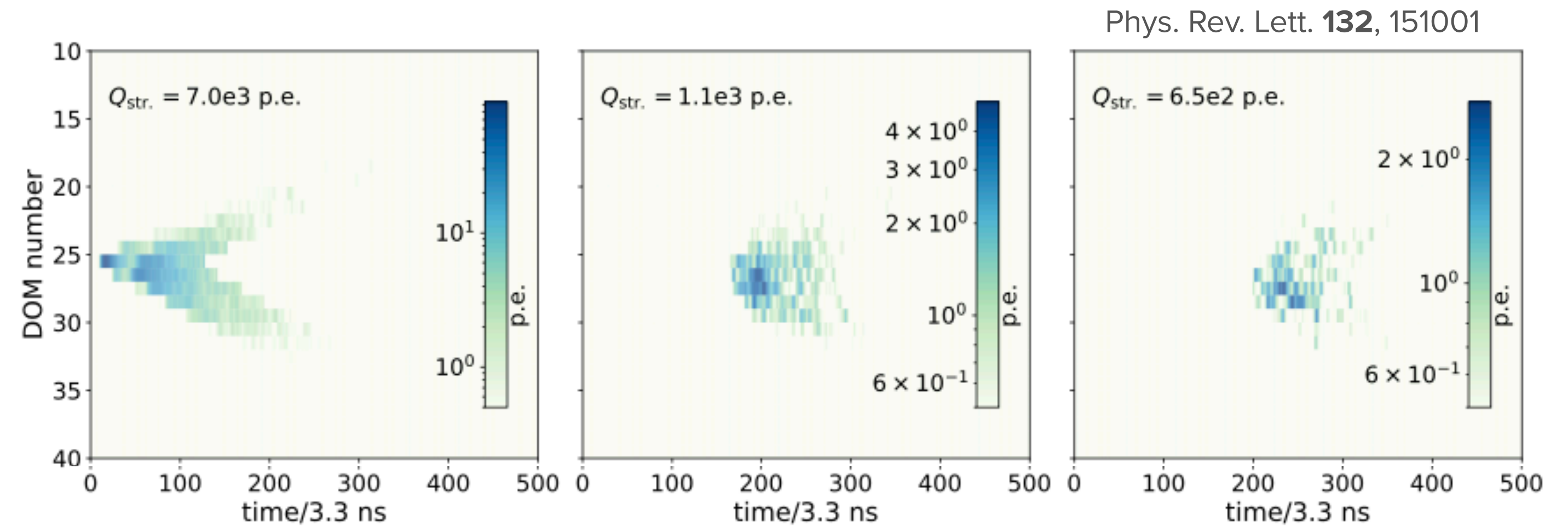
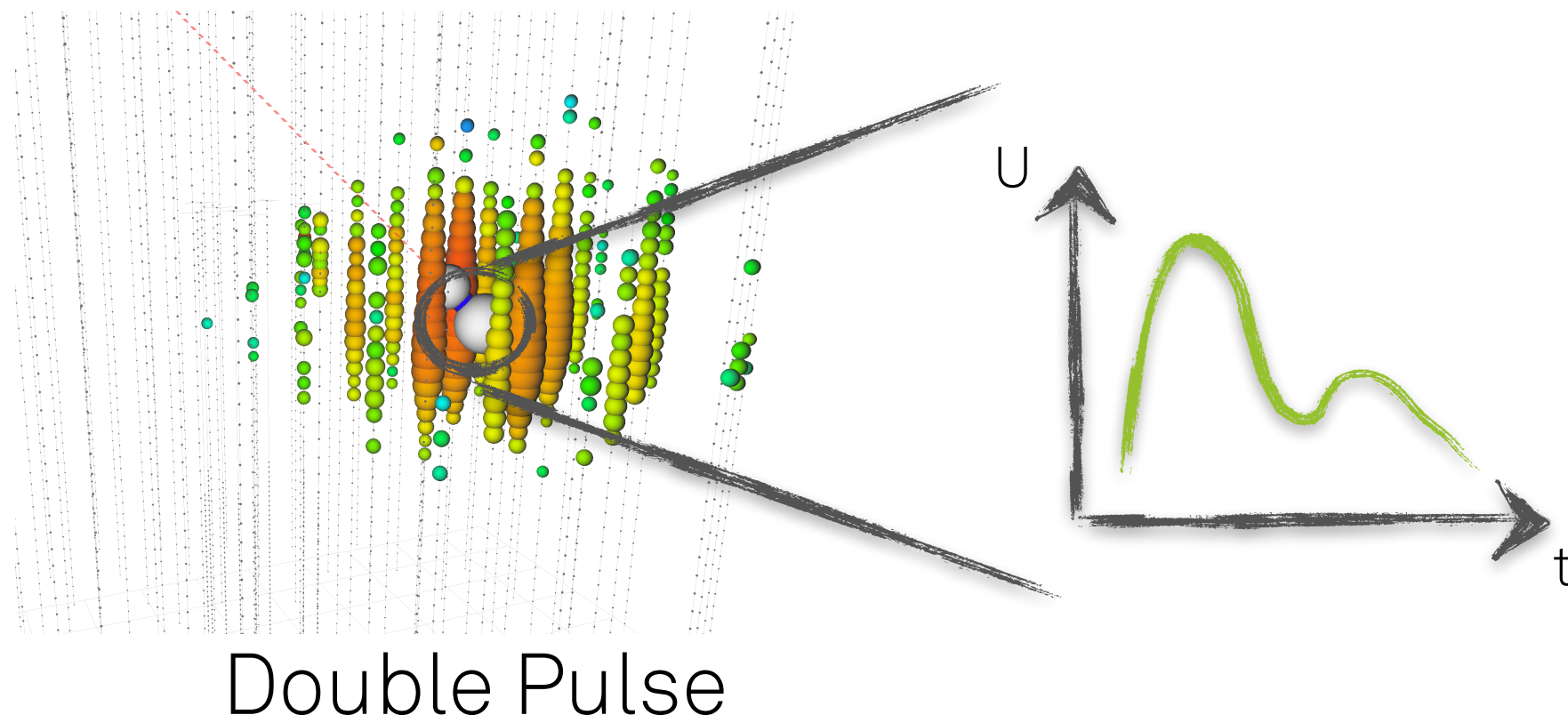
Neutrino Alerts

Astrophysical tau neutrino measurement

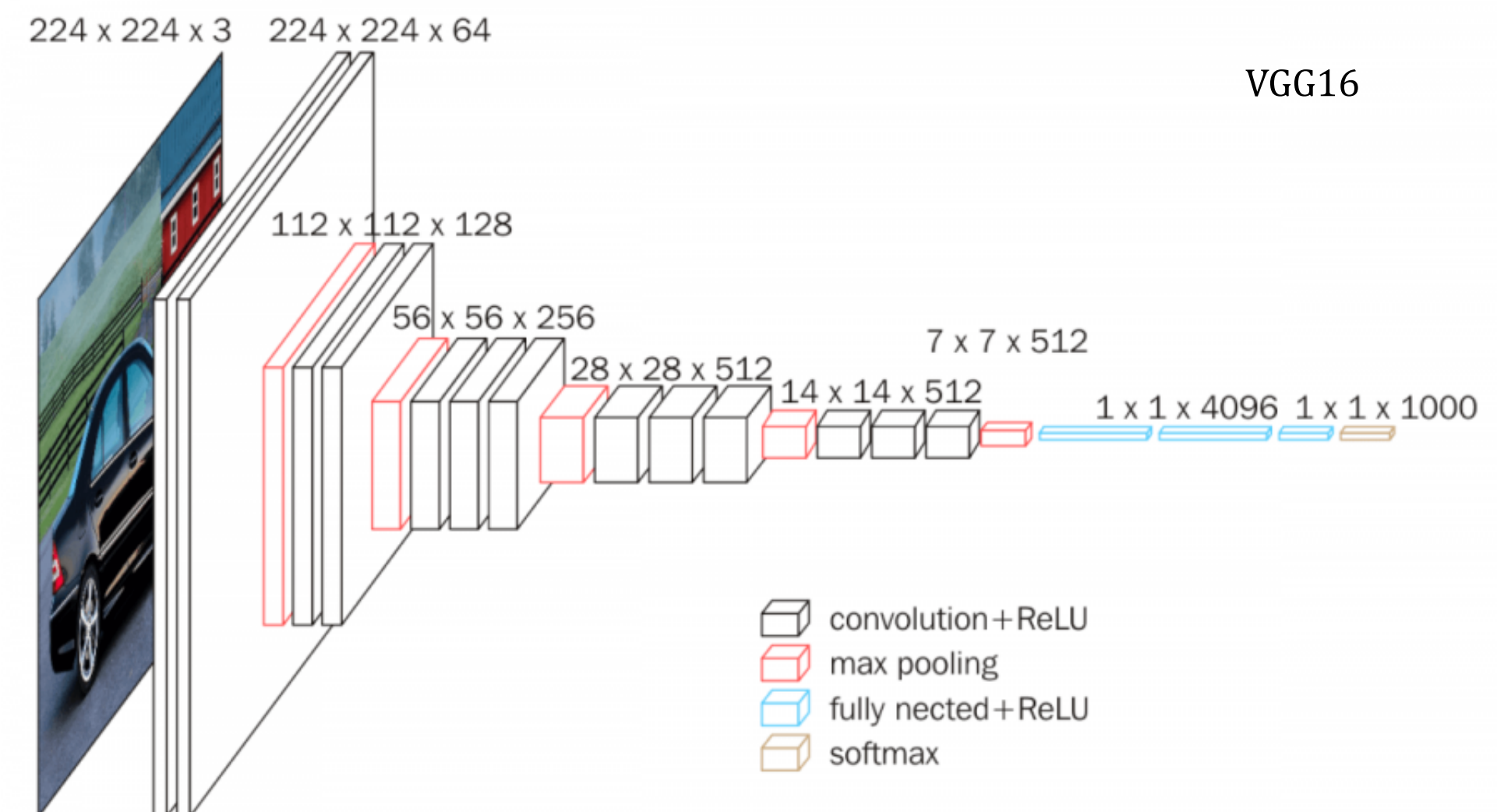


- High-energy tau neutrinos produce challenging signatures for IceCube
- Two overlapping cascades with small spatial separation: $\ell_\tau \simeq 50 \text{ m} \frac{E_\tau}{\text{PeV}}$
- Strongest signature in DOMs close to the cascade vertices
- Events are well described by images with each row represented by a waveform

Astrophysical tau neutrino measurement



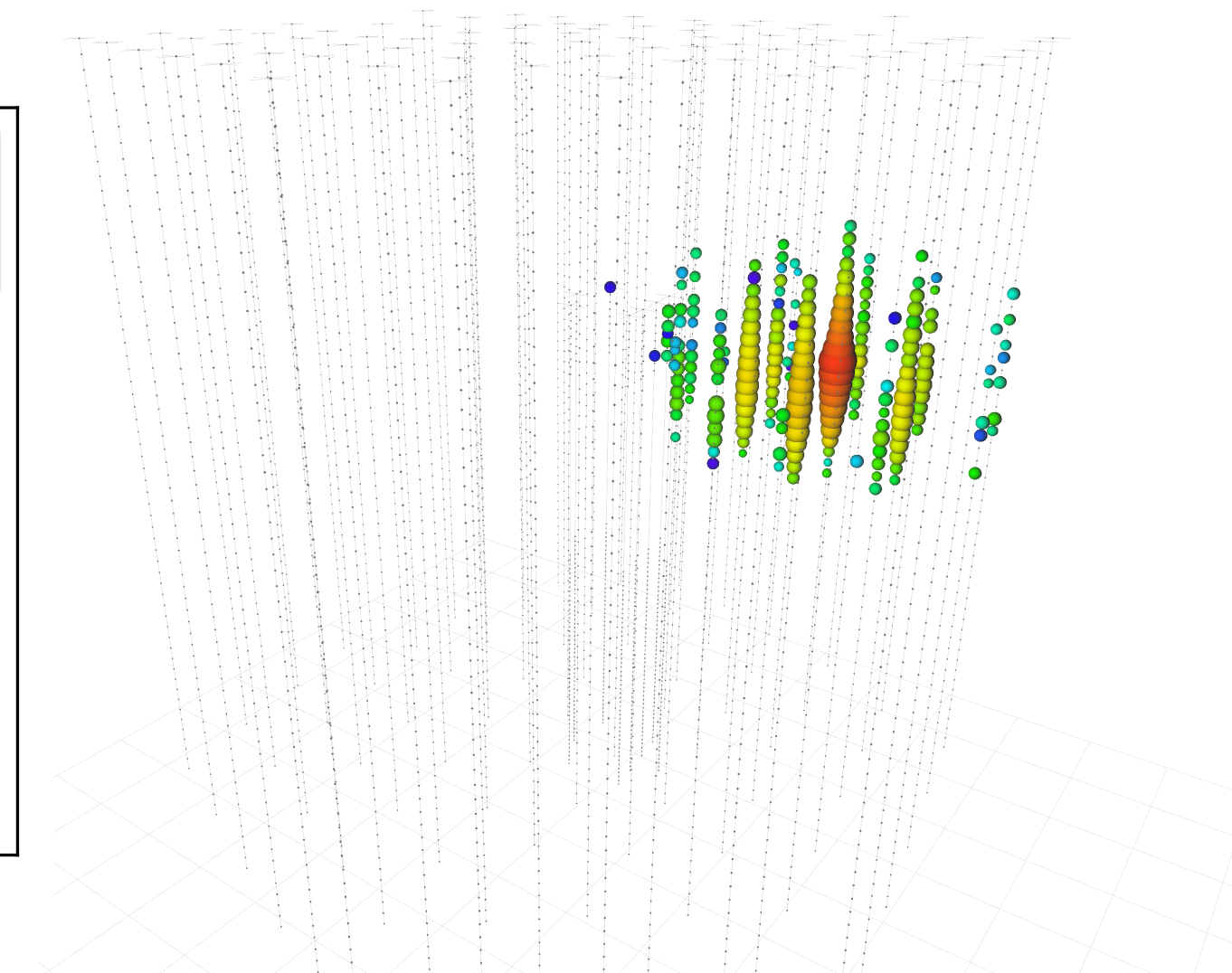
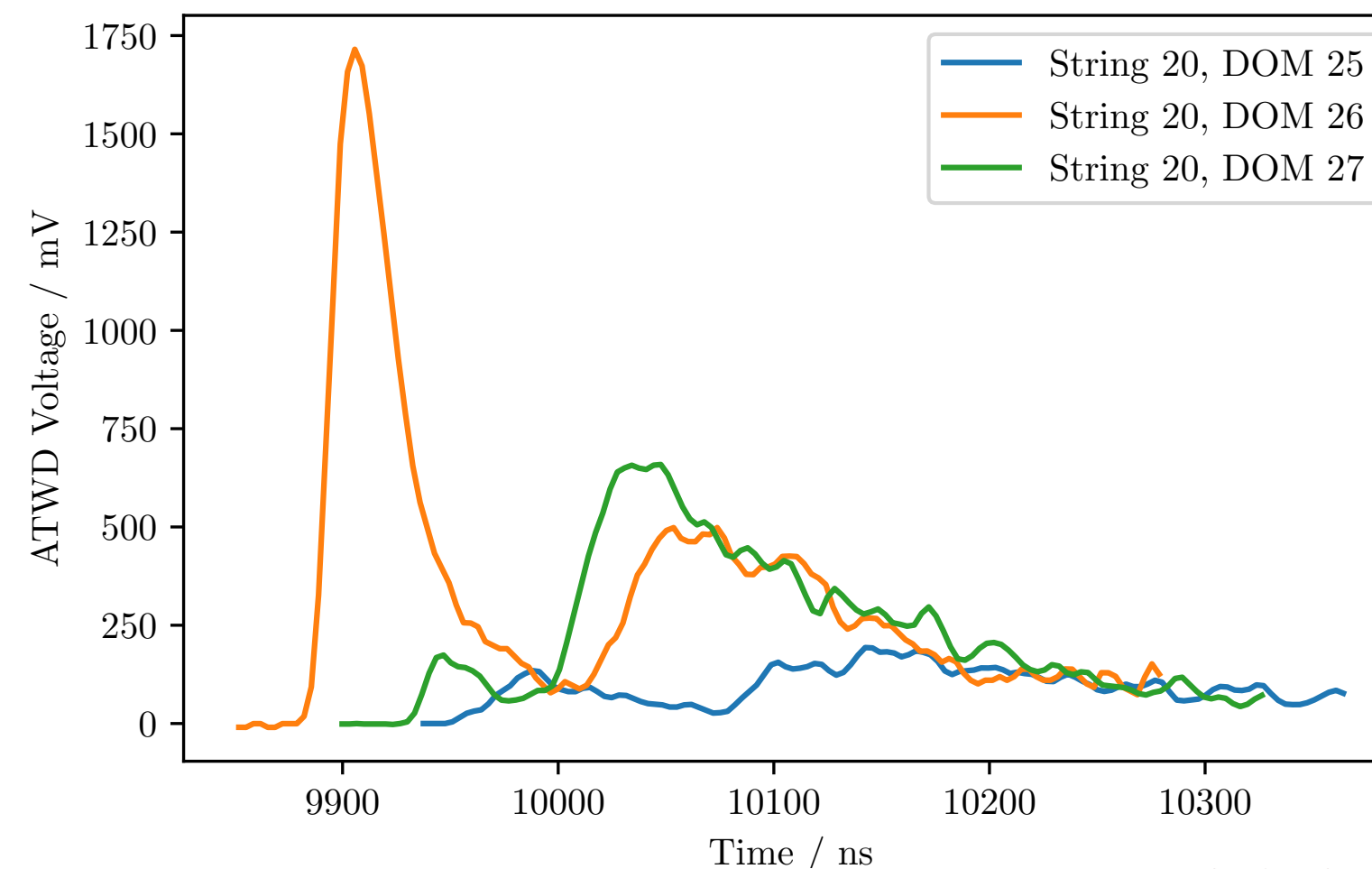
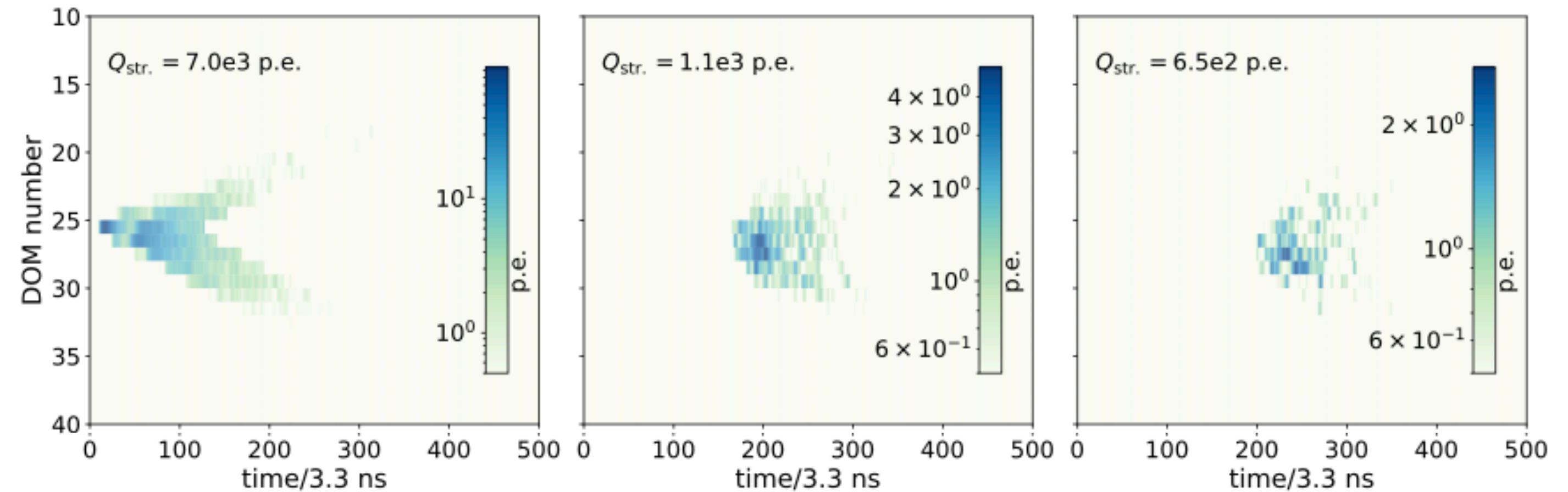
- Events are well described by images with each row represented by a waveform
- Utilize CNNs optimized for computer vision tasks to distinguish signal from background



Simonyan & Zisserman, 1409.1556

Astrophysical tau neutrino measurement

- Expecting 4-8 ν_τ events with a background of ~ 0.5 in almost 10 years
- Found 7 ν_τ candidates
- Excluding the absence of ν_τ in the astro flux with $> 5\sigma$
- Detection of high energy ν_τ is a powerful confirmation to IceCube's detection of astrophysical neutrinos
- Allows flavour measurements to study neutrino production in their astrophys. sources



Neutrinos from the Galactic Plane

Astrophysical tau neutrinos

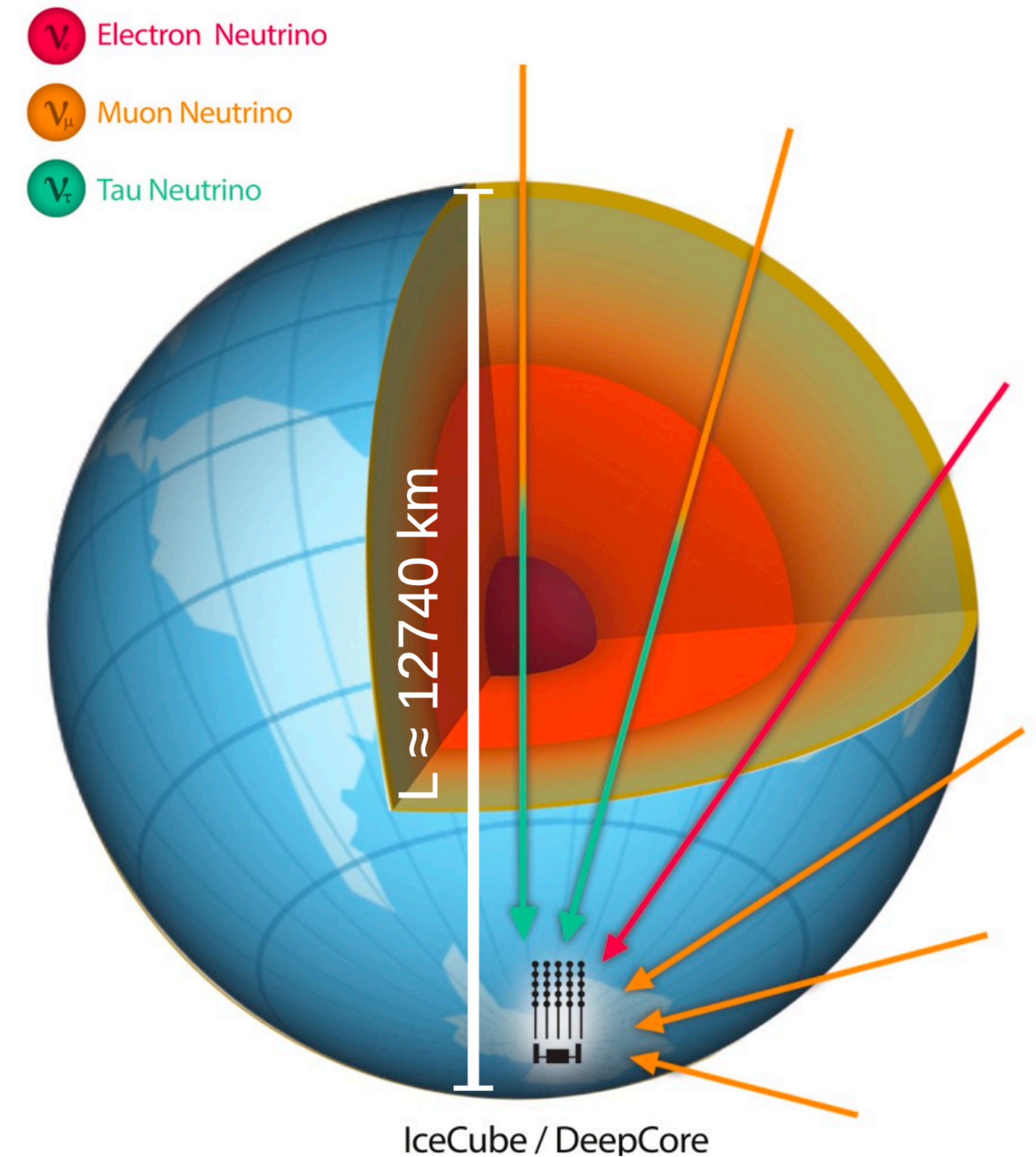
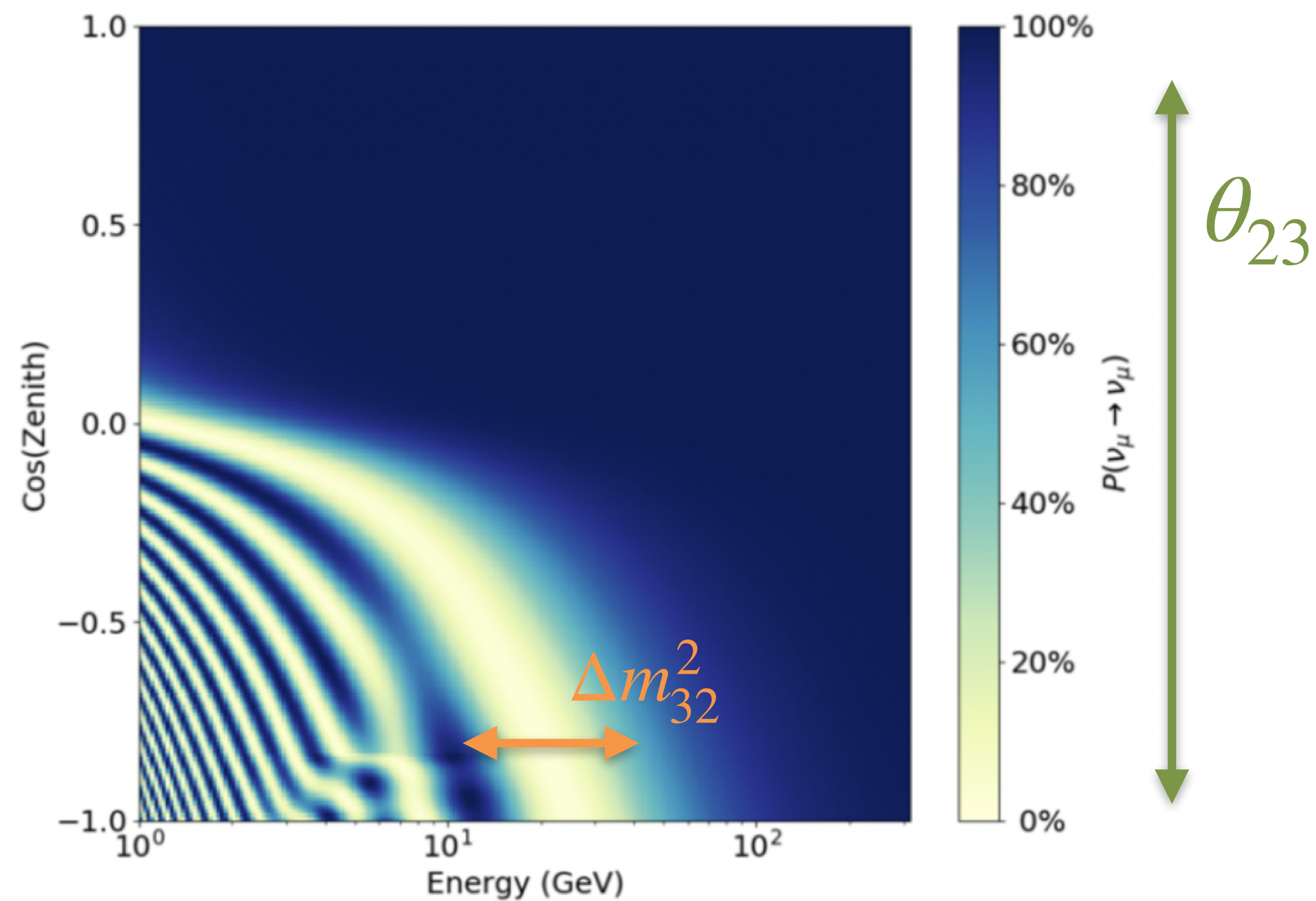
Neutrino Oscillation measurement

Neutrino Alerts

Neutrino Oscillations — ν_μ disappearance

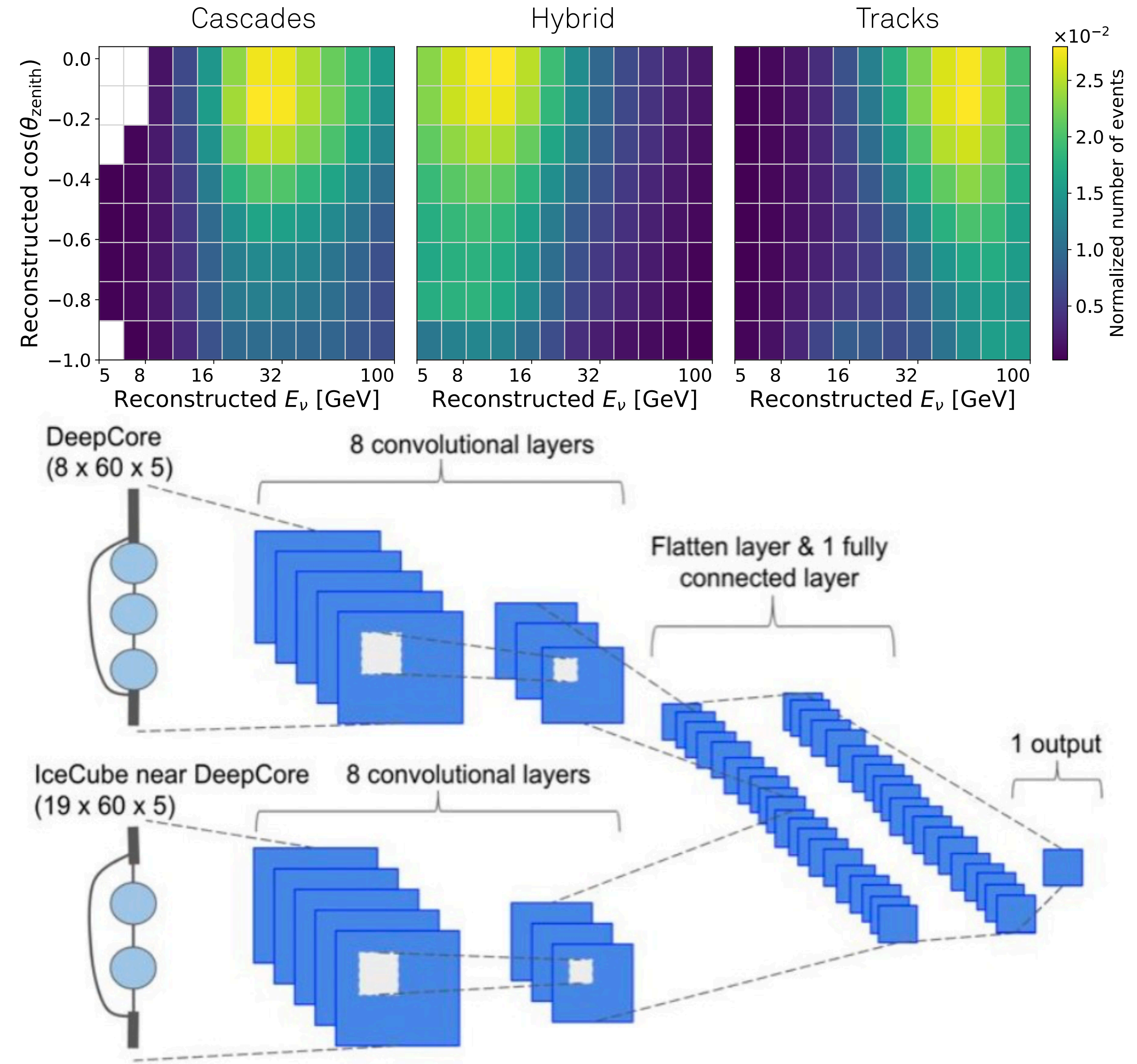
- Leading term — vacuum oscillations

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m_{32}^2 \frac{L}{E}\right)$$



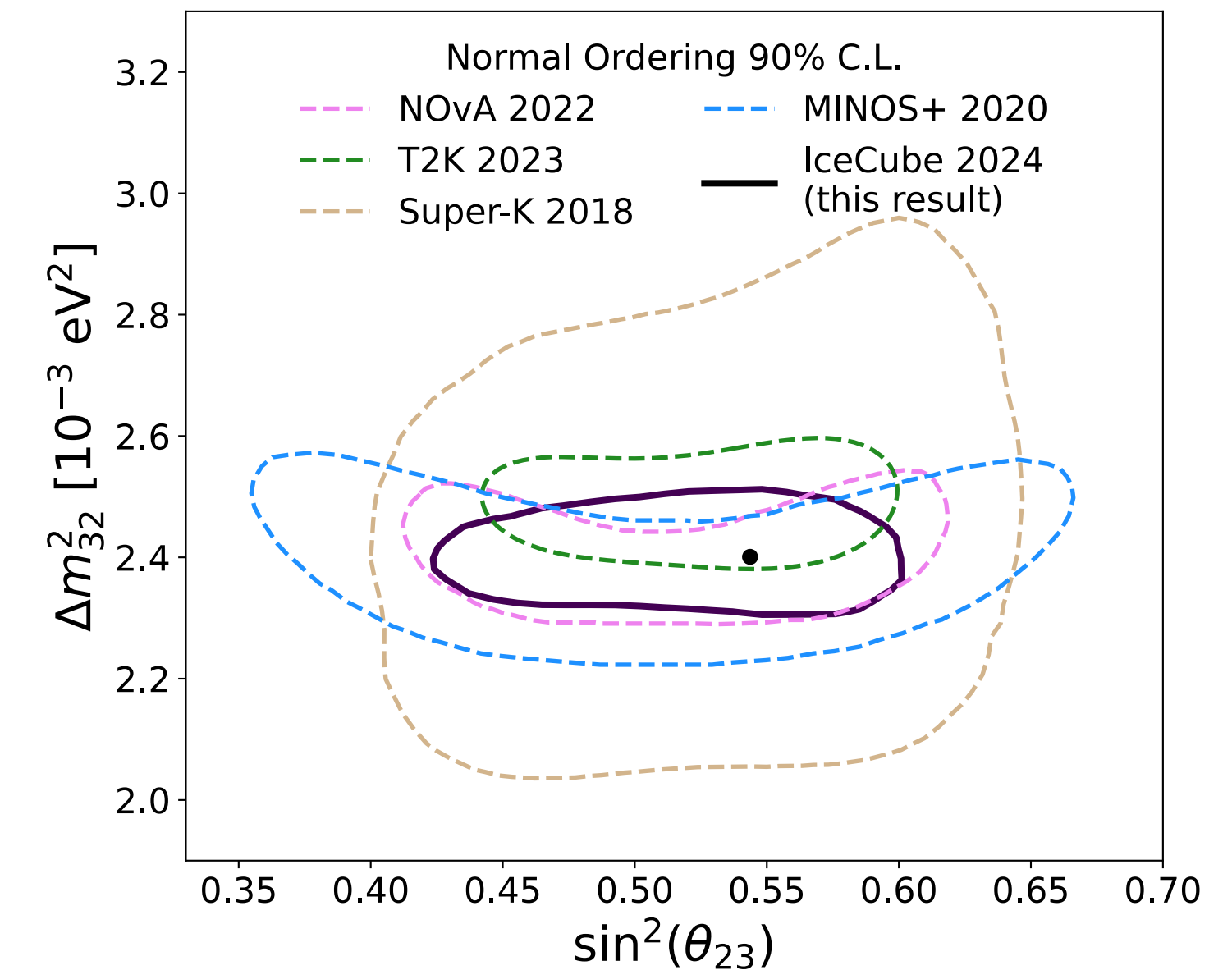
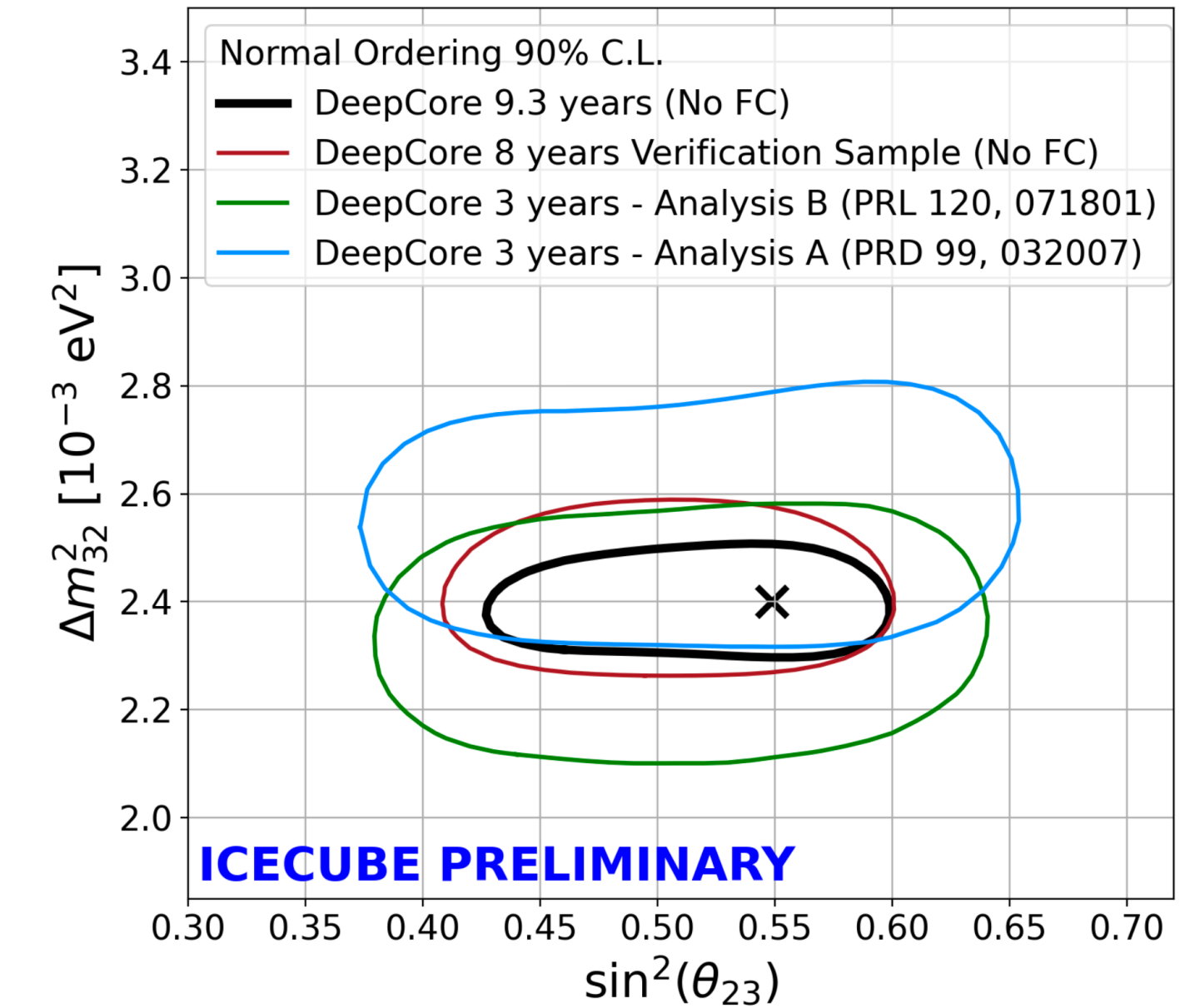
Neutrino Oscillations — ν_μ disappearance

- Analysis strategy
 - Oscillation parameters fitted using histograms binned in reconstructed energy and zenith
- 5 CNNs employed for specific tasks
 - Particle identification (PID)
 - Atm. μ rejection
 - Energy reconstruction
 - Angular reconstruction
 - Vertex position
- Processing time for events decreased by a factor of 5000



Neutrino Oscillations — ν_μ disappearance

- High statistics and high purity
 - 150.000 neutrinos → increased by a factor of 5 to prev. selection
 - > 99 % purity
- Competitive with long baseline accelerator experiments
- Complementary to accelerator measurements
 - probes higher energies
 - deep inelastic scattering regime
 - above τ lepton production threshold
 - different systematics
- New analysis underway introducing Graph Neural Networks (GNNs)



Neutrinos from the Galactic Plane

Astrophysical tau neutrinos

Neutrino Oscillation measurement

Neutrino Alerts

Attention for High-Energy Neutrino Alerts (ATHENA)

- Transformer-based model to reconstruct high-energy neutrinos

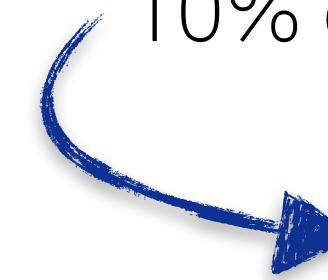
- Multi-task model reconstructs

- Energy (at entrance and deposited)
- Direction
- Position
- Topology (starting and trackness)

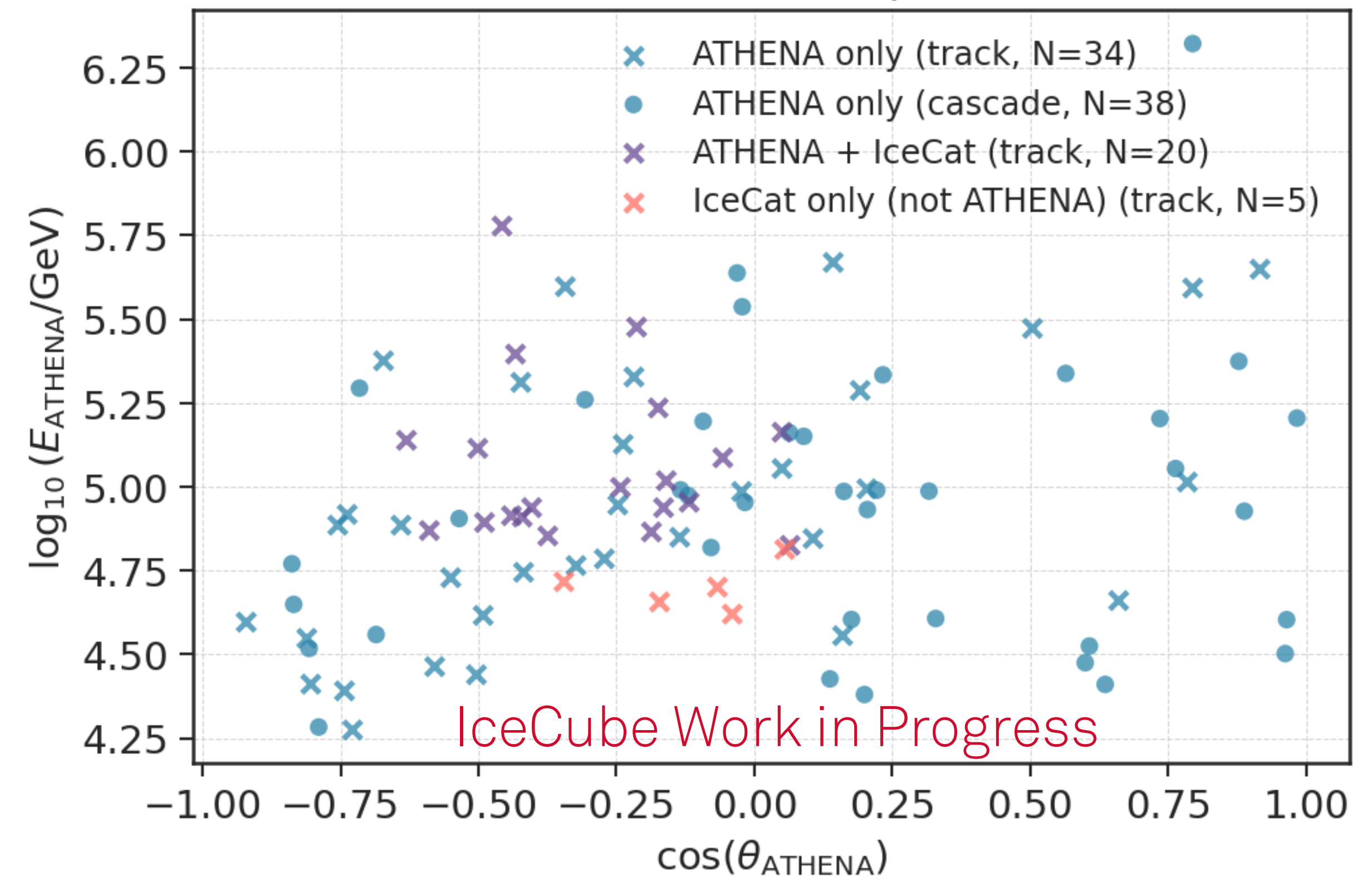
- Goal:

- Build a new event selection with robust directional reconstruction for neutrino alerts
- Increasing number of neutrino candidates for multi messenger observations
- Opens up the Southern sky for IceCube alerts!
- Naturally also expands to cascades

Initial consistency checks on
10% of the data



ATHENA vs. IceCat-2 burn events (x = track, o = cascade)

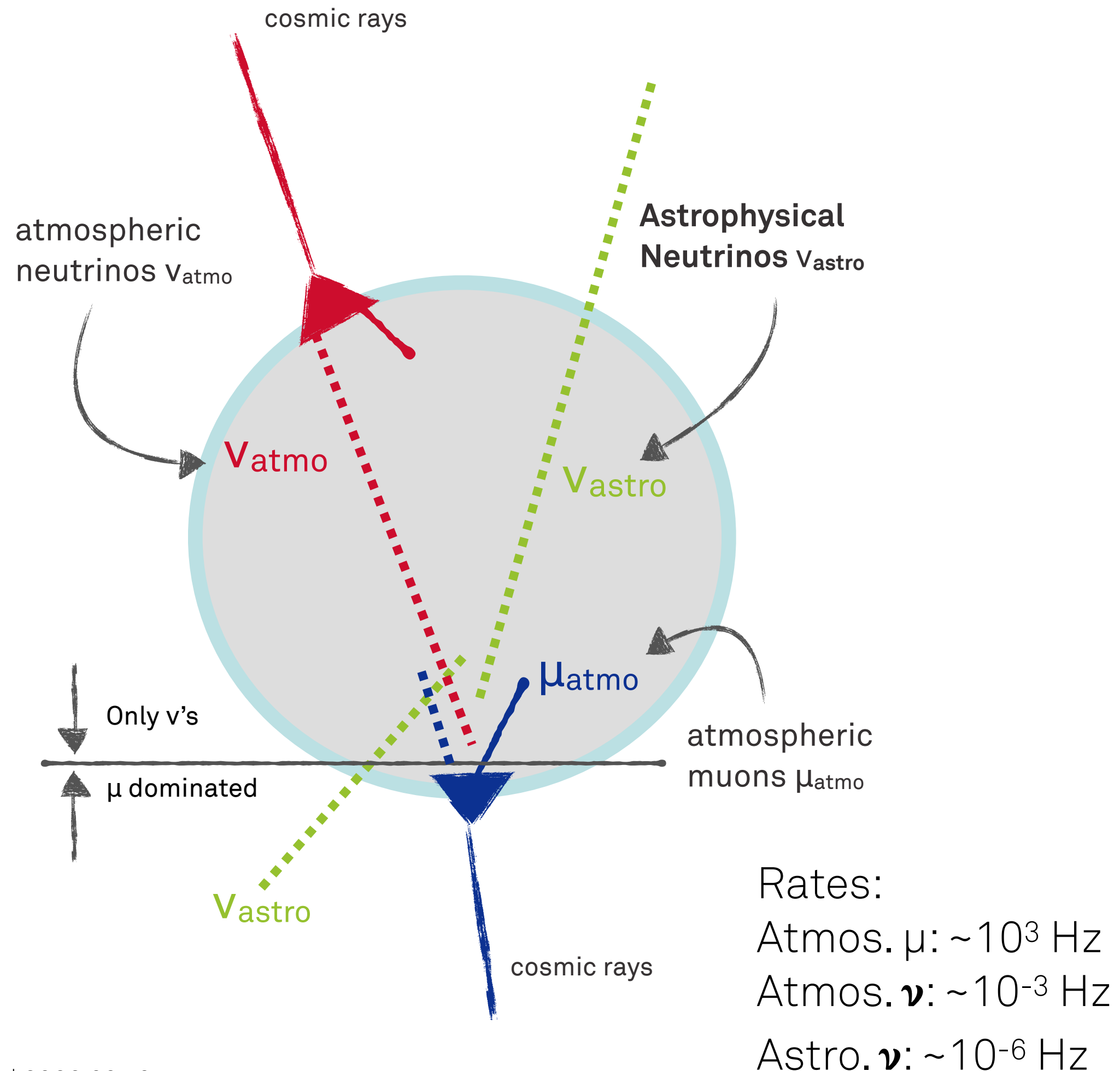


Summary/Outlook

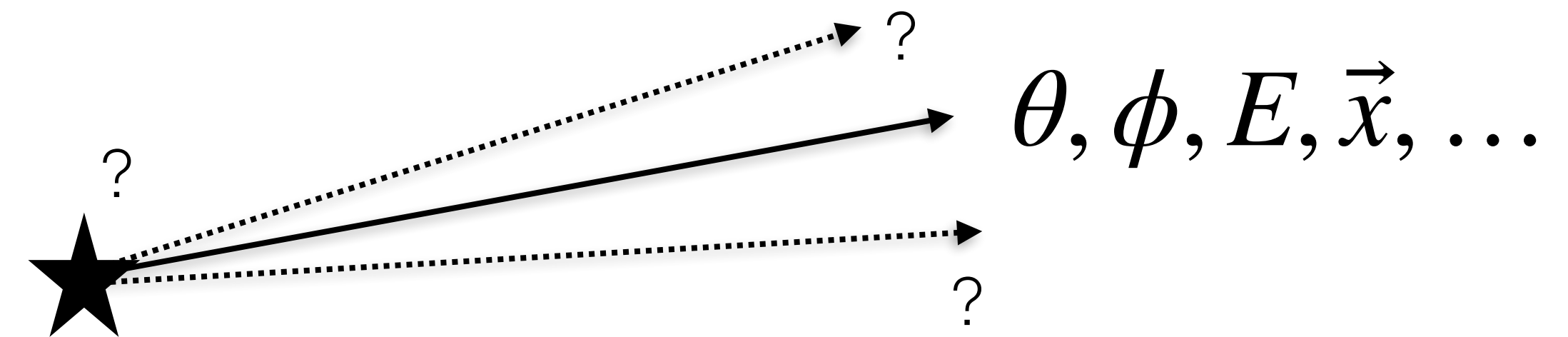
- IceCube is a data-analysis-driven experiment
- ML models have become an integral part of many physics analyses
- Moving from simple models trained on high-level features towards complex, multi-purpose models based on low-level data
- Enhancing the physics reach of analyses in diverse areas of IceCube's physics program
- Only covered a subset of the ML efforts
- Many not-yet-public developments

Main Reconstruction tasks

Event Selection and Classification

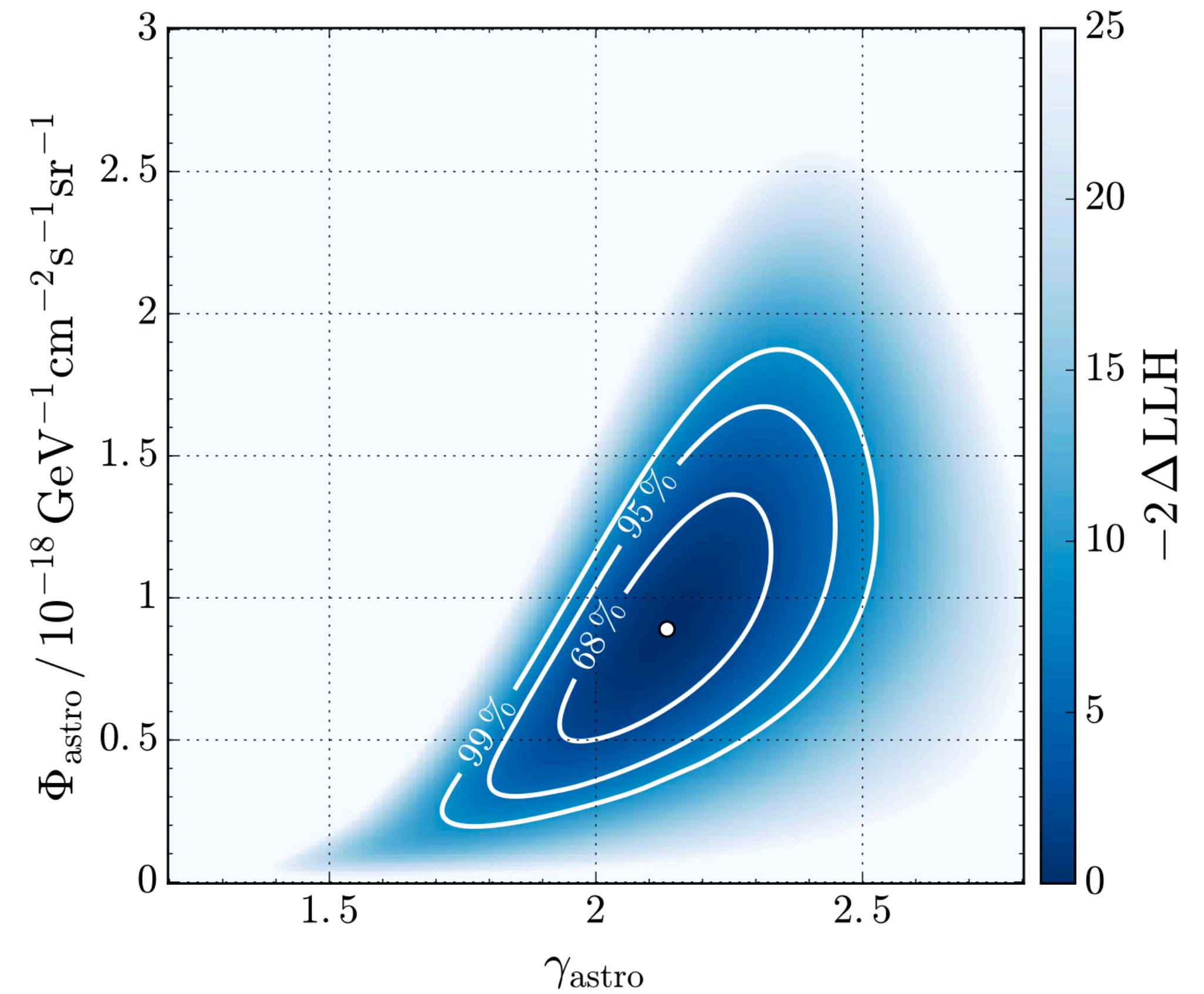
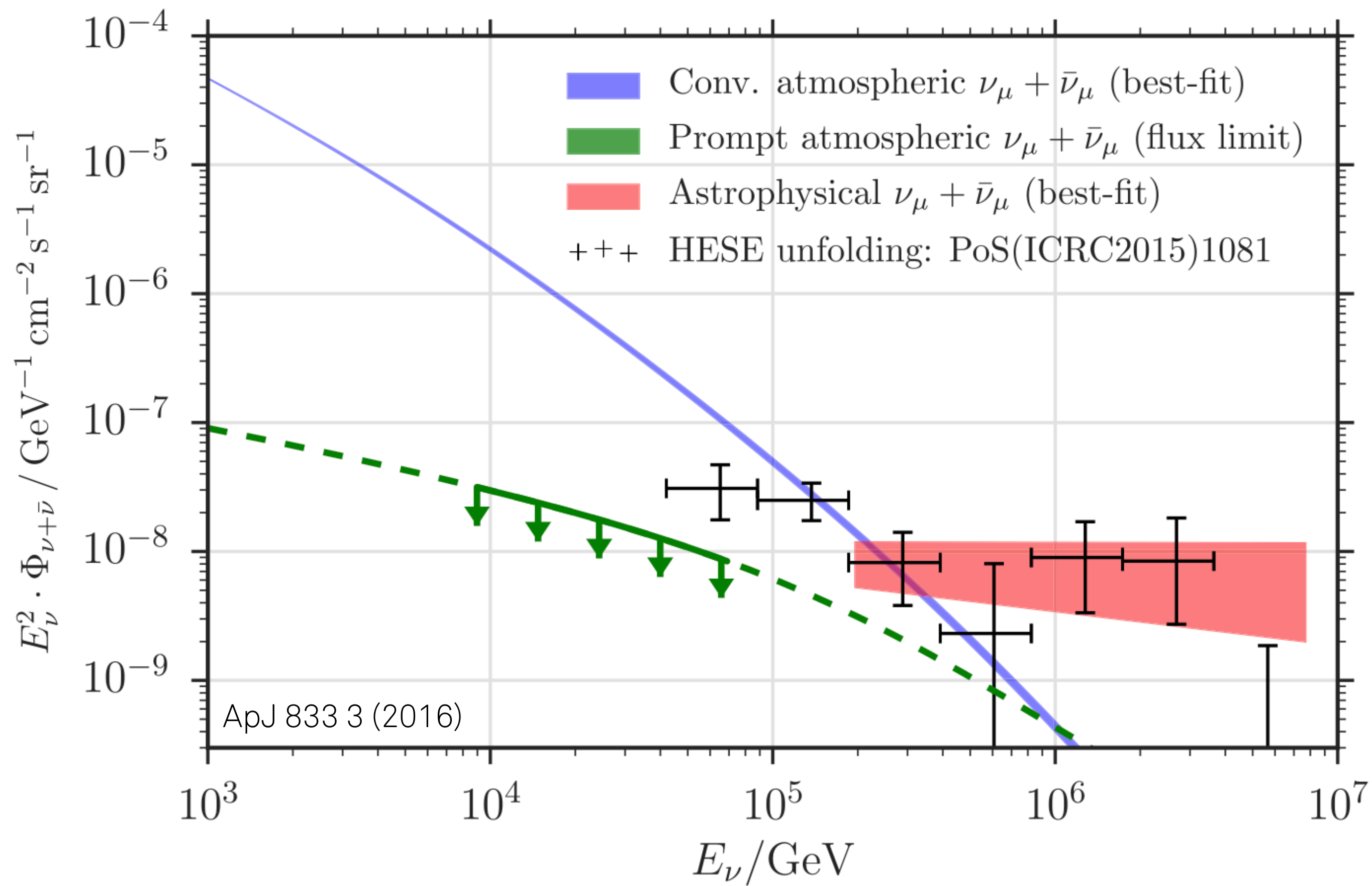


Event Reconstruction



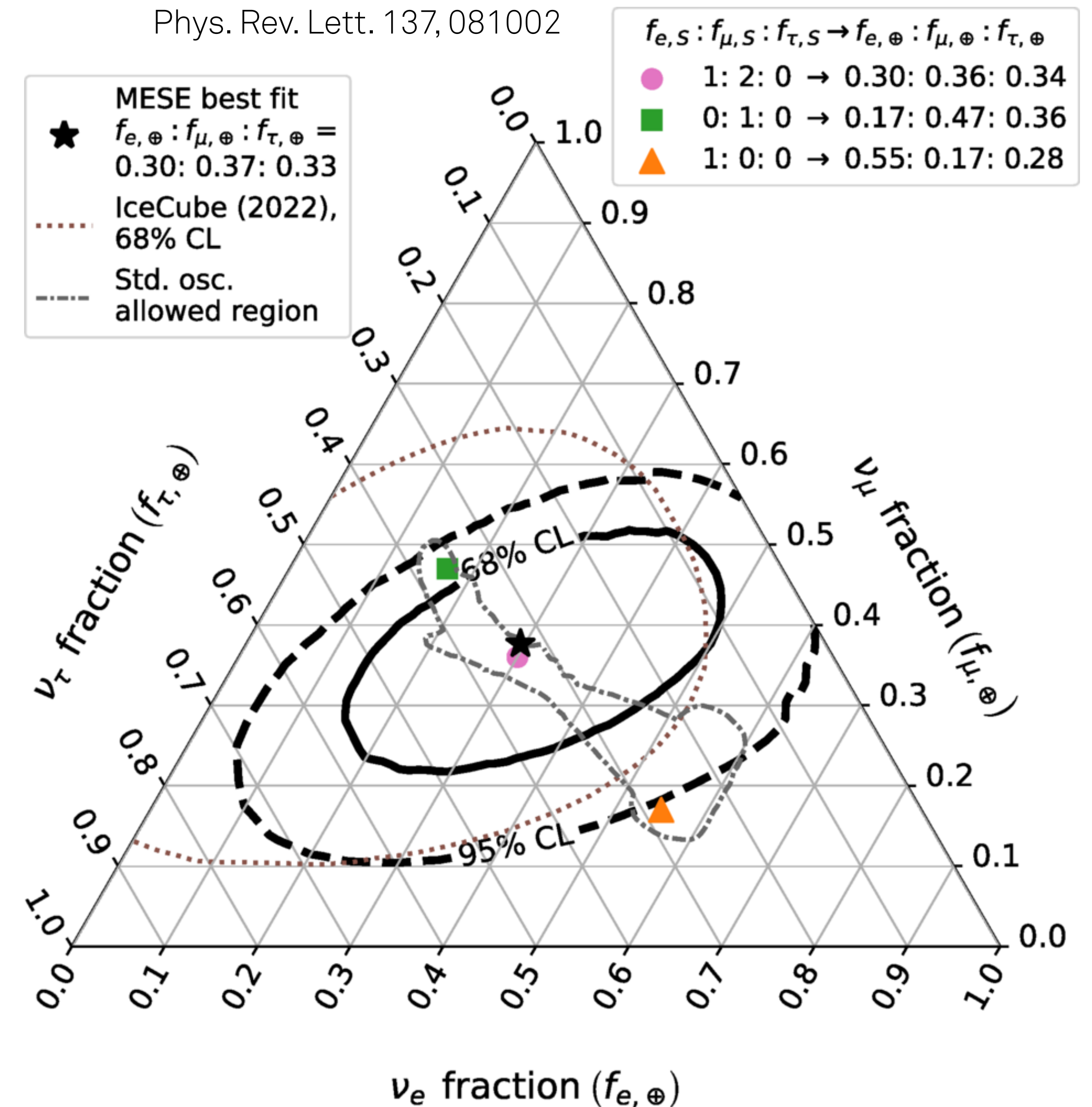
Uncertainty Estimation

Northern Tracks (2016)

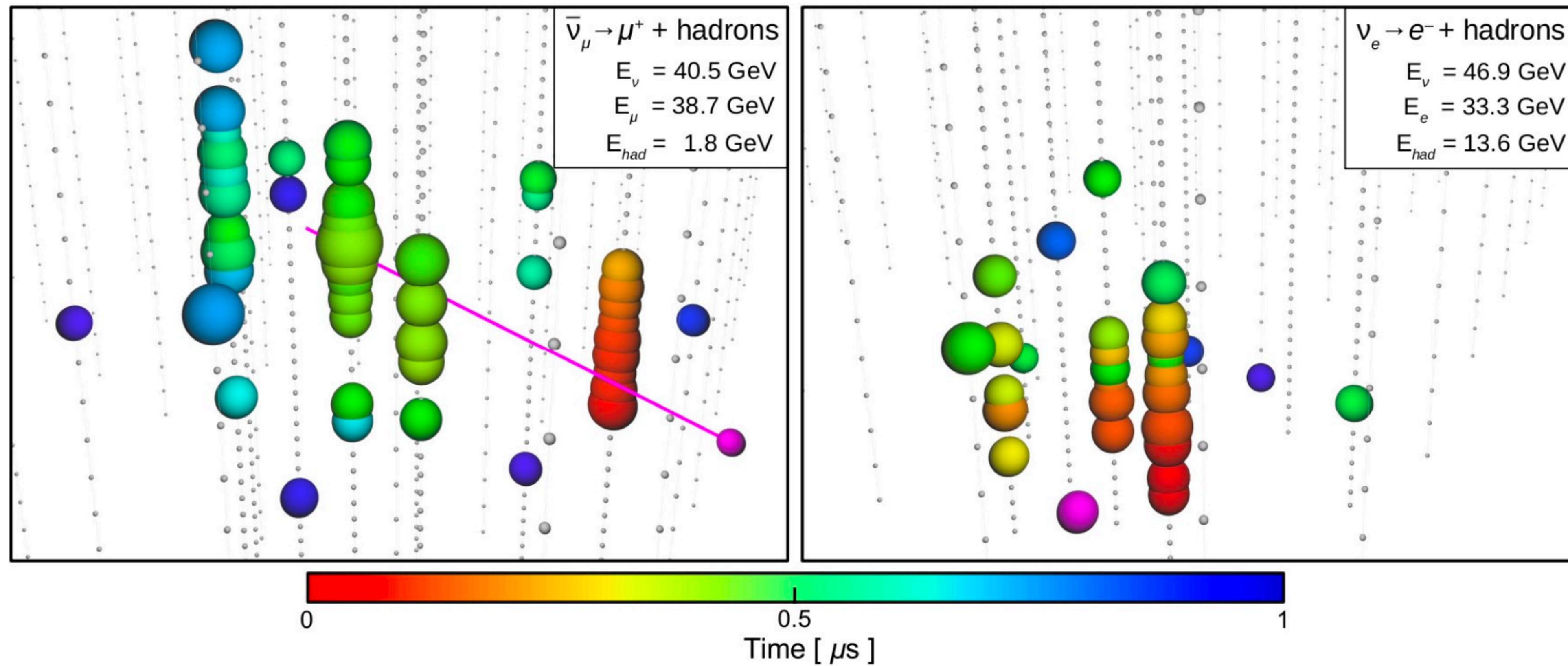


Flavour measurement

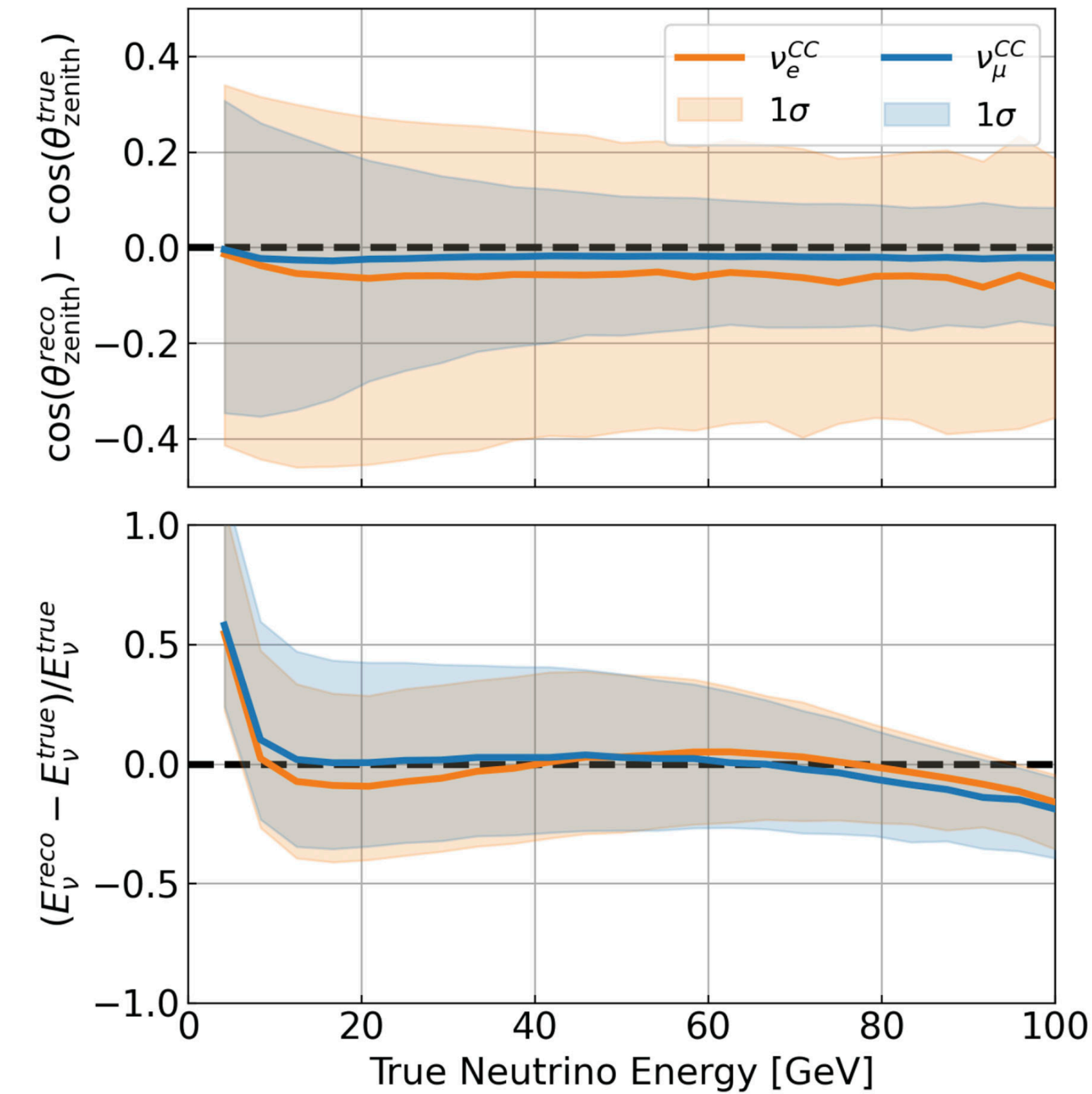
- Using starting events sample
- Sort starting events into three classes
 - Tracks
 - Cascades
 - Double cascades
- Fit the contribution of each neutrino flavour to the astrophysical flux separately
- First time to constrain the fraction of each flavour to be non-zero at 68% CL
- Exclude neutron-decay scenario at ~95% CL



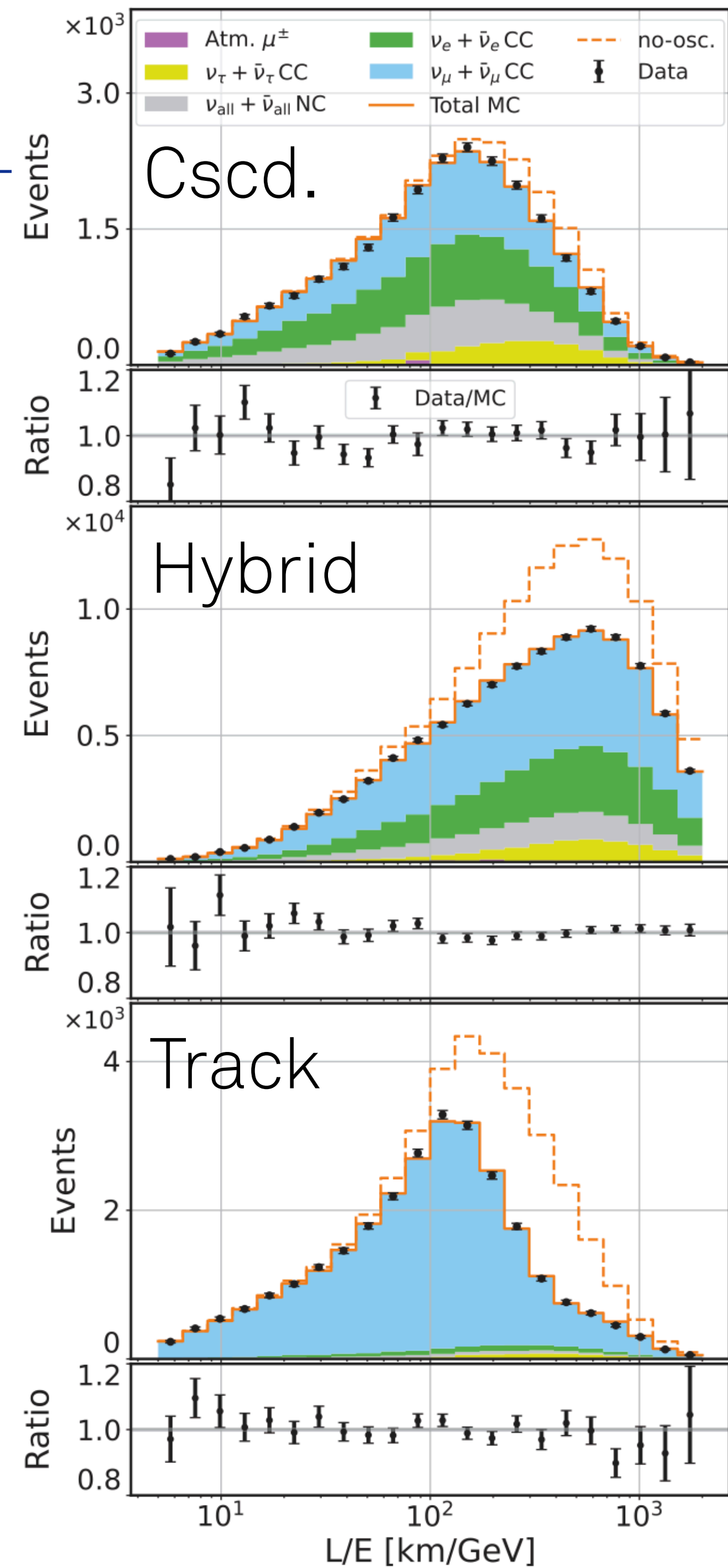
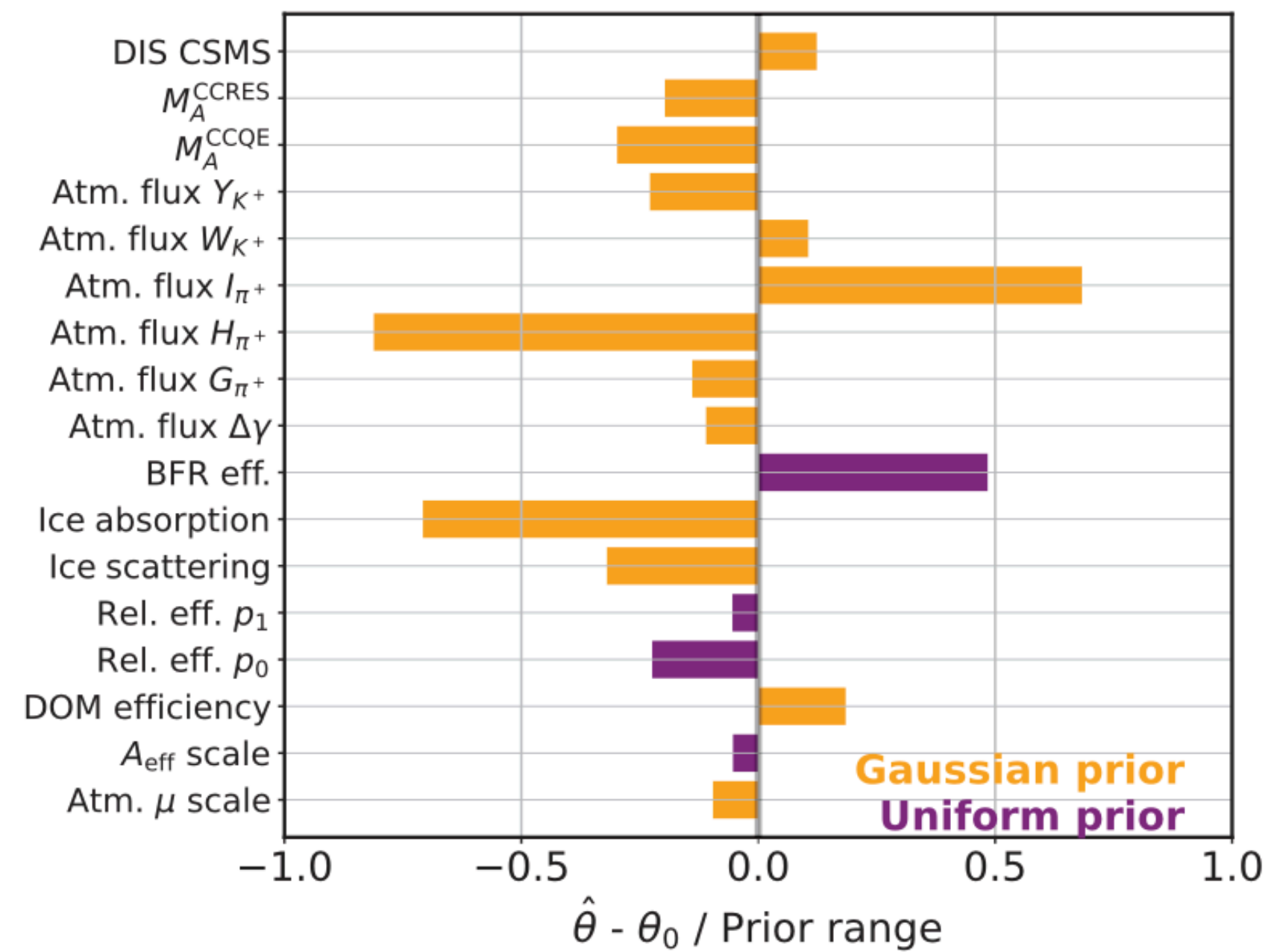
Low energy event topologies



Neutrino Oscillations



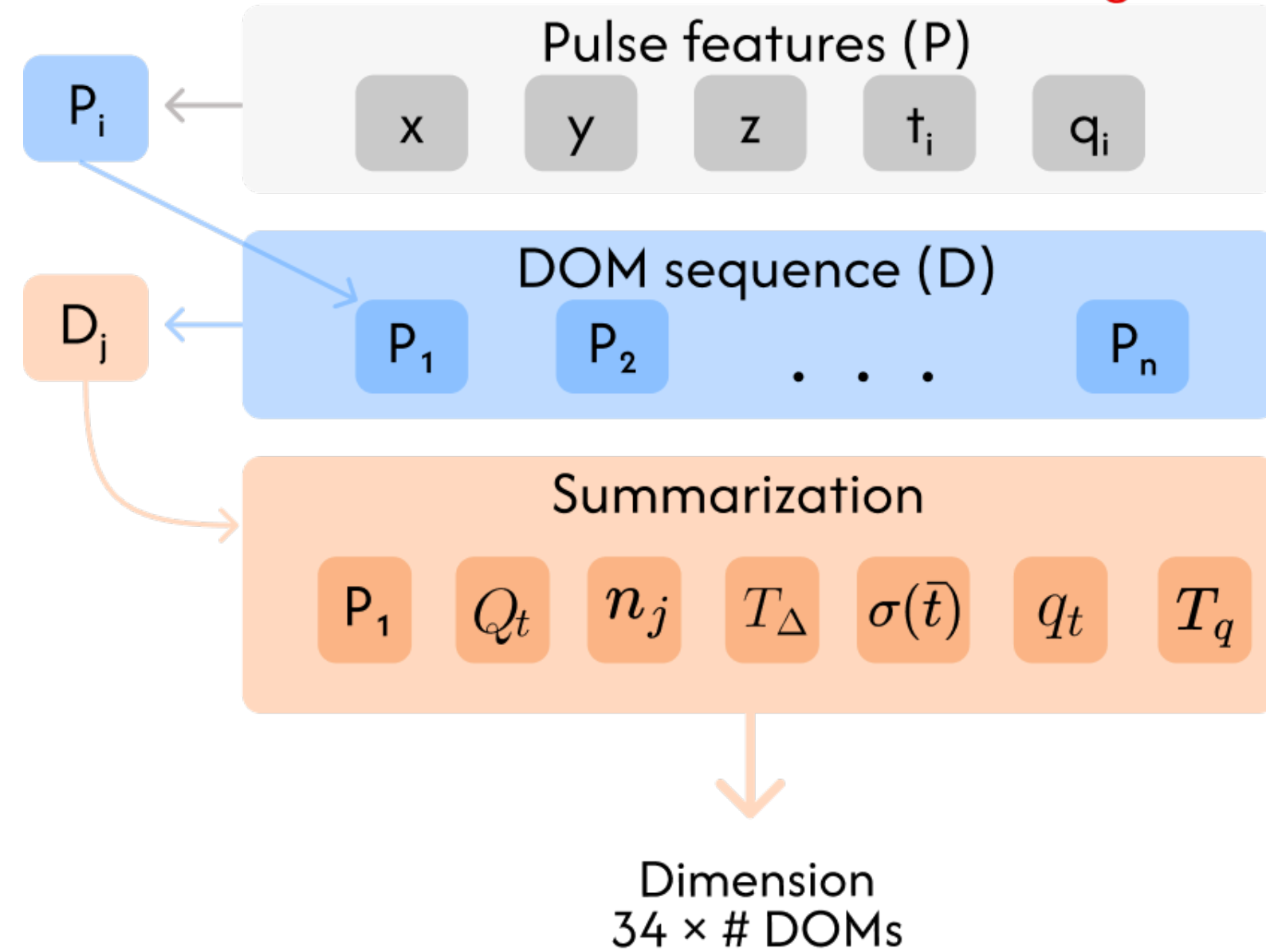
	$N_{\text{events}}(9.3 \text{ yr})$	% of MC sample
ν_μ CC	88 306	58.8
ν_e CC	35 296	23.5
ν_τ CC	8 772	5.8
ν NC	16 981	11.3
Atmospheric μ	917	0.6
Total MC	150 272	...
Data	150 257	...



Attention for High-Energy Neutrino Alerts (ATHENA)

Summarization of pulses

IceCube Work In Progress



n : number of pulses
per DOM

$$Q_t = \sum_{i=0}^{n_j} q_i$$

$$T_\Delta = t_n - t_1$$

$$T_q = \text{Timing at fraction of total charge}$$

$$q_t = \text{Charge after } t \text{ time}$$

$$\sigma(\bar{t}) = \text{time standard deviation}$$

Multi-task Transformer

IceCube Work In Progress

