Open-Source Tools for Neutrino Astronomy

Jeff Lazar
8th Symposium on Particle Physics and Cosmology
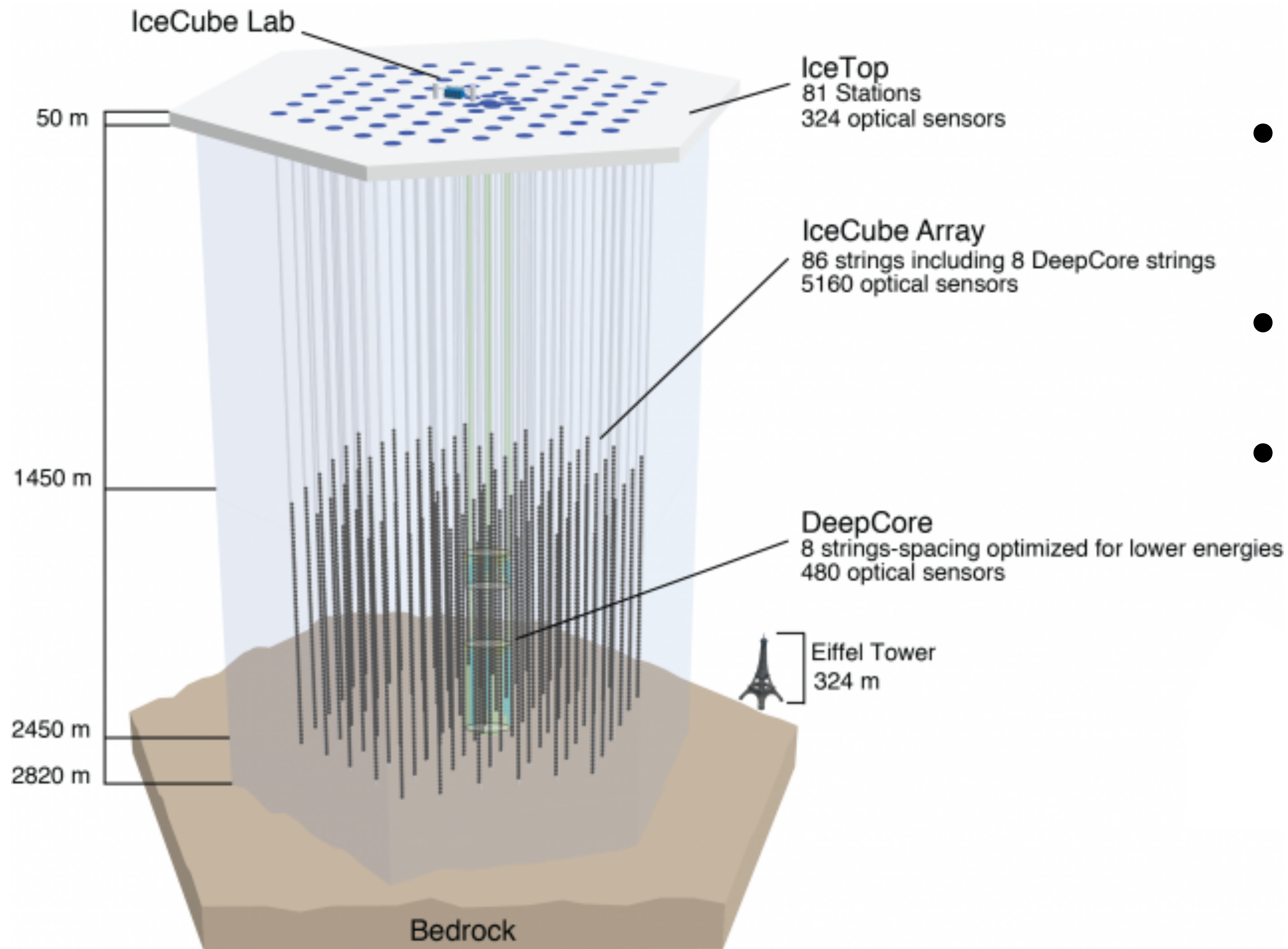**Shanghai, China**
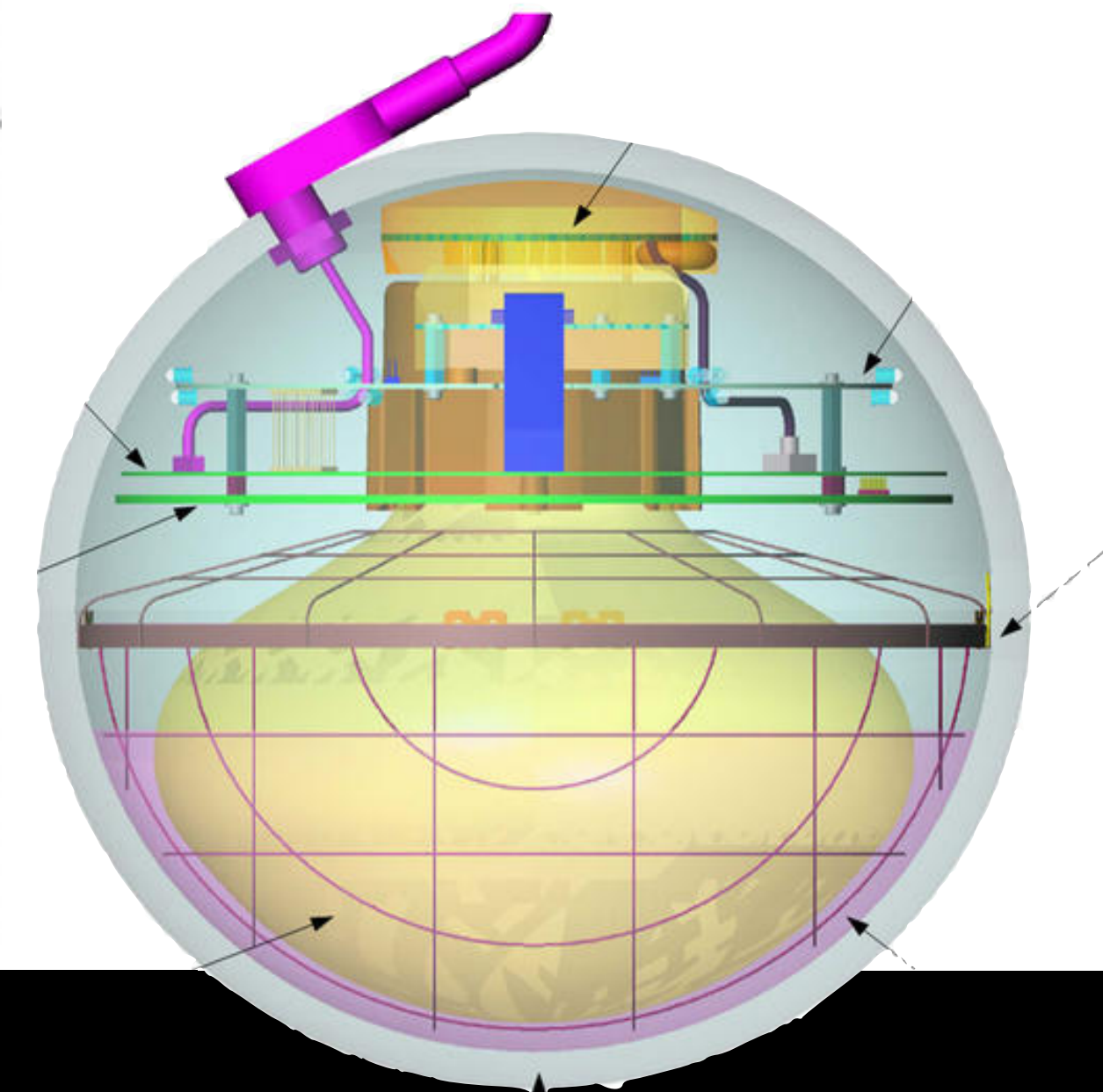**14 Nov., 2024**

UCLouvain

fnrs
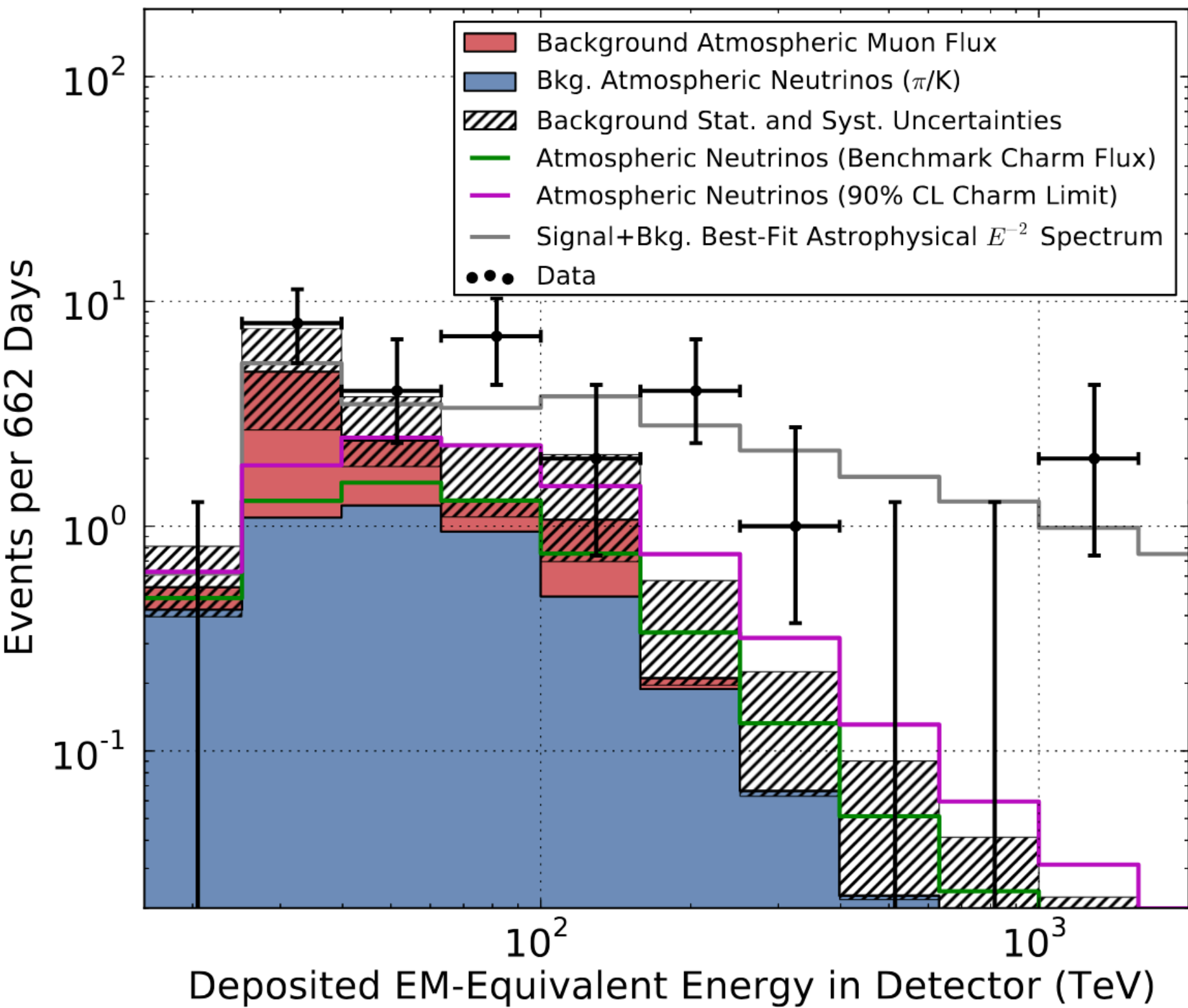FREEDOM TO RESEARCH

IceCube: The First Gigaton Observatory

- Gigaton scale detector of 5,160 light detecting digital optical modules (DOMs)
- Fully deployed and operational since 2012
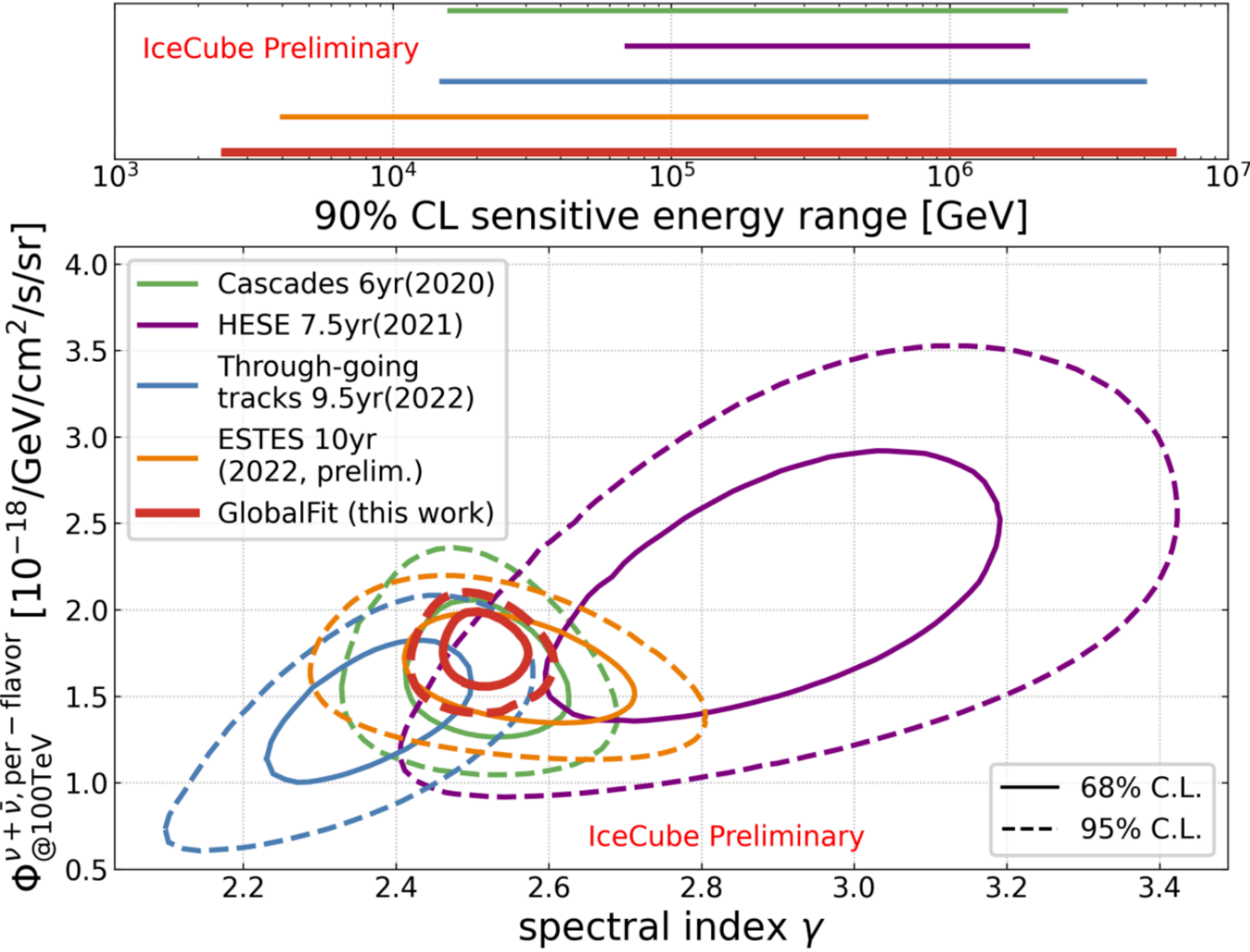- >99% up time in that time
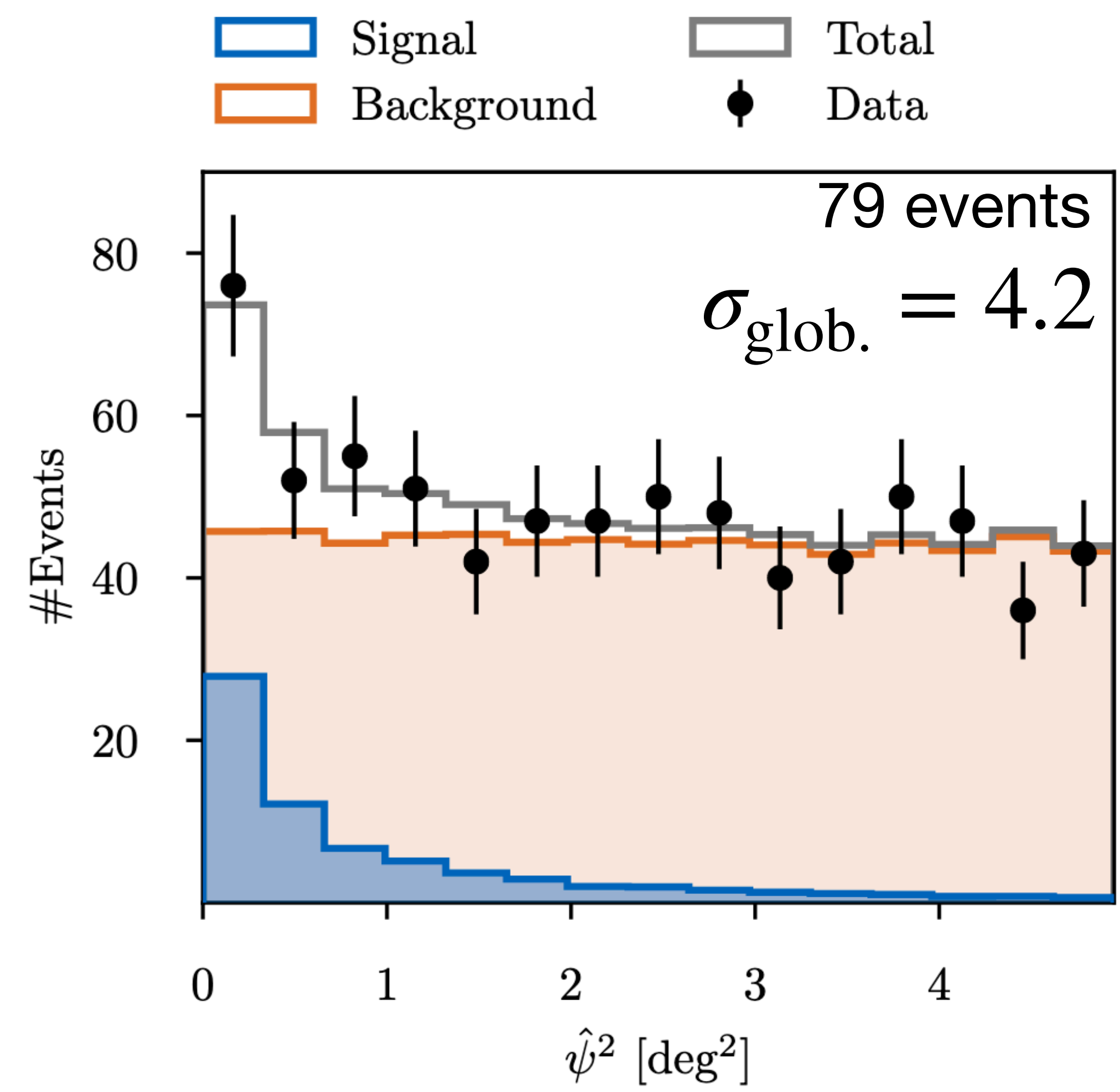
Progress, a Decade On

Diffuse neutrino flux

Progress, a Decade On

Neutrino sources

Progress, a Decade On

Particle physics
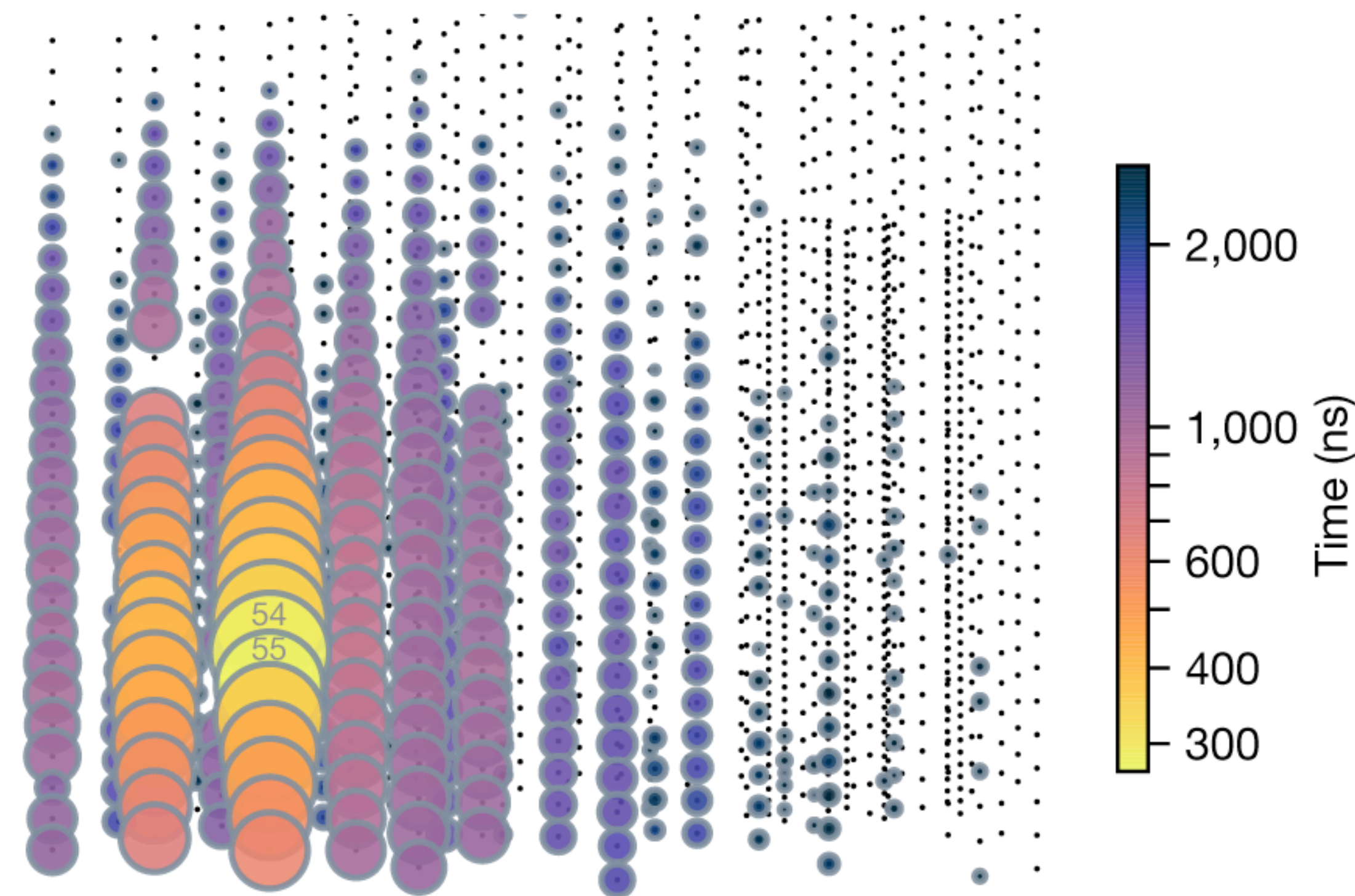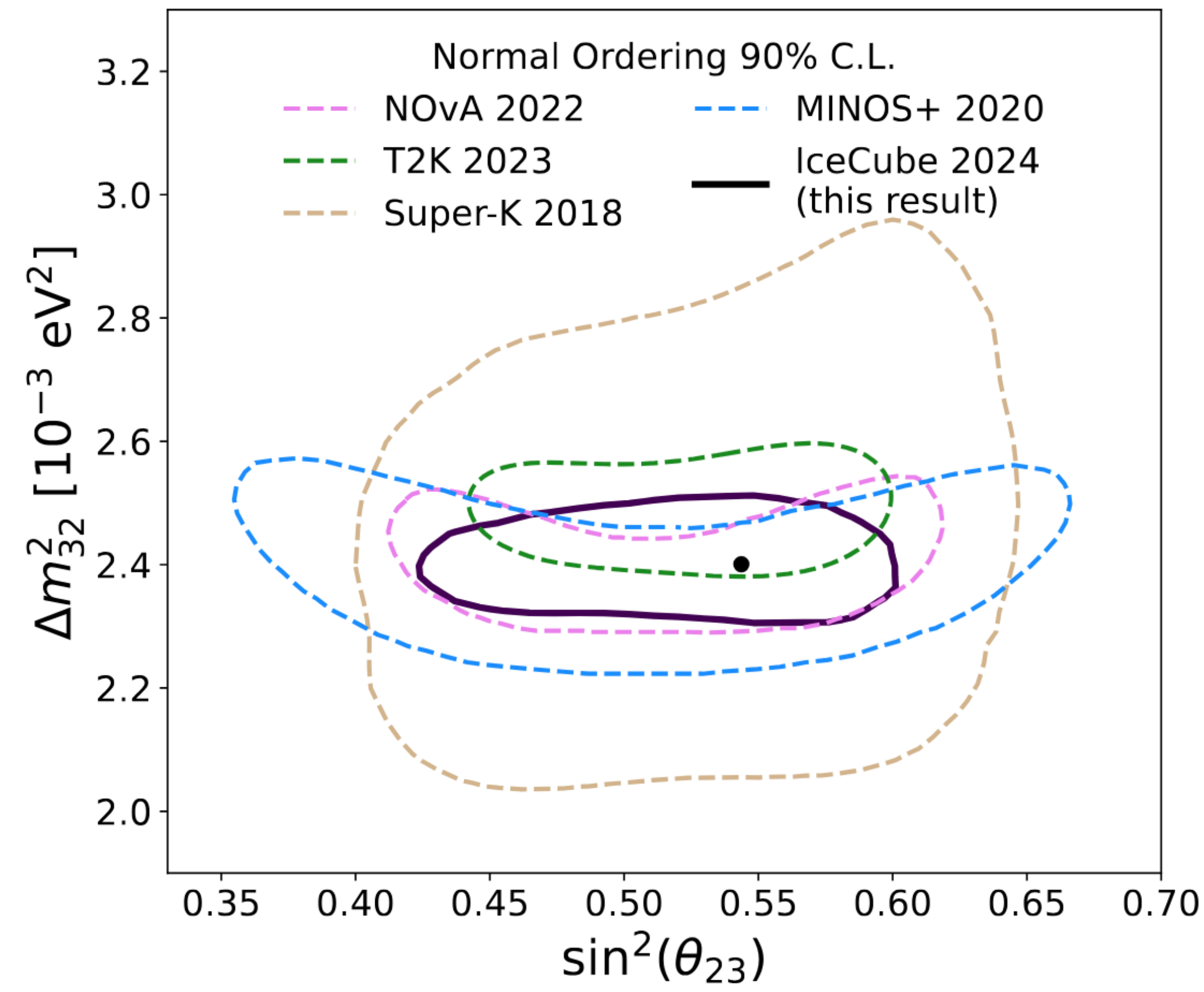
Entering a Multi-Detector Era
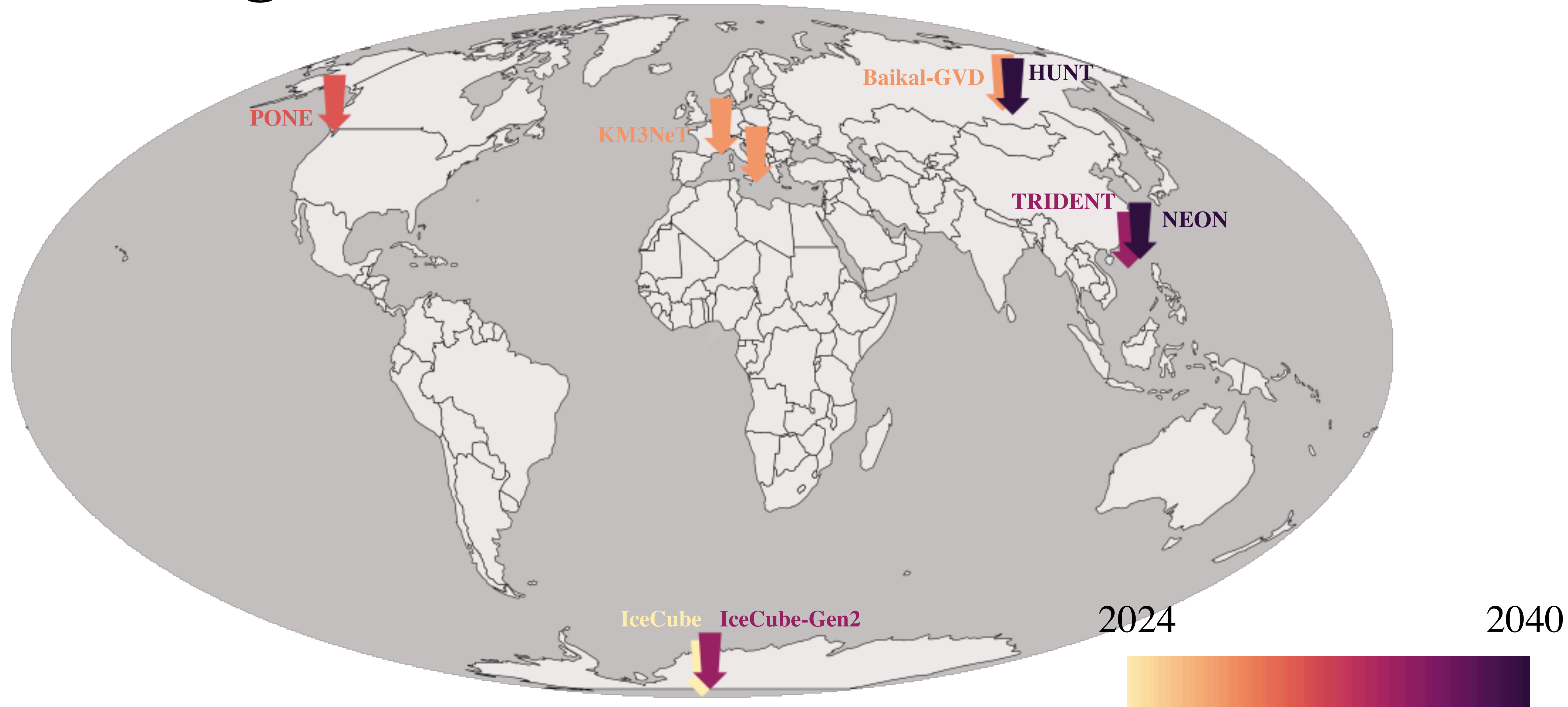
The future

Build bigger

Build different

Work together

Courtesy of M. Bustamente

The future

Build bigger

Build different

Work together

Courtesy of M. Bustamente

We Work Better When We Work Together

Schumacher, Agostini, **MB**, Oikonomou, *In prep.*

Courtesy of M. Bustamente
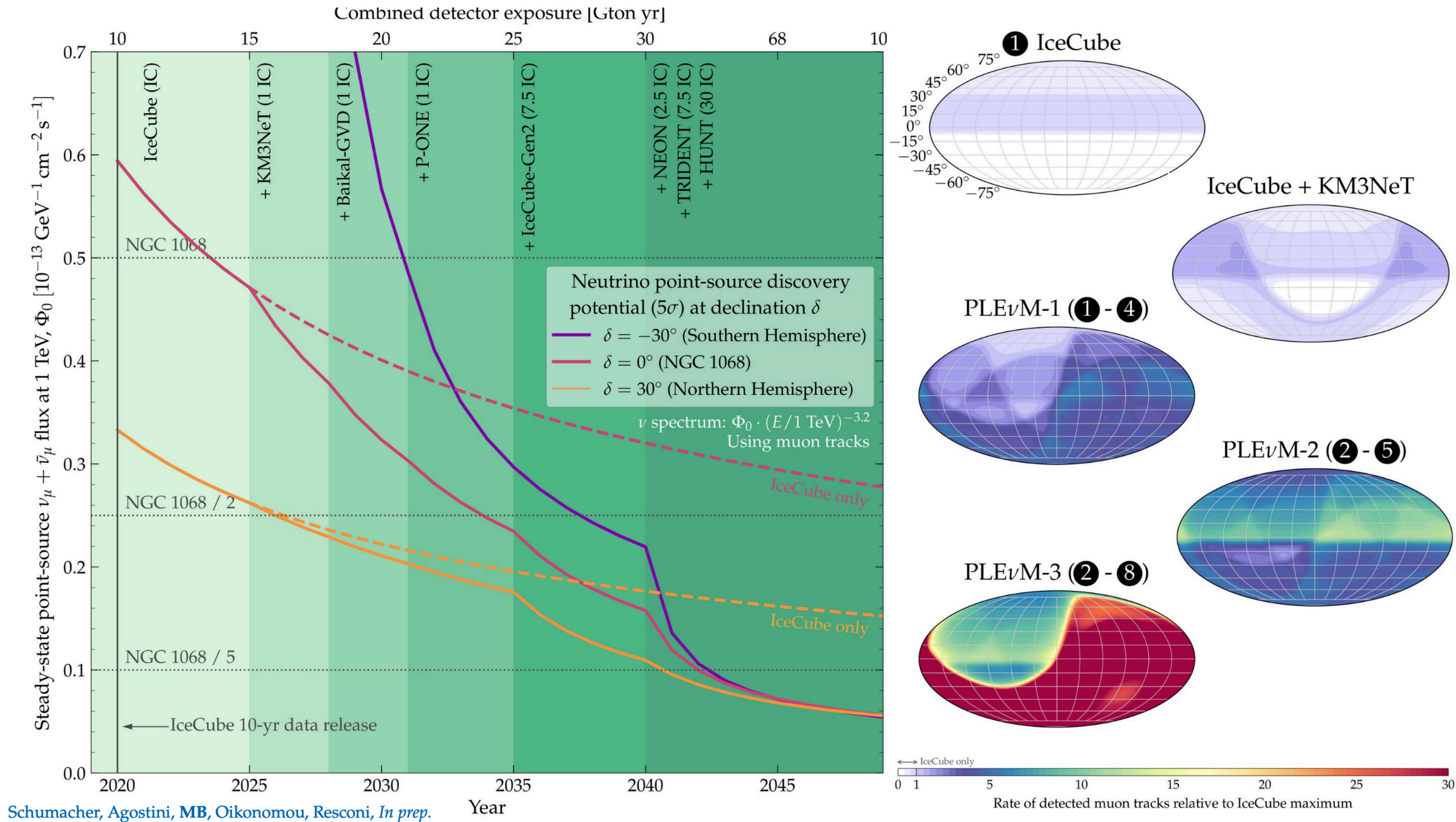
- When neutrino telescopes combine data, we dramatically improve our sensitivity to point sources

We Work Better When We Work Together

C. A. Argüelles, P. Fernández, I. Martinez-Soler, M. Jin: DOI: 10.1103/PhysRevX.13.041055
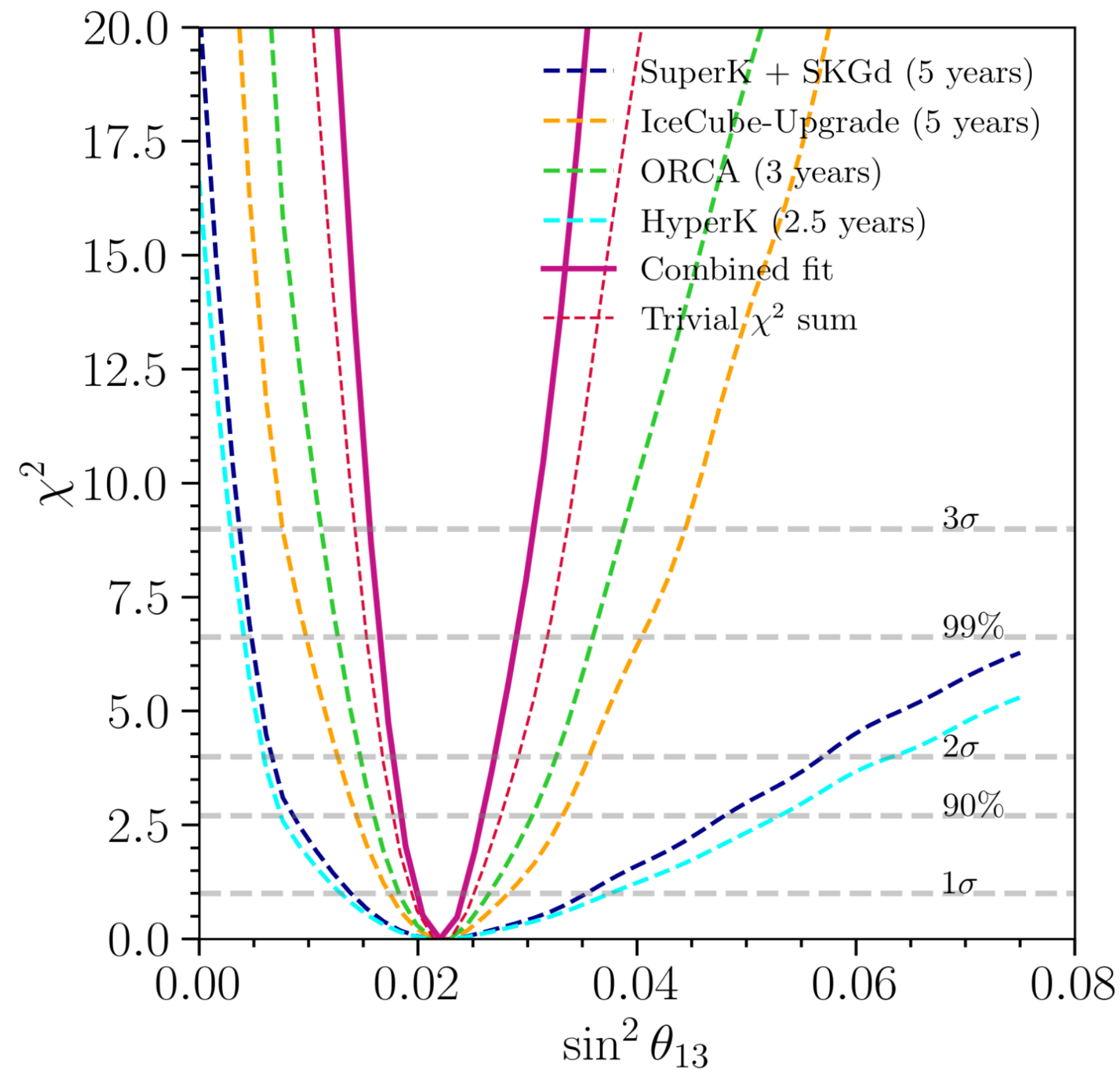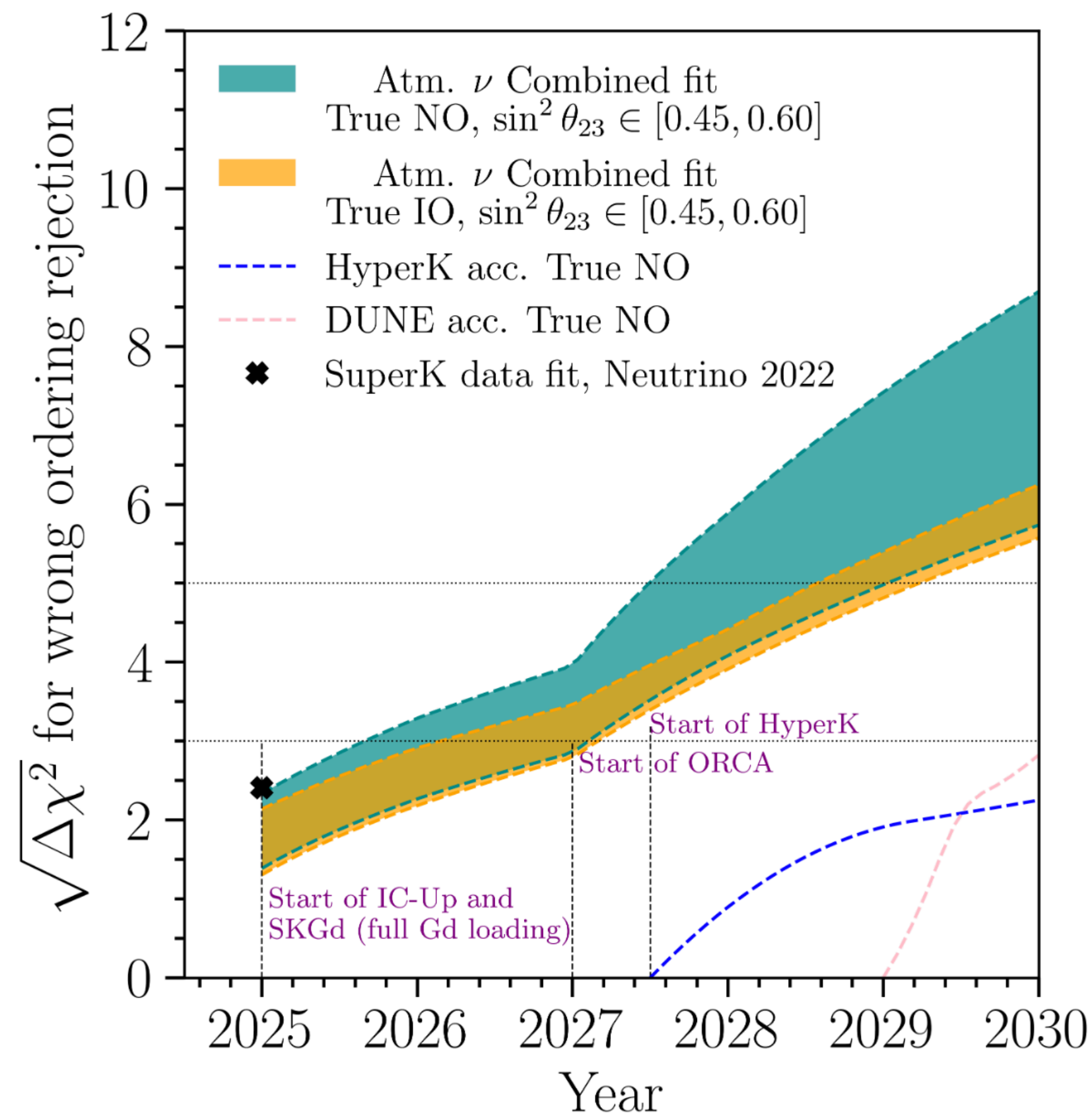
- When neutrino telescopes combine data, we dramatically improve our impact
  - Point sources
  - Oscillations

An Opportunity to Move Closer to the Metal

- Cherenkov neutrino telescopes operate in extremely similar ways
- Opportunities to build common techniques and compare methods between detectors
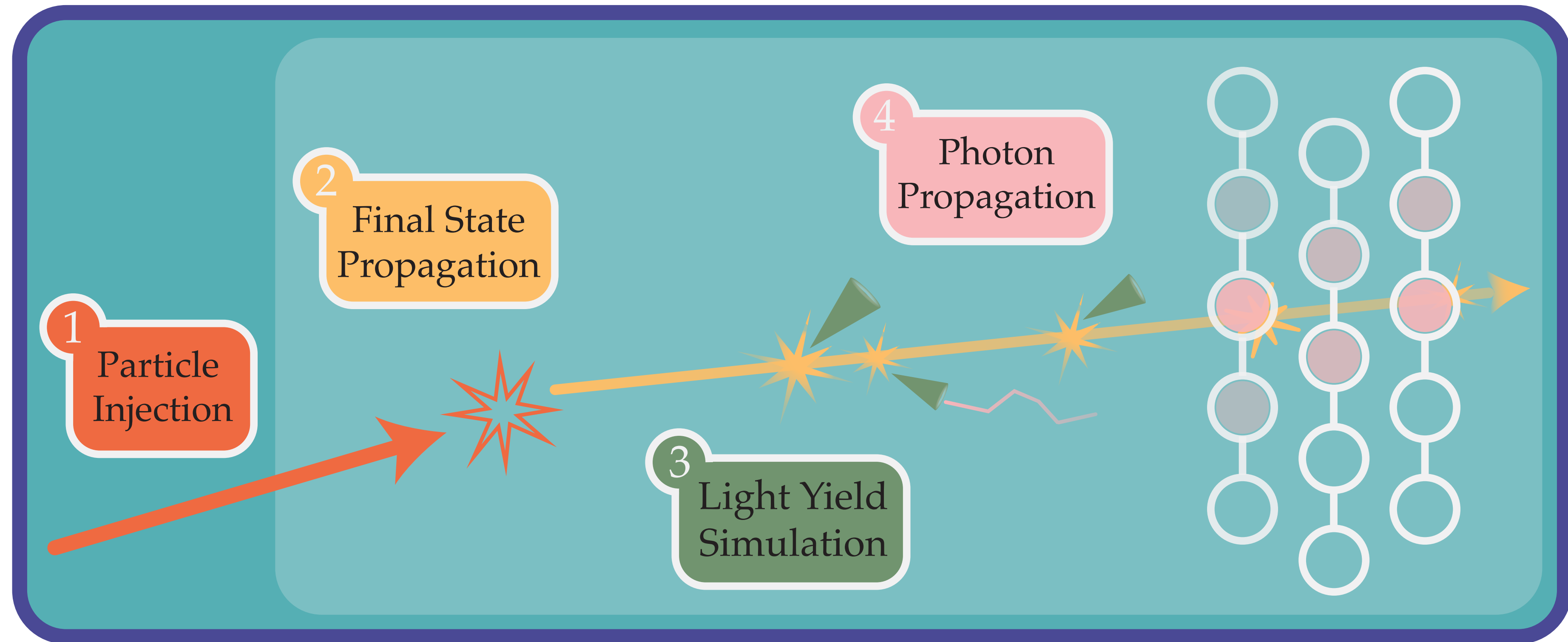
Machine Learning in Ascendence
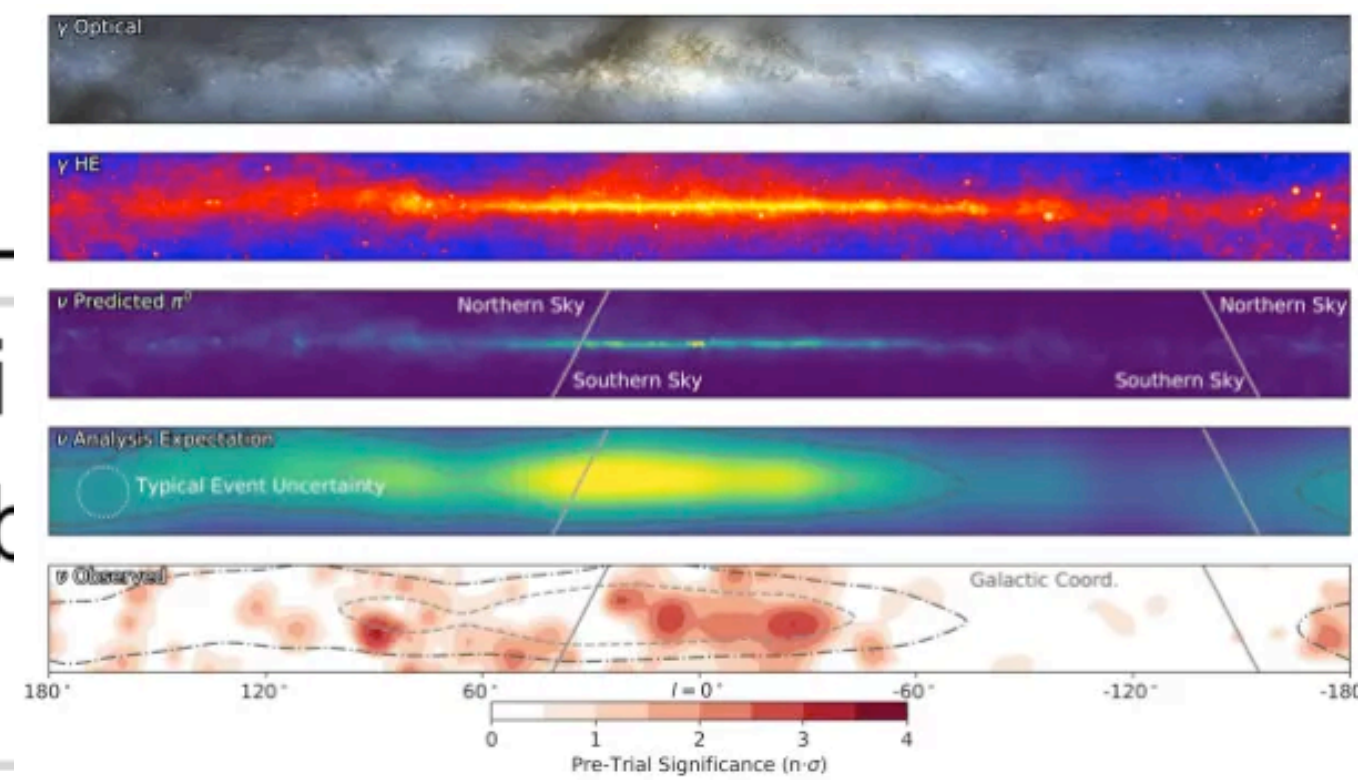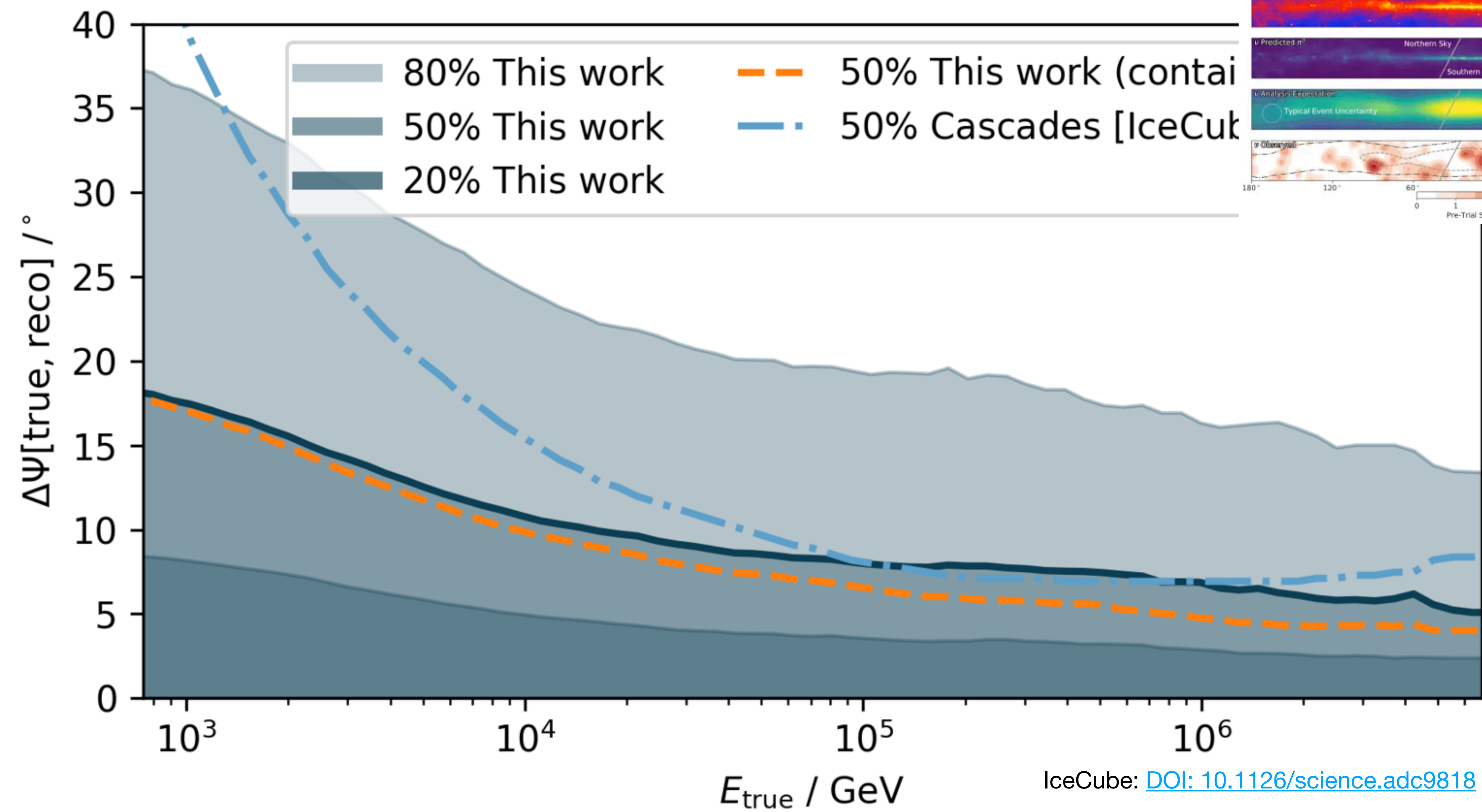
IceCube: DOI: 10.1126/science.adc9818

We're Behind the Curve
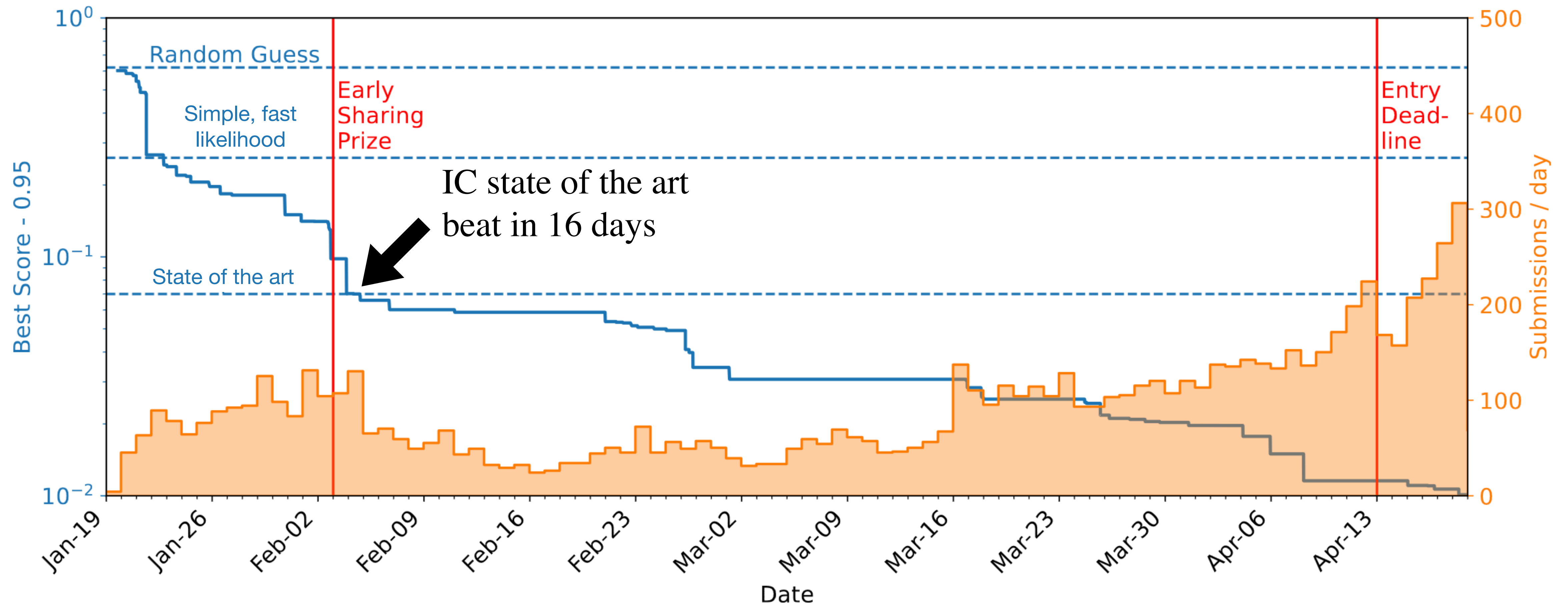
Prometheus **Simulation Package**
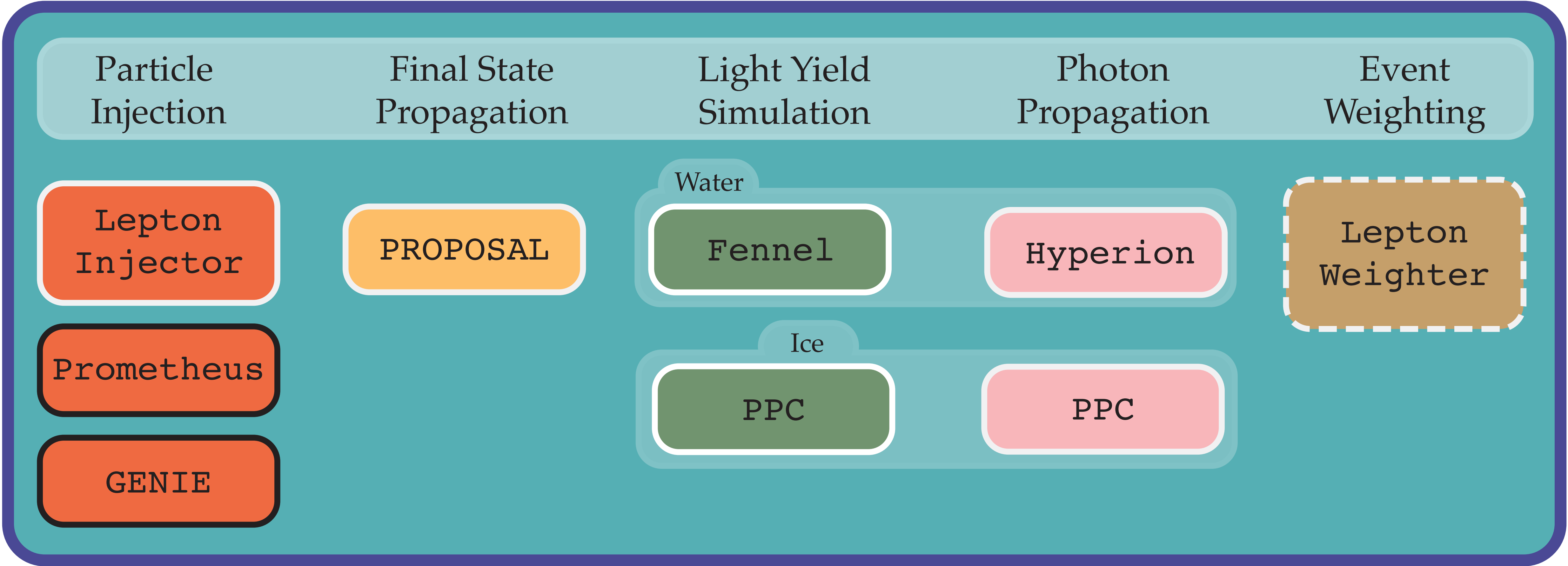
Photon-Level Output

`Prometheus` is the first-of-its-kind simulation that gives photon-level information for arbitrary detectors in ice and water
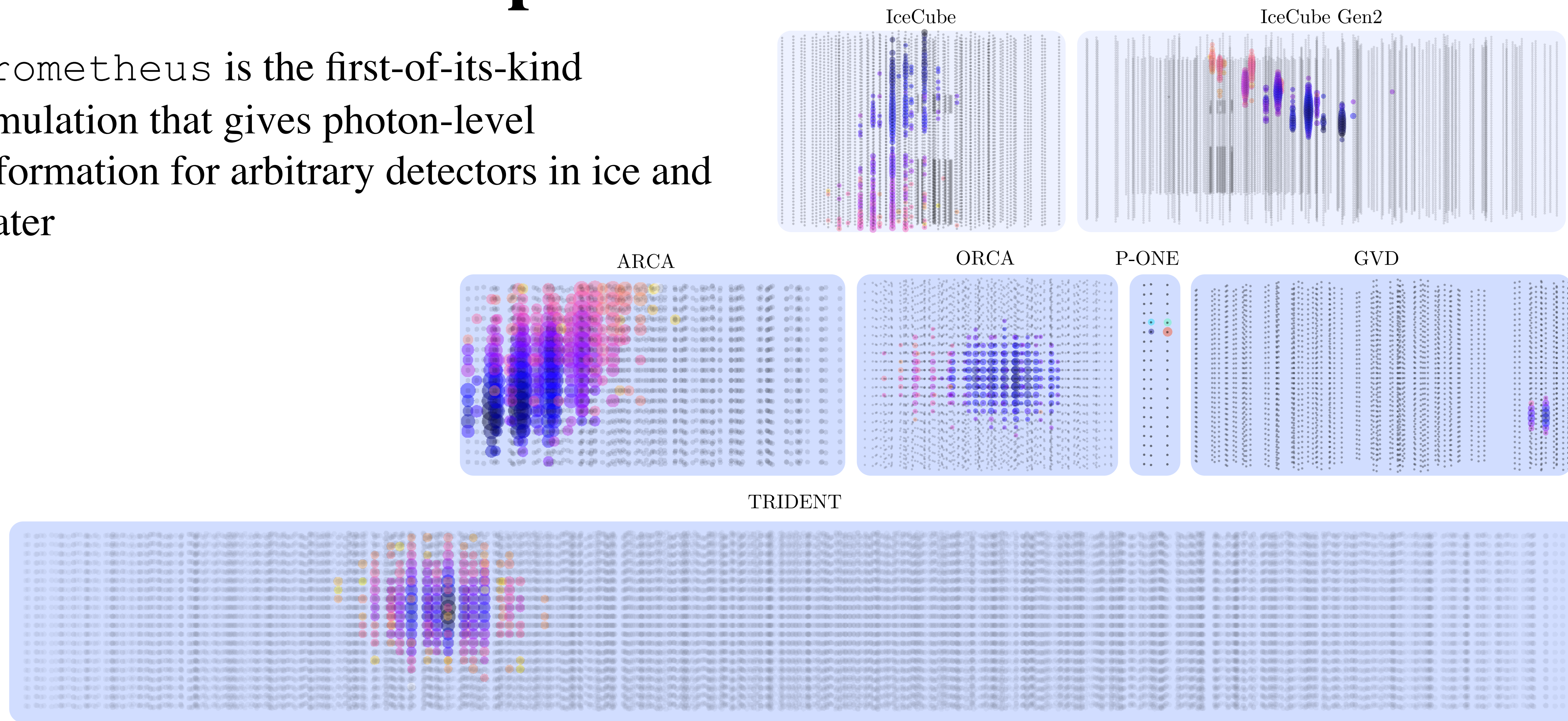
IceCube

IceCube Gen2

ARCA

ORCA

P-ONE

GVD

TRIDENT

Effective Area Comparisons
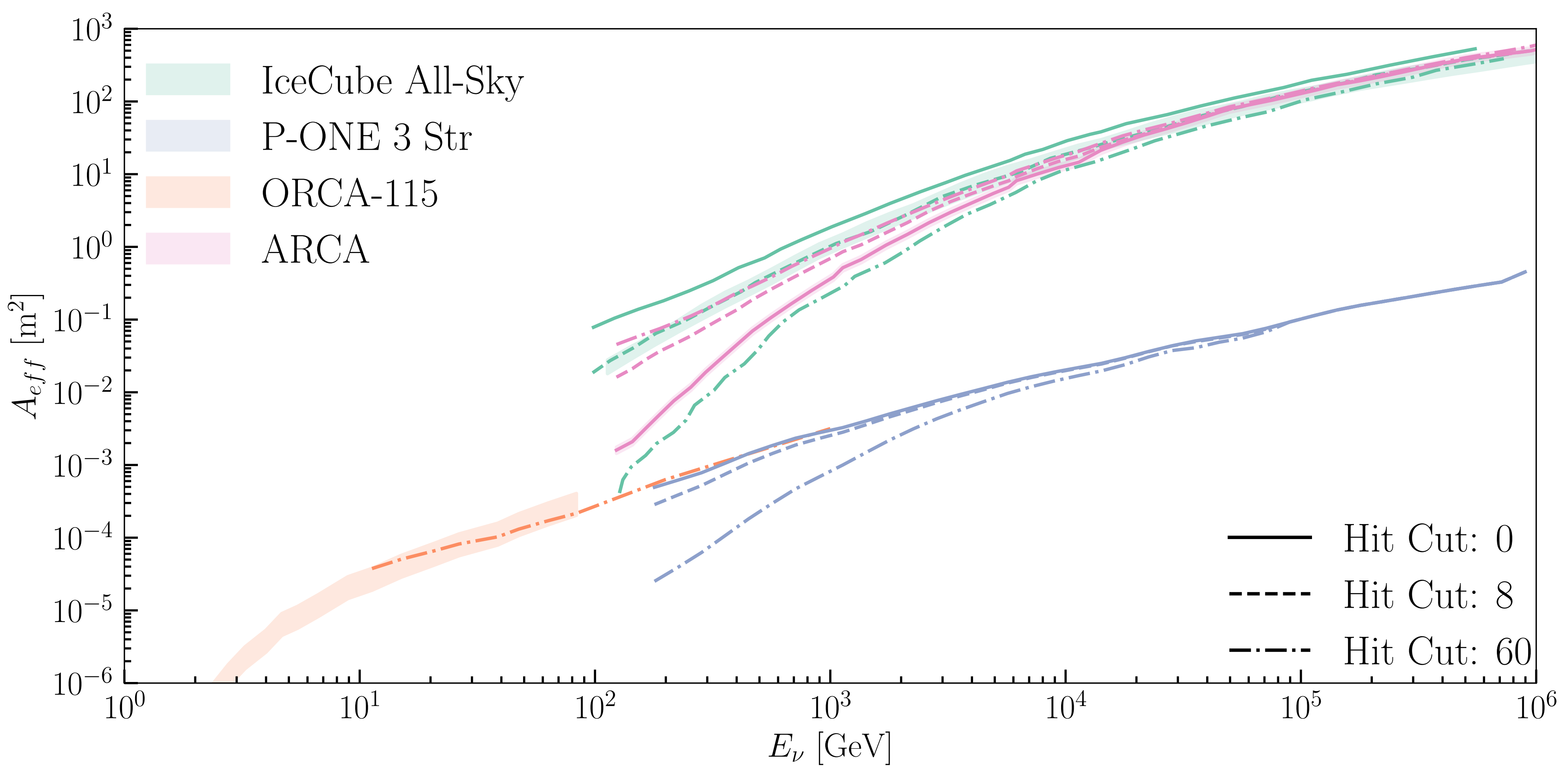
Current Prometheus Features

- Injection via:
  - built-in LeptonInjector interface for CC, NC, and GR
  - Reader for GENIE files
  - Arbitrary injection provided by user
- Photon-level information, including time, parent particle, and, for ice, position on an OM

- Position of photon arrival for water
- Support for non-spherical OMs
- Interface to inject events using MadGraph

$\mu^+ + \mu^-$
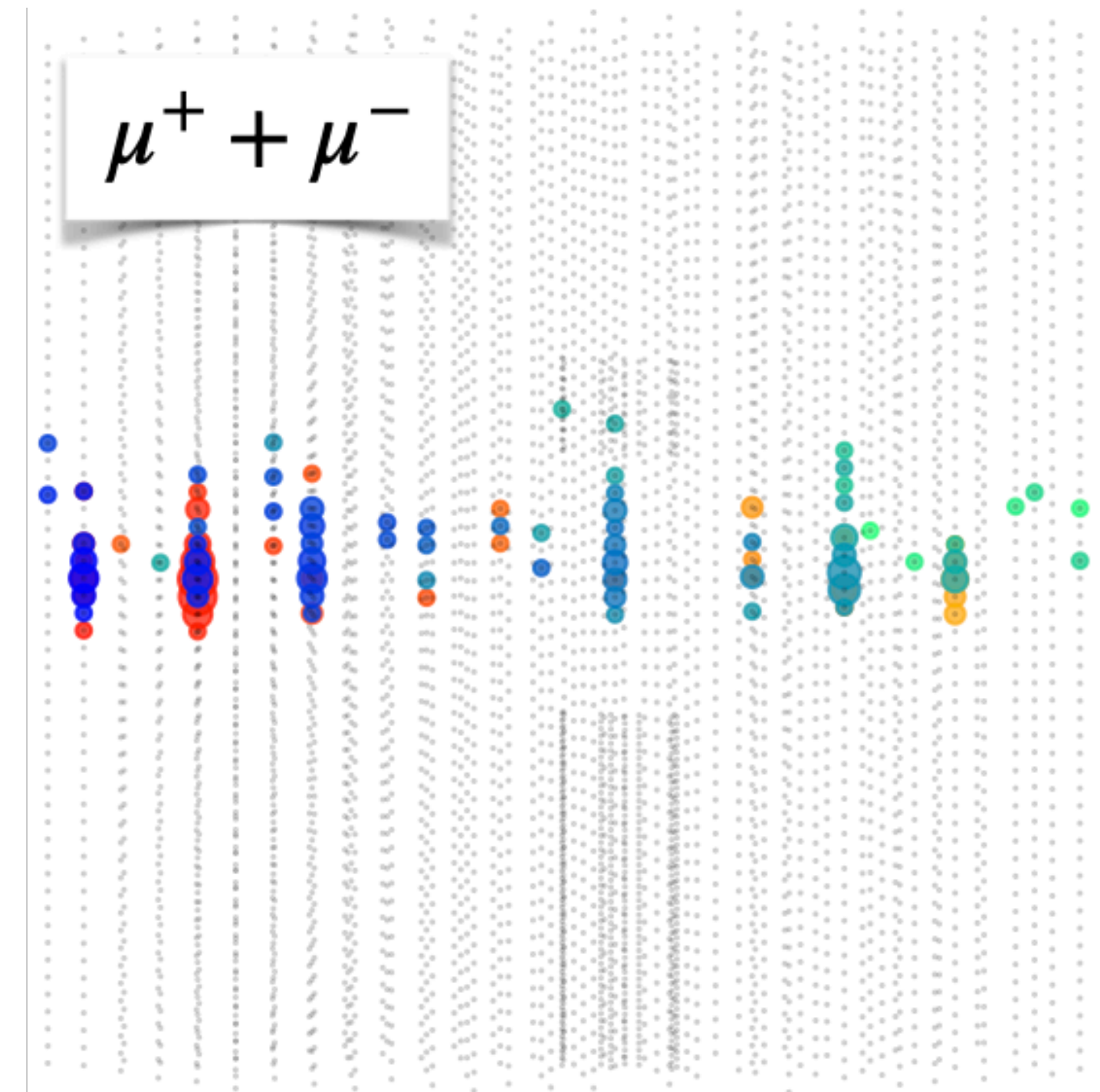
GraphNeT

- An open-source library to facilitate deep learning in neutrino telescopes
- Support for many different architectures— CNNs, GNNs, RNNs, transformers, *etc*.
- Straightforward interfaces to apply these to new data formats
- **No need to be a machine learning expert !!!**
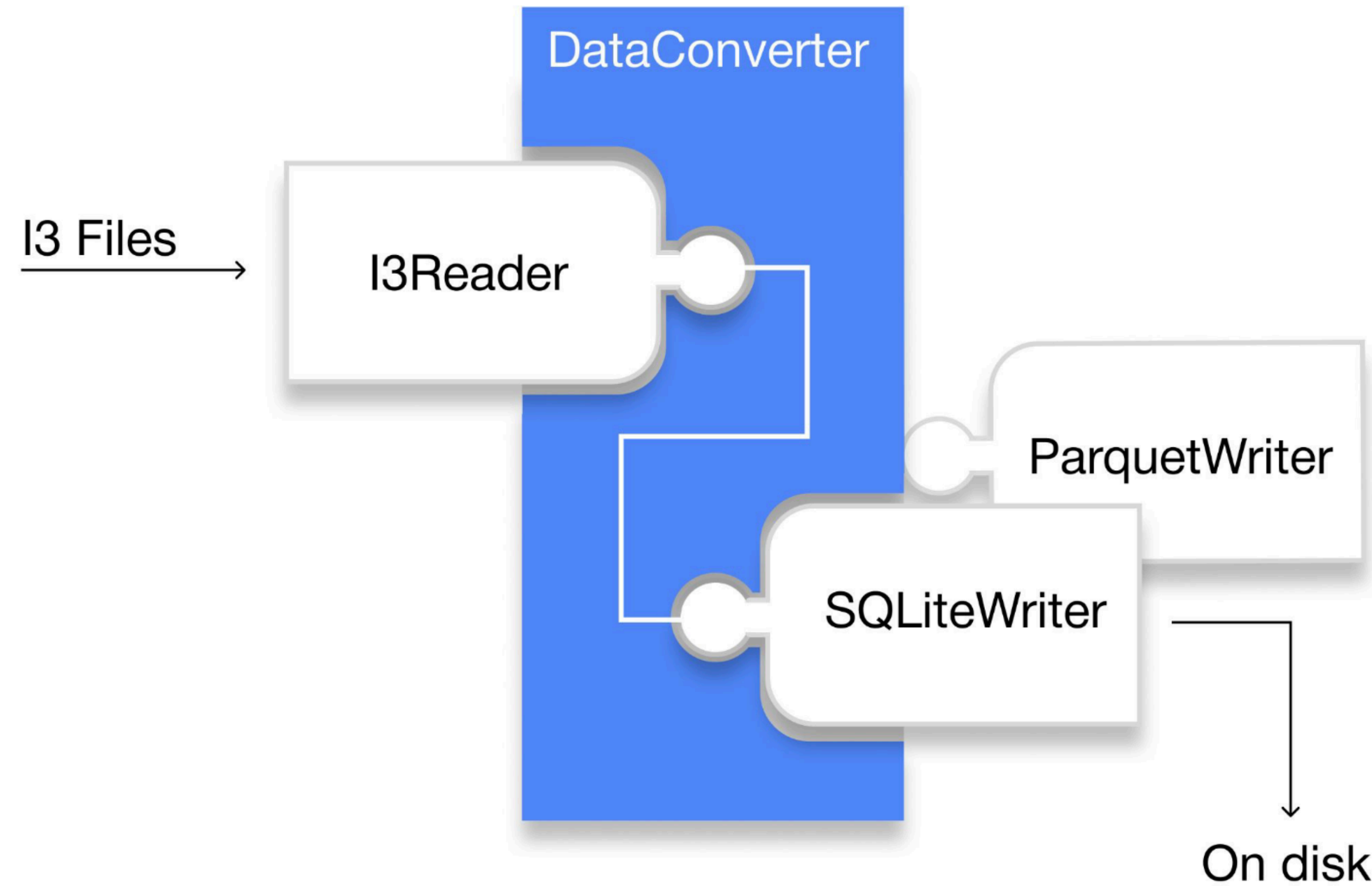
Courtesy of R. Ørsøe

GraphNeT around Town

- [Several](#) [publications](#) from IceCube use this package

- In use within KM3NeT, P-ONE, and TRIDENT among others
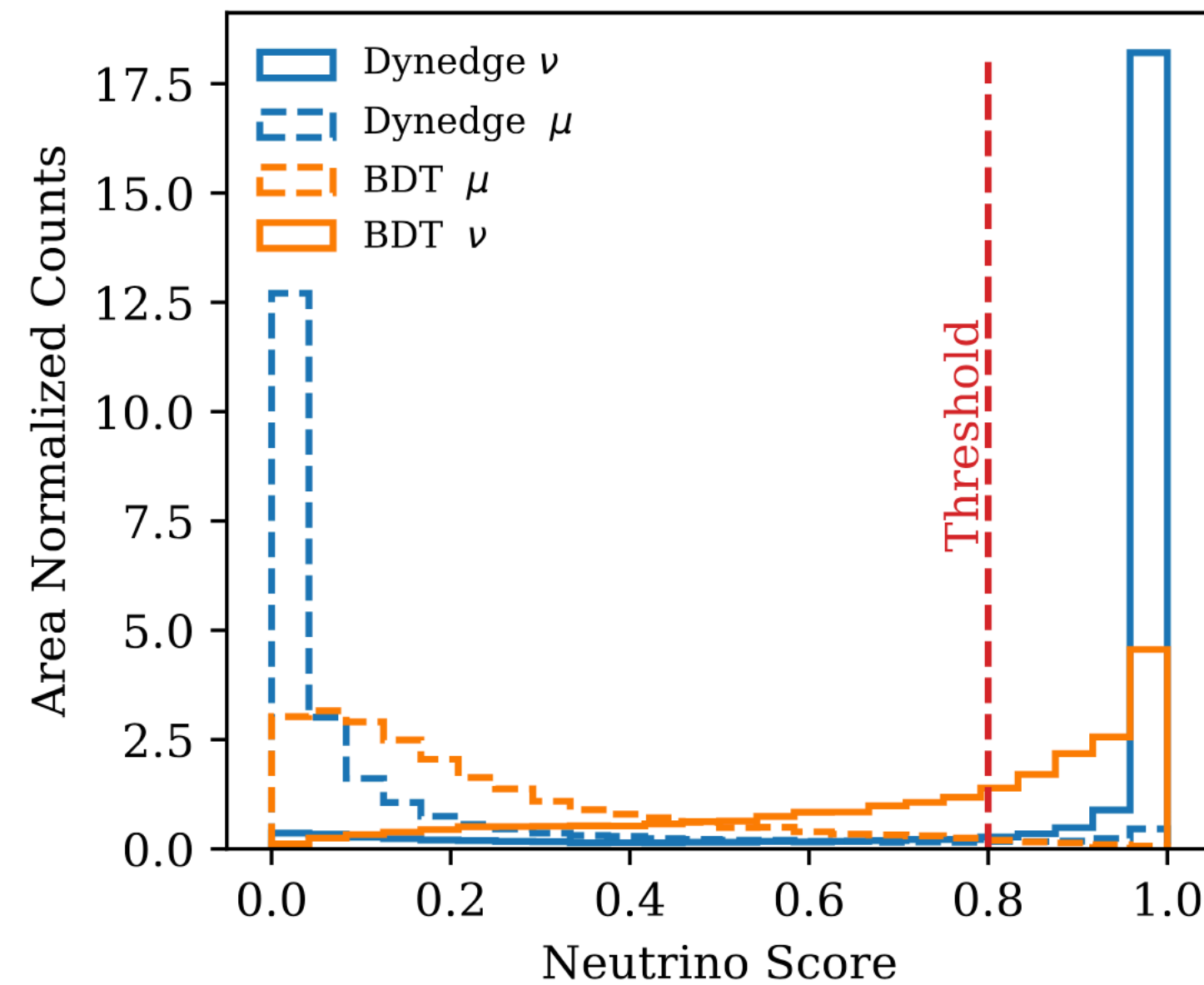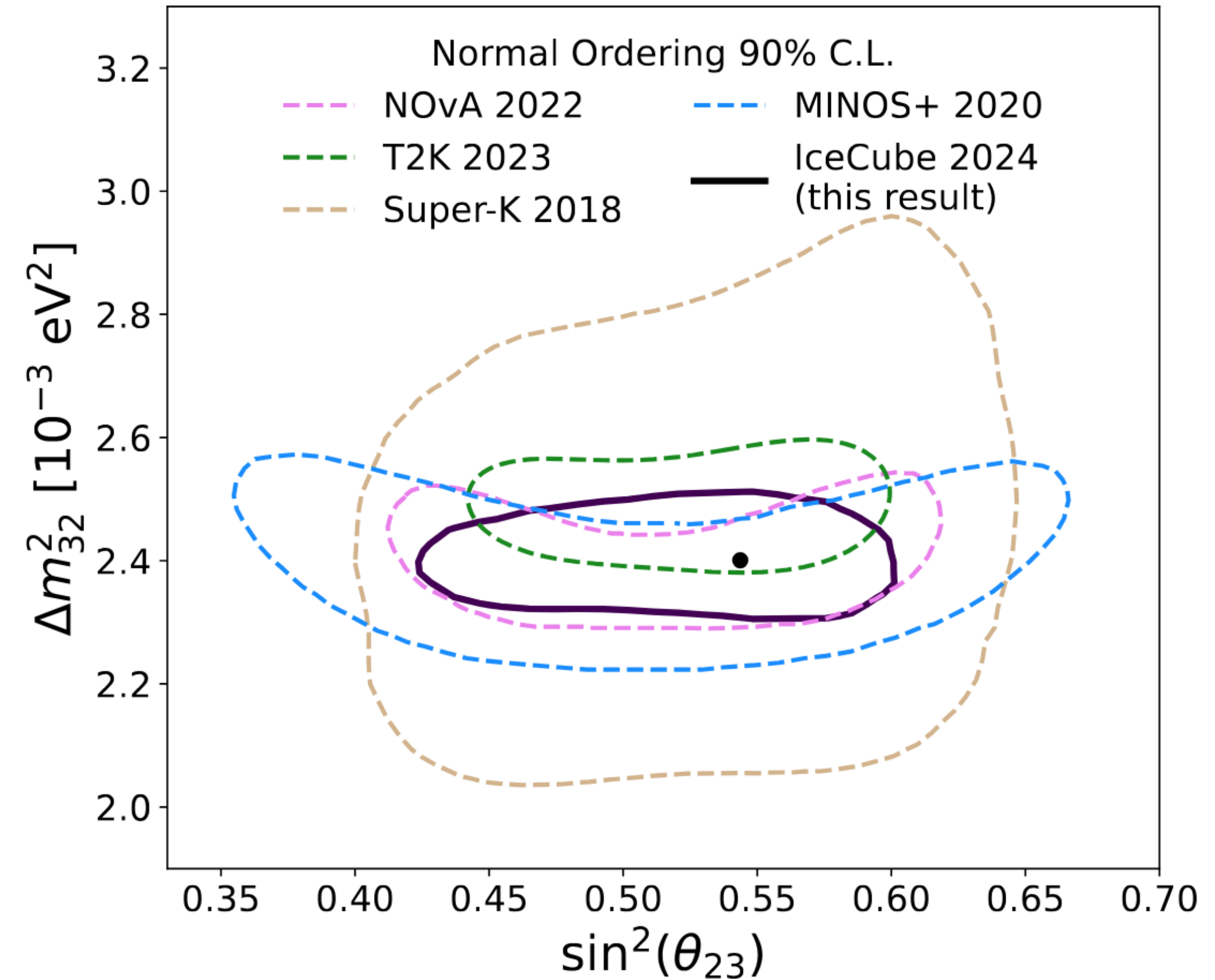
Prometheus + GraphNeT = Cross-Detector Comparisons

- Recently, we have begun an effort to compare performance of machine-learning reconstructions across seven existing and planned detectors

- For each detector* we have produced ~10 million events with different flavors and interaction types

- Running inference on particle identification, energy prediction, direction reconstruction, inelasticity
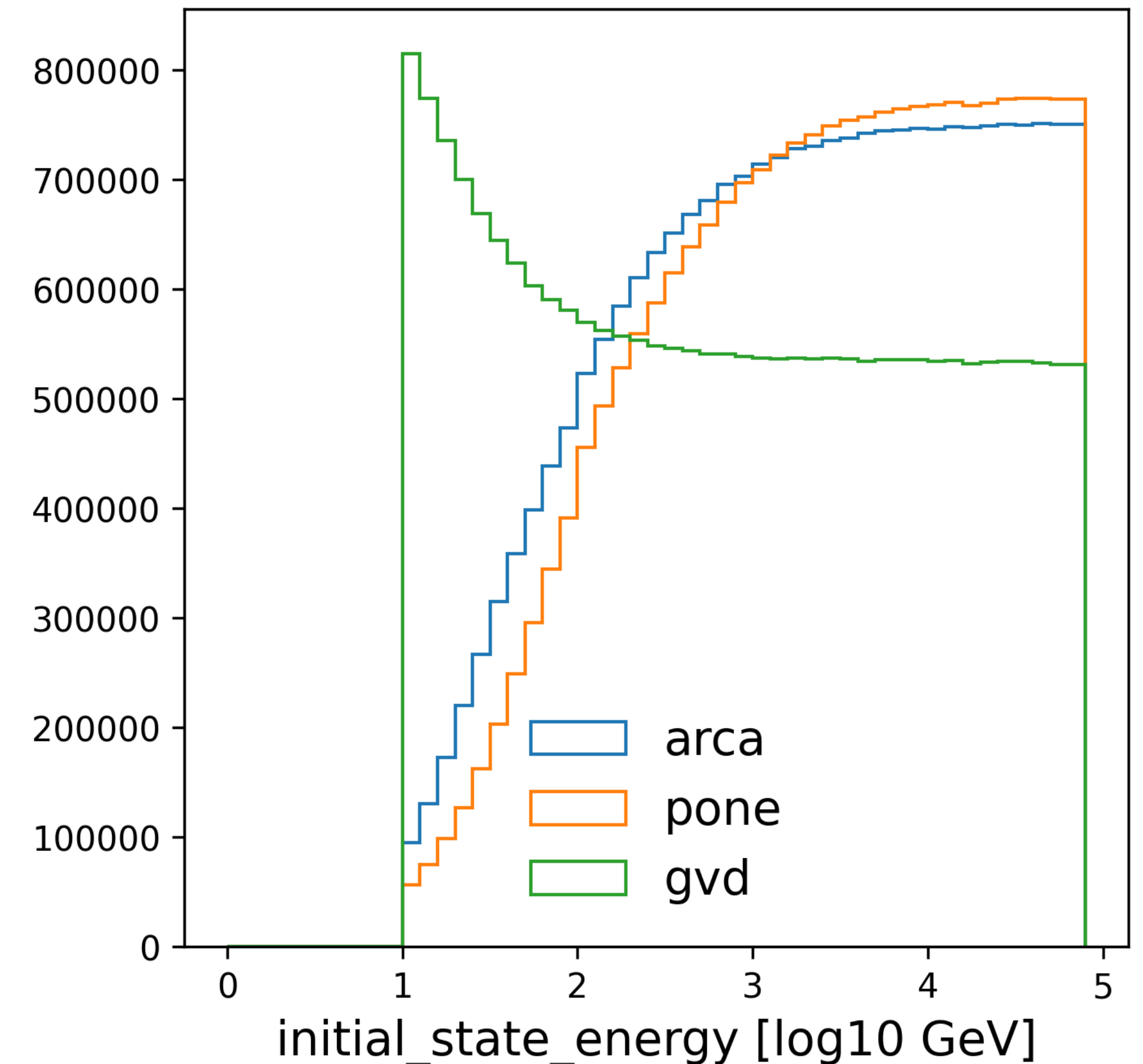
Community-Developed Pulse Merging

- We found that using individual photons could case issues with training

- Rasmus Ørsøe developed a simple pulse merging algorithm to combine photons into "pulses"

- Significantly speeds training and reduces data storage

- This is being merged as an output option for Prometheus !
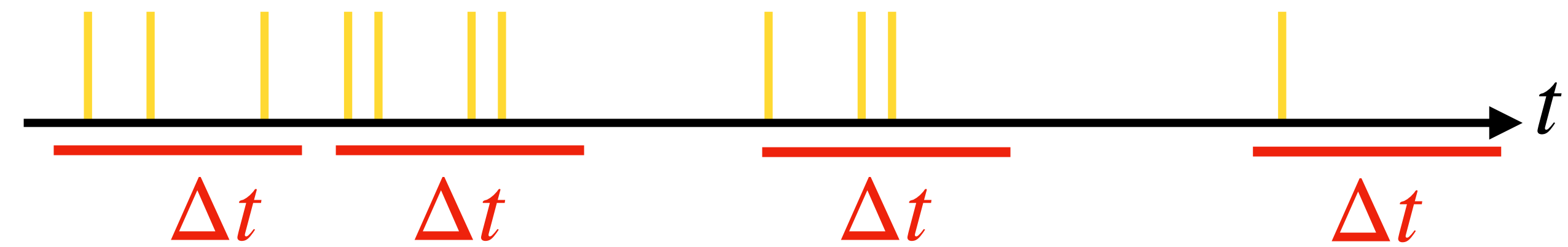
Preliminary Results
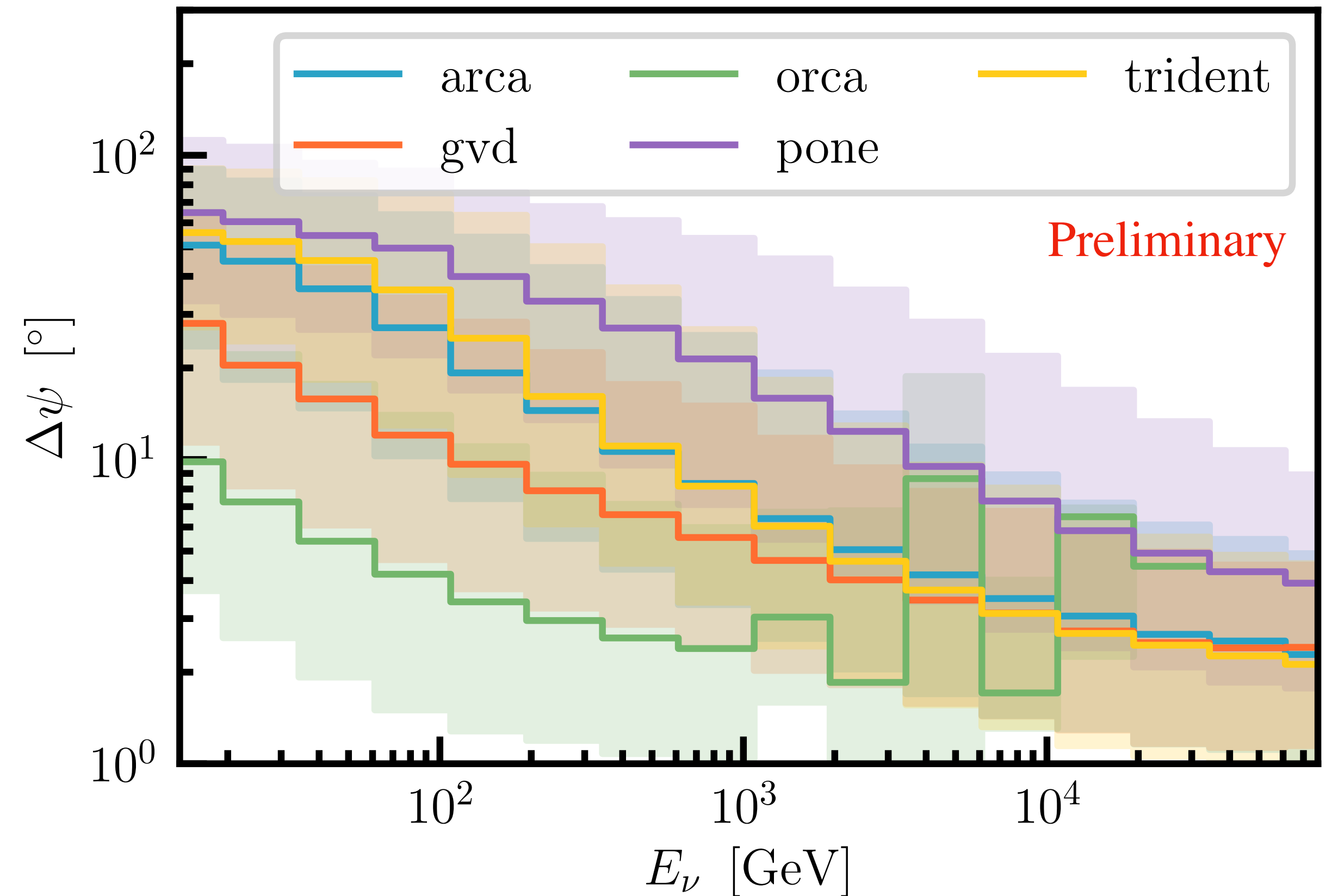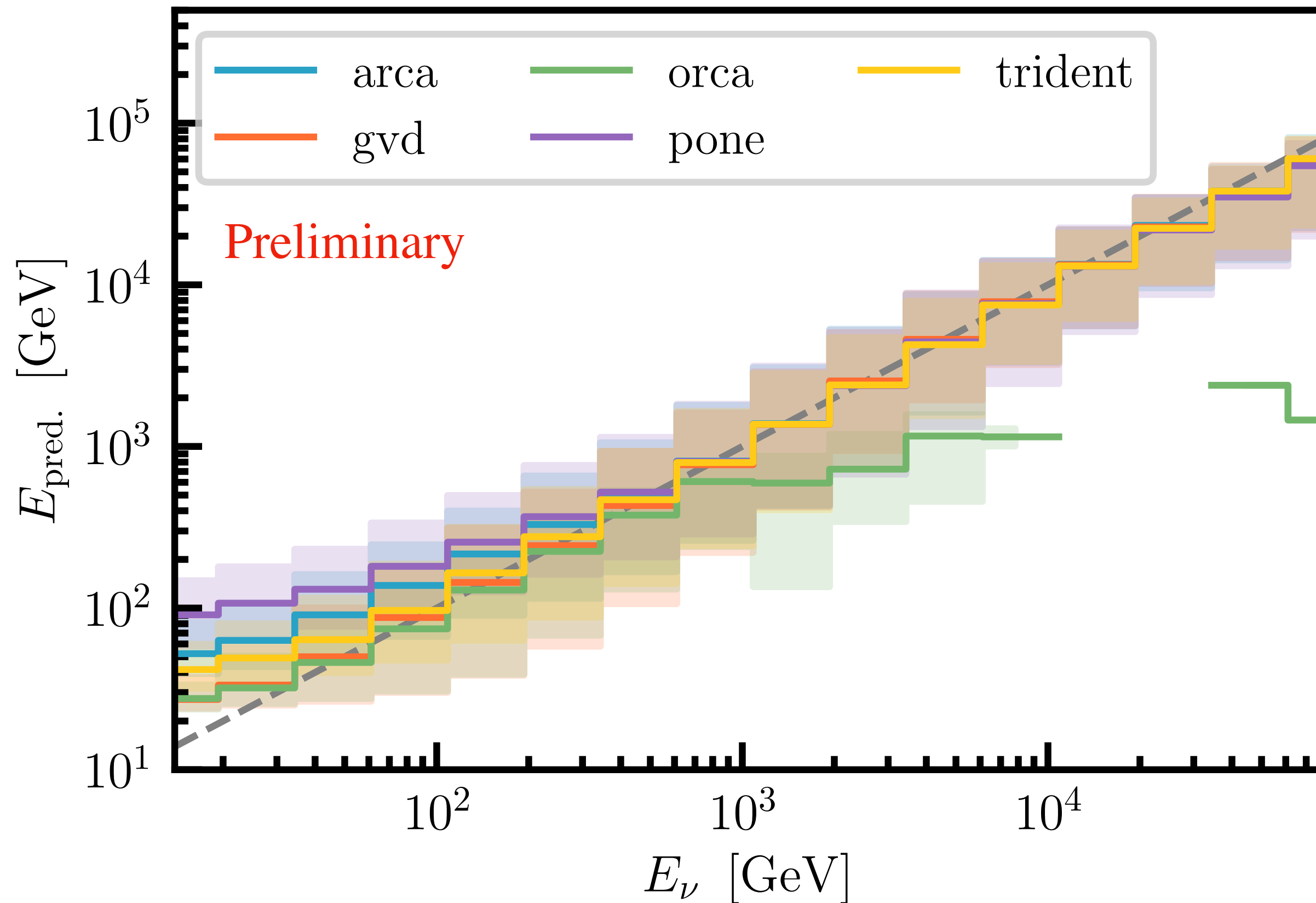
Initial results for energy and low-energy directional reconstruction. Inelasticity, high-energy directional reconstruction, particle ID, and more are in progress. Data from more experiments in process of being uploaded

An Open-Source Repository

- In the spirit of open-source science, all code used for this project, as well as all data sets will be made available at the time of publication

- We will be hosting this on a database at the university of Copenhagen

- They will also be cross-listed on [nu-MC.org](nu-MC.org), where will be tracking existing, open-source MC and analysis tools for community use
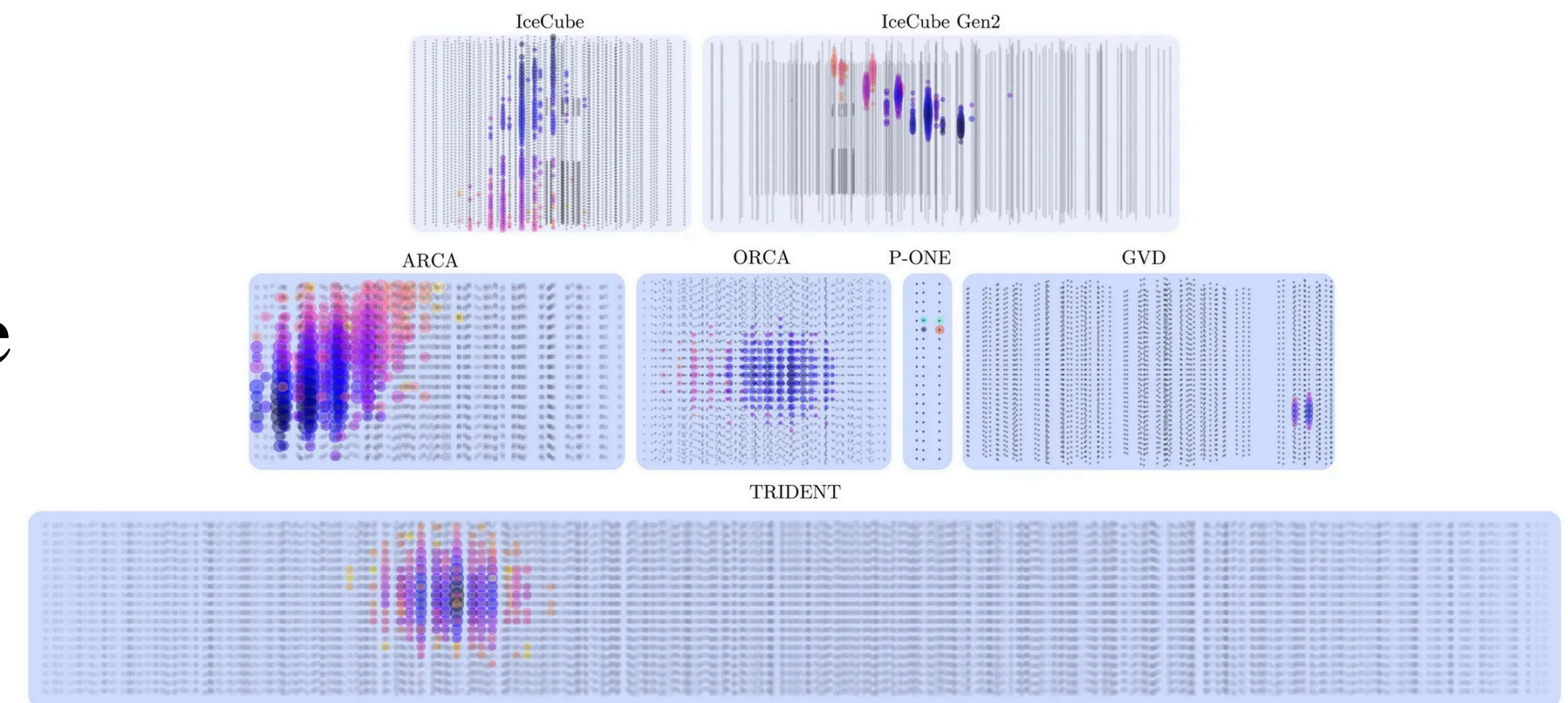
Open Source Neutrino Monte Carlo Sets

An Open-Source Repository
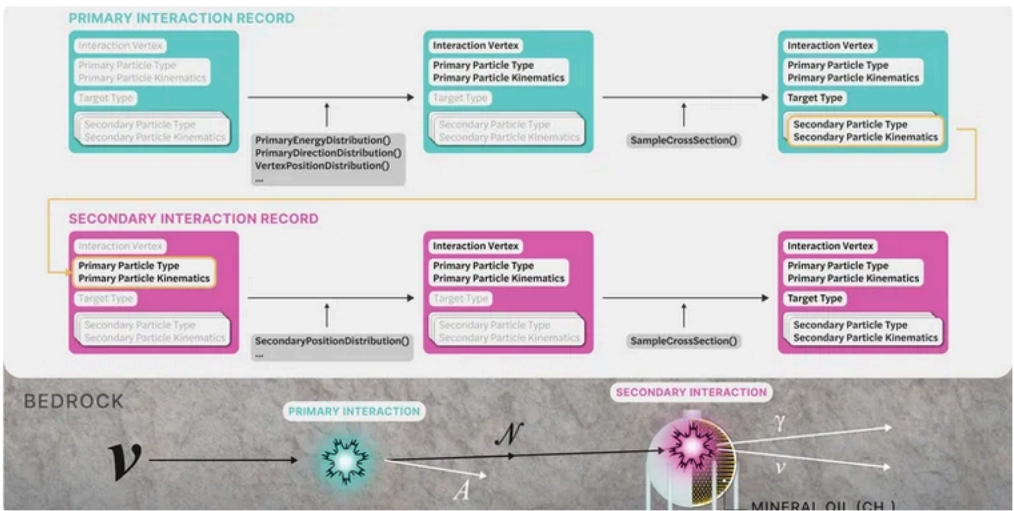
Related Applications

GraphNet

MadGraph

SIREN

Link to Repository

Link to Repository

Link to Repository

This work is funded by

Thank you very much :-)

谢 谢 ~

Backups

Atmospheric Systematic Summary

Systematic source	1σ-range
CCQE	10%
CCQE $\nu/\overline{\nu}$	10%
CCQE e/μ	10%
CC1π production	10%
CC1π $\pi^0/\pi^\pm$	40%
CC1π $\nu_e/\overline{\nu_e}$	10%
CC1π $\nu_\mu/\overline{\nu_\mu}$	10%
Coh. π production	100%
Axial Mass (M_A)	10%
CC DIS	5%
NC hadron prod.	10%
NC over CC	20%
ν_τ	25%
Neutron prod. (SuperK only) [120]	15%

TABLE II. Summary of neutrino-water interactions systematic uncertainties used in this work.