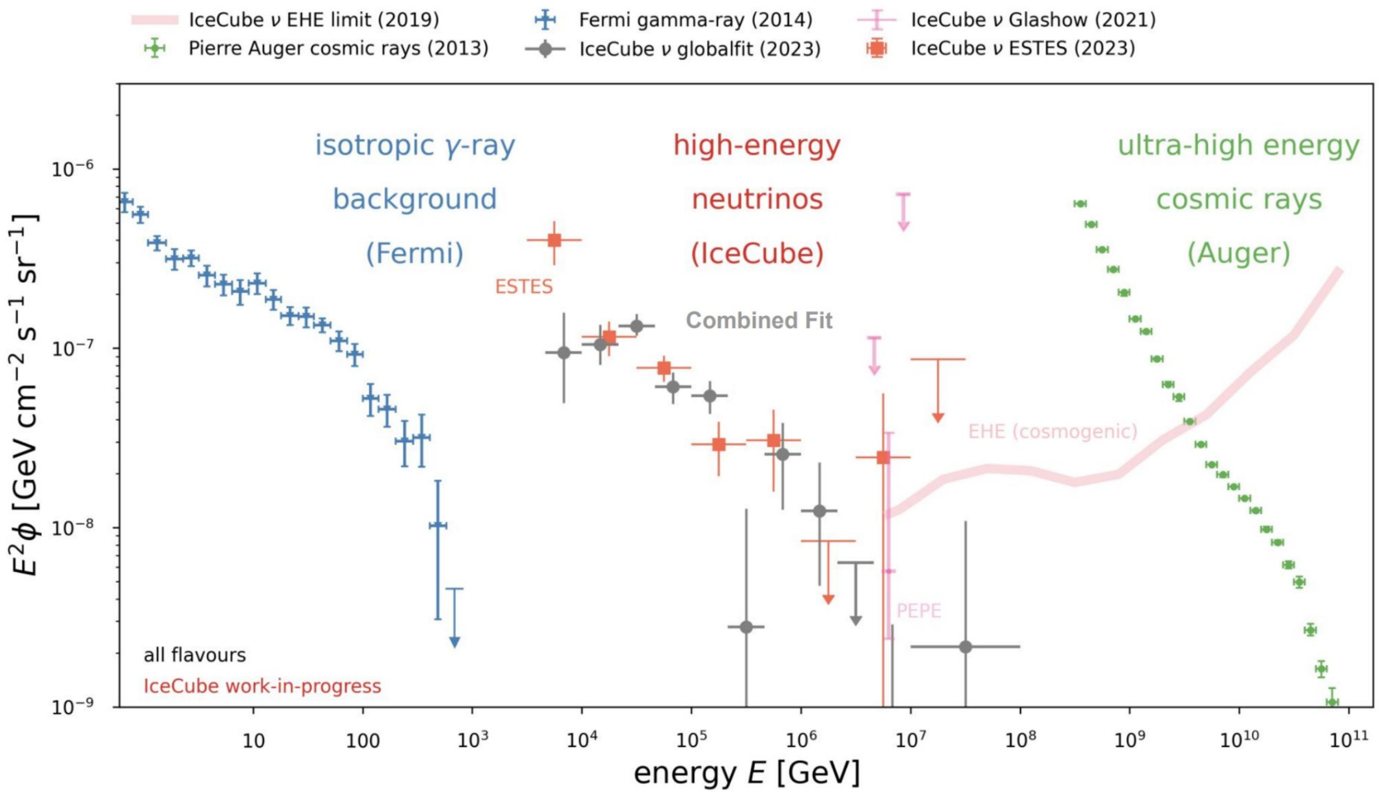
Prospects for All-Flavor PeV–EeV Neutrino Detection with IceCube

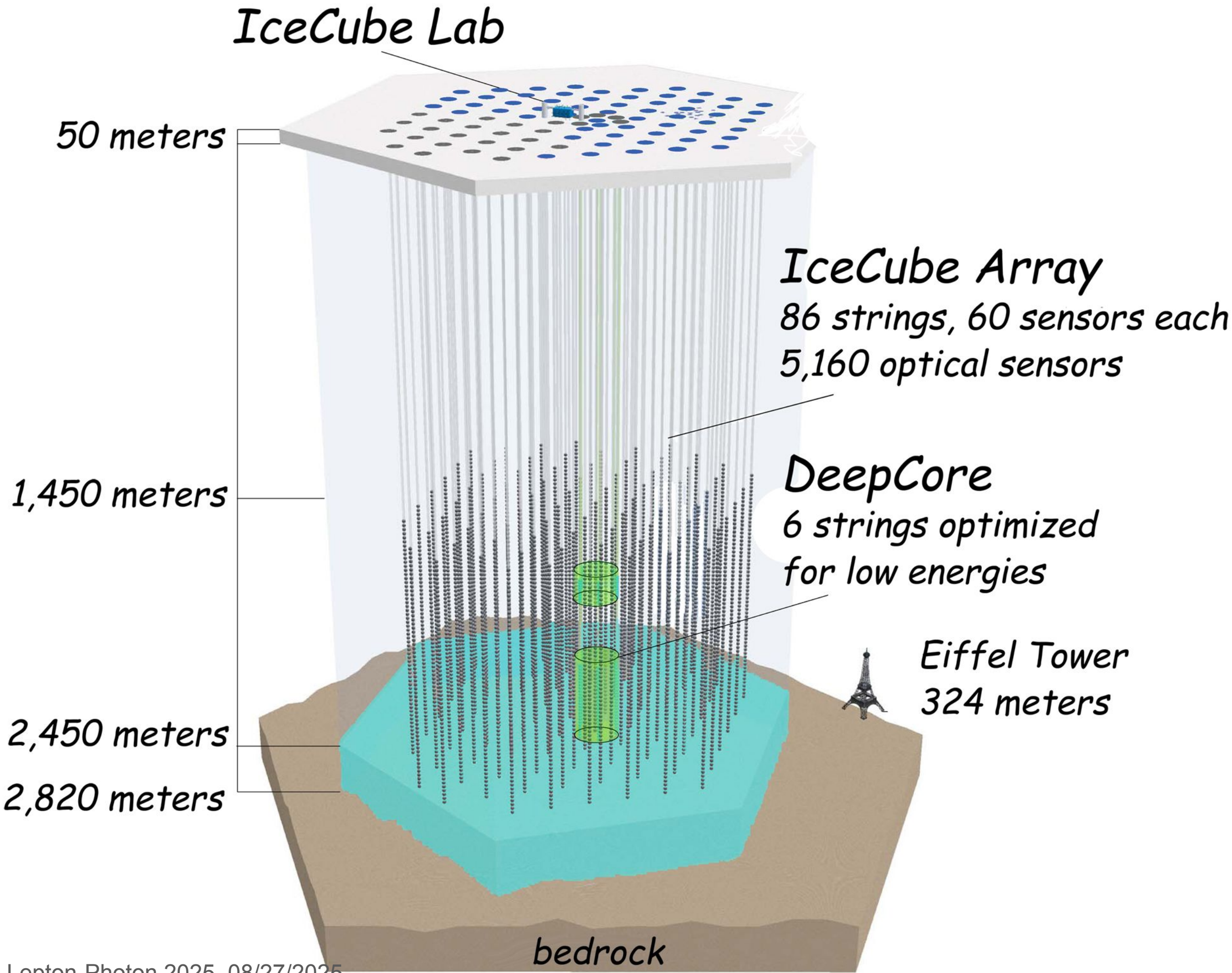
Emre Yildizci, Zoe Rechav, Lu Lu

Lepton-Photon, 27 August 2025

Multimessenger Astrophysics

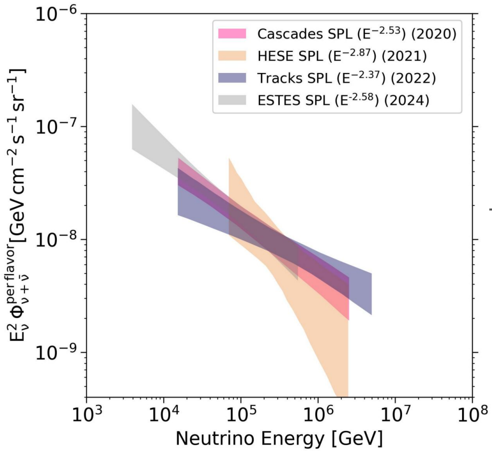
Similar energy densities → Common origins?



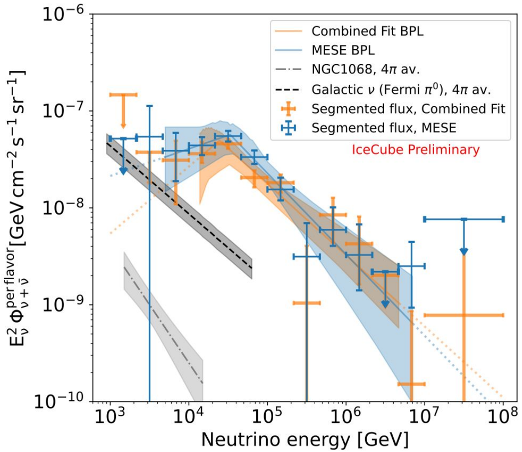



Digital Optical Module

Characterizing the Diffuse Cosmic Neutrino Spectrum



Consistent w/ SPL



First evidence of spectral feature at low energies w/ **MESE** & **Combined Fit**

Features at PeV?

How?

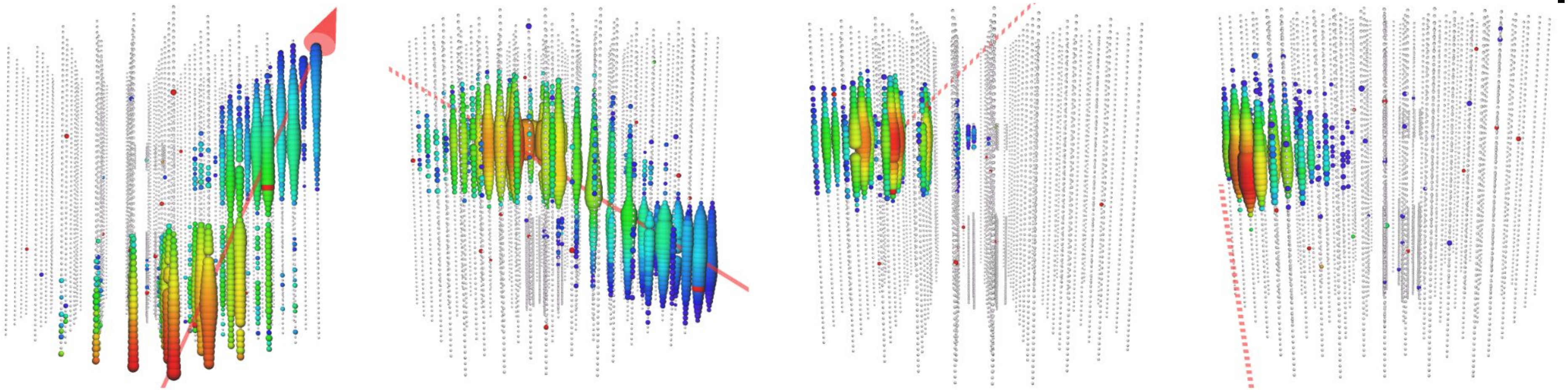
- Increased statistics
- Updated event reconstructions
- Improved modeling of
  - Ice
  - Atmospheric backgrounds

Questions to answer

- UHECR source scenarios
- Tension between
  - KM3NeT 220^{+570}_{-110} PeV
  - IceCube non-observation >20PeV

Ice**C**ub**E** **M**ulti-flavor **A**strophysical **N**eutrino **Diffuse** Sample

ICEMAN Diffuse



(a) Throughgoing track **(b)** Starting track **(c)** Contained cascade **(d)** Uncontained cascade

Combined Fit Sample

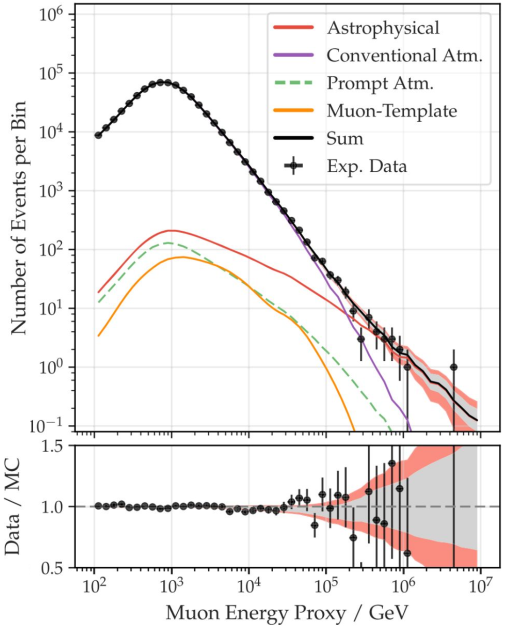
Medium Energy Starting Events (MESE) Sample

Throughgoing Tracks

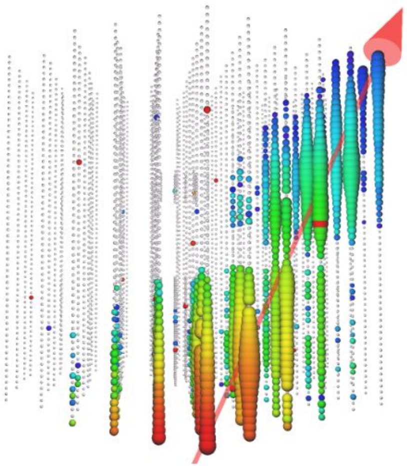
Northern Sky

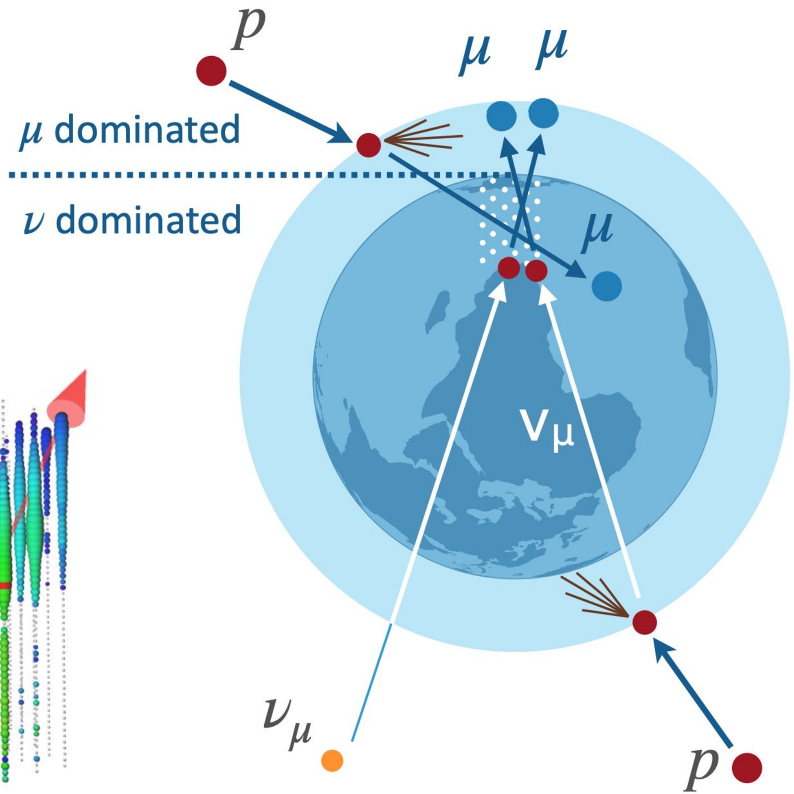
Earth as a shield against atmospheric muons
(99.8% neutrino purity)

High statistics & angular resolution



R. Abbasi *et al* **2022**
ApJ 928 50





Strong constraints on atmospheric neutrino flux and detector systematics

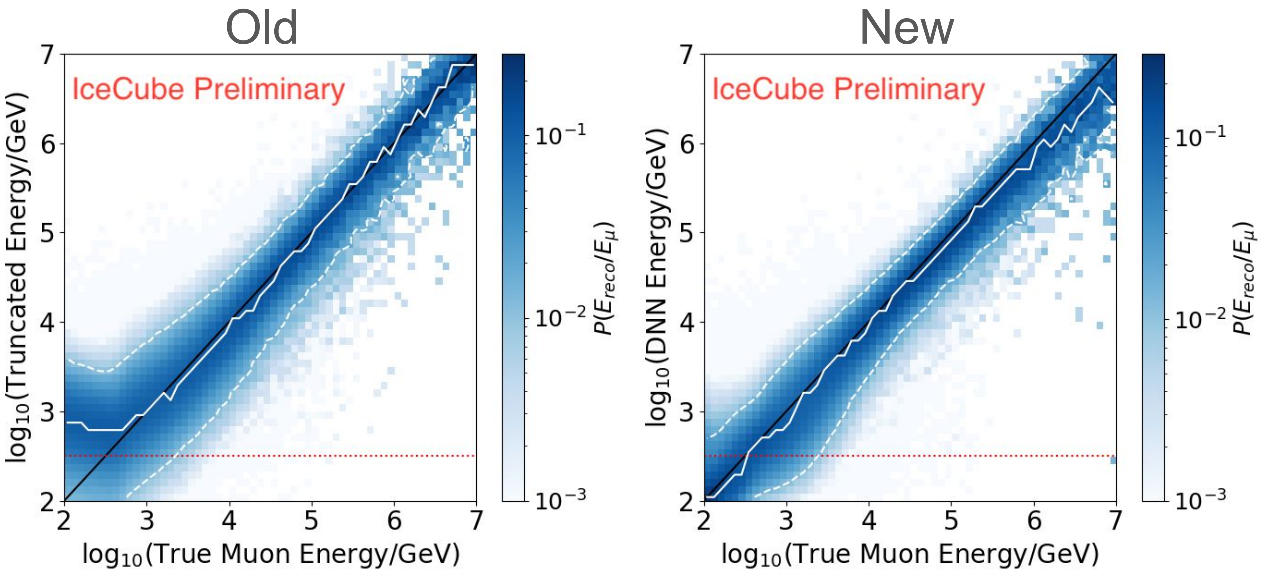
Throughgoing Tracks - Updates

New Reconstruction

Old: Muon differential energy loss (dE/dx) based
Ineffective below ~1 TeV

New: DNN-based

- Bias < 1 TeV removed
- Better resolution



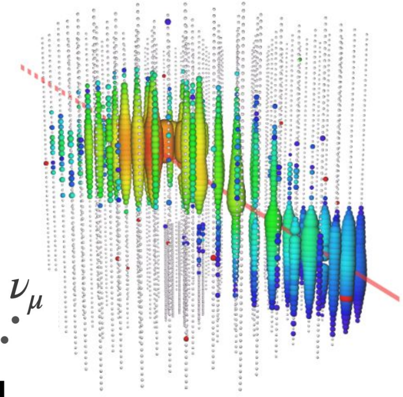
New atmospheric muon template based on hadronic interaction models SIBYLL 2.3 c&d

Starting Tracks

All sky

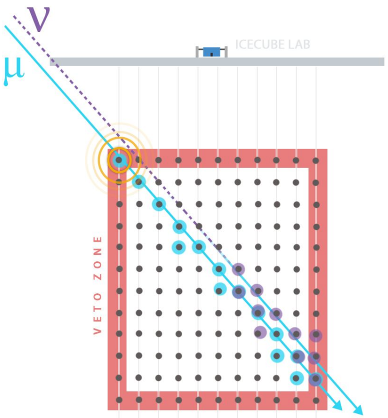
Derived from High Energy Starting Events (HESE)

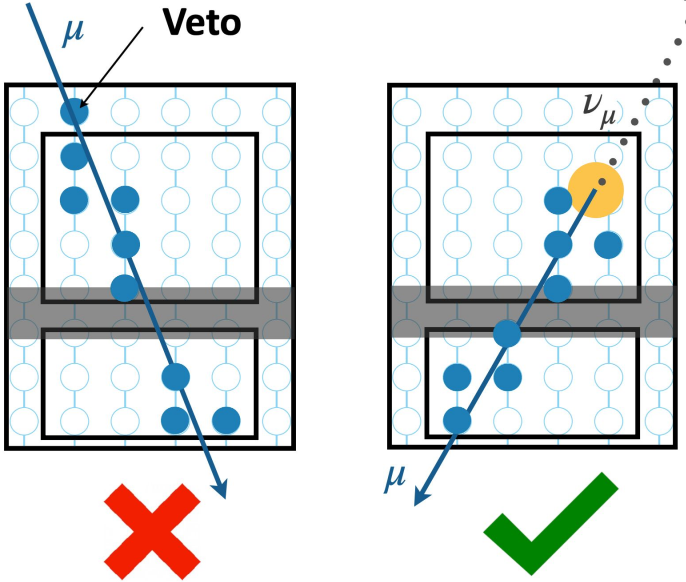
- Veto layer based cuts + neural network based track score cut



Self-veto effect in southern sky

- Suppressed atmospheric neutrino flux





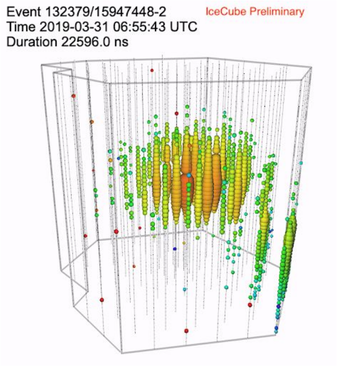
Inclusion of high energy downgoing muon neutrinos
(Earth absorbs >100 TeV upgoing neutrinos)

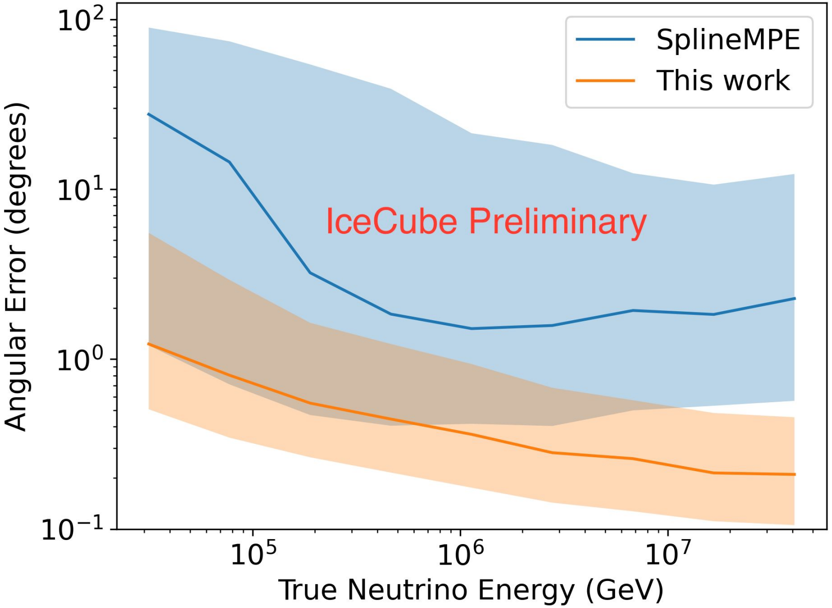
Starting Tracks - Updates

New Reconstruction

Directional reconstruction is challenging for starting tracks

- Hadronic cascade is visible
- Short lever arm





Updated atmospheric muon background modeling

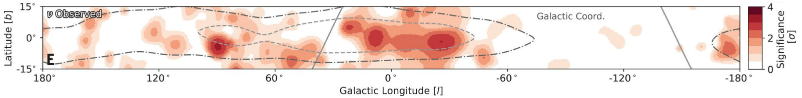
- Prompt muon (from charmed mesons) background included
- Muon dominated “muon-tagged” region for data-driven scaling

Contained and Uncontained Cascades

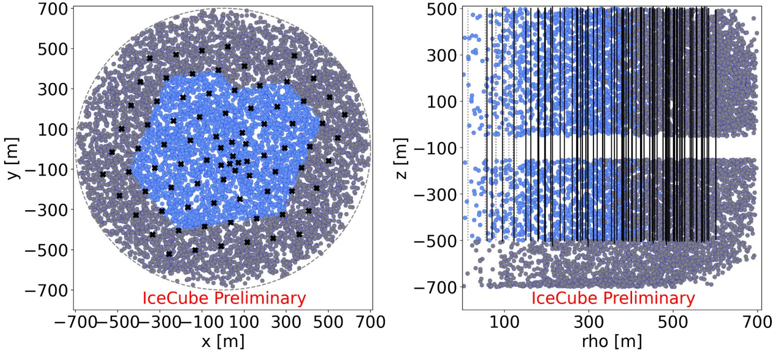
All sky

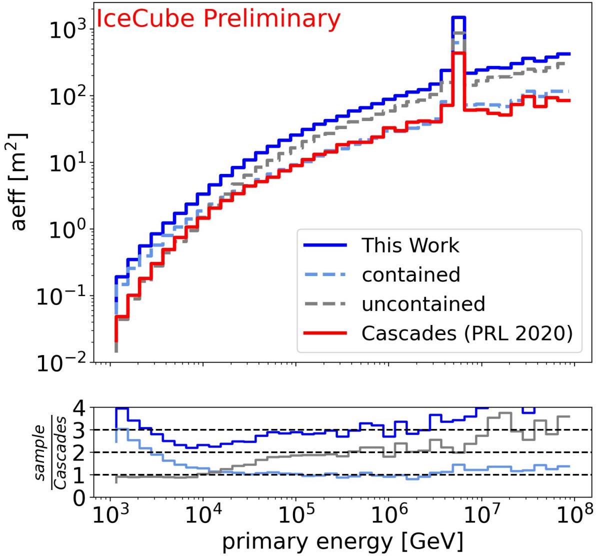
Deep Neural Network Cascades (DNNCascades)

Observation of neutrinos from Galactic Plane



Science 380 no. 6652, (**2023**) 1338−1343





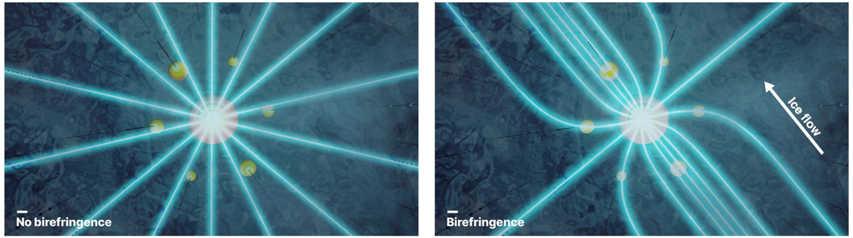
Self-veto effect in southern sky

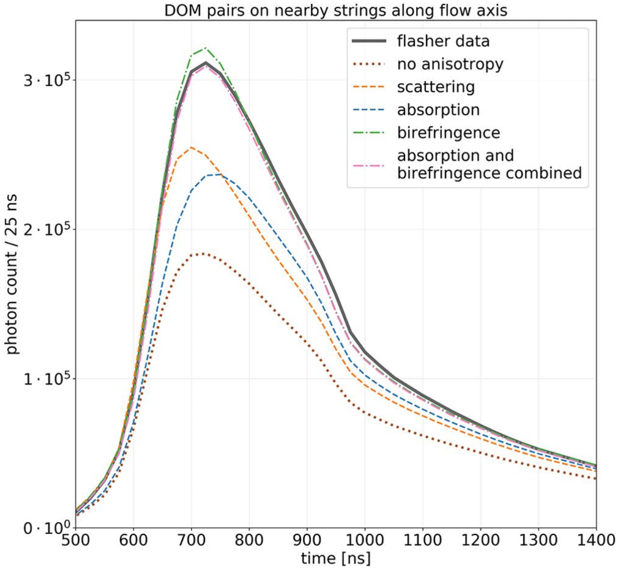
Contained cascades statistics are comparable to previous contained-only cascades sample

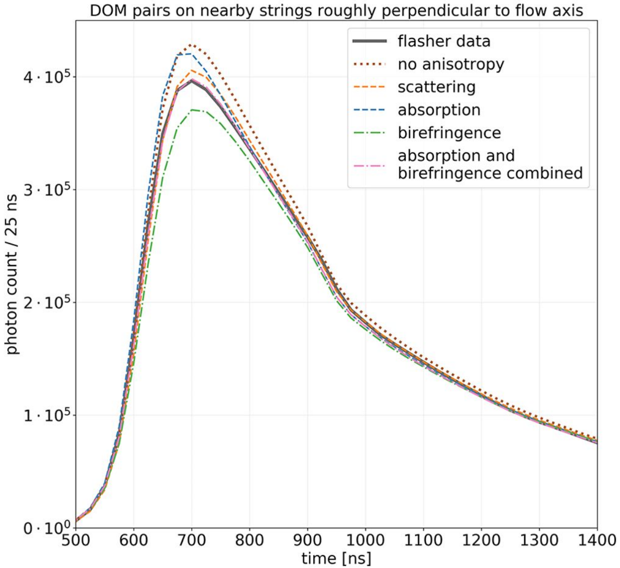
Overall, DNNCascades have 2-4 times the previous effective area

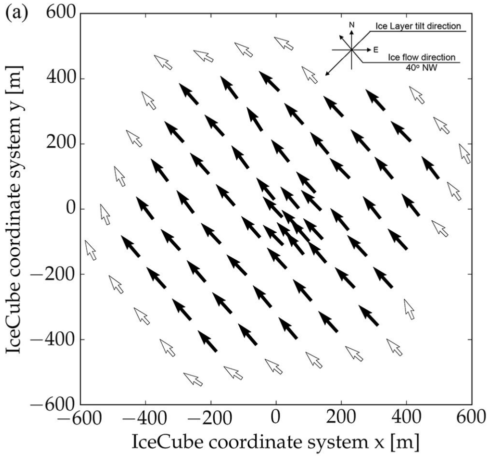
Improved Ice Modeling - Birefringence

First time ice microstructure has been included in the modeling of ice optical properties at macroscopic scales (In situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory ([TC, 18, 75–102, 2024](#)))





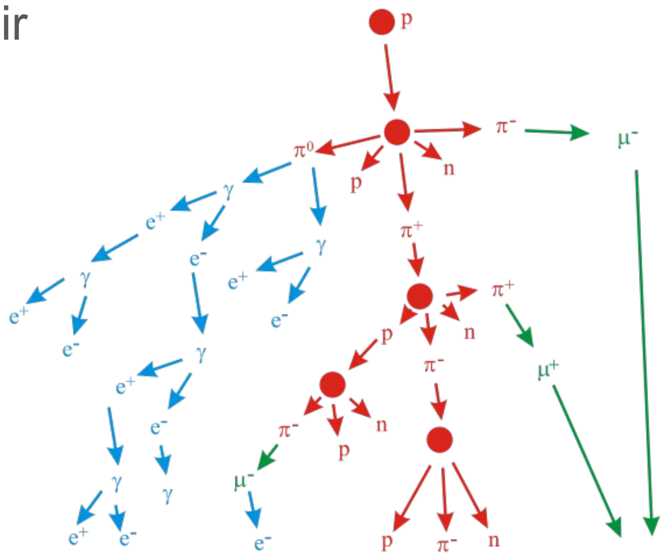




Atmospheric Neutrino Background

Cosmic rays interacting in the atmosphere induce air showers where neutrinos are produced

- Conventional - charged pion & kaon decays
  - Dominant at low energies
  - Follows ~$E^{-3.7}$
- Prompt - charmed meson decays
  - Similar zenith & energy distribution as astrophysical neutrinos



Wikimedia commons

Atmospheric Neutrino Modeling Update

Old: **Barr et al. (2006)** parametrization (+2 interpolation parameters for Cosmic Ray flux)

Propagating uncertainties originating from hadron productions

6 + (2 normalization) fit parameters used in IceCube

Nominal flux: GaisserH4a + SIBYLL 2.3c

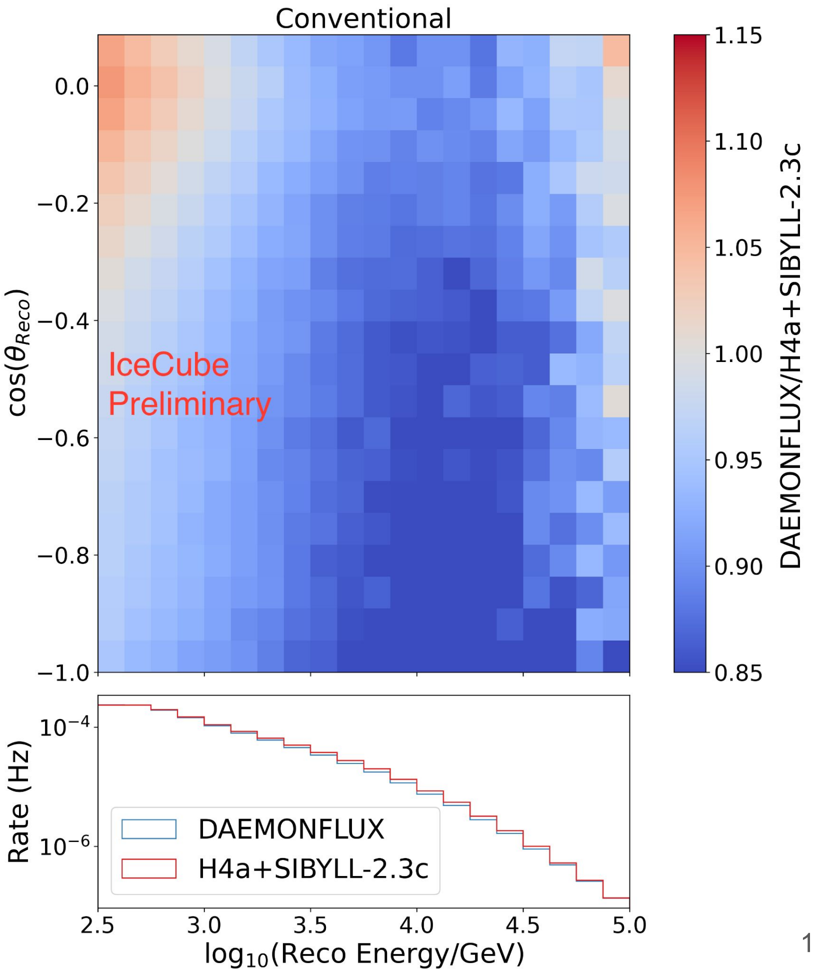
New: **DAEMONFLUX**

Calibration from **cosmic muon data** and constraints from **fixed-target experiments**

16 + (2 normalization) fit parameters used in IceCube

Conventional Neutrino Flux

Up to 15% difference



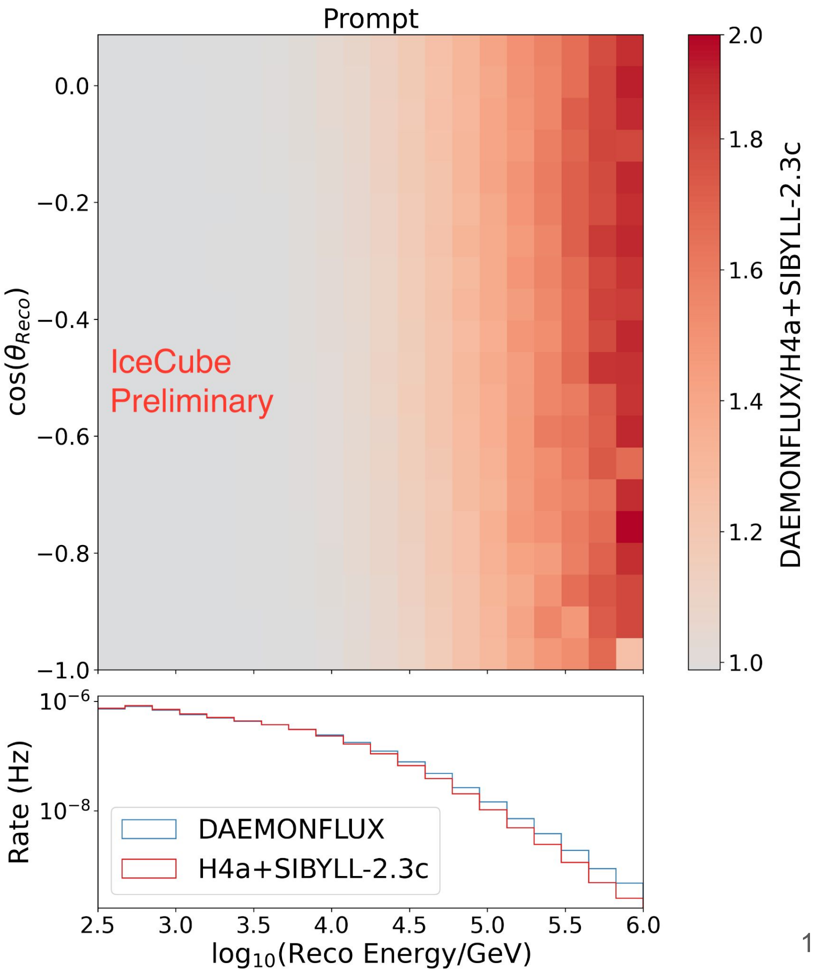
Next: Prompt neutrino flux

Prompt Neutrino Flux

Up to a factor of 2 difference at high energies

DAEMONFLUX predicts higher prompt flux → stronger degeneracy between prompt and astrophysical fluxes

Impact on sensitivity?



Sensitivity Tests

Throughgoing Tracks (Northern sky) only

Lower astrophysical normalization

↓

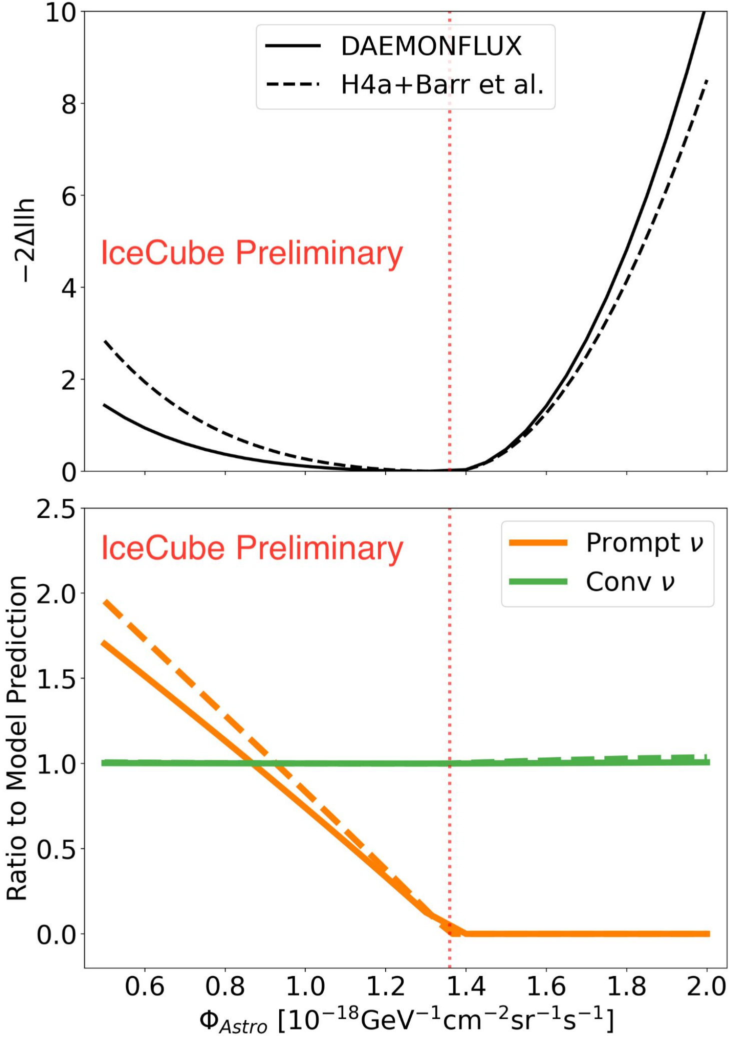
Prompt flux increases to compensate

↓

Stronger degeneracy in DAEMONFLUX

↓

Worse sensitivity



Sensitivity Tests

Entire Sample (all-sky)

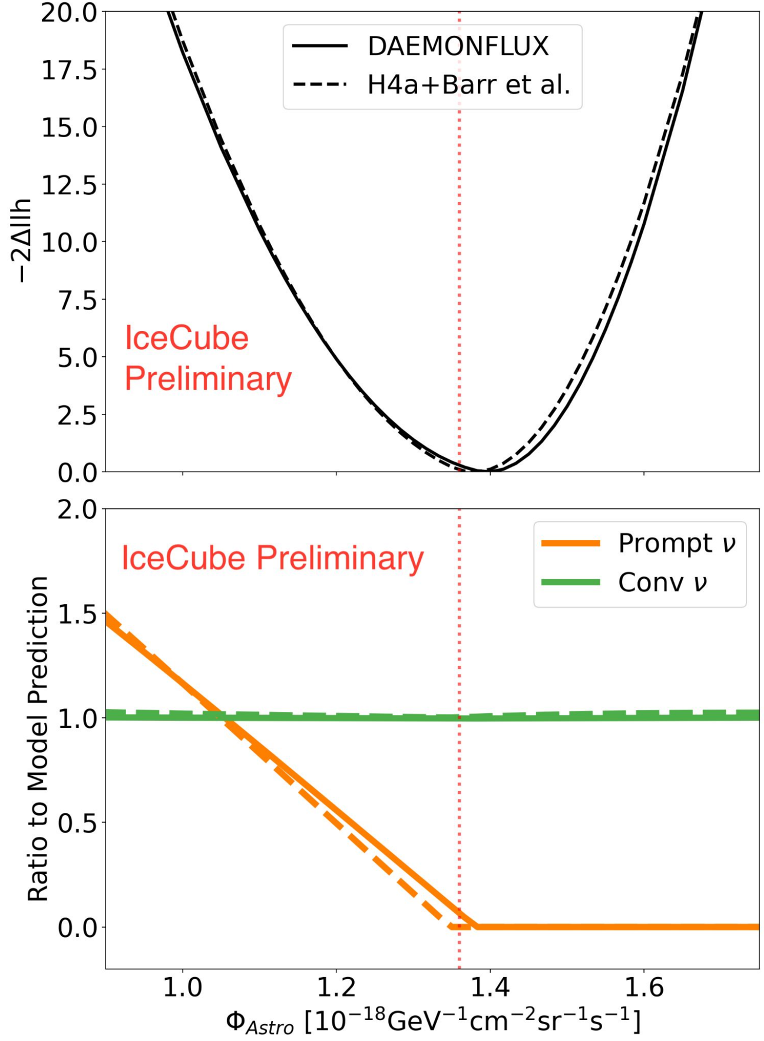
Lower astrophysical normalization

Prompt flux increases to compensate

~~Stronger degeneracy in DAEMONFLUX~~

Degeneracy broken by self-veto

Similar sensitivity



Potential to Probe PeV Region

Injected 2 models (solid lines)

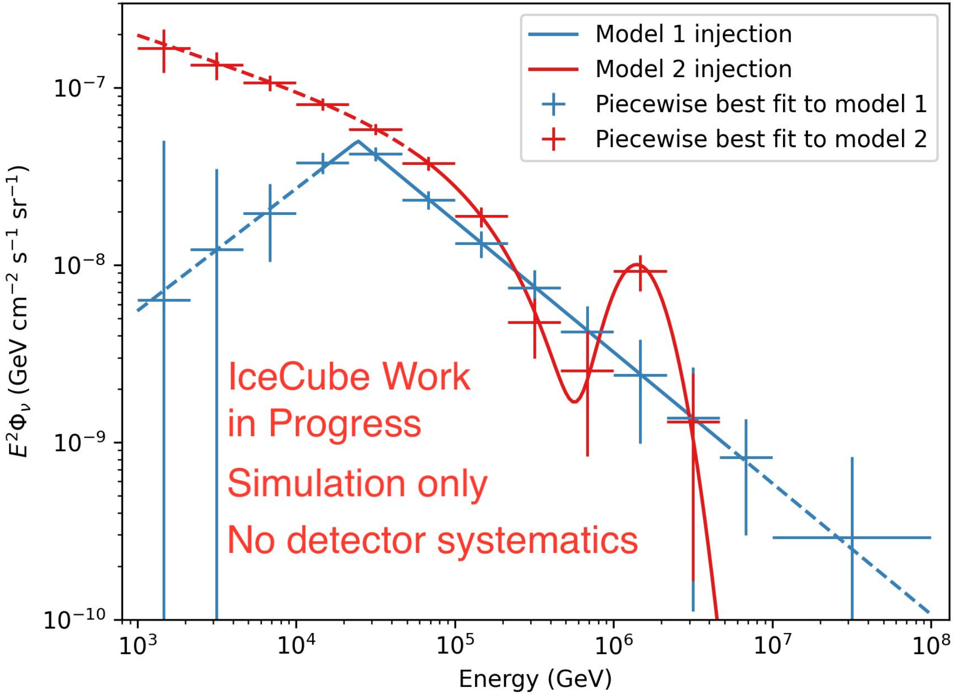
BPL

Combined Fit result

SPL w/ cutoff **+ PeV bump**

External fit to public HESE data

Best fit differential fluxes with ICEMAN Diffuse (crosses)

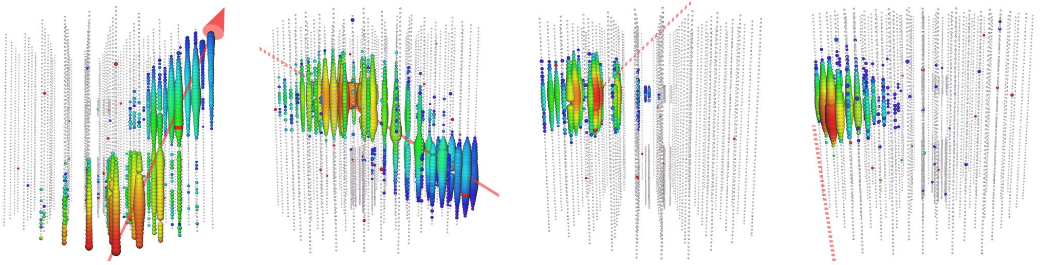


Summary and outlook

- Characterize the diffuse flux with
  - Increased statistics
  - Updated event reconstructions
  - Improved modeling of
    - Ice
    - Atmospheric backgrounds
- Probe the PeV region
  - Constrain UHECR source scenarios
  - KM3NeT UHE neutrino (220^{+570}_{-110}PeV) and IceCube non-observation above 20 PeV

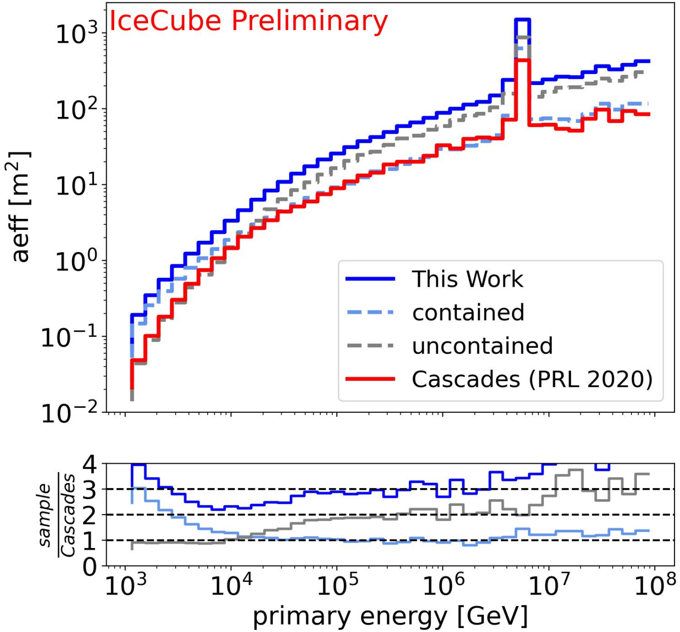
Future

- Flavor measurement
- BSM tests



(a) Throughgoing track (b) Starting track (c) Contained cascade (d) Uncontained cascade

Last used in 2021
[Nature volume 591, pages 220–224 (2021)]



Inclusion of uncontained cascades

↓

4x cascade effective area above 10PeV

Backup

Final Level Histograms