From Detector to Astrophysics: Building Experiments & Data Samples That Power Discovery

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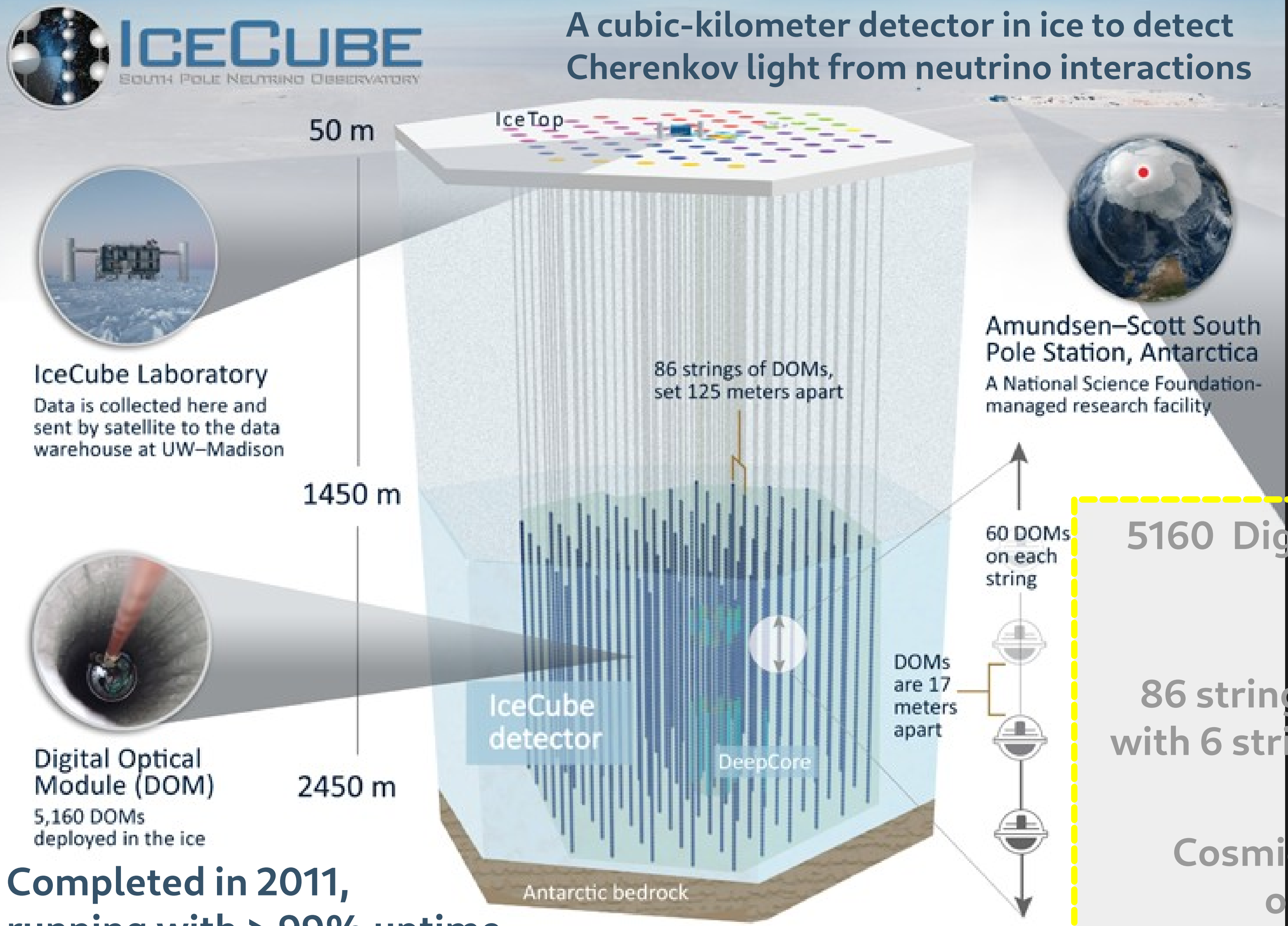
Tata Institute of Fundamental Research, November 26 2025

Outline

- Development of a neutrino dataset for astrophysical measurements
- Standardizing a filter stream
- Cosmic-ray projects
- Roles of leadership
- Future projects

A cubic-kilometer detector in ice to detect Cherenkov light from neutrino interactions



Completed in 2011, running with > 99% uptime

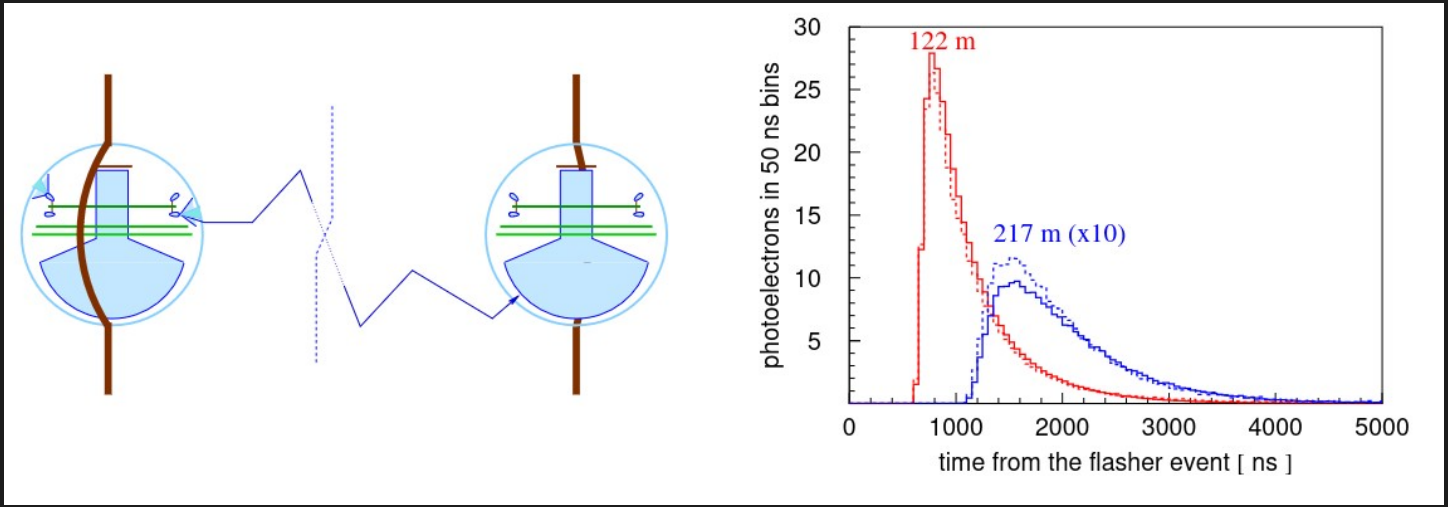
5160 Digital Optical Modules (DOMs)

86 strings, dense infill array with 6 strings, called DeepCore

Cosmic-ray array IceTop on the surface

Calibration of ice

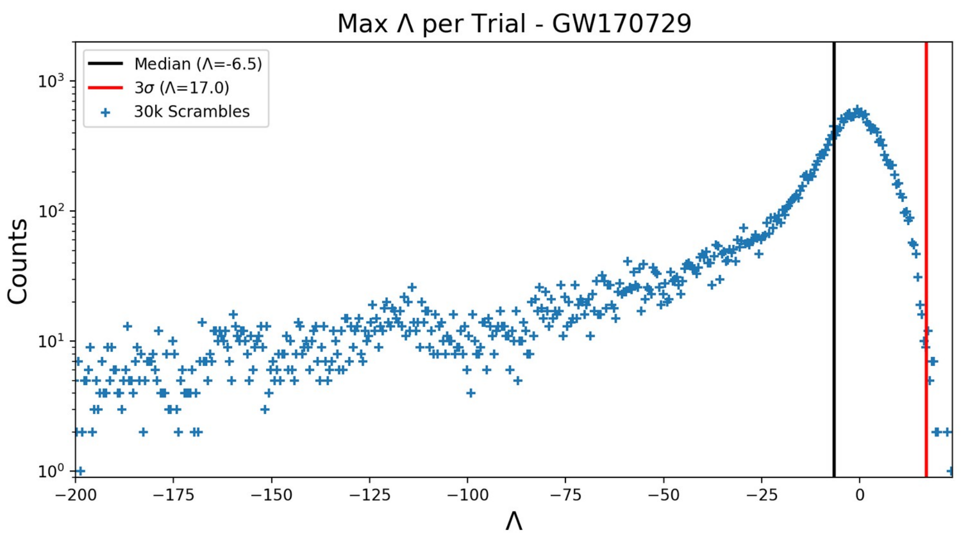
- Each DOM is equipped with 12 LEDs
- Light pulses with known intensity, position, orientation, and wavelength are emitted into the ice during dedicated calibration runs
- Neighboring DOMs record arrival times and charge



[NIM A711:73,2013]

Test statistic & p-value

- Time window: 1000 s (± 500 s)
- Scan over the sky, look for overlap between neutrino and GW events
- Spatial prior (w) from healpix skymap of GW events
- Maximum best-fit value (TS) recorded for each trial for each GW event



Spatial prior term

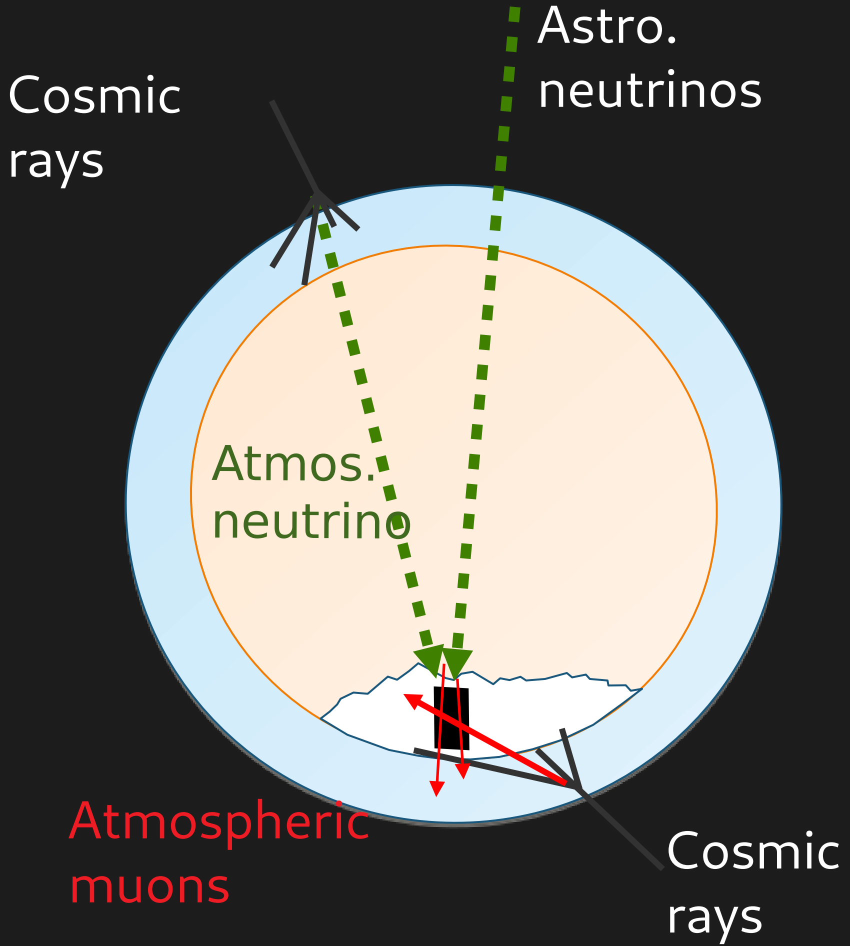
Hypothesis testing

$$\text{Test Statistic (TS)} = \max.\left\{ 2\ln\left(\frac{\mathcal{L}_k(n_s, \gamma) \,.\, w_k}{\mathcal{L}_k(n_s = 0)} \right) \right\}$$

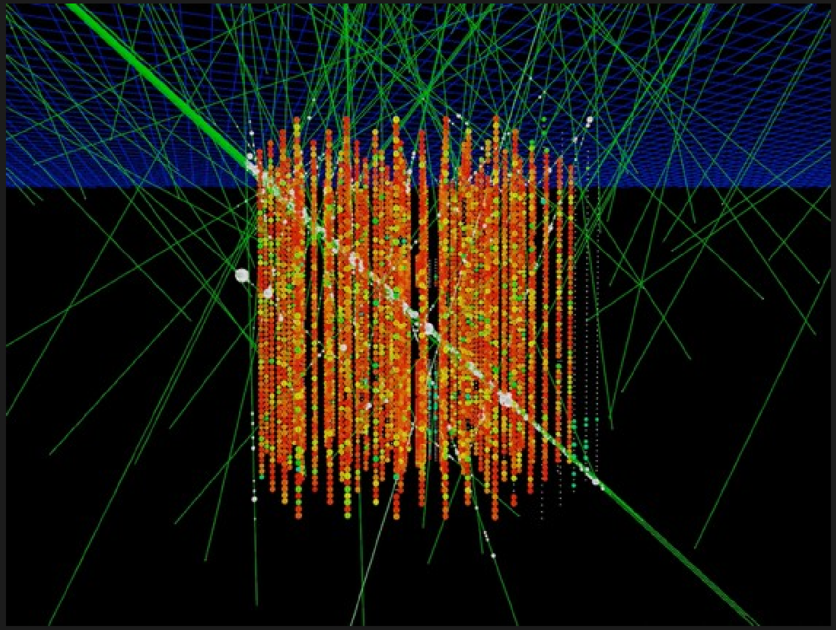
Evaluate at all pixels

Preparing a neutrino-rich dataset

Events in IceCube



3000 cosmic-ray muons in 1 second
1 atmospheric neutrino in a minute
1 astrophysical neutrino in a day



10 ms of IceCube data

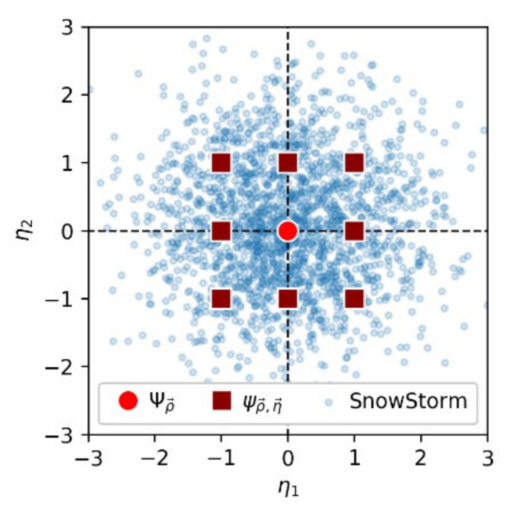
MESE dataset

- IceCube's flagship data sample HESE (High Energy Starting Events) gives a neutrino-rich data sample at 60 TeV and above
- Goal: to push this down to lower energies
- Motivation: 2 year data sample with Medium Energy Starting Events (MESE)
- New improved MESE selection with starting events above 1 TeV

Work with V. Basu (student supervision)

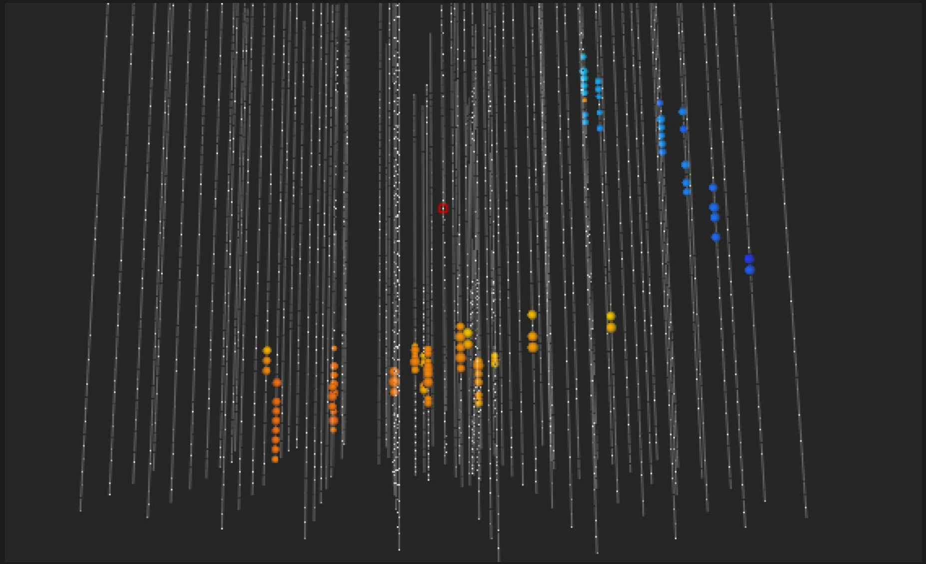
Highlights

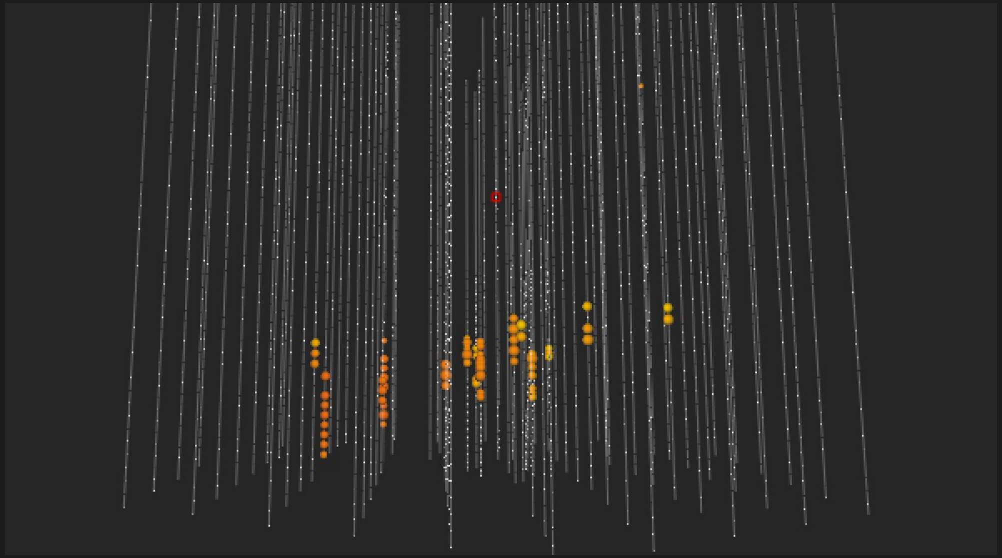
- Updated simulations using calibration information
- Updated treatment of systematics
  - "SnowStorm method, with perturbations of calibration-informed parameters
- DNN for cascades/tracks disrimination
- 11.4 years of data



Pre-selection cuts

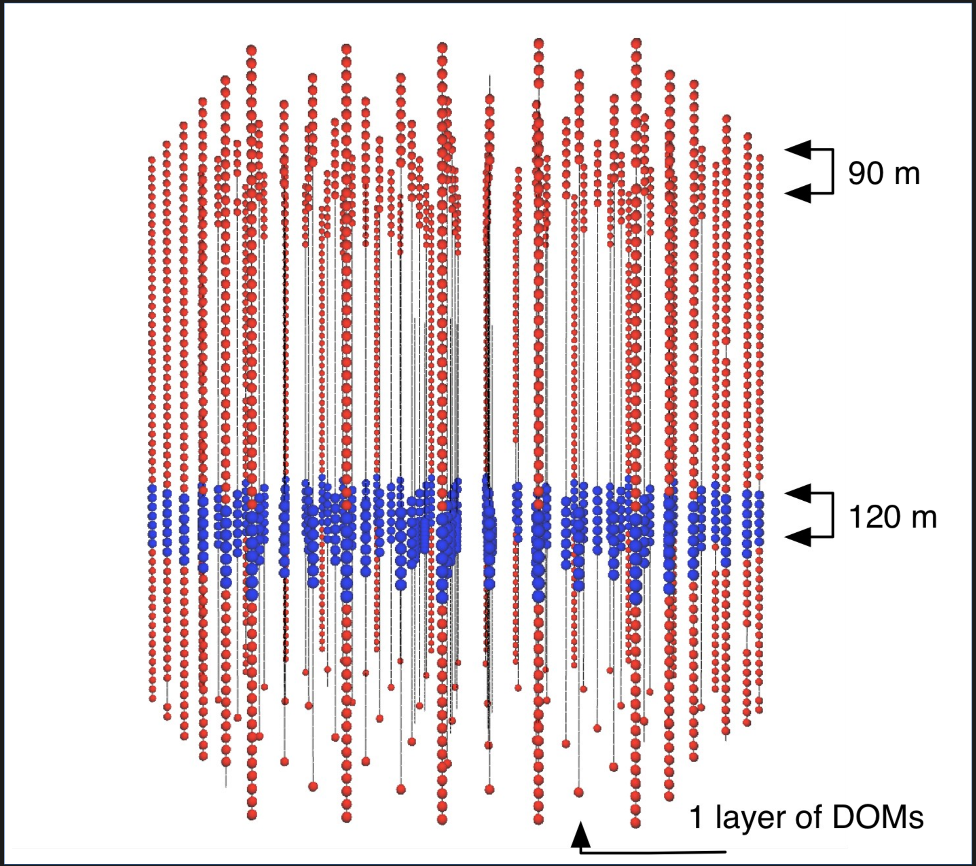
- Topological splitter applied to remove coincident events and retain neutrino events
- Events with charge < 100 pe are removed
- Number of hit strings > 3





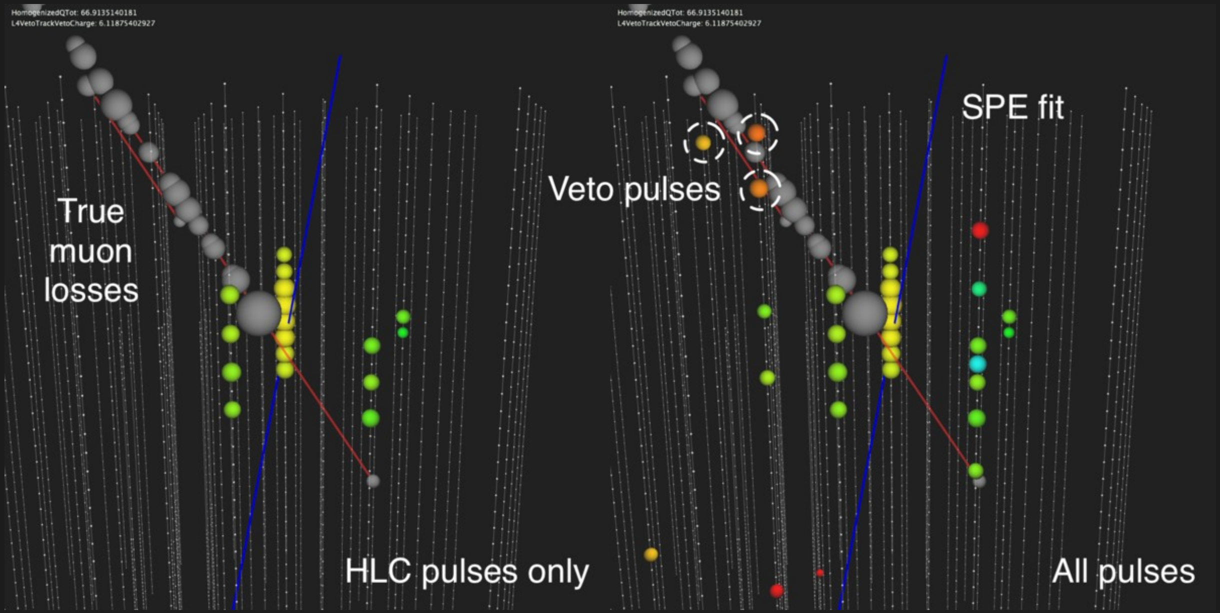
Level 3: Outer Layer Veto

- Inspired by the outer layer veto of HESE selection
- Cut dependent on total charge of the event
- 3 pe in the veto region for events with total charge > 6000 pe and 0 pe for lower charge events
- Reduces atmospheric muon rate by ~ 5 orders of magnitude
- Remaining low-charge muons dominate the lower energy range



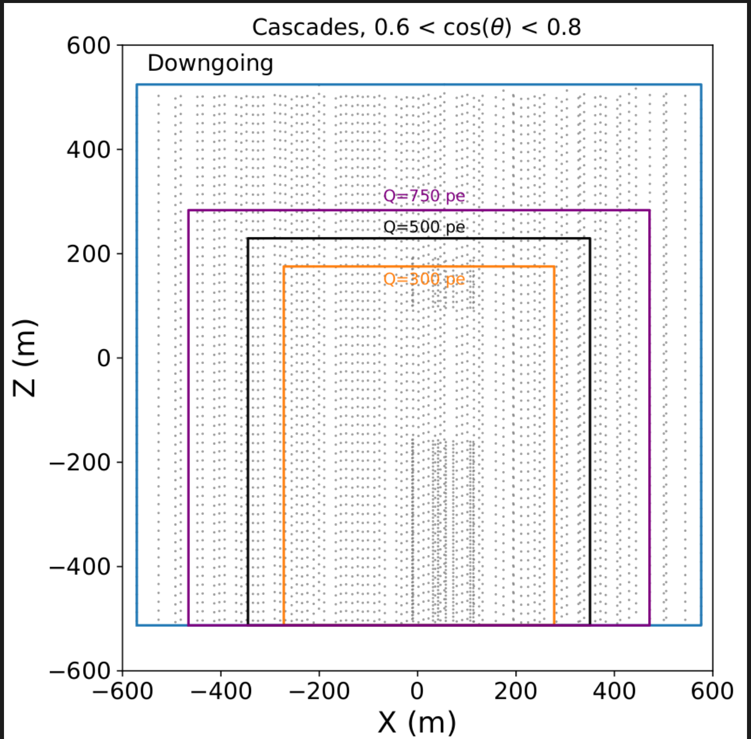
Level 4: Downgoing Track Veto

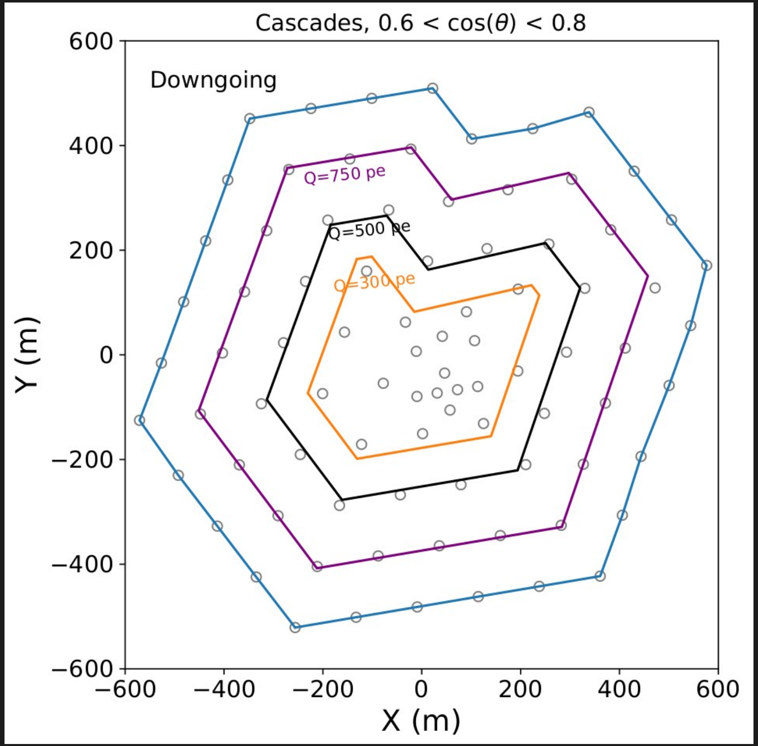
- Next stages are targeted at removing the remaining dim muons
- Dim muons that don’t show up in a cleaned pulse series might show up as single isolated hits
- Reject events with veto charge > 2pe (>0.5 pe) if total charge >1000 pe (< 1000 pe)
- Reduces the rate of muons by an order of magnitude



Level 5: Fiducial Volume Cut

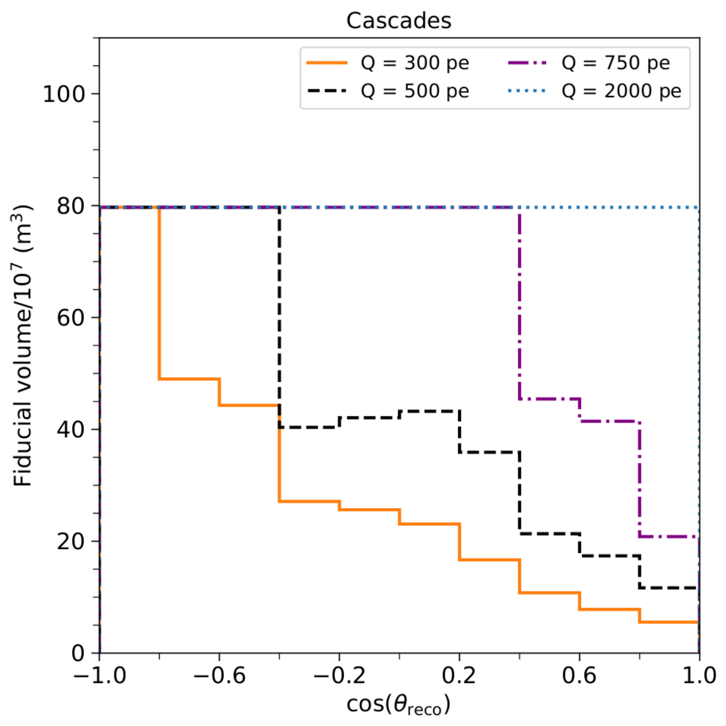
- Changing scales of veto region based on the charge and zenith angle of the event
- Downgoing events undergo harsher cuts
- Cuts are also separately defined for cascades and tracks

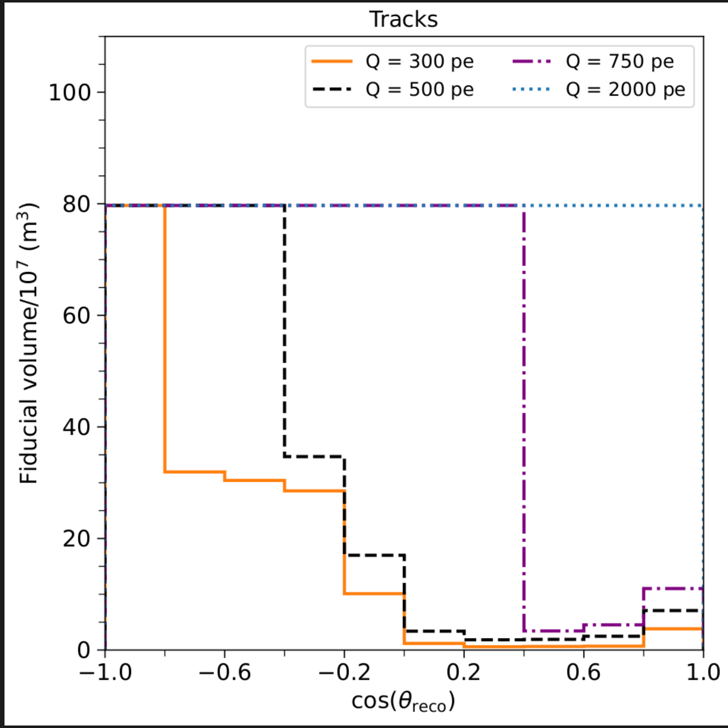




Level 5: Fiducial Volume Cut

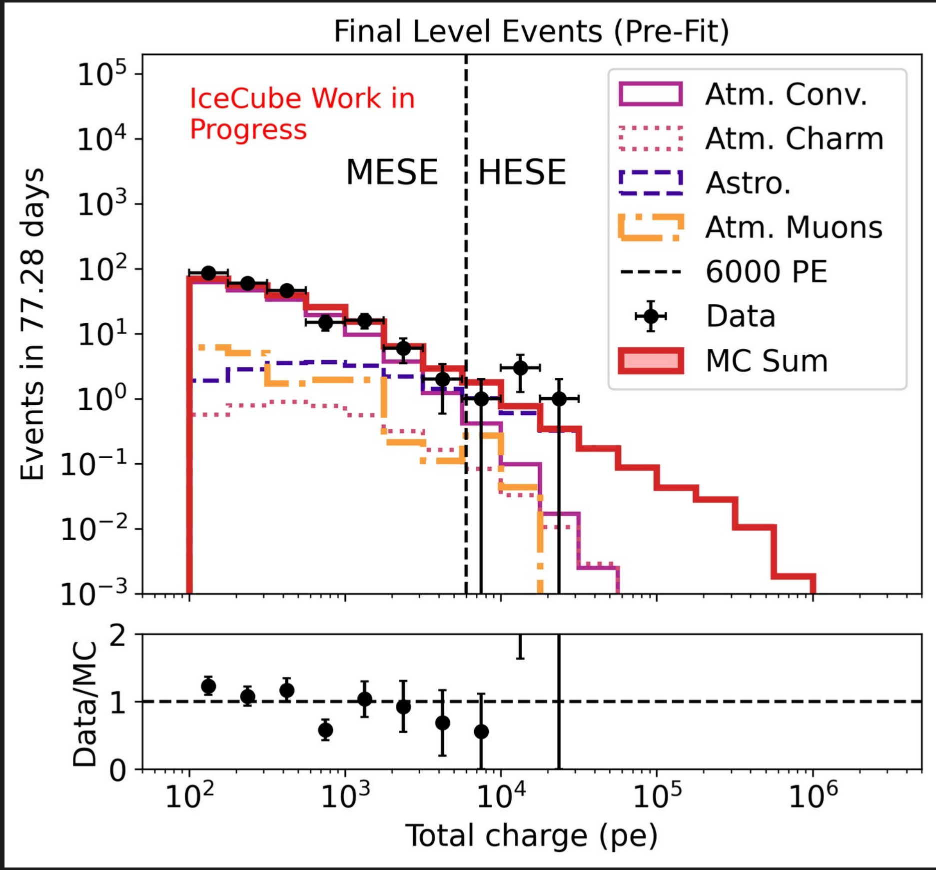
Zenith dependence of fiducial volume cuts



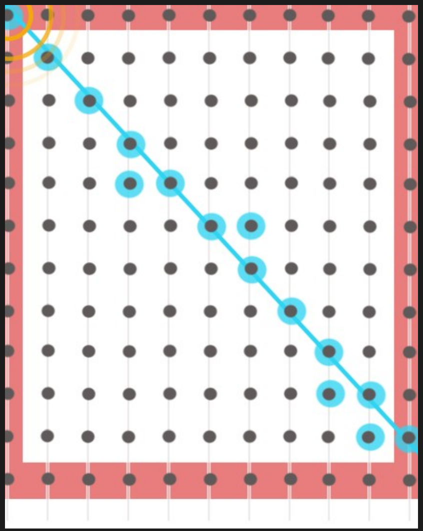


Level 5: Fiducial Volume Cut

- These series of cuts gives a neutrino-dominated sample
- Fiducial volume cut reduces muon rate by ~ 4 orders of magnitude

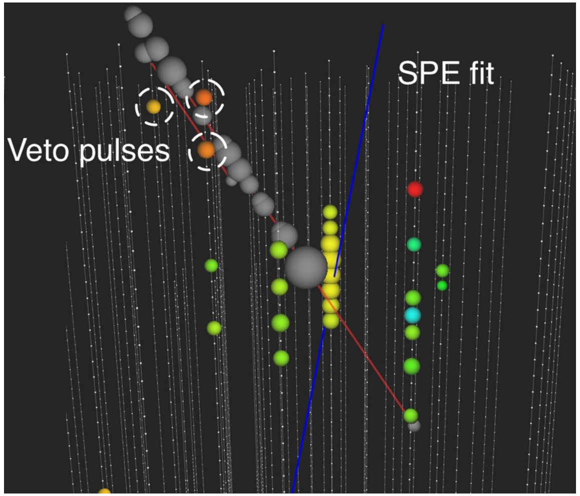


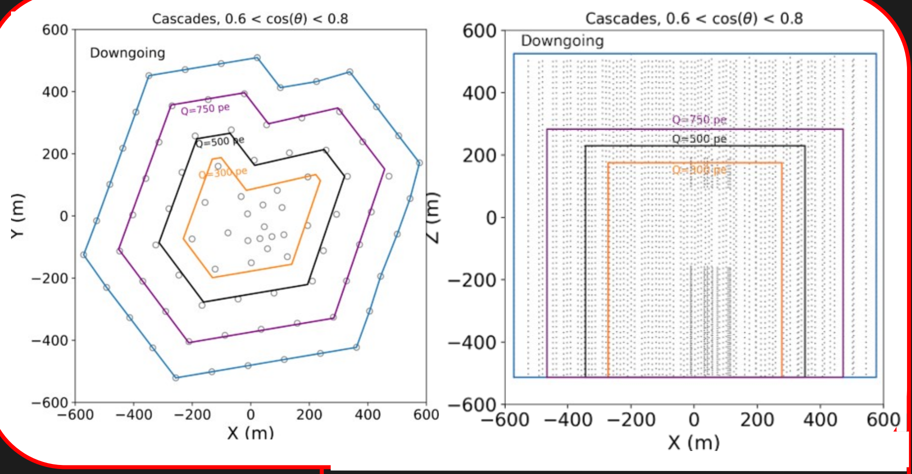
MESE Selection Procedure Summary



L3: **Outer Layer Veto**, reject atmospheric muons starting outside detector

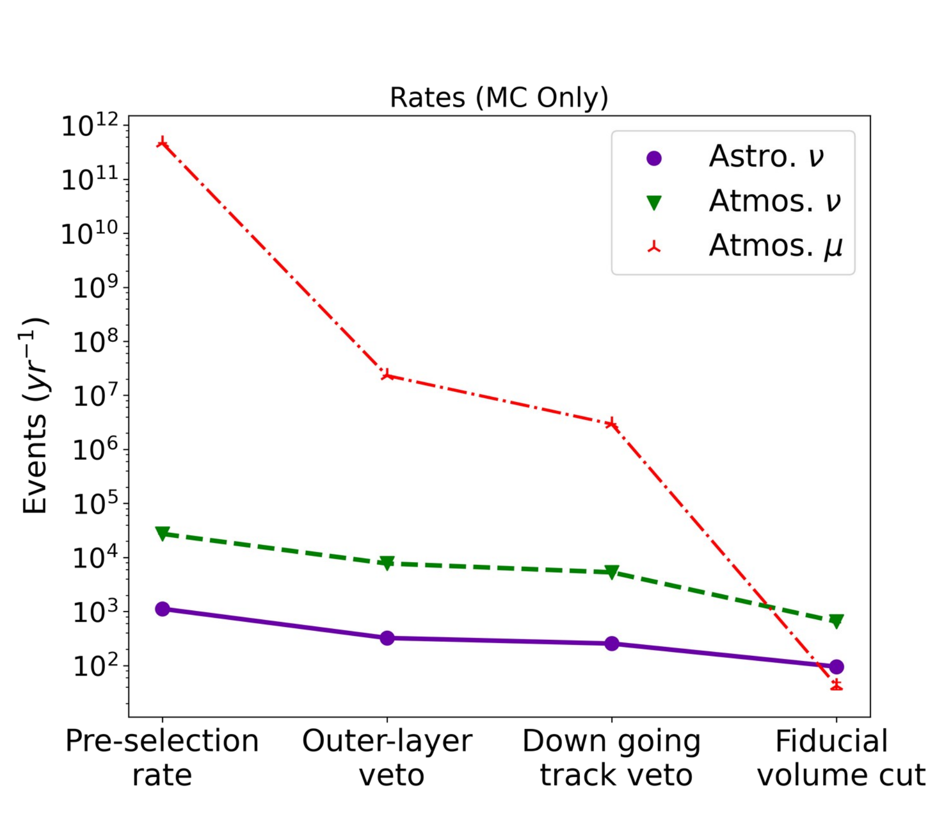
L4: **Downgoing Track Veto**, link isolated hits with muon hypotheses





L5: **Fiducial Volume Scaling** for dim events, veto hits closer to the reconstructed vertex.

Event rates with MESE



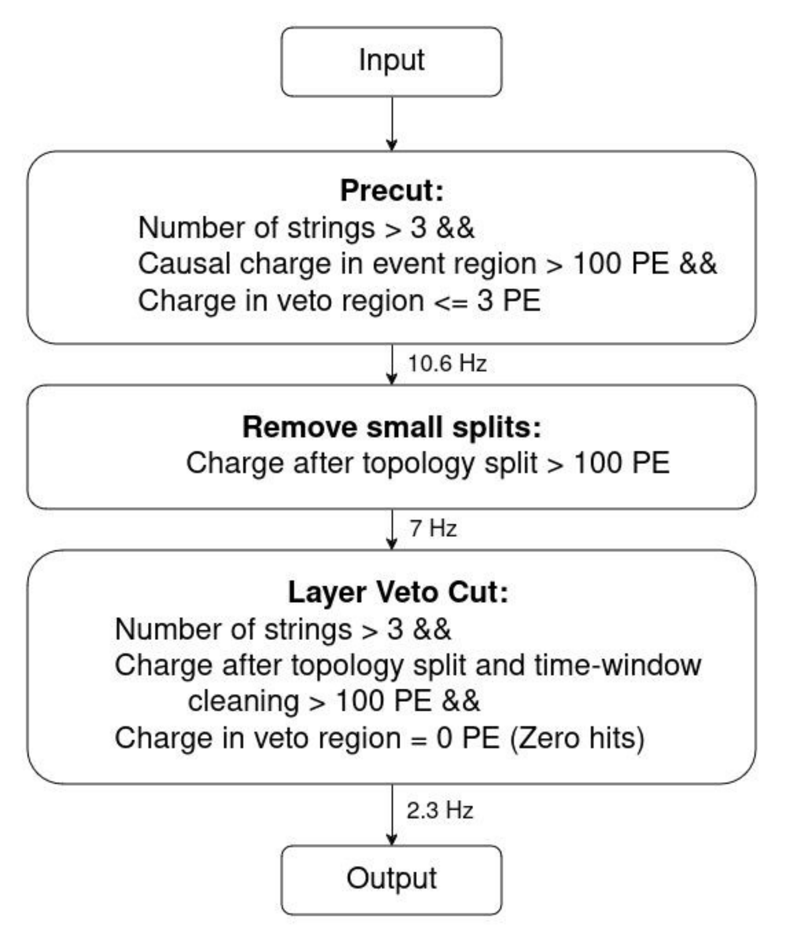
Rates (yr^{-1}) (sim.)	Astro. ν	Atm. ν	Atm. μ
Total	95.3	644.3	40.9

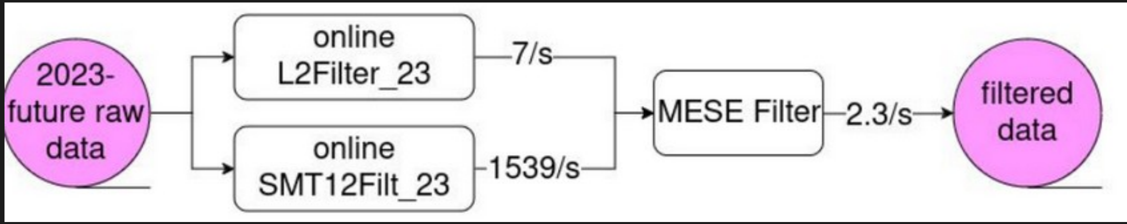
Event sample successful in making measurements of cosmic neutrino spectrum and energy composition!

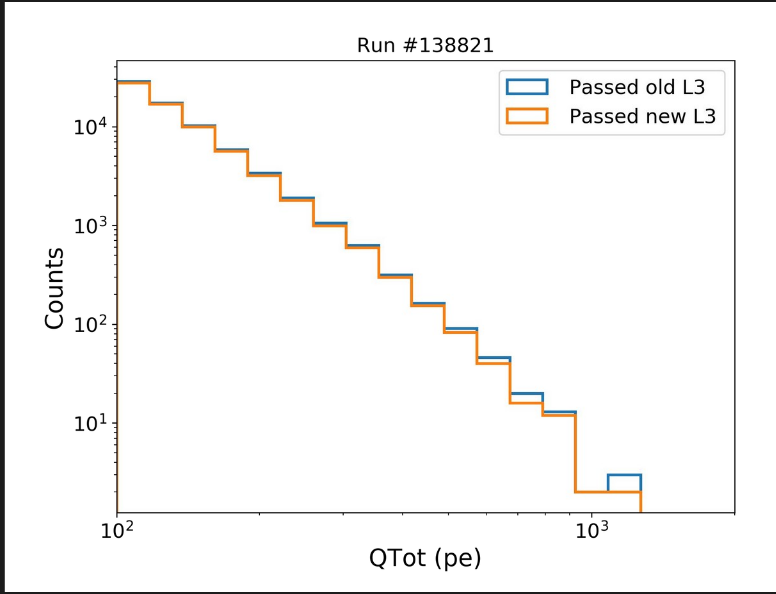
Filter Updates in IceCube

- IceCube updated its filters in 2023 to streamline data collection and processing
- MESE filter included during this stage, ensured consistent processing of the data sample
- As technical lead, I also managed all filters handled by the neutrino sources working group (more later)

Standardizing MESE filter





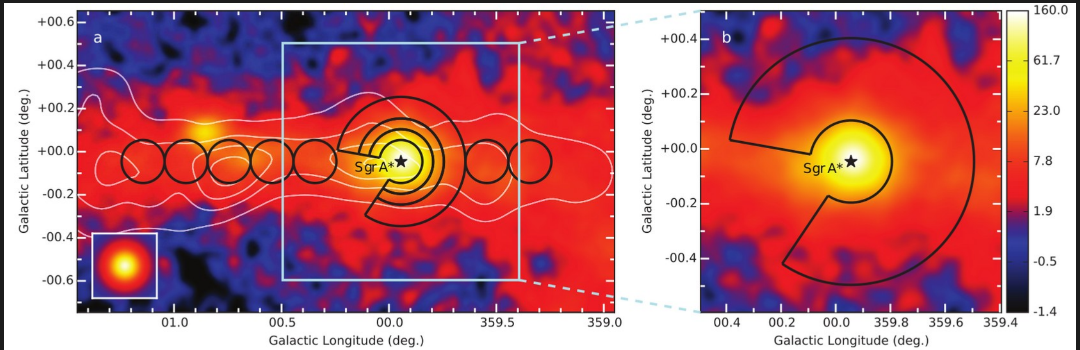


Work by H. Erpenbeck (student supervision)

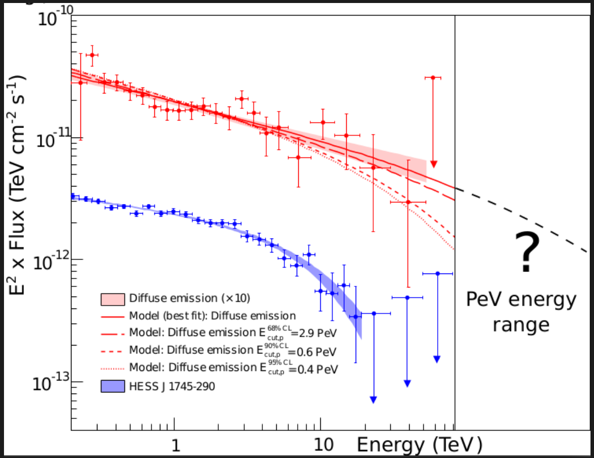
Cosmic-ray projects

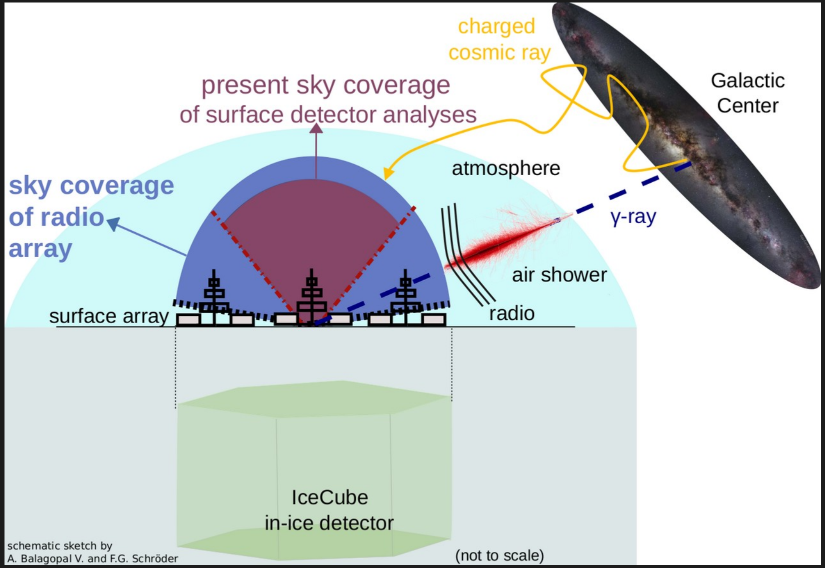
Searching for PeVatrons at the Galactic Center

with a radio array at the South Pole



- Detection of a PeVatron by HESS at the Galactic Center
- Do we have PeV energy gamma rays from here?
- Can a radio air shower array at the South Pole detect this?





Searching for PeVatrons at the Galactic Center

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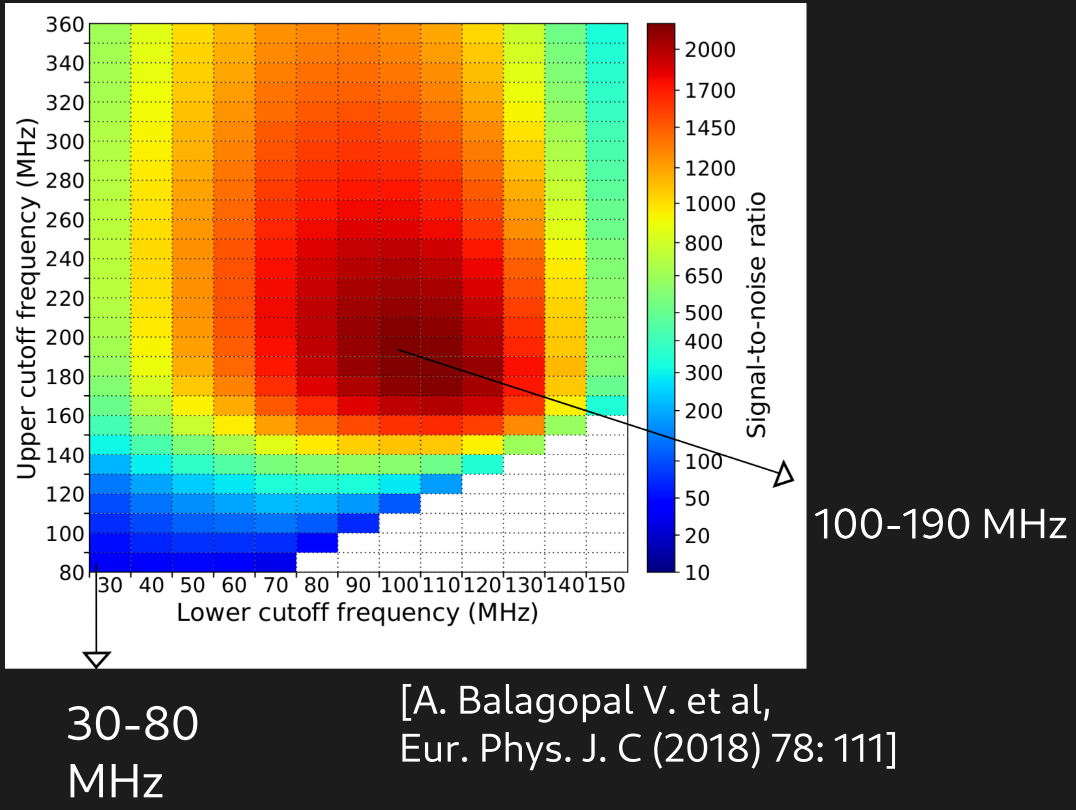
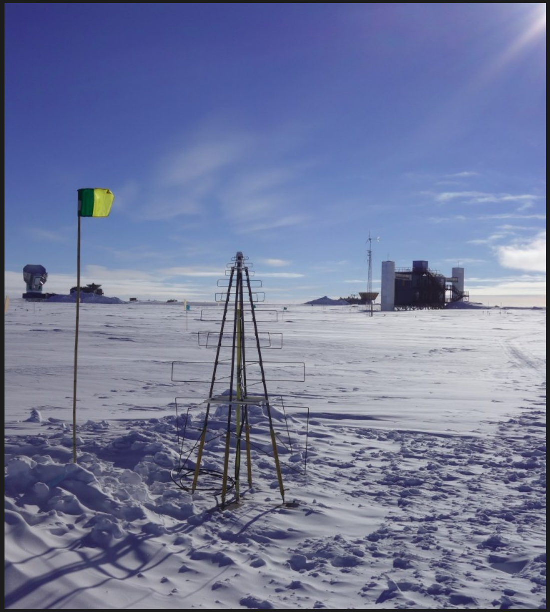


[A. Balagopal V. et al, Eur. Phys. J. C (2018) 78: 111]

Resulted in the approval of a radio array as a part of the Surface Enhancement of IceTop

- Optimized the radio signal-to-noise ratio at different frequencies
- Operation at 100-190 MHz lowers the energy threshold by ~10 orders of magnitude

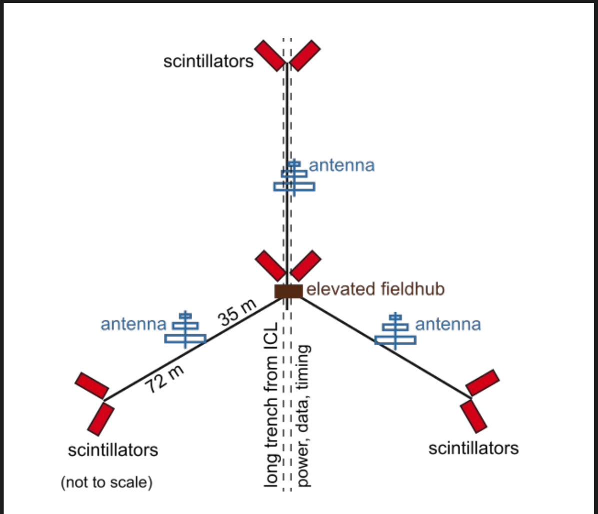


Prototype radio antennas at the Pole

PhD thesis work

Small roof station at University of Delaware

- Station similar to surface-array enhancement of IceTop
- 8 scintillator panels per station, each with ~1.5 m² sensitive area
- 3 radio antennas operating at 50-350 MHz
- Helps in calibration, stabilizing the system



Small roof station at University of Delaware

- Lots of space on the roof of the building
- Can be used for coincident studies with the neutron monitor at UD, NuDot (double beta decay experiment) at UD
- Currently establishing stable configuration for roof deployment

Work during summer 2025

- Cabling done successfully
- Heat tests (need white paint), concrete slabs for stability

- Next steps:
  - Moving to the main roof, connecting scintillators and antennas to the DAQ
  - Future solar panels for power supply

Testing at roof courtyard

Work by J. Canchala
(F. Schroeder's intern)

Roles of leadership

Roles of leadership, past and present

- KSETA PhD representative (2017-2018): graduate school for the PhD researchers of Karlsruhe Institute of Technology
- IceCube Neutrino Sources Working Group Technical Lead (2022-2024):
  - Set up a streamlined structure for reproducibility review, training junior reproducibility reviewers, and giving the final technical green light for the analysis to proceed towards unblinding.
  - Managed the filter changes from the working group, coordinated with the operations and software team

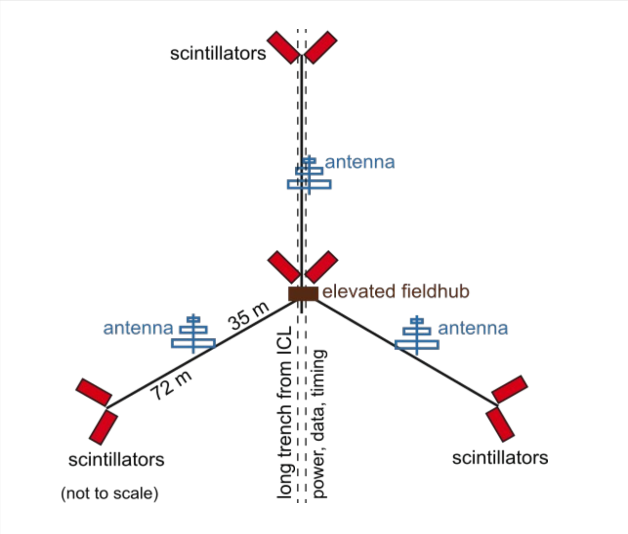
Roles of leadership, past and present

- IceCube's sub-TeV Neutrino Sources Group Coordinator (2023-2024): technical support group for low-energy astrophysical searches within IceCube
- IceCube Impact Award Committee Member (2023-Present)
- IceCube Low-Energy Astrophysics Working Group Lead (2024-Present):
  - Newly formed group covering MeV-TeV scale astrophysics
  - Helped lay the foundation, structure, and guidelines for the working group
  - Provide guidance and direction to the studies conducted in the group

Future Focus

Surface enhancement of IceTop

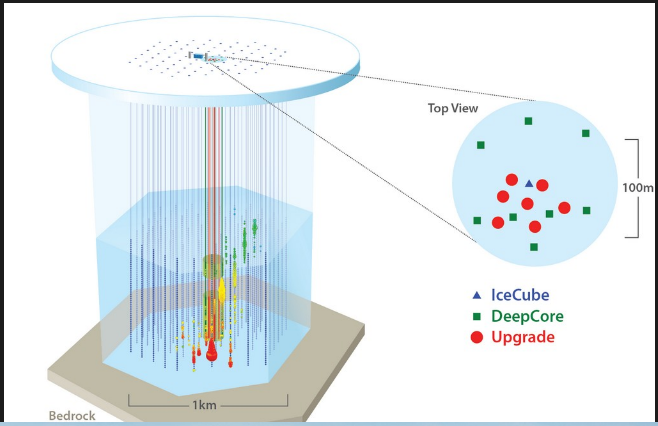
- Currently 3 prototype stations deployed
- Lots of scope for improving data taking, streamlining triggering, processing and filtering, since regular IceCube trigger and filtering stream is separate
- With this, move towards studying air showers, and prepare for expansion to full array
- With my connections at KIT and Delaware, we can set up a detector testing centre at TIFR to support full-scale deployment
- Can start optimization tests for IceCube-Gen2 surface array
- Can utilize connection with NCRA to support this

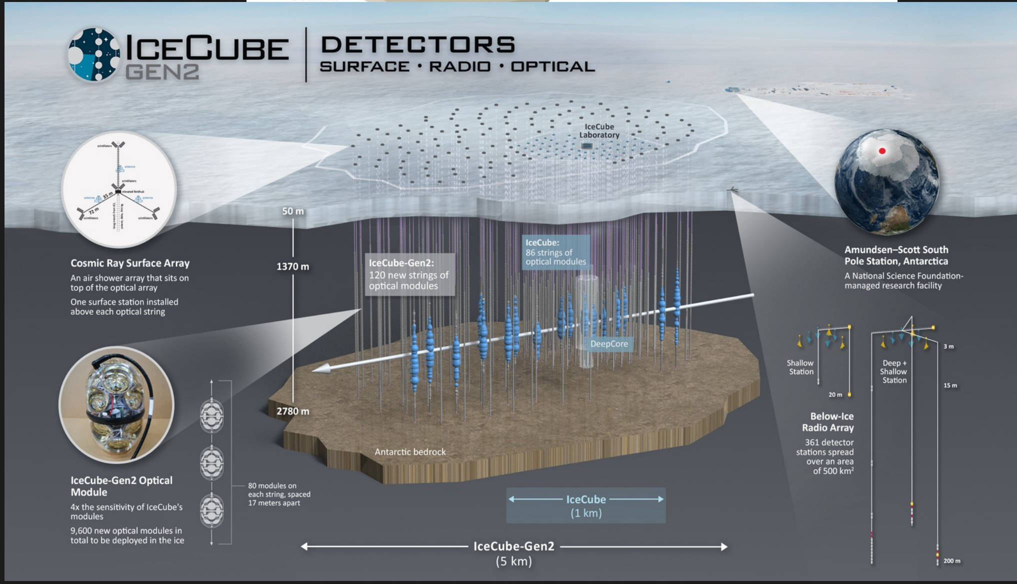


IceCube Upgrade & IceCube-Gen2

- The new strings will also hold several calibration devices
- Support understanding ice systematics (hole ice, bulk ice, anisotropy) with these calibration devices
- Use input from better calibration to improve reconstructions of low energy events
- This can be used for low-energy astrophysics analyses

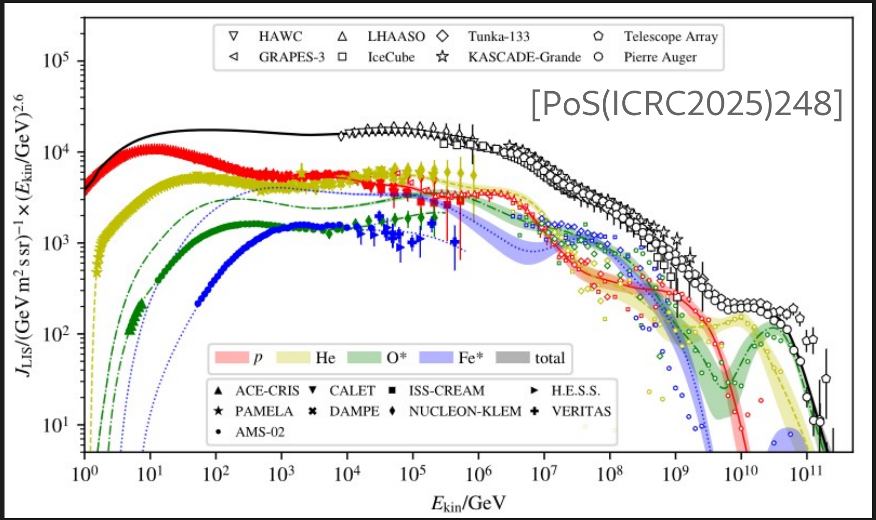
- Involvement in IceCube -Gen2 by providing infrastructure like cabling
- Expansion to in-ice radio detection support (synergy with surface radio setup)





Other Projects: GRAPES-3

- GRAPES-3 can help understand hadronic interaction models better
- At the sweet spot in energy where data is needed for global spline fit
- Synergies with IceCube cosmic-ray science allows us to perform joint studies (MoU)
- Air-shower physics with GRAPES-3 can be advanced by including radio detectors



- Possibility to collaborate with LIGO-India or IACTs at Hanle for advancing multi-messenger studies

Backup

Requirements

- ~500 sq-feet room for assembly and testing
- Prefer low-RF conditions
- Access to outdoor space for testing station functionalities
- Coordinate with CRL for outdoor testing
- Computing resources
- Expected budget: ~2-3 crores

Source search likelihood

$$\mathcal{L} = \frac{(n_s + n_b)^N}{N!} e^{-(n_s+n_b)} \prod_{i=1}^{N} \left(\frac{n_s \mathcal{S}_i}{n_s + n_b} + \frac{n_b \mathcal{B}_i}{n_s + n_b} \right)$$

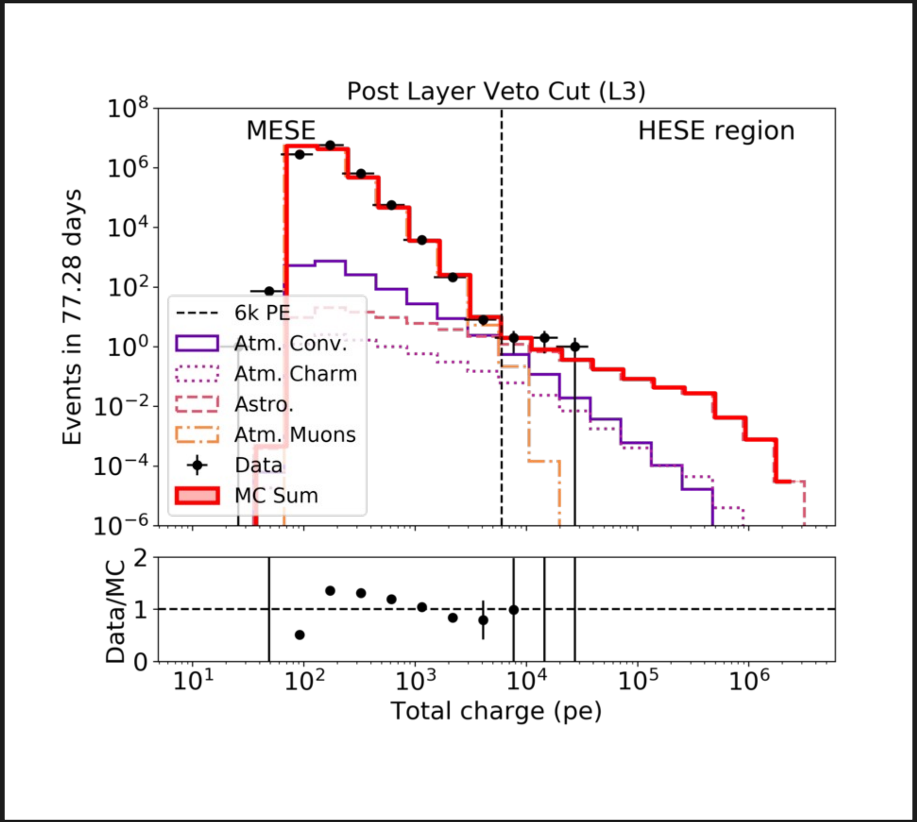
Likelihood ratio test for spectrum

Analysis	SPL $[\phi_0(\Lambda)^{-\gamma}]$	SPE $\left[\phi_0(\Lambda)^{-\gamma} e^{\frac{-E_\nu}{E_{\text{cutoff}}}}\right]$	BPL $\left[\phi_{0,\text{broken}}(\frac{E_\nu}{E_{\text{break}}})^{-\gamma_{\text{BPL}}}\right]$	LP $\left[\phi_0(\Lambda)^{-\alpha_{\text{LP}}-\beta_{\text{LP}}\log_{10}(\Lambda)}\right]$
MESE	$\phi_0 = 2.13^{+0.18}_{-0.17}$ $\gamma = 2.55^{+0.04}_{-0.04}$	$\phi_0 = 3.98^{+1.14}_{-1.32}$ $\gamma = 2.16^{+0.23}_{-0.16}$ $\log_{10}(\frac{E_{\text{cutoff}}}{\text{GeV}}) = 5.40^{+0.51}_{-0.23}$	$\phi_0 = 2.28^{+0.22}_{-0.20}$ $\gamma_1 = 1.72^{+0.26}_{-0.35}$ $\gamma_2 = 2.84^{+0.11}_{-0.09}$ $\log_{10}(\frac{E_{\text{break}}}{\text{GeV}}) = 4.52^{+0.11}_{-0.09}$	$\phi_0 = 2.58^{+0.26}_{-0.26}$ $\alpha_{\text{LP}} = 2.67^{+0.13}_{-0.06}$ $\beta_{\text{LP}} = 0.36^{+0.10}_{-0.08}$
		$-2\Delta\ln\mathcal{L} = 1.8$	$-2\Delta\ln\mathcal{L} = 27.3$	$-2\Delta\ln\mathcal{L} = 18.8$
CF	$\phi_0 = 1.80^{+0.13}_{-0.16}$ $\gamma = 2.52^{+0.04}_{-0.04}$	$\phi_0 = 2.20^{+0.30}_{-0.25}$ $\gamma = 2.39^{+0.08}_{-0.08}$ $\log_{10}(\frac{E_{\text{cutoff}}}{\text{GeV}}) = 6.15^{+0.37}_{-0.24}$	$\phi_0 = 1.77^{+0.15}_{-0.11}$ $\gamma_1 = 1.31^{+0.50}_{-1.21}$ $\gamma_2 = 2.74^{+0.06}_{-0.07}$ $\log_{10}(\frac{E_{\text{break}}}{\text{GeV}}) = 4.39^{+0.09}_{-0.08}$	$\phi_0 = 2.13^{+0.16}_{-0.19}$ $\alpha_{\text{LP}} = 2.57^{+0.06}_{-0.05}$ $\beta_{\text{LP}} = 0.23^{+0.10}_{-0.07}$
		$-2\Delta\ln\mathcal{L} = 7.5$	$-2\Delta\ln\mathcal{L} = 24.7$	$-2\Delta\ln\mathcal{L} = 16.4$

Astrophysical model: SPL, SPE, BPL, LP

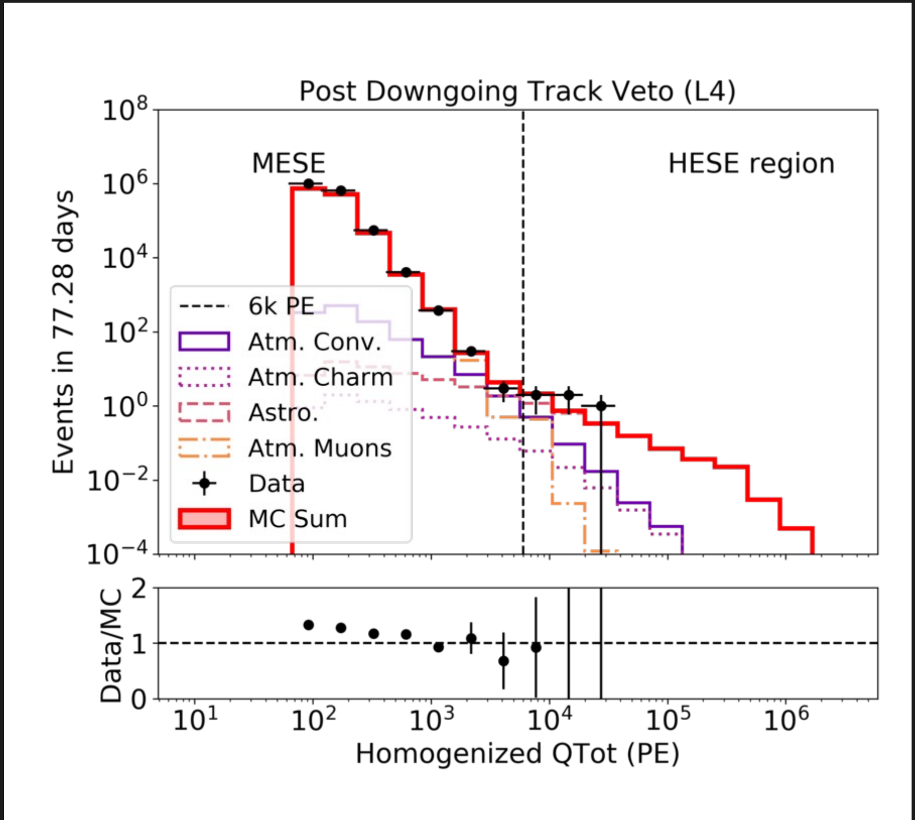
Level 3: Outer Layer Veto

- Reduces atmospheric muon rate by ~ 5 orders of magnitude
- Remaining low-charge muons dominate the lower energy range



Level 4: Downgoing Track Veto

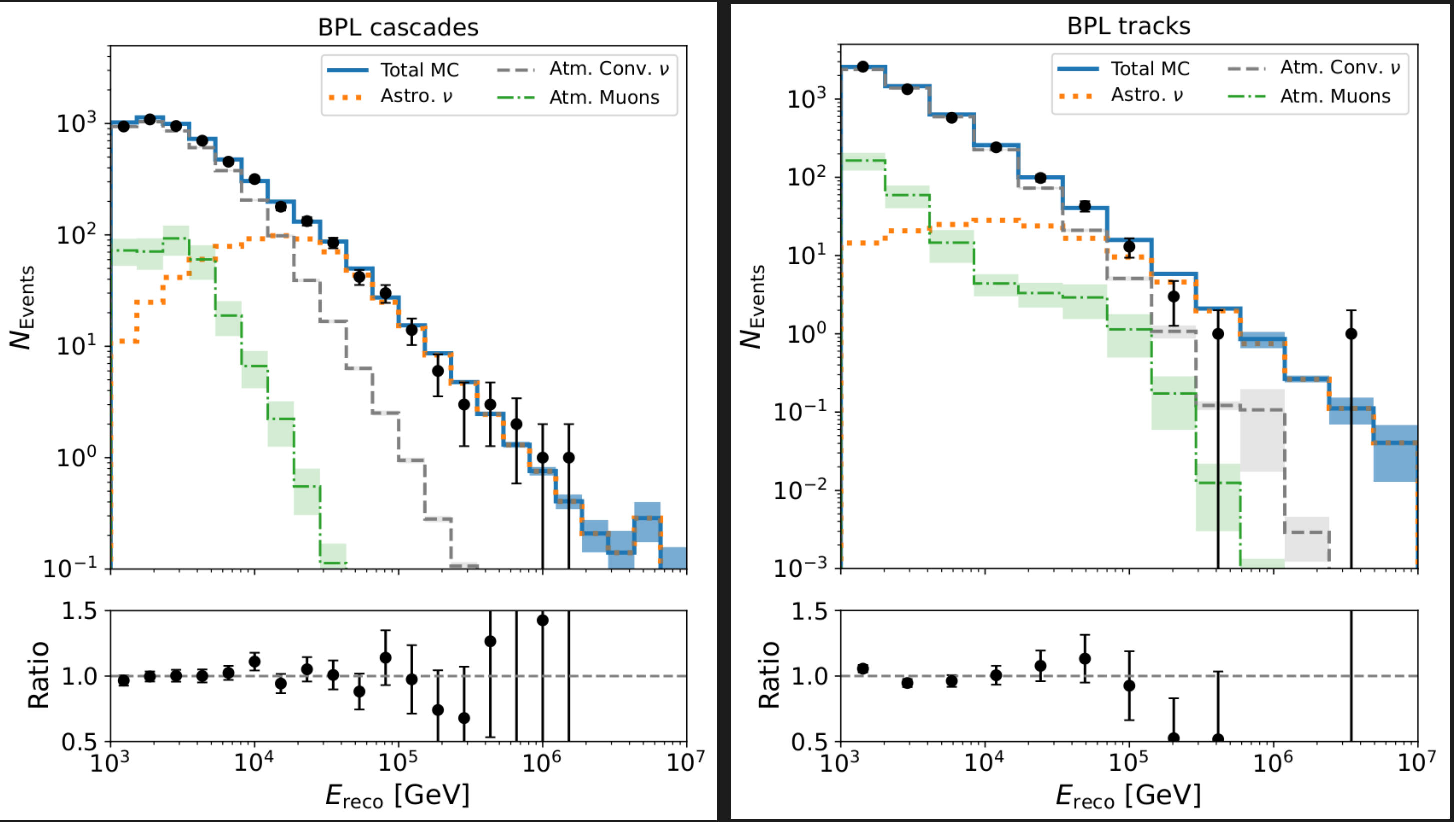
- Reduces the rate of muons by an order of magnitude
- Mostly medium-scaled energy muons are removed
- At this stage, we also apply a deep neural network to separate cascade and track events



MESE Data/MC Comparison

Best fit astro. flux of 2.27 x $\begin{cases} (E/33.1\text{TeV})^{-1.72}, & E < 33.1\text{ TeV} \\ (E/33.1\text{TeV})^{-2.84}, & E > 33.1\text{ TeV} \end{cases}$

Atm. Flux model: GaisserH4a + Sibyll 2.3c



Observed
4968 cascades
and
4920 tracks

MESE Data/MC Comparison

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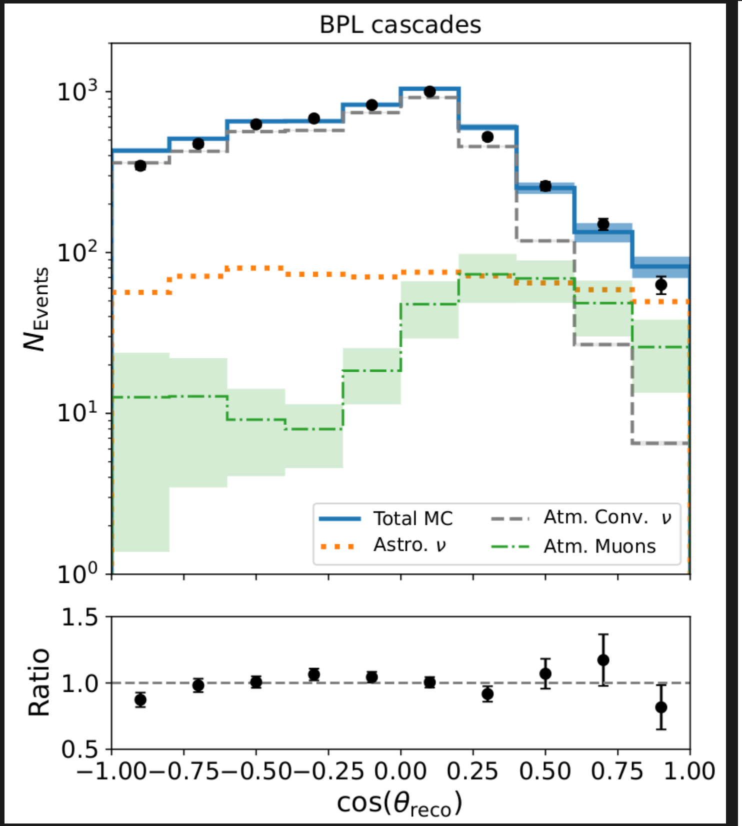

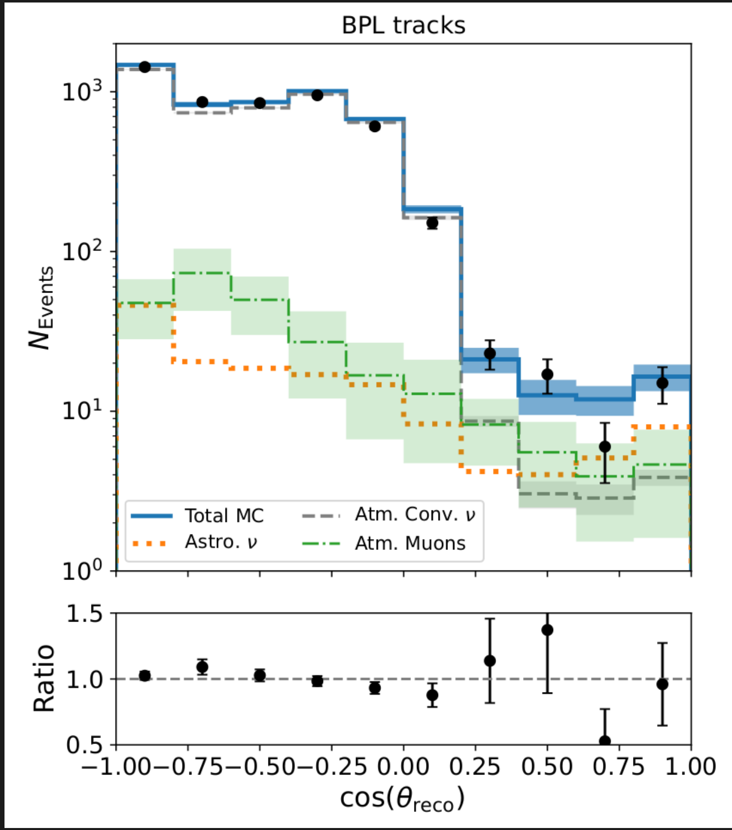

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