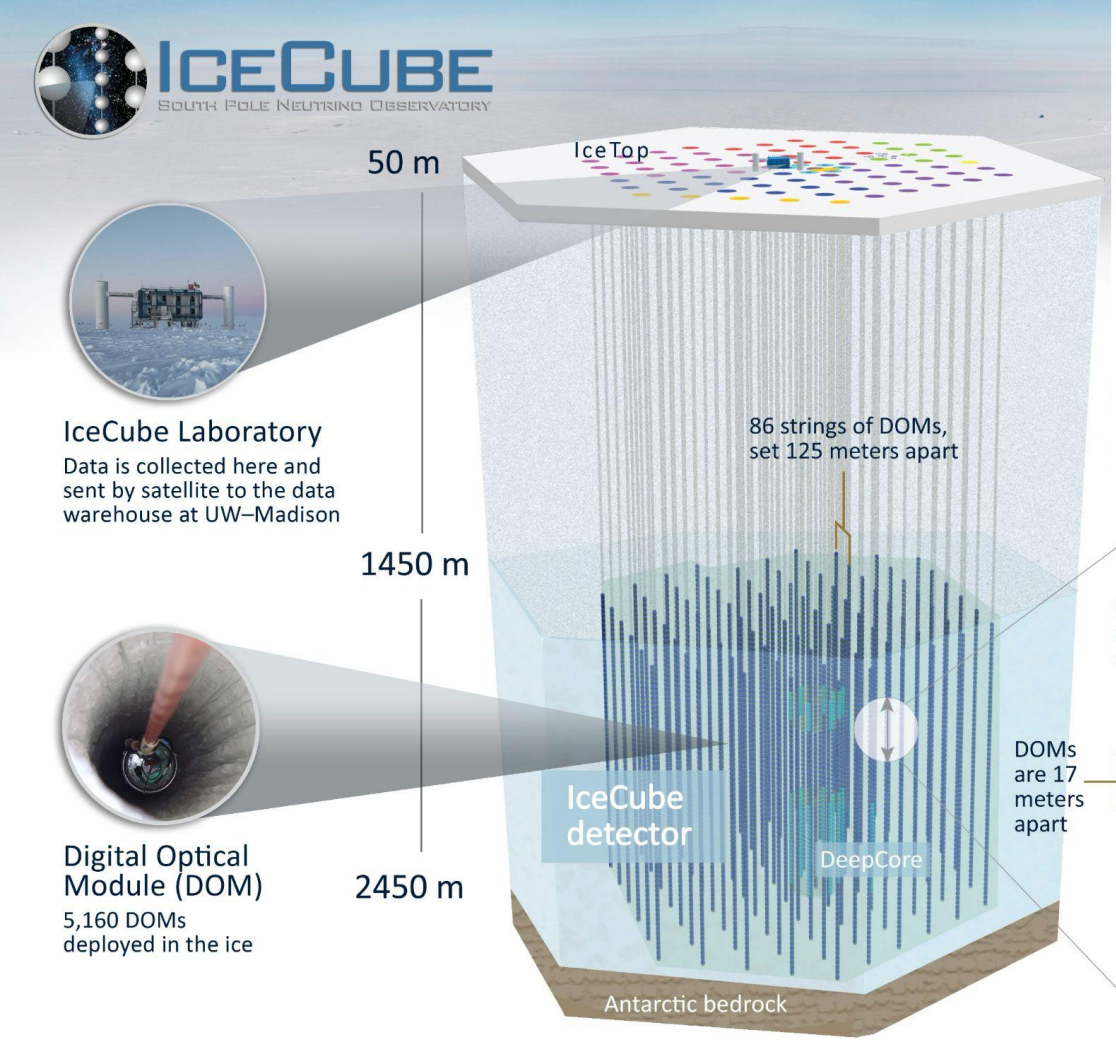
All-Sky High-Energy Neutrino Source Searches with IceCube

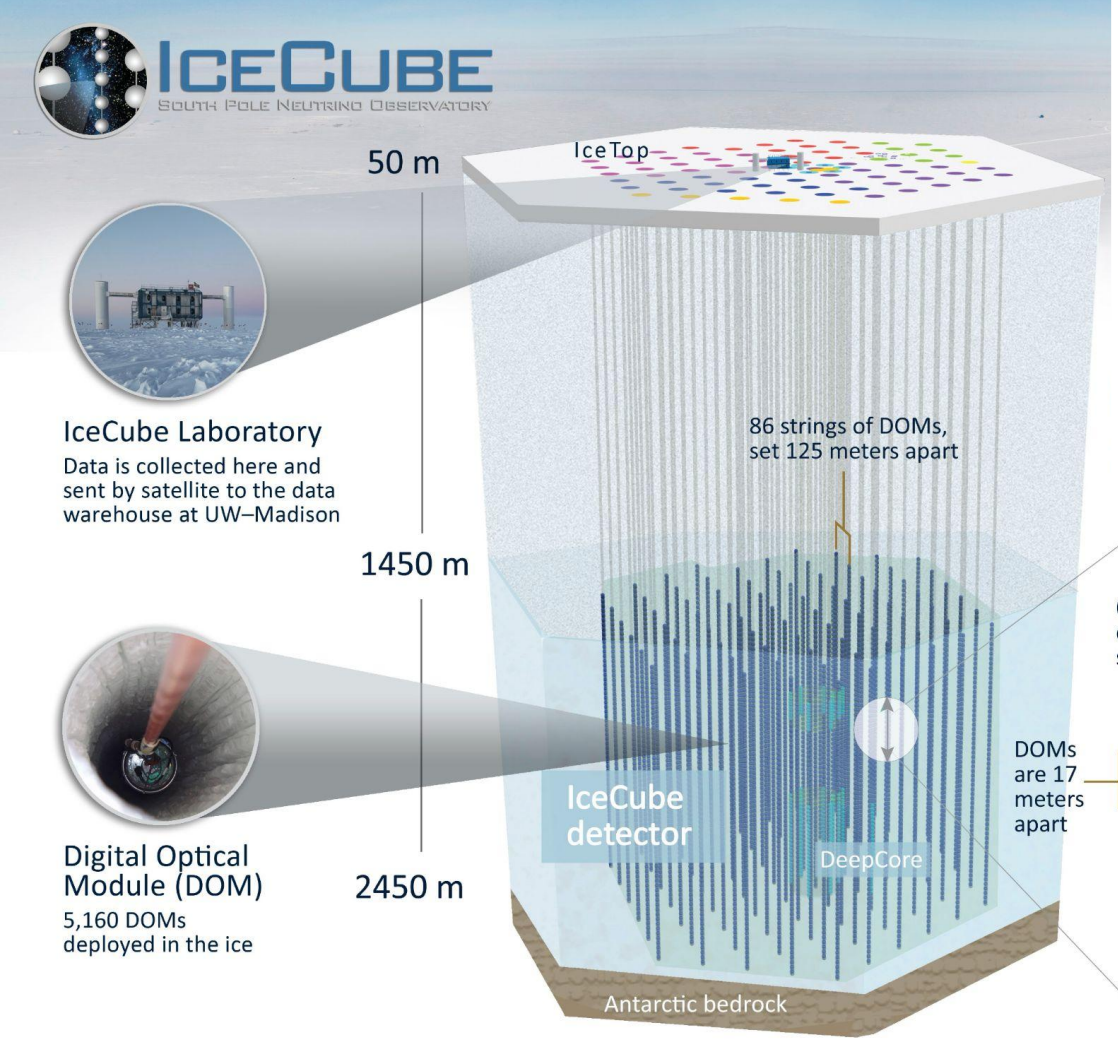
Riya Shah for the IceCube Collaboration

NNN 2025, Sudbury

Outline

- Intro to IceCube
- Potential high-energy cosmic-ray/neutrino sources
- IceCube Event Signatures
- IceCube's Background & Effects on Data Selections
- Recent results
- New Era in IceCube Neutrino Source Searches


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

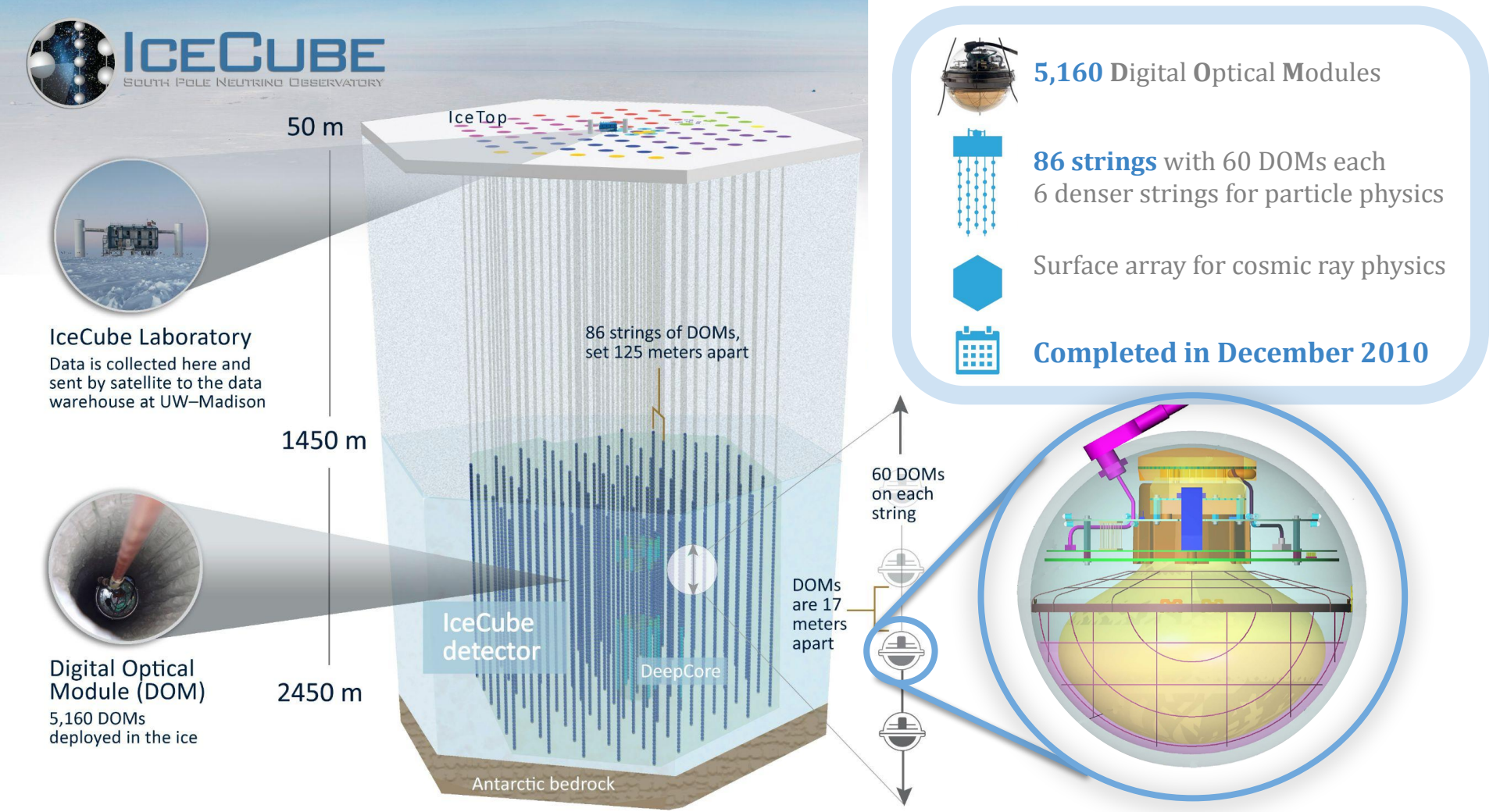


5,160 Digital Optical Modules

86 strings with 60 DOMs each
6 denser strings for particle physics

Surface array for cosmic ray physics

Completed in December 2010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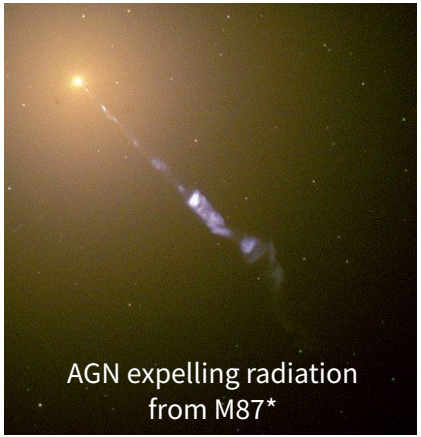
  - X-Ray Bright



*Credit: NASA

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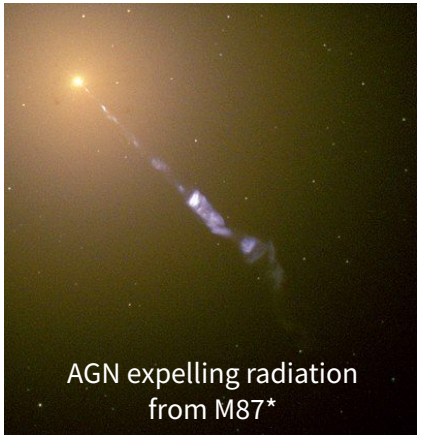
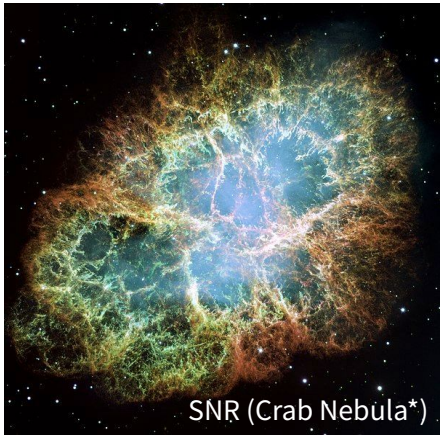

AGN expelling radiation from M87*


SNR (Crab Nebula*)

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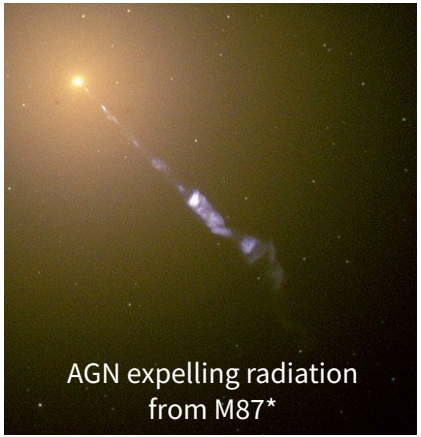
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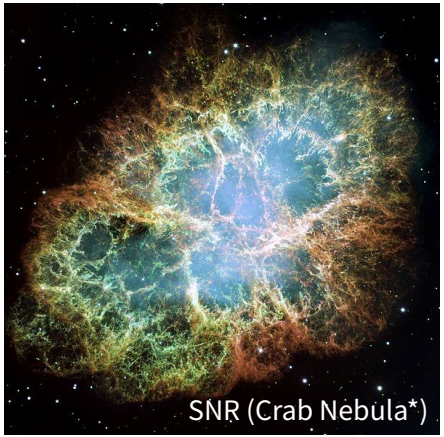
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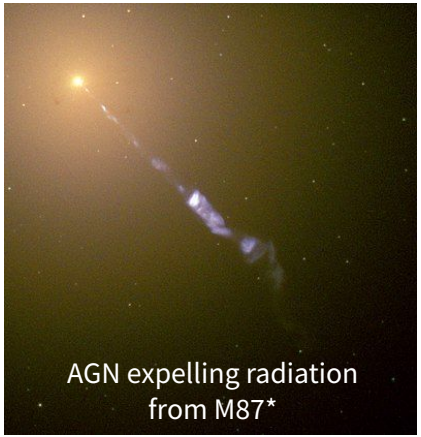

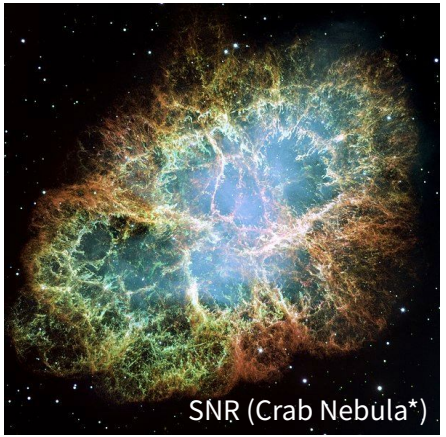

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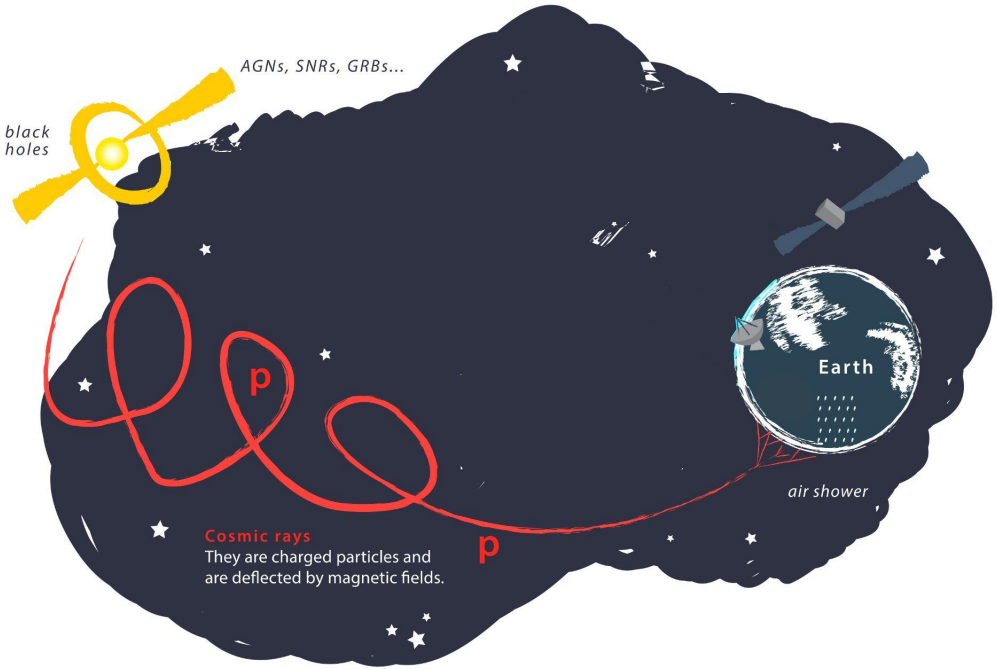

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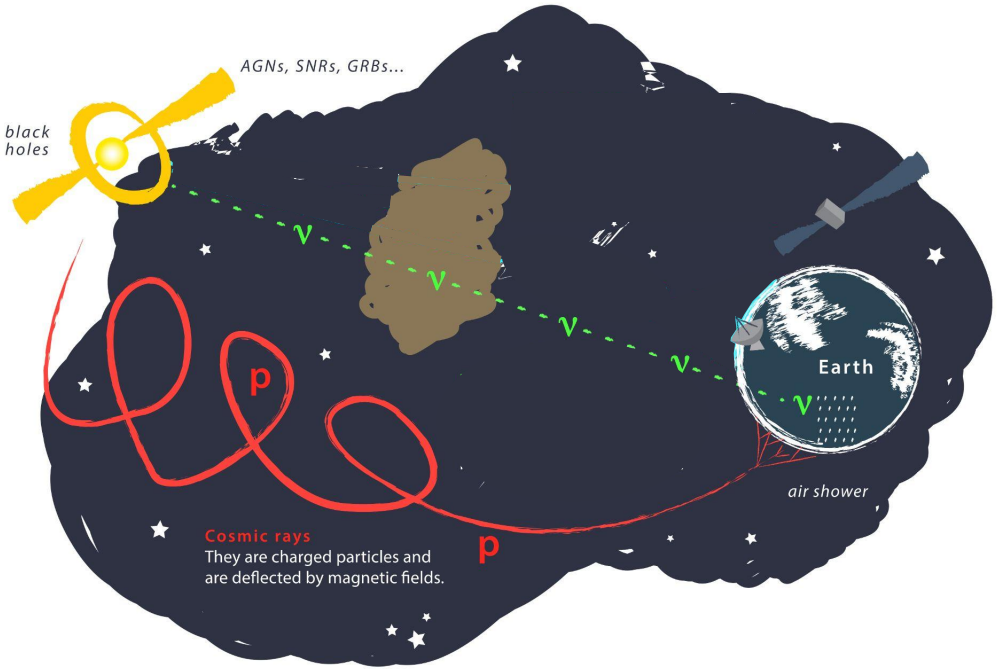

IceCube Event Signatures

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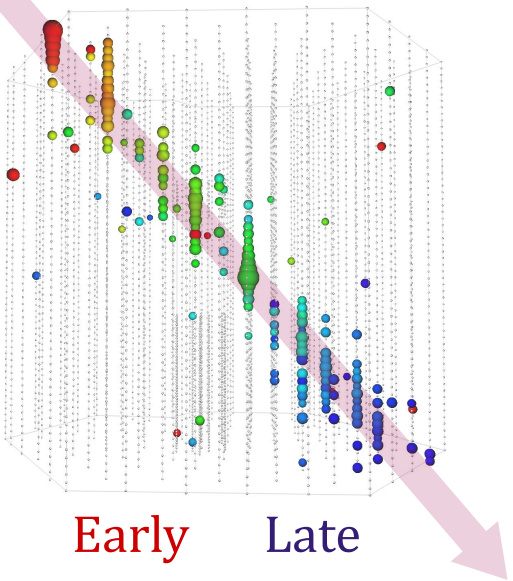
Tracks



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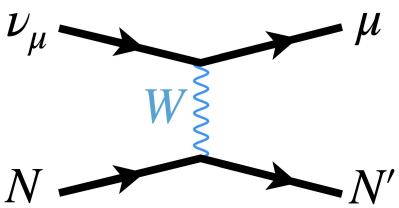

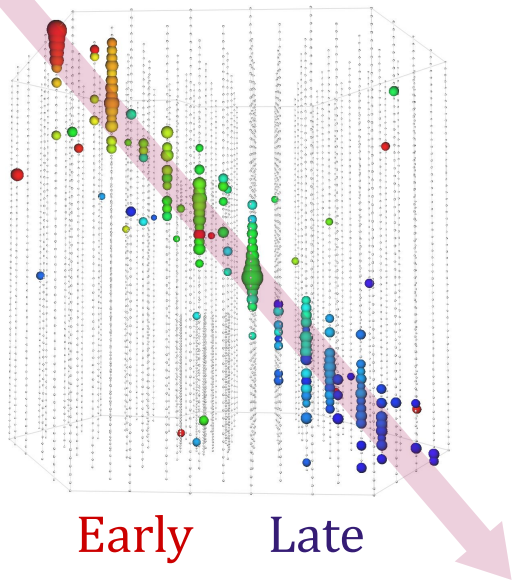

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- **Median angular resolution ~0.5°**
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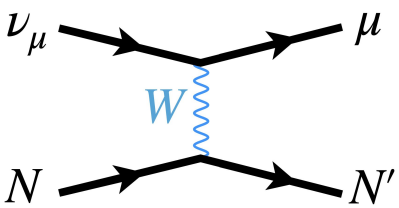

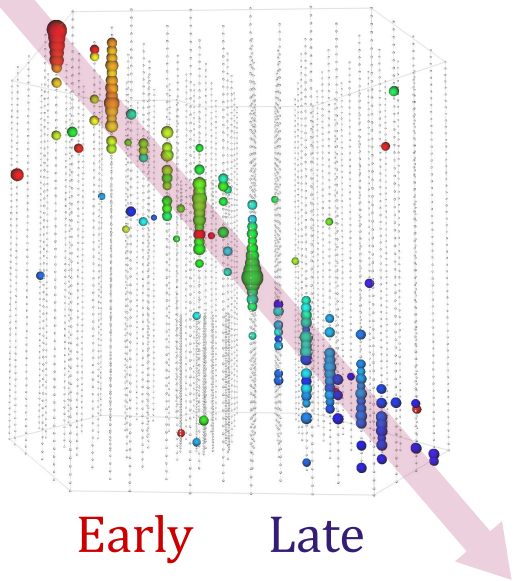

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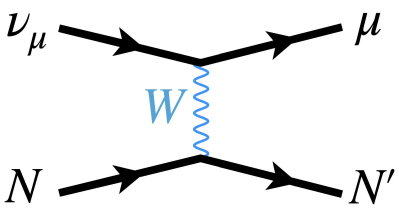
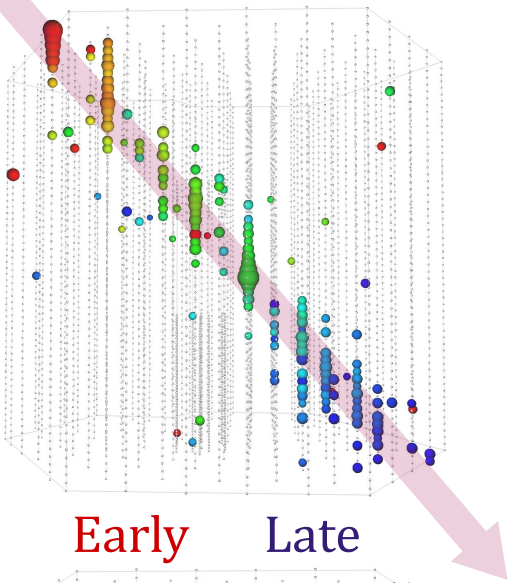
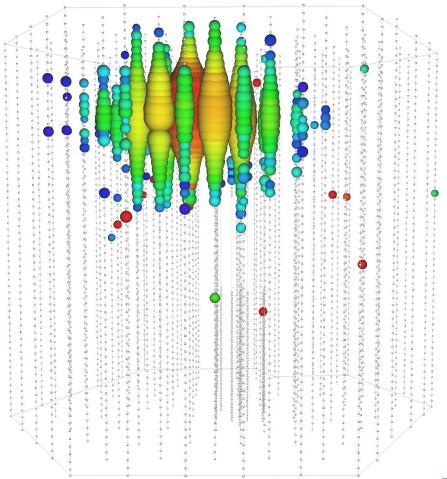




Cascades



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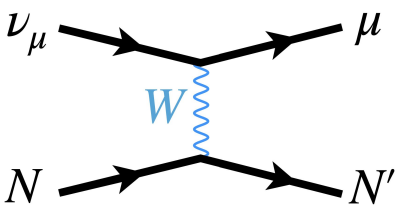

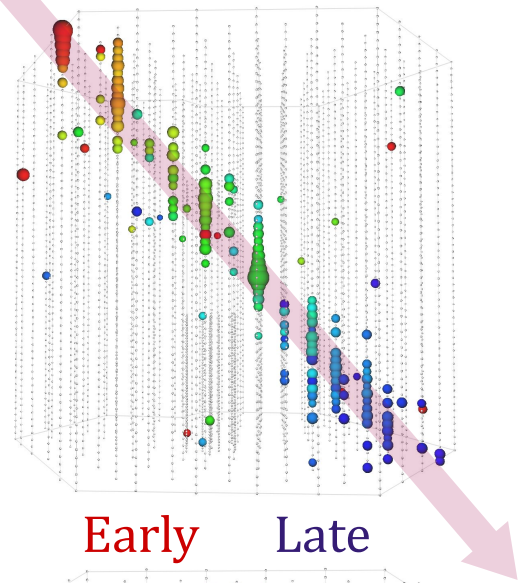

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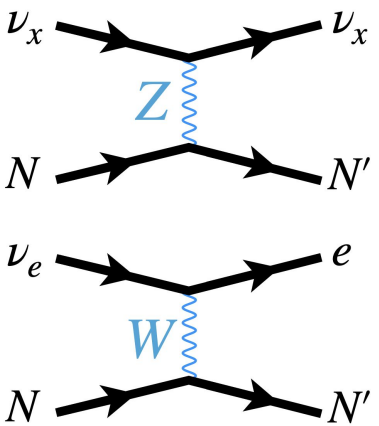

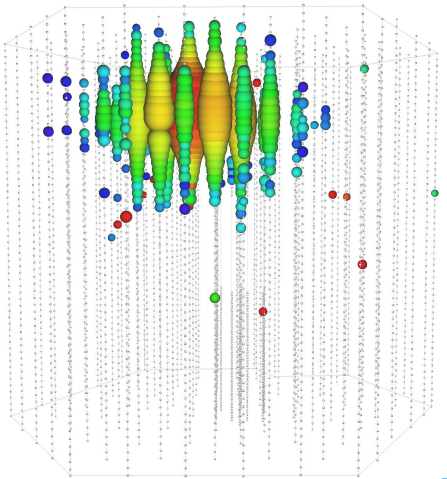

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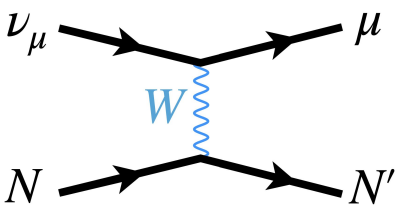
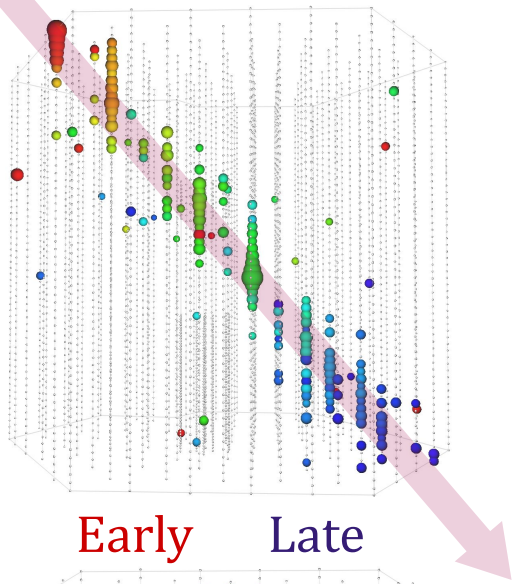
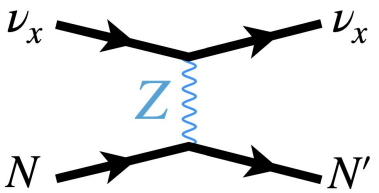
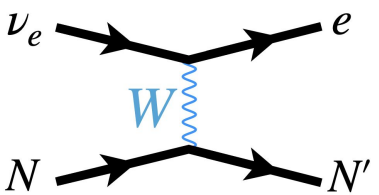


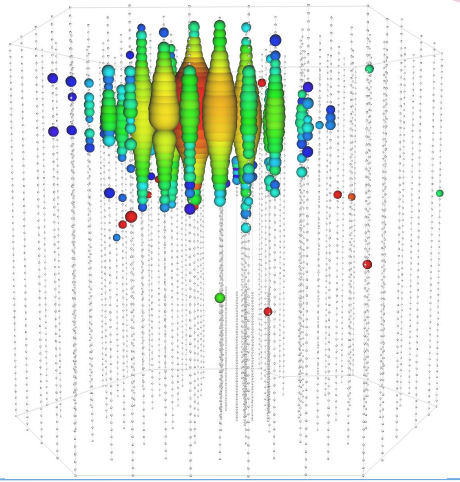


Cascades

- Median angular resolution ~8° at E > 100 TeV
- Vertex in or near detector
- Better energy resolution







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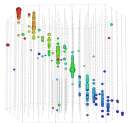

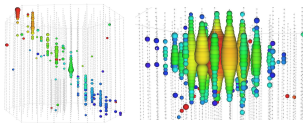

Atm. μ: ~ 10^{11} per year

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Astro. ν: ~100 per year

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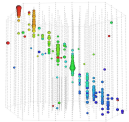

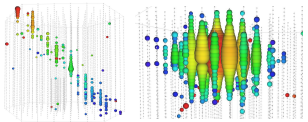

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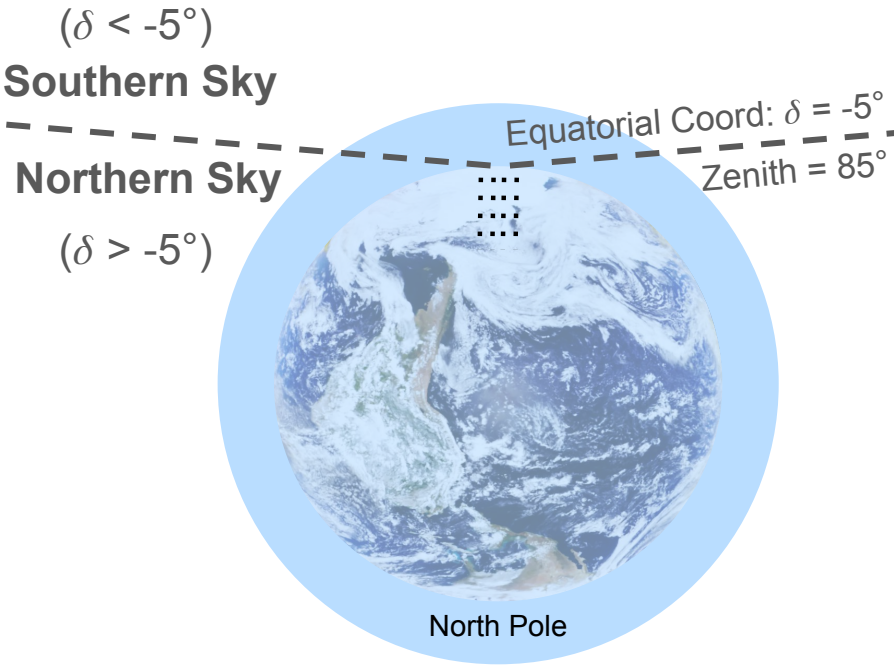

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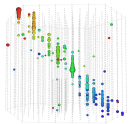

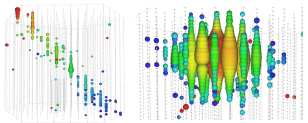

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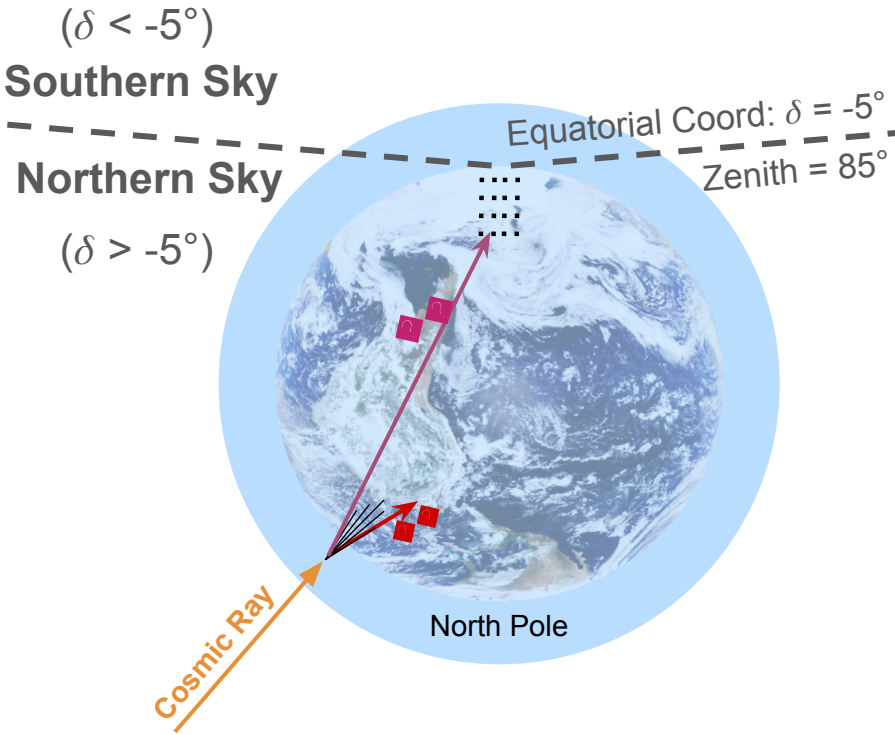

δ : Equatorial Declination

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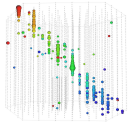

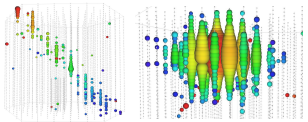

- **Earth absorbs almost all background μ from Northern Sky** (zenith > 85°)

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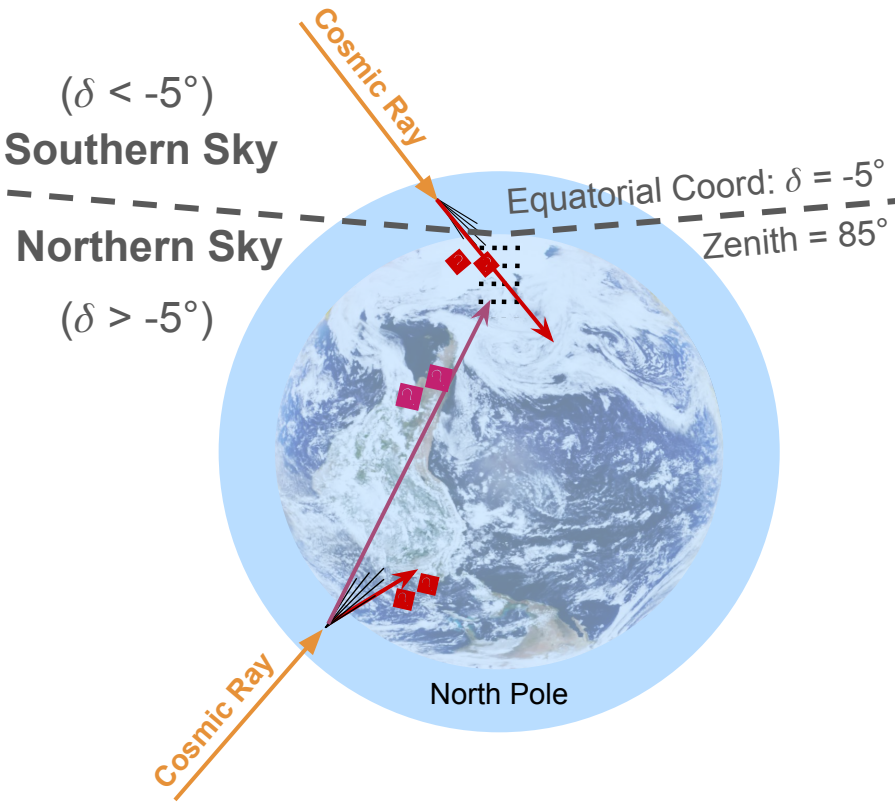

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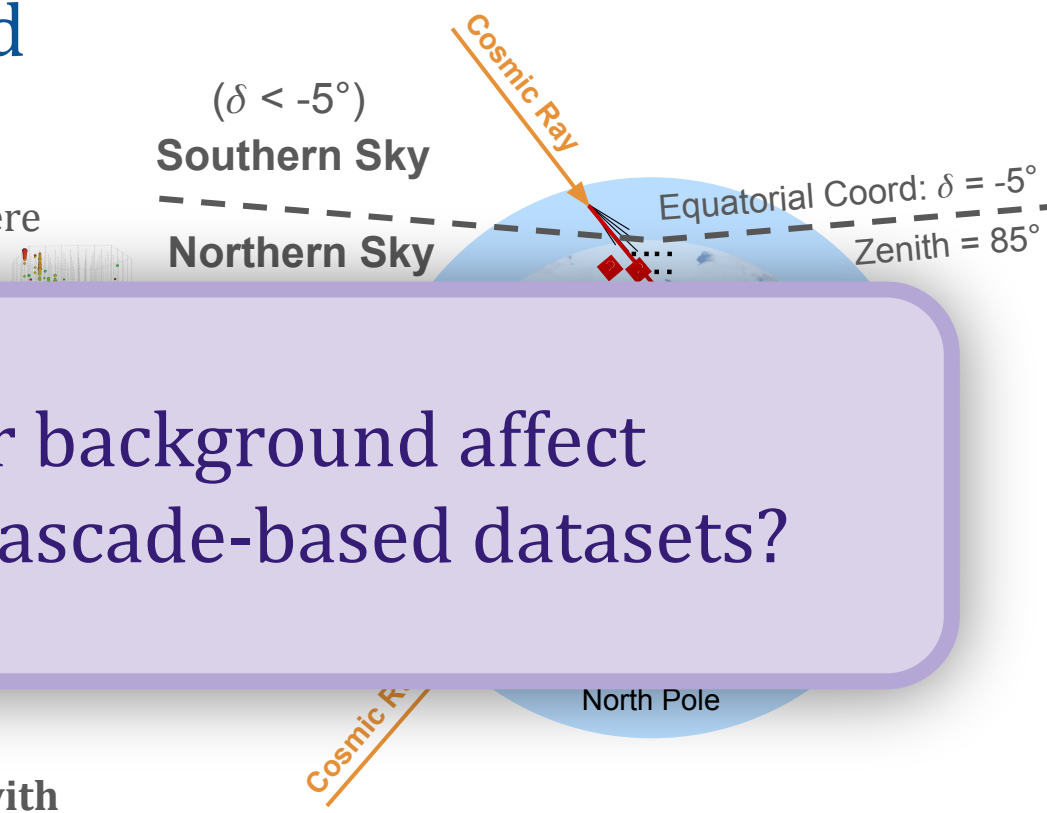

How does our background affect track-based and cascade-based datasets?

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Background Effects on Datasets

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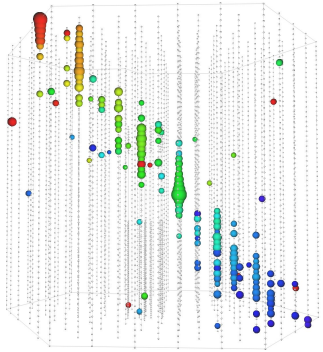

Southern Sky background μ require harsh low-energy cuts on Southern Sky track events

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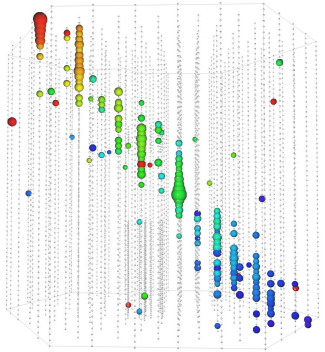

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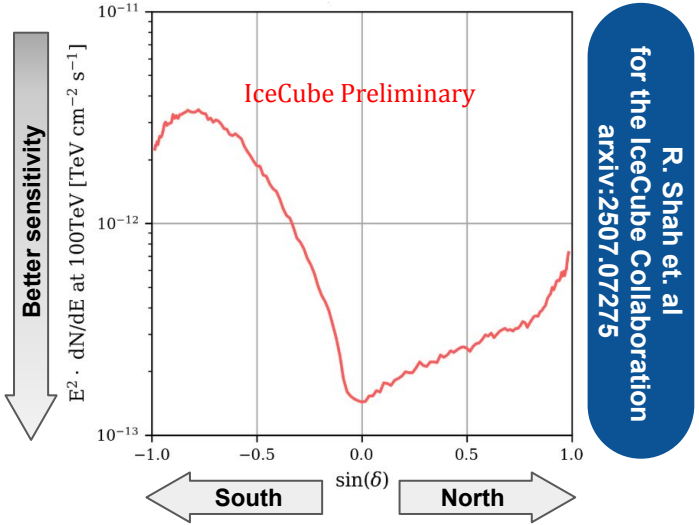

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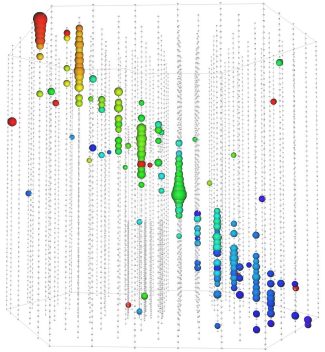

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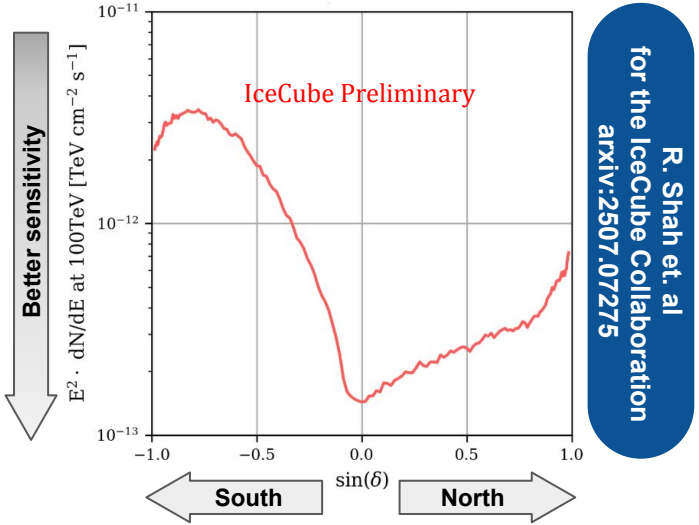

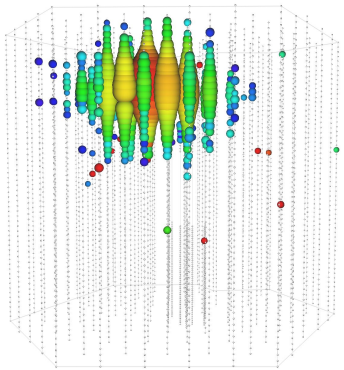

Since μ do not appear as cascades, no low-energy cuts necessary in Southern Sky

Cascade-Based

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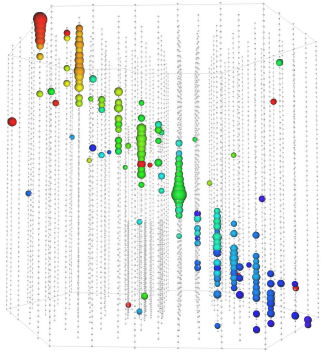

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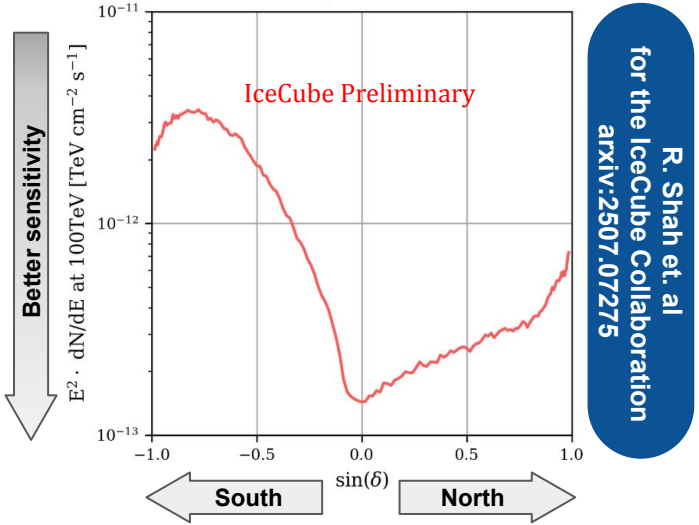
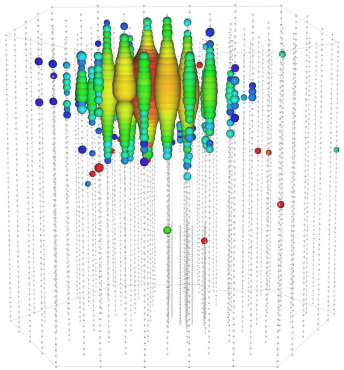


R. Shah et. al for the IceCube Collaboration arxiv:2507.07275



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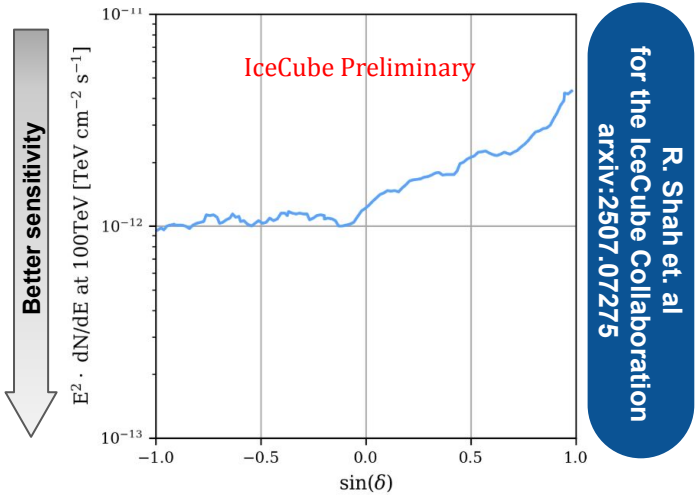

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Recent High-Energy Neutrino Source Search Results

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- Active Galactic Nuclei (AGN)
  - Blazars
  - Seyferts
  - X-Ray Bright
- Supernova Remnants (SNRs)
- Gamma-ray Bursts (GRBs)
- Galactic plane

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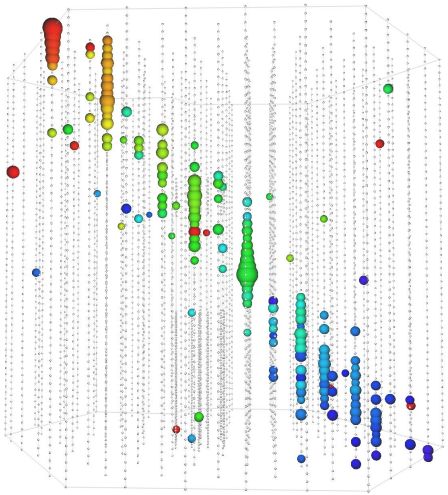
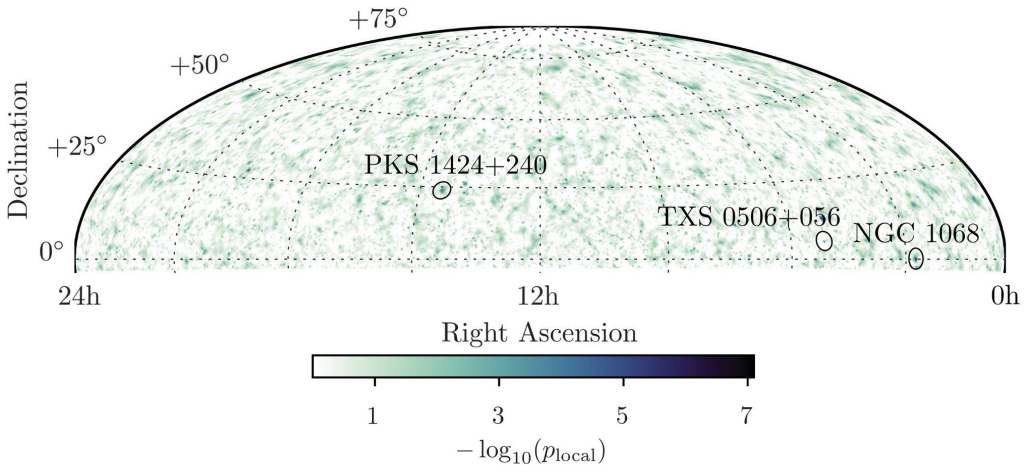
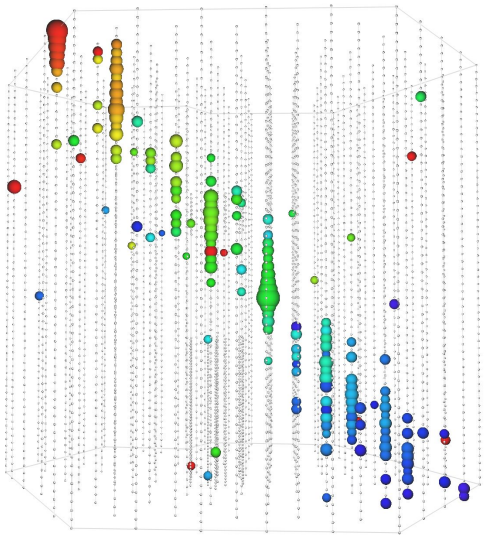
Point Sources



Recent High-Energy Neutrino Track-Based Search Results

IceCube Collaboration
Science 378 (2022) 538-543





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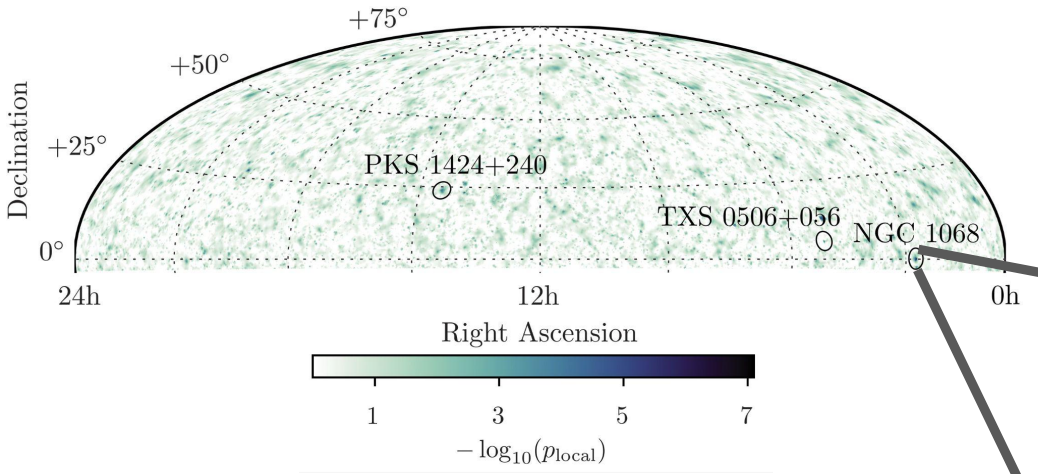
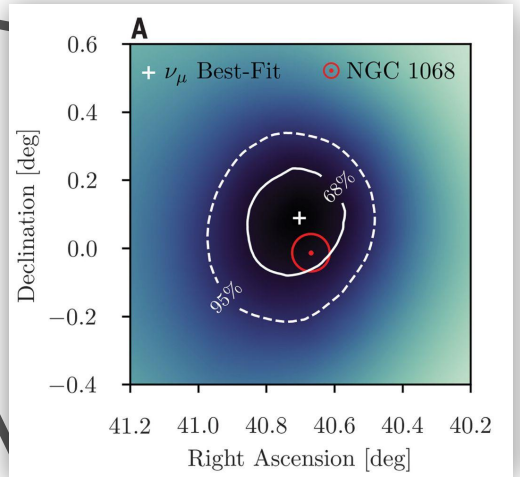
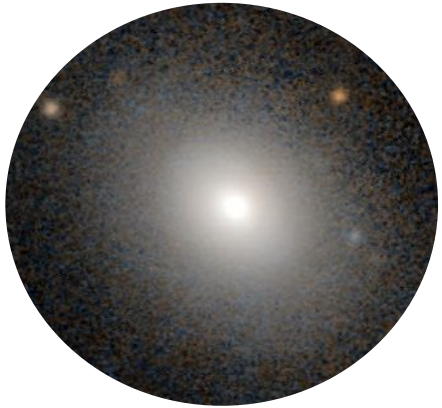




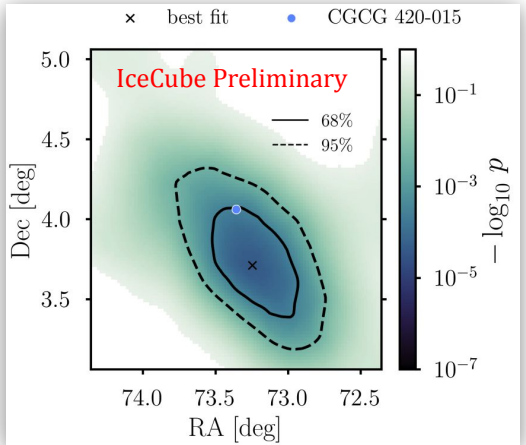
Global Significance: 4.2σ

* Galaxy Image Credit: NASA

Recent High-Energy Neutrino Track-Based Search Results



Global Significance: **2.5σ**



IceCube Collaboration
arxiv:2406.07601

* Galaxy Image Credit: NASA

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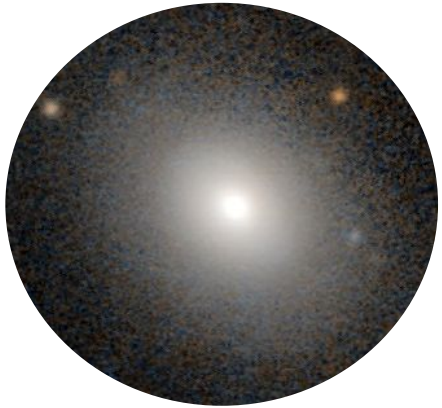

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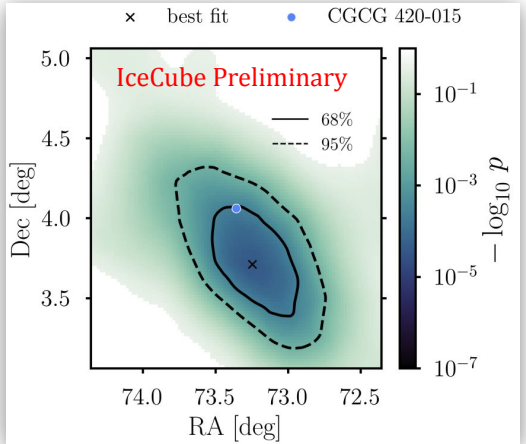
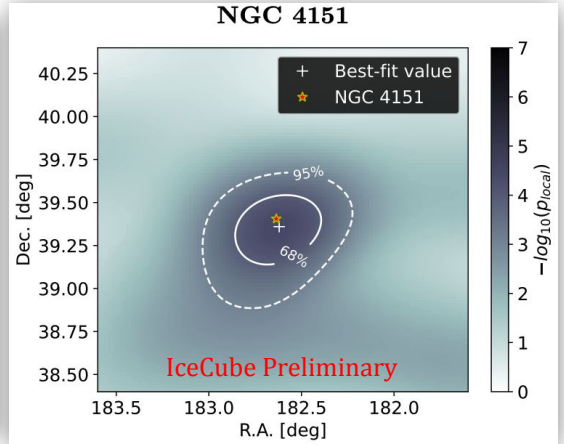


IceCube Collaboration
arxiv:2406.07601

Global Significance: **2.9σ**

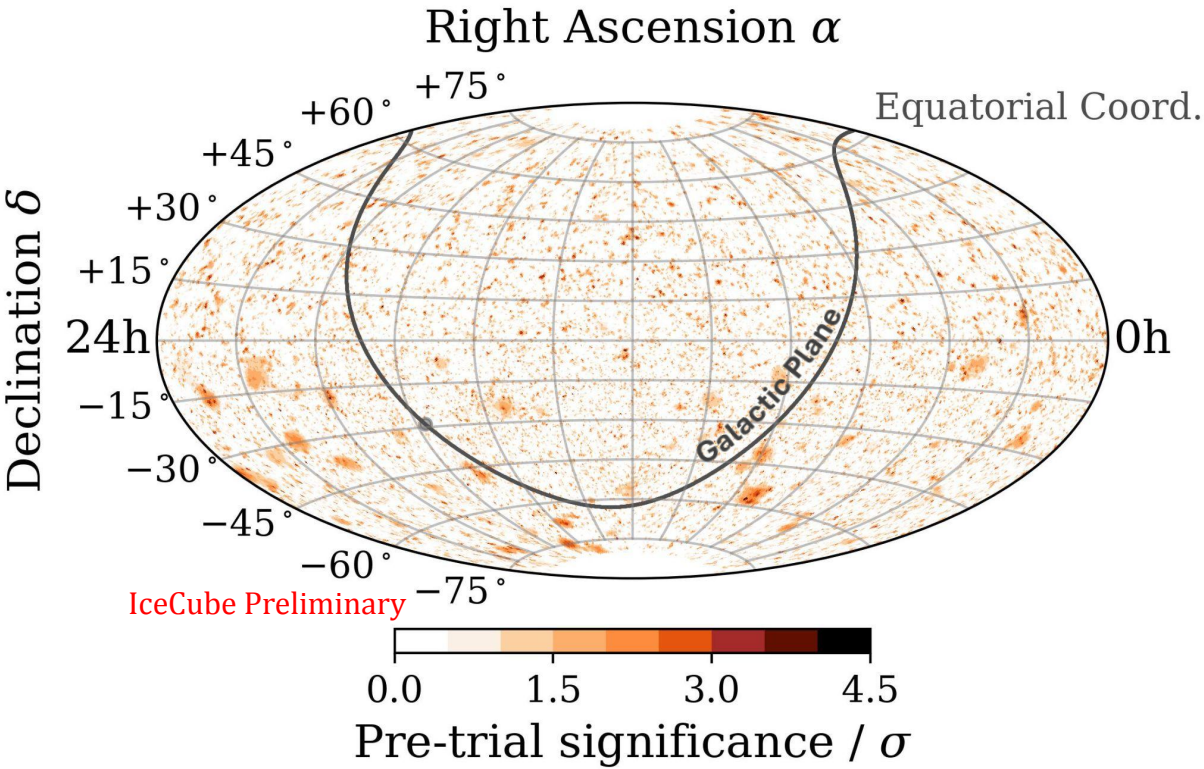


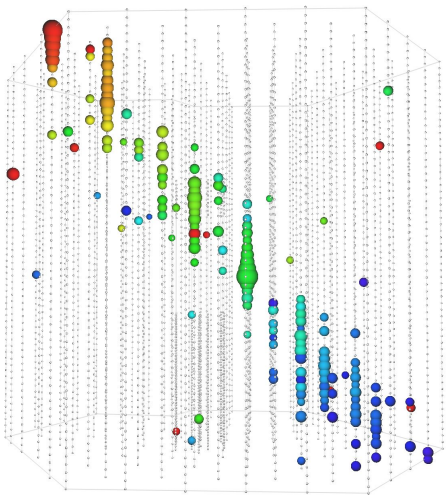
IceCube Collaboration
arxiv:2406.07601

* Galaxy Image Credit: NASA

Recent High-Energy Neutrino Track-Based Search Results

R. Shah et. al
for the IceCube Collaboration
arxiv:2507.07275





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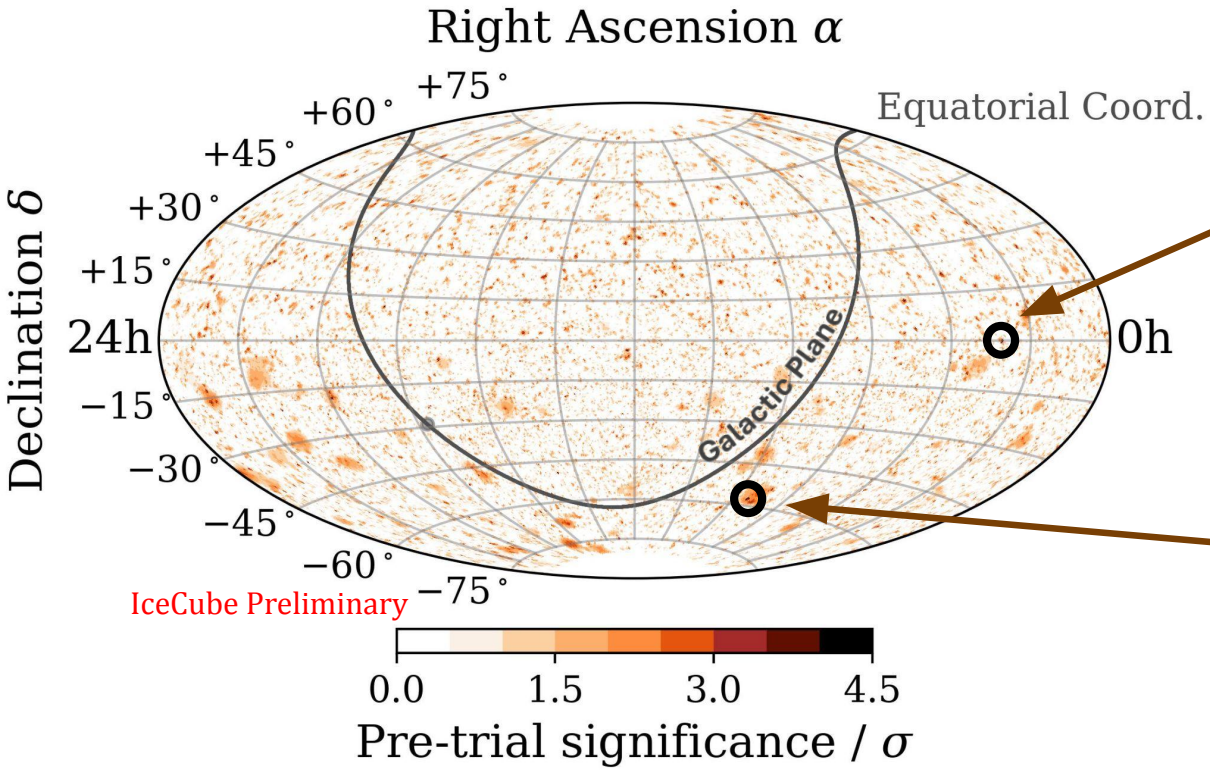

NGC 1068

(RA: 112°, Dec: -57.4°)

* Galaxy Image Credit: NASA

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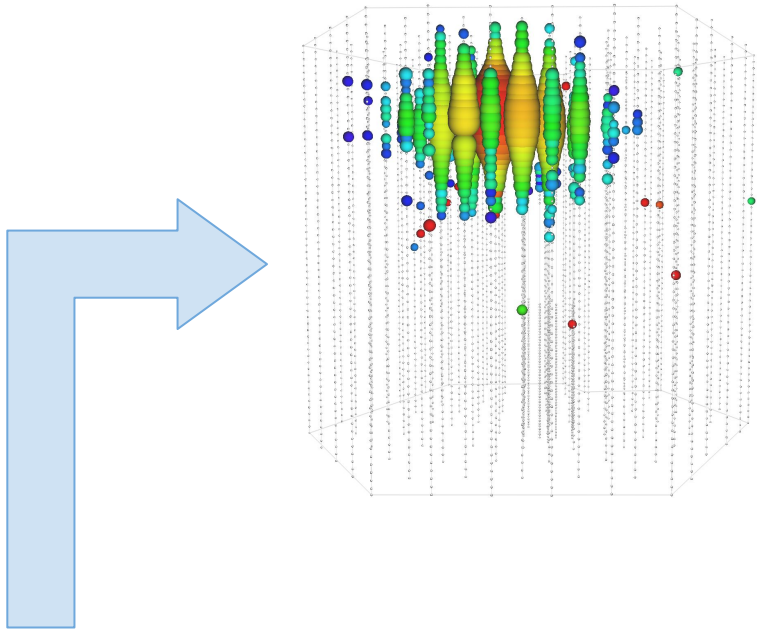
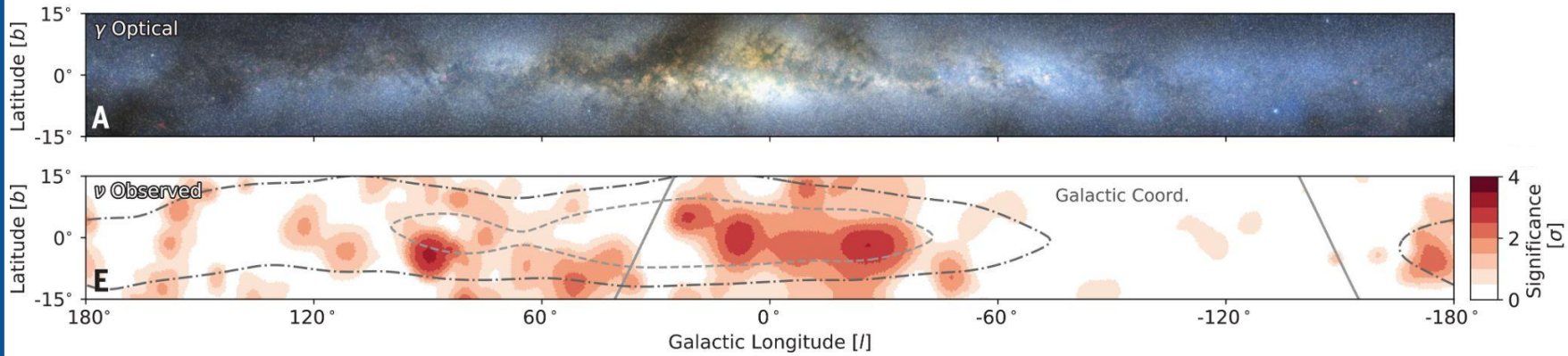


Extended Sources

Recent High-Energy Neutrino Cascade-Based Search Results

Recent High-Energy Neutrino Cascade-Based Search Results

IceCube Collaboration
Science 380 (2023) 1338-1343



Galactic Plane Global Significance (from π_0 model best-fit): **4.5σ**

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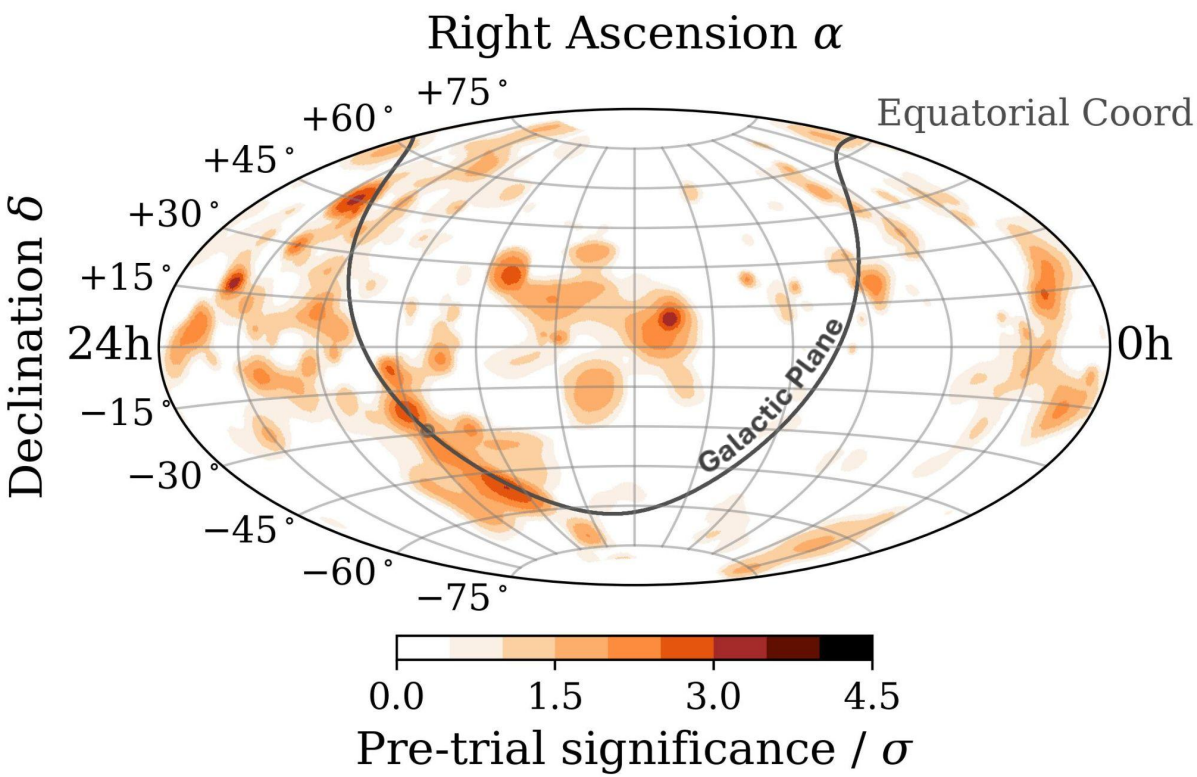
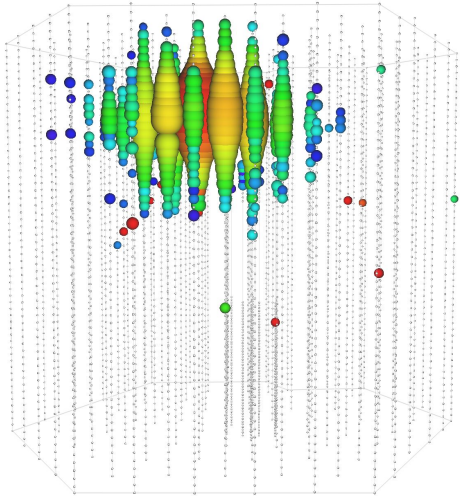
IceCube Collaboration
Science 380 (2023) 1338-1343





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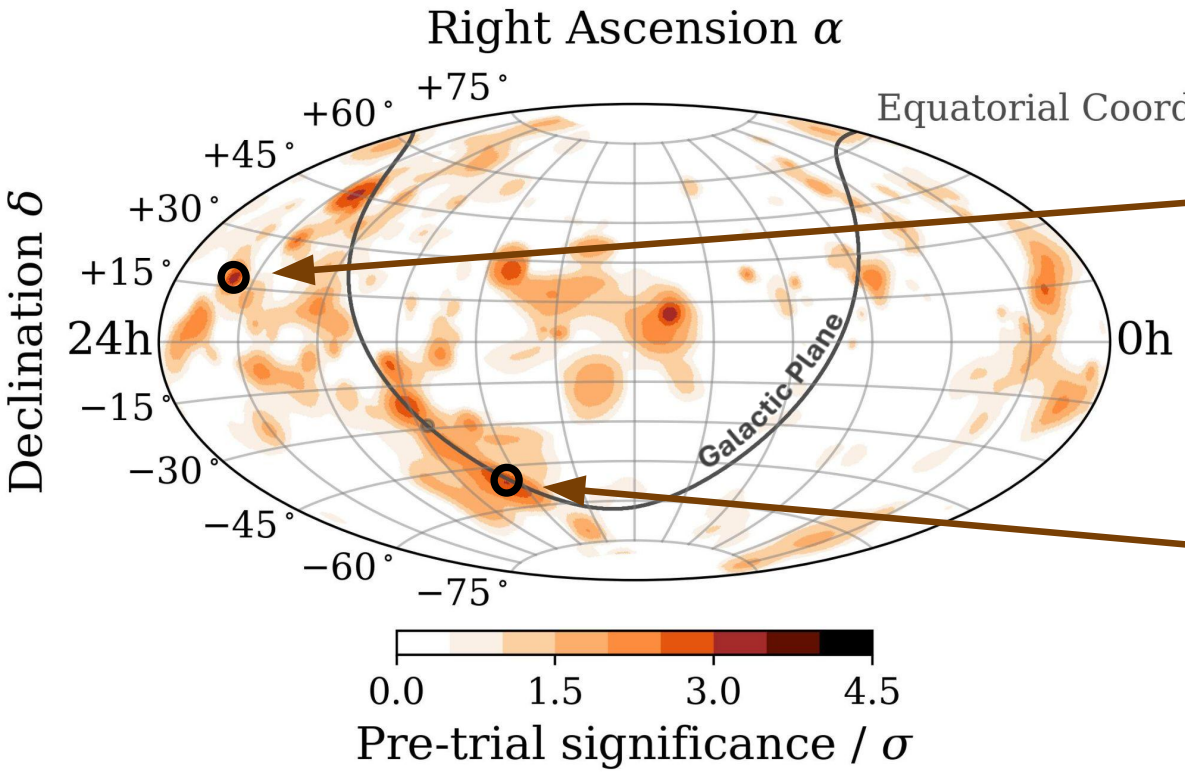

(RA: 338°, Dec: 17.6°)

(RA: 248°, Dec: -50.9°)

Beginning a New Era of IceCube Neutrino Source Searches

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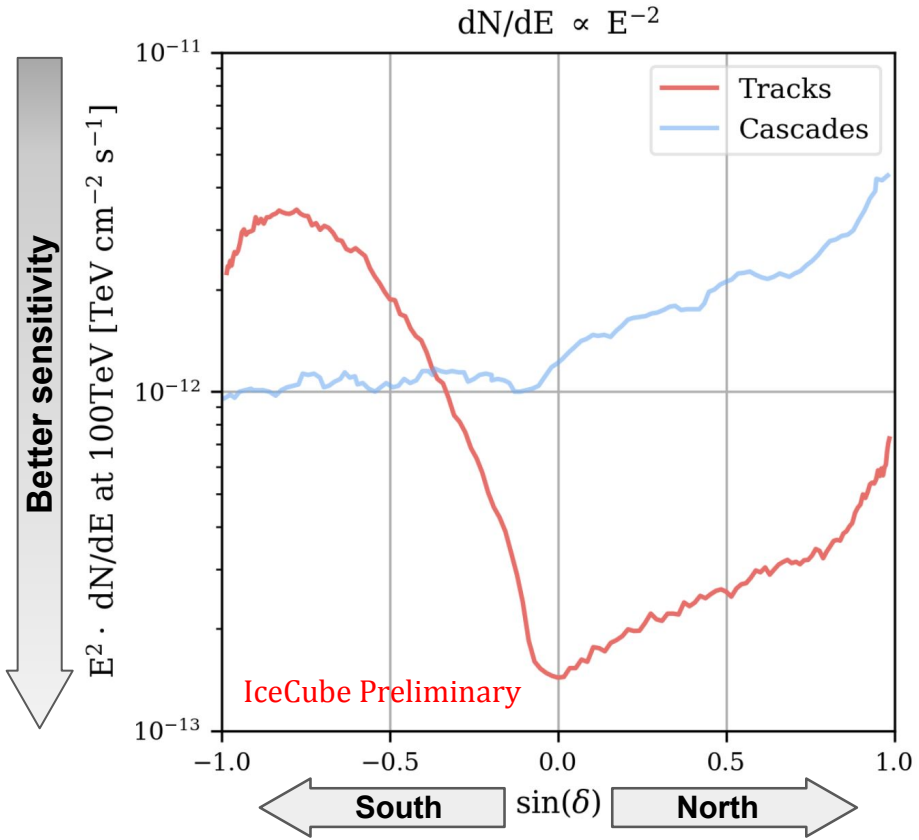
★ **My work:** Creation and implementation of simultaneous fit of different event signatures

Simultaneous Fit - Sensitivity Improvement

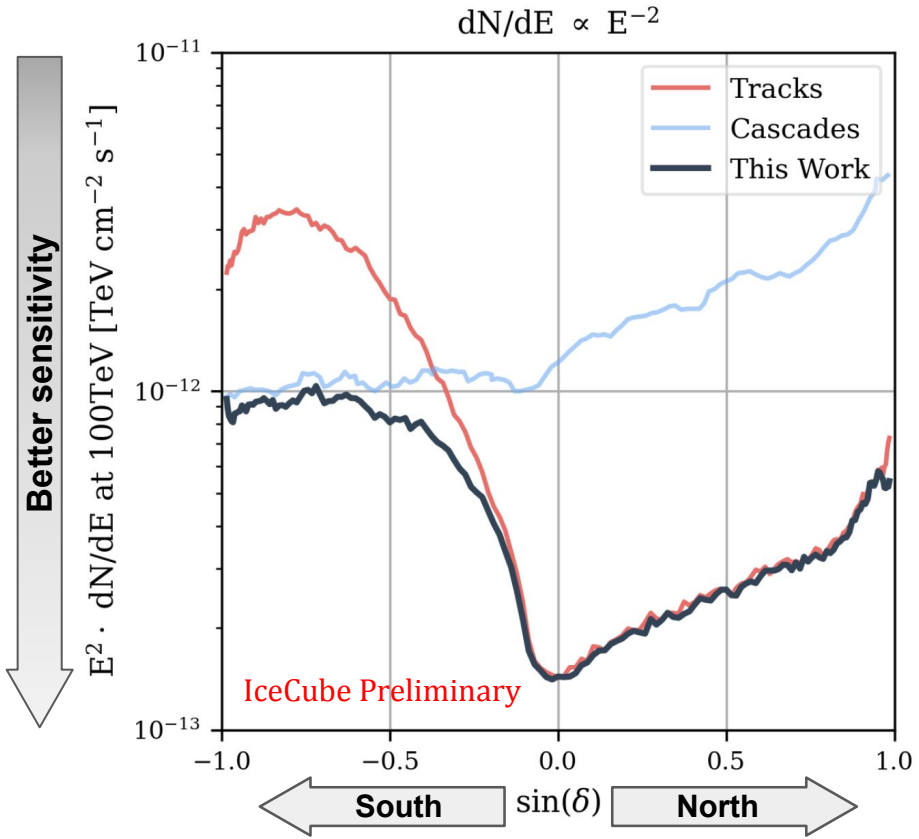


R. Shah et. al
for the IceCube Collaboration
arxiv:2507.07275

Simultaneous Fit - Sensitivity Improvement

★ Results in **best** all-sky sensitivity

★ **Improvement in south** over both single-signature datasets



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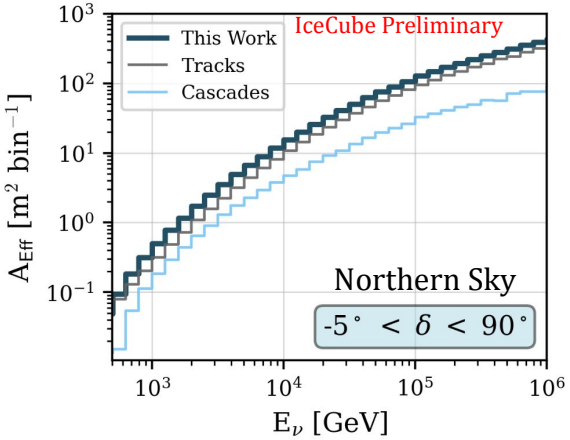
Simultaneous Fit - Effective Area Improvement

- ★ Northern Sky
  - ○ **30% avg. improvement** compared to **tracks**



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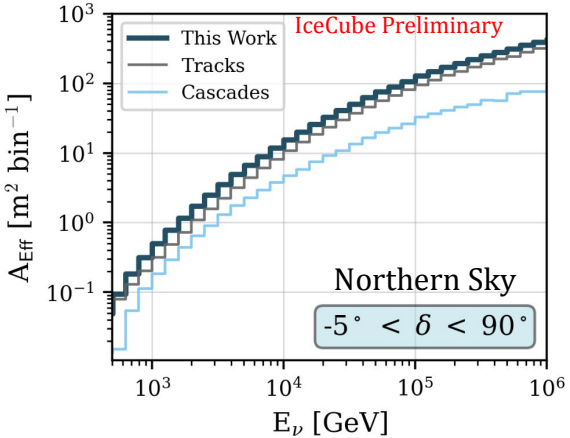
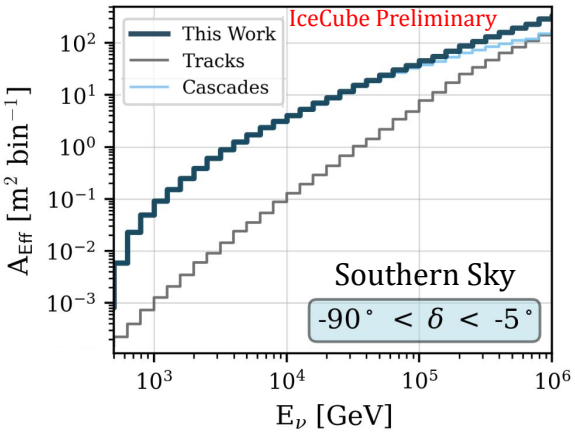
arxiv:2507.07275

Simultaneous Fit - Effective Area Improvement

- ★ Northern Sky
  - **30% avg. improvement** compared to **tracks**
- ★ Southern sky
  - **40% avg. improvement** compared to **cascades**





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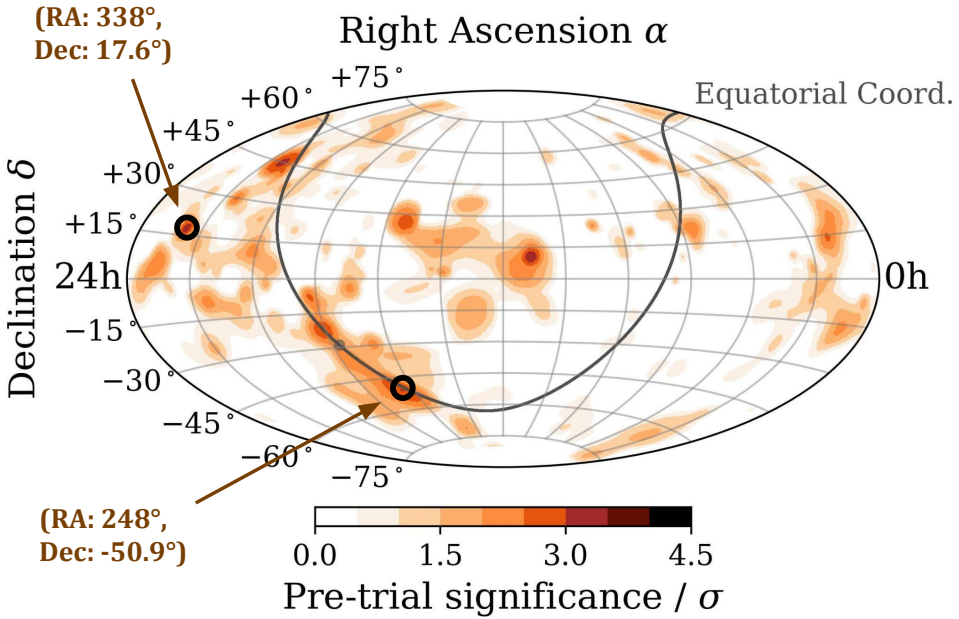
Simultaneous Fit - Results

Simultaneous Fit - Results

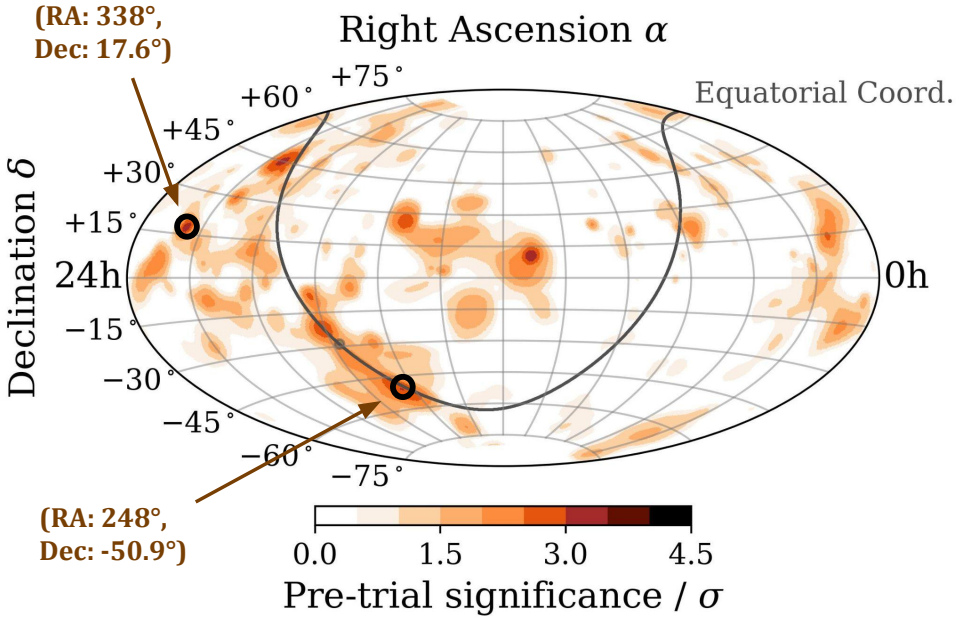
Cascades



IceCube Collaboration
Science 380 (2023) 1338-1343

Simultaneous Fit - Results

Cascades



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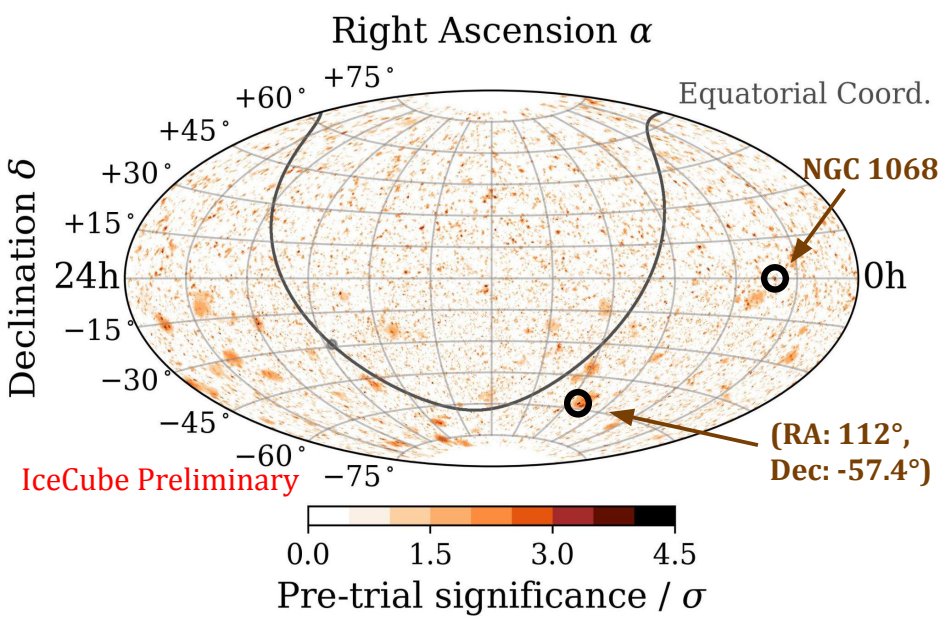
Tracks



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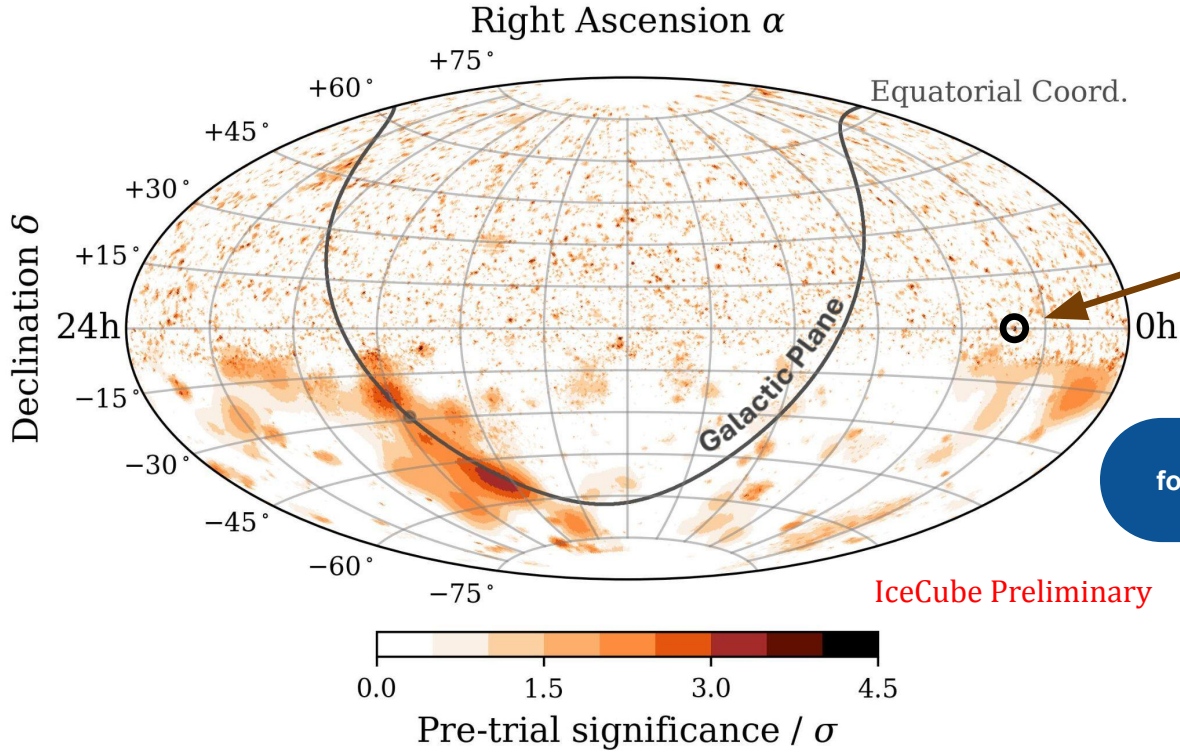
Simultaneous Fit - Results

Cascades + Tracks



NGC 1068

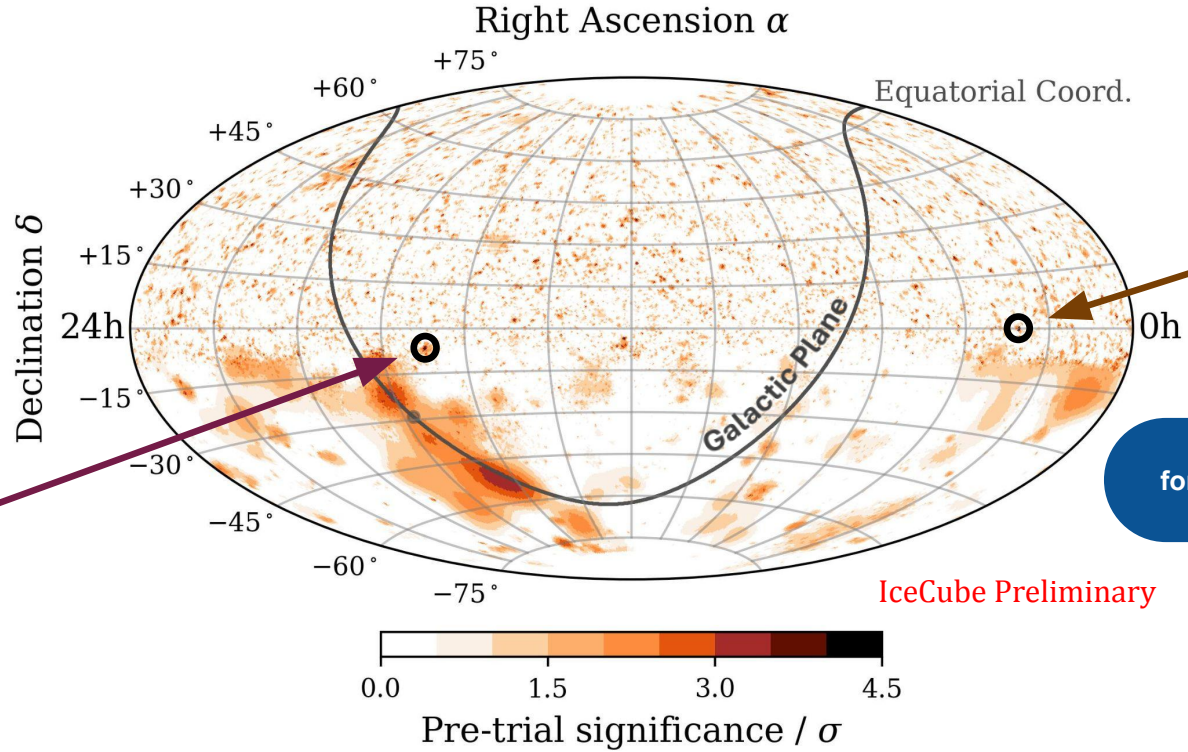
R. Shah et. al
for the IceCube Collaboration
arxiv:2507.07275

IceCube Preliminary

* Galaxy Image Credit: NASA

Simultaneous Fit - Results: New Hotspot!

Cascades + Tracks



NGC 1068

New!
(RA: 255,
Dec: -6.9)

R. Shah et. al
for the IceCube Collaboration
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IceCube Preliminary

* Galaxy Image Credit: NASA

Maximum Likelihood Modification

Single Signature Likelihood

$$L(\gamma, n_s) = \prod_i \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N} \right) B_i \right]$$

Maximum Likelihood Modification

Single Signature Likelihood

$$L(\gamma, n_s) = \prod_i \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right]$$

Multi-Signature Likelihood

$$L(\gamma, n_s) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

Product over dataset

Product over events in dataset j

Summary

➢ Many new and interesting IceCube results with **single signatures**

Summary

- Many new and interesting IceCube results with single signatures
- New era in IceCube neutrino source searches
  - Simultaneous fit of tracks and cascades provides current **best Southern Sky sensitivity** across all IceCube datasets
  - **Uncovers a new southern hotspot** previously unseen in single-signature searches

Summary

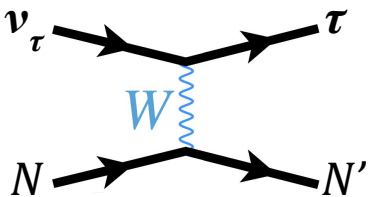
- Many new and interesting IceCube results with single signatures
- New era in IceCube neutrino source searches
  - Simultaneous fit of tracks and cascades provides current best Southern Sky sensitivity across all IceCube datasets
  - Uncovers a new southern hotspot previously unseen in single-signature searches
- Can **combine any number of individual datasets** while accounting for differences between tracks and cascades
  - Many new analyses across the IceCube Collaboration have started using my method & combined fit dataset

Supplementary Material

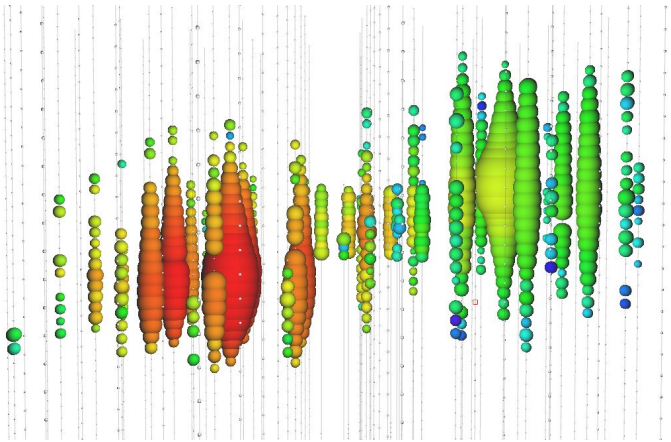
IceCube Event Signatures - Tau Neutrinos

Double Bang

- Limited phase space for detection
- $\lambda_\tau \simeq \frac{50\ \text{m}}{1\ \text{PeV}} E_\tau$
- Hard to distinguish from single cascade



Simulated 10 PeV Double Bang Event



Early Late

Combining Datasets: Further Considerations

- Needed to retain optimal settings for tracks and cascades individually
  - Background scrambling for cascades needs to be bigger due to larger angular uncertainty
- Must remove overlapping data
  - Kept overlapping events in cascade dataset to keep it robust
- Tested overlapping MC effects on sensitivity
  - Does not affect sensitivity by an appreciable amount

Time-Integrated Likelihood

$$L(\gamma, n_s) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

Spectral Index

Number of signal events

Total number of events

Signal PDF

Background PDF

Time-Integrated Likelihood

$$L(\gamma, n_s) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

Spatial Component - 2D Gaussian

$$S_i^j = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}}$$

Reco direction

source location

uncertainty

Time-Integrated Likelihood

$$L(\gamma, n_s) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j} \right) B_i^j \right]$$

Test Statistic

$$TS = -2 \log \left[\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s, \hat{\gamma})} \right]$$