Search for High-Energy Neutrinos from Blazars with IceCube

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TeVPA 2021
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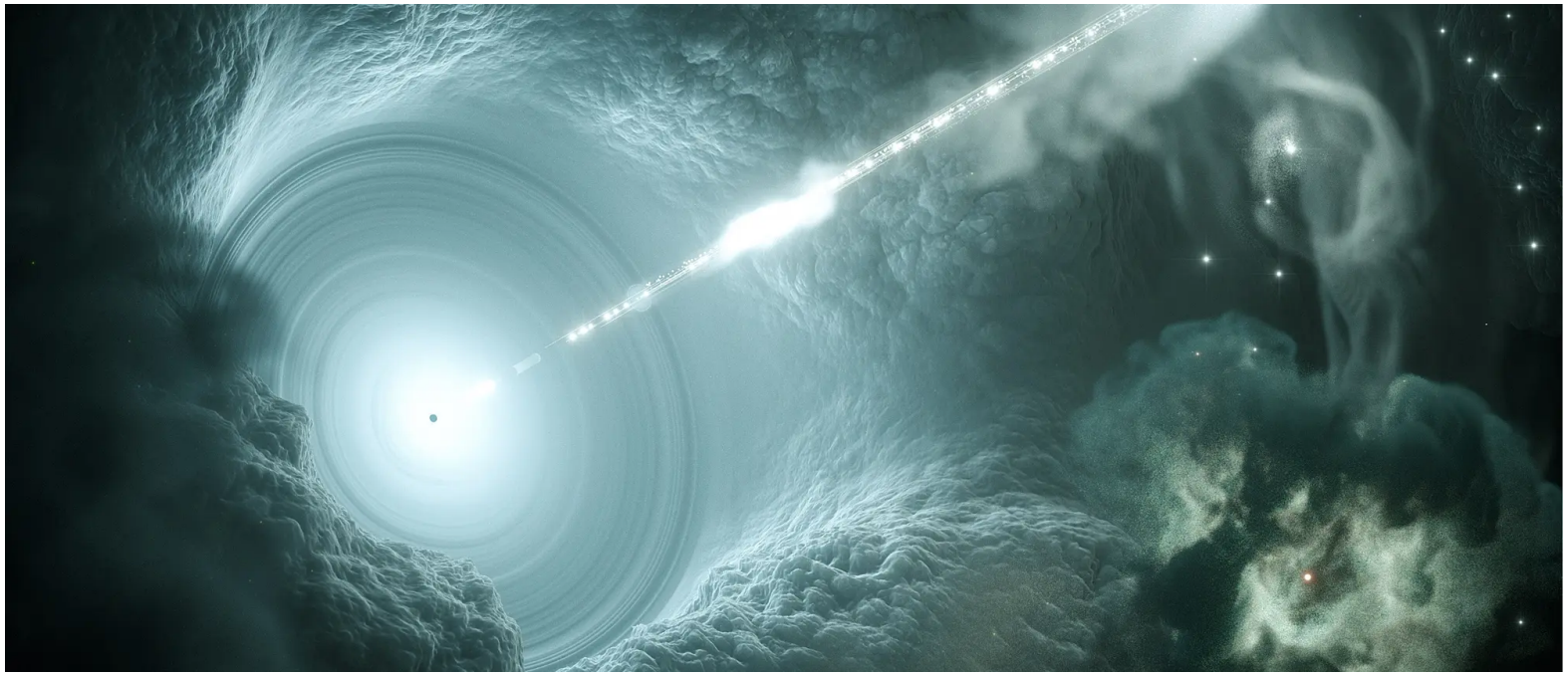
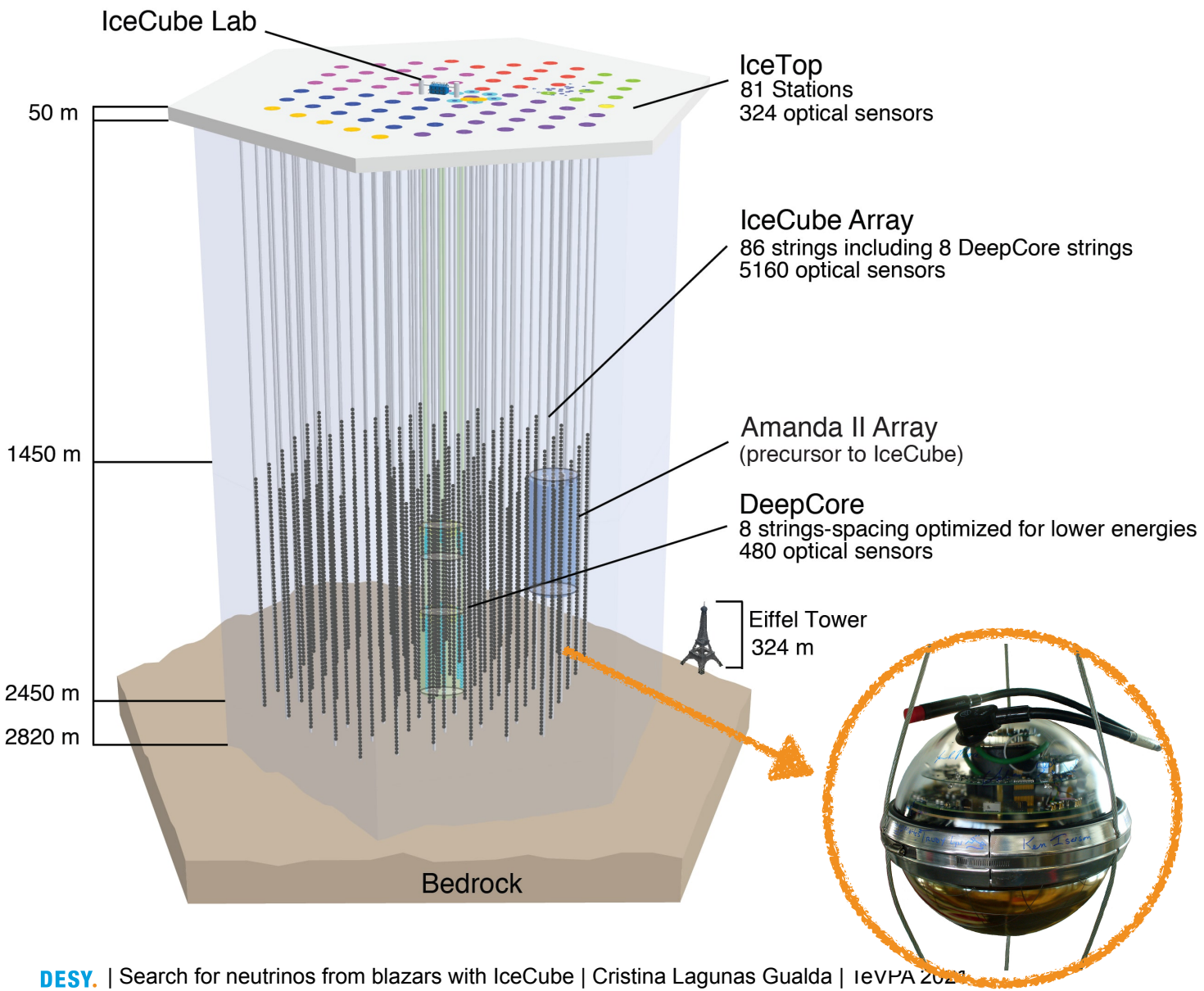


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

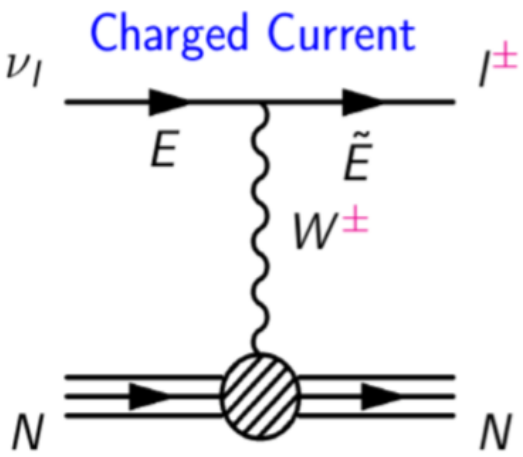
DESY.

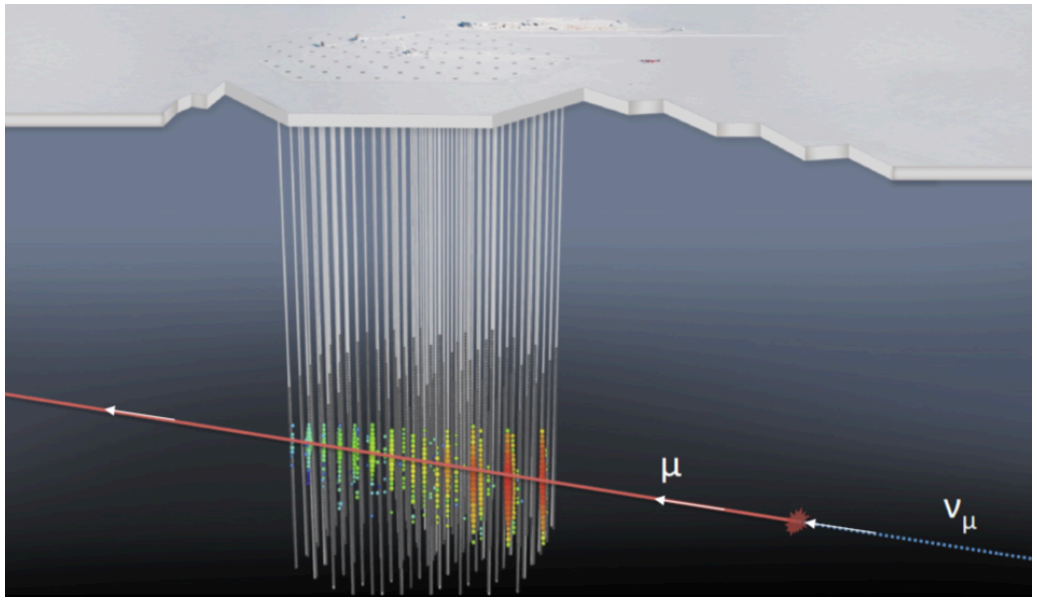
IceCube



- First km3-scale neutrino detector.
- Construction finished in 2010.
- 5160 digital optical modules (DOMs) deployed at depths between ~1.5-2.5 km.
- Each DOM contains a photomultiplier.
- Surface air shower array (IceTop).
- Denser region for GeV neutrinos (DeepCore).

IceCube





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- Lepton produces photons (Cherenkov).
- Photons are detected by the photomultipliers in the DOMs.

IceCube

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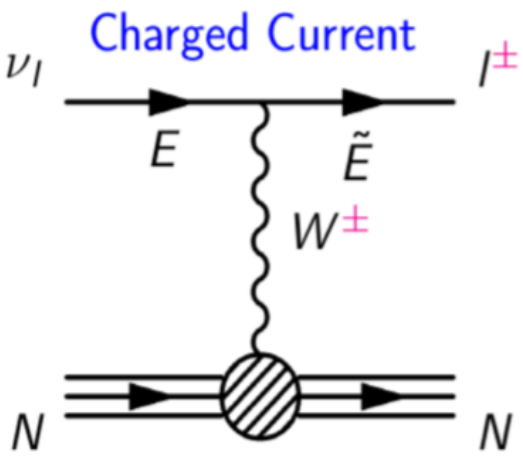
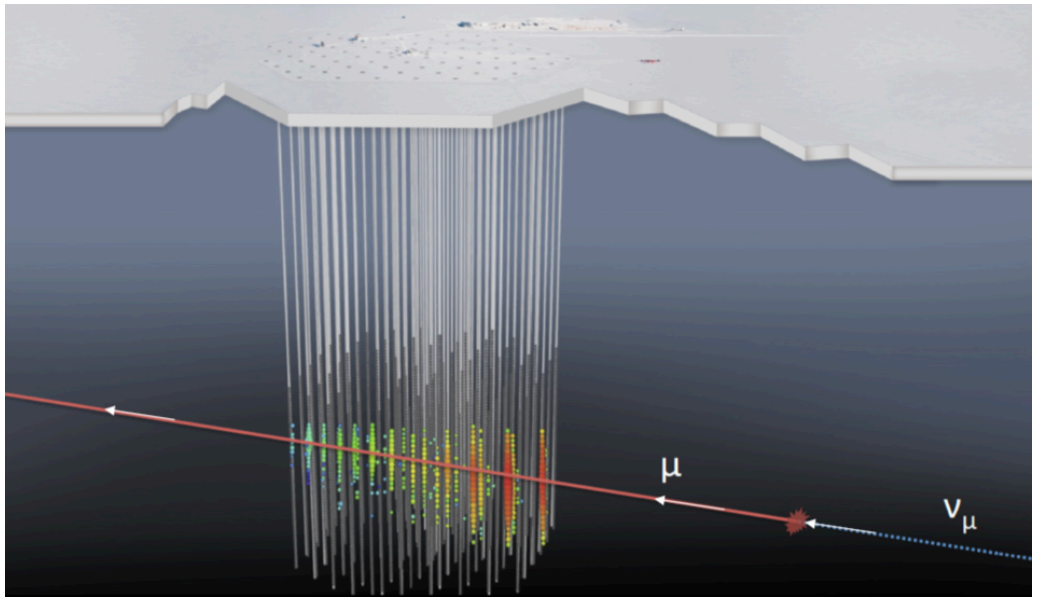
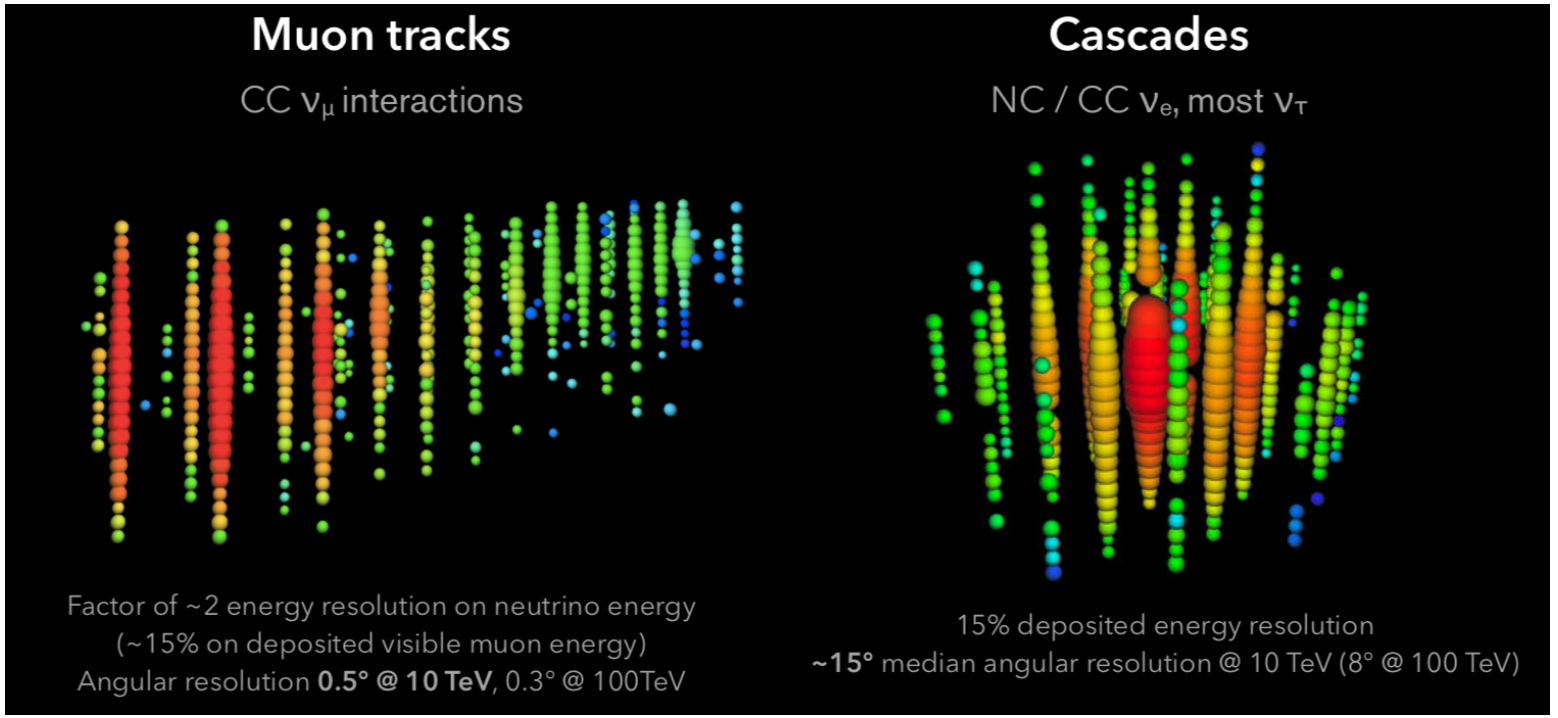
- Two neutrino event topologies.







IceCube

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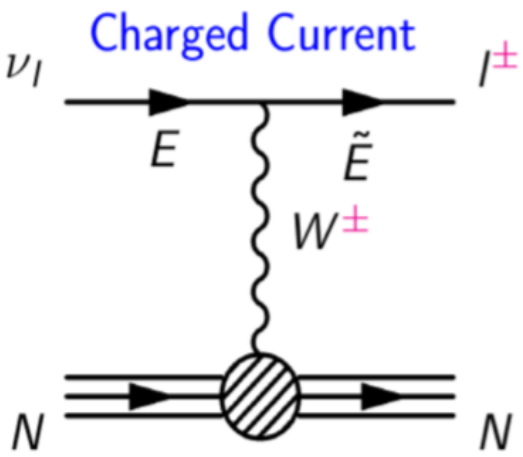
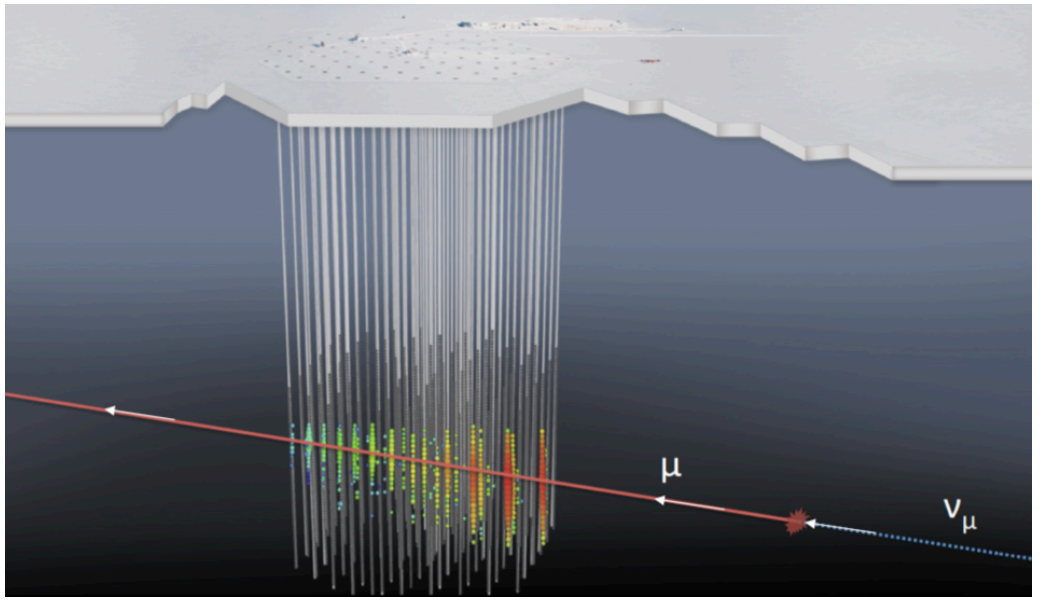
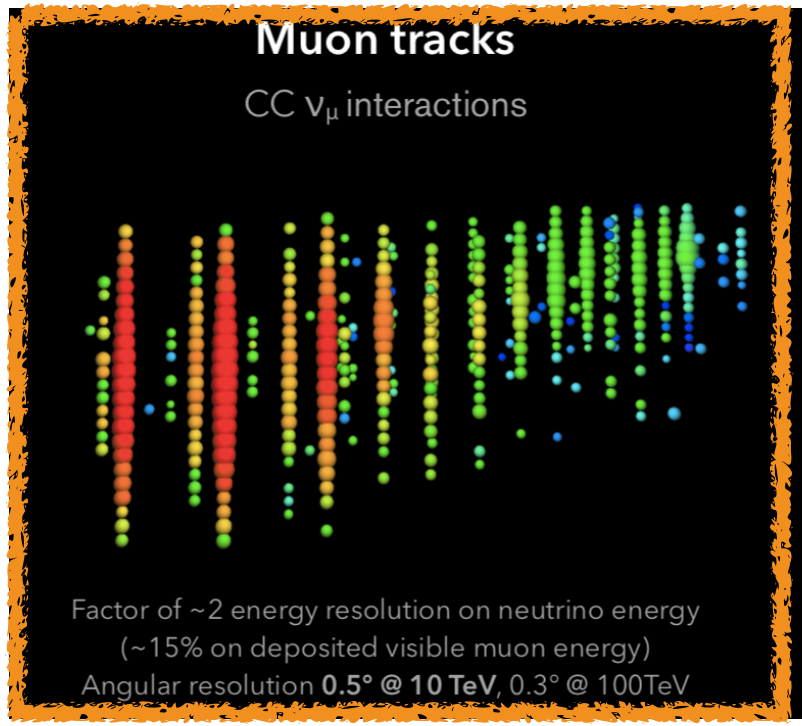
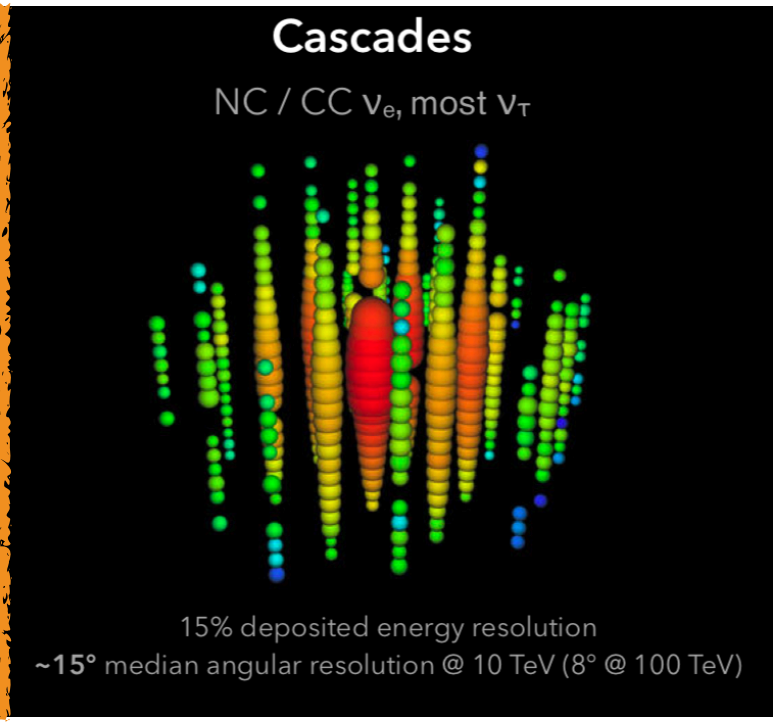
- Photons are detected by the photomultipliers in the DOMs.
- Two neutrino event topologies.
- This talk will focus on very high-energy muon neutrinos that are likely astrophysical in origin (**real-time neutrino alerts**).



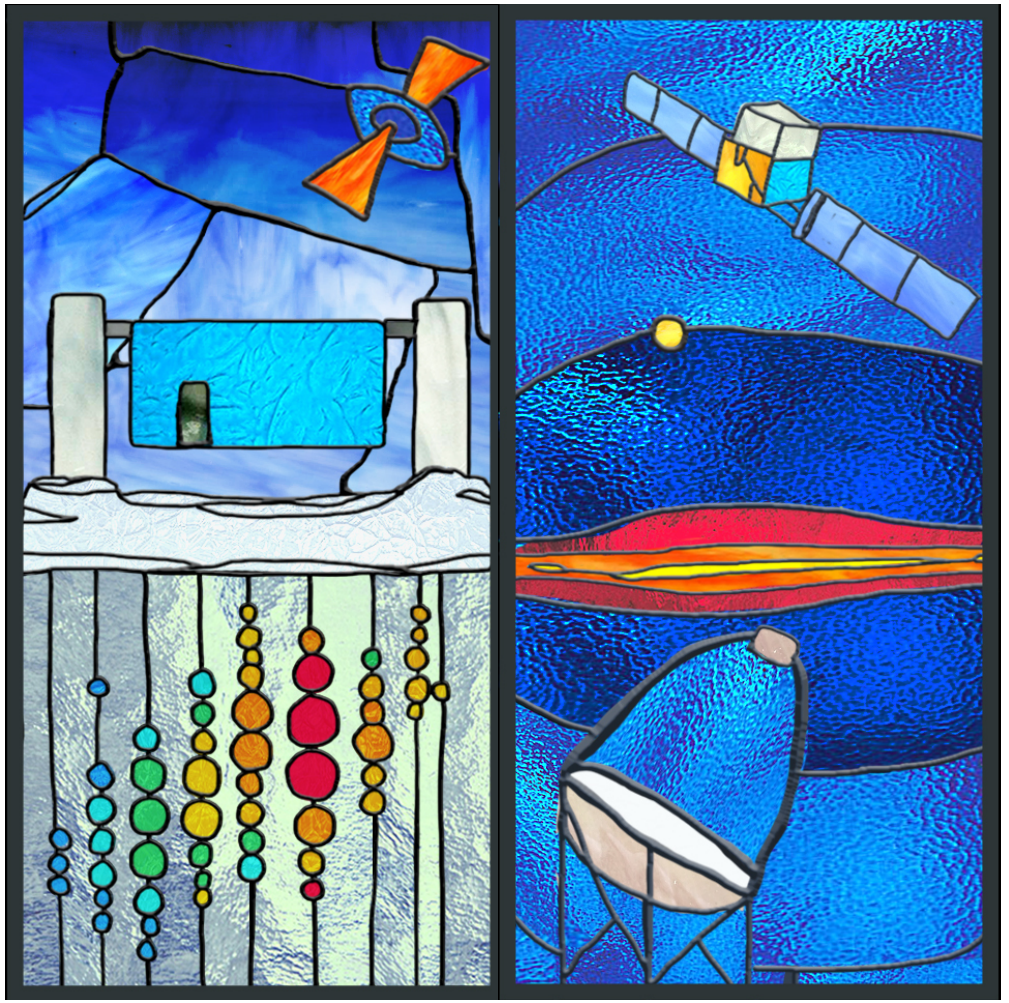






Real-time neutrino alerts

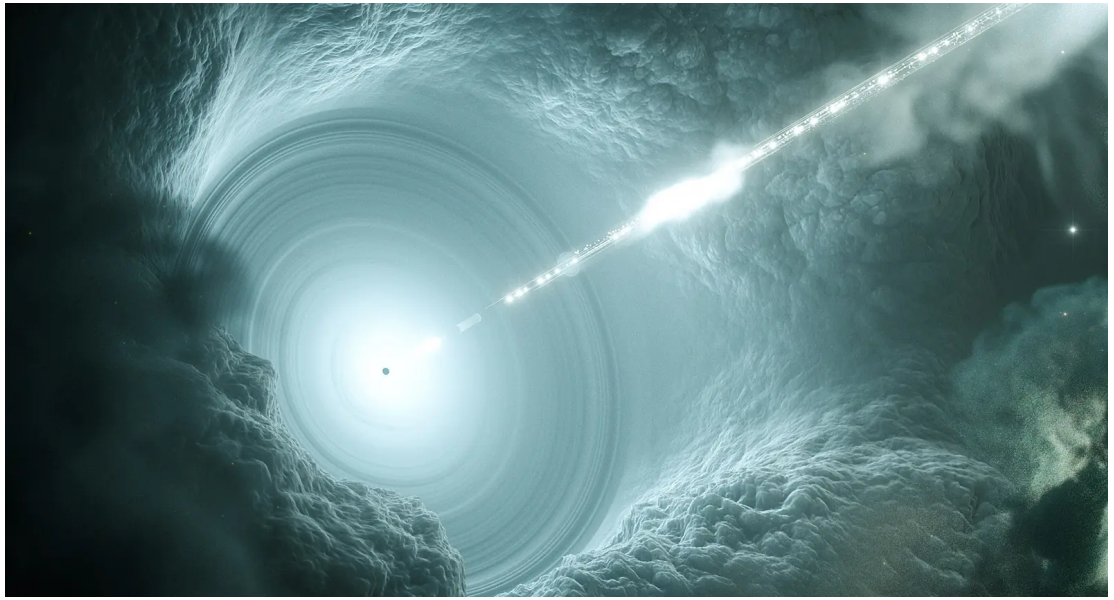
- IceCube detects a high-energy neutrino with high probability of being astrophysical
- Alert is issued as a public GCN Notice
- The alert includes
  - Direction and uncertainty
  - Signalness and expected yearly rate
  - Most likely neutrino energy
- Updated GCN circular follows ~3-4 hr later
  - Detailed direction likelihood scan results
  - Uncertainty includes systematic uncertainties
- Encourage followup from other observatories!



Search for neutrinos from blazars

Why blazars?

- Blazars are AGN with jets aligned towards Earth.
- They dominate the high-energy sky and have long been suggested as likely sources of UHECRs and neutrinos.
- 3σ p-value for the spatial and temporal correlation of an IceCube neutrino alert and a blazar, IC170922A - TXS 0506+056 [1].
- First indication of a cosmic neutrino source!

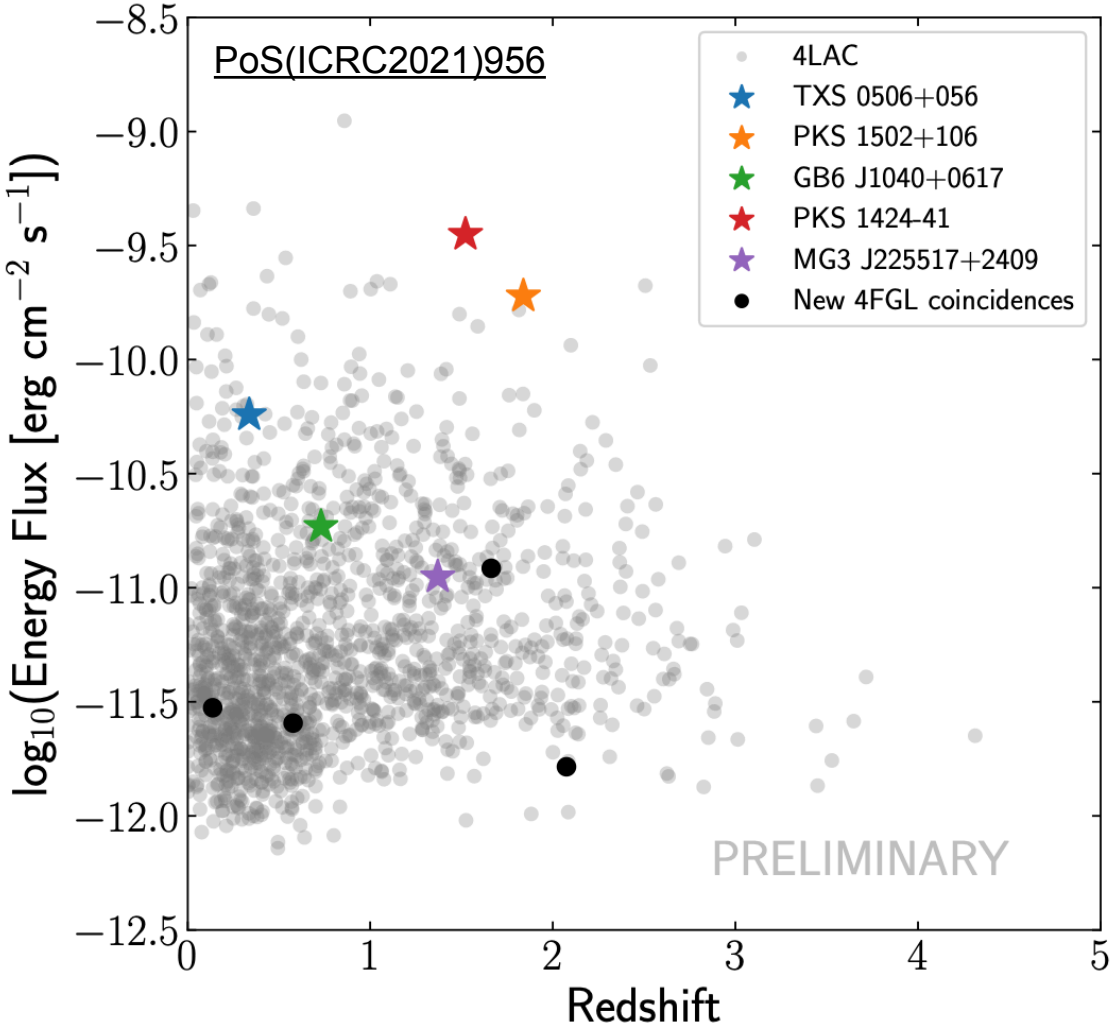


[1]: IceCube, Science 361 (2018) 6398

Search for neutrinos from blazars

Why blazars?

- Other interesting coincidence is IC190730A and PKS 1502+106 [2], 15th brightest GeV blazar.
- Also have GB6 J1040+0617 blazar coincident with IC141209A [3] and other low-significance coincidences.
- How can we combine these coincidences to calculate a global p-value?



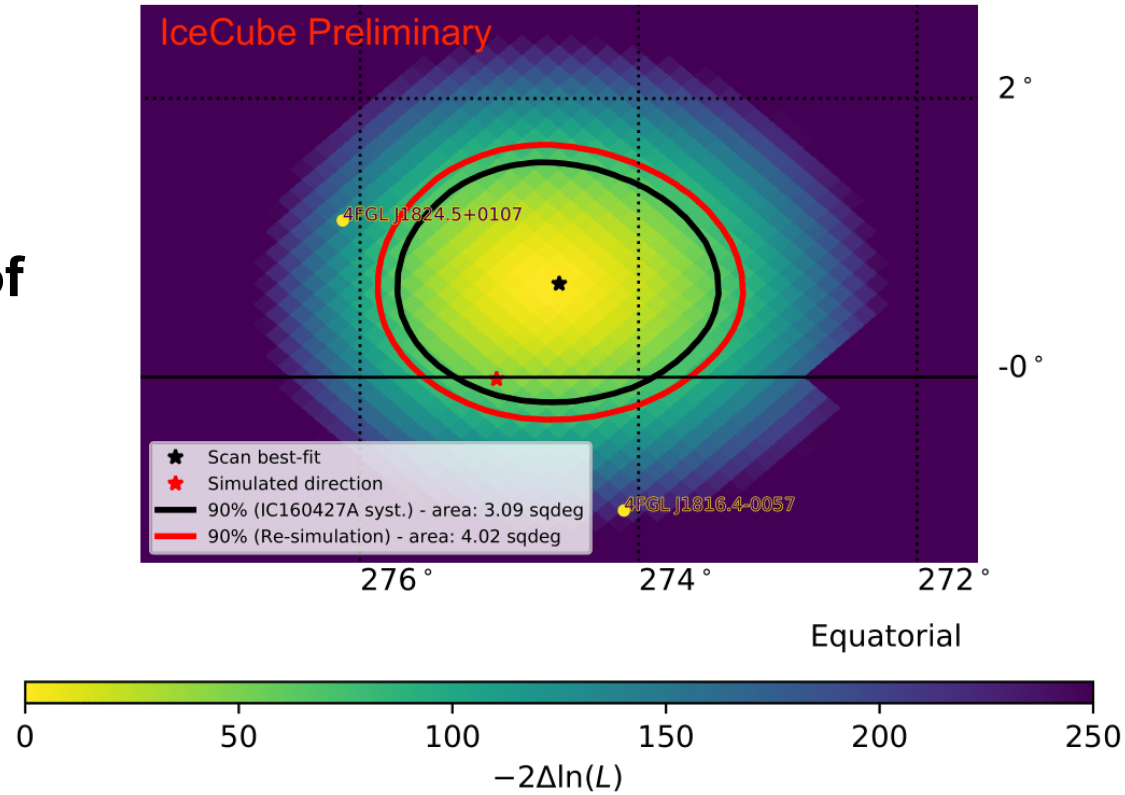
[2]: Rodrigues, X. *et al* 2020 *ApJ* 912

[3]: Garrappa, S. *et al* 2019 *ApJ* 880 103

Search for neutrinos from blazars

How do we do it?

- Perform a stacking analysis to calculate the overall correlation between neutrino alerts and blazars.
- To compute trials to test the significance of the analysis we use the real neutrino alerts with directions and **randomly scramble the position of the blazars**.
- We can use the likelihood map that the realtime reconstruction method creates. This gives us more information about the probability that the blazar is correlated with a neutrino.



Likelihood to test for correlations

Signal Hypothesis: the neutrino is correlated with one of the coincident blazars.

Null Hypothesis: the neutrino is not correlated with any blazar (could be astrophysical or atmospheric).

Calculate Test Statistic for each neutrino:

$$\mathrm{TS}_i = -2\log\left(\frac{\mathscr{L}(n_s = 1)}{\mathscr{L}(n_s = 0)}\right) = -2\log\frac{\hat{S}}{B}$$

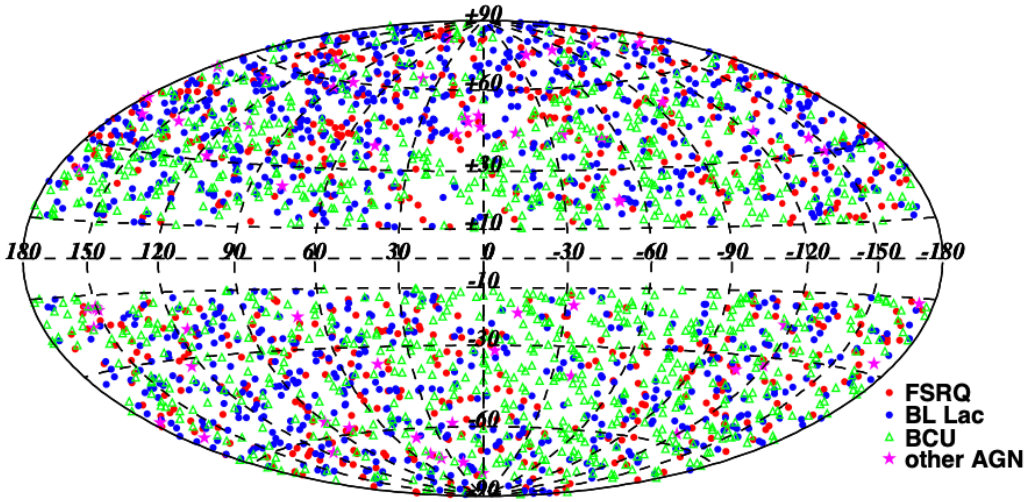
$$\hat{S} = max(S_{spatial,\nu}(\overrightarrow{x_b})\ p_{signalness}\ w_b) \qquad B = B_{spatial}$$

For each trial we sum over each neutrino alert $\mathrm{TS} = \sum_i \mathrm{TS}_i$

Dataset

Blazar catalog: Fermi 4LAC (1916 blazars)

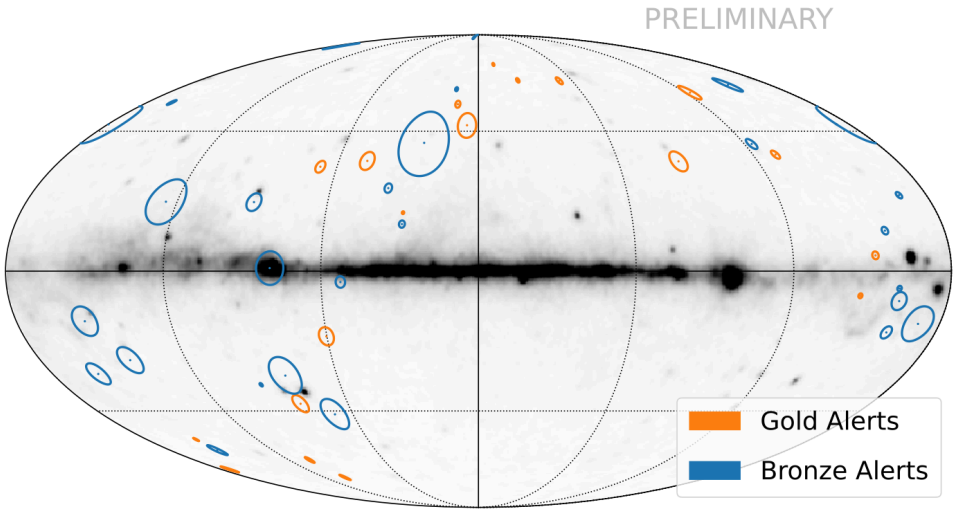
- Full description here: Ajello, M. *et al* 2020 *ApJ* 892 105
- Galactic Plane is masked 10 degrees
- Weight: 8 year energy flux



M. Ajello *et al* 2020 *ApJ* 892 105

Neutrino catalog: v2 alert catalog (275 alerts)

- Paper in preparation
- Likelihood maps
- Weight: signalness [4]



PoS(ICRC2021)956

[4]: PoS(ICRC2019)1021

Sensitivity

Sensitivity: At ~6% of flux (expectation of ~7/275 associations)

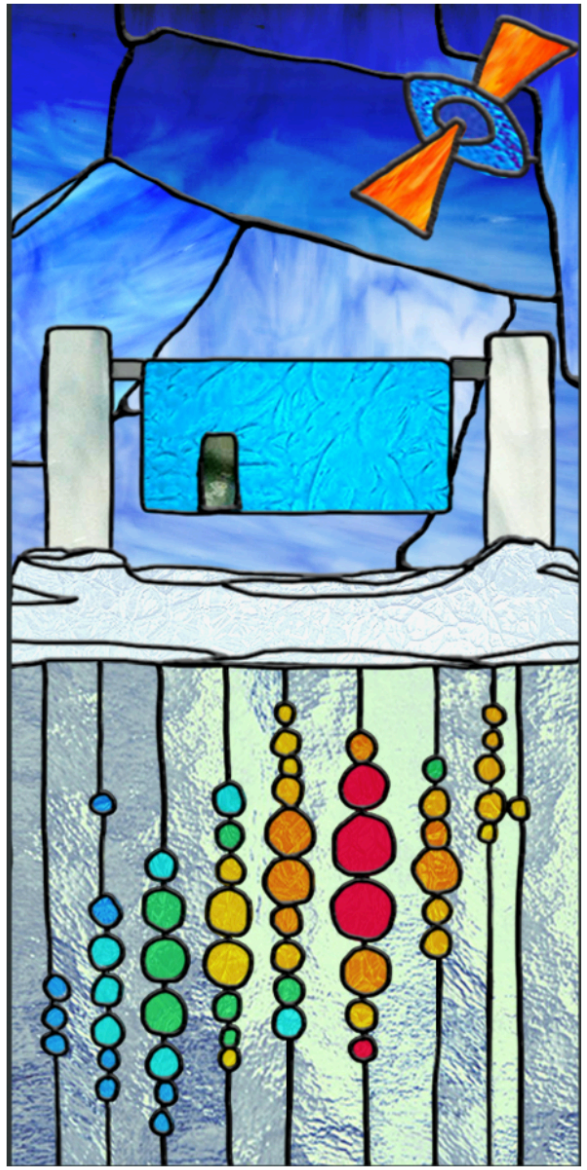
3σ discovery: At ~11% of flux (expectation of ~14/275 associations)

5σ discovery: At ~22% of flux (expectation of ~27/275 associations)

➡ **Values are comparable to previous IceCube analyses that use a larger sample of neutrino events (e.g. PoS(ICRC2019)916)**

Summary

- Blazars dominate the high energy sky and have been suggested as neutrino sources.
- Search for correlation of blazars (4LAC) and neutrino alerts (v2 alert catalog).
- Perform a stacking analysis using event information (direction, signalness, likelihood maps).
- **Sensitivity at 6% of flux, 3σ discovery at 11%, 5σ discovery at 22%.**
- Method can be applied to test other catalogs (e.g. radio catalog by A. Plavin [5]).



[5]: Plavin, A. ApJ 908 (2021) 157