Multi-Messenger Astrophysical Neutrino Alerts from IceCube

Erik Blaufuss
University of Maryland
Astro-COLIBRI Multi-Messenger Astrophysics Workshop
September 16-20, 2024

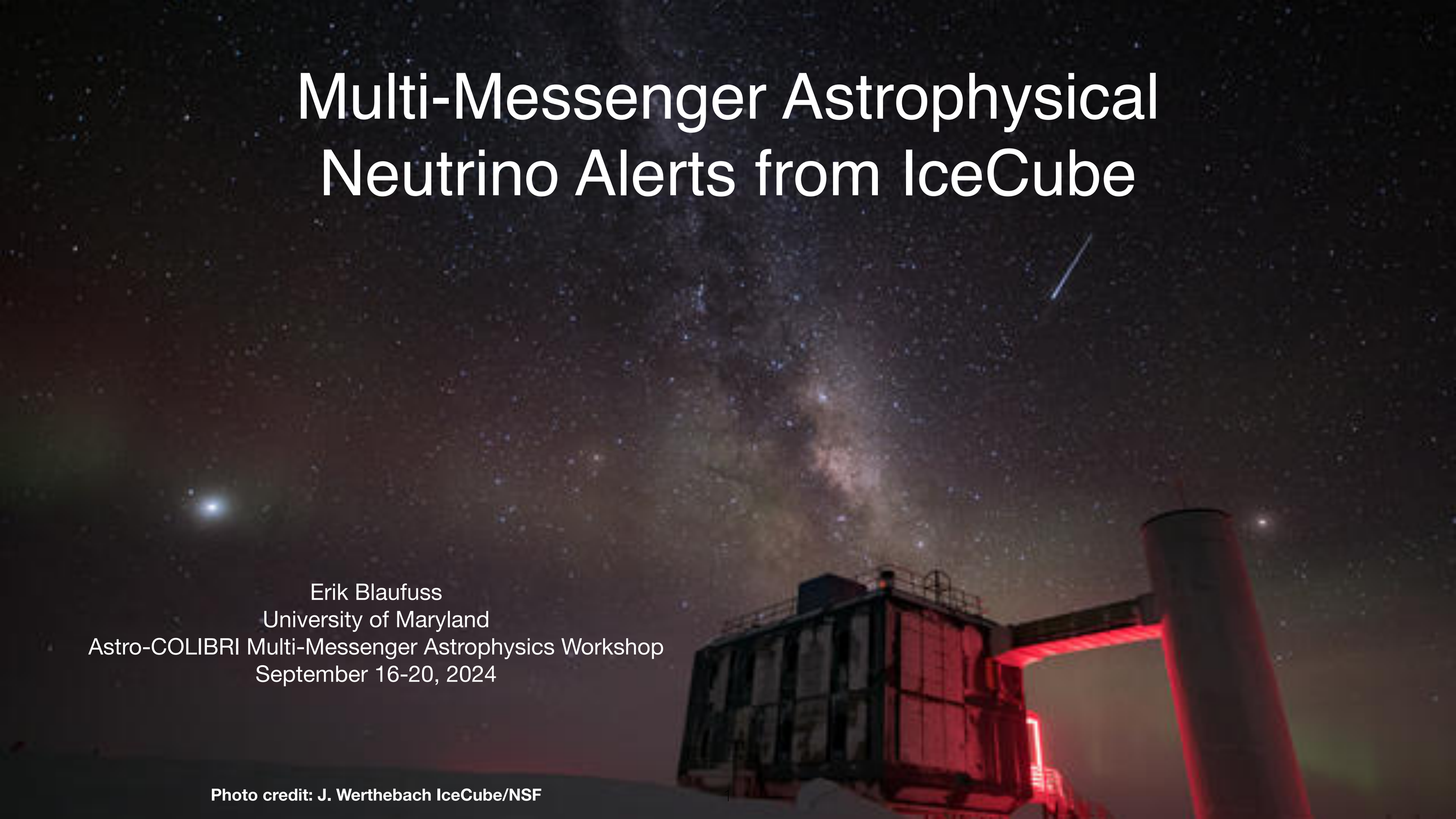
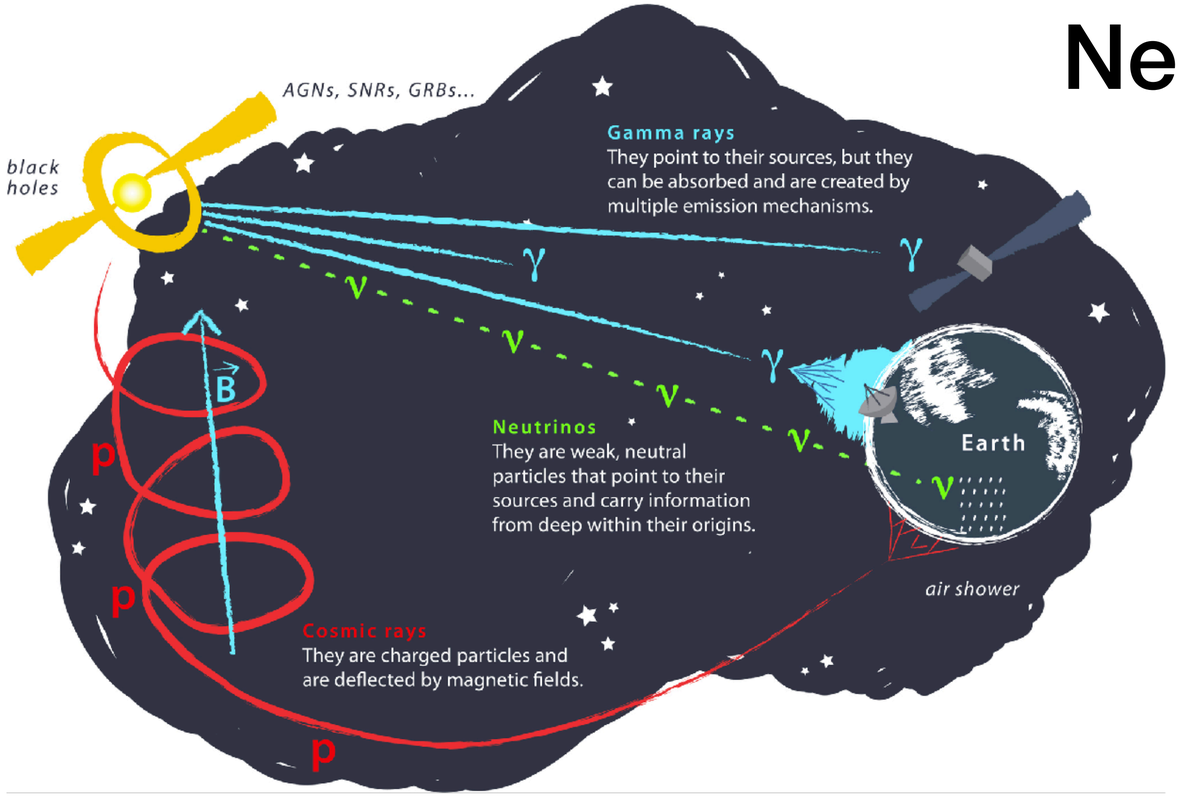
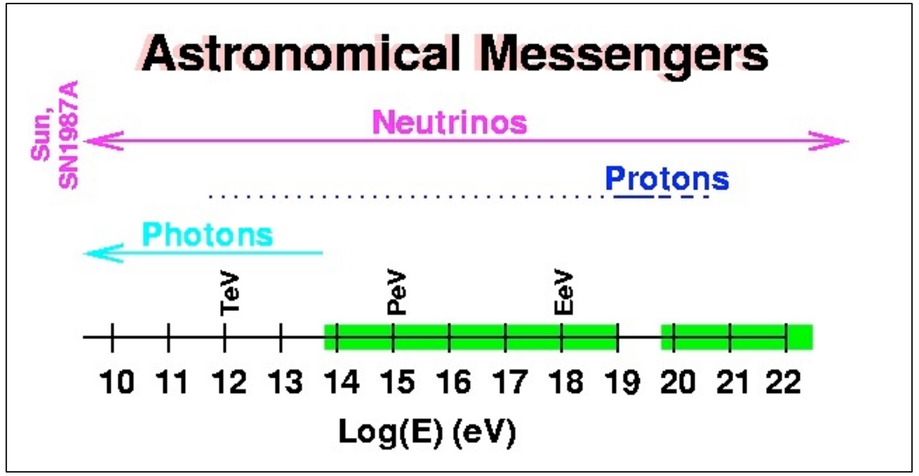


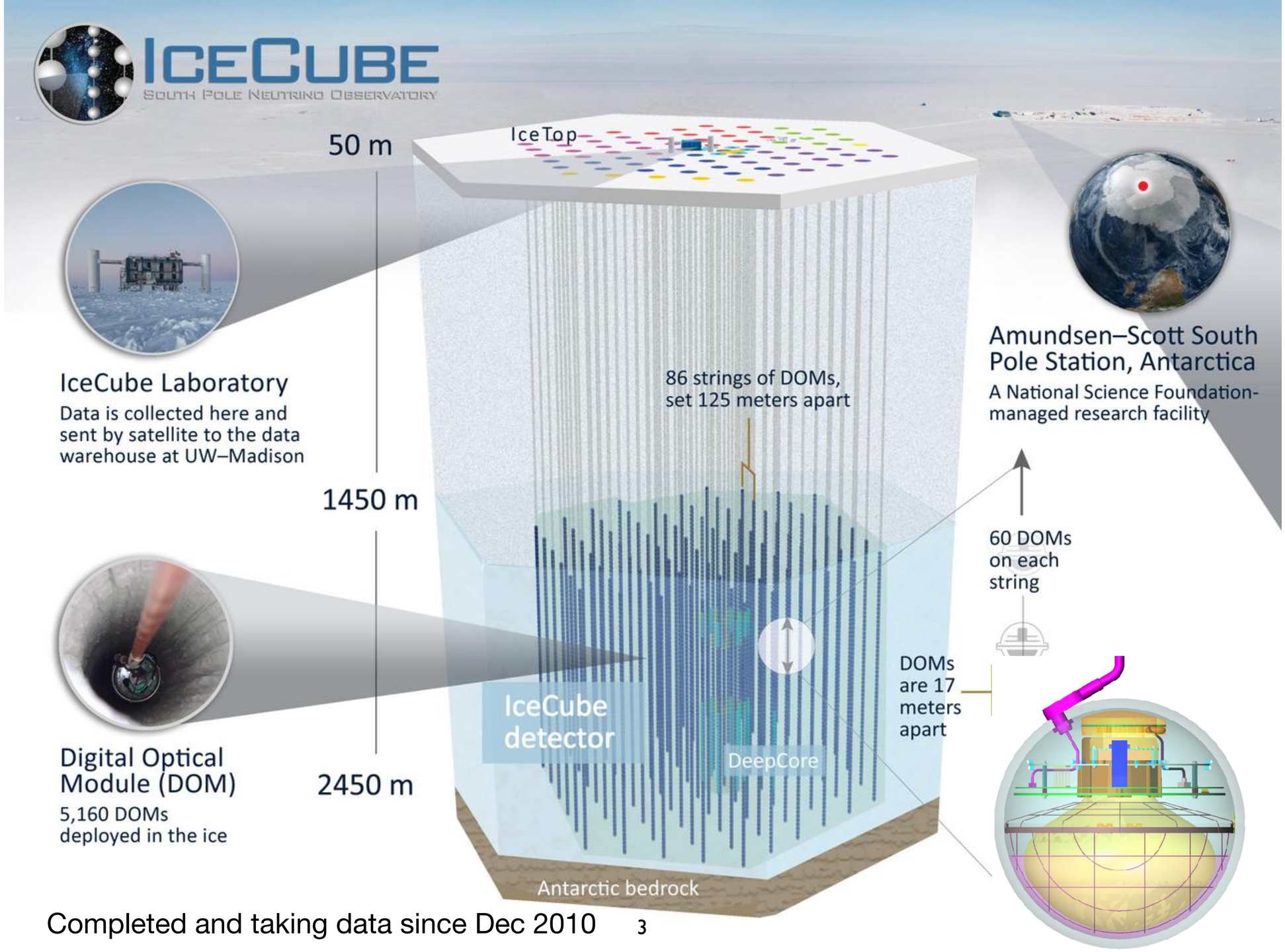
Photo credit: J. Werthebach IceCube/NSF

Neutrinos: Astronomical messengers





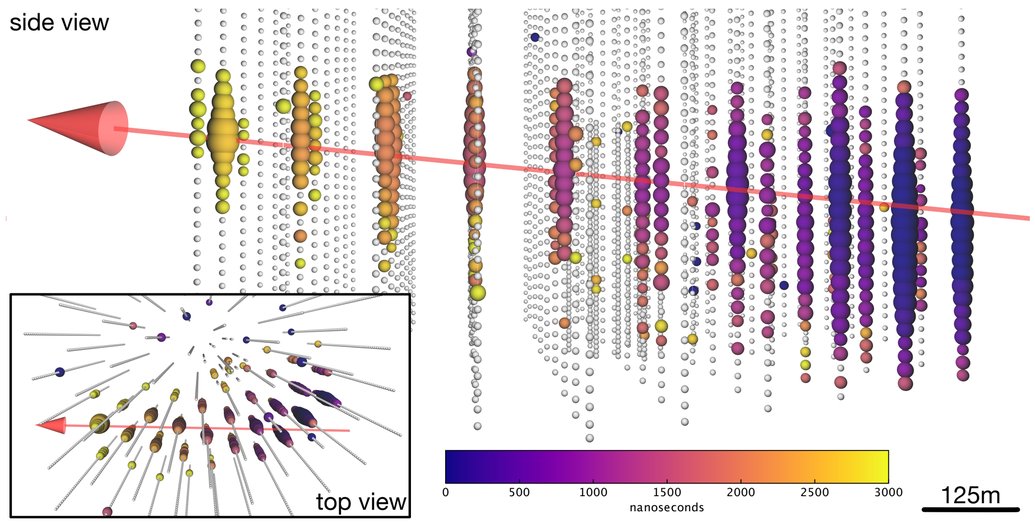
- Neutrinos can be created by hadronic interactions within or near cosmic accelerators
- At the highest energies, neutrinos are an astronomical messenger with several advantages:
  - Neutral
  - Freely propagate from source regions



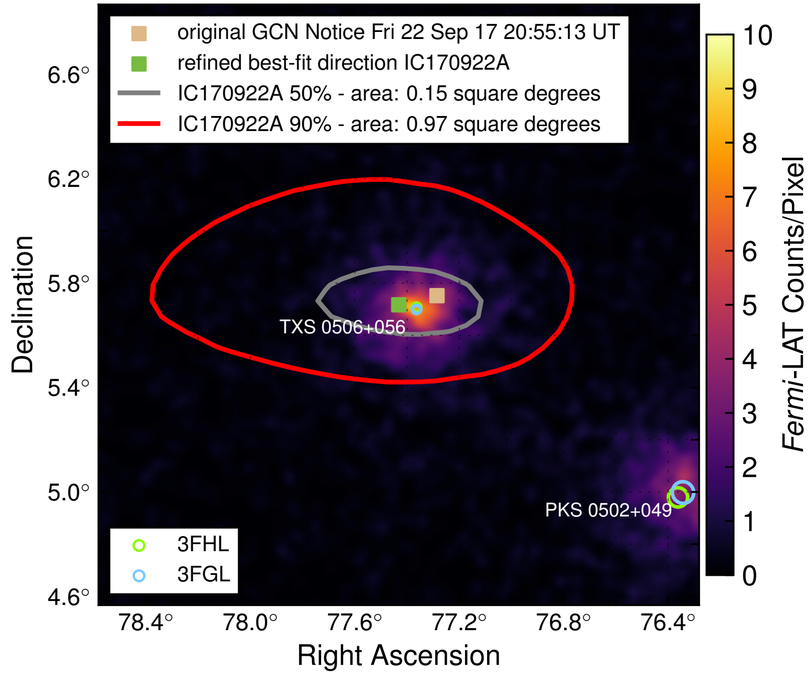
Completed and taking data since Dec 2010

Multi-Messenger Astrophysics with Neutrinos

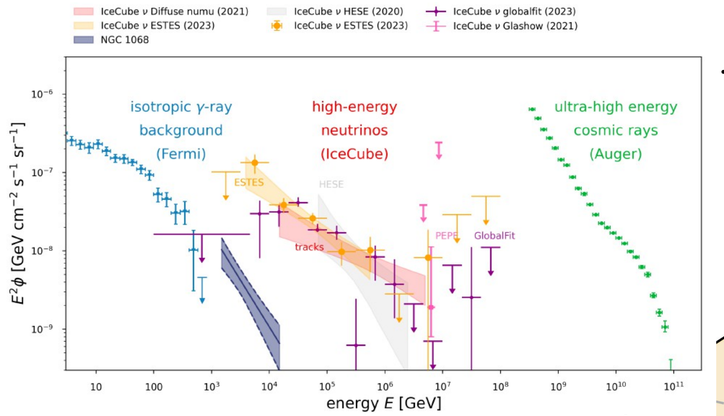
- Since the detection of a diffuse astrophysical neutrino signal, IceCube has become an active participant in MMA observations of the high-energy universe
  - Notifying observational community when we detect neutrino events that are likely to be astrophysical
  - Perform realtime neutrino point-source searches when community identifies transient objects that are potential neutrino sources.
- My talk today will focus will describe our realtime alerts and followup programs.
  - We've also got several improvements coming online soon and are looking for suggestions on how we can improve alert clarity when communicating with you.

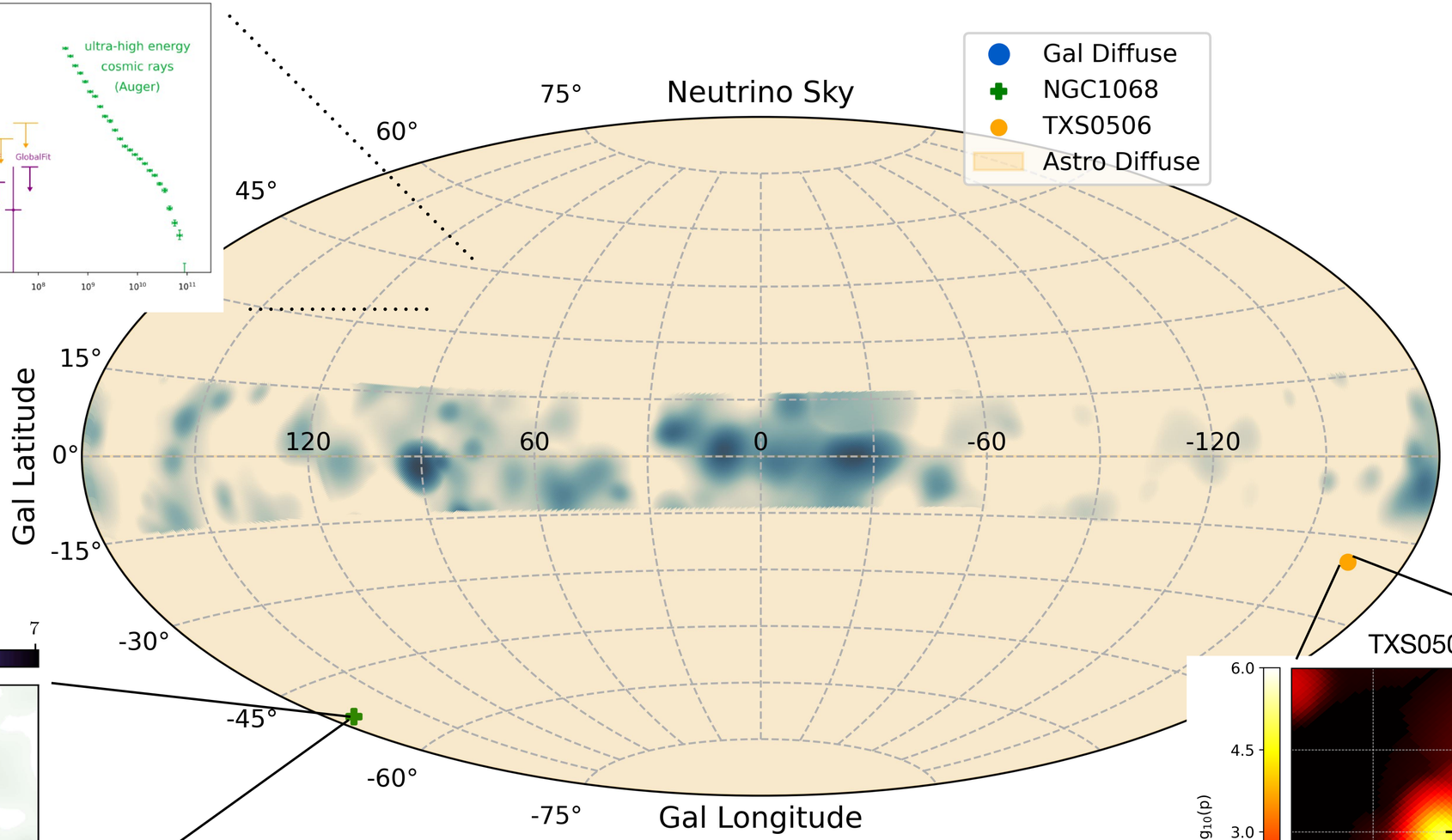


Multi-messenger alert: TXS 0506+056

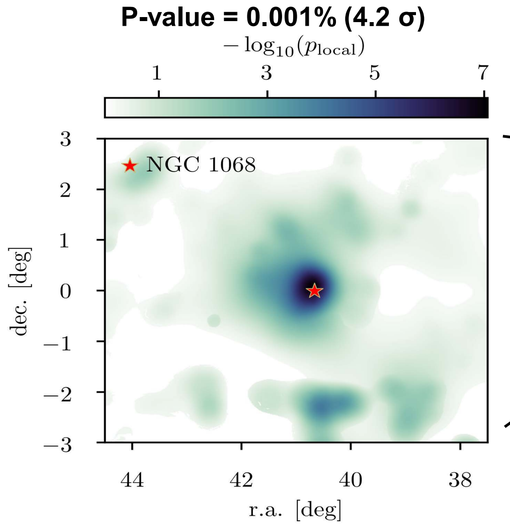


The High Energy Neutrino Sky

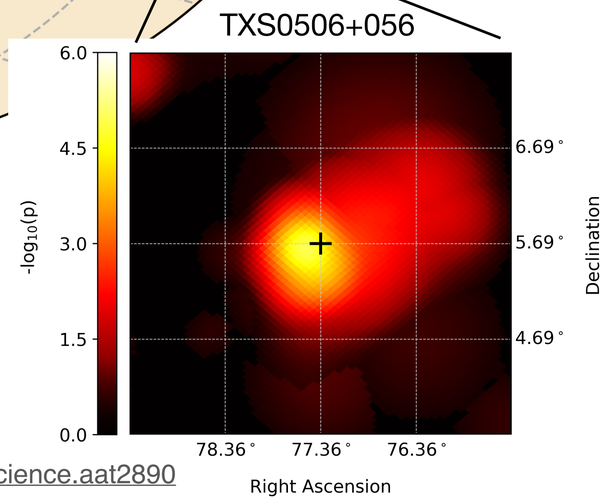




DOI: 10.1126/science.adc9818

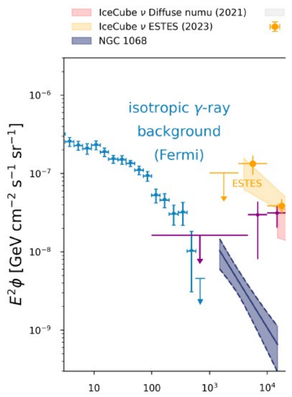


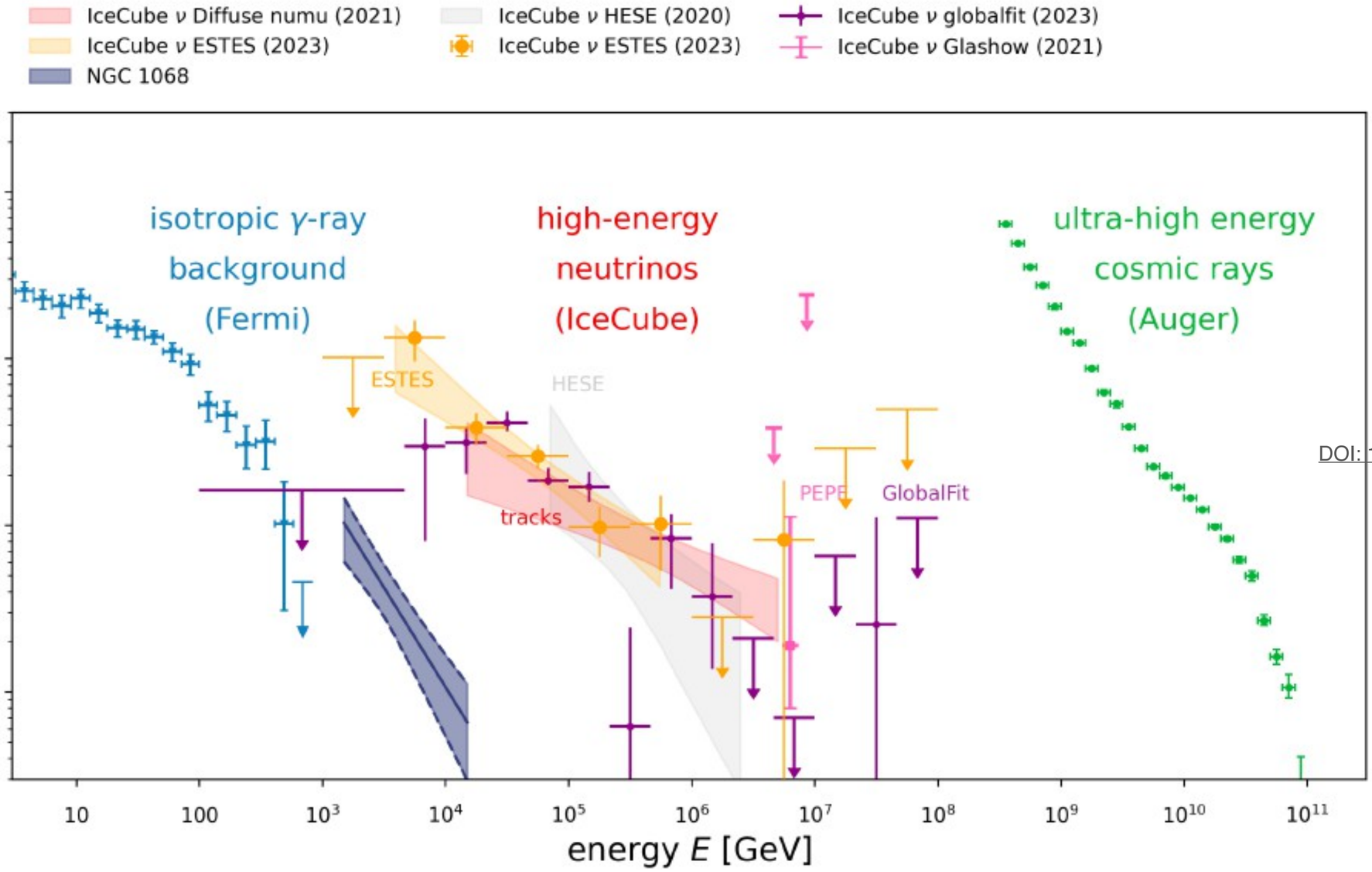
Science 378, 6619 (2022)

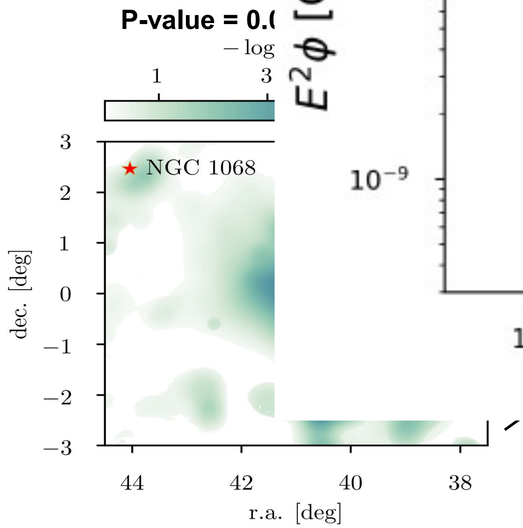


DOI: 10.1126/science.aat2890

The High Energy Neutrino Sky







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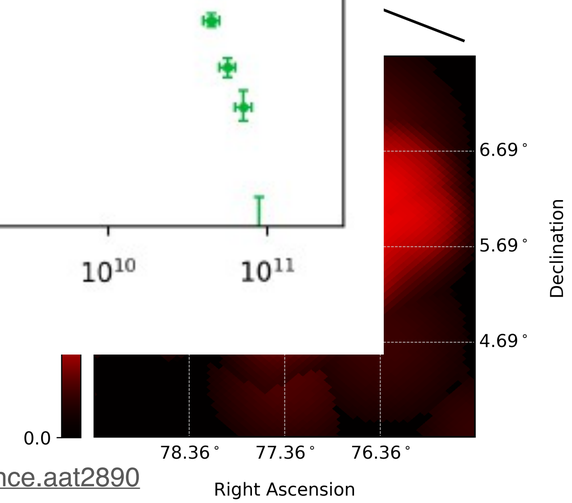

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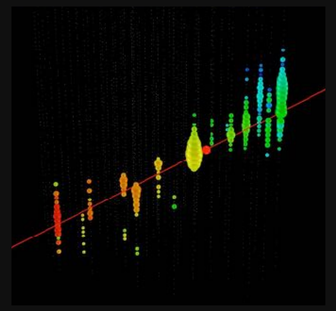
IceCube sensitive to all ν flavors

CC Muon Neutrino

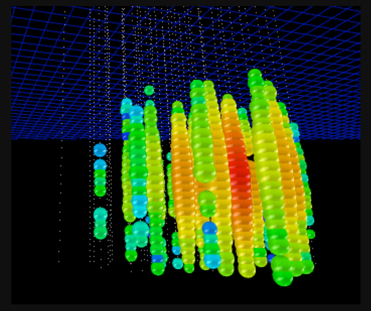


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / CC Electron Neutrino

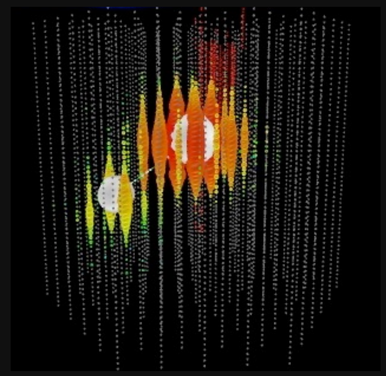


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

shower (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

CC Tau Neutrino

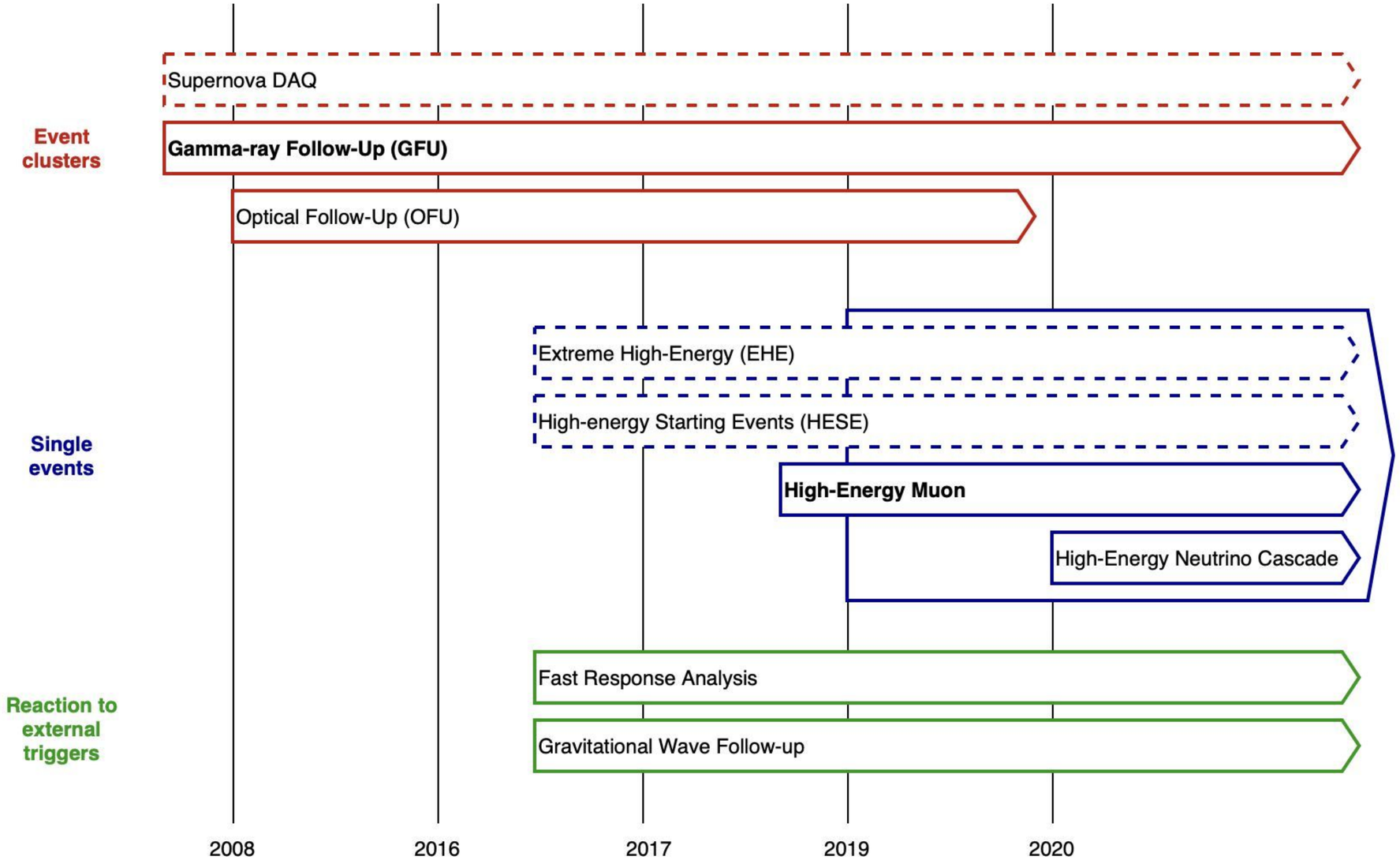


$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

(not observed yet)

IceCube Astrophysical Realtime Program

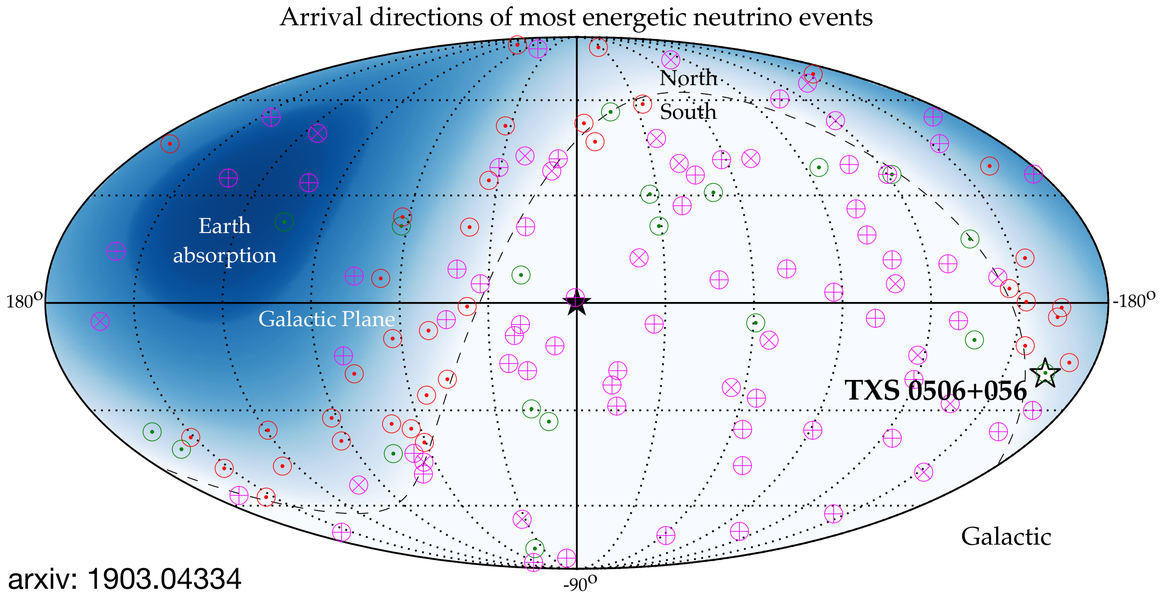


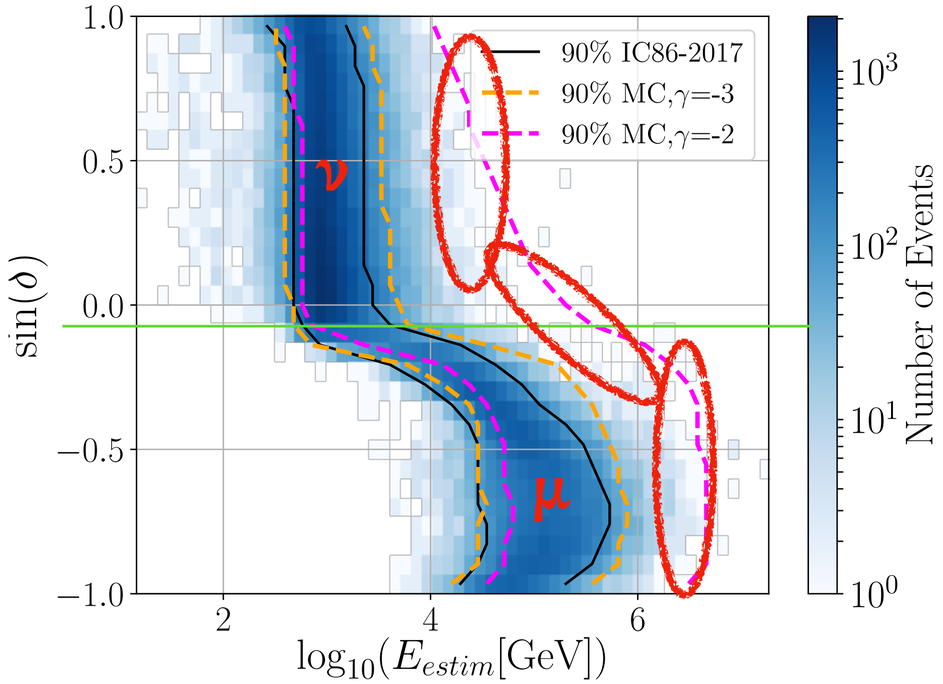
- Alerts coordinate on public alert systems
  - GCN
  - SNEWS
- Collaboration response coordinated by internal Realtime Oversight Committee
  - Ensure rapid response

Credit: M. Lincetto

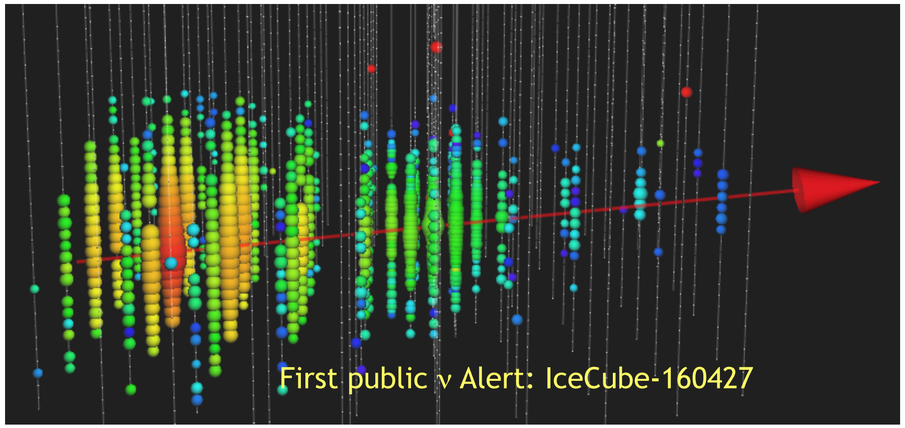
Realtime Oversight Committee

IceCube Astrophysical single neutrino alerts



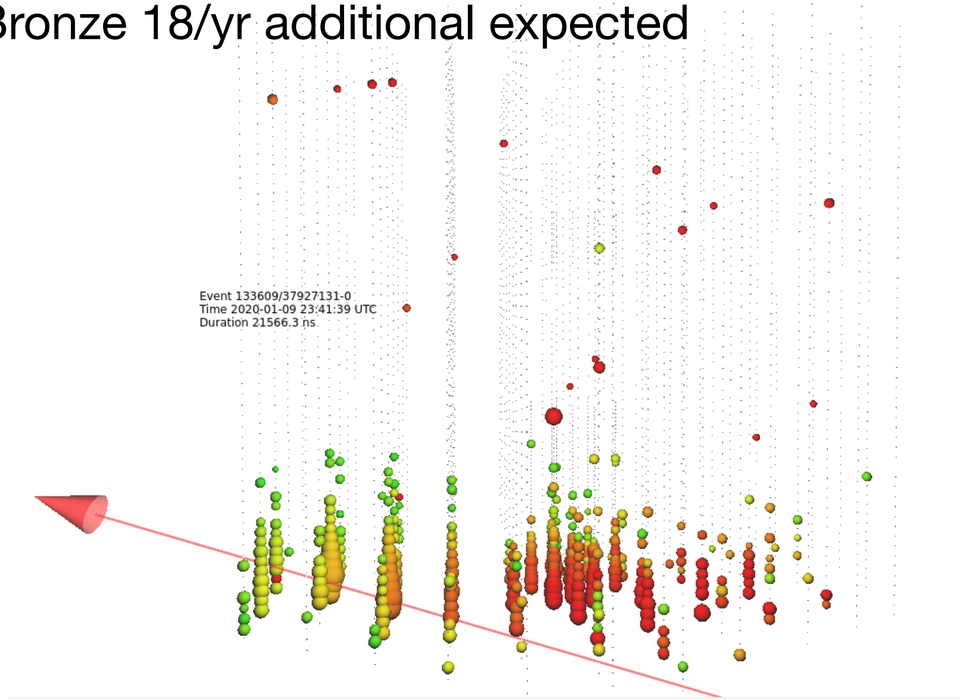


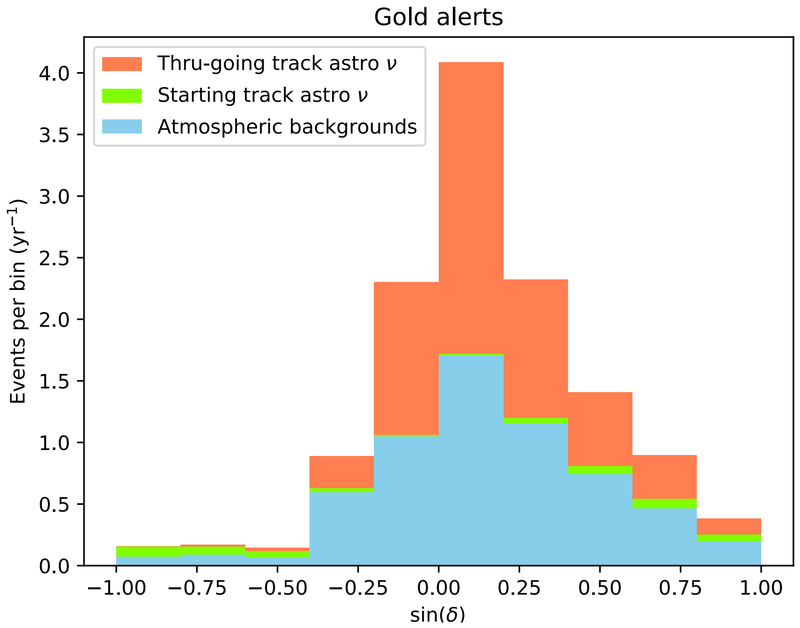
- Identify well reconstructed, high-energy neutrino candidates in real-time
  - Must be higher energy that most background events
- Transmit them to the North and advertise
  - Latency from detection to alert typically less than 1 minute
  - Detector uptime > 99%
- Community observations to search for multi-messenger signals
- In operation since April 2016

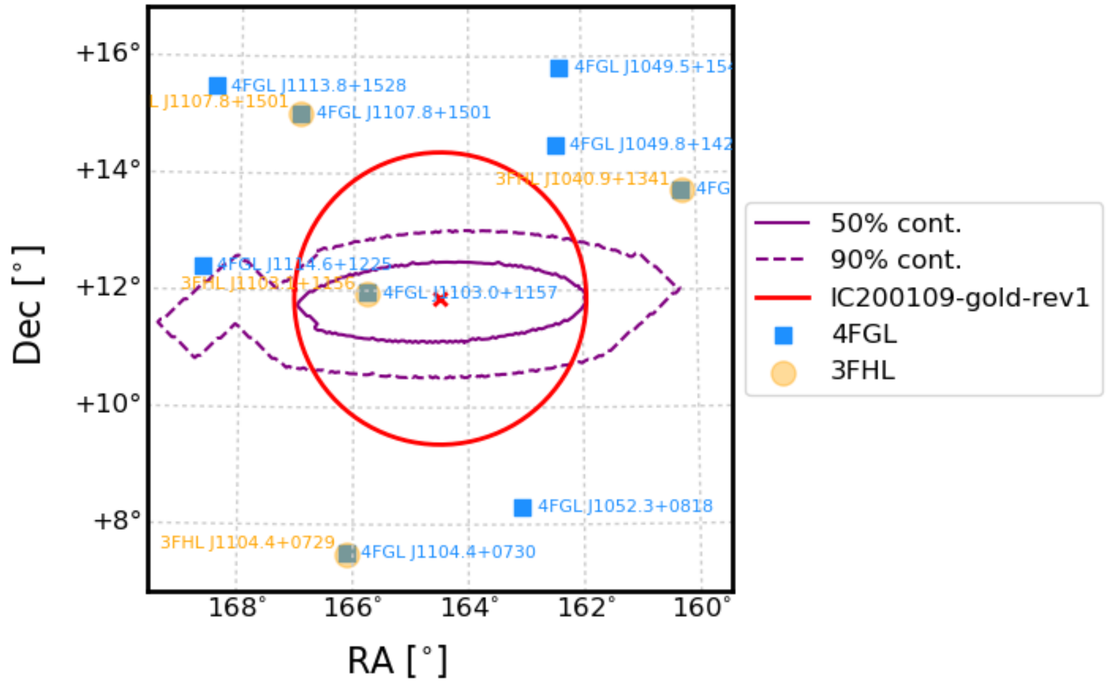


IceCube Realtime Track Alerts

- Two selection levels
  - Gold alerts : average 50% likely astrophysical origin
  - Bronze alerts: average 30% likely astrophysical origin
- More alerts per year
  - Gold: 12/yr expected
  - Bronze 18/yr additional expected







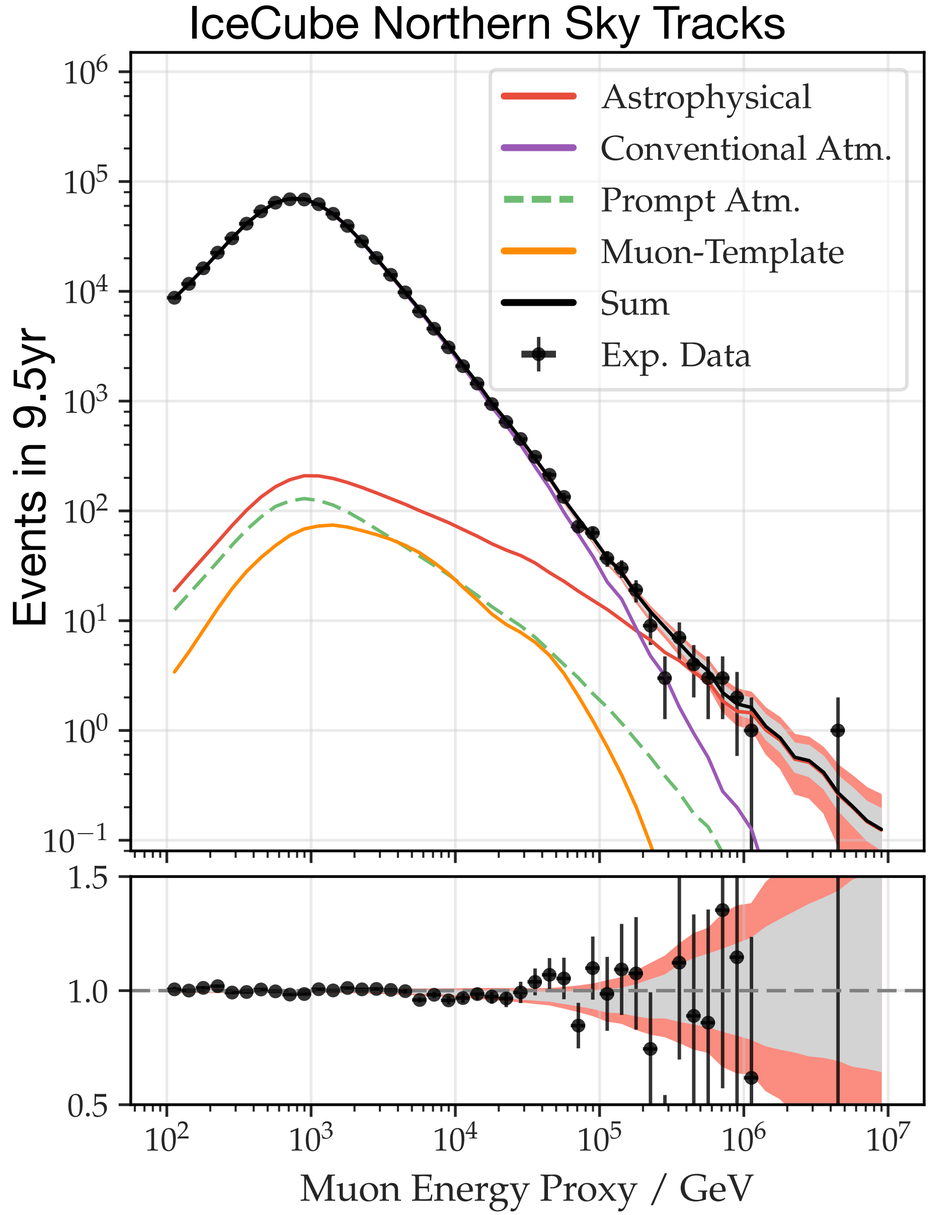
IceCube issues Cascade Alerts as well

IceCat-1 https://arxiv.org/abs/2304.01174

Realtime Point Source Searches

- Along with alerts, generate an all-sky track sample for rapid searches for point sources.
  - Sample dominated by atmospheric backgrounds, need event excess over background
- Rapidly respond to community generated alerts (GCN/ATels) of interesting astrophysical transient events
  - Gravitational Wave Events, reported Flaring AGN, etc
  - IceCube track and cascade alerts
- Dedicated flaring source searches for catalog of known gamma-ray bright, variable sources (hours to 180 days)

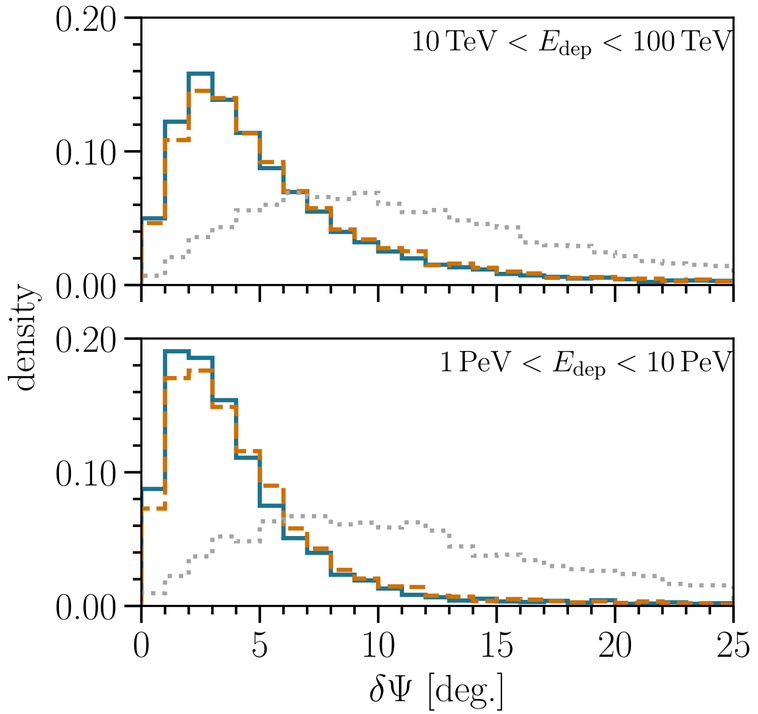
Details 10.1088/1748-0221/11/11/P11009



IceCube, Astrophys. J. 928 (2022) 50

Upcoming improvements

- We have several improvements to our realtime system in the pipeline
- For single neutrino alerts (tracks AND showers)
  - New, faster followup reconstruction toolbox
  - Improvements to followup reconstructions
- Updating flaring multi-neutrino source search
  - All-sky and catalog of potential sources from EM observations
  - Make alerts from searches for transient point sources public
- Move to new alert platforms
  - GCN over Kafka, SCiMMA



Arxiv: 2403.02470

All expected to be deployed in next few months

Challenges, issues and opportunities

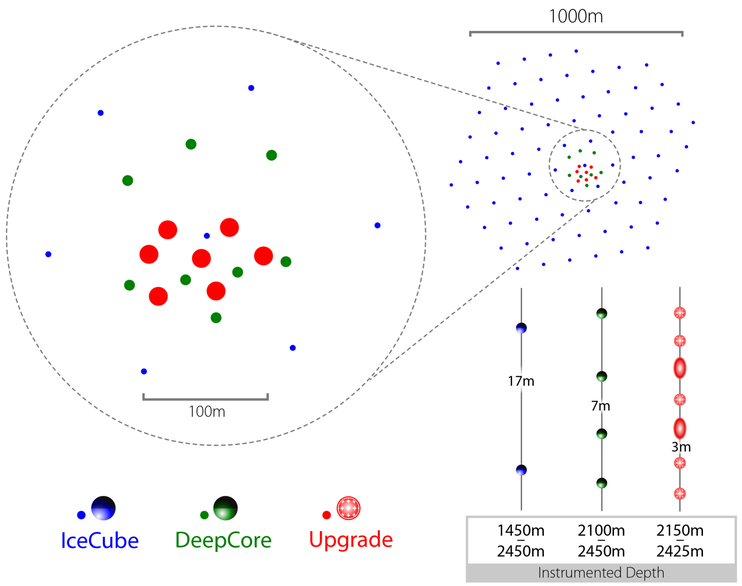
- We'd love input from the community on how we can improve things
  - How can we best update our alert messages to make them more useful for followup observations?
    - Considering including p-value maps, generally useful?
  - How best to communicate alert system changes and details?
  - Use multiple alert systems in parallel?
  - How to raise the profile of our shower alerts
    - They have high astrophysical purity!
  - How to highlight the "really special events" when we find these rarer alerts?

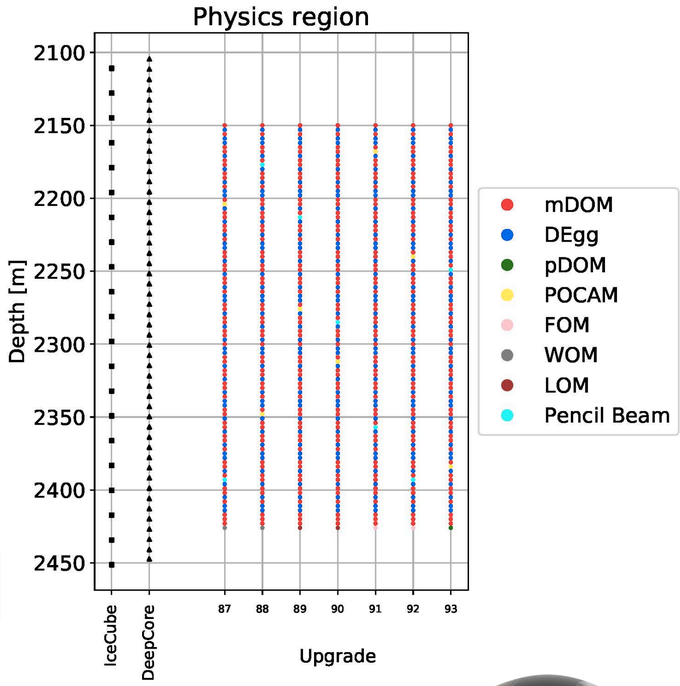
Let's meet this week and discuss!

Upgrade plans

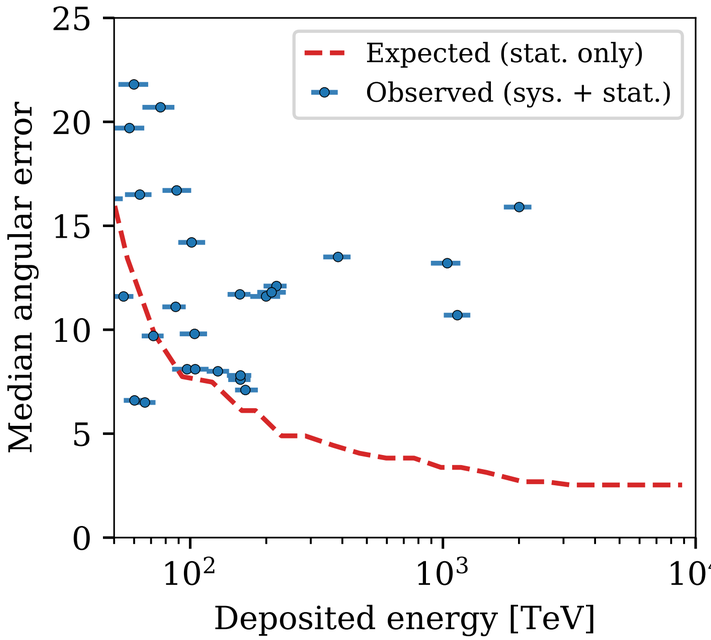
- Two-tier effort
  - IceCube Upgrade - in progress
    - Focus on improved calibration and low energy neutrino physics
    - Test new technologies
    - Deployment in 2025/26 polar season
  - IceCube Gen2
    - Focused on larger samples of astrophysical neutrinos over a wide energy range

Ice is stable: Able to reprocess decade+ of neutrinos with improved analyses and systematics



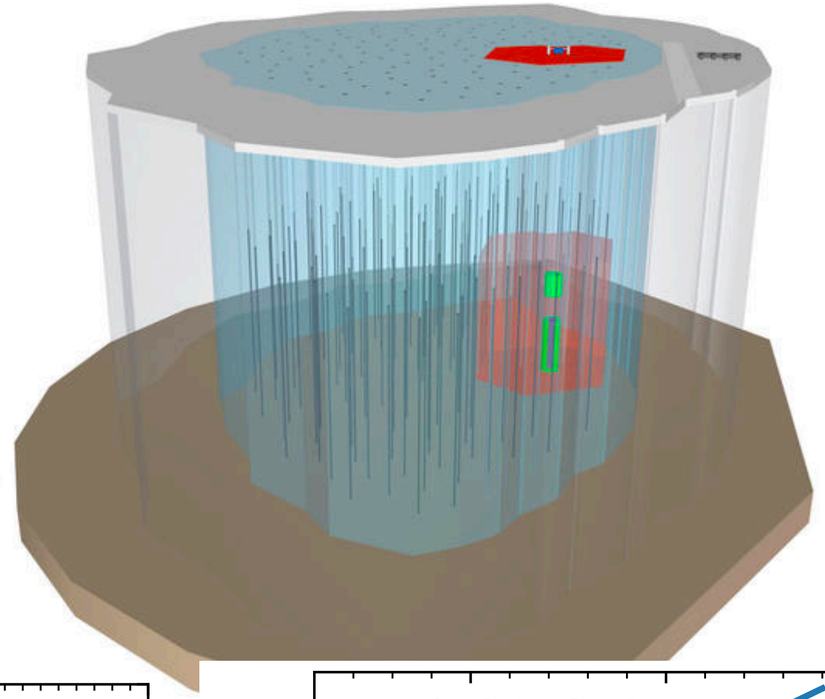


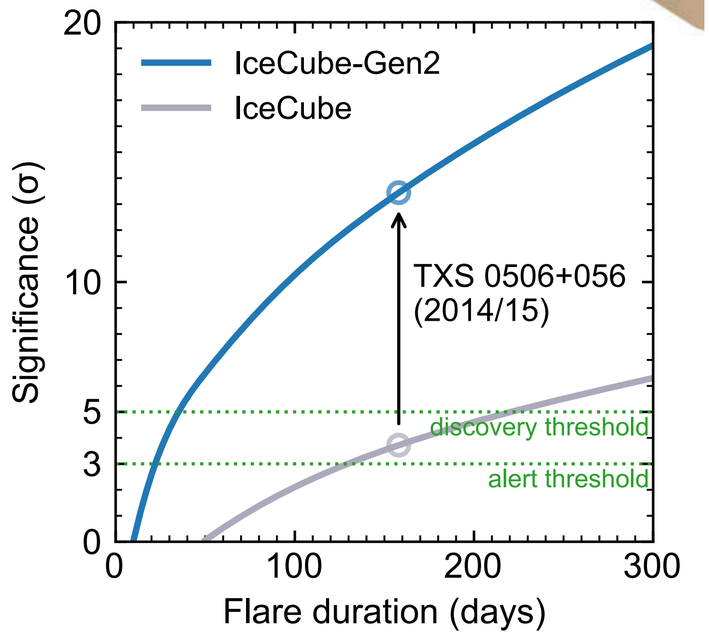
IceCube Upgrade Arxiv: 1908.09441

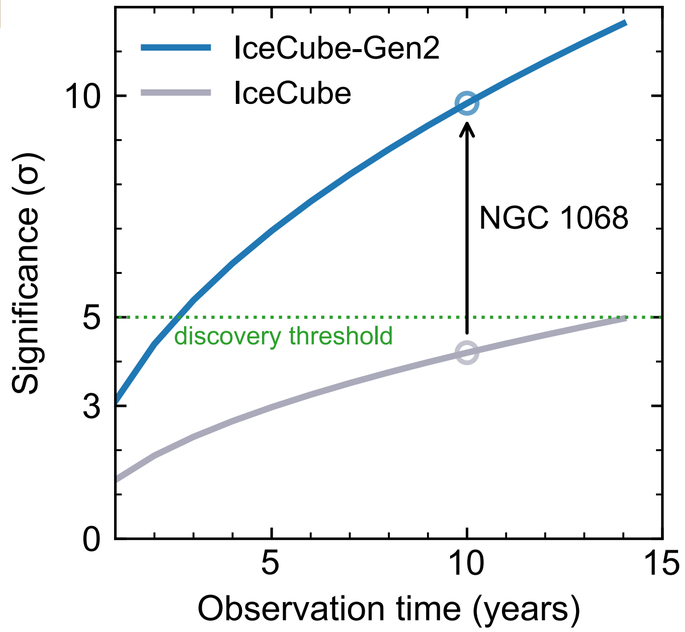


IceCube Gen2

- Looking forward, to get larger and better samples of astrophysical neutrinos, a larger detector is needed
- Envision a wide-band neutrino observatory
  - 8-10 x larger optical Cherenkov detector
    - Neutrino astronomy and multi-messenger astrophysics
  - Askaryan radio detector array
    - Probe neutrinos beyond EeV energies
  - Surface particle detector
    - Detailed cosmic ray spectrum and composition measurements and veto capabilities







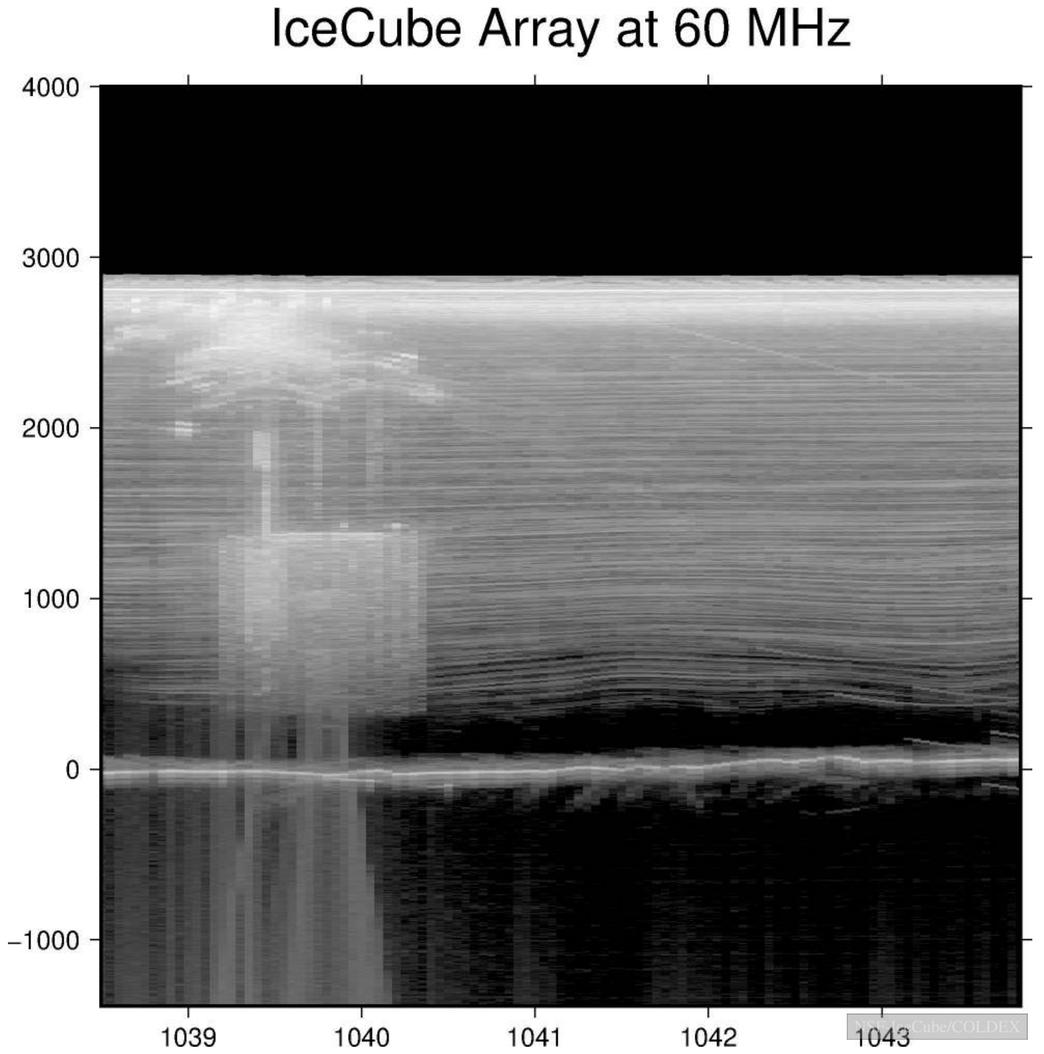
IceCube Gen2 TDR

https://icecube-gen2.wisc.edu/

Thanks!

Skua

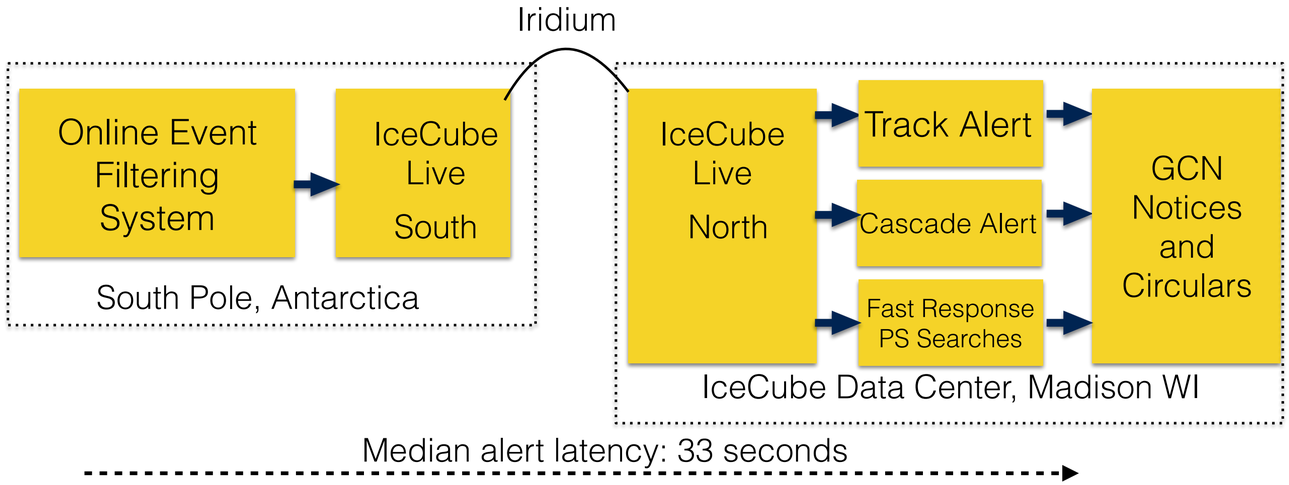
Adelie penguin



A ground-penetrating radar capture of the IceCube detector deployed in the ice.

NSF/COLDEX

IceCube Neutrino Alerts - MMA Tools



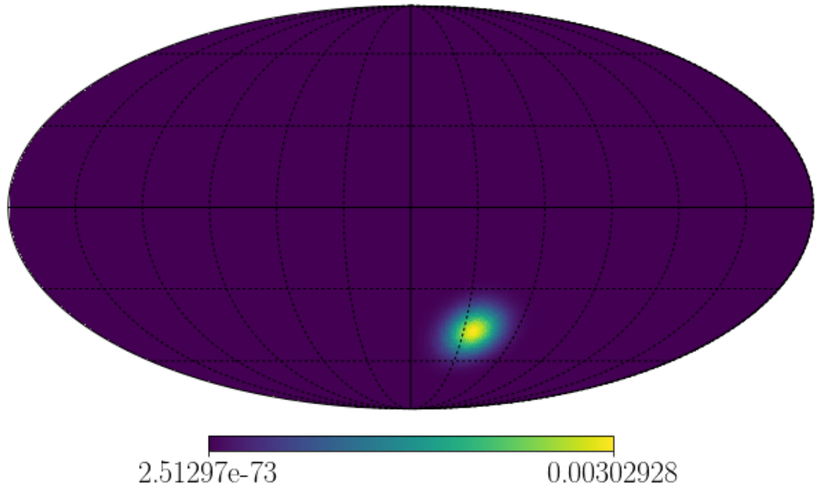
- Select events passing alert criteria in online filter computing farm at South Pole
  - Make wise choices to optimize limited realtime connectivity to Pole
  - Neutrino candidates: ~1 in 10^6
  - Astrophysical neutrino candidates: ~1 in10^9
  - Significant computing resources (~500 cores) needed to properly characterize and filter O(3kHz) of events
    - Results also used to measure realtime data quality and detector health.
- Transmit event data north via IceCube dedicated Iridium system
  - 24x7 data connection via Iridium (~10 kbps connection)
- Once in the North, significance computing to refine alert direction
  - O(1000) cpu-hours per event to complete scans to full precision
- Coordination is also significant effort - Realtime Oversight Committee
  - Provide immediate oversight and rapid vetting of alerts and realtime point source searches

- Alert communications
  - GCN “classic” Notices are migrating to new Kafka-based brokers.
    - New systems support richer alert content and more rapid development of new alerts
  - GCN Circulars for higher visibility for significant results.

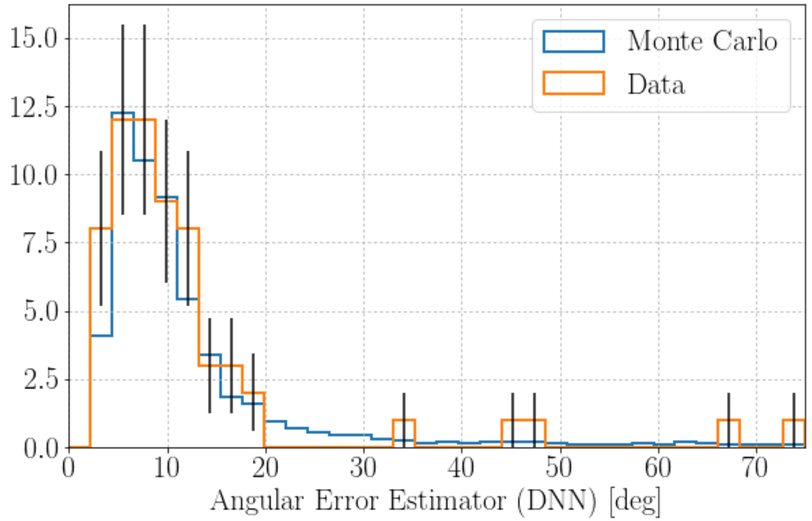
Alerts from Cascades

New Cascade neutrino alert stream added to GCN in July 2020

- Dominated (~85%) by astrophysical neutrinos
- Novel DNN tools used for event reconstruction
- Skymap probability maps published with GCN alert as FITS files



		Number of events/year	Proportion
Astrophysical	Cascades	6.7	85%
	Tracks	0.1	1%
	Total	6.8	86%
Atmospheric	Neutrinos	1.1	14%
	Muons	0.0	0.0%
Total Monte Carlo		7.9	100%
Data		8.1±1.0	



GCN High Energy Cascade Alert Documentation