

# Software and Realtime Multi-Messenger Operations

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NSF Mid-Term Review  
29 April 2024



# Presenter Background

- Research scientist at the University of Maryland
- Research focus on realtime multi-messenger science
- Active in IceCube since 2002; have served many roles
  - L3 for Software and Data Filtering in Gen1 MREFC project
  - L2 lead for Data Systems and IceCube integration for IceCube Upgrade
  - Former WG leader and Collaboration Analysis Coordinator
  - Former TFT board chair
  - Tech Lead for Realtime Working group and former Realtime coordinator

# Outline

- IceCube Software
  - Core software
  - Broader software ecosystem
  - Software program effort
- Realtime Multi-Messenger Program
  - IceCube generated alerts
  - Multi-Messenger Astrophysics participation
  - Realtime program coordination
- Challenges

# IceCube Software

# Software

- IceCube requires a diverse and complex software stack to
  - Calibrate and process raw detector data
  - Classify, reconstruct and filter  $\sim 2.5$  kHz of data to neutrino samples
  - Simulate IceCube detector: background, neutrino and exotic signals
  - Perform high level analysis tasks
    - LLH point source searches, oscillation analyses, complex spectral fits, etc...
- Many tasks are done in our core software analysis framework: IceTray
  - Provides standard tools/libraries for data decoding, file IO (.i3 files), standard data container classes, utilities
  - Build, testing, and development environment; documentation also supported.
  - Many pieces are [public](#) and used by other neutrino experiments
- Effort
  - Much of the IceCube software effort is contributed by the collaboration
    - Largely “analysis adjacent” tasks supported by students and post-docs
  - Core development team focuses on infrastructure, framework, reconstruction and simulation readiness for production environments
    - Core, experienced developer team supported by M&O funding, and in-kind support
    - Coordination of overall software effort, student training, and advice.

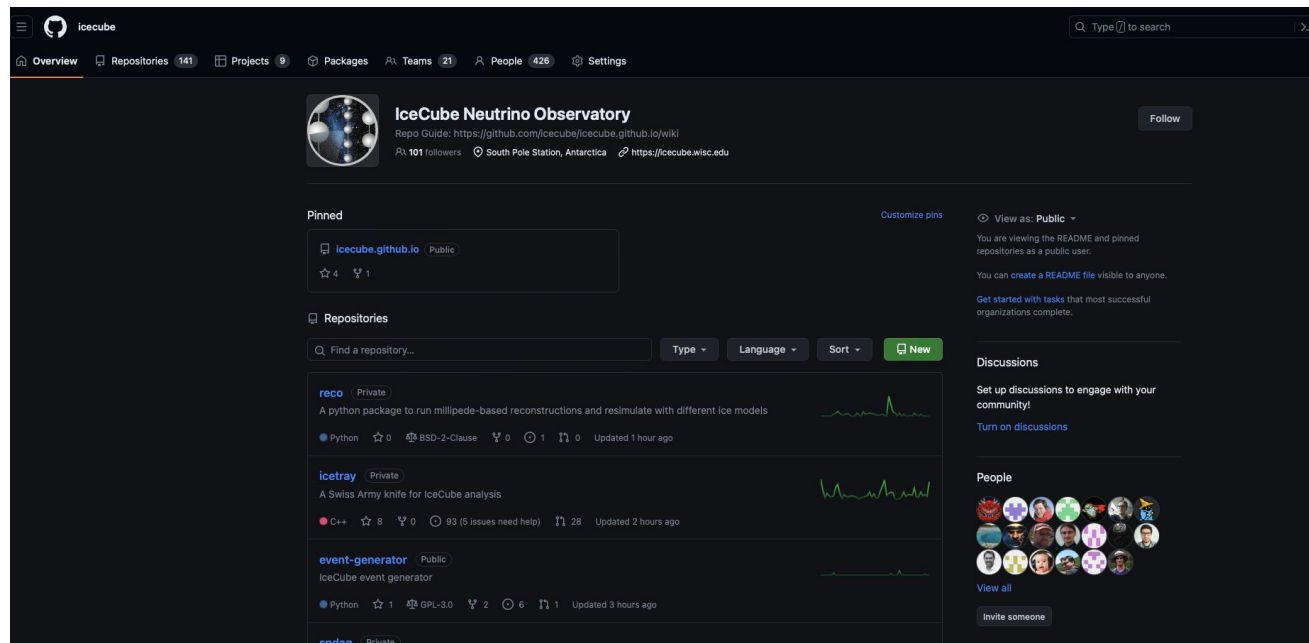
# GitHub organizations

Over the past few years, all IceCube software development has moved to GitHub

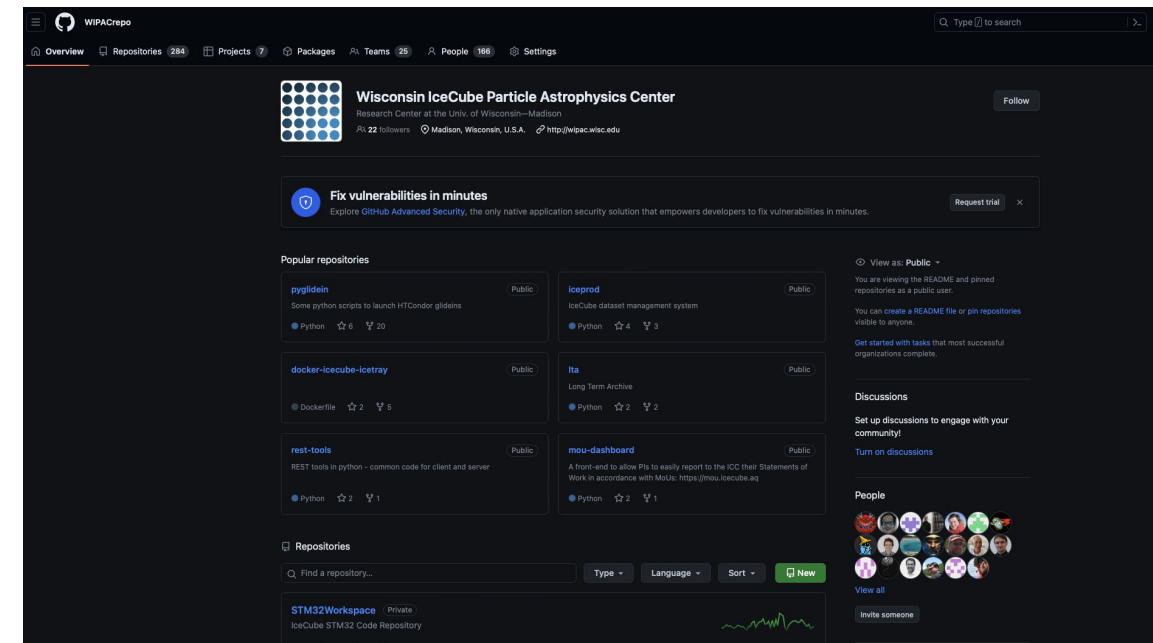
Two active GitHub Organizations

- [IceCube](#) - analysis framework, tools and analysis scripts
- [WIPACrepo](#) - online and offline supporting tools

Extremely helpful in lowering barriers for people to contribute to code efforts.



The screenshot shows the GitHub organization page for "IceCube Neutrino Observatory". The organization has 101 followers and is located at South Pole Station, Antarctica. The page displays a list of pinned repositories, including "IceCube.github.io", "reco", "icetray", "event-generator", and "sndaq". The "reco" repository is highlighted, showing it is a Python package for running millipede-based reconstructions and resimulating with different Ice models. The page also features a "Discussions" section and a "People" section with a grid of member avatars.



The screenshot shows the GitHub organization page for "Wisconsin IceCube Particle Astrophysics Center". The organization has 22 followers and is located in Madison, Wisconsin, U.S.A. The page displays a list of popular repositories, including "pyglidein", "iceprod", "docker-icecube-icetray", "Ita", "rest-tools", and "mou-dashboard". The "iceprod" repository is highlighted, showing it is an IceCube dataset management system. The page also features a "Discussions" section and a "People" section with a grid of member avatars.

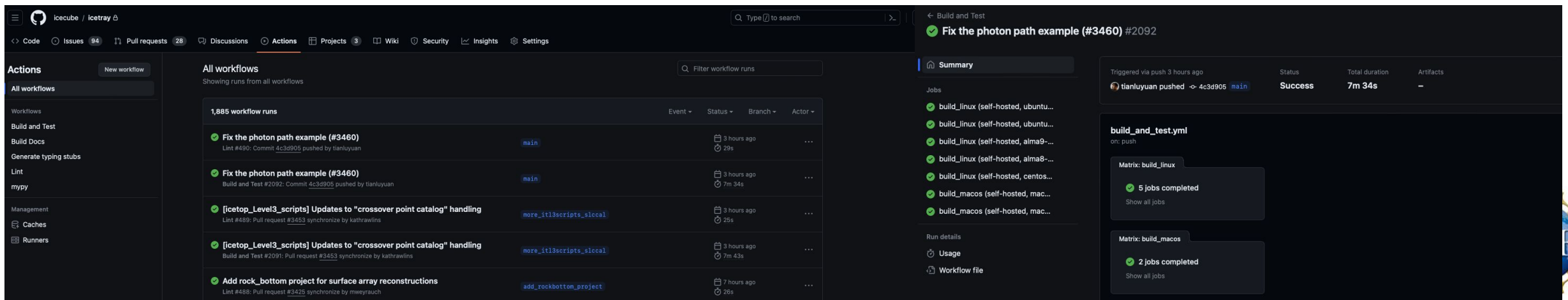


# Software metrics

Metric	Target	Achieved	Comment
IceTray releases per year	4	4	Major releases, additional bugfix releases as needed
Test Coverage	66% minimum	65.5% (C++) 64% (python)	Large push to increase, especially for new projects
CI min tests passing	90%	95%	Moved to GitHub Runners
Critical ticket max lifetime	1 month	2 months	Few critical issues

Several software metrics used to evaluate software team performance

- Note: these software metrics are focused on IceTray package releases, not wider software ecosystem
- Automated CD system not supportable - now manually run as needed



The screenshot displays the GitHub Actions interface for the repository 'icecube / icetray'. The main view shows a list of workflow runs under the 'Build and Test' workflow. The selected run is 'Fix the photon path example (#3460) #2092', which is in a 'Success' state and took 7m 34s to complete. The job details for 'build\_and\_test.yml' are visible, showing a matrix of jobs for different operating systems (ubuntu, alma9, alma8, centos, macos) and architectures (self-hosted). The matrix shows that 5 jobs for 'build\_linux' and 2 jobs for 'build\_macos' were completed successfully.

# Impact of Upgrade

Support for the IceCube Upgrade requires us to update large portions of our core software:

- Ensure all software properly handles multiple PMTs per Optical Module
- Implement classes to handle new module readouts, calibrations, pulse extraction.
- Extend compact data formats to support old and new OMs (SuperDST)
- Implement decoders from new DAQ payloads

Additionally simulation and reconstruction software need updating as well:

- Full fidelity simulation of new hardware (electronics/daq simulations)
  - Implementation of onboard or surface pulse extraction
  - Implementation of the mDOM's onboard noise cleaning
- Improved reconstructions that take full advantage of multi-PMT readouts

Many things are being added to software that has seen few updates in ~10 years

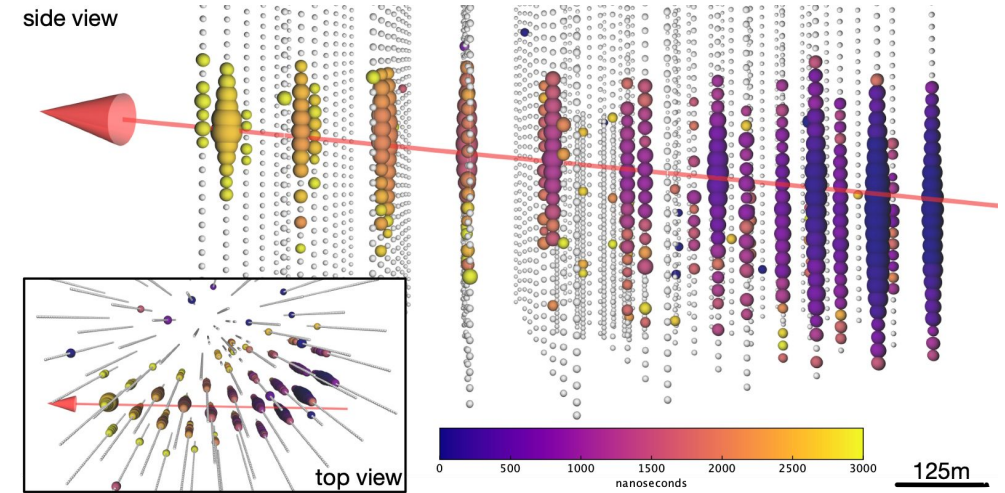
- Code improvements can also require deeper updates, and re-understanding of code details
- GitHub project boards/issues being used to coordinate work.



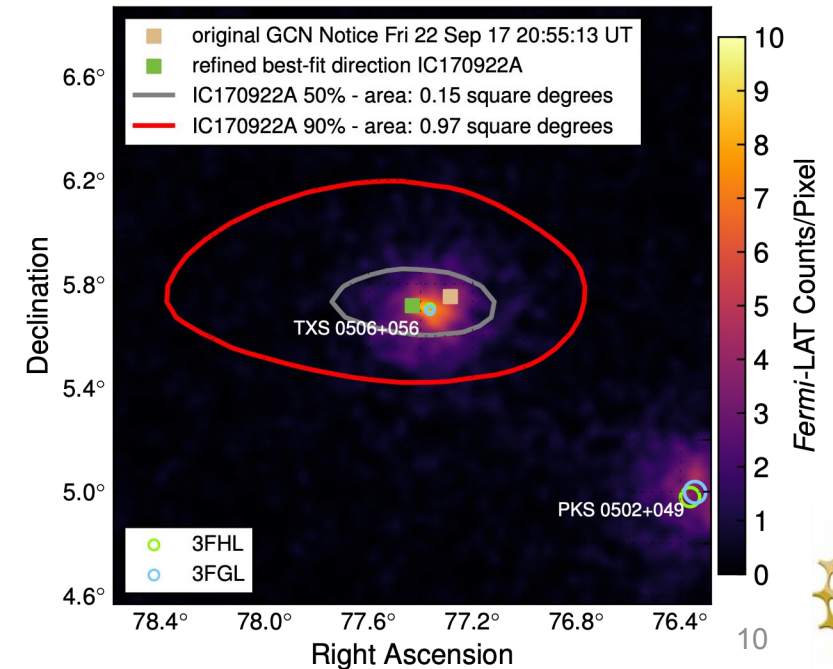
# Realtime Multi-Messenger Program

# Multi-Messenger Astrophysics with Neutrinos

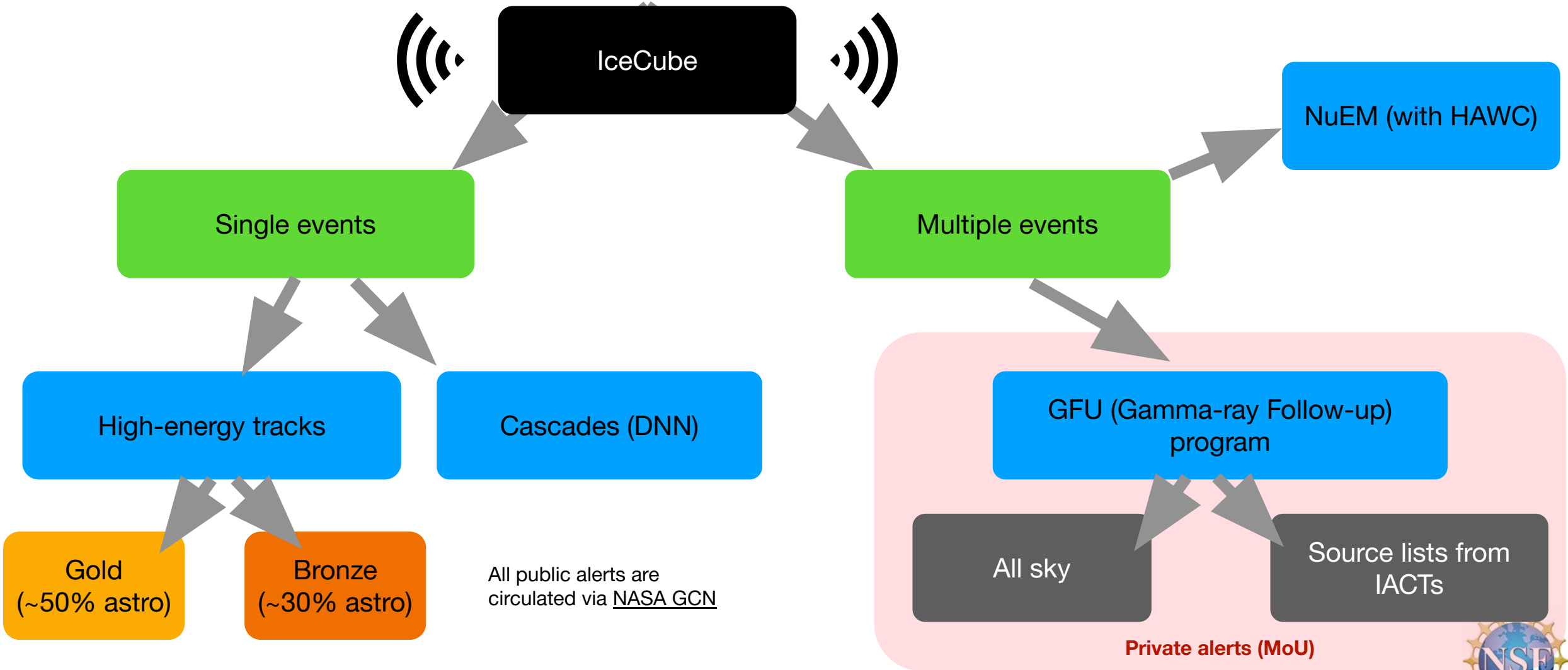
- Since the detection of a diffuse astrophysical neutrino signal, neutrino telescopes have become an active participant in MMA observations of the high-energy universe
- Quickly notifying observational community when we detect neutrino events that are likely to be of astrophysical origin
- Quickly perform realtime neutrino point-source searches when community identifies transient objects that are potential neutrino sources.
- Neutrino telescopes provide a unique view in MMA searches: clear indication of hadronic acceleration



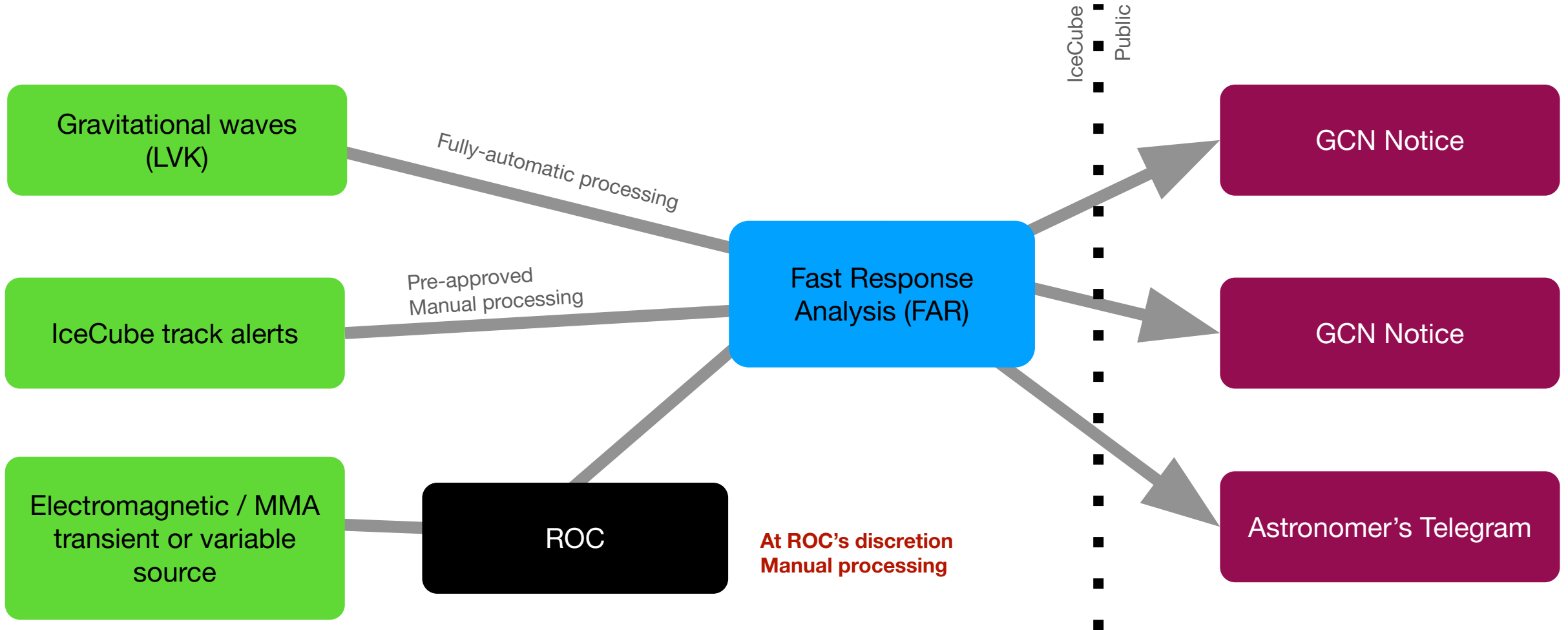
Multi-messenger alert: TXS 0506+056



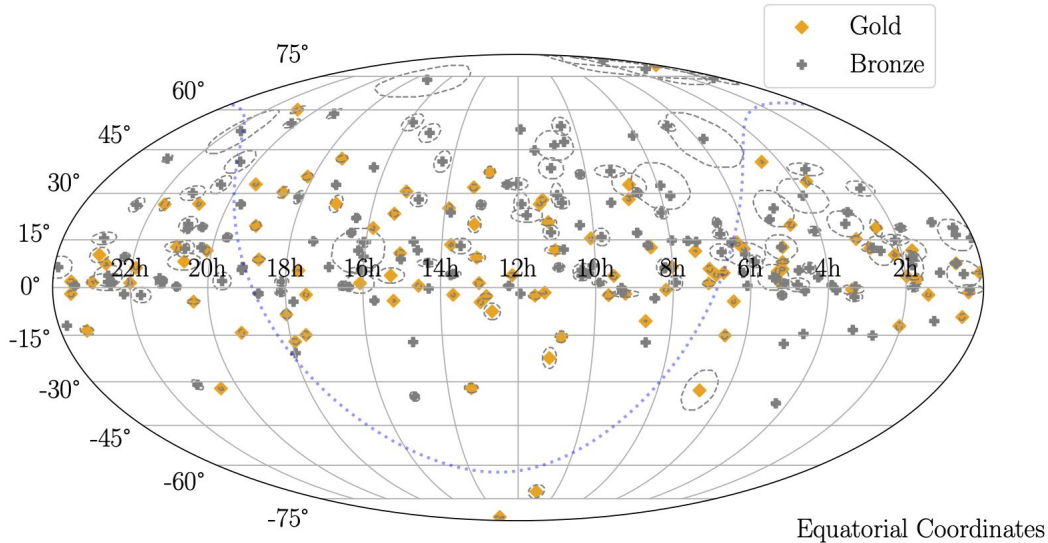
# IceCube Generated Alerts



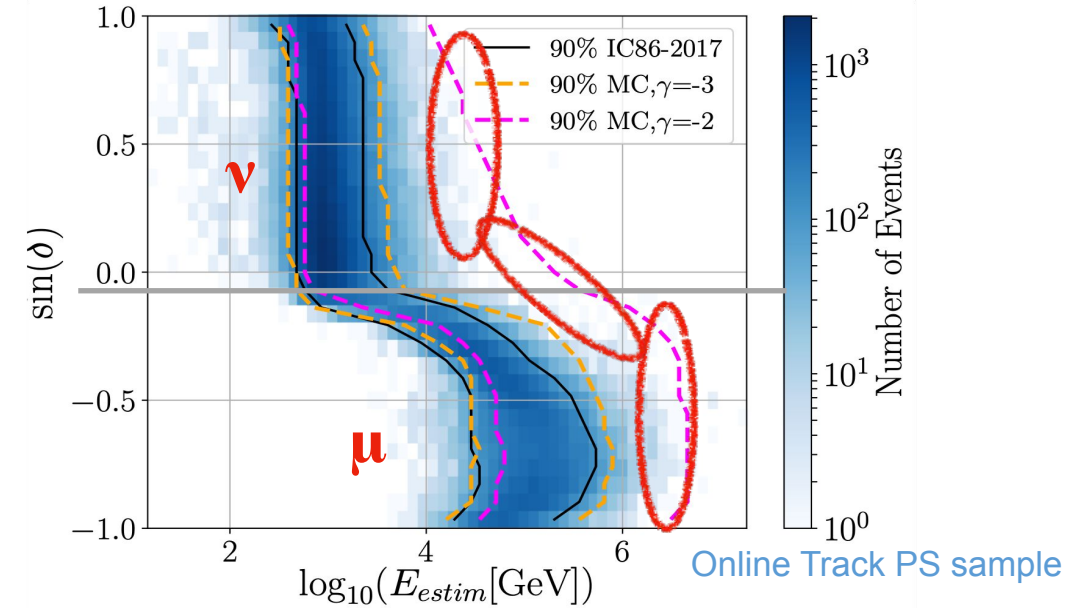
# IceCube responses to external triggers



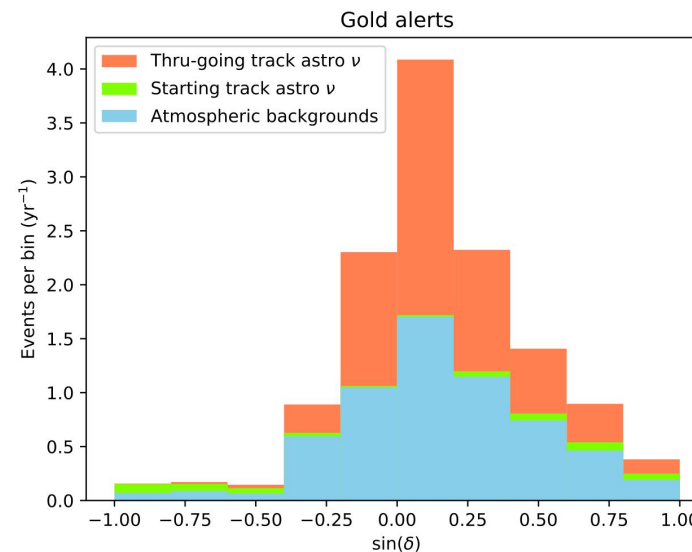
# IceCube Astrophysical neutrino track alerts



IceCat-1 arxiv: 2304.01174



- Identify well-reconstructed, high-energy neutrino candidates in real-time
- 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



- 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



# Neutrinos and Gravitational Waves

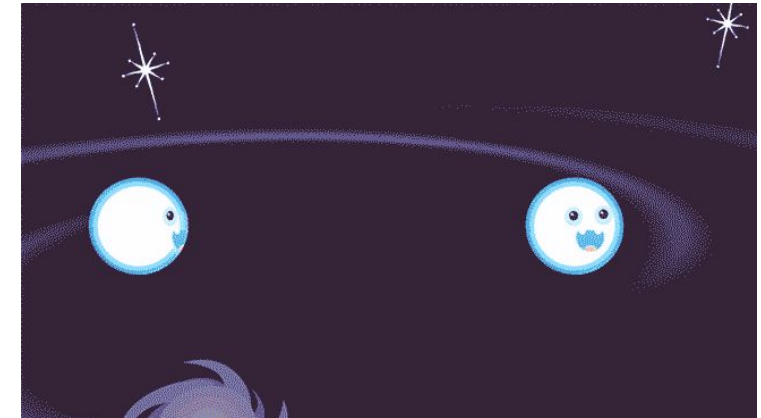
- Neutrinos are **~500x better** localized than Gravitational Wave Events - send results from searches with low-latency (via General Coordinates Network - GCN)
  - GCN circulars and neutrino direction included when p-value is below threshold (1%)
  - <https://roc.icecube.wisc.edu/public/LvkNuTrackSearch/>
- Follow up significant alerts from **all types** of mergers sent by LVK in realtime
  - All mergers with +/- 500 second time window (centered on merger time)
  - Mergers with NS - additional 2 week follow-up (merger time [-0.1,+14] days)
- Now running with LVK Run 04b

*Merger Types:*

BNS - Binary Neutron Star

NSBH - Neutron Star Black Hole

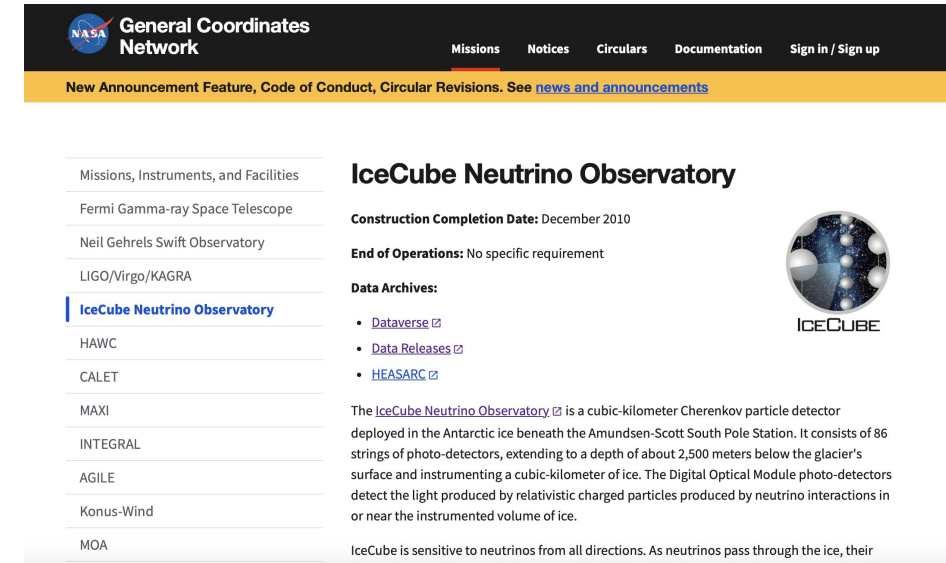
BBH - Binary Black Hole



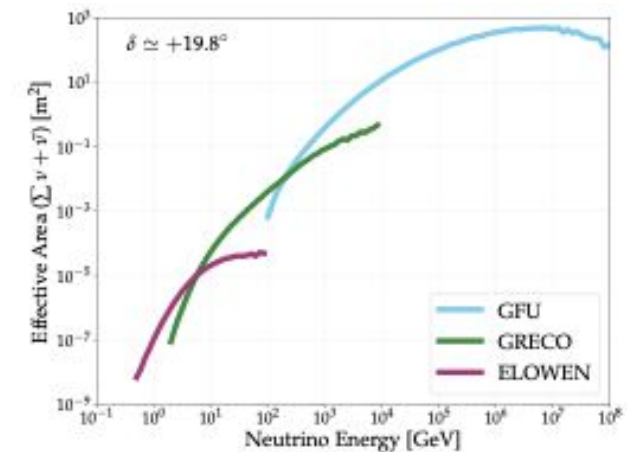
Credit: [NASA/](#)  
[wikimedia commons](#)

# Realtime Ongoing Improvements

- Migrate to new GCN system: <https://gcn.nasa.gov/>
  - [Track alerts](#) (v1 and v2) and [Cascade alerts](#) both still active
  - LVK follow-up search results are [GCN notices](#) in this system.
- Automate more of our alert response systems
  - Reduce the need for intense human-in-the-loop response followup
- New online point source searches in aimed at new energy ranges and flavors currently being developed for transient searches
  - GRECO/ELOWEN - DeepCore based neutrino selections below 100 GeV
  - DNN Cascades - Contained high energy cascades
- New public alerts
  - GFU all-sky and catalog source list searches made public
  - Short duration transients aimed at nearby sources



The screenshot shows the NASA General Coordinates Network (GCN) website. The main navigation bar includes 'Missions', 'Notices', 'Circulars', 'Documentation', and 'Sign in / Sign up'. A yellow banner below the navigation bar reads: 'New Announcement Feature, Code of Conduct, Circular Revisions. See [news and announcements](#)'. The main content area is titled 'IceCube Neutrino Observatory' and includes a sidebar with a list of missions: Fermi Gamma-ray Space Telescope, Neil Gehrels Swift Observatory, LIGO/Virgo/KAGRA, IceCube Neutrino Observatory (highlighted), HAWC, CALET, MAXI, INTEGRAL, AGILE, Konus-Wind, and MOA. The main text area provides details about the IceCube Neutrino Observatory, including its construction completion date (December 2010), end of operations (no specific requirement), and data archives (Dataverse, Data Releases, HEASARC). A small circular image of the IceCube detector is also visible.



# Challenges - Software and Realtime

Realtime infrastructure and software share many common challenges

- Developer manpower
  - Both have limited funding from core M&O to support and expand functionality
  - Both are complex software systems that require deep knowledge and programming skills
- In-kind contributions
  - Both efforts have historically had large amounts of in-kind student/post-doc contributions that have been critical to the projects.
  - But, these contributions have been from a rare few outstanding early career people with strong software skills and focus
    - These folks are rare and temporary - hard to build plans around
  - Can be difficult for new people to get up to speed given the large history and depth of code
- Solutions being explored
  - Better coordination with other collaborations - shared tools where possible
  - Wide appeals to collaboration and PIs for help
  - Encouraging in-kind contributions of professional software development efforts



Thanks!