Software and Realtime Multi-Messenger Operations

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IceCube
South Pole Neutrino Observatory

NSF

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 ~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.

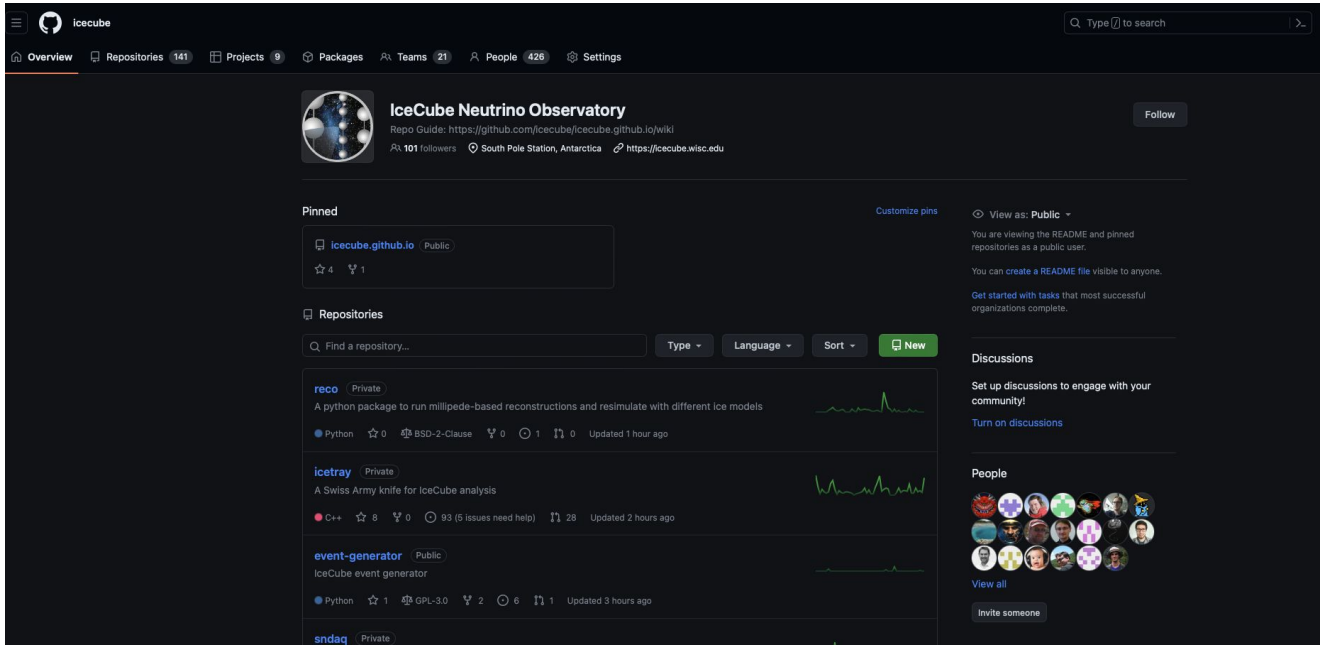
GitHub organizations

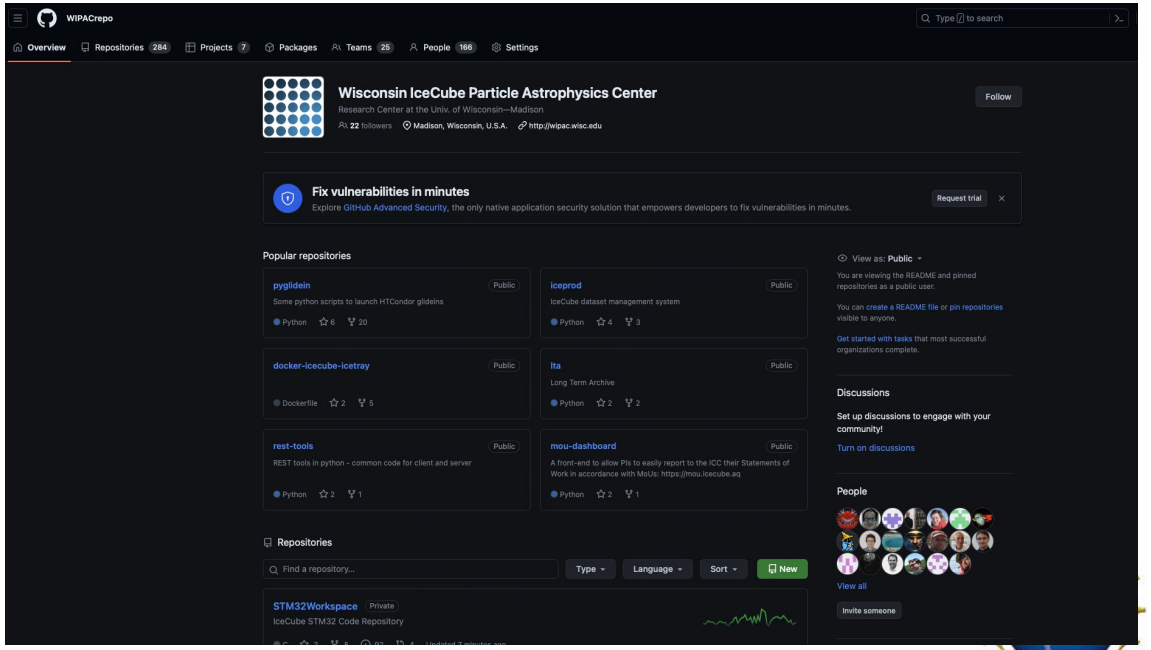
Over the past few years, all IceCube software development has moved to GitHub

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.



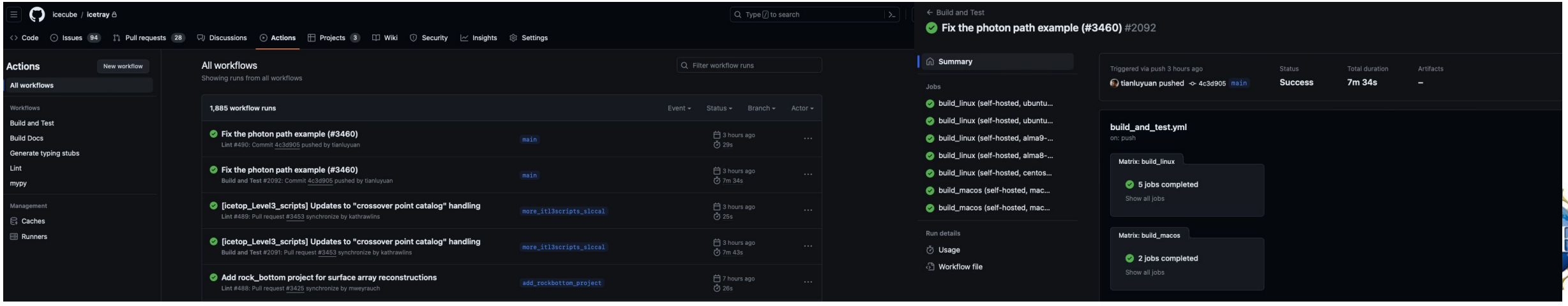


Software metrics

Metric	Target	Achieved	Comment
IceTray releases per year	4	4	Major releases, additional bugfix releases as needed
Test Coverage	66% minumum	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



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

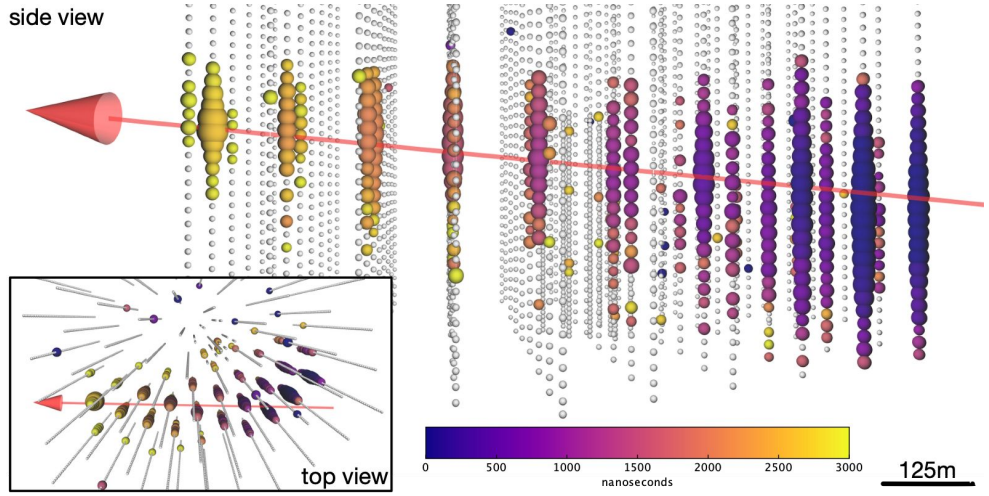
Many things are being added to software that has seen few updates in ~10 years

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

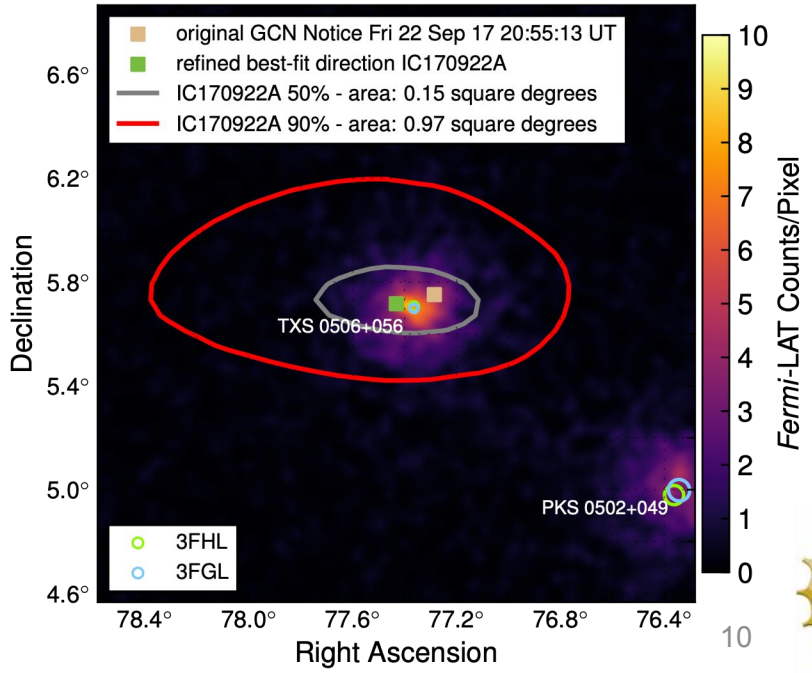
Realtime Multi-Messenger Program

Multi-Messenger Astrophysics with Neutrinos

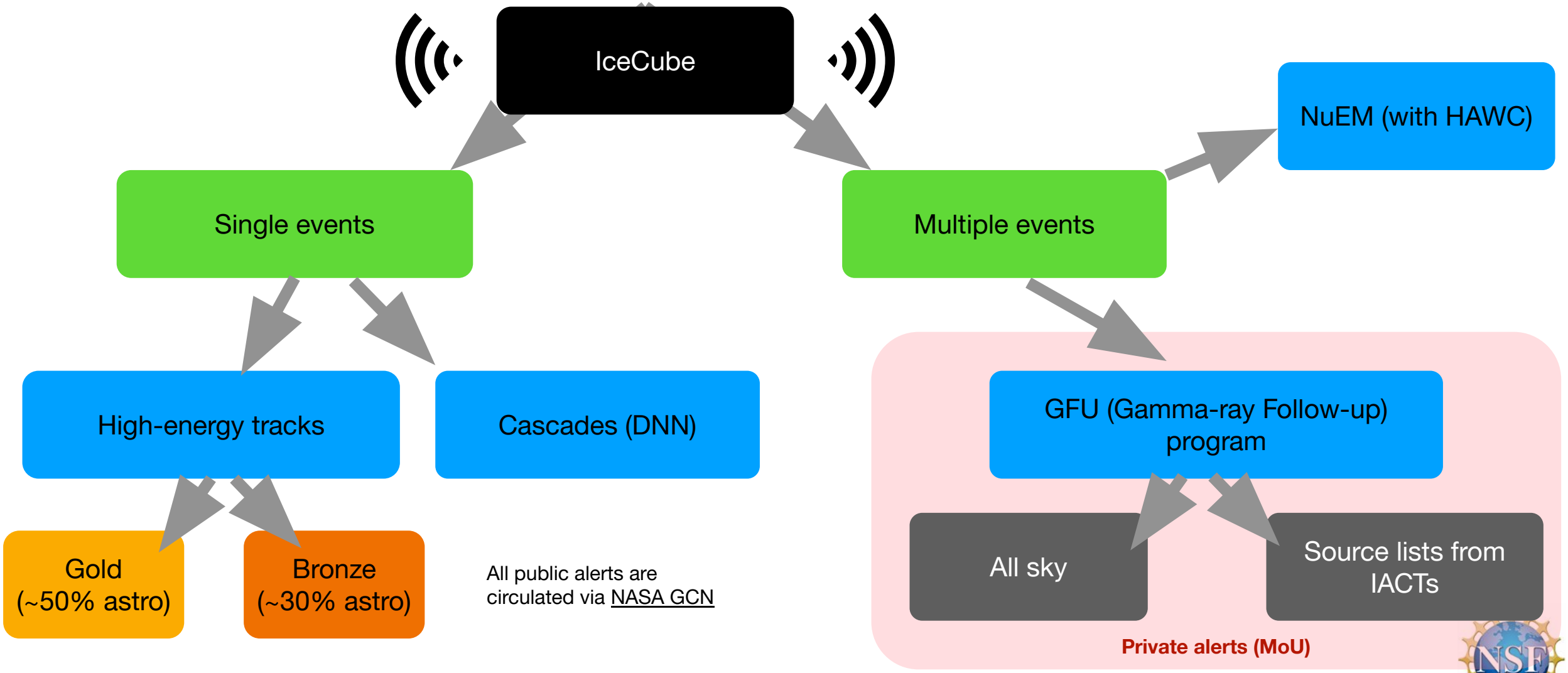
- Since the detection of a diffuse astrophysical neutrino signal, neutrino telescopes have become an active participant in MMA observations of the high-energy universe
  - Quickly notifying observational community when we detect neutrino events that are likely to be of astrophysical origin
  - Quickly 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

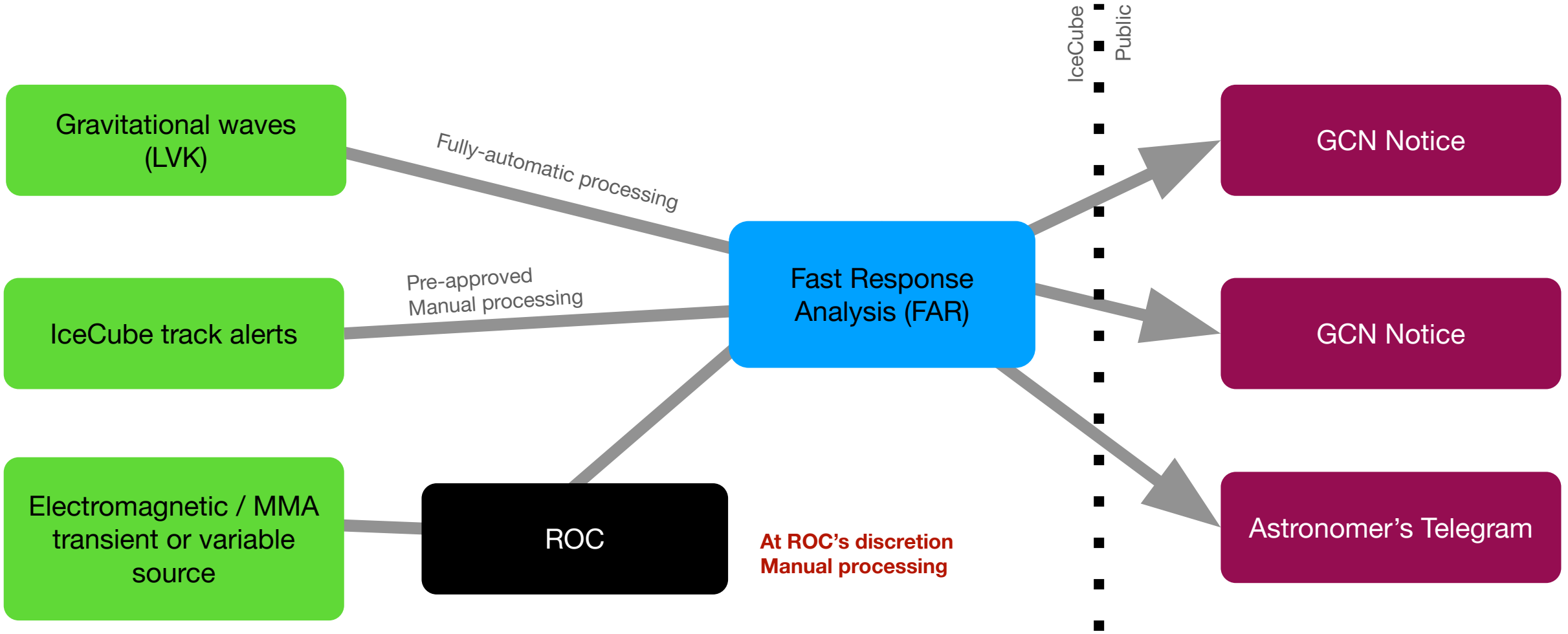


IceCube Generated Alerts

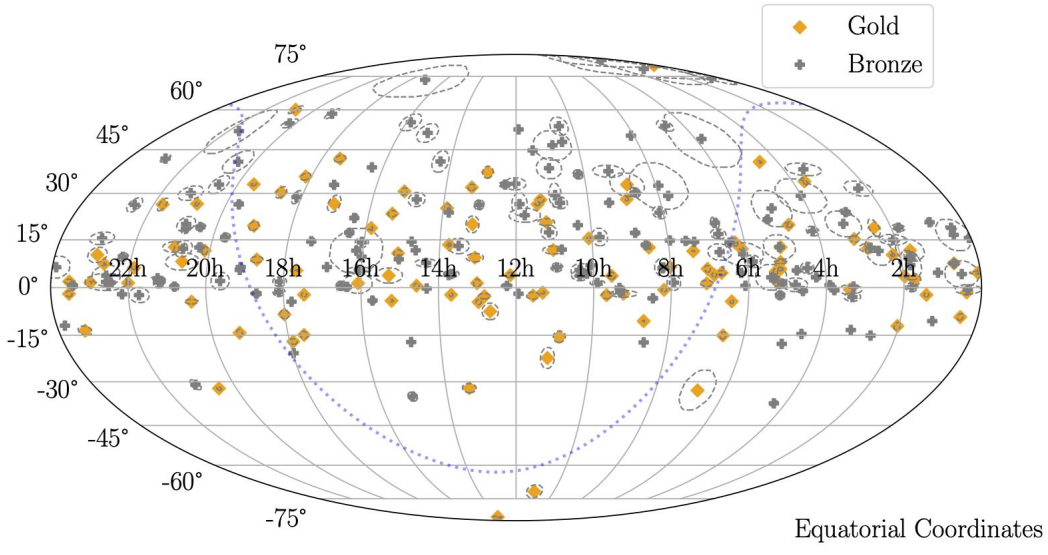


All public alerts are circulated via NASA GCN

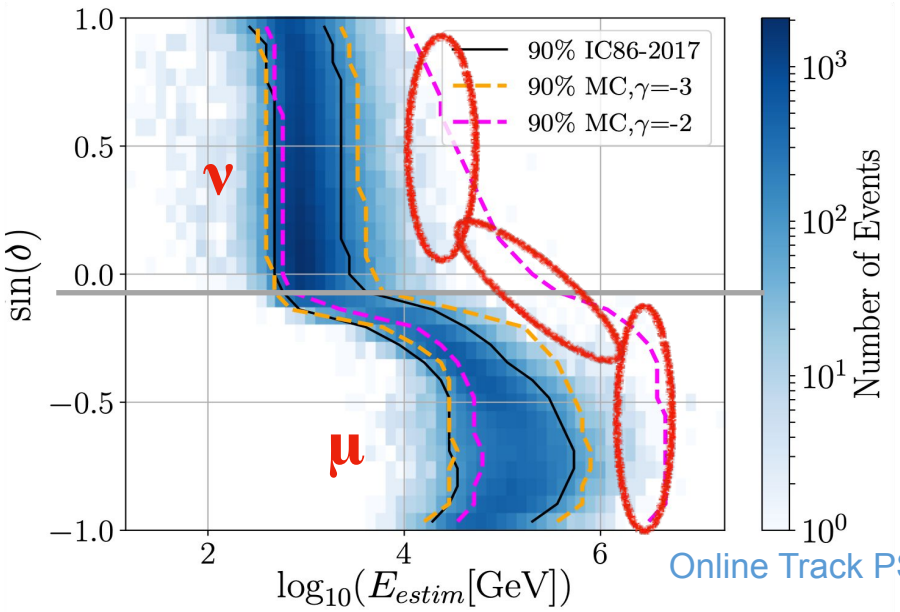
IceCube responses to external triggers



IceCube Astrophysical neutrino track alerts

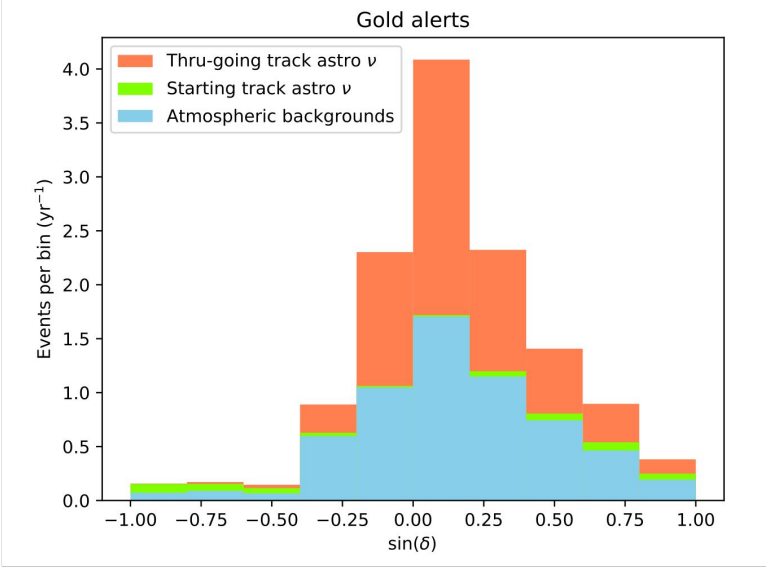


IceCat-1 arxiv: 2304.01174



Online Track PS sample

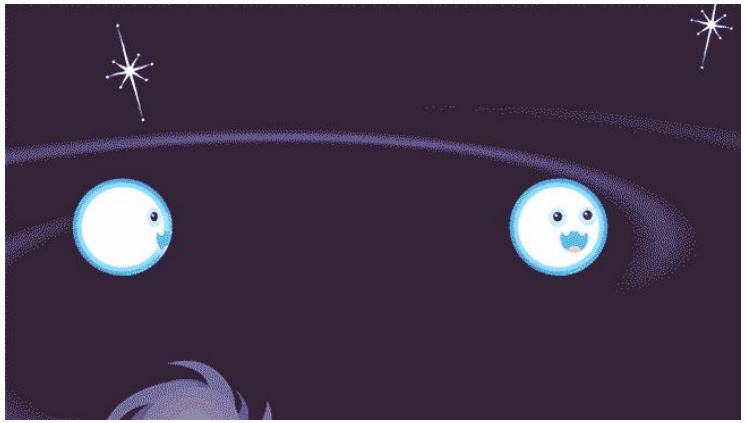
- Identify well-reconstructed, high-energy neutrino candidates in real-time
- Transmit them to the North and advertise
  - Latency from detection to alert typically less than 1 minute
  - Detector uptime > 99%
- Community observations to search for multi-messenger signals
- In operation since April 2016



- 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

Merger Types:
BNS - Binary Neutron Star
NSBH - Neutron Star Black Hole
BBH - Binary Black Hole



Credit: NASA/ wikimedia commons

- 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

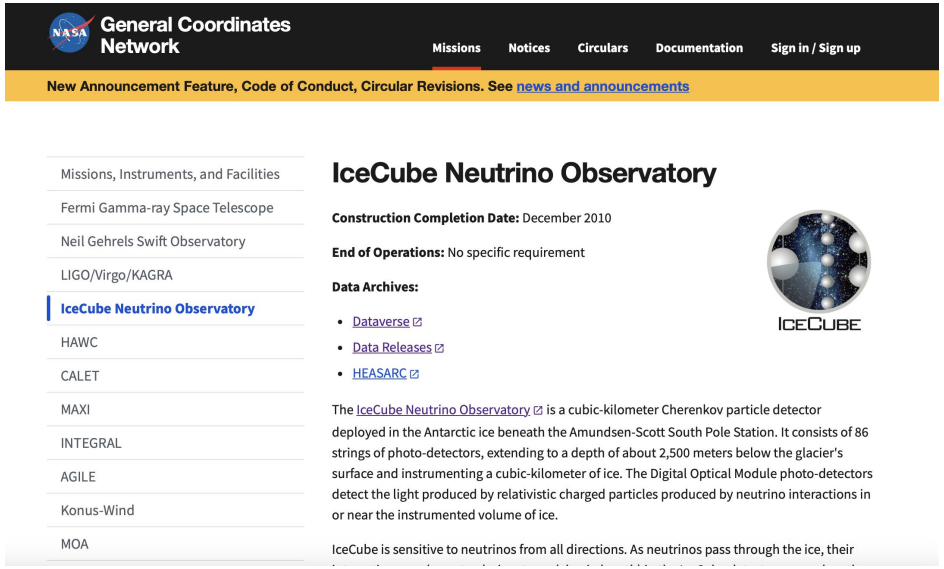
Realtime Ongoing Improvements

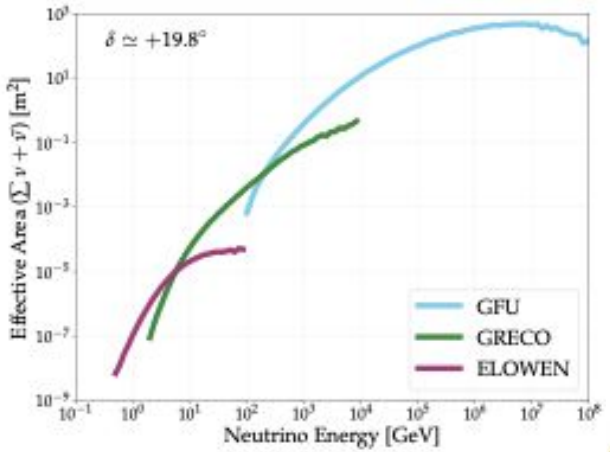
- Migrate to new GCN system: https://gcn.nasa.gov/
  - Track alerts (v1 and v2) and Cascade alerts both still active
  - LVK follow-up search results are GCN notices in this system.

- 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





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!