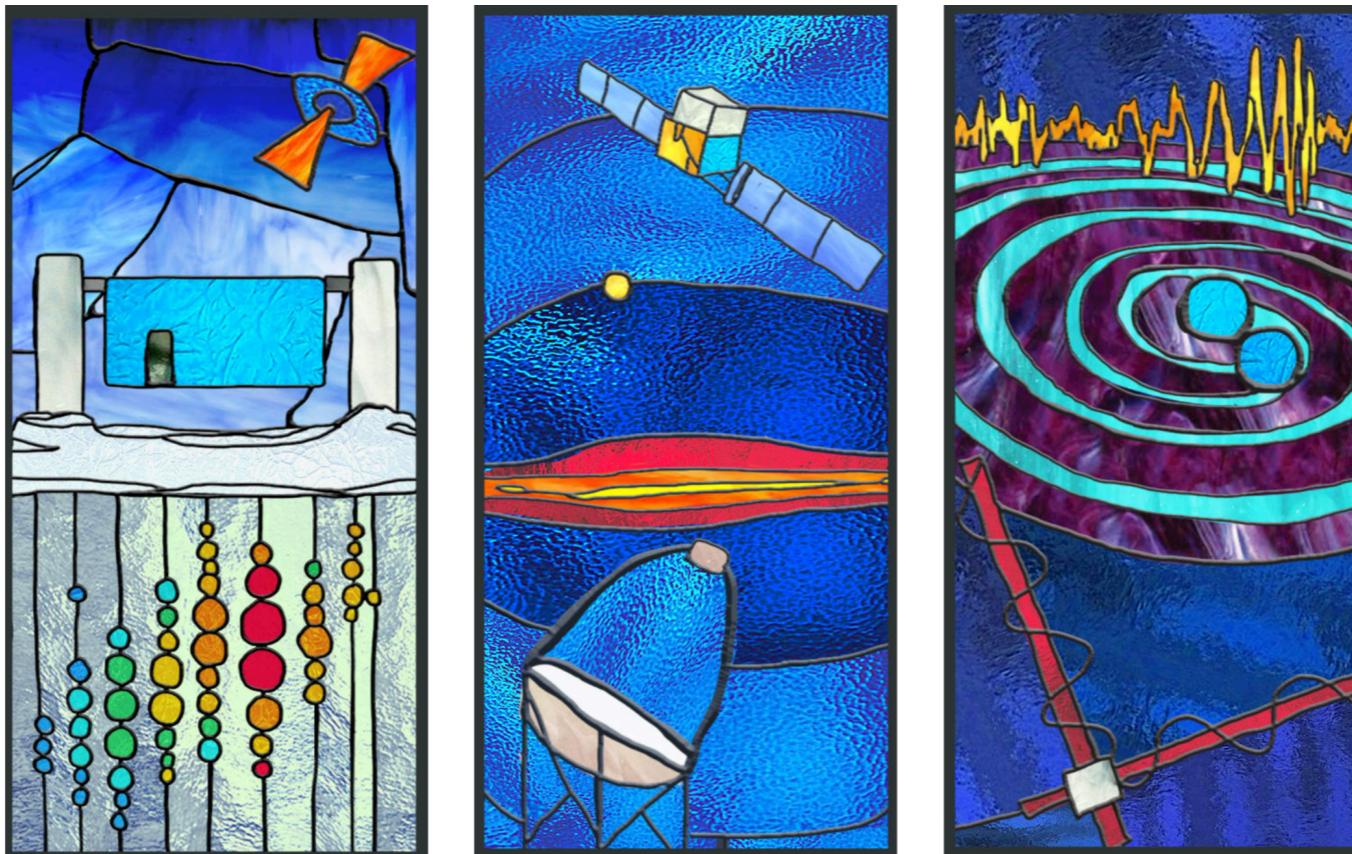


# Advancing Multi-Messenger Astronomy: IceCube's Enhanced Real-Time Neutrino Alert System



Elisa Bernardini for the IceCube Collaboration



**ICECUBE**  
NEUTRINO OBSERVATORY



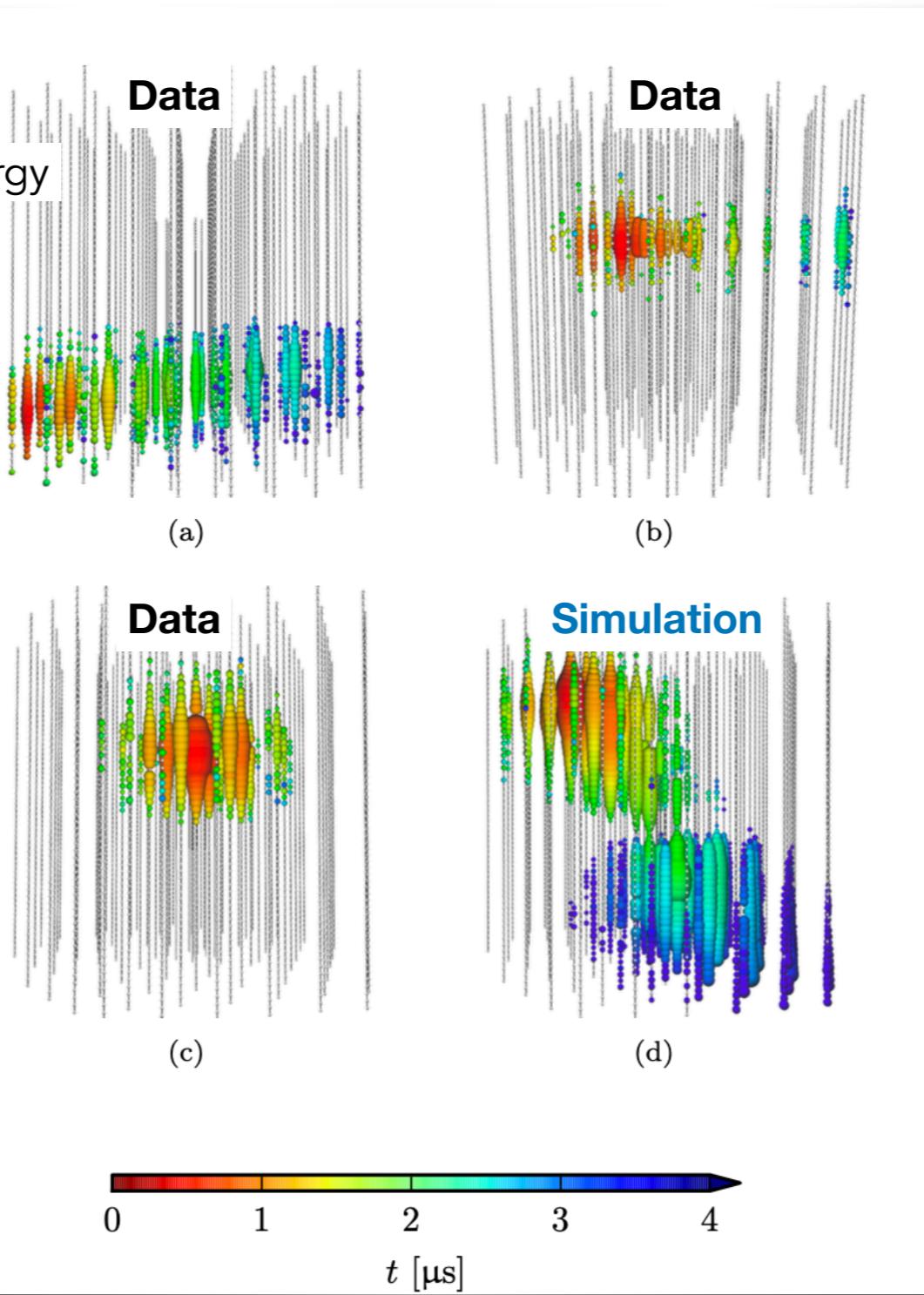
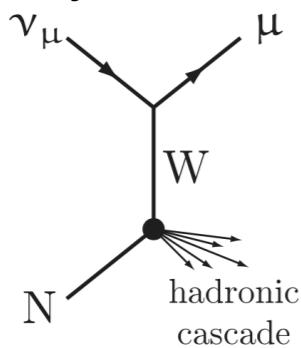
# Neutrino event topologies

## Through-going track ( $\nu_\mu$ )

angular resolution  $< 0.5^\circ$  for  $E > 10$  TeV

log energy resolution  $\sim 20\%$  of muon energy

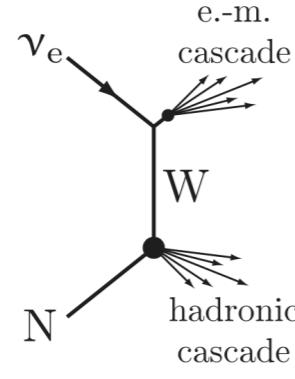
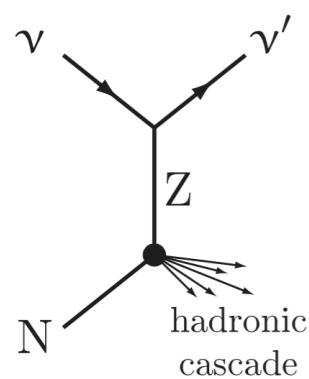
at detector entry for  $E > 10$  TeV



## Cascade ( $\nu_e, \nu_\mu, \nu_\tau$ )

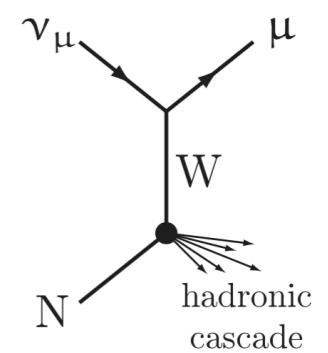
angular resolution down to  $\sim 5^\circ$

log energy resolution  $\sim 15\%$  of neutrino energy for  $E > 10$  TeV



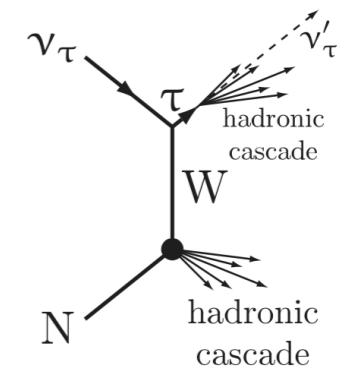
## Starting track ( $\nu_\mu$ )

$dE/dx +$  energy at vertex



## Double-Bang ( $\nu_\tau$ )

$E > O(PeV)$



# The IceCube realtime pipeline

Filters run on computing system at South Pole and events of interest are fast tracked to north via Iridium satellites

## Processing at South Pole:

- Median latency: 2 s

## Event rates (trigger level):

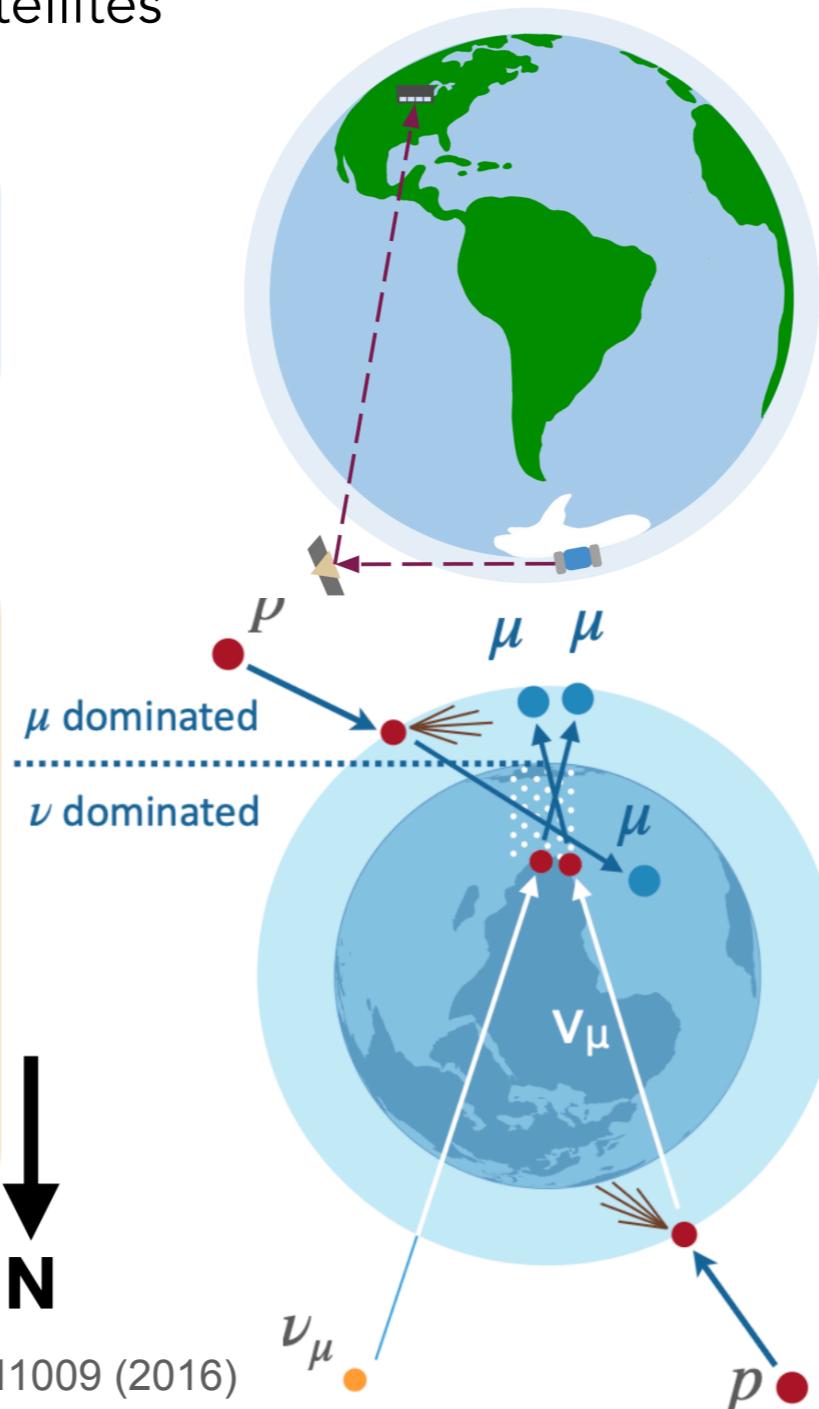
- Atmospheric muons (South only):  $\sim 3000 \text{ s}^{-1}$
- Atmospheric neutrinos:  $\sim 1 \text{ s}^{-1}$
- Astrophysical neutrinos:  $\sim 1 \text{ day}^{-1}$

## Event transmission to Madison (USA):

- Event summary received: 30 s
- Full event received: 40 s

## Event rates (filter level):

- Good quality muon tracks (GFU): few mHz

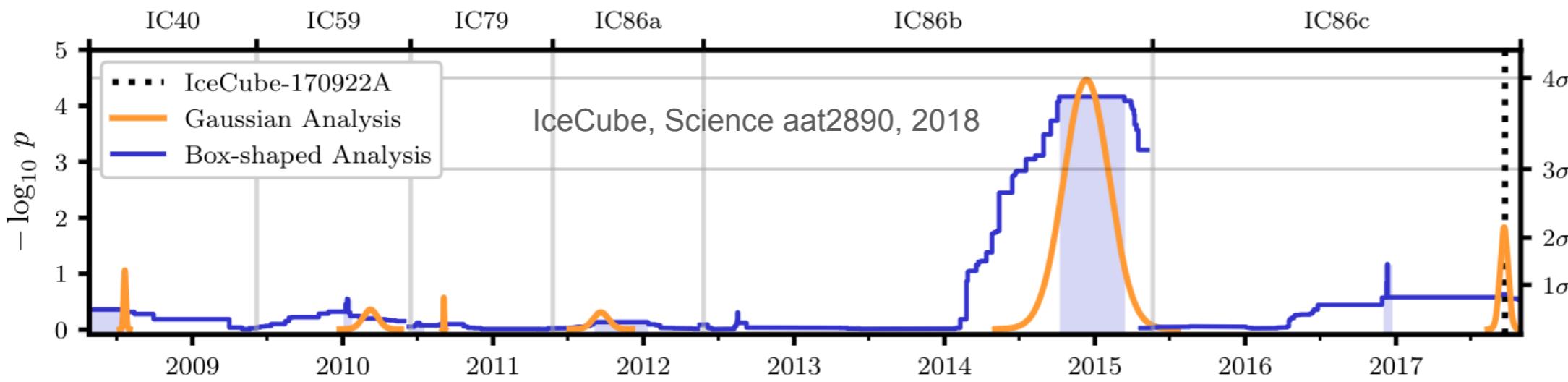
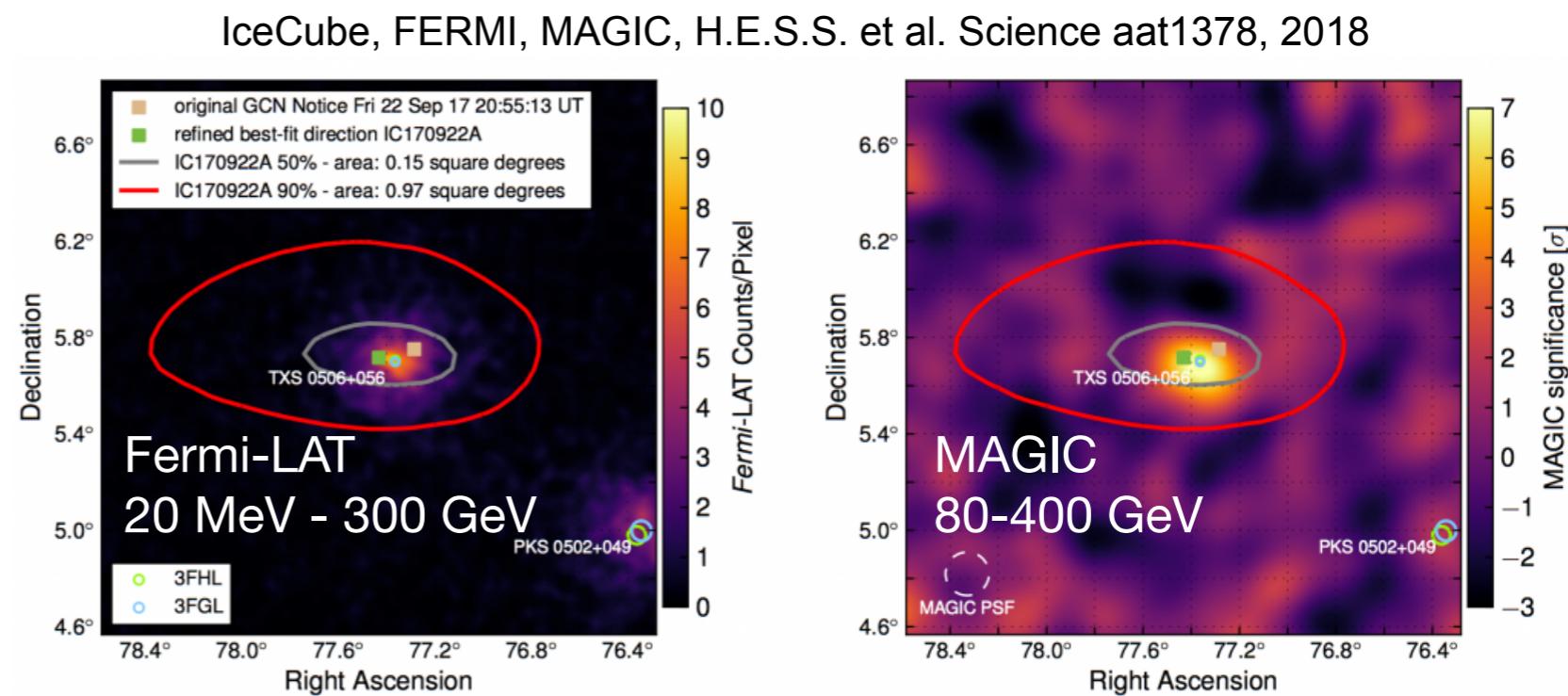


# Neutrino astronomy in realtime

(2017) High energy neutrino coincided with **flare from blazar TXS 0506+056** (3 $\sigma$  significance)

Flare observed across electromagnetic spectrum

**Archival neutrino flare** also found (at 3 $\sigma$ )

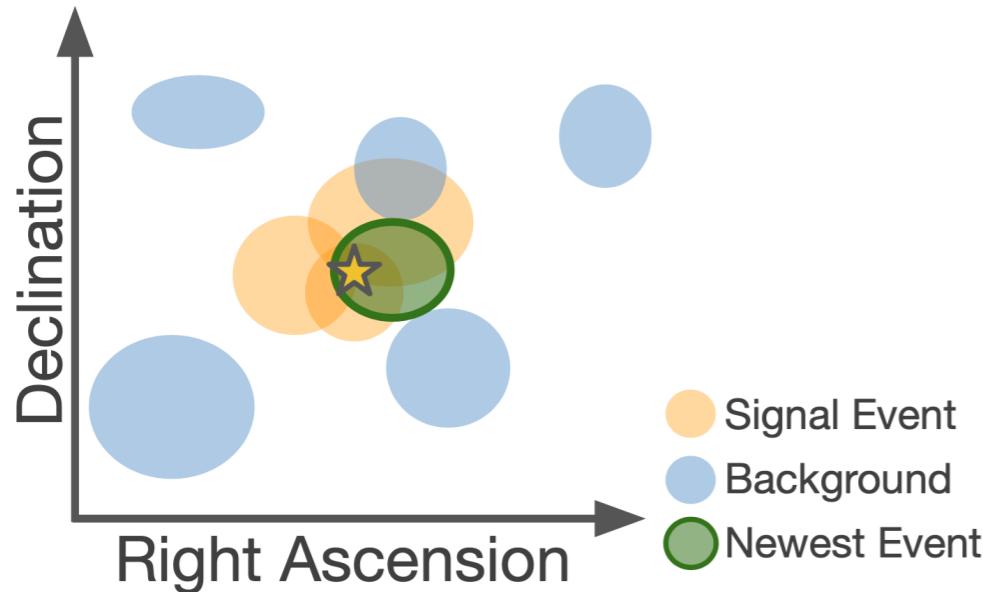


UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

Elisa Bernardini — Padova University & INFN — TeVPa 2025

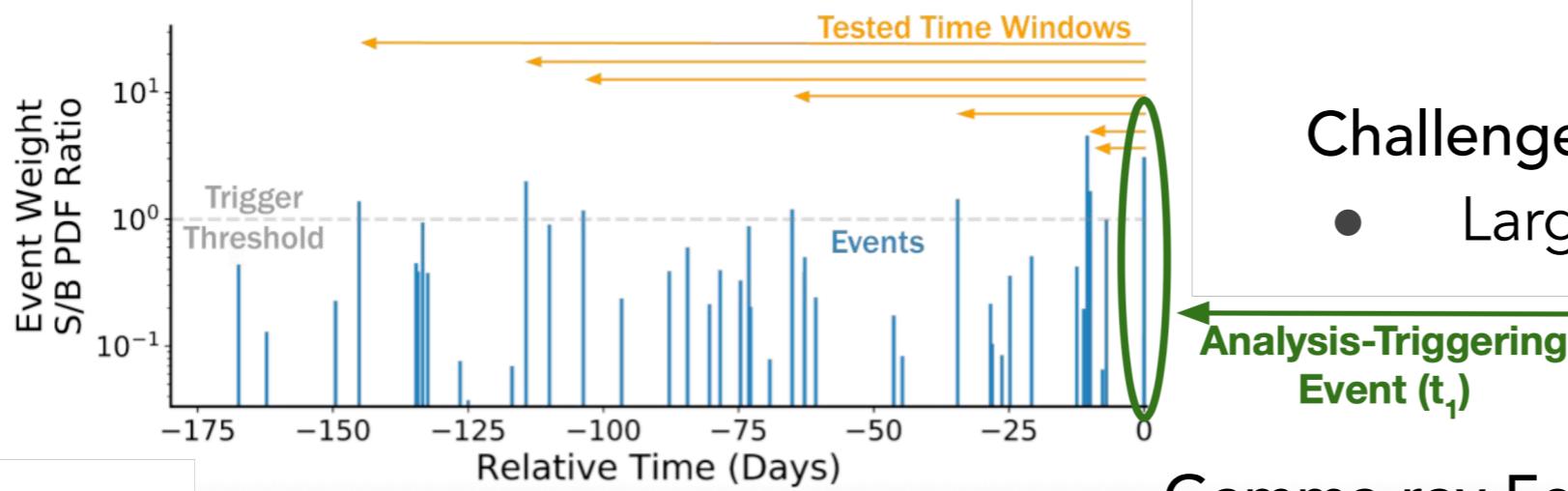
# IceCube alerts for event clusters

Goal: Identify potential neutrino flares in realtime using multiple events to issue alerts to MWL partners



## Advantages over single events:

- Biased towards closer sources
- Provides time-scale information
- Ability to trigger with  $<100$  TeV events
- Better directional resolution from multiple events ( $\sim 0.2^\circ$ )
- Enables sub-threshold multi-messenger studies



## Challenges:

- Large number of trials performed

## Gamma-ray Follow-up (GFU):

- Developed to trigger observations by IACT

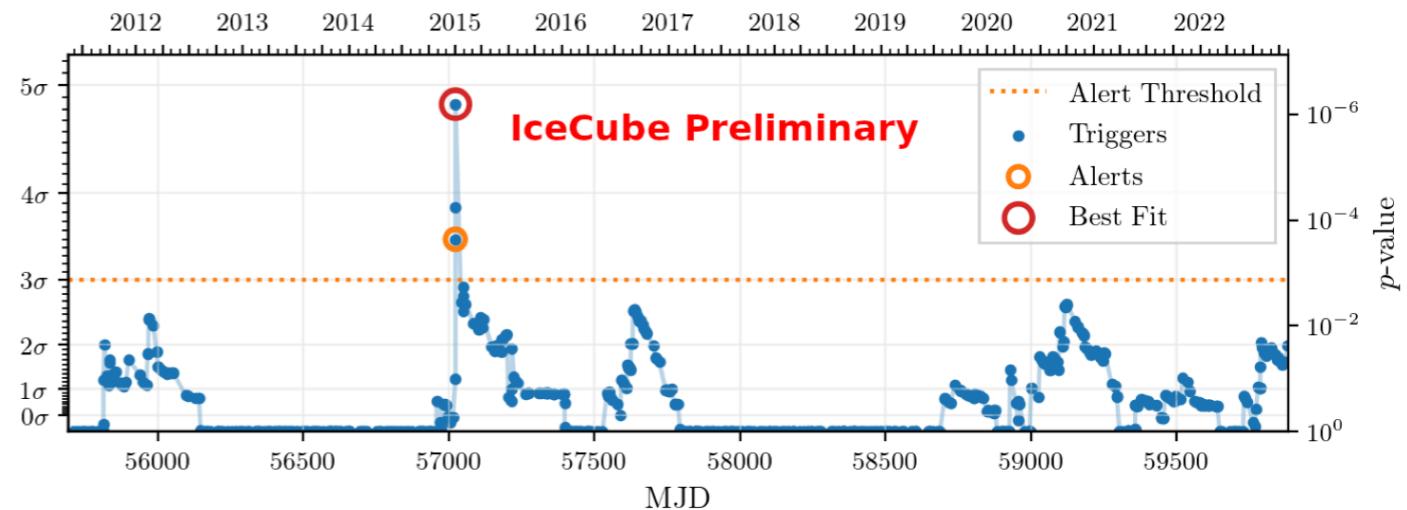
# Gamma-ray Follow-Up (GFU) cluster alerts

Searches for neutrino clusters over timescales up to 180 days (maximum likelihood analysis). The GFU analysis pipeline sends **private alerts** to IACT, now feeds many online and offline searches.

## Pre-selected source list mode:

- Monitors fixed sky locations
- Mostly nearby AGNs that are bright and highly variable in gamma-rays
- Pro: reduces trials factor
- Con: relies on model assumptions
- Con:  $z \leq 1$  bias (IACT follow-up)

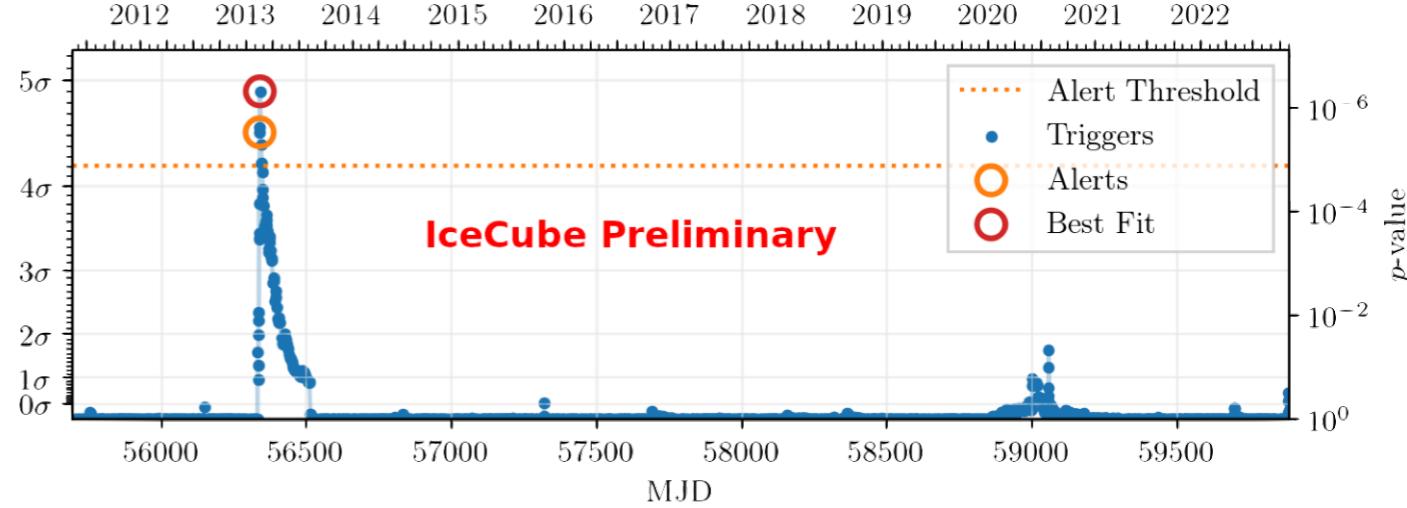
Best fit from archival analysis (source **1ES 0347-121**),  
**1.81 $\sigma$  post-trial significance**



## All-sky mode:

- Searches for neutrino clusters from any sky direction
- Pro: can identify previously unexpected sources
- Con: large number of trials

Best fit from archival analysis (all-sky),  
**0.482 $\sigma$  post-trial significance**



POS-ICRC2023-1500

Elisa Bernardini — Padova University & INFN — TeVPA 2025

# Enhancing the cluster alerts

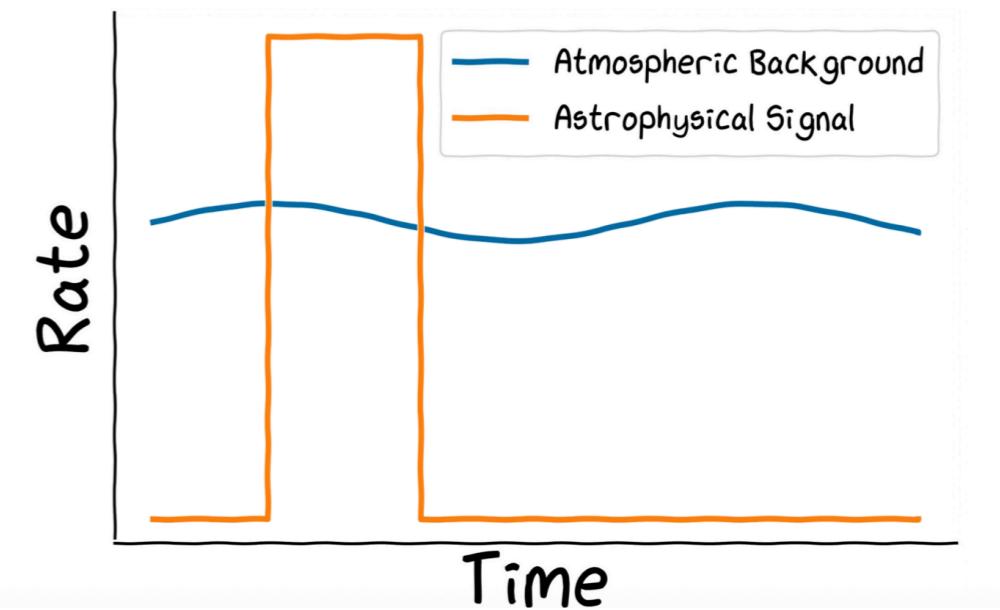
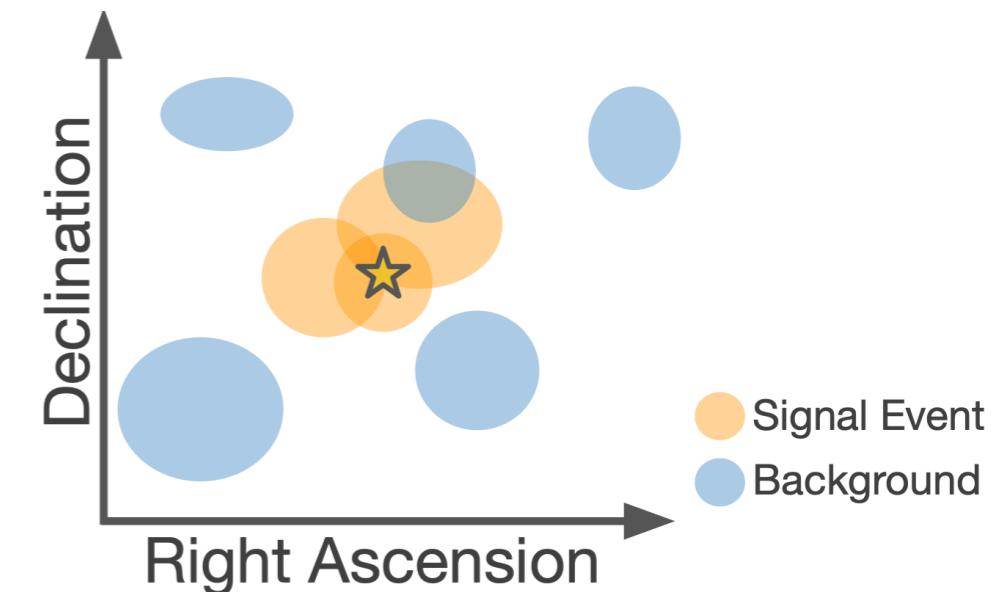
Several improvements coming soon towards a more inclusive and accessible alerts stream

- Multiplet Alerts (WIP):

- Searches for doublets/triplets of neutrinos close together in direction and time

- Updates to GFU:

- Revised source catalogue (address MWL counterparts complementary to  $\gamma$ -ray)
- Live updates on significance (enables to monitor the time evolution of potential neutrino flares)
- Multiple significance classification for earlier flare tagging (low, medium high)
- Public release through a web-interface (Neutrino Flarewatch)



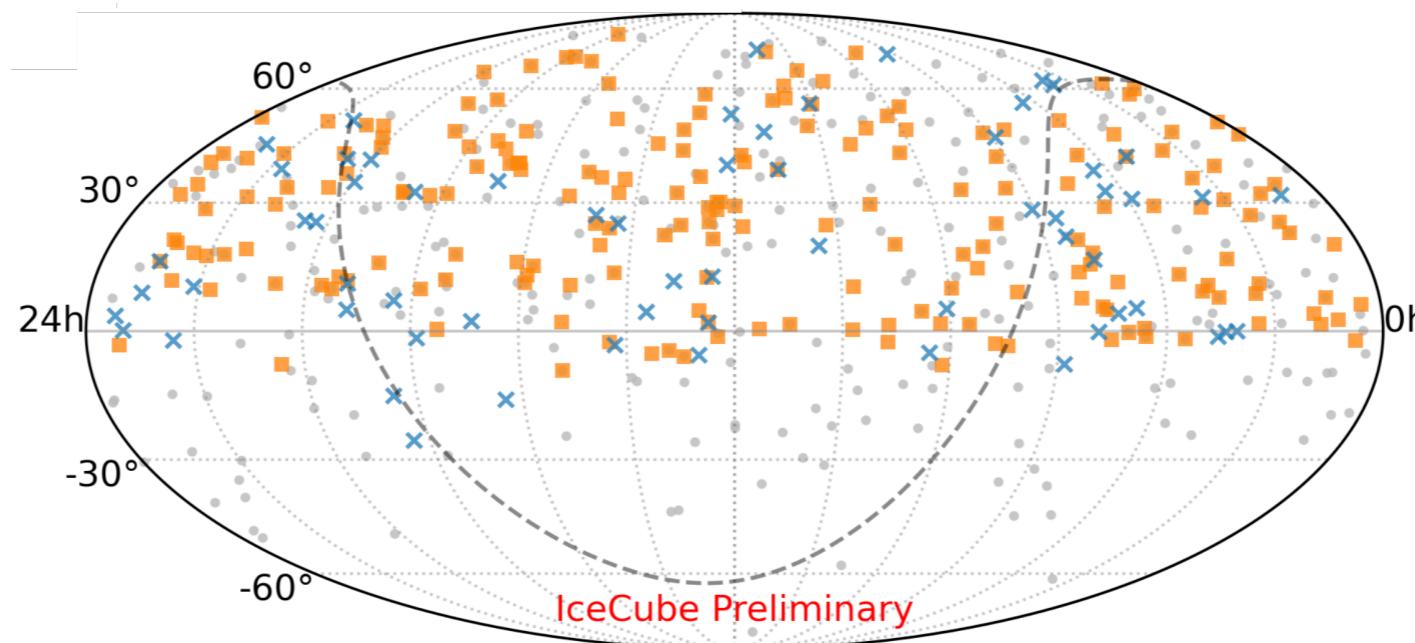
# New source list

Multiple  $\sim 3\sigma$  correlation analyses between X-ray AGNs and IceCube data [IceCube, TeVPA 2024, ApJ 988, 141 (2025), ApJ 981 131 (2025), PoS-ICRC2025-1219]

Selection	Motivation	Sub-selection	Catalog	Flux for FoM	Sources
<b>GeV <math>\gamma</math>-ray motivated</b>	AGN (e.g., blazars, TXS 0506+056). GeV emission highly variable and well-characterized.	AGN	4FGL [2]	Photon Flux (1-100 GeV)	200
<b>keV X-ray motivated</b>	AGN (e.g., Seyfert galaxies) and Galactic sources (e.g. Microquasars). Neutrinos produced and $\gamma$ -ray reprocessed in optically thick environments.	AGN Galactic Sources Microquasars	BASS [3] Swift/BAT [4] Refs. [5, 6, 7]	Intrinsic Flux (14-195 keV) Observed Flux (14-195 keV) -	44 10 12

To be complemented by a TeV  $\gamma$ -ray motivated selection (focus on IACTs, coming soon)

**Unique sources** **259**



POS-ICRC2025-919

■ GeV gamma-ray selection	● old IACT-motivated list
✖ keV X-ray selection	--- Galactic Plane



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

Elisa Bernardini — Padova University & INFN — TeVPA 2025

# Neutrino FlareWatch website - archival alerts page



REALTIME GFU ALERTS

☆ Alerts ▾ i Support

## IceCube Preliminary

### Realtime Gamma-Ray Follow-Up — Archival Alerts

This page provides a table of **historical events** detected by the [IceCube Neutrino Observatory](#), featuring events from the past year where the **significance initially exceeded 3 sigma** but has since dropped below this threshold. These events highlight some of the most significant detections in IceCube's history.

For additional information about these events or the IceCube project, please visit our [support page](#).

Source name	Right ascension (deg)	Declination (deg)	Duration (days)	Latest event time (UTC)	Signal events	Spectral index	Pre-trial p-value	Level
SIM XXXX+056	77.36	5.69	171.16	2017/11/17 21:57:54	19.99	-3.12	0.00093	★
SIM XXXX+056	77.36	5.69	135.11	2017/09/22 20:54:30	17.82	-3.05	0.0007	★
SIM XXXX+056	77.36	5.69	176.74	2017/08/28 07:04:56	21.13	-3.08	0.00087	★
SIM XXXX+056	77.36	5.69	127.84	2014/12/21 19:47:11	6.53	-2.14	0.000082	★★
SIM XXXX+056	77.36	5.69	43.07	2014/09/28 01:19:02	8.06	-2.25	0.0000063	★★
SIM XXXX+056	77.36	5.69	0.57	2014/08/16 13:22:25	1.35	-1.40	0.0011	★

Showing 1 to 6 of 6 entries

Previous 1 Next

- ★ Low Threshold (20 bkg per year)
- ★★ Medium Threshold (1 bkg per year)
- ★★★ High Threshold (0.05 bkg per year)

POS-ICRC2025-949



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

Elisa Bernardini — Padova University & INFN — TeVPA 2025

# Neutrino FlareWatch website - source detail page



## REALTIME GFU ALERTS

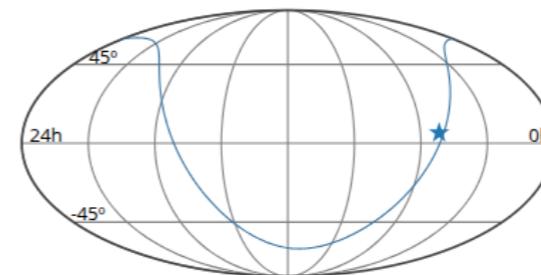
☆ Alerts ▾  Support

IceCube Preliminary

[← Go back](#)

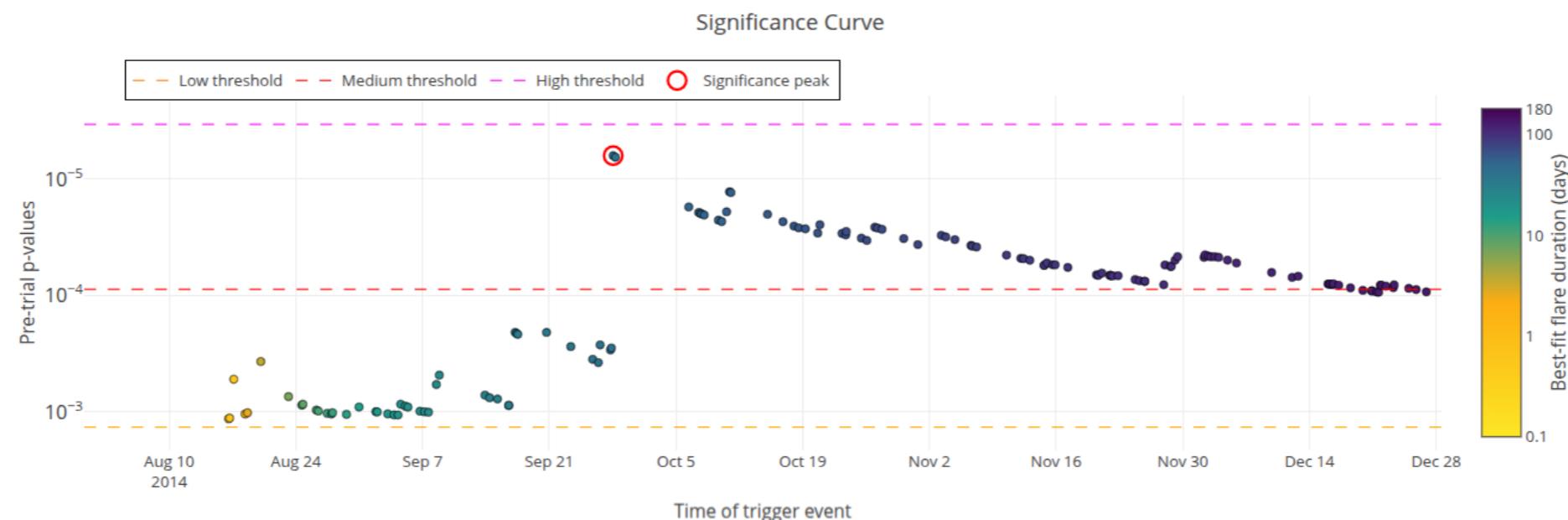
SIM XXXX+056 

<b>Name</b>	SIM XXXX+056
<b>Other associations</b>	Simulated Source with 50 Day Flare Injected
<b>Right ascension</b>	77.36 °
<b>Declination</b>	5.69 °



## Significance curve

## Alert history



POS-ICRC2025-949

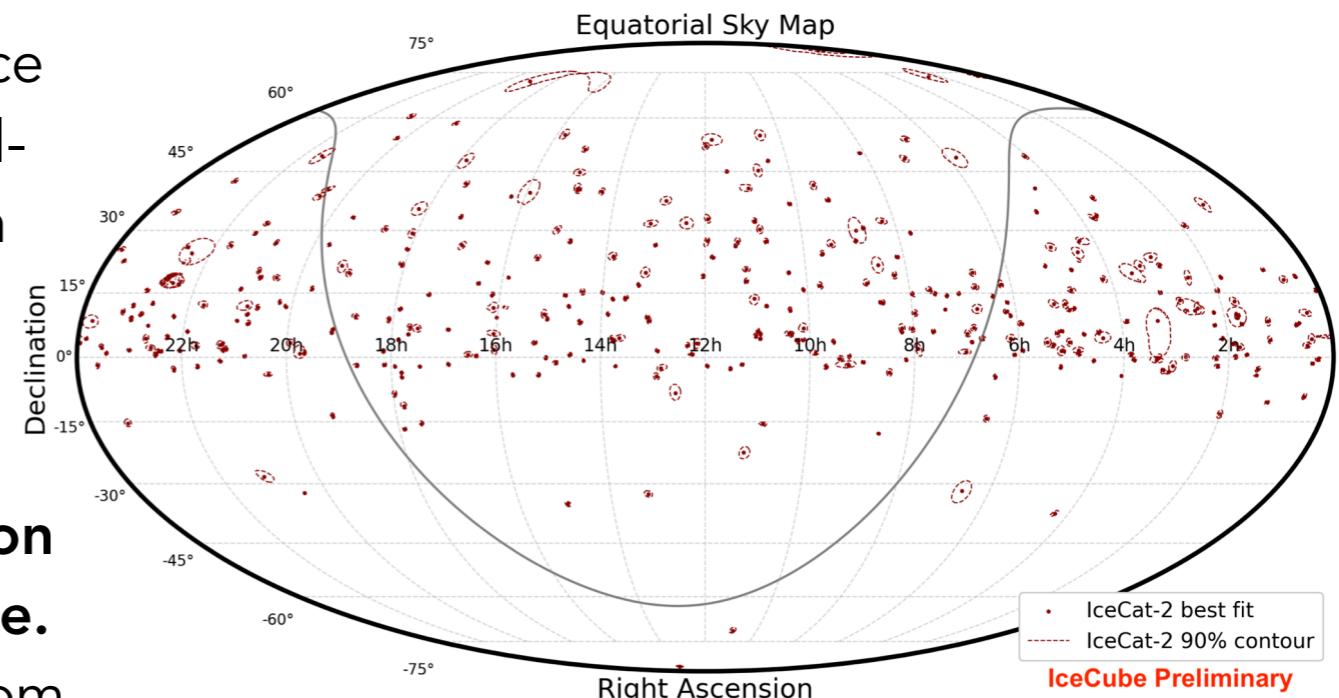


UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

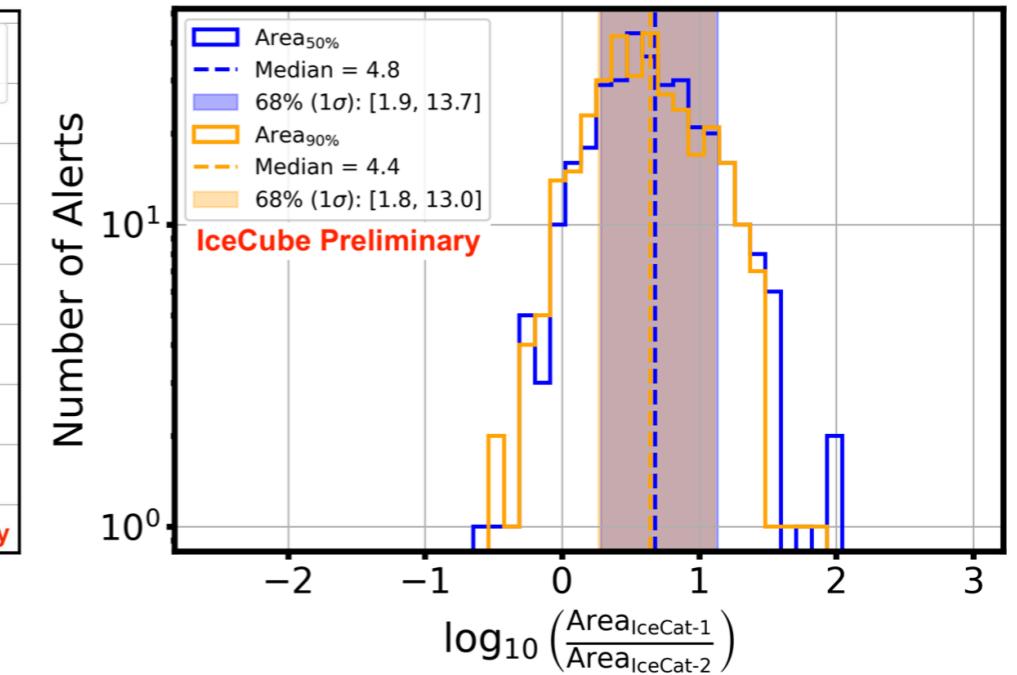
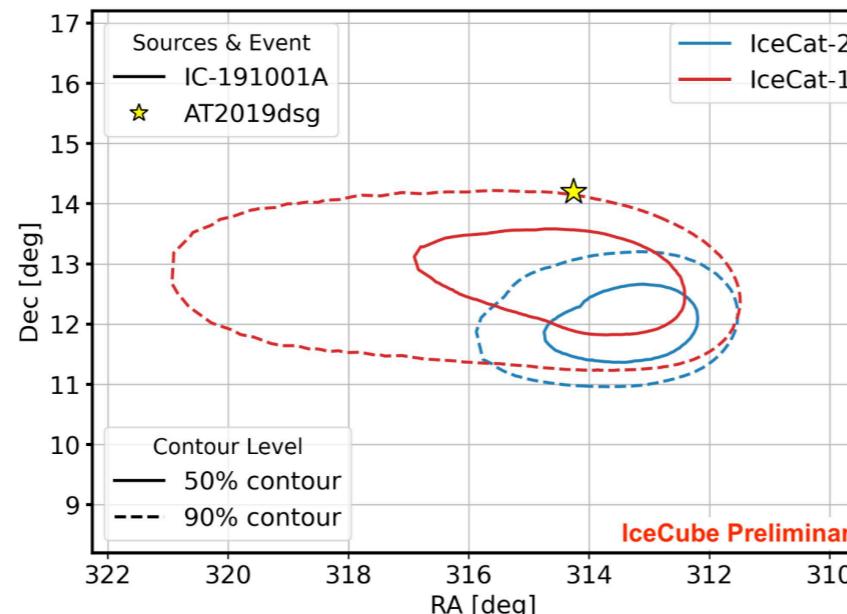
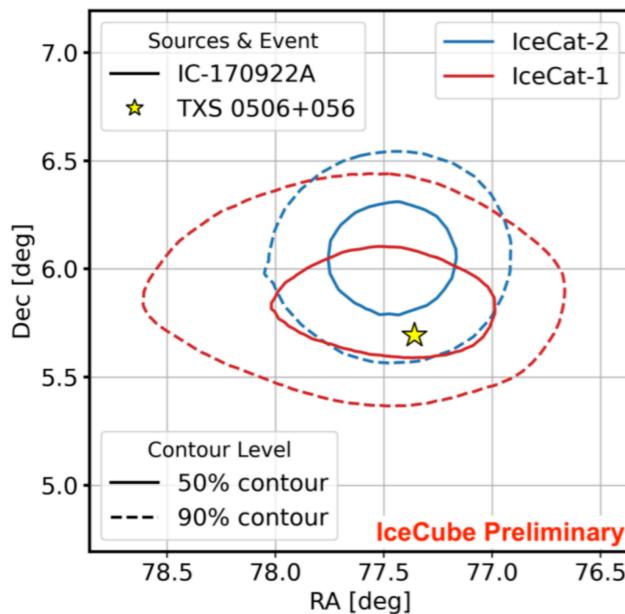
# IceCat-1: IceCube's 1st Event Catalog of Alert Tracks

**IceCat-1: 348 alert-like events**, issued since 2016 + archival events since the start of full-detector data that would have triggered an alert [IceCube Coll., ApJS 29, 25 (2023)]

**IceCat-2:** coming soon with more data and improved reconstruction. **Confidence region areas reduced by factor of 4-5 on average.**  
New reconstruction contours shifts away from potential TDE counterparts

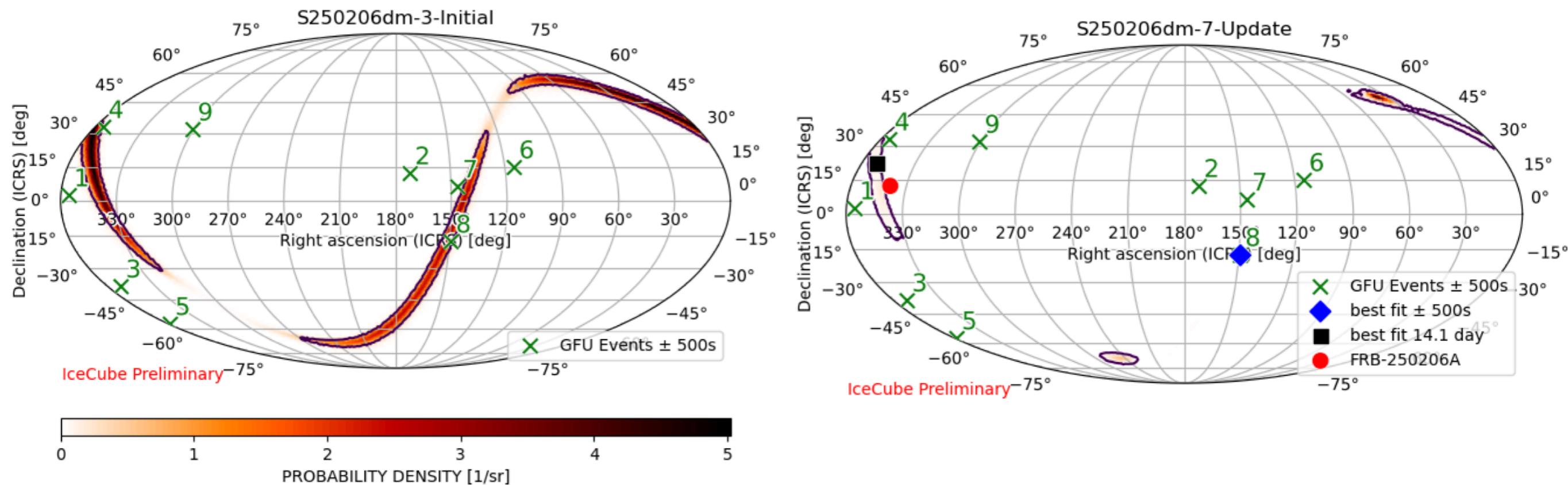


ApJS 269 25 (2023), POS-ICRC2025-1224, POS-ICRC2025-1184



# Follow-up of external triggers

The IceCube realtime pipeline enables user-driven checks for clusters of IceCube events during interesting transient phenomena, e.g. Gravitational waves, IceCube single alert events, GRBs, AGN flares etc.



ApJ 910 4 (2021), ApJ 951 45 (2023), ApJL 946 L26 (2023), PoS-ICRC2025-1113, PoS-ICRC2025-956

# Summary

Realtime platform consists of:

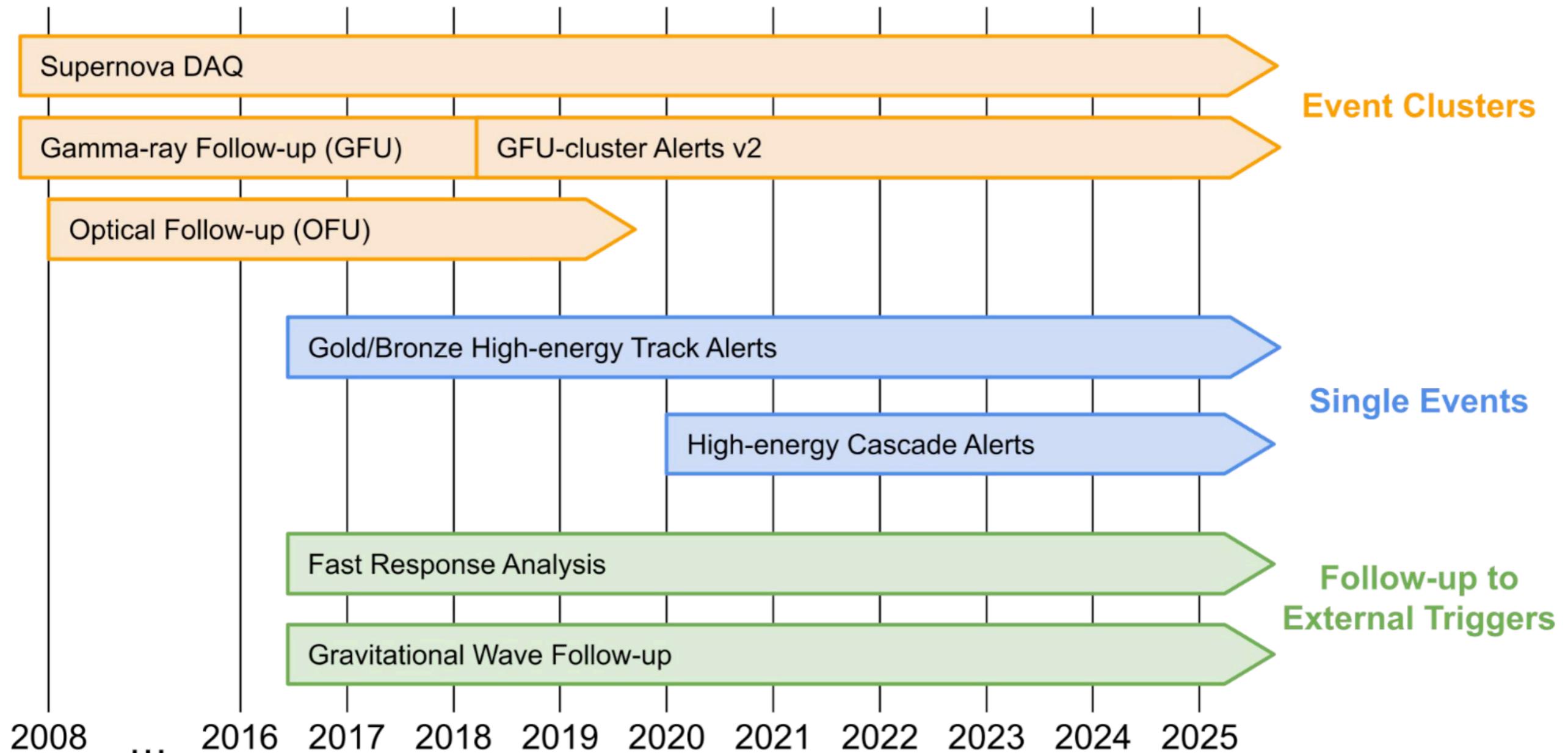
- Single high-energy event alerts
- Neutrino cluster alerts
- Follow-up of external triggers

New IceCat-2 with improved directional contours to be available soon

GFU-cluster alerts soon to be public with Neutrino Flarewatch website for source monitoring

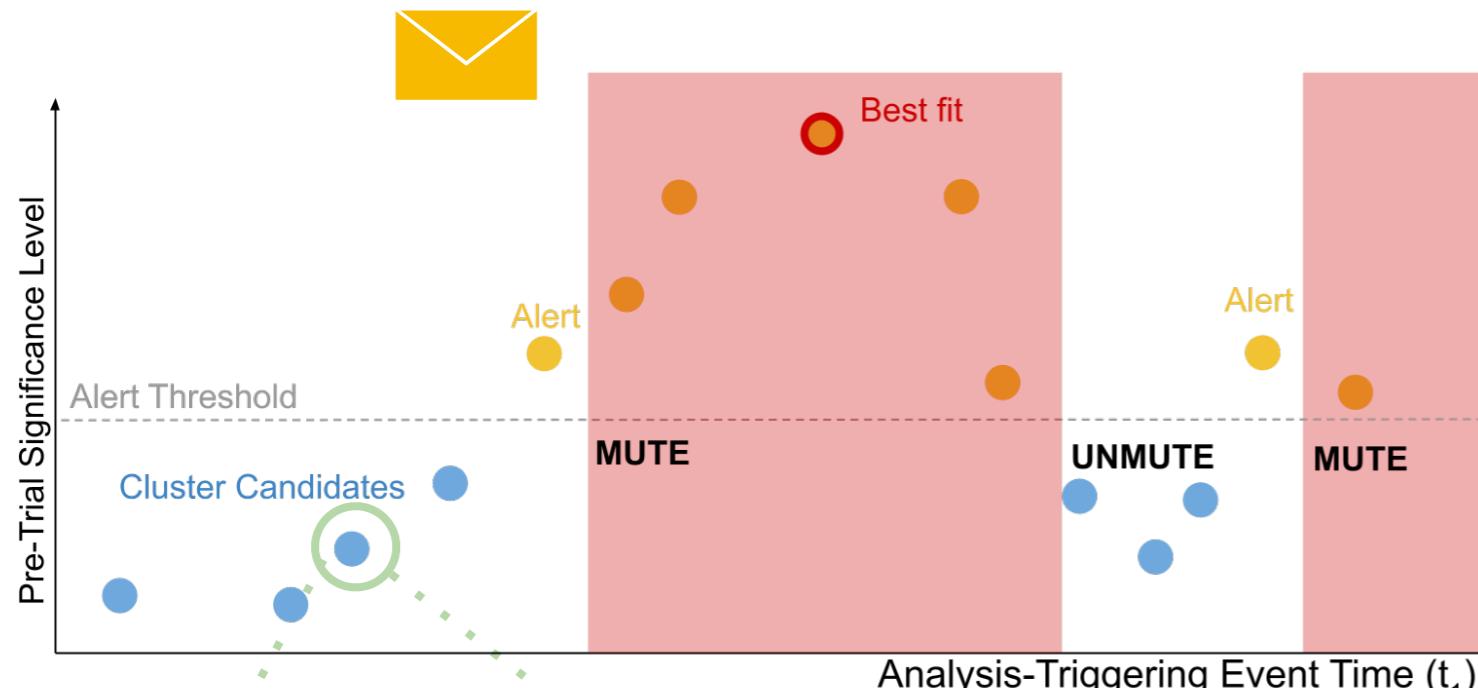
More improvements on-going to enhance the potential of multi-messenger correlation studies in realtime

# The IceCube realtime program timeline

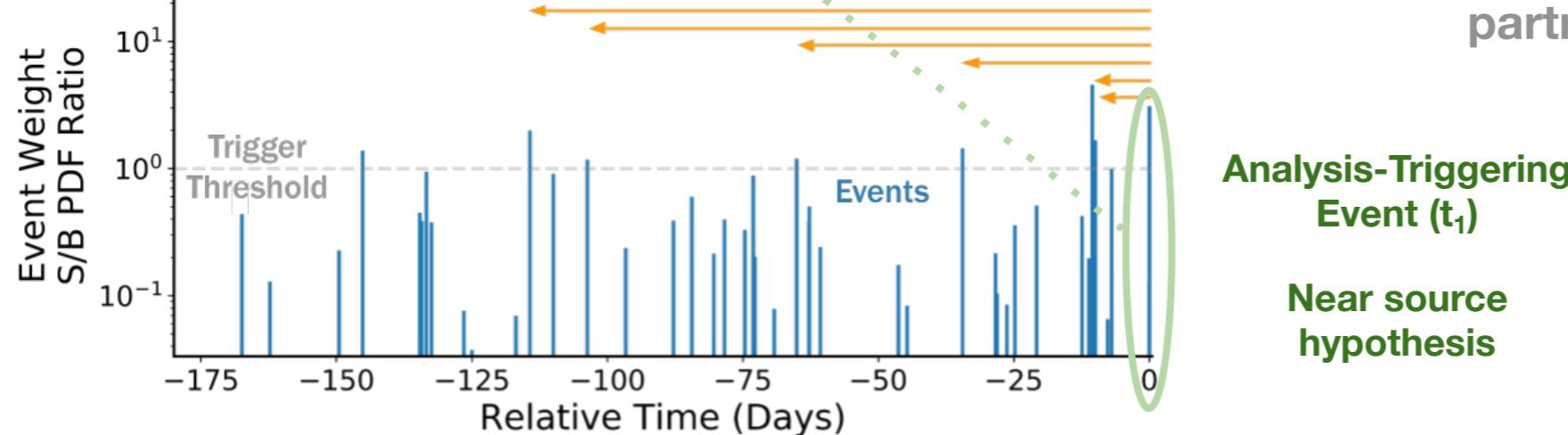


# Old GFU-cluster alert algorithm (still running as to today)

e-mail to IACT (no event cache, no archival information stored)



time evolution of significance is blinded, no update available for interesting occurrences



Every incoming high-level event triggers the analysis pipeline

Combinations of current event + past events from same direction tested to search for neutrino flares

Tested all possible time-windows up to 180 days

Each analysis-triggering event results in a pre-trial p-value

Alert sent if passes a pre-trial significance threshold

Current: Alerts sent under MoU to partner telescopes only