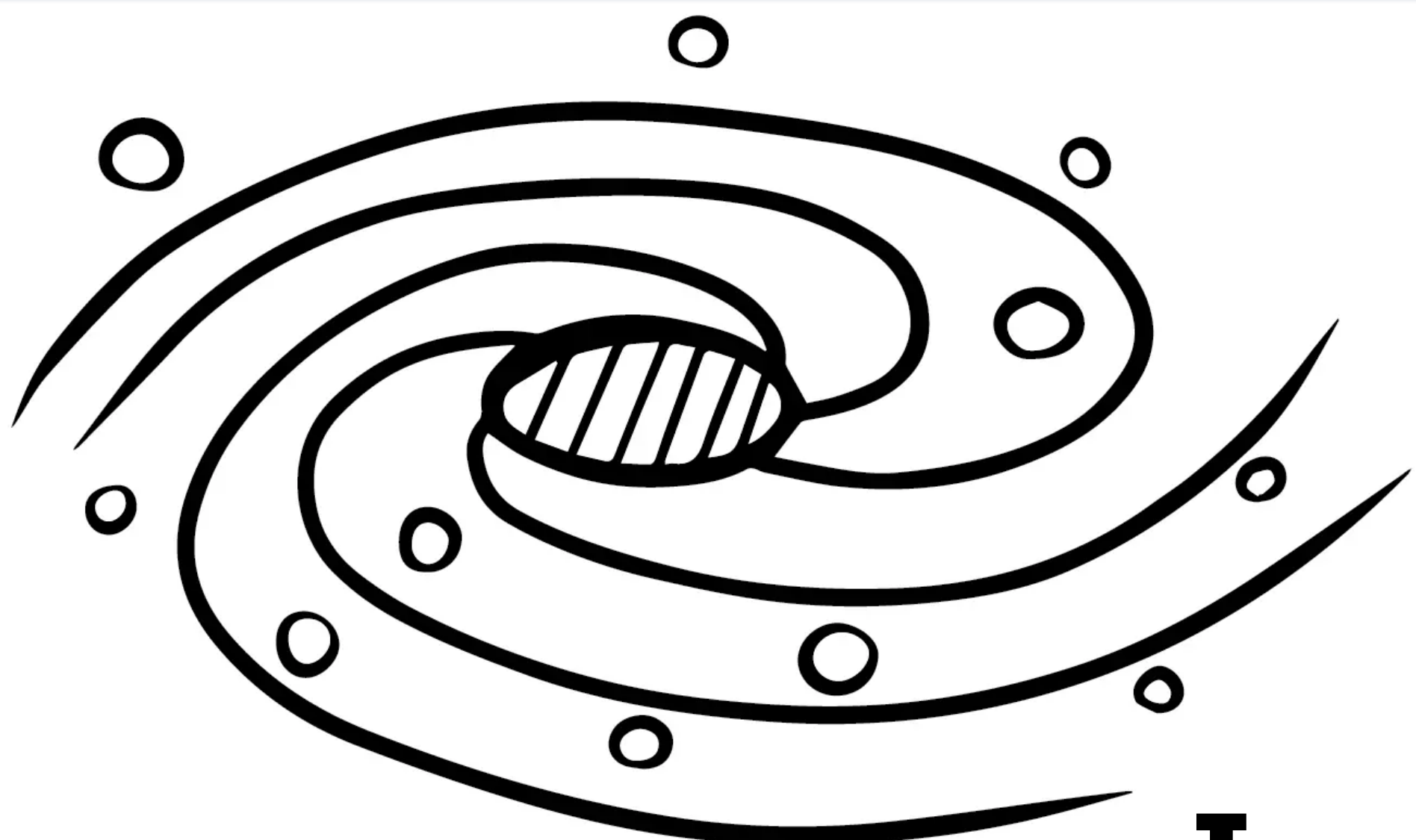


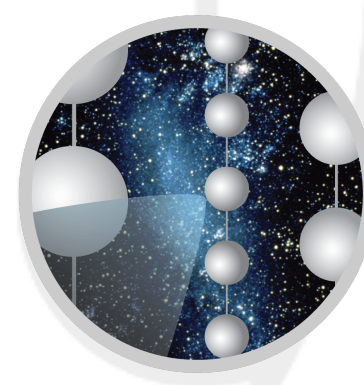


IceCube Realtime Program

*Connecting high-energy neutrinos to
the multi-messenger sky*



A. Zegarelli, Prof. Dr. A. Frankowiak, Dr. Erik Blaufuss,
on behalf of the IceCube Collaboration



ICECUBE
NEUTRINO OBSERVATORY

Gefördert durch:



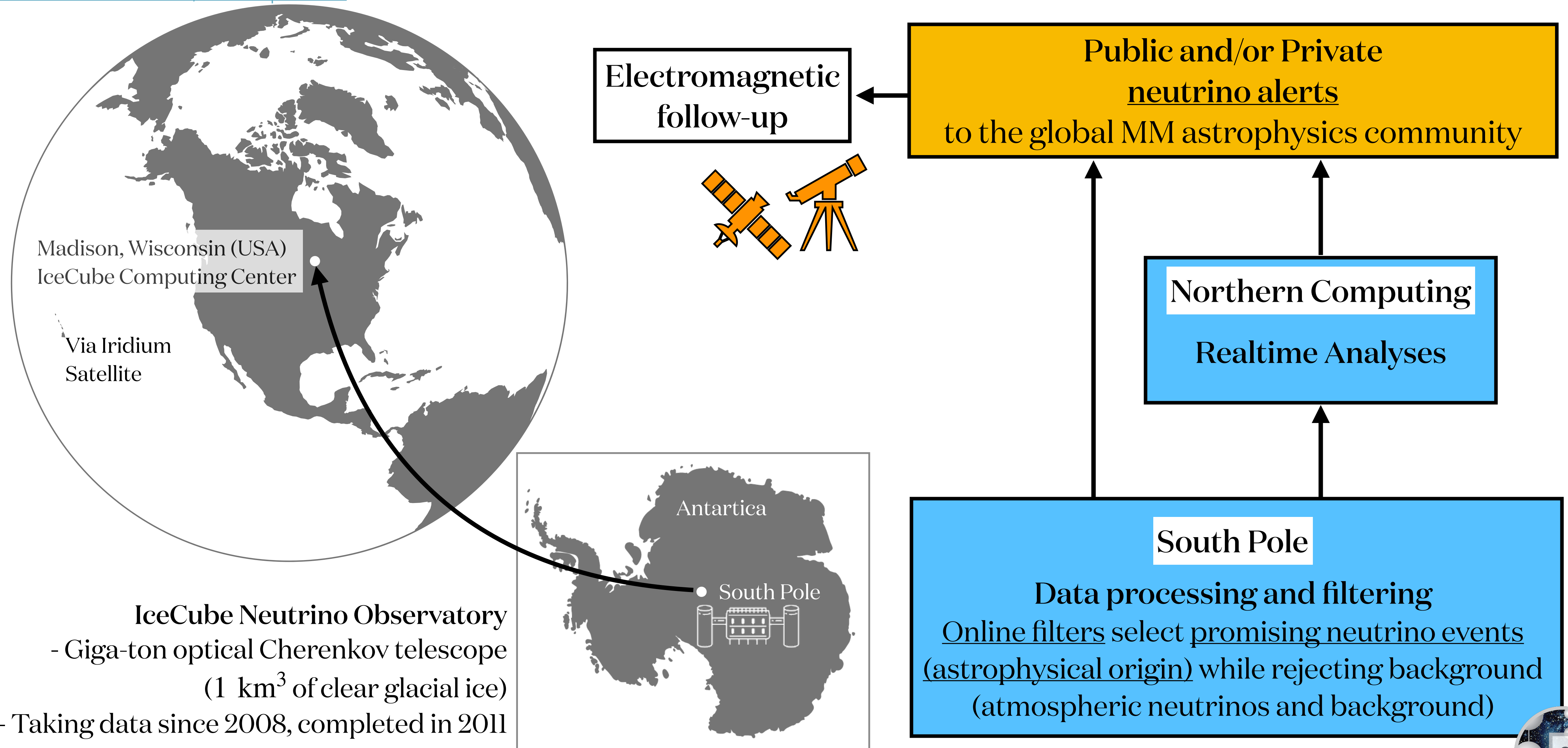
Bundesministerium
für Forschung, Technologie
und Raumfahrt



IceCube Realtime Program - *Alert generation*

Active since 2016

IceCube Collaboration, 2017 ApJ 92 30

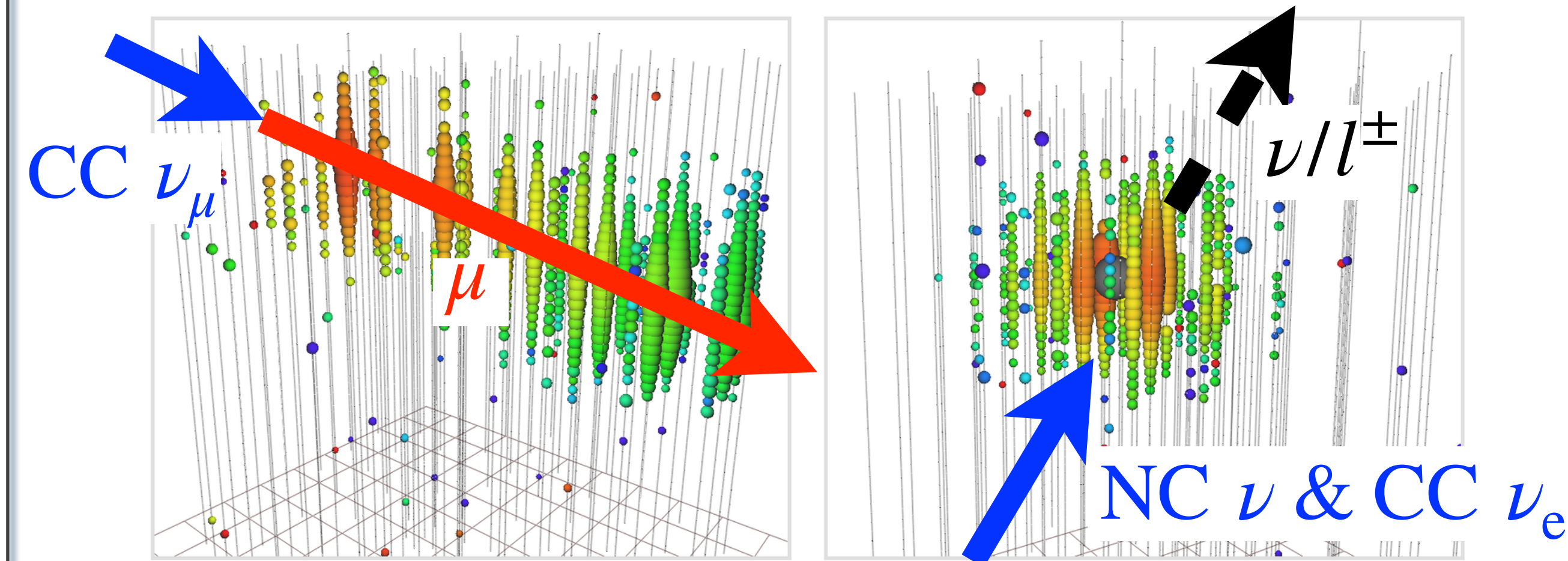


IceCube Realtime Program - *Alert generation*

(*) Gamma-ray Coordinates Network

High-energy single neutrino events

Public alerts
via GCN(*) Notices
and GCN Circulars



- Track alerts (*since 2016*)
→ ~30 alerts/year

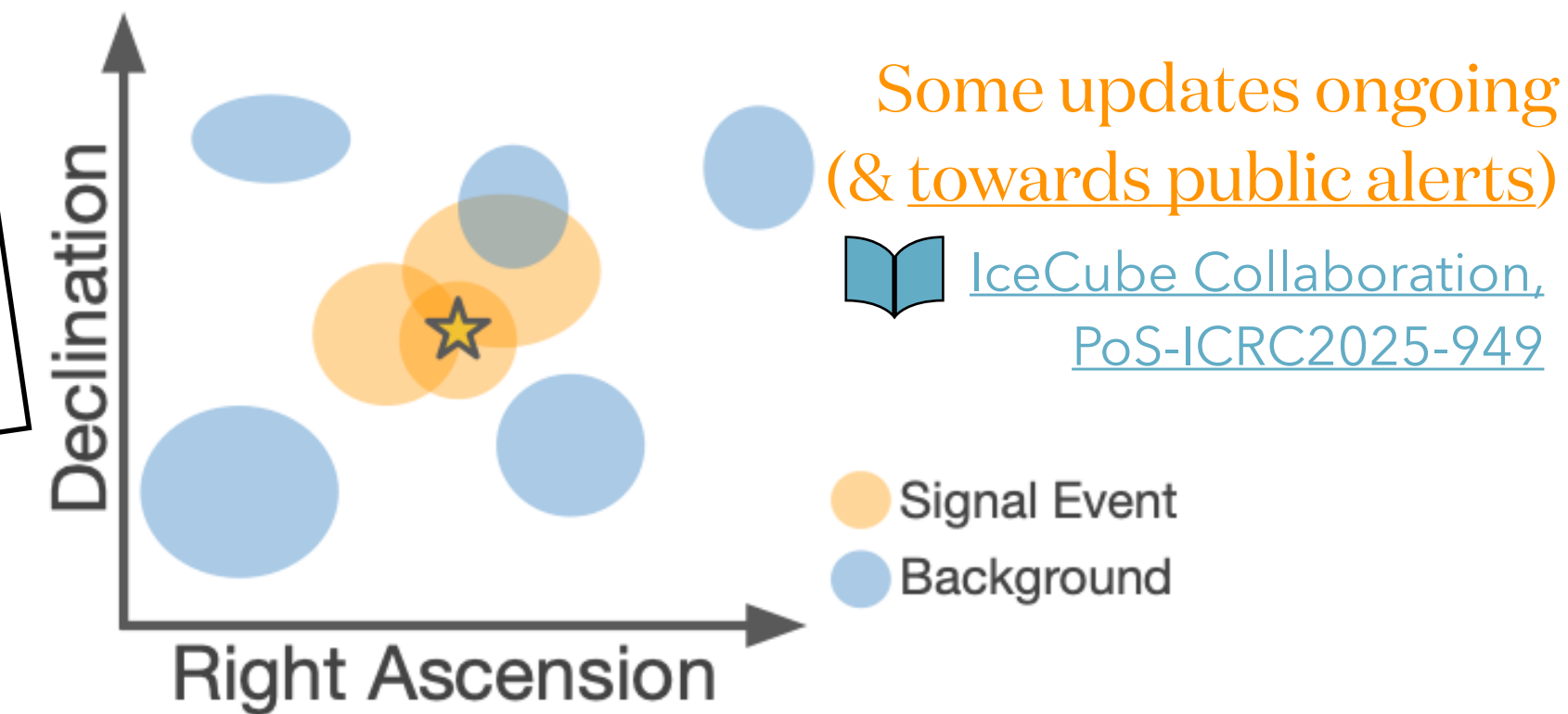
- Cascade alerts (*since 2020*)
→ ~8 alerts/year



Long muon paths inside the detector
→ best-potential source localisation

Neutrino Cluster Search

Private alerts
Email under
Memorandum of
Understanding



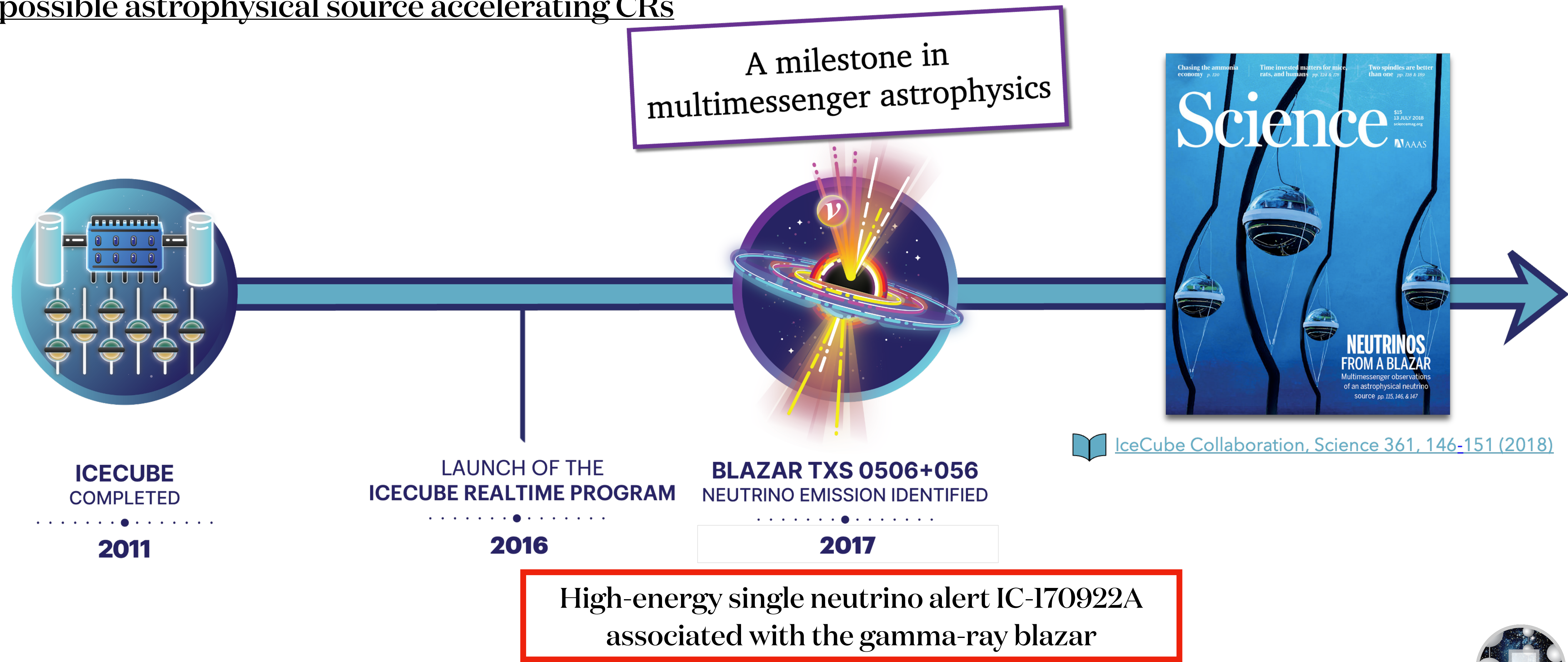
≥ 2 neutrino events (tracks)
correlated in time and direction

- Gamma-Ray Follow-Up (GFU) clusters (*active since 2016*) →
focused on γ -ray sources, time scales up to 180 days
 - Unbinned maximum-likelihood method
 - Goals: (i) identify potential neutrino flares as early as possible; (ii) send alerts to partner Imaging Cherenkov Telescopes (IACTs) for follow-up studies
 - Two modes: (1) all-sky (~1 alert/year); (2) source lists from IACTs (<10 alerts/year)



2017: IceCube Realtime Program success

An IceCube alert (disseminated after 30 seconds from its detection) enabled the first identification of a possible astrophysical source accelerating CRs

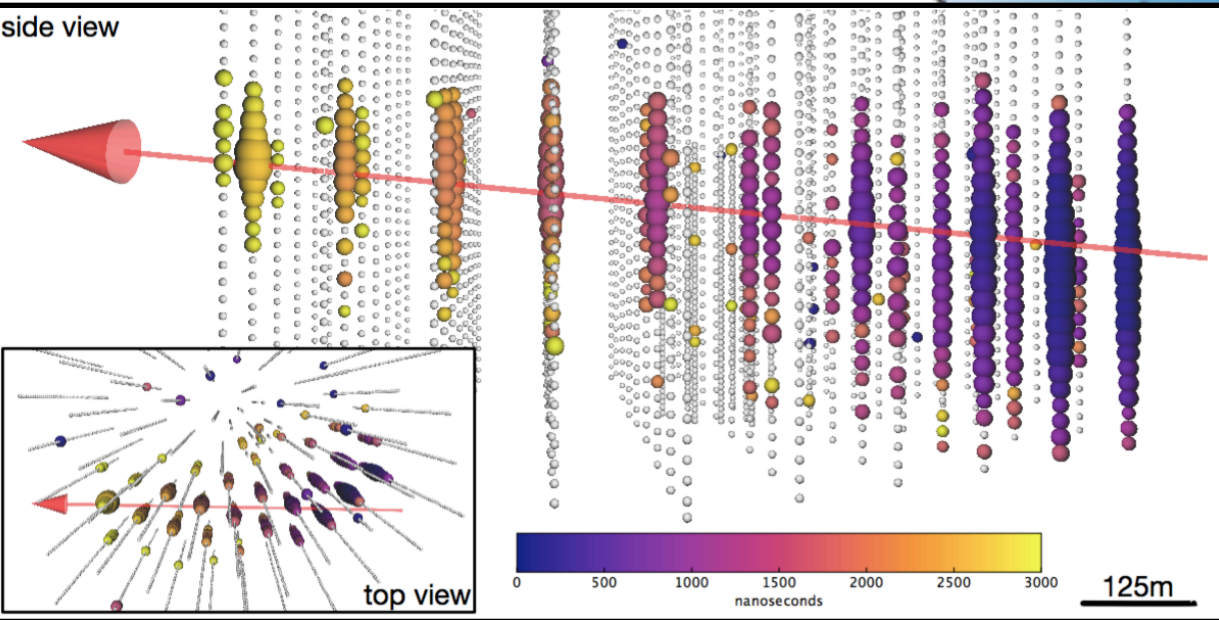


2017: IceCube Realtime Program success

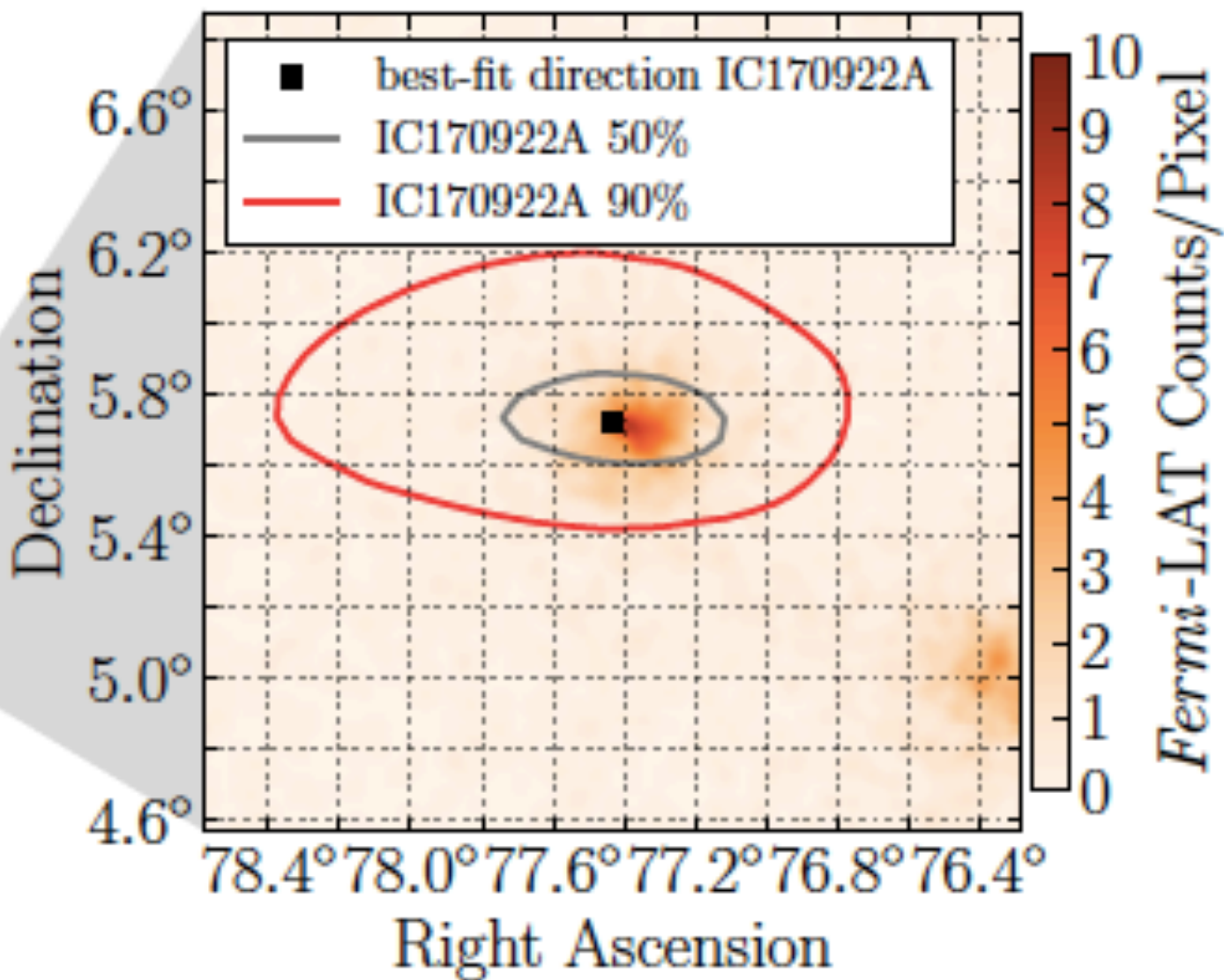
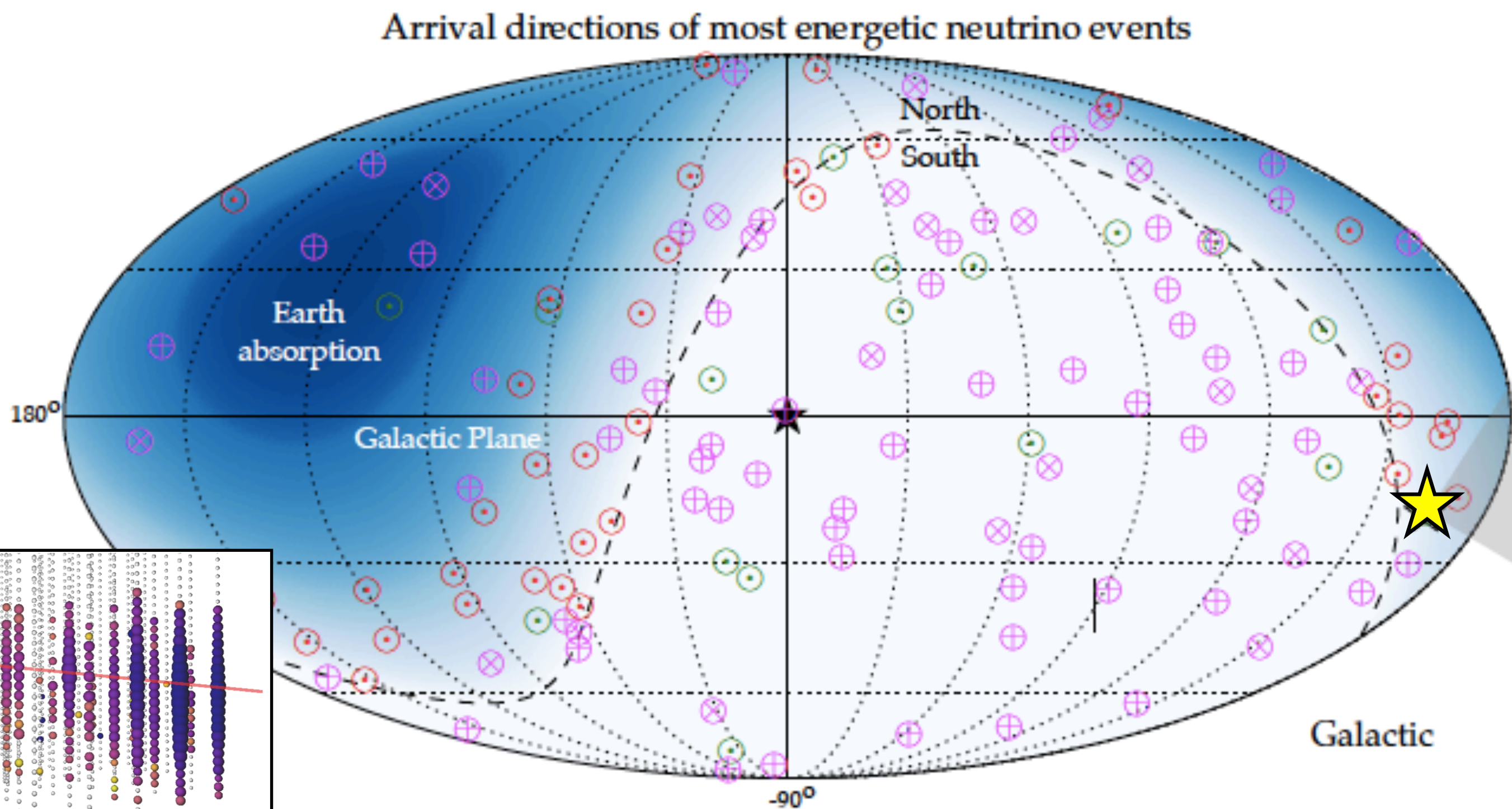
TXS 0506+056

Blazar flare observed by Fermi-LAT and MAGIC ($z = 0.3365 \pm 0.0010$)

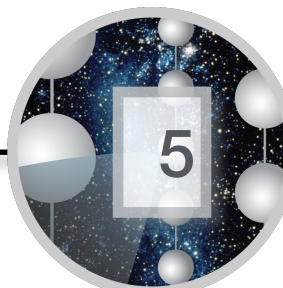
IC-170922A



Track with most probable energy between 250 and 300 TeV

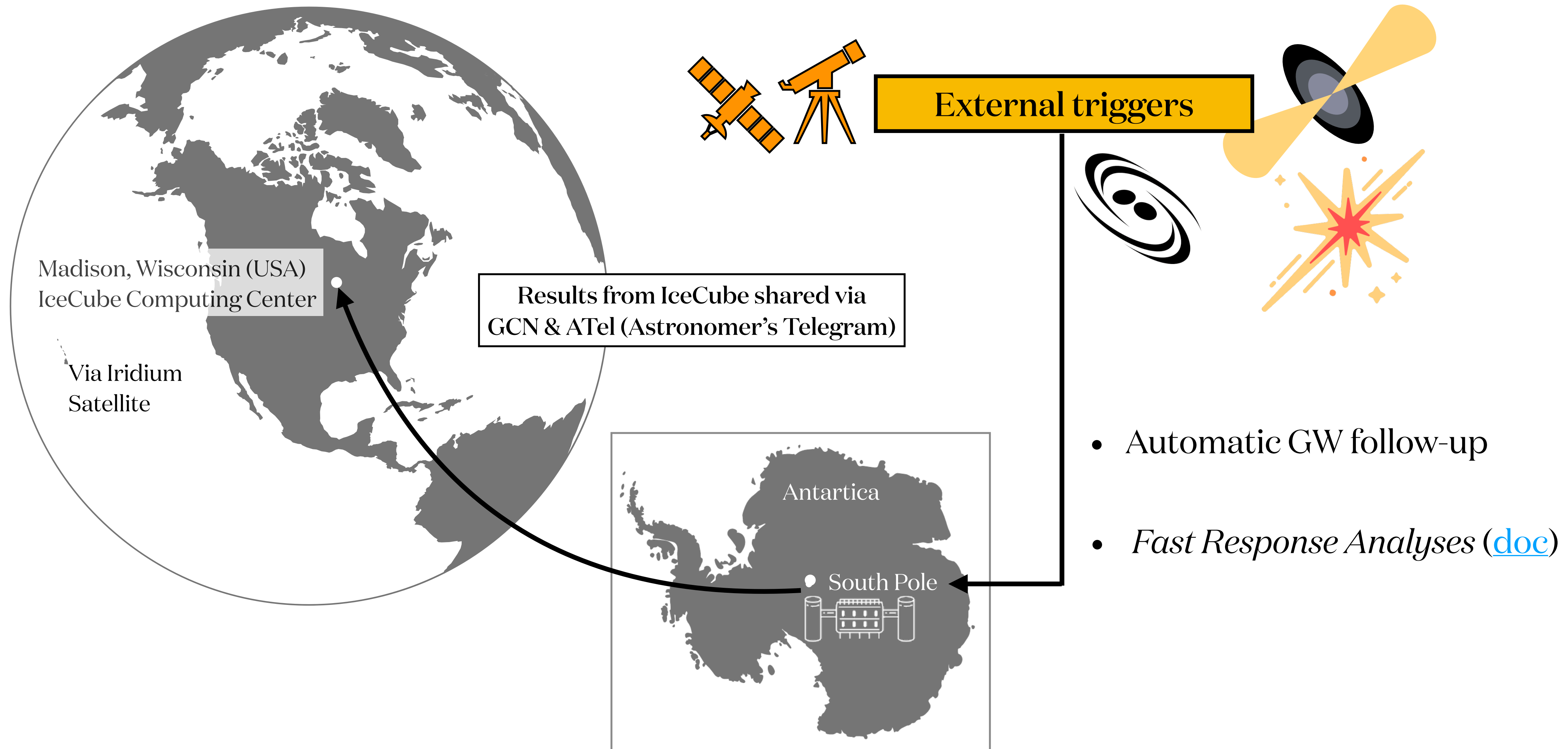


Correlation significance: $\sim 3\sigma$



IceCube Realtime Program - *Followup to external triggers*

Since 2016, IceCube also follows up alerts sent by other telescopes in real-time using high-energy tracks



IceCube Realtime Program - *Followup to external triggers*

Since 2016, IceCube also follows up alerts sent by other telescopes in real-time using high-energy tracks

Search for neutrinos associated with GWs

- Unbinned maximum likelihood analysis on significant alerts
- Bayesian analysis accounting for prior information about astrophysical sources on both significant and low-significance alerts

IceCube Real-time Searches for High-energy Neutrinos Coincident with LIGO/Virgo/KAGRA Gravitational-Wave Alerts in O4a

 [IceCube Collaboration, arXiv:2606.13762](#)

Fast Response Analysis

Tool for rapid response to astrophysical transients (maximum-likelihood method)

- Generic externally triggered transients  [IceCube Collaboration, 2021 ApJ 910 4](#)
 - (1) Interesting external events (e.g. exceptional blazar flare, close-by supernova) are brought to the attention of the Realtime Oversight Committee (ROC)
 - (2) ROC discusses the benefit of running FRA and defines coordinates and time window used for the search
 - IceCube single alerts  [IceCube Collaboration, 2023 ApJ 951 45](#)
 - GWs events  [IceCube Collaboration, 2023 ApJ 944 80](#)
- 1000 seconds and 2 days around each event
(always run; no decision to be made)



Summary (I)

- IceCube Realtime Program has been active since 2016
 - ♦ Alert sending
 - High-energy single neutrino alerts (Tracks & Cascades)
 - Event cluster searches (currently active, the GFU program, sending private alerts to partner gamma-ray telescopes, i.e., Imaging Cherenkov Telescopes)
 - ♦ Follow-up of external trigger
 - Automatic GW follow-up
 - Fast Response Analyses around GWs, IceCube single alerts, and for specific sources discussed among the Realtime Oversight Committee

Association $\sim 3\sigma$ between an IceCube high-energy track alert and the gamma-ray blazar TXS 0506+056 on September 22nd, 2017

No other statistically significant associations were identified, with only upper limits obtained





IceCube Realtime Program *Track Alerts*

Track Alerts' dissemination

Average rate of ~30 evt/year

1. General Coordinate Network
(GCN) Notice

2. GCN Circular
+
Updated GCN Notice

Results from a fast and simplified
reconstruction algorithm
(processed at South Pole)

Updated reconstruction with
more sophisticated algorithms
(processed at North)

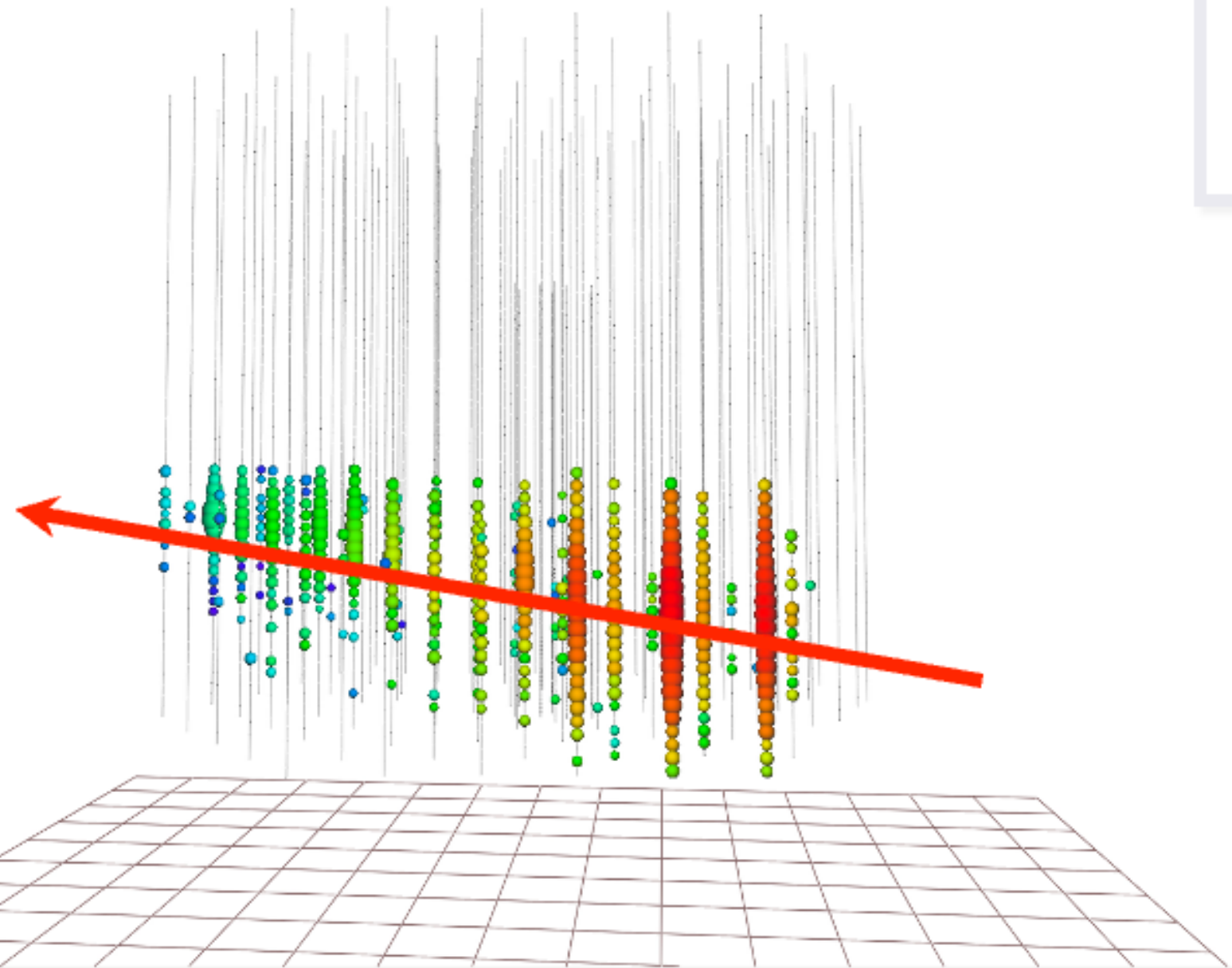
< 1 min

< a few hours

For high-energy track alerts, a first alert is disseminated within ~1 minute, and a few hours later an updated reconstruction is also provided to the community

September 2024: Update on Track Alert system

Average rate of ~30 evt/year



1. General Coordinate Network
(GCN) Notice

Results from a fast and simplified
reconstruction algorithm
(processed at South Pole)

< 1 min

2. GCN Circular
+
Updated GCN Notice

Updated reconstruction with
more sophisticated algorithms
(processed at North)

< a few hours

Recent update of reconstruction
algorithms to improve the angular
resolution of muon track alerts and
the statistical coverage of their
directional uncertainties

Announced via
[GCN Circular 38267](#)

Refined best-fit direction and
angular coordinates
(rectangular error region)



Updated Public Catalog of Track Alerts - IceCat-2

Most notable improvement

Significant reduction in localization uncertainties
around the best-fit direction (on median, factor ~5)

IceCat-2 = IceCat-1 events (2011-2023)

reprocessed + new events

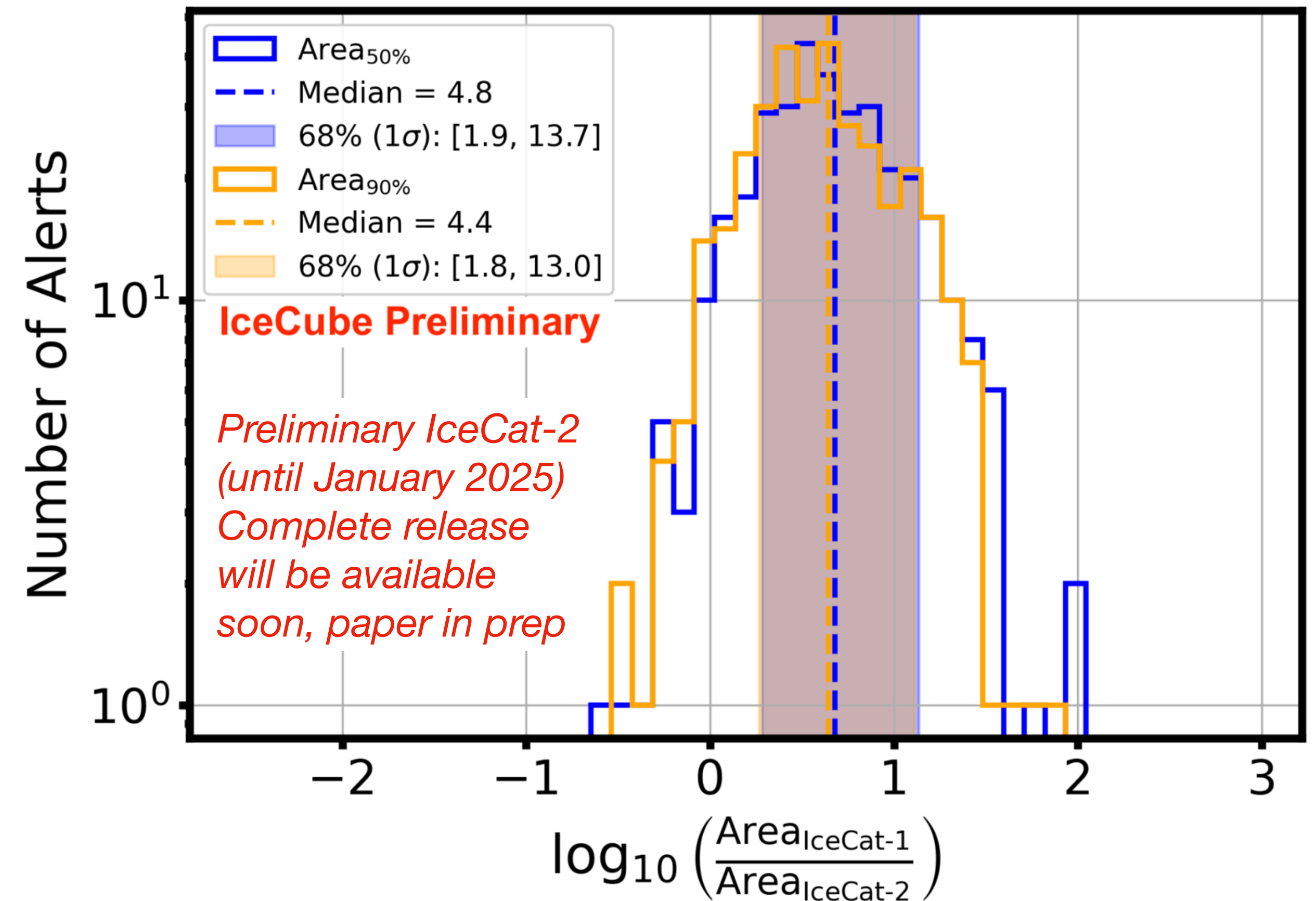
Using improved reconstruction algorithms
deployed in real time since September 2024

New reco:  [IceCube Collaboration, PoS-ICRC2025-1184](#)

IceCat-1:  [IceCube Collaboration, ApJS 29, 25 \(2023\)](#)

Coming Soon!

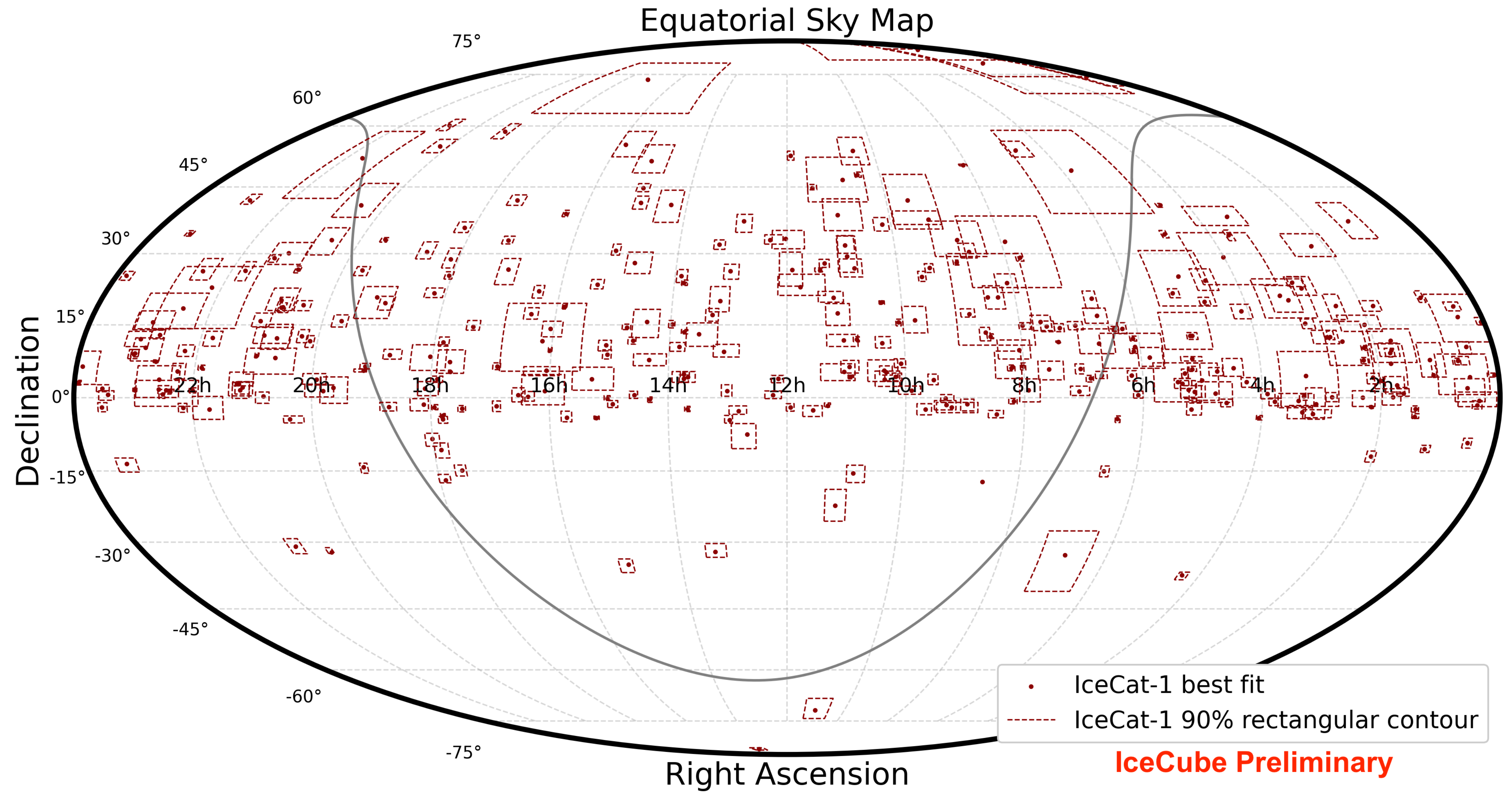
Preliminary release with a few
events already public [here](#)



 [IceCube Collaboration, PoS-ICRC2025-1224](#)

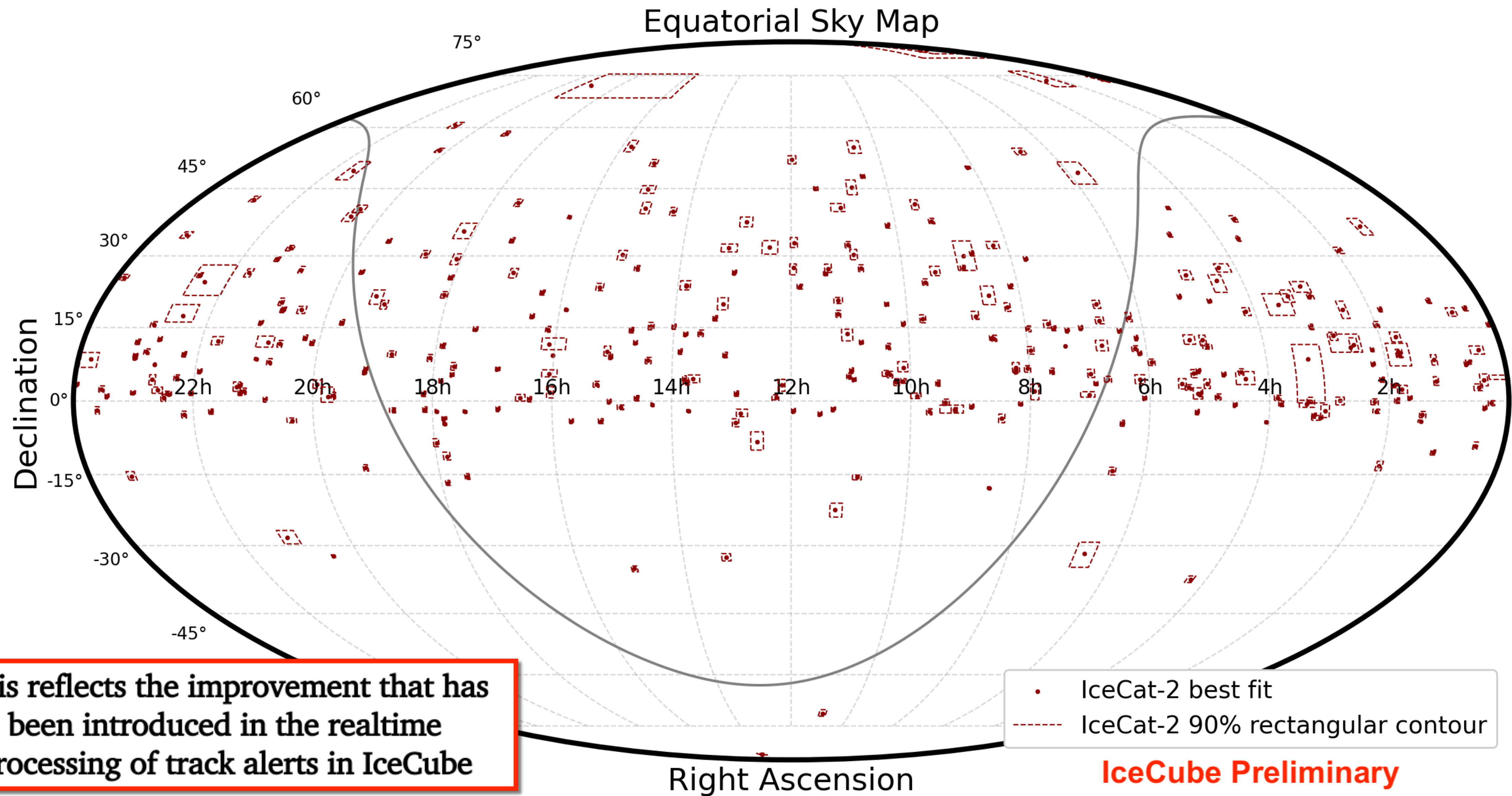
Equatorial skymap with IceCat-1 events + rectangular errors (original reco)

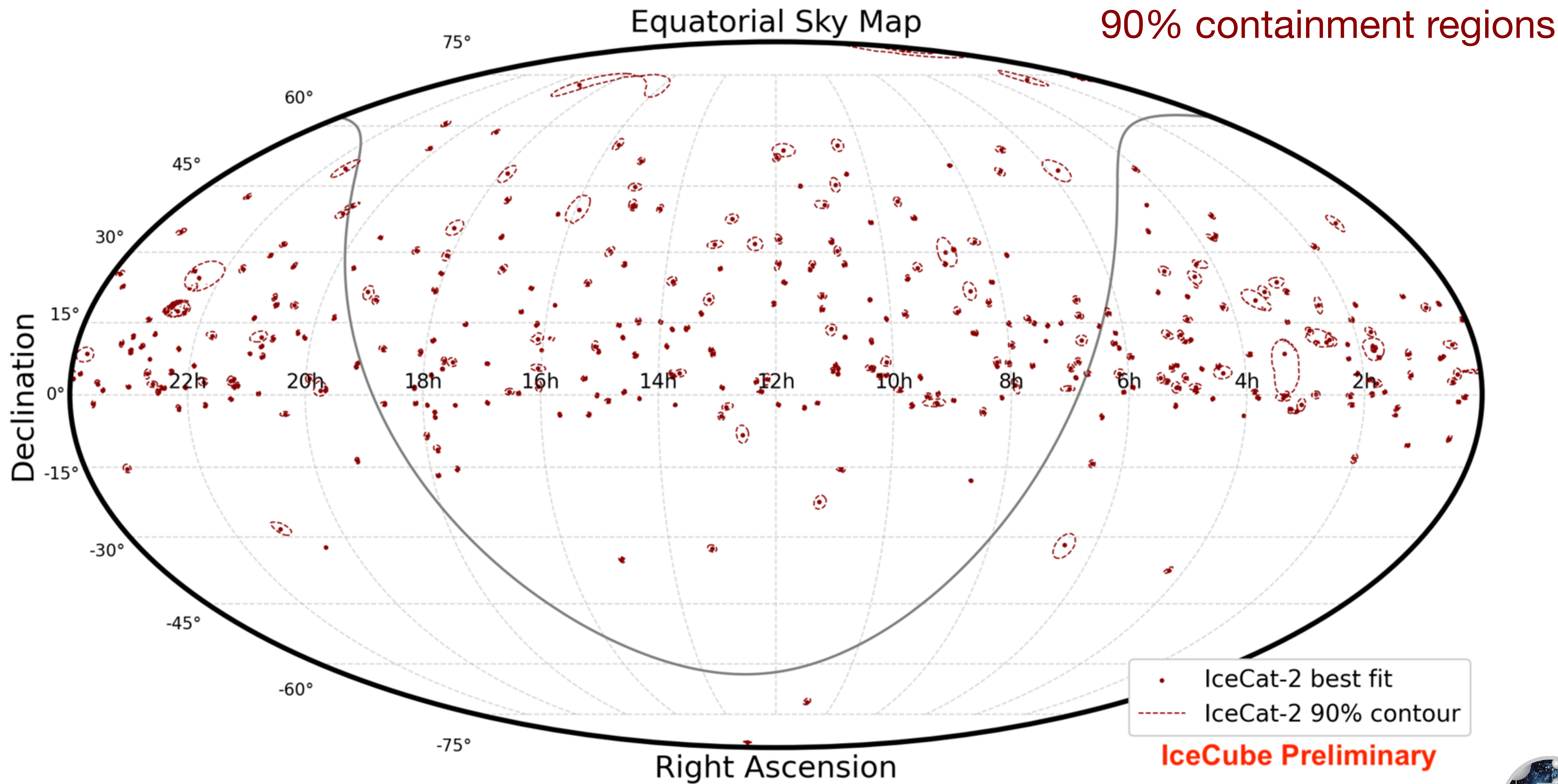
Rectangular box contours are the ones provided to the external community through GCN Circulars for real-time High-Energy Track Alerts (Gold/Bronze Alerts)

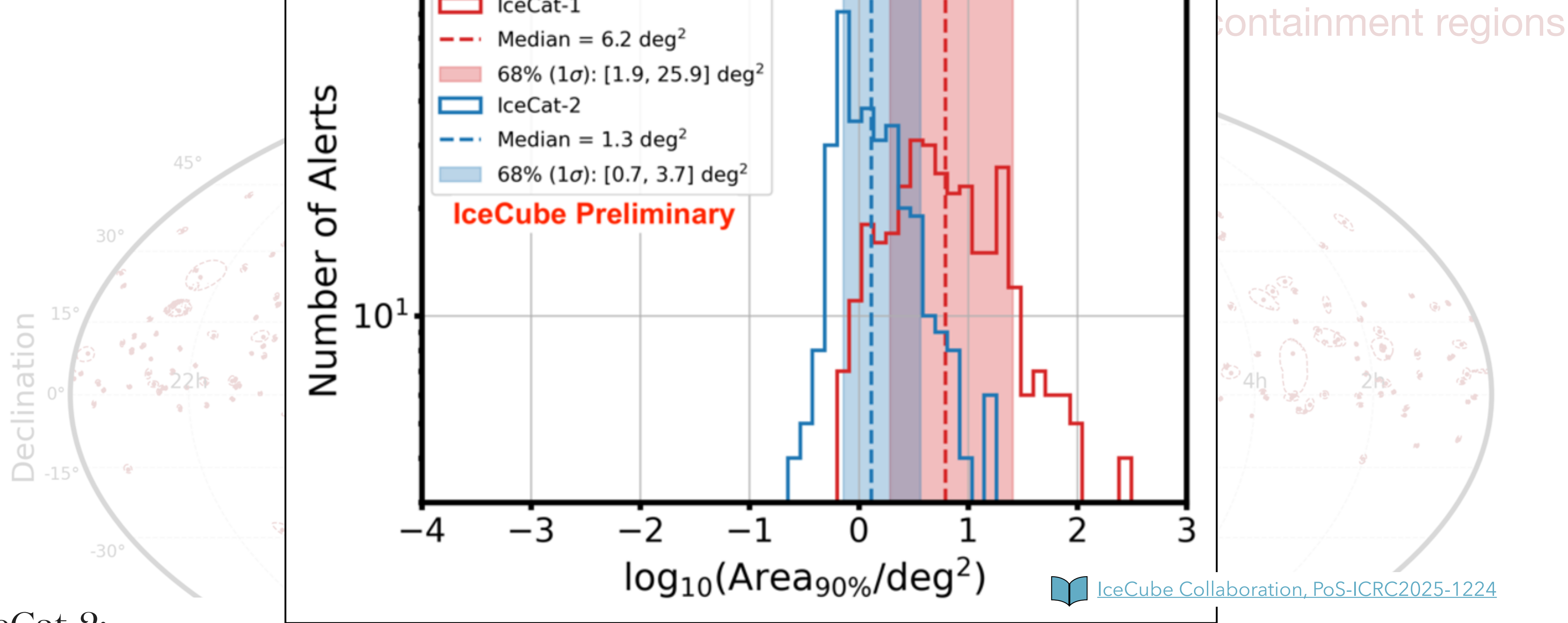


Equatorial skymap with IceCat-1 events + rectangular errors (new reco from IceCat-2)

Rectangular box contours are the ones provided to the external community through GCN Circulars for real-time High-Energy Track Alerts (Gold/Bronze Alerts)







IceCat-2:

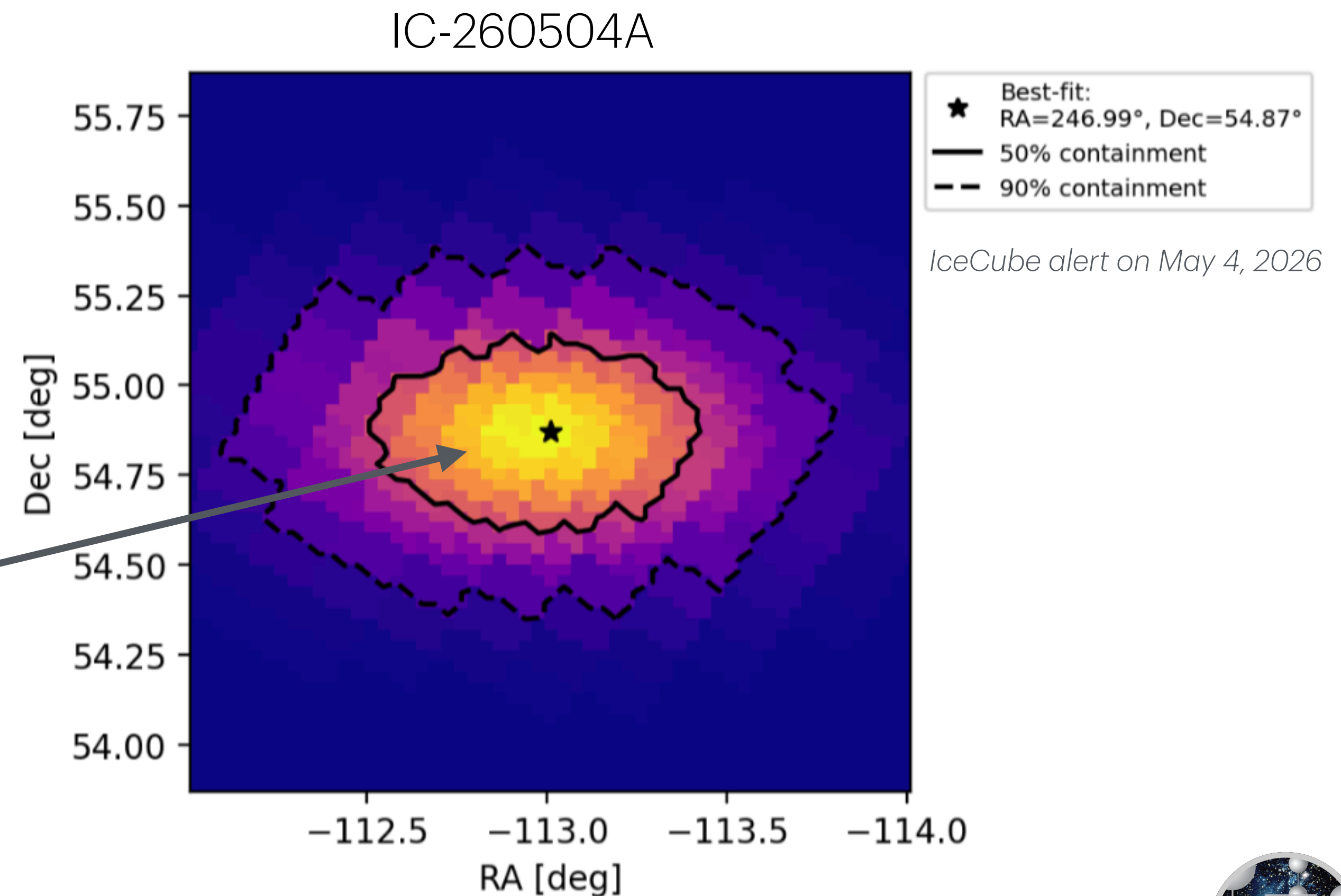
- Median area at 90% reduced from 6.2 squared deg to 1.3 squared deg
- IceCat-2 distribution is considerably narrower, with the spread around the median, quantified by the 16th-84th percentiles, reduced by a factor ~9

Better EM follow-up with multi-order probability maps

Multi-order probability maps (MOC/HEALPix)

- Publicly released for track alerts since January 2026 (streamed via GCN Notice for the revised reconstruction, and available at [this link](#)). Previously, alerts provided only a rectangular uncertainty region and the corresponding circularized error radius
- Maps for all alerts in IceCat-2 will be made public

- Each pixel contains the probability density that the true event direction lies within that region of the sky
- In the file, it is provided in sr^{-1} and it can be converted to deg^{-2} → Knowing the pixel area, this can be converted into the actual probability contained in each pixel → *A Jupyter notebook in the preliminary IceCat-2 public release shows how*



Better EM follow-up with multi-order probability maps

Multi-order probability maps (MOC/HEALPix)

- Publicly released and available corresponding

- Maps for all a

- Each pixel c
true event c

- In the file, it
converted to
can be conv
contained in
preliminary IceCat-2 public release shows how)

Two levels of improvement

1. Online (real-time followup)

- Optimized EM follow-up strategies
(e.g., telescope pointing; each telescope can choose its own strategy based on a given containment probability)

2. Offline analyses

- More accurate cross-correlation with source catalogs
- Proper likelihood-based analyses possible
- Improved joint analyses with other observatories

construction,

Best-fit:
RA=246.99°, Dec=54.87°
— 50% containment
— 90% containment

ast IceCube alert

54.00

RA [deg]
-112.5 -113.0 -113.5 -114.0



Summary (II) - *Crucial improvements to the Track Realtime System*

- Since September 2024: track-alert angular uncertainties reduced by $\sim 5\times$, reaching a median 90% containment area of 1.3 squared degrees $\rightarrow$ dramatically improving source localization and follow-up efficiency
- Since January 2026: probability maps released with alerts $\rightarrow$ enabling more precise and targeted multi-messenger follow-up
- Updated high-energy track-alert catalogue (IceCat-2): ready for public release (paper in preparation) $\rightarrow$ improved angular uncertainties, probability maps, and updated calibrations on all IceCube alerts since 2011 $\rightarrow$ a more accurate and complete dataset for multi-messenger and population studies

Stay tuned!





Thank you for the attention

ご清聴ありがとうございました



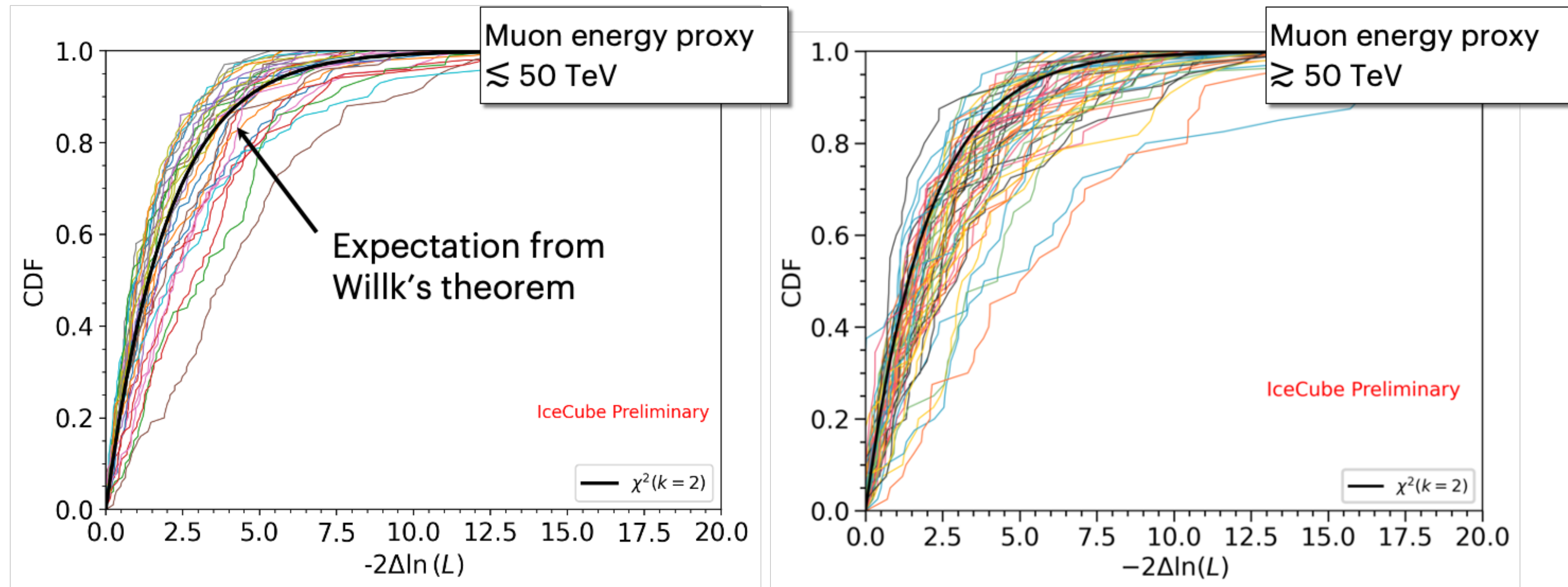
Backup

Coverage and robustness of new reco algorithms...

From realtime benchmark simulations,
each resimulated 100 times

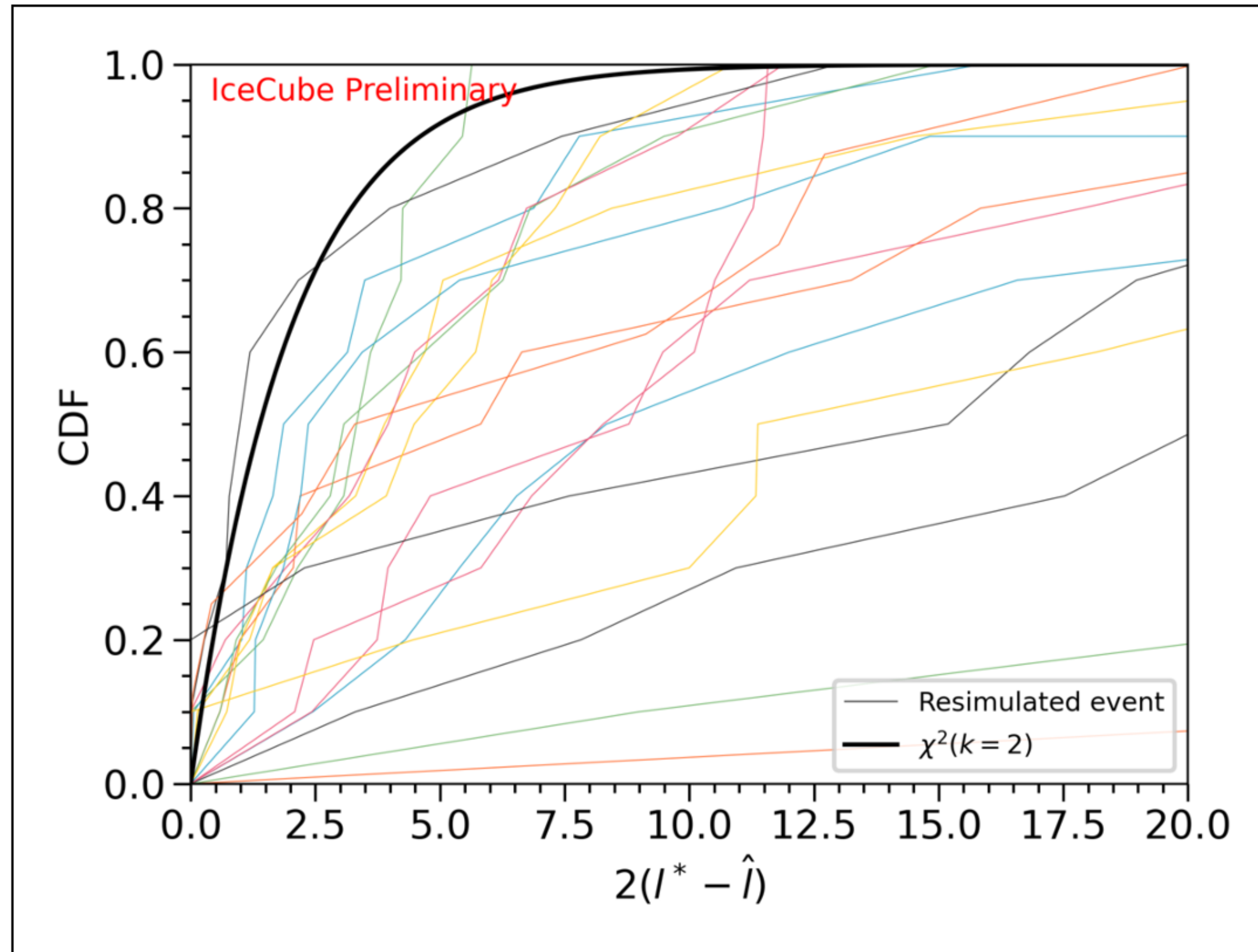
 IceCube Collaboration, PoS-ICRC2025-1184

These plots refer to the two reconstruction algorithms
currently used for the refined track alert reconstruction, and therefore also adopted in IceCat-2



CDF → Cumulative distribution function
 $\Delta\ln(L)$ → Log-likelihood diff between true and reconstructed best-fit directions (simulations)

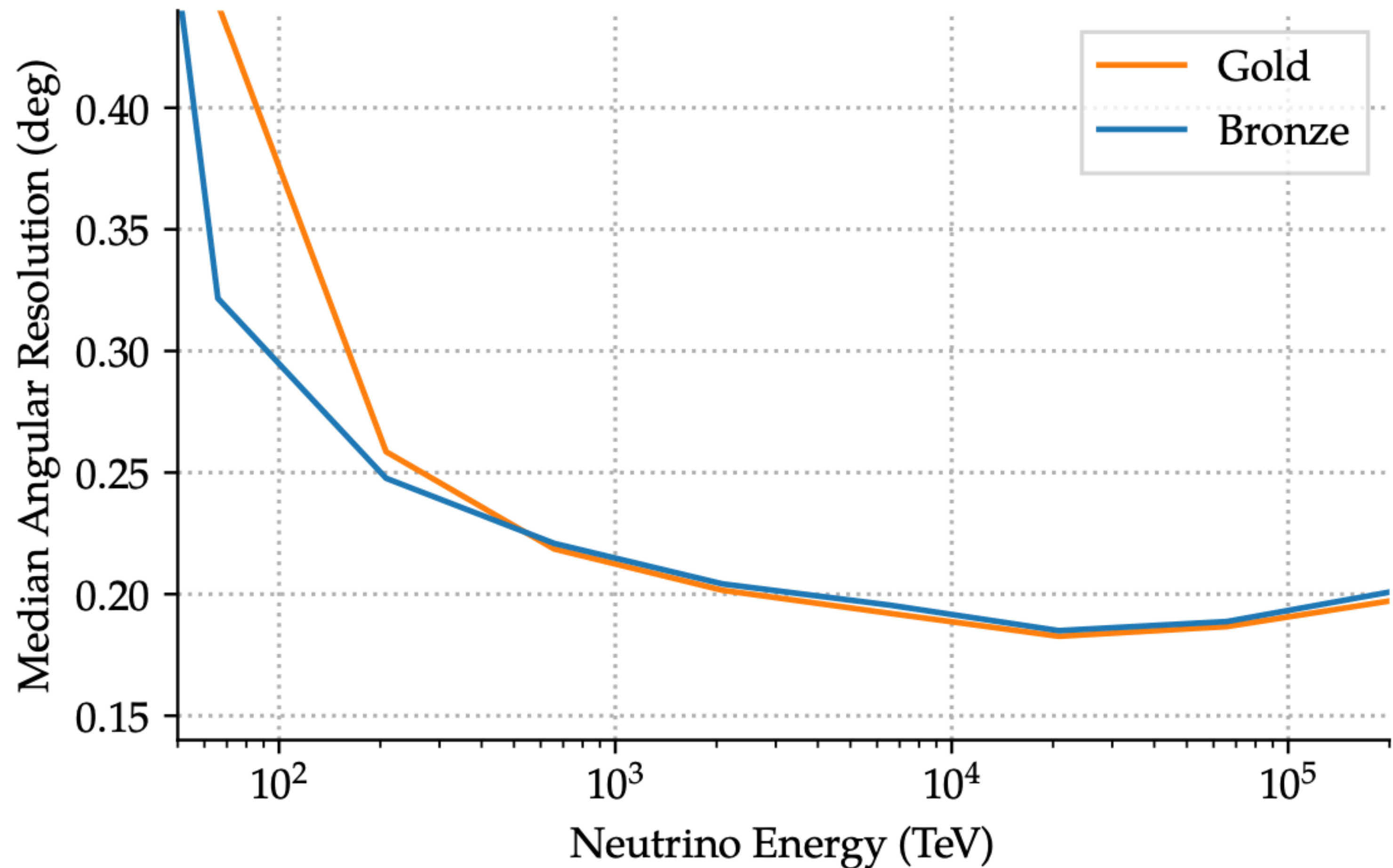
... compared to the previously used algorithm



This refers to the reconstruction algorithms used for the refined track alert reconstruction before September 2024, and therefore also adopted to process IceCat-1

IceCube realtime astrophysical neutrino alert ang. resolution

At alert selection value (based on results from reconstructions sent out via the first GCN notice)



New GCN Notices for Track Alerts via Kafka

```
{
  "$schema": "https://gcn.nasa.gov/schema/v6.1.1/gcn/notices/icecube/single_neutrino_alerts.schema.json",
  "mission": "IceCube",
  "instrument": "IC86",
  "messenger": "Neutrino",
  "pipeline": "Bronze Track Alert",
  "record_number": 1,
  "event_name": [
    "IceCube-260504A"
  ],
  "id": [
    "142545_58544625"
  ],
  "alert_datetime": "2026-05-05T01:46:38.5Z",
  "alert_type": "update",
  "alert_tense": "current",
  "alert_topology": "Track",
  "number_of_events": 1,
  "ra": 246.99,
  "dec": 54.87,
  "ra dec error": 0.67,
  "containment_probability": 0.9,
  "systematic_included": true,
  "healpix_url": "https://roc-2.icecube.wisc.edu/public/alerts/IceCube-260504A_skymap_probdensity_multiorder.fits.gz",
  "trigger_time": "2026-05-04T21:11:20.958Z",
  "nu_energy": 114.78,
  "p_astro": 0.4303,
  "far": 1.5983e-08
}
```

In the GCN Notice, we report circularized uncertainties for Gold and Bronze alerts. Even though we do release now the full probability healpix maps, the GCN still contains a field for a circularized uncertainty (“ra_dec_error”), that is intended to represent the radius of a circle enclosing the 90% probability to contain the true direction

$$r = \sqrt{\Delta RA \cos(\text{Dec}) \Delta \text{Dec}}$$

p_{astro} definition

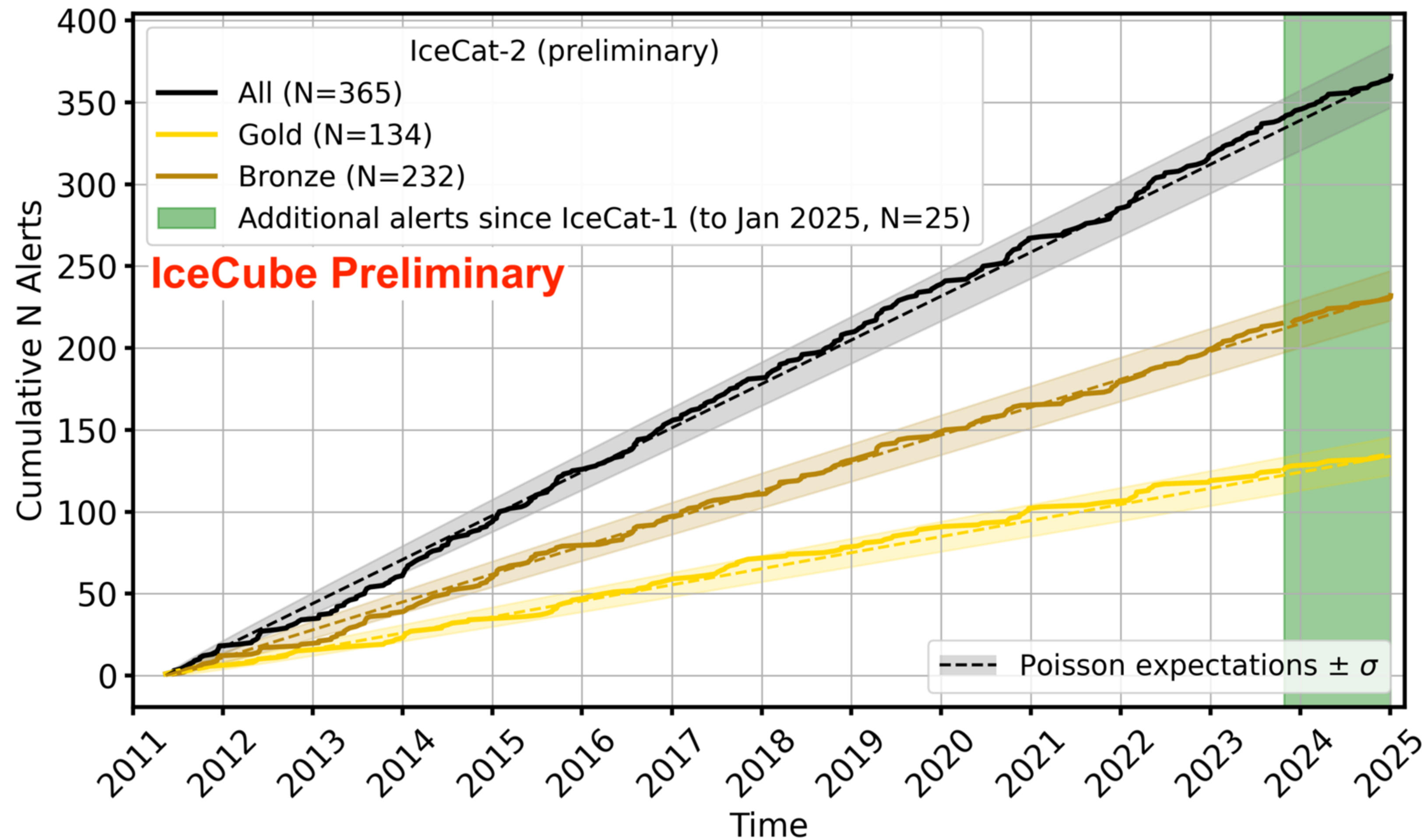
$N_{\text{signal}}, N_{\text{background}} \rightarrow$ expected signal/background events with $E > E_{\text{event}}$ at declination δ , derived from MC simulations under the assumption of a neutrino signal following a simple power-law spectrum with spectral index -2.19

$$p_{\text{astro}}(E > E_{\text{event}}, \delta) = \frac{N_{\text{signal}}(E > E_{\text{event}}, \delta)}{N_{\text{signal}}(E > E_{\text{event}}, \delta) + N_{\text{background}}(E > E_{\text{event}}, \delta)}$$

$E \rightarrow$ most likely neutrino energy (derived from muon energy proxy)

$N_{\text{background}} \rightarrow$ Includes both atmospheric neutrinos and muons

IceCat-2 sample: Cumulative number of alerts

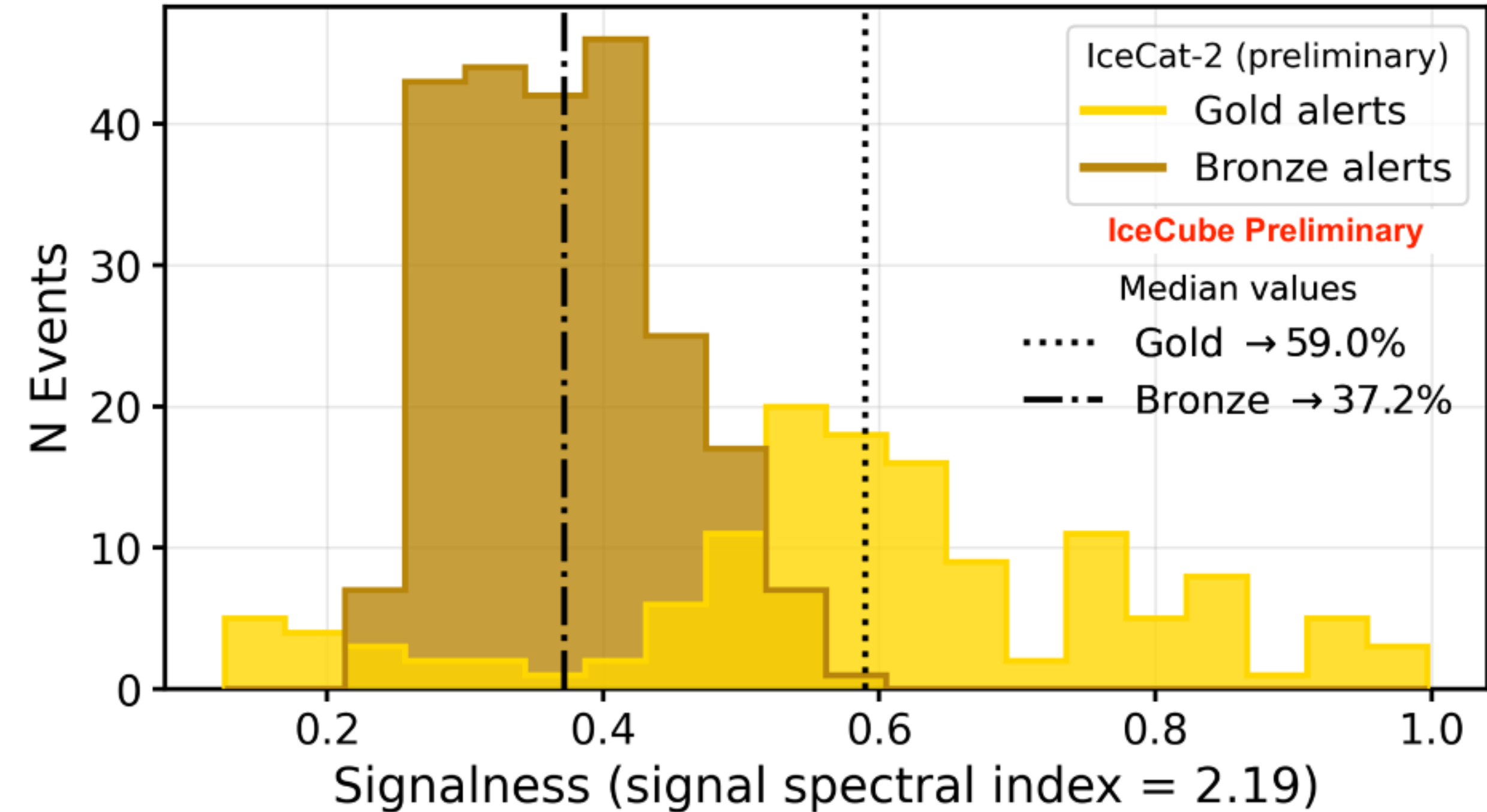
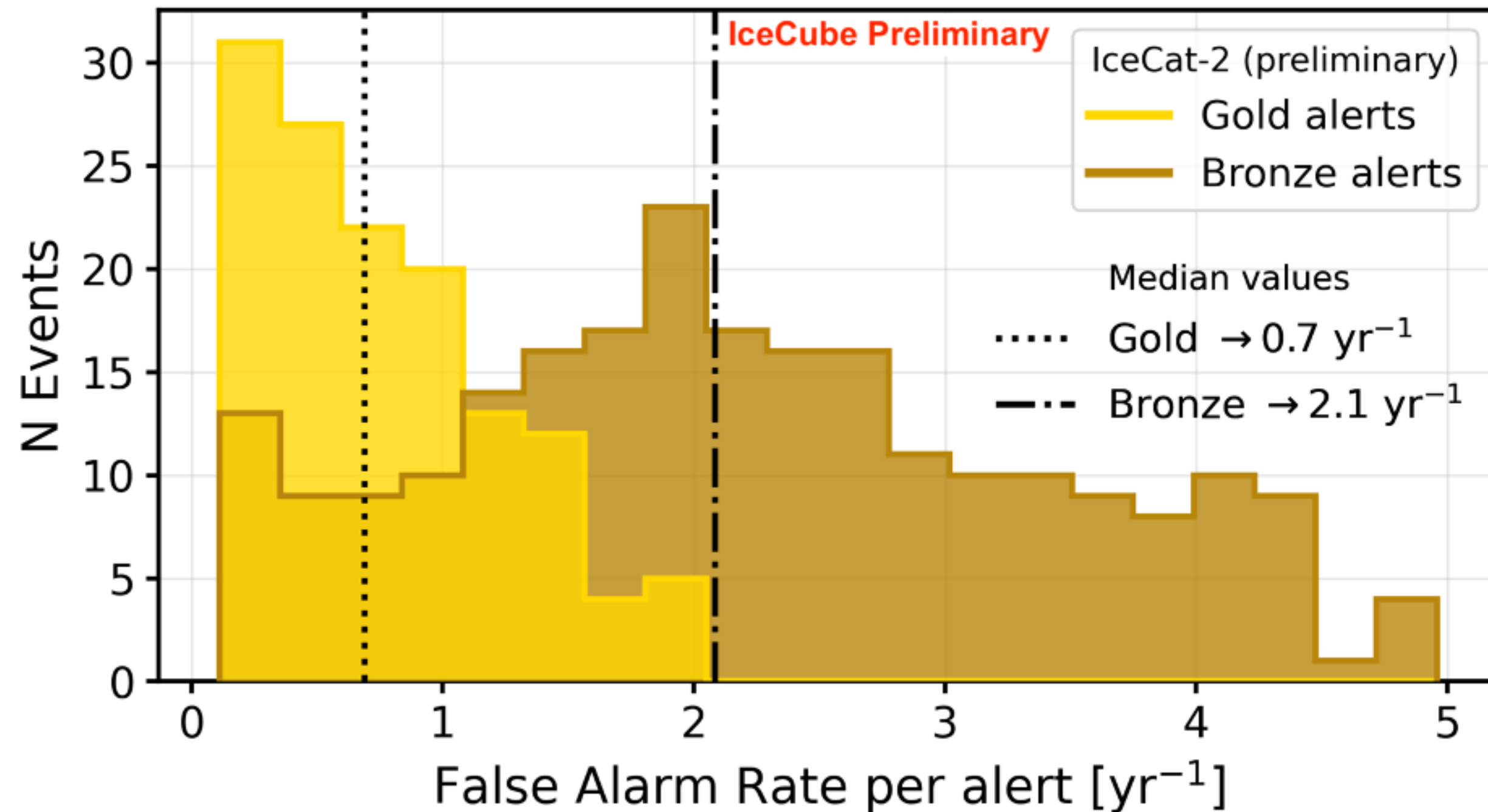


Average rate of 26.8 evt/year

~9.9 evt/yr → Gold

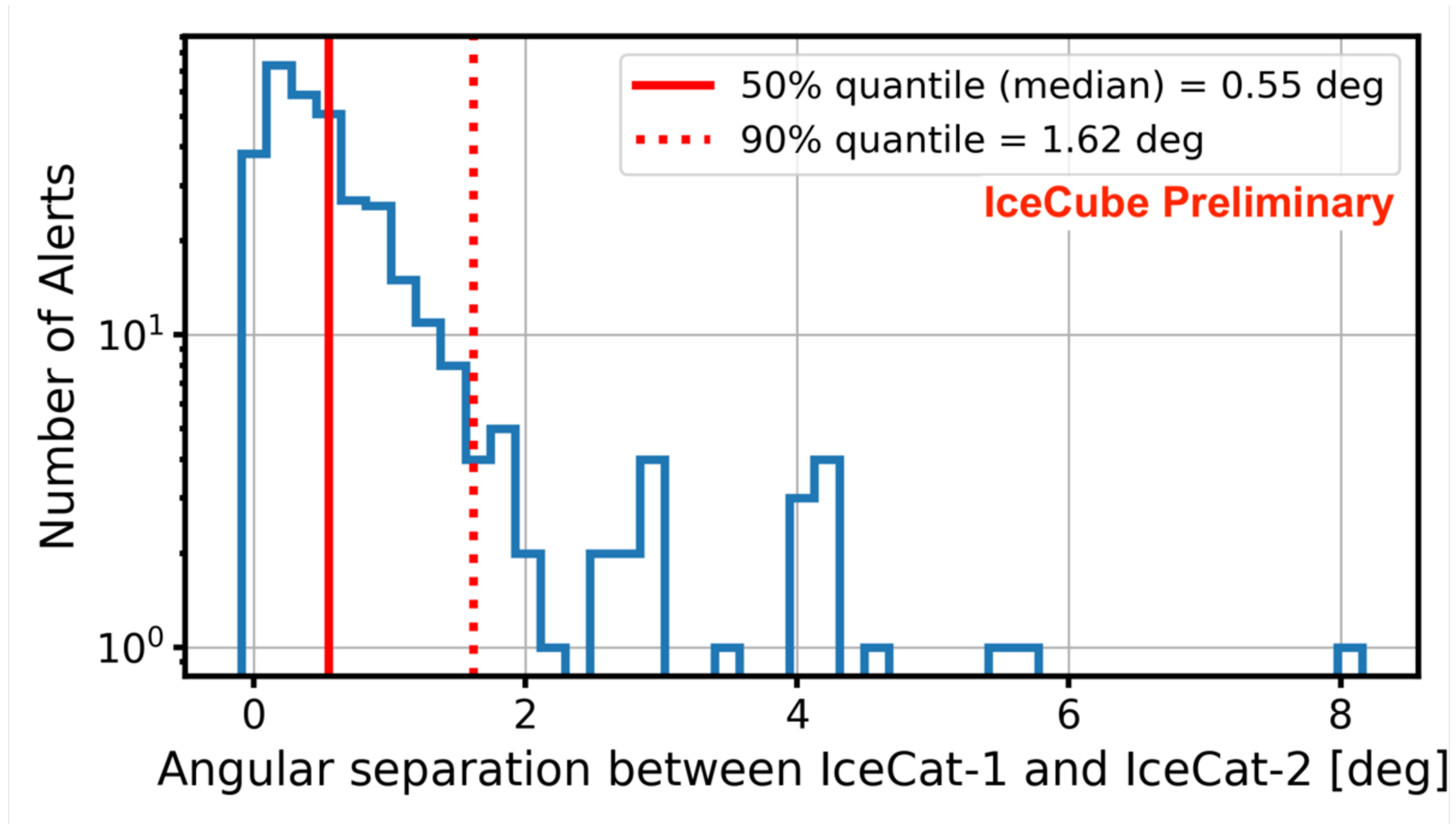
~17 evt/year → Bronze

IceCat-2 sample: False Alarm Rate and Signalness/Pastro



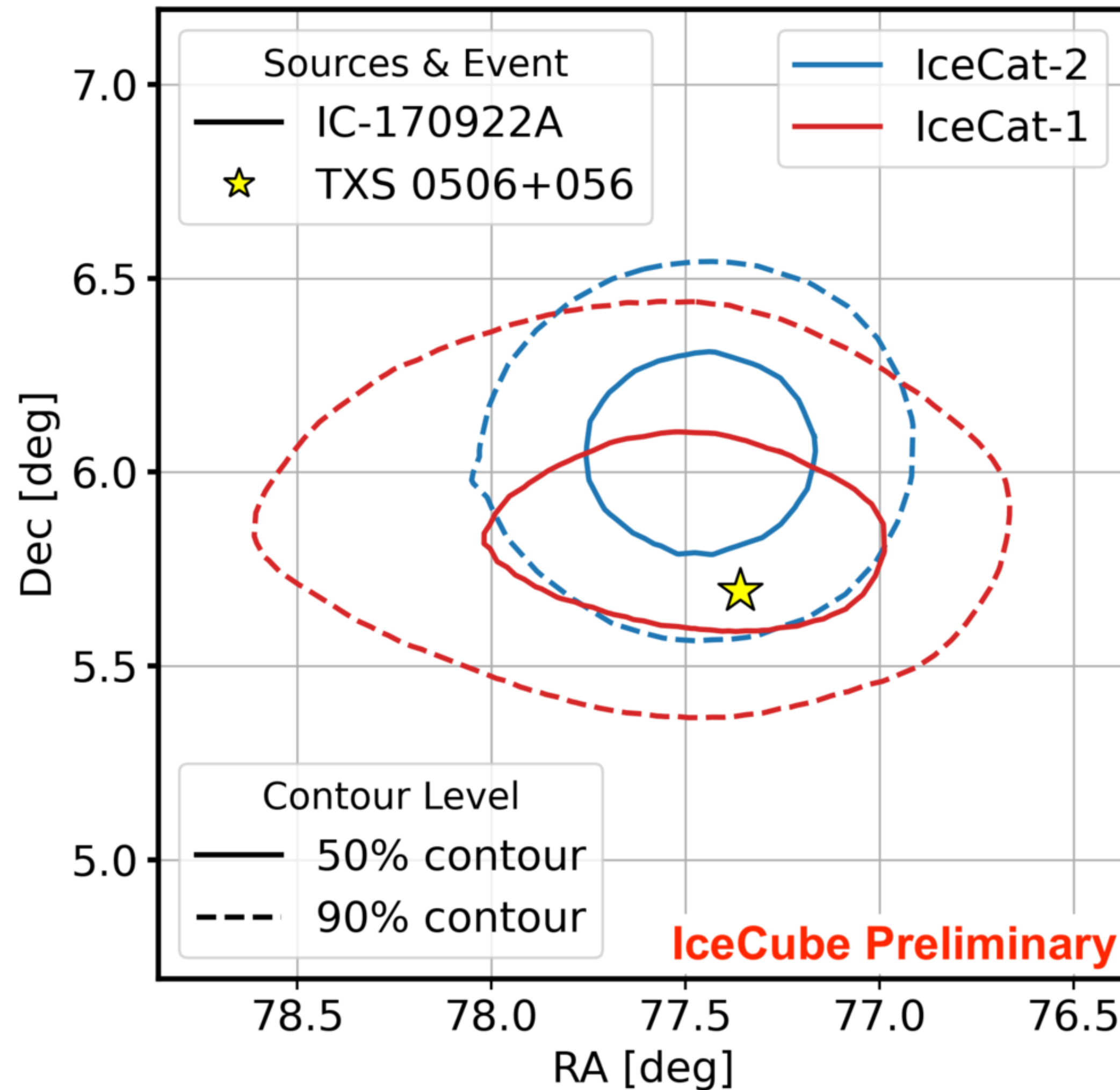
- Gold and Bronze channels correspond to average astrophysical probabilities of 50% and 30%, assuming a power-law spectrum with index 2.19
- This spectral index, adopted in IceCat-1 and currently used in real-time alerts, is based on an earlier IceCube measurement. Future versions of the catalog will incorporate an updated value, reflecting the softer spectrum observed in muon track events by IceCube

Angular distance between IceCat-1 and IceCat-2 events



50(90)% of the alerts with angular separation below 0.55(1.62) deg

Revisiting TXS 0506+056 with IceCat-2



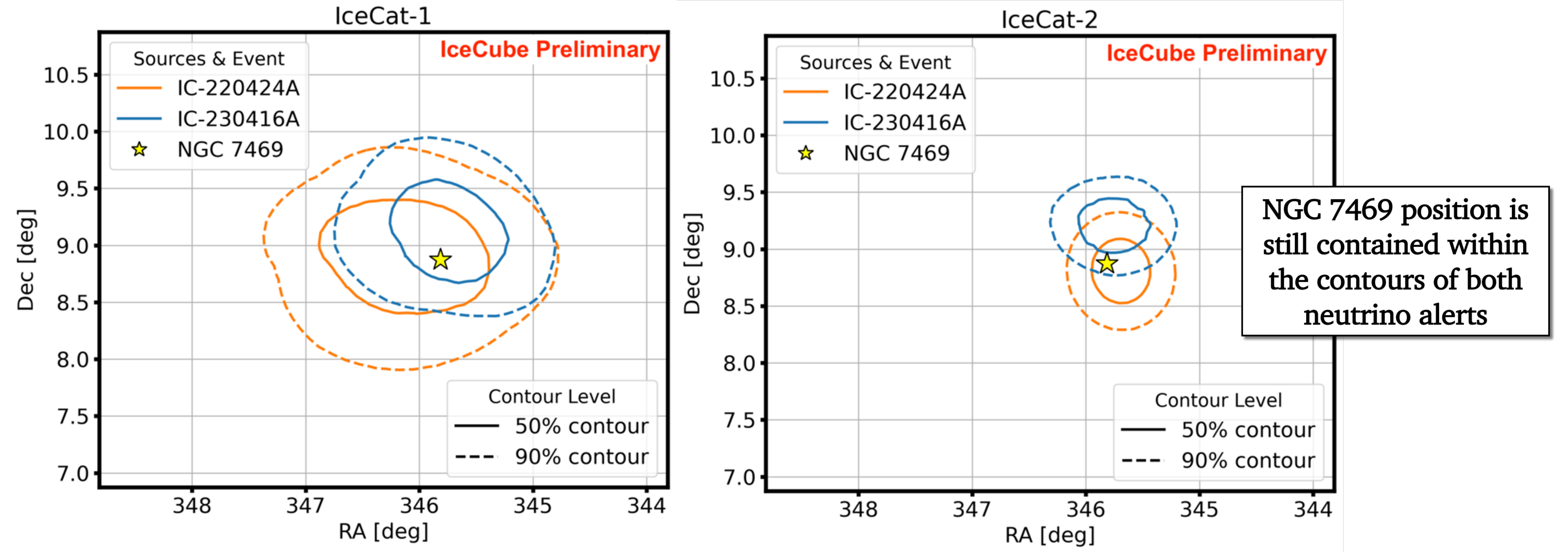
TXS 0506+056 remains spatially coincident with the revised IC-170922A localisation, although it now lies within the 90% containment region rather than the 50% contour



The first transient identified as a potential neutrino source is still a neutrino candidate

NGC 7469

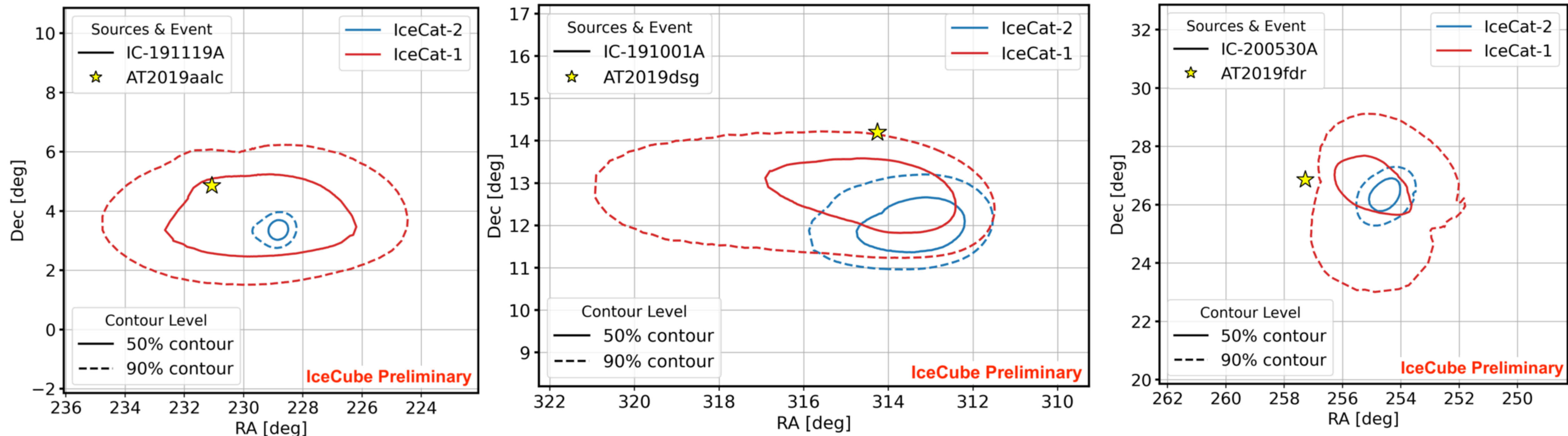
Two coincident $>$ TeV IceCube neutrino alerts coincident with NGC 7469  [Sommani et al., ApJ 981 103 \(2025\)](#)



High-interest Tidal Disruption Events (TDEs)

Three TDE candidates (AT2019dsg, AT2019fdr, AT2019aalc) have been associated with high energy astrophysical neutrinos in multi-messenger follow-ups occurring O(100) days after the maximum of the optical-ultraviolet luminosity

 [Stein et al. 2021](#), [Reusch et al. 2022](#), [van Velzen et al. 2024](#)



TDE positions are well outside the updated containment regions
Associations between these TDEs and the corresponding IceCube alerts are disfavoured

 [IceCube Collaboration, PoS-ICRC2025-1224](#)

IceCat-2: correlation with source candidates

Following the approach previously adopted for IceCat-1:

- We re-evaluated the directional correlation of the updated alert tracks with several gamma-ray catalogs (3FHL, 4FGL-DR4, 3HWC, TeVCat) as well as the Swift-BAT X-ray catalog. For each of the 365 alerts in the preliminary IceCat-2 sample, we searched the aforementioned catalogs for sources located within the 90% uncertainty contour of the alert's updated reconstructed direction.
- To estimate the number of coincidences expected by chance, we randomized the alert directions in right ascension 1000 times and recorded the number of matches for each iteration.

Catalog	Observed Coincidences	Expected Coincidences
4FGL-DR4	93	89
3FHL	29	28
3HWC	2	2
TeVCat	6	5
Swift-BAT	35	32

The number of coincidences is consistent with the median expectation due to chance correlation

IceCube Preliminary



[IceCube Collaboration, PoS-ICRC2025-1224](#)

Multi-order probability maps (MOC/HEALPix)



- **Multi-order map (MOC/HEALPix)** <https://gcn.nasa.gov/docs/sample/healpix>

This format retains the pixels originally scanned by IceCube with their original areas. Areas nearby the best-fit direction were scanned using a finer pixelization while further away a coarser pixelization is used. This ensures efficient storage while preserving the accuracy of the probability distribution.

- **Flat skymap**

All pixels have the same area. Pixels that are larger than the maximum defined resolution are subdivided into smaller pixels until it is reached, so that every pixel has the same area. This provides a uniform representation of the sky, but results in comparatively large file sizes since no hierarchical pixelization is applied. The total information content remains the same as in the multi-order map, but the uniform high resolution makes flat maps less storage-efficient. They remain convenient for quick use and simple plotting.



Multi-order probability maps (MOC/HEALPix)

Old likelihood maps were showing, for the i -th pixel, $-2 \log(\text{LR}_i) = \text{TS}_i$, assuming that the Test Statistics (TS) follows a χ^2 distribution (from Wilk's theorem)

$$\text{Likelihood Ratio (LR)}_i = \frac{\mathcal{L}(\theta_i, \phi_i)}{\mathcal{L}(\theta_{\text{best}}, \phi_{\text{best}})}$$

$(\theta, \phi) \rightarrow$ zenith, azimuth

$\rightarrow$ the probability of TS value can be expressed as $p(\text{TS}) = \frac{1}{2}e^{-\frac{\text{TS}}{2}} \sim \chi^2 \rightarrow$ **Info provided now in the probability maps**

Normalised probability per pixel

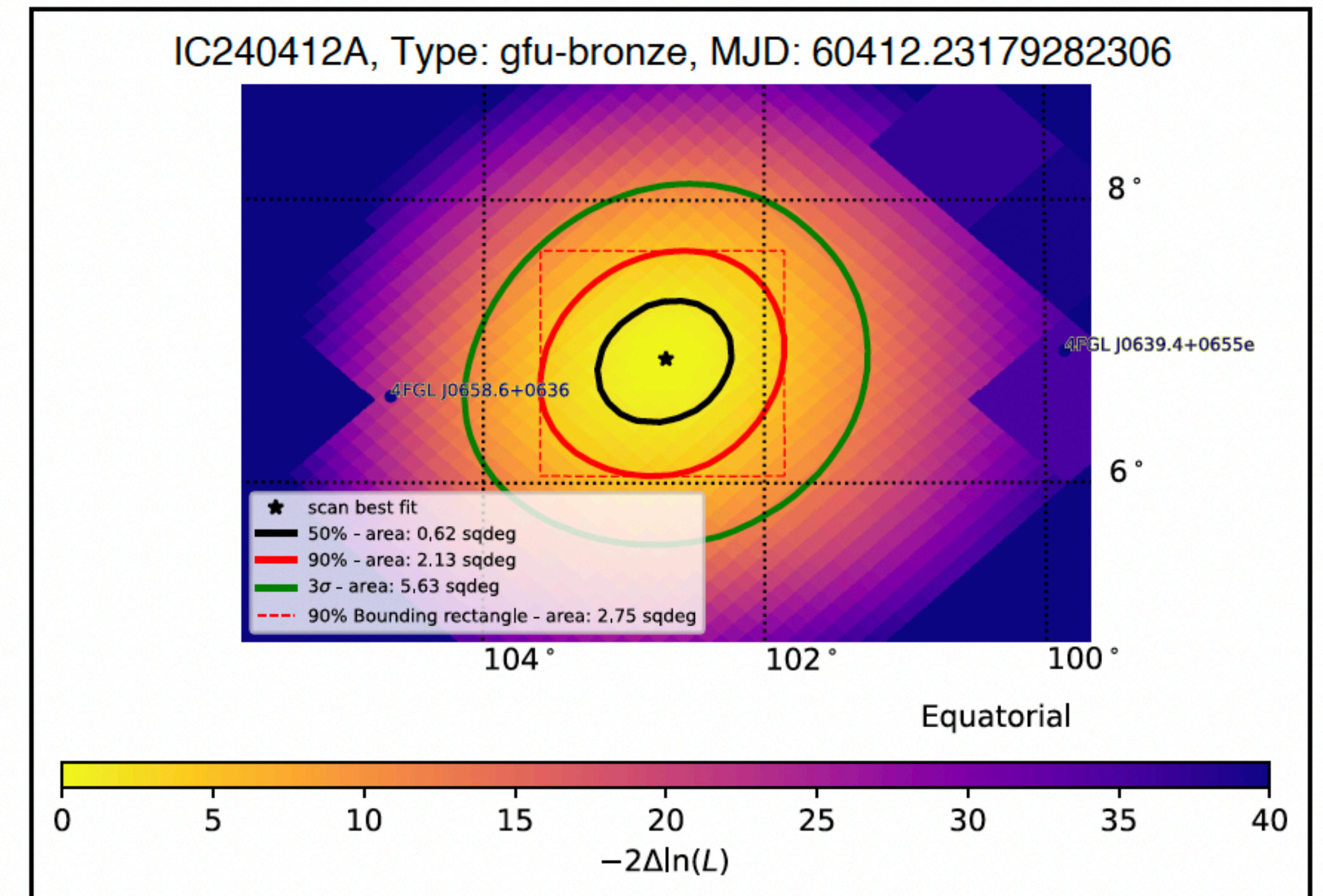
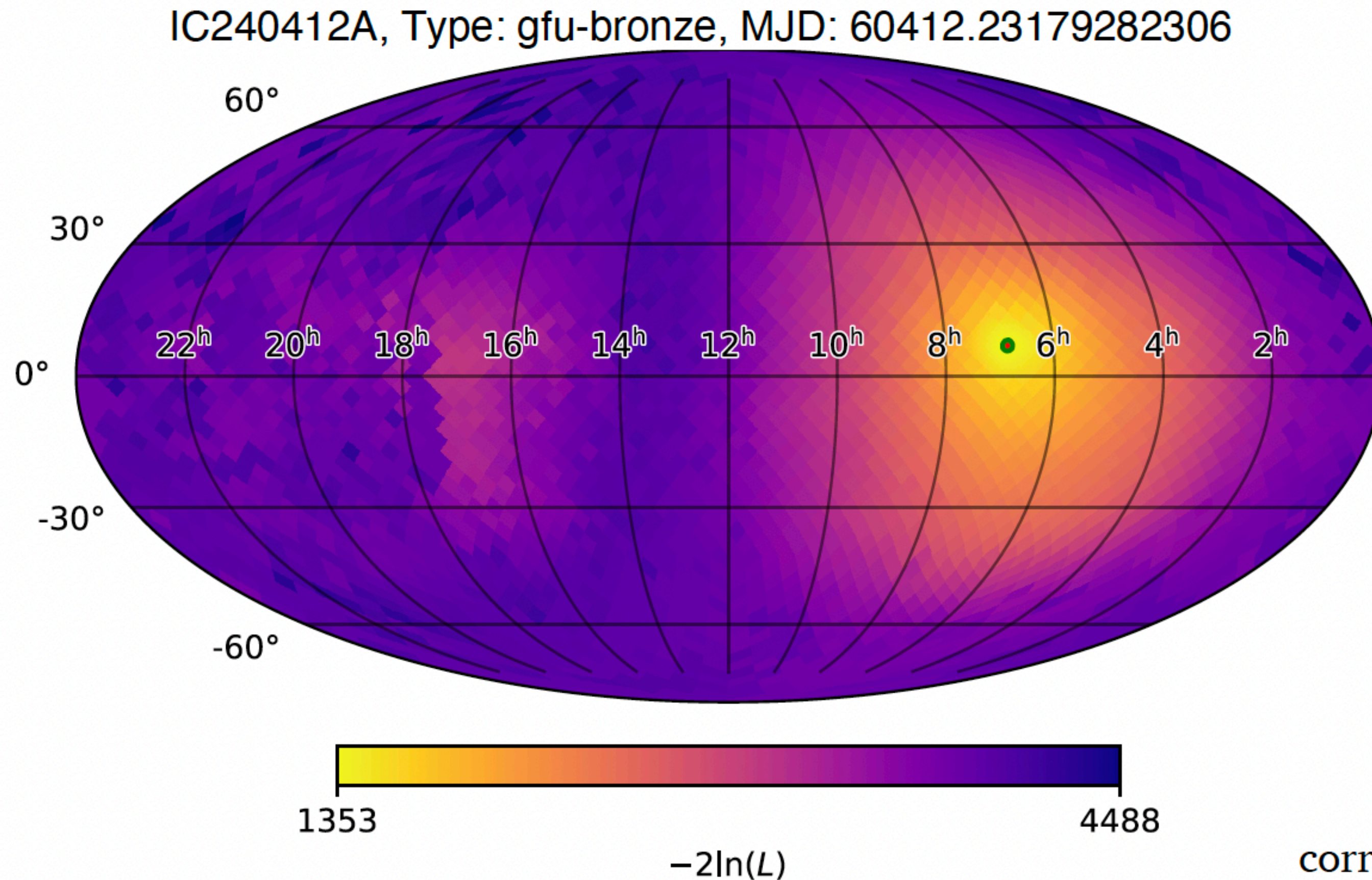
$$p_i = \frac{e^{-\frac{\text{TS}_i}{2}}}{\sum_{j=1}^{N_{\text{pix}}} e^{-\frac{\text{TS}_j}{2}}} \rightarrow$$

Probability Density per pixel [sr^{-1}]

$$\frac{p_i}{A_i} \rightarrow \text{Area for the } i\text{-th pixel}$$

This ensures that the 50% and 90% uncertainty areas are the same as those in likelihood maps

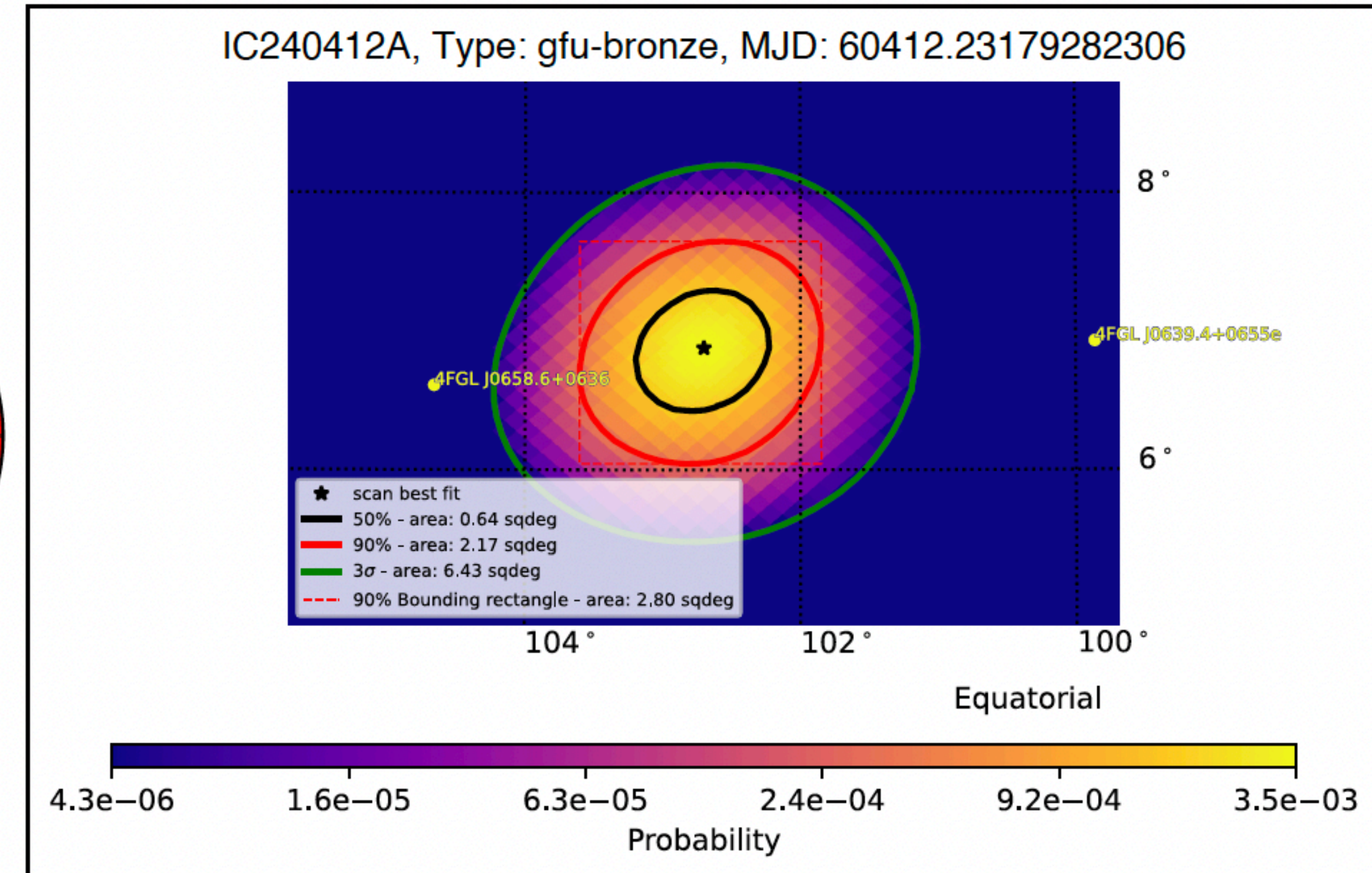
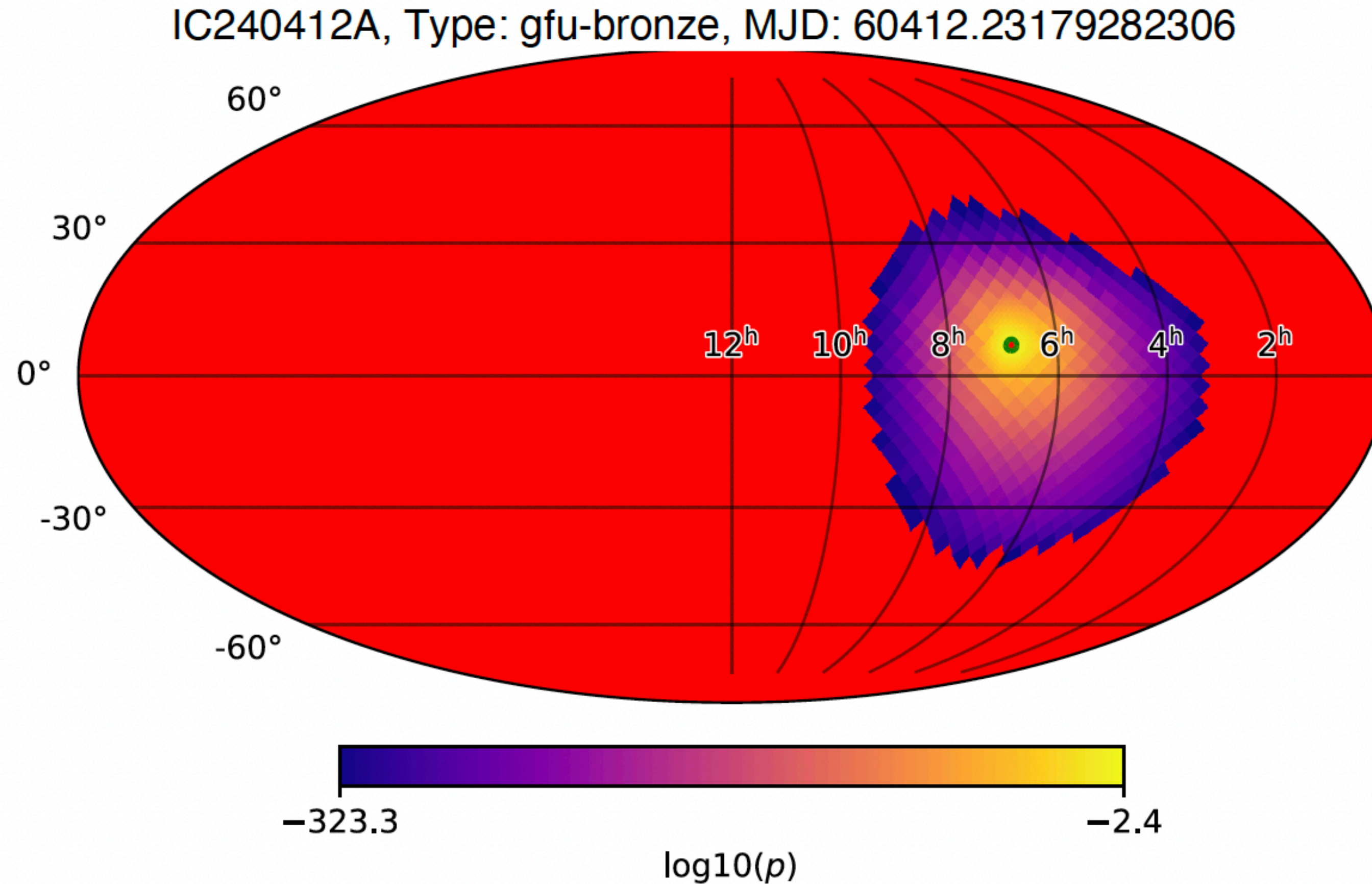
Likelihood map - Example



Confidence contours defined by $TS < TS_{\chi^2}(CL, \nu = 2)$
corresponding to the $\chi^2_{\nu=2}$ quantile at the chosen confidence level
(50% and 90%), with $\nu = 2$ degrees of freedom

Probability - Example

Example of a skymap from multi-order map



Confidence contours defined by summing the probability of each pixel around the best fit (max probability) until 50% and 90%

GFU cluster search: current algorithm



Incoming events trigger the analysis pipeline

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

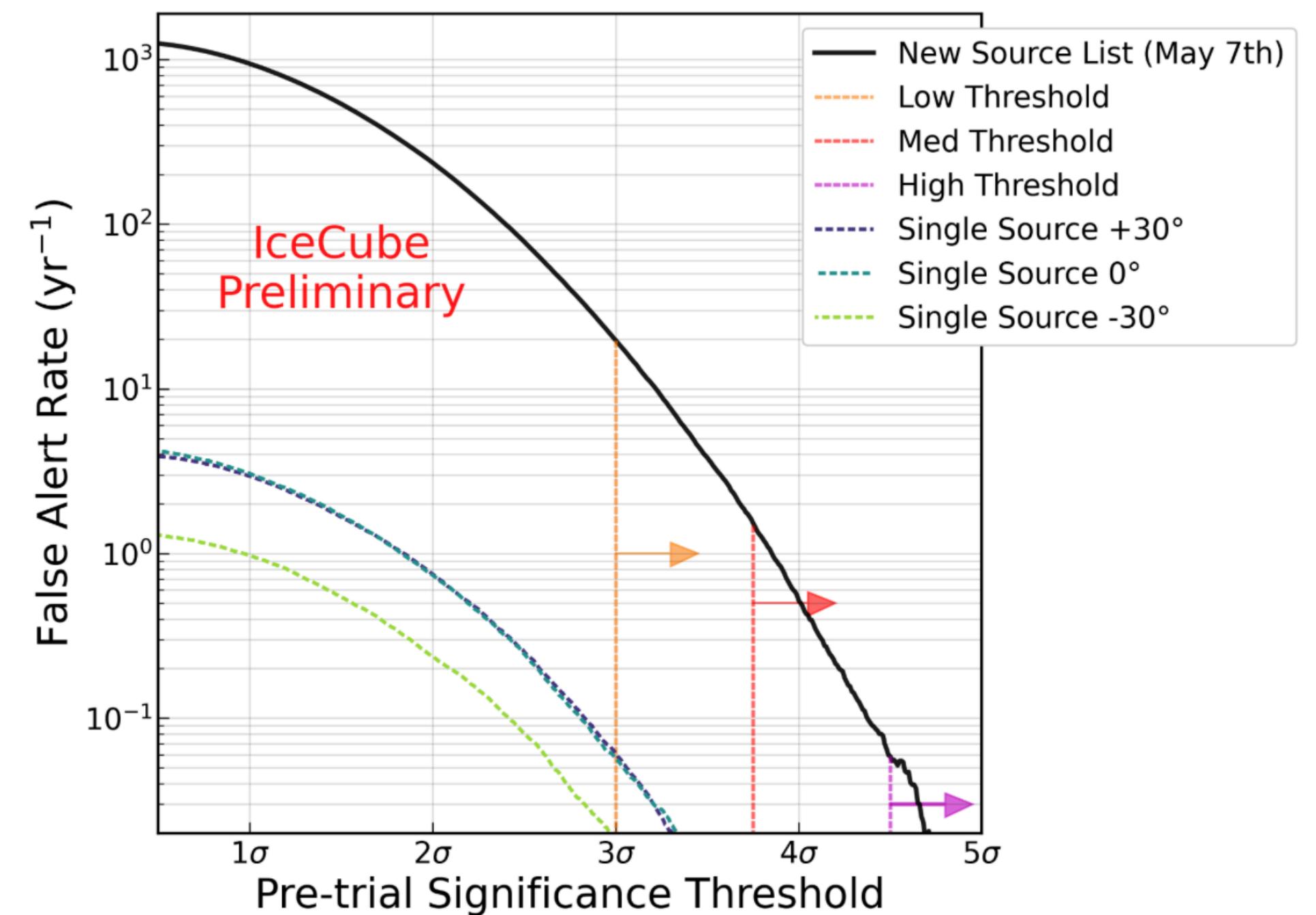
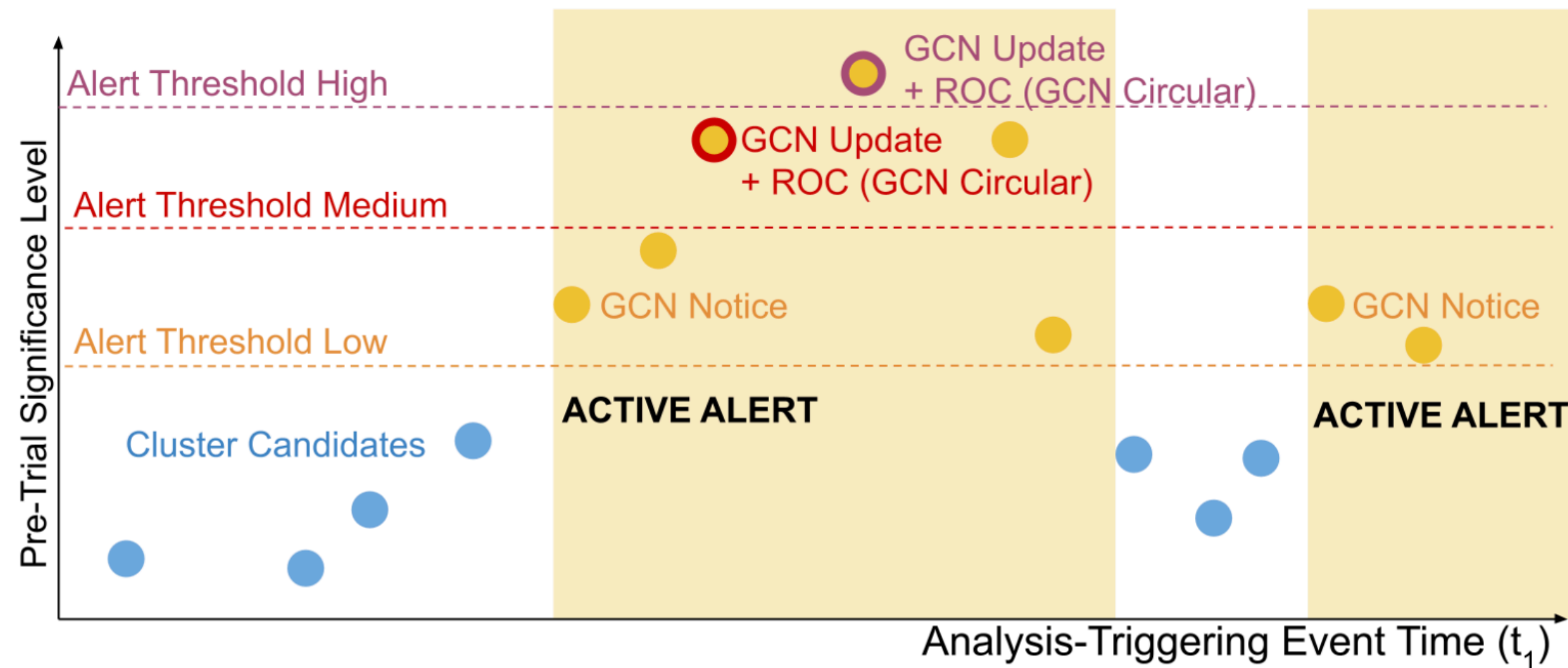
Alert sent if passes a pre-trial significance threshold

Current: Alerts sent under MoU to partner telescopes

Slide's credit: Sarah Mancina, for the IceCube Collaboration

GFU cluster search: proposed public alerts distribution

WORK IN PROGRESS



NASA GCN: Multi-threshold system to provide updates on interesting activity

FlareWatch Website: Provide updates on sources without notifications

False alarm rate calculated by running simulations of 1 year of scrambled data

Proposed thresholds:

- $\sigma_{\text{pre}} = 3.00\sigma$, ~20 bkg alerts per year
- $\sigma_{\text{pre}} = 3.75\sigma$, ~1 bkg alert per year
- $\sigma_{\text{pre}} = 4.50\sigma$, ~0.05 bkg alerts per year

Slide's credit: Sarah Mancina, for the IceCube Collaboration

Neutrino FlareWatch website

WORK IN
PROGRESS



REALTIME GFU ALERTS

☆ Alerts ▾

📘 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](#).

Search:

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)

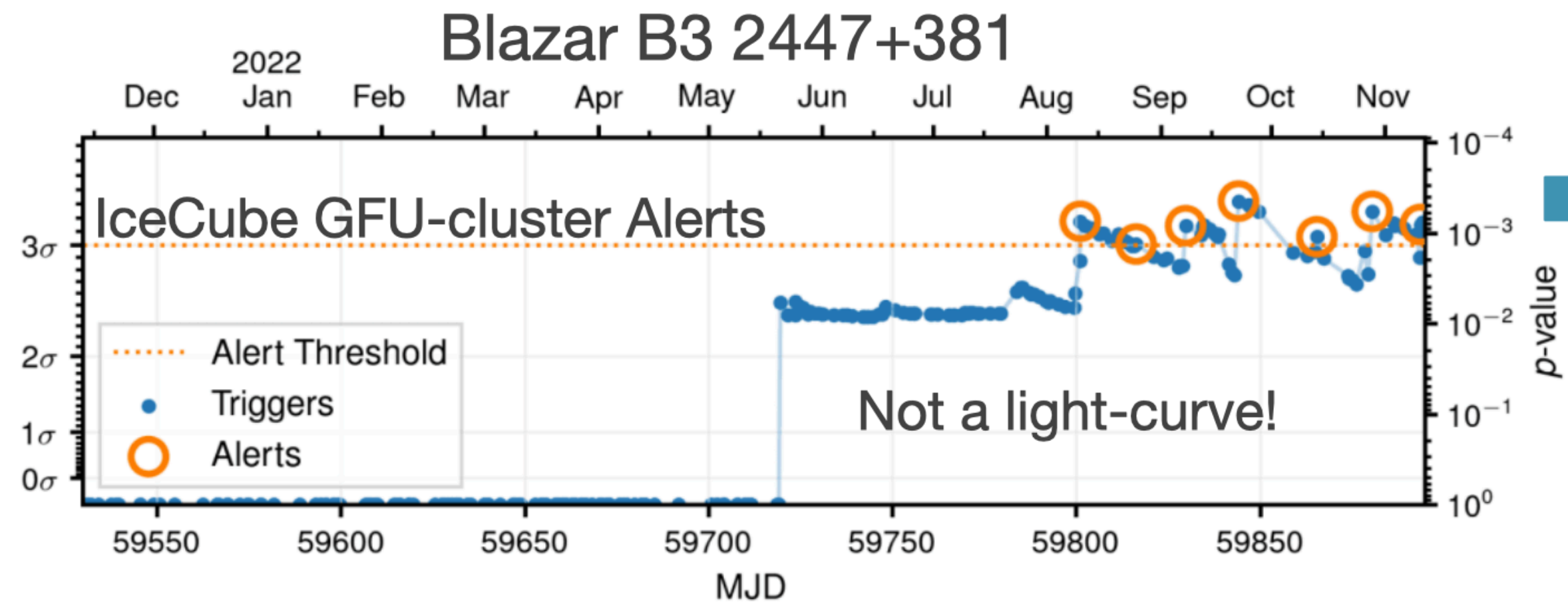
★★ Medium Threshold (1 bkg per year)

★★★ High Threshold (0.05 bkg per year)

Slide's credit: Sarah Mancina, for the IceCube Collaboration

Angela Zegarelli, IceCube Realtime Program: Connecting high-energy neutrinos to the multi-messenger sky, TeVPA2026, Tendō (Japan), 02/09/2026

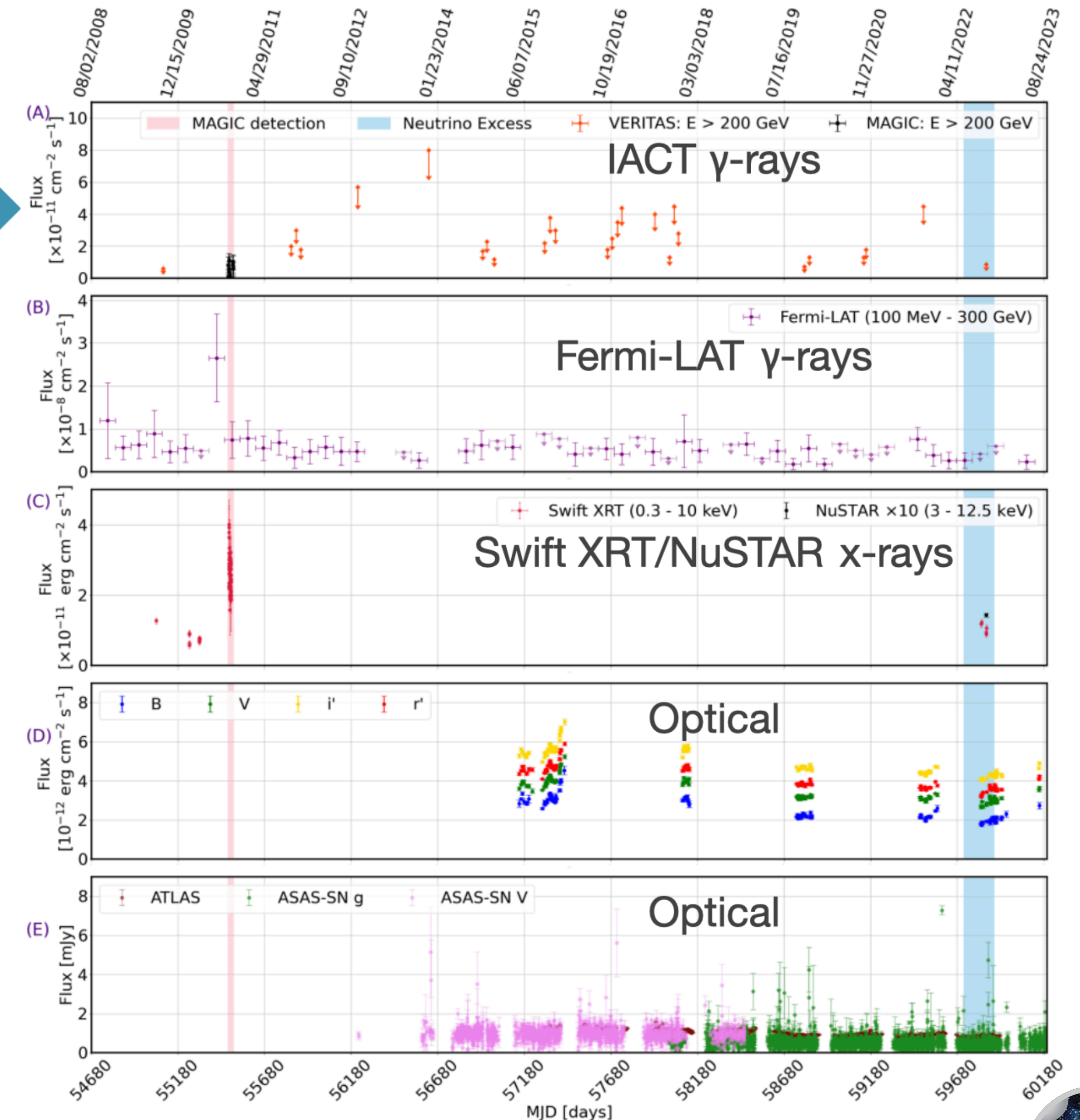
Example of a IACT follow-up: VERITAS and B3 2447+381



IACT can request a more complete report for GFU-cluster alerts

IACT analysers look at multiwavelength (MW) data for more evidence of transient activity

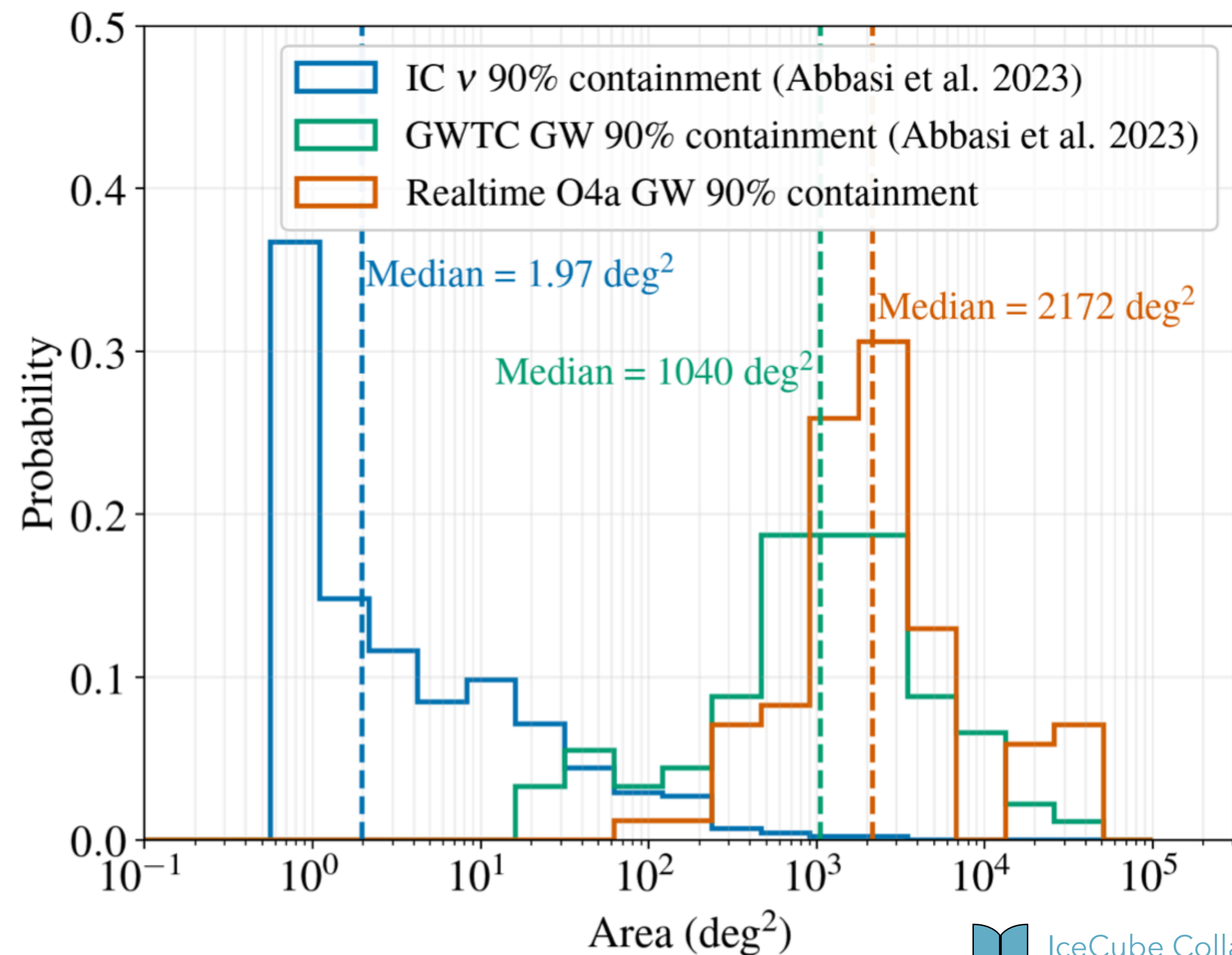
VERITAS sends ToO to NuSTAR (hard X-ray) for further follow-up



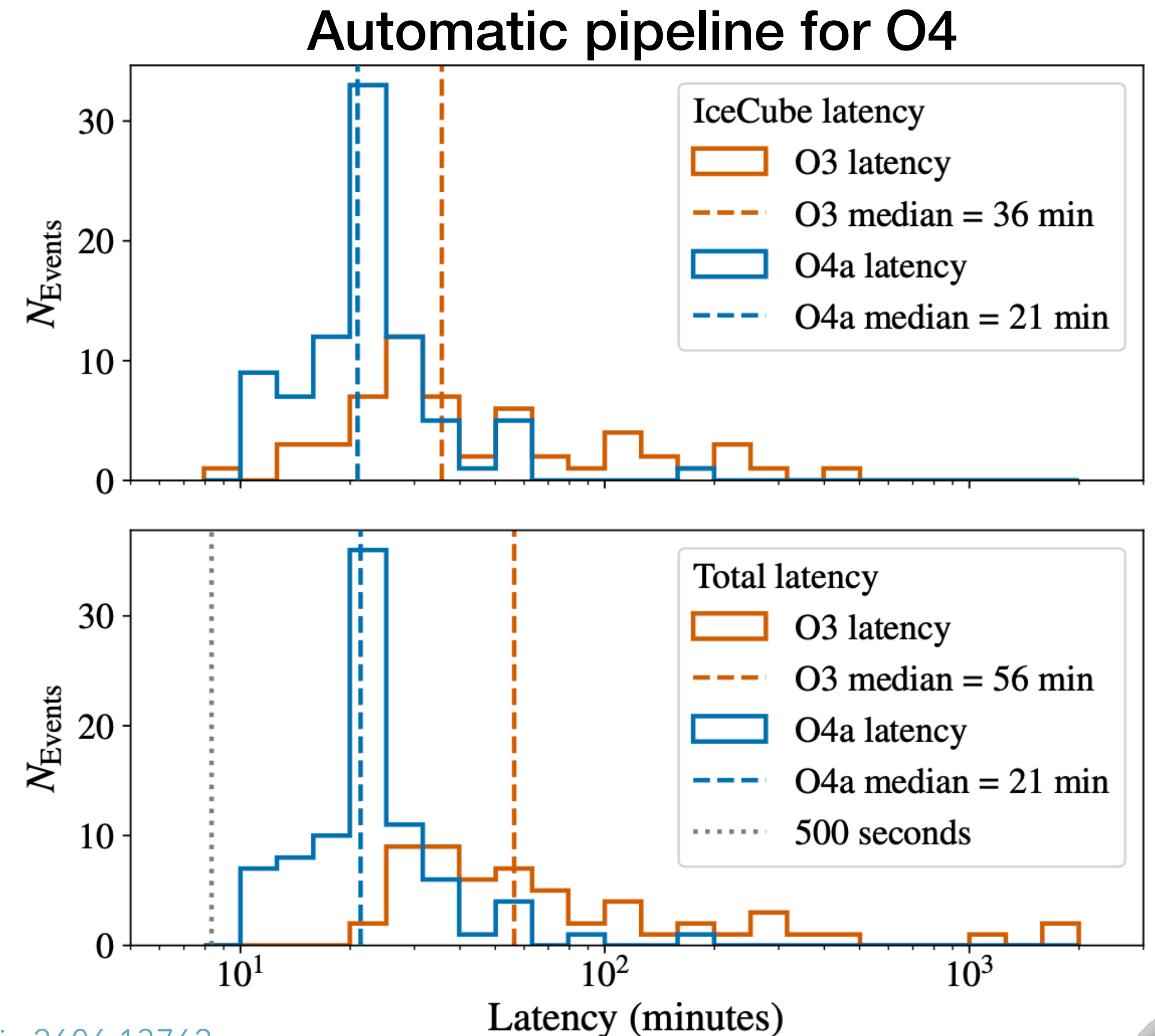
Gravitational Waves - Neutrinos searches in O4

Neutrino search coincidence with 85 significant and 945 low-significance GW candidates

Time window = ± 500 seconds around the GW event



 [IceCube Collaboration, arXiv:2606.13762](https://arxiv.org/abs/2606.13762)



Gravitational Waves - Neutrinos searches in O4

In addition to the ± 500 second analyses, events which have high probability of at least one neutron star progenitor are analyzed with the extended time window of $[-0.1, +14]$ days. An event must pass at least one of three criteria:

- 1. $p_{\text{BNS}} + p_{\text{NSBH}} > 0.5$
- 2. Probability to have a NS in the binary system > 0.5
- 3. Probability that a nonzero mass was ejected during the merger of the two objects > 0.5

Event	Pre-trial <i>p</i> -value	$E^2 F$ 90% UL (GeV cm ⁻²)	IceCube GCN Circular
S230518h	0.754	1.04	33907
S230529ay	0.394	0.94	33980
S230619bd/GBM-230619	0.343	0.10	34142