Look at our work here!

IceCat-2
Updated IceCube Event Catalog of Alert Tracks

G. Sommani,

A. Franckowiak, N. Valtonen-Mattila, T. Yuan, A. Zegarelli,

On behalf of the IceCube Collaboration

NSF

IceCube Neutrino Observatory

RUB RESEARCH SCHOOL

SFB1491 RUHR UNIVERSITÄT BOCHUM

RUB AIRUB Astronomisches Institut RUHR-UNIVERSITÄT BOCHUM

IceCube Neutrino Observatory
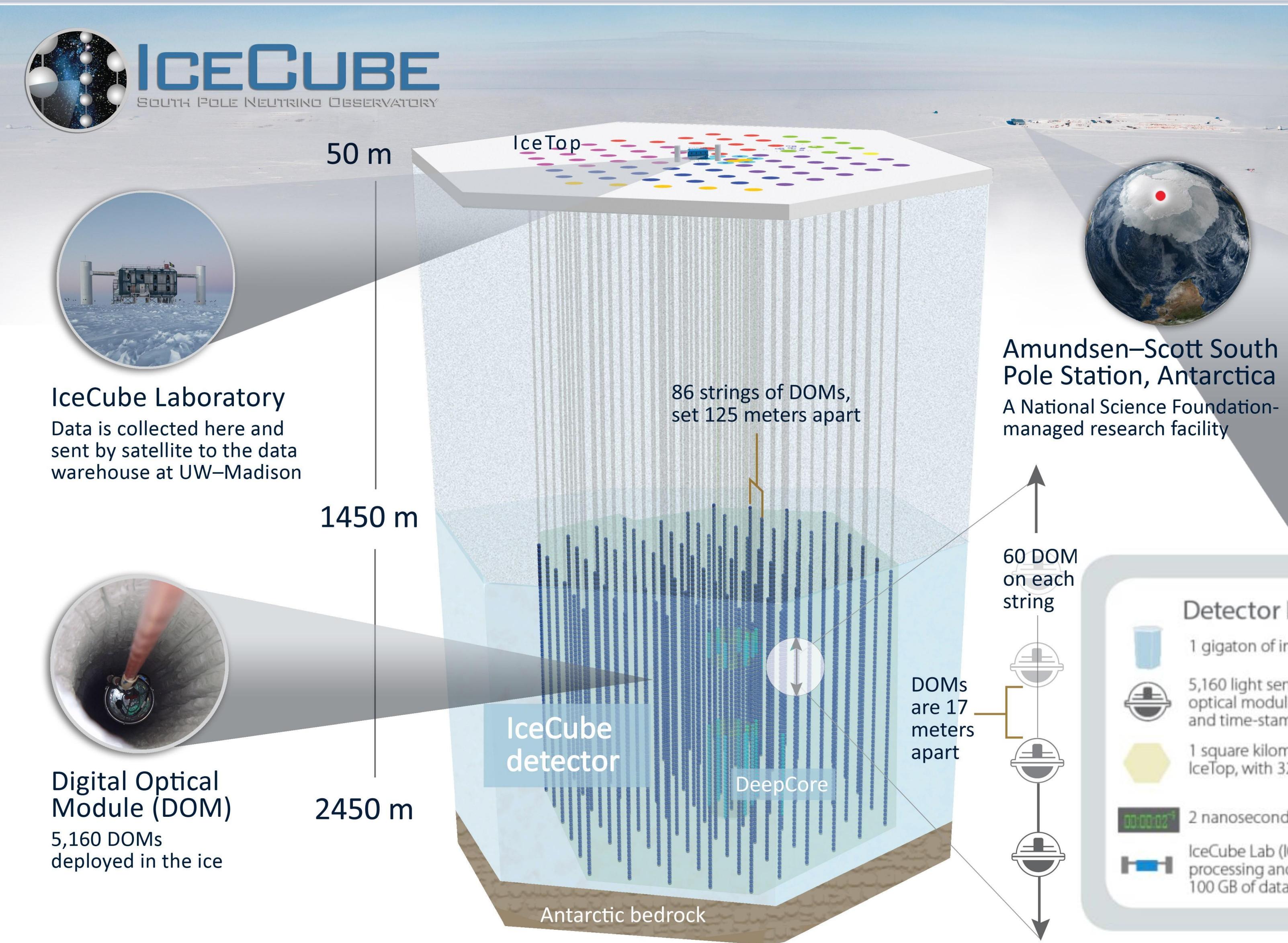
- Giga-ton optical Cherenkov telescope at the South Pole

- 86 strings, with 60 Digital Optical Modules (DOMs) attached to each string

- 1km^3 of clear glacial ice

- 81 IceTop stations for cosmic ray shower detections

Taking data with its full configuration since 2011

IceCube Realtime Program: Track Alerts

ICECUBE
COMPLETED
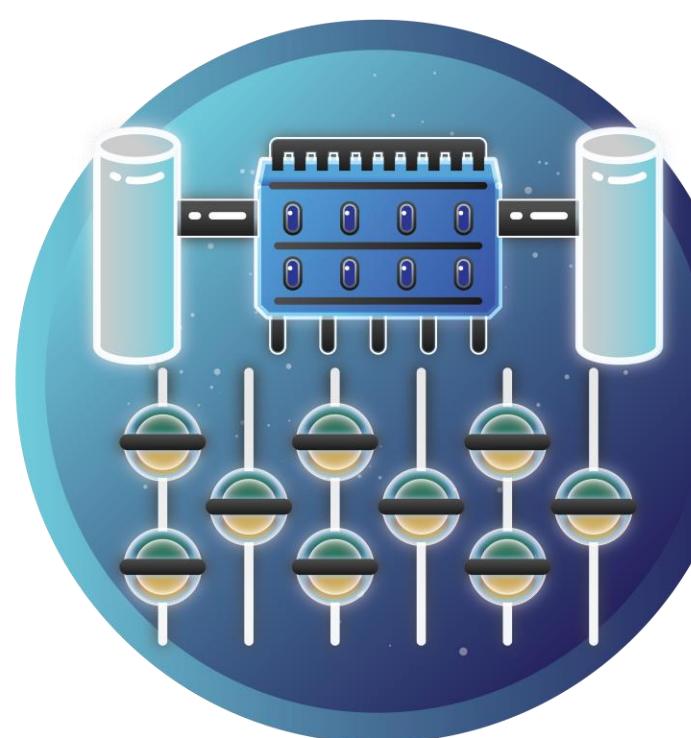
2011

IceCube Realtime Program: Track Alerts

p
cosmic rays

ν
neutrinos

MULTIMESSENGER ASTRONOMY

GW
gravitational waves

γ
gamma rays

ICECUBE
COMPLETED

2011

LAUNCH OF THE
ICECUBE REALTIME PROGRAM

2016

Public Neutrino Alerts
issued within one minute

IceCube Collaboration, Astropart. Phys., 92, 30 (2017)

IceCube Realtime Program: Track Alerts

MULTIMESSENGER ASTRONOMY

p — cosmic rays

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IceCube Collaboration, Astropart. Phys., 92, 30 (2017)
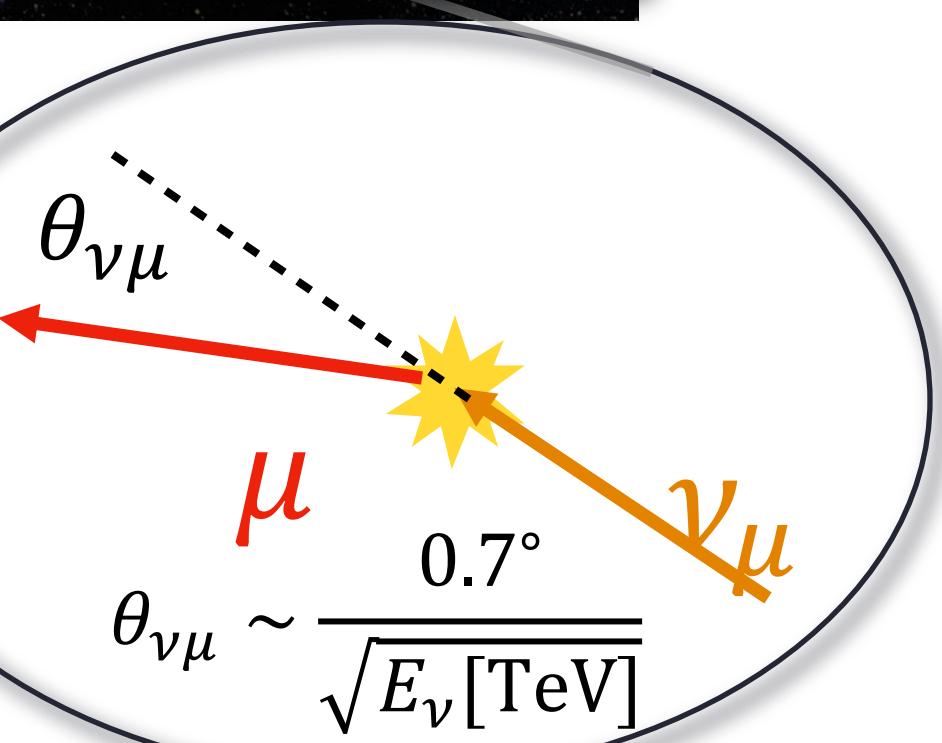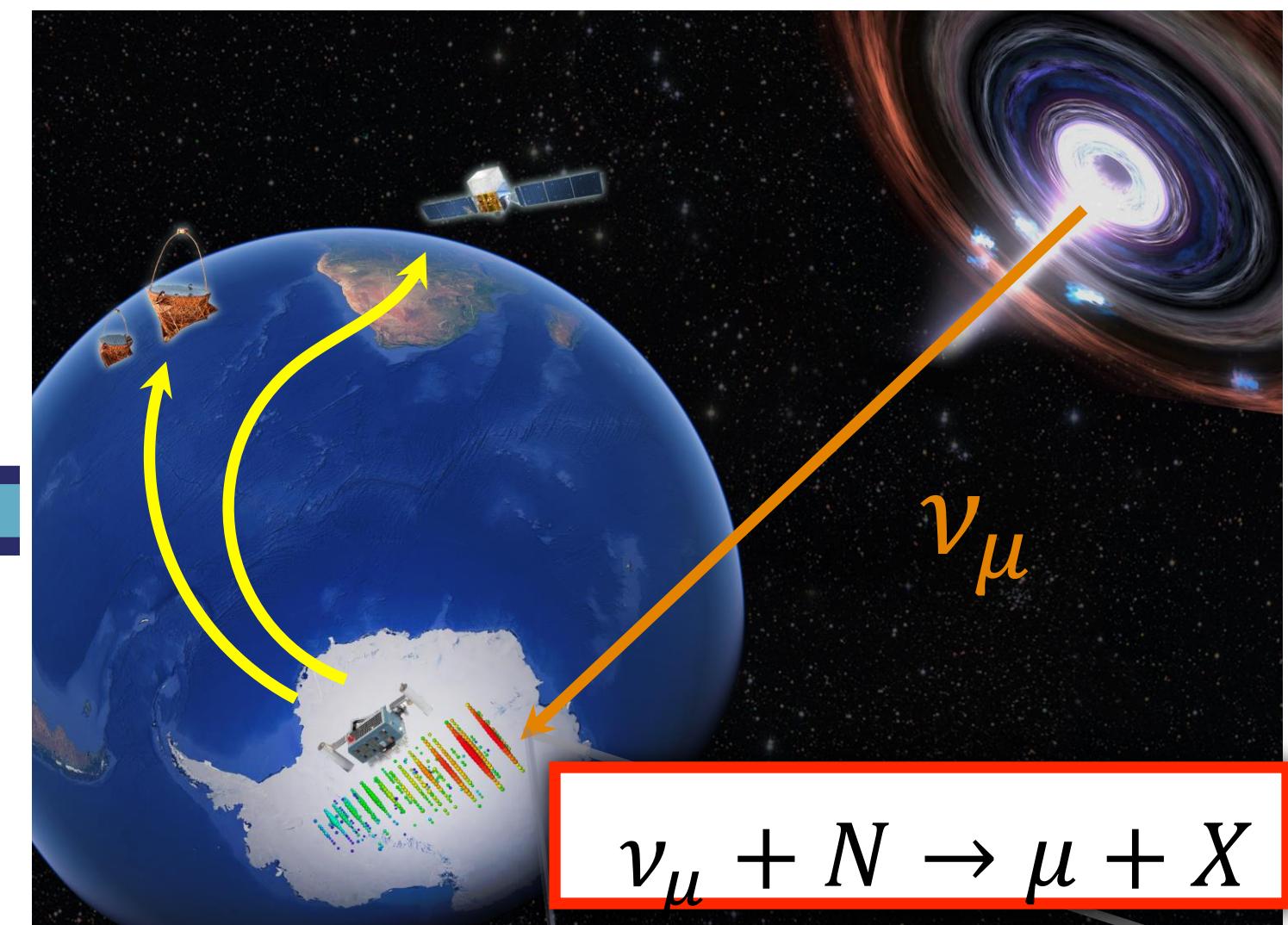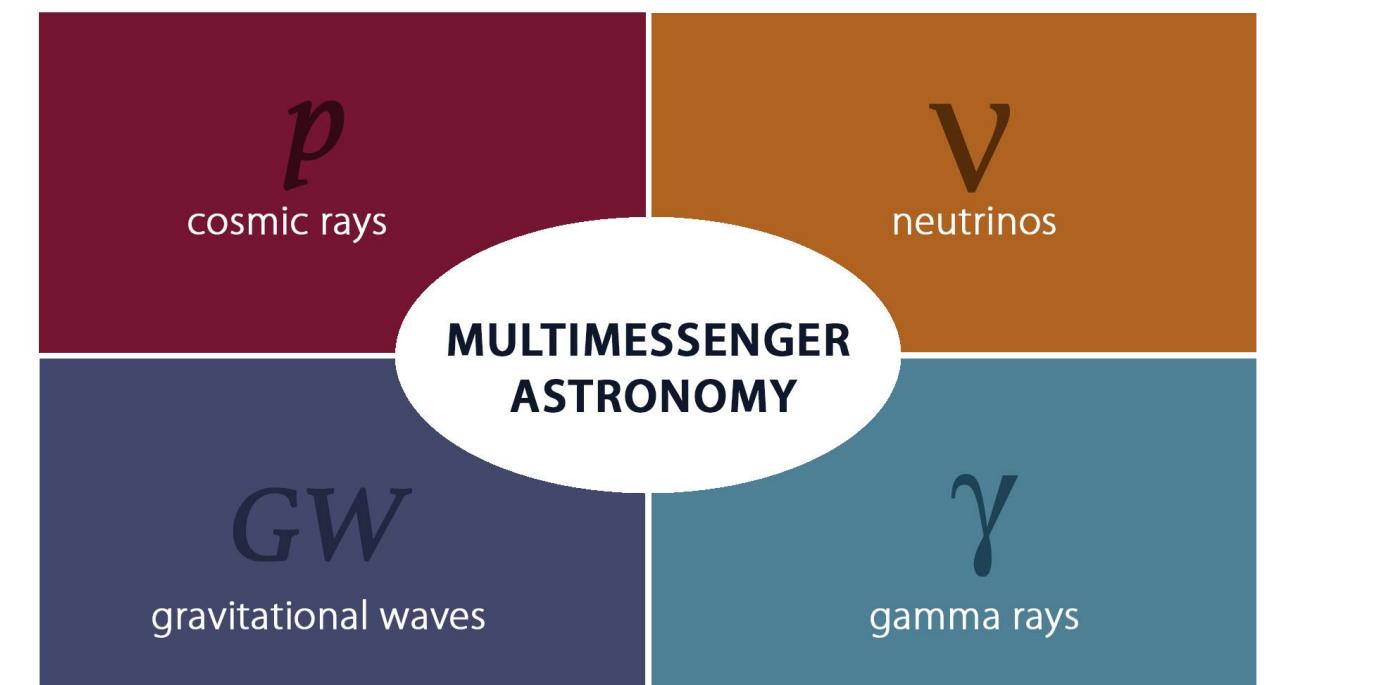
Alerts focus on identifying **tracks** from **charged current interactions of** ν_μ originating from **astrophysical cosmic-ray accelerators**

$\downarrow$

Long muon paths inside the detector

$\rightarrow$ best-potential source localisation
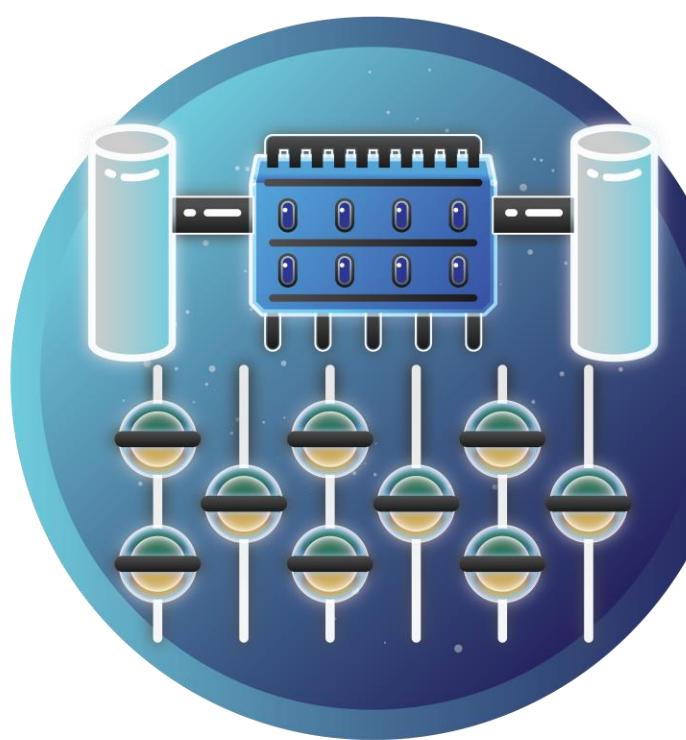
ν_μ

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

$\theta_{\nu\mu}$

μ

ν_μ

$$\theta_{\nu\mu} \sim \frac{0.7°}{\sqrt{E_\nu\,[\mathrm{TeV}]}}$$

IceCube Realtime Program: Track Alerts

A milestone in multimessenger astrophysics

ICECUBE COMPLETED

2011

LAUNCH OF THE ICECUBE REALTIME PROGRAM

2016

BLAZAR TXS 0506+056 NEUTRINO EMISSION IDENTIFIED

2017

IceCube Collaboration, Science 361, 146-151 (2018)

- First *transient* source of high-energy neutrinos identified
- Success of the IceCube realtime system
  → **TXS 0506+056** & IceCube Track Alert **IC-170922A**

IceCube Realtime Program: Track Alerts

Two categories of track alerts:
**Gold** → average ~50%
Bronze → average ~30%
Of being of astrophysical origin

Still active now ...

ICECUBE COMPLETED
2011

LAUNCH OF THE ICECUBE REALTIME PROGRAM
2016

BLAZAR TXS 0506+056 NEUTRINO EMISSION IDENTIFIED
2017

UPGRADE OF THE ICECUBE REALTIME PROGRAM
2019

Expanded and improved alert selection

Blaufuss et al., PoS(ICRC2019) 1177

Track alerts workflow
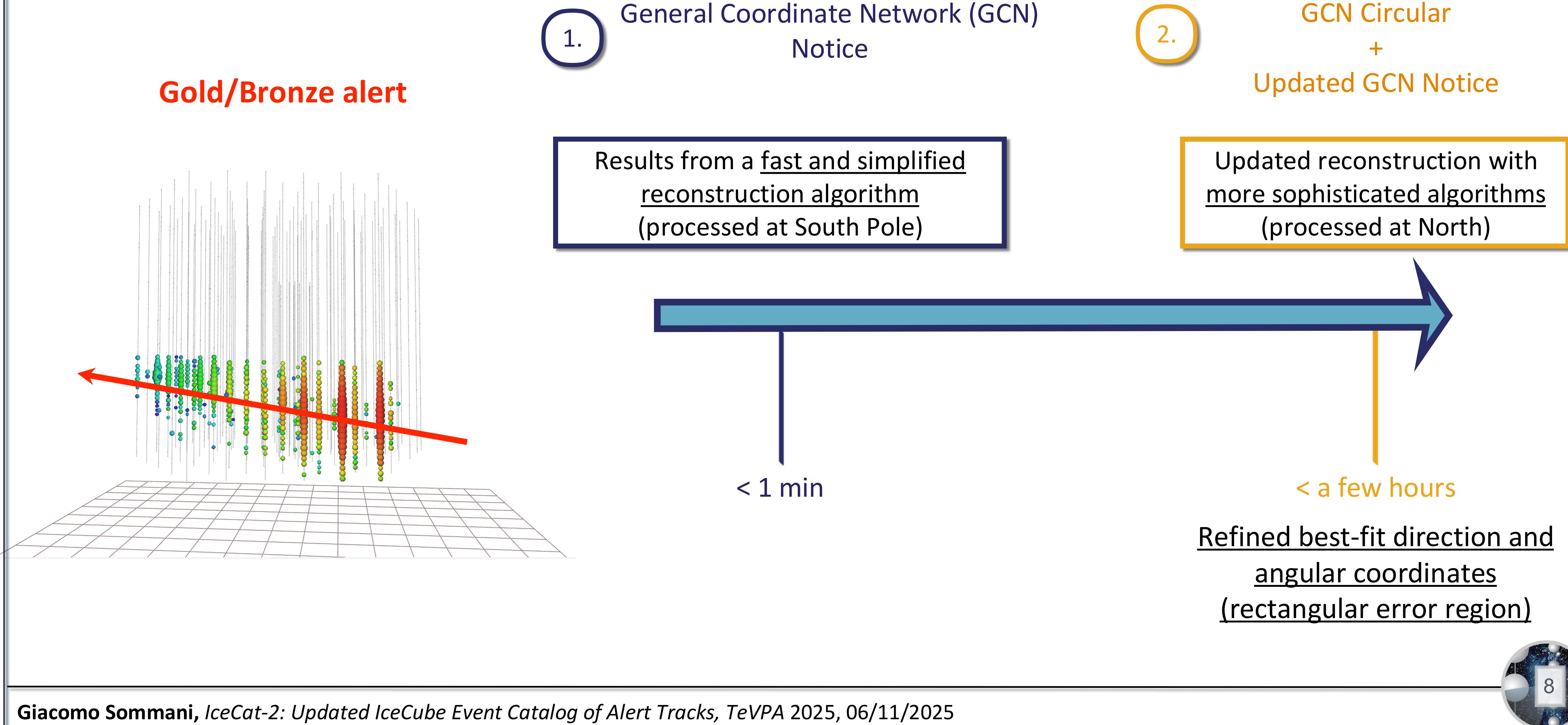
Gold/Bronze alert

1. General Coordinate Network (GCN) Notice

2. GCN Circular + Updated GCN Notice

Results from a <u>fast and simplified reconstruction algorithm</u> (processed at South Pole)

Updated reconstruction with <u>more sophisticated algorithms</u> (processed at North)

< 1 min

< a few hours

<u>Refined best-fit direction and angular coordinates</u> (rectangular error region)

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

Public release of 348 alerts (from 2011 to October 2023)

All real-time alerts issued since 2016 + events observed since the start of full-detector data collection in 2011 that would have triggered an alert if the program had been in place at that time
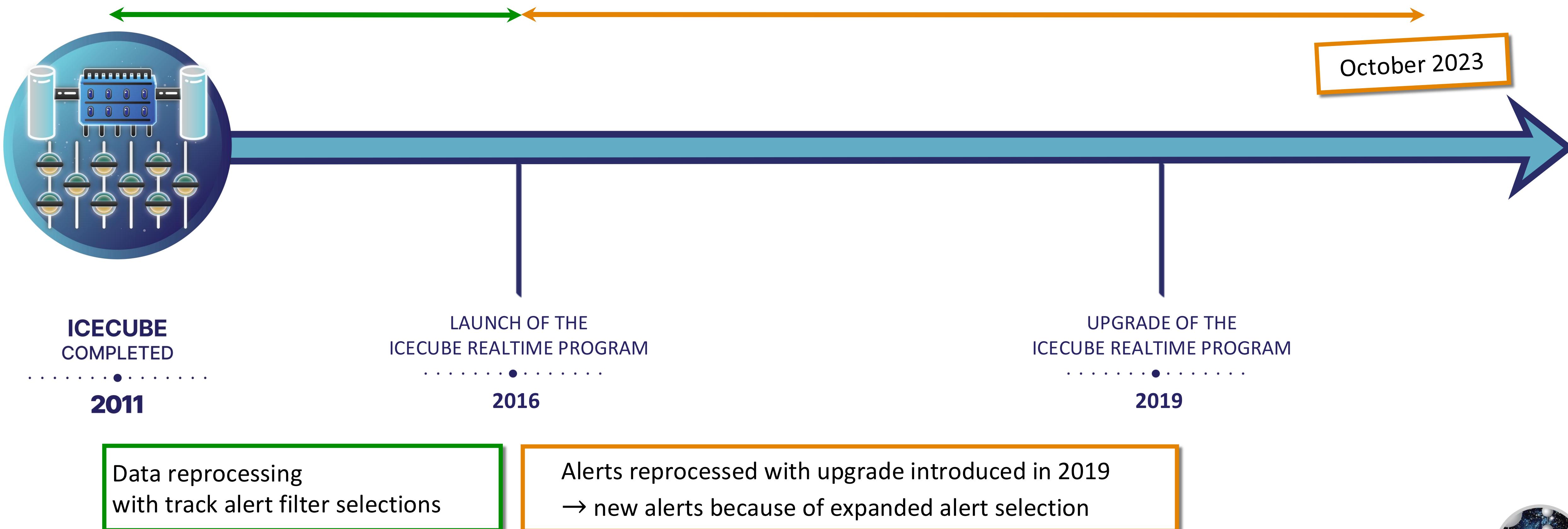
October 2023

ICECUBE
COMPLETED

2011

LAUNCH OF THE
ICECUBE REALTIME PROGRAM

2016

UPGRADE OF THE
ICECUBE REALTIME PROGRAM

2019

Data reprocessing
with track alert filter selections

Alerts reprocessed with upgrade introduced in 2019
→ new alerts because of expanded alert selection

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

Public release of 348 alerts (from 2011 to October 2023)

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 Sky Map

- • IceCat-1 best fit
- --- IceCat-1 90% rectangular contour

IceCube Preliminary
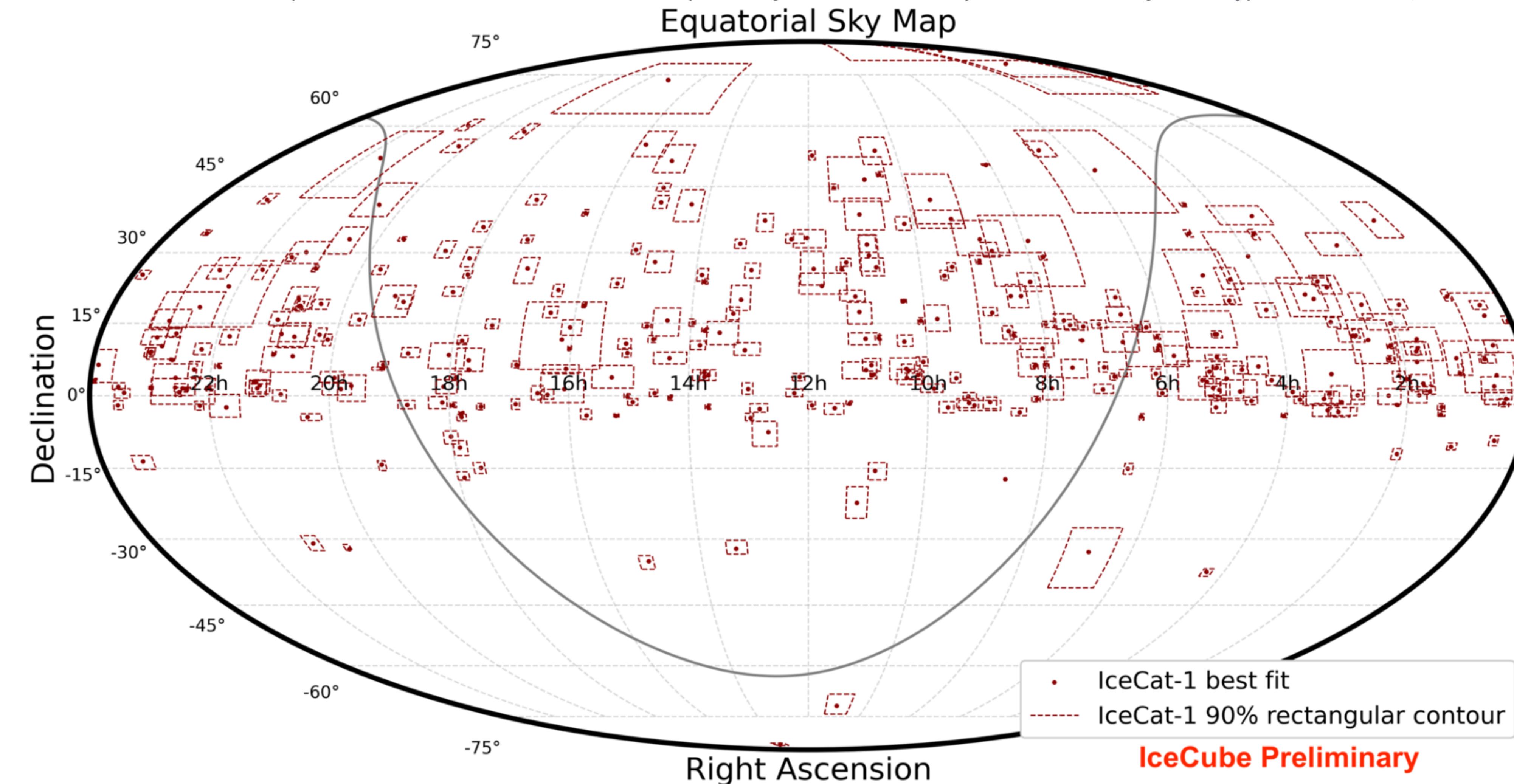
Now …
Almost time for IceCat-2

Let's come back to the track alerts workflow

Gold/Bronze alert

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< 1 min

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< a few hours

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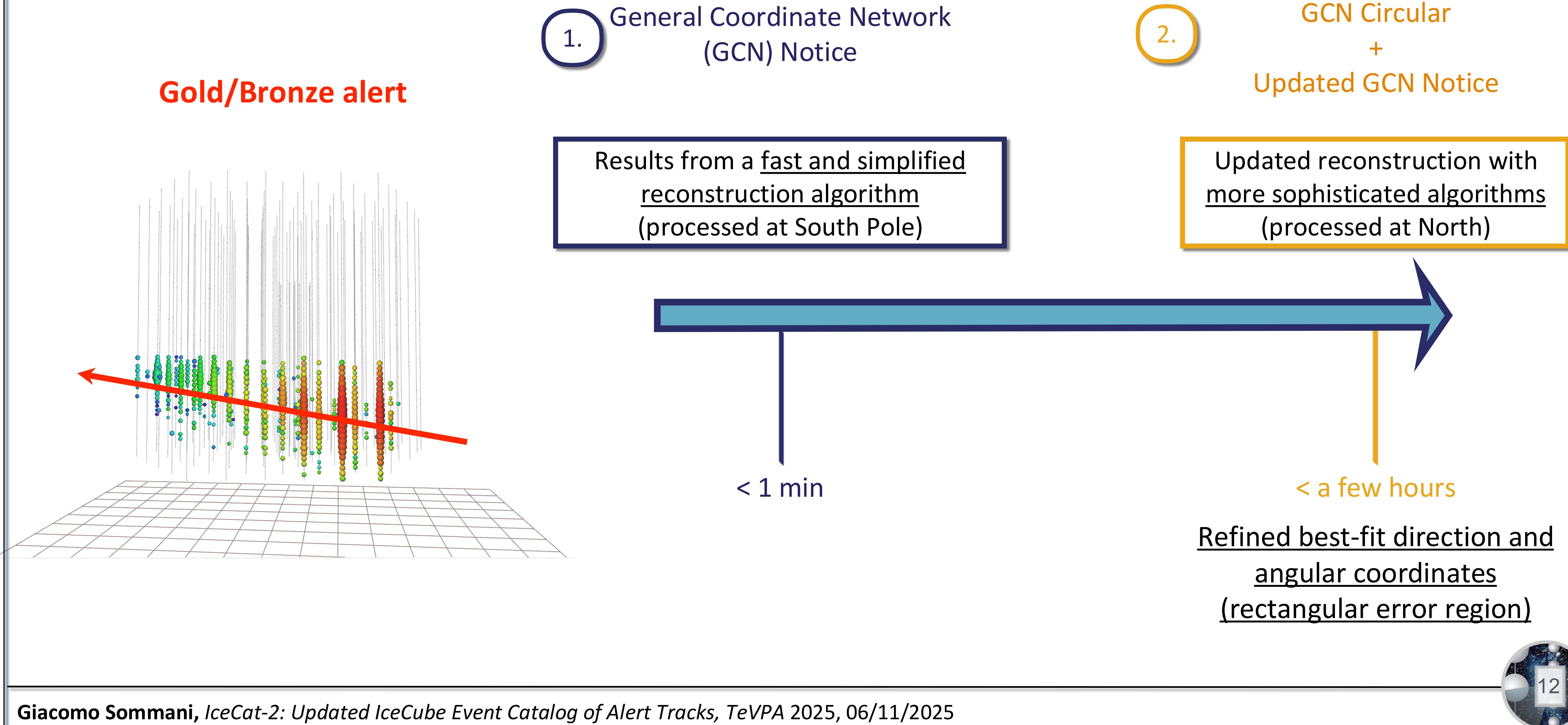
September 2024: Update on Track Alert alert system

Gold/Bronze alert

1. General Coordinate Network (GCN) Notice

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

2. GCN Circular
+
Updated GCN Notice

Updated reconstruction with more sophisticated algorithms (processed at North)

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

< 1 min

Announced via
GCN Circular 38267

< a few hours

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

See PoS(ICRC2025)1184
Improvements in the Reconstruction of IceCube Realtime Alerts

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IceCat-2: what's new?

- **Improved directions** for **IceCat-1** events using **latest reconstructions**
  → currently used in the real-time alert system (since September 2024)

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  Introduced in October 2022 a new veto based on coincidences with IceTop, the array of ice-Cherenkov tanks located on the surface 📖 Amin et al.m J. Phys. Conf. Ser. 2156, 012217 (2021)
  → 340 out of 348 events retained from the IceCat-1 dataset

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- **25 new track-like alerts** since October 2023 (last IceCat-1 update) and up to January 2, 2025 (IC-250102A)
  → preliminary catalog presented in this talk
  Further updates will follow towards the peer-review publication + public data release

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- **Full reprocessing of all alerts**
  → **most up-to-date data processing framework and calibrations** across the dataset

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IceCat-2 sample: Equatorial sky-map + 90% contours

The **preliminary IceCat-2 catalog** includes **365 track-like alerts**

Equatorial Sky Map

- IceCat-2 best fit
- – – IceCat-2 90% contour

IceCube Preliminary
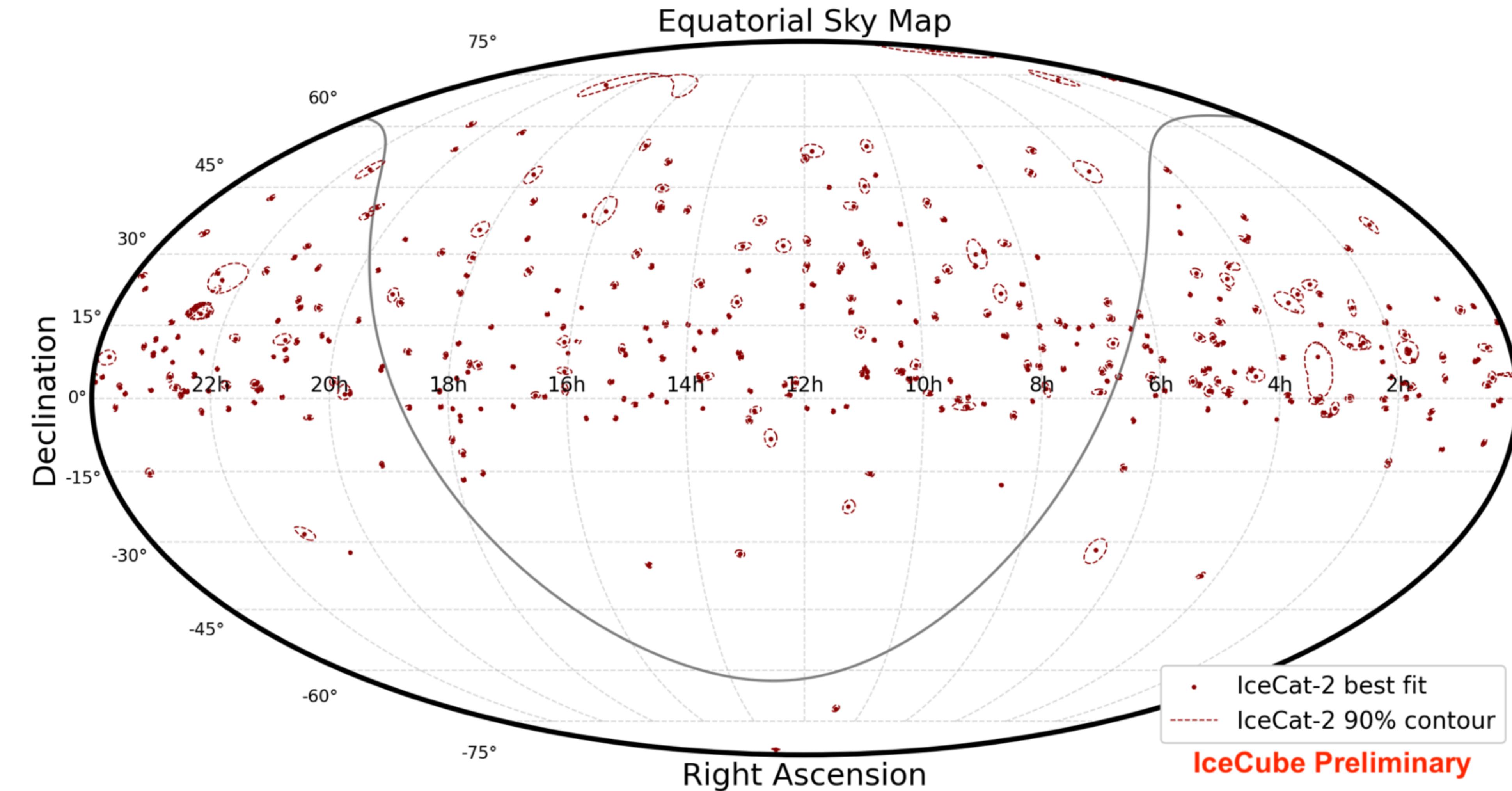
# Comparison between IceCat-1 and IceCat-2

Ang. distance between IceCat-1 and IceCat-2 best fit directions
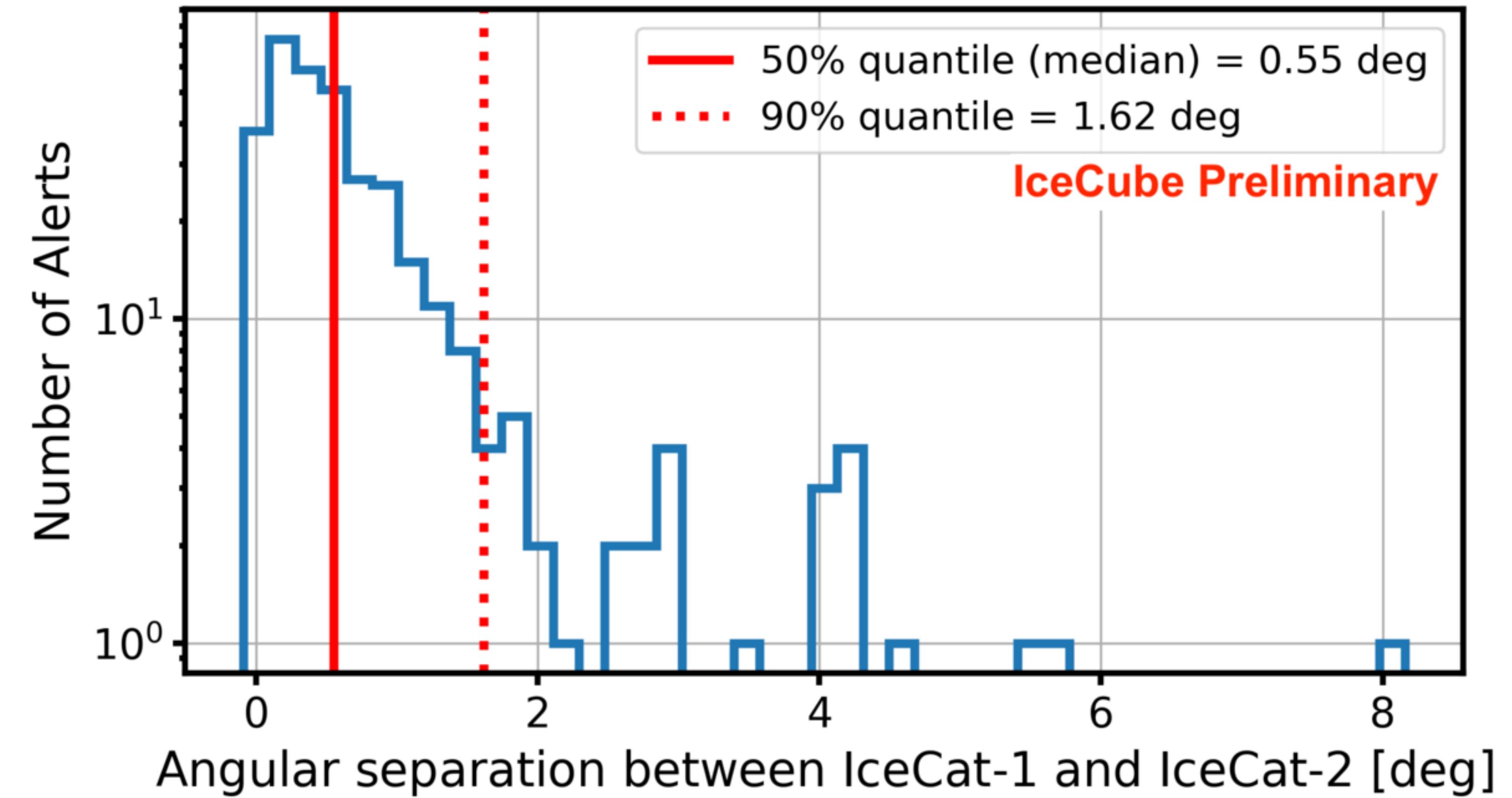
50(90)% of the alerts with angular separation below 0.55(1.62) deg

Reduction in localization uncertainties between IceCat-1 and IceCat-2

Most notable improvement → significant reduction in localization uncertainties around the best-fit direction
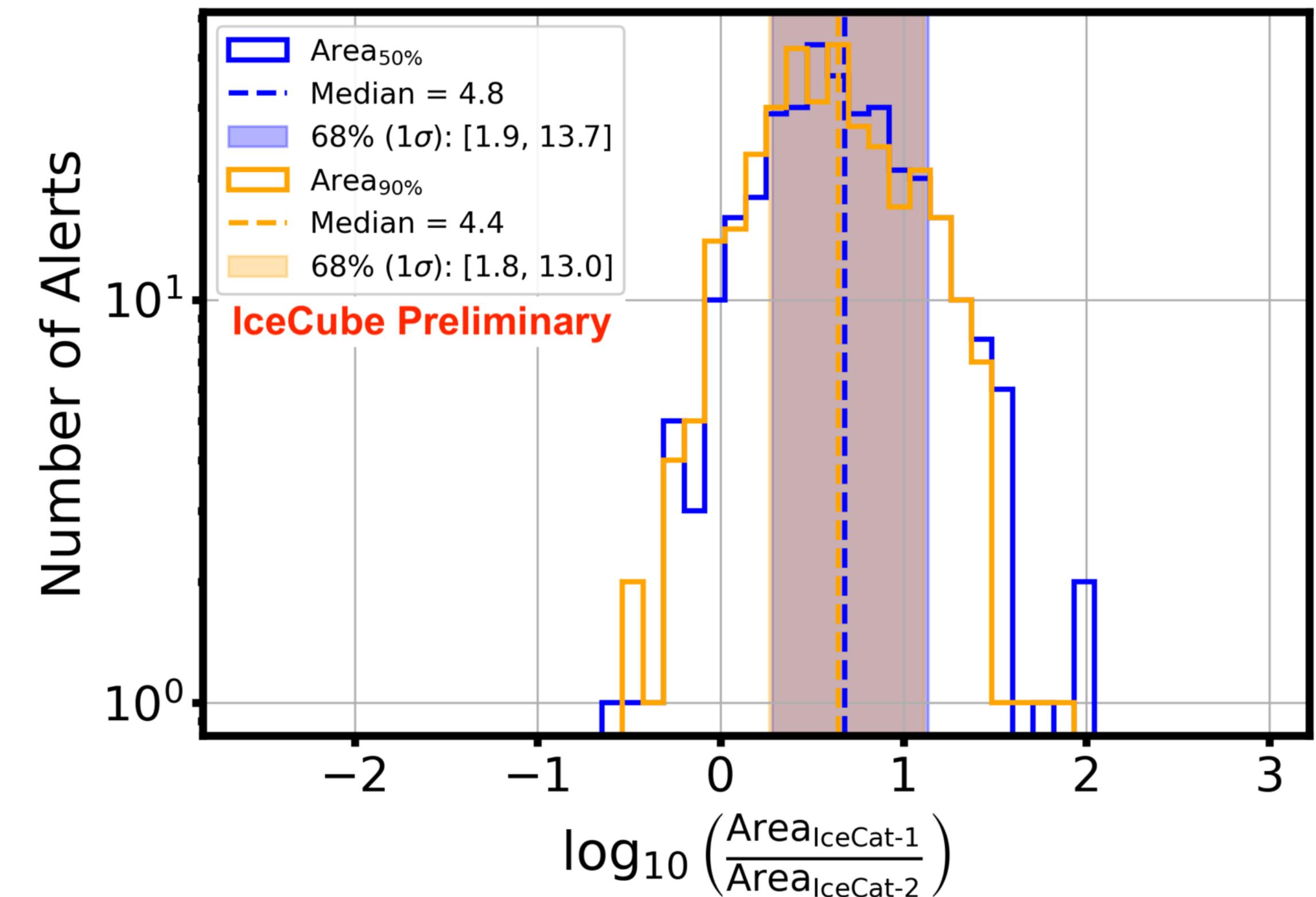
IceCat-2:
- **Median improvement on area at 50% and 90% by a factor around 5 and 4**, respectively

Equatorial skymap with IceCat-1 events + rectangular errors (<u>original reco</u>)

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 Sky Map

IceCube Preliminary

Legend:
- • IceCat-1 best fit
- - - - IceCat-1 90% rectangular contour
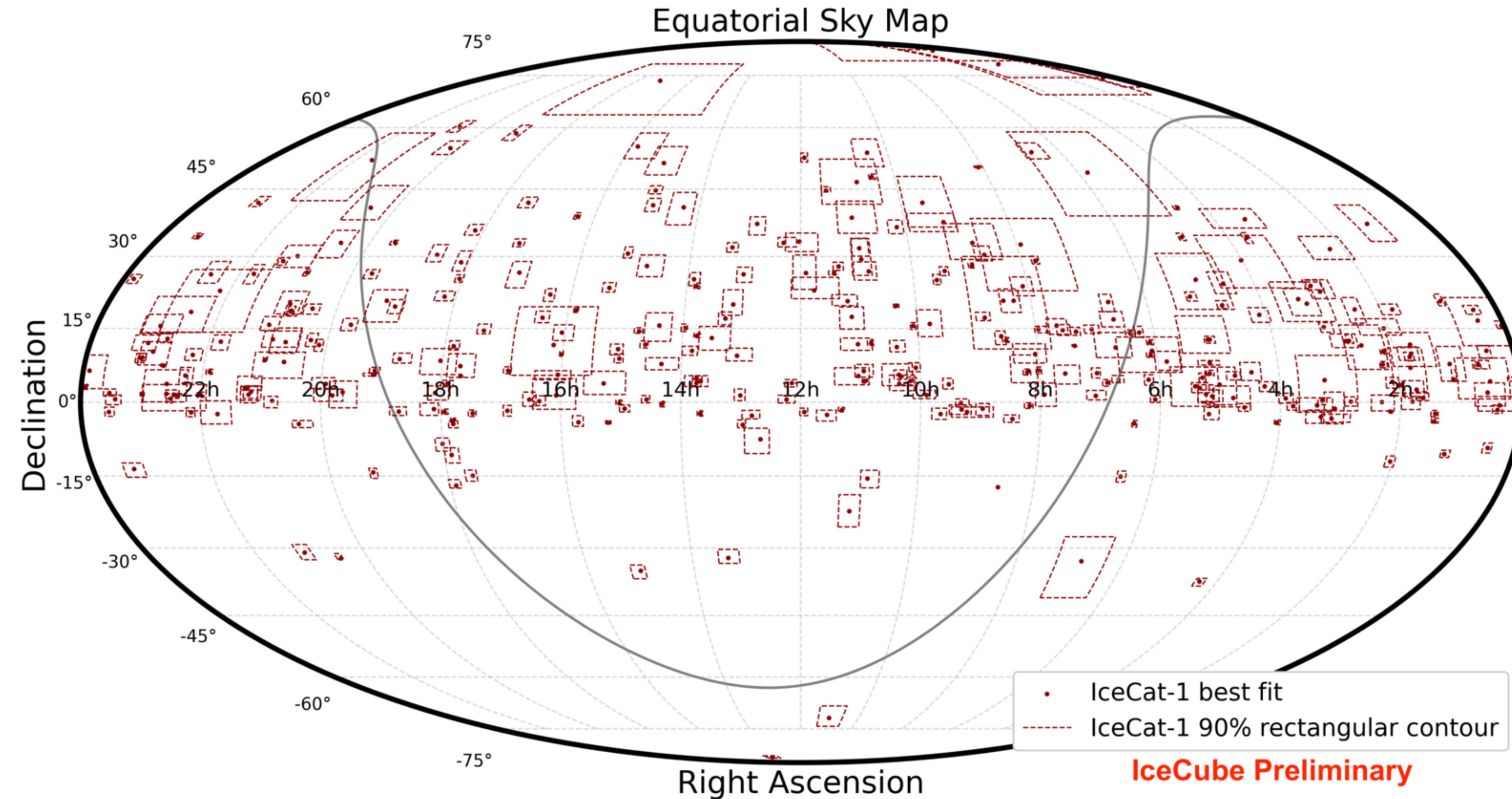
Equatorial skymap with IceCat-1 events + rectangular errors (new reco from IceCat-2)

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

Equatorial Sky Map

This reflects the improvement that has been introduced in the realtime processing of track alerts in IceCube

Legend:
- IceCat-2 best fit
- - - - IceCat-2 90% rectangular contour

IceCube Preliminary
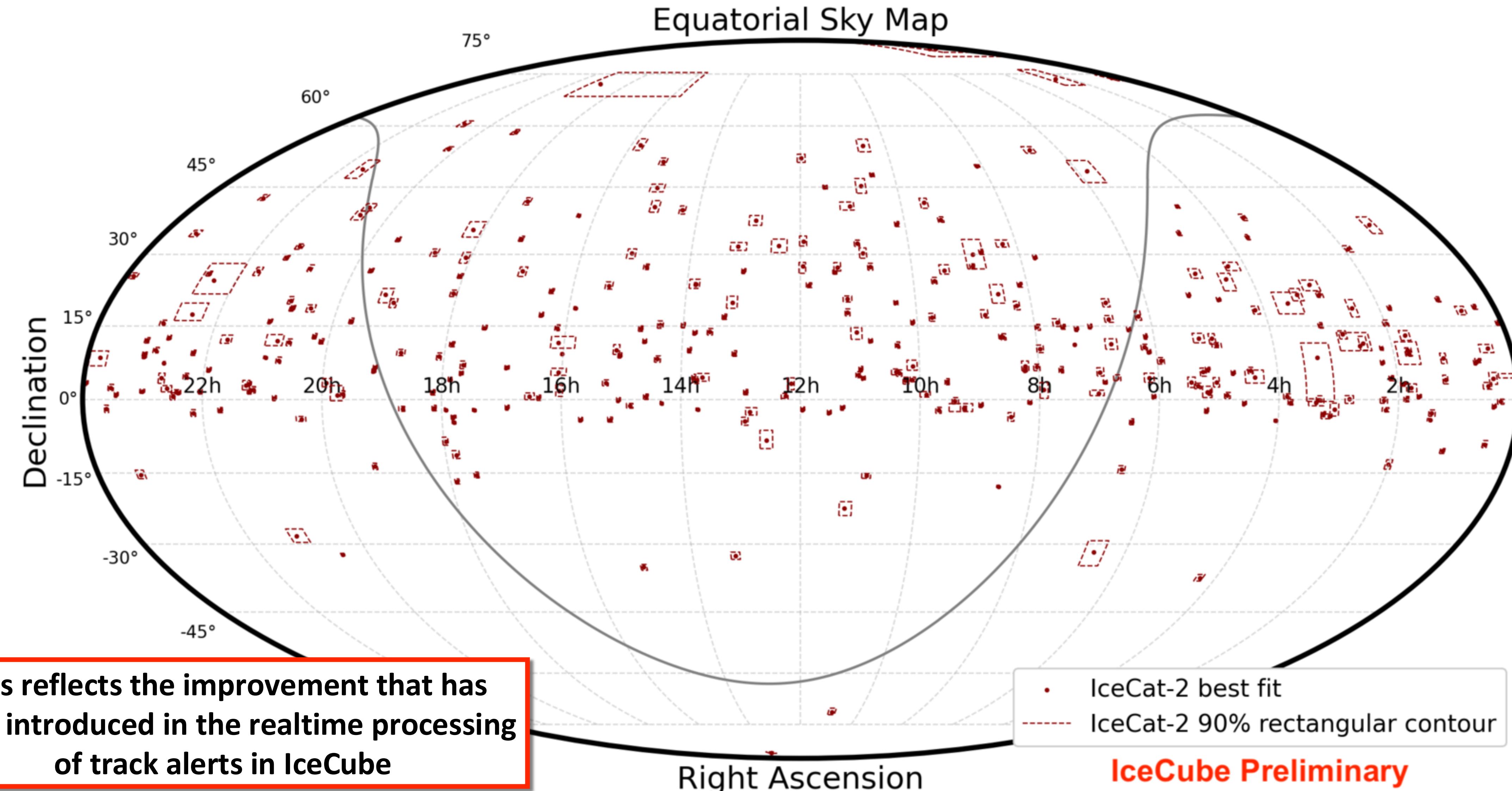
Revision of spatial coincidence with relevant sources

Possible neutrino emitters identified over the years with IceCube alerts

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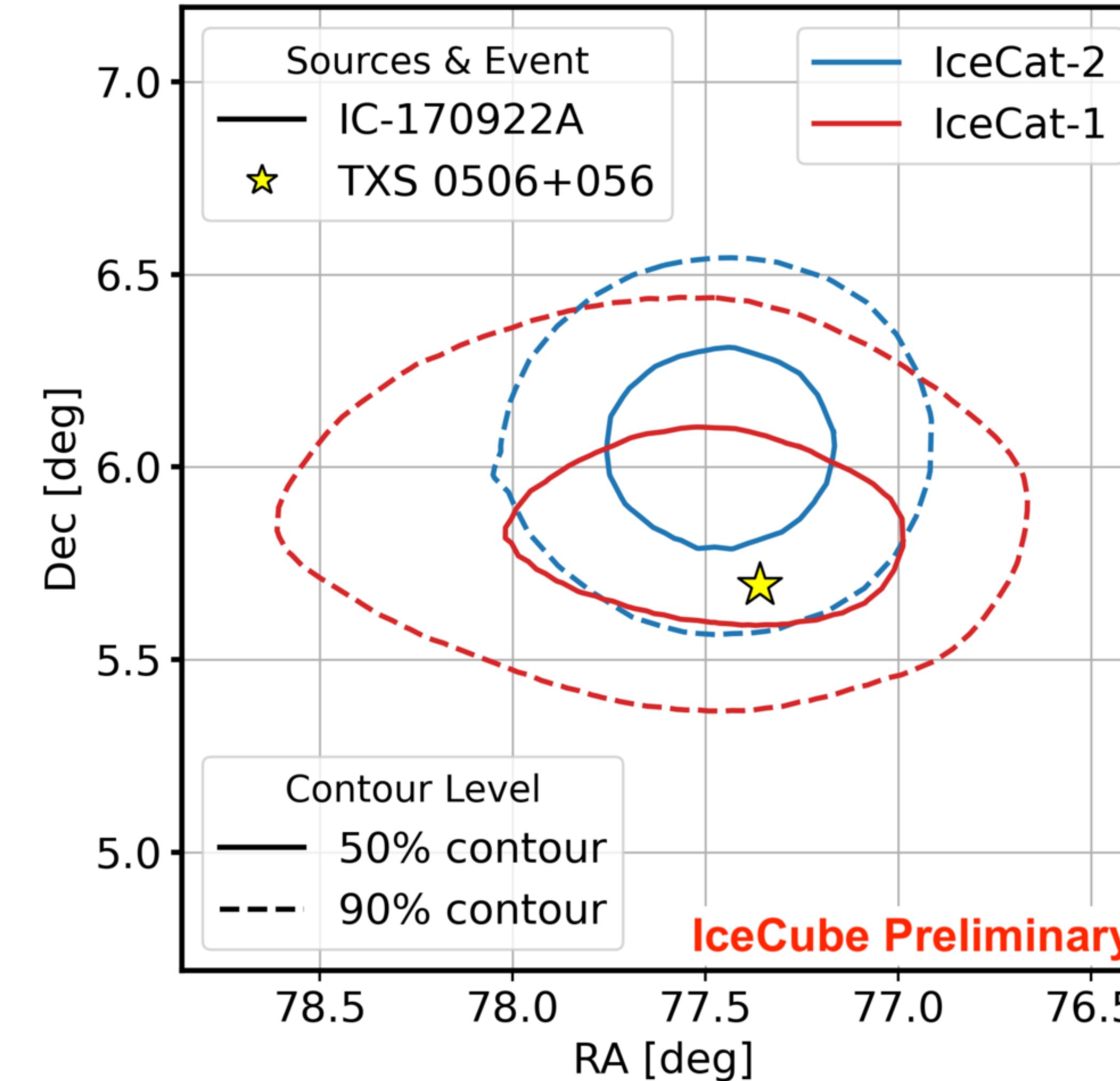
TXS 0506+056 remains spatially coincident
with the revised IC-170922A localisation,
although it now lies within
the 90% containment region
rather than the 50% contour

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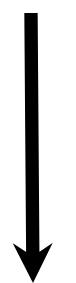
The first transient identified as
a potential neutrino source is still
a neutrino candidate

NGC 7469

Two coincident O(100) TeV IceCube neutrino alerts (IC220424A and IC230416A)
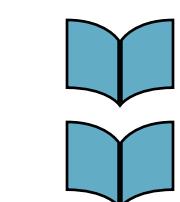
Sommani et al., ApJ 981 (2025), 103
IceCube Coll., arXiv:2510.13403
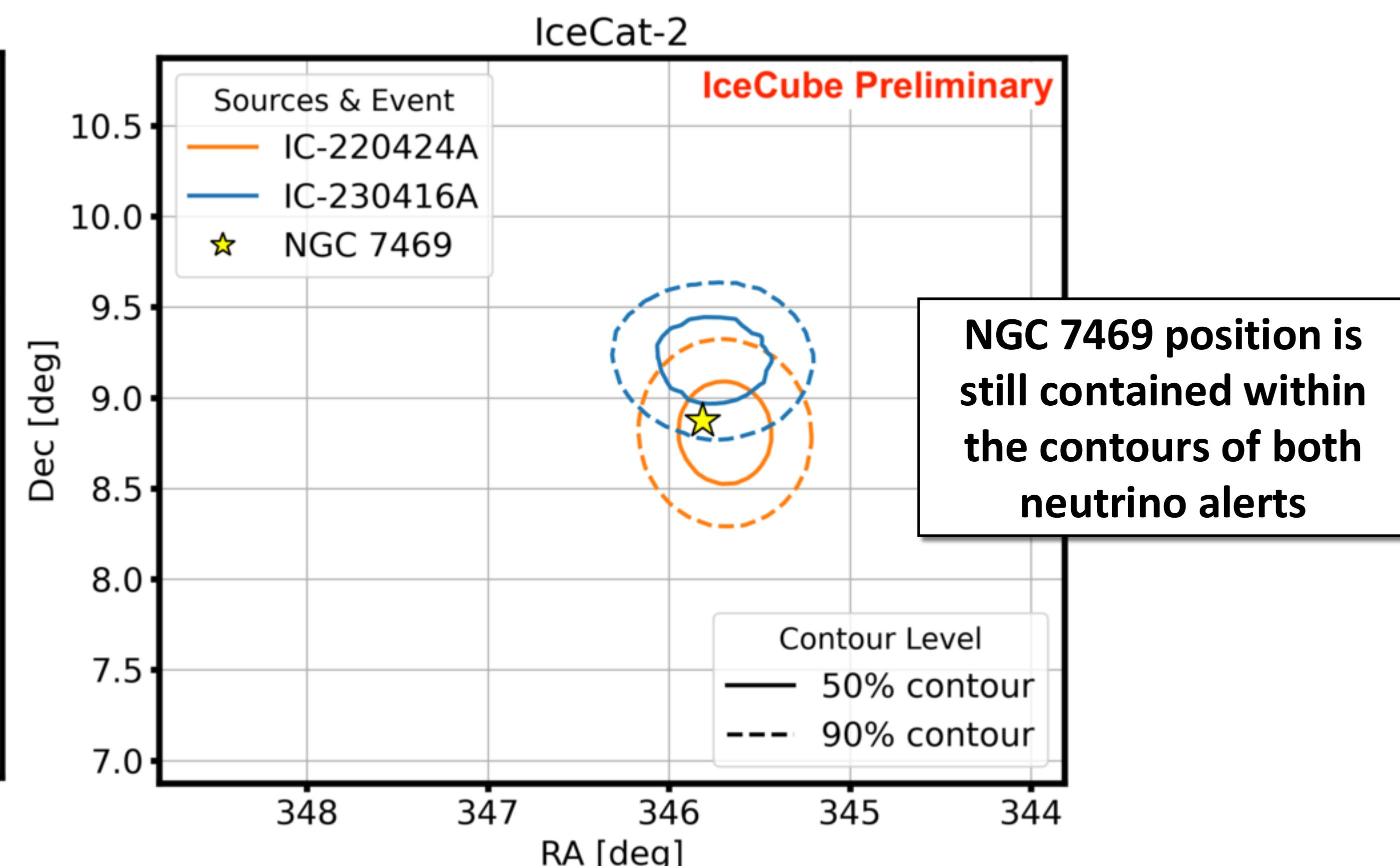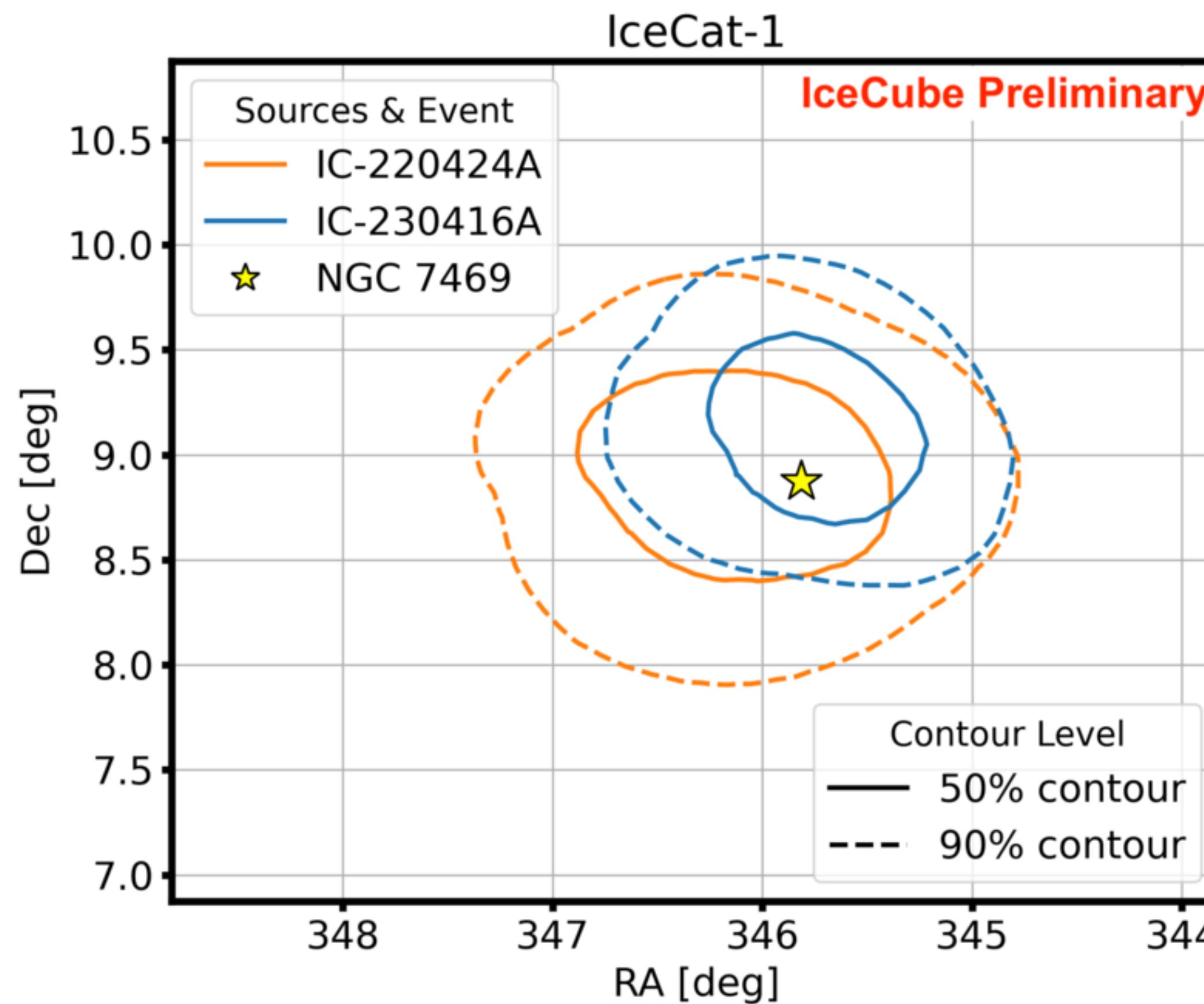
NGC 7469 position is still contained within the contours of both neutrino alerts

Giacomo Sommani, *IceCat-2: Updated IceCube Event Catalog of Alert Tracks, TeVPA* 2025, 06/11/2025

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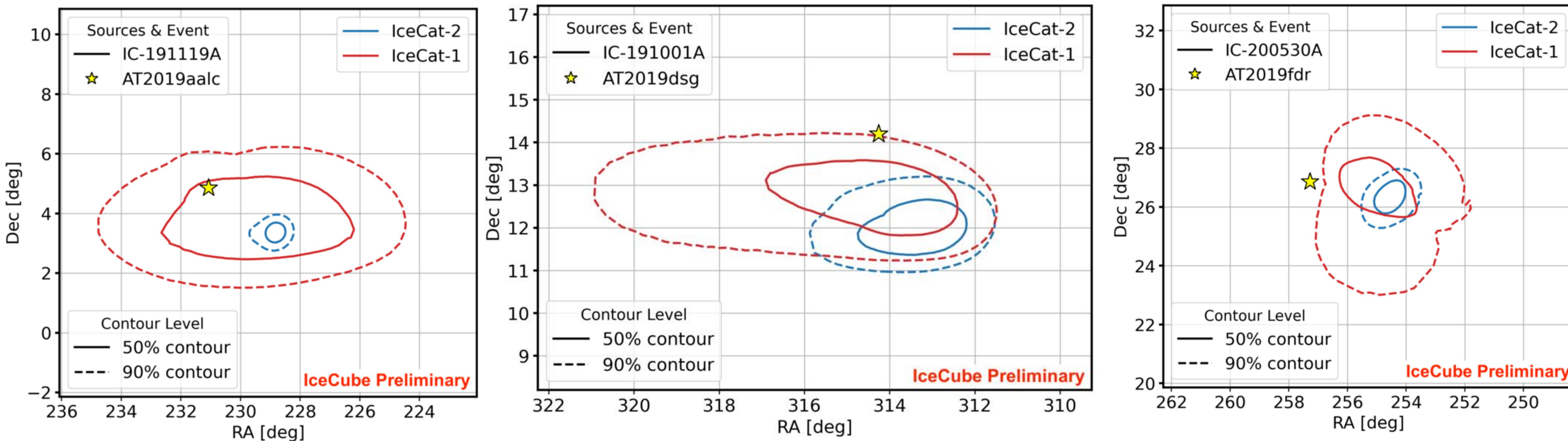
TDE positions are well outside the updated containment regions
Associations between these TDEs and the corresponding IceCube alerts are disfavoured

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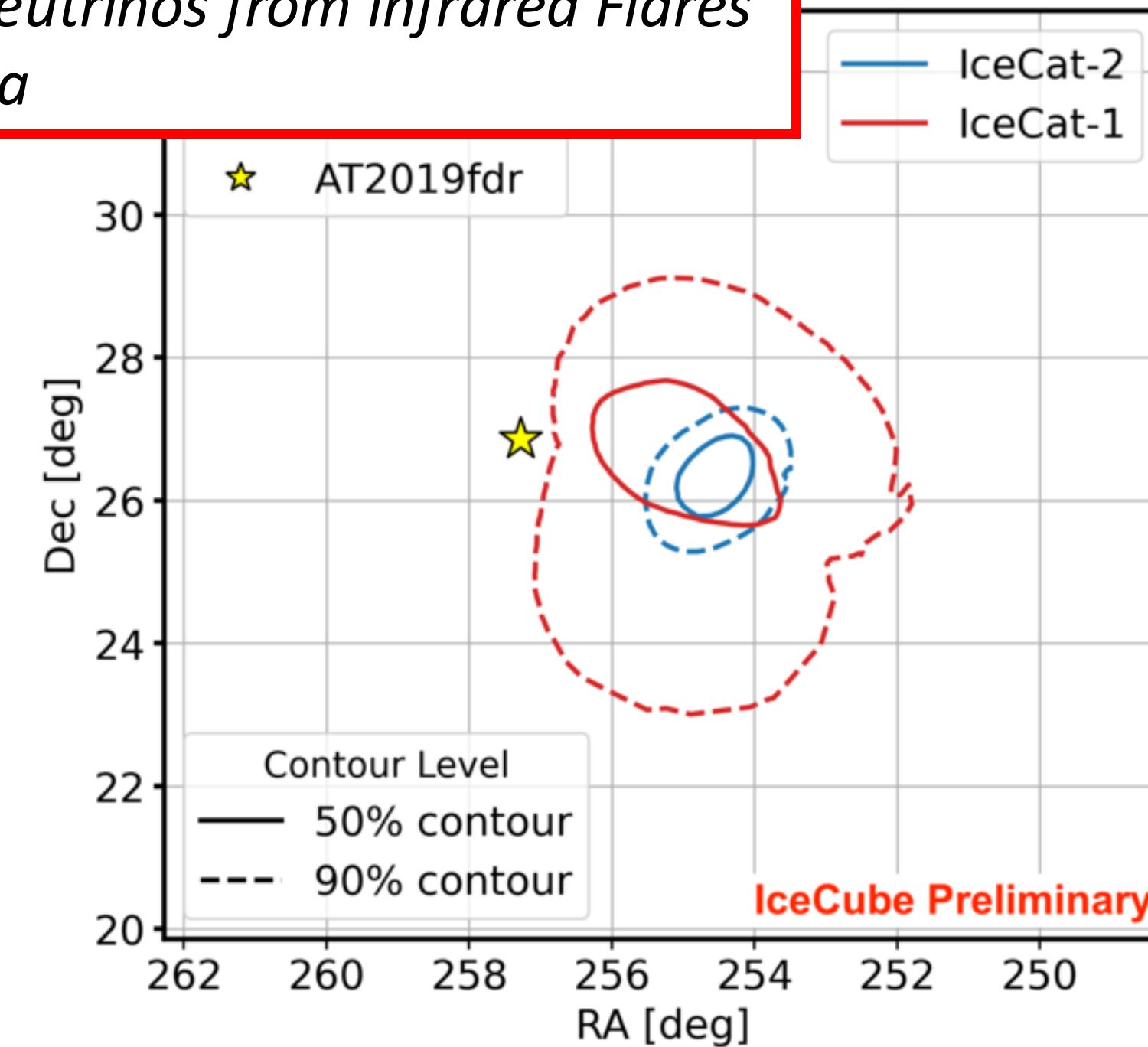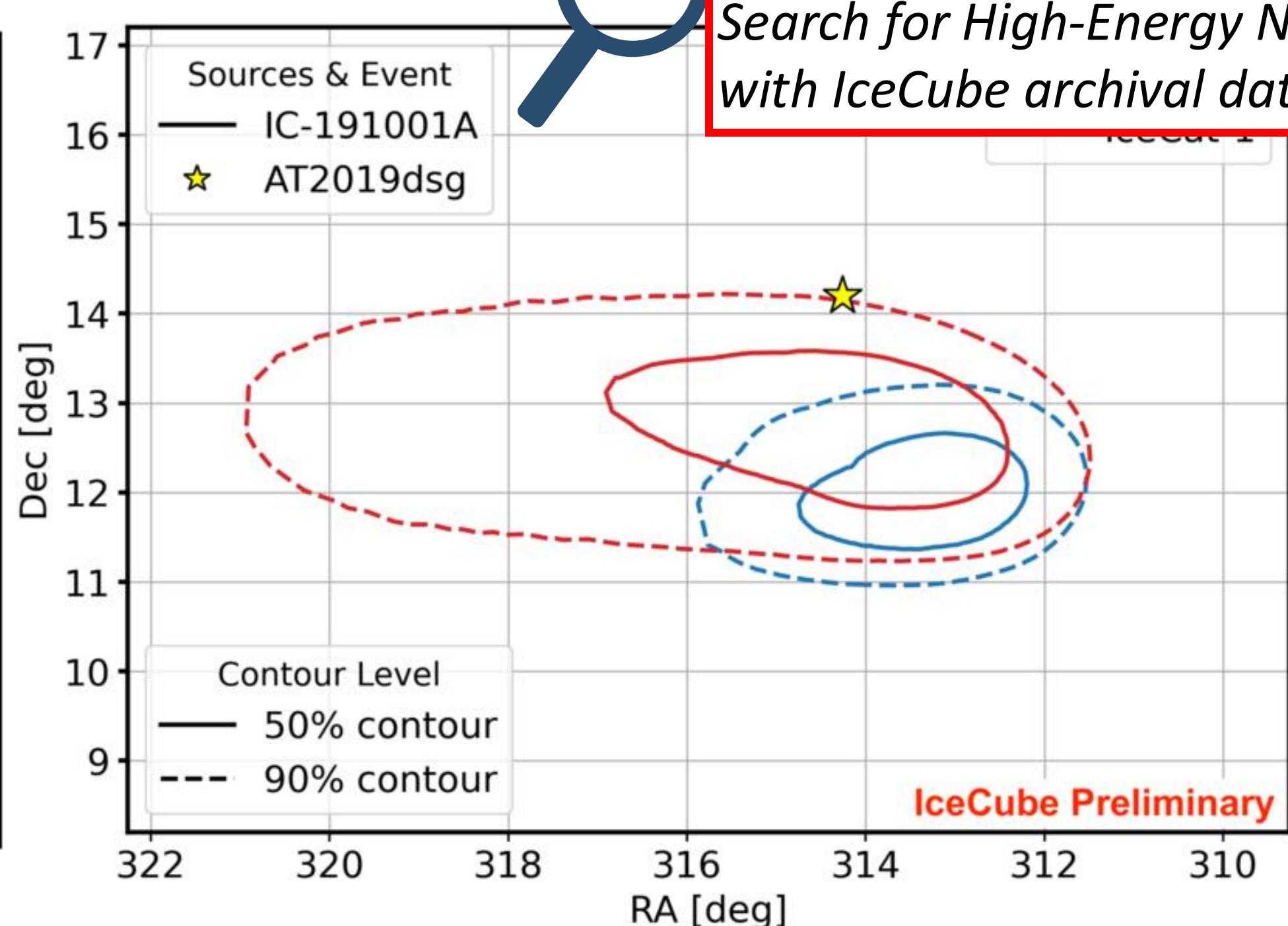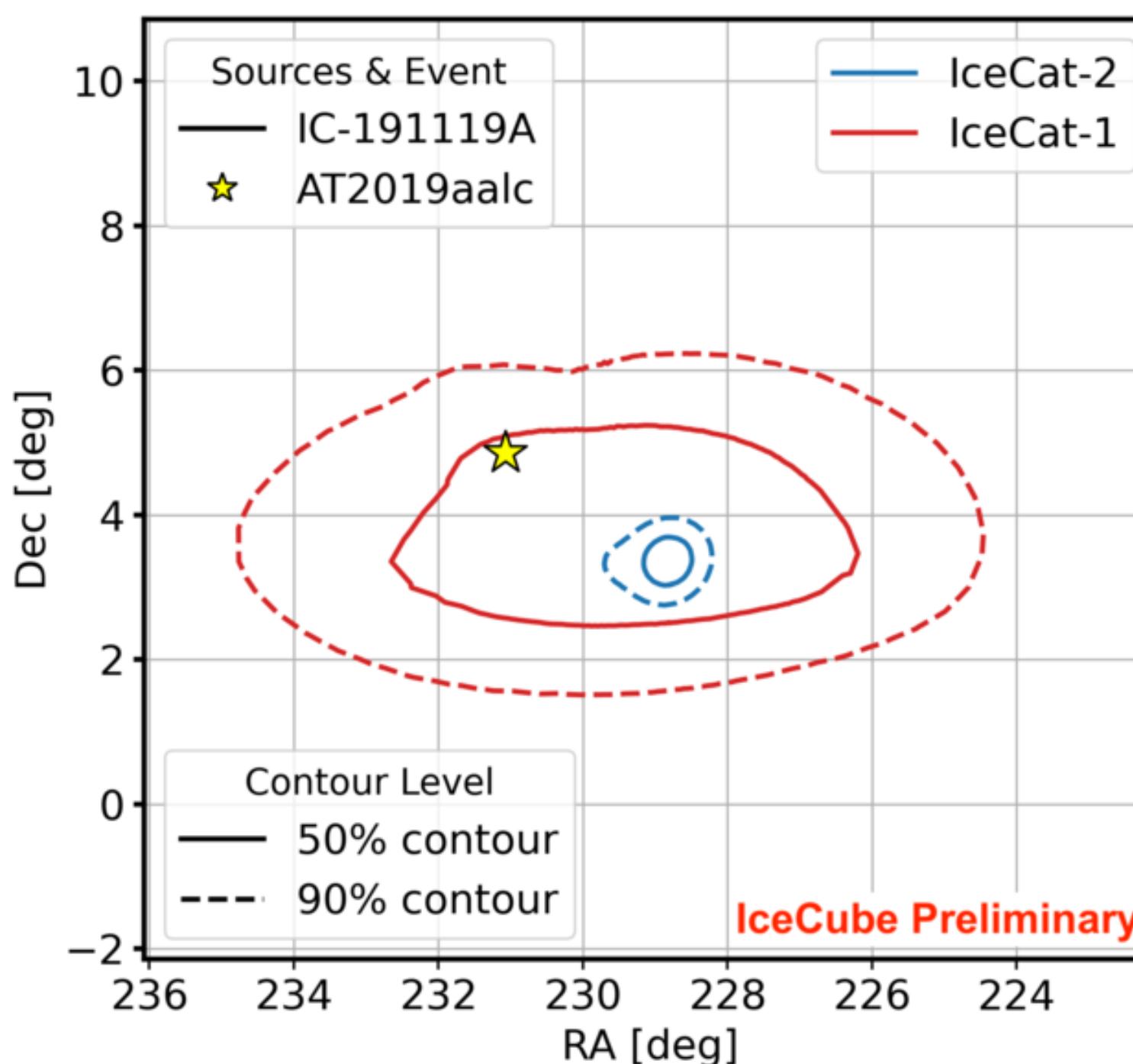
See Teresa's talk on Tuesday
Search for High-Energy Neutrinos from Infrared Flares with IceCube archival data

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

Cross-correlation with known source catalogs

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

[PoS(ICRC2025)1224] **IceCube Preliminary**

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

Summary

- IceCat-2 incorporates **new reconstructions, updated calibrations, exclusion of likely CR-induced events,** and **new alerts** since the last IceCat-1 release

- The preliminary IceCat-2 catalog contains **365 track-like alerts** from May 2011 (IC-110514A) to January 2, 2025 (IC-250102A)

- **IceCat-2 improves the angular uncertainty areas by a factor ~ 5** → crucial for follow-up studies

- Cross-check of IceCube coincidences with a few interesting possible neutrino sources:
    - TXS 0506+056 and NGC 7469 are still inside the contours
    - The TDE candidates AT2019dsg, AT2019fdr, AT2019aalc are not anymore in the 90% contours

- Work on IceCat-2 and its comparison with IceCat-1 presented at ICRC 2025 (PoS(ICRC2025)1224). A public release of the full catalog will follow a peer-reviewed publication, alongside several analyses on source population correlations

Stay tuned!

Thank you for the attention
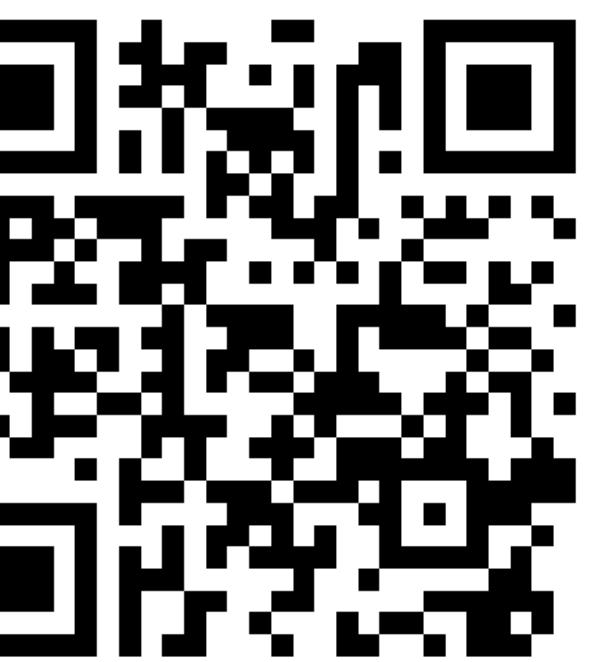
Backup

IceCat-1 alerts with updated IceCat-2 reco
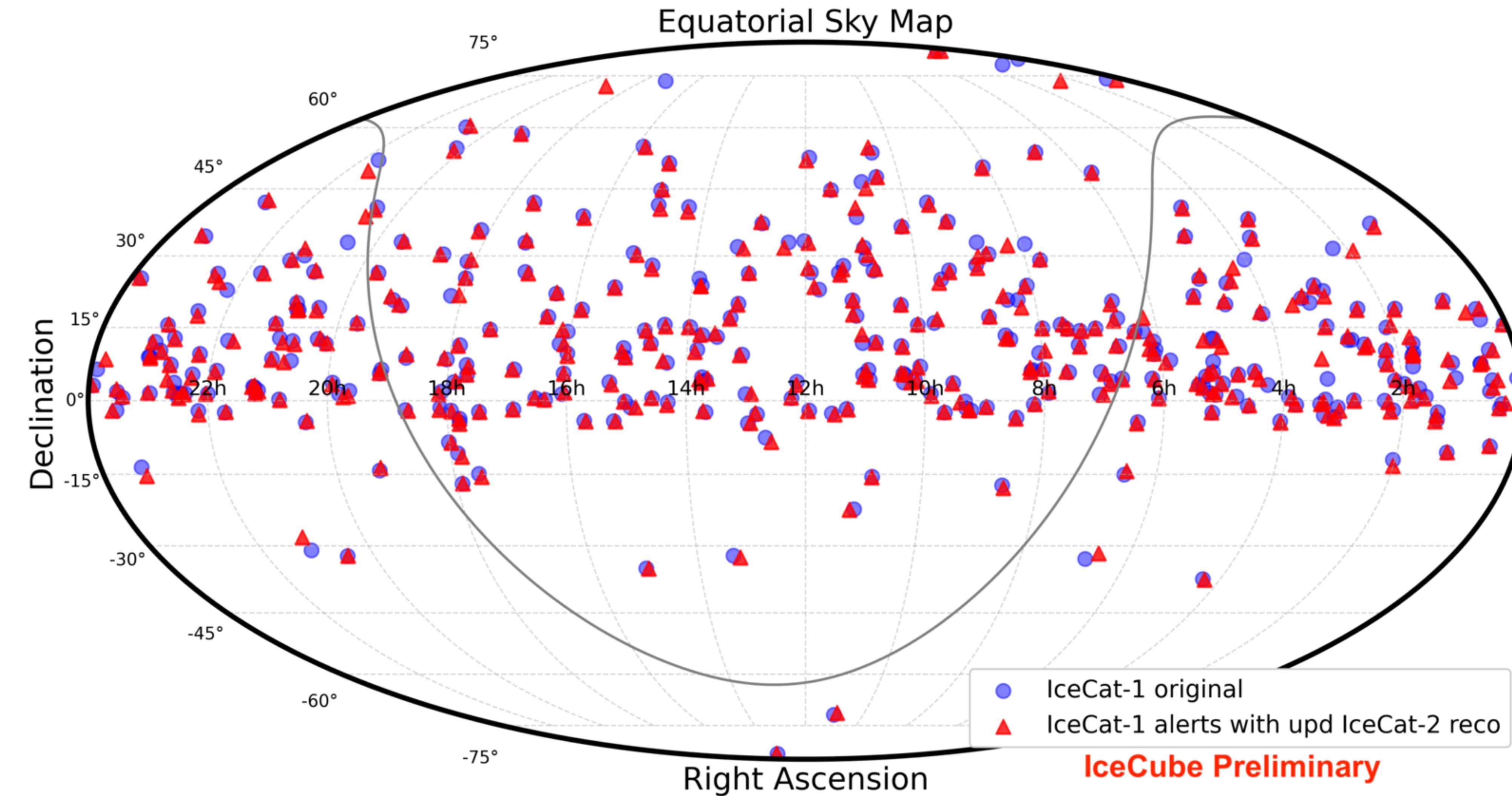
Equatorial Sky Map

- IceCat-1 original
- ▲ IceCat-1 alerts with upd IceCat-2 reco

IceCube Preliminary

Reduction in localization uncertainties between IceCat-1 and IceCat-2

**Most notable improvement → significant reduction in localization uncertainties around the best-fit direction**
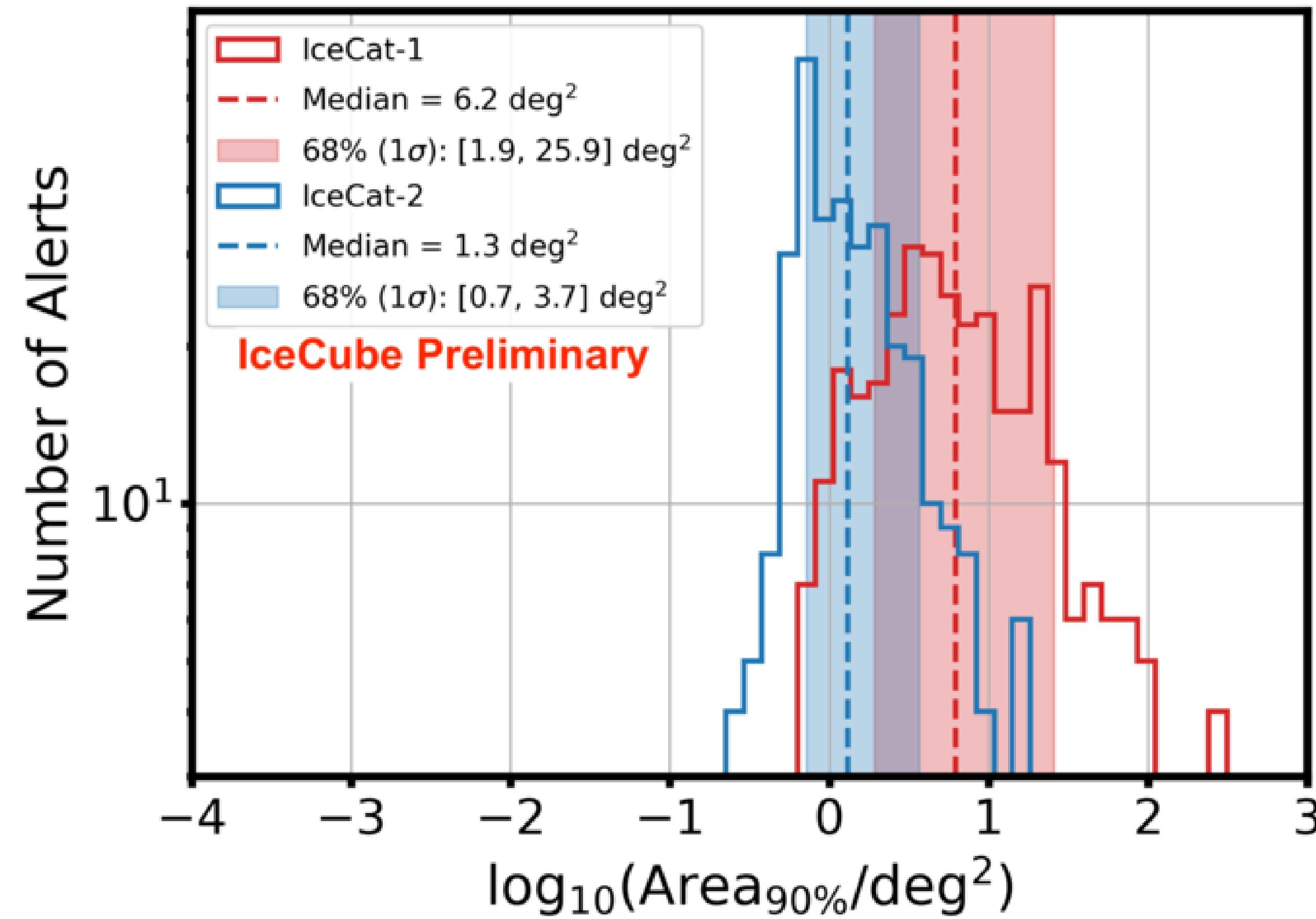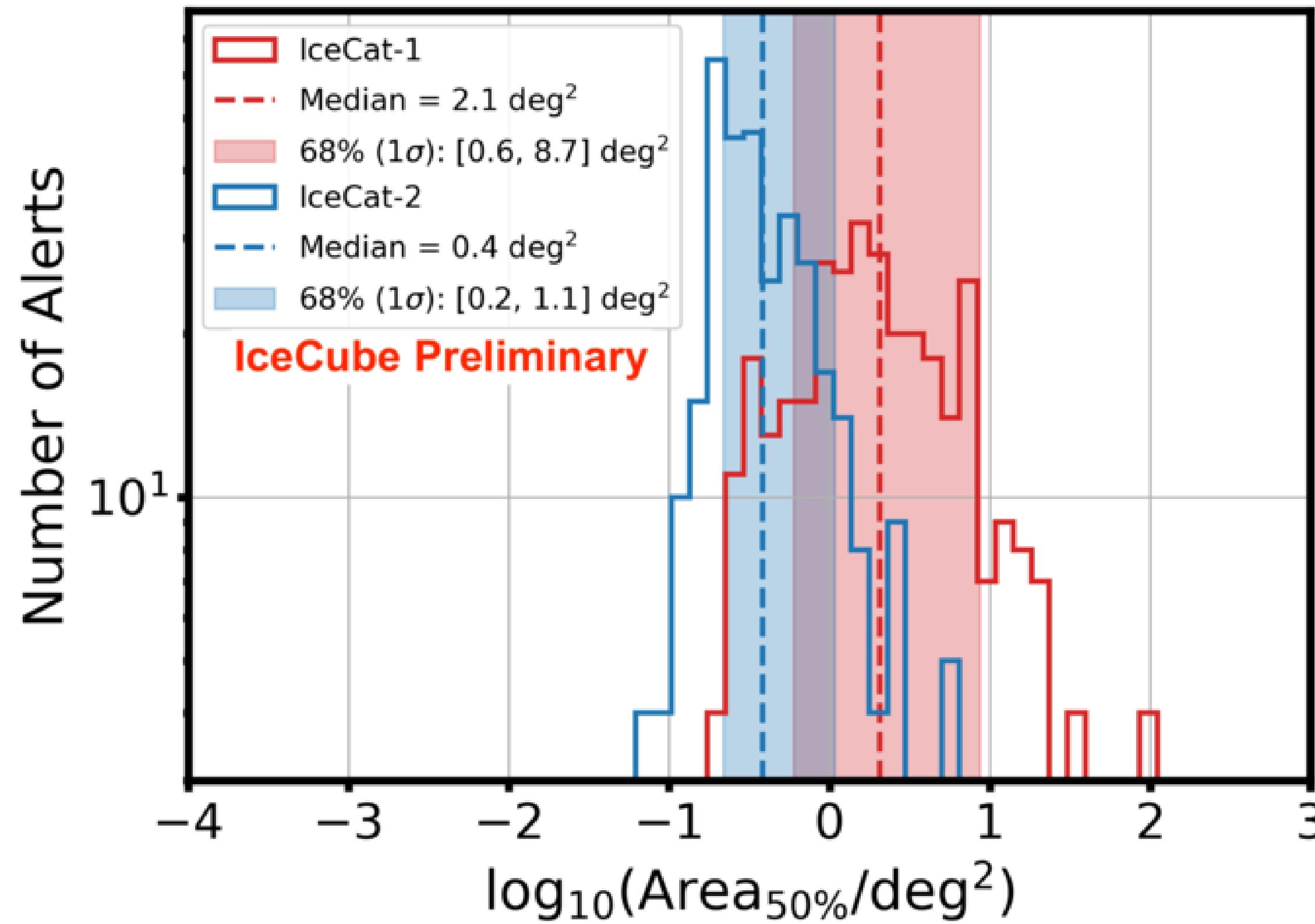
IceCat-2:
- **Median improvement on area at 50% and 90% by a factor around 5 and 4**, respectively
- Distributions are considerably narrower, with the spread around the median, quantified by the standard deviation σ, reduced by a factor between 8 and 9

IceCat-2 sample: Cumulative number of alerts

The **preliminary IceCat-2 catalog** includes **365 track-like alerts**
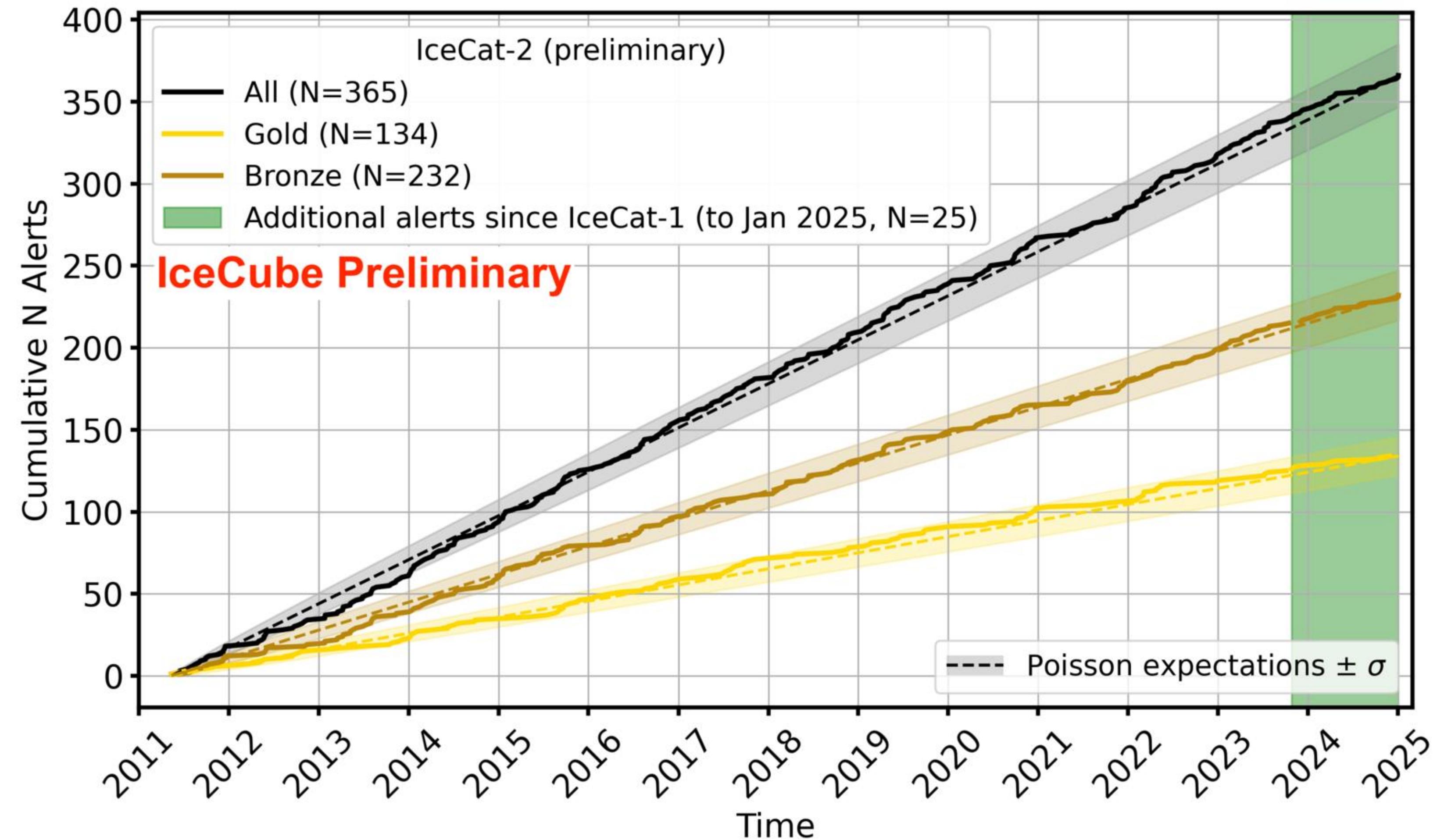
Average rate of **26.8 evt/year**

~9.9 evt/yr → Gold

~17 evt/year →Bronze

IceCat-2 sample: False Alarm Rate and Signalness

The **preliminary IceCat-2 catalog** includes **365 track-like alerts**
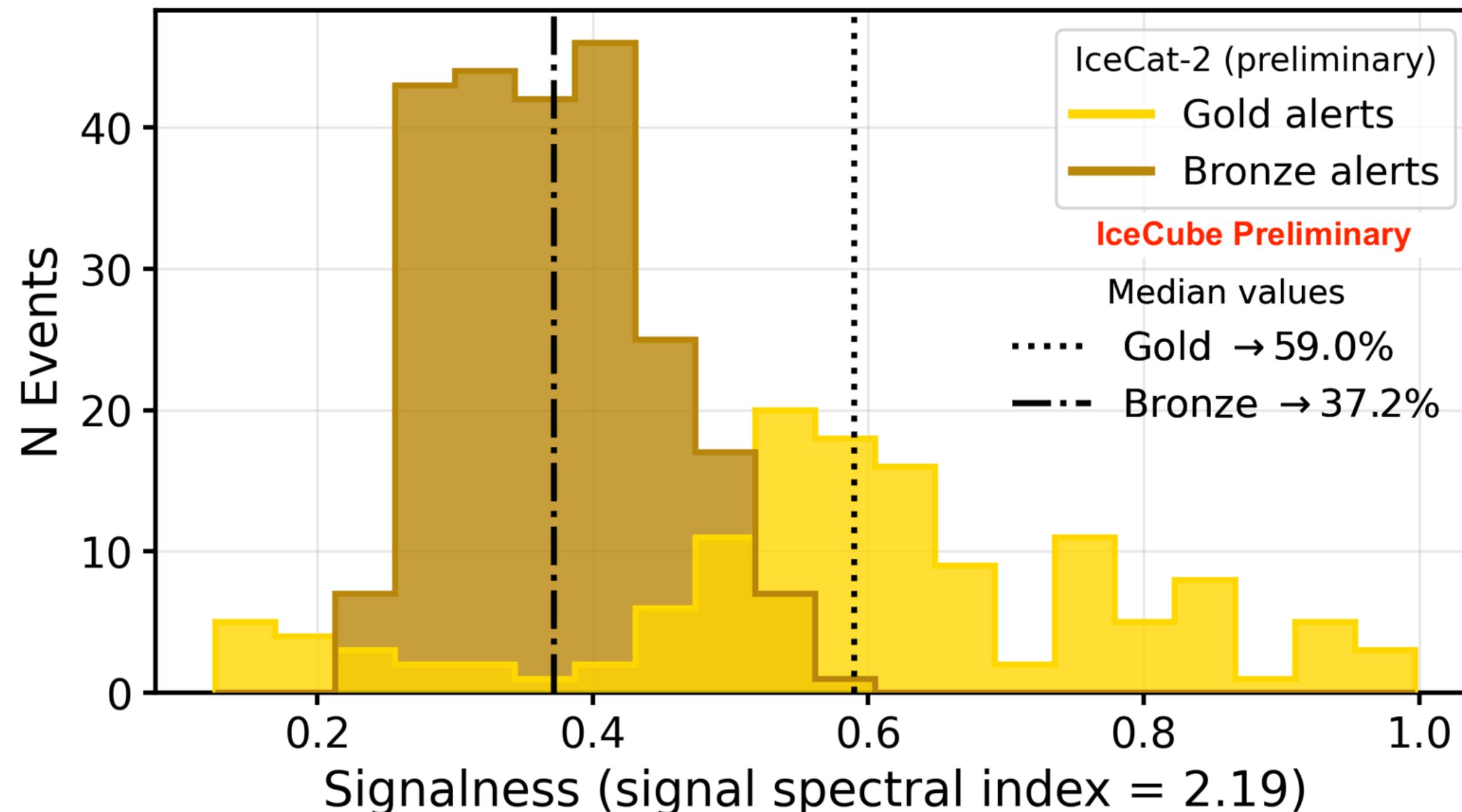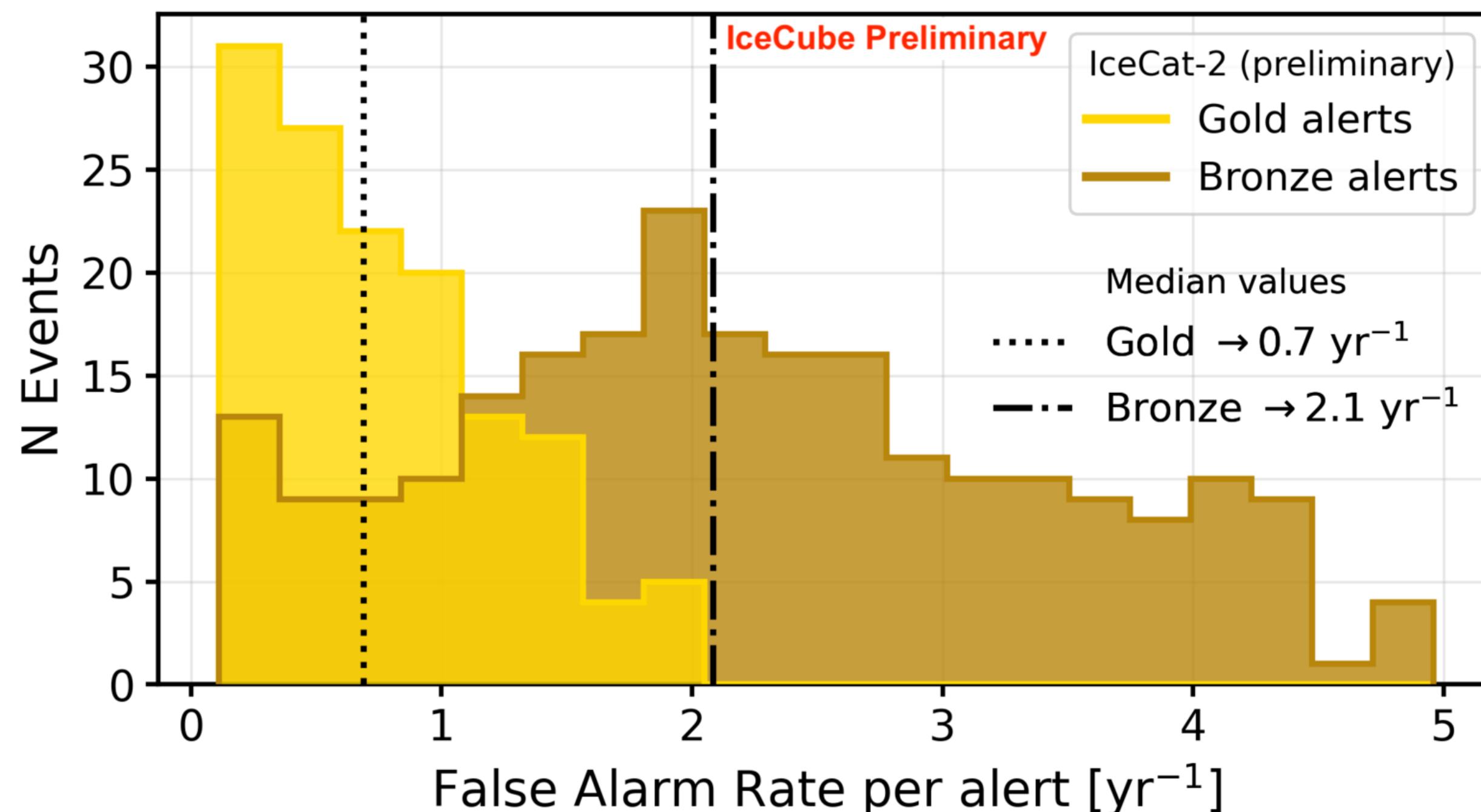
- Gold and Bronze channels correspond to average astrophysical probabilities of 50% and 30%, assuming a power-law spectrum with index 2.19

- 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

Signalness definition

Probability estimate that the event is an astrophysical neutrino based on the observed characteristics, relative to background

$$\text{Signalness} = \frac{N_{\text{signal}}(E, \delta)}{N_{\text{signal}}(E, \delta) + N_{\text{background}}(E, \delta)}$$

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

$\delta \rightarrow$ Event declination

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

Chance correlation with gamma-ray source candidates
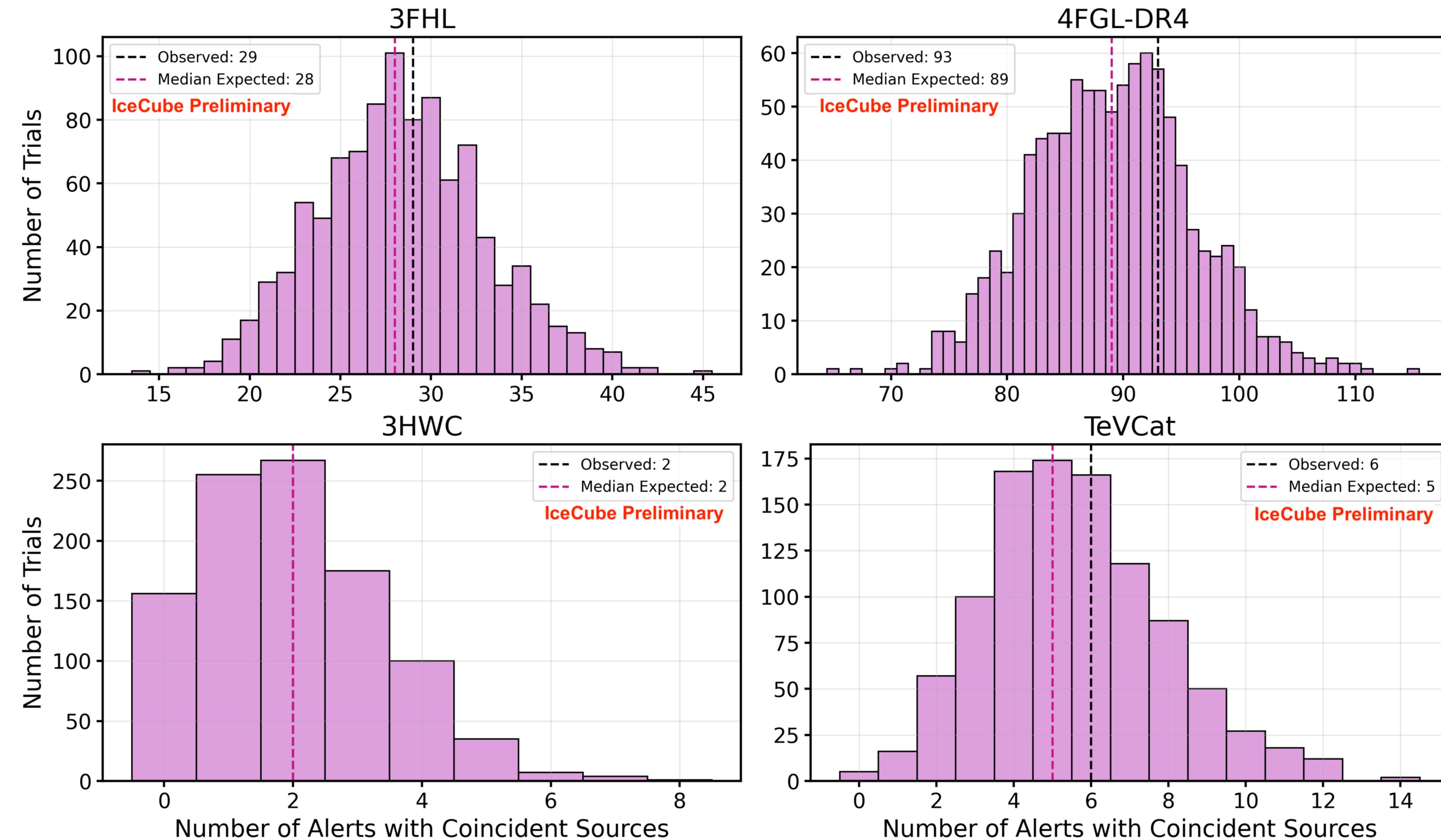
Chance correlation with X-ray source candidates

Swift BAT (157 months)

Legend:
- Observed: 35
- Median Expected: 32

IceCube Preliminary

X-axis: Number of Alerts with Coincident Sources
Y-axis: Number of Trials
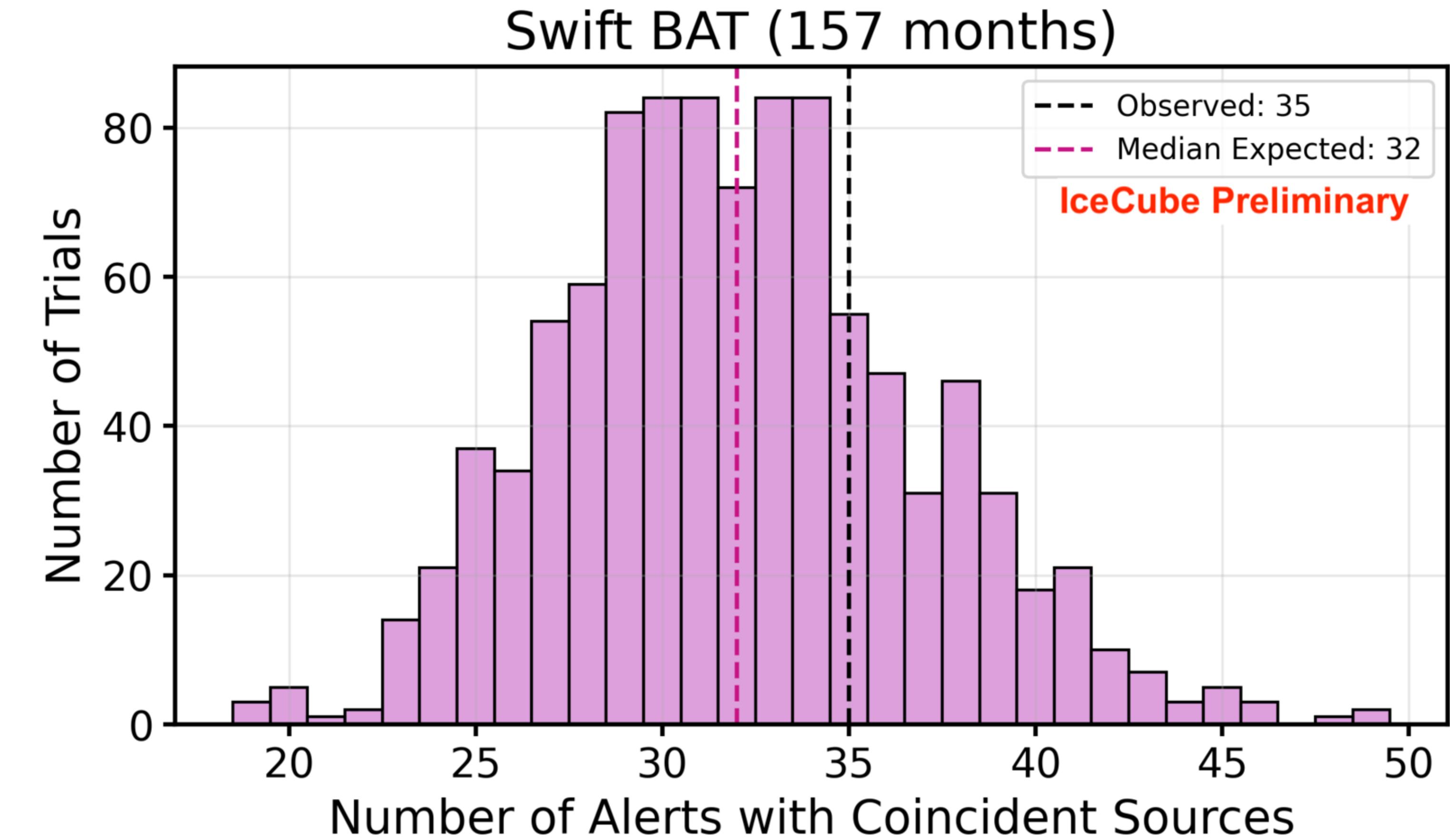
Correlation with source candidates: IceCat-2 vs IceCat-1

IceCat-2

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

PoS(ICRC2025) 362   **IceCube Preliminary**

IceCat-1

Catalog	Observed Coincidences	Expected Coincidences
4FGL	119	140
3FHL	67	77
3HWC	8	6
TeVCat	12	16
BAT	66	73

IceCube Collaboration, ApJS 29, 25 (2023)

The reduced number of expected coincidences in IceCat-2 with respect to IceCat-1 is consistent with the significant improvement in directional reconstruction we are going to introduce in IceCat-2

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Coverage and robustness of new reco algorithms...

From realtime benchmark simulations, each resimulated 100 times

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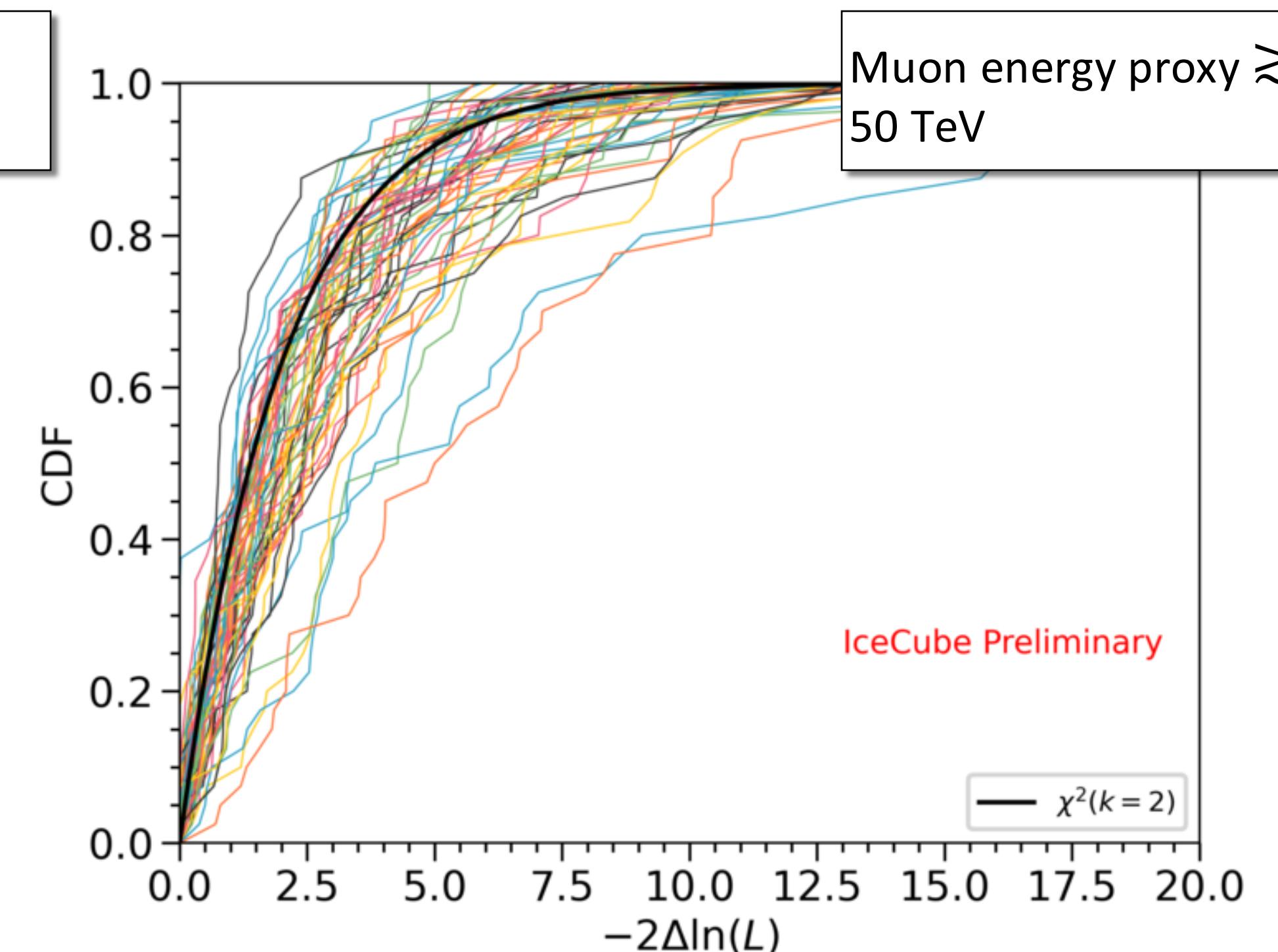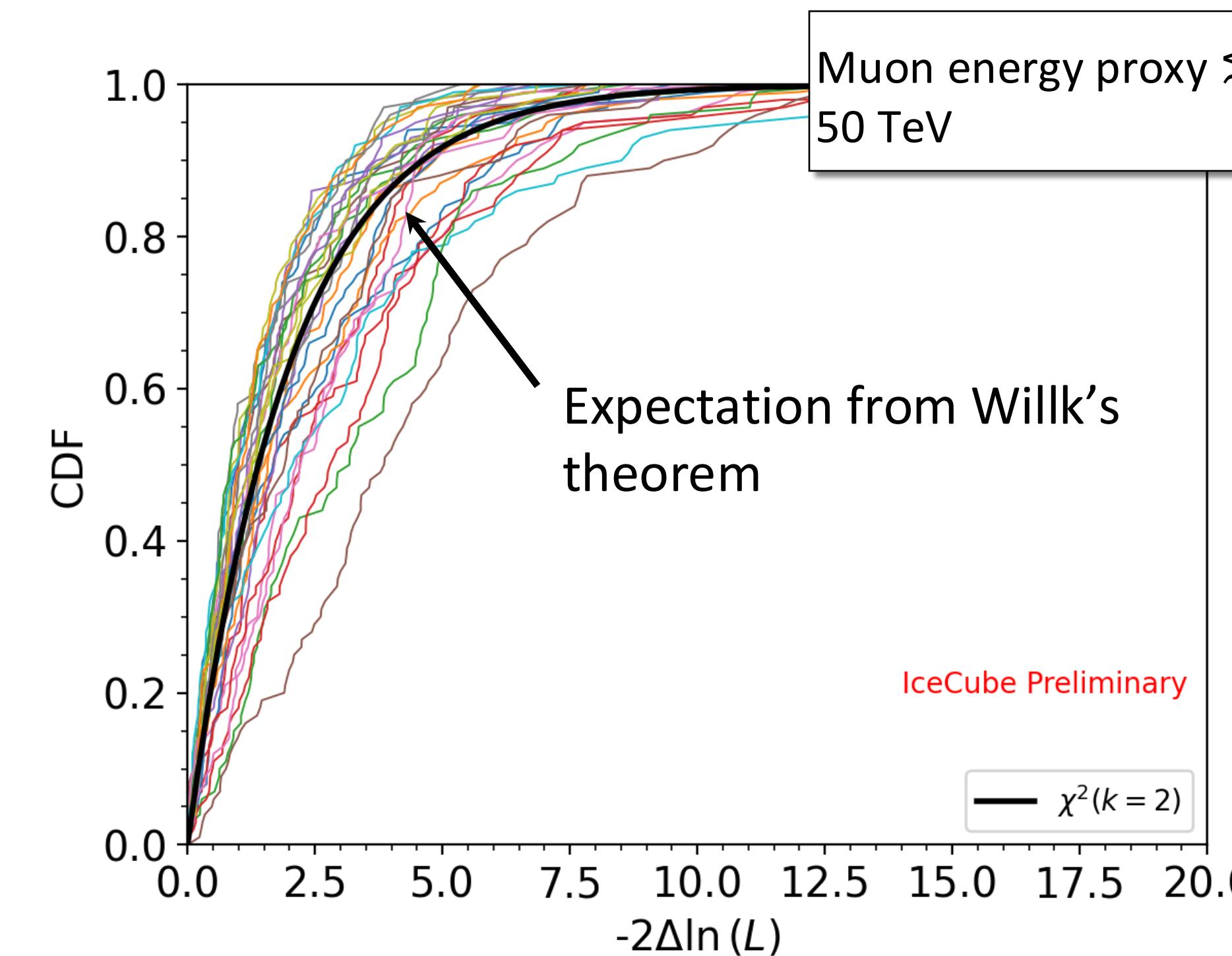

$\text{CDF} \rightarrow$ Cumulative distribution function

$\Delta\ln(L) \rightarrow$ Log-likelihood diff between true and reconstructed best-fit directions (simulations)

Giacomo Sommani, *IceCat-2: Updated IceCube Event Catalog of Alert Tracks, TeVPA* 2025, 06/11/2025

IceCube Preliminary

CDF

$2(l^* - \hat{l})$

Resimulated event
$\chi^2(k=2)$

T. Yuan., PoS(ICRC2023) 1005
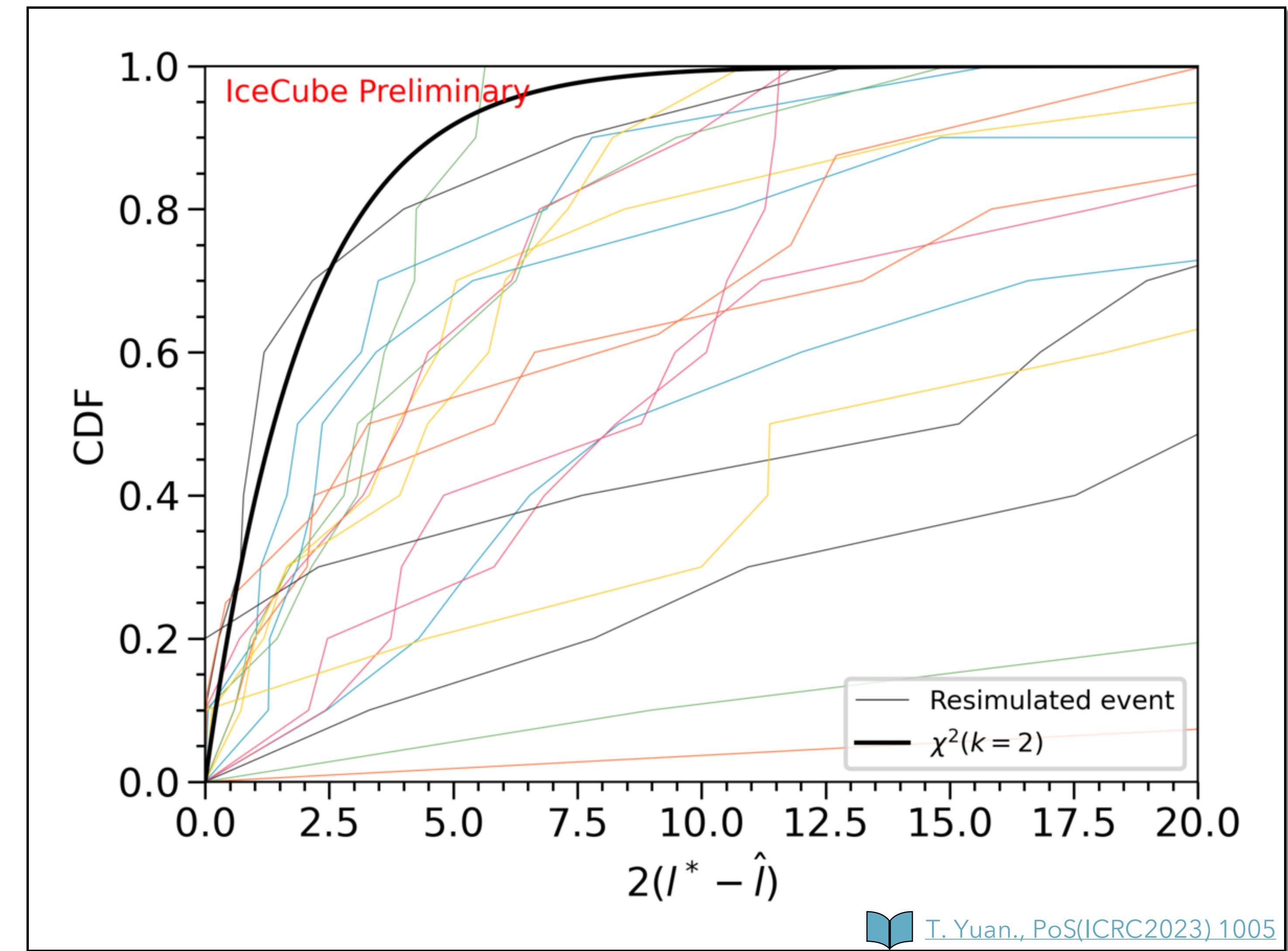
This refers to the reconstruction algorithms used for the refined track alert reconstruction before September 2024, and therefore also adopted to process IceCat-1

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IceCube realtime astrophysical neutrino alert ang. resolution

At alert selection value (based on results from reconstructions sent out via the first GCN notice)
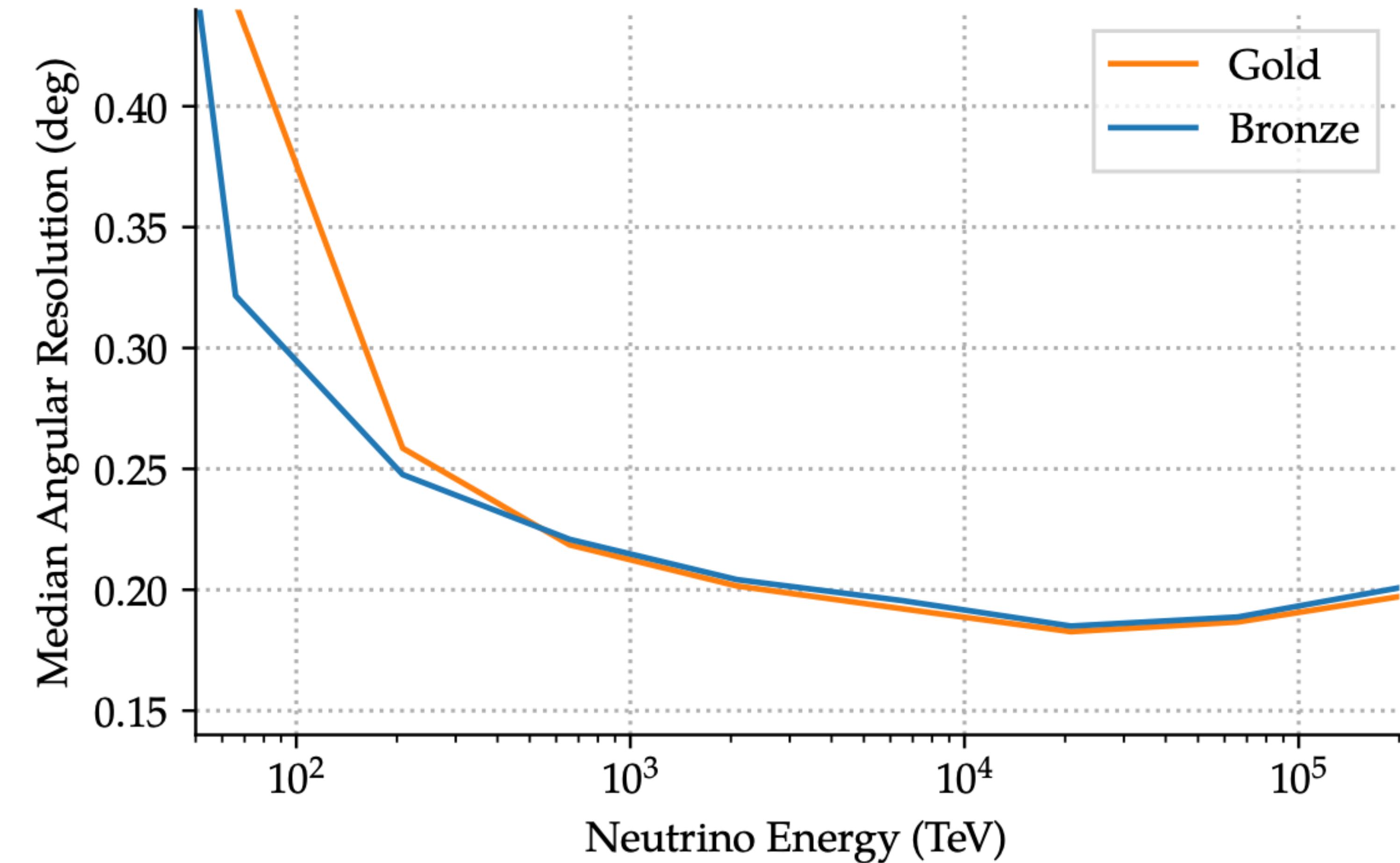
IceCube + IceTop Veto
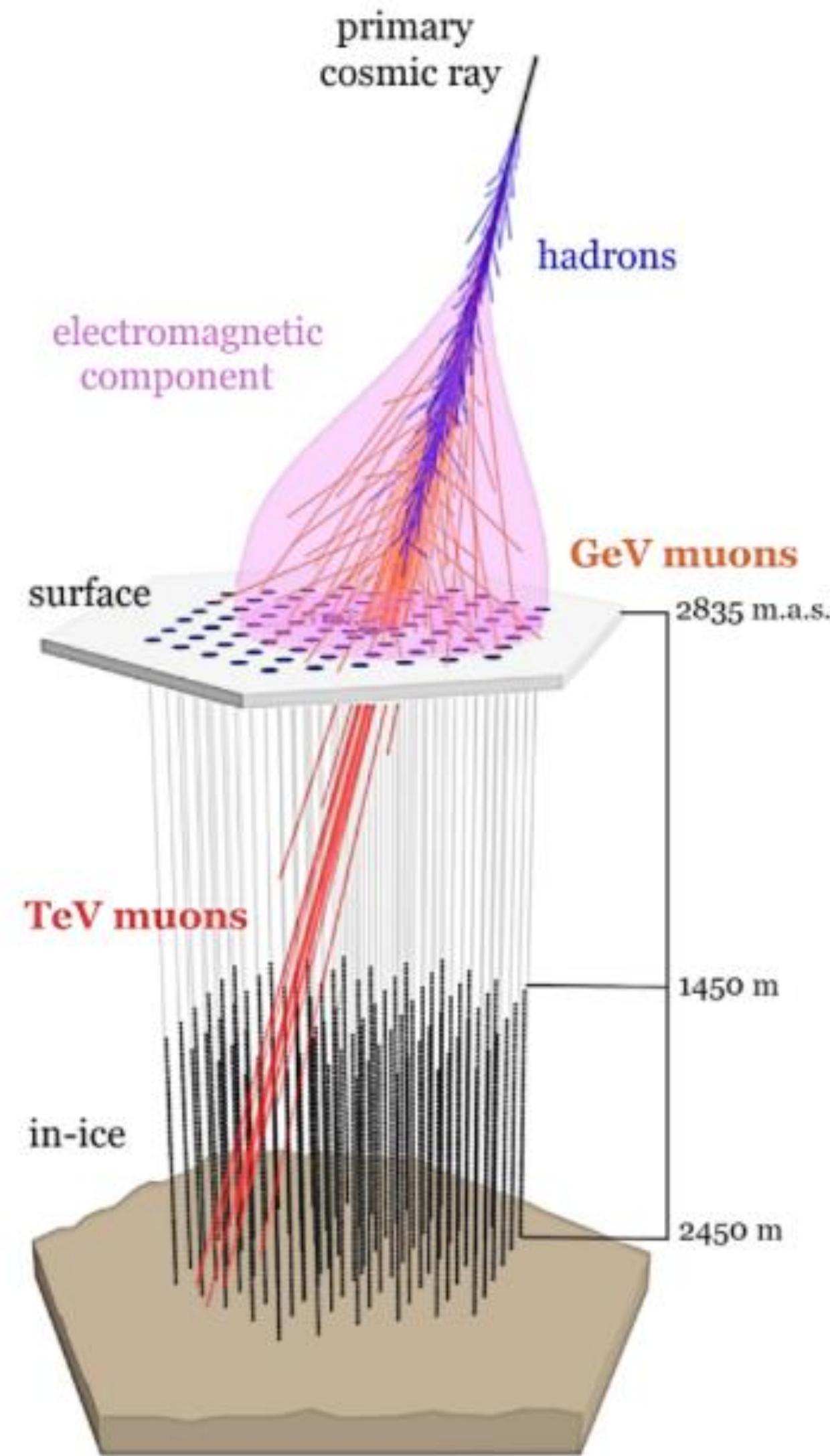
Measurements from the IceCube surface array, called IceTop, combined with tracks of high-energy muons in the ice, allow us to remove from the sample those track alerts associated with extensive air showers caused by cosmic-ray interactions with nuclei in the Earth's atmosphere.