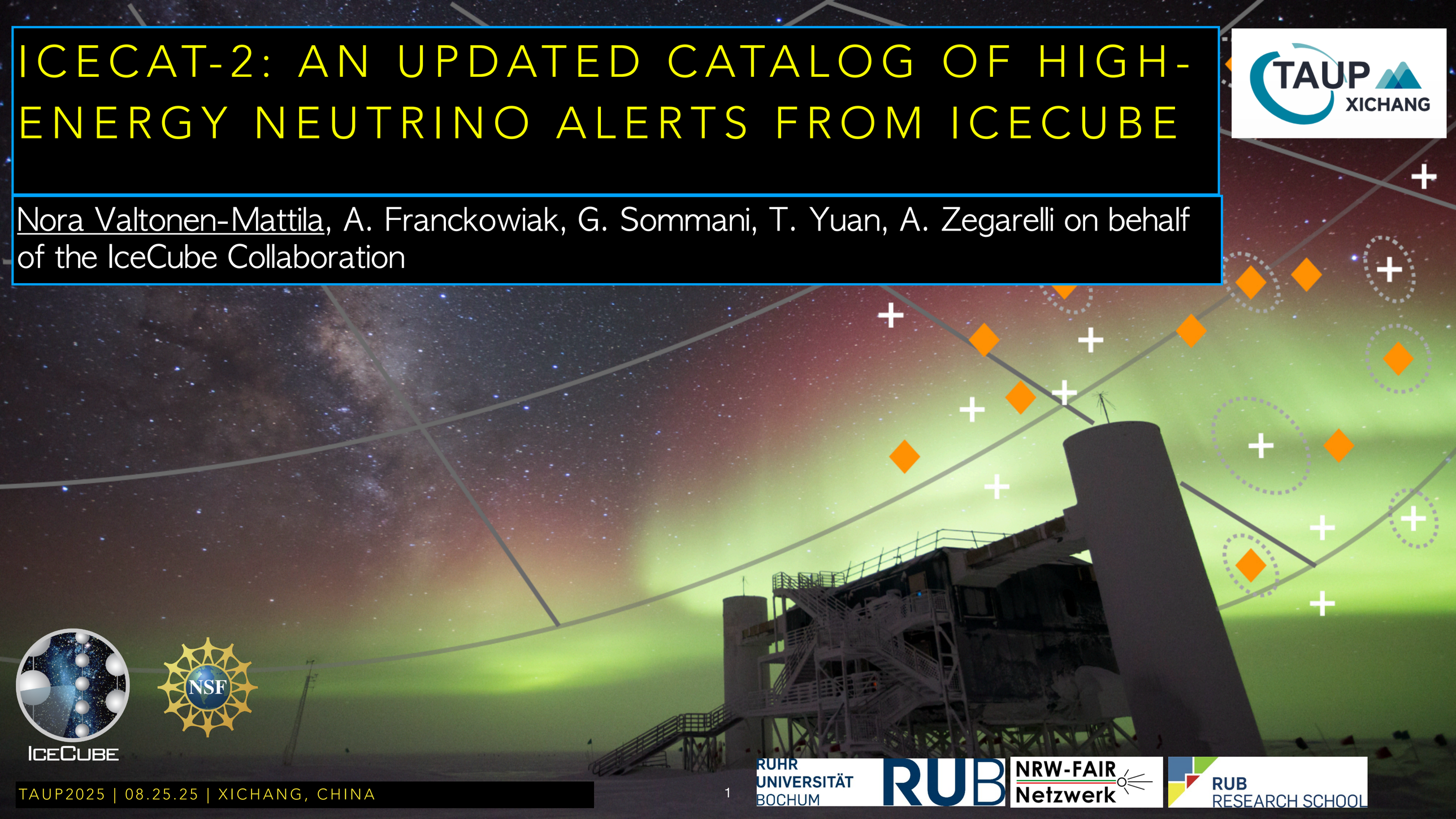
ICECAT-2: AN UPDATED CATALOG OF HIGH-ENERGY NEUTRINO ALERTS FROM ICECUBE

Nora Valtonen-Mattila, A. Franckowiak, G. Sommani, T. Yuan, A. Zegarelli on behalf of the IceCube Collaboration



ASTROPHYSICAL NEUTRINO PRODUCTION

Supernovae

Death of stars

Neutron Star Mergers

Gamma-ray Burst (GRB)

Arise from death of stars & mergers

Active Galaxies

And more…

They can produce a plethora of messengers, including low and high energy neutrinos.

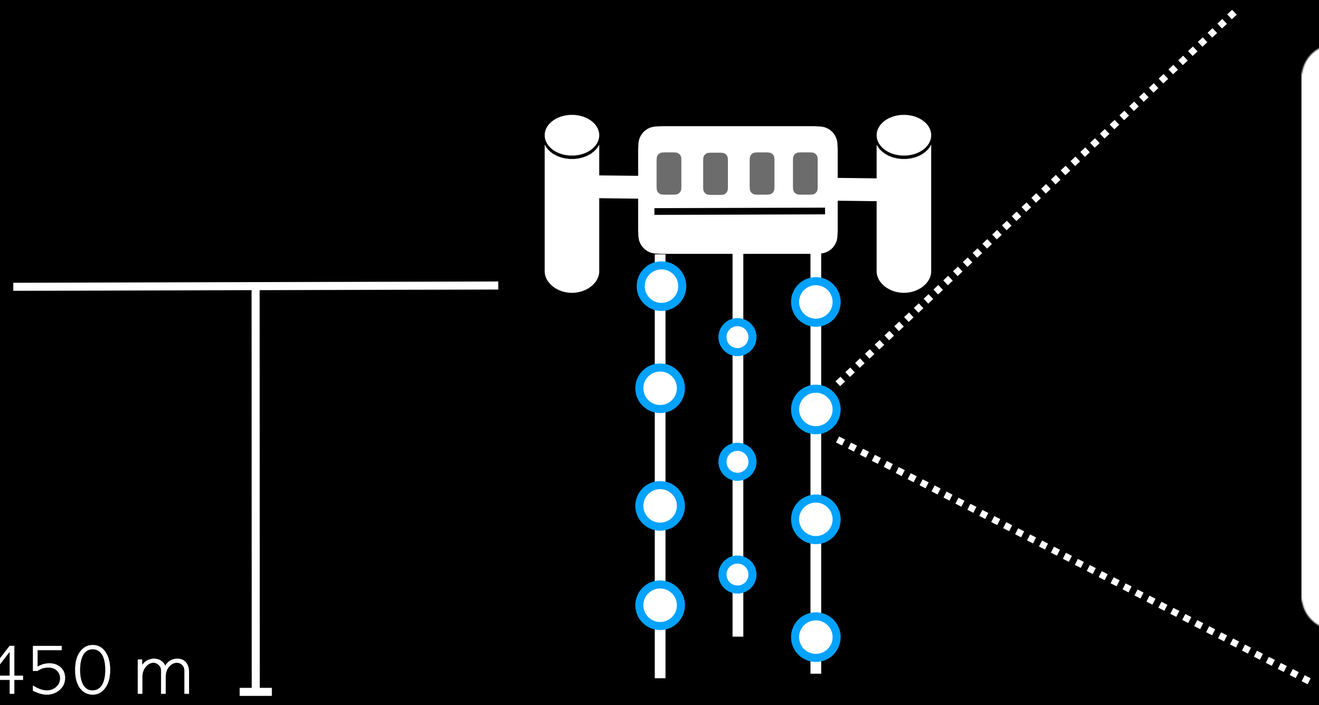
Cosmic-ray (CR) acceleration

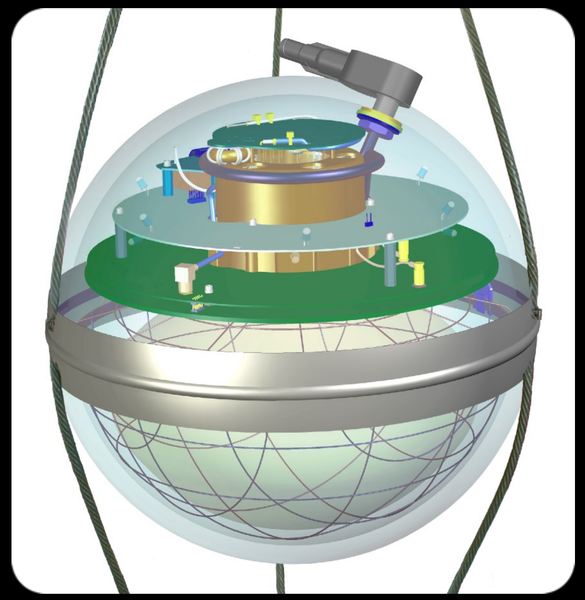
$$X + \pi^{\pm} \rightarrow X + e^{\pm} + \nu$$

ICECUBE NEUTRINO OBSERVATORY

Located at the South Pole

5160 sensors buried in 1km^3 of ice





We detect Cherenkov light produced when charged particles pass through ice

All-sky observatory monitoring 24/7, with over 10 years of data

ASTROPHYSICS IN ICECUBE

We can do astrophysics in a wide range of neutrino energy: MeV to PeV

〈 GeV

- Understand EoS
- Understand neutrino properties from very dense environments

〉 GeV

- Understand the diffuse flux origin
- Understand CR acceleration

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Multi-Messenger astronomy

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Multi-Messenger astronomy

↓

Transient sources

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Multi-Messenger astronomy

↓

Transient sources

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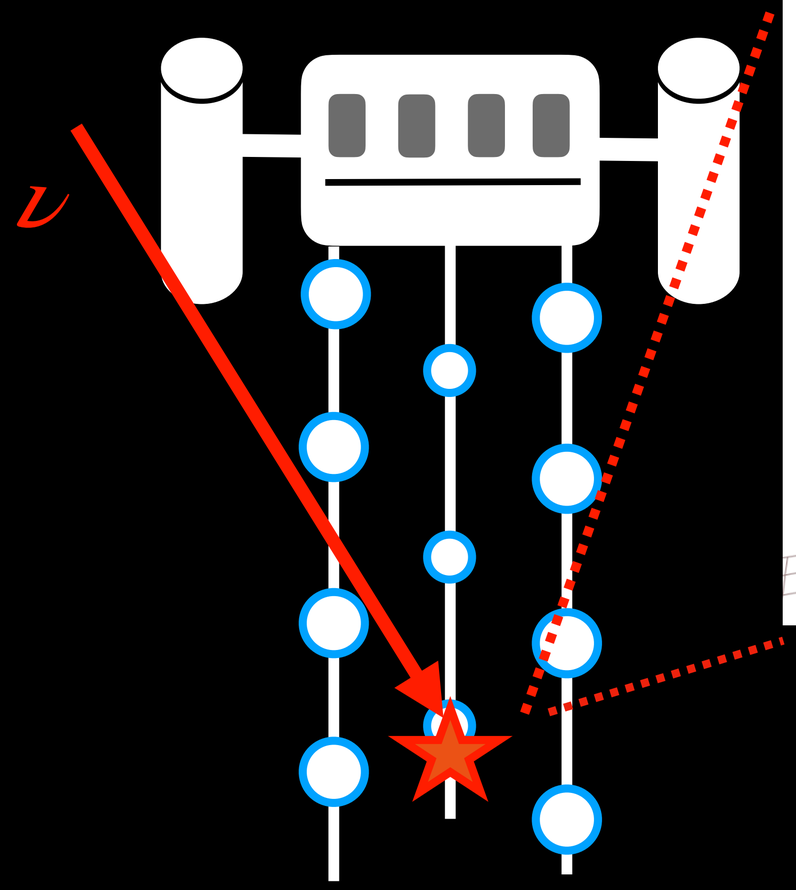
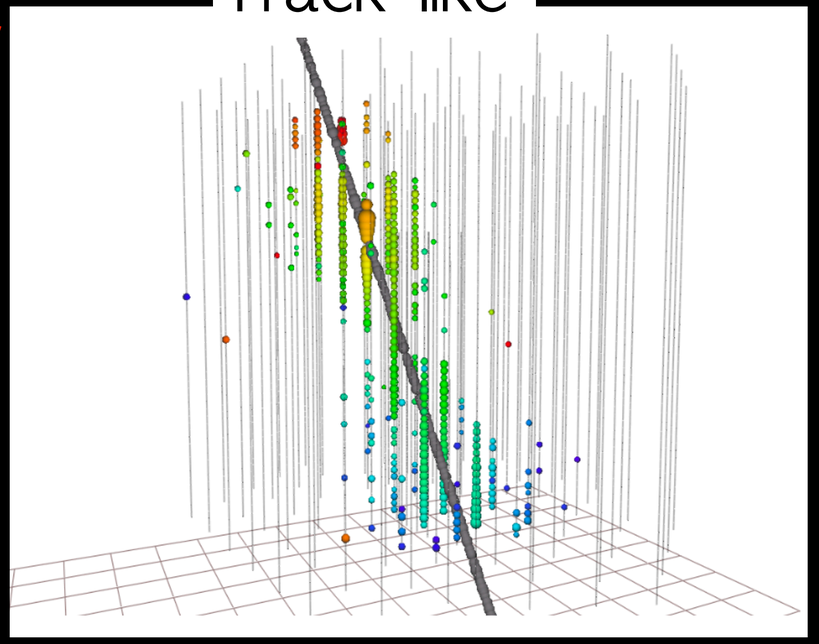
We need to respond fast to the community —〉 Realtime program

HOW WE OBSERVE HIGH-ENERGY NEUTRINOS



Track-like

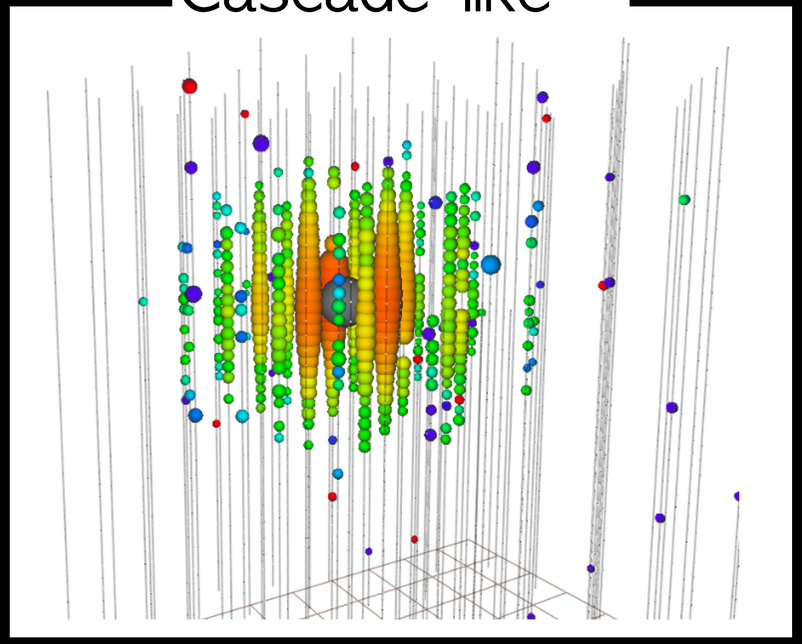


ν_μ CC interactions

Good for directionality:

$$\theta_{\nu_\mu} \sim \frac{0.7^\circ}{\sqrt{E_\nu[TeV]}}$$

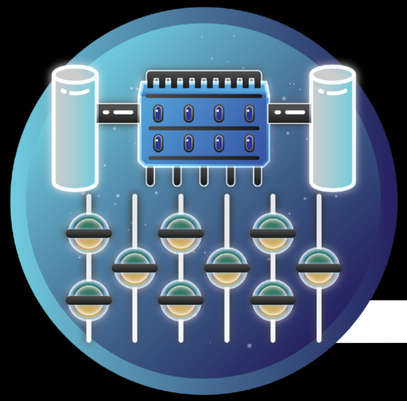
Cascade-like



ν_e, ν_τ CC interactions and all flavor NC

Angular resolution
$\sim 5^\circ - 15^\circ$

INCEPTION OF ICECUBE REALTIME TRACK ALERTS



ICECUBE
COMPLETED

2011

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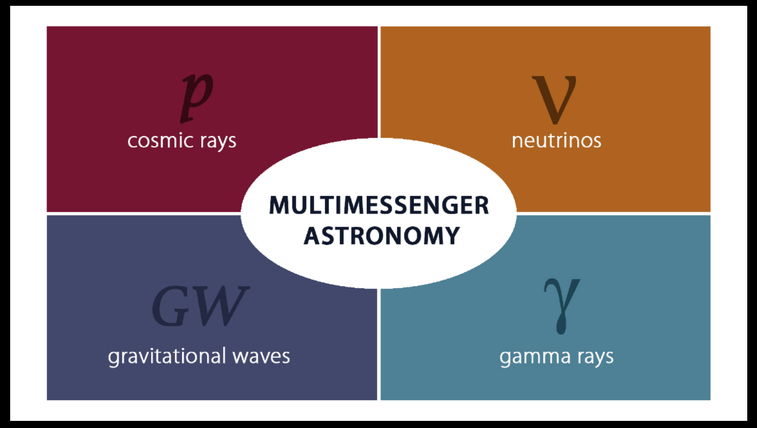

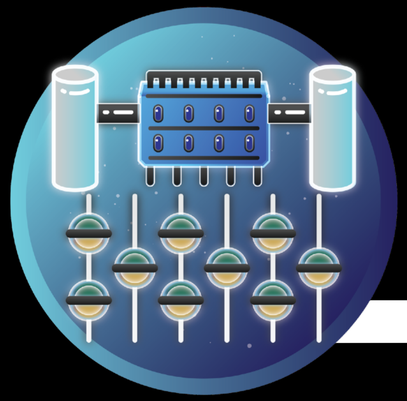

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2011

LAUNCH OF THE
ICECUBE REALTIME PROGRAM

2016

Public Neutrino Alerts
issued within one minute

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

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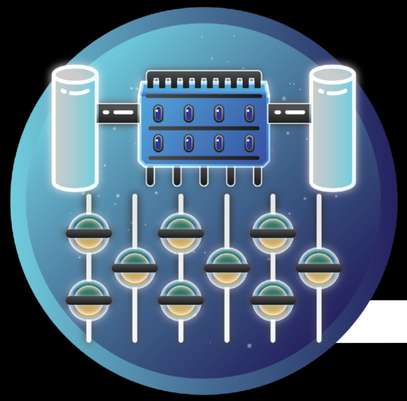

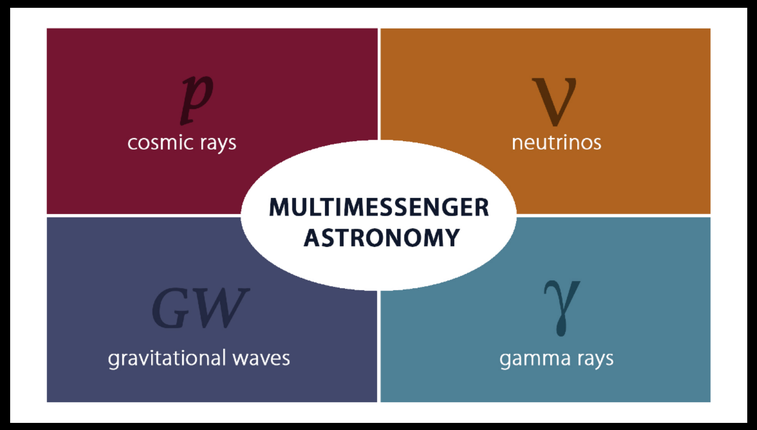

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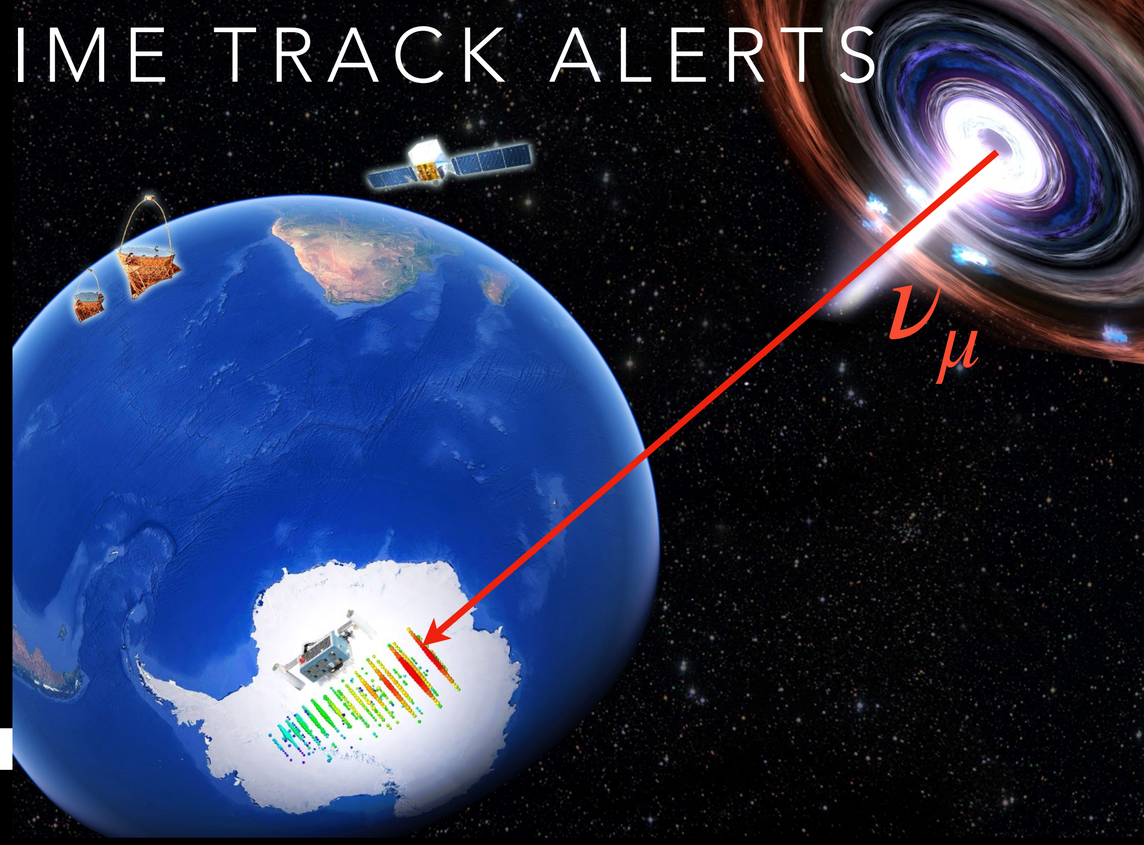

Alerts target muon tracks from CC interactions of astrophysical origins for best source localization

Public Neutrino Alerts
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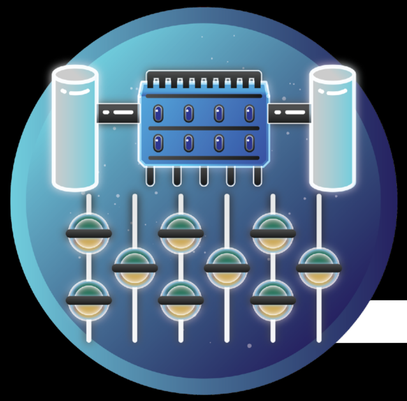

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A milestone in multi messenger astrophysics!

BLAZAR TXS 0506+056
NEUTRINO EMISSION IDENTIFIED

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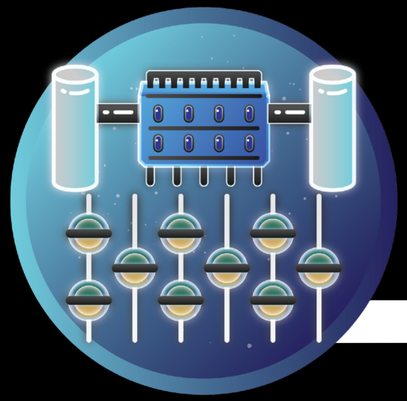

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IceCube Collaboration, Science 361, 146-151 (2018)

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

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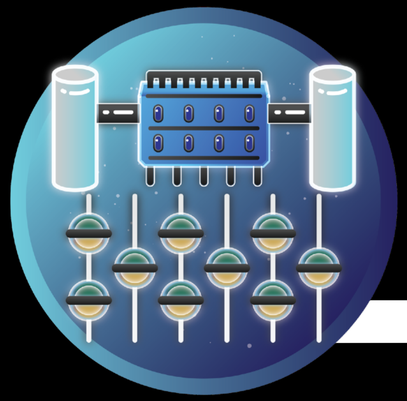

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Two categories of track alerts

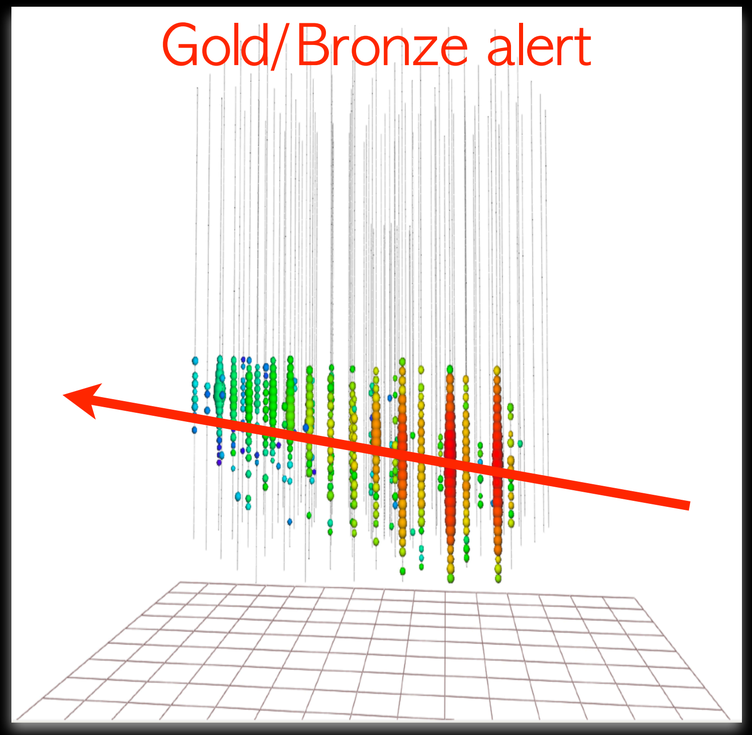
- Gold: average $\sim 50\,\%$
- Bronze: average $\sim 30\,\%$ of being astrophysical origin

Still active now…

Expanded and improved alert selection

Blaufuss et al., PoS(ICRC2019) 1177

TRACK ALERTS WORKFLOW



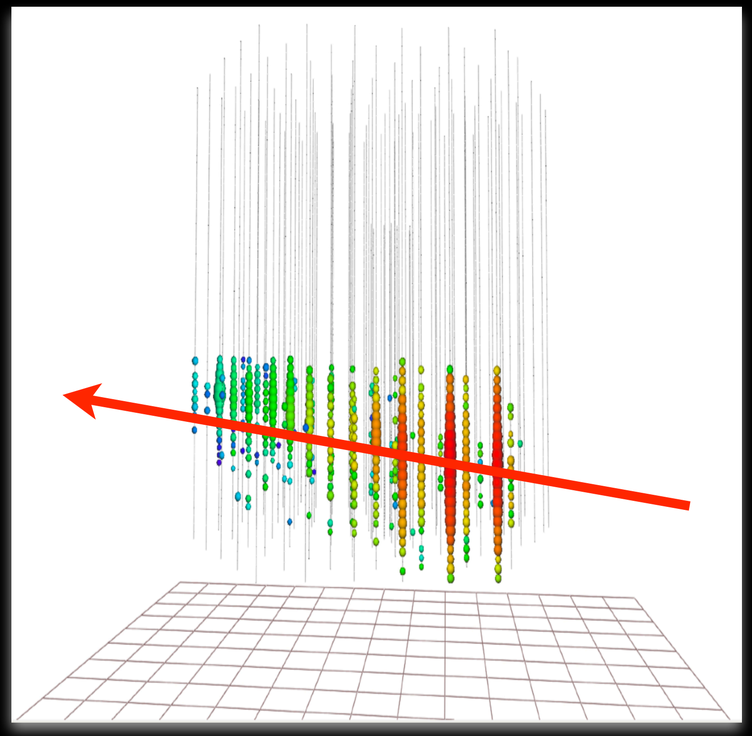
1. General Coordinate Network (GCN) Notice

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

〈 1 min

TRACK ALERTS WORKFLOW

Gold/Bronze alert



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2. GCN Circular + Updated GCN Notice

Updated reconstruction with more sophisticated algorithms (processed at North)

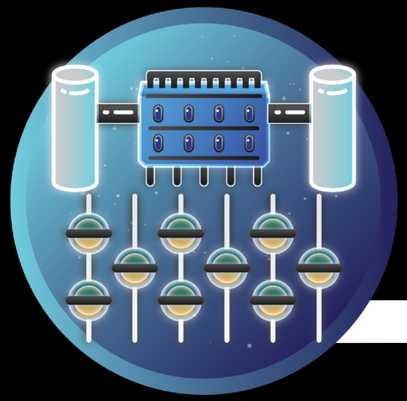
〈 a few hours

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

ICECAT-1: ICECUBE'S 1ST EVENT CATALOG OF ALERT TRACKS

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

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

IceCube Collaboration, ApJS 29, 25 (2023)

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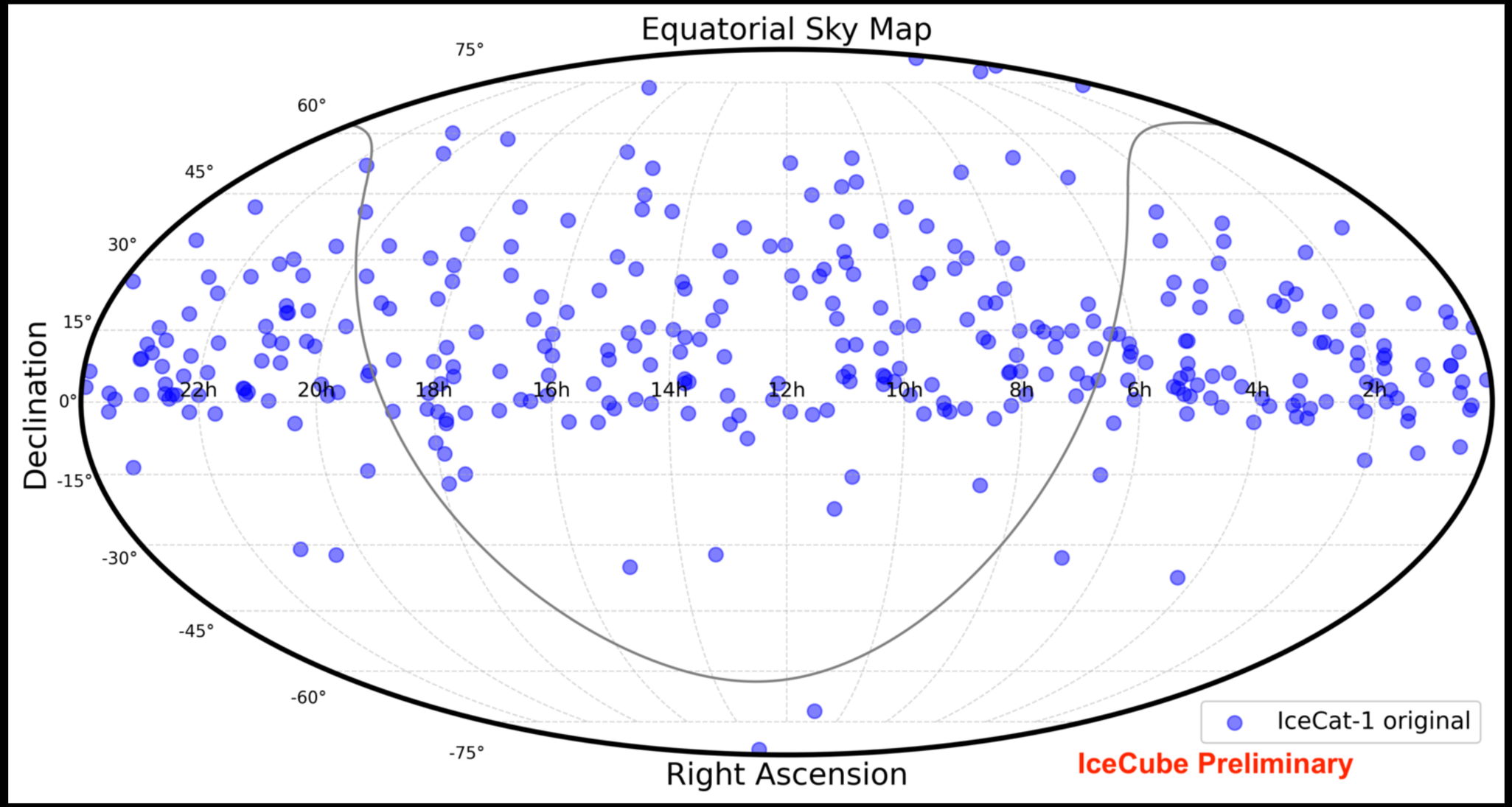

TOWARDS ICECAT-2 RELEASE

What is new

The preliminary sample

Comparison
IceCat-1 / IceCat -2

Correlation with sources:
Individual and catalogs

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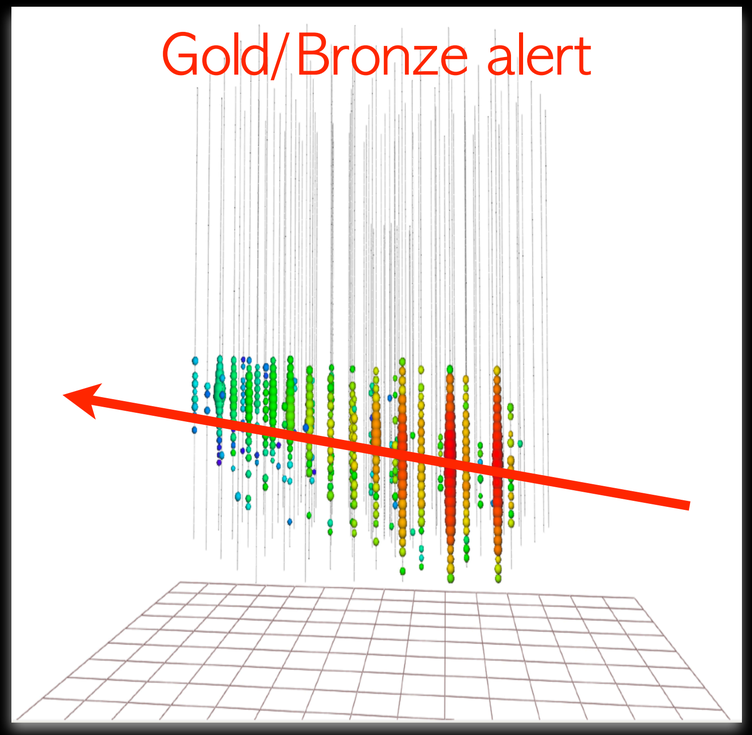

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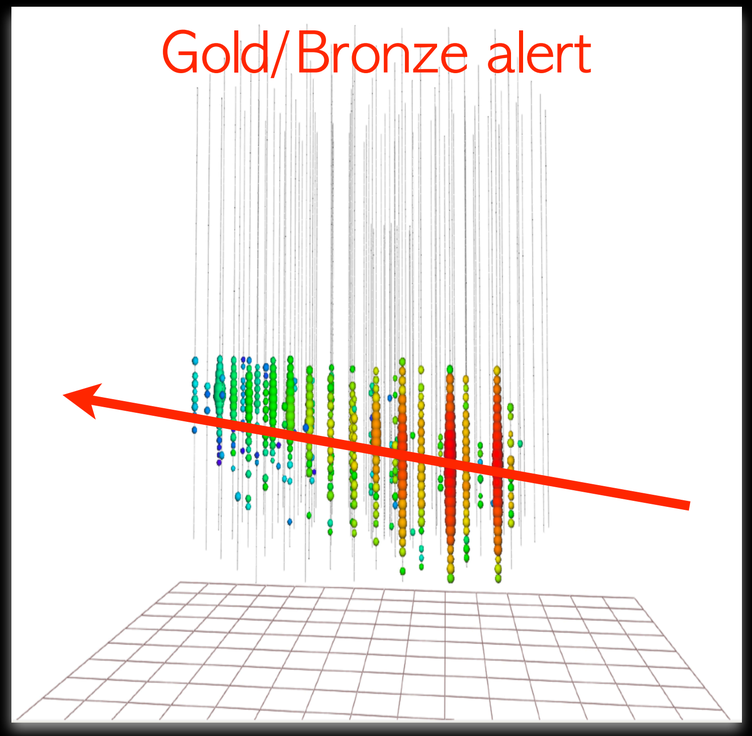
UPDATE ON TRACK ALERT SYSTEM



September 2024 Track Alert System Update

1. Announced via GCN Circular 38267

Results from a fast and simplified

- Reconstruction algorithm was updated
- Improvement in:
  - Angular resolution
  - Coverage of directional uncertainty

G. Sommani & T. Yuan PoS(ICRC2025)1184

〈 1 min

2. GCN Circular + Updated GCN Notice

Updated reconstruction with more sophisticated algorithms (processed at North)

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ICECAT-2: WHAT IS NEW

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- Excluded likely atmospheric-muon events from IceCat-1:
  - Oct. 2022: a veto method has been applied to reject atmospheric muons that might pass the alert selection criteria. 📖 Amin et al.m J. Phys. Conf. Ser. 2156, 012217 (2021)
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  - Preliminary catalog presented in this talk
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- 25 additional track-like alerts since IceCat-1:
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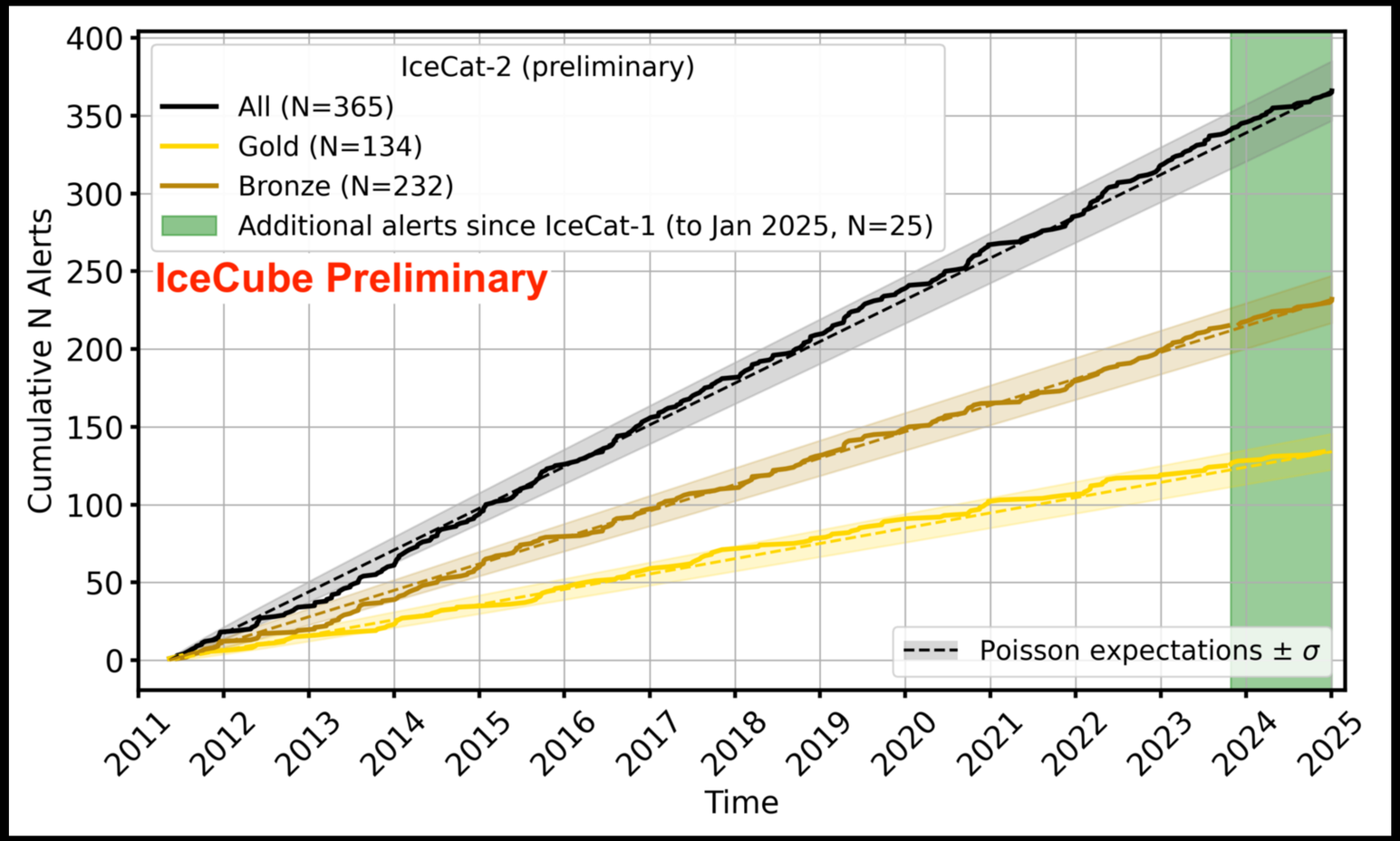
- Full reprocessing of all alerts: used most up-to-date processing and calibration

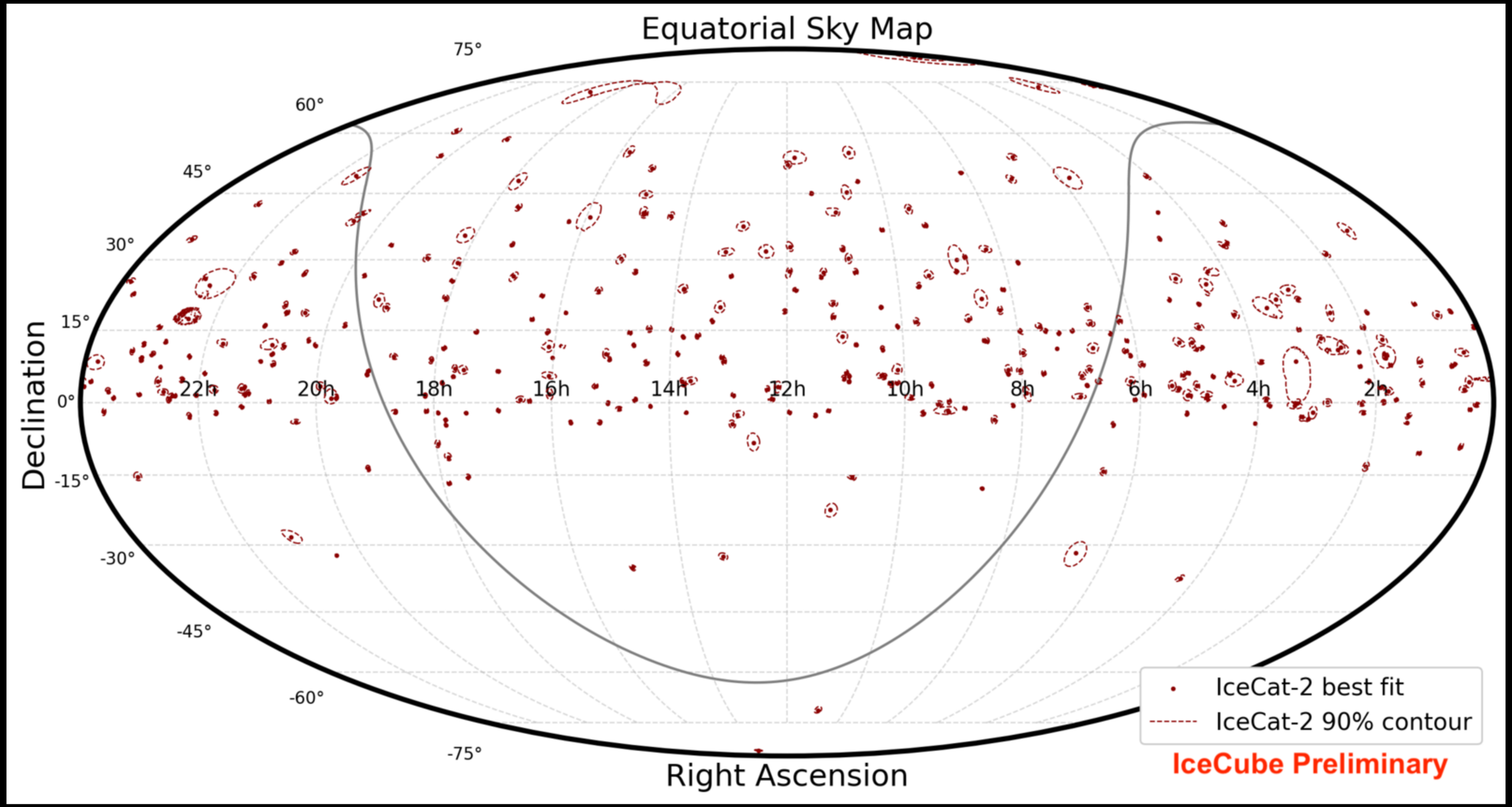
PRELIMINARY ICECAT-2 SAMPLE

Preliminary IceCat-2 catalog includes 365 track-like alerts



- Average rate: 26.8 evt/yr
- Gold: ~9.9 evt/yr
- Bronze: ~17 evt/yr

PRELIMINARY ICECAT-2 SAMPLE: SKYMAP



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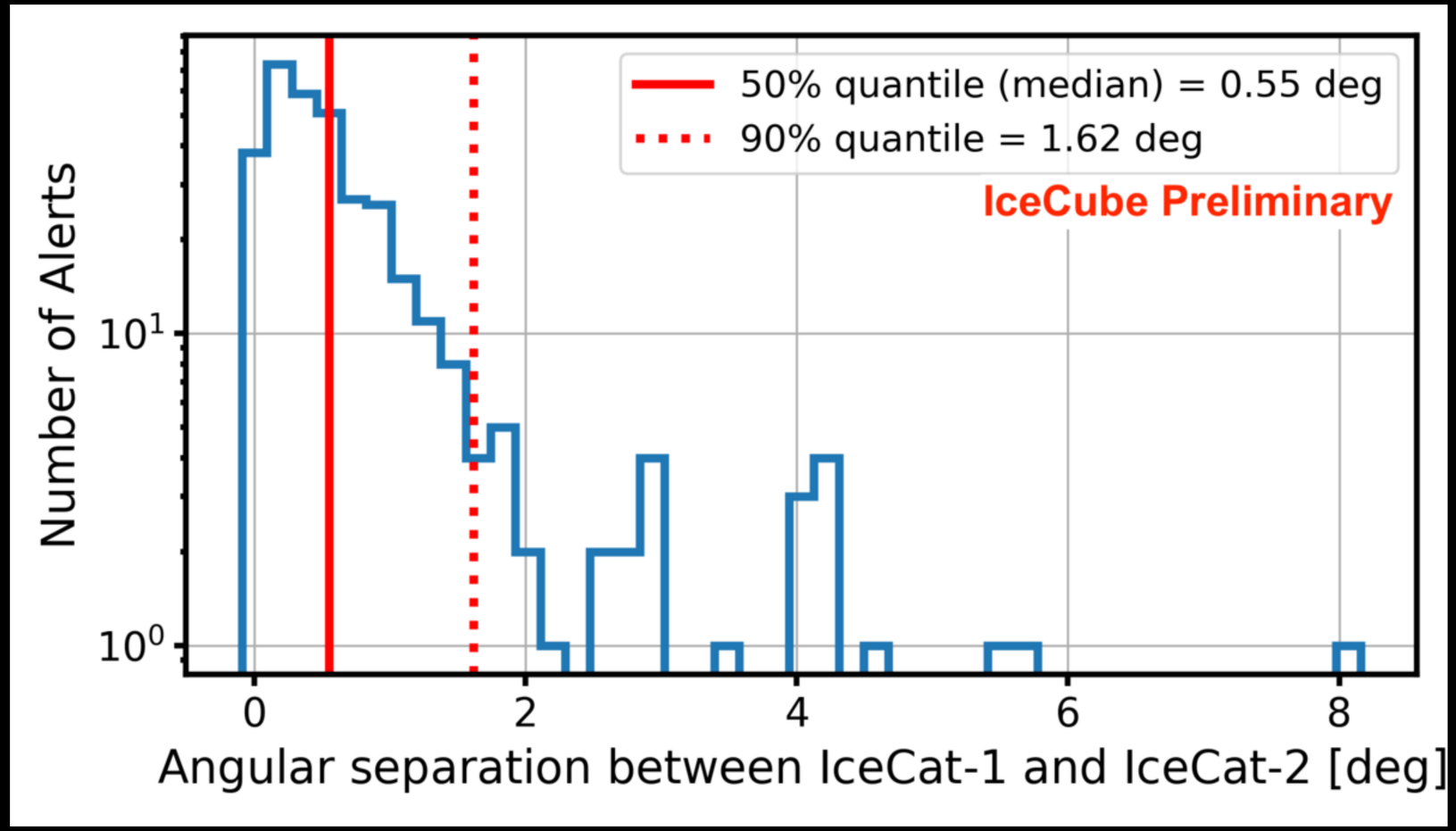
Comparison
IceCat-1 / IceCat -2

Correlation with sources:
Individual and catalogs

ANGULAR DISTANCE BETWEEN BEST FIT DIRECTIONS

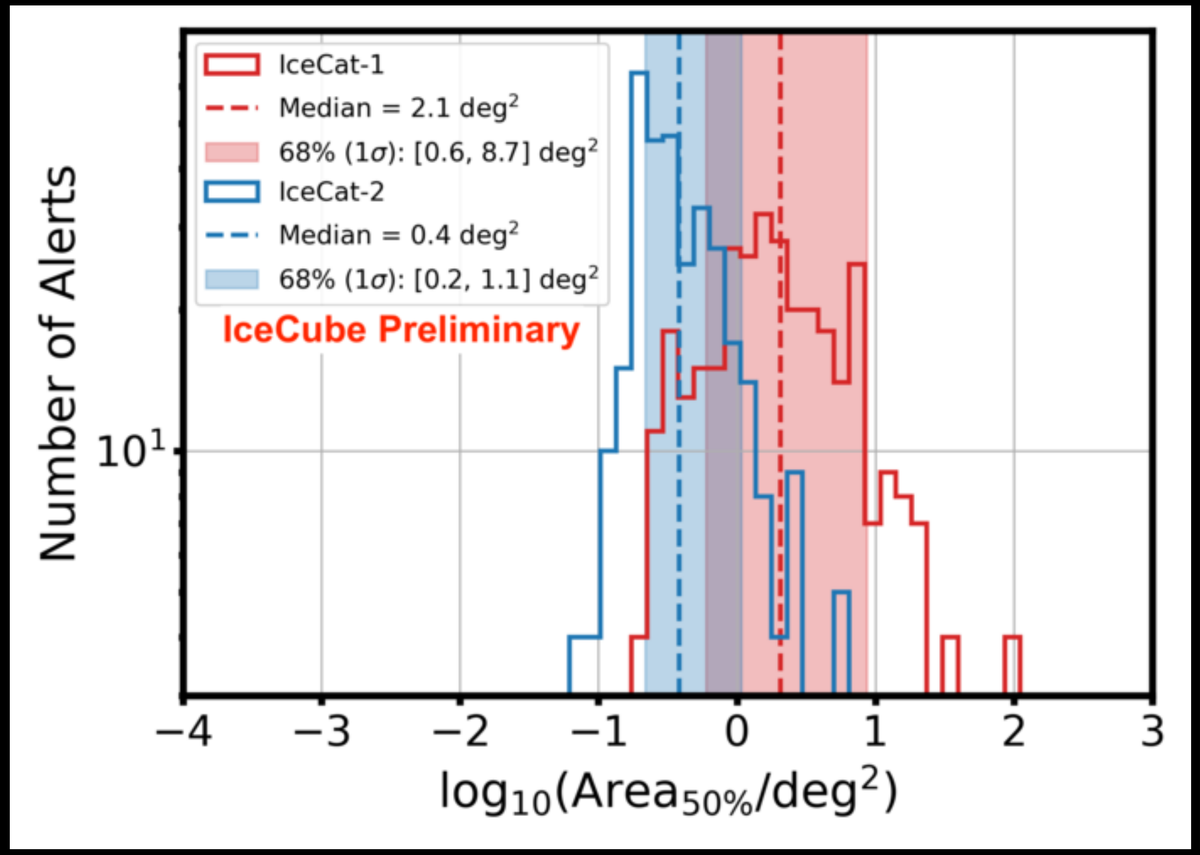


50(90)% of the alerts with angular separation below 0.55(1.62) deg

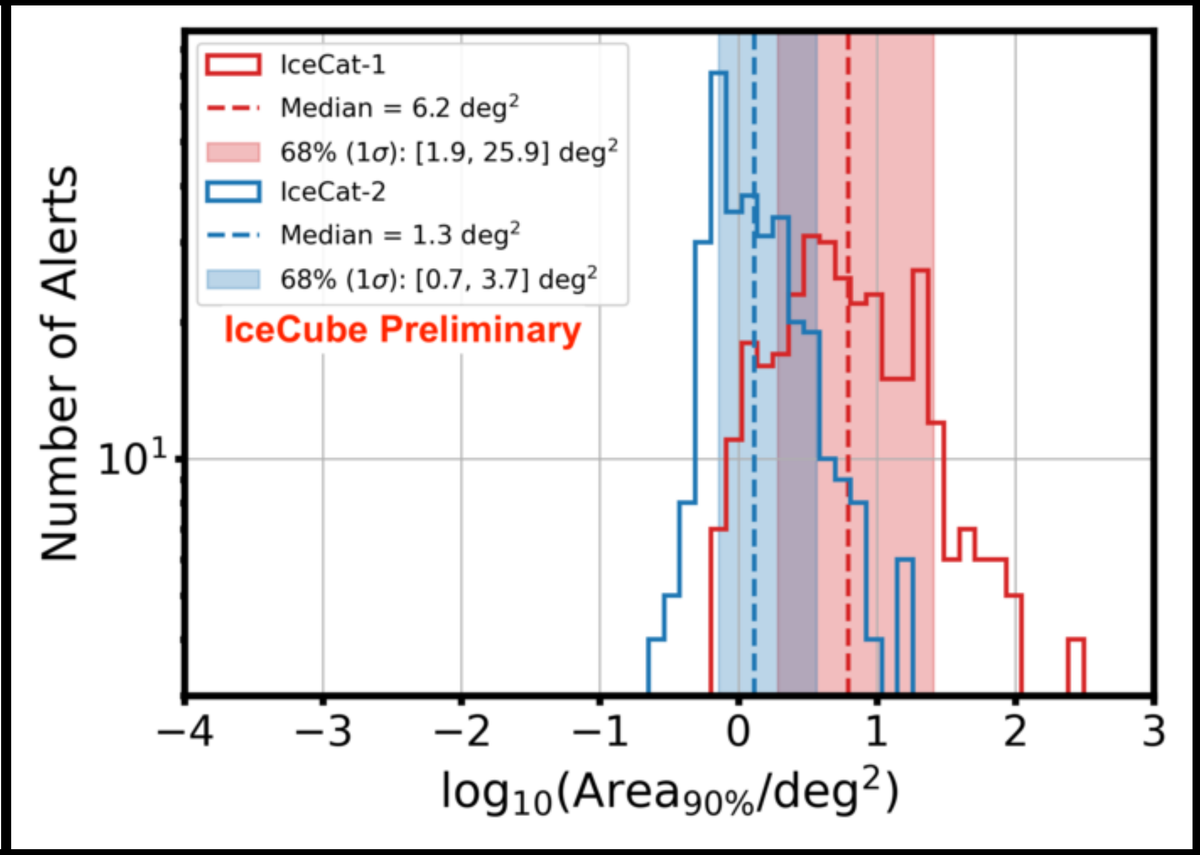
ANGULAR DISTANCE BETWEEN BEST FIT DIRECTIONS

Most notable improvement → significant reduction in localization uncertainties around the best-fit direction

50%



90%



IceCat-2:

- Median improvement on area at 50%(90%) by a factor around 5(4).
- Distributions are considerably narrower, with the spread around the median, quantified by the standard deviation σ, reduced by a factor between 8 and 9

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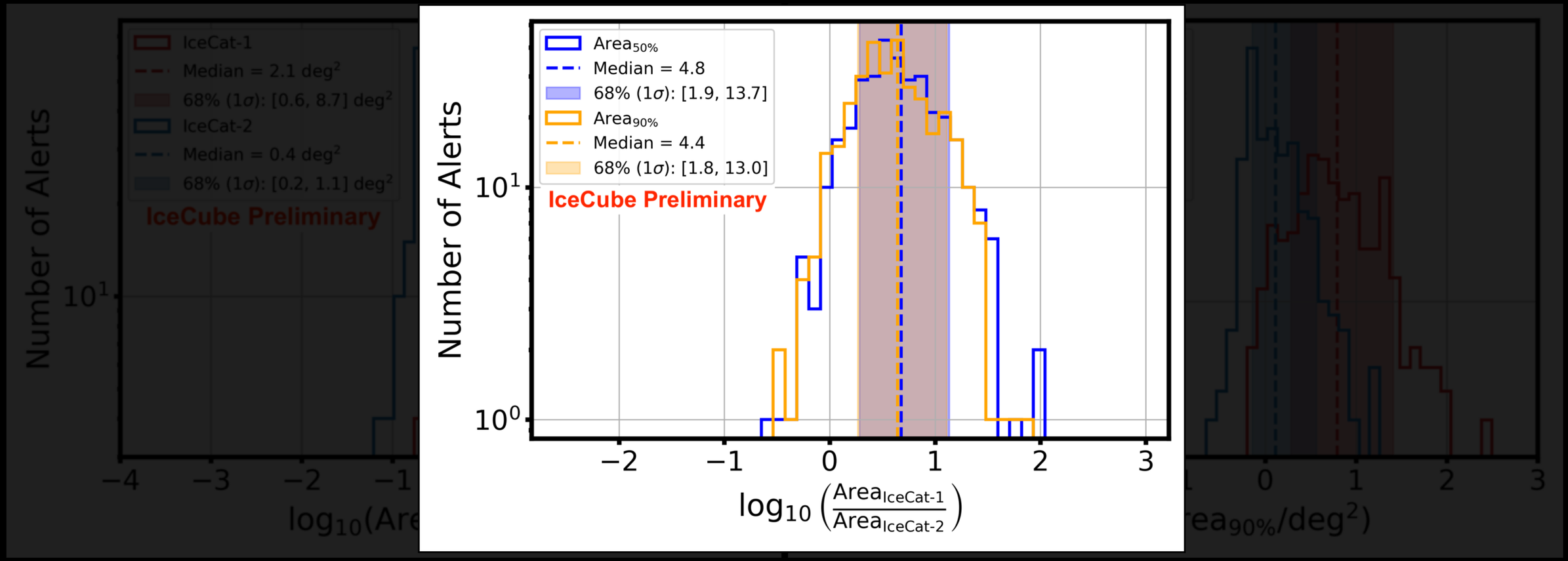

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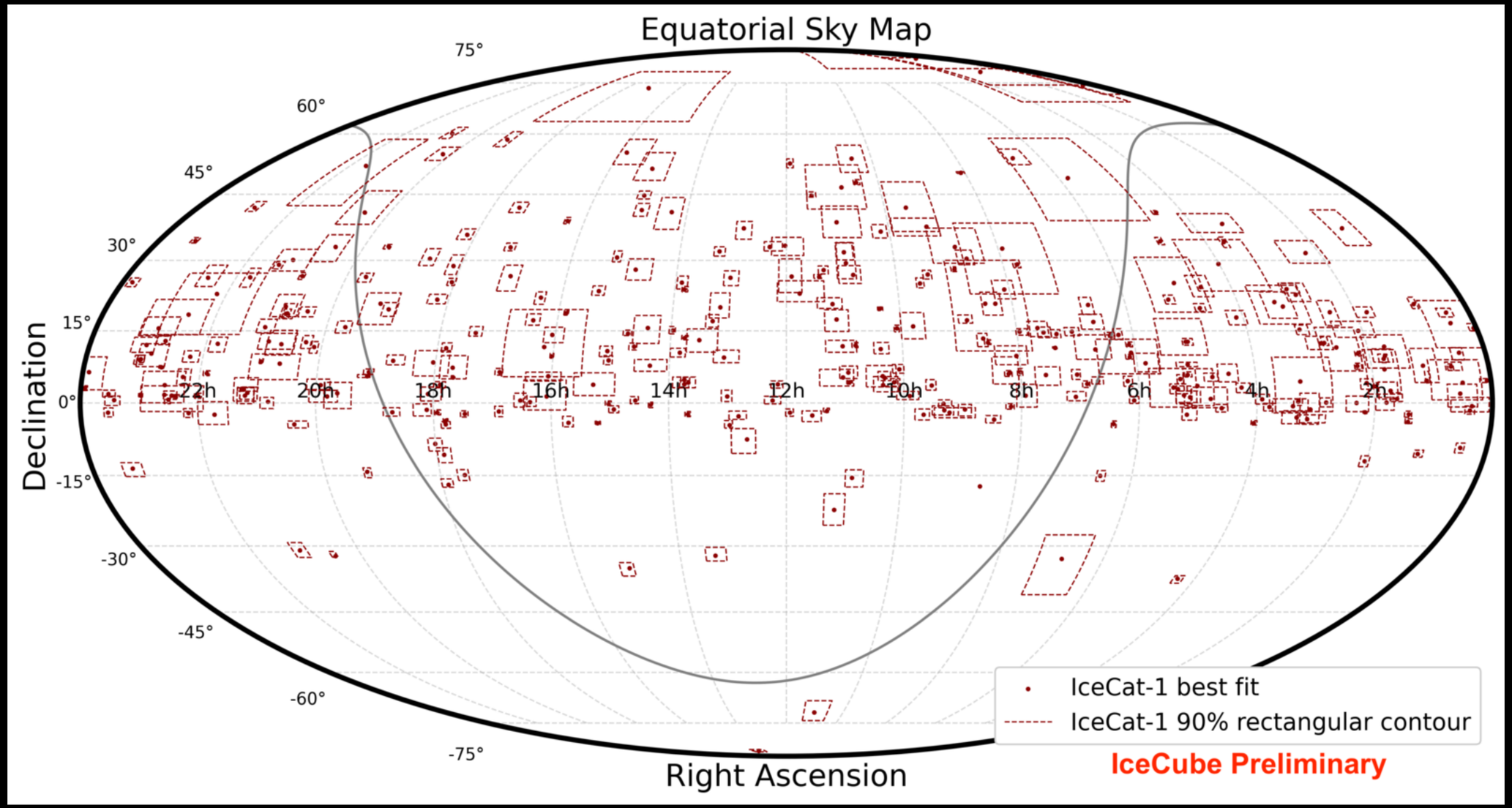
COMPARISON RECONSTRUCTION: ICECAT-1 (ORIGINAL)

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



COMPARISON RECONSTRUCTION: ICECAT-1 (NEW RECO FROM ICECAT-2)

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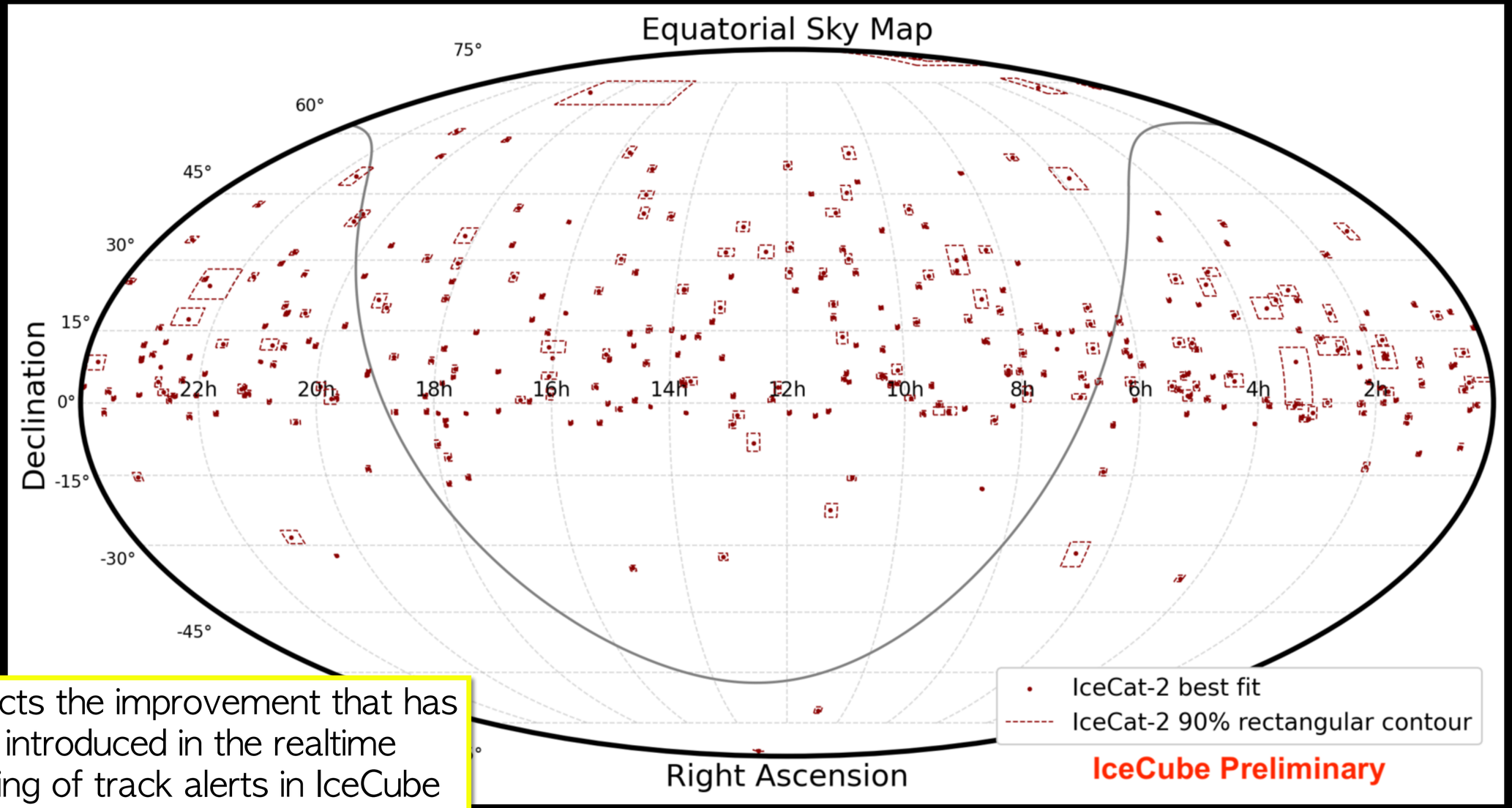

This reflects the improvement that has been introduced in the realtime processing of track alerts in IceCube

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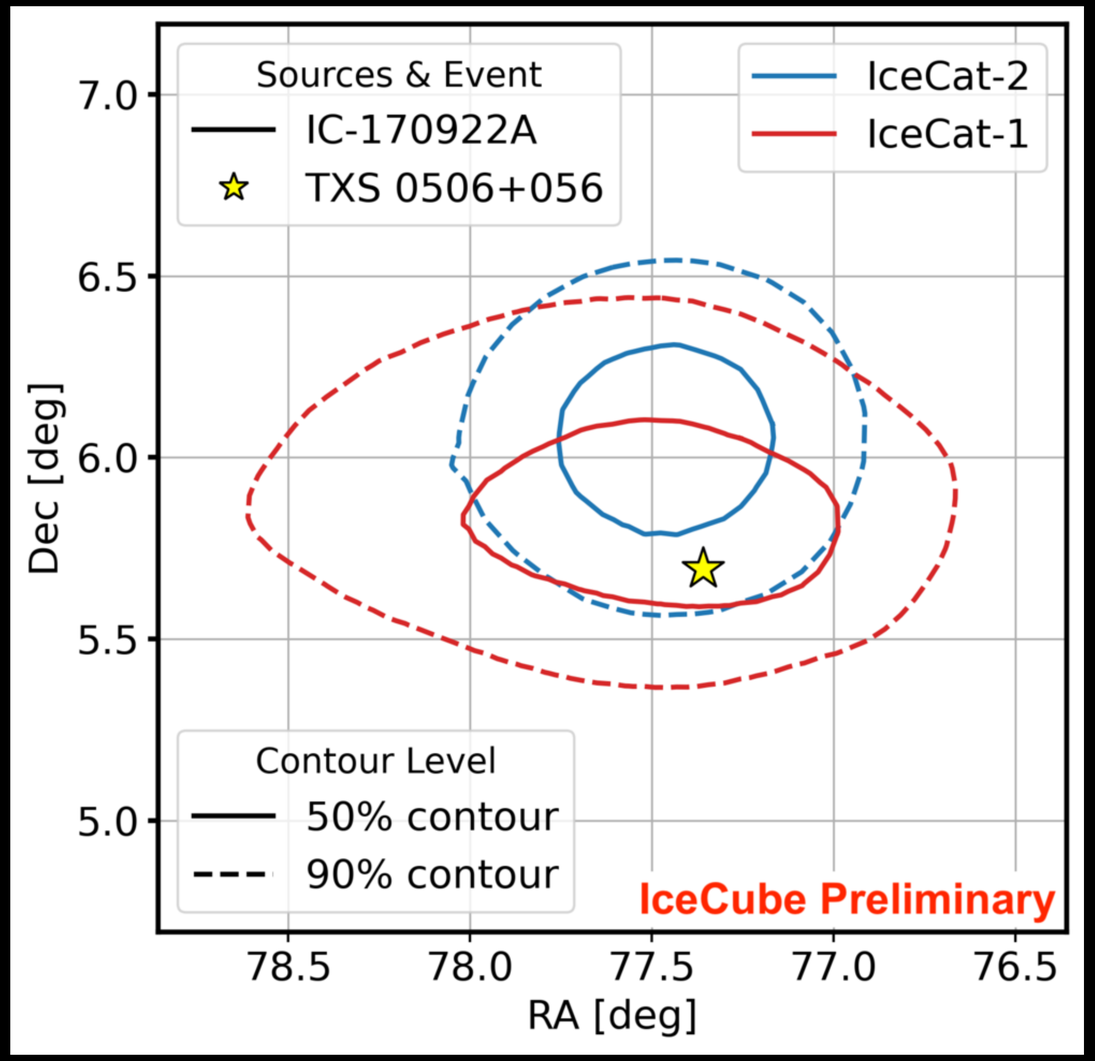
INDIVIDUAL SOURCES: TXS 0506+056

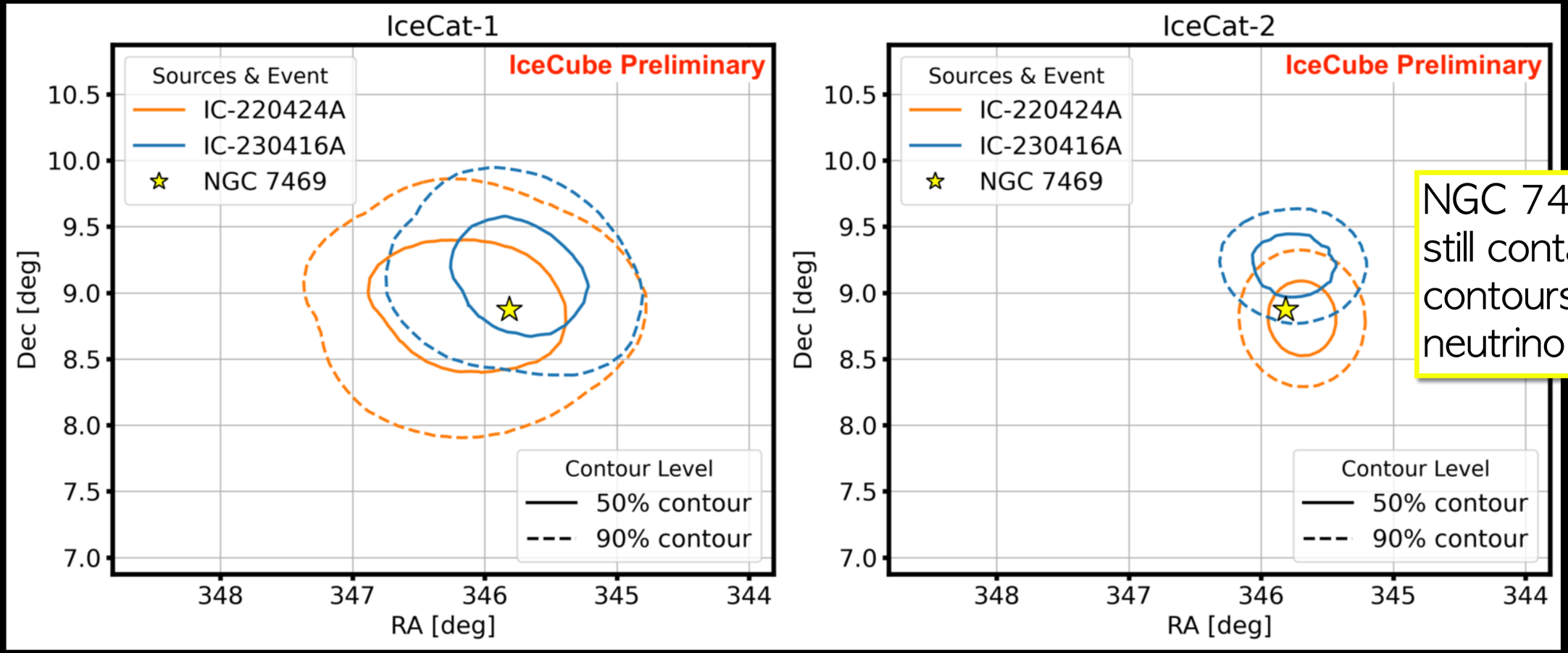


First high-energy transient identified as a potential neutrino source

- Still spatially coincident with revised IC-170922A localization
- Now lies within 90% containment vs. 50%.

INDIVIDUAL SOURCES: NGC 7469

Two coincident O(100) TeV IceCube neutrino alerts (IC220424A and IC230416A)



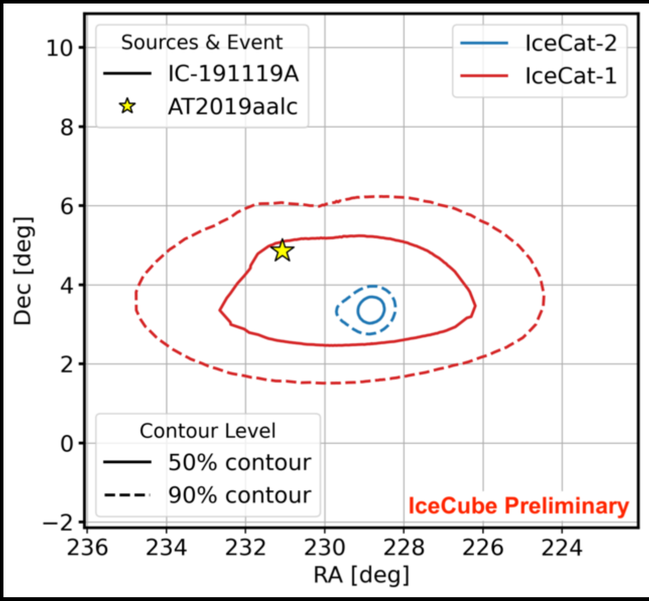
NGC 7469 position is still contained within the contours of both neutrino alerts

Sommani et al., ApJ 981 (2025), 103

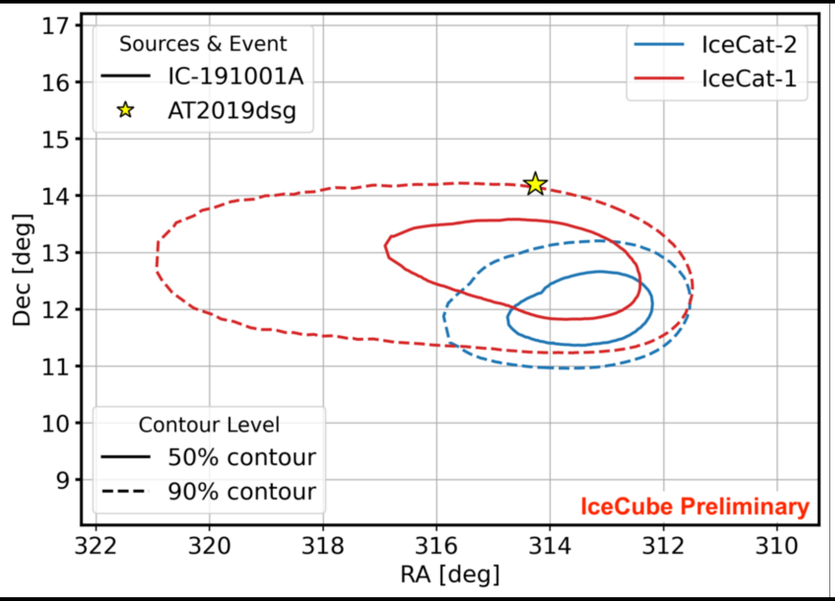
INDIVIDUAL SOURCES: TIDAL DISRUPTION EVENTS (TDE)

Three TDE candidates 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

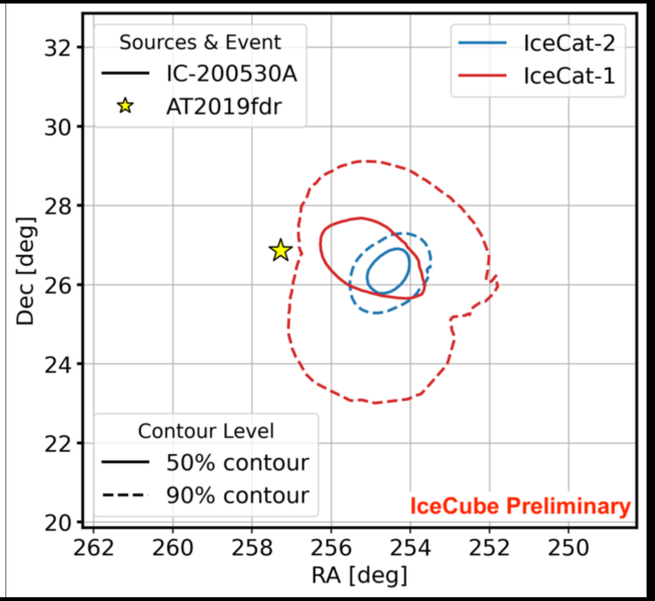
AT2019aal



AT2019dsg



AT2019fdr



TDE positions are outside the updated containment regions

Associations between these TDEs and the IceCube alerts are disfavored

Stein et al. 2021, Reusch et al. 2022, van Velzen et al. 2024

CATALOG CORRELATION WITH SOURCE CANDIDATES

- Directional correlation with catalogs:
  - Gamma-ray: 3FHL, 4FGL-DR4, 3HWC and TeVCat.
  - X-ray: Swift-BAT
- 365 IceCat-2 alerts: search sources within 90% positional uncertainty
- Chance rate: 1000 RA randomizations and matches counted

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

IceCube Preliminary

Consistent with median expectation

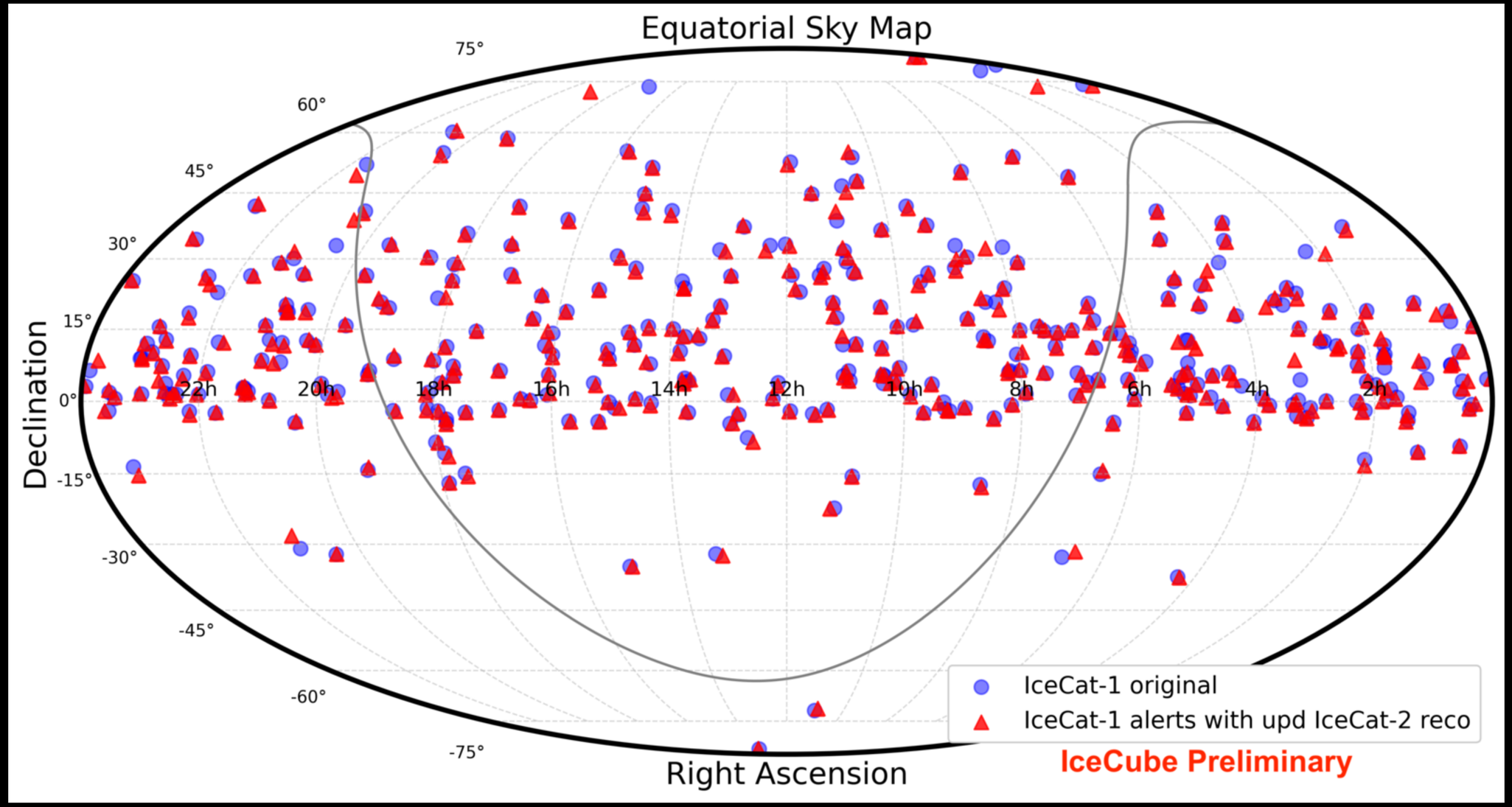
PoS(ICRC2025) 362

ICECAT-2 SUMMARY

- Incorporates new reconstructions, updated calibrations, exclusion of likely cosmic-ray induced events, and new alerts since IceCat-1.
- Preliminary catalog: 365 track-like alerts from May 2011 (IC-110514A) to January 2, 2025 (IC-250102A).
- Angular resolution: ~5x improvement; median 50% and 90% containment areas of 0.2 and 1.3 deg^2 —〉 Crucial for follow-up.
- Source cross-checks:
  - TXS 0506+056 and NGC 7469 remain within contours.
  - TDE candidates AT2019dsg, AT2019fdr, AT2019aalc now outside 90% contours.
- Next steps: Full catalog to be publicly released after peer-reviewed publication, with analyses on source-population correlations.


THANK YOU!

PRELIMINARY ICECAT-2 SAMPLE: ALERTS WITH UPDATED ICECAT-2 RECO



SIGNALNESS DEFINITION

Blaufuss et al., PoS(ICRC2019) 1177

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

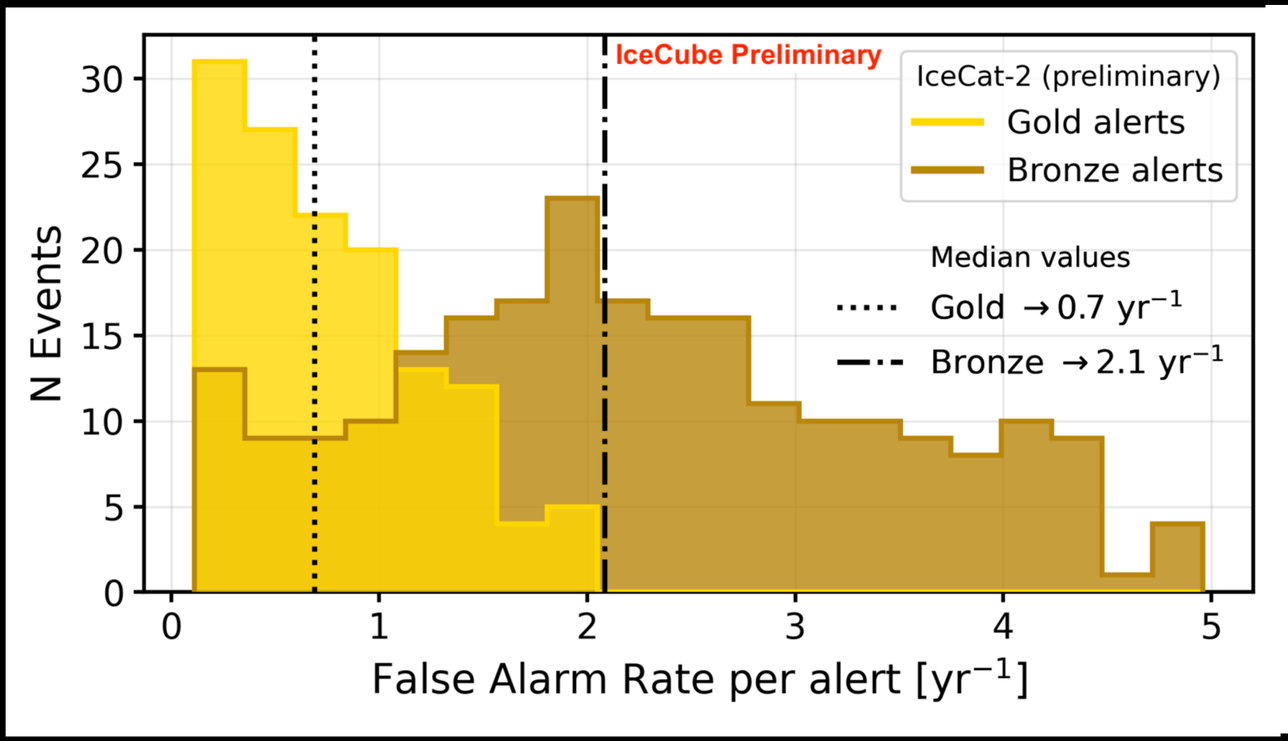
$$\text{Signalness} = \frac{N_{\text{signal}}(E, \delta)}{N_{\text{signal}}(E, \delta) + N_{\text{background}}(E, \delta)}$$

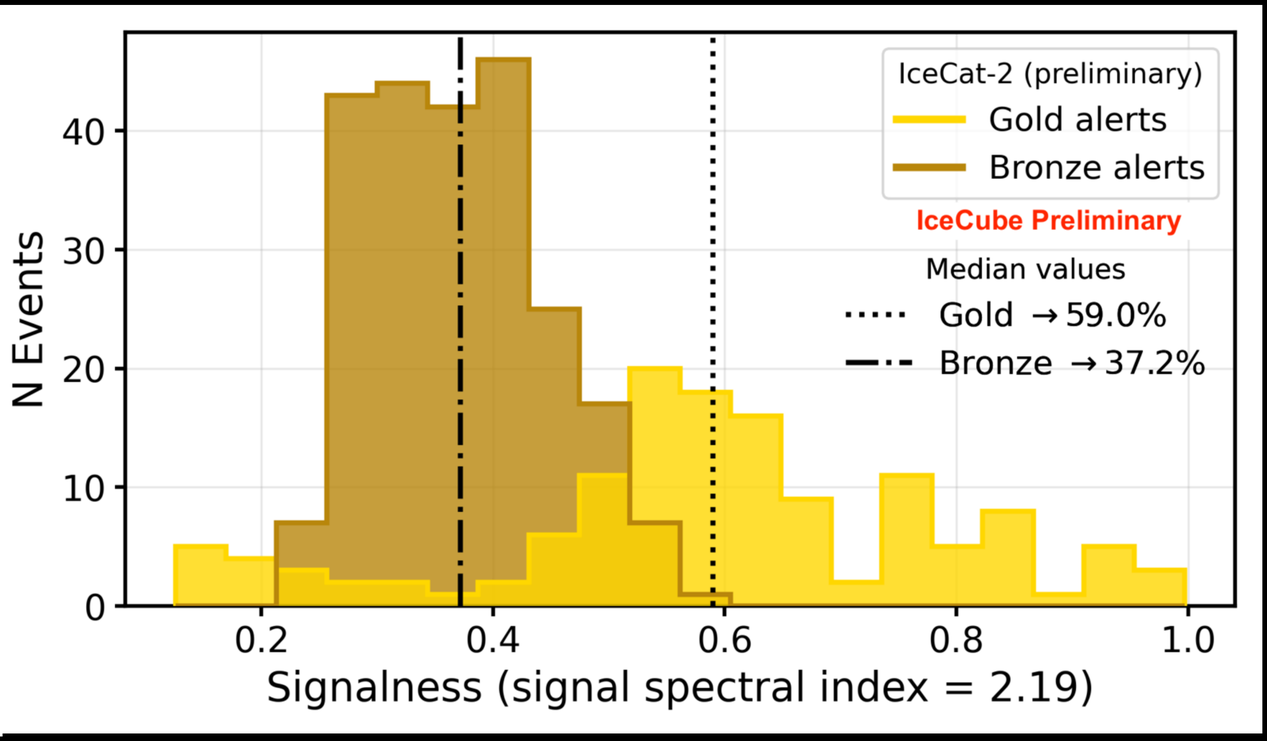
$E \rightarrow$ Most likely neutrino energy (derived from muon energy proxy)

$\delta \rightarrow$ Event declination

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

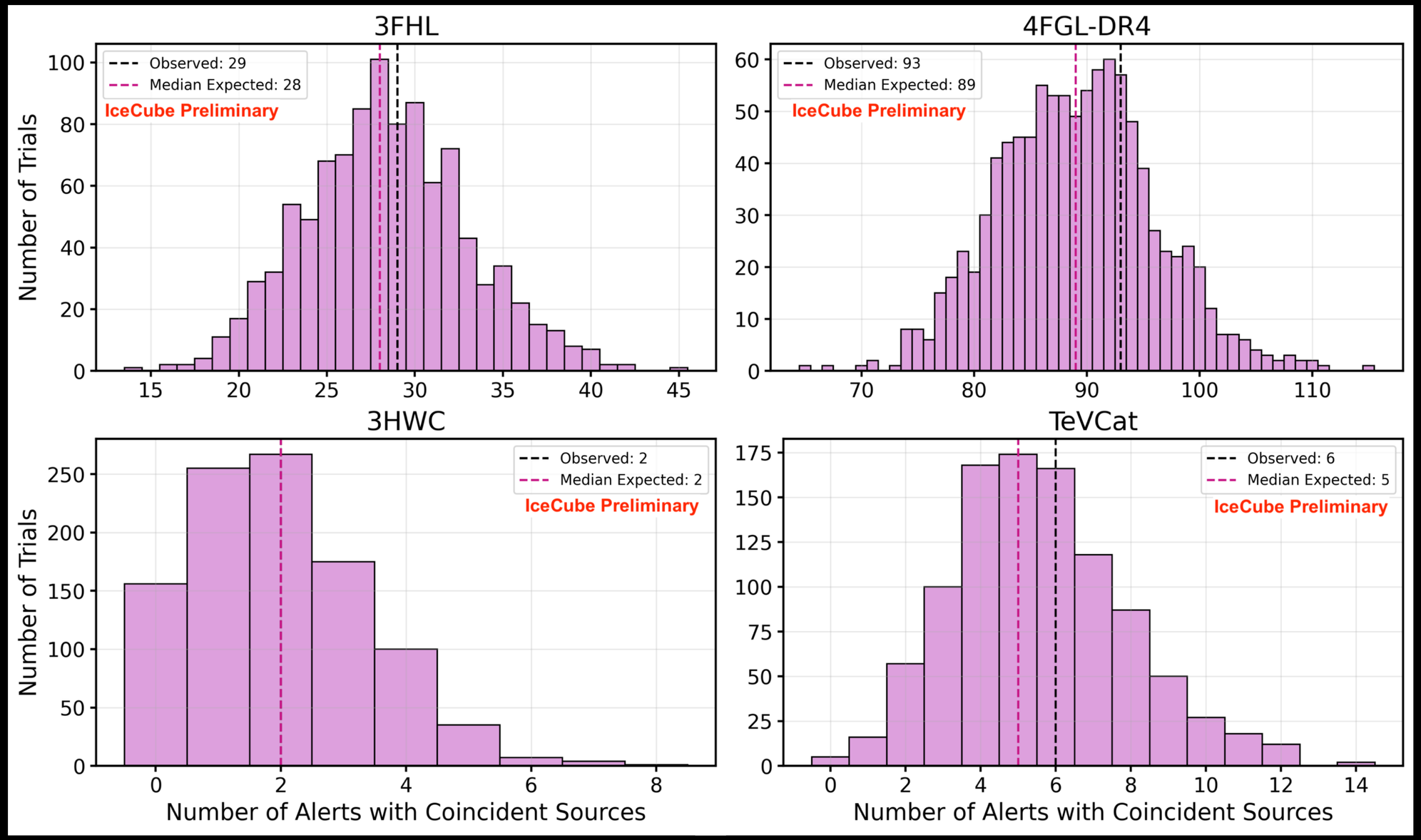
ICECAT-2: FAR AND SIGNALNESS



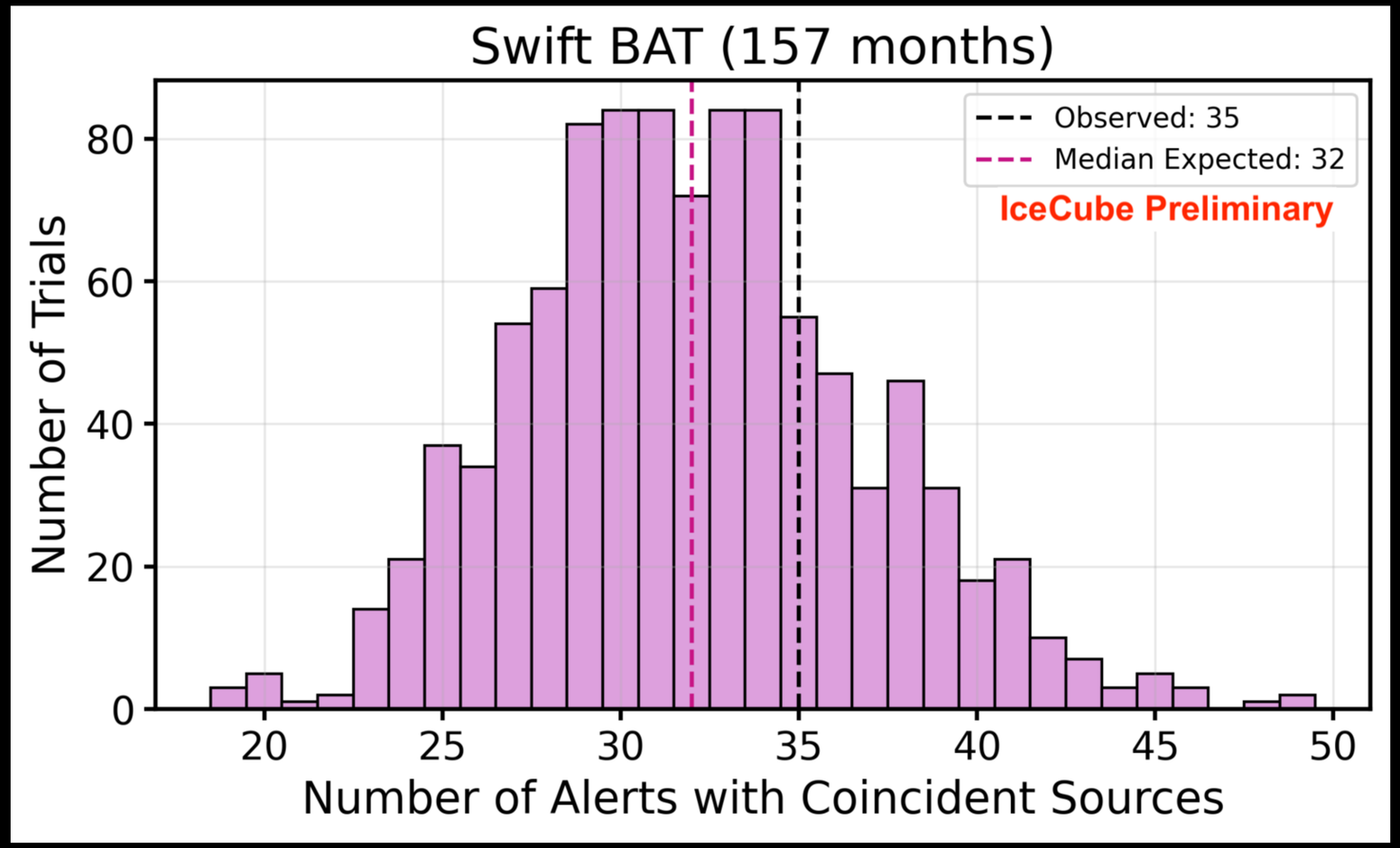


- Gold and Bronze channels correspond to average astrophysical probabilities of 50% and 30%, assuming a power-law spectrum with index 2.19
- This spectral index, adopted in IceCat-1 and currently used in real-time alerts, is based on an earlier IceCube measurement. Future versions of the catalog will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

CORRELATION WITH GAMMA-RAY SOURCE CANDIDATES



CORRELATION WITH X-RAY SOURCE CANDIDATES



COMPARISON: CORRELATION WITH SOURCE CANDIDATES

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)

IceCat-2

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

IceCube Preliminary

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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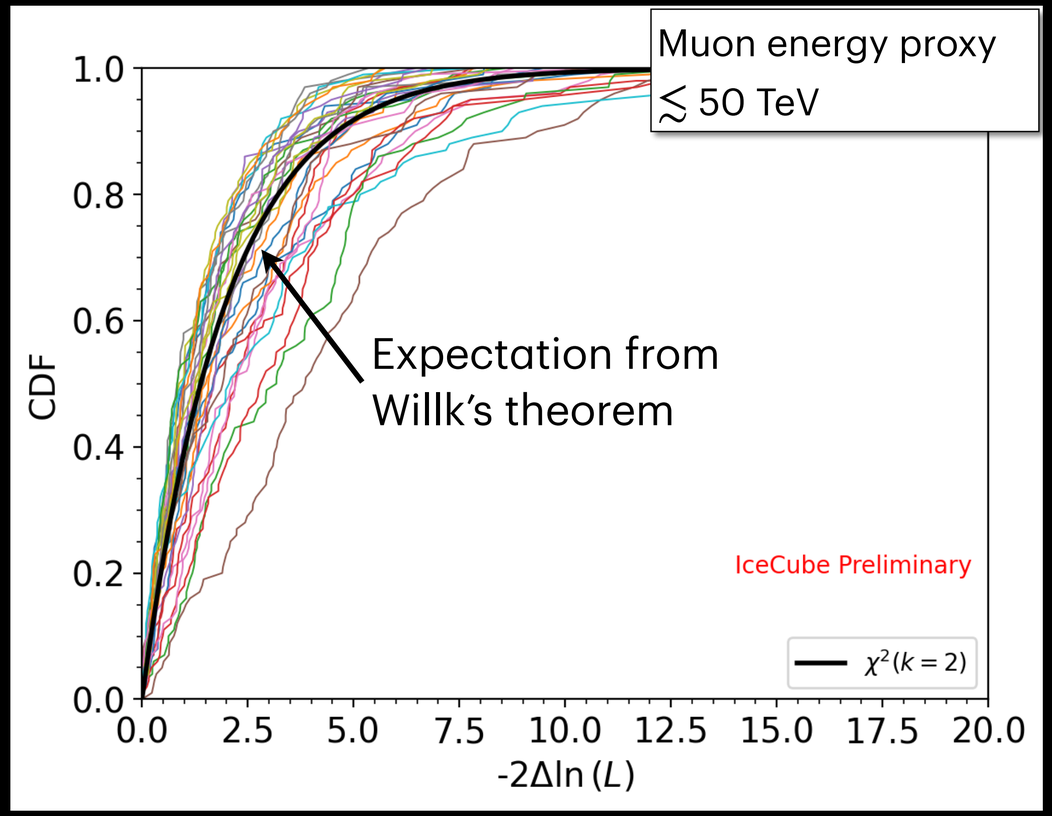
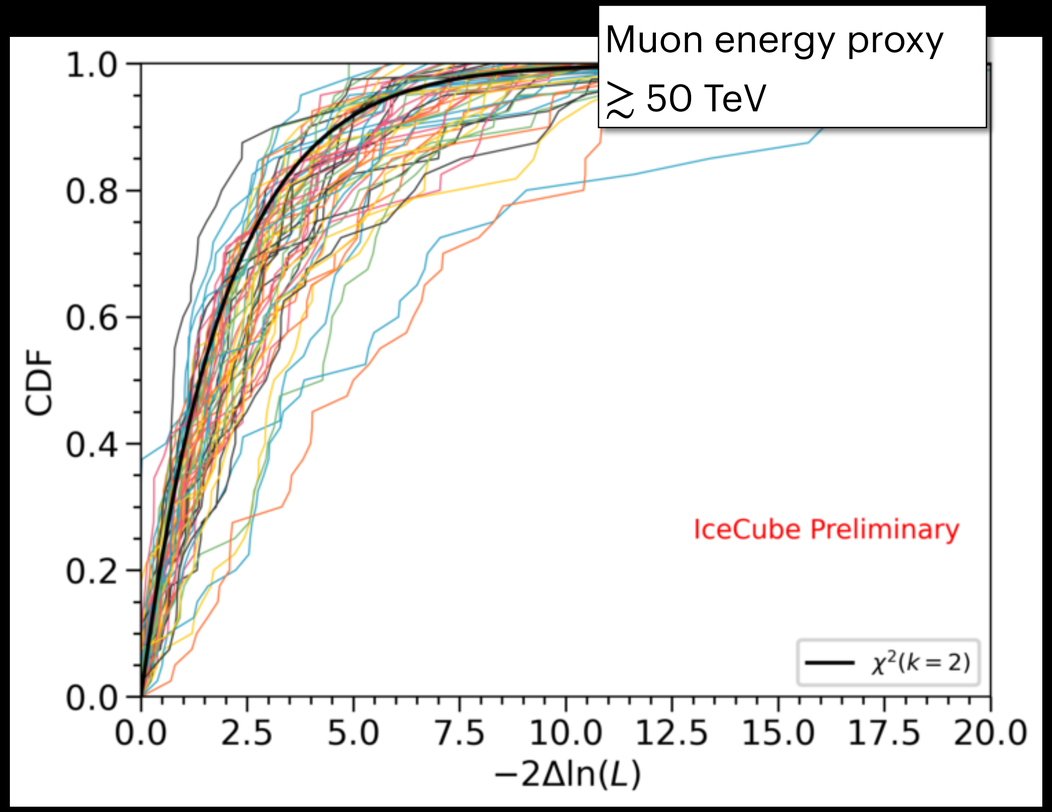
COVERAGE/ROBUSTNESS OF NEW RECO ALGORITHMS

From realtime benchmark simulations, each re-simulated 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

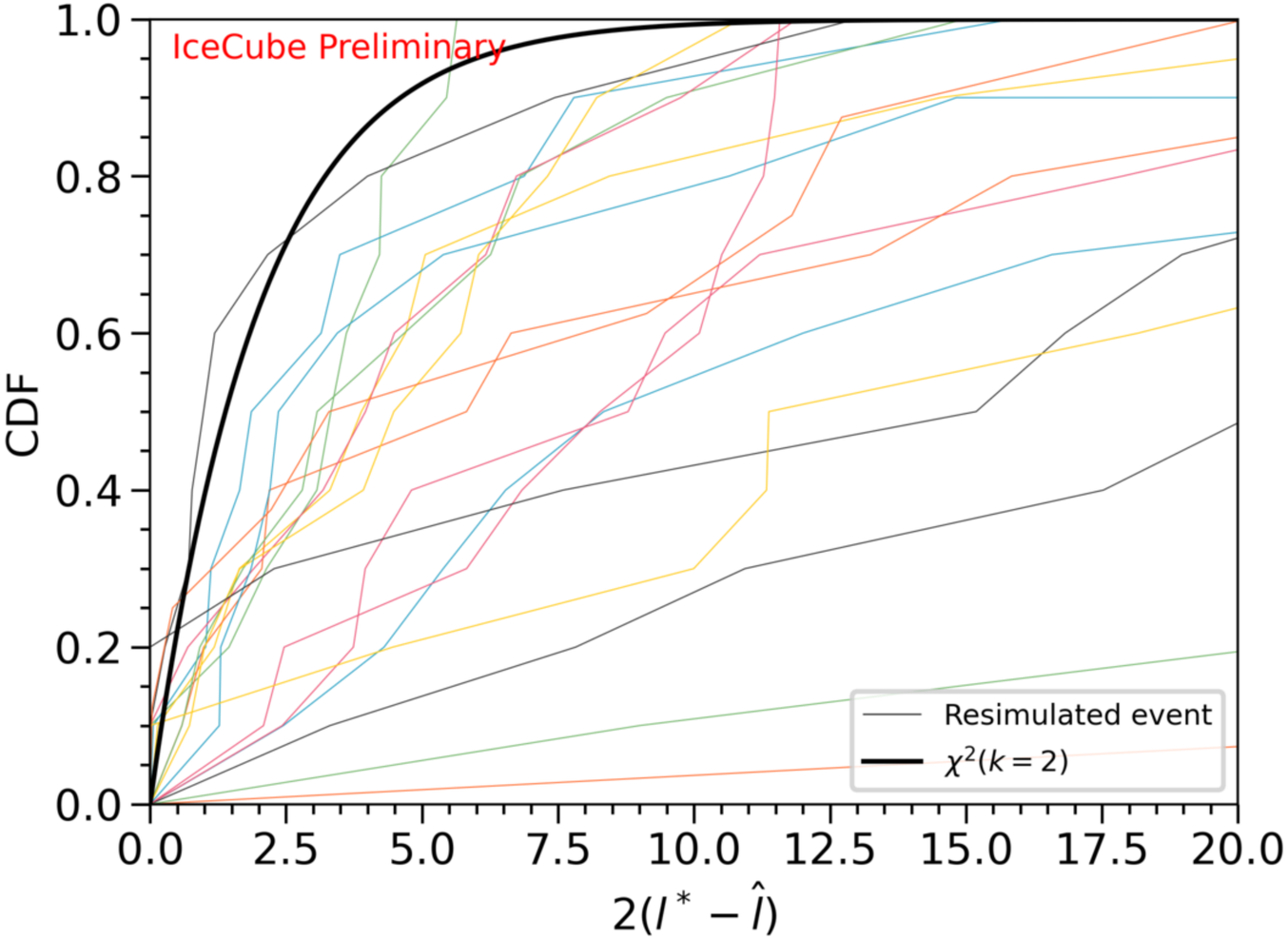




$\mathrm{CDF} \rightarrow$ Cumulative distribution function

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

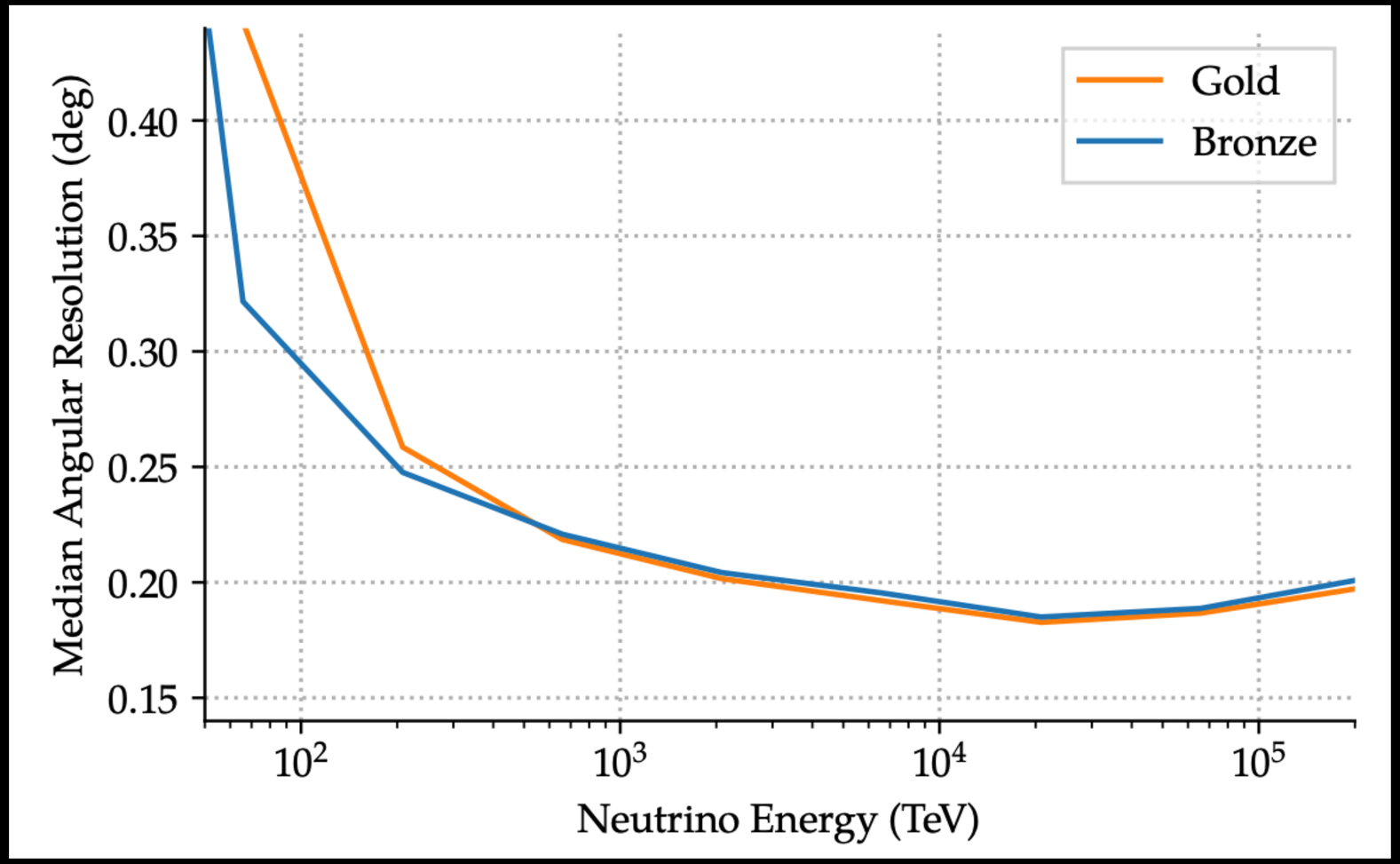
COMPARISON TO PREVIOUS ALGORITHM



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

T. Yuan., PoS(ICRC2023) 1005

ANGULAR RESOLUTION OF REALTIME NEUTRINO ALERT



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

PubDoc: IceCube High-Energy Neutrino Track Alerts