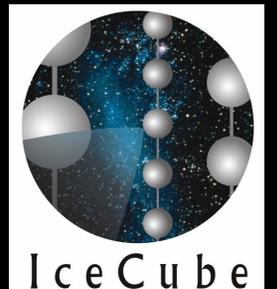


The IceCube Neutrino Observatory



Yuya Makino, IceCube/NSF



Justin Vandenbroucke (UW–Madison)

4th TDAMM Workshop

Huntsville, AL, October 27, 2025



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WISCONSIN
MADISON

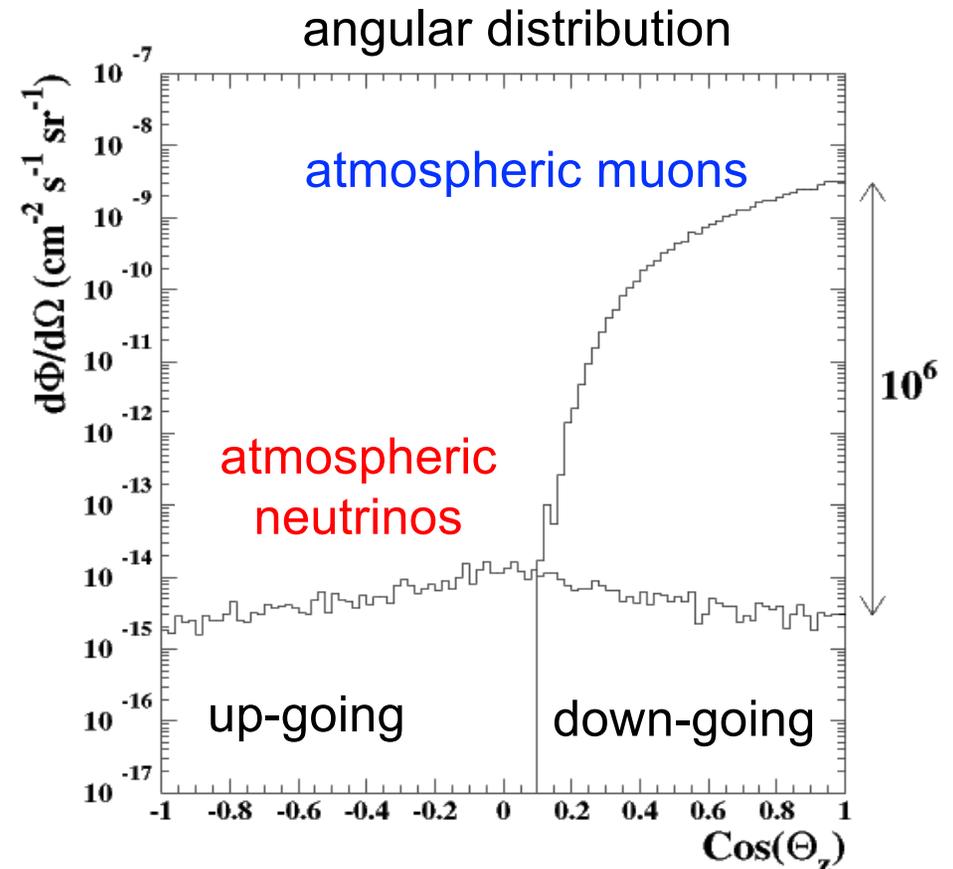
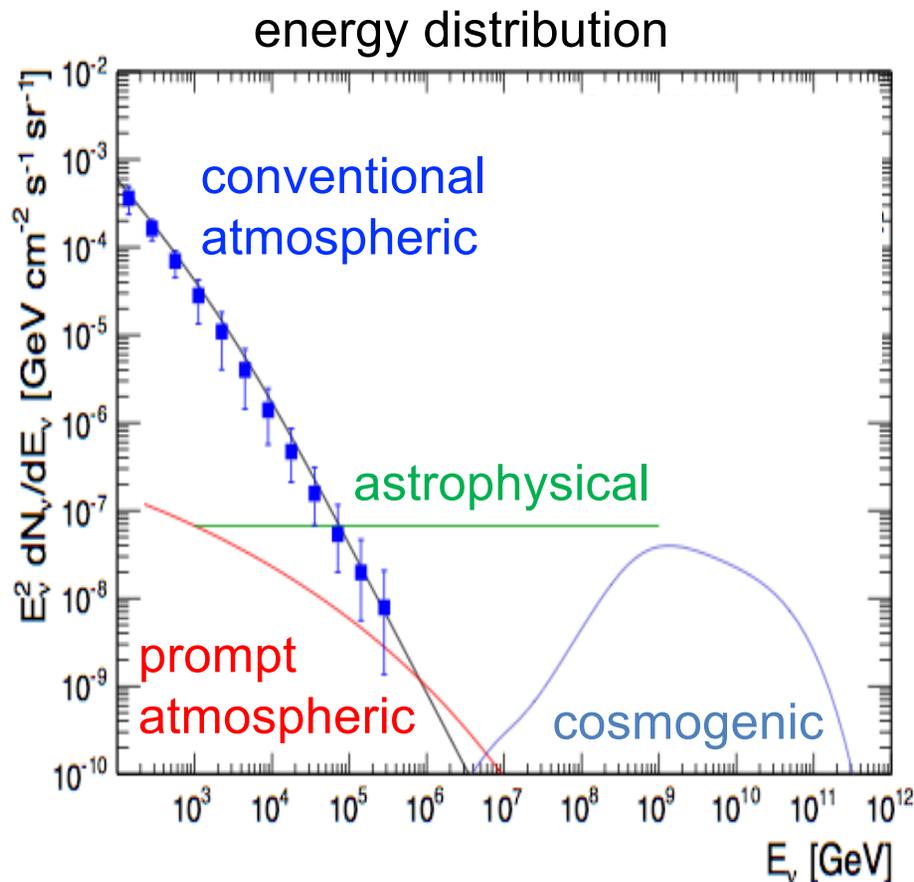


Signals and backgrounds in neutrino telescopes

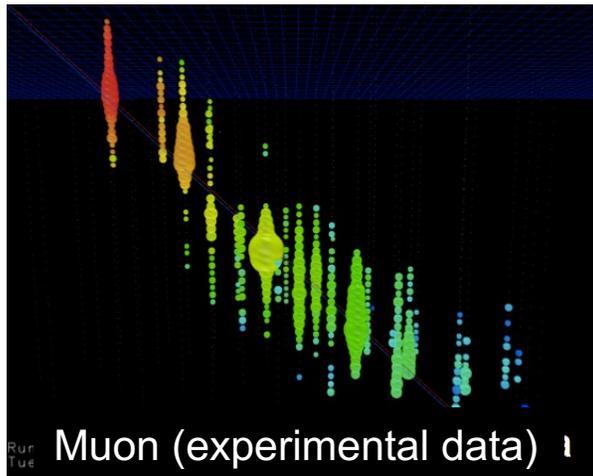
Most events detected by neutrino telescopes are not astrophysical neutrinos

- atmospheric μ ~ 70 billion / year / km³
- atmospheric $\nu_\mu \rightarrow \mu$ ~ 80 thousand / year / km³
- astrophysical $\nu_\mu \rightarrow \mu$ ~ 10 / year / km³ (above 200 TeV)

Background and signal differ in spectrum and angular distribution

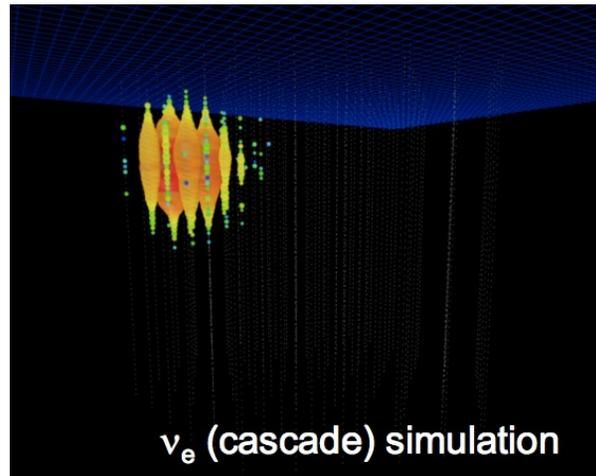


Interaction channels and flavor identification



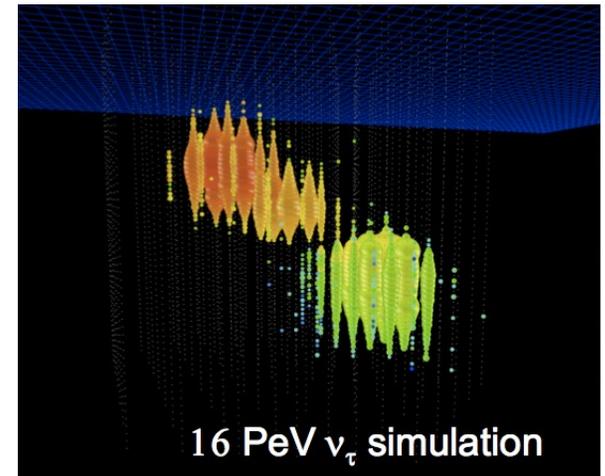
Muon neutrino

- + Straight track,
good angular resolution
- Cosmic-ray muon background



Electron neutrino

- + Good energy resolution
- Cascade, ideally in detector



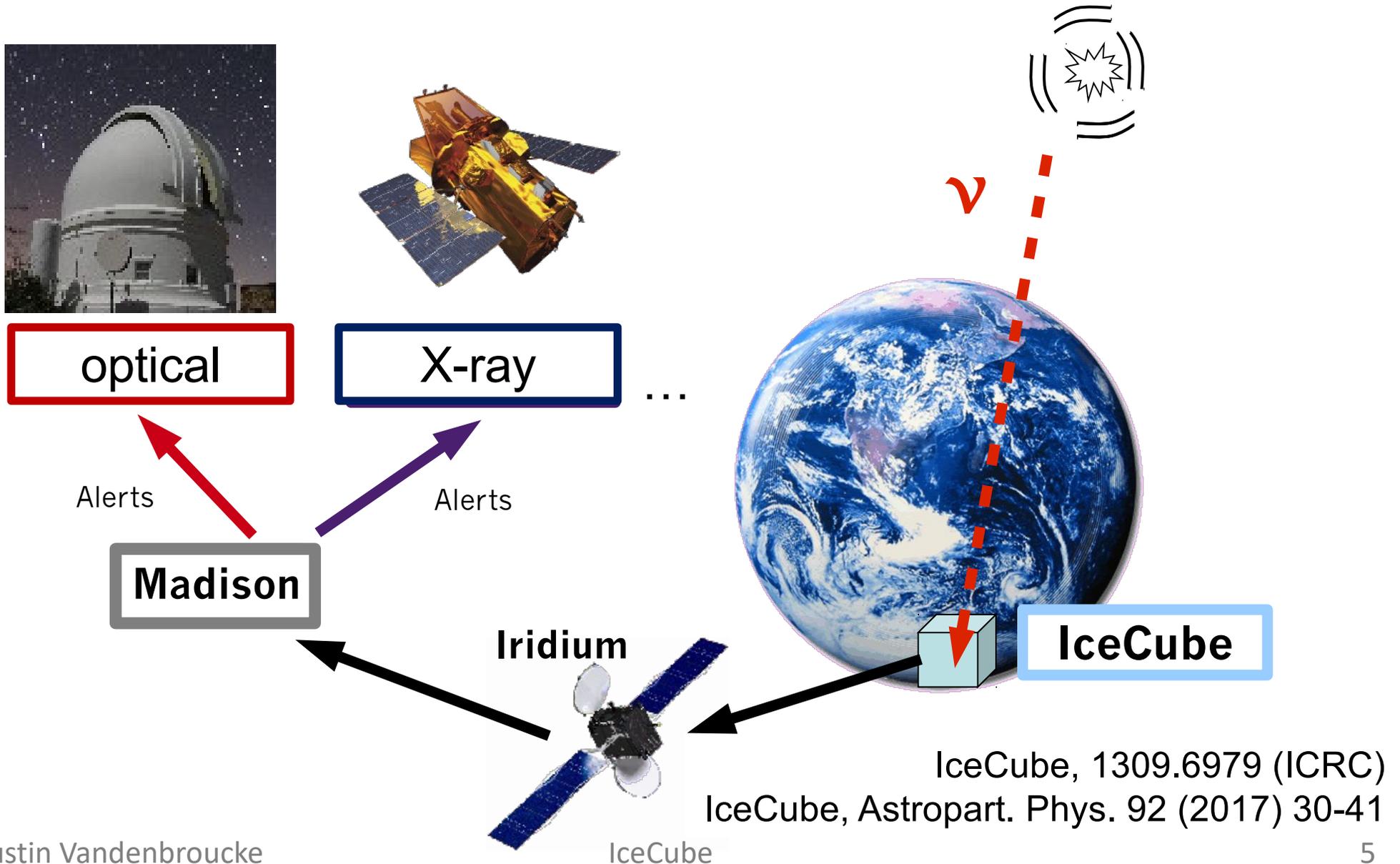
Tau neutrino

- + Double bang signature,
low background
- + Pointing capability
- Low rate

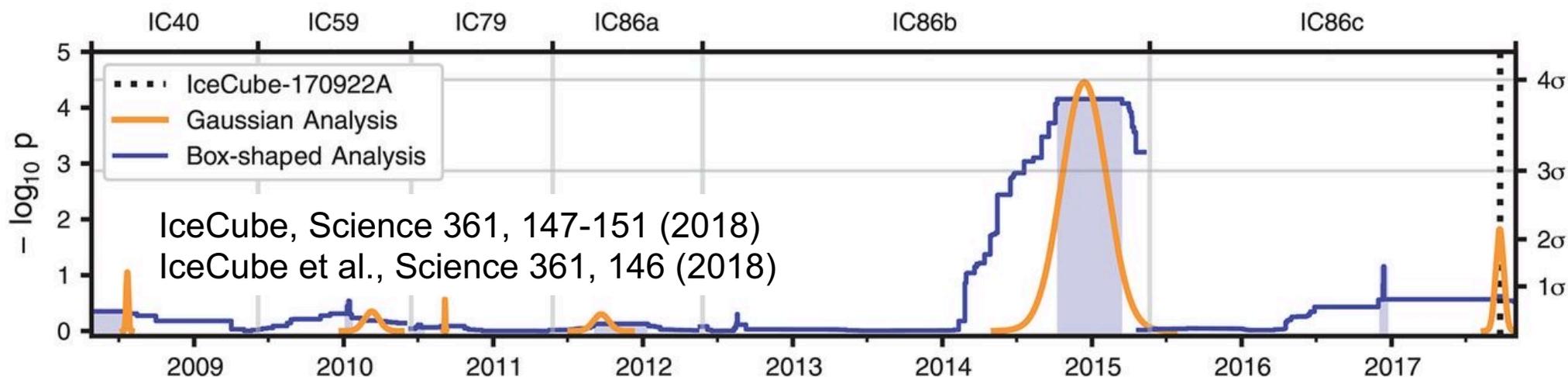
- Tracks: $\sim 0.5^\circ$
- Cascades/showers: $\sim 7^\circ$

IceCube real-time alerts

- Public alerts at low latency (~1 minute) since 2016
- Currently ~30 alerts per year



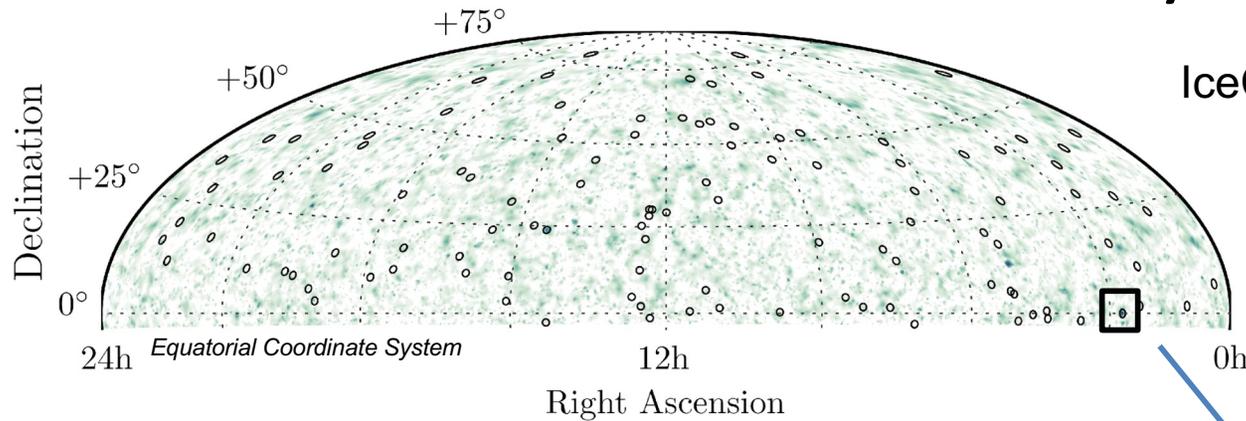
Evidence for neutrino flares from blazar TXS 0506+056



- IceCube-170922A coincident with GeV-TeV flaring blazar
- 3.5σ evidence for a neutrino flare in late 2014 – early 2015 (long before 170922A)
- 13 ± 5 excess neutrinos above atmospheric background



Evidence for neutrinos from Seyfert galaxy NGC 1068



IceCube, Science 378, 538-543 (2022)



Two analyses

- 1) Northern hemisphere scan
- 2) 110 gamma-ray-selected candidate sources

Hottest scan direction consistent with hottest candidate source direction

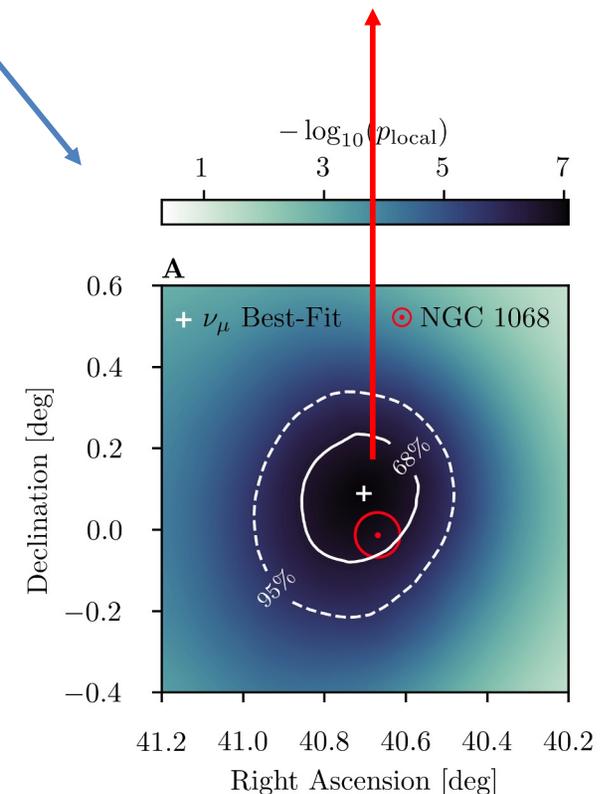
Seyfert galaxy NGC 1068 (M77)

After correcting for 110 trails:

4.2 sigma significance

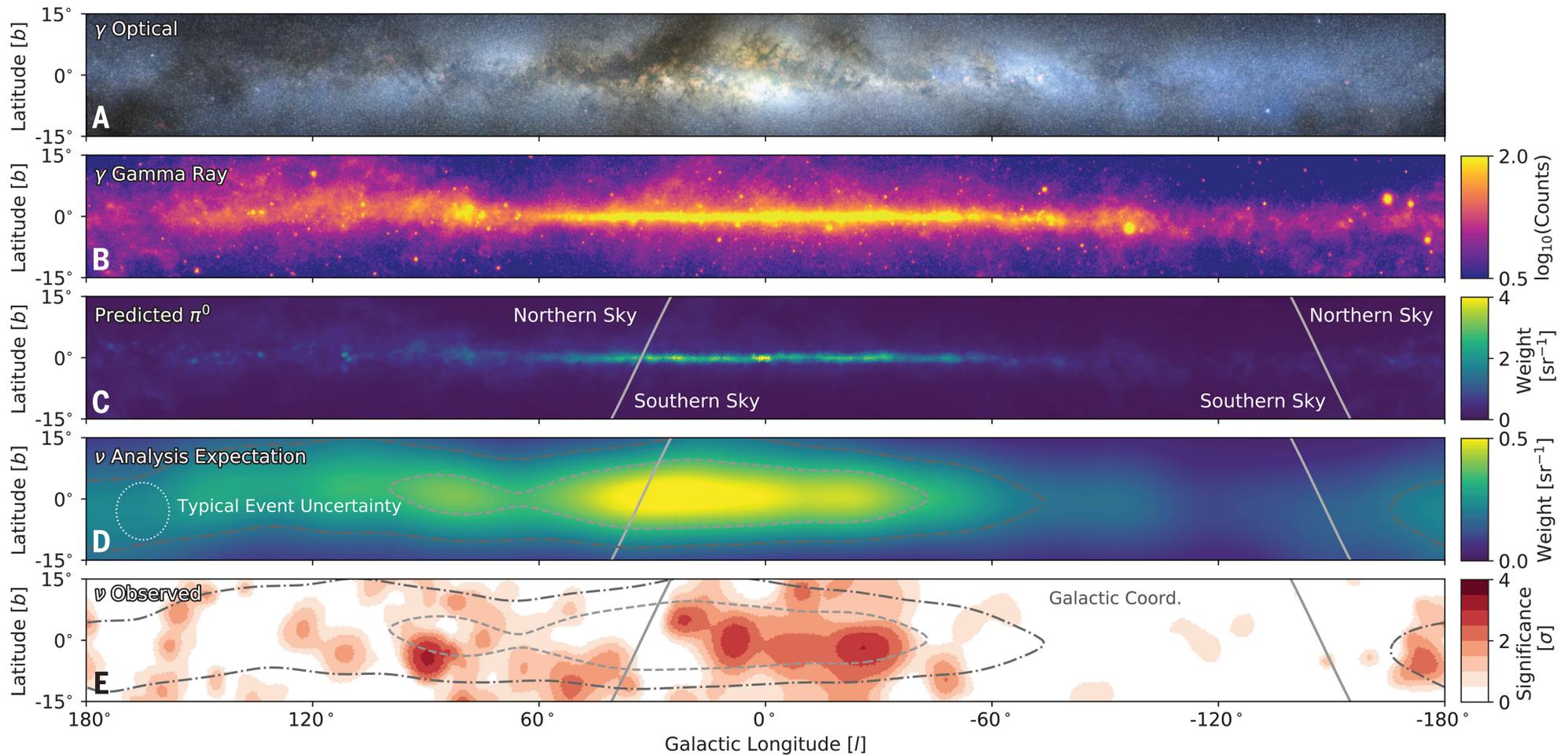
79 (+22, -20) astrophysical neutrino events

Spectral index = 3.2 ± 0.21



Galactic plane viewed in multiple wavelengths and multiple messengers

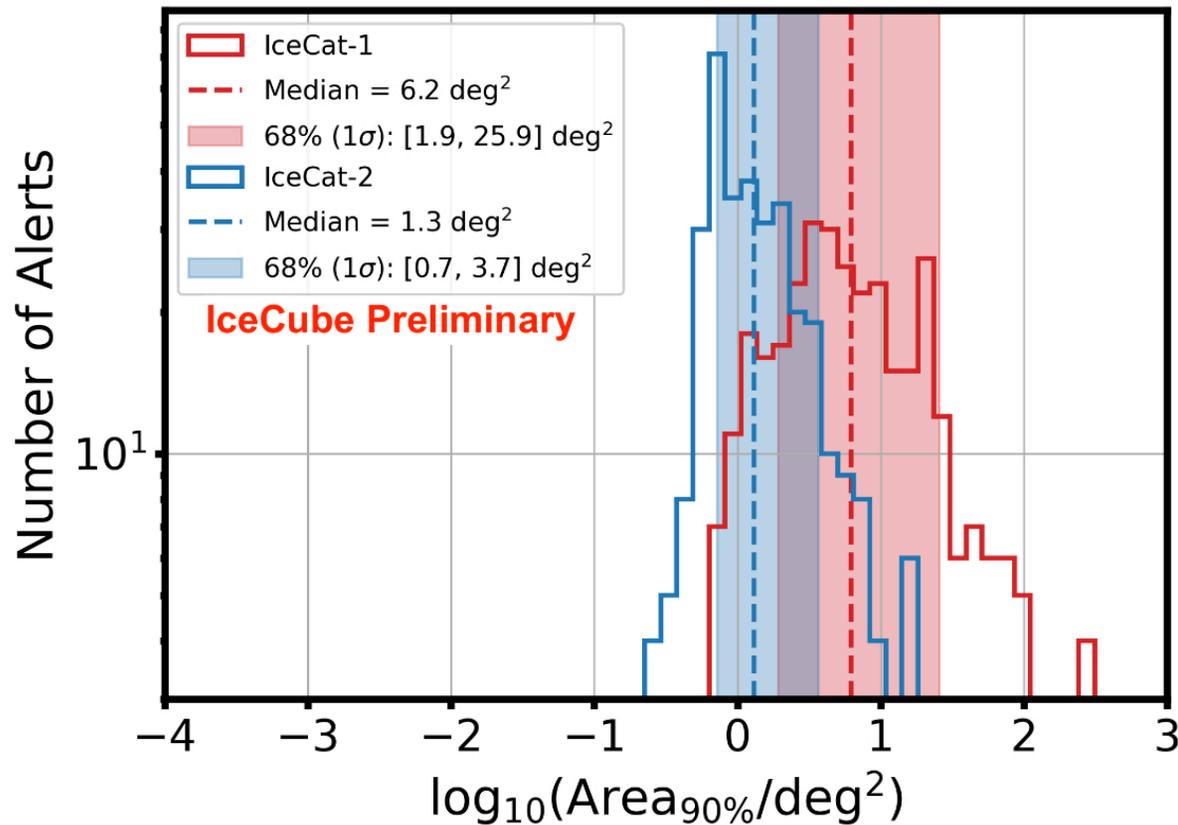
IceCube, Science 380, 1338-1343 (2023)



About 10% of astrophysical neutrinos are Galactic

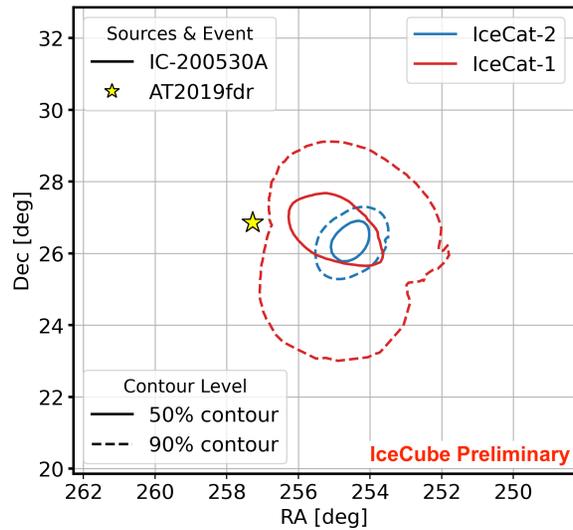
Recently improved high-energy neutrino public alerts

IceCube, PoS-ICRC2025-1224

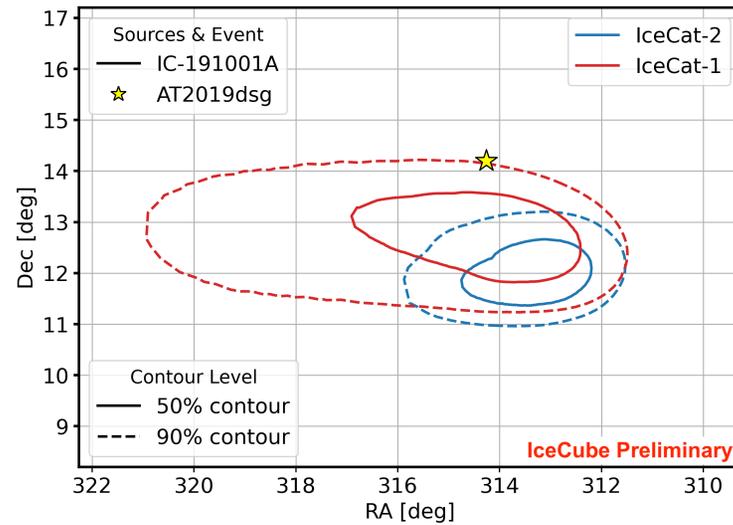


- New reconstruction procedure running online since September 2024
- Median 90% localization area is now 1.3 deg^2 , improved by a factor of ~ 5 from 6.2 deg^2
- Catalog of improved alerts in preparation
- 27 track alert events per year
- “Signalness” (equivalent to p_{astro}) provided for each alert

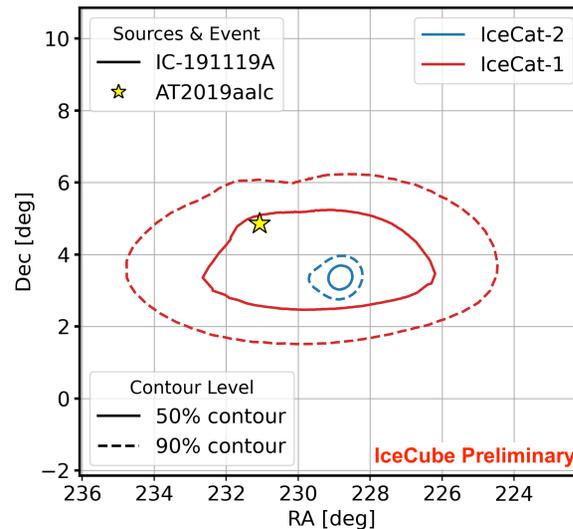
Refined directions of 3 alert events no longer consistent with TDEs



(a) AT2019fdr

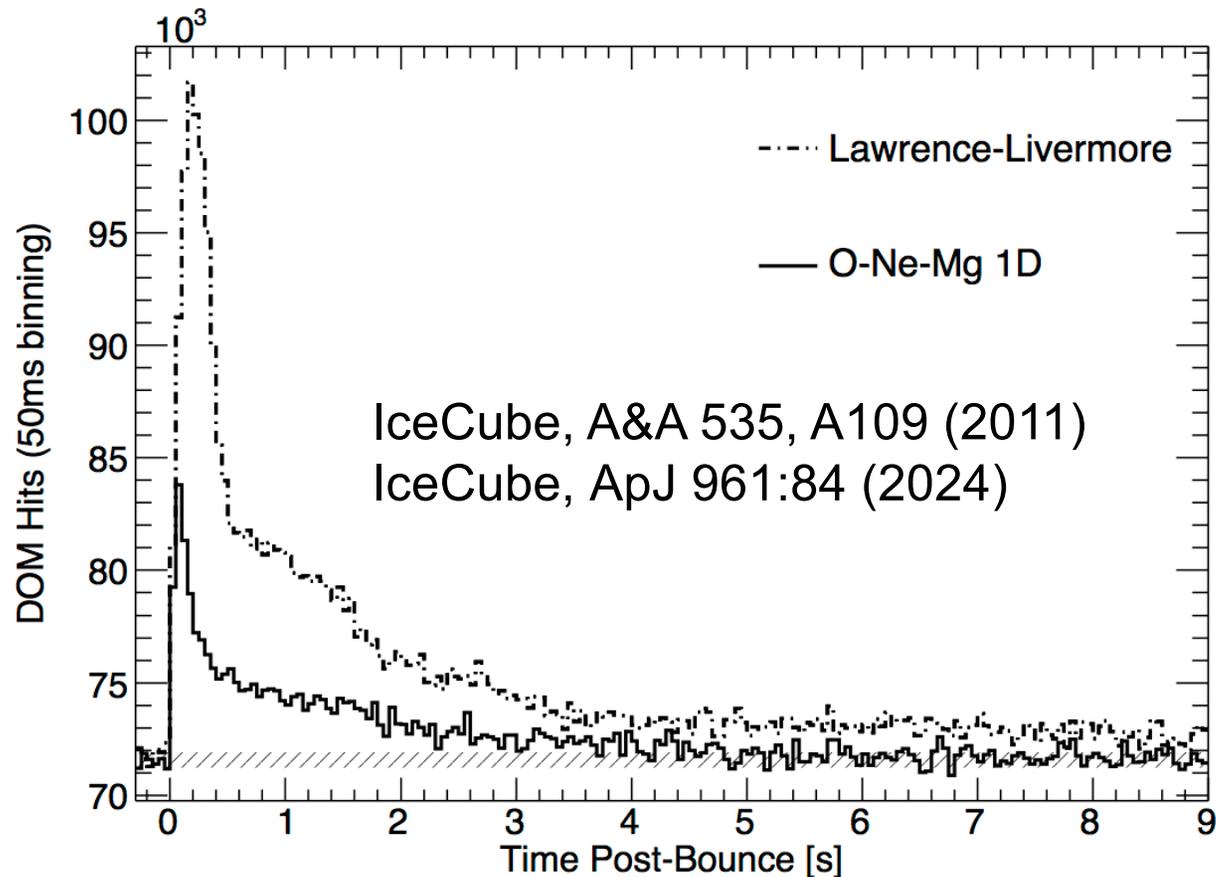


(b) AT2019dsg



(c) AT2019aalc

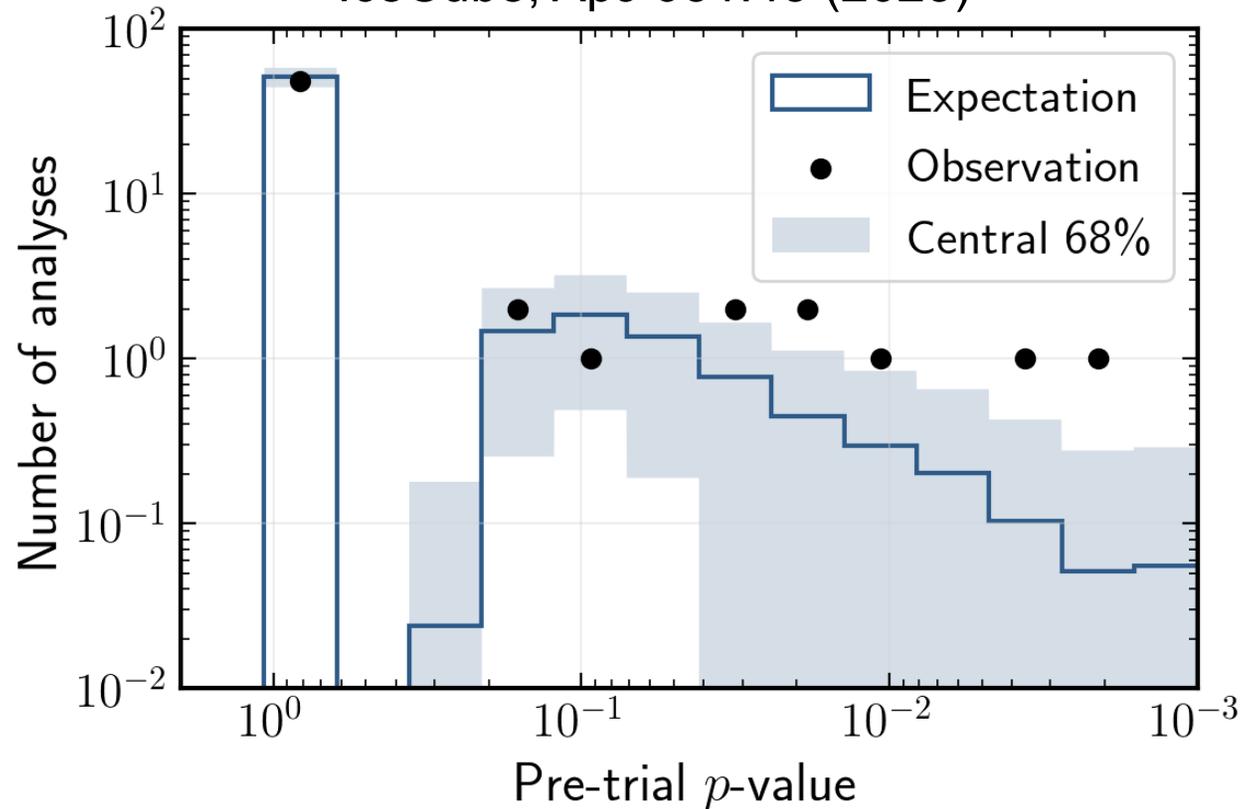
Galactic supernova neutrino alert system



- MeV neutrino burst causes burst in rates across many photomultipliers
- Member of the Supernova Early Warning System (SNEWS)
- Will issue a public alert several hours before optical signal
- Will measure the neutrino time series with exquisite precision
- Will learn even more about supernova astrophysics and neutrino physics than from 1987A

IceCube follow-up of external triggers

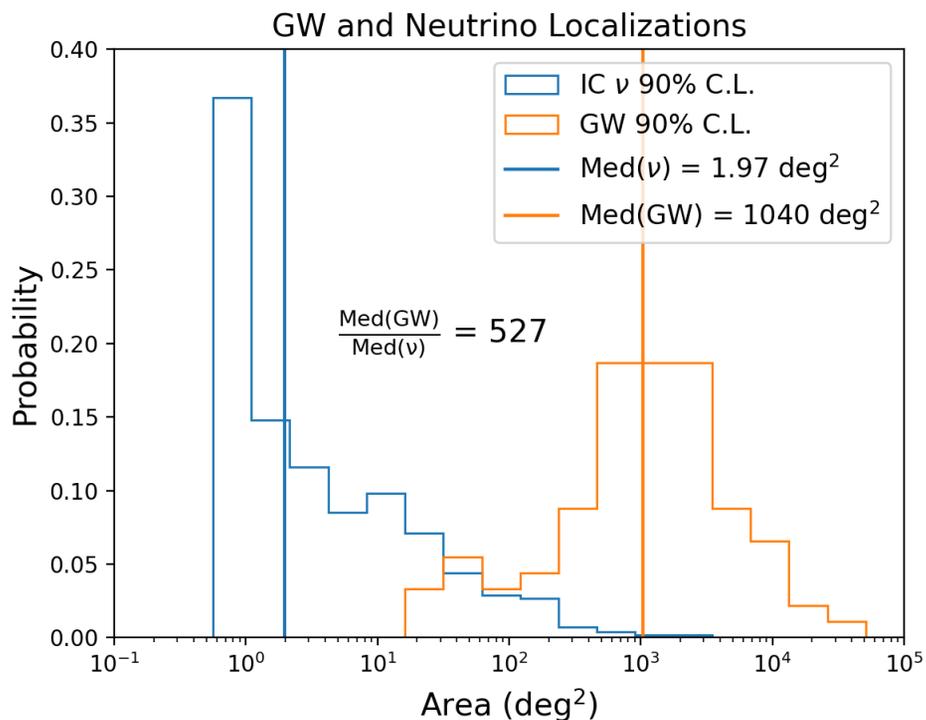
IceCube, ApJ 910:4 (2021)
IceCube, ApJ 951:45 (2023)



- “Fast Response Analysis” pipeline: rapid search for ν counterparts of transients reported by other observatories
- Blazar flares, novae, GRBs, X-ray binaries, compact binary mergers, magnetars, magnetars, supernovae, TDEs, ...
- IceCube observes all directions at all times, well suited for transient follow-up

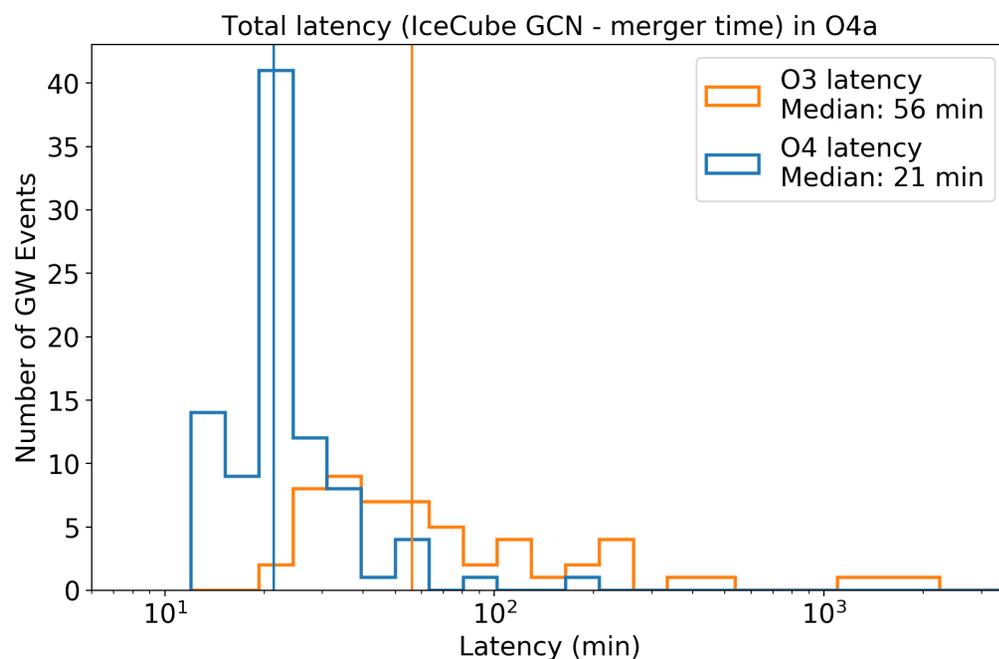
Real-time IceCube follow-up of gravitational waves

Neutrinos are hundreds of times better localized than GW



IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)

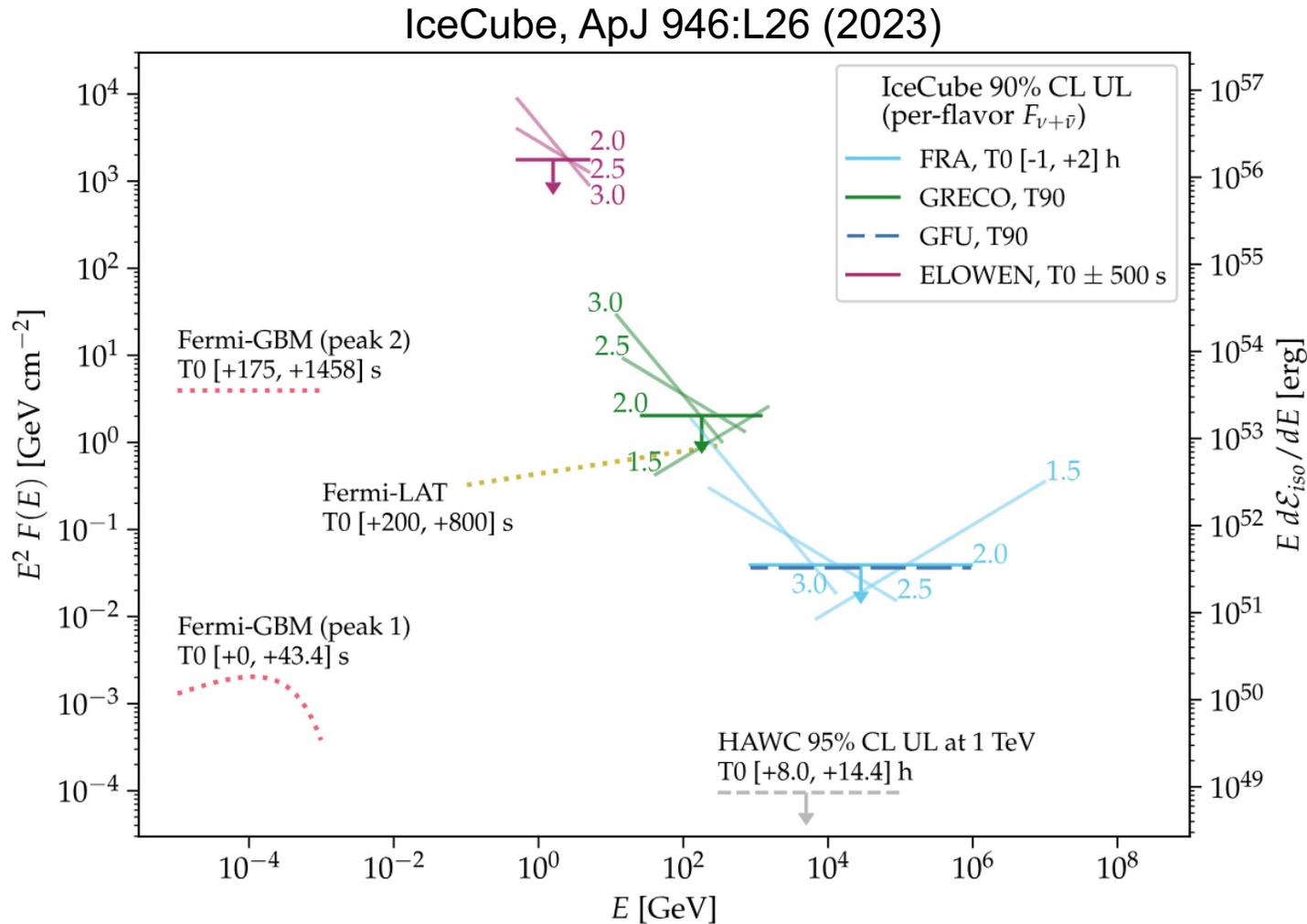
Rapid, automated follow-up



IceCube, ApJ Letters 898 (2020) L10
IceCube, ApJ 944:80 (2023)
PoS-ICRC2025-1113

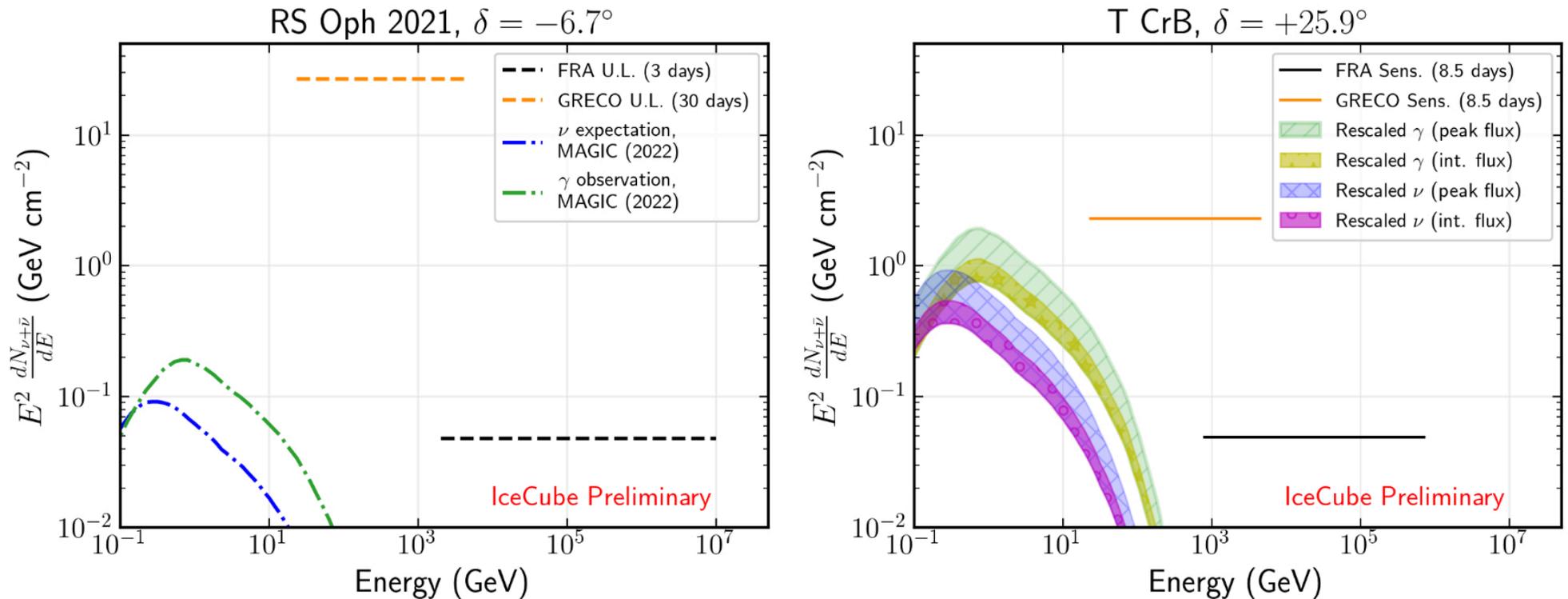
- Two automated, real-time pipelines operating in O3 and O4
- Rapidly publish neutrinos coincident in direction and time
- No statistically significant correlation so far

Gamma-ray burst 221009A: the brightest of all time



- IceCube GCN (upper limits) published within hours
- Neutrino limits from MeV to PeV
- Strong constraints on baryons in GRBs

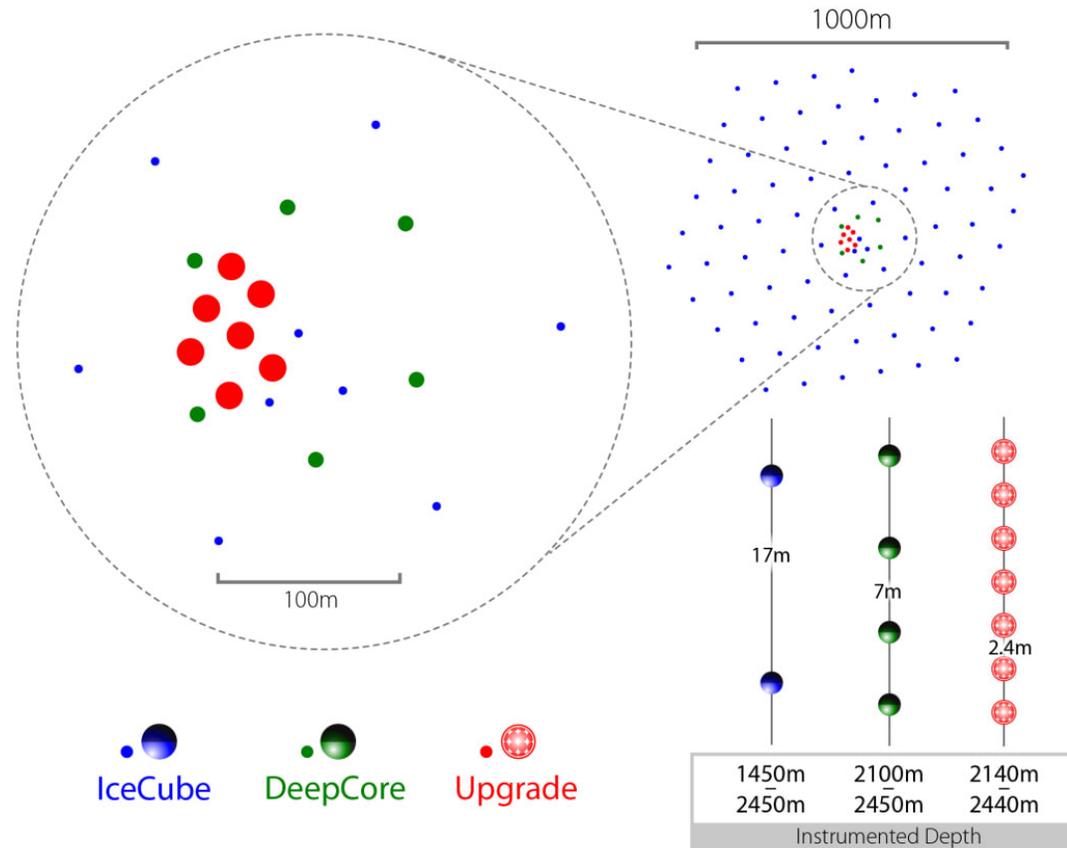
Novae including RS Ophiuchi and T Coronae Borealis



IceCube, PoS-ICRC2025-1200

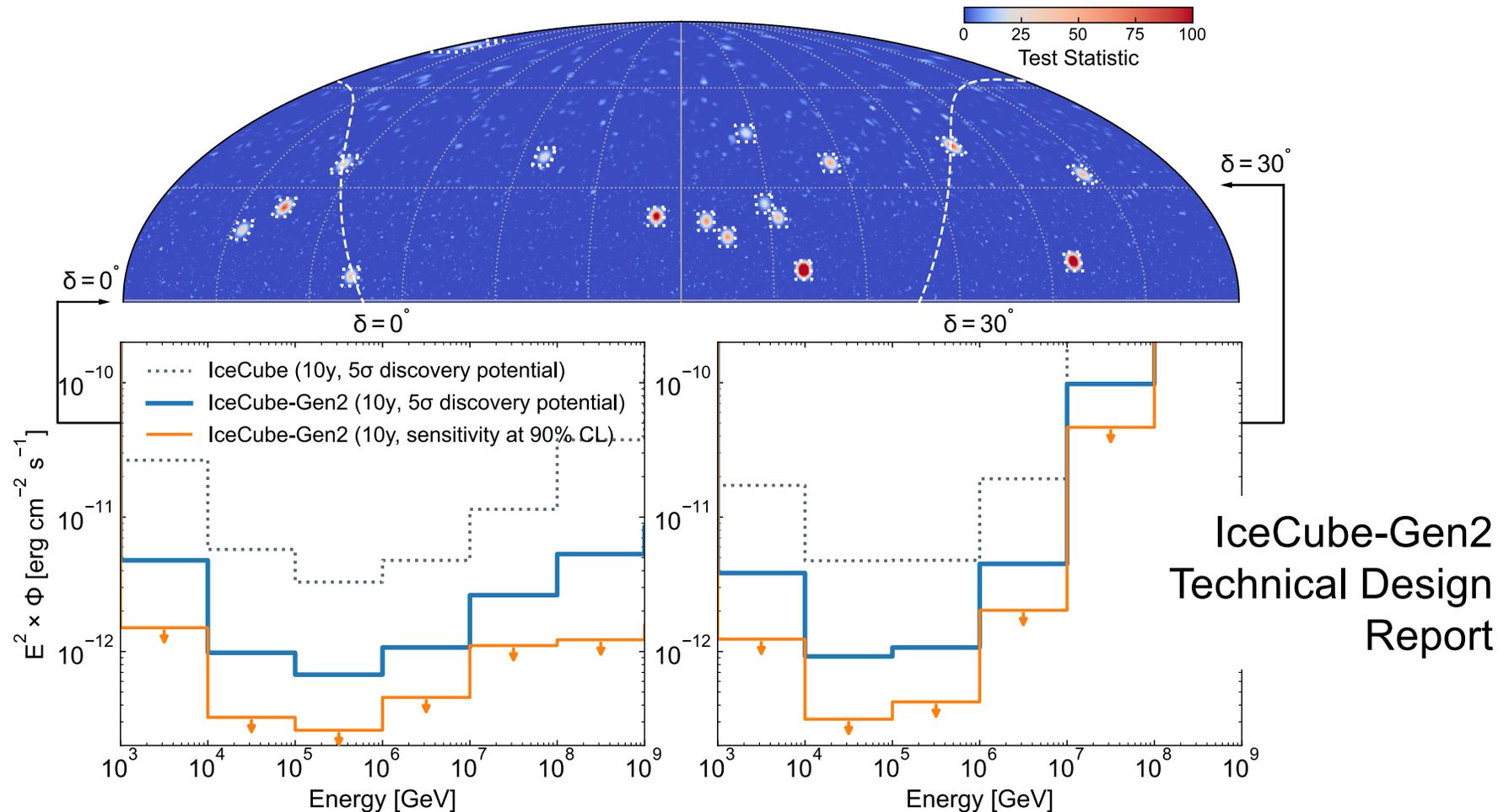
- IceCube DeepCore and (soon) IceCube Upgrade are sensitive to <1 TeV neutrinos
- “I have enough faith in the hadronic model that [neutrinos are] a pretty sure bet.”
– Brian Metzger, March 6, 2020 email
- T CrB expected to be brighter than RS Oph, and better declination for IceCube
- Preparing for a rapid search for T CrB neutrinos

IceCube Upgrade (a step toward IceCube-Gen2) will be installed in 2025–2026



- Dense infill with 7 new strings
- Improved sensitivity in the GeV (Fermi LAT) band, especially for transients
- Build on prior GeV searches (all-sky transients, GRBs, novae, GW, ...)
- Ice calibration to improve high-energy (TeV-EeV) instrument response and data archive

IceCube-Gen2: the next generation



- High energy extension: Instrument 8 km³ (sparsely with 120 new strings) to increase sensitivity to high-energy muon and cascade events
- Surface array for improved southern sky sensitivity and cosmic-ray physics
- Radio component for EeV neutrinos

Conclusion and outlook



- IceCube detects neutrinos from 4π sky with >99% uptime
- We both publish and consume alerts: input at this workshop on improving both?
- Automated pipelines alongside human-in-the loop decisions
- IceCube Upgrade (completion in 2026) will improve GeV transient astrophysics
- Only $\sim 1\%$ of the neutrino flux so far resolved into individual sources
- The neutrino sky may be as surprising, diverse, and dynamic as the electromagnetic sky

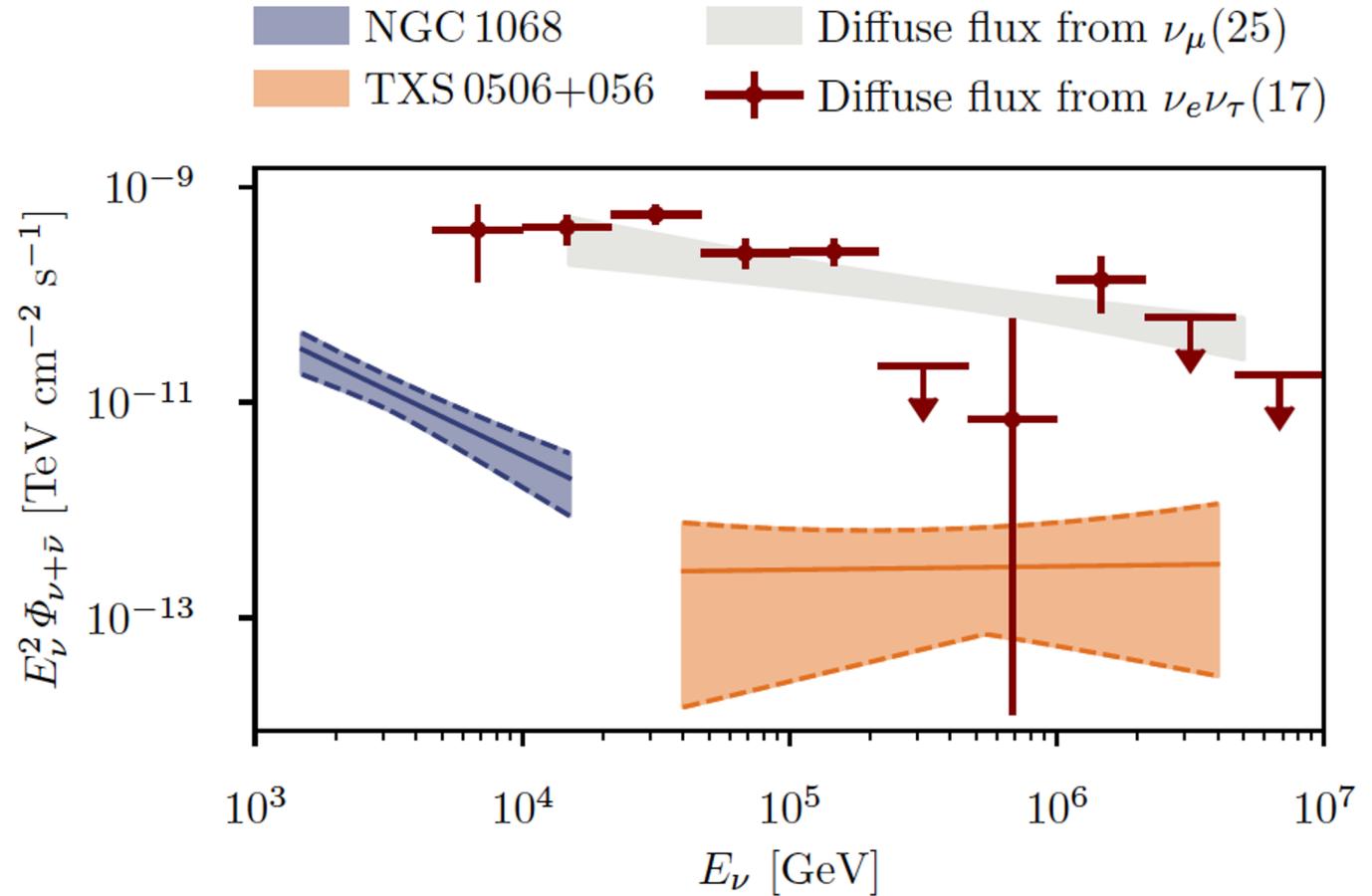
Additional slides

NGC 1068 and TXS 0506+056 can explain only ~1% of the total neutrino signal

Active galactic nuclei contribute a fraction of the extragalactic neutrino flux

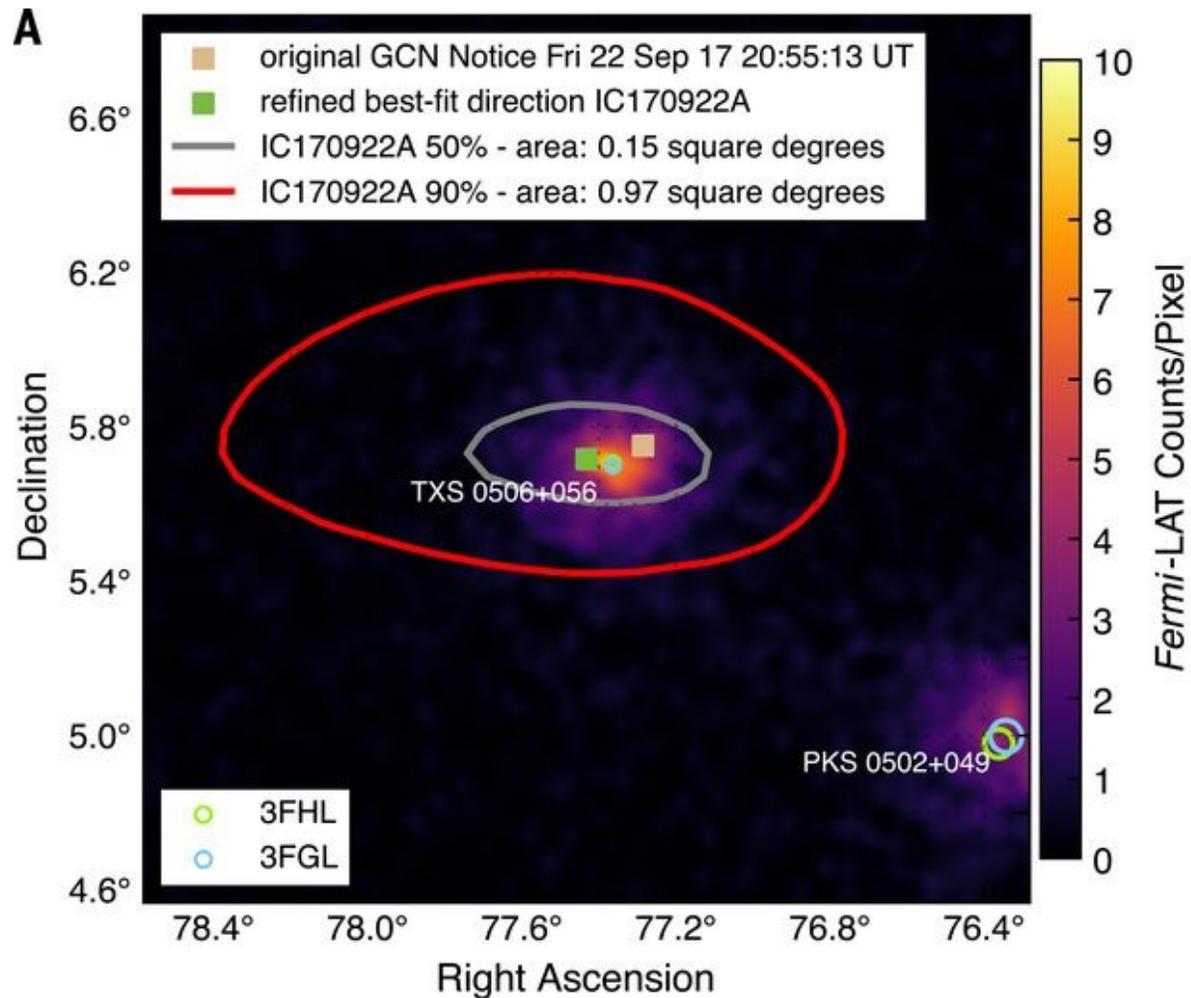
NGC 1068 is opaque to high-energy gamma-rays

NGC 1068 and TXS 0506+056 are very different sources



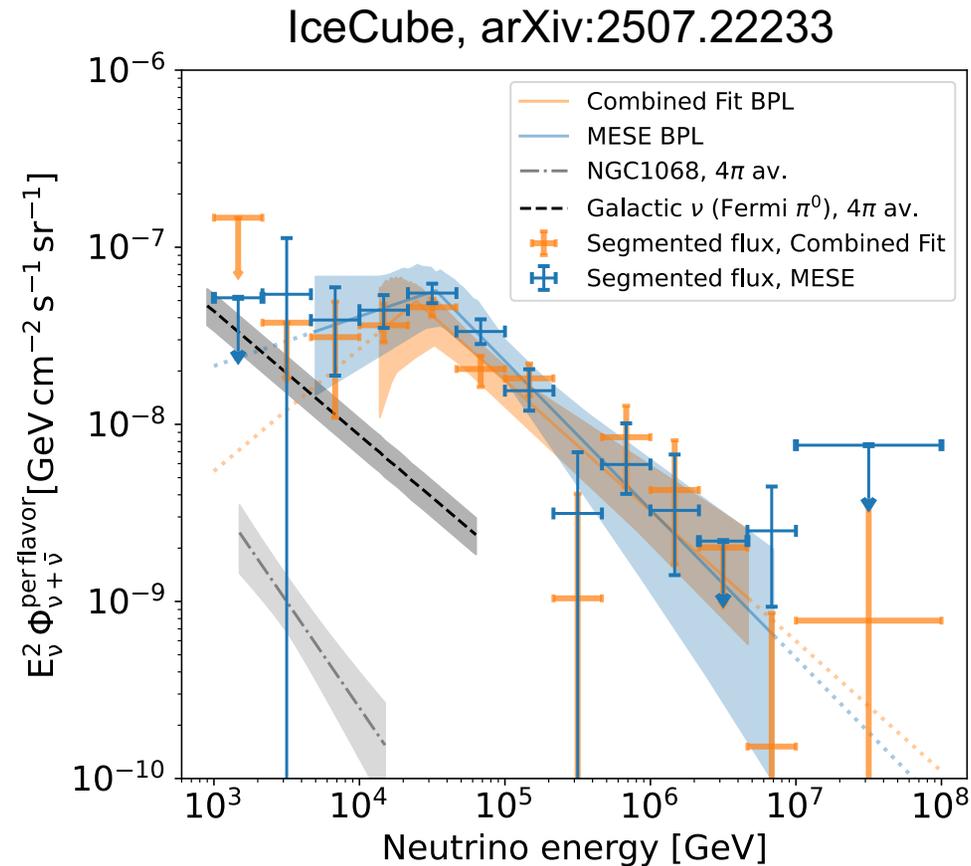
IceCube, Science 378, 538-543 (2022)

A flaring GeV–TeV gamma-ray blazar in the same direction as IC-170922A



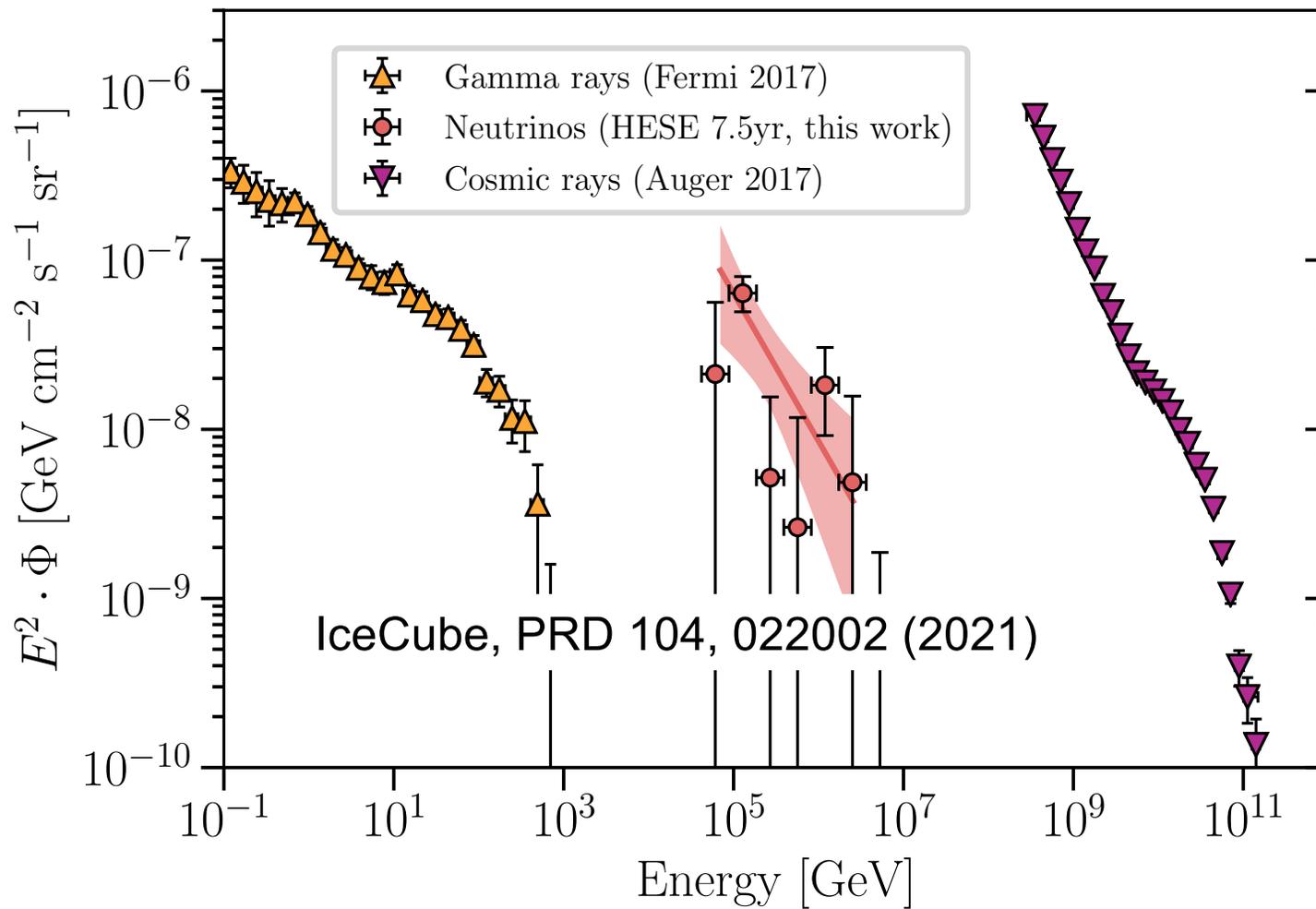
- 0.1° separation between blazar and best-fit neutrino direction
- MAGIC detected blazar for first time in VHE band

Beginning to resolve the astrophysical neutrino origins



- A knee in the total neutrino spectrum
- $\sim 10\%$ of astrophysical neutrinos are Galactic
- $\sim 1\%$ are from NGC 1068

The sky is **bright** in neutrinos!



- As bright as the most optimistic pre-IceCube models predicted
- Comparable energy flux in GeV gamma rays, PeV neutrinos, EeV cosmic rays