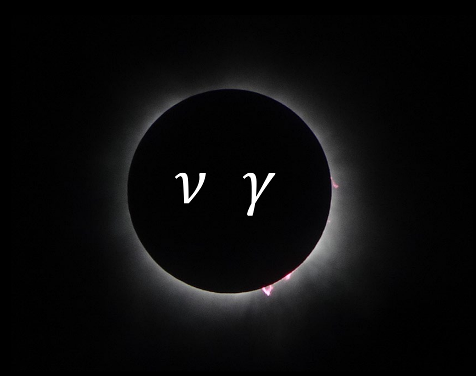
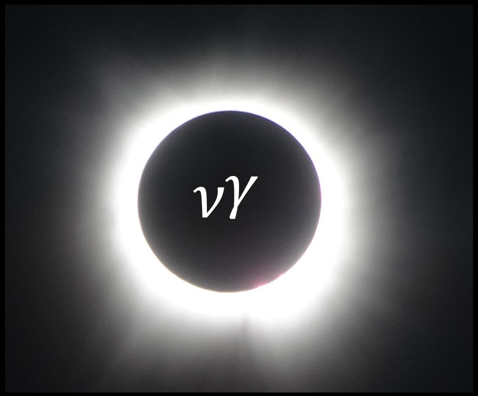
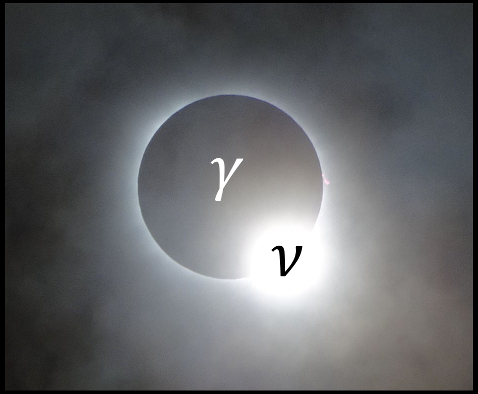
Connections between neutrinos and gamma rays







Justin Vandenbroucke (University of Wisconsin)

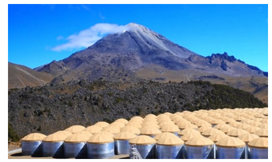
HEAD 21 GR SIG Splinter Session

Horseshoe Bay, Texas, April 10, 2024

Gamma-ray astrophysics over 10 orders of magnitude in energy

1 PeV LHAASO

(SWGO)



HAWC

1 TeV H.E.S.S., MAGIC, VERITAS, CTA

1 GeV Fermi LAT

(AMEGO)

1 MeV (COSI)

Fermi GBM

100 keV INTEGRAL

100 keV

X-ray

1 keV

ultraviolet

optical

1 eV

infrared

1 meV

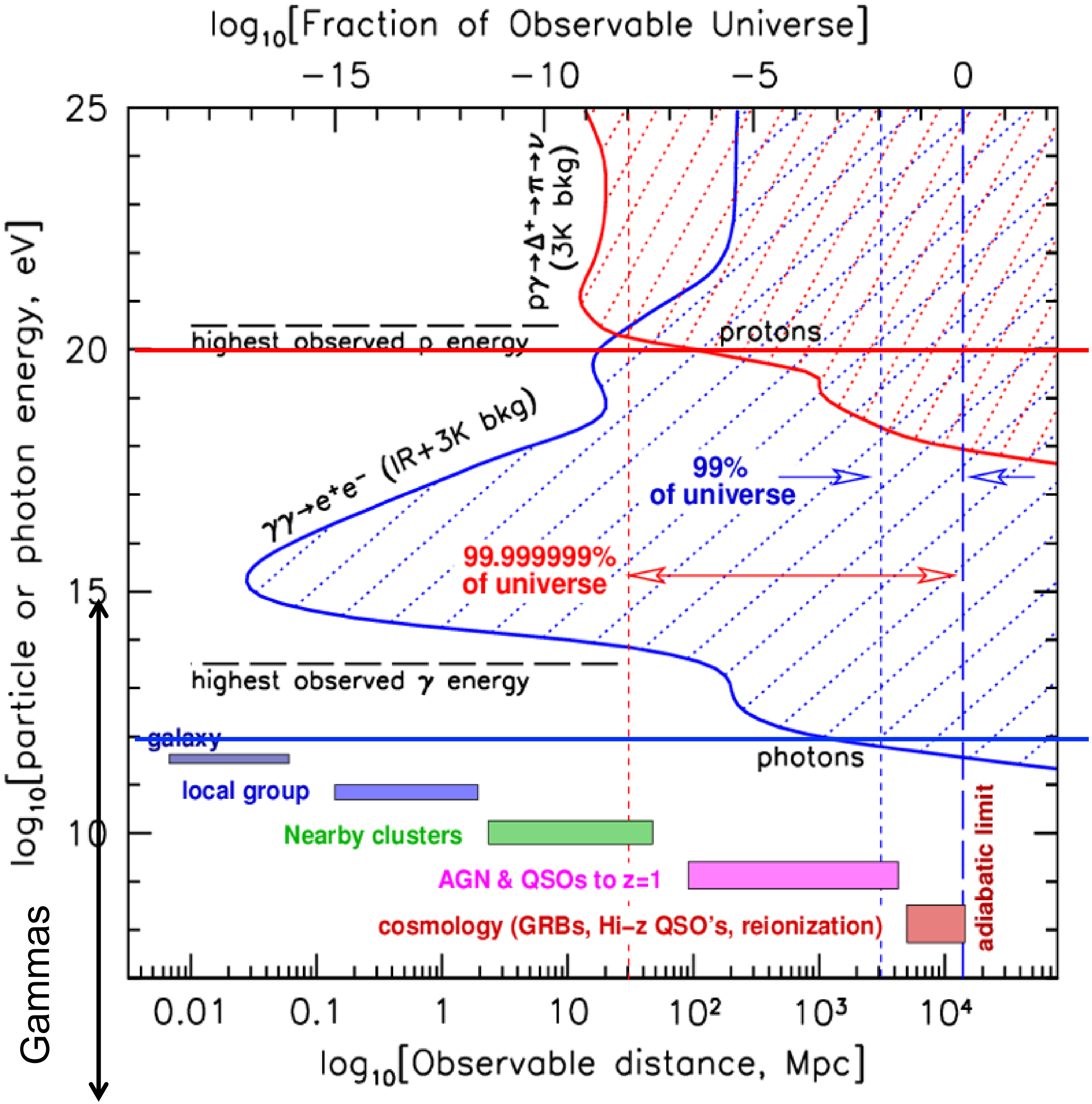
microwave

1 μeV

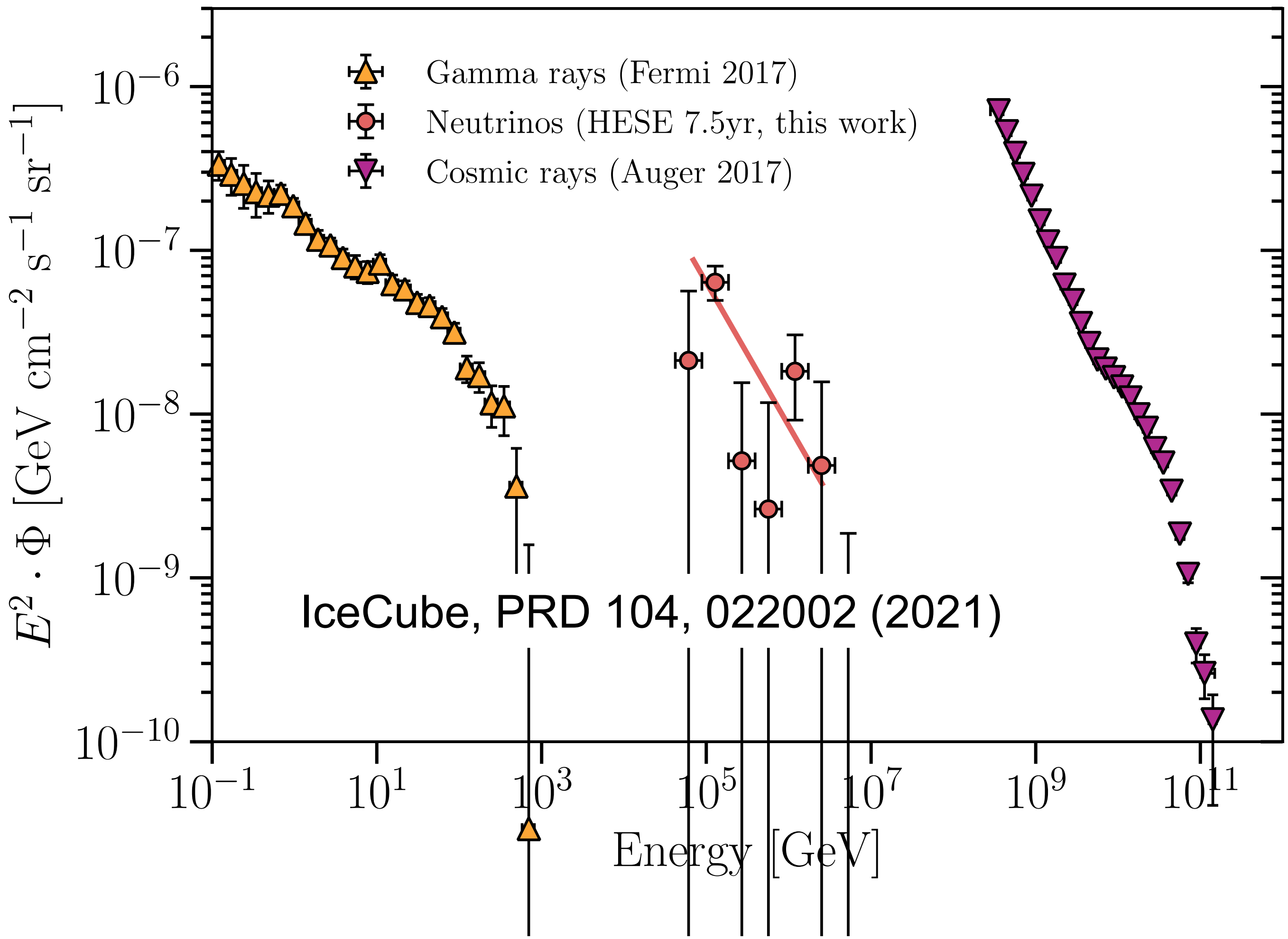
radio

100 neV

Neutrinos probe large energies and distances

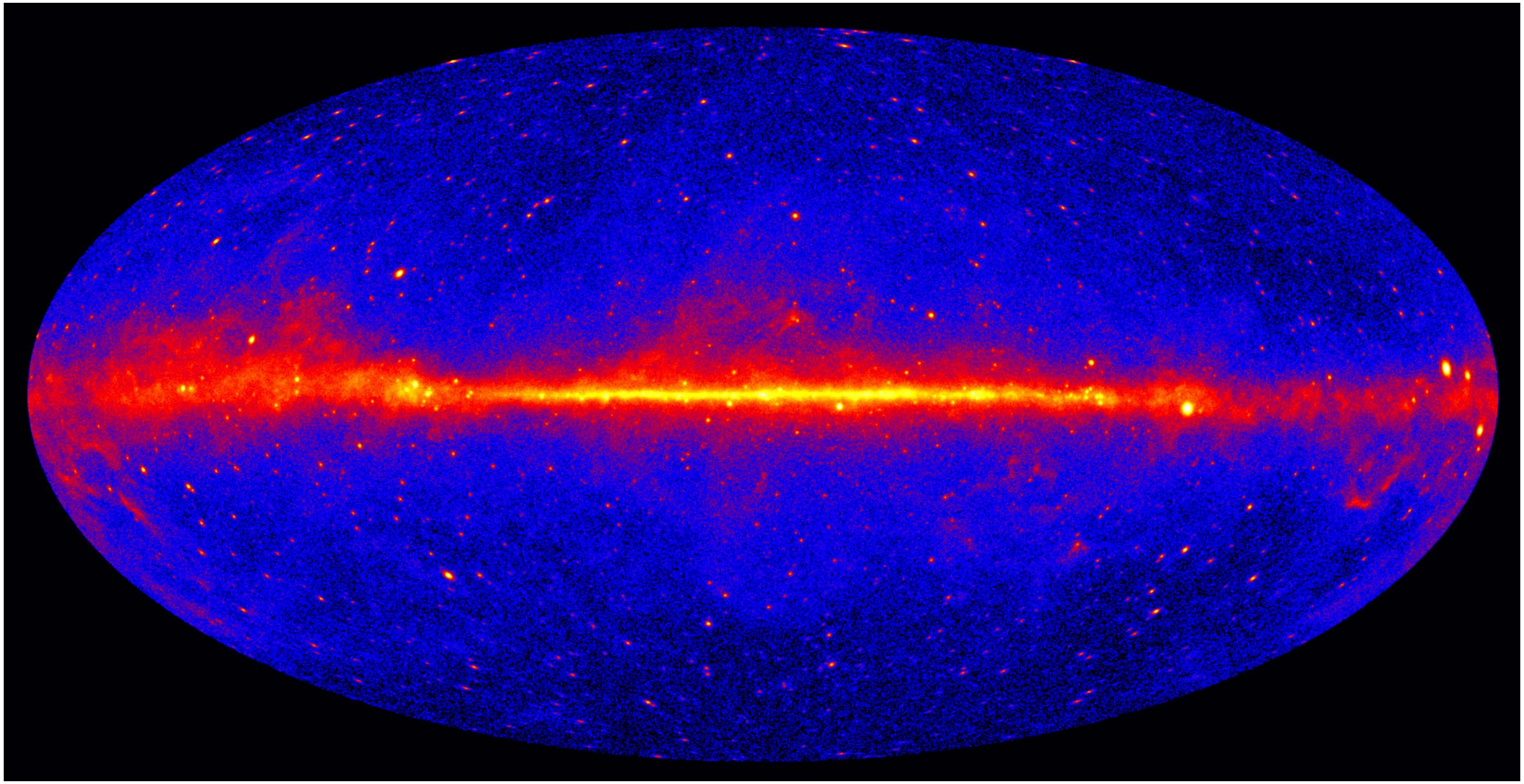


The sky is bright in neutrinos



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

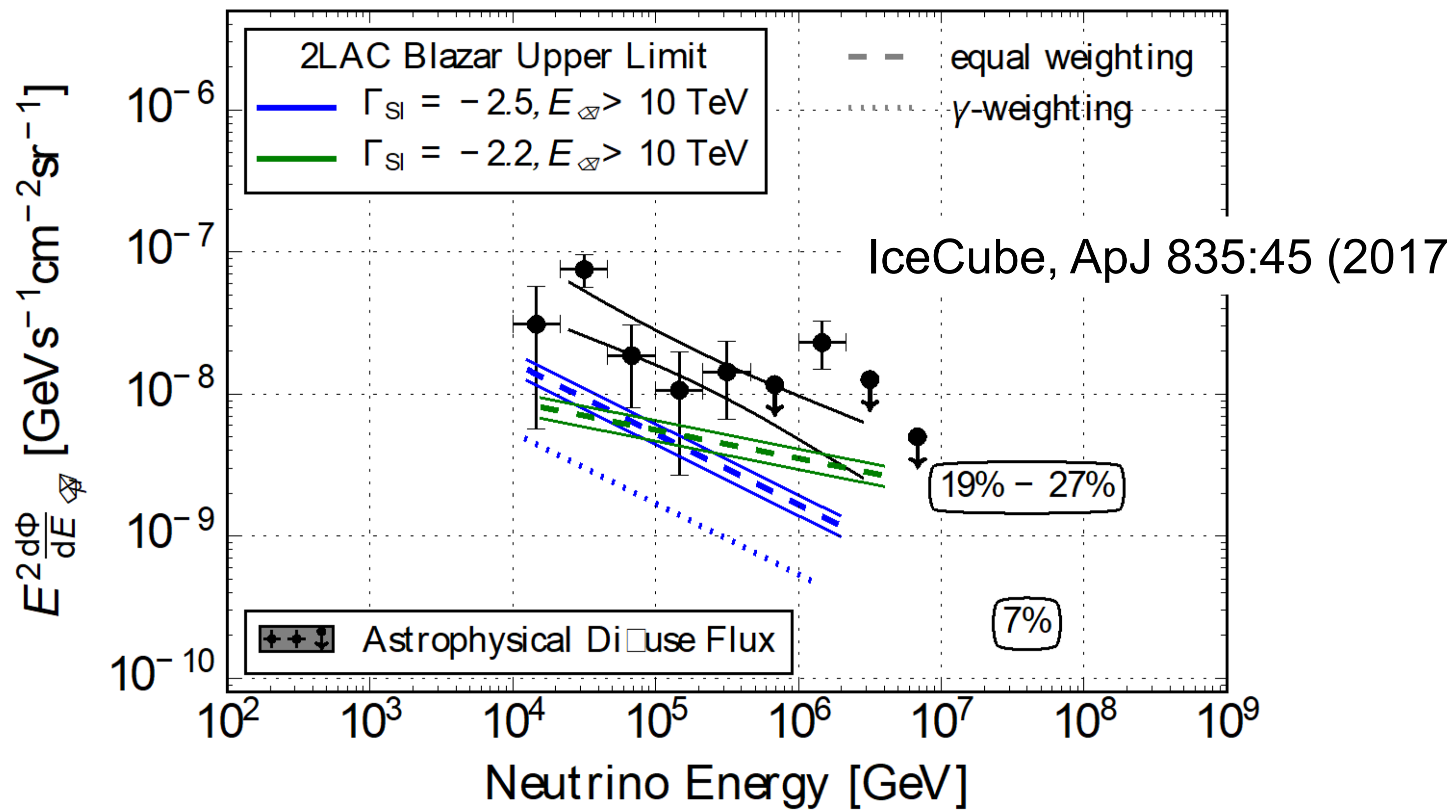
The gamma-ray sky



blazars, gamma-ray bursts, star-forming galaxies, non-blazar AGN, compact object mergers, …

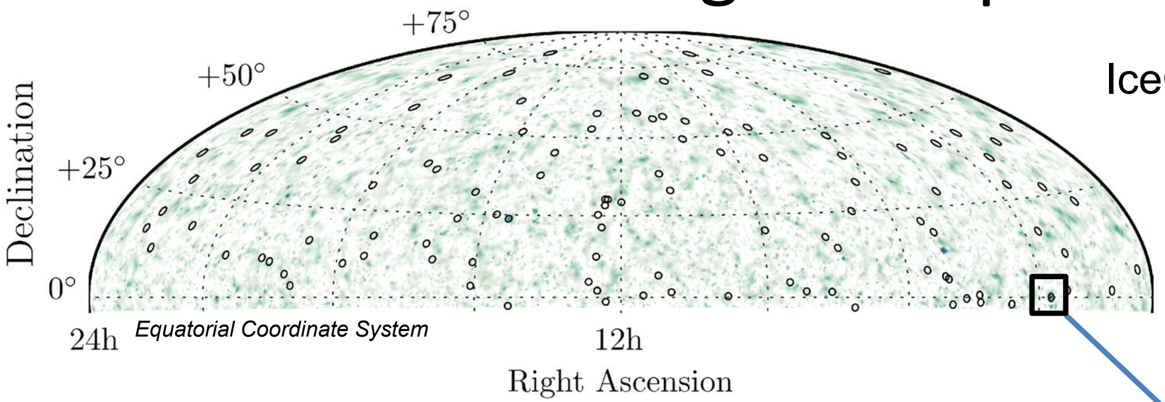
pulsars, supernova remnants, pulsar wind nebulae, star-forming regions, binaries, novae, …

Neutrinos are not generally associated with GeV gamma-ray sources including blazars

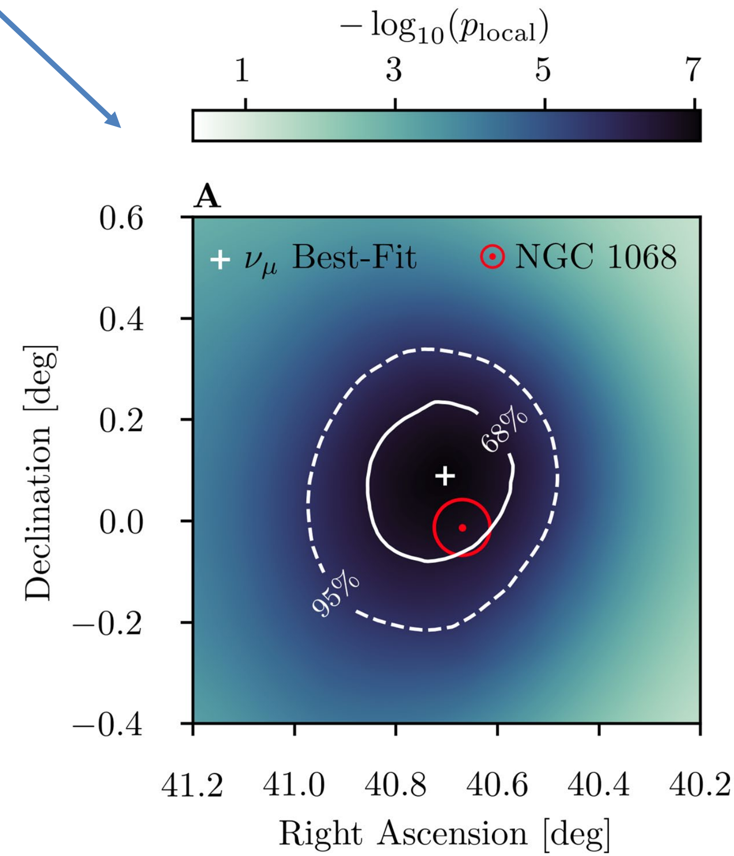


- Search for correlation between IceCube neutrinos and GeV blazars
- Fermi 2LAC sample: 862 blazars
- Lack of correlation constrains contribution of 2LAC blazars to neutrino signal
- Similar constraints from 3FHL (hard sources) and 1FLE (low energy sources)

Latest IceCube general point source search



IceCube, Science 378, 538-543 (2022)



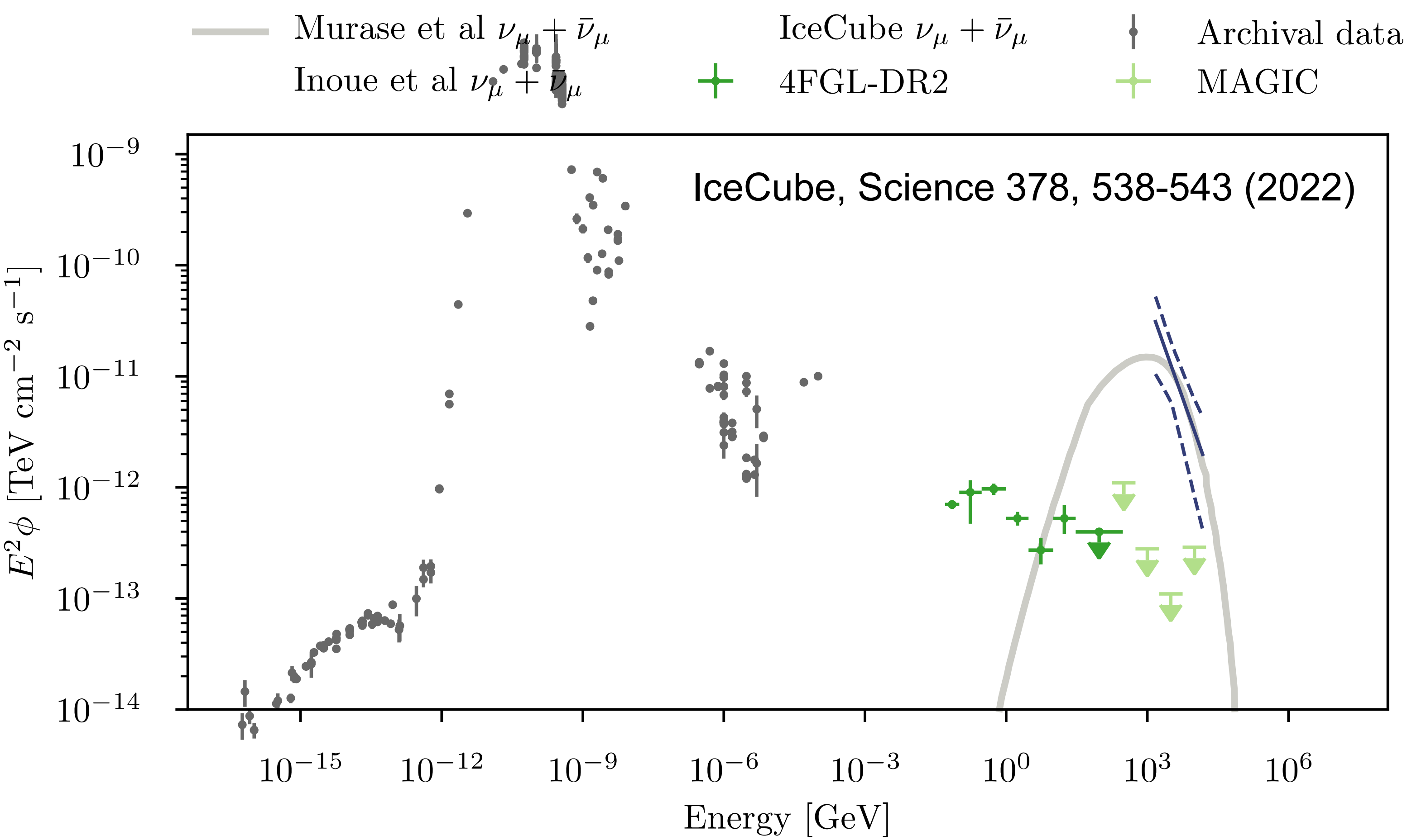
Two analyses
1) Northern hemisphere scan
2) 110 gamma-selected candidate sources

Hottest scan direction consistent with hottest candidate source direction

Seyfert galaxy NGC 1068 (M 77)
After correcting for 110 trails:
4.2 sigma significance

79 (+22, -20) astrophysical neutrino events
Spectral index = 3.2 ± 0.21

Neutrinos from NGC 1068



- A Seyfert II detected in GeV gamma rays but not TeV gamma rays (IceCube band)
- Interpretation: GeV from starburst, TeV from obscured AGN with gamma absorption
- To explain absorption, neutrinos must be produced within ~30 Schwarzschild radii

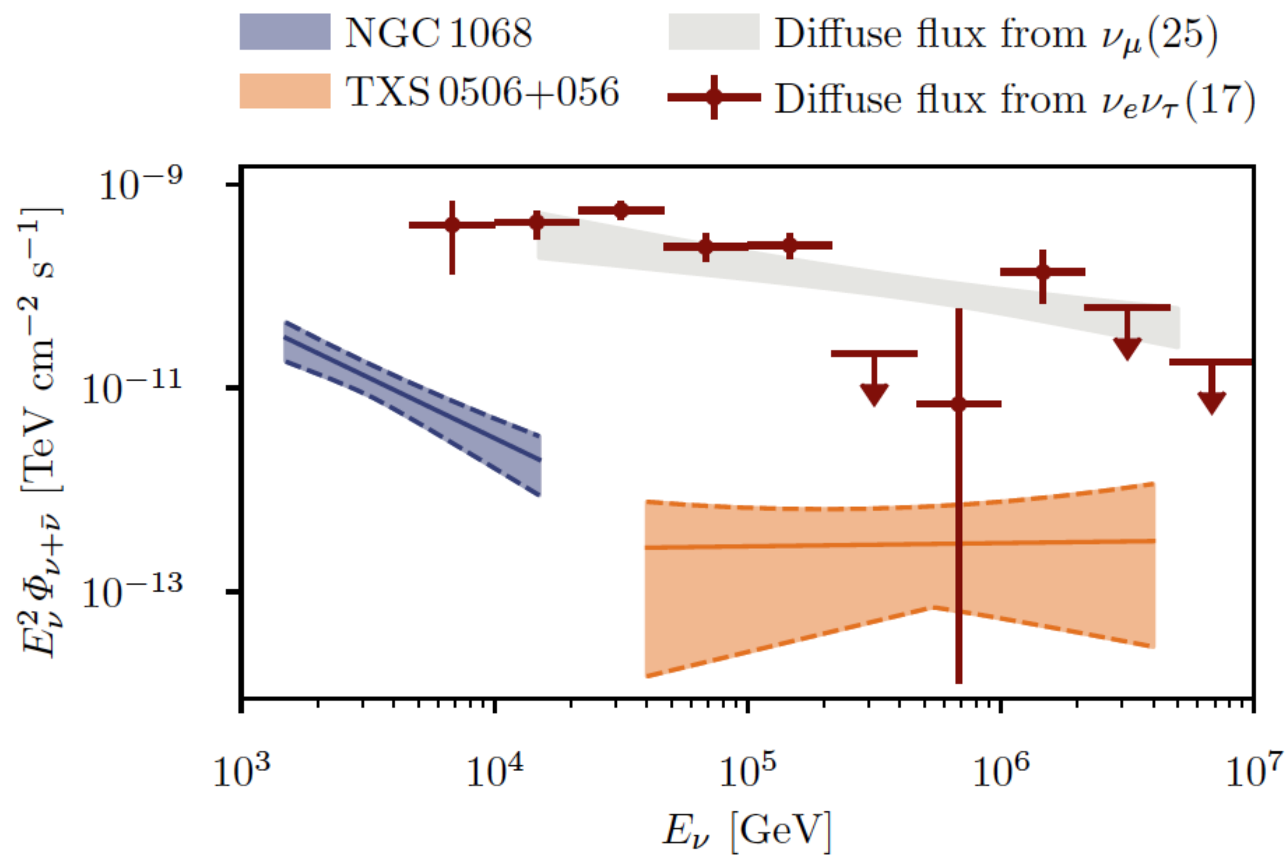
[K. Murase, 2022 ApJL 941:L17 (2022)]

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

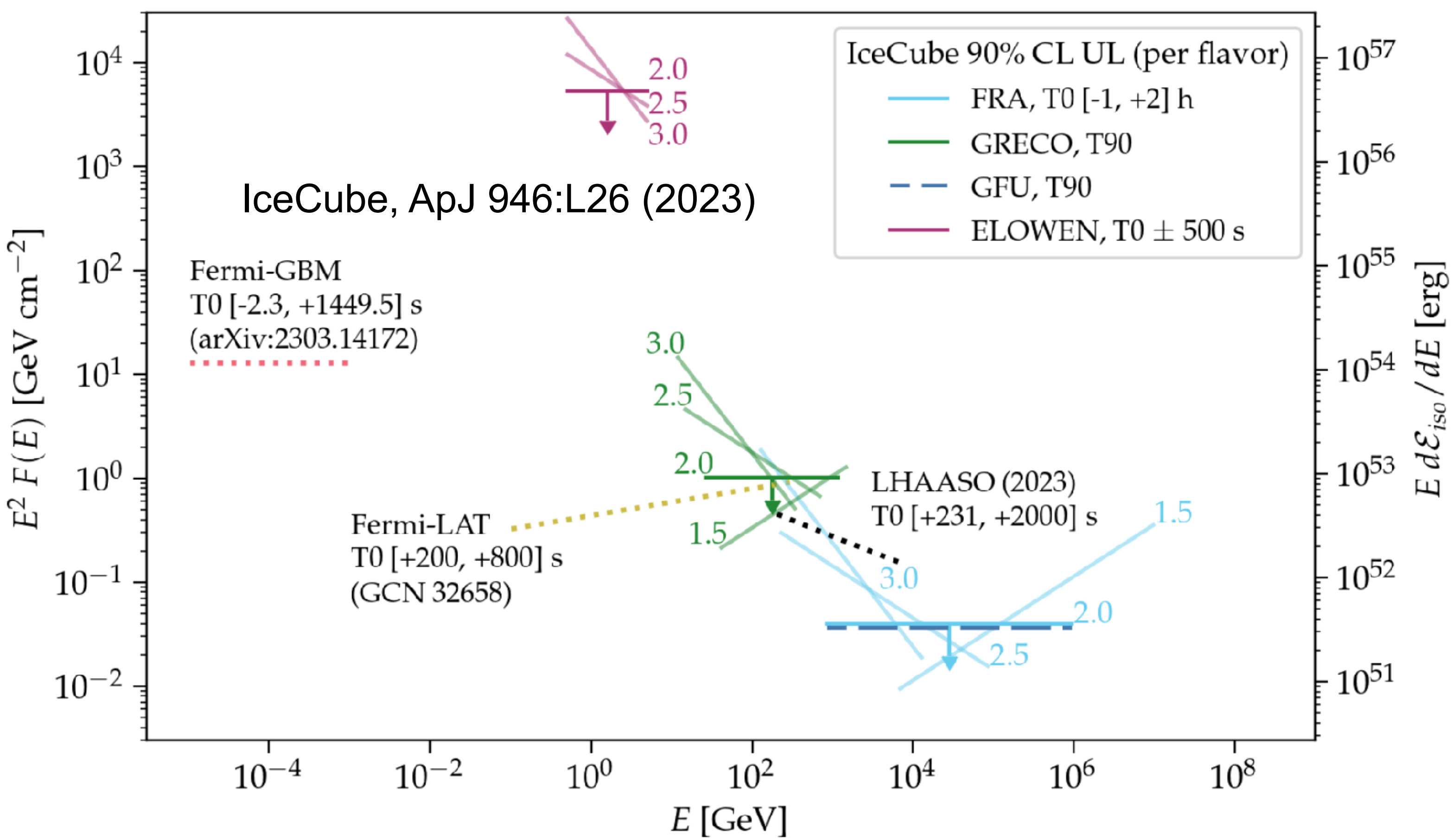
Active galaxies contribute a fraction of the extragalactic neutrino flux

NGC 1068 is opaque to high-energy gamma-rays

NGC 1068 and TXS 0506+056 are very different sourcdes

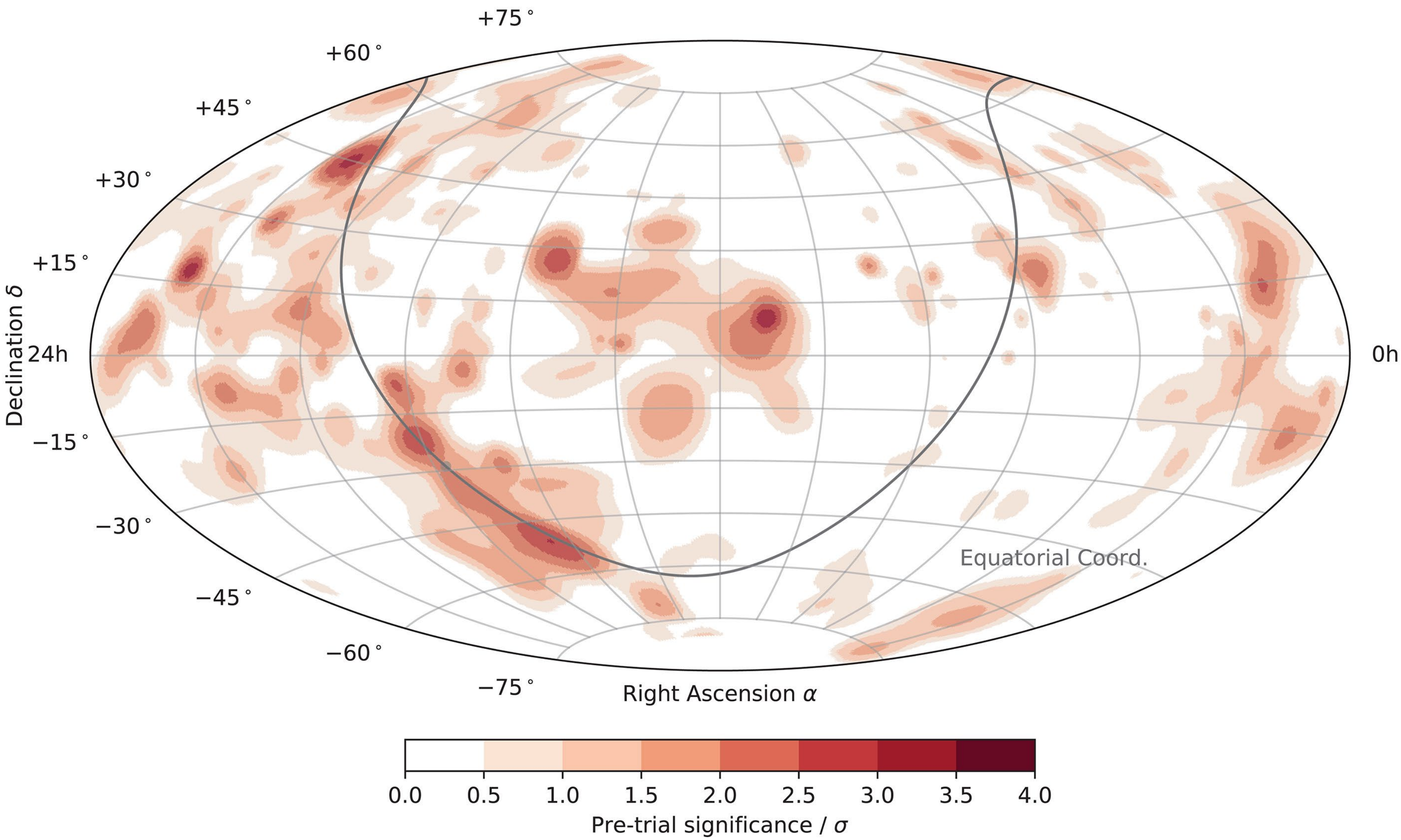


Gamma-ray burst 221009A: the brightest of all time



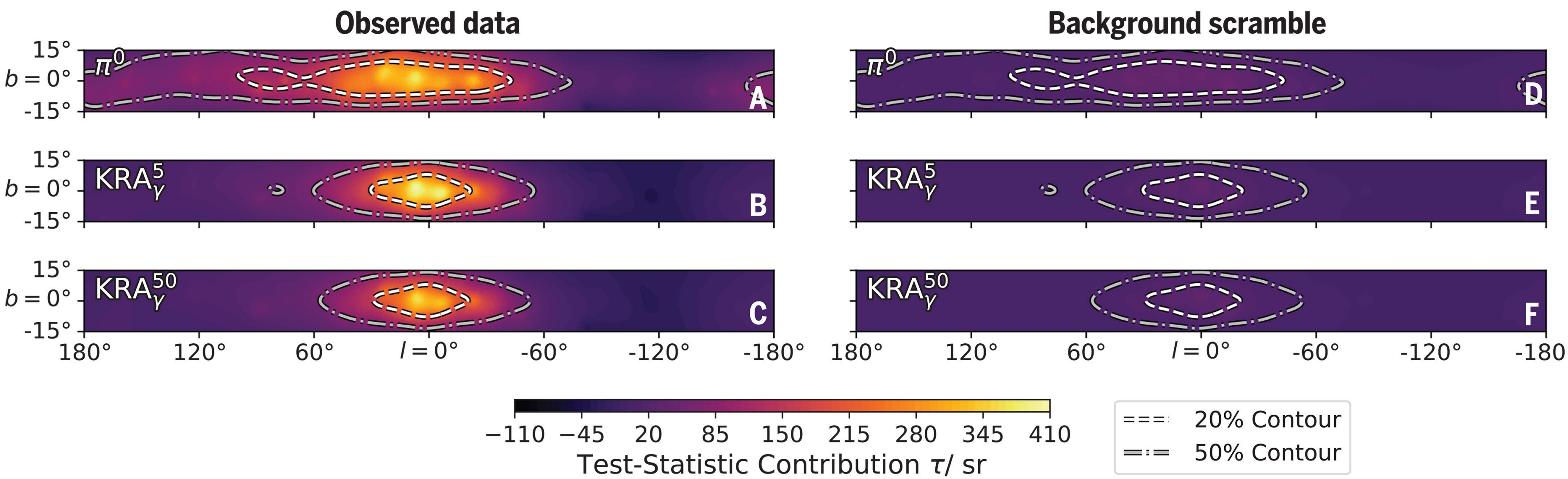
- Highest ever measured gamma-ray peak flux and bolometric energy
- IceCube neutrino search published within hours via GCN
- Neutrino limits from MeV to PeV
- Strong constraints on baryons in GRBs

IceCube's view of the full sky as seen in neutrino-induced cascades



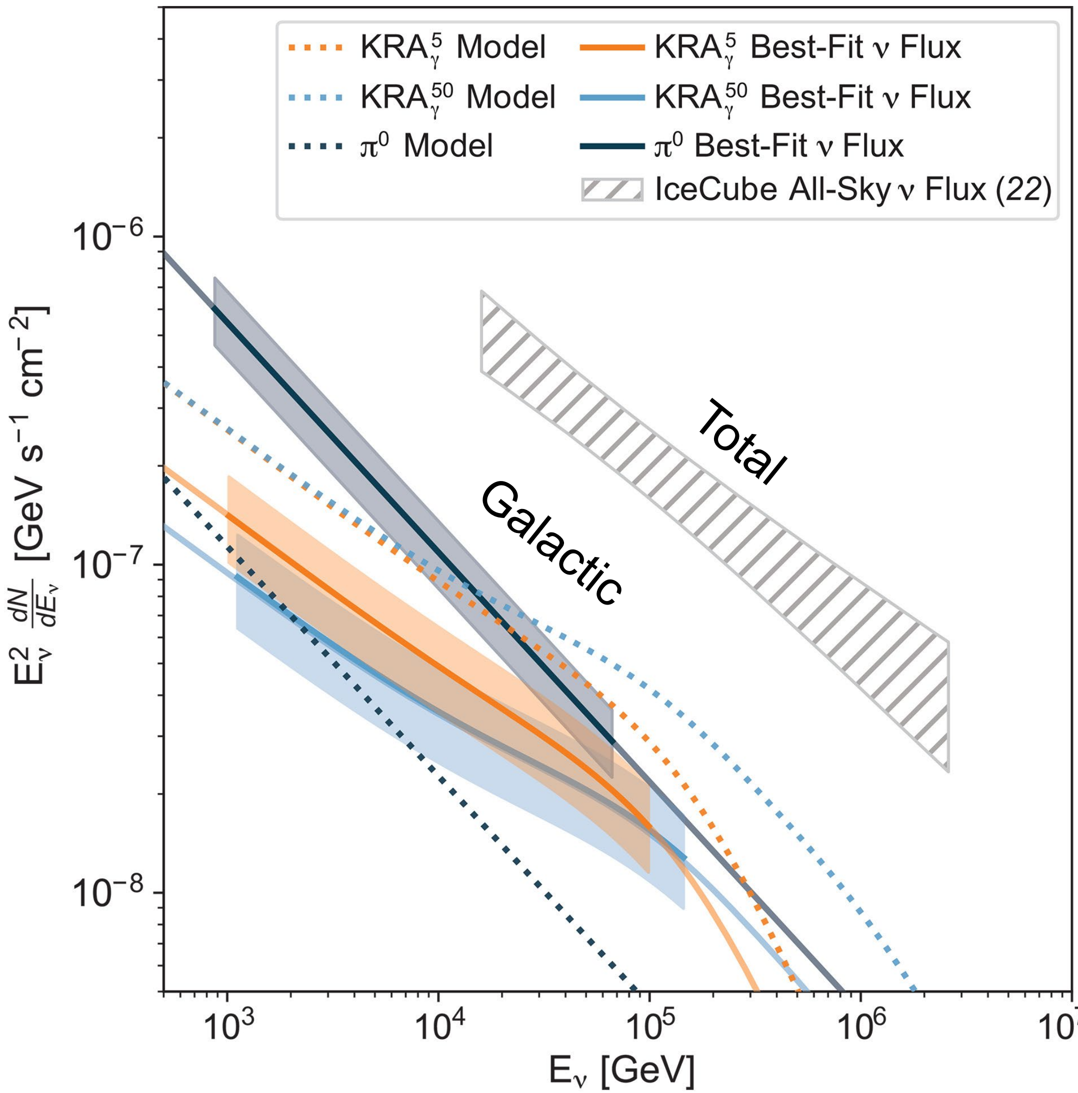
IceCube, Science 380, 1338-1343 (2023)

4.5 sigma evidence for Galactic neutrinos



IceCube, Science 380, 1338-1343 (2023)

About 10% of astrophysical neutrinos are Galactic



IceCube, Science 380, 1338-1343 (2023)

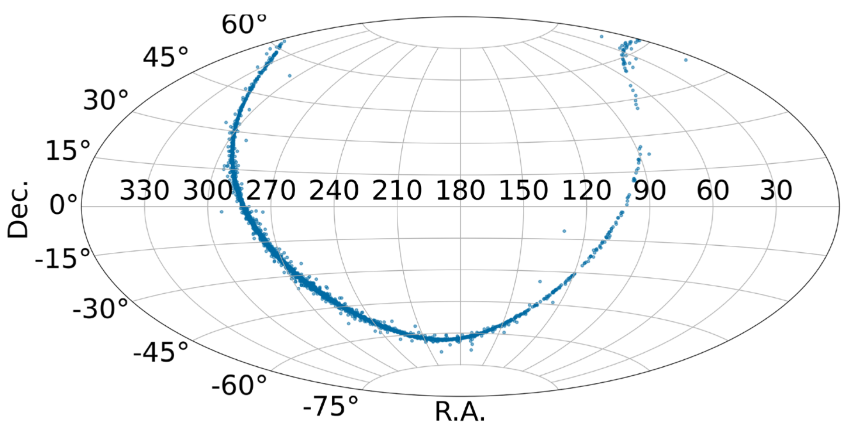
- Fist detection of Galactic neutrinos tests several diffuse models each with fixed spatial and spectral shape, free normalization
- Signal is brighter than prediction from Fermi LAT π^0 model extrapolation
- Signal could include both diffuse emission and Galactic sources

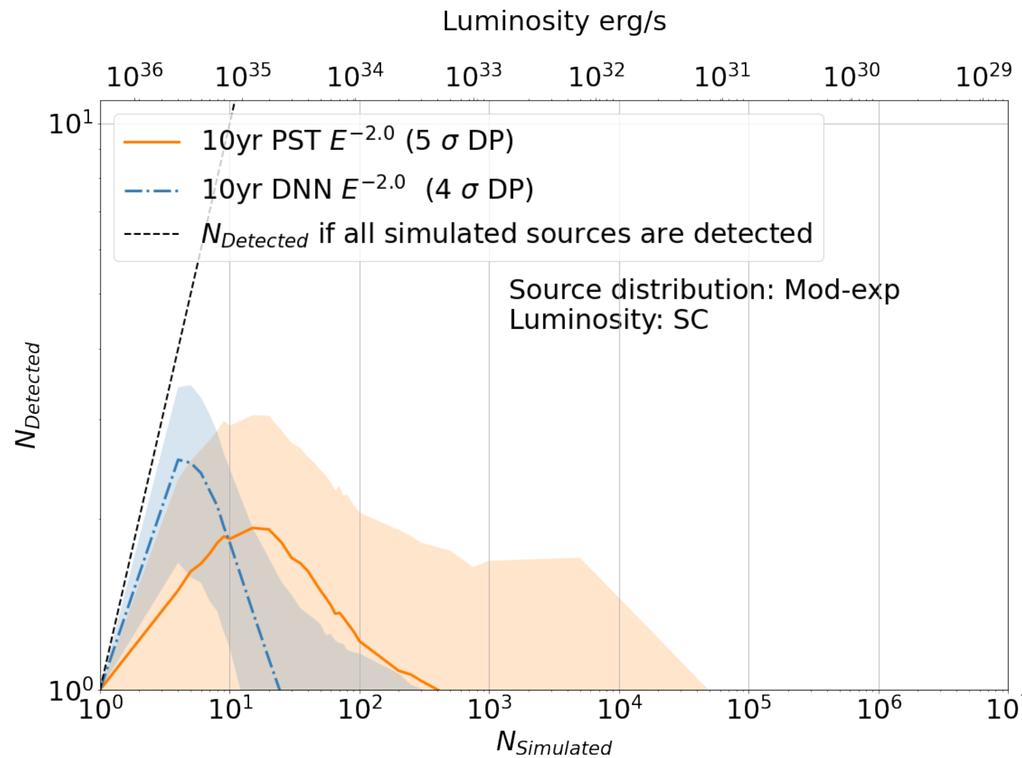
Constraints on the origins of the Galactic neutrino flux

Simulation of the Neutrino and Gamma-ray Galactic Yield: SNuGGY software

There must be >10 sources, each with luminosity <10^{35} erg/s

Galactic source distribution

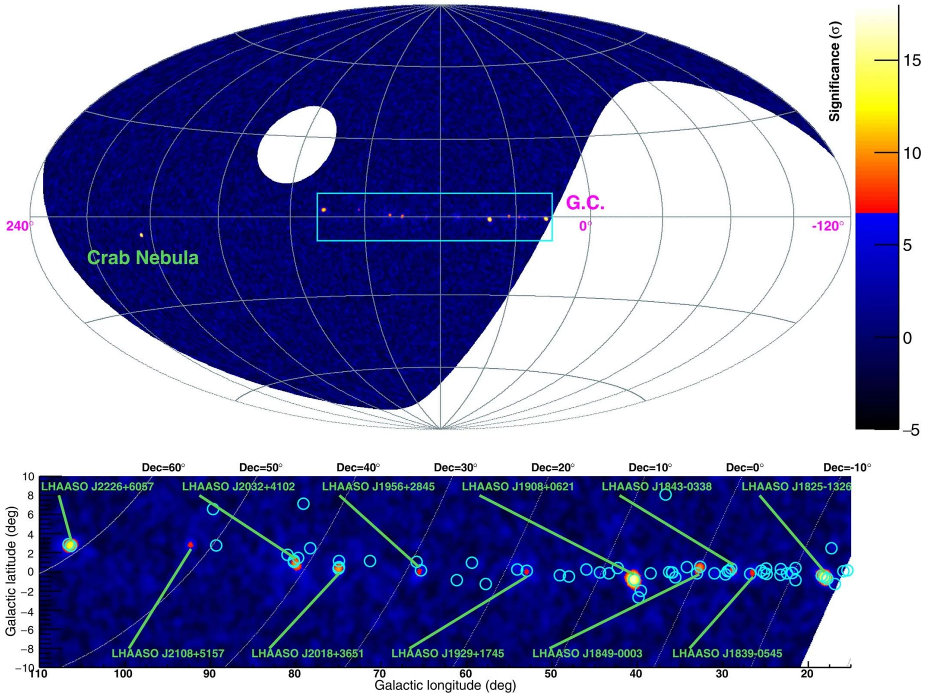




A. Desai, J. Vandenbroucke, et al., ApJ in press, 2306.17305

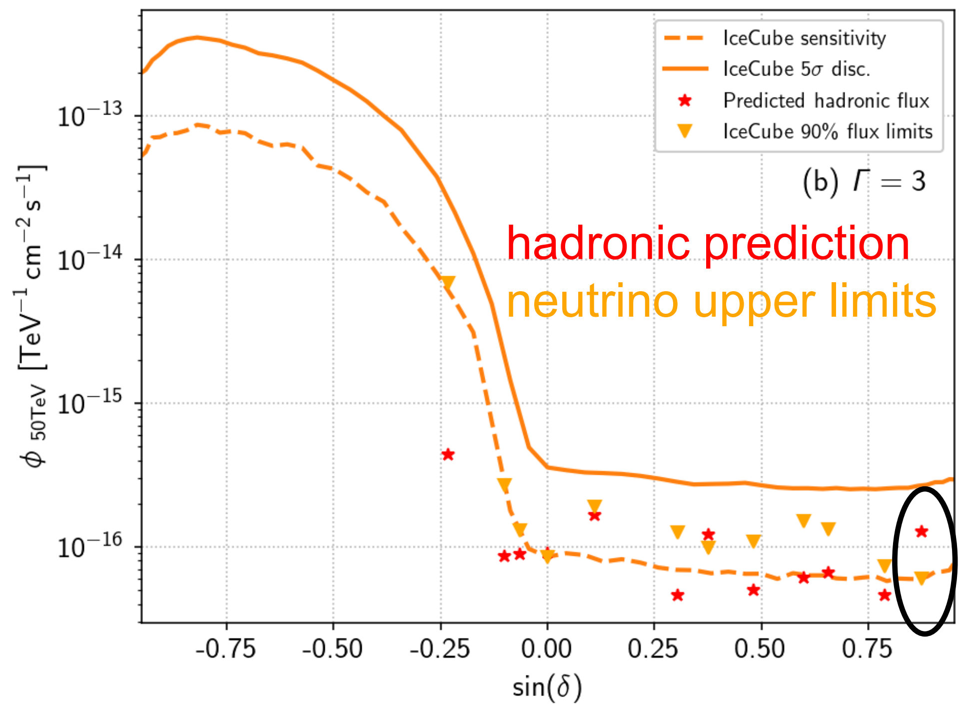
Are the sources of the highest energy photons ever detected also neutrino sources?

LHAASO, Nature 594, 33-36 (2021)



12 sources at 0.1–1.4 PeV

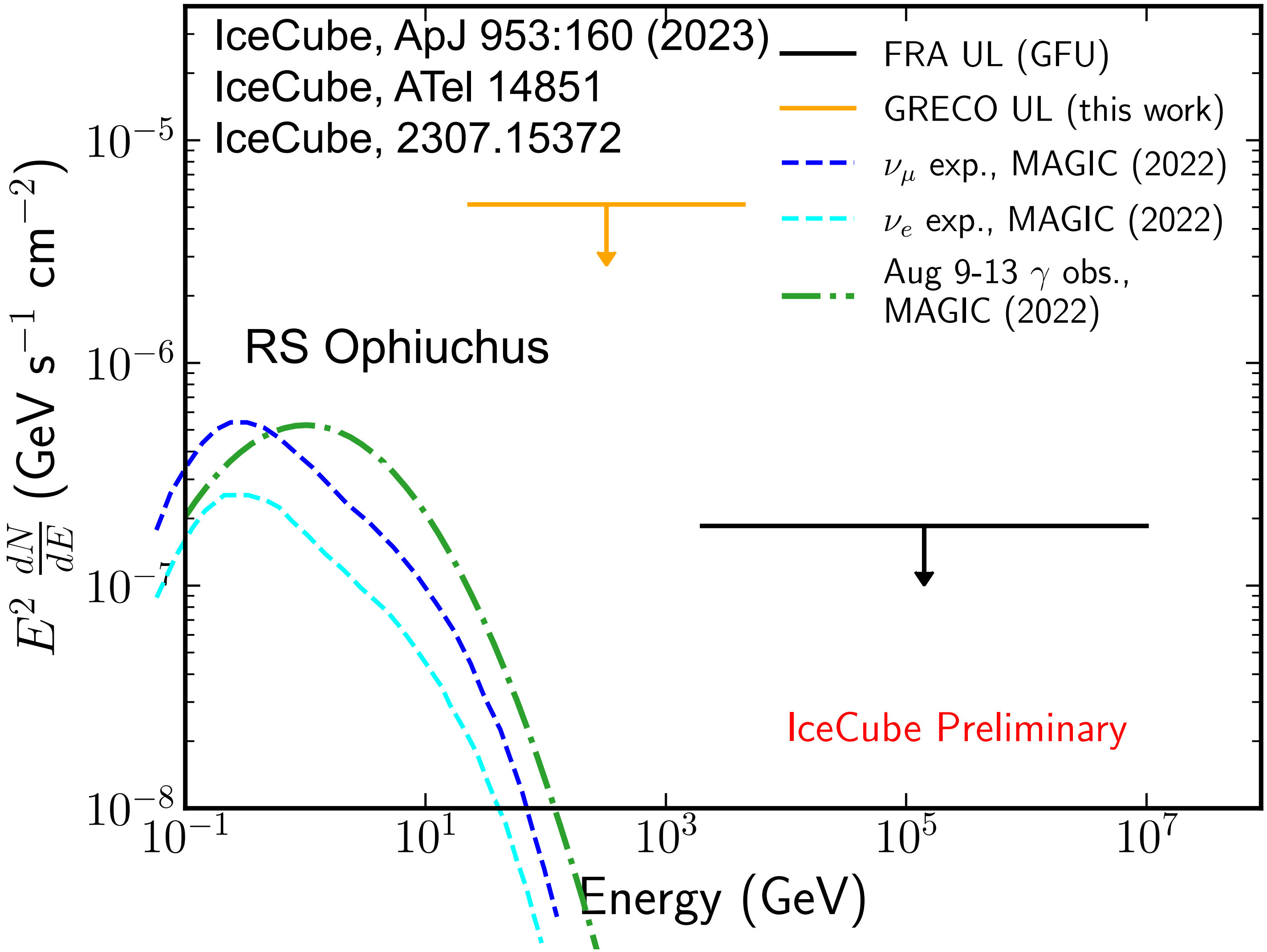
IceCube, ApJL 945:L8 (2023)



SNR G106.3+02.7:

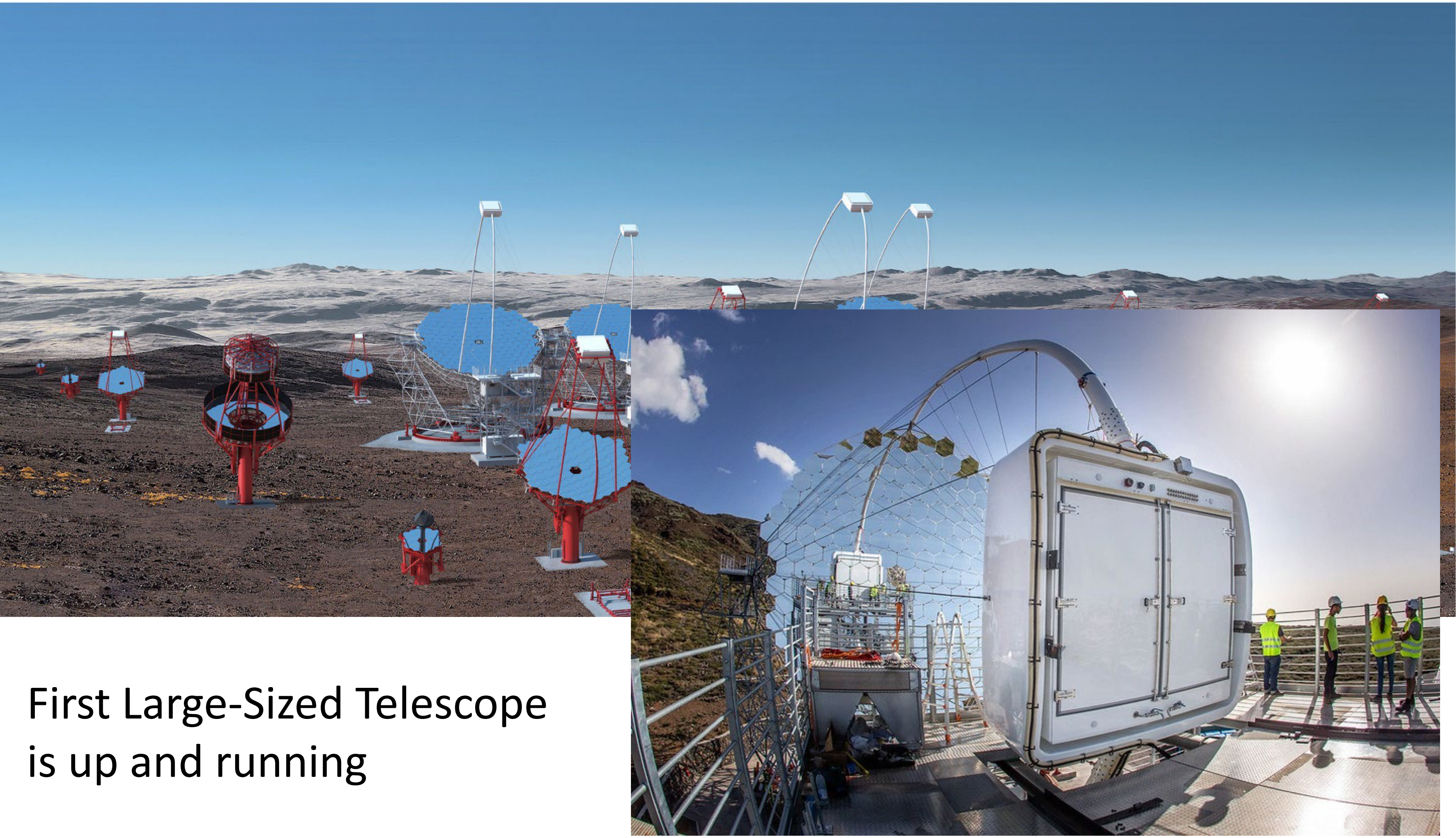
upper limit is 47% of hadronic prediction

Neutrinos from novae?



T Coronae Borealis, expected to outburst in 2024, will be ~10x brighter than RS Oph and with ~10x better IceCube sensitivity

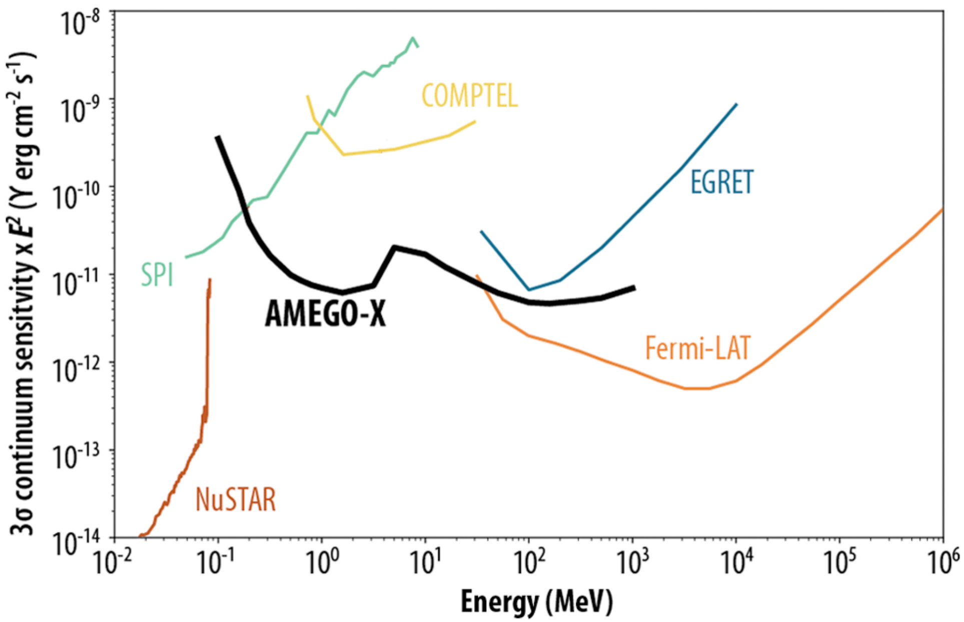
The Cherenkov Telescope Array: 20 GeV – 300 TeV gamma-ray observatory

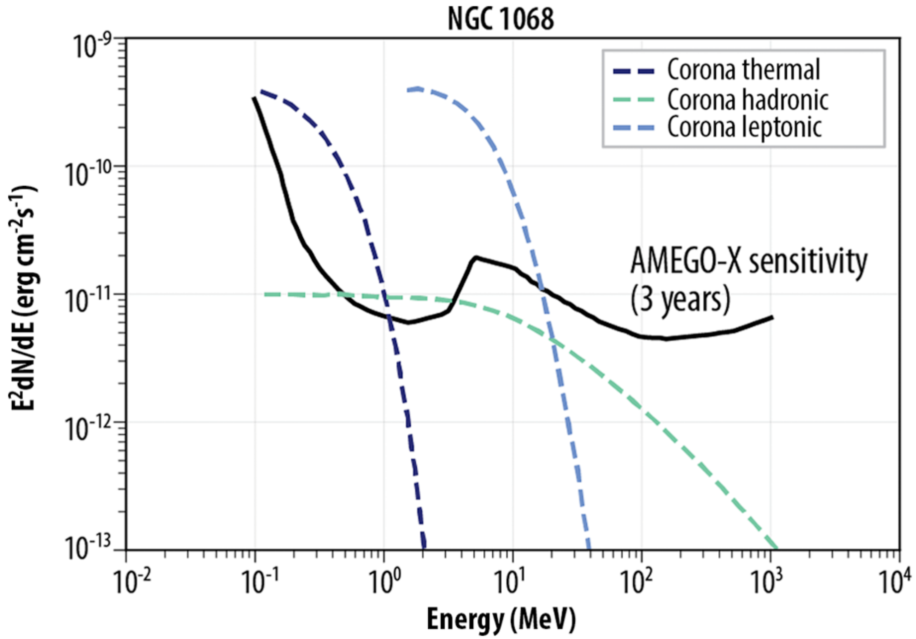


First Large-Sized Telescope
is up and running

MeV gamma rays, e.g. with AMEGO(X)

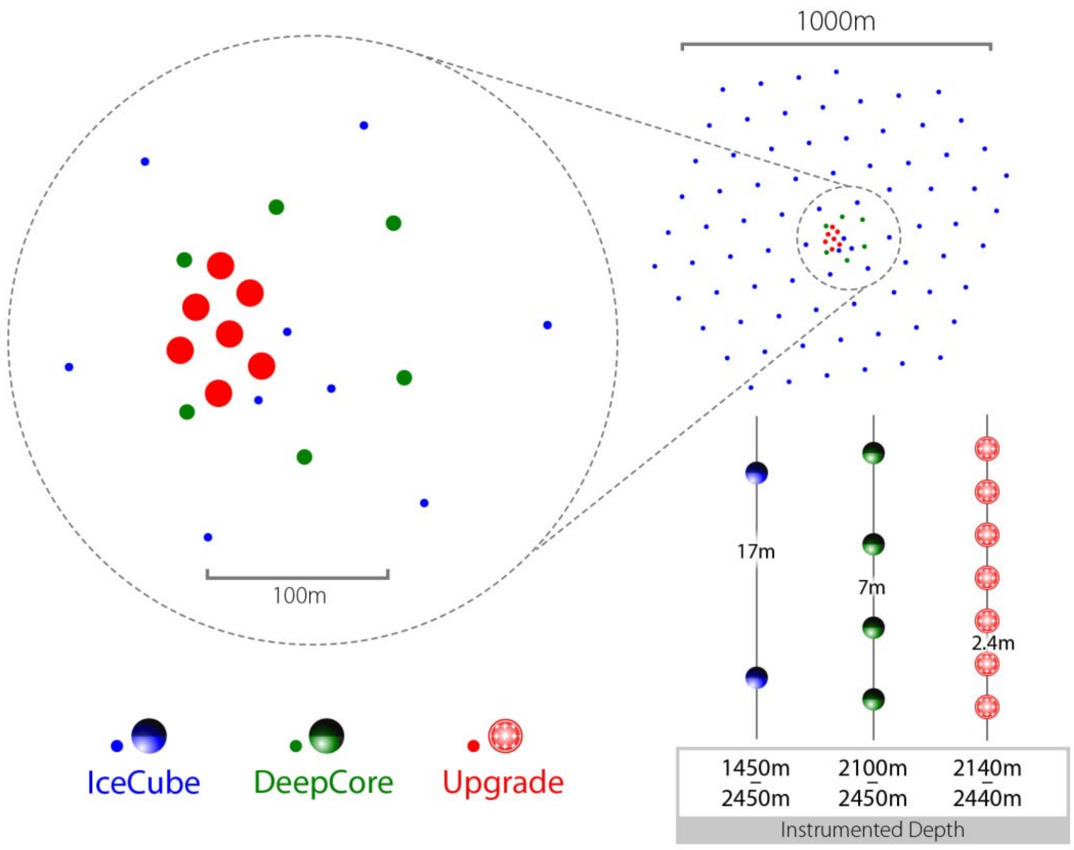
GeV-TeV gamma-rays that interact within obscured sources can cascade down to MeV band and escape





R. Caputo et al., JATIS 044003-2 (2022)
K. Murase et al., PRL 125 011101 (2020)

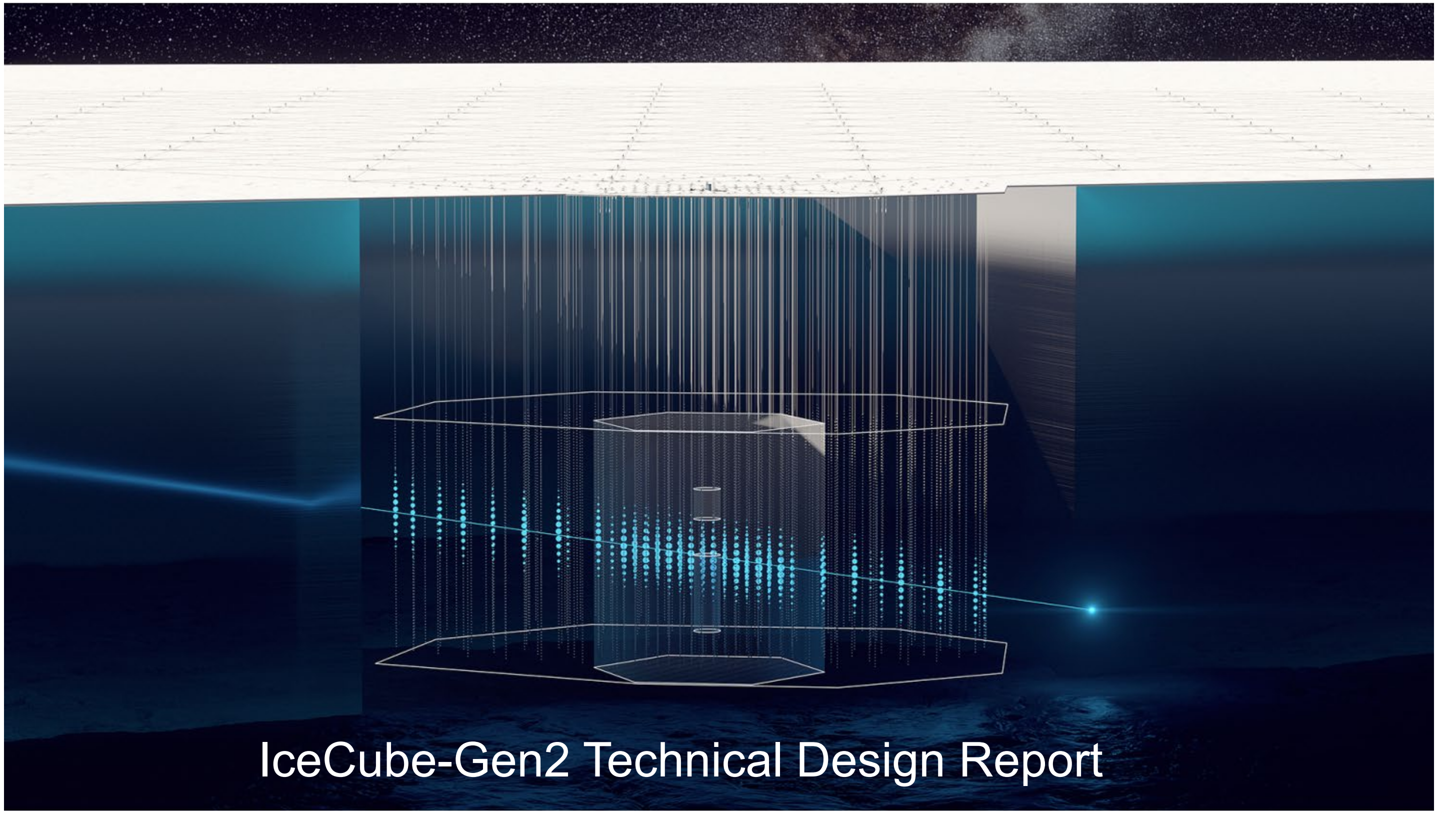
The IceCube Upgrade will be installed in 2025–2026



- Dense infill with 7 new strings
- Improved sensitivity in the GeV (Fermi LAT) band
- Ice calibration to improve high-energy (TeV-EeV) instrument response and data archive
- Technology R&D for IceCube-Gen2

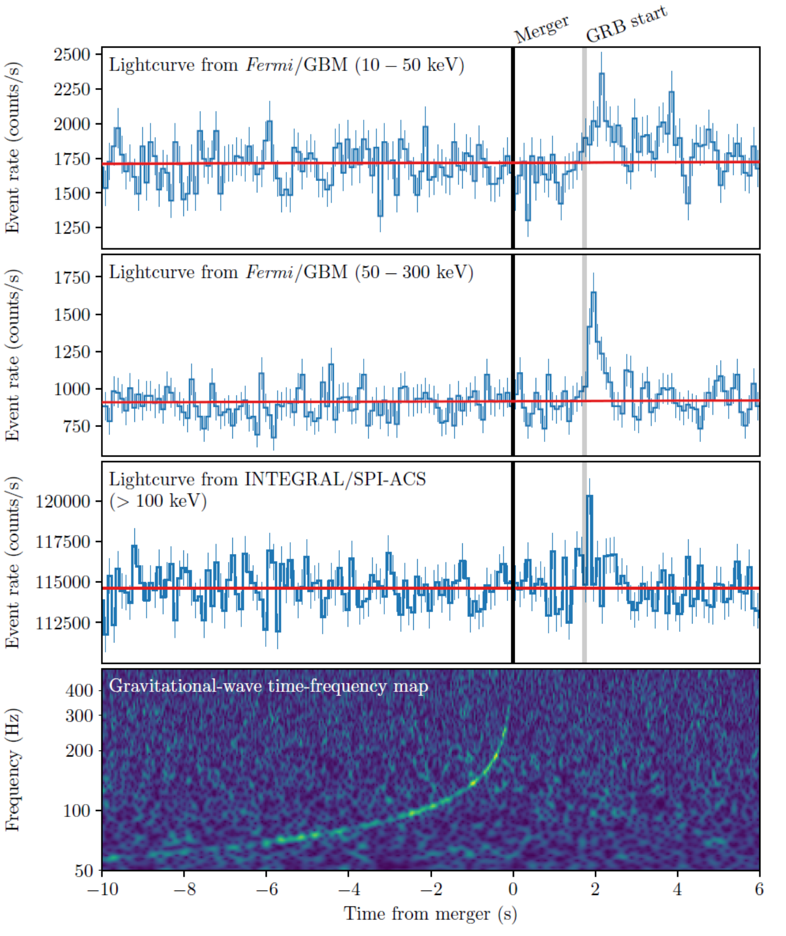
IceCube-Gen2: the next generation

ICECUBE-GEN2 TECHNICAL DESIGN



- High energy extension: Instrument ~10 km^3 (sparsely with ~120 new strings) to increase sensitivity to high energy (0.1-10 PeV) muon and cascade events
- Surface array for increased southern sky sensitivity and cosmic-ray physics
- Radio component for EeV neutrinos

Gamma rays are the key to multi-messenger science



- 170817: LVK, Fermi-GBM, INTEGRAL
- NGC 1068: IceCube, Fermi-LAT, MAGIC

- Gamma rays have provided the bridge from both neutrinos and gravitational waves to the electromagnetic spectrum
- Broad energy, sky, and temporal coverage in gamma rays can enable multi-messenger science to continue into the future

Conclusions

- The hadronic sky is comparably bright to the leptonic sky, but is still full of mysteries
- Gamma rays generically accompany neutrinos in hadronic sources
- The neutrino sky is very different from the gamma-ray sky: messengers are complementary
- Neutrino data cannot be fully understood without gamma rays and other photons
- Gamma rays are the key bridge from neutrinos (and GW) to the electromagnetic spectrum
- Gamma-ray coverage across all bands, all sky, and all time is essential
- "Time-domain and multi-messenger astrophysics with neutrinos" tomorrow 12:05-1:35pm