Neutrino astronomy IceCube results and the future of multimessenger searches

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on behalf of the IceCube collaboration.

Astronomy Institute
Ruhr-University Bochum

5th Zeldovich Meeting
Yerevan, 12-16 June 2023

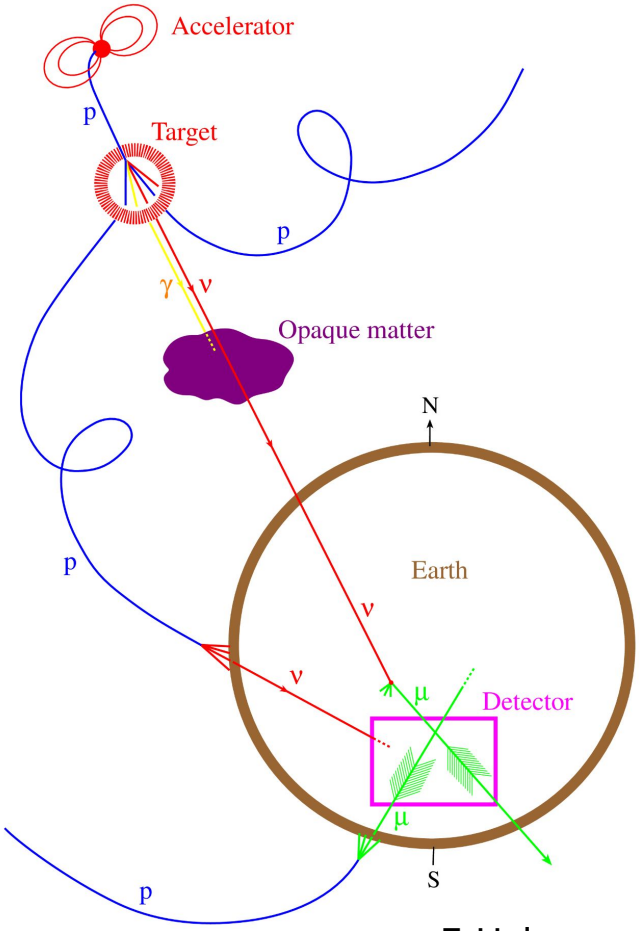
Making astrophysical neutrinos

Unequivocal signature of hadronic acceleration and interaction.

$$\mathbf{p\,p} \rightarrow \textit{had.} \rightarrow \pi\,(+, -, 0)$$
$$\mathbf{p\,\gamma} \rightarrow \Delta \rightarrow \pi\,(+, -, 0)$$

$$\pi\,(+, -) \rightarrow \mu, e, \nu$$
$$\pi\,(0) \rightarrow \gamma$$

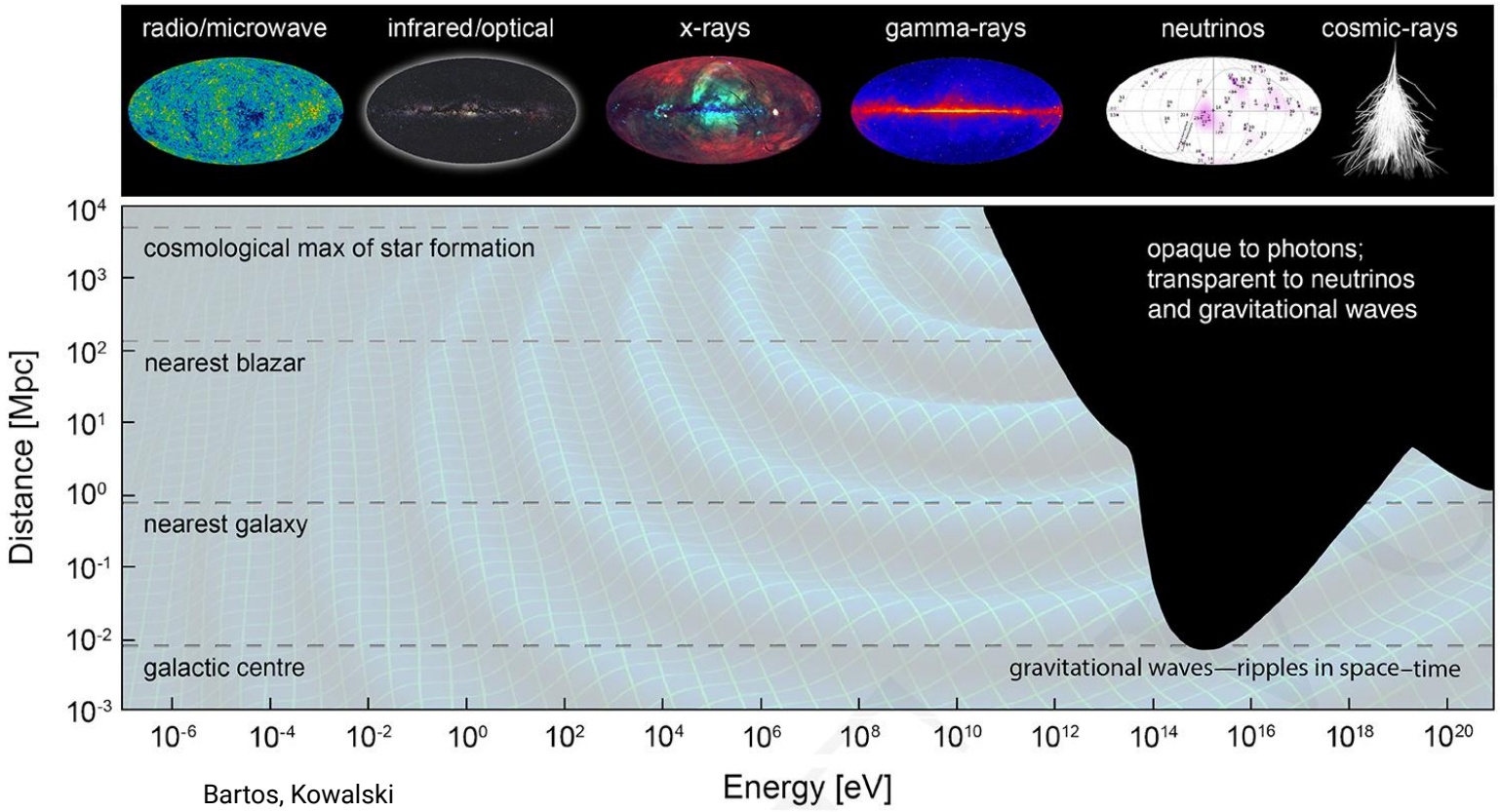
Gamma-rays can originate in purely leptonic scenarios.



F. Halzen

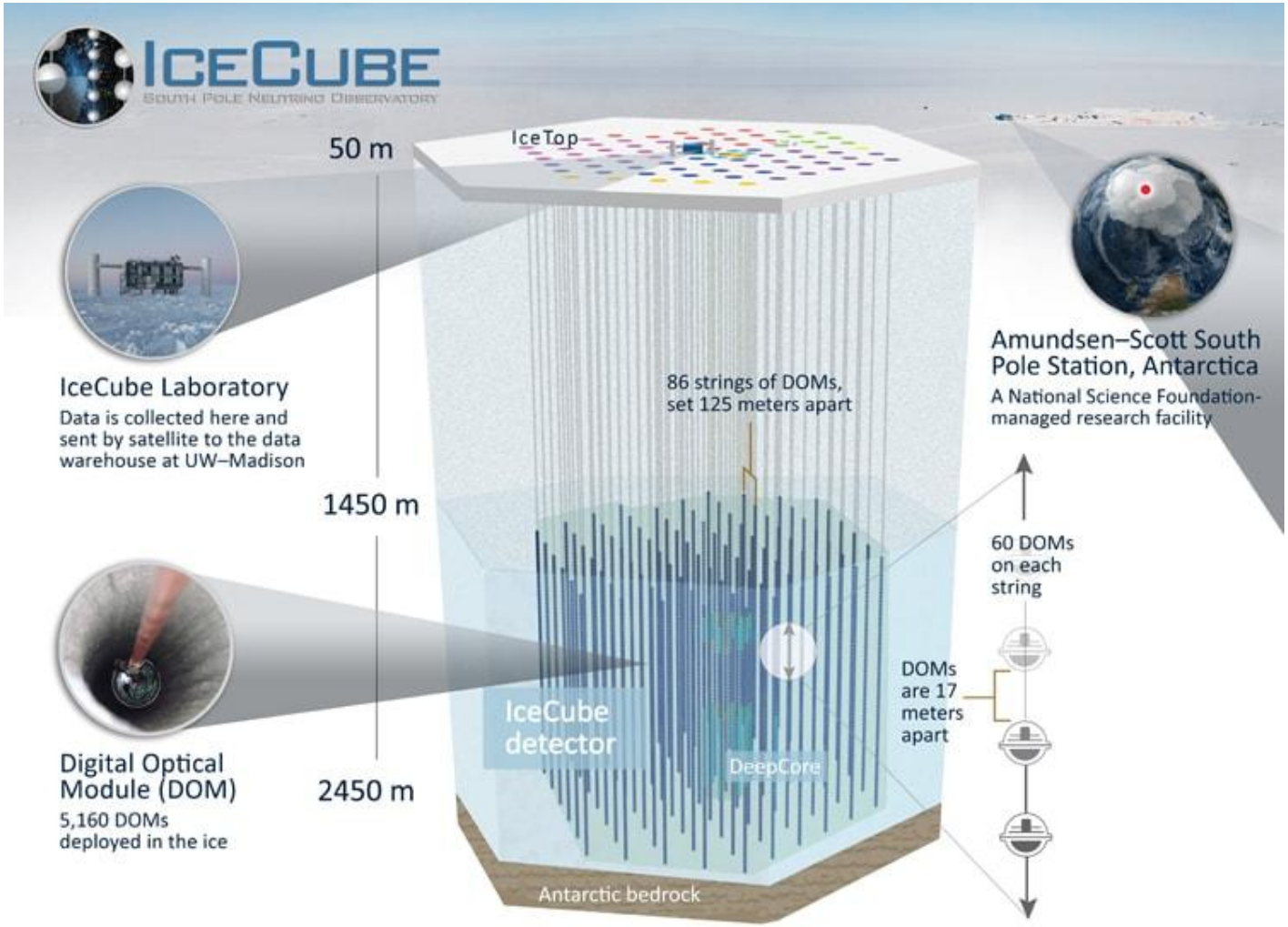
Great astrophysical messengers

Neutrino probe dense environments and cross undeflected the great cosmic distances.

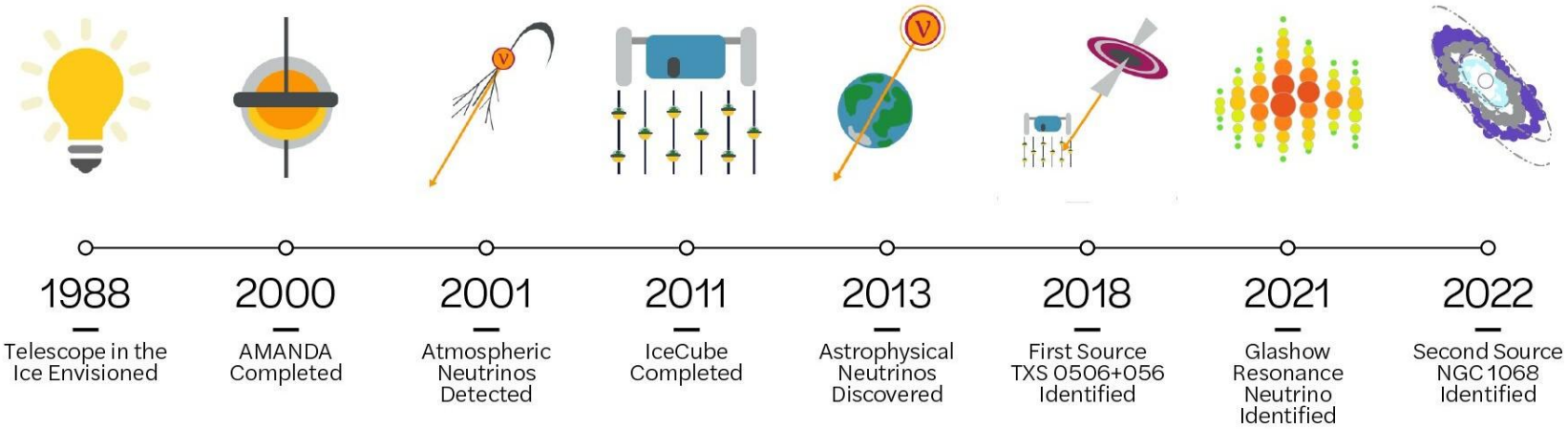


Bartos, Kowalski

The IceCube Neutrino Observatory

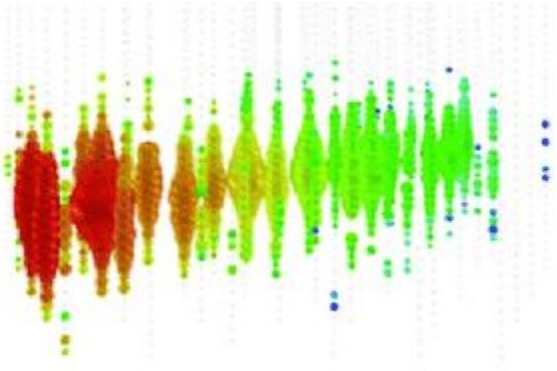


Three decades in Antarctica



High-energy neutrinos in IceCube

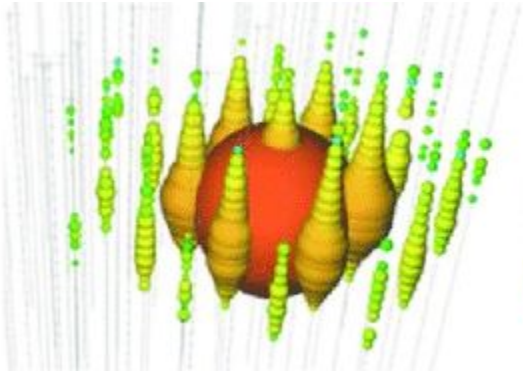
Tracks ($\nu_\mu + \bar{\nu}_\mu$)



~ 0.5 deg resolution

point sources

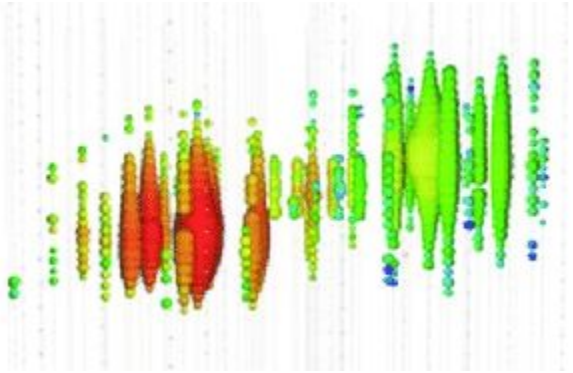
Cascades (all flavour)



~ 20-30 deg resolution

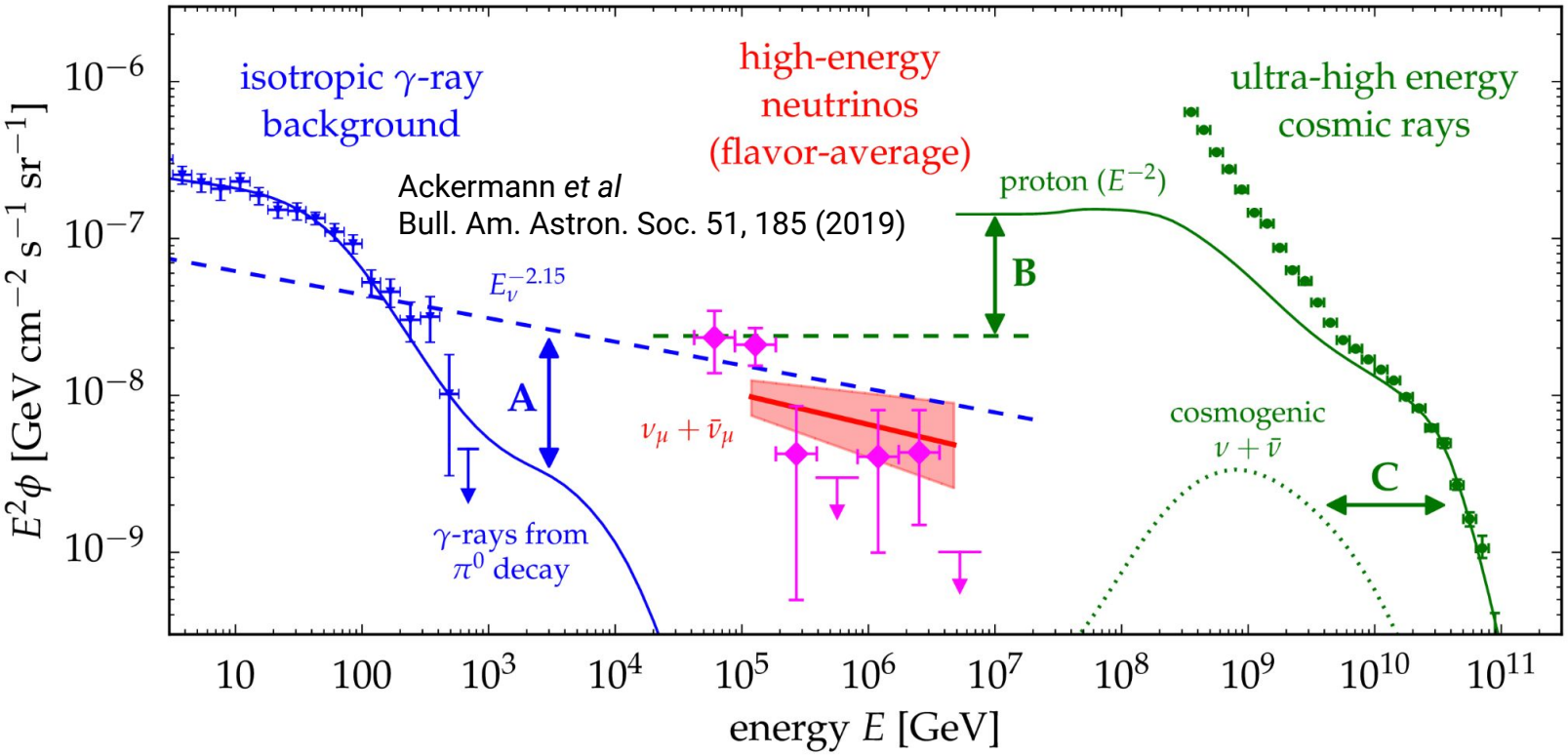
very good energy resolution

Double bang (ν_τ)



The astrophysical diffuse flux

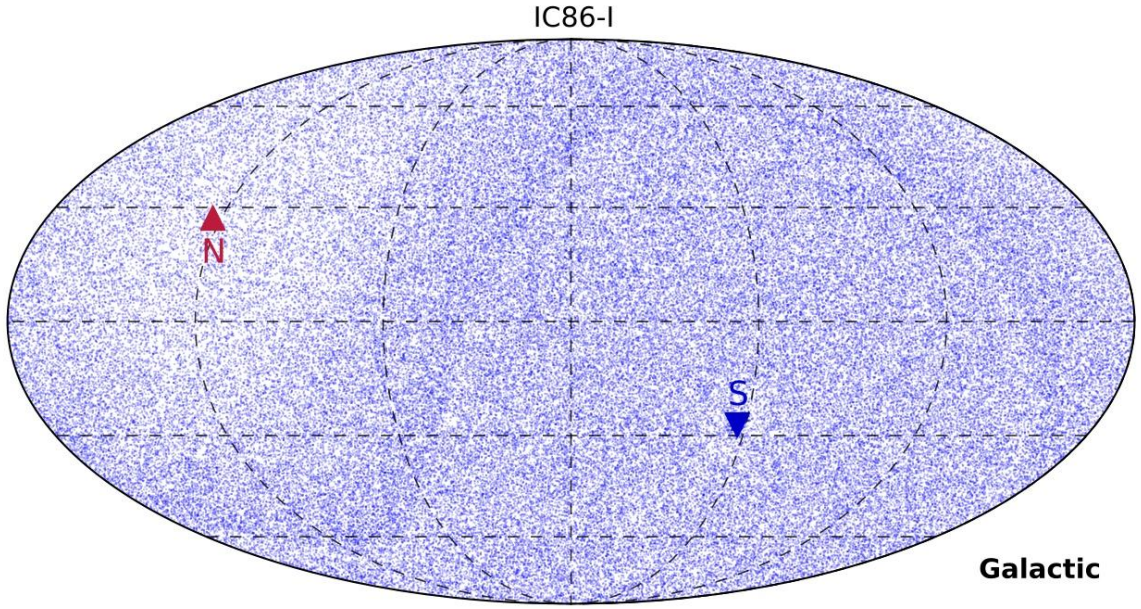
Comparable energy densities between gamma, neutrino and UHECR.



Neutrino flux high compared to isotropic gamma-rays hints at gamma faint sources.

A signal in a haystack

How to identify a signal of O(200) cosmic neutrinos on top of ~ 140000 atmospheric background events?



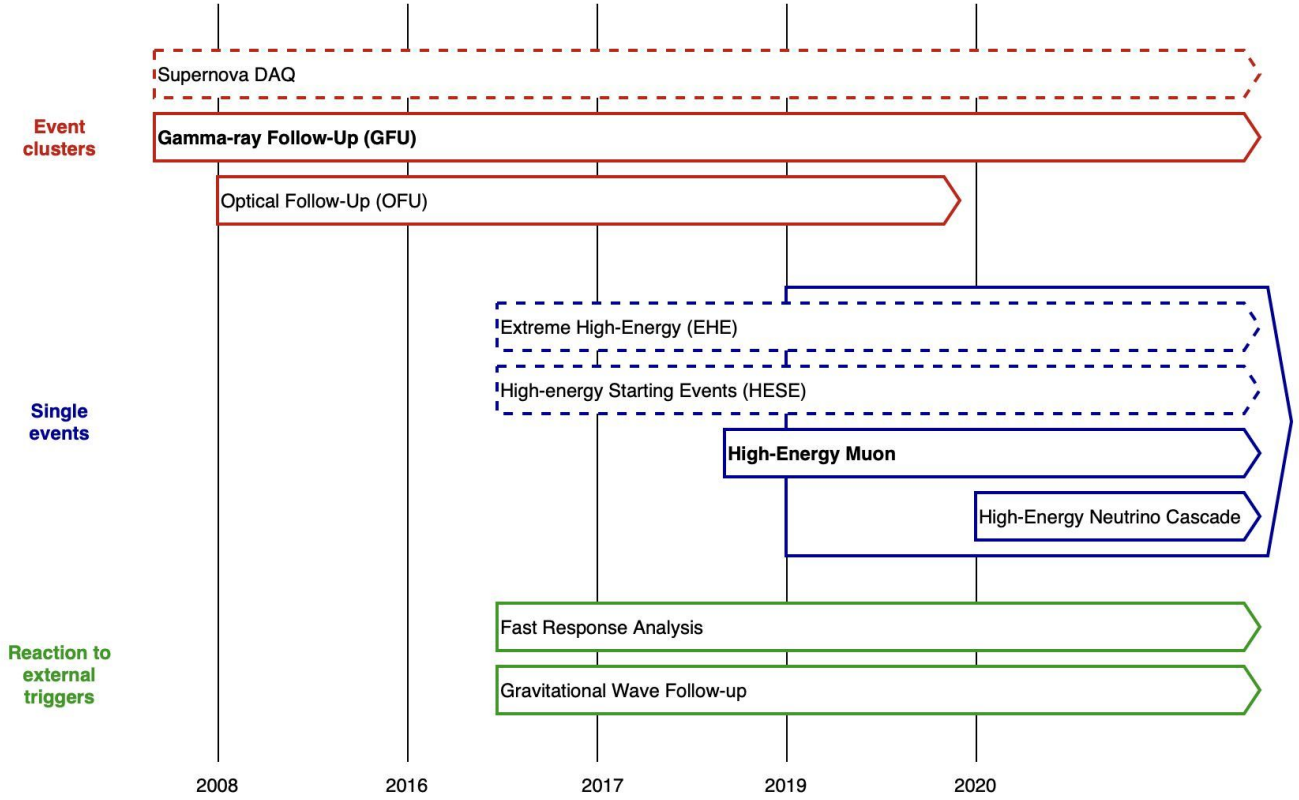
138322 neutrino candidates in one year

Spatial clustering

Spatial and temporal coincidences with astrophysical messengers

The IceCube realtime program

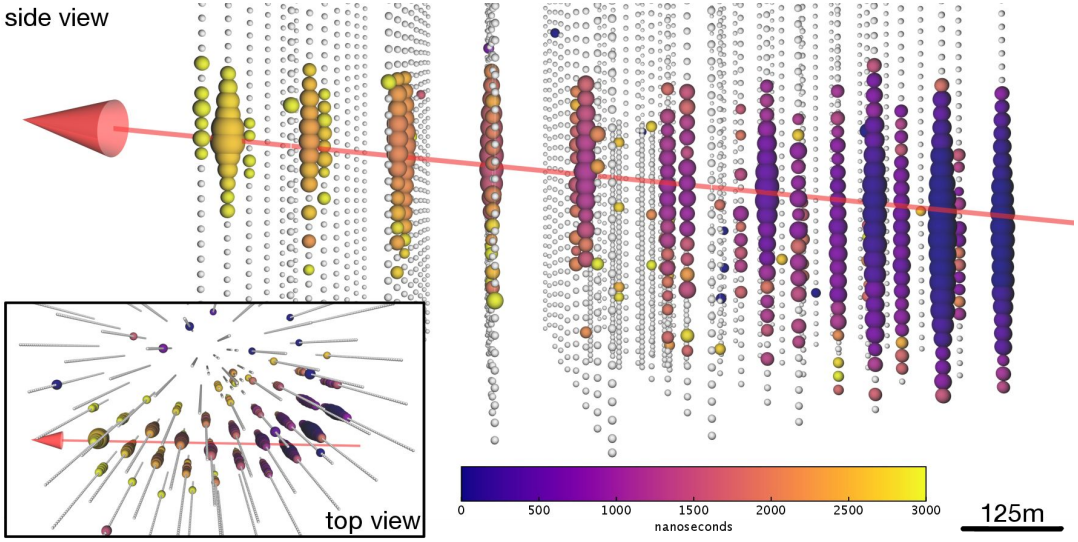
Find counterparts to IceCube neutrinos.



Follow-up interesting events with neutrino data.

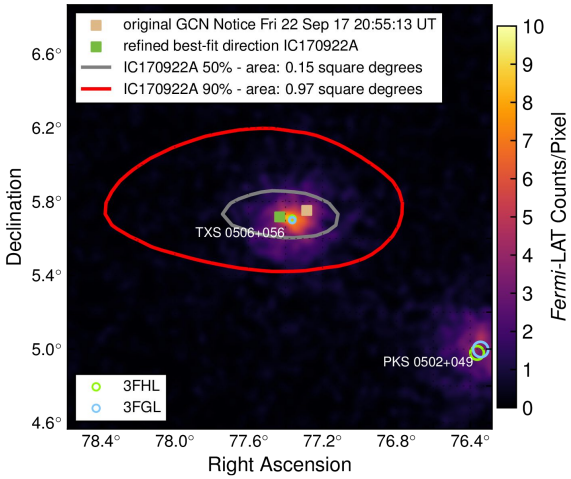
The first transient source: TXS 0506+056

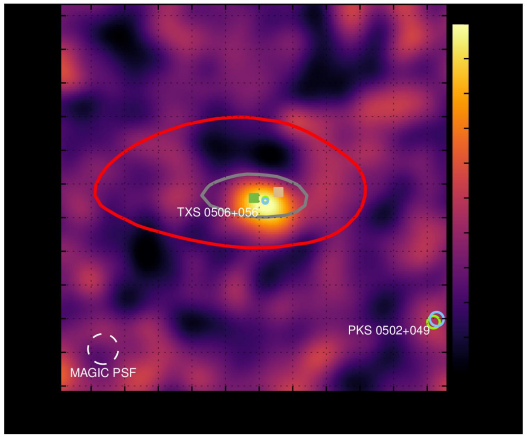
IceCube-170922A 290 TeV neutrino
coincident with the TXS0506+056 blazar.



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 **Science 361, eaat1378 (2018)**

Fermi-LAT γ flare



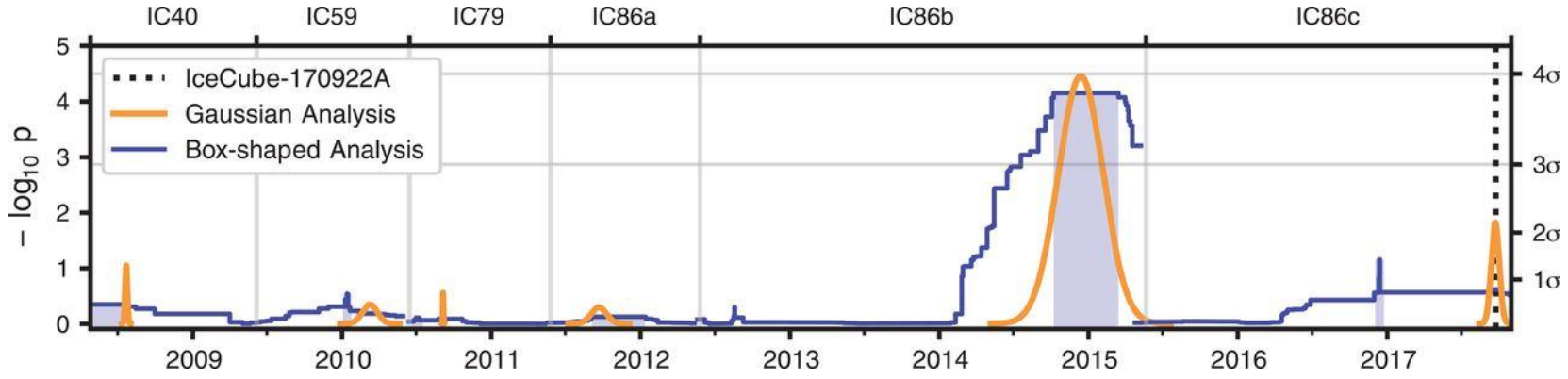


MAGIC VHE γ detection

Gamma flares and neutrino flares

Flare from TXS 0506+056 discovered in 2015 archival neutrino data!

However, no significant gamma-ray activity in coincidence.

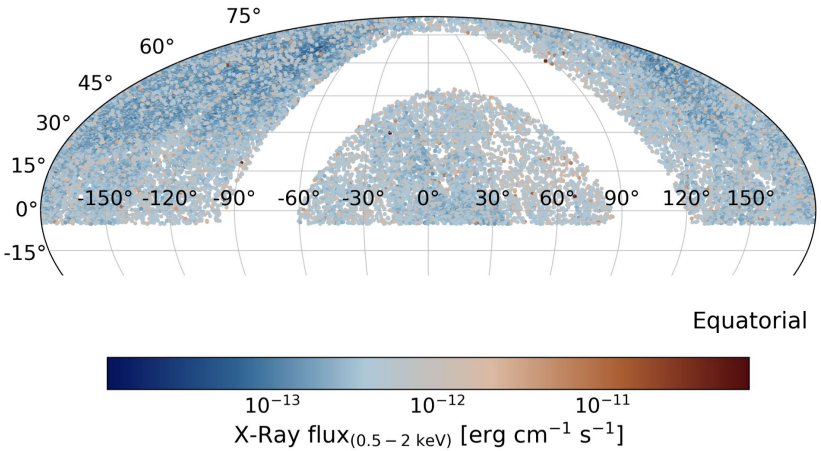


Neutrino may be not always correlated to gamma rays.

Note: different energy range compared to individual alerts.

Neutrinos from blazars and active galactic nuclei?

Search from neutrinos from AGN cores (Phys. Rev. D 106, 022005)

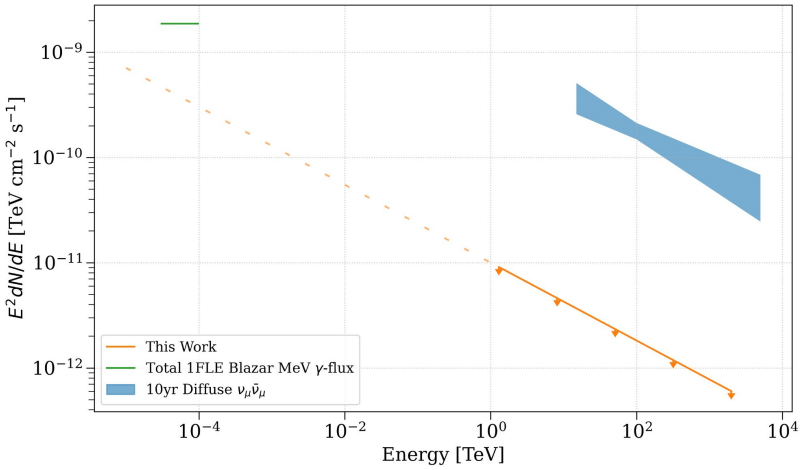


2.6 σ significance for neutrino excess.

Allows a contribution of 27-100% of the diffuse astrophysical flux.

Limit on emission from Fermi-LAT MeV catalogue (1FLE) of blazars (ApJ 938 38 (2022))

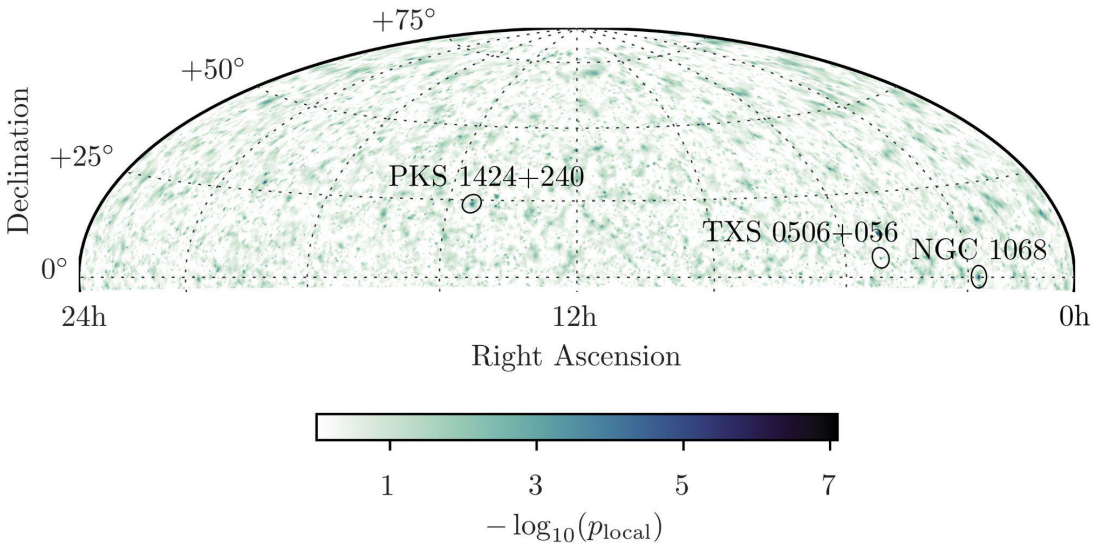
< 1% of the diffuse astrophysical flux.



The first steady source: NGC 1068

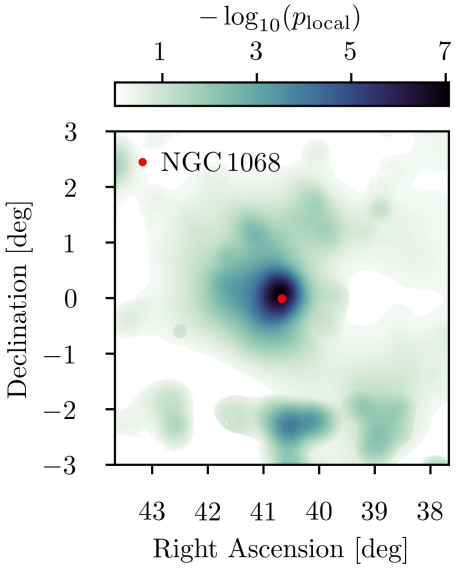
Uniform analysis neutrino data spanning 9 years.

Scan of the Northern sky with improved calibrations and reconstruction methods.



NGC 1068

nearby active galaxy



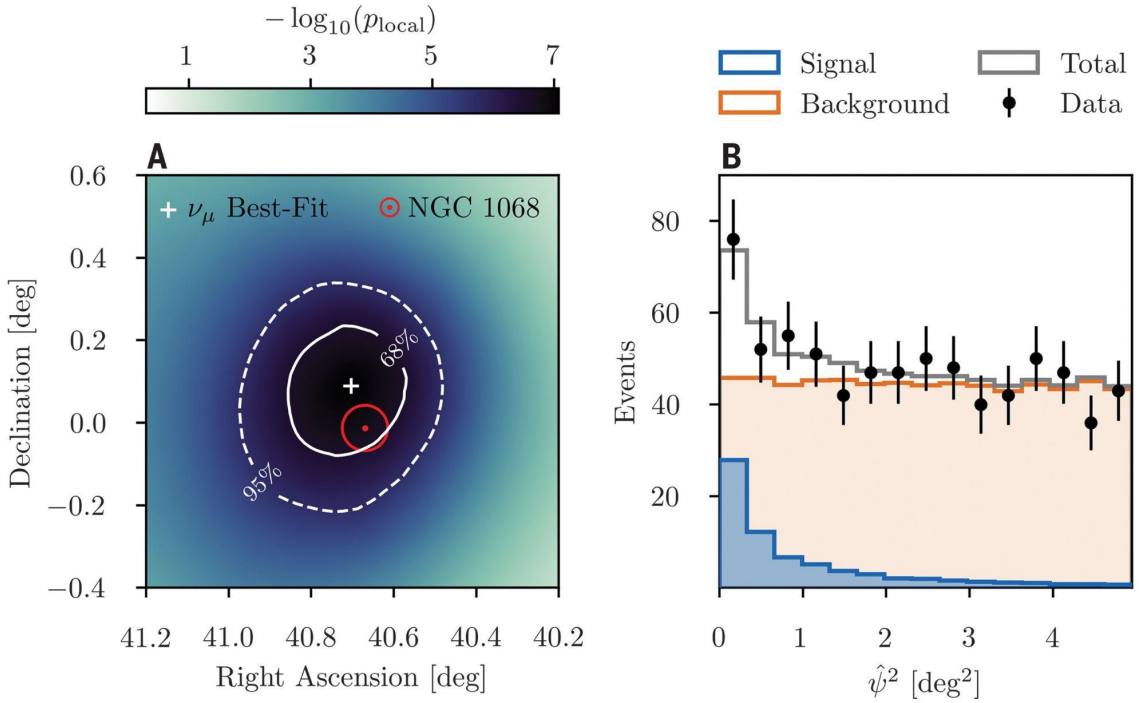
4.2 σ evidence of steady emission.

IceCube Coll., Science 378, 6619, 538-543 (2022)

Improved point source search

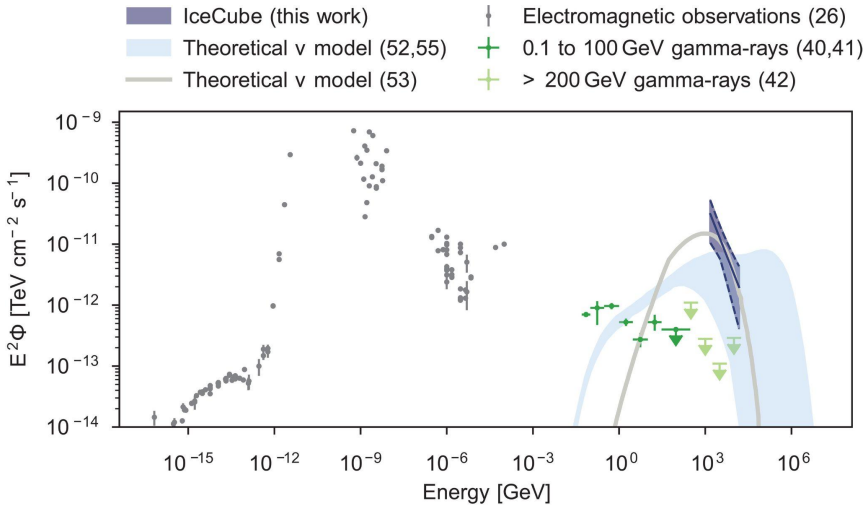
Significant improvement in the understanding of the detector point-spread function.

Excellent agreement between data and point-source simulation.



The multimessenger picture of NGC 1068

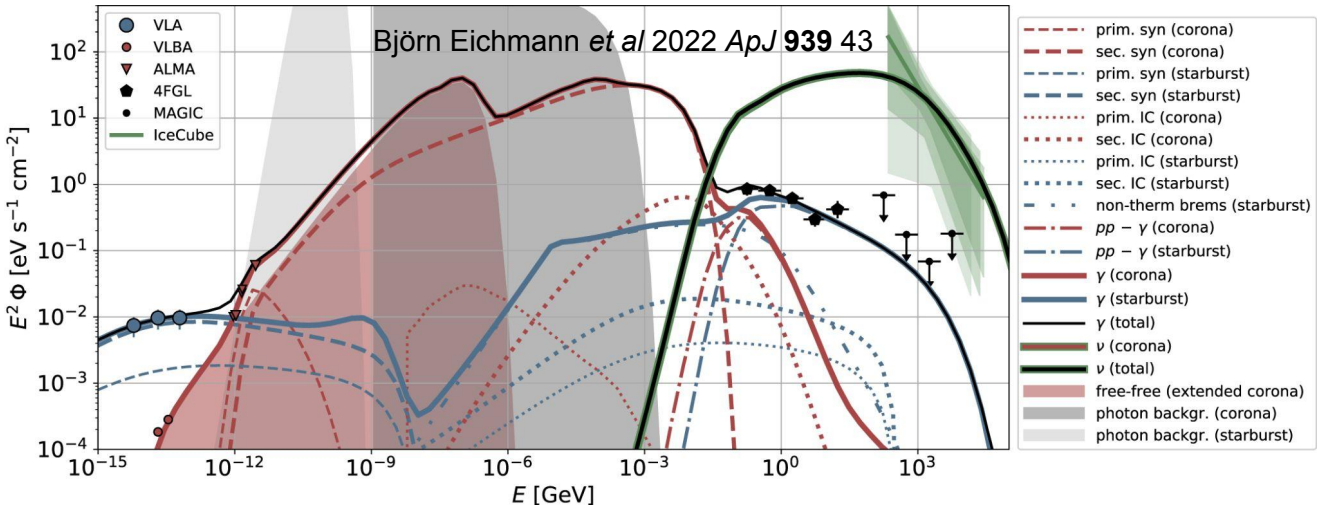
IceCube Coll. Science 378, 6619, 538-543 (2022)



Neutrino emission dominated by the magnetised AGN corona.

NGC 1068: E^-3.2

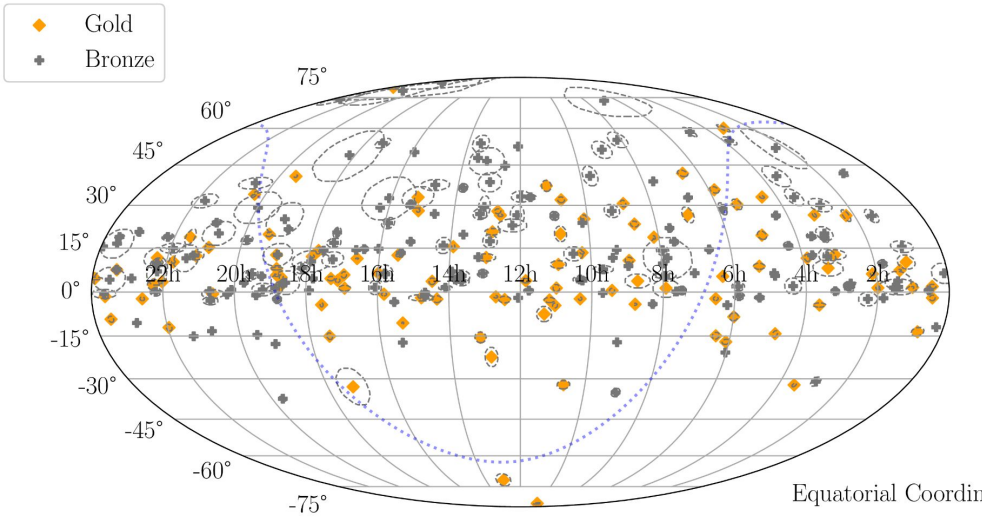
Diffuse flux (IceCube): E^-2.3



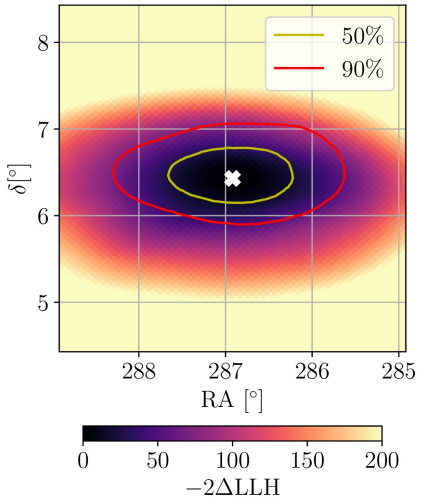
Electromagnetic emission from starburst activity (radio, gamma) and AGN corona (X-ray).

IceCat-1: the first catalogue of alert tracks

Archival search for neutrinos with moderate (Bronze) to high (Gold) probability of being astrophysical. Extension of the realtime selection back to 2011.



Individual neutrino localisation maps



arXiv:2304.01174 **[astro-ph.HE]**

Public data release on Harvard Dataverse.

Where do the IceCat-1 events come from?

No significant correlations with gamma-ray and X-ray catalogues:

- 4FGL/3FHL
- 3HWC
- TevCat
- BAT

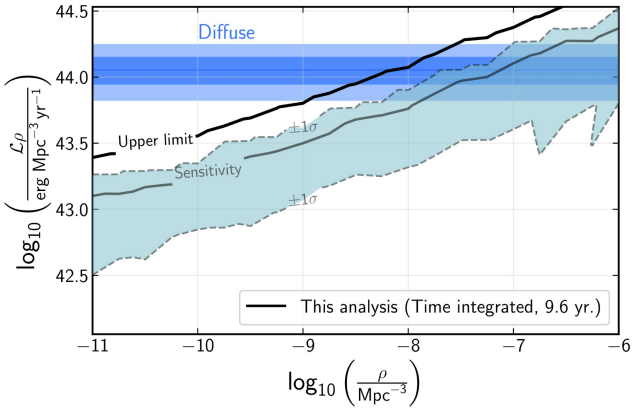
Additional searches for correlations:

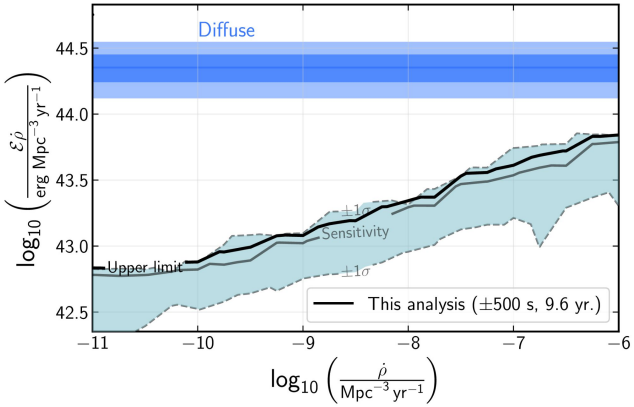
- Fermi-LAT 4LAC-DR2 catalogue
- 3413 AGNs from the **Radio Fundamental Catalog**

no significant correlation found.

arXiv:2304.12675 [astro-ph.HE]

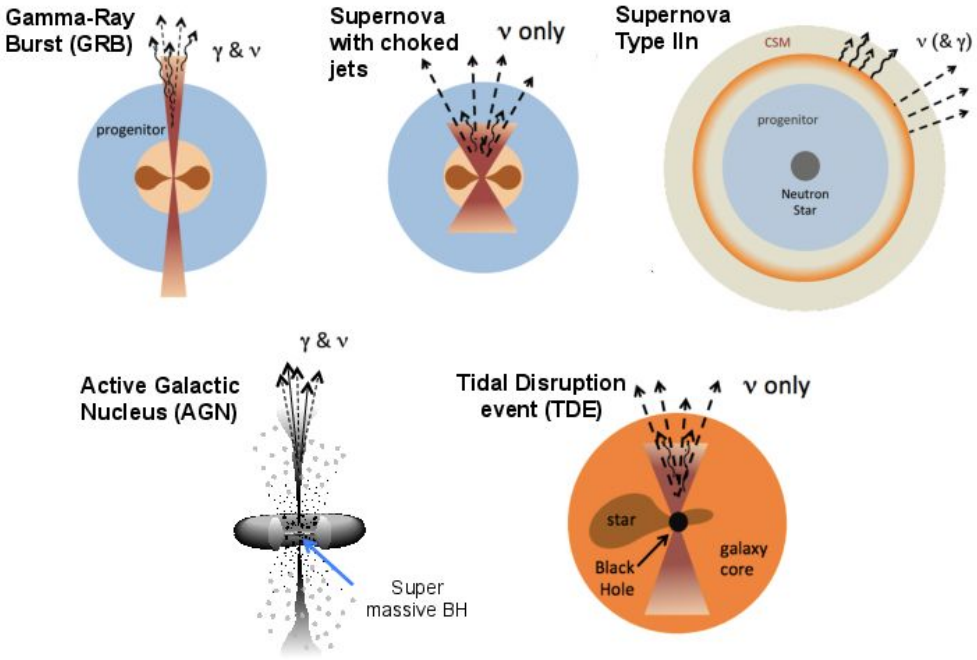
Follow-up of alerts with neutrino data
arXiv:2210.04930 [astro-ph.HE]



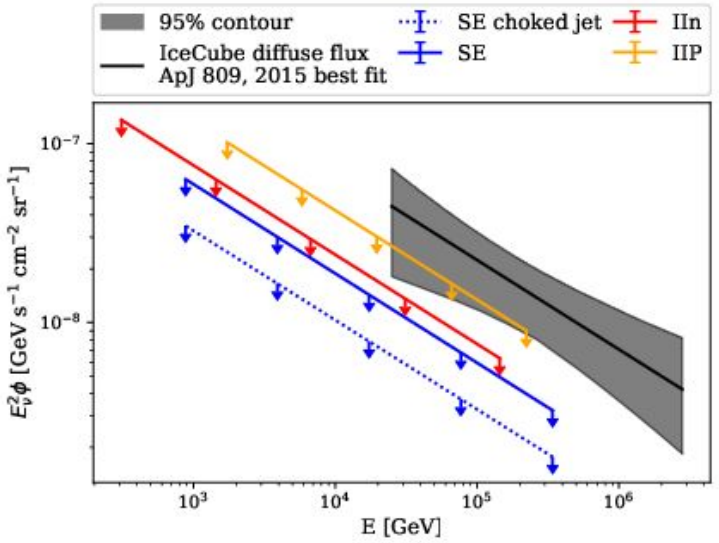


No excess from alert directions.
Sources must be *many and faint*.

Are there more candidate sources?



Constraints on neutrino emission from extragalactic core-collapse supernovae



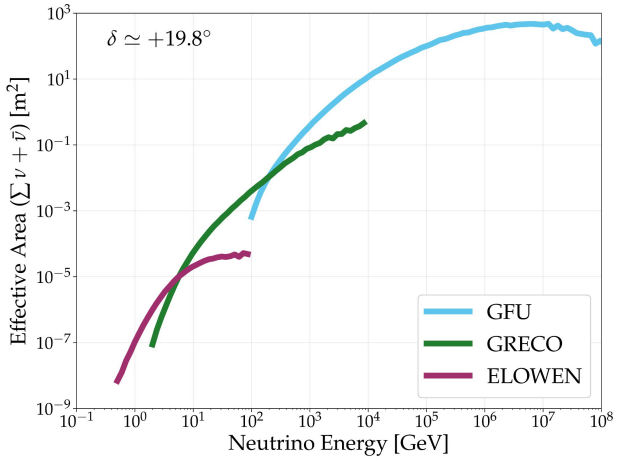
ApJL 949 L12, 2023

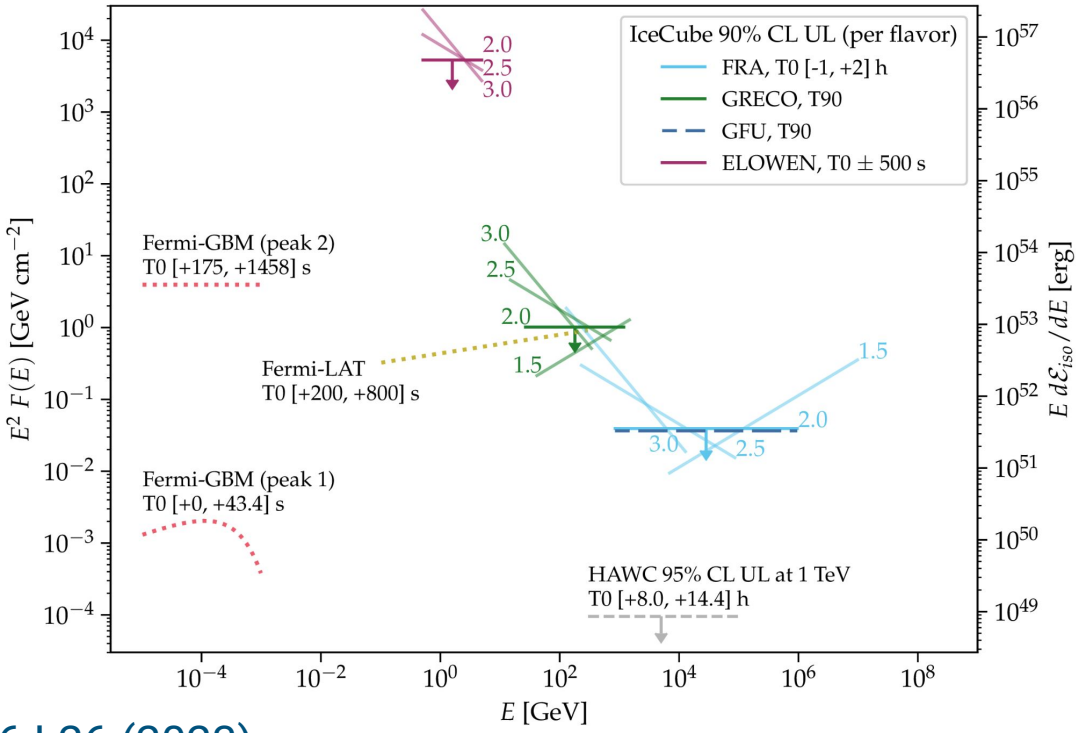
Limits on Neutrino Emission from GRB 221009A

IceCube follow-up of **exceptionally bright and energetic GRB.**

IceCube data selections cover from GeV to PeV.

~ 8 order of magnitudes

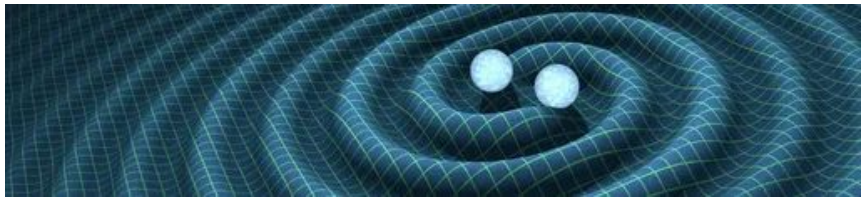




ApJL 946 L26 (2023)

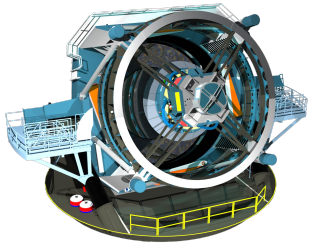
Present and future of multimessenger searches

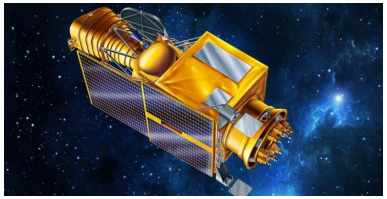
Gravitational waves



IceCube follow-up of **LIGO-Virgo-Kagra O4** alerts has begun.

Electromagnetic spectrum

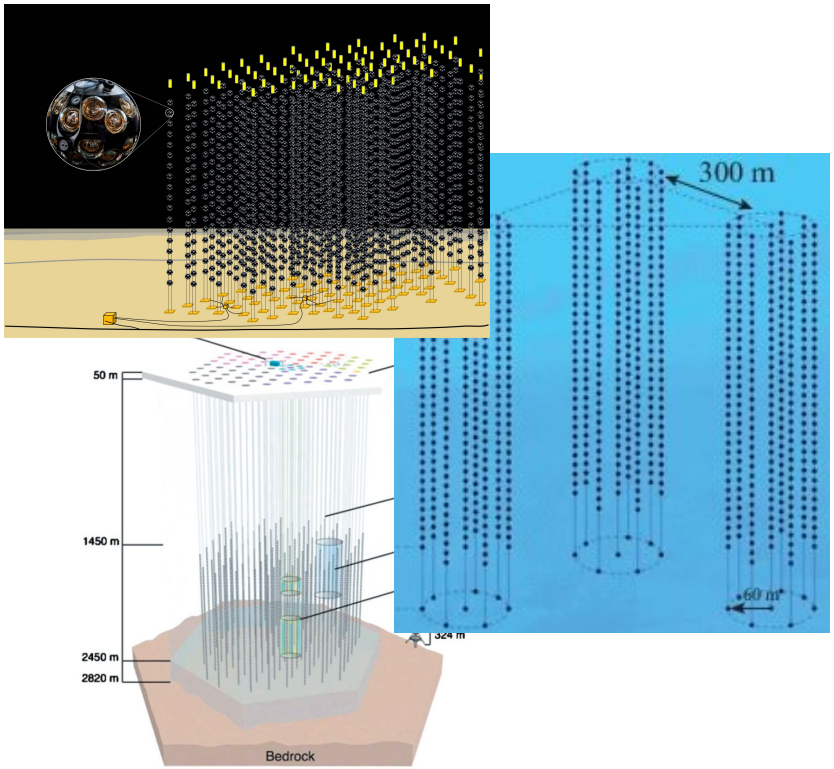




Will future facilities (e.g. Rubin Observatory, ULTRASAT) allow to unveil new counterparts to IceCube neutrinos?

Neutrino telescopes

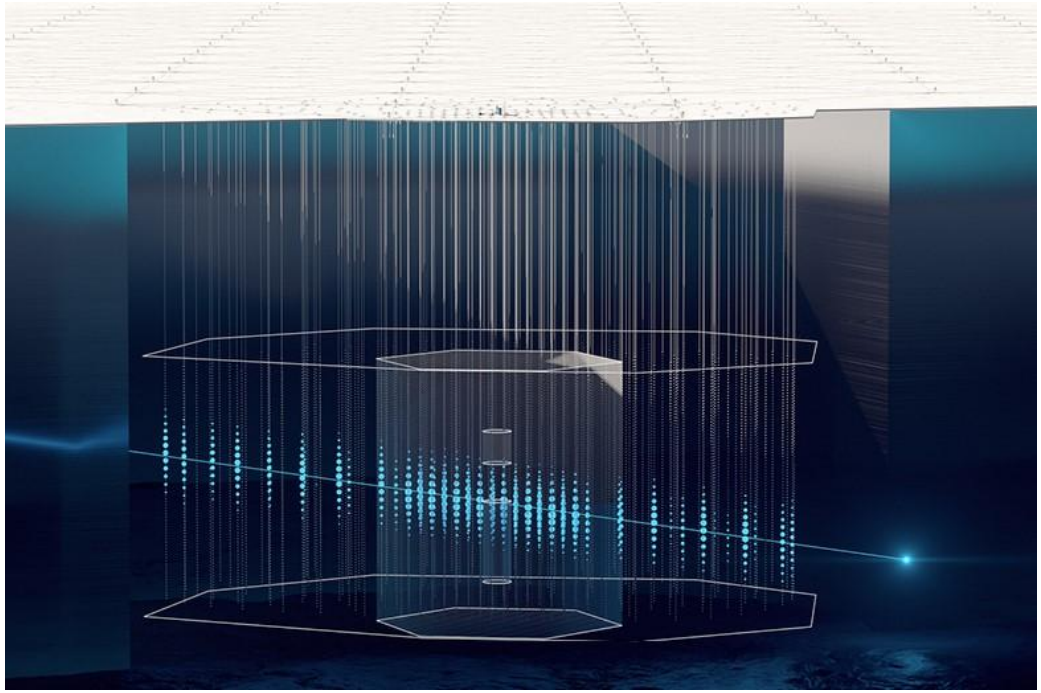
Possible synergies with KM3NeT and Baikal-GVD for realtime searches.



The future of IceCube: IceCube-Gen2

Optical and radio array.

5 times improvement of IceCube point-source sensitivity.



Beginning of construction expected in 2026.

Summary and outlook

IceCube has discovered and characterised the astrophysical diffuse neutrino flux and is hunting for its sources.

The **flaring blazar TXS 0506+056** and the **nearby active galaxy NGC1068** have been identified as the first sources of astrophysical neutrinos.

IceCube is a formidable player in the multi-messenger community.

The connection between the candidate source populations and the diffuse flux is still enigmatic.

Future observational facilities and **IceCube Gen2** will allow steps forward in resolving the sources of astrophysical neutrinos.