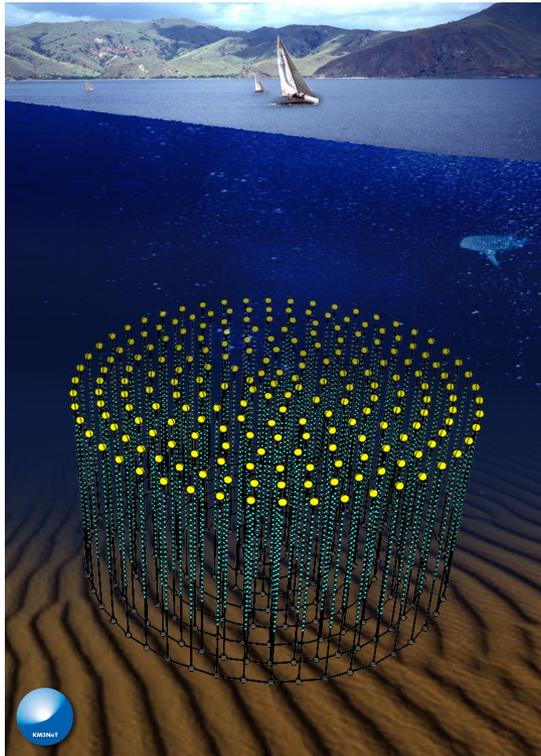
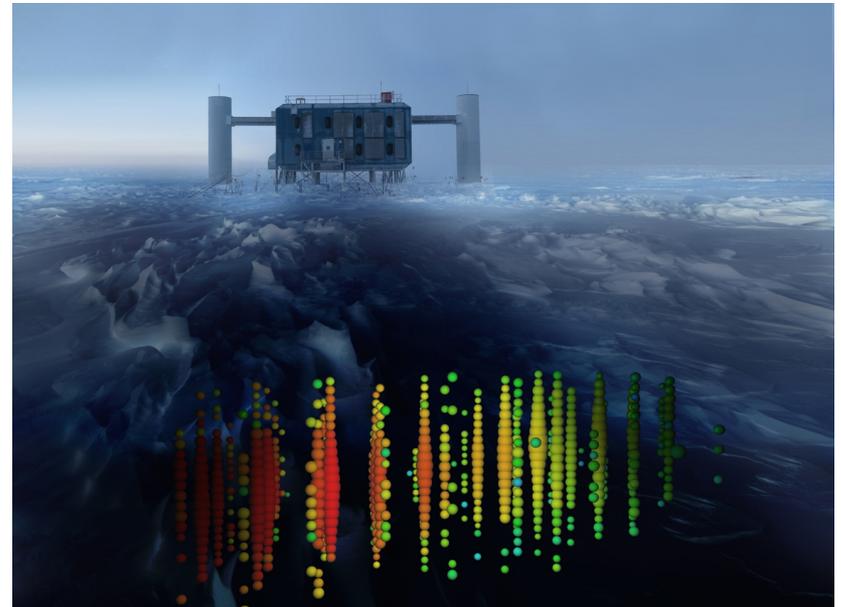


KM3NeT e IceCube: 2 eyes to scan neutrino-emitting AGNs



Filippo D'Ammando (INAF-IRA Bologna)



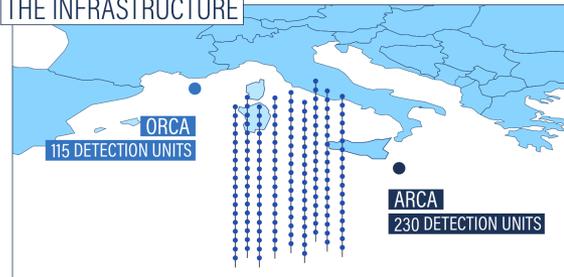
KM3NeT

A GIANT DEEP-SEA NEUTRINO TELESCOPE

KM3NeT, once completed, will be one of the largest astronomical telescopes in the world. Located at the bottom of the Mediterranean Sea, it comprises two detectors: ARCA off the coast of Sicily, in Italy, and ORCA off the coast of Toulon, in southern France. Its main goal is to detect and study neutrinos: extremely light, fast and hard-to-catch elementary particles. The ARCA detector is optimised for the study of high energy cosmic neutrinos, which carry with them valuable information about the most energetic phenomena in the universe.

The ORCA detector is optimised to measure the fundamental properties of the neutrino itself using atmospheric neutrinos.

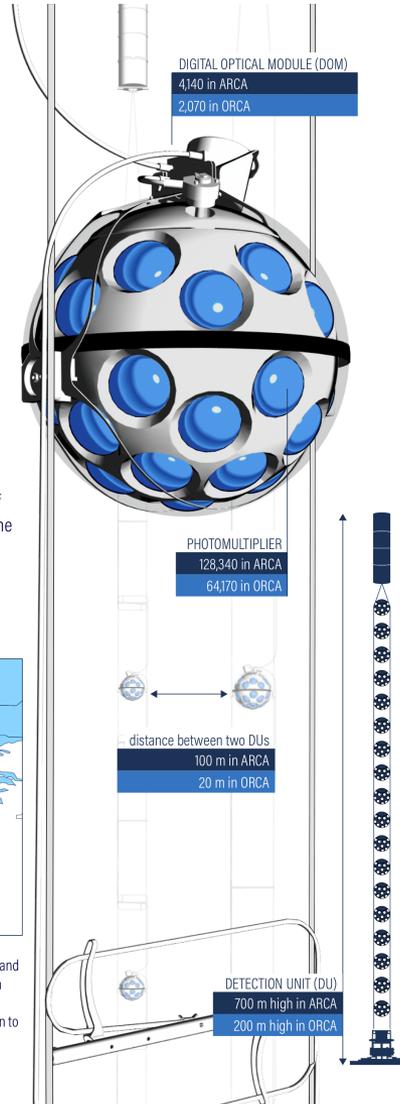
THE INFRASTRUCTURE



The KM3NeT infrastructure consists of an array of hundreds of detection lines, "detection units", which stand on the sea bottom and are equipped with thousands of hi-tech eyes. Its final configuration will occupy a volume of over 1 km³, hence its name.

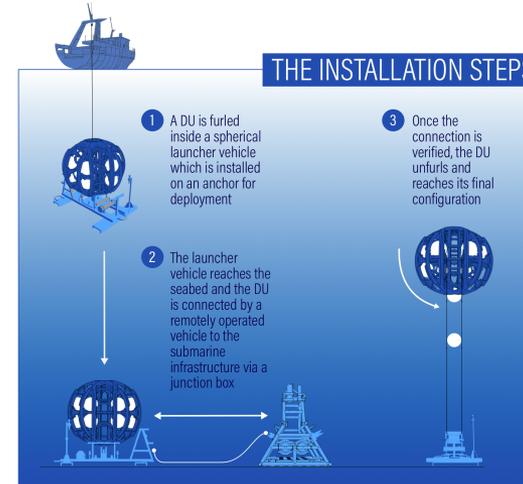
The detection units are connected to a submarine network of cables and junction boxes. The connection to shore is via a submarine cable of many tens of kilometres long.

KM3NeT is also a valuable multidisciplinary laboratory for Earth and Ocean Sciences.



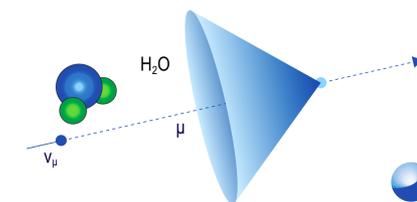
KM3NET IS A LARGE INTERNATIONAL COLLABORATION THAT INVOLVES OVER 360 SCIENTISTS, ENGINEERS, TECHNICIANS AND STUDENTS OF 68 INSTITUTIONS FROM 21 COUNTRIES.

THE INSTALLATION STEPS

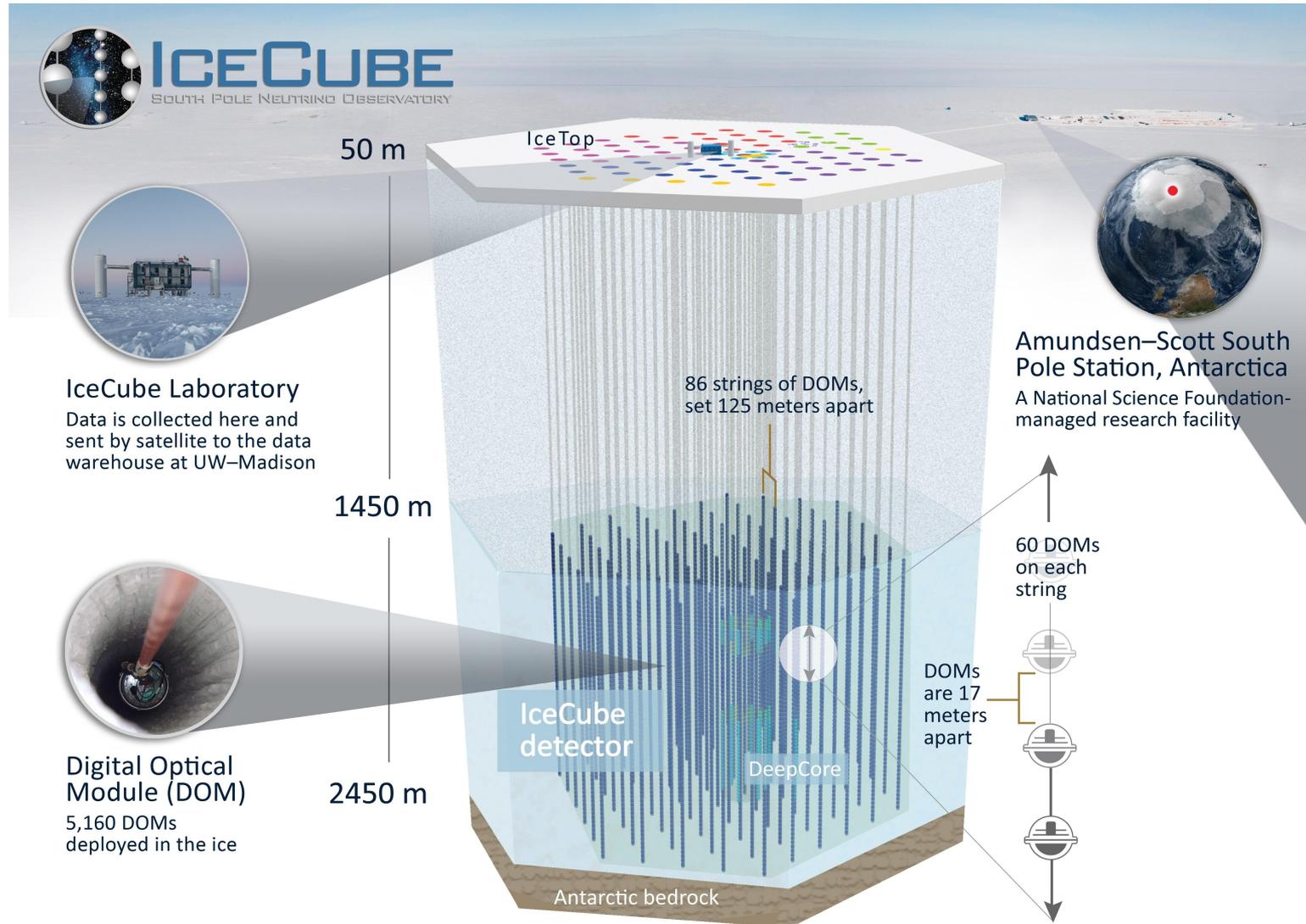


NEUTRINO DETECTION

KM3NeT uses sea water as interaction medium. Neutrino interactions generate charged particles that propagate at a speed higher than the speed of light in sea water, producing a faint bluish glow called "Cherenkov light". The Cherenkov radiation is emitted at a characteristic angle with respect to the trajectory of the particle. This glow is detected by KM3NeT's hi-tech eyes. Analysis of these signals provides fundamental information on the neutrinos direction, energy and nature.

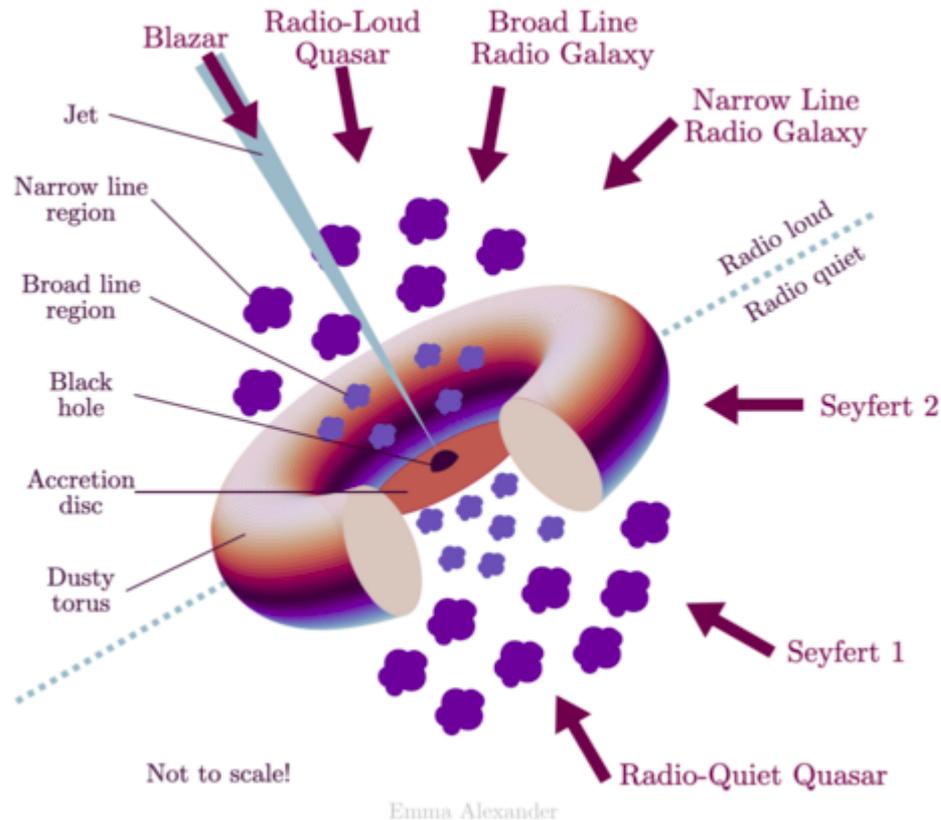


IceCube



Active Galactic Nuclei

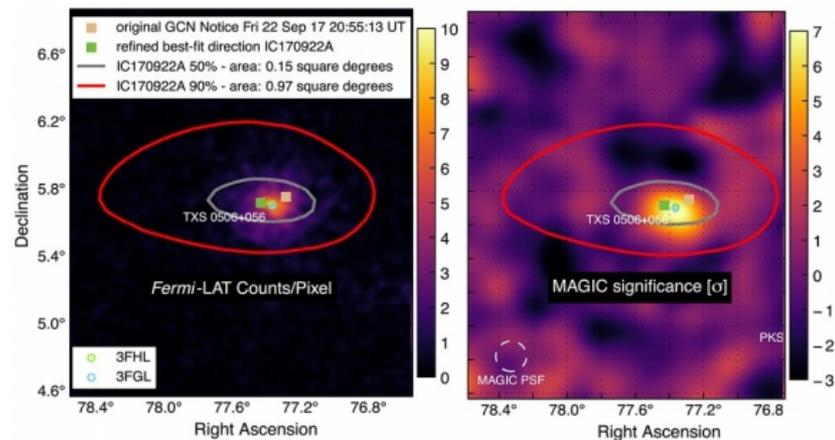
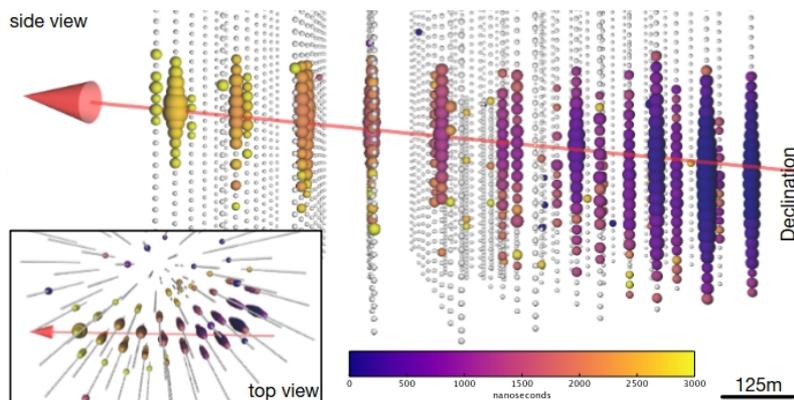
AGN are considered the most luminous persistent sources of high-energy radiation and promising candidate neutrino sources



AGN with relativistic jets have been considered as promising sites of cosmic-rays acceleration and thus neutrinos in interactions with photon fields or matter

The blazar TXS 0506+056

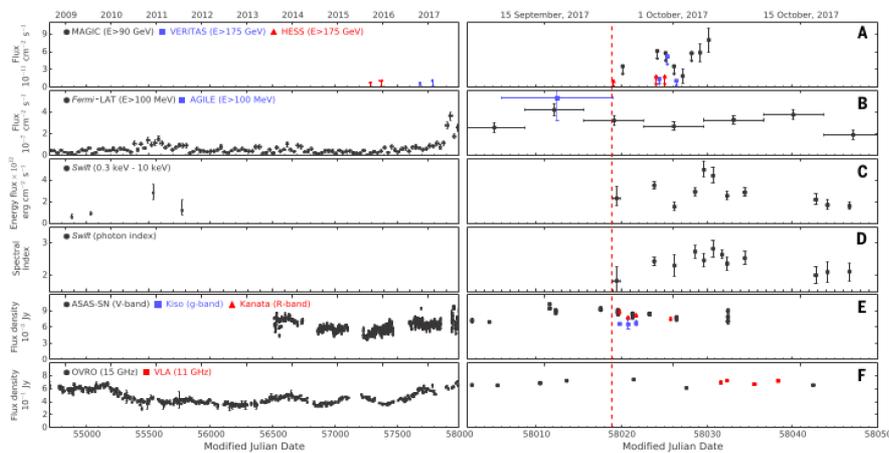
The first time an extragalactic neutrino has been traced to its source



Correlation of neutrino with TXS 0506+056 preferred to chance coincidence at 3σ level

Over 20 follow-up ATels including Fermi-LAT, MAGIC, H.E.S.S., VERITAS, Swift, NuSTAR, MAXI, AGILE, ASAS-SN, Kanata, VLA, Subaru, Antares, HAWC

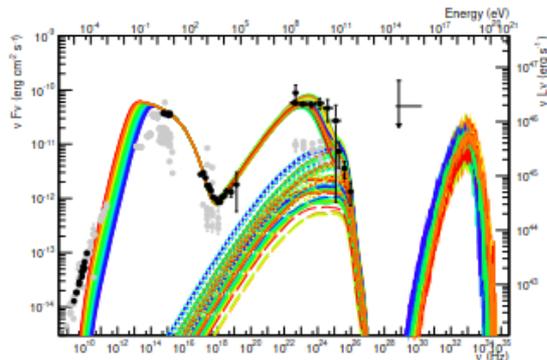
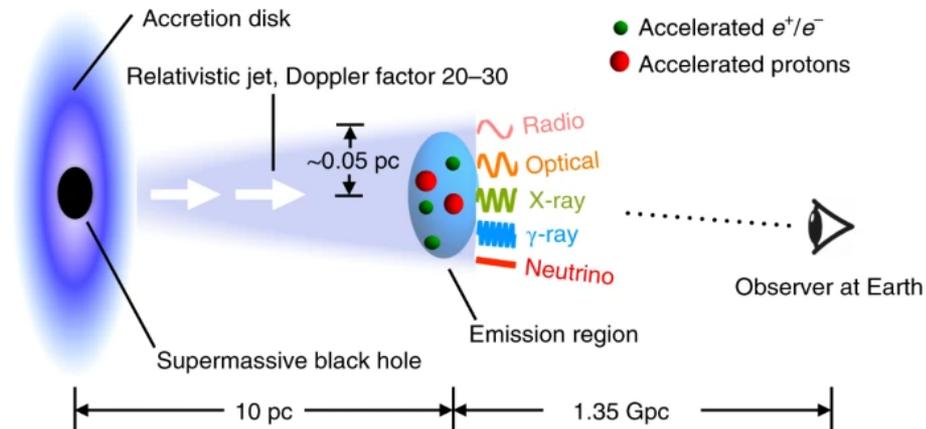
Science 13 Jul 2018: Vol. 361, Issue 6398
IceCube, Fermi, MAGIC and 13 additional collaborations



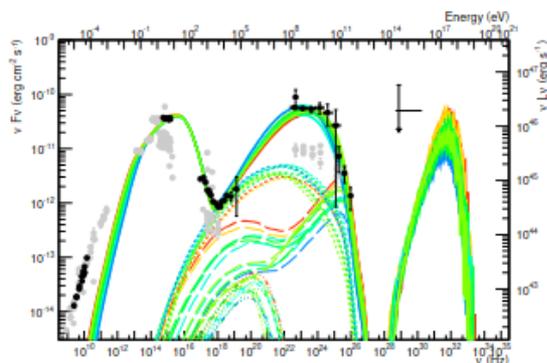
On 2017 September 22, IceCube detected a 290 TeV neutrino from a direction consistent with the blazar TXS 0506+056 found to be in a gamma-ry flaring state

Neutrino emission in TXS 0506+056

Due to the small viewing angle, the EM emission and potential neutrino emission from the jet become strongly boosted



(a) Proton synchrotron modeling of TXS 0506+056



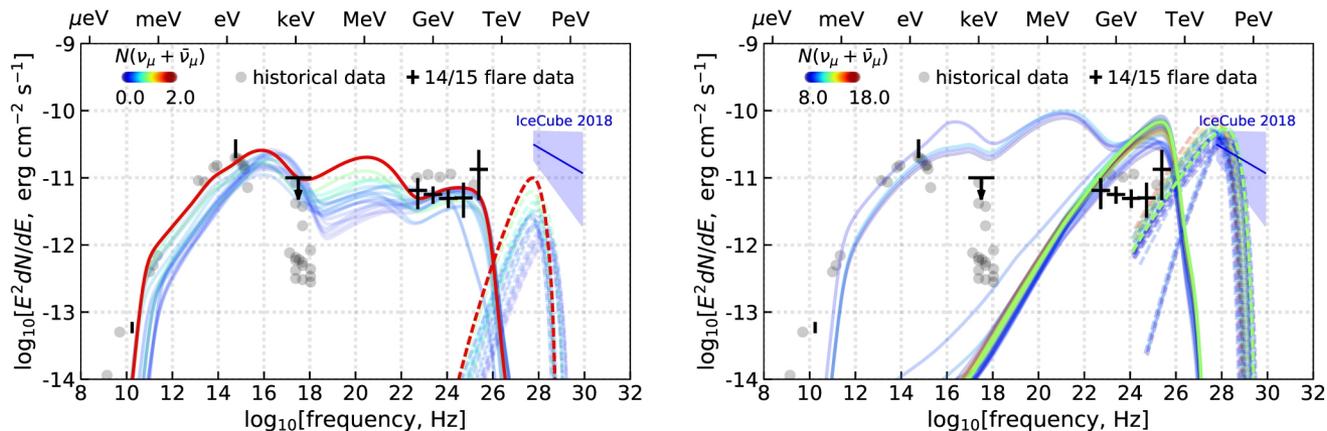
(b) Lepto-hadronic modeling of TXS 0506+056

dashed lines: emission from **pion cascades**
dotted lines: emission from **Bethe-Heitler cascades**
dotted-dashed lines: **proton synchrotron emission**

Cerruti et al. 2019, MNRAS, 483, L12

Neutrino from TXS 0506+056 during 2014/2015

A neutrino flare of ~ 110 days from TXS 0506+056 was observed during 2014-2015 with a 3.7-sigma significance level with no corresponding flaring activity in the EM spectrum



Rodrigues et al. 2019, ApJ, 874, L29

Models invoking two radiation zones have been proposed (Rodrigues+19):

- i) an IC-dominated compact-core model
- ii) external radiation field from accretion disk radiation isotropized in a BLR

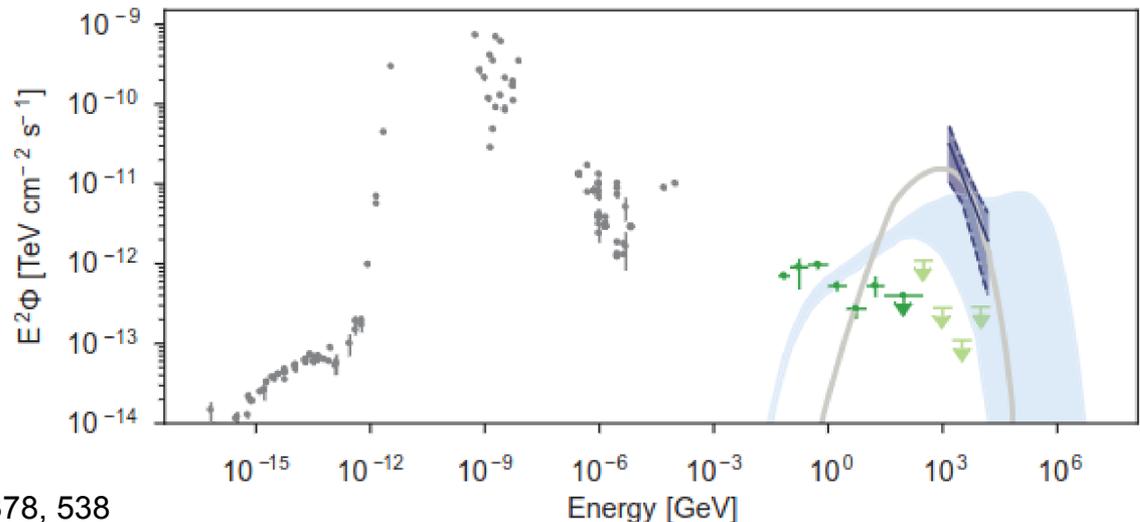
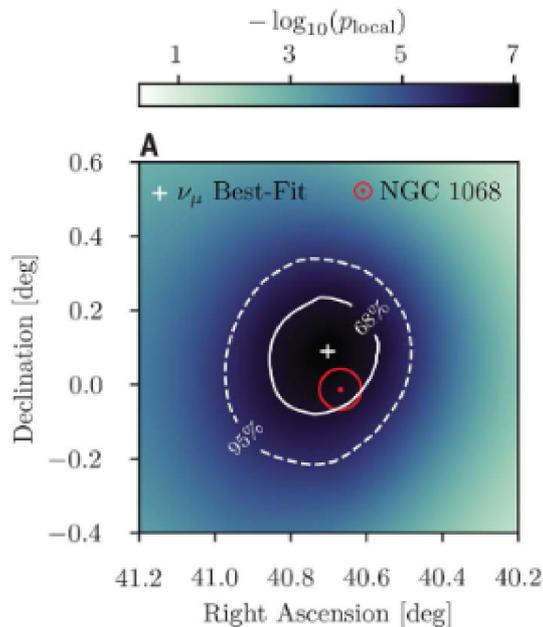
But challenging to explain >5 neutrino without violating the observational X-ray constraints (case i) or the observed gamma-ray fluxes (case ii)

- iii) the emergence of a relativistic neutral beam in the blazar jet due to interaction of accelerated cosmic rays with photons (Zhang+20)

NGC 1068

The first non-jetted AGN associated with high-energy neutrino emission

In 2022, the IceCube Collaboration reported 4.2- σ evidence for an excess of TeV neutrinos from the Seyfert II galaxy NGC 1068



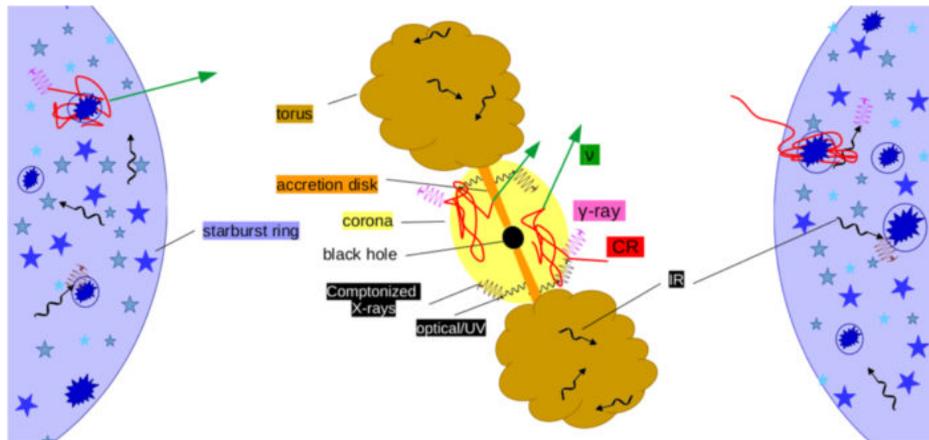
The IceCube Collaboration 2022, Science, 378, 538

The observed neutrino flux in the 1-50 TeV energy range, more than one order of magnitude higher than the gamma-ray emission level observed by Fermi-LAT and MAGIC, forced us to review the theoretical models to explain the SED of AGN

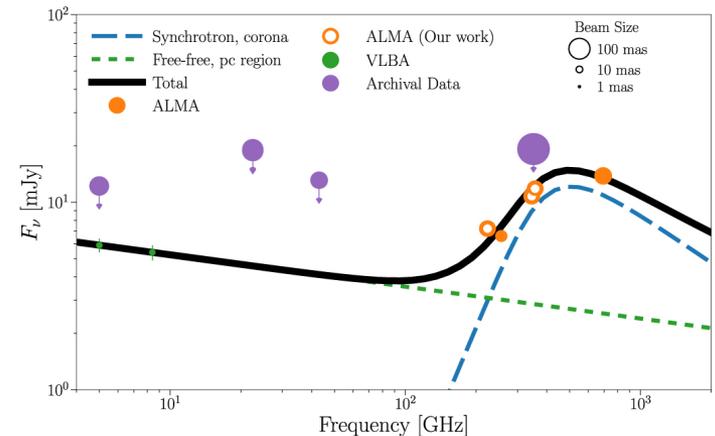
NGC 1068

Different theoretical scenarios proposed:

- i) diffuse shock acceleration at shock waves
- ii) stochastic acceleration in magneto-hydrodynamic turbulence
- iii) systematic acceleration in magnetic reconnection



Eichmann et al 2022, ApJ, 939, 43

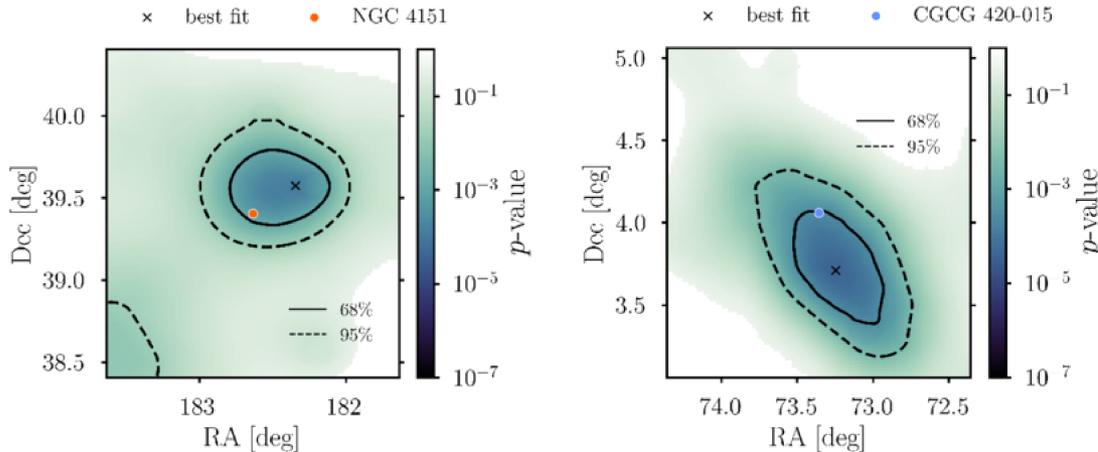


Inoue et al 2020, ApJ, 891, L33

Among the different possible regions, **the accretion-disc corona** is the favourable one for

- an adequate density of X-ray photons to provide targets for protons needed for neutrino emission
- a sufficient density of optical and IR photons to absorb the gamma-ray emission
- ALMA observed a mm excess consistent with non-thermal emission from the corona

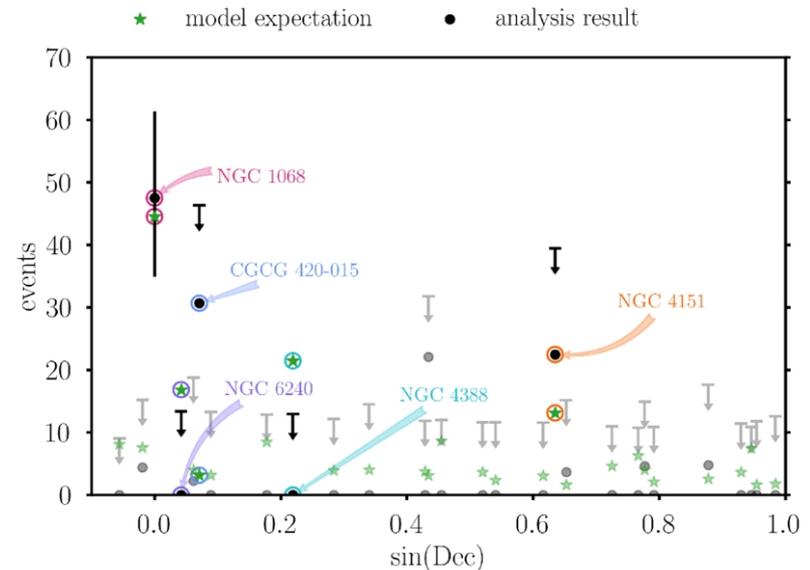
X-ray bright Seyfert galaxies



Abbasi et al. 2025, ApJ, 988, 141

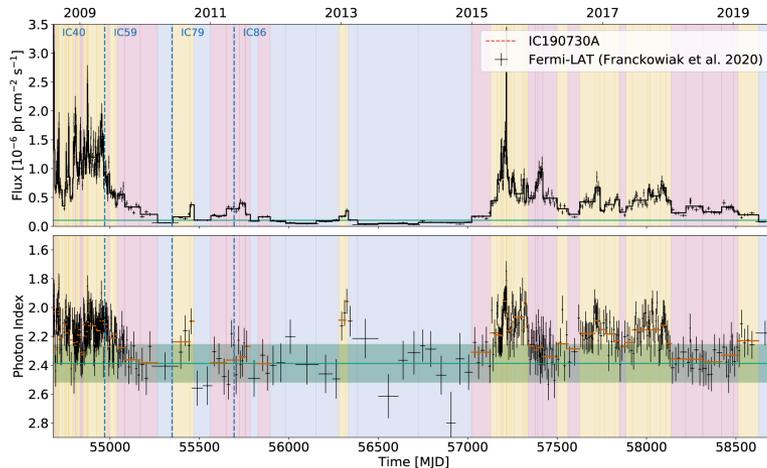
New evidence identifying X-ray bright Seyfert galaxies as a class of high-energy neutrino emitting sources

A binomial test of 27 northern-sky Seyfert galaxies found a combined significance of $2.7\text{-}\sigma$, suggesting that a subset of these Seyfert share similar properties with NGC 1068



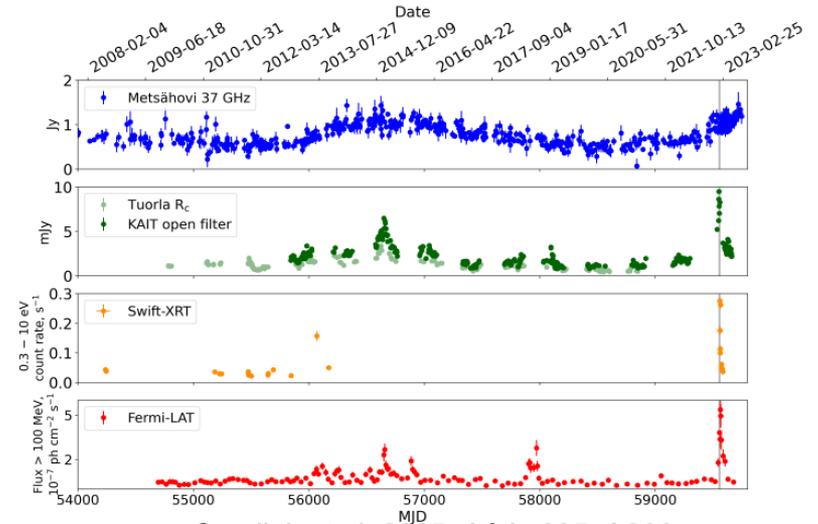
Other potential association with blazars

PKS 1502+106: no contemporaneous gamma-ray flaring activity

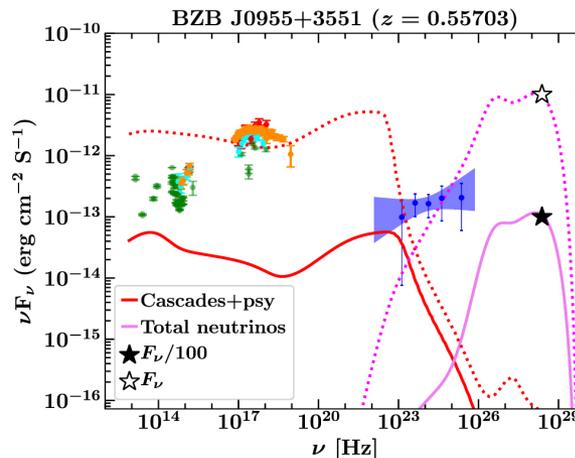
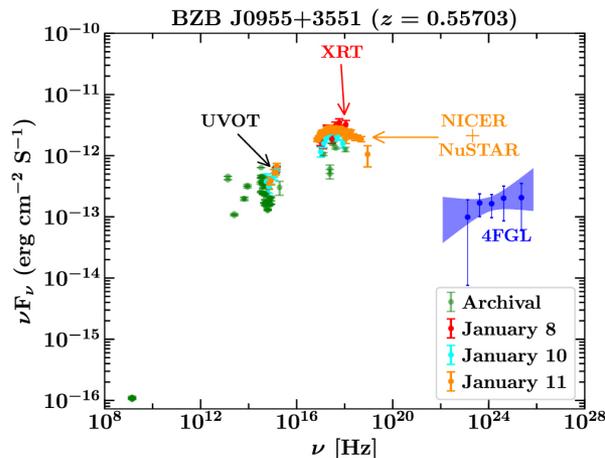


Rodrigues et al. 2021, ApJ, 912, 54

PKS 0735+178: neutrino emission contemporaneous to an optical-to-gamma-ray flaring activity



Omeliuk et al. 2025, A&A, 695, A266



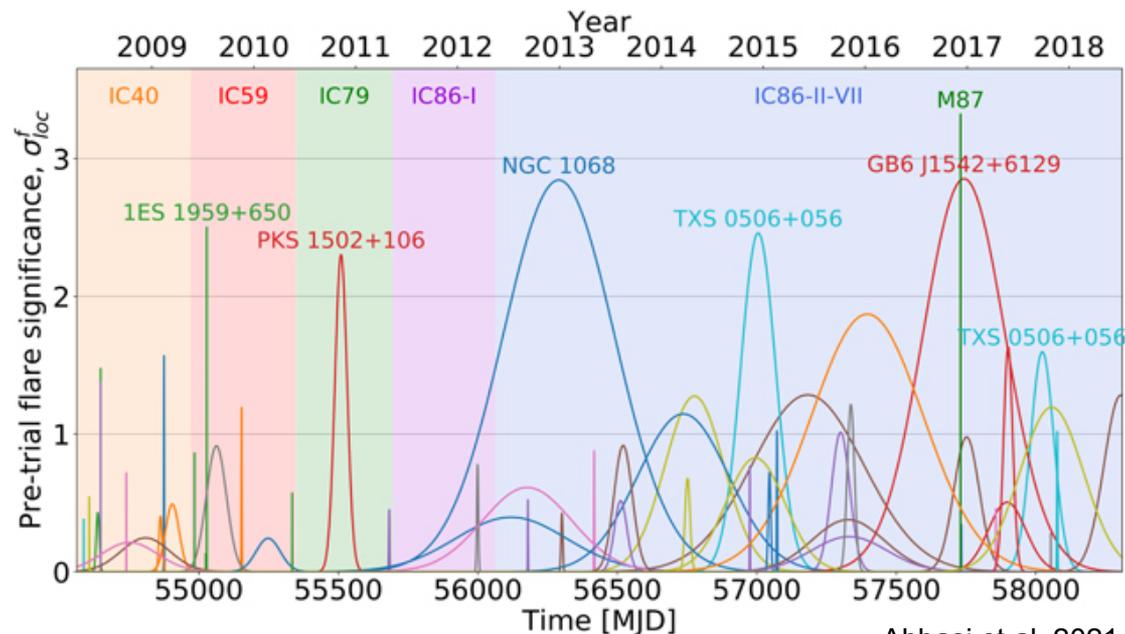
BZB J0955+3551 has not been detected in gamma-rays at the time of the IC-200107A event, but a strong X-ray flare has been observed

Paliya et al. 2020, ApJ, 902, 29

Search for multi-flare neutrino emission

In a time-integrated analysis of neutrino emission from 110 gamma-ray emitters over 10 years of IceCube data, a cumulative neutrino excess in the Northern sky at $3.3\text{-}\sigma$ level was identified using a maximum likelihood method

The major contributors to this excess are NGC 1068, TXS 0506+056, GB6 J1542+6129 and PKS 1424+240

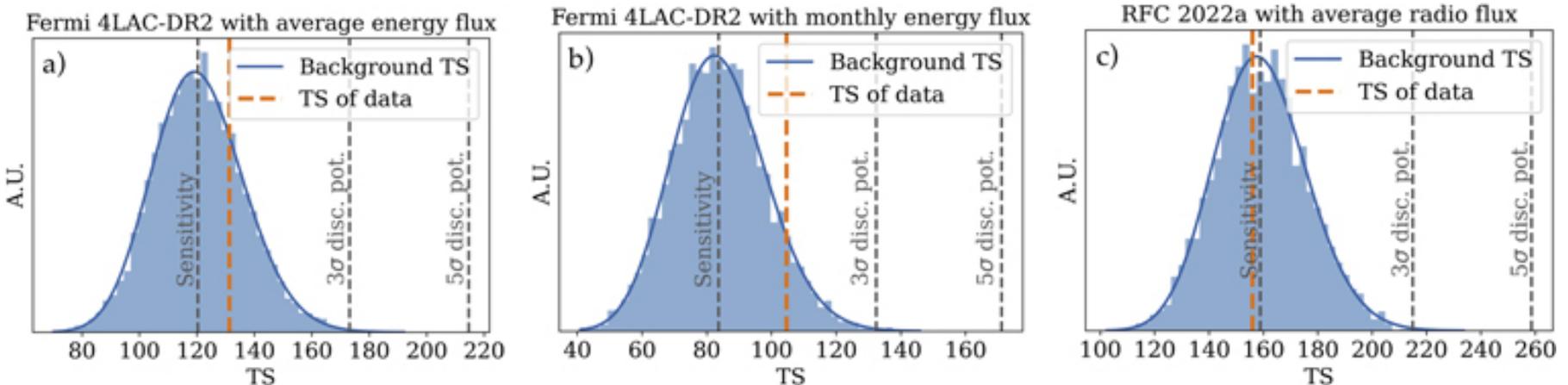


Abbasi et al. 2021, ApJ, 920, L45

Based on a binomial population test, a cumulative time-dependent neutrino excess has been identified in the Northern Hemisphere at $3.0\text{-}\sigma$ level, associated with 4 sources : M87, TXS 0506+056, GB6 J1542+6129 and NGC 1068

Correlation between neutrino events and Fermi-LAT or bright radio AGN

No statistical correlation has been found by the IceCube Collaboration between 2089 Fermi-LAT blazars (4LAC-DR2 catalog) / 3413 bright radio sources (RFC catalog) and the catalog of IceCube alerts (IceCat-1) using a stacking analysis method



Abbasi et al. 2023, ApJ, 954, 75

- Among the 10 pairs of blazar-neutrino with the highest TS using 4LAC-DR2 and average flux, the two strongest correlations have been found for TXS 0506+056 and PKS 1502+102 with IC170922A and IC190730A; the third and fourth for 3C 454.3 and Mrk 421 but the area of the error region of the associated neutrino is very large
- A tentative correlation between neutrino and bright radio blazars has been claimed by Plavin+20, Plavin+21 not confirmed by the analysis in Abbasi+23, adding more events, using a more sophisticated description of the spatial probability density function for neutrino events and not scaling up the angular error

KM3-230213A: the most energetic neutrino event detected so far

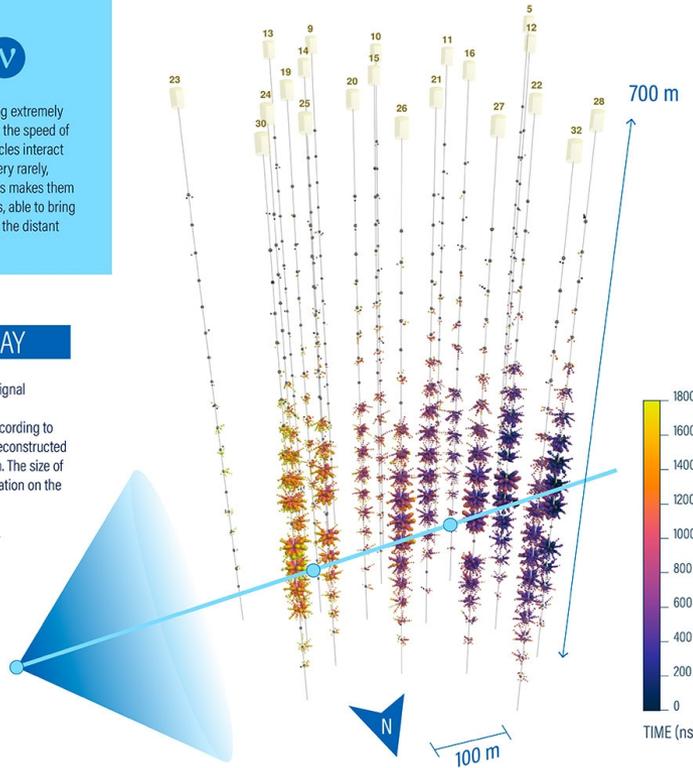
NEUTRINOS



With no electric charge, being extremely light and travelling almost at the speed of light, these elementary particles interact only weakly, and therefore very rarely, with matter. Their elusiveness makes them valuable cosmic messengers, able to bring us unique information about the distant universe.

THE EVENT DISPLAY

A view of the KM3-230213A signal detected by KM3NeT. The spheres are coloured according to the detection time and the reconstructed track of the particle is shown. The size of the blue cone gives an indication on the amplitude of the signal.



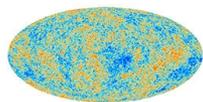
THE RECORD NEUTRINO

On 13 February 2023, at a depth of 3450 metres off the coast of Sicily, in Italy, the ARCA detector of the KM3NeT submarine neutrino telescope recorded an extraordinary signal: produced by a neutrino with a record energy of about 220 PeV, corresponding to 220 million billion electronvolts. This signal, named KM3-230213A, provides the first evidence that neutrinos with such extreme energies exist in the universe.

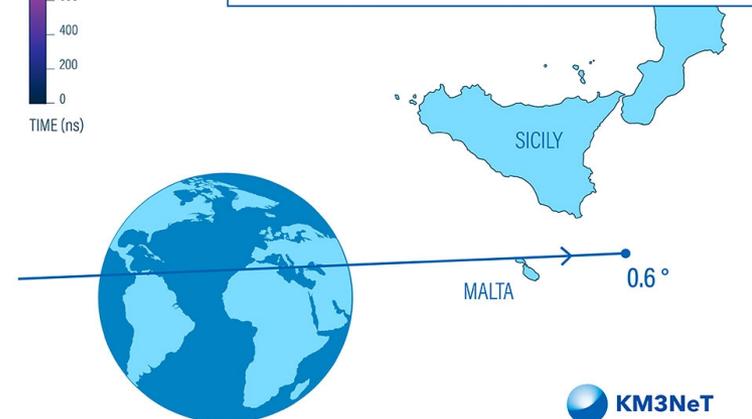
KM3-230213A IDENTIKIT

The cosmic neutrino plunged into the Mediterranean Sea and crossed the Malta continental shelf with an inclination of 0.6° above the horizon. During this journey, it travelled almost at the speed of light and interacted with an atomic nucleus, generating an ultra-relativistic muon, which crossed the whole detector.

THE SOURCES

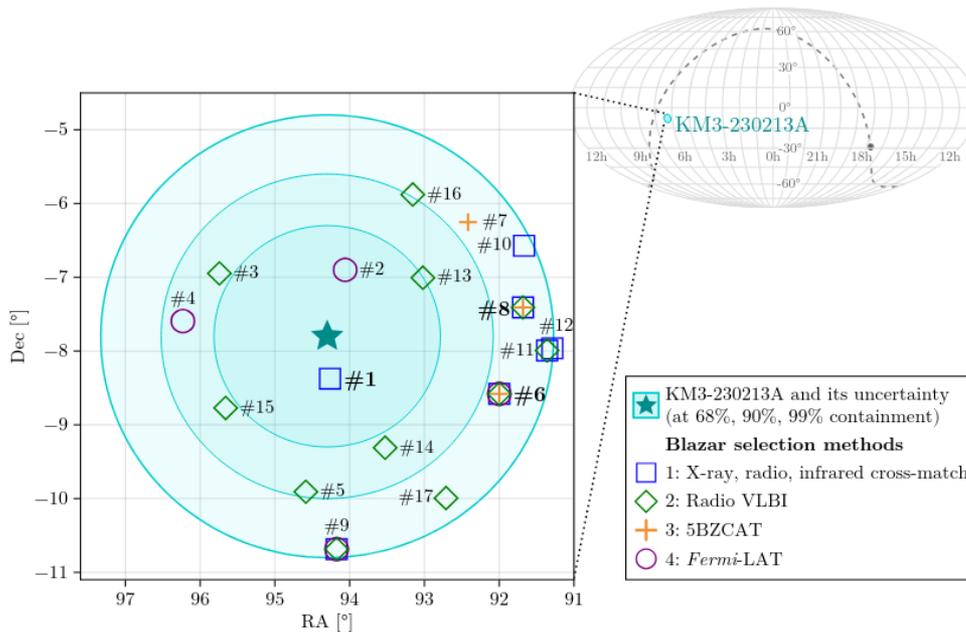


The origin of the ultra-high energy neutrino could have been one of the cataclysmic events that animate our universe, such as an active galactic nucleus or a gamma-ray burst. Or it could be a neutrino generated by the interaction of an ultra-high energy cosmic-ray particle with the cosmic background radiation that permeates the universe.



Candidate blazar counterparts

17 candidate blazars within the 99% confidence level region



ArXiv:2502.08484

PMN J0606-0724 exhibits a radio flare coinciding with the neutrino arrival (pre-trial chance probability of 0.26%)

MRC 0614-083 displays a rising trend in X-ray flux in a one-year window around the neutrino arrival time

0605-085 displays a rising trend in gamma-ray flux in a one-year window around the neutrino arrival time

KM3-230213A cannot be conclusively associated with enhanced multiwavelength emission from any single blazar

Concluding Remarks

- The identification of the sites of cosmic-ray acceleration in the Universe is one of the most intriguing questions in astrophysics. Part of the neutrino flux arises from our own Milky Way, but most neutrino have an extragalactic source. ***AGN, jetted and non-jetted ones, is a promising class of neutrino-emitting sources but a clear picture is not established yet***
- The challenge in identifying sources is caused by low signal statistics along with relatively large uncertainties in the angular localization. In this context, ***electromagnetic observations are essential for the identification and characterization of the neutrino sources at the time of the neutrino arrival but also with long-term monitoring of candidates***
- With the next generation neutrino experiments we will push sensitivity, angular resolution, energy band, dramatically expanding the wealth of information available. However, ***for a rapid coordination of multi-messenger and multi-frequency facilities it will be important that neutrino facilities implement an automated release of fully-machine-readable neutrino alerts***
- Another important aspect will be an ***improvement of numerical simulations*** on source dynamics and particle acceleration processes with a direct connection to the observational evidence for a coherent picture of the multi-messenger scenarios related to the neutrino physics of the AGN