The KM3NeT Ultra-High Energy Neutrino and its Possible Astrophysical Origins

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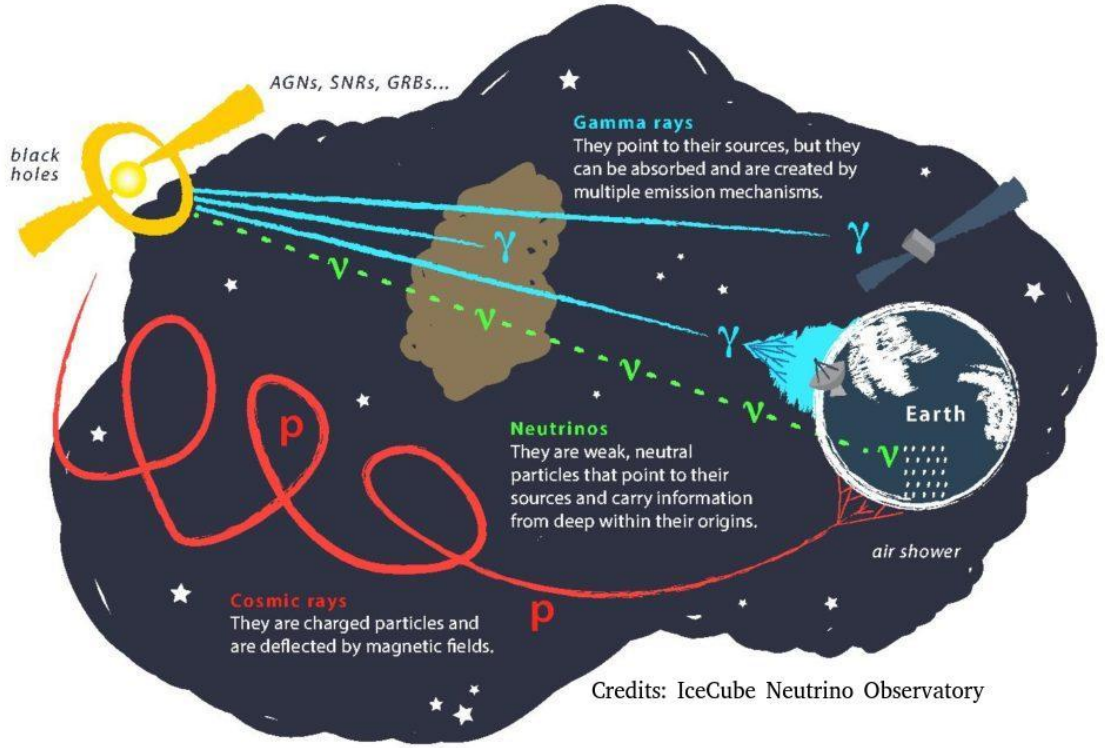
KM3NeT Collaboration

DPG-Frühjahrstagung 2025
Göttingen, 01-04-2025

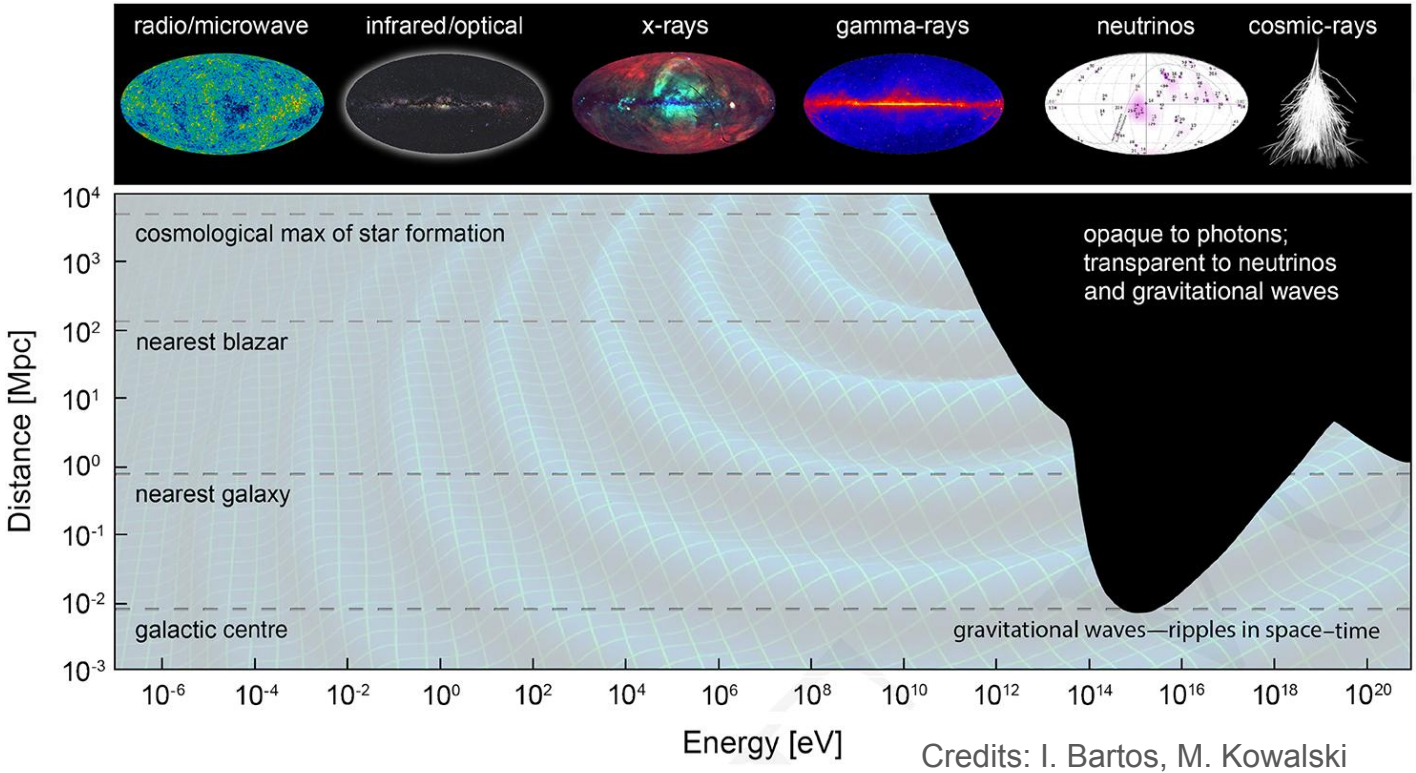
Art: Leo Pfeiffer

Neutrinos: unique cosmic messengers

Addressing a century old question…

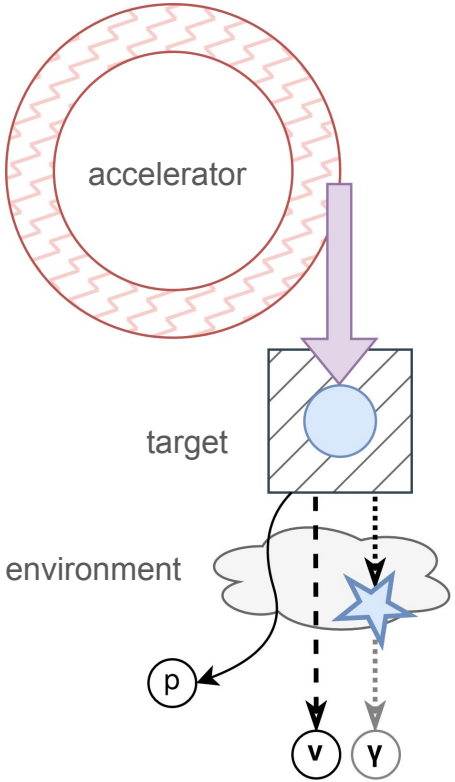


Neutrinos: beyond conventional horizons



Credits: I. Bartos, M. Kowalski

Astrophysical neutrino production



Proto-hadronic (hadro-nuclear)

$$p + p/N \rightarrow (\text{had.}) \rightarrow \pi^{0,\pm}$$

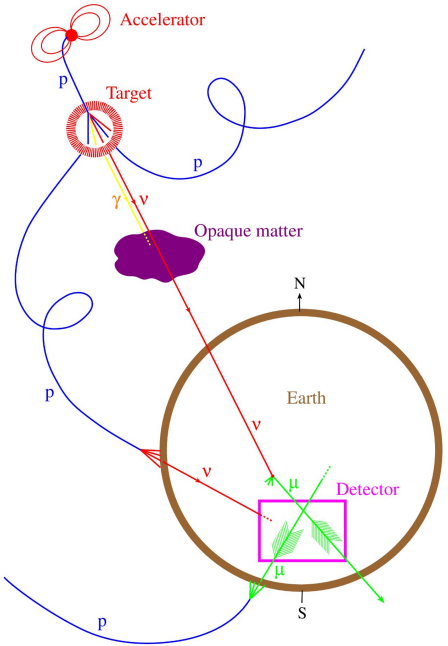
Photo-hadronic

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{0,+}$$

$$\pi^0 \rightarrow \gamma\gamma \qquad \pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$$

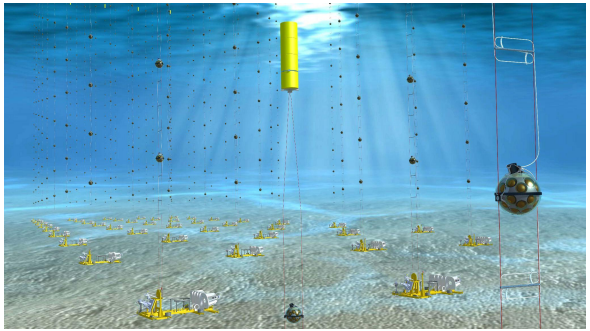
$$\mu^{\pm} \rightarrow e^{\pm}\ \nu_e\ \nu_{\mu}$$

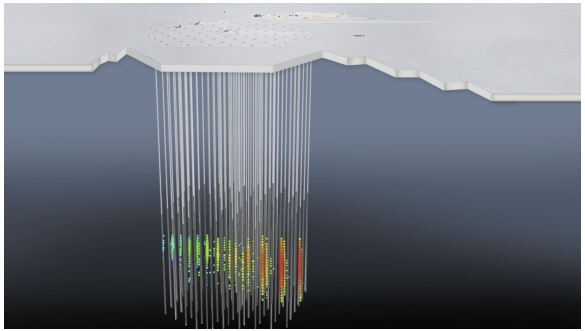
Astrophysical neutrinos detection



Credits: F. Halzen

- **Expected flux** x **neutrino cross sections** imply the necessity for **~ km³ sized detectors**.
- Reservoirs of **natural, transparent mediums** are the only way to achieve such scales.
- Arrays of photosensors to detect Cherenkov light in ice or water: **IceCube, ANTARES, KM3NeT, Baikal-GVD**



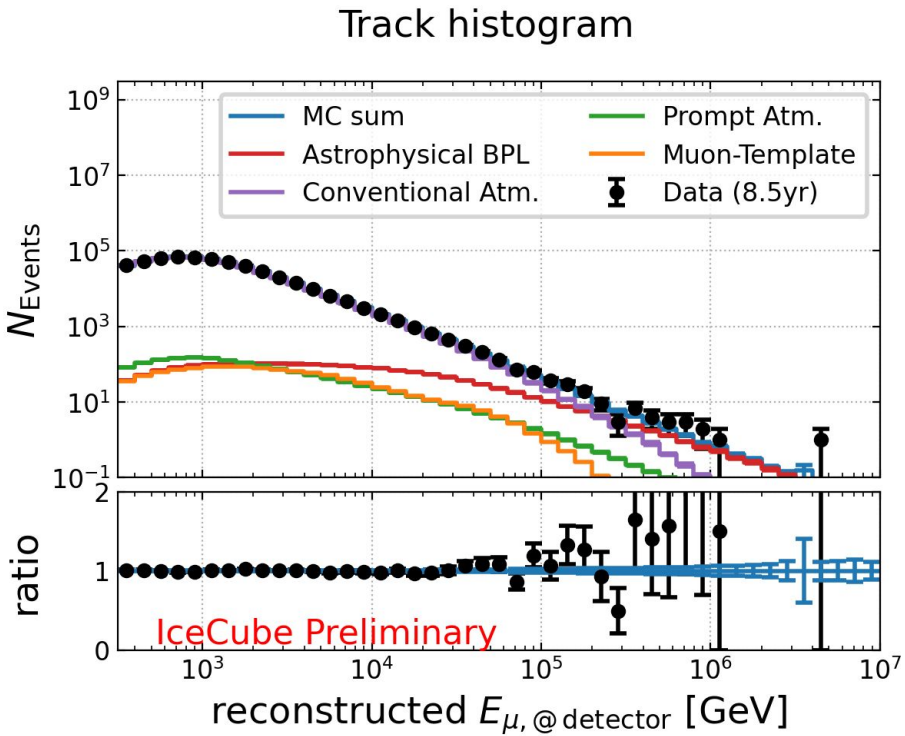


Diffuse astrophysical flux

The IceCube Neutrino Observatory has observed a **diffuse astrophysical flux** of neutrinos.

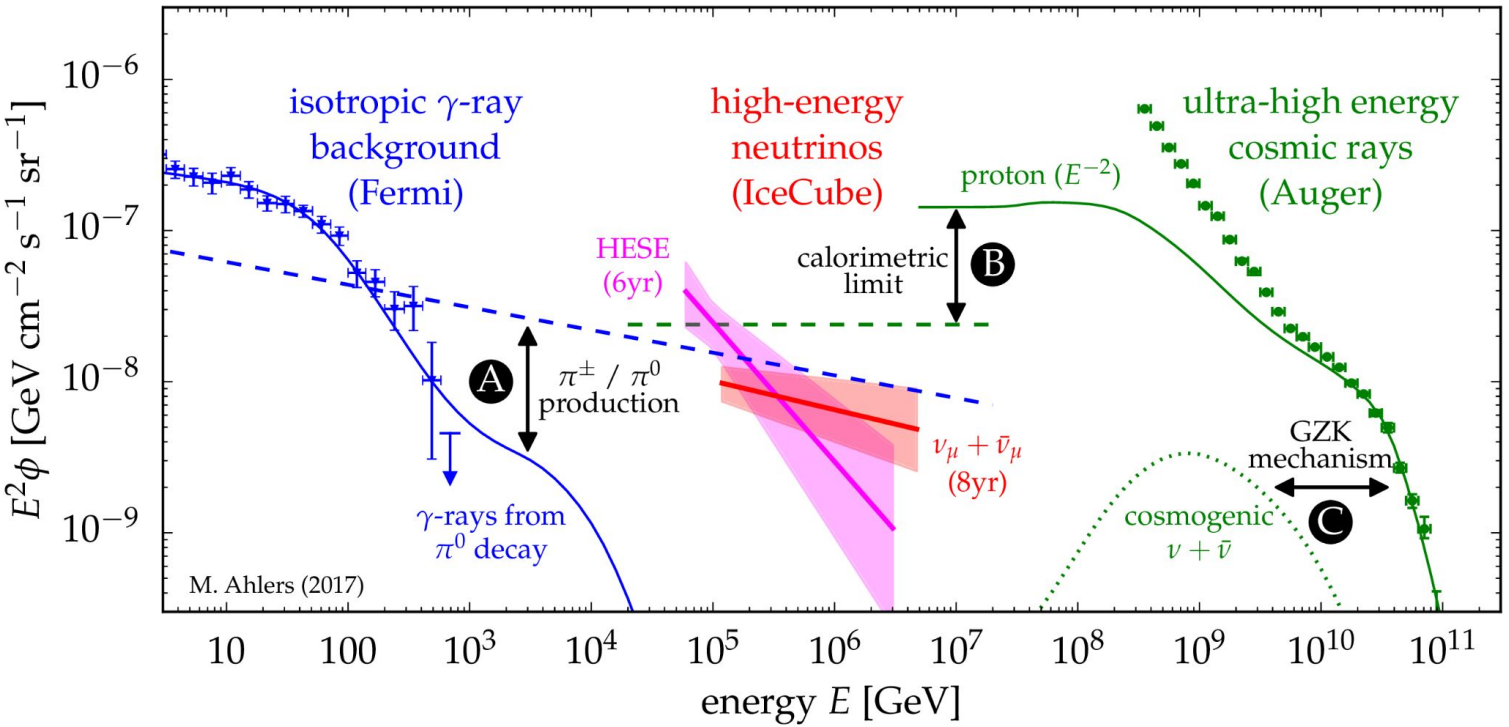
Shape: power law with spectral index ~ 2.3

Hint for a break in the spectrum in the tens of TeV range.



Naab+ [IceCube], ICRC 2023

Gamma – Neutrino – Cosmic-ray connection



The KM3NeT detectors

Digital Optical Modules (DOMs) with 31 PMTs each.

Lines with 18 DOMs each.

Two instrumented sites:

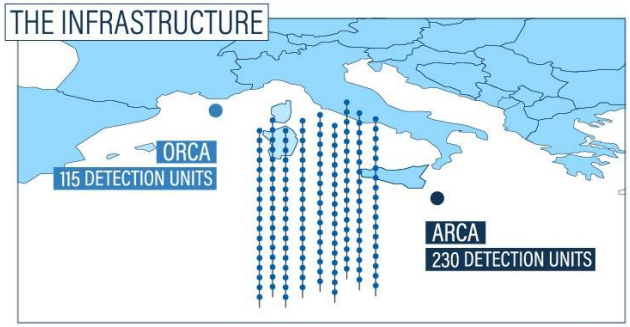
ARCA (IT): km³ scale for astrophysics

33 out of 230 lines deployed.

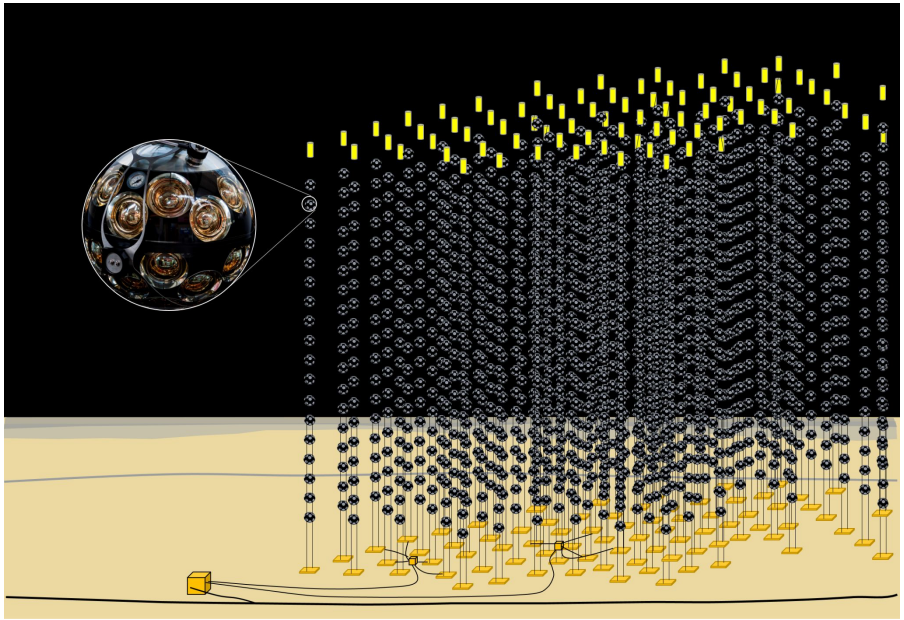
ORCA (FR): 8 Mton scale for neutrino oscillations

24 out of 115 lines deployed.

Completion planned for 2028



Credits: KM3NeT



see T. Eberl, O. Janik talk
in T 32: Neutrino Astronomy II

KM3-230213A

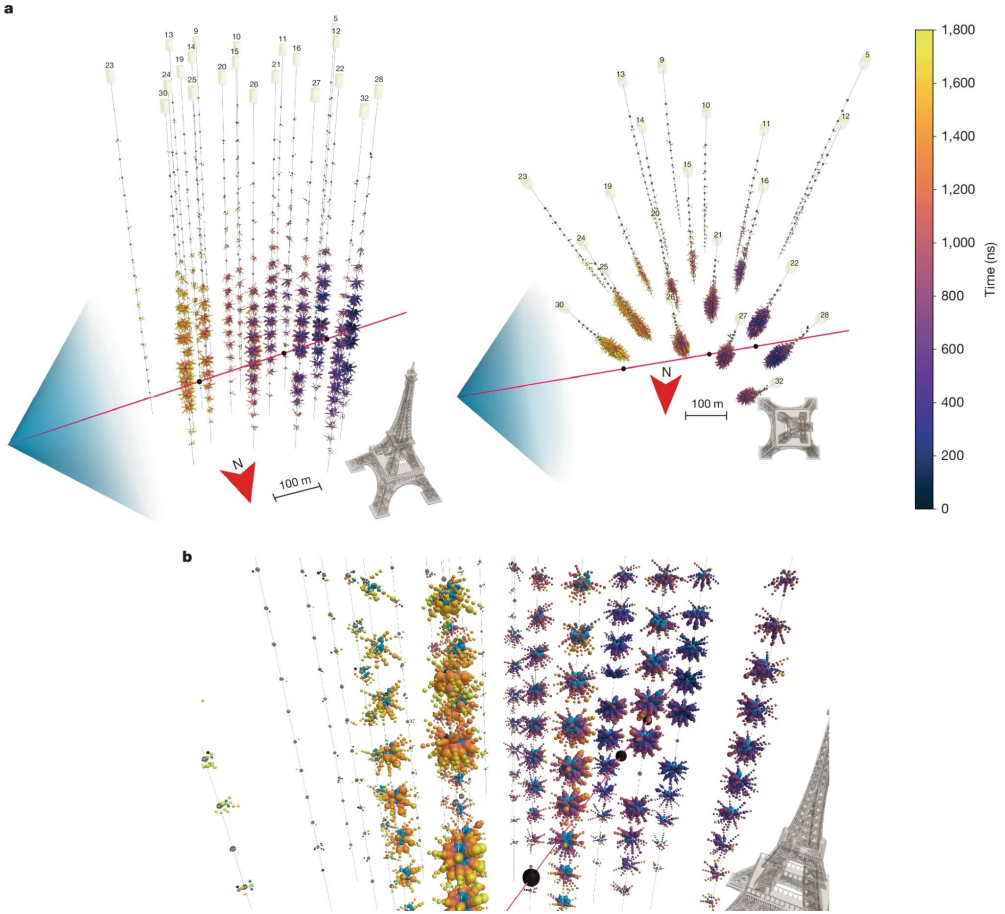
Detected by KM3NeT/ARCA

21 detection lines in operation at the time.

Photons activating 3672 PMTs (30% of the detector).

Muon energy in the 100 PeV range!

Almost horizontal event (0.5 deg above horizon), as expected at the highest energies.



KM3NeT. *Nature* **638**, 376–382 (2025)

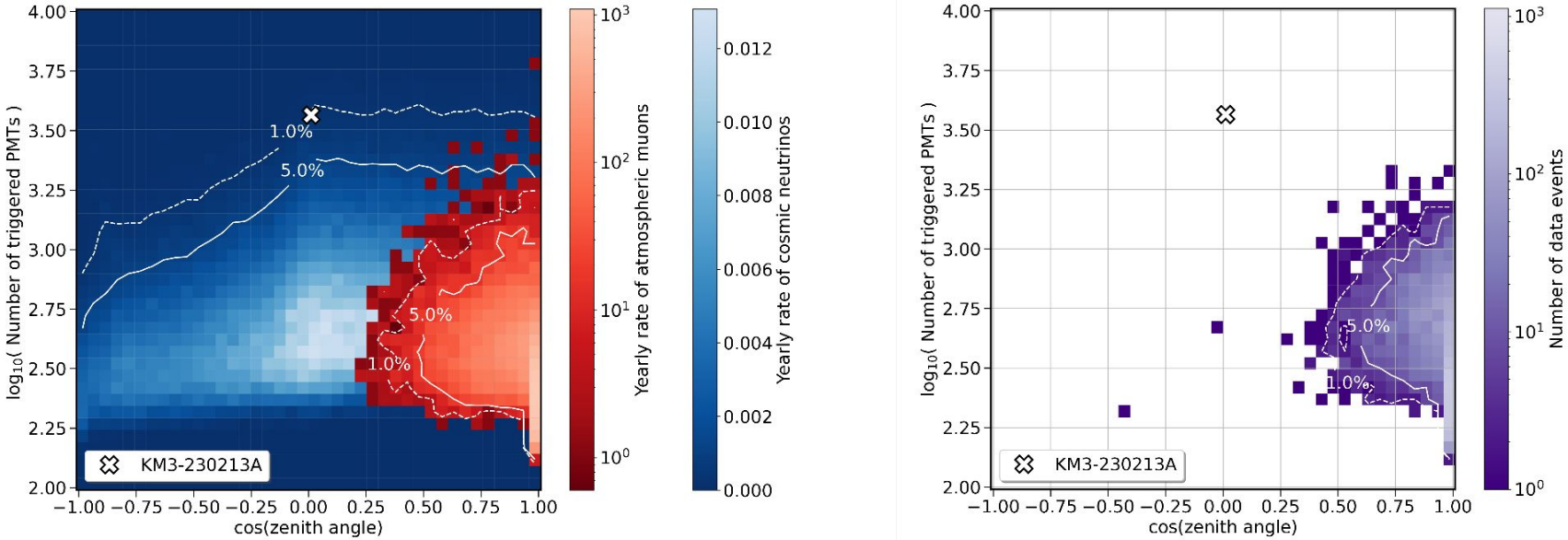
Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT. *Nature* **638**, 376–382 (2025).
https://doi.org/10.1038/s41586-024-08543-1

One of a kind

Impressive amount of light seen in the detector (ARCA, 21 lines).

Distributions of well-reconstructed tracks (> 250 m), log LLHR > 500 => 0.02% atm. muon/nu; 2% cosmic nu.



KM3NeT. *Nature* **638**, 376–382 (2025)

KM3-230213A on Earth

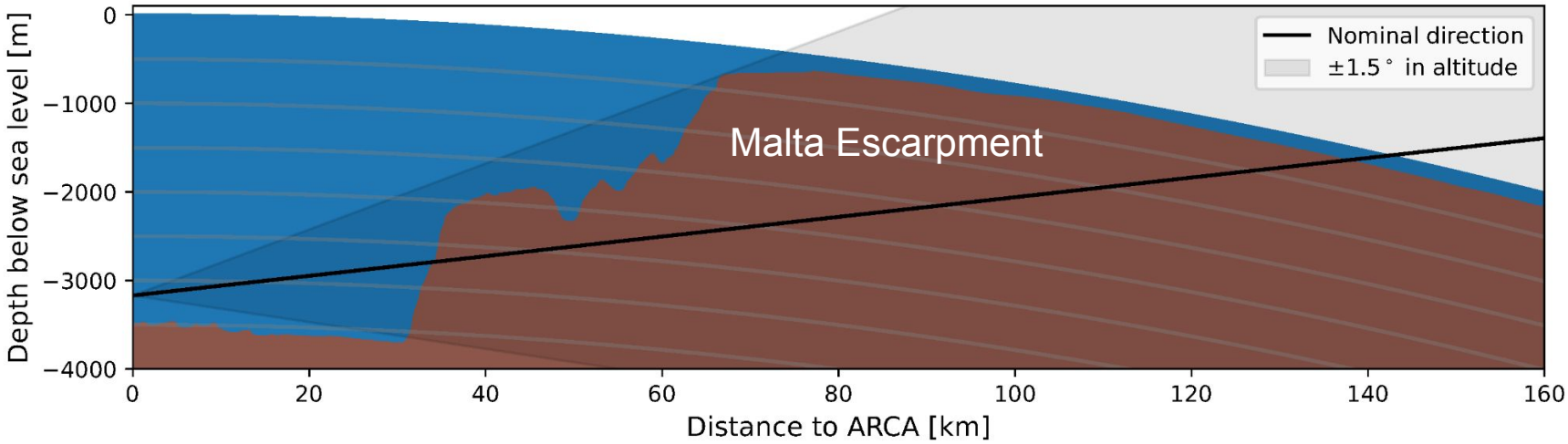
Originates 0.6 deg above the horizon.

300 km water equivalent of material overburden (60 km for a 2 deg deviation)

Max range of EeV muons ~60km (with 10 PeV at the detector ~30km)

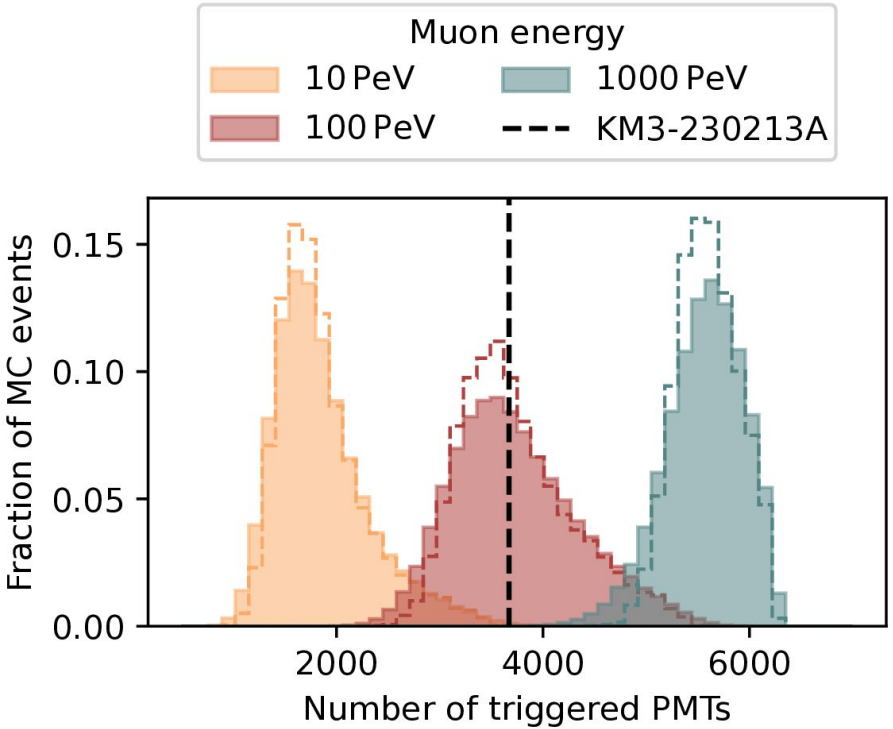
Muon rate << 1e-10/yr within 2 sigma of direction. 1e-4/yr within 5 sigma for single muons, 1e-3/yr for bundles.

Atm. neutrinos ~ 1e-5 / yr



KM3NeT. *Nature* **638**, 376–382 (2025)

Energy estimation



Muon energy 120 (-60/+110) PeV

Neutrino energy ~ 220 PeV

68%: 110 PeV – 790 PeV

95%: 72 PeV – 2.6 EeV

for E^{-2} spectrum.

Neutrino may have higher energy if spectrum is harder or peaked.

Parent proton energy

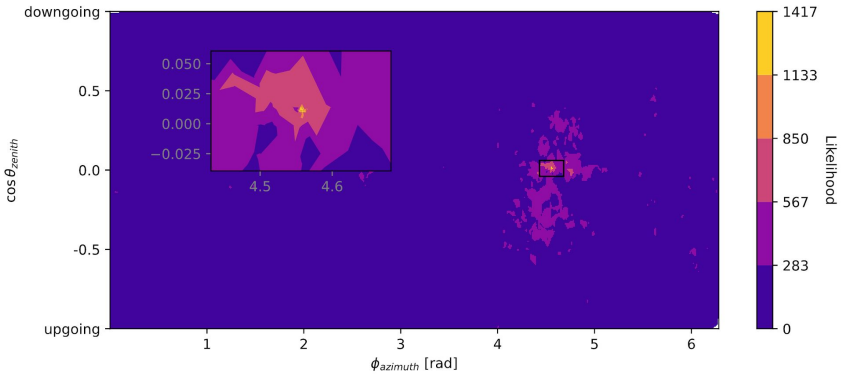
$$E_p = 20\ E_{nu} = O(5\ EeV)$$

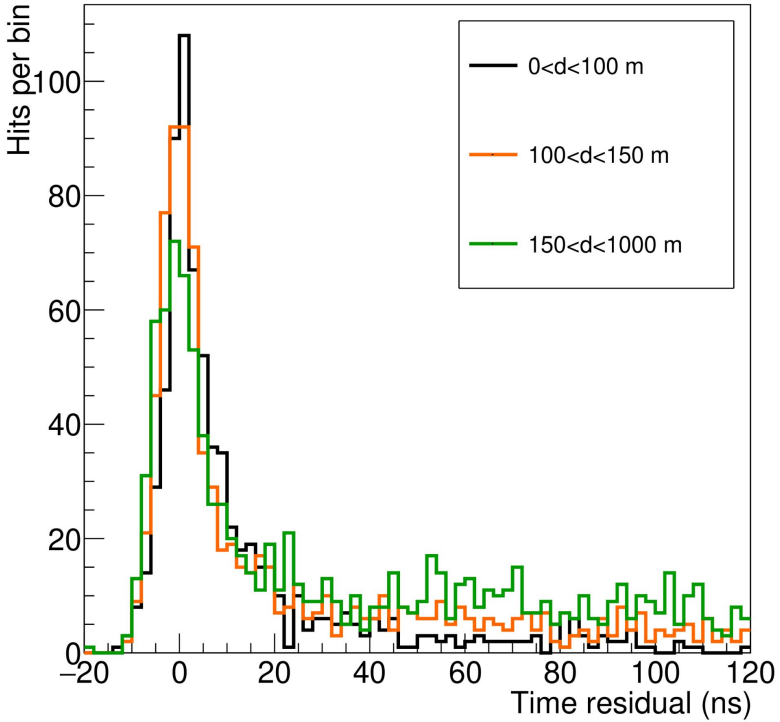
KM3NeT. *Nature* **638**, 376–382 (2025)

Directional reconstruction

Thanks to the excellent optical properties of seawater, light arrives *on time* (within ns).

100 PeV muons are reconstructed within 0.12° (50% CL), 0.28° (90% CL) from the nominal direction.

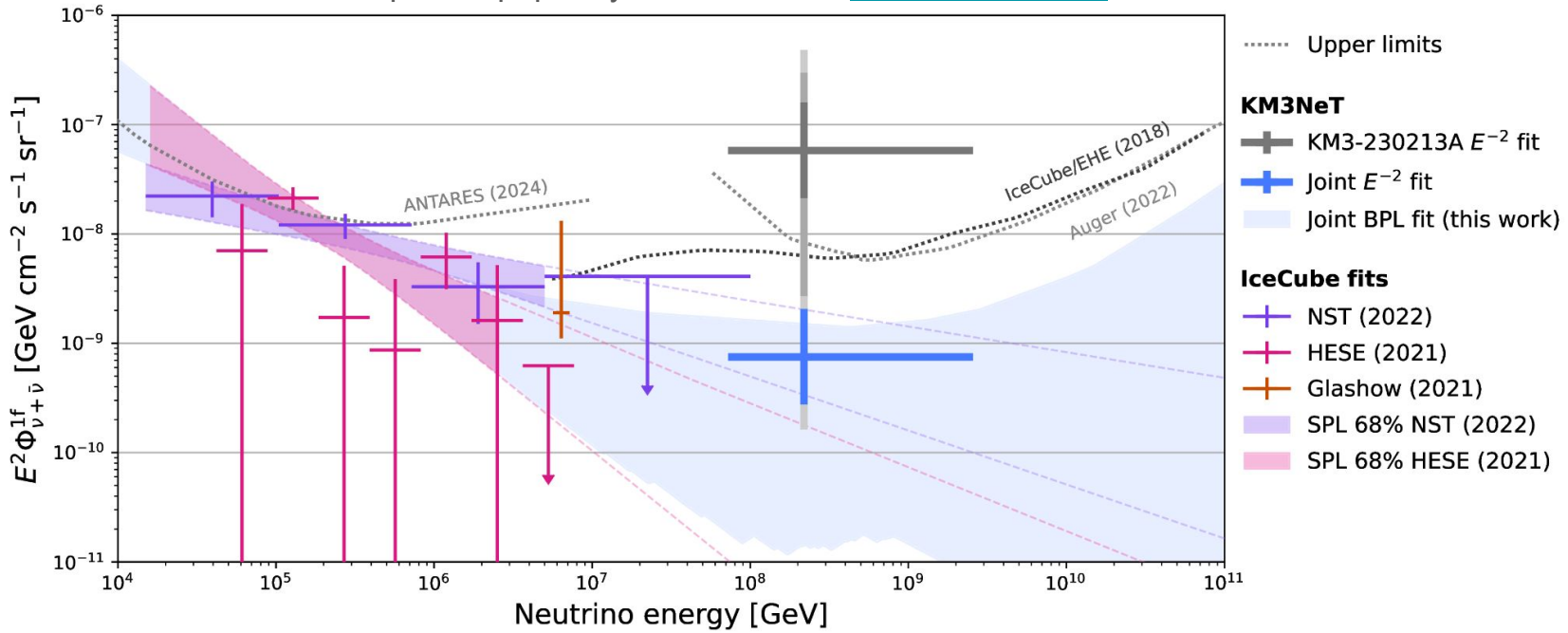




KM3NeT. *Nature* **638**, 376–382 (2025)

The KM3NeT event in the global neutrino landscape

Companion paper by KM3NeT coll., arXiv:2502.08173



Joint Poisson probability of one event in KM3NeT and zero in IceCube and Auger is about 0.5% (2.6σ)

KM3NeT. *Nature* **638**, 376–382 (2025)

Celestial localisation

RA, Dec: (94.3, -7.8) deg

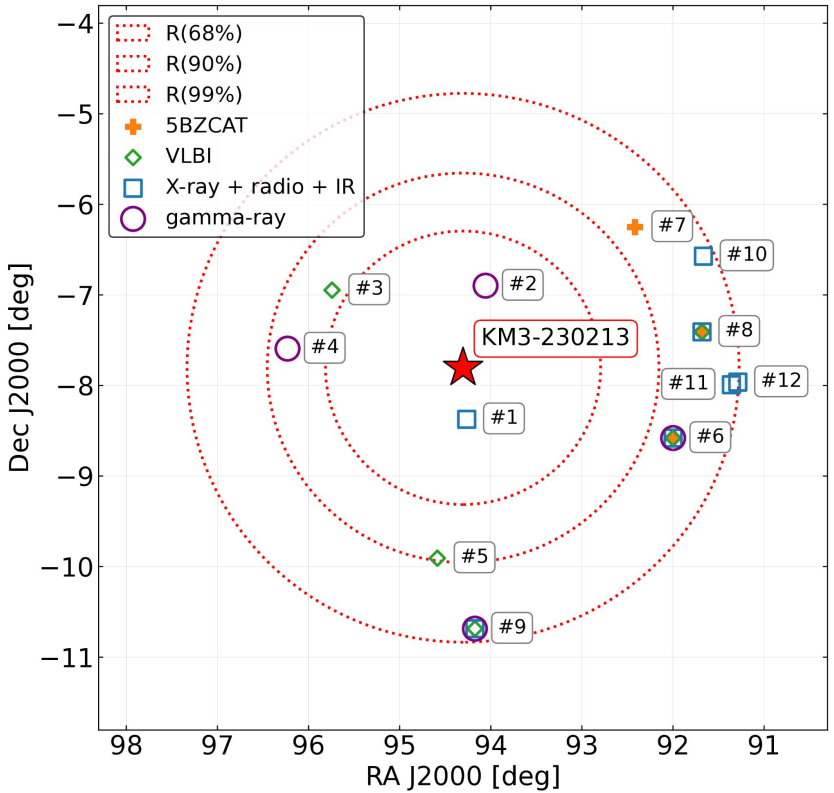
Directional error:

1σ (68%): 1.5 deg

99%: 3.0 deg

Dominated by uncertainty on the absolute orientation of the detector on Earth.

Localisation will improve with upcoming calibration campaigns at sea.



KM3NeT. *Nature* **638**, 376–382 (2025)

Search for steady point-like neutrino sources

Dataset				Method	
Detector	Covered Period dd/mm/yyyy	Livetime [days]	Type of Data	Analysis Approach	Radius [deg]
ARCA6-21	12/05/2021 - 11/09/2023	640	offline	binned likelihood [91]	3
ORCA6-18	11/02/2020 - 31/08/2023	1005	offline	ON/OFF [92]	4
ORCA18-23	01/09/2023 - 29/07/2024	126	online	ON/OFF [92]	4
ANTARES	29/01/2007 - 31/12/2017	3125	public	unbinned likelihood	3
IceCube	06/04/2008 - 08/07/2018	3577	public [93]	unbinned likelihood	3

Dataset	n_{sig}	$-\log_{10}(p\text{-value})$	Flux Upper Limit [$\mathrm{GeV^{-1}cm^{-2}s^{-1}}$]	(RA, Dec) [deg, deg]	Distance [deg]	P-value
ARCA6-21	0.4	0.044	1.8×10^{-8}	(94.3, −7.8)	0.0	-
	1.3	1.308	1.9×10^{-8}	(96.7, −6.8)	2.6	0.44
ORCA6-18	0	-	2.1×10^{-7}	-	-	-
ORCA18-23	0	-	2.3×10^{-6}	-	-	-
ORCA-combined	-	-	2.0×10^{-7}	-	-	-
ANTARES	0	-	1.1×10^{-8}	(94.3, −7.8)	0.0	-
	1.9	1.936	1.7×10^{-8}	(94.4, −5.3)	2.5	0.53
IceCube	1.4	0.327	1.2×10^{-9}	(94.3, −7.8)	0.0	-
	15.1	3.782	6.3×10^{-9}	(93.9, −10.1)	2.4	0.07

ANTARES, KM3NeT and public IceCube data studied.

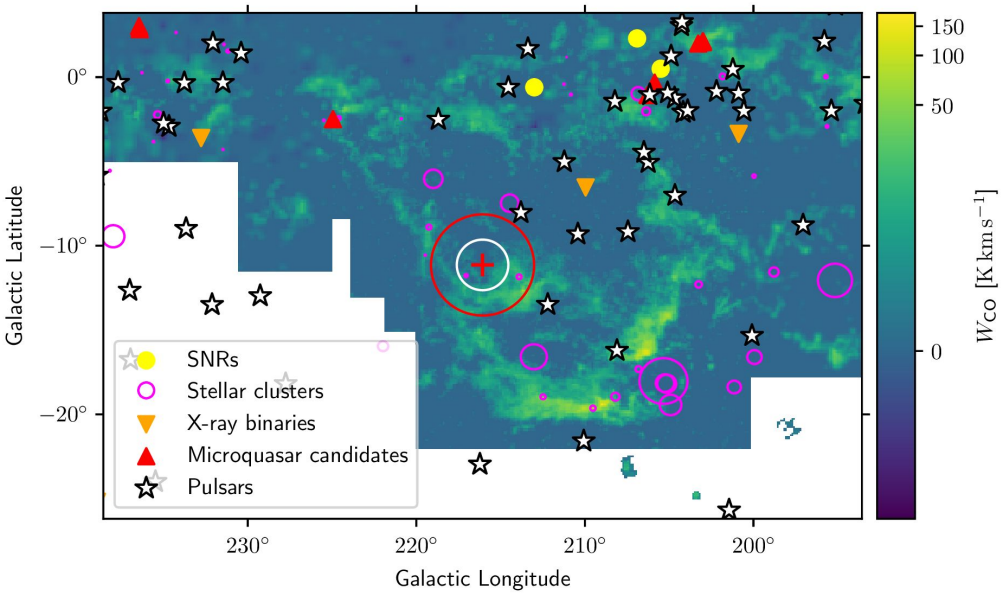
Most strict limits coming from IceCube public data (up to 2018).

Analysis conducted with **IceCubePy** likelihood framework (Lincetto et al., *in prep.*)

No significant signal in the ROI after trial correction.

KM3NeT. *Nature* **638**, 376–382 (2025)

Galactic origin?



Milky Way is a confirmed neutrino source (IceCube) although at lower energies.

But can the KM3NeT UHE neutrino originate in the Galaxy?

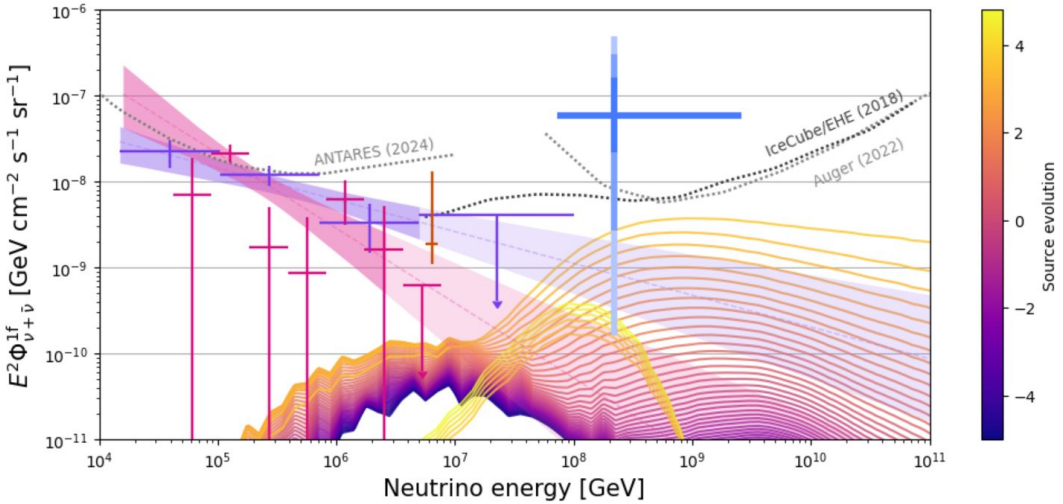
Companion paper by KM3NeT coll. arXiv:2502.08387v2 [astro-ph.HE]

No credible counterpart.

EeV CR energies on Galactic scales are not plausible.

Galactic origin unlikely.

Cosmogenic origin?



Cosmogenic model with subdominant proton component at the highest energies

Companion paper by KM3NeT Coll.

arXiv:2502.08508 [astro-ph.HE]

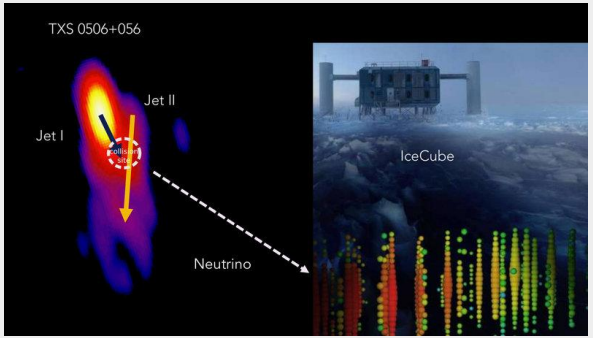
Cosmogenic origin is possible, but not unequivocally favoured.

Extragalactic neutrino source candidates

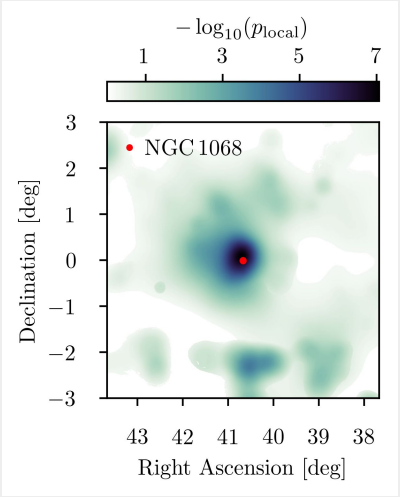
First candidate sources from IceCube data are of AGN (blazar or Seyfert) nature.

Gamma-ray flare of **blazar TXS 0506+056** coincident with 290 TeV neutrino IC170922A

IceCube, Science



IceCube, Science (2022)



Seyfert-II NGC 1068

4.1 σ evidence steady emission

soft spectrum

likely coronal origin

IceCube hotspots correlated with blazars
Buson+ ApJL (2022)
Buson+ arXiv:2305.11263

Two IC alerts from Seyfert NGC 7469
Sommani, Franckowiak, Lincetto+, ApJ, (2025)

TDEs (AT2019dsg)
Stein+, Nature (2021)

Extragalactic counterparts of KM3-230213A

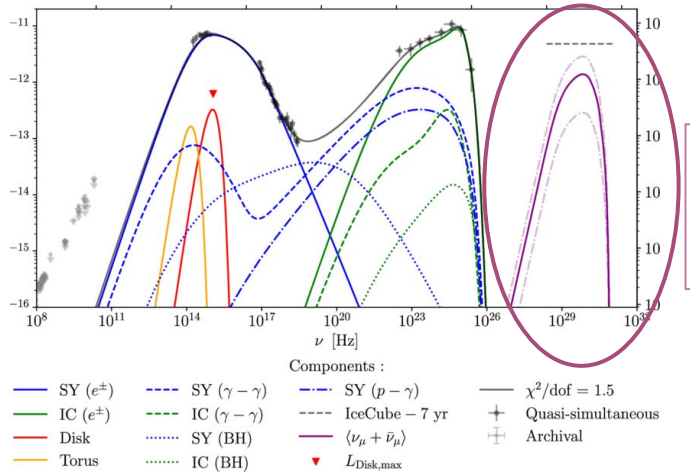
No transients (GRB, SNe, …) identified in coincidence.

Several extragalactic objects can be positionally consistent by chance (large error region).

Corona-driven emission by AGN unlikely to power neutrino emission > 100 PeV.

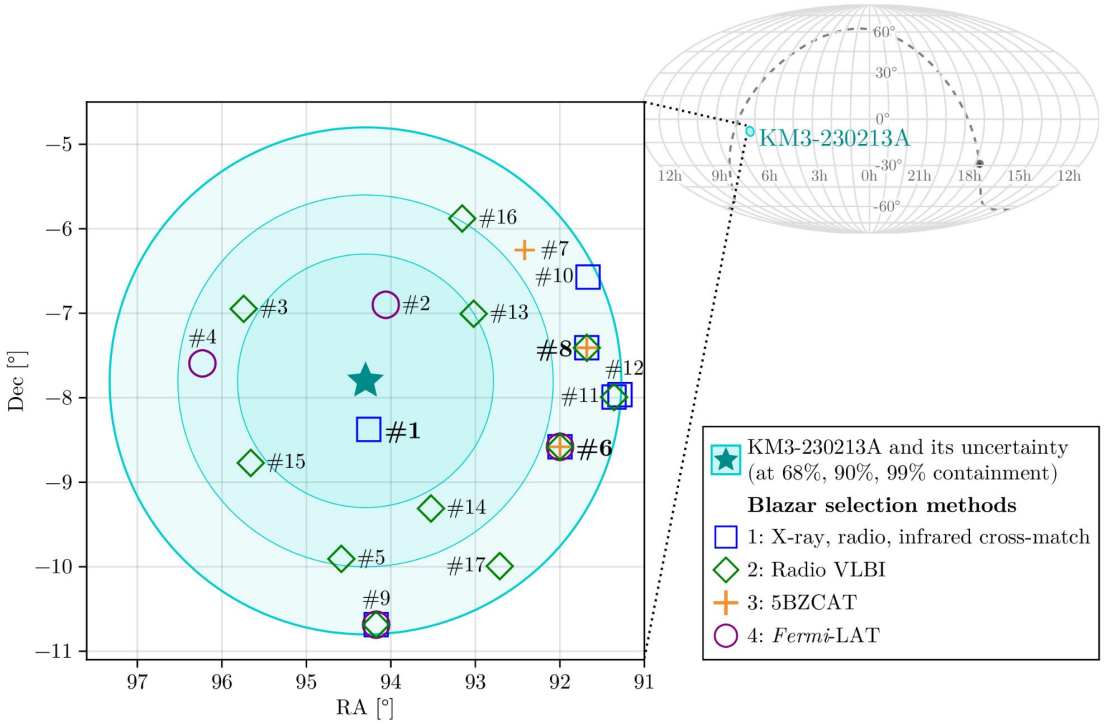
Neutrino emission at UHE is well consistent with modelling of **blazar spectral energy distributions**.

Example: blazar SED model (Fichet de Clairfontaine+, 2023)



neutrinos above PeV scale

Candidate blazars in the KM3-230213A ROI



Four methods

(1) X-ray, radio, IR cross-match starting from eROSITA 1eRASS catalogue;

(2) VLBI from RFC and VLBA observation;

(3) Roma 5th Blazar Catalog

(4) *Fermi*-LAT 4FGL-DR4 Catalog

17 sources

2 in the 68% region

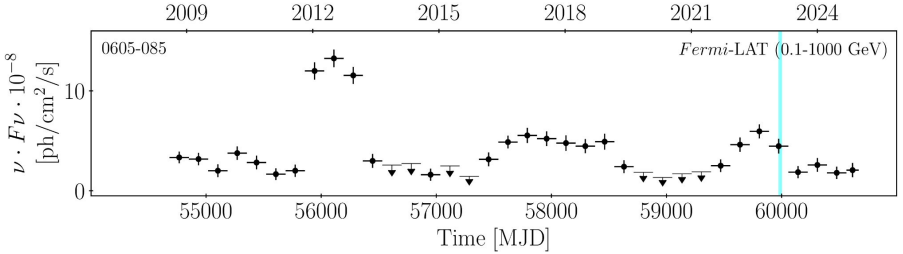
Lincetto, Pfeiffer, Plavin
[KM3NeT+] arXiv:2502.08484

Blazar flaring activity in the KM3-230213A ROI

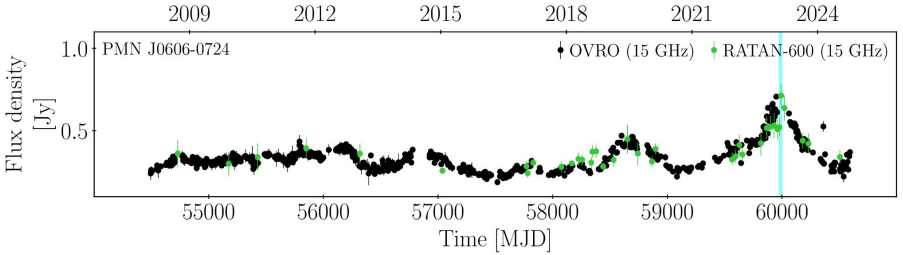
Beyond the TXS 0506+056 gamma-ray flare, research has highlighted correlations between neutrino emission and radio flares or X-ray activity.

Electromagnetic flares may be of peculiar interest.

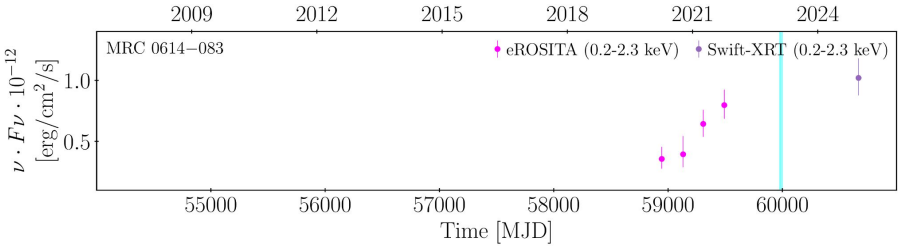
Gamma-ray flare in QSO 0605-085



Radio flare in PMN J0606-0724



X-ray flare in MRC 0614-083

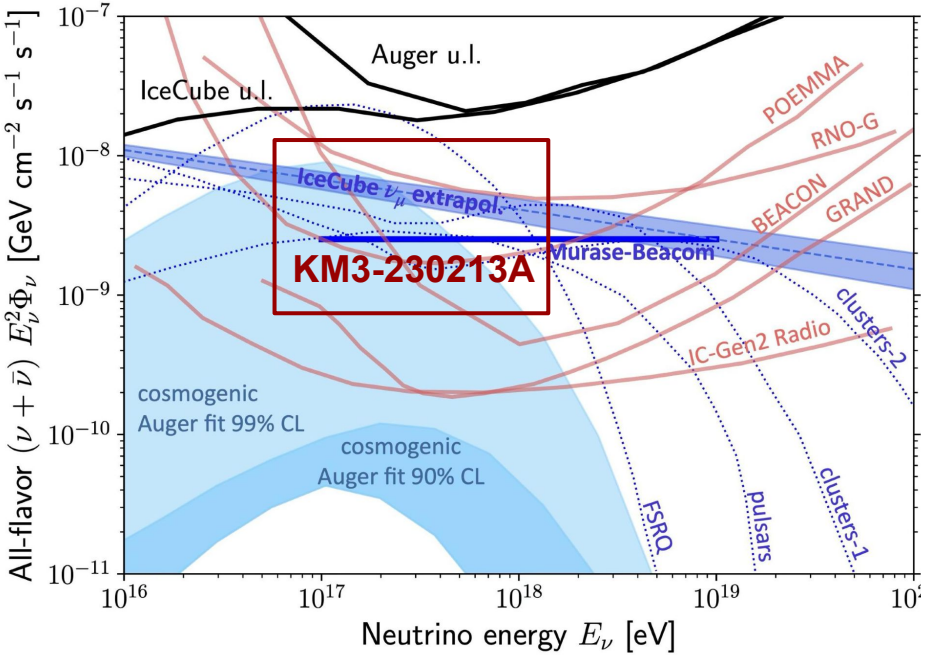


KM3NeT+ arXiv:2502.08484

Life at the UHE frontier

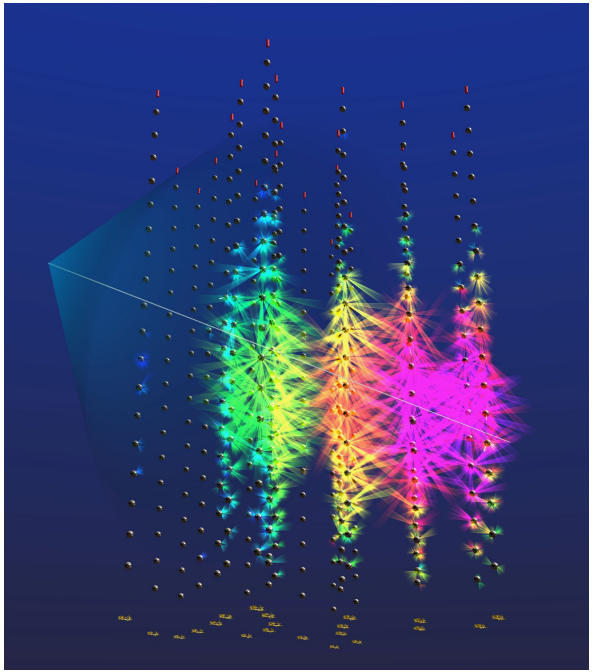
Observation of the KM3NeT event is promising for future detectors aimed at the UHE/EHE frontier.

Best-fit IC + Auger + KM3NeT E^{-2} flux including the observation of KM3-230213A is at sensitivity of planned observatories.



Plot adapted from K. Kotera

Conclusion and outlook

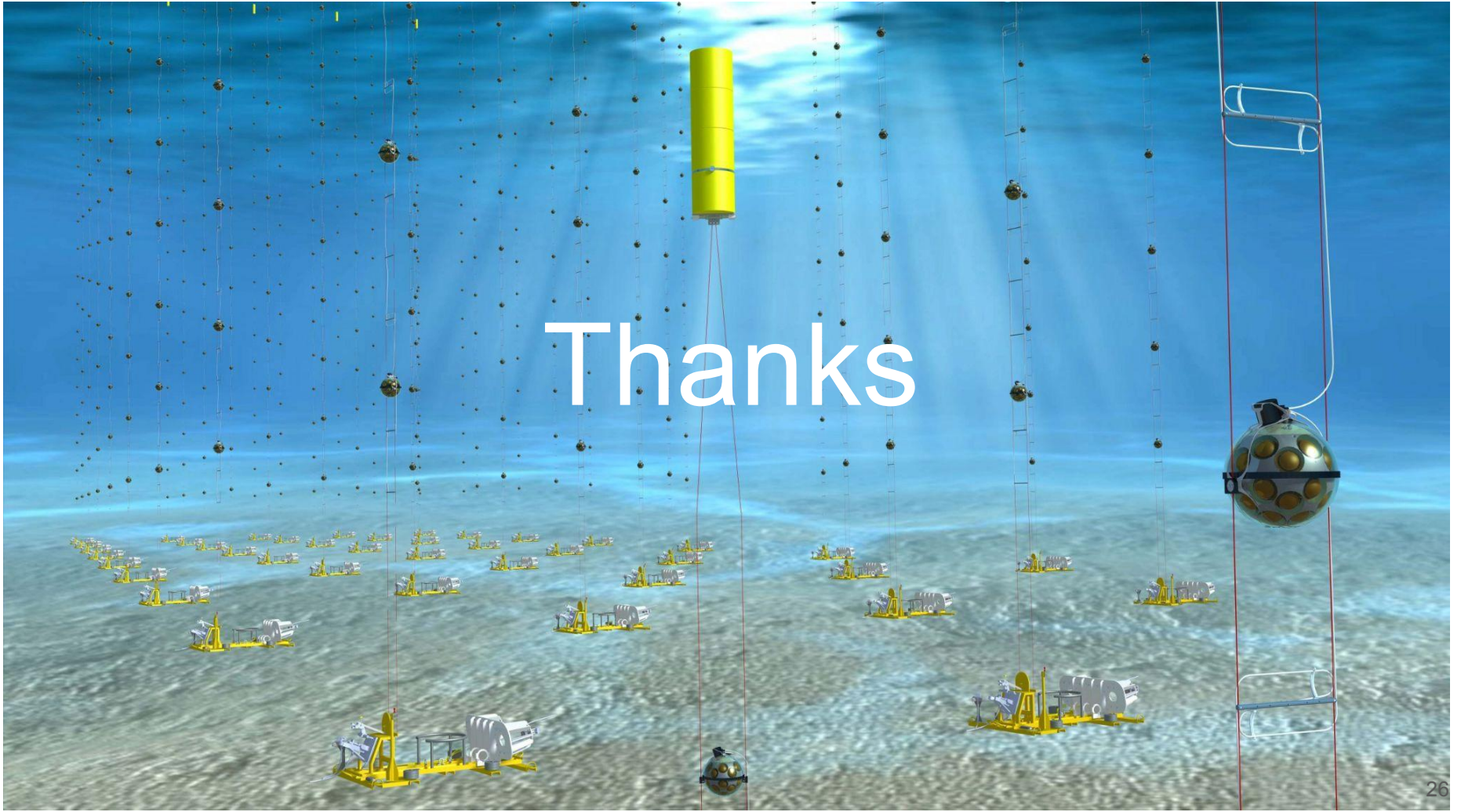


KM3-230213A is the most energetic cosmic neutrino observed to date.

KM3NeT. Nature 638, 376–382 (2025).
https://doi.org/10.1038/s41586-024-08543-1

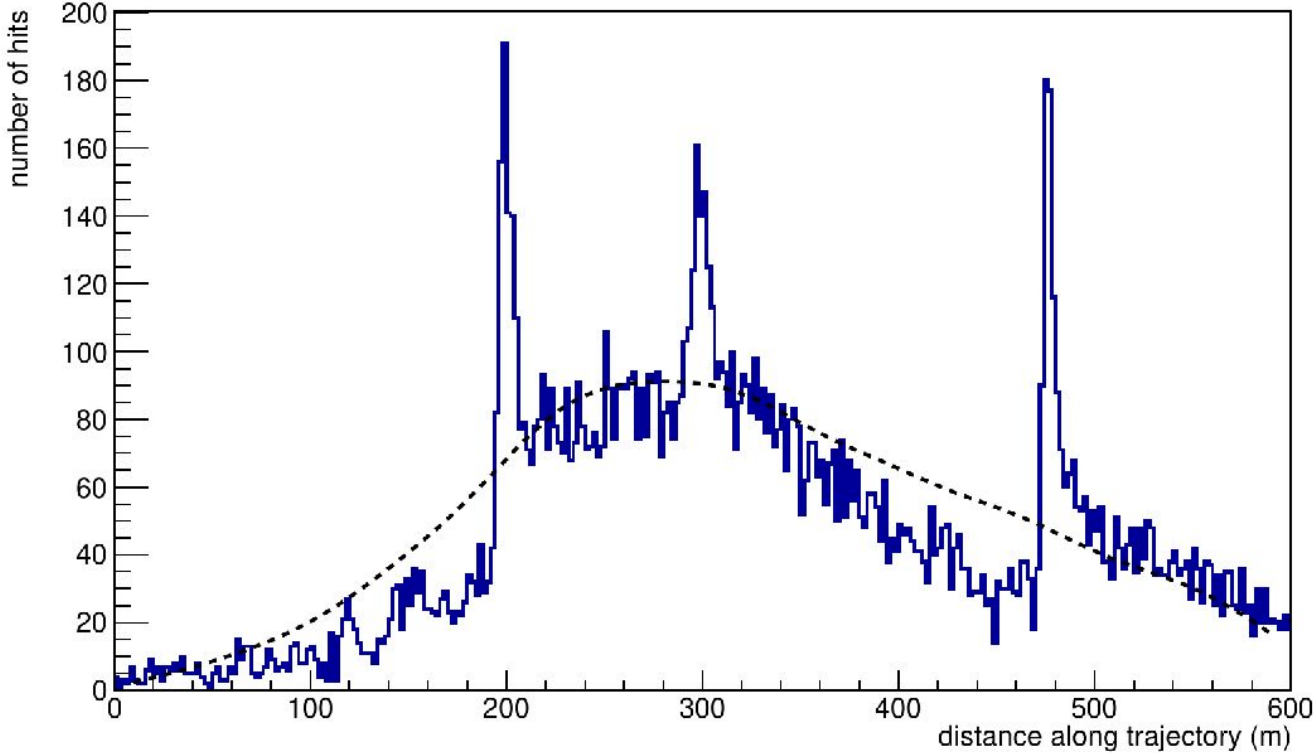
Seventeen **blazar candidates** potentially associated with KM3-230213A have been studied. A **blazar flare** at the origin of the UHE neutrino is an intriguing possibility, but current evidence is not sufficient.

The field of **neutrino astronomy** harbors many intriguing questions, to be tackled from multiple fronts (new experiments, MM synergies, theory…)


Thanks

Backup

Light deposition along muon track



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