The KM3NeT Ultra-High-Energy Event from the Perspective of Neutrino Astronomy

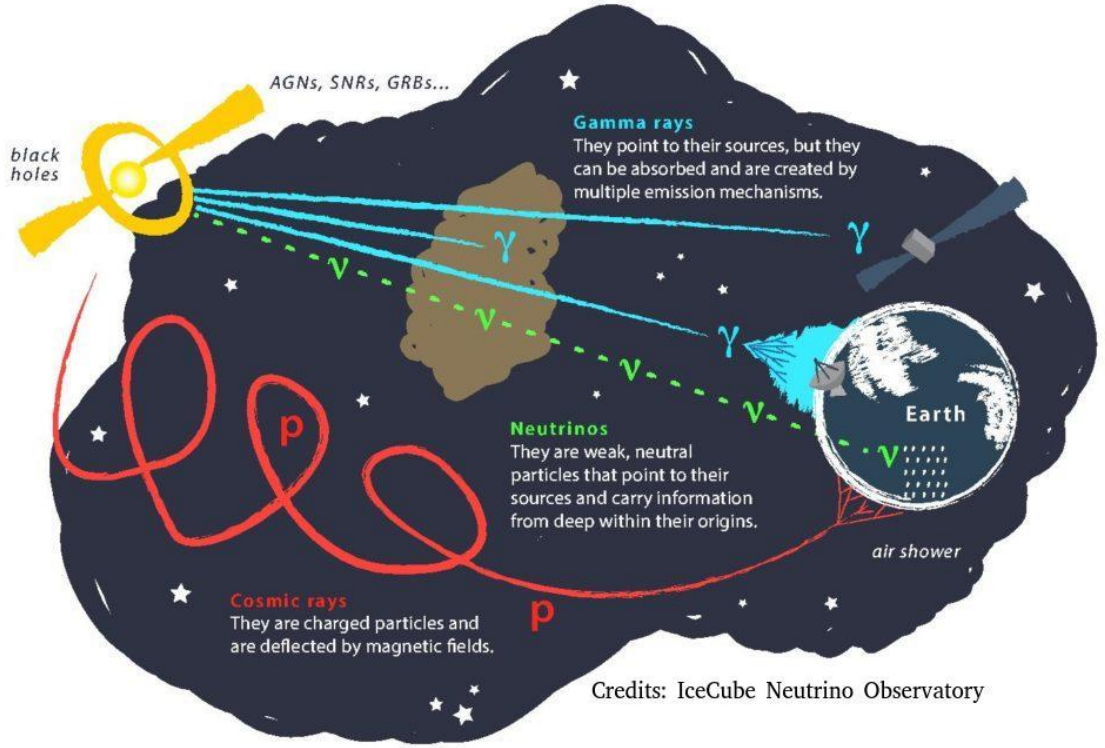
Massimiliano Lincetto

Art: Leo Pfeiffer

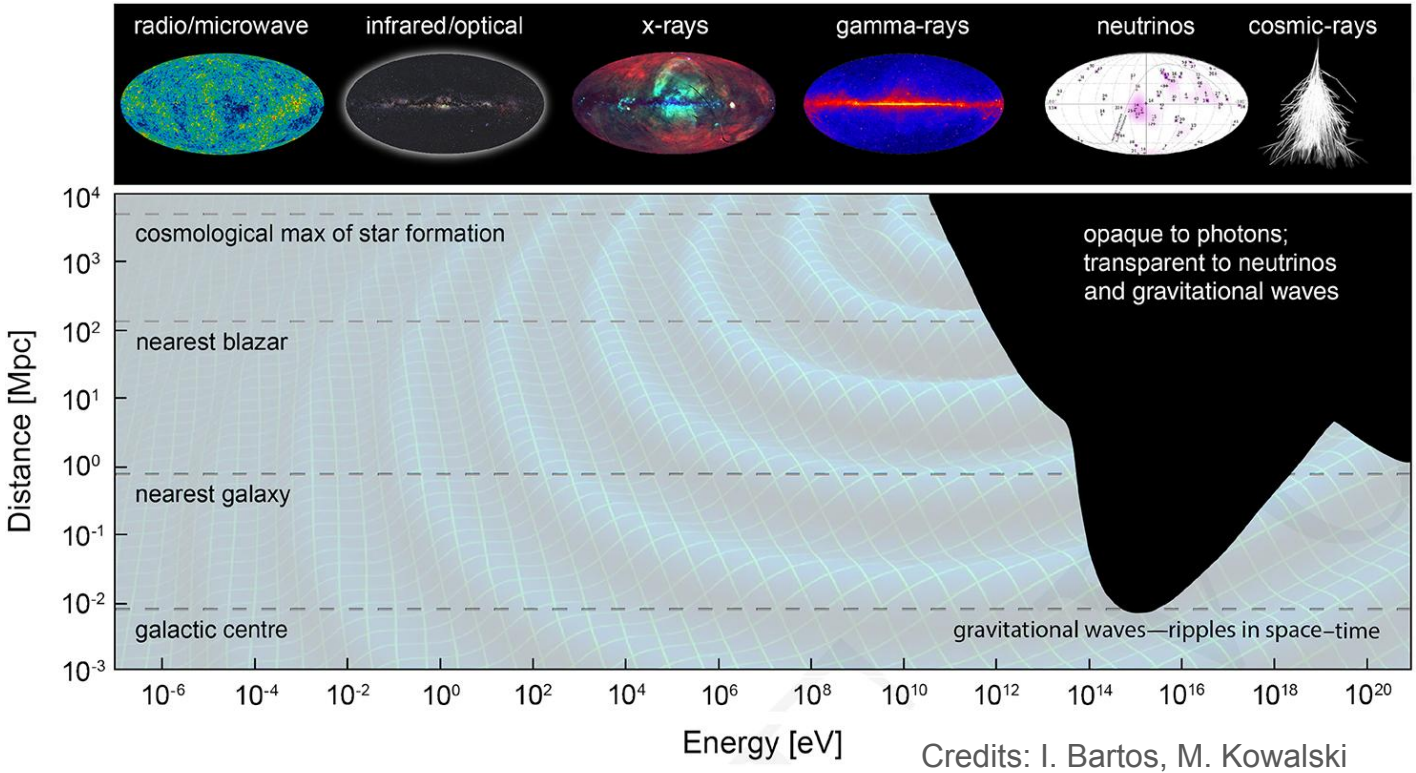
AP Seminar
DESY Zeuthen - March 14, 2025

Neutrinos as cosmic messengers

Addressing a century old question…

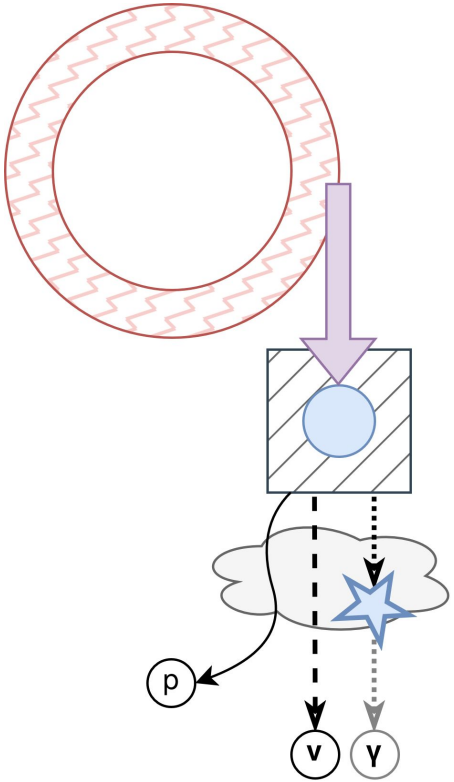


Neutrinos as cosmic messengers



Credits: I. Bartos, M. Kowalski

Astrophysical neutrino production



Proto-hadronic (hadro-nuclear)

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

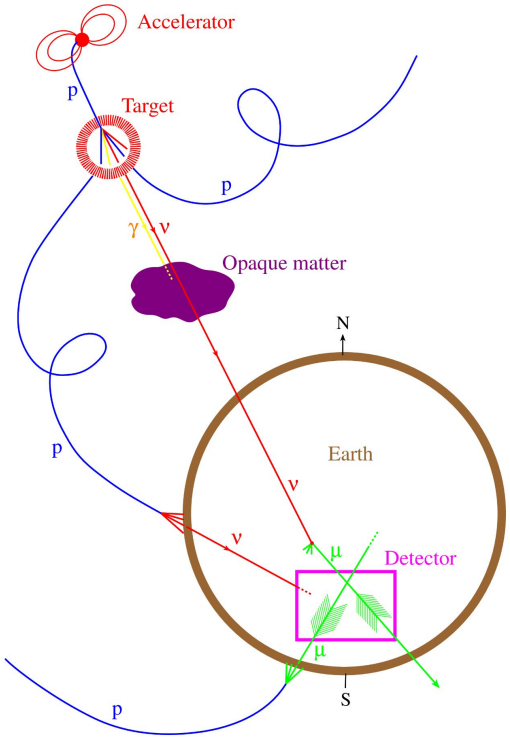
Photo-hadronic

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

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

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

Astrophysical neutrinos detection



Credits: F. Halzen

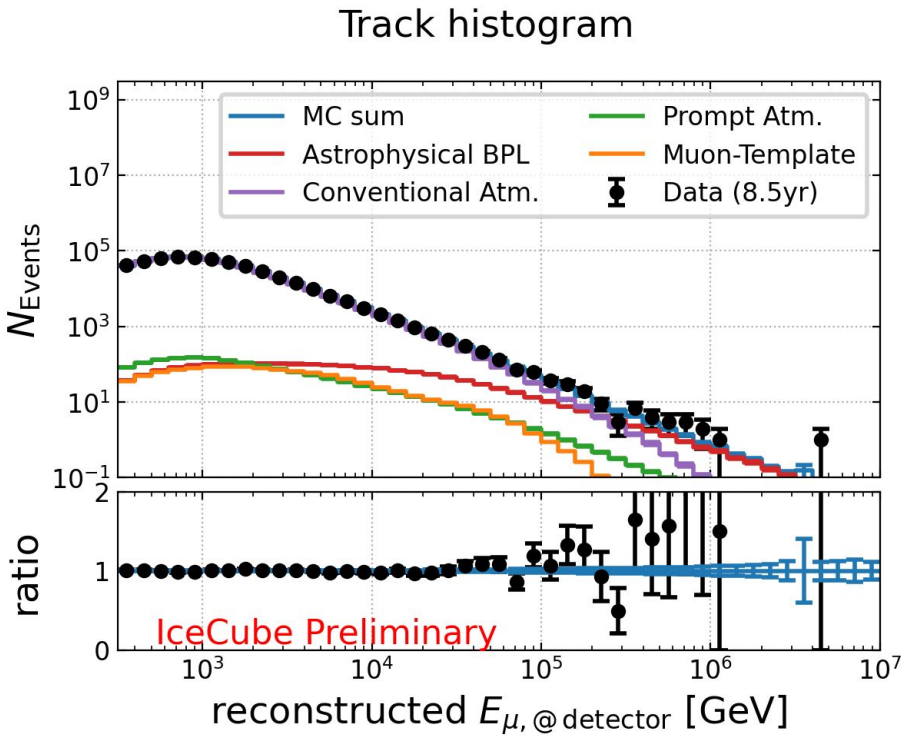
- From expected flux and neutrino cross sections, the necessity for **~ km³ sized detectors** has been known since decades.
- Large reservoirs of **natural, transparent mediums** are the only way to achieve such scales.
- Detectors based on Cherenkov effect in ice or water + arrays of photosensors: **IceCube, ANTARES, Baikal-GVD, KM3NeT**

Diffuse astrophysical flux

Thanks to the IceCube Neutrino Observatory, a diffuse astrophysical flux of neutrinos has been observed.

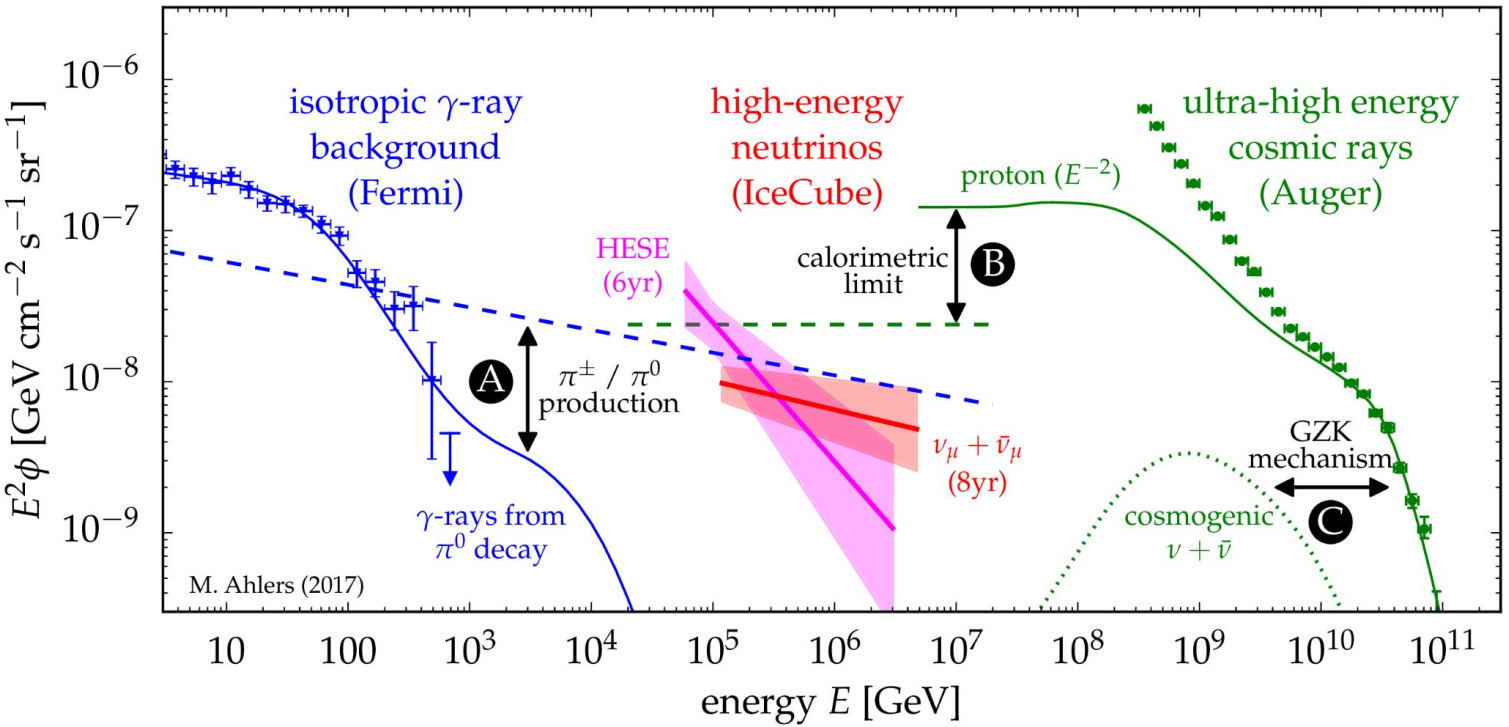
Approx, power law with spectral index ~ 2.3

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



Naab+ [IceCube], ICRC 2023

Gamma – Neutrino – CR connection



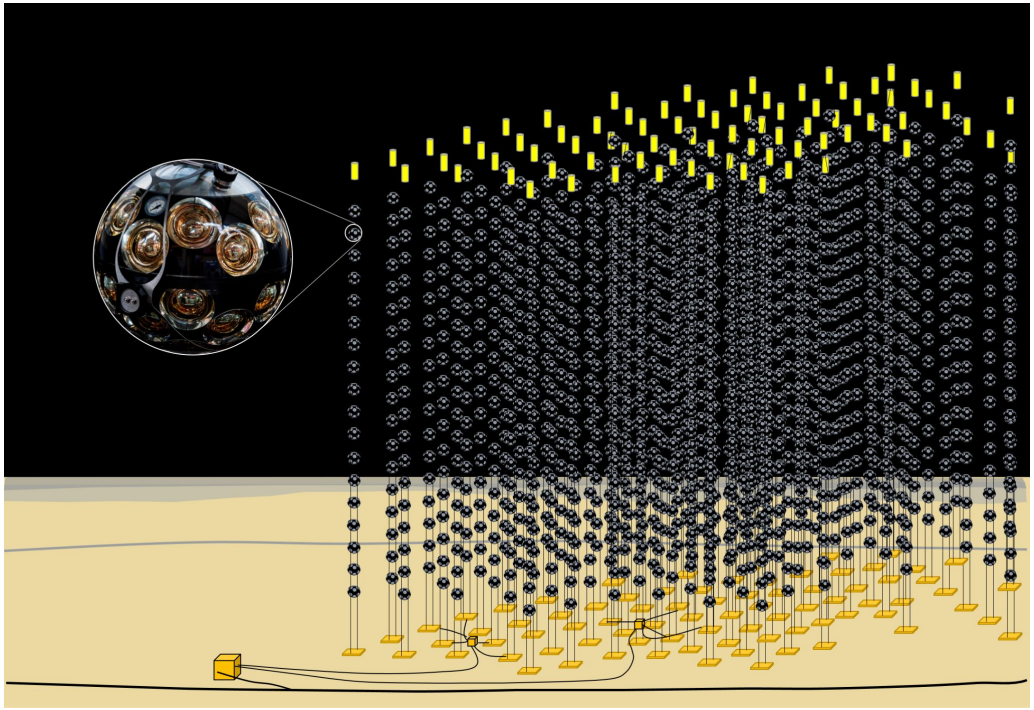
The KM3NeT detectors

Digital Optical Modules (DOMs) with 31 PMTs each. Lines with 18 DOMs each.

Two instrumented sites:

ARCA (IT): km³ scale for astrophysics – 33/230 lines deployed.

ORCA (FR): 8 Mton scale for neutrino oscillations – 28/115 lines deployed.



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

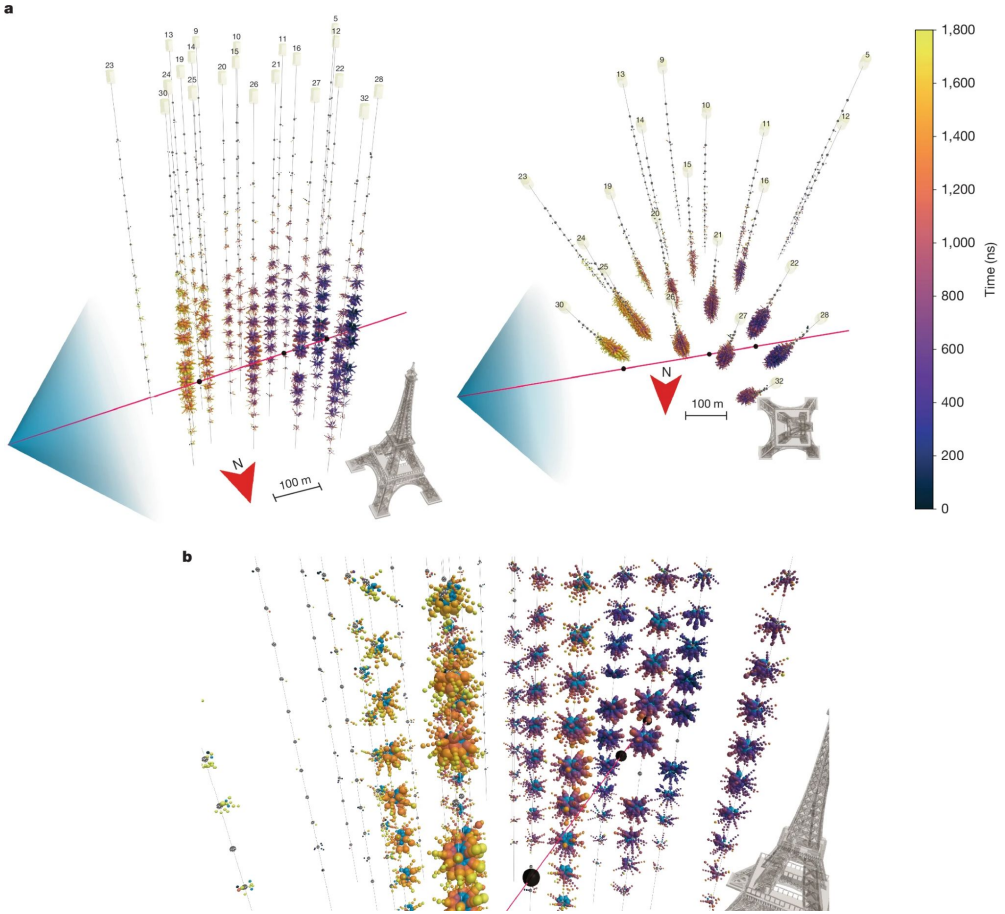
KM3-230213A

Detected by KM3NeT/ARCA

21 detection lines in operation at the time.

Photons activating 3672 PMTs (30% of the detector)

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

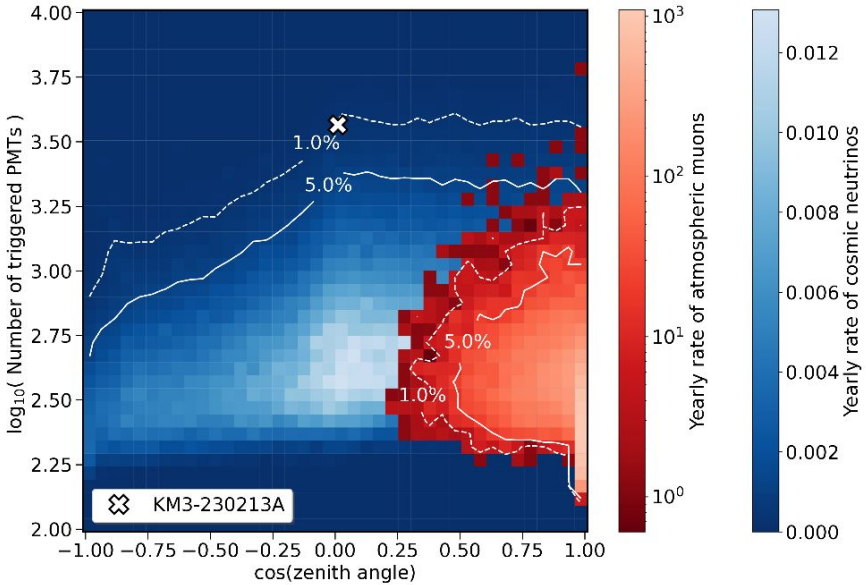


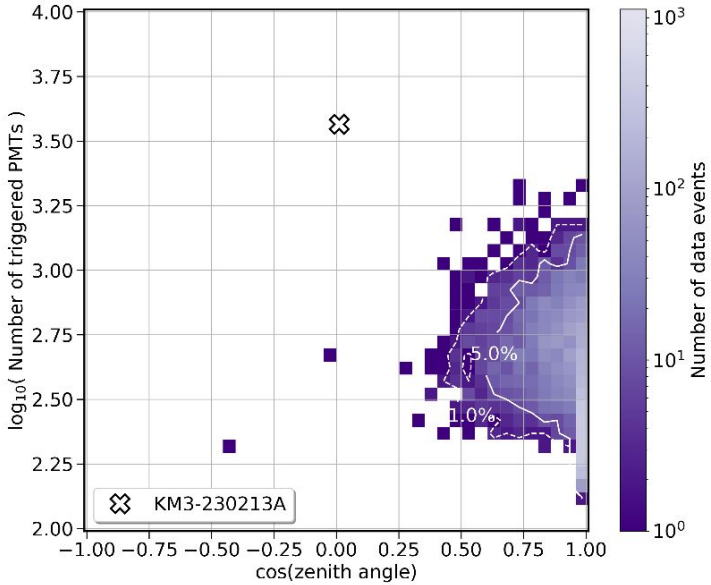
KM3NeT. *Nature* **638**, 376–382 (2025)

One of a kind

Outlier in terms of light generated in the detector (ARCA with 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

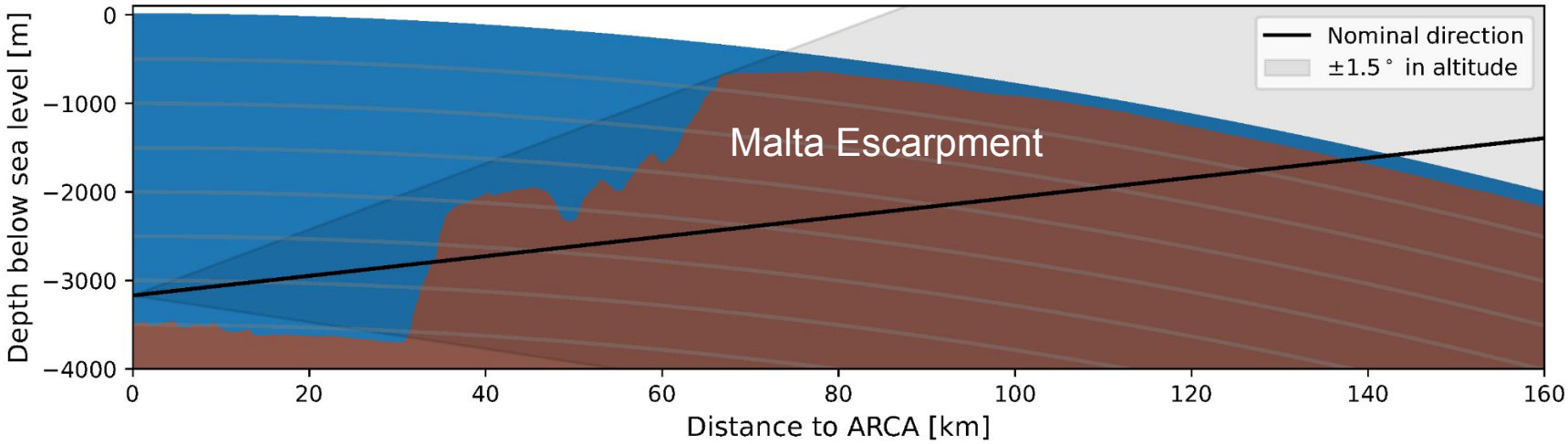
Originates 0.6 deg above the horizon.

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

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

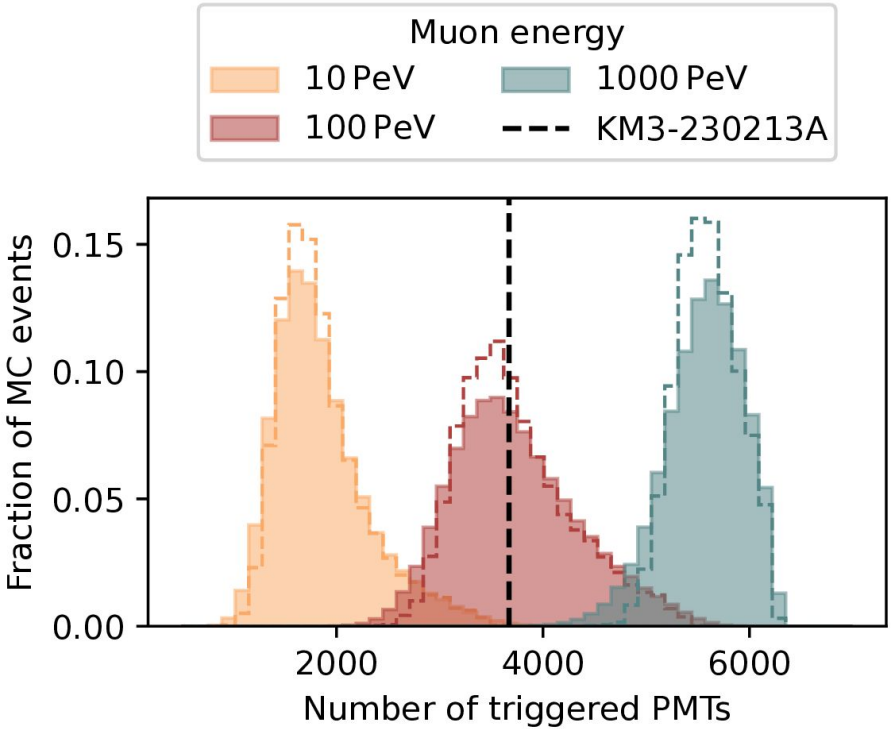
Muon rate << 1e-10/yr within 2 sigma of direction. 1e-4/yr within 5 sigma for single muons, 1e-3/yr for bundles.

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

All-sky simulation, E^-2 spectrum.

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

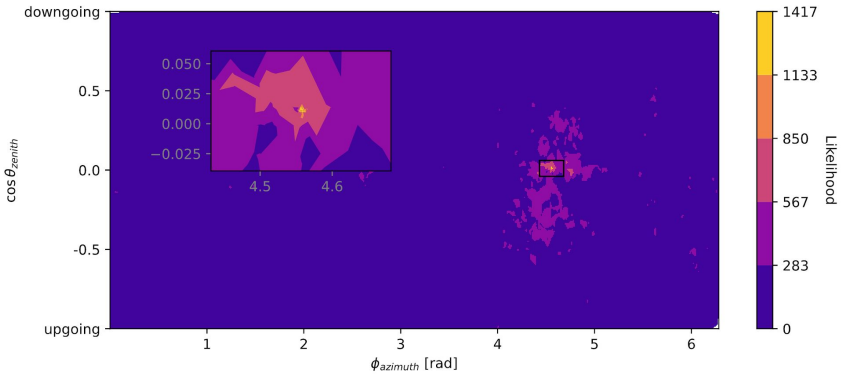
Parent proton energy ~ 5 EeV scale.

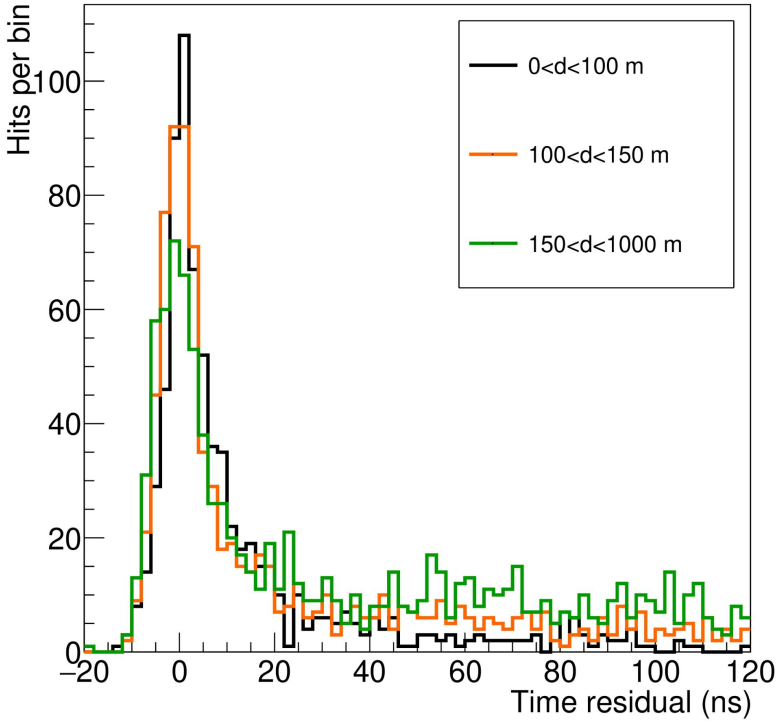
KM3NeT. *Nature* **638**, 376–382 (2025)

Directional reconstruction

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

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

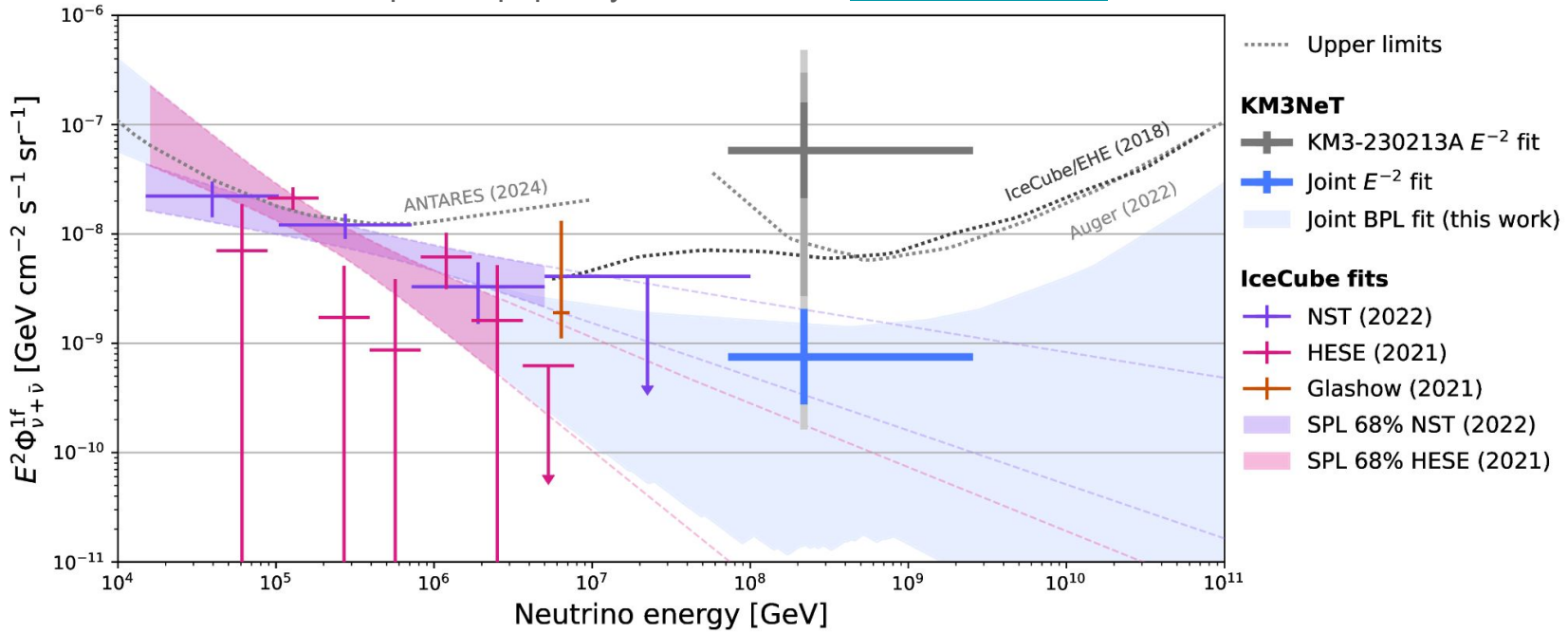




KM3NeT. *Nature* **638**, 376–382 (2025)

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

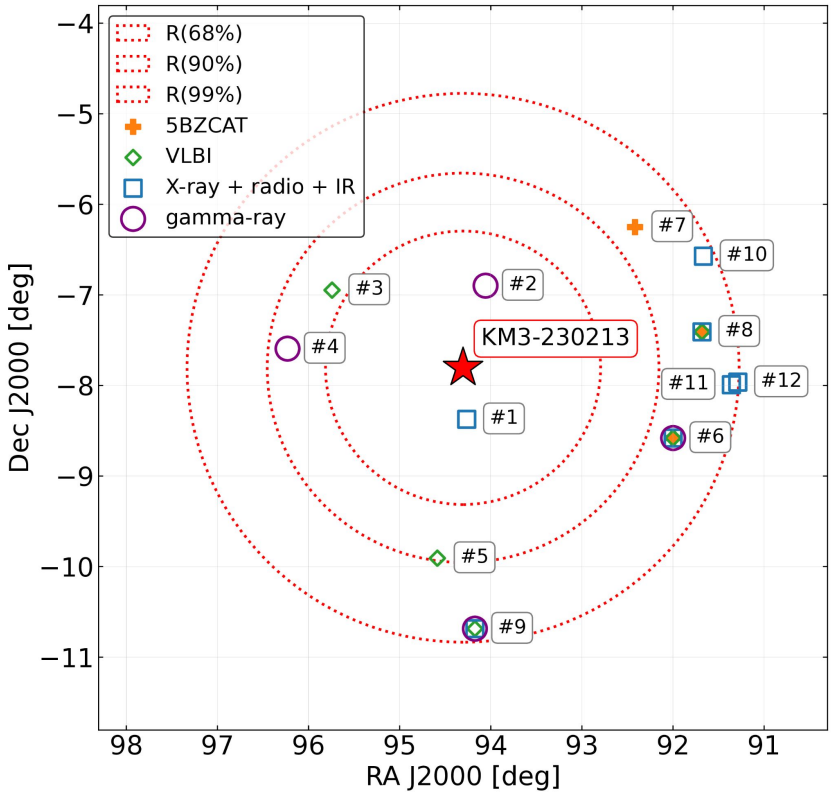
Directional error:

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 sea campaigns.



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 [$GeV^{-1}cm^{-2}s^{-1}$]	(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.

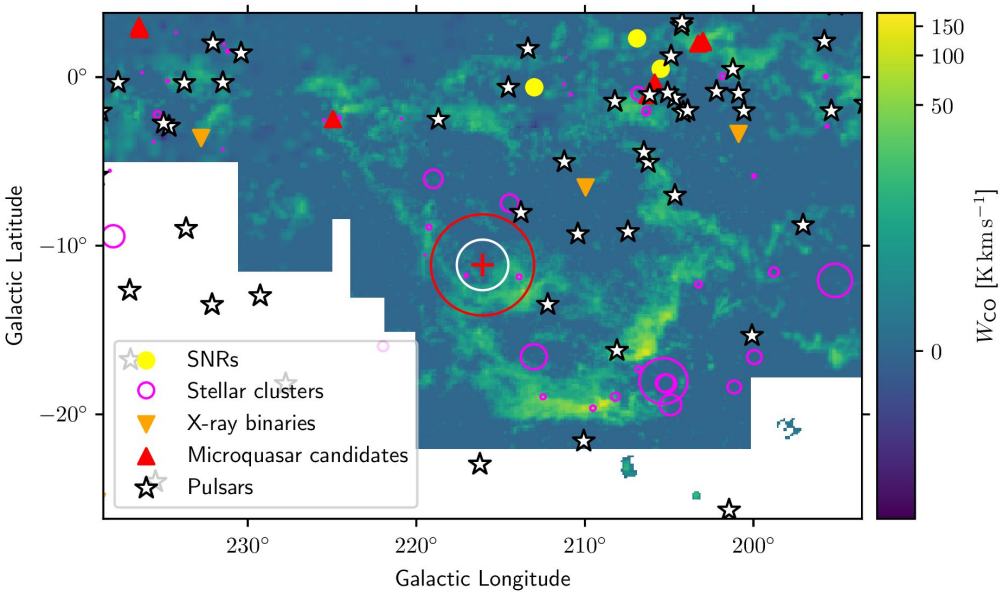
Strictest limits coming from IceCube public data (up to 2018).

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?

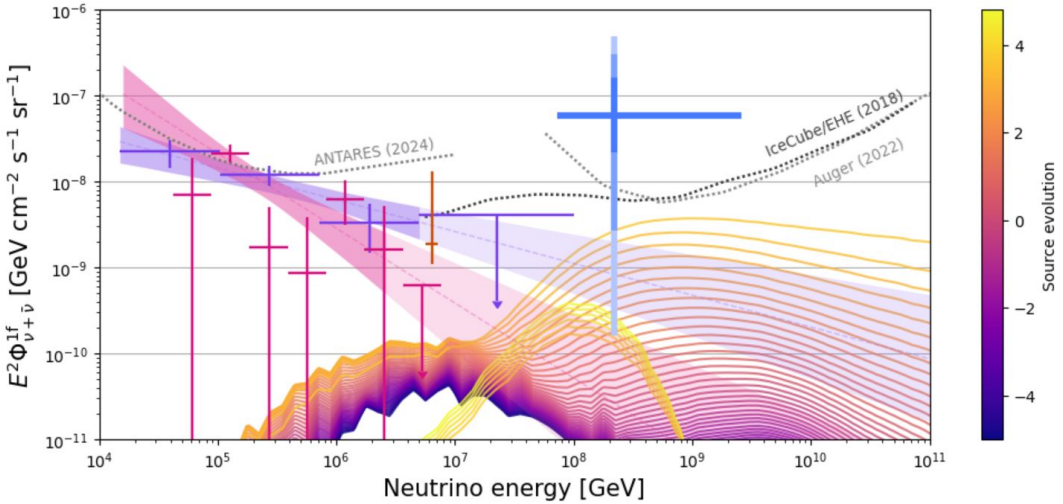
Companion paper by KM3NeT coll. arXiv:2502.08387v2 [astro-ph.HE]

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]

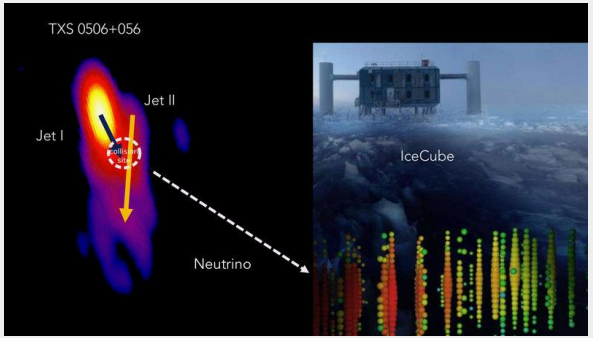
Cosmogenic origin is possible but not necessarily the most likely.

Extragalactic neutrino source candidates

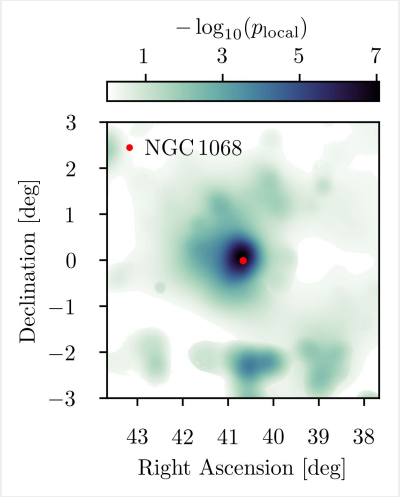
First candidate sources from IceCube data are of blazar or AGN (Seyfert) origin.

Gamma-ray flare of **blazar TXS 05056+056** coincident with 290 TeV neutrino IC170922A

IceCube, Science



IceCube, Science (2022)



Seyfert-II NGC 1068

4.1 σ evidence time-integrated

soft spectrum

likely corona emission

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.

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

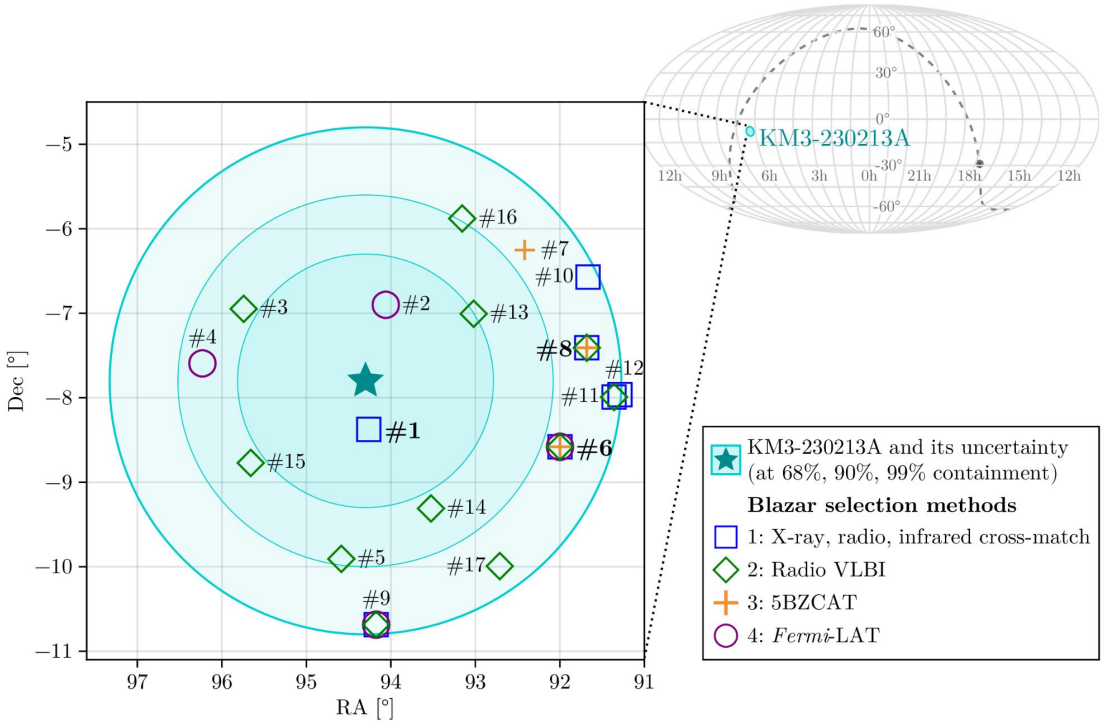
Corona-driven emission by AGN is unlikely to power neutrino emission > 100 PeV.

Emission peaked at UHE is well consistent with modelling of **blazar spectral energy distributions**.

Companion paper: focus on blazar-like counterparts

Lincetto, Pfeiffer, Plavin [KM3NeT, MessMapp, *Fermi*-LAT, OVRO, SVOM]
arXiv:2502.08484

Identifying 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

KM3NeT+ arXiv:2502.08484

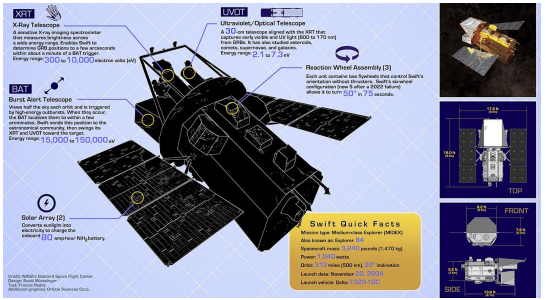
Multiwavelength follow-up campaign

Archival data

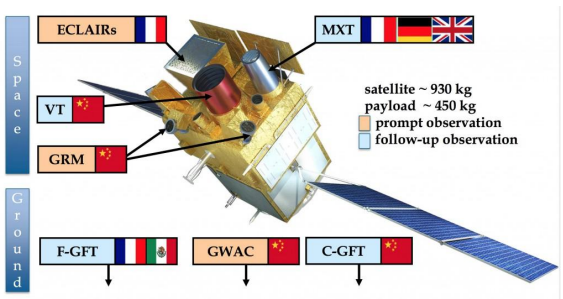
- OVRO
- RATAN-600
- ALMA
- WISE-NEOWISE
- ZTF, CRTS
- *Gaia*
- Chandra
- ROSAT
- eROSITA
- Swift-XRT
- Fermi-*LAT*

ToO observations

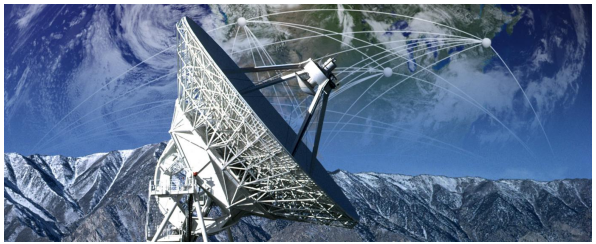
***Swift* (targeted)**



SVOM (tiling)



VLBA (field survey)



Time-dependent study

With a 3-deg radius region of interest, many blazars are positionally consistent with KM3-230213A.

Steady source with a typical power-law spectrum disfavoured by the non-observation of strong neutrino excesses at lower energies.

Variable and **flaring** behaviour may be exploited as additional ingredients to discriminate between candidate counterparts

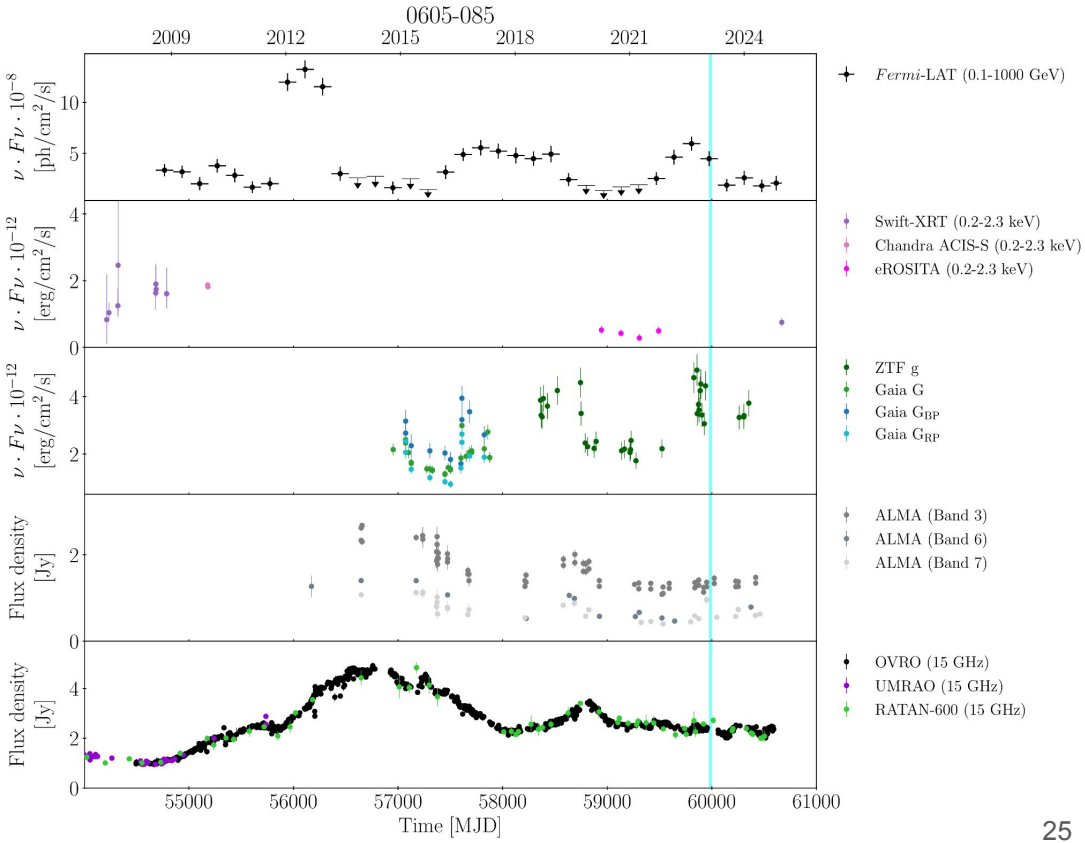
Gamma-ray flare in 0605+085

Year-long gamma-ray flare.

Optical variability?
Nearby star contamination cannot be excluded.

Very bright radio object (top 50 in the sky in VLBI flux).

KM3NeT+ [arXiv:2502.08484]

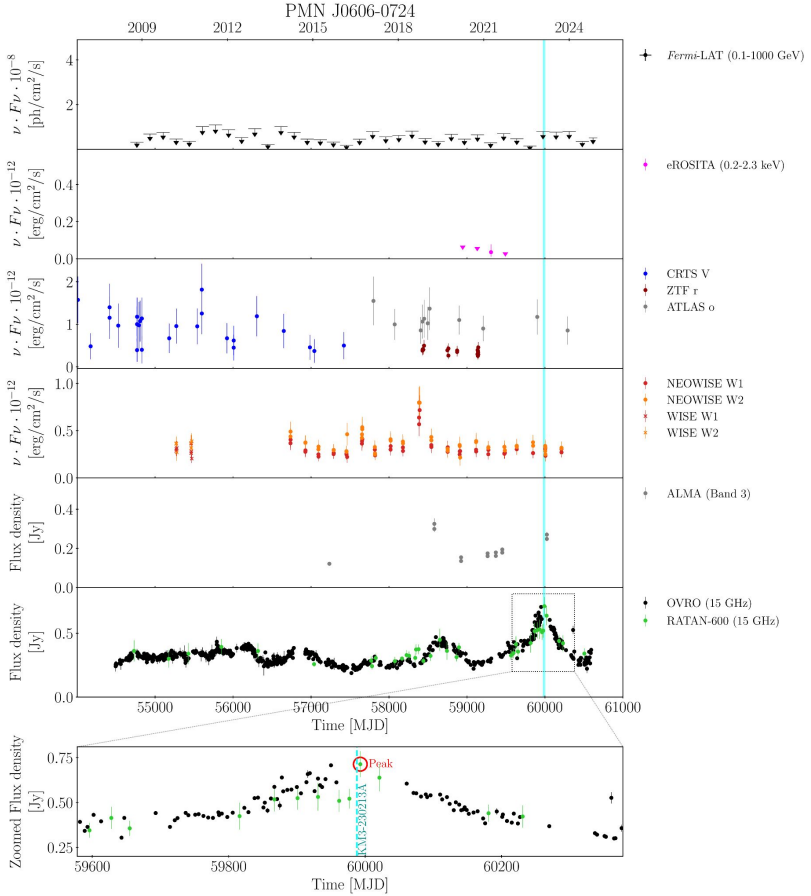


Radio flare in PMN J0606-0724

Neutrino arrival time is ~5 days apart from the largest radio flare in the historical radio data of the object (~15 yr).

Chance probability of 0.26% (pre-trial) to observe an equal or smaller difference by chance.

KM3NeT+ arXiv:2502.08484

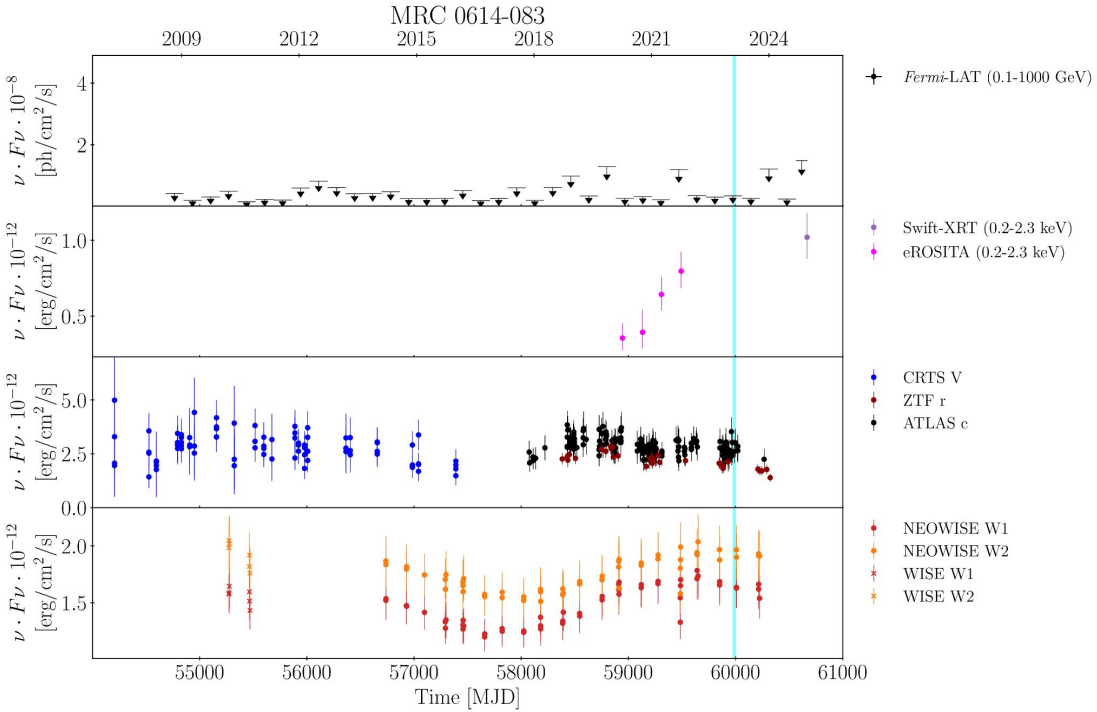


X-ray flare in MRC 0614-083

Closest source to the neutrino best-fit position.

Rising trend in the eROSITA 4-epoch data.

High X-ray state persistent in *Swift*-XRT ToO observation (however, years-long gap in coverage).



KM3NeT+ arXiv:2502.08484

The “flaring blazars” case

Gamma

TXS 05056+056

Coincidence between gamma-ray flare and IC neutrino alert.

Radio

Correlations between radio flares and IceCube, ANTARES neutrinos
Hovatta+ 2021, Plavin+ 2020, 2022

X-ray
X-ray emission is shown to correlate with hadronic processes in blazar SED modelling
Fichet de Clairfontaine+, 2023

Flaring origin for KM3-230213A is possible, but cannot be confirmed or ruled out.

UHE neutrino emission and energetics

Proton energy O(5 EeV) associated to UHE neutrino, below the highest energies observed for CR particles (300 EeV).

AGN jets have been already proposed as sources for the most energetic UHECR (Rieger, 2022)

In general, blazar modelling can easily accommodate neutrinos > 100 PeV (Rodrigues+, 2024)

For an event rate < 1 / 75 yr in ARCA21, the observation of a UHE neutrino does not require a jet power above typ. luminosities of 1e45 erg/s.

Assuming a source at z ~ 1 and beaming factor ~ 1000.

Summary of follow-up activities

Seventeen blazar candidates have been identified within 3-deg region of the KM3-230213A best-fit position.

Multi-collaboration effort (KM3NeT, *Fermi*-LAT, eROSITA, SVOM, OVRO, RATAN-600) and wide campaign based on archival data and new, dedicated, observations.

Studying variability properties to characterise the candidate associated sources.

Three candidates exhibit flaring behaviour in one of the examined bands.

Multiwavelength strategy and **target of opportunity observations** will be a prototype for future KM3NeT alert followups.

Near and mid-future perspectives

- Localisation of KM3-230213A is expected to improve by the end of 2025
  - < 0.5 deg accuracy is realistically achievable

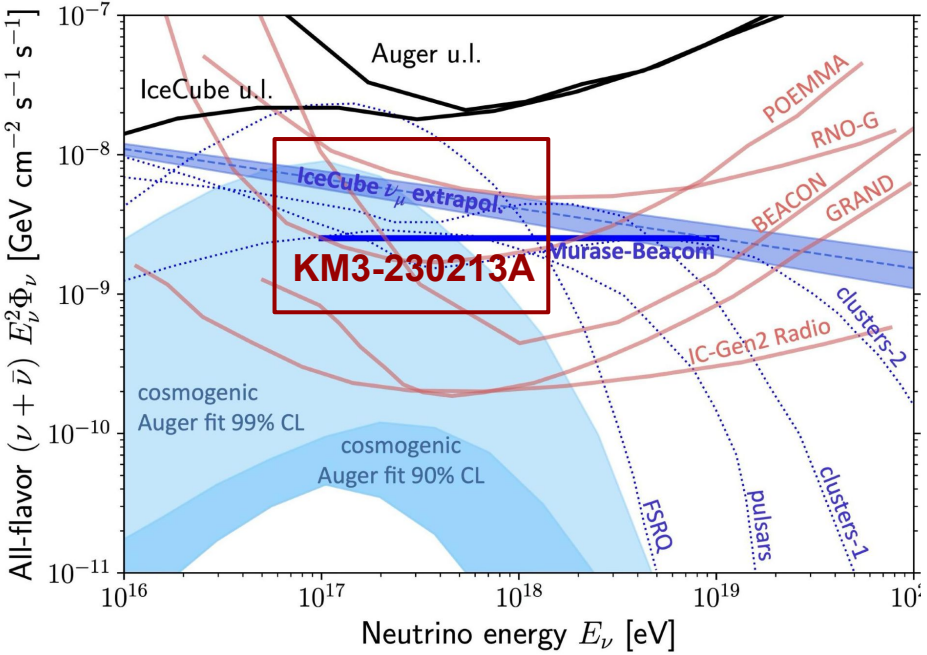
- Several colleagues have expressed interest in the multi-messenger modelling of sources in the field.
  - Stay tuned for follow-up works!

- Number of positionally consistent counterparts may reduce to one or zero
  - Look into a broader class of sources?

Life at the UHE frontier

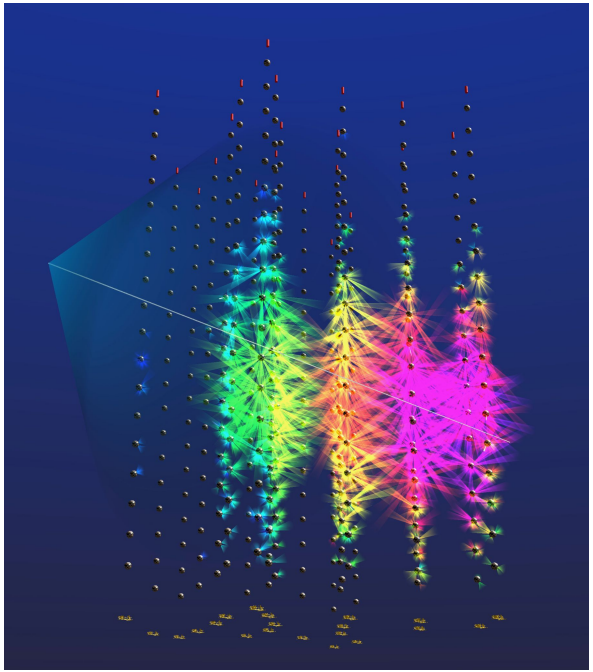
Observation of the KM3NeT event is promising for future detectors aimed at the UHE/EHE frontier.

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



Base plot: K. Kotera

Conclusion and outlook

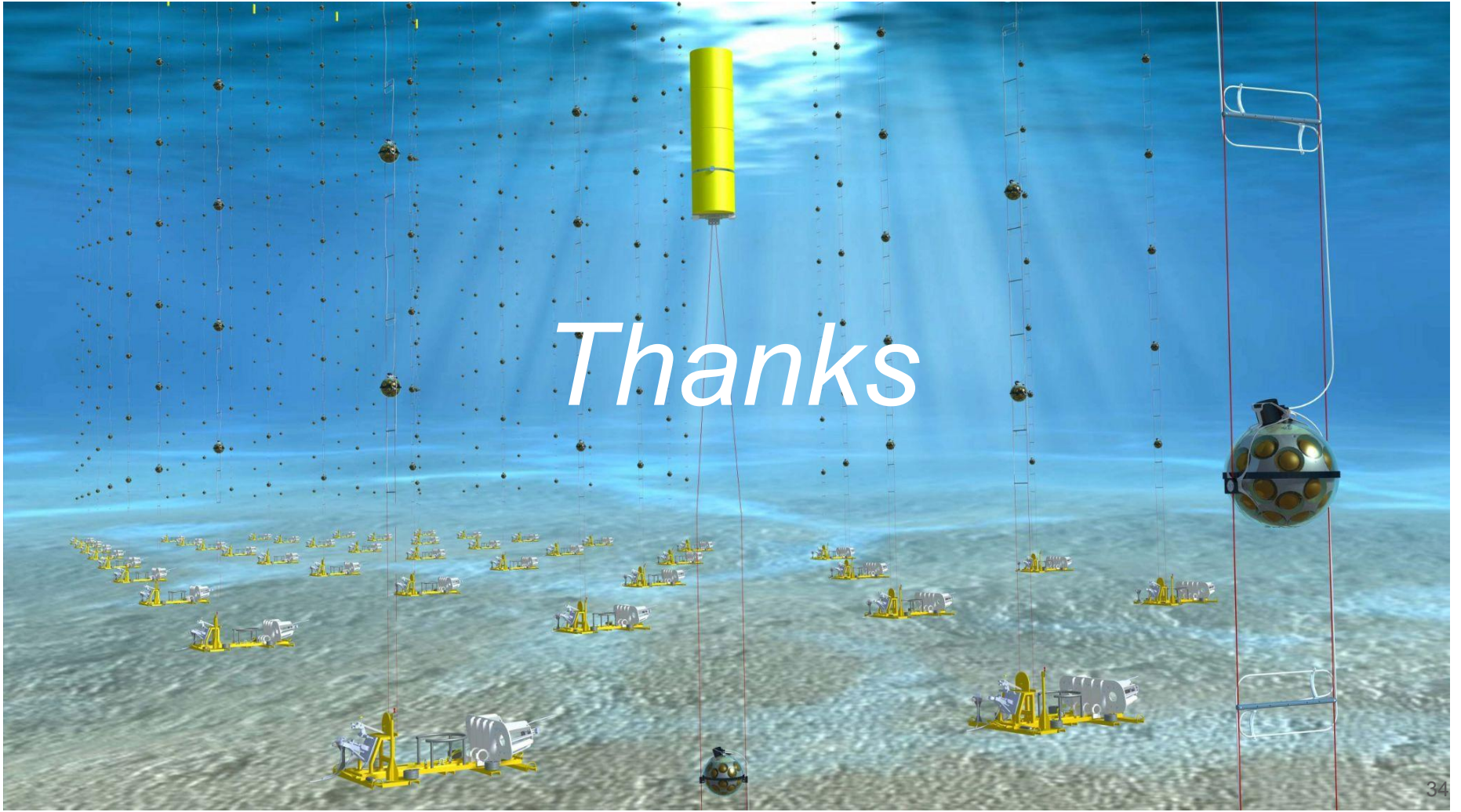


KM3-230213A is the most energetic cosmic neutrino observed to date.

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 lacks enough evidence.

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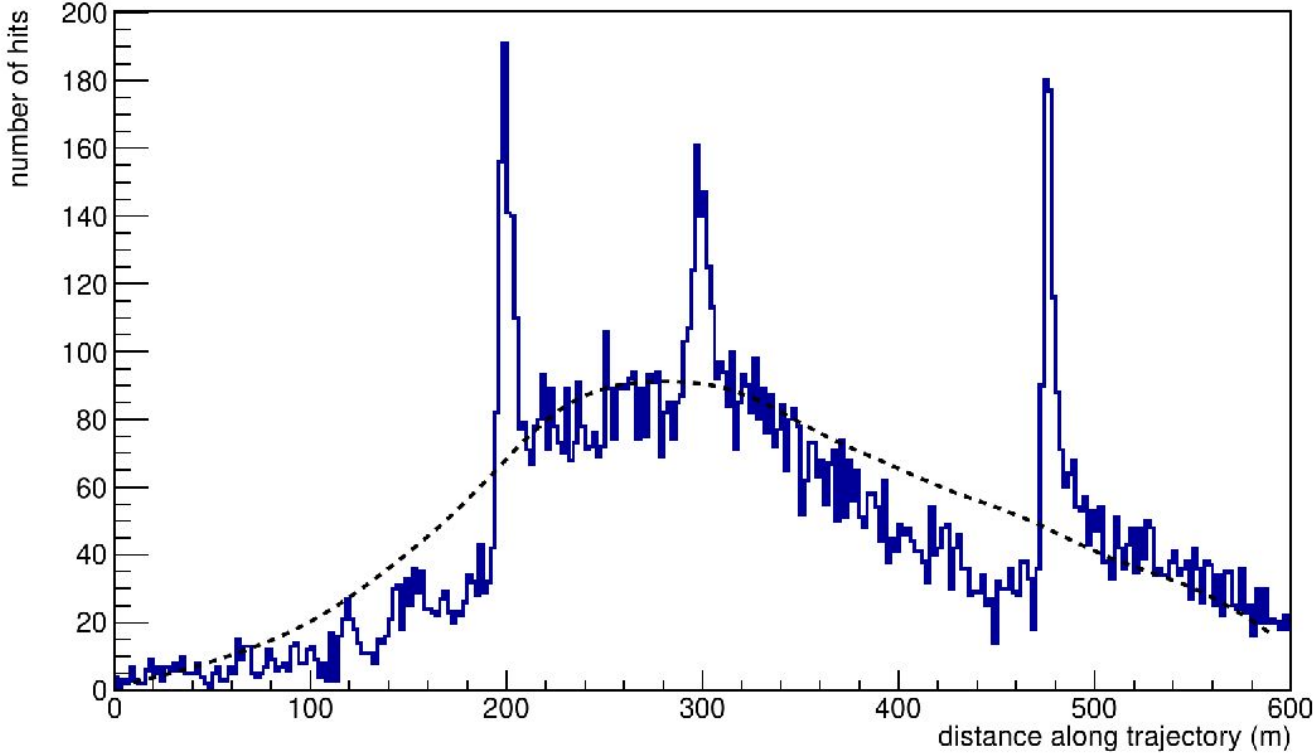
Backup

Light deposition along muon track



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

KM3-230213A containment radii

$R(50\%) = 1.2°$

$R(68\%) = 1.5°$

$R(90\%) = 2.2°$

$R(99\%) = 3.0°$