First observation of an UHE neutrino event with KM3NeT

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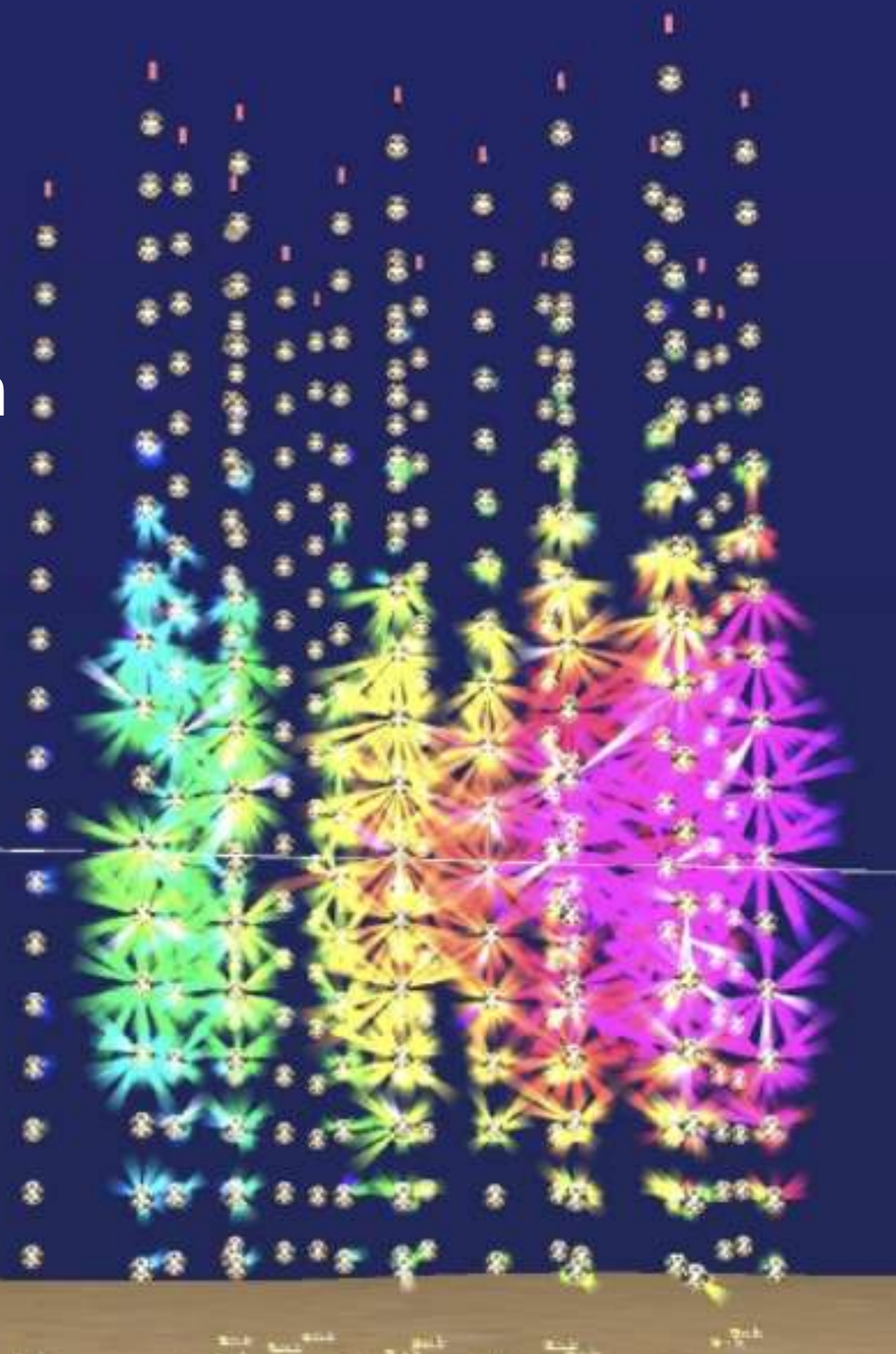
Outline of the talk:

- The KM3NeT infrastructure
- KM3NeT/ARCA observation of KM3-230213A
- Possible origin
- Conclusions



KM3NeT at a glance

Main detector elements:

- Digital Optical Modules (DOMs)
- Detection Units (DUs)
- Seafloor network: Junction Boxes (JBs) and electro-optical cables

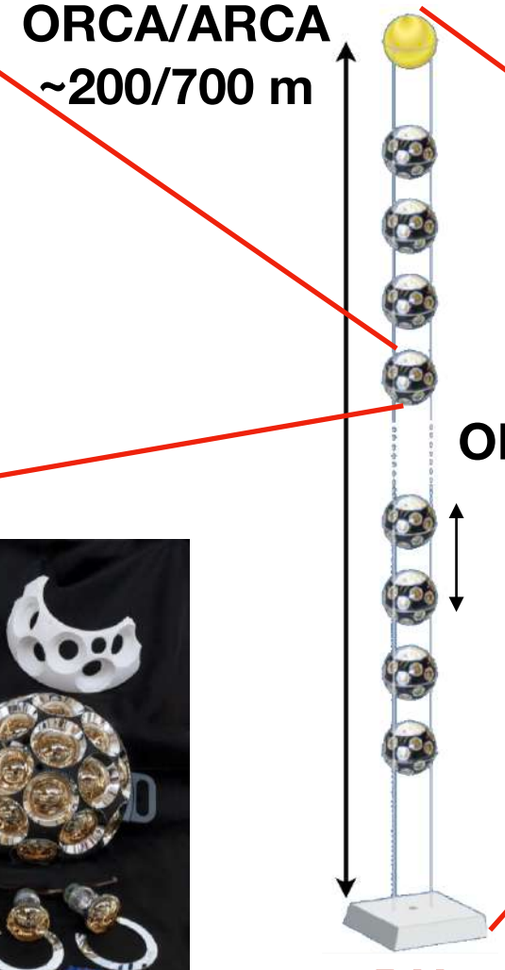
DOM:

17” glass sphere containing:
31x3” PMTs
LED and Piezo
Front end electronics

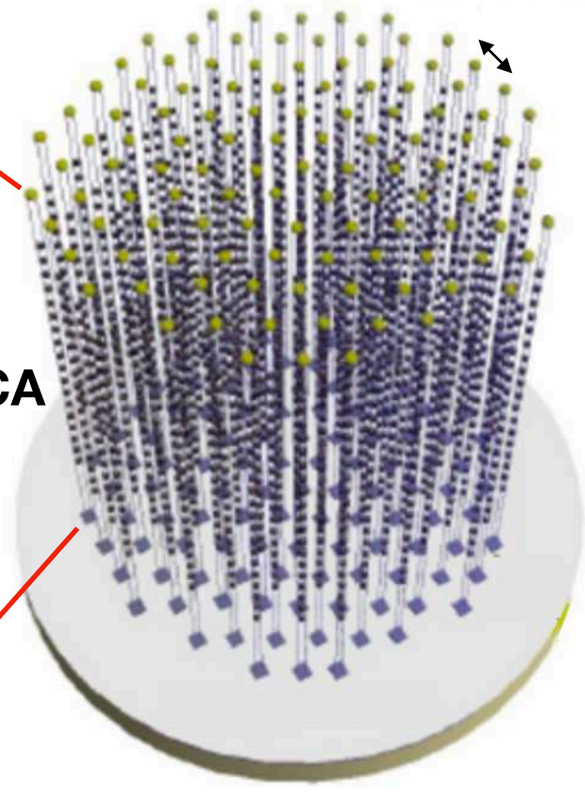
- Uniform coverage
- Directional information
- Digital photon counting
- All data to shore

DOM

Launcher of Optical Modules



DU
18 DOMs+1base module/DU



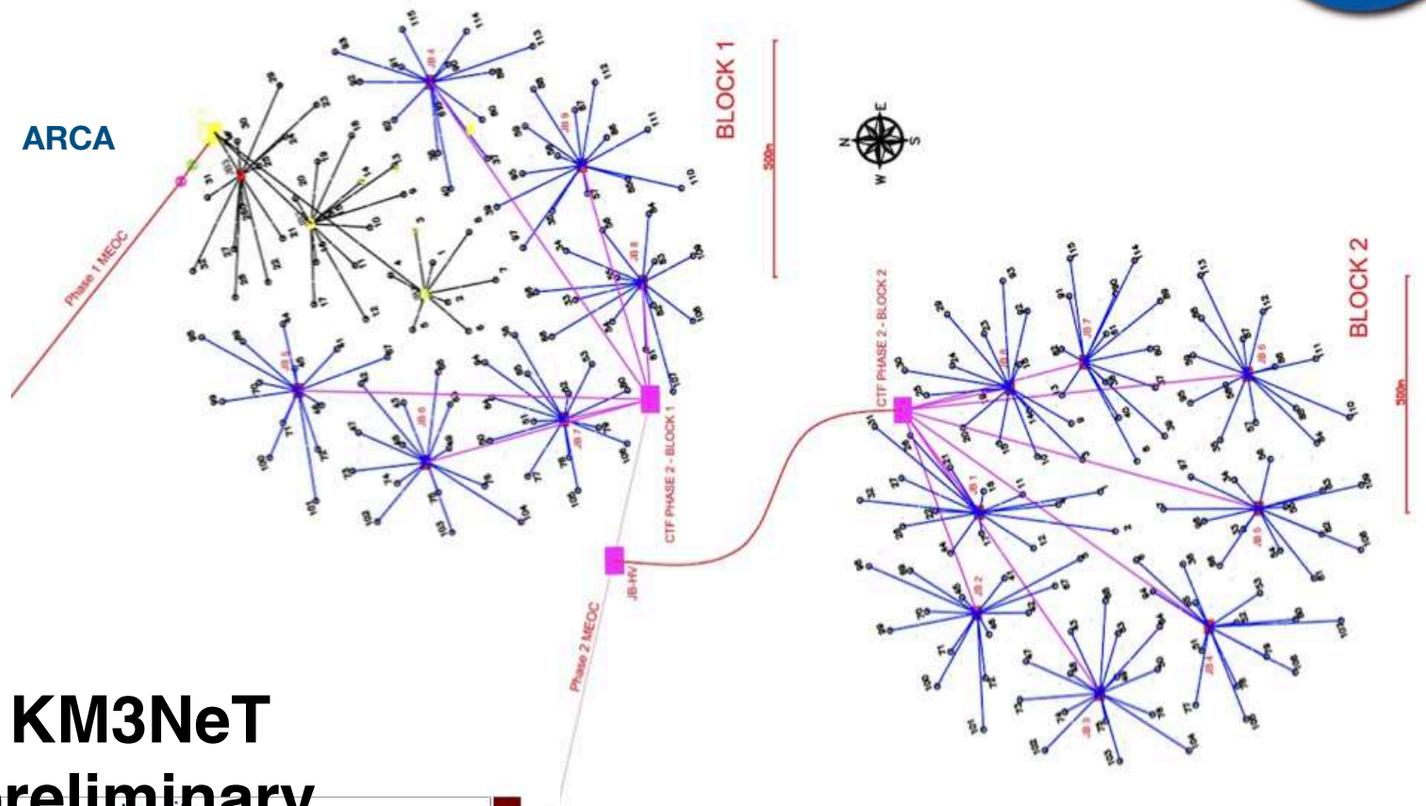
BUILDING BLOCK
115 DUs/building block

KM3NeT: a top view

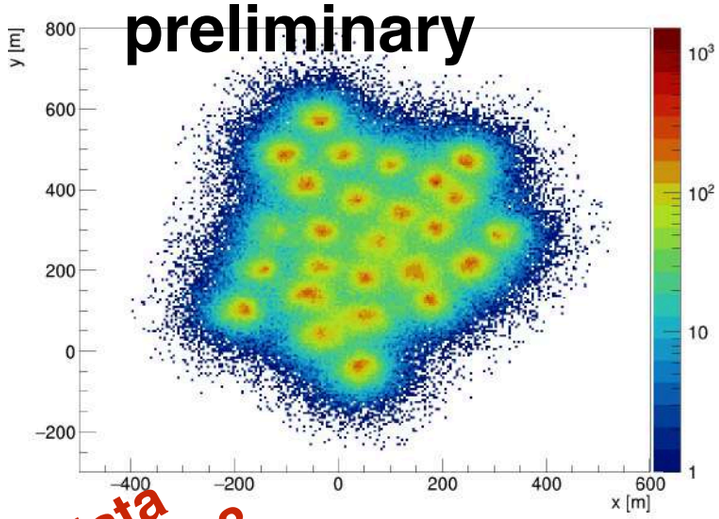
ARCA (1 GTon)

Astroparticle Research
with Cosmics in the Abyss

3500 m depth,
offshore Sicily



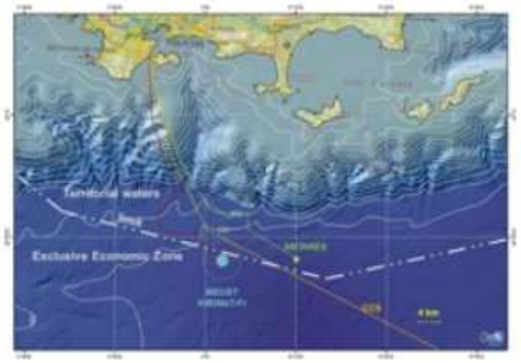
KM3NeT
preliminary



real data from ARCA28

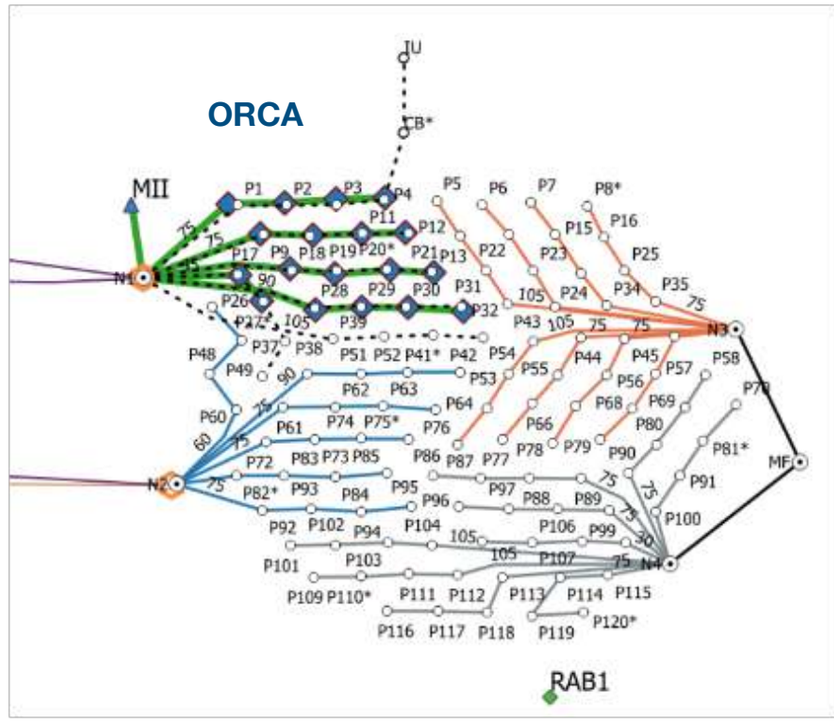
ORCA (6 MTon)

Oscillation Research
with Cosmics in the Abyss



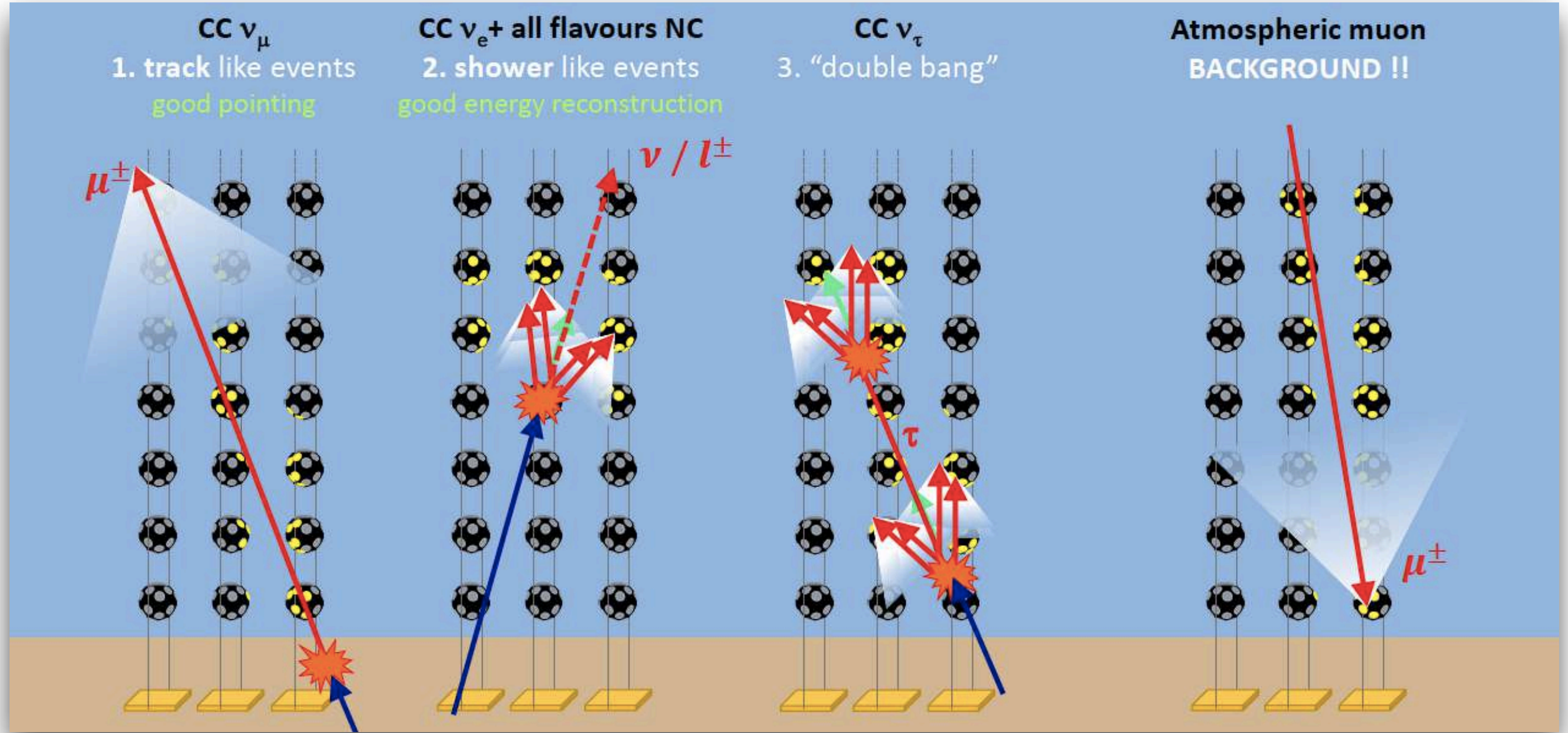
2500 m depth,
offshore Toulon

KM3NeT Coll., JPGNPP 43 (2016)



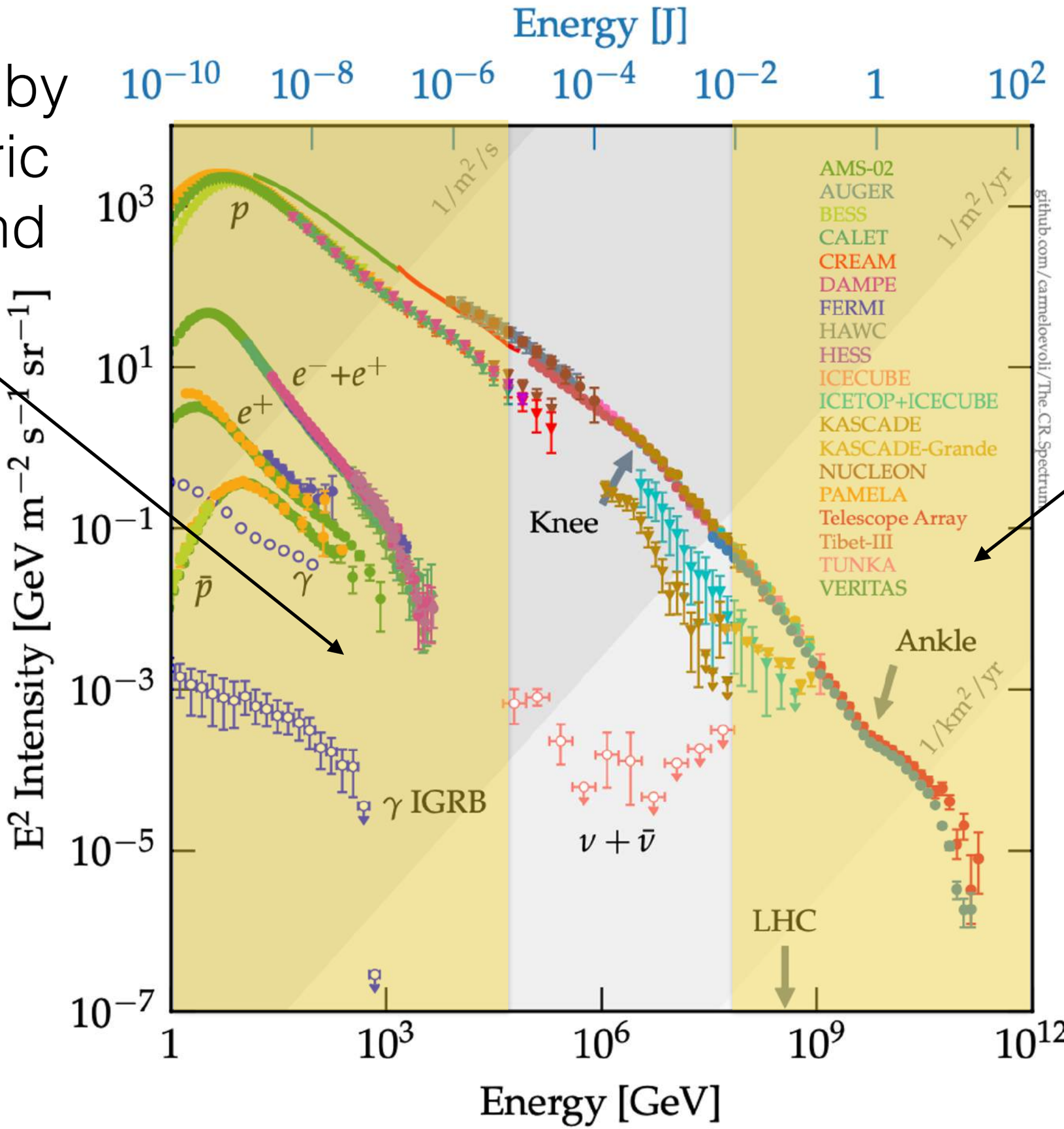
Neutrino detection principle & event topologies

- Track like events ⟶ golden astronomical channel
- Shower like events ⟶ calorimetric ⟶ diffuse analyses



The neutrino landscape before Feb 2023

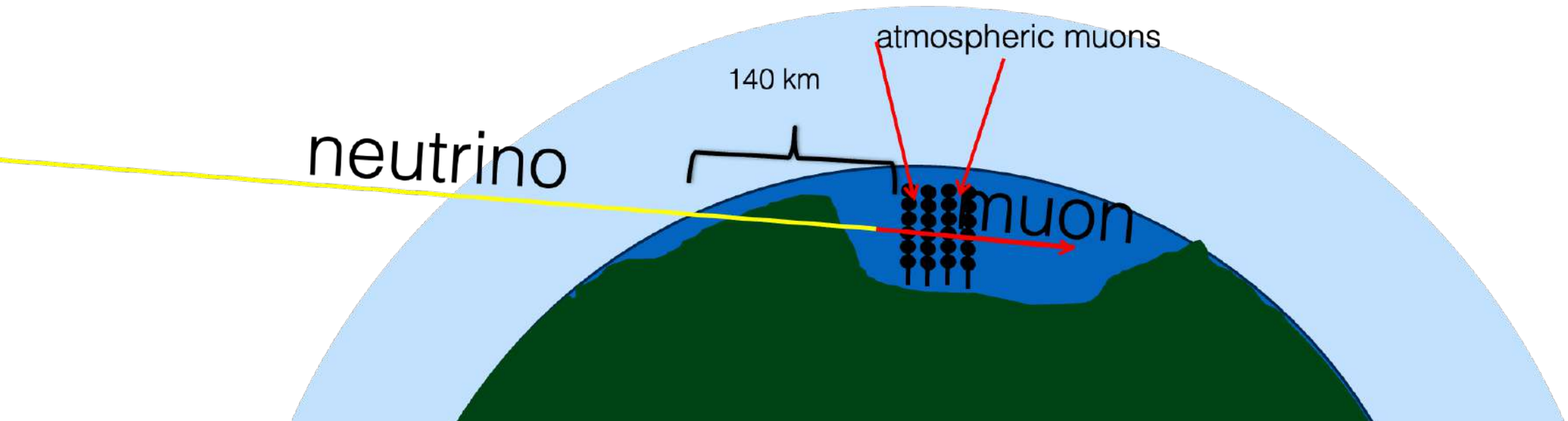
dominated by atmospheric background



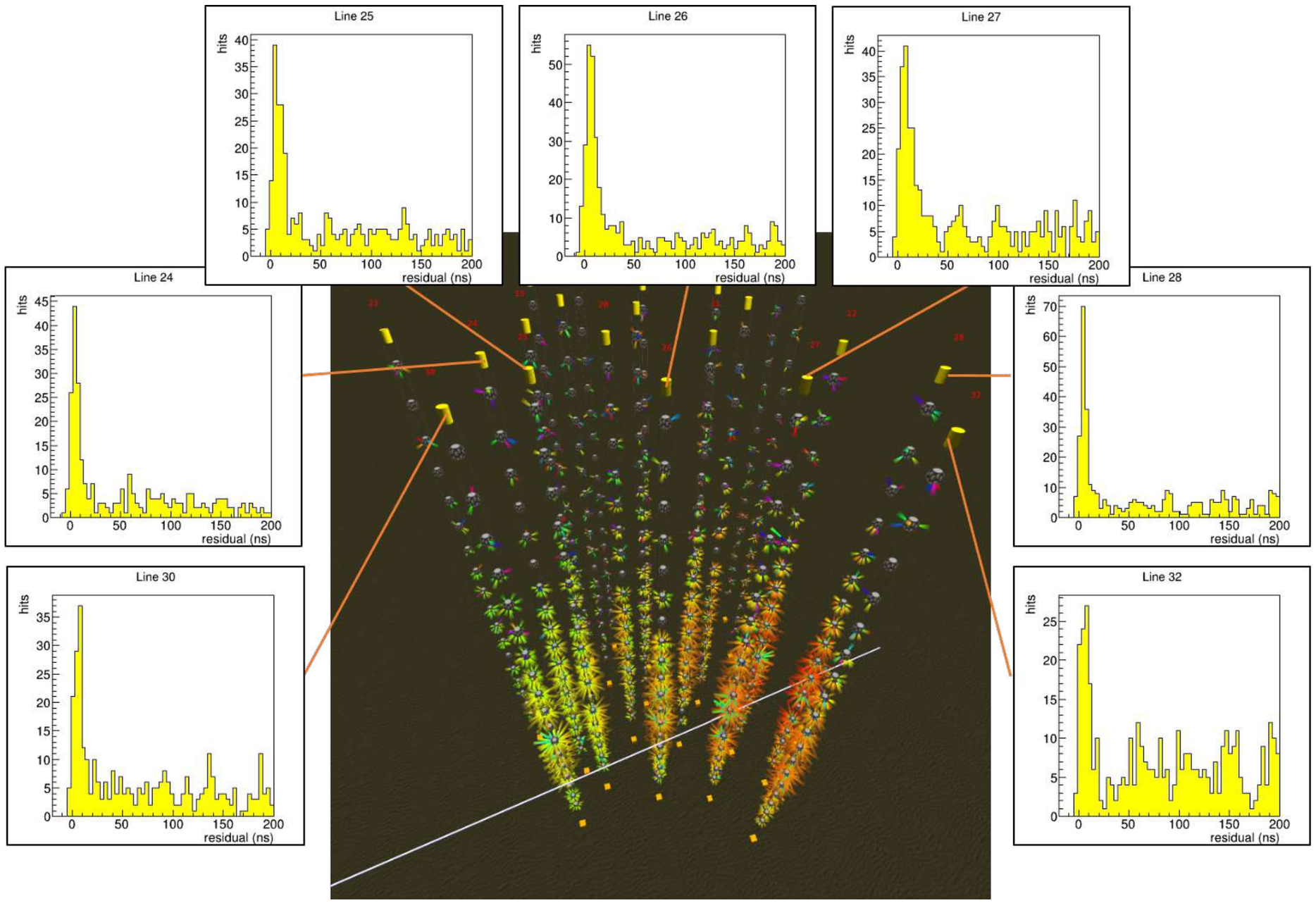
"terra incognita" (F. Halzen)

KM3-230213A: features

- Trigger time: Feb 13th 2023, 01:16:47 UTC
- **ARCA21** configuration (21 DUs, ~0.2 km^3), **335 days** of livetime
- Bright track selection (length > 250 m, $N^{trigPMT}$ > 1500, logL > 500)
- KM3-230213A: **nearly horizontal** event (0.6° above horizon), **RA=94.3°, DEC=-7.8°** (l=216.1°, b=-11.1°)
- Containment radii: **R(68%)=1.5°**, R(90%)=2.2°, R(99%)=3.0°

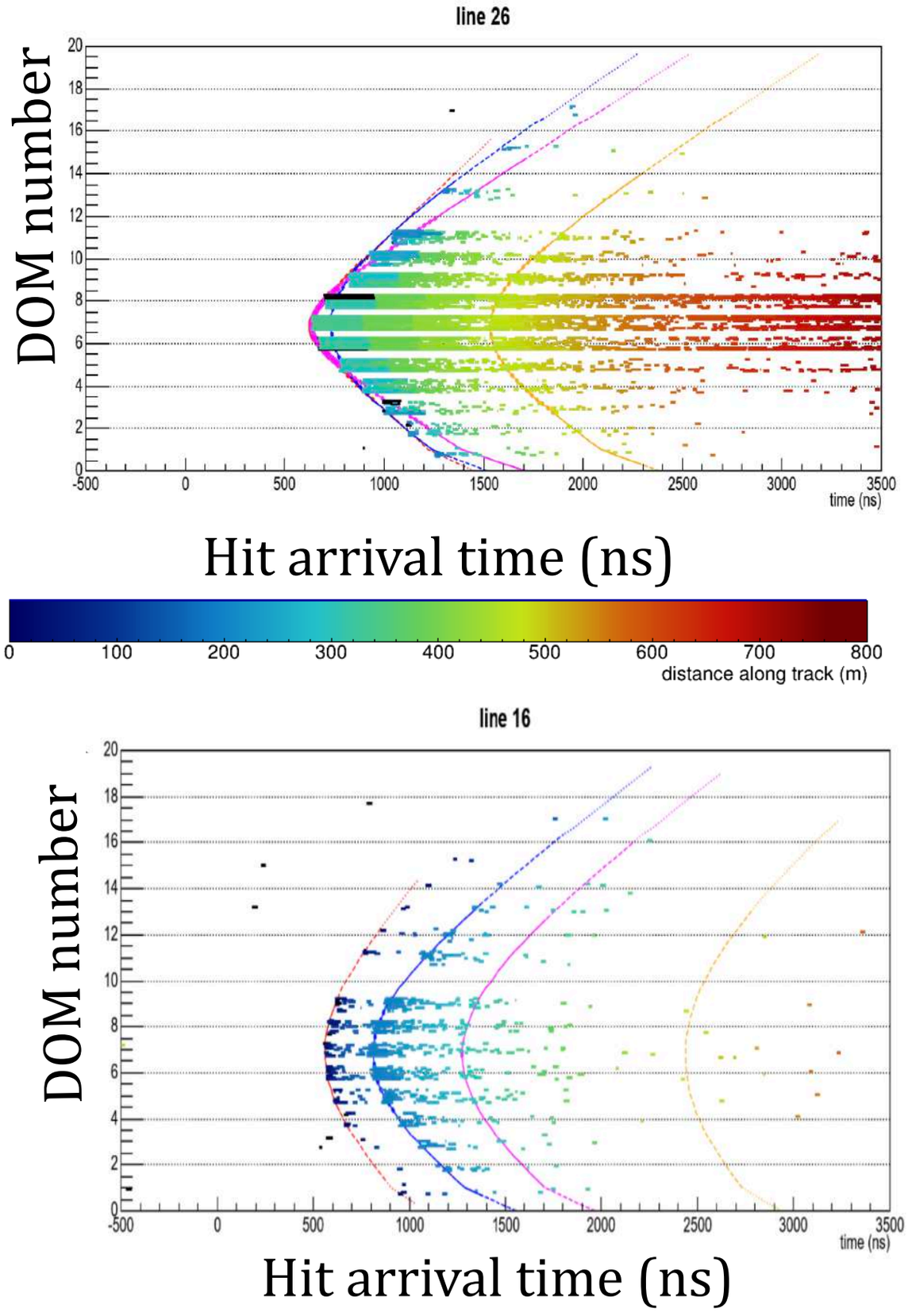


A very well reconstructed muon track

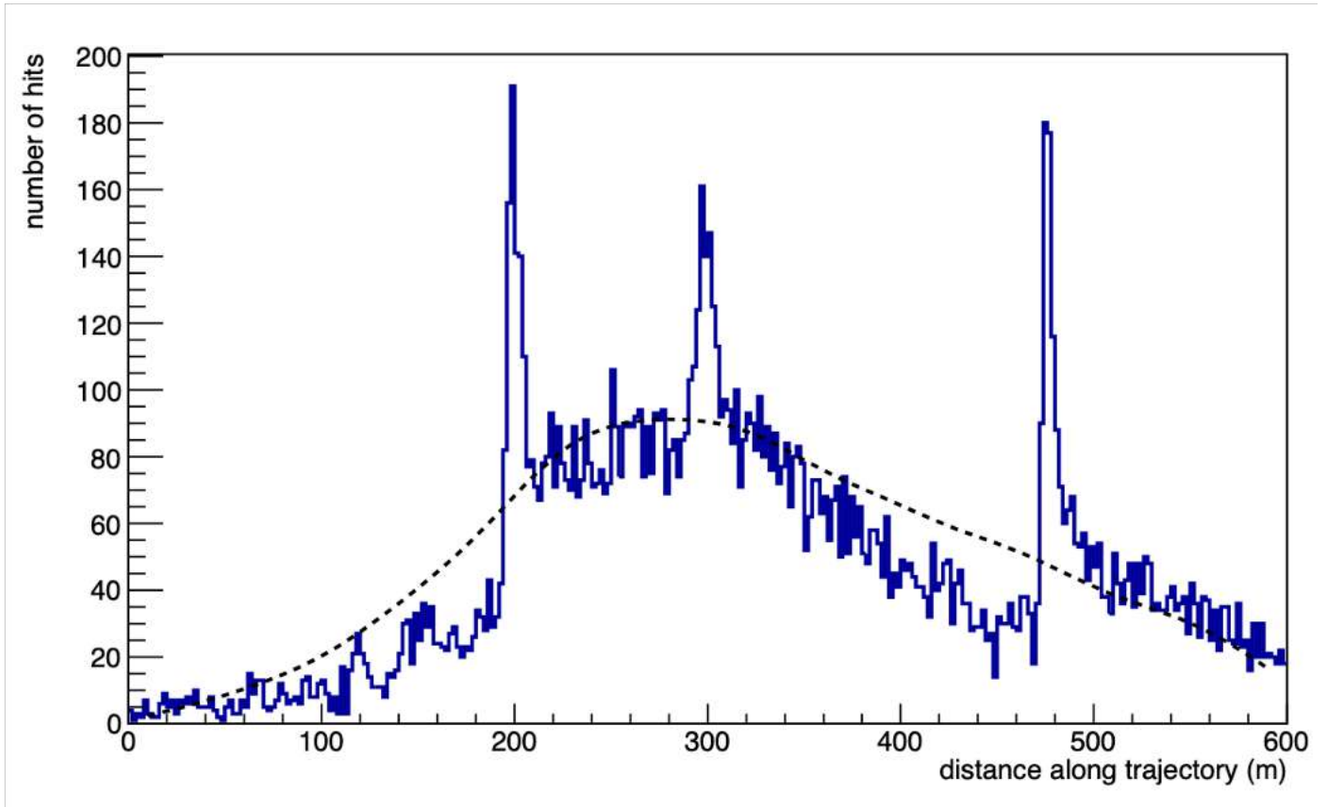


Time residual distributions on different DUs

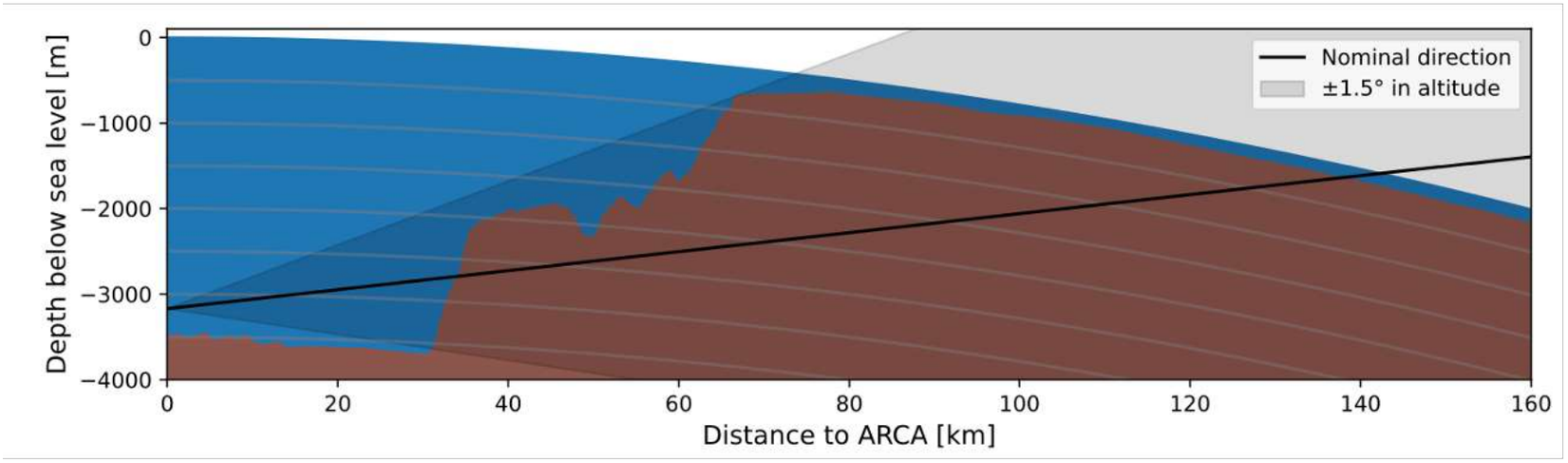
KM3-230213A: direction

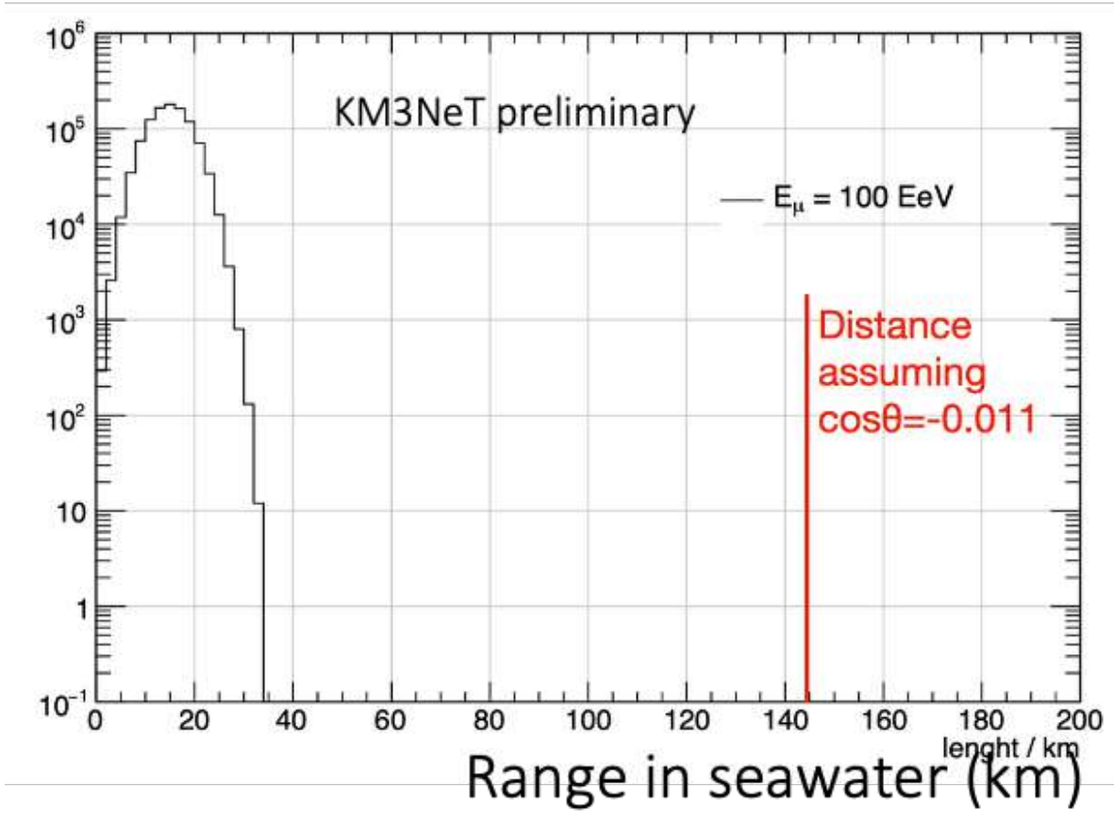


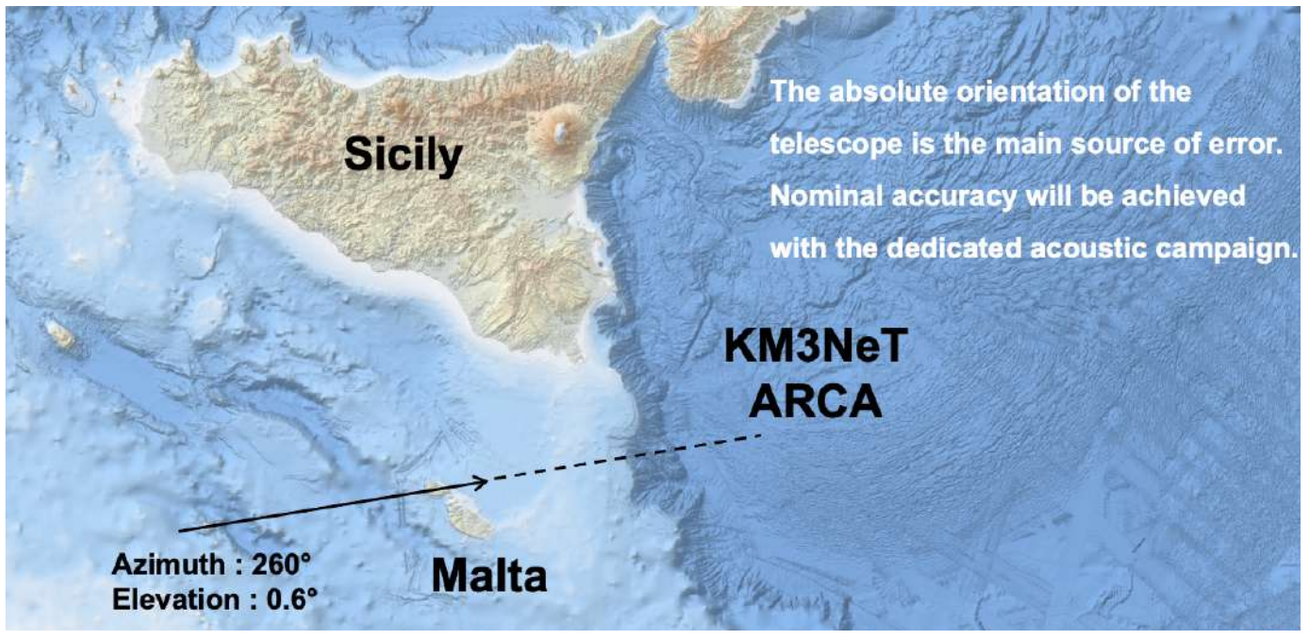
- Hit times fully consistent with **Cherenkov photons**
- From reconstruction algorithms, a muon track and three showers detected, as expected in muon stochastic energy losses
- The collinearity of showers supports the **single muon** hypothesis



Not an atmospheric muon



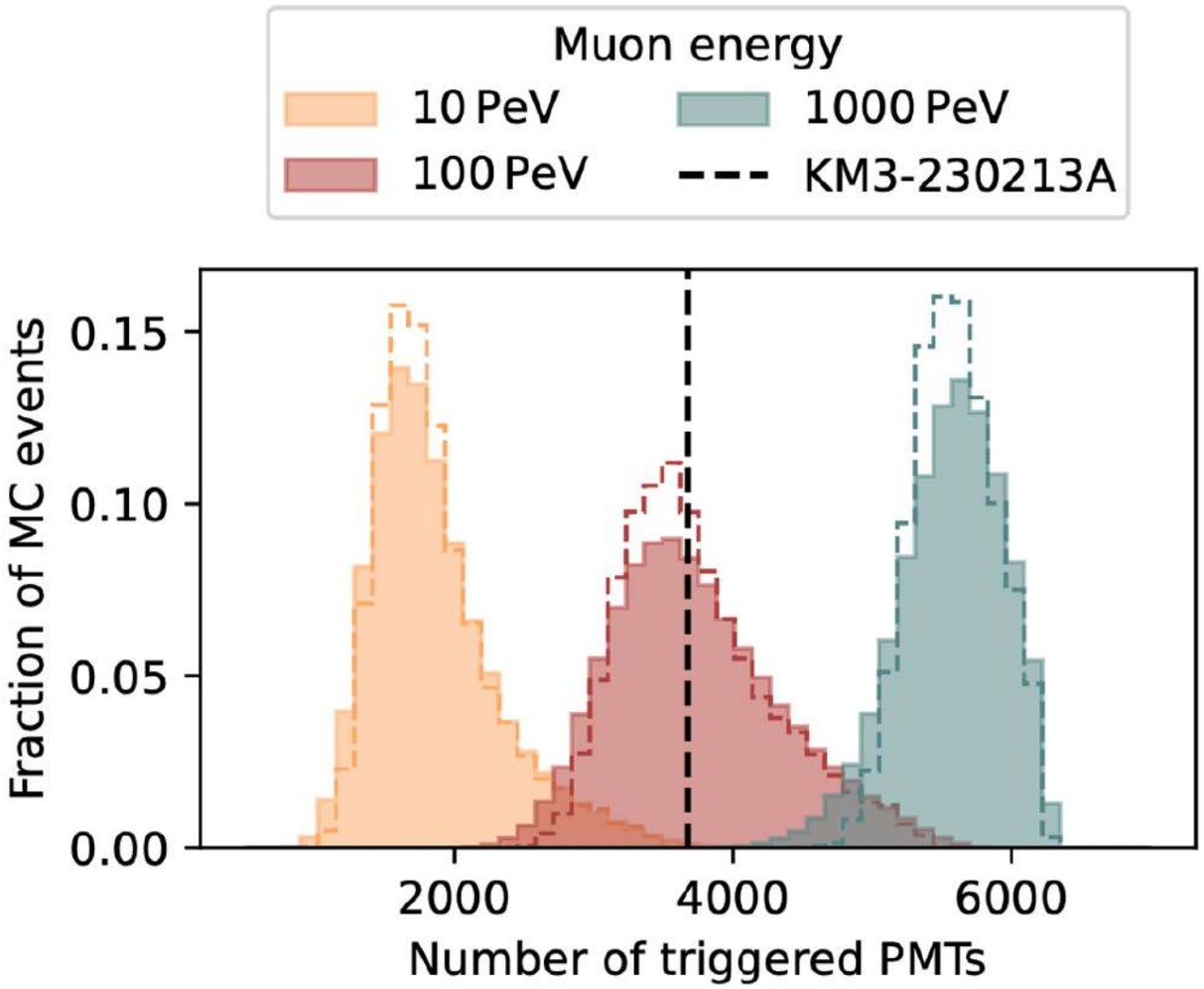




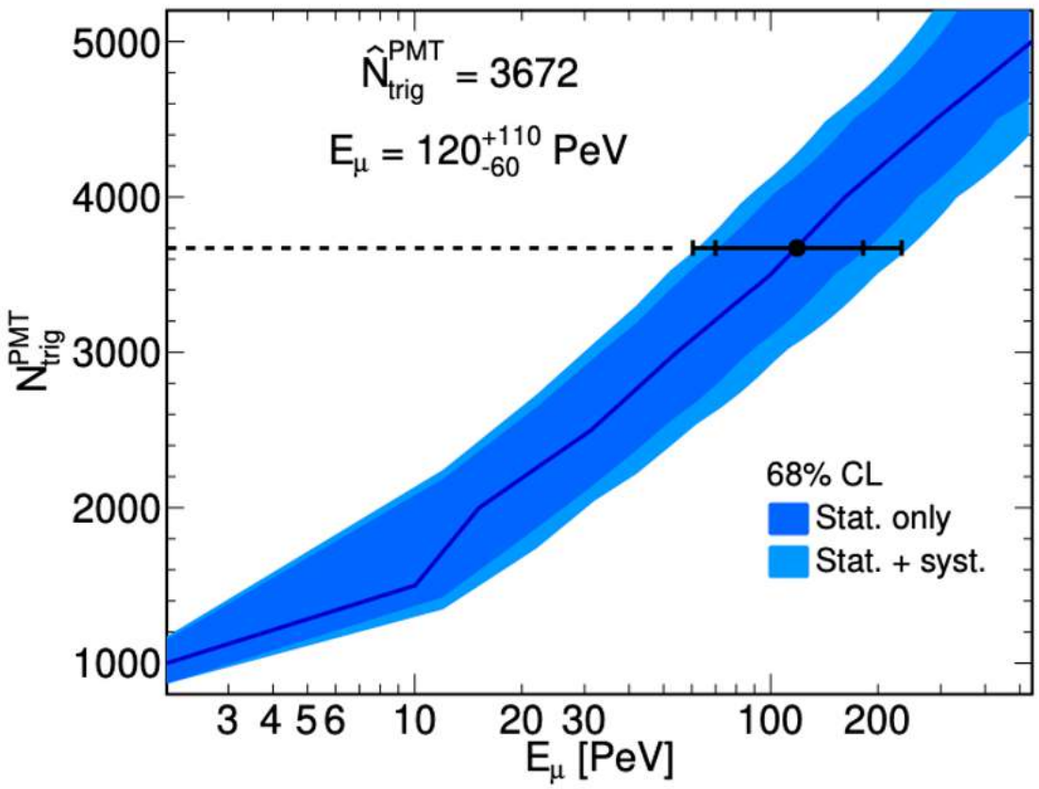
Passes through continental shelf/Malta

Actual amount of crossed matter is even larger…

KM3-230213A: energy



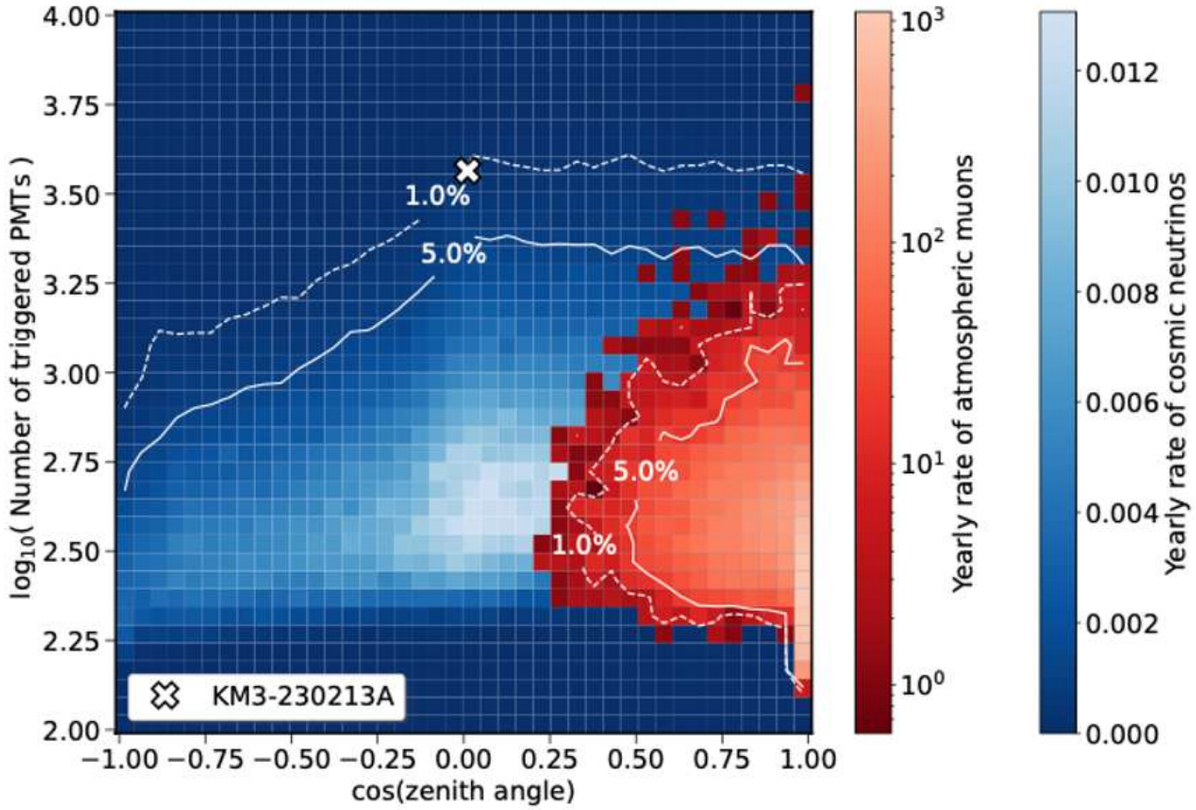
KM3NeT Coll., Nature 638 (2025) 8050

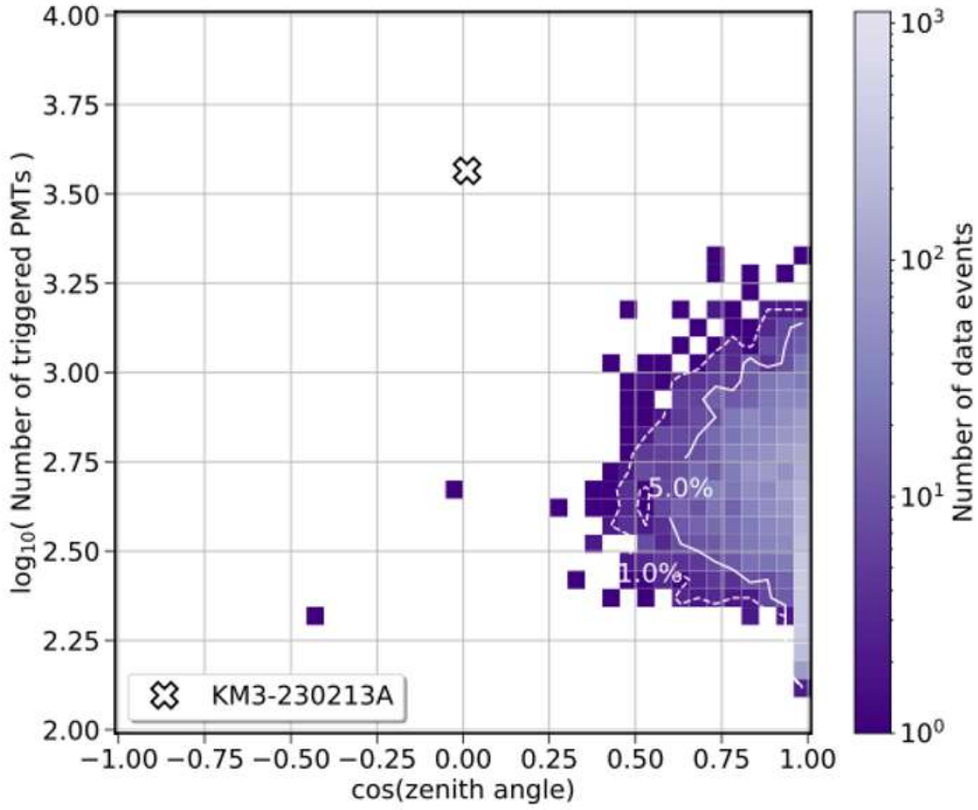


~35% of the detector was recording light

- Energy is measured from the amount of light: $E_\mu = 120^{+110}_{-60}$ PeV
- The parent neutrino energy is estimated to be (E^{-2} source flux): $E_\nu = 220^{+570}_{-100}$ PeV

KM3-230213A

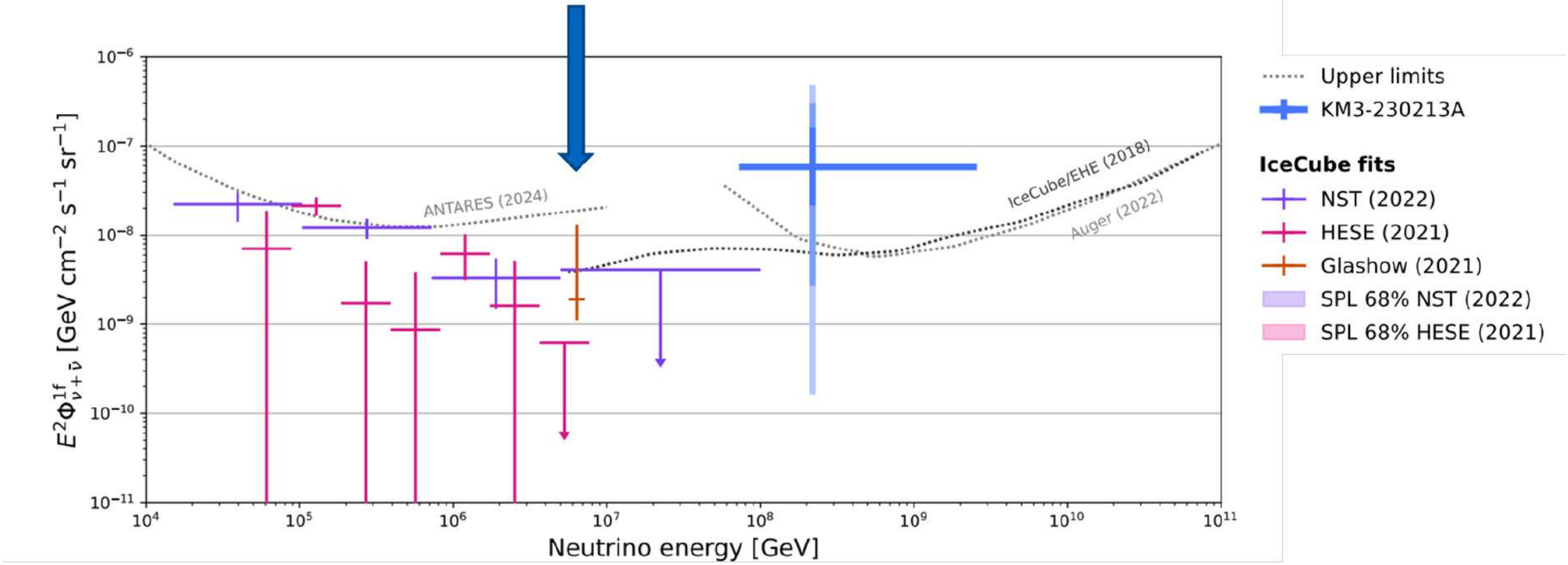




- Assuming reconstructed energy and direction
  - Expected atmospheric muon contamination @ 100 (10) PeV:
    $<< 10^{-10}$ (10^{-9}) event/year within 2σ of reconstructed direction
    $<< 10^{-4}$ event/year within 5σ of reconstructed direction
  - Expected rate of atmospheric neutrinos >100 PeV:
    $<< (1\text{-}5) \times 10^{-5}$ event/year

The most energetic neutrino ever probed

Previous highest energy neutrino



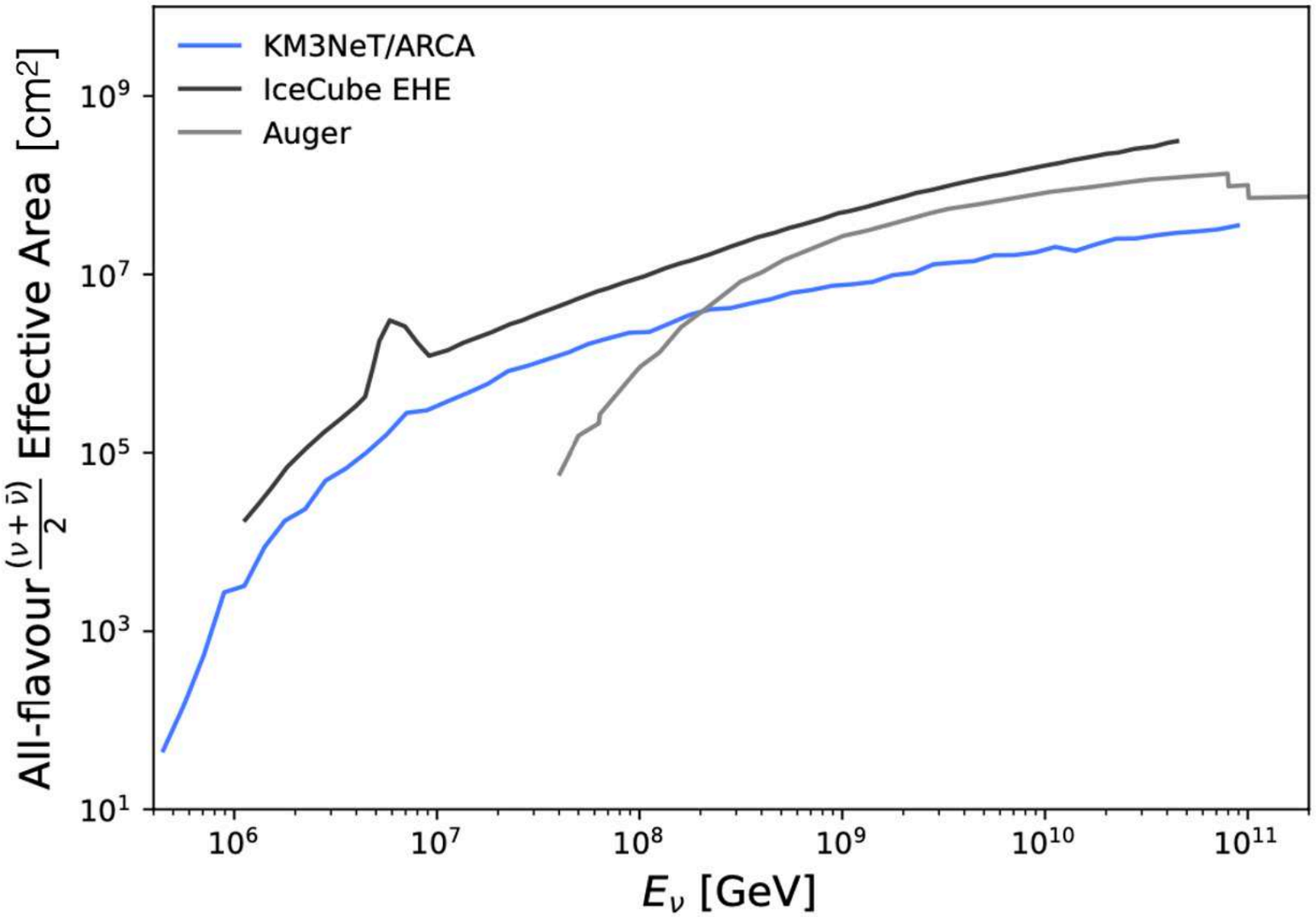
KM3-230213A

$$E^2\phi_\nu = 5.8 \times 10^{-8}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

KM3NeT Coll., Nature 638 (2025) 8050

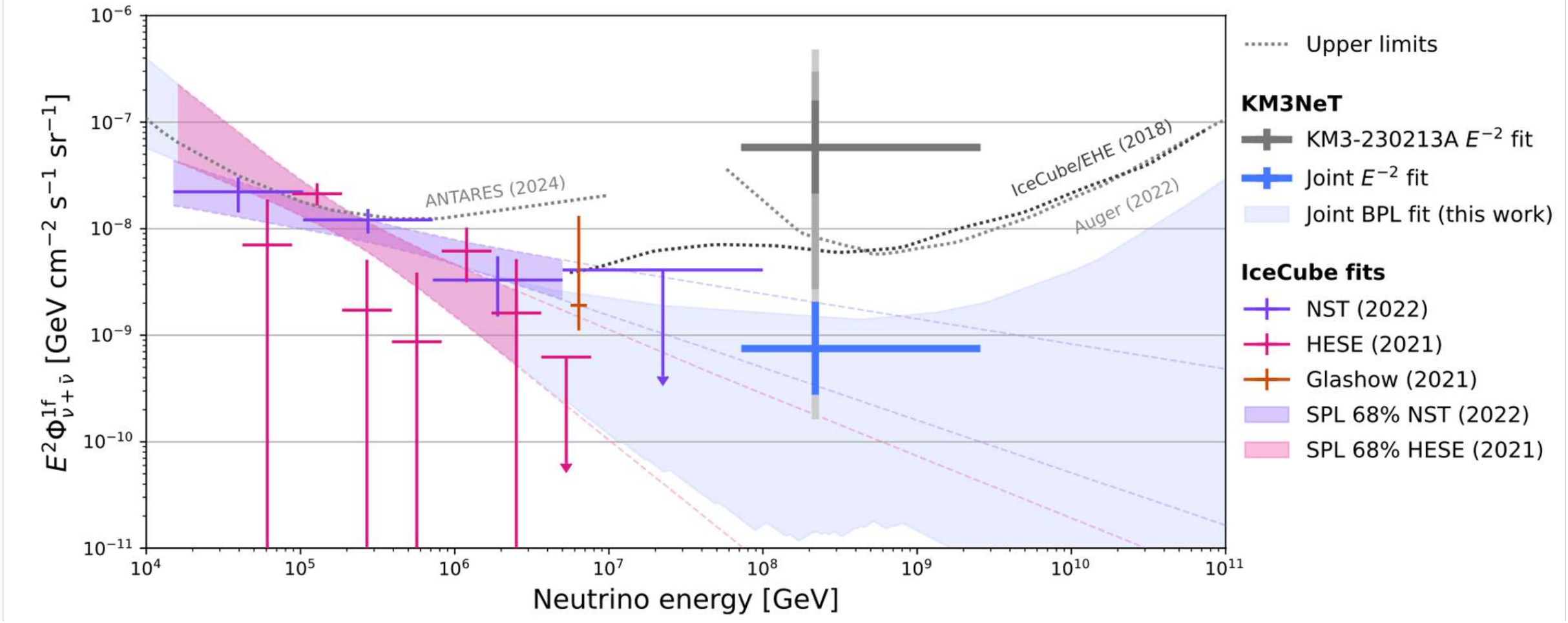
A global fit to existing data

- Non-observations by IceCube & Auger place stringent constraints on the neutrino flux associated with KM3-230213A



KM3NeT Coll., arXiv:2502.08173

A global fit to existing data



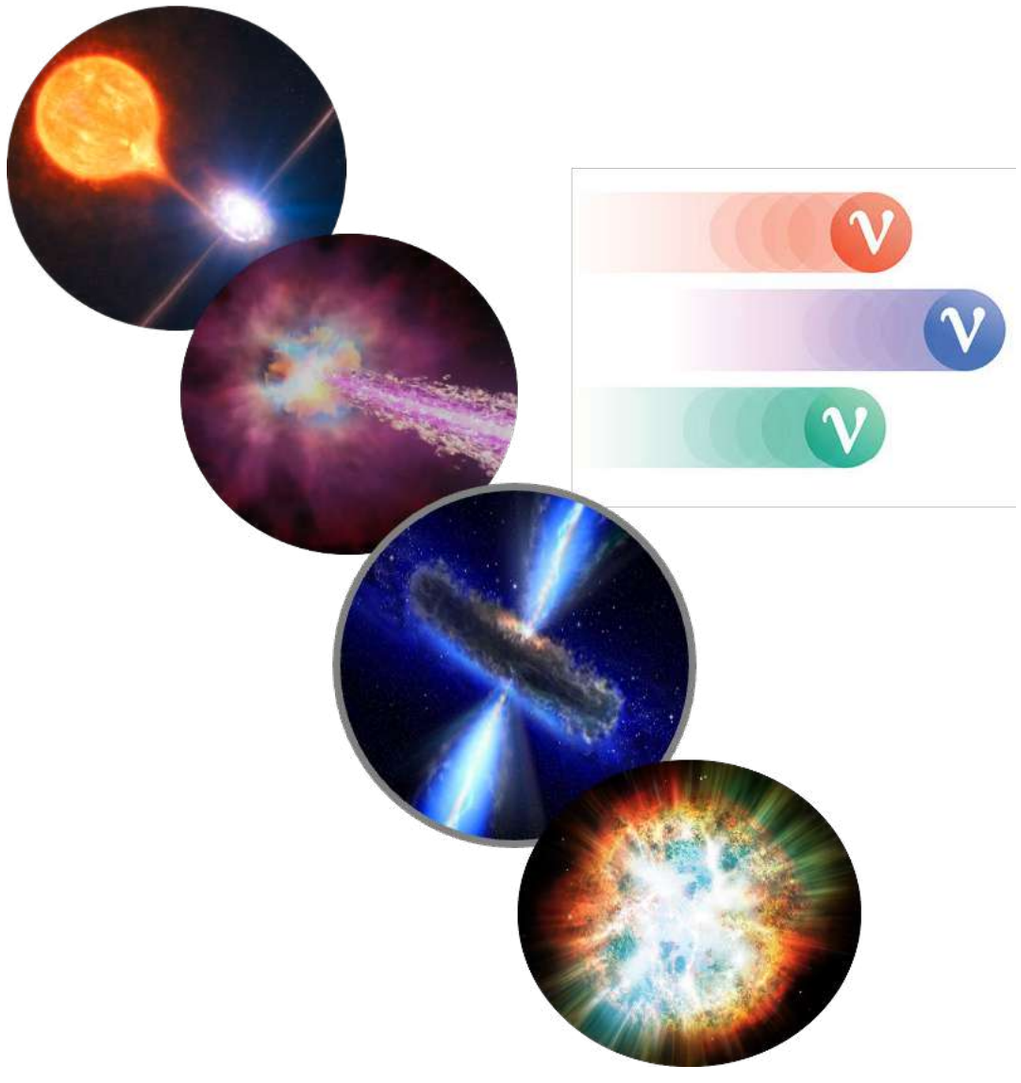
Accounting for IceCube & Auger non-observations we could estimate

$$E^2\phi_\nu = 5.7 \times 10^{-10}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

KM3NeT Coll., arXiv:2502.08173

Cosmic or cosmogenic?

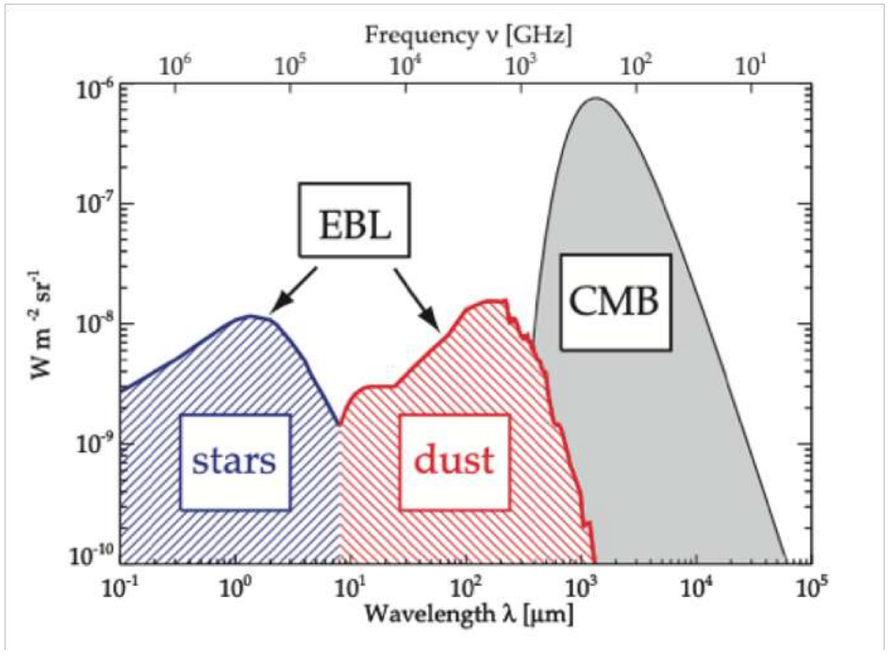
COSMIC = in situ production at an extreme astrophysical accelerator



COSMOGENIC = resulting from UHECR interaction with background radiation fields permeating the Universe

$$p + \gamma \longrightarrow p + \pi^0, n + \pi^+$$

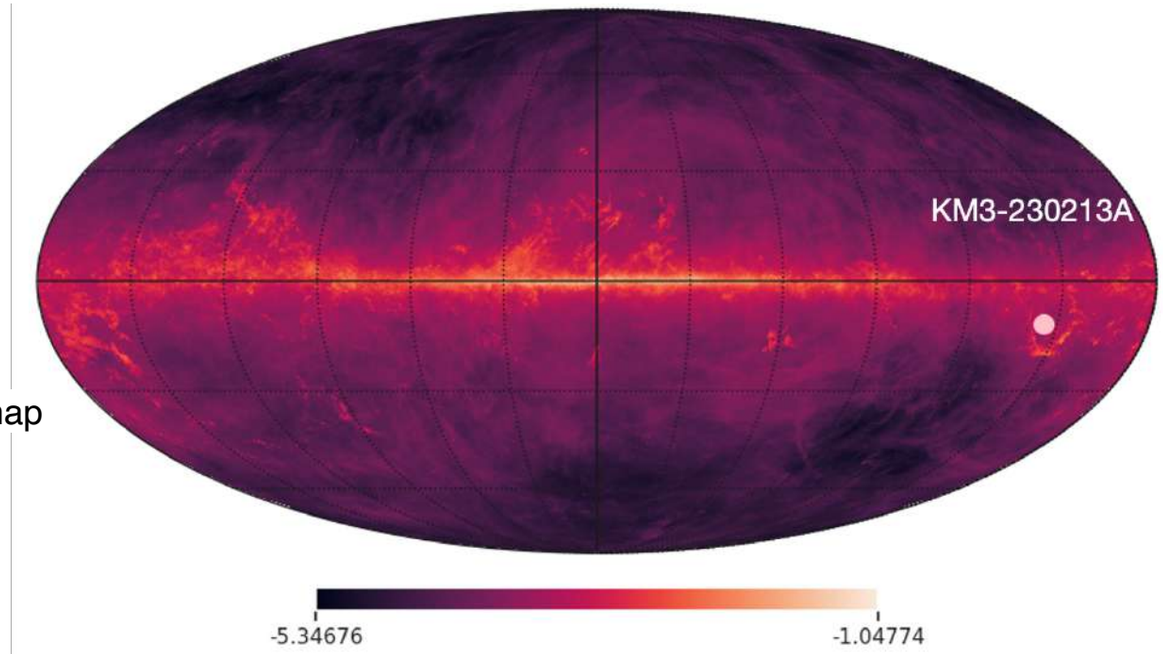
$$(A, Z) + \gamma \longrightarrow (A - 1, Z) + N$$



Testing the cosmic origin

- Out of the Galactic Plane, in the Orion molecular cloud region

Diffuse neutrino sky map from KRA-γ model



- Neutrino counterparts searched for in ANTARES, KM3NeT/ORCA & IceCube datasets

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

Upper limit on potential point-like source flux set to:

$$(E^2\phi_\nu)^{90\%CL} \leq 1.2 \times 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1}}$$

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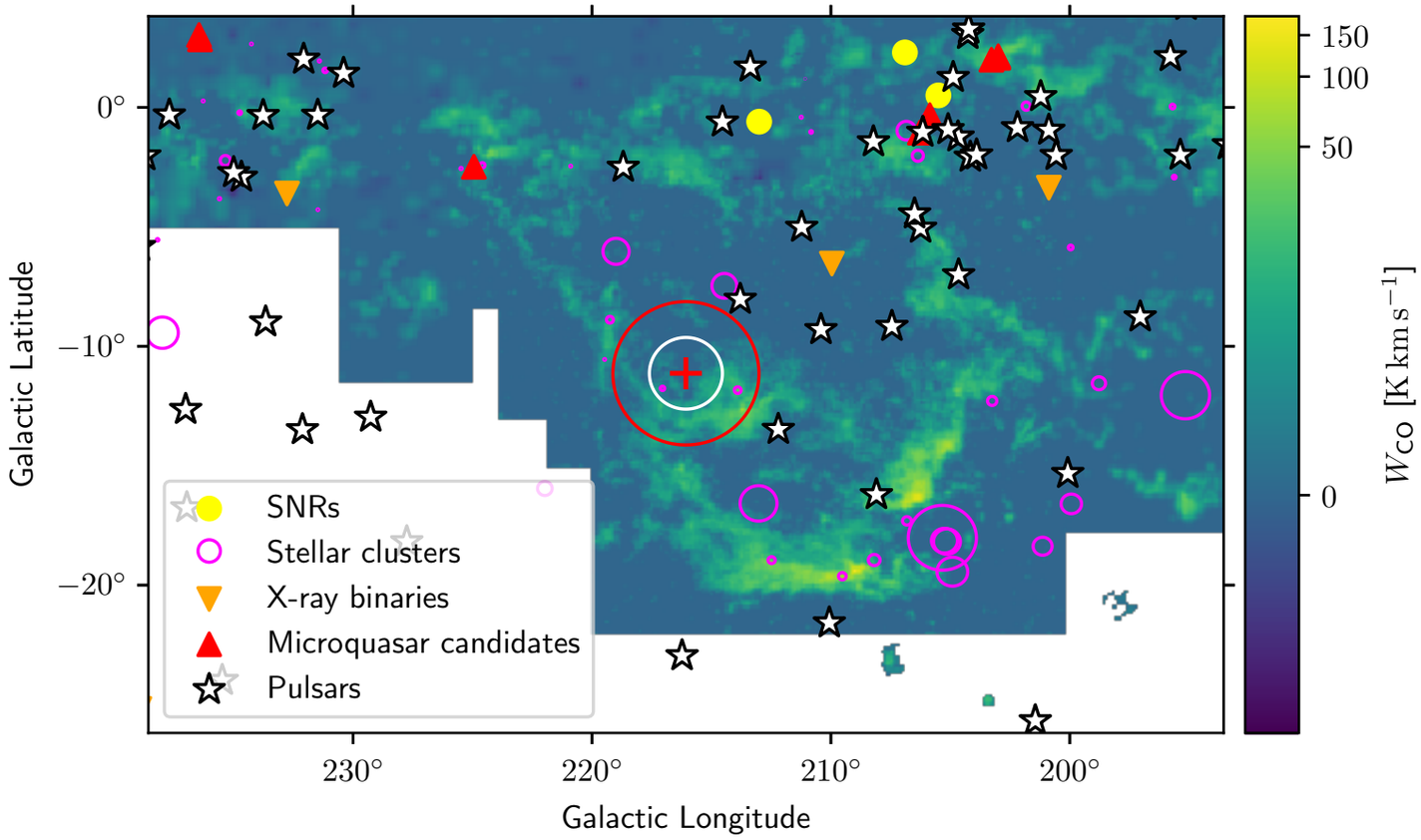
Hardly of Galactic nature

Potential nearby accelerators searched among:

- SNRs (GreenCat)
- Young star clusters (Gaia DR2)
- X-ray binaries and microquasars (eRosita)
- Pulsars and PWNe (ATNF)
- Gamma-ray catalogs (4FGL, 3HWC, 1LHAASO)



KM3NeT Coll., arXiv:2502.08387

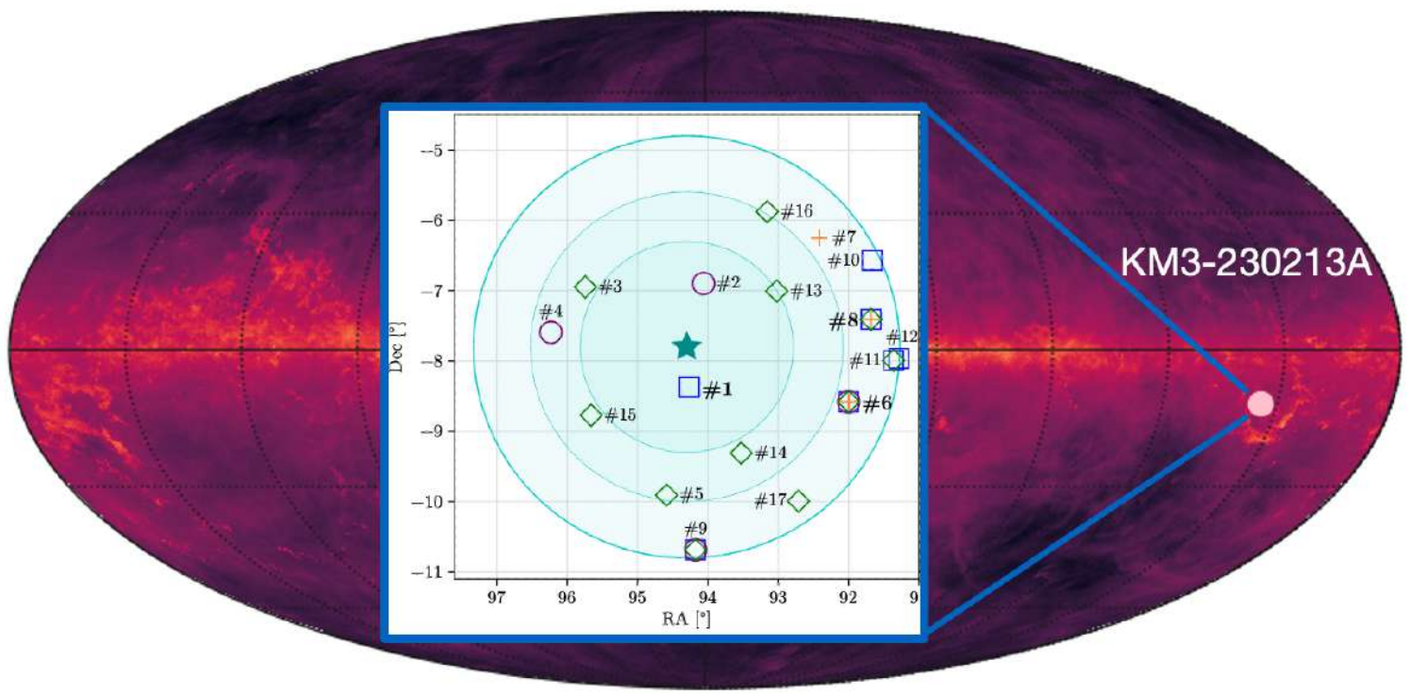
No plausible counterparts found

Testing the extra-galactic origin

Electromagnetic counterparts searched in a 3° cone around the event direction

- Fermi 4FGL sources
- TeVCat and 3HWC data
- Optical transients (ZTF)
- GCN, TNS and AT transients
- Blazars (radio VLBI/ALMA, infrared WISE/, optical ATLAS/CRTS/ZTF/ Gaia, X rays SWIFT/Chandra/ROSAT/SVOM, gamma rays Fermi)

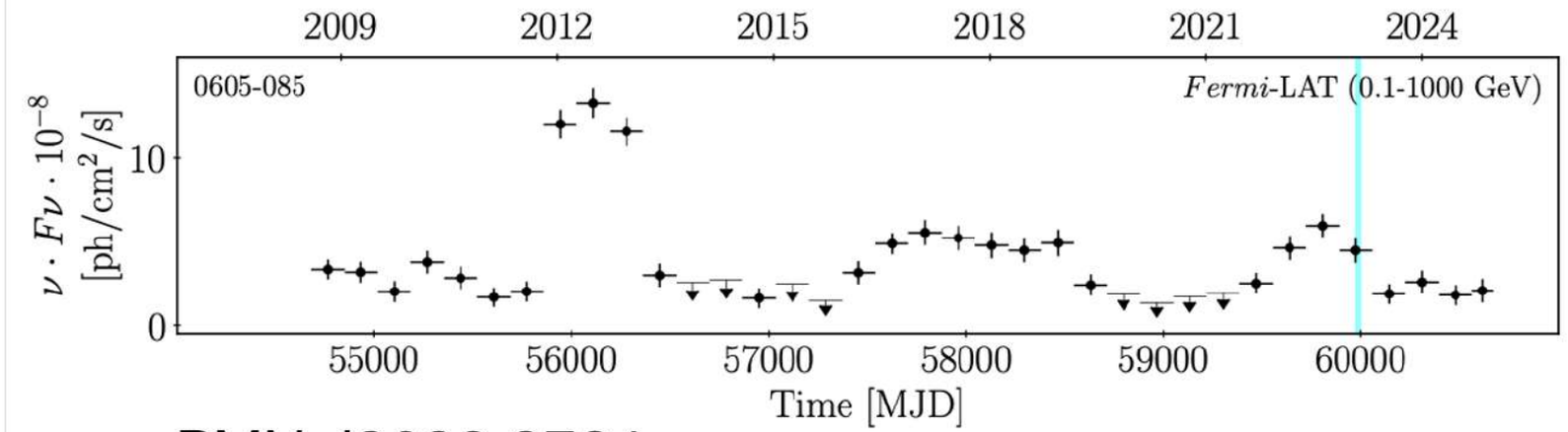
17 (2) blazars found in the 3σ (1σ) uncertainty region of 3° (1.5°) radius

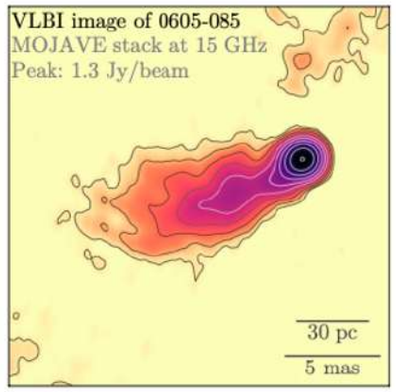


KM3NeT Coll., arXiv:2502.08484

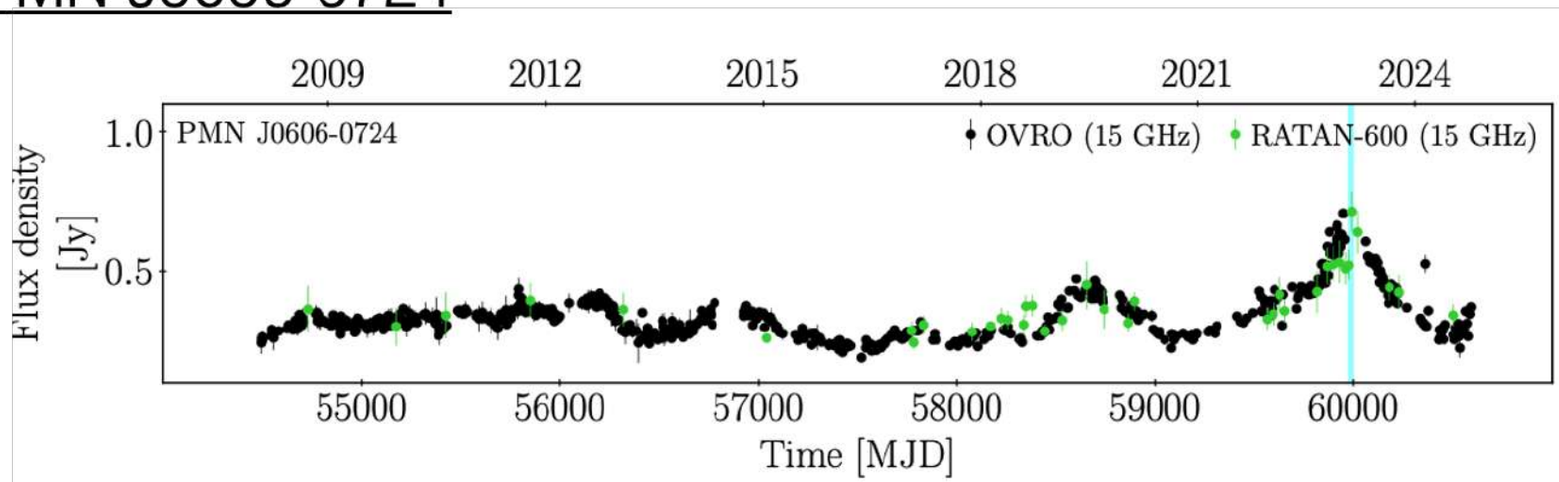
Possible flaring blazar counterparts

- 0605-085

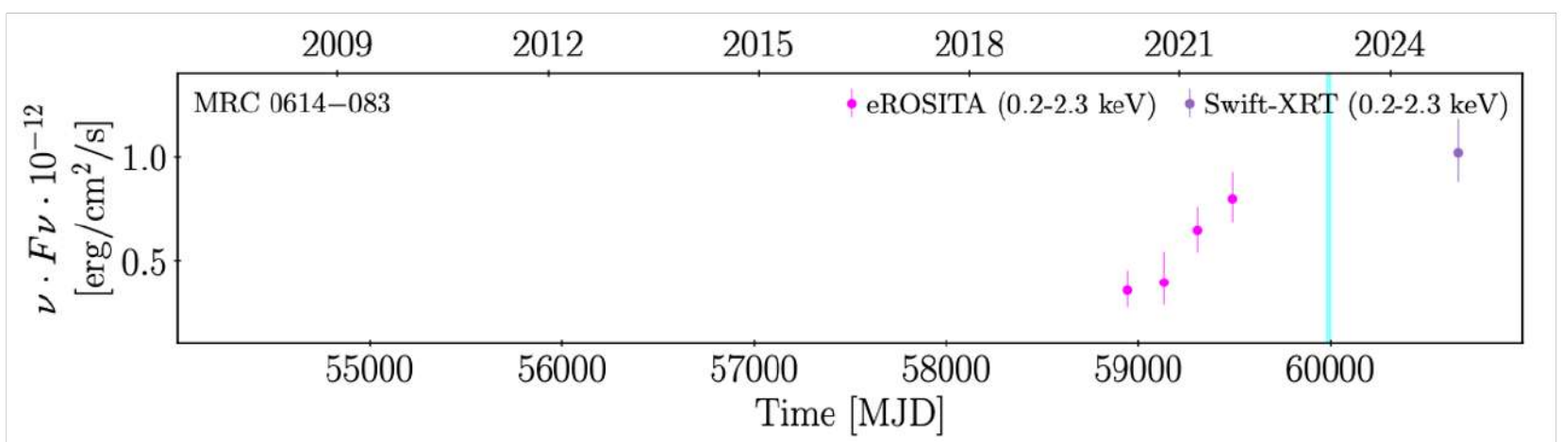




- PMN J0606-0724



- MCR 0614-083

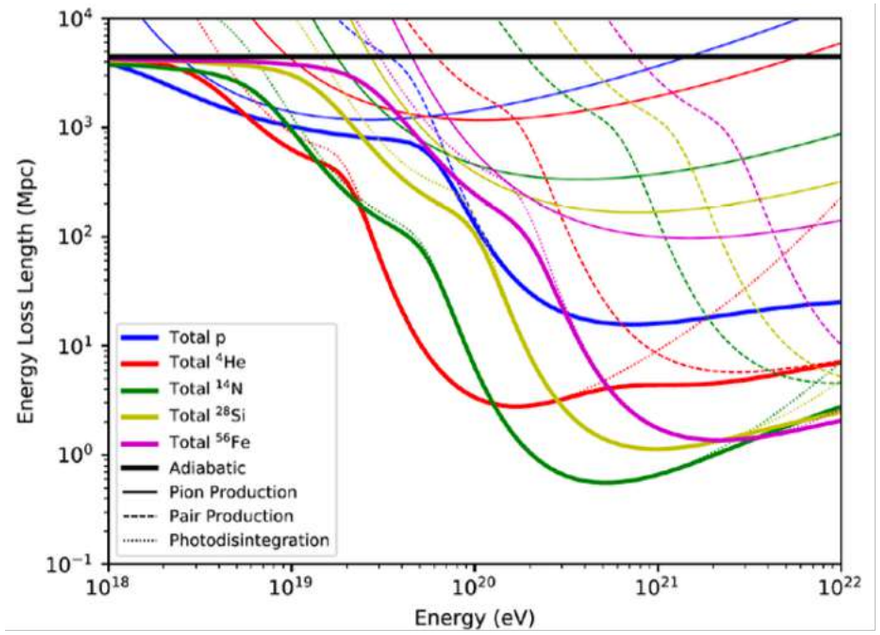


No conclusive evidence

KM3NeT Coll., arXiv:2502.08484

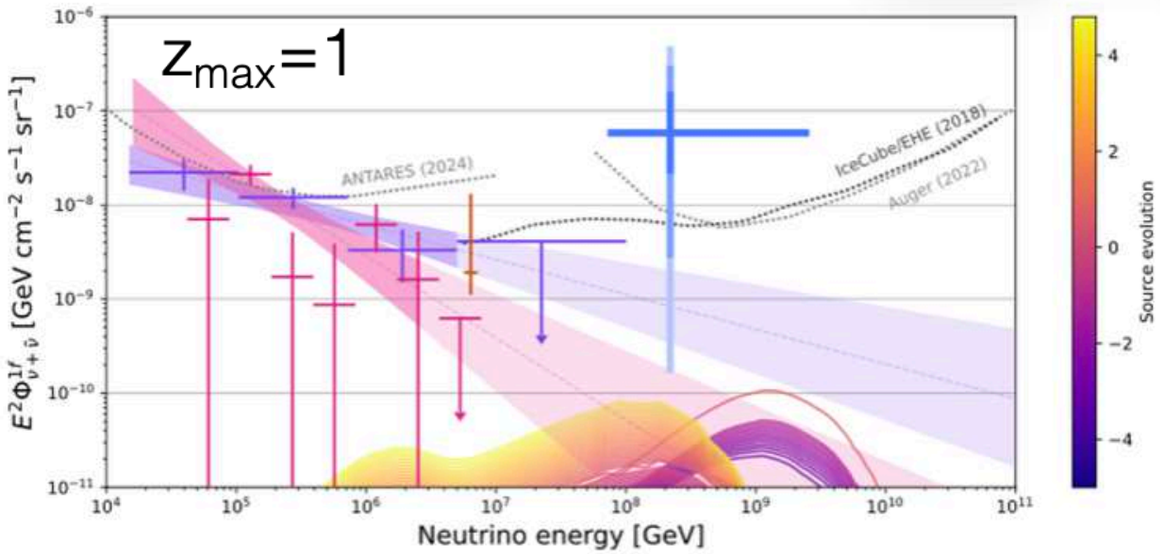
Testing the cosmogenic origin

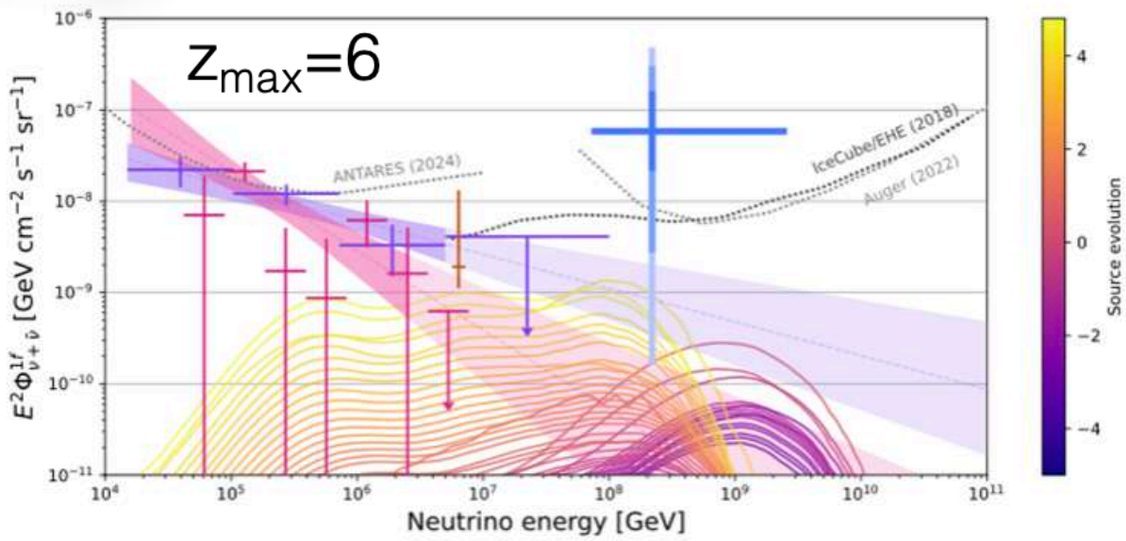
UHECR interaction length depends on their energy distribution and mass composition



On Earth fluxes also vary with cosmological source evolution:

$$S(z) = (1+z)^m$$





KM3NeT Coll., arXiv:2502.08508

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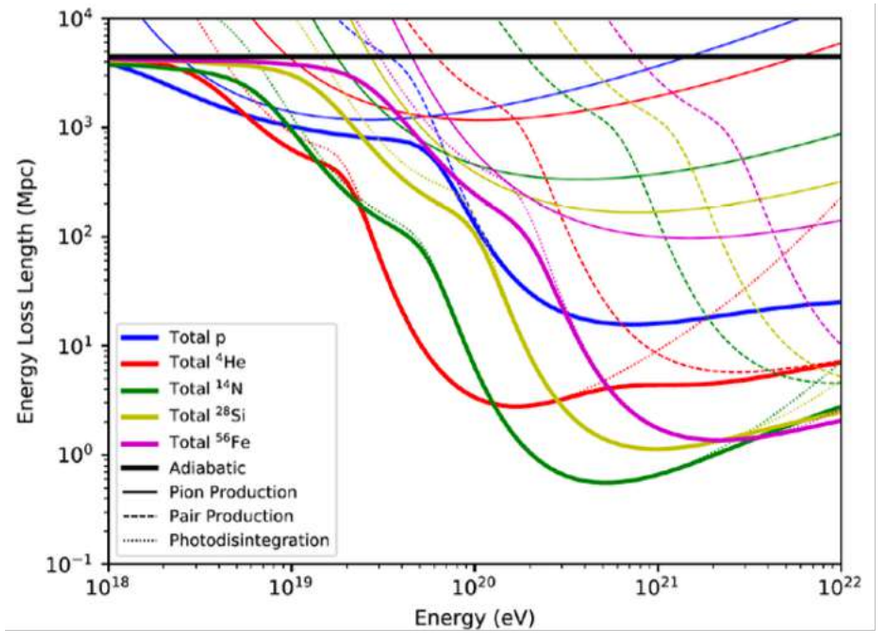

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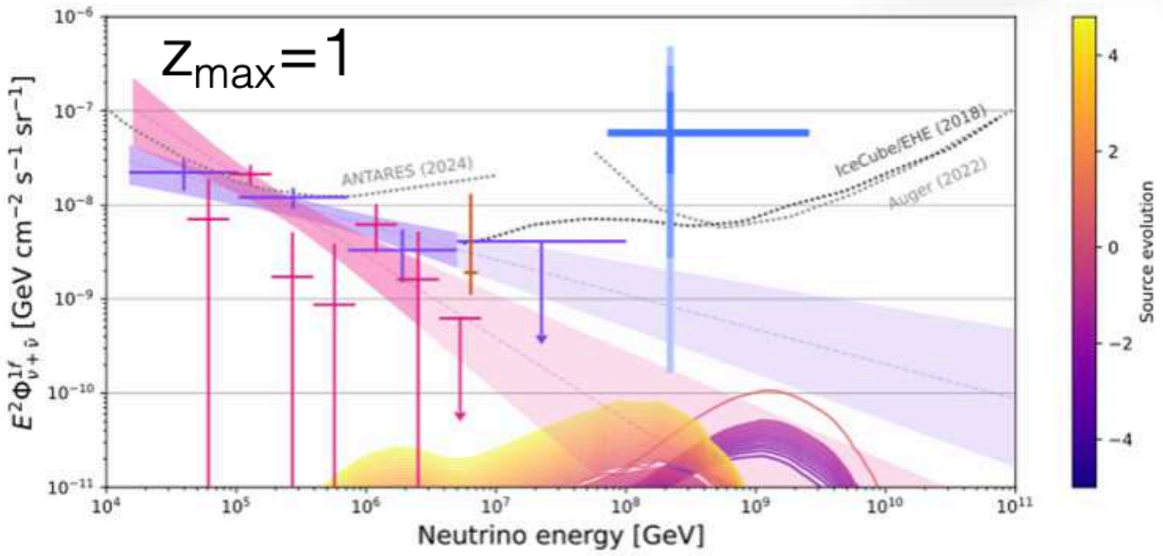

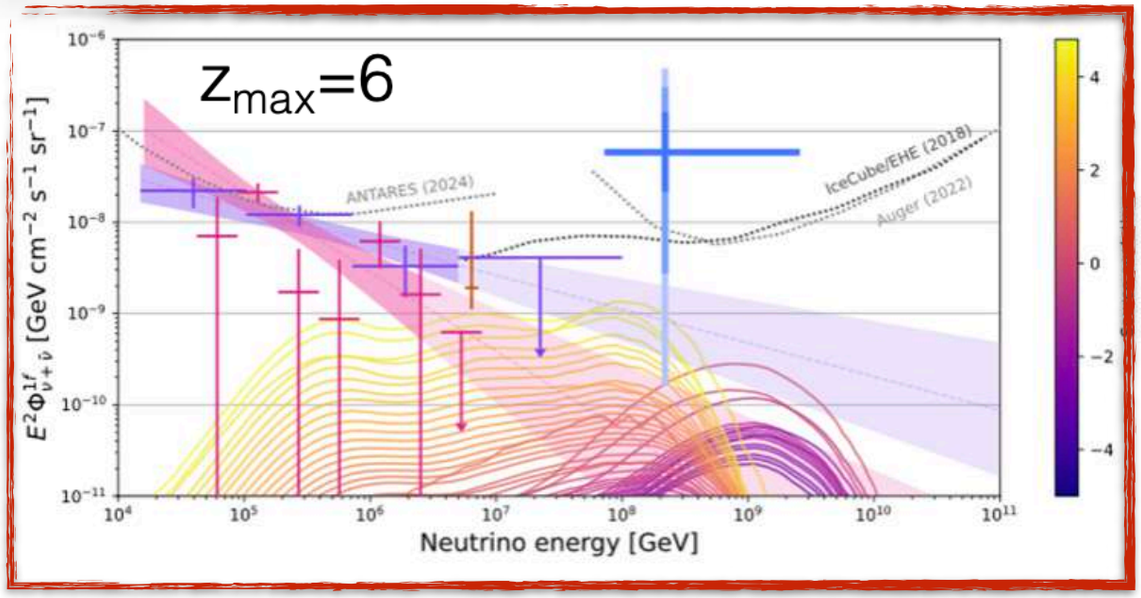

KM3NeT Coll., arXiv:2502.08508

A milestone in neutrino astronomy

- **KM3-230213A** is by far the most energetic neutrino measured so far
- It is the **first UHE neutrino detected**, opening the explorations of physics in a new energy region
- Several plausible scenarios might explain its nature
- More observations to come will clarify the origin of UHE neutrinos
- KM3NeT is taking data and growing rapidly

STAY TUNED FOR UPDATES!

Thanks for your kind attention!