#### The blazar origin of the KM3-230213A ultra high energy neutrino event



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### I. Introduction: the KM3-230213A event

#### What to expect (before the refereed paper was released)?



Neutrinos from TXS 0506+056 (z= 0.33, Aartsen et al., 2018) and NGC 1068 (z = 0.0038, IceCube 2022) See also Aartsen et al., 2018b (~dozen-TeV neutrinos from a low state of TXS 0506+056) and Kadler et al., 2016 (one neutrino event possible associated with a blazar)

### What to expect (before the refereed paper was released)?



Neutrino signal from the Galactic plane (IceCube, 2023) and effective areas (Adriani et al, astro-ph/2502.08173) Our (naive) expectations: powerful blazar (FSRQ) at z~1, theoretical scenario: neutrino production on external photon field

The KM3-230213A event in the ARCA detector (Aiello et al., Nature, 638, 8050 (2025))

1.600

1,400

1,200

800

600

400

200

: 1,000 <u>ල</u>





offshore Portopalo di Capo Passero, Sicily, Italy, 3450 m depth track event (probably from a  $\mu$ ) 120 (+110-60) PeV The parent particle: probably muon or tauon neutrino E = [72 PeV, 2.6 EeV] (90 % C.L.) direction reconstruction uncertainty 0.12° (stat.) + up to 1.5 ° (syst.) 0.6° above the horizon 11.1° from the Galactic plane (Adriani et al., astroph/2502.08387)

## II. On the cosmogenic neutrino scenario

## At least some diffuse isotropic / cosmogenic neutrino models are disfauvored (Li et al., astro-ph/2502.04508)

#### Clash of the Titans: ultra-high energy KM3NeT event versus IceCube data

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KM3NeT has reported the detection of a remarkably high-energy through-going muon. Lighting up about a third of the detector, this muon likely originated from a neutrino exceeding 10 PeV in energy. The crucial question we need to answer is where this event comes from and what its source is. Intriguingly, IceCube has been operating with a much larger effective area for a considerably longer time, yet it has not reported neutrinos above 10 PeV. We quantify the tension between the KM3NeT event and the absence of similar high-energy events in IceCube. Through a detailed analysis, we determine the most likely neutrino energy to be in the range of 23 - 2400 PeV. We find a  $3.5\sigma$  tension between the two experiments, assuming the neutrino is from the diffuse isotropic neutrino flux. Alternatively, assuming the event is of cosmogenic origin and considering three representative models, this tension still falls within  $3.1-3.6\sigma$ . The least disfavored scenario is a steady or transient point source, though still leading to  $2.9\sigma$  and  $2.0\sigma$  tensions, respectively. The lack of observation of high-energy events in IceCube seriously challenges the explanation of this event coming from any known diffuse fluxes. Our results indicate the KM3NeT event is likely the first observation of a new astrophysical source. Mind the "pre-cosmogenic" neutrinos (!!): generated immediately before the release of the accelerated UHECR from the sources (!)

## Ultra high energy cosmic rays: implications of Auger data for source spectra and chemical composition

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**Abstract.** We use a kinetic-equation approach to describe the propagation of ultra high energy cosmic ray protons and nuclei and calculate the expected spectra and mass composition at the Earth for different assumptions on the source injection spectra and chemical abundances. When compared with the spectrum, the elongation rate  $X_{max}(E)$  and dispersion  $\sigma(X_{max})$  as observed with the Pierre Auger Observatory, several important consequences can be drawn: a) the injection spectra of nuclei must be very hard,  $\sim E^{-\gamma}$  with  $\gamma \sim 1 - 1.6$ ; b) the maximum energy of nuclei of charge Z in the sources must be  $\sim 5Z \times 10^{18}$  eV, thereby

#### Hard injection spectra: e.g. Aloisio et al, JCAP, 020, 10 (2014)



CR at 1 EeV: the light component is extragalactic (see works on the anisotropy: Abreu et al., 2011; AUGER 2012a,b; Giacinti et al, 2012)

Interaction of the CR during the confinement phase (?!) → neutrino production

### III. The blazar candidate sources of the KM3-230213A event

# The blazar origin of the KM3-230213A event (KM3Net et al., astro-ph/2502.08484)



# The blazar origin of the KM3-230213A event (KM3Net et al., astro-ph/2502.08484)

Source	Names	Sep.	RA	Dec	z	Methods	VLBI	Xray
		[°]	[°] (J2000)	[°] (J2000)			mJy	$[10^{-13}  \frac{\mathrm{erg}}{\mathrm{cm}^2 \mathrm{s}}]$
#1	MRC 0614-083	0.6	94.2623	-8.3749	_	1	_	$5.58^{+1.16}_{-0.99}$
	NVSS J061703-082225							(R,e,S)
	VLASS1QLCIR J061702.97-082229.2							
	WISE J061702.95-082229.5							
	1 e RASS J061702.8-082230							
	WIBRaLS J0617-0822							
110	0005 085	9.4	01 0097	0 5005	0.97	1 9 9 4	9940 L 996	11 c+9.25
<b>#0</b>	0005-085	2.4	91.9987	-8.3803	0.87	1, 2, 3, 4	$2240 \pm 220$	$11.0_{-2.89}$
	NVSS J060759-083450							(R,C,S,e)
	VLASS1QLCIR J060759.69-083450.3							
	RFC J0607-0834							
	WISE J060759.61-083451.6							
	1 e RASS J060759.7-083448 (H)							
	4FGL J0608.0-0835							
	CGRaBS J0607-0834							
	BZQ J0607-0834							

#### IV. PKS 0605-085 as the origin of the KM3-230213A event (Dzhatdoev, astro-ph/2502.11434)

The spine-sheath scenario (following Ghisellini et al.,

A&A, 432, 401, 2005)



Ansoldi et al., ApJ Lett., 863, L10 (2018)



Probably a ~pc-scale structure in our case

respectively. We define the neutrino production efficiency  $f_{\gamma}(E_p)$  as follows:

$$f_{\nu}(E_p) = \frac{\frac{dN_{p\gamma}}{dE_p}(E_p)}{\frac{dN_p}{dE_p}(E_p)},\tag{1}$$

where  $dN_{p\gamma}/dE_p$  is the number of photohadronic interactions experienced by the accelerated protons in the energy interval  $(E_p, E_p + dE_p)$  and  $dN_p/dE_p$  is the number of these protons in the same energy interval. We estimate the neutrino luminosity of the source

The neutrino production efficiency easily reaches  $\sim 0.1$ -1 at the proton energy of 1-3 EeV; the mean expected number of the observable neutrino events  $\sim 10^{-2}$  is achievable

# IV. The blazar PKS 0605-085 (z= 0.87) as the origin of the KM3-230213A (Dzhatdoev, astro-ph/2502.11434)

energy interval. We estimate the neutrino luminosity of the source averaged over the duration of the flare in the energy interval  $(E_{\nu}, E_{\nu} + dE_{\nu})$  as follows:

$$< L_{\nu}(E_{\nu}) > = \frac{< M_{\nu}(E_p) > f_{\nu}(E_p) < P_p(E_p) >}{K_{E_{p\nu}}},$$
 (2)

where  $\langle M_{\nu}(E_p) \rangle$  is the average neutrino multiplicity (i.e. the average number of the neutrinos generated per one photohadronic interaction),  $E_p \sim K_{E_{p\nu}} \times E_{\nu}$  is the characteristic energy of the proton producing the neutrino with the energy  $E_{\nu}$ ,  $K_{E_{p\nu}} \approx 20$ , and  $\langle P_p(E_p) \rangle$  is the power transferred to the accelerated protons in the energy interval  $(E_p, E_p + dE_p)$  averaged over the duration of the flare. The total jet power and the total (bolometric) power

$$K_{N\nu} = \frac{N_{\nu P}(E_{\nu-thr} \leq E_{\nu} \leq E_{\nu-max})}{N_{\nu T}(E_{\nu-thr} \leq E_{\nu} \leq E_{\nu-max})}$$
$$= \frac{\delta t_P \int_{E_{\nu-thr}}^{E_{\nu-max}} J_{\nu P}(E_{\nu}) A_A(E_{\nu}) dE_{\nu}}{\delta t_T \int_{E_{\nu-thr}}^{E_{\nu-max}} J_{\nu T}(E_{\nu}) A_I(E_{\nu}) dE_{\nu}}$$

The neutrino beaming pattern may be sharper than the gamma-ray emisssion pattern; thus, the gamma-ray constraints on the neutrino luminosity are relaxed by ~ X 10 times

Comparable number of the neutrino events from PKS 0605-085 ( $H_{pl} = 10^{13.7}$  Hz,  $E_{pl} = 0.207$  eV,  $L_{pl} = 10^{46.28}$  erg/s,  $L_{\gamma} = 10^{46.29}$  erg/s,  $L_{X} = 10^{45.17}$  erg/s) and TXS 0506+056 ( $H_{pl} = 10^{14.3}$  Hz,  $L_{pl} = 10^{45.81}$  erg/s,  $L_{\gamma} = 10^{45.72}$  erg/s,  $L_{X} = 10^{44.19}$  erg/s) V. MRC 0614-083 as the origin of the KM3-230213A event What if MRC 0614-083 was an extreme TeV blazar? See e.g. Dzhatdoev et al., 2021 for the case of 1ES 0229+200 (plotted below). ~0.01 neutrino events achievable.



### VI. Conclusions

1. The source of the unique event KM3-230213A is still unclear.

- 2. This event was probably indeed produced by a muon or a tauon neutrino.
- 3. At least some models of the cosmogenic origin for the KM3-230213A event are disfavoured.

4. The blazar PKS 0605-085 (z=0.87) is one of the best candidates for the source of the KM3-230213A event. The spine-sheath scenario (neutrino production on external photon field) is a viable neutrino production mechanism in this case.

5. MRC 0614-083 could be a viable candidate source of the KM3-230213A event if it was an extreme TeV blazar.

## Additional slides

### 1+67 papers in total; many of these do not provide a detailed discussion

#### Article

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

https://doi.org/10.1038/s41586-024-08543-1 The KM3NeT Collaboration\*

Received: 19 August 2024

Accepted: 18 December 2024

Published online: 12 February 2025

Open access

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The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena<sup>1-3</sup>. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons, and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea<sup>4</sup>, which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of  $120^{+110}_{-60}$  petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now<sup>5-7</sup> falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino<sup>8</sup>, resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

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

KM3NeT Collaboration • S. Aiello (INFN, Catania and Catania U. and Catania, CSFNSM) Show All(286) Feb 12, 2025

#### 7 pages

Published in: Nature 638 (2025) 8050, 376-382, Nature 640 (2025) E3 (erratum)

Published: Feb 12, 2025

DOI: 10.1038/s41586-024-08543-1 (publication), 10.1038/s41586-025-08836-z (erratum) Experiments: KM3NeT

View in: HAL Science Ouverte





Typical effective area vs. the zenith angle (not to scale) ALCM2] 100 Pell 100 Tél 100 Per B. Even 100 Ter 0<TT/2 Fully 0= TC [reads hozboh houson below, Orrac

The cosmogenic origin of the KM3-230213A event (interaction of cosmic rays on isotropic extragalactic photon fields) is disfavoured (Adriani et al., ApJ, **984**, L41, 2025) "(...) if the event is indeed cosmic, it is most likely of extragalactic origin" (Adriani et al., astro-ph/2502.08387)



Intergalactic EM cascade counterpart (Fang et al., ApJ Lett., 982, L16, 2025, see also Crnogorcevic et al., astro-ph/2503.16606) for z= 0.1

Mind the low redshift (!!) (z= 0.1)
Mind the need to fit into EGRB (!!)
Mind the internal absorption (!!)
The actiual value of the neutrino intensity

5) The actiual value of B

+(...)