KM3-230213A – The most energetic neutrino event ever detected

Mischa Breuhaus, CPPM Seminar, 7.4.25

The event KM3-230213A

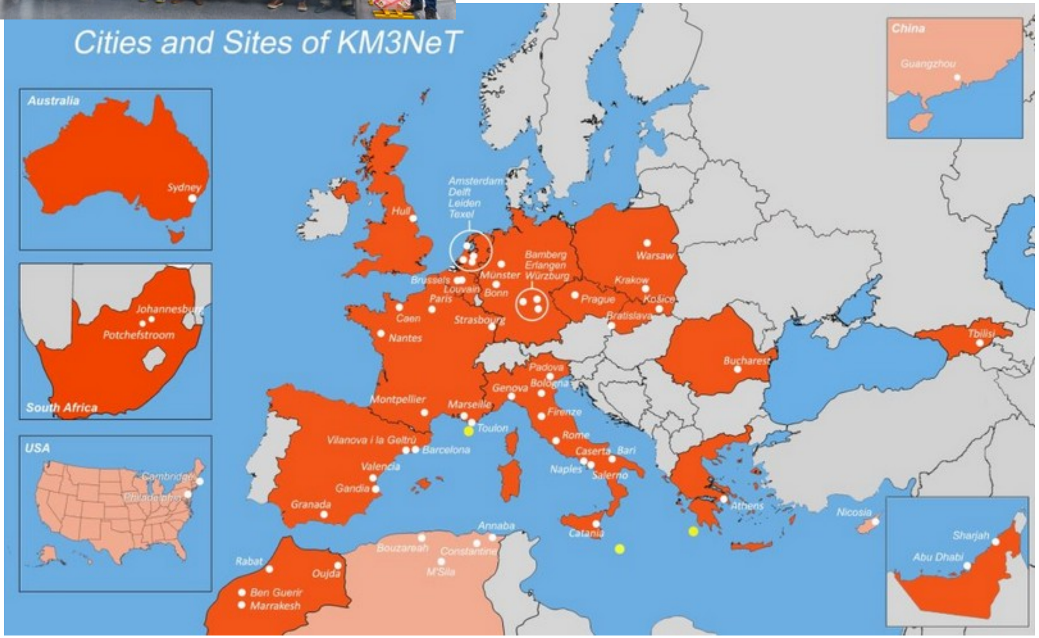
- Detected on 13. February 23 at 01:16:47 UTC
- Published in nature on 12.2.25, 5 companion papers in arXiv
- With very high probability a neutrino
- Median neutrino energy 220 PeV
- New window of neutrino universe
- How was it detected?
- Why are we sure it is a neutrino?
- Where does it come from?

Outline

- KM3NeT
- Detection, energy and direction
- Comparison with other experiments
- Interpretation and implications

The KM3NeT collaboration

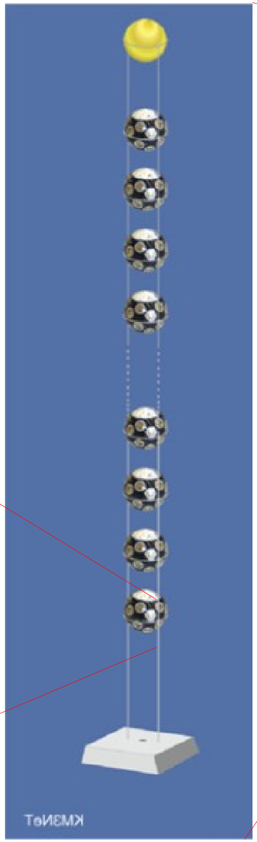
20 countries, 52 institutes,
more than 250 collaborators



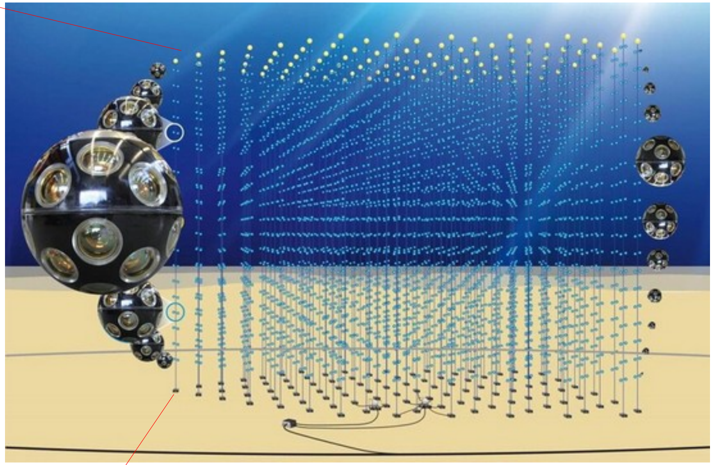
The KM3NeT detector

- Each DU: 18 DOMs
- Each DOM: 31 PMTs

DOM

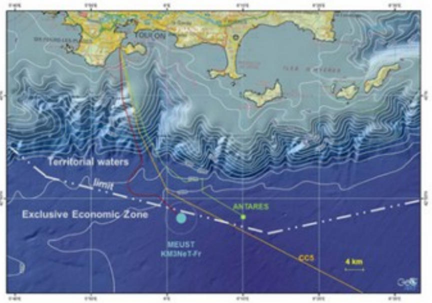


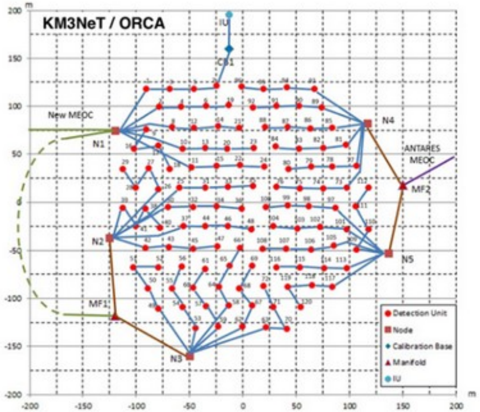
DU



The planned KM3NeT detector

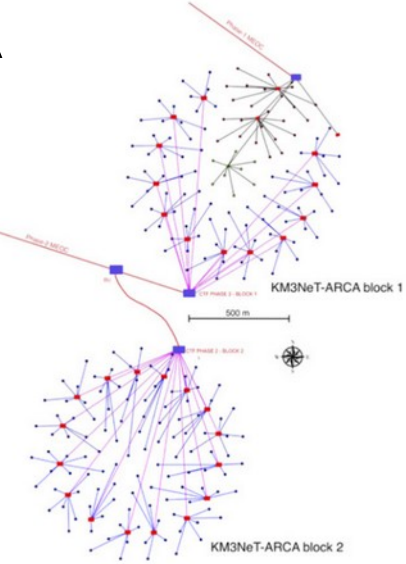
ORCA





- Offshore Toulon
- Depth 2440 m
- Average horizontal spacing ~ 20 m
- Vertical DOM spacing: 9 m
- Lower energies in GeV regime

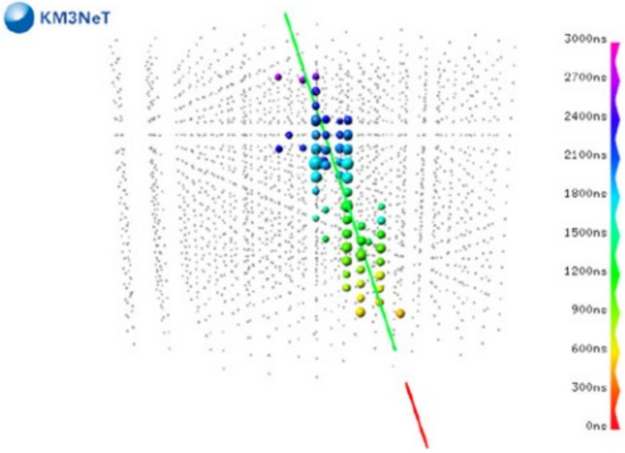
ARCA

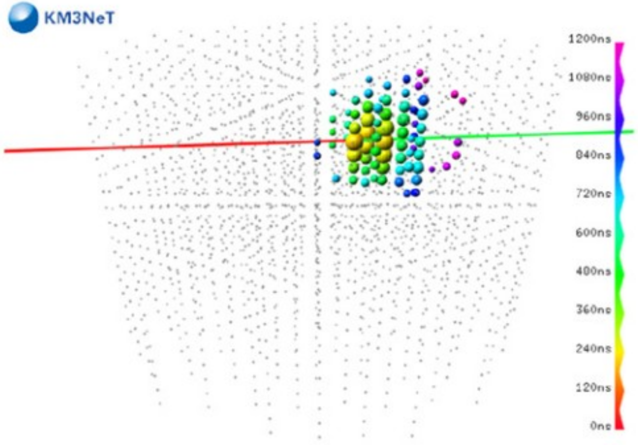


- Offshore Sicily
- Depth 3500 m
- Average horizontal spacing: ~ 95 m
- Vertical DOM spacing: 36 m
- Higher energies > TeV

Detection principle of neutrinos

- ν interacts in charged and neutral current interactions
- Production of Cherenkov light of secondary particle
- Tracks & Showers

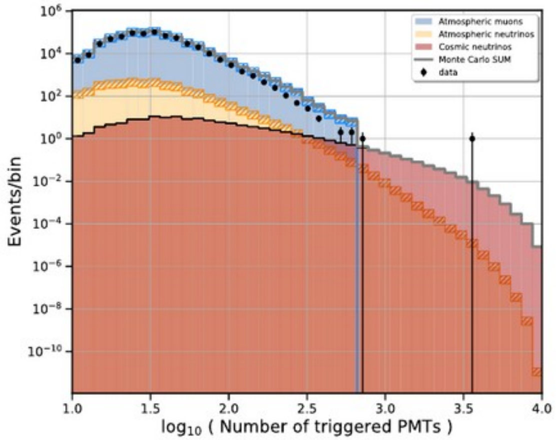


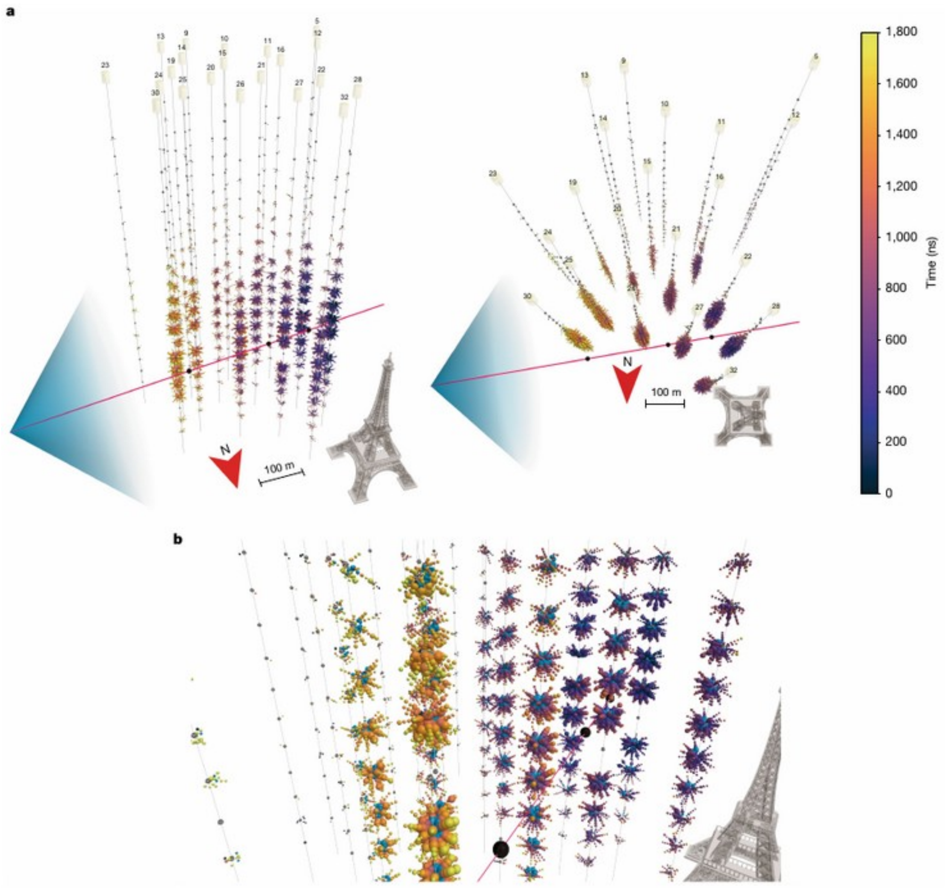


KM3NeT coll. 2016

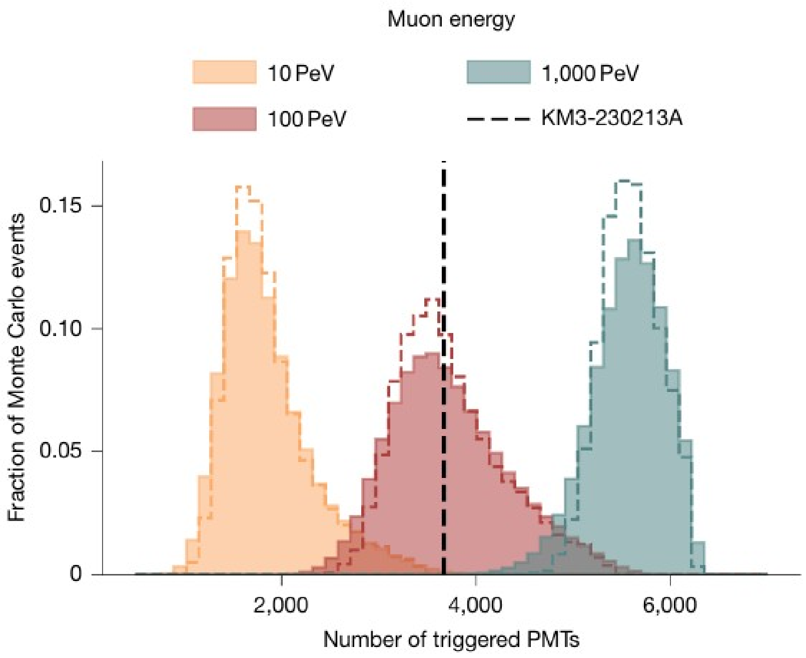
KM3-230213A

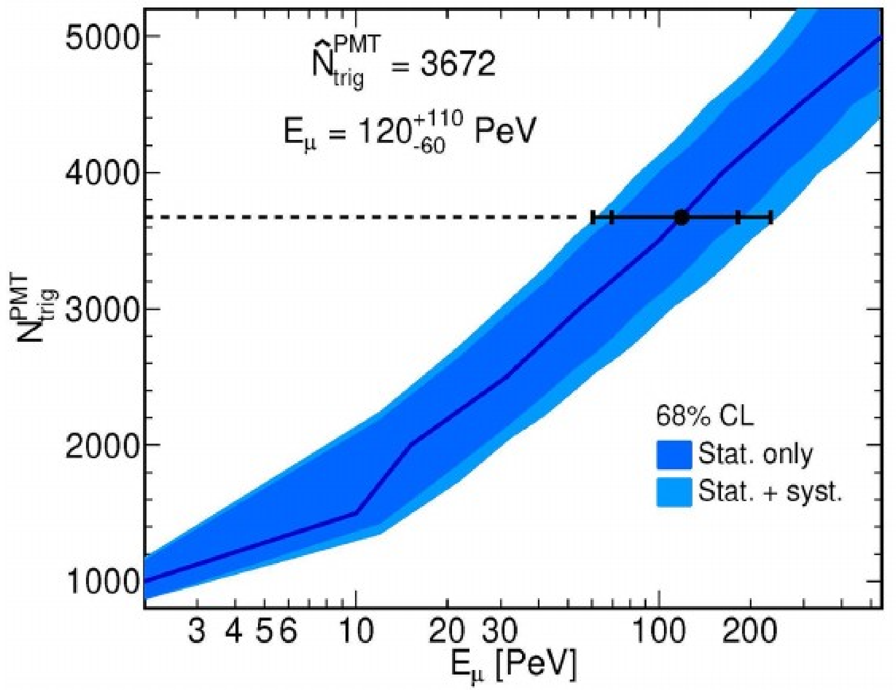
- Detected with ARCA, 21 lines in operation
- 3672 triggered PMTs (35% of all active PMTs)





Energy determination



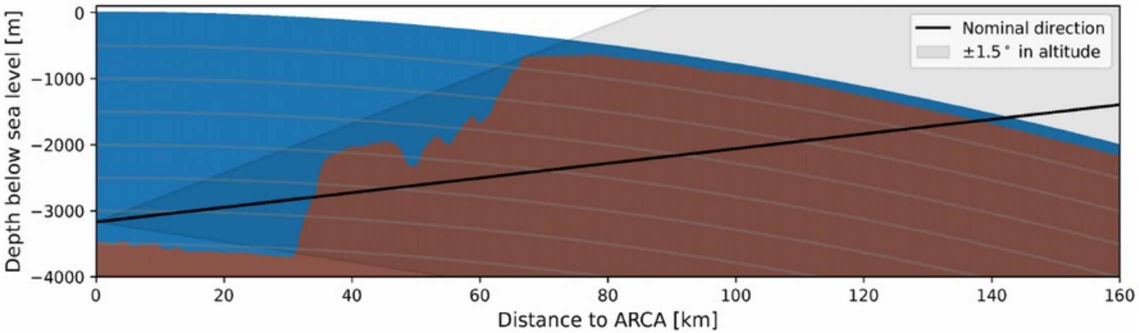


- Directly related to number of triggered PMTs
- Estimated from dedicated MC simulations
- Uncertainties from absorption length, PMT efficiencies

90% confidence interval: 35-380 PeV
Inferred neutrino energy: 220 PeV, 68% confidence 110-790 PeV, 90% confidence 72 PeV – 2.6 EeV

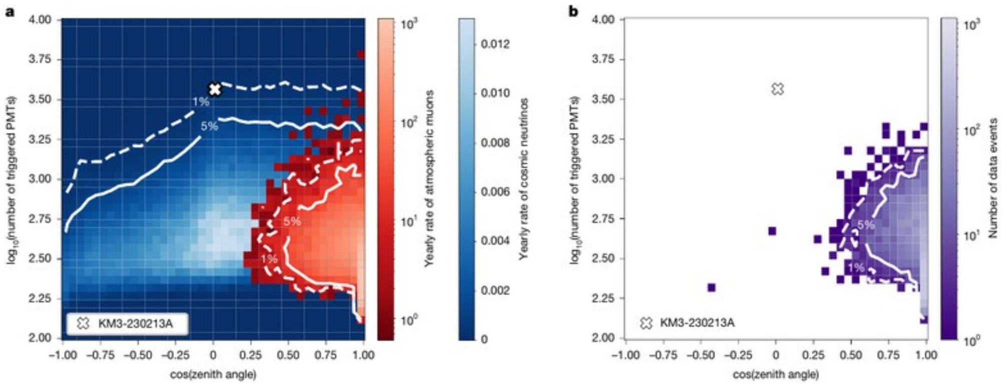
Direction determination

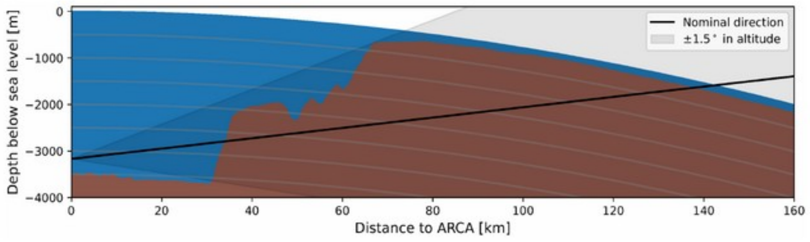
- Dominated by uncertainty on absolute positioning of detector → improvement in the future (up to 0.12°)
- Acoustic positioning, compass data for tilt
- RA = 94.3°, Dec = -7.8°
- R(68%) = 1.5°
- R(99%) = 3.0°



Why are we very sure it is an astrophysical neutrino?

- Background: Muons, atm. Neutrinos
- Muons: $10^{-9} - 10^{-10}$ evt/yr, dependent on direction
- Atm. Neutrinos > 100 PeV: 1-5x10^{-5} evt/yr



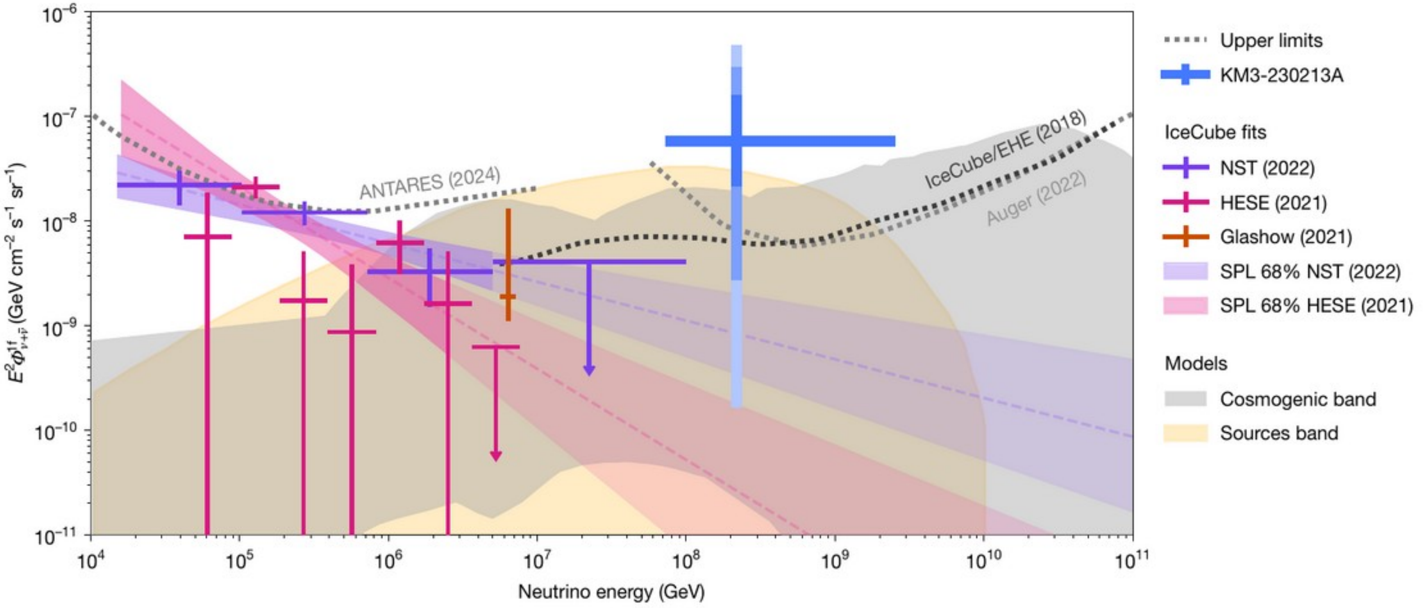


Neutrino flux point

- Apply certain selection cuts, ARCA detector with 19 and 21 detection lines

$$E^2\Phi(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Also: Search for neutrinos in event direction. No significant neutrino source detection by ARCA/ORCA, ANTARES and IceCube



Comparison with other measurements/potential tension

- Why did other experiments detected nothing so far?
- Comparison/joint analysis with IceCube and Pierre Auger observatories

The ultra-high-energy event KM3-230213A within the global neutrino landscape

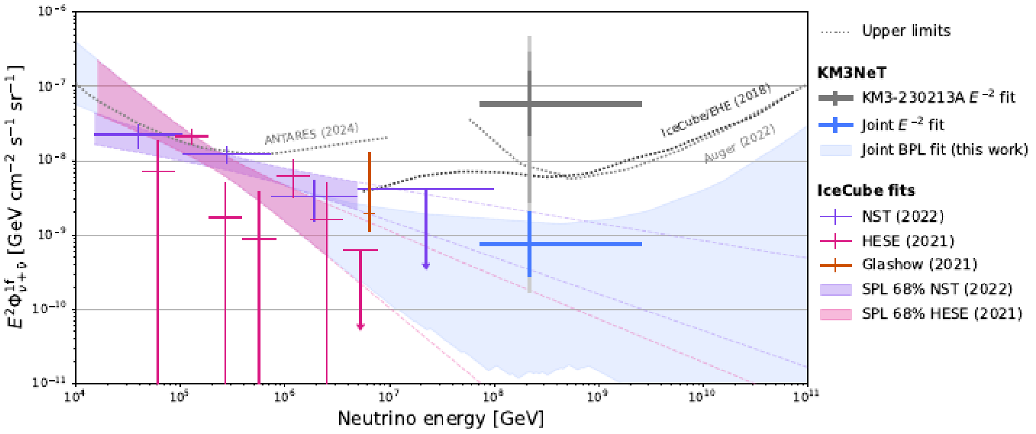
(The KM3NeT Collaboration)

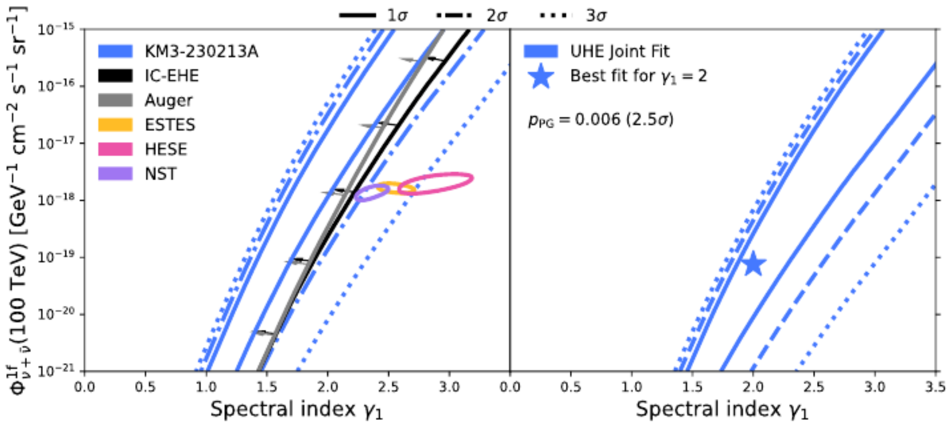
O. Adriani,[1,2] S. Aiello,[3] A. Albert,[4,5] A. R. Alhebsi,[6] M. Alshamsi,[7] S. Alves Garre,[8] A. Ambrosone,[9,10]
F. Ameli,[11] M. Andre,[12] L. Aphecetche,[13] M. Ardid,[14] S. Ardid,[14] C.Argüelles,[15] J. Aublin,[16] F. Badaracco,[17,18]
L. Bailly-Salins,[19] Z. Bardačová,[20,21] B. Baret,[16] A. Bariego-Quintana,[8] Y. Becherini,[16] M. Bendahman,[10]
F. Benfenati Gualandi,[22,23] M. Benhassi,[24,10] M. Bennani,[19] D. M. Benoit,[25] E. Berbee,[26] E. Berti,[1] V. Bertin,[7]
P. Betti,[1] S. Biagi,[27] M. Boettcher,[28] D. Bonanno,[27] S. Bottai,[1] A. B. Bouasla,[29] J. Boumaaza,[30] M. Bouta,[7]
M. Bouwhuis,[26] C. Bozza,[31,10] R. M. Bozza,[9,10] H.Brânzaş,[32] F. Bretaudeau,[13] M. Breuhaus,[7] R. Bruijn,[33,26]
J. Brunner,[7] R. Bruno,[3] E. Buis,[34,26] R. Buompane,[24,10] J. Busto,[7] B. Caiffi,[17] D. Calvo,[8] A. Capone,[11,35]

https://arxiv.org/abs/2502.08173

Comparison with UHE data

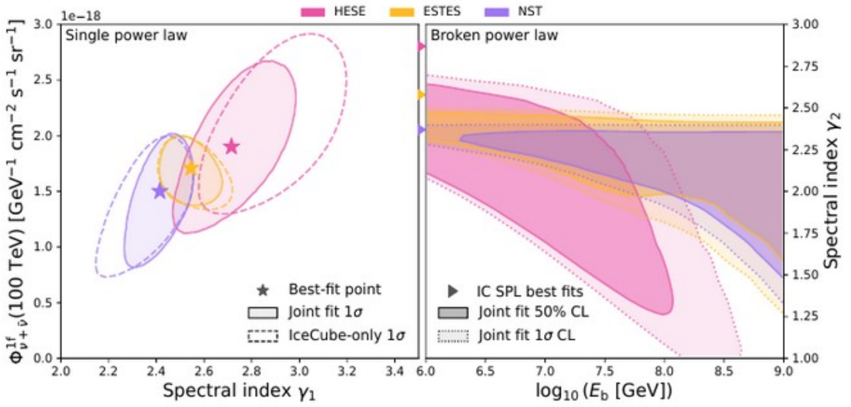
- Include exposures from IceCube + Auger → reduced flux
- Discrepancies up to ~ 3σ, depending on method





Global fit, KM3NeT + IceCube

- Single power-law
- Broken power-law
- Using HESE sample: Slight preference for break

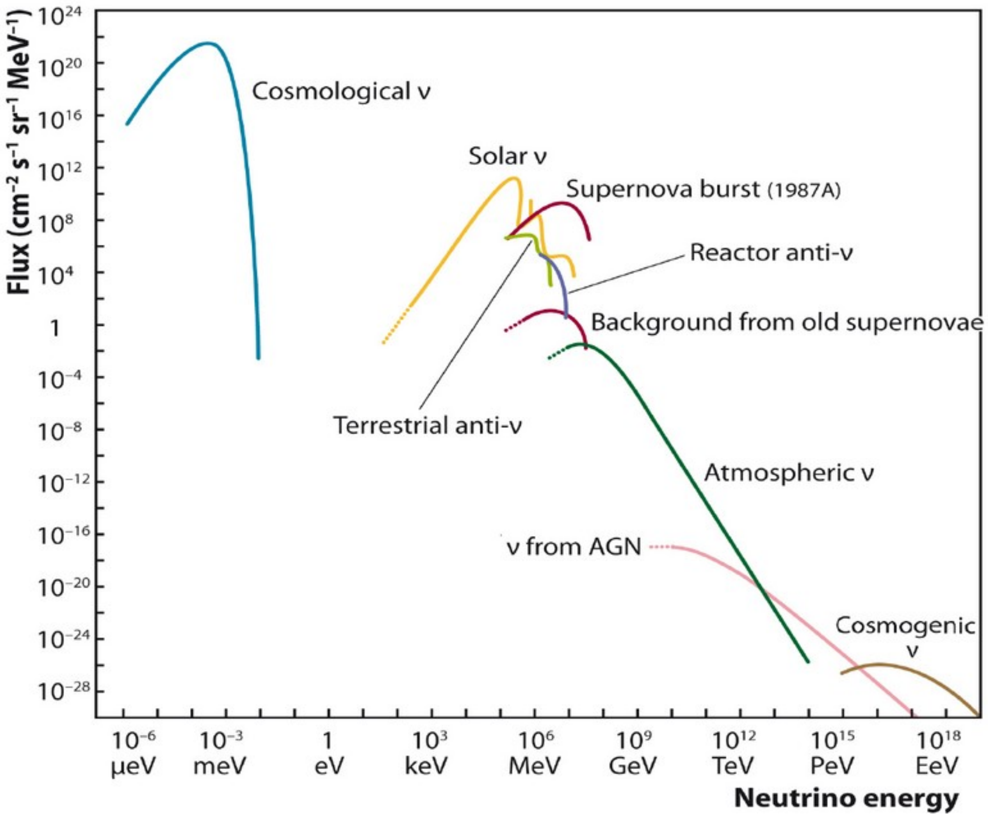


Conclusion:

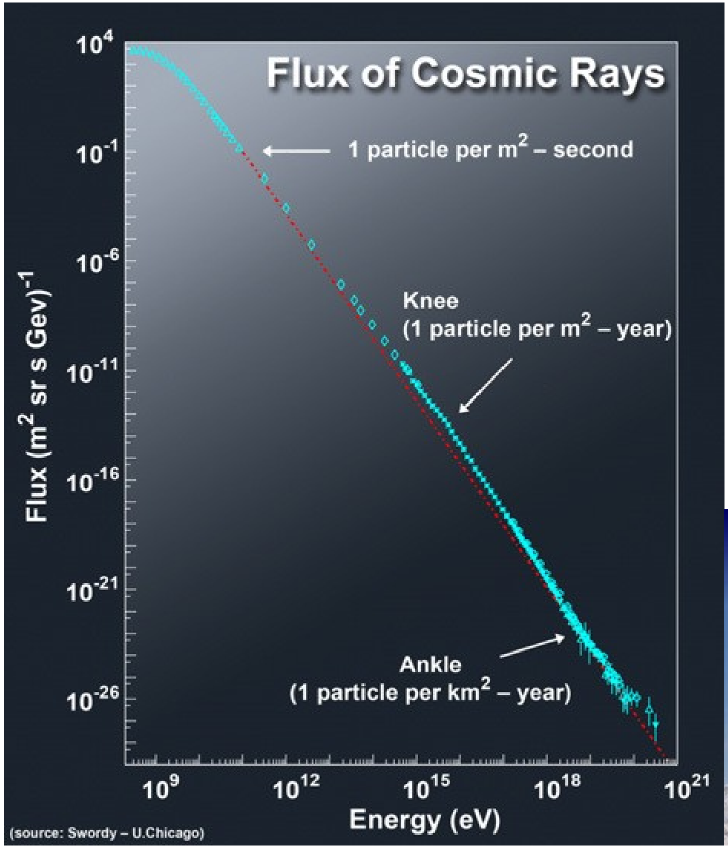
- Tension with non-detection between 2.5σ and 3σ → In line with assumption that KM3-230213A is upward fluctuation of neutrino flux
- Not yet possible to confirm hardening of neutrino spectrum

Neutrino production

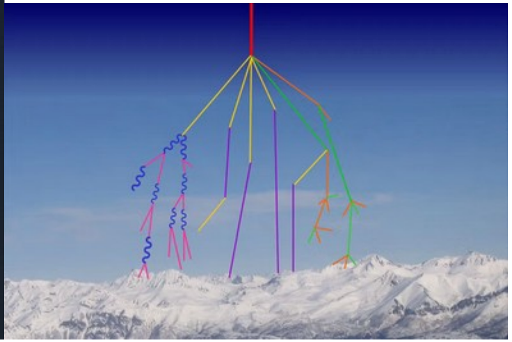
- Atmospheric neutrinos: Background
- Astrophysical neutrinos: Produced by CRs

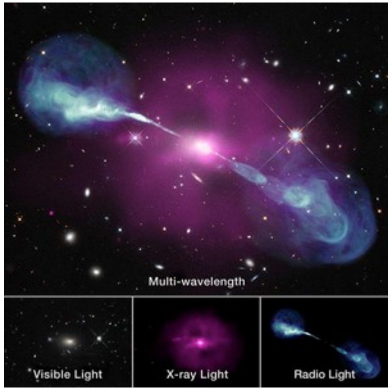


Cosmic Rays



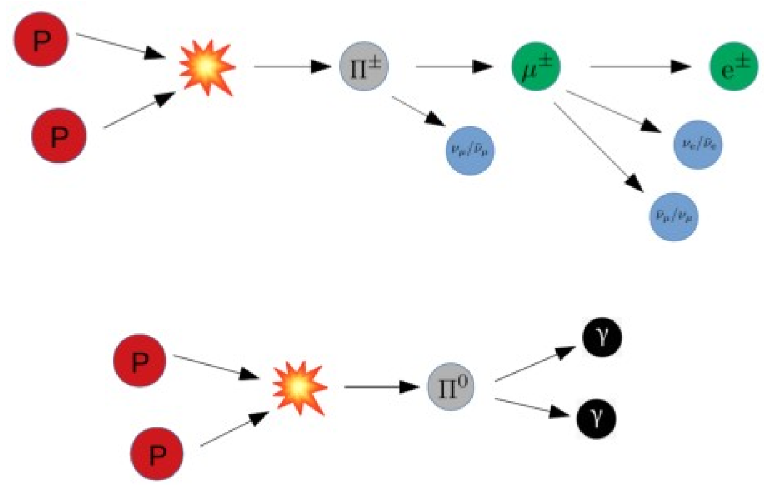
- Highly energetic particles
- Accelerated by various sources and mechanisms
- Measured at Earth, produce atmospheric neutrinos in air showers
- ν production within sources, direct information about CR origin and sources. These are the ones we are looking for in neutrino astronomy





Neutrino production by CRs

Collisions with hadrons



Collisions with photons

Photo-meson production

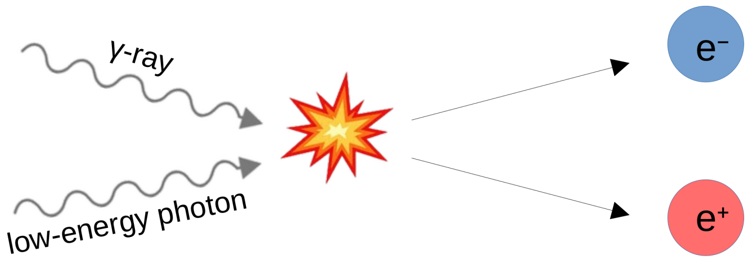
$$p + \gamma \rightarrow p + k \cdot \pi^0/\pi^\pm$$

Also: Photo-disintegration of nuclei, photo-pair production

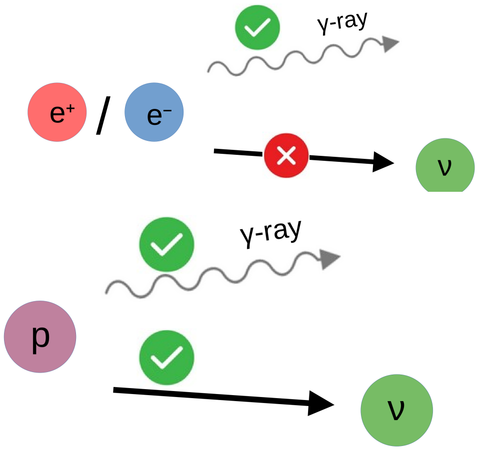
- γ-rays are produced too

Why are neutrinos unique messengers?

γ-ray absorption



ν only produced by hadronic particles

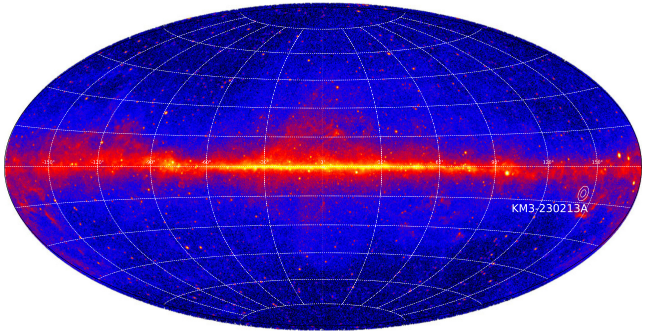


ν are not absorbed and clear proof of hadronic CRs

Astrophysical origin

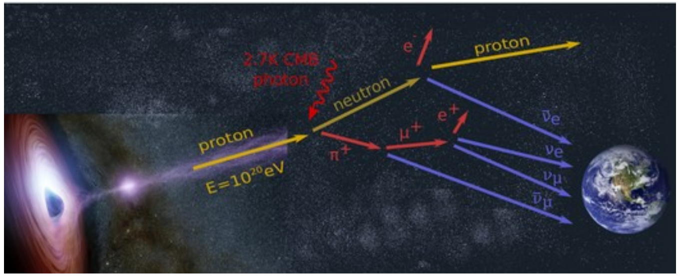
- No transient source, such as e.g. a GRB, found
- Neutrino could originate from ‘steady’ source

Galactic origin



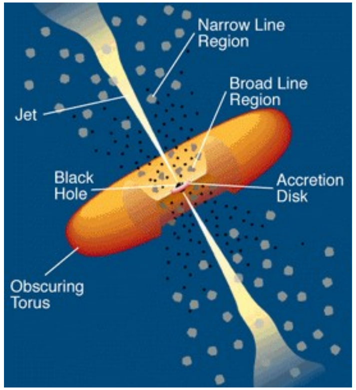
https://arxiv.org/abs/2502.08387

Cosmogenic origin



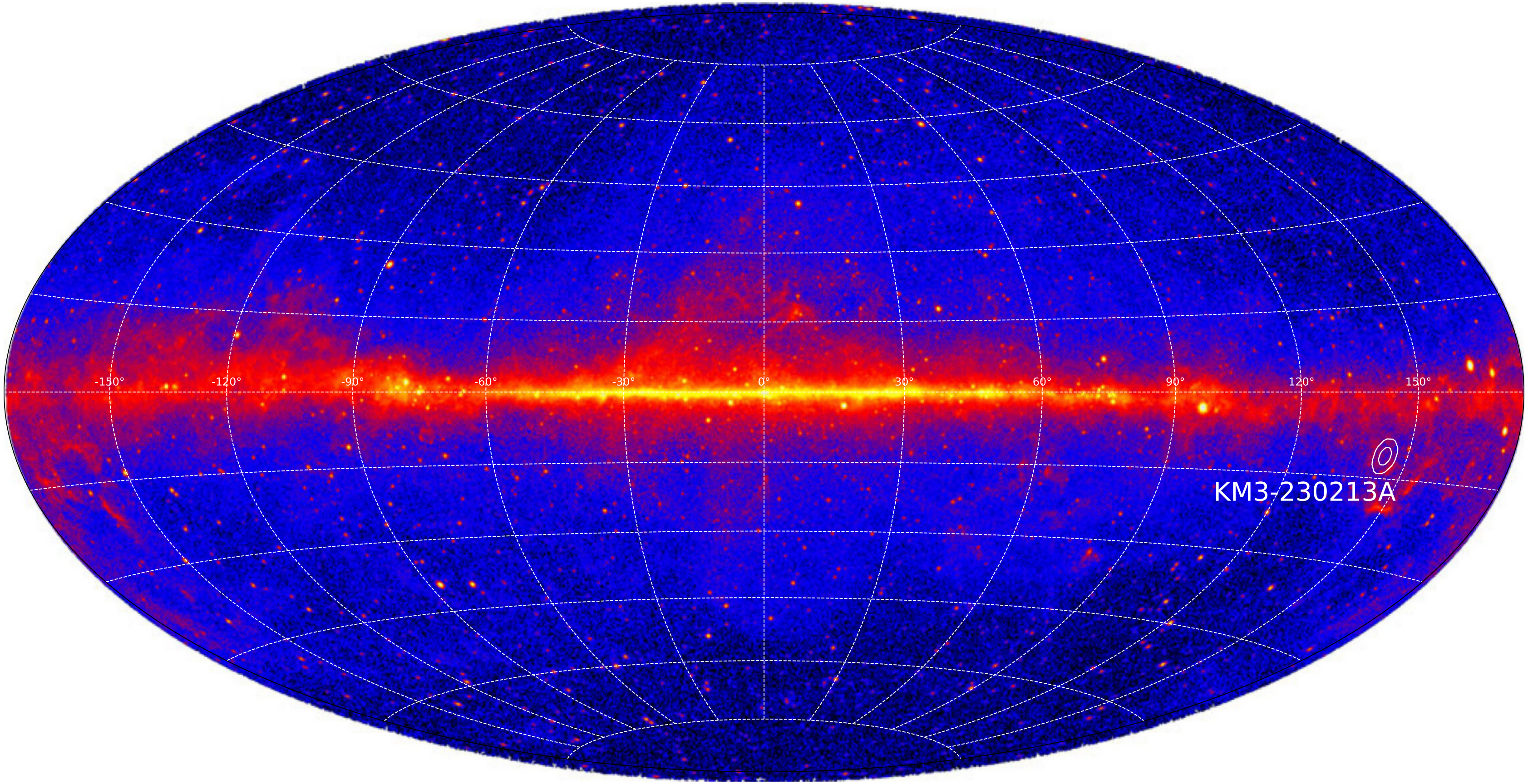
https://arxiv.org/abs/2502.08508

Blazar

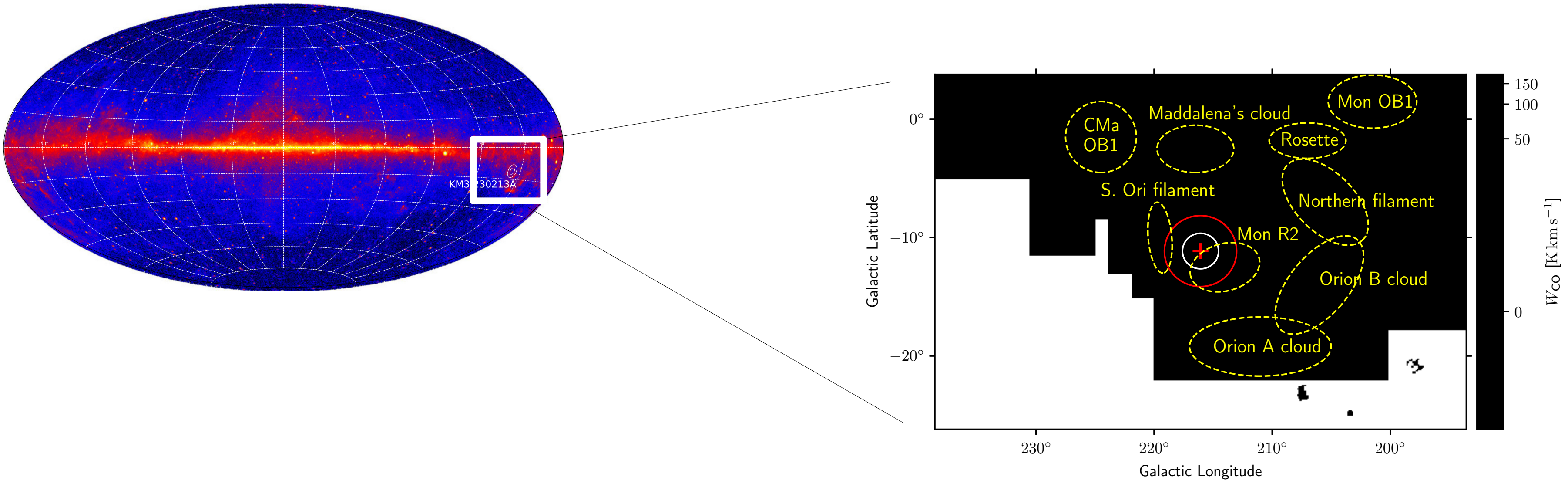


https://arxiv.org/abs/2502.08484

The potential Galactic origin

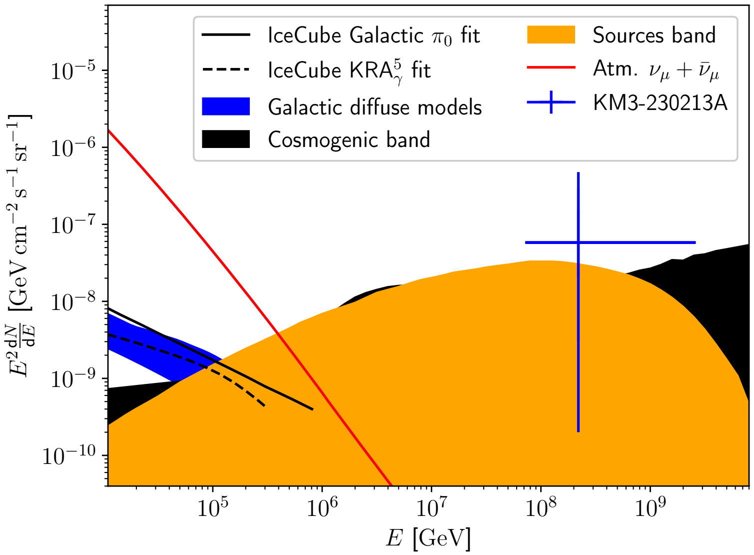


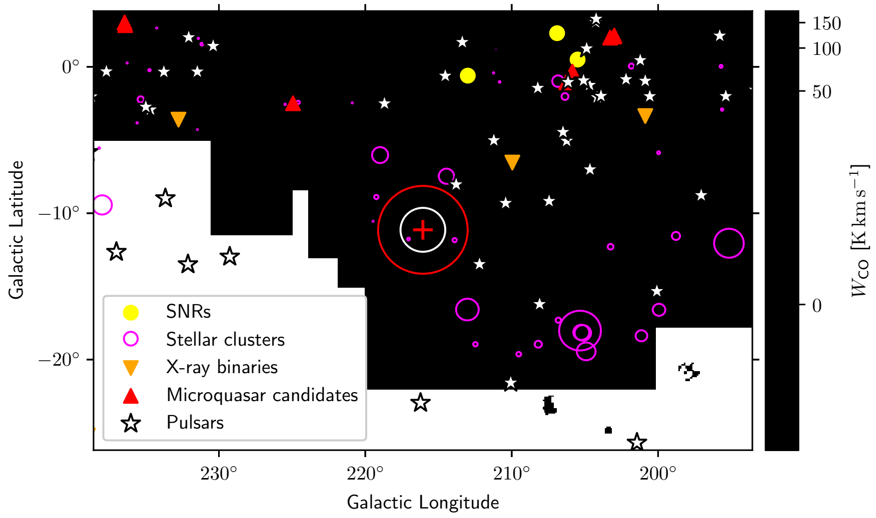
Gas target



- Monoceros R2 molecular cloud: potential gas target for CRs
- Distance: ~830 pc, $9\mathrm{x}10^4$ solar masses

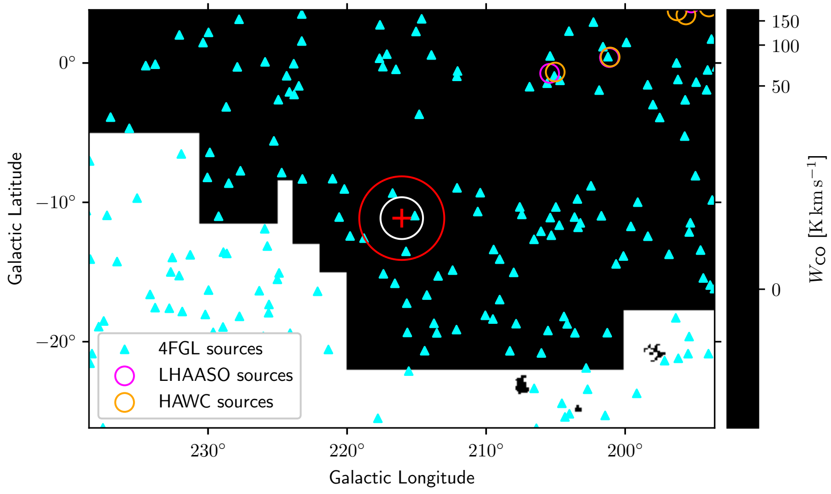
Diffuse Galactic emission and potential CR accelerators

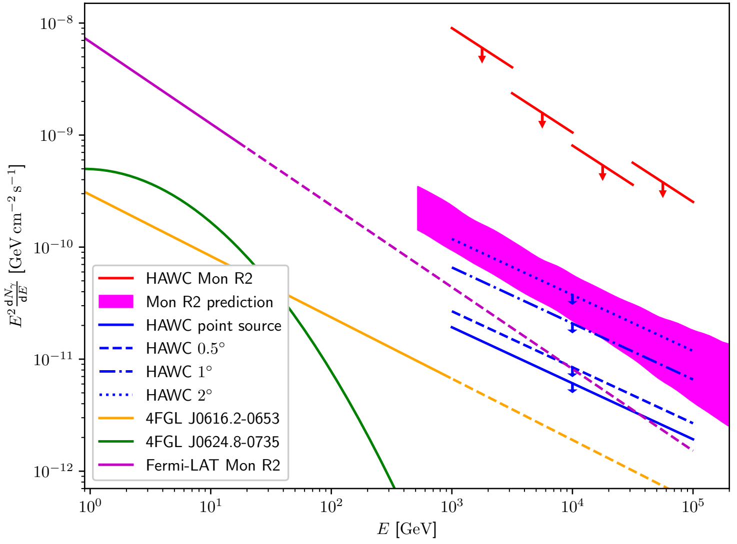




- Galactic diffuse emission: negligible
- No known potential CR accelerator nearby

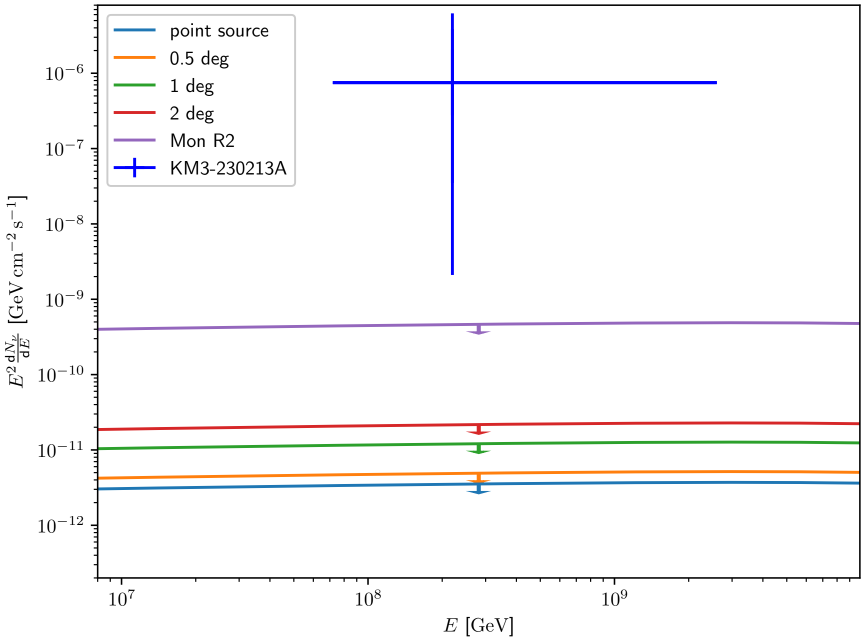
Gamma-ray observations





- Only two potential Galactic Fermi-LAT sources
- Nothing from HAWC or LHAASO

Limits on neutrino emission

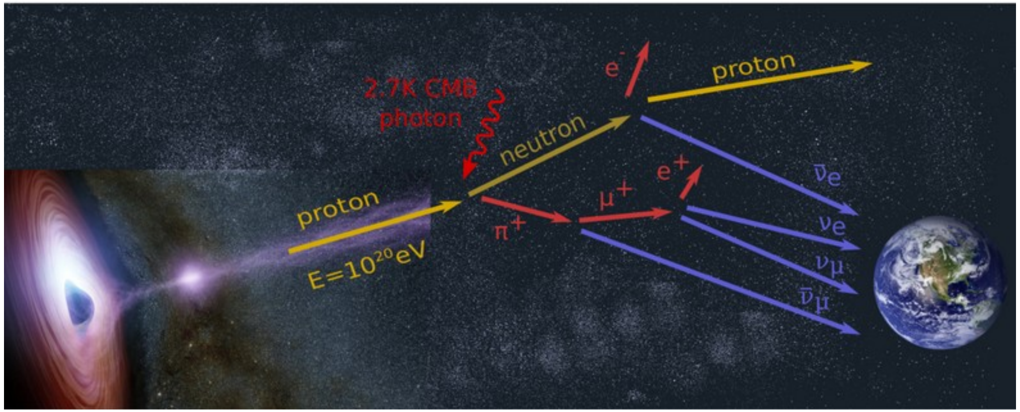


- Limits from HAWC non-observations below PS flux

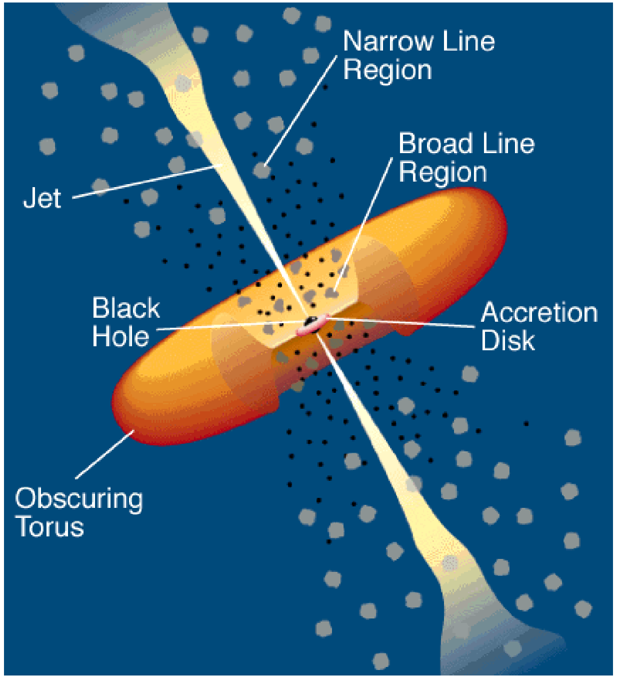
→ Conclusion: Galactic origin of KM3-230213A highly unlikely

Extragalactic origin

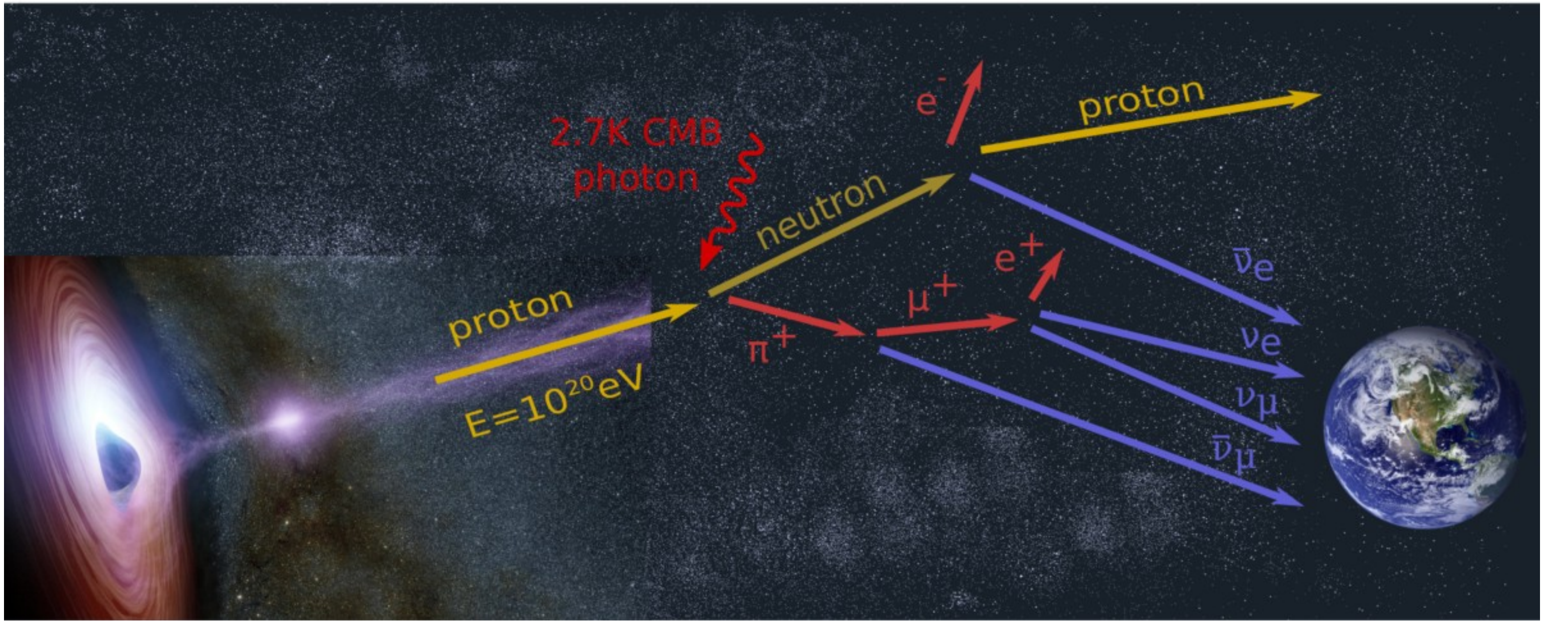
Cosmogenic



Active Galactic nuclei

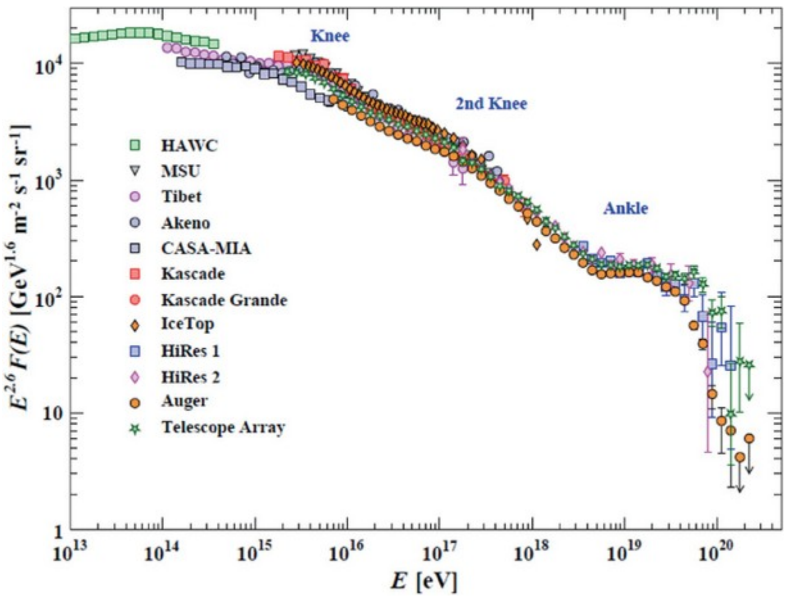


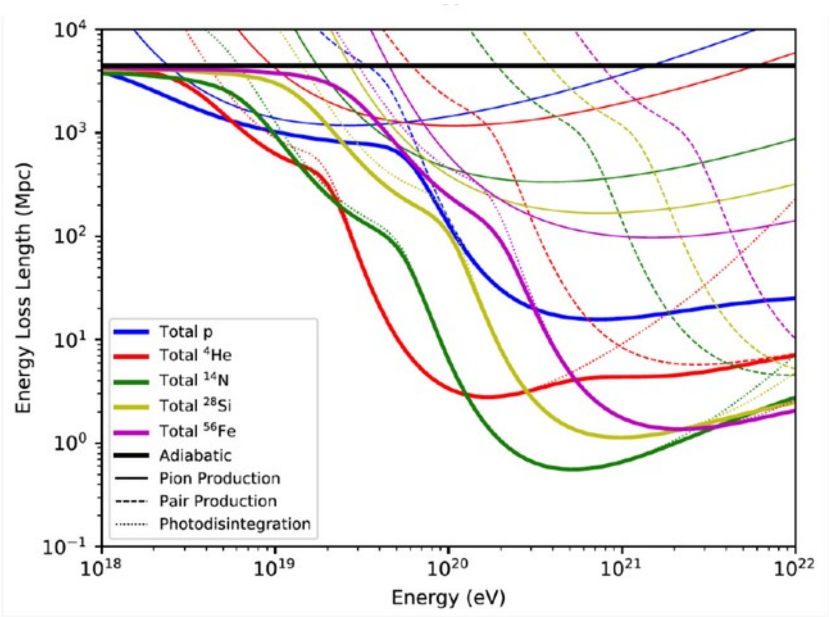
Cosmogenic origin



- CRs interacting with EBL and CMB
- Diffuse, isotropic neutrino flux

Cosmogenic origin



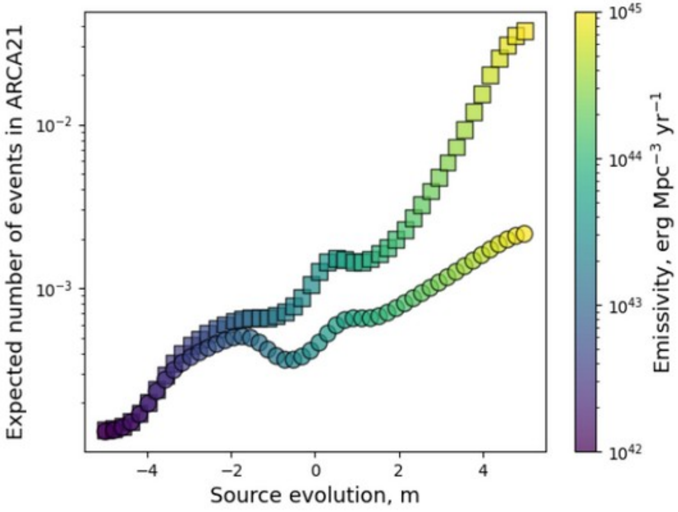


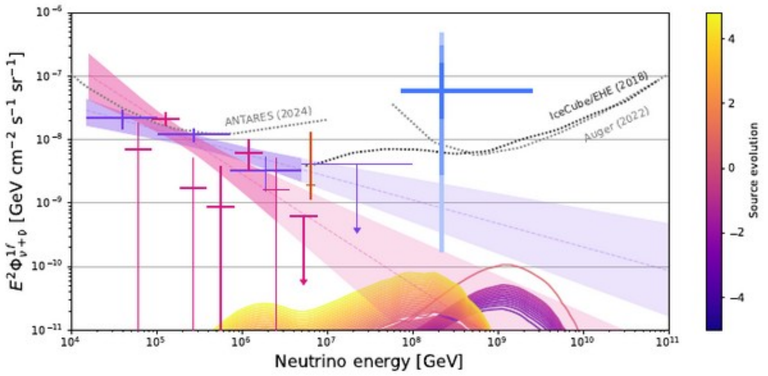
- Only UHE-CRs contribute
- CRs until z ~ 1 contribute to UHE-CRs on Earth

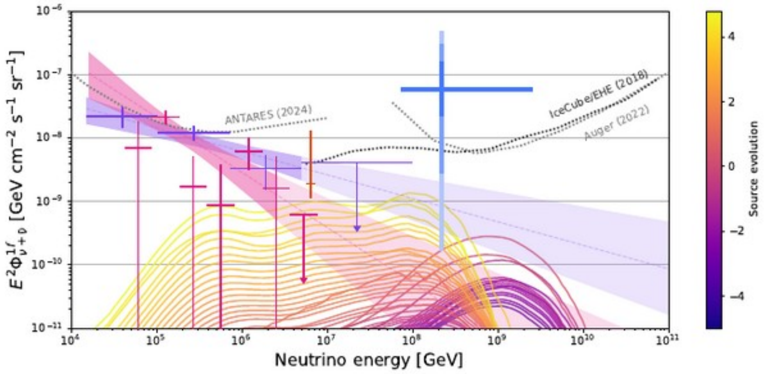
Cosmogenic origin

- Comoving source density:

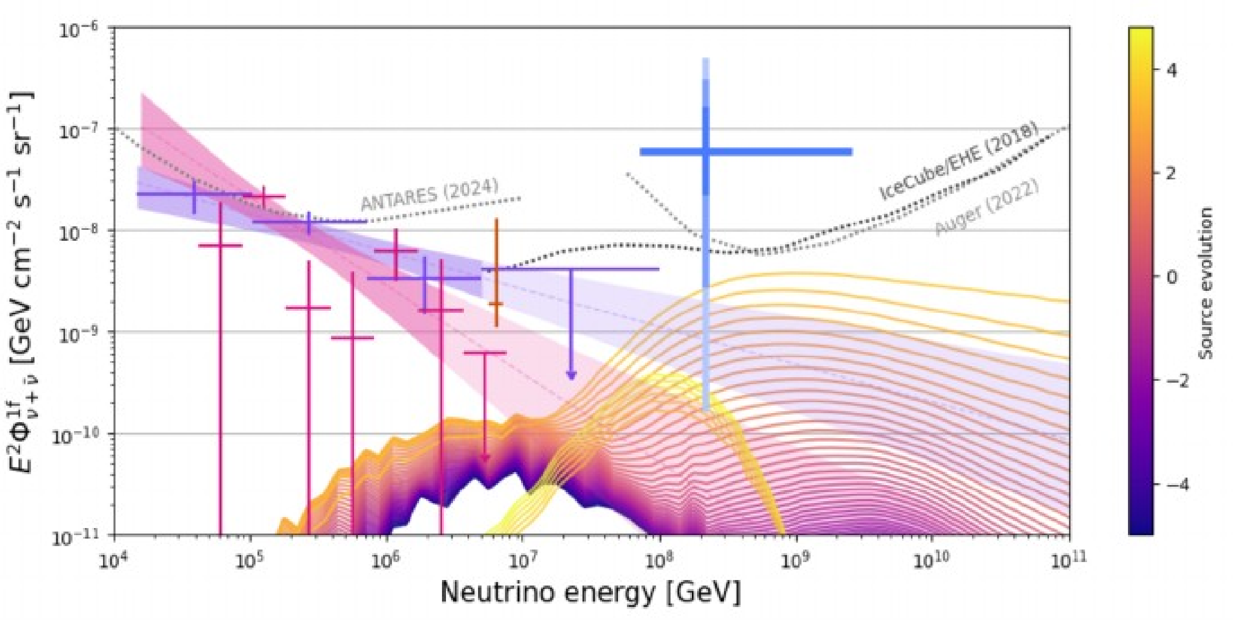
$$S(z) \propto (1+z)^m$$







Cosmogenic origin



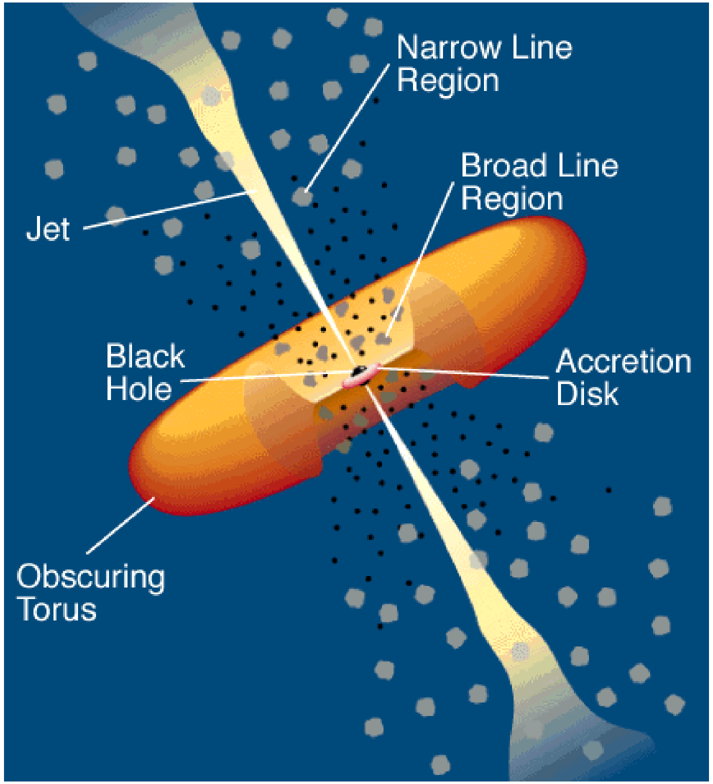
- A CR composition involving more protons leads to higher fluxes

Cosmogenic origin

- Uncertainties in EBL models negligible
- UHE-CR formation rate might be different than the one of matter
- Large uncertainties, but cosmogenic origin is possible
- Could tune cosmogenic models to explain UHE neutrinos and constrain relevant model parameters

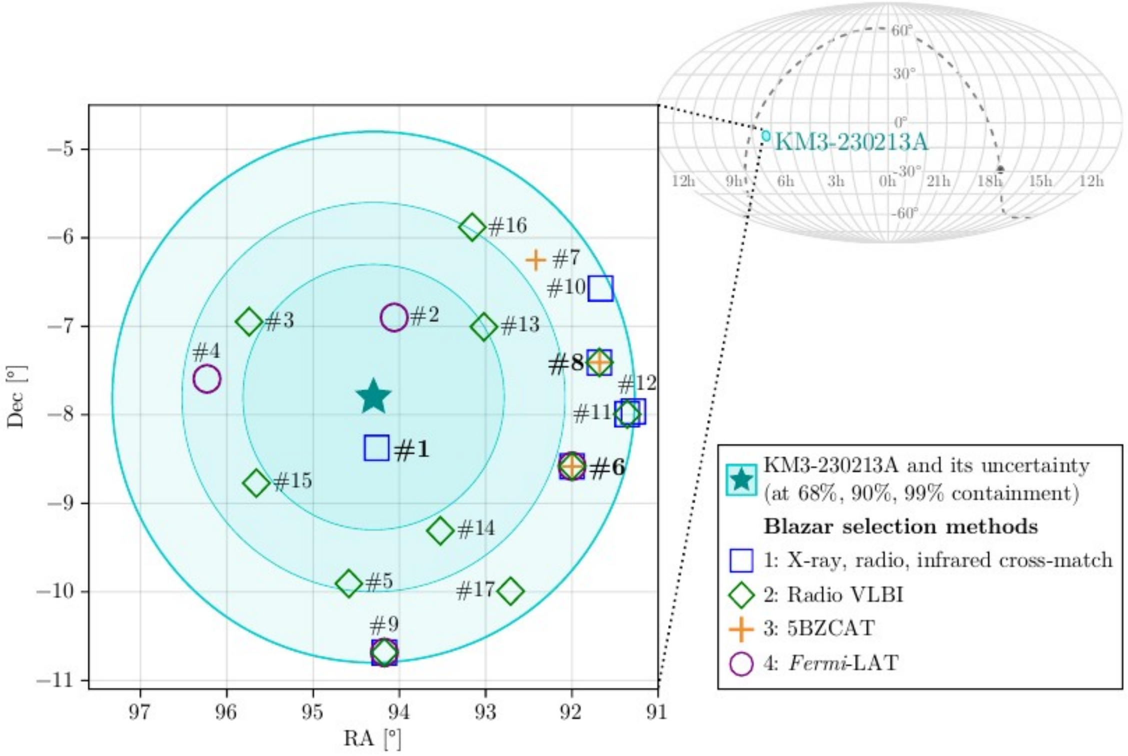
Potential blazar origin

- Supermassive black hole accreting matter
- Accretion disk, jet formation
- CR acceleration and ν production in jet
- Blazar: AGN with jet pointing towards Earth
- Very strong evidence that blazars emit neutrinos



Potential blazar origin

- 17 sources found
- Method 1: eROSITA (X-rays) + NVSS (radio) + in WISE blazar strip (infrared)
- Method 2: VLBI observations
- Method 3: 5th Roma BZ Catalog blazar catalog
- Method 4: Fermi-LAT DR4 catalog (γ-rays)

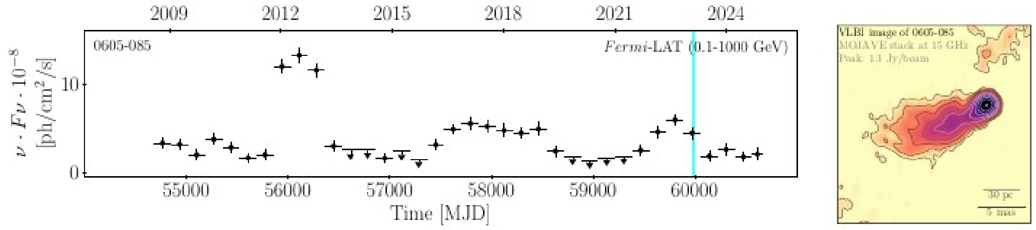


Potential blazar origin

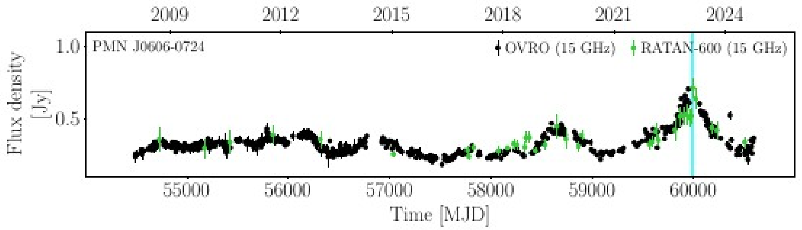
- Dedicated VLBA observations performed in November 2024, archival infrared, X-ray and γ-ray data from Fermi-LAT
- 10 sources show strong radio emission at pc and sub-pc scale → strong jet beaming
- 3 blazars show flaring activity

Potential blazar origin

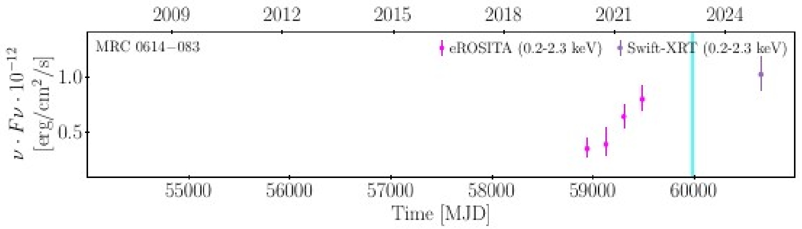
- Source 0605-085: brightest in radio, γ-ray flaring activity
- PMN J0606-0724: major radio flare
- MRC 0614-083: X-ray flaring activity
- No clear association with specific source



(a) The *Fermi*-LAT light curve and a VLBI image of 0605-085: the brightest radio source in the neutrino localization region that experiences a gamma-ray flaring activity around the neutrino arrival (Section 5.1).



(b) The radio light curve for PMN J0606-0724 that experiences a major flare in close coincidence to the neutrino arrival (Section 5.2).



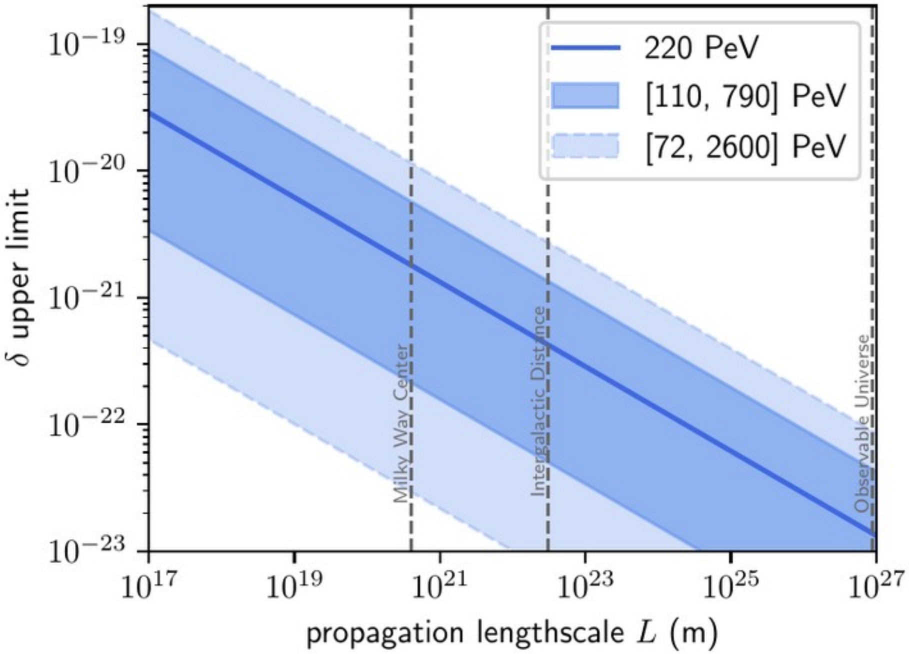
(c) The X-ray light curve for MRC 0614-083 that indicates a flaring activity around the neutrino arrival (Section 5.3).

Lorentz invariance violation

- Superluminous ν: energy loss via pair production:

$$\nu \to \nu + e^+ + e^-$$

- Assume propagated distance of $L = 10 c_\nu / \Gamma$ for interaction length Γ



$$\delta \equiv c_\nu^2 - 1$$

https://arxiv.org/abs/2502.08508

Lorentz invariance violation

Method	Limit
IceCube atmospheric	6.2×10^{-11}
IceCube NGC 1068	1.5×10^{-15}
IceCube TXS 0506+056	2.4×10^{-18}
Stecker et al. (Ref. [20])	5.2×10^{-21}
KM3-230213A (conservative)	1.8×10^{-21}
KM3-230213A (likely)	4.2×10^{-22}

- Improves previous limits by one order of magnitude

Conclusion

- KM3-230213A: Highest energetic neutrino ever detected ~220 PeV
- Directional uncertainty 1.5° - 3°, improved in the future
- Not produced in the Milky Way, cosmogenic as well as blazar origin possible