

# Astrophysical Neutrinos at KM3NeT

**Silvia Celli**

**on behalf of the KM3NeT Collaboration**

[silvia.celli@roma1.infn.it](mailto:silvia.celli@roma1.infn.it)

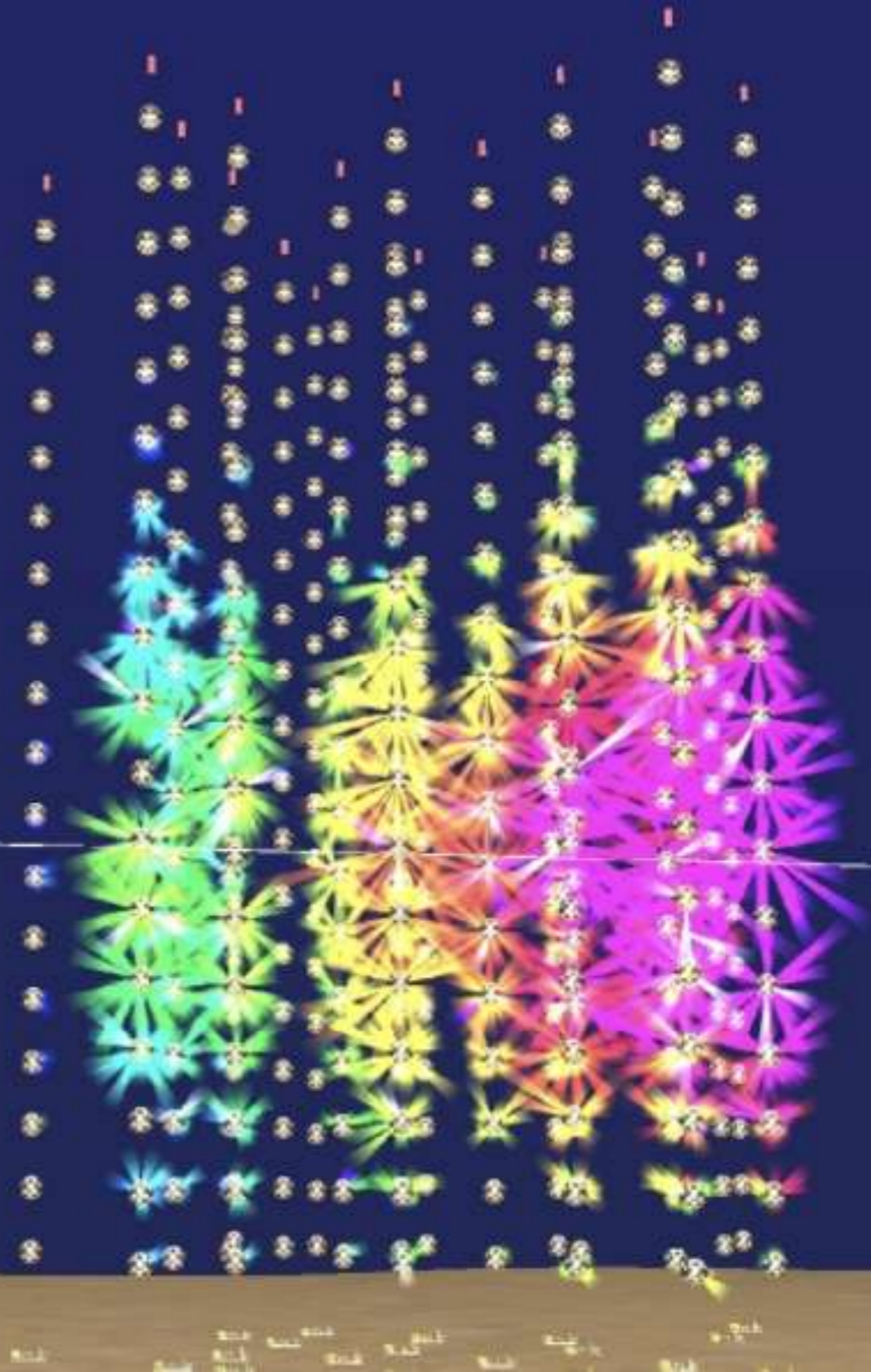
Sapienza Università di Roma, Italy

INFN - Sezione di Roma, Italy



# Outline

- **The KM3NeT infrastructure**
- **Latest KM3NeT/ARCA results in neutrino astronomy**
- **KM3-230213A: first observation of an UHE neutrino by KM3NeT/ARCA**
- **Summary & conclusions**



# KM3NeT at a glance

## Two detectors

- **Astronomy Research with Cosmic in the Abyss (ARCA)**
- **Oscillation Research with Cosmic in the Abyss (ORCA)**

## 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

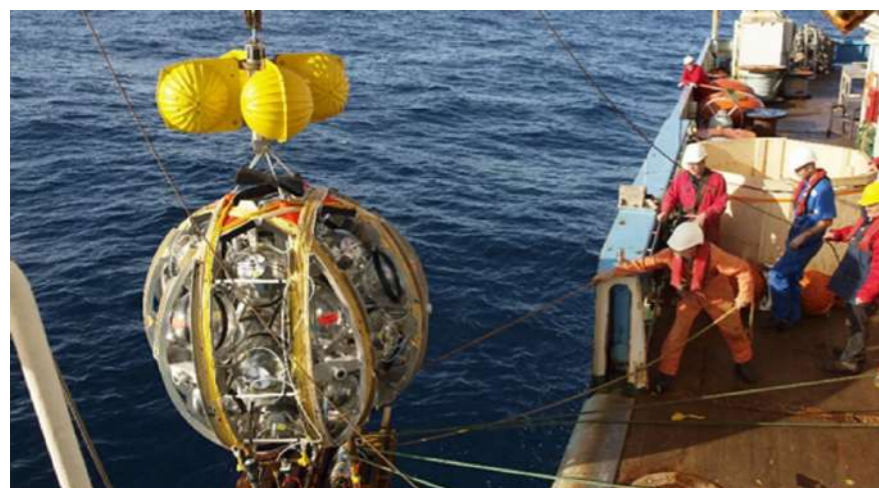
Front end electronics

- Uniform coverage
- Directional information
- Digital photon counting

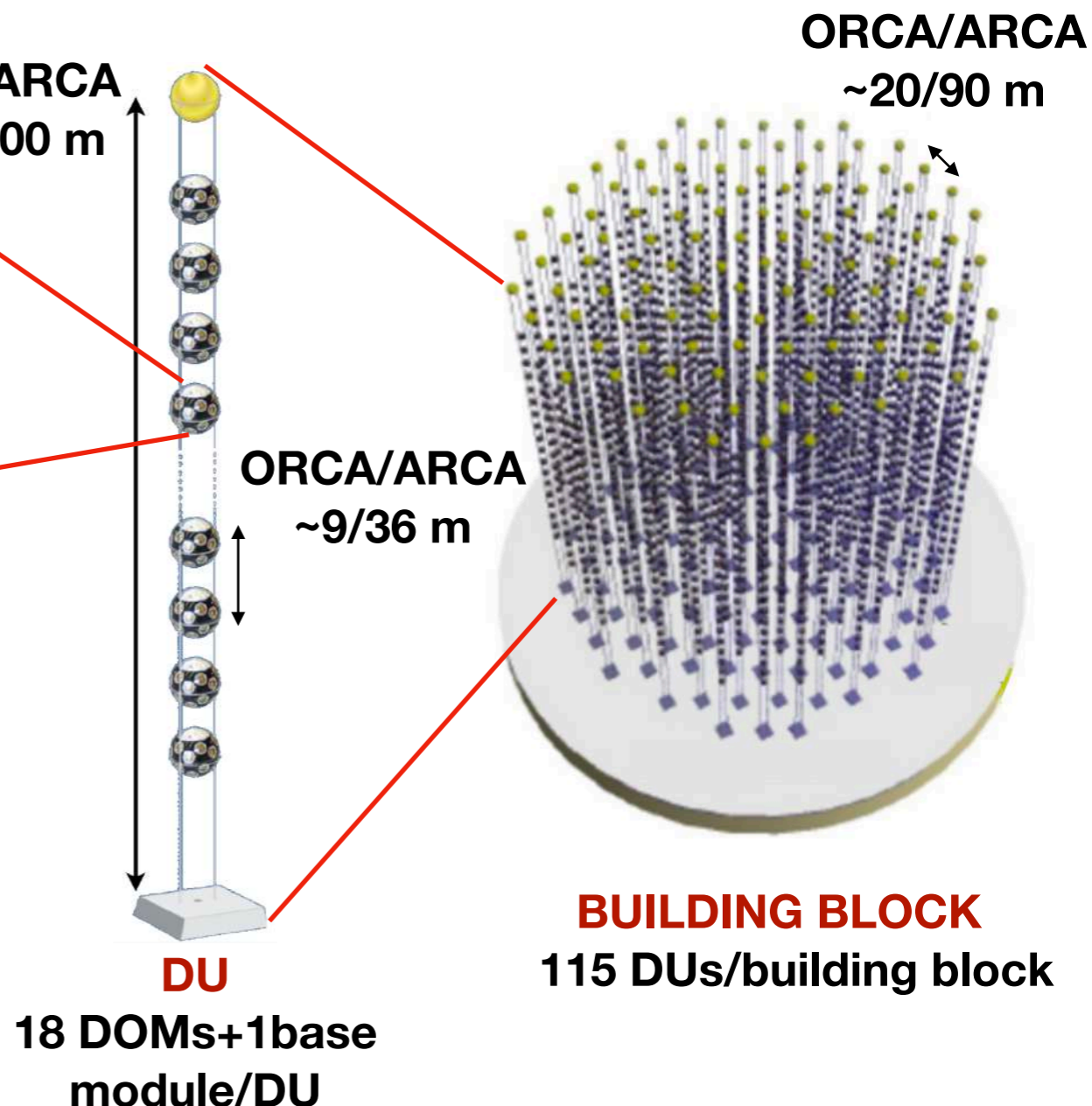


DOM

ORCA/ARCA  
~200/700 m



Launcher of Optical Modules



All data to shore DAQ

# KM3NeT: a top view



## ARCA (1 GTon)

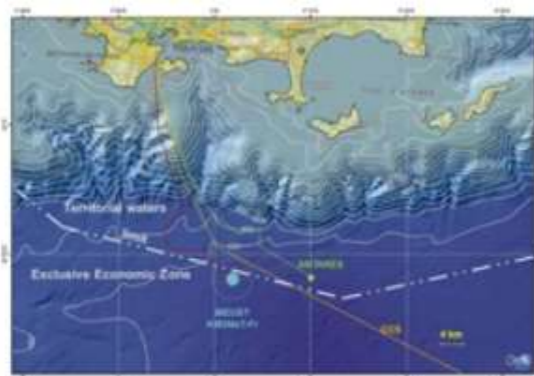
Astroparticle Research  
with Cosmics in the Abyss



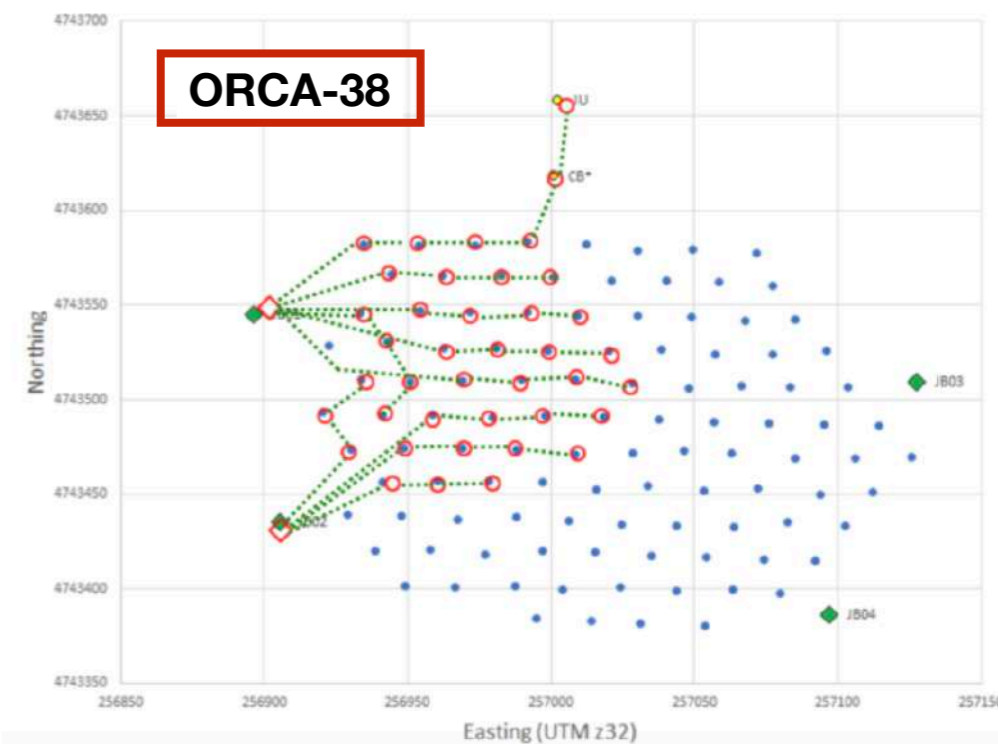
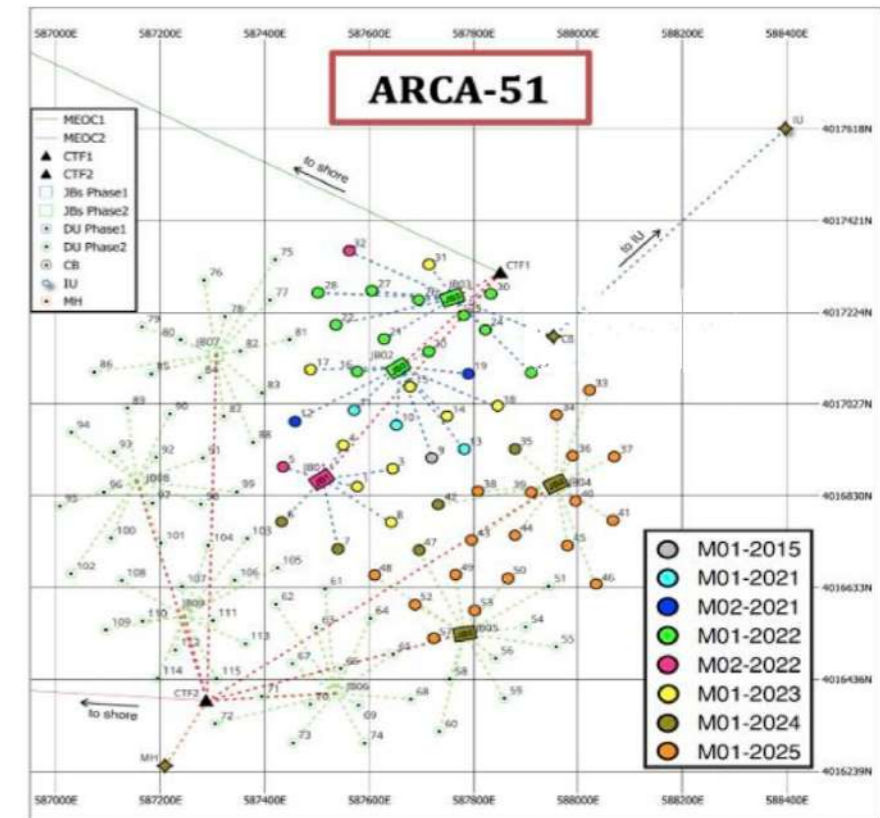
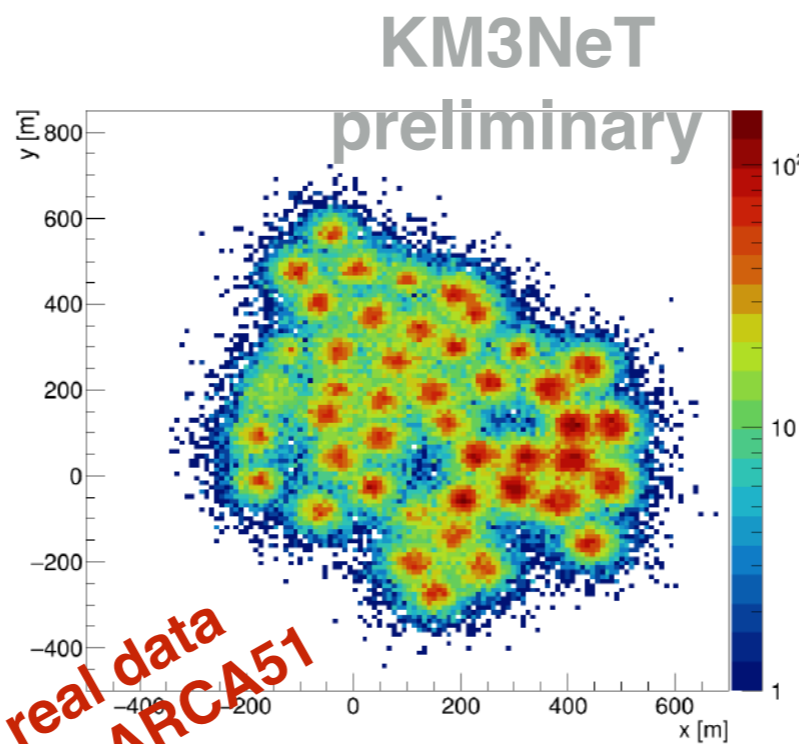
**3500 m depth,**  
offshore Sicily

## ORCA (6 MTon)

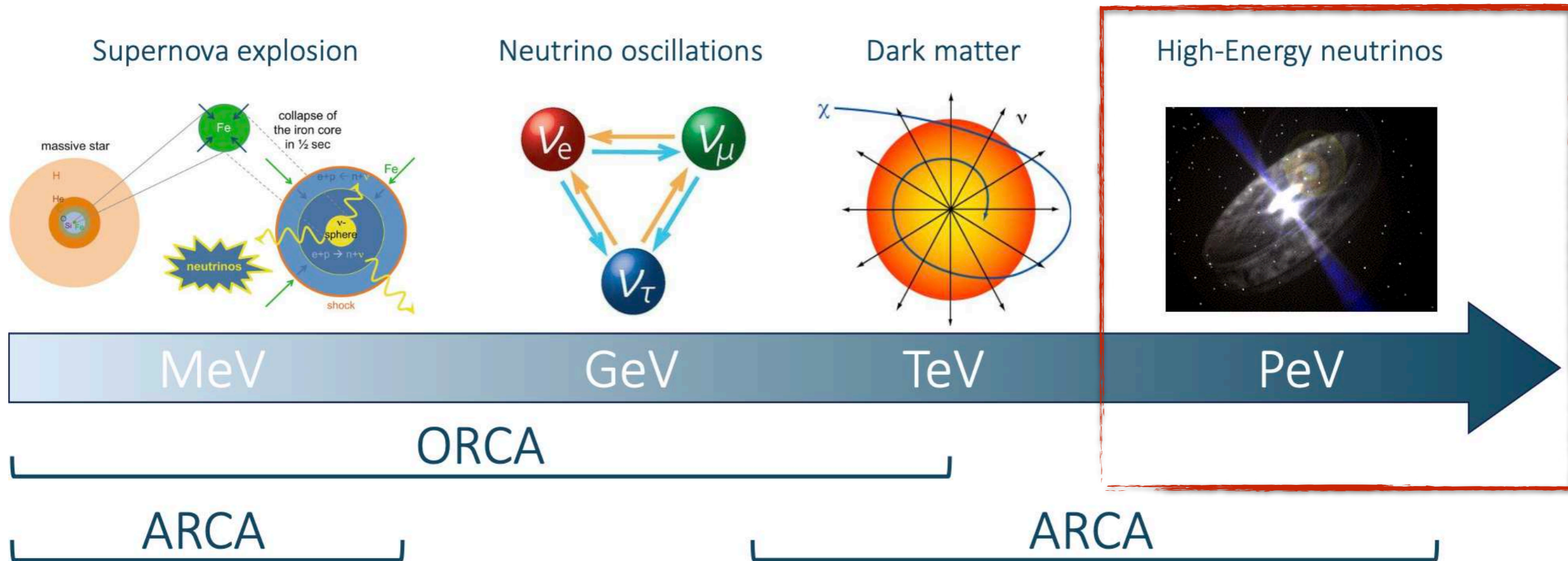
Oscillation Research  
with Cosmics in the Abyss



**2500 m depth,**  
offshore Toulon



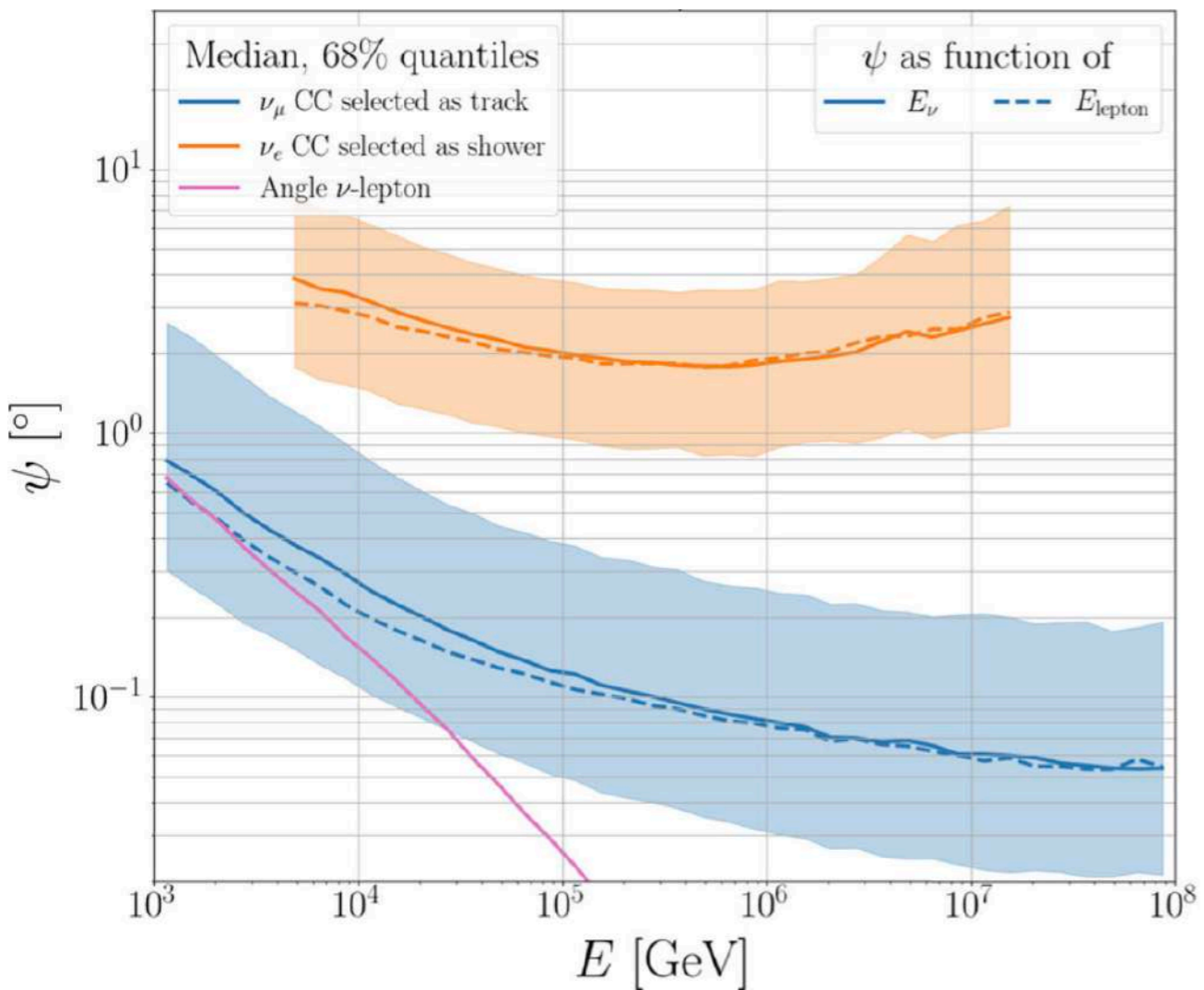
# The KM3NeT multi-energy scale science program



Same technology, complementary science goals

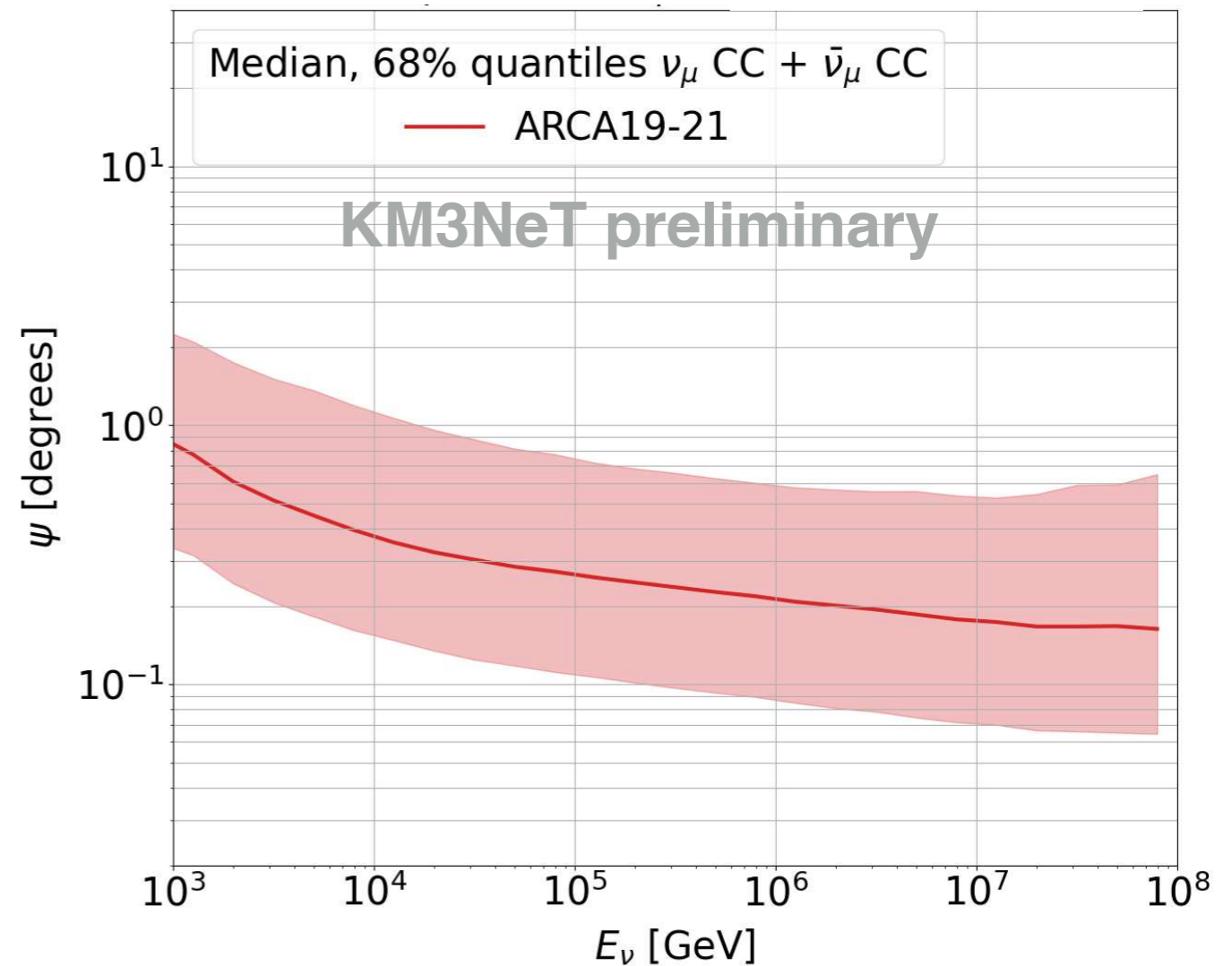
# The KM3NeT/ARCA angular resolution

## Full ARCA



Aiello et al. [KM3NeT], EPJC 84 (2024) 885

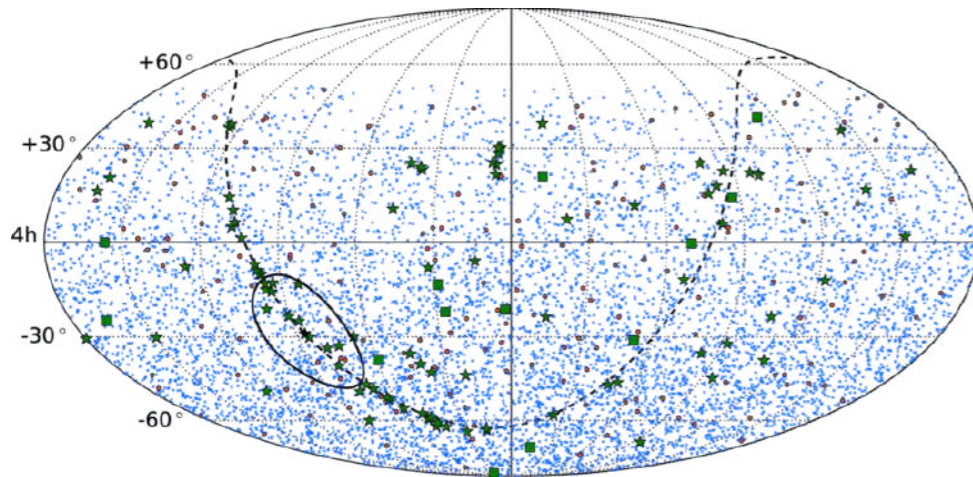
## ARCA19-21



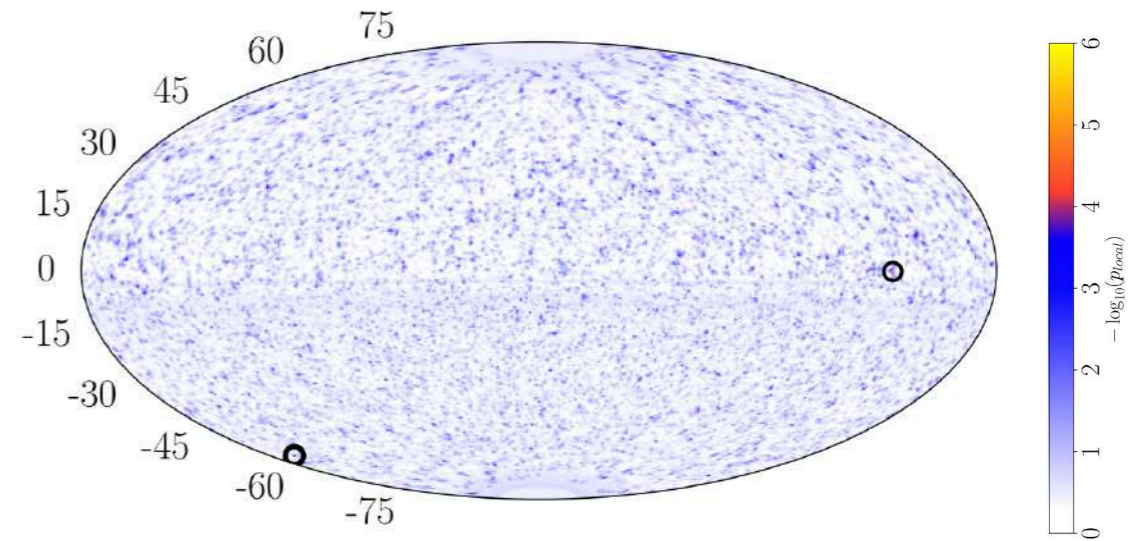
Adriani et al. [KM3NeT], in prep.

# Cosmic neutrino search methods

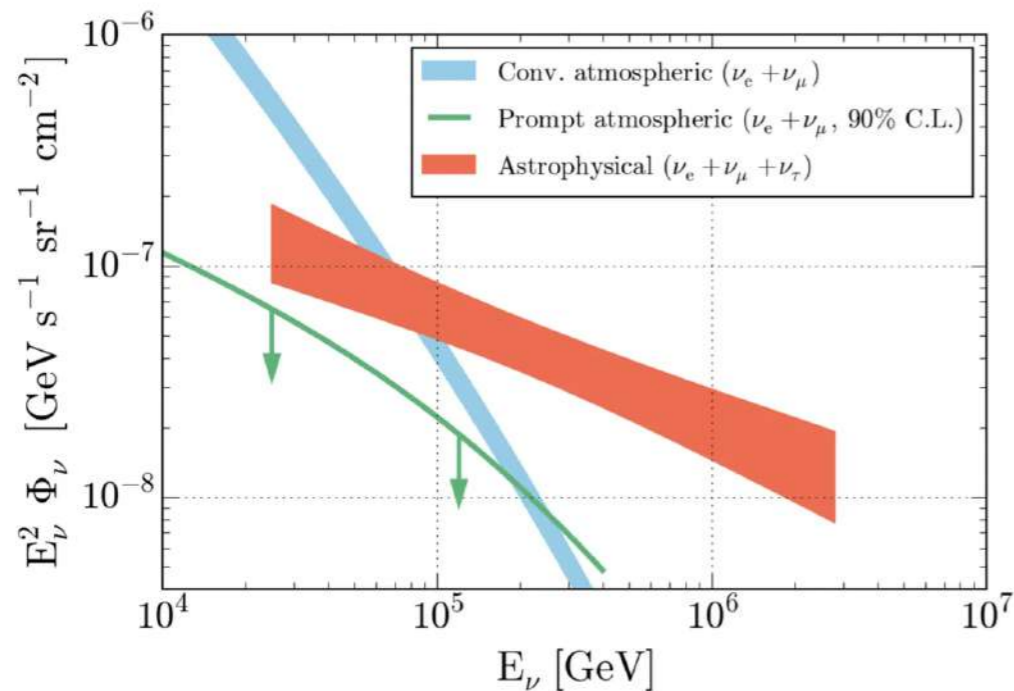
## Point source search (catalog search)



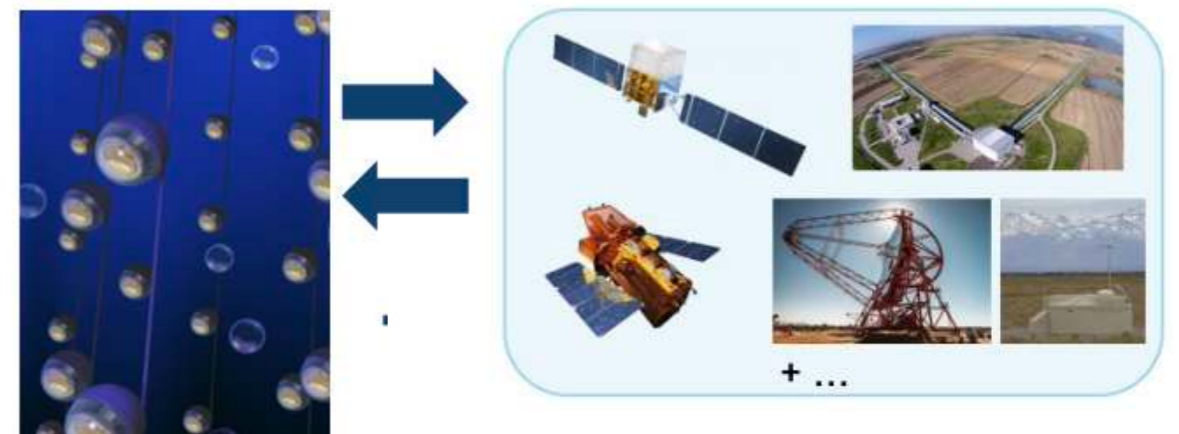
## Point source search (auto-correlation)



## Diffuse search



## Real-time multi-messenger search



# KM3NeT/ARCA point-like neutrino source search

- ARCA 19-21 dataset (336 days of livetime)
- **Up-going track-like** event selection (KM3-230213A not in this sample)
- Binned log-likelihood approach in energy and direction, with data-driven background computation

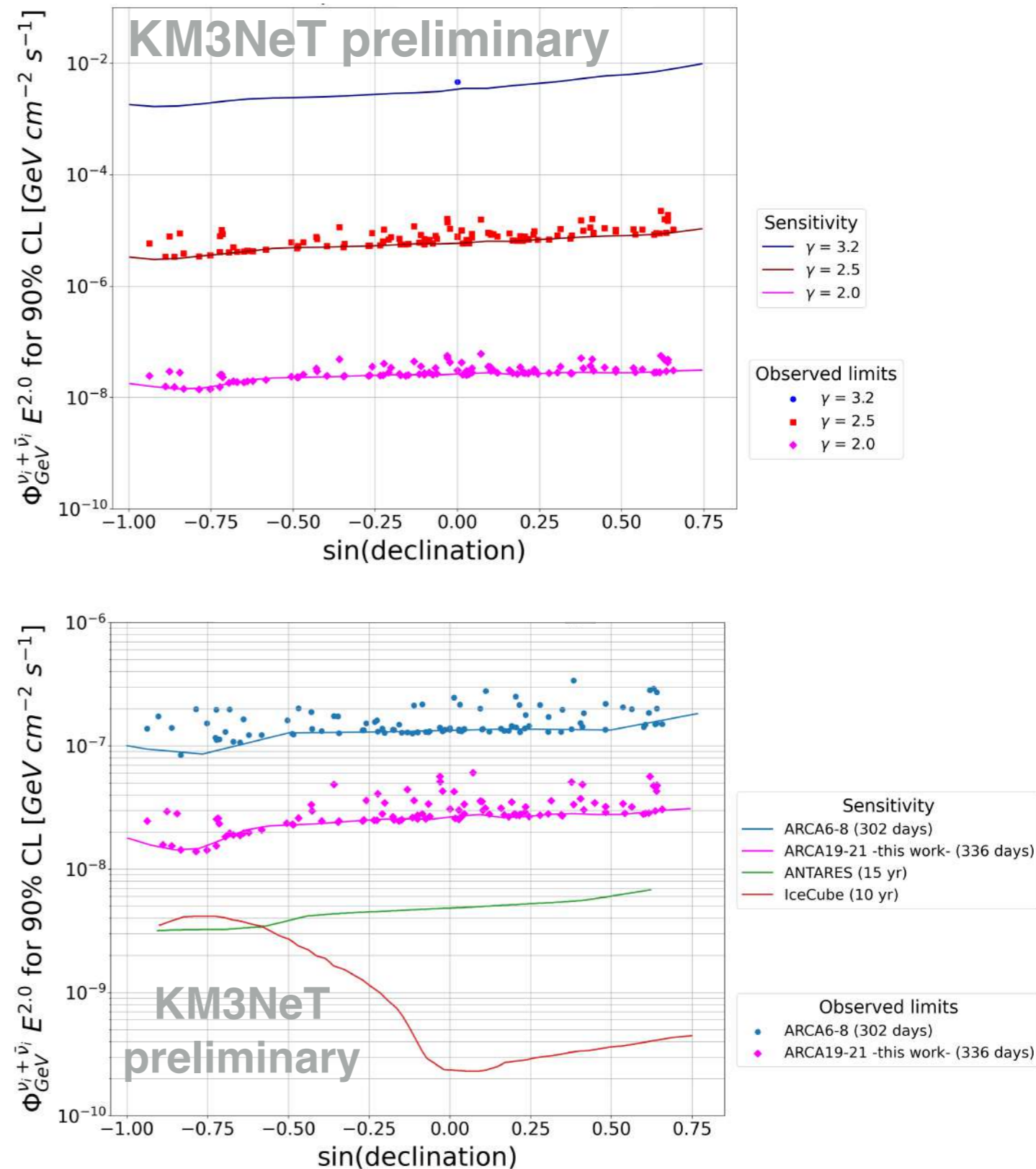
$$\lambda = \log L(\xi = \hat{\xi}) - \log L(\xi = 0)$$

$$\log L = \sum_i [N_i \log(B_i + \xi S_i) - (B_i + S_i)]$$

- Catalog-based search: 106 sources tested with different signal spectral hypotheses:  $E^{-2}$ ,  $E^{-2.5}$  &  $E^{-3.2}$  (NGC1068 only), **5° semi-aperture angular search** region of around each source, lowest  $p$ -value (pre-trial  $5.0 \times 10^{-3}$ ) at CGCG 420-015 for  $E^{-2}$  spectrum



Adriani et al. [KM3NeT], in prep.



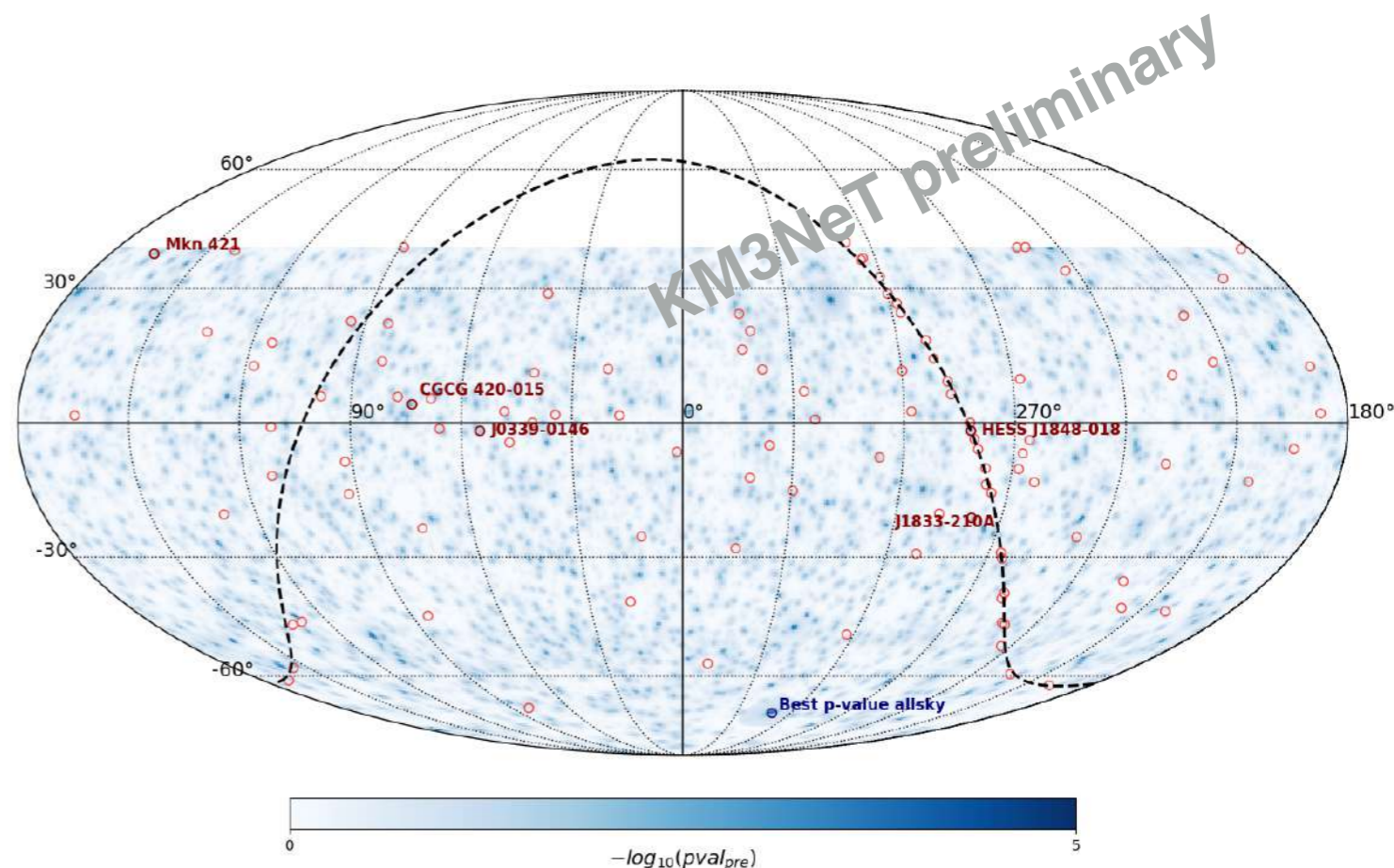
# KM3NeT/ARCA point-like neutrino source search

- ARCA 19-21 dataset (336 days of livetime)
- **Up-going track-like** event selection (KM3-230213A not in this sample)
- Binned log-likelihood approach in energy and direction, with data-driven background computation

$$\lambda = \log L(\xi = \hat{\xi}) - \log L(\xi = 0)$$

$$\log L = \sum_i [N_i \log(B_i + \xi S_i) - (B_i + S_i)]$$

- All-sky scan: searches for excess on top of uniform bkg, 2.6 million bins with  $\delta < 40^\circ$ , signal spectral hypothesis:  $E^{-2}$ , lowest *p-value* (pre-trial  $4.1 \times 10^{-5}$ ) at  $RA=310.8^\circ$ ,  $\delta=-71.3^\circ$



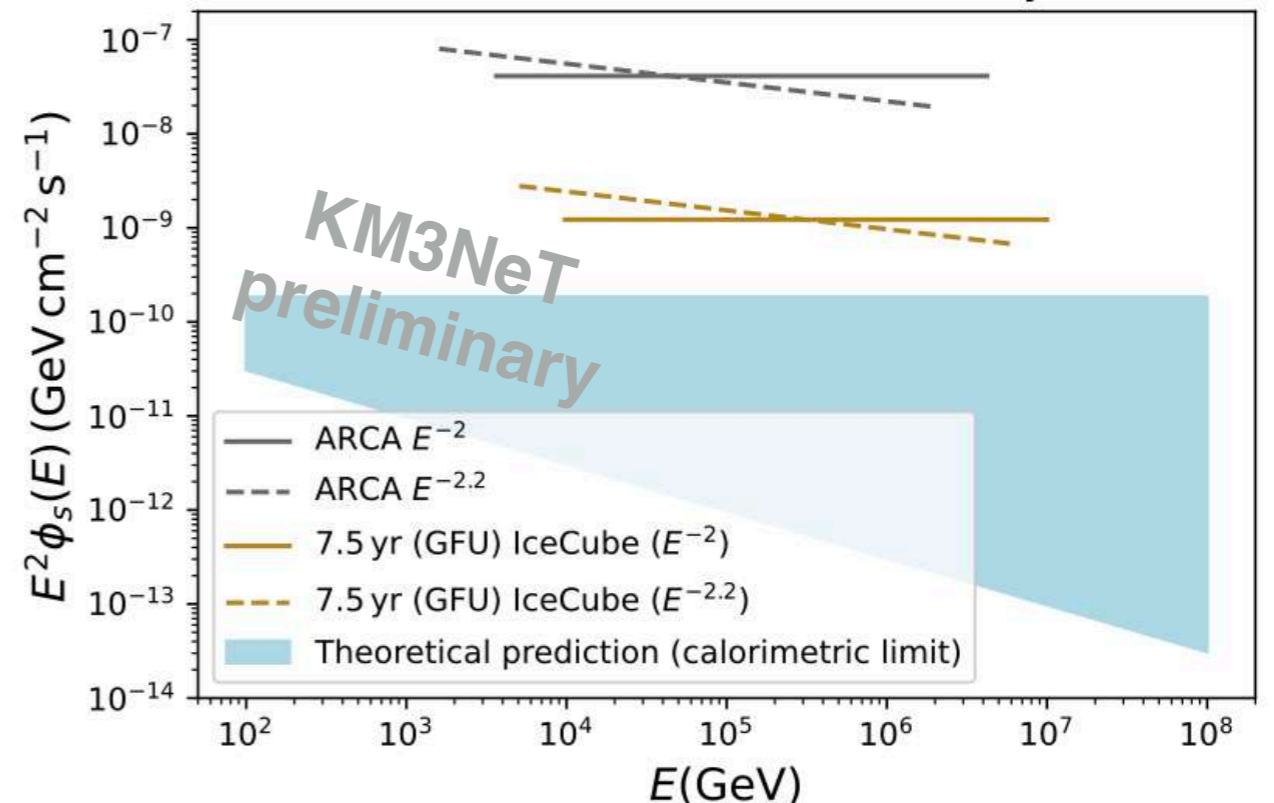
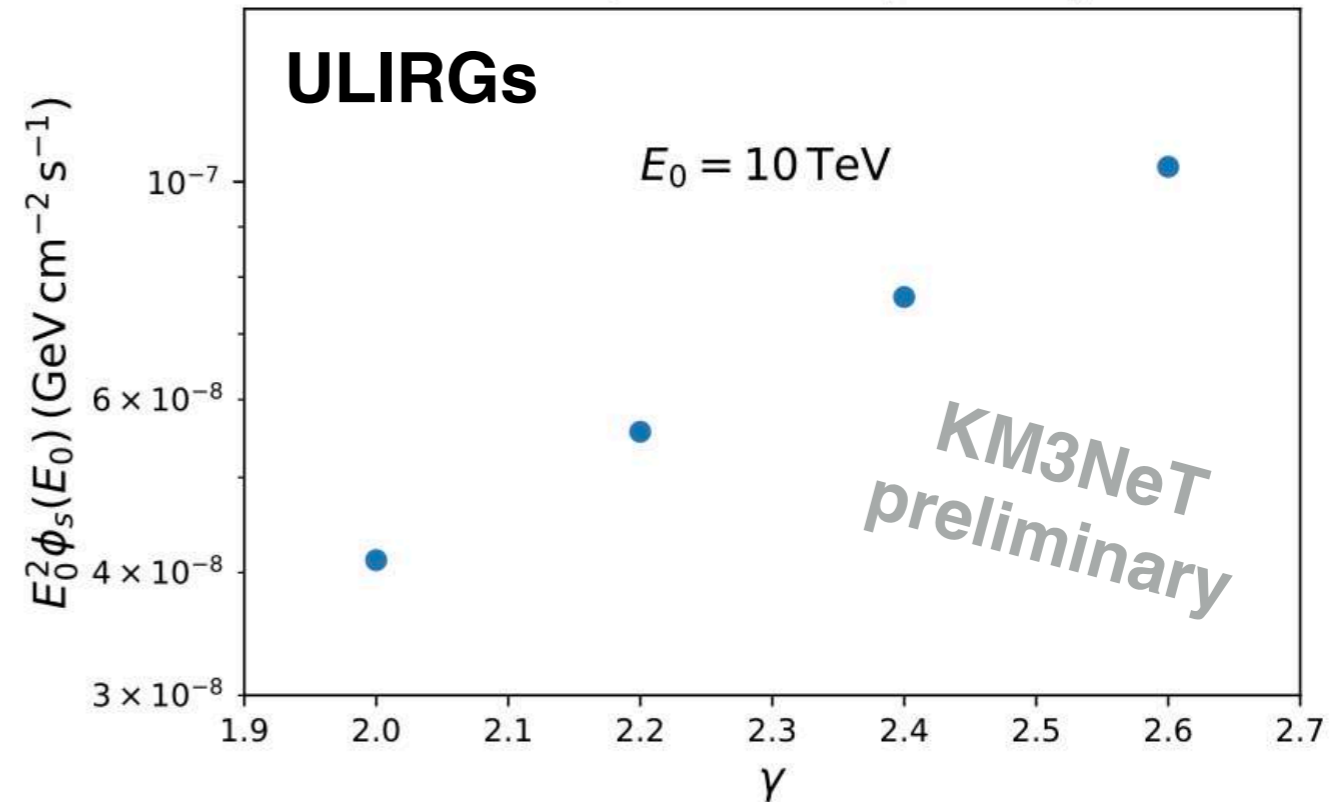
Adriani et al. [KM3NeT], in prep.

# ARCA19-21 stacking analyses

- ARCA19-21 dataset (336 days livetime) with **up-going track-like** reconstruction (KM3-230213A not in this analysis)
- Binned log-likelihood approach in energy and direction, with data-driven bkg computation
- 3 candidate source populations:
  - 75 **ultra luminous IR galaxies (ULIRGs)**, from IRAS dataset (1 Jy @ 60  $\mu\text{m}$ , i.e. with distances between 80 and 630 Mpc), modeled via different spectral hypothesis for neutrinos using a weight proportional to IR flux
  - No significant detection so far

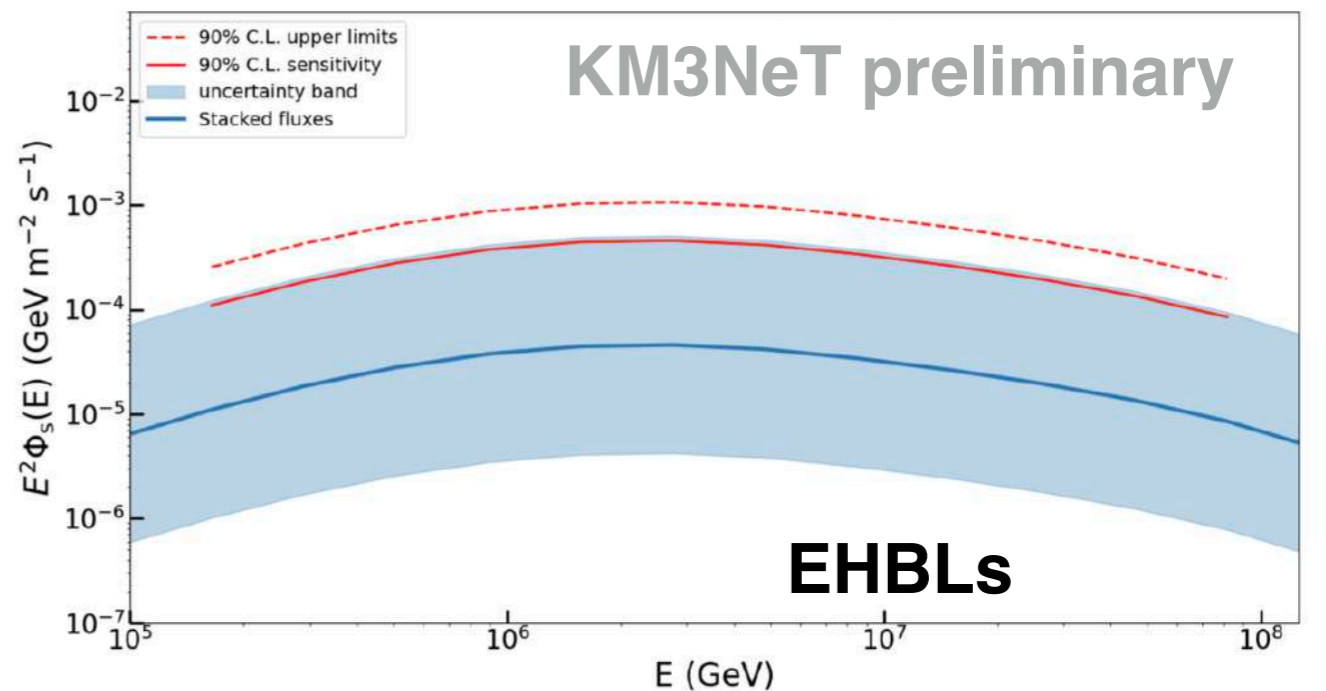
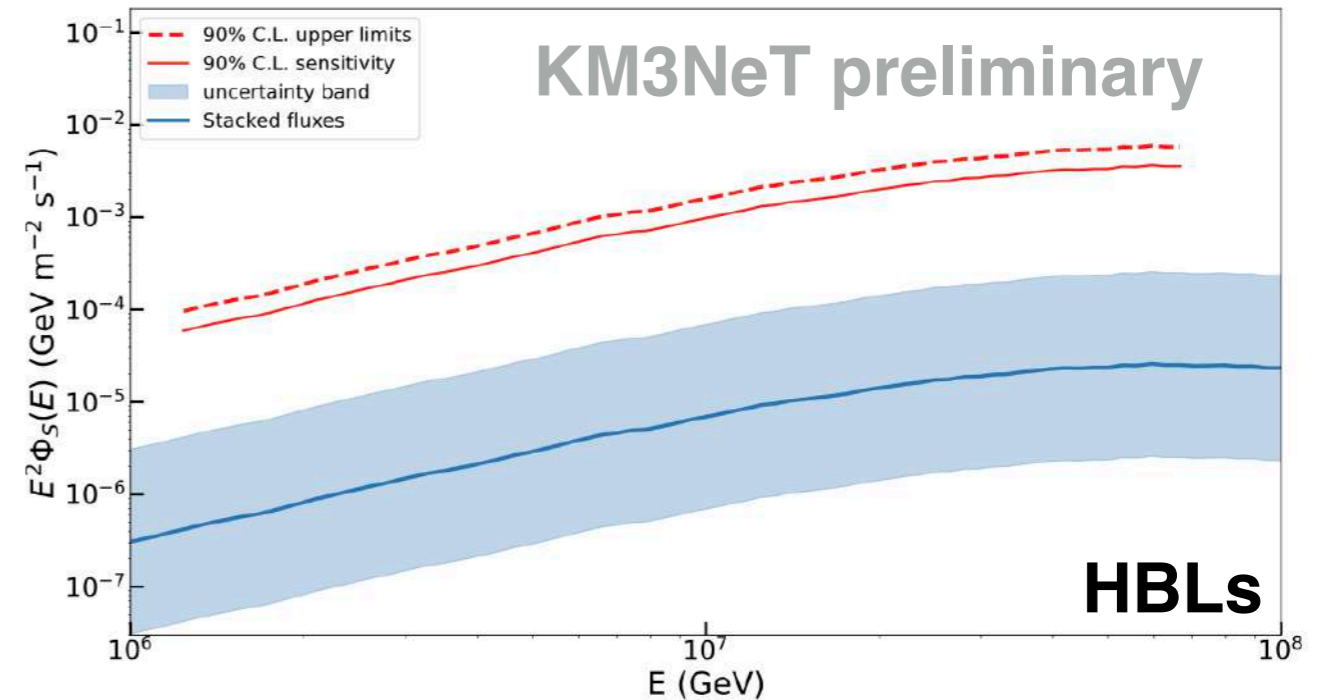


Adriani et al. [KM3NeT], in prep.



# ARCA19-21 stacking analyses

- ARCA19-21 dataset (336 days livetime) with **up-going track-like** reconstruction (KM3-230213A not in this analysis)
- Binned log-likelihood approach in energy and direction, with data-driven bkg computation
- 3 candidate source populations:
  - 232 **high-synchrotron peaked blazars (HBLs)**, selected from 3HSP catalog with known redshift,  $\delta < 40^\circ$  &  $10^{15} < v_{\text{syn}} / \text{Hz} < 10^{16.8}$
  - 88 **extreme synchrotron peaked blazars (EHBLs)**, with  $v_{\text{syn}} / \text{Hz} > 10^{16.8}$  & counterpart in Fermi 4FGL
  - Both blazar sample consider neutrino spectra from lepto-hadronic modeling (LeHa-Paris for HBLs & LeHaMoC for EHBLs)
  - No significant detection so far

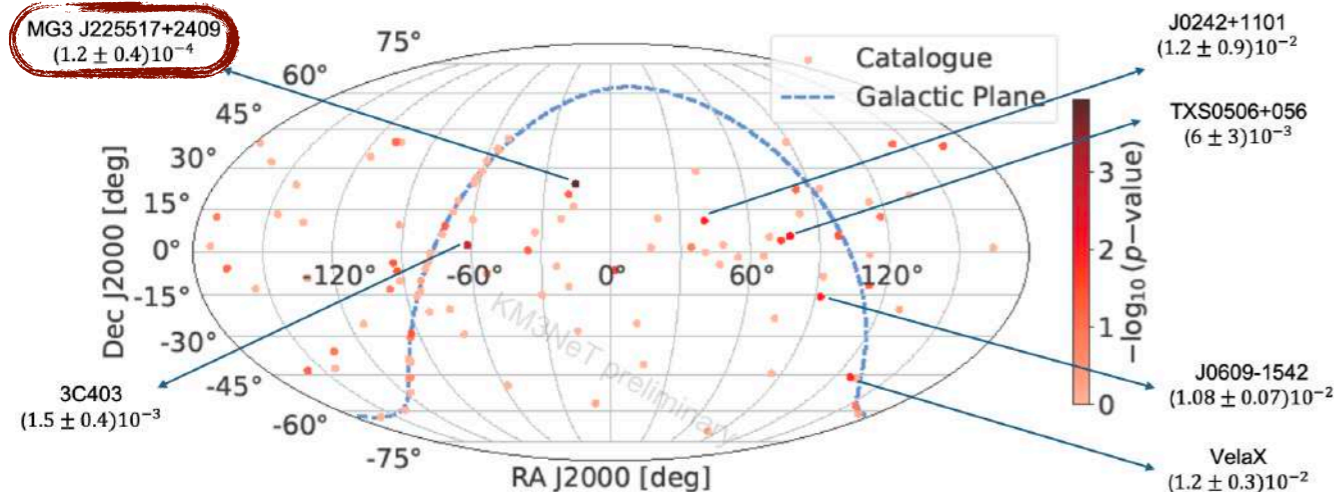
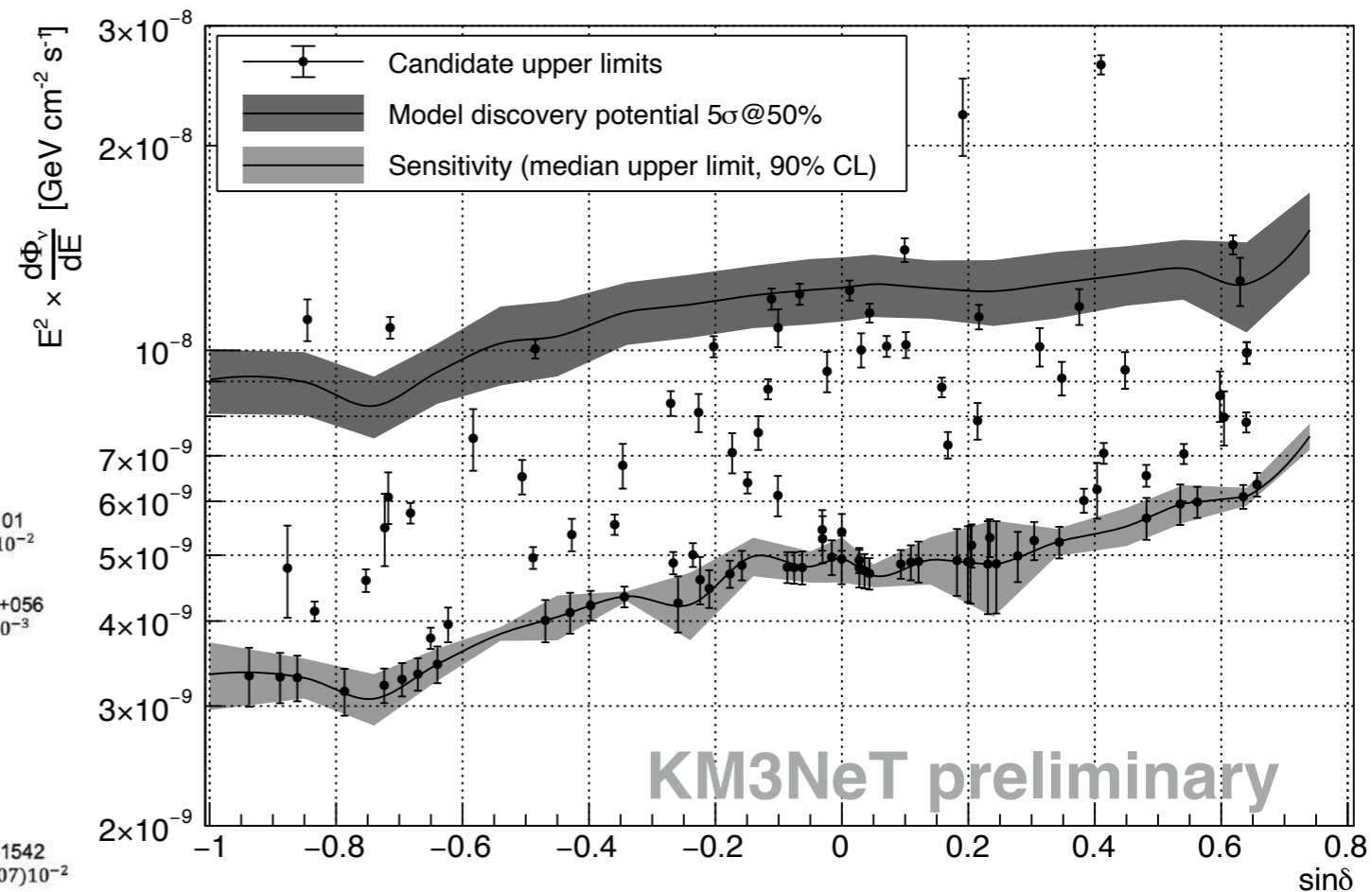
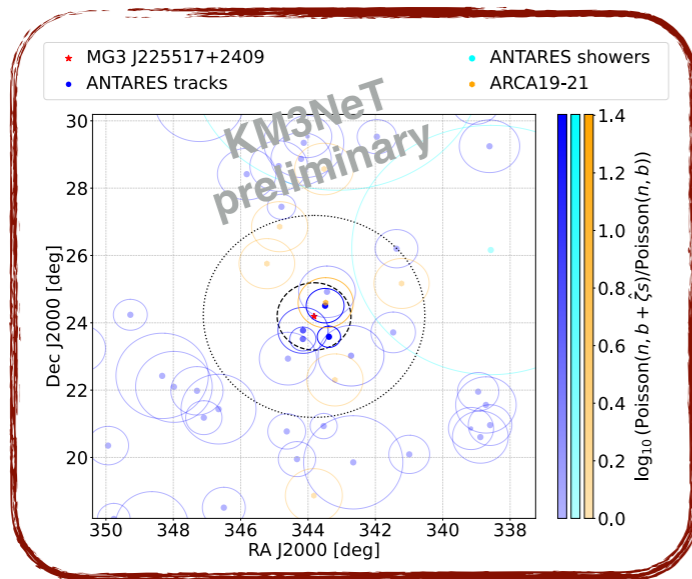


# Combined ANTARES/ARCA catalog stacking analysis

- **ANTARES tracks+showers**, 4541 days livetime
- **ARCA19+21 tracks**, 336 days livetime
- Common analysis framework applied to **catalog search of 106 sources**
- Combined **up-going** dataset in binned likelihood analysis
- 20% sensitivity & discovery flux improvement wrt ANTARES-only
- Most significant source is MG3 J225517+2409, a blazar from Fermi 3LAC catalog



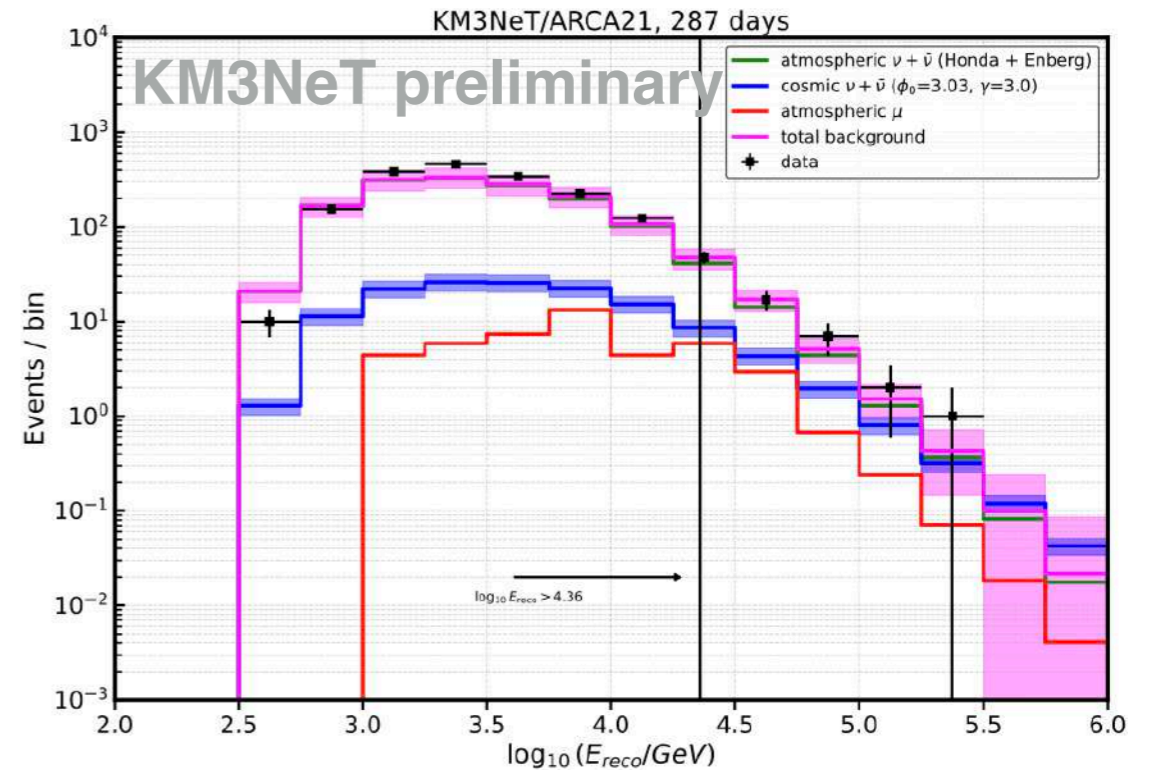
Albert et al. [ANTARES], arXiv:2511.07239



Adriani et al. [KM3NeT], in prep.

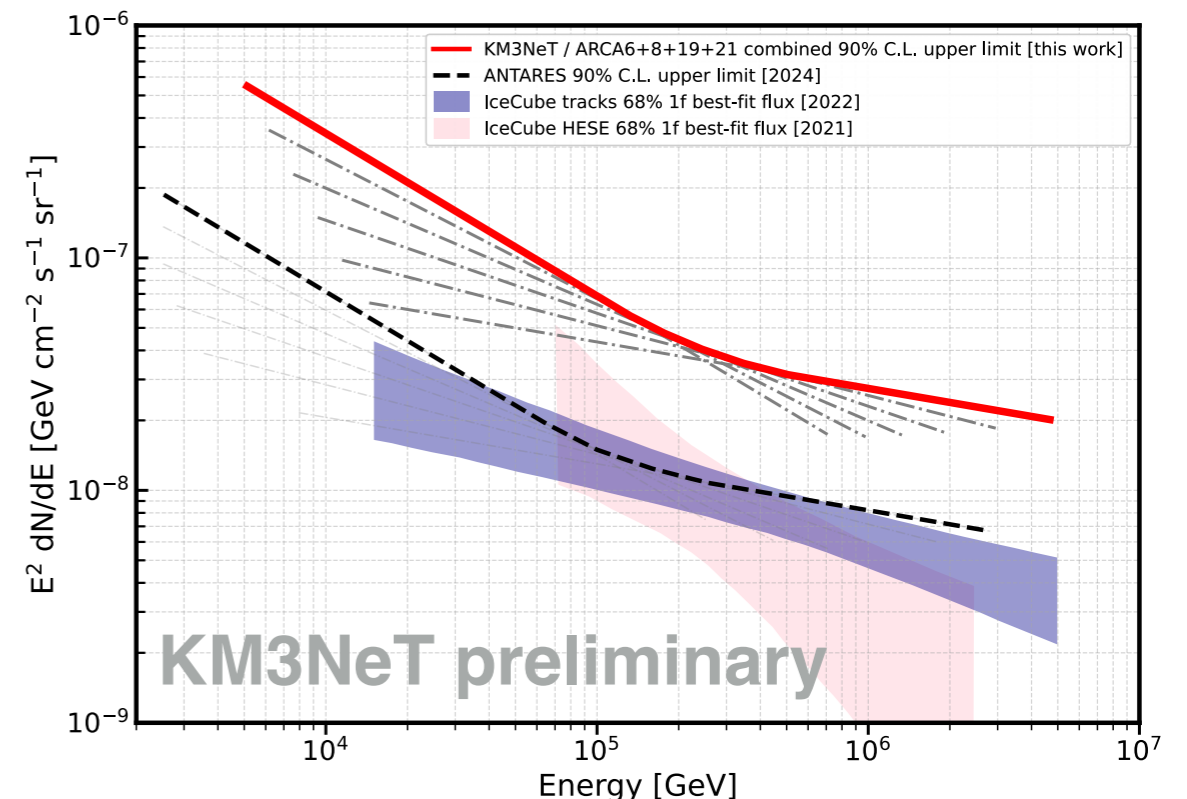
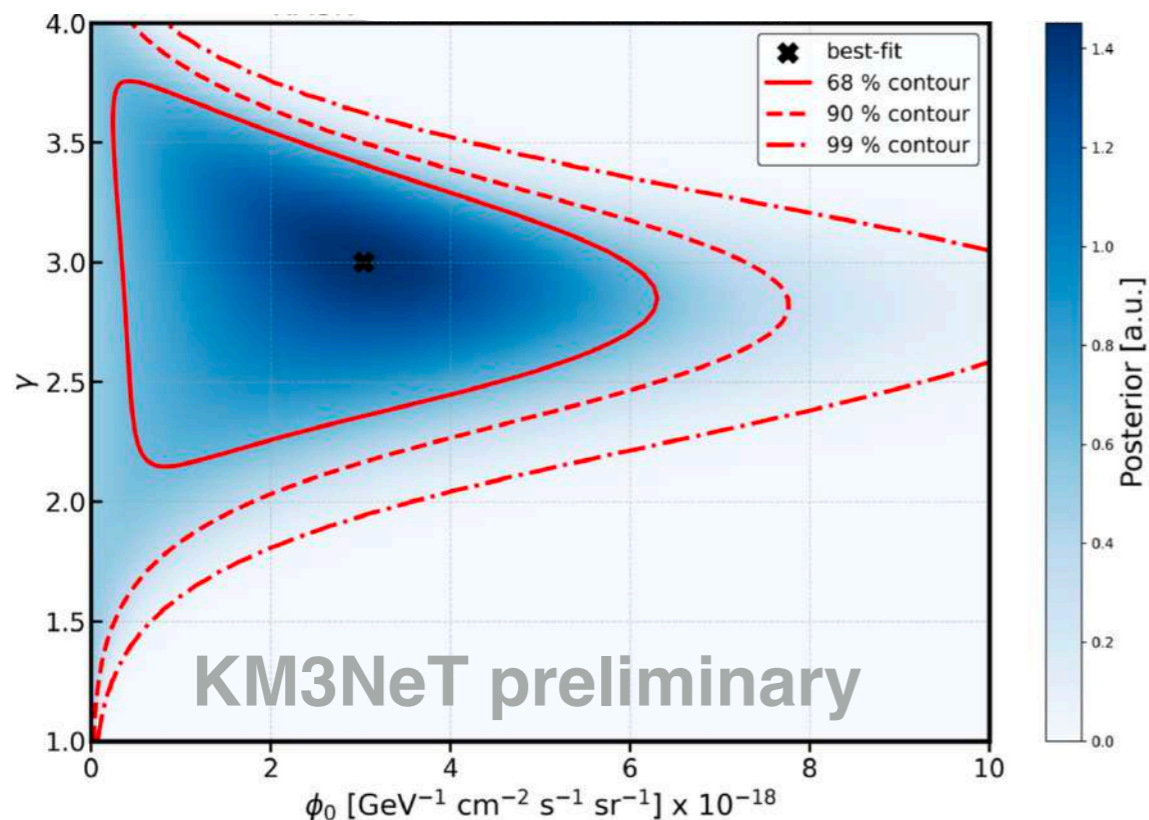
# ARCA diffuse cosmic neutrino search

- **ARCA 6-8-19-21 dataset** (640 days of livetime, up to Sept. 2023)
- **Up-going track-like events** (KM3-230213A not in this sample), including BDT to further suppress mis-reconstructed atmospheric muons
- MC driven background calculation including systematic uncertainties
- MRF metrics for energy & BDT cut optimization, leading to **97% neutrino purity** in ARCA19-21 dataset



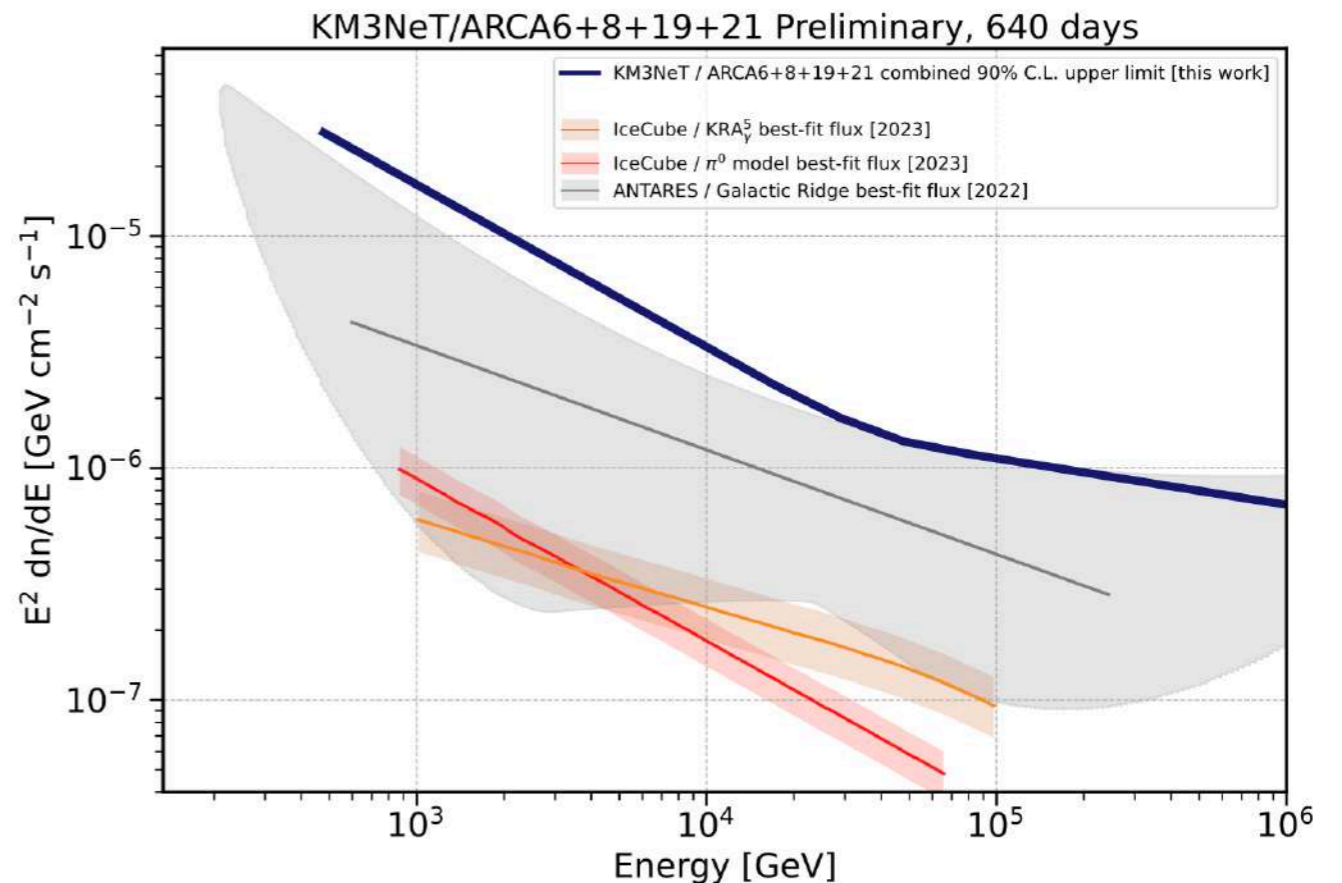
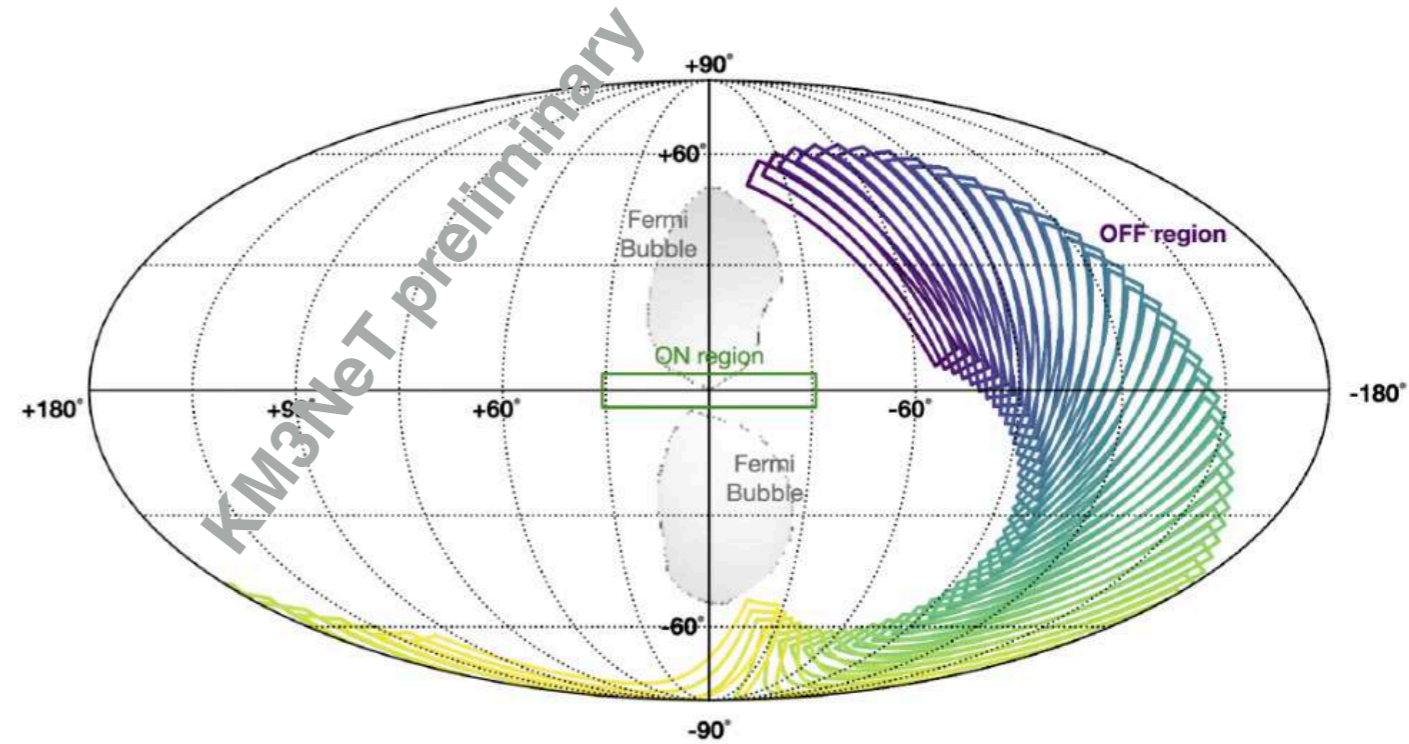
Adriani et al. [KM3NeT], in prep.

$$\Phi_{\nu+\bar{\nu}}(E) = \frac{dN}{dE} = \phi_0 \cdot 10^{-18} \left( \frac{E}{100 \text{ TeV}} \right)^{-\gamma} \quad [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$$



# ARCA Galactic Ridge analysis

- **ARCA 6-8-19-21 dataset** (640 days of livetime, up to Sept. 2023)
- **Up-going track**-like events, including BDT cuts to further suppress mis-reconstructed atmospheric muons
- $|l| < 30^\circ$  &  $|b| < 2^\circ$ , where CR spectral hardening has been claimed
- **Model independent approach** based on **cut&count** method, comparing event counts & energy distributions in pre-defined signal (ON) region & in signal-depleted (OFF) control regions (data-driven background)
- MRF as metrics for cut optimization for different spectral hypotheses, leading to  $\mu$  contamination after BDT selection  $< 5\%$  & signal efficiency  $> 80\%$  for well reconstructed tracks (angular resolution within  $10^\circ$ )
- No excess identified so far, upper limits getting closer to ANTARES best-fit flux



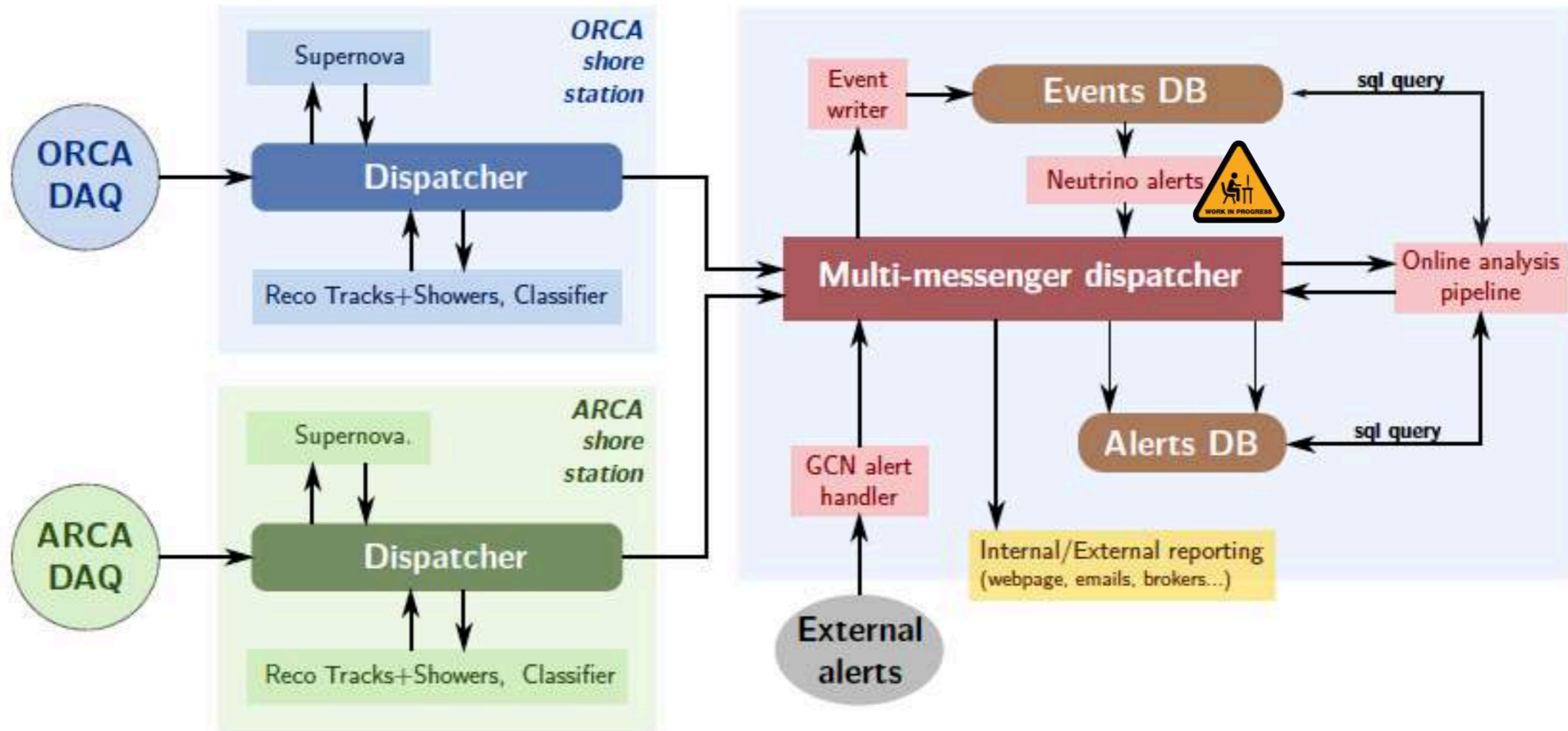
# KM3NeT real time analysis system

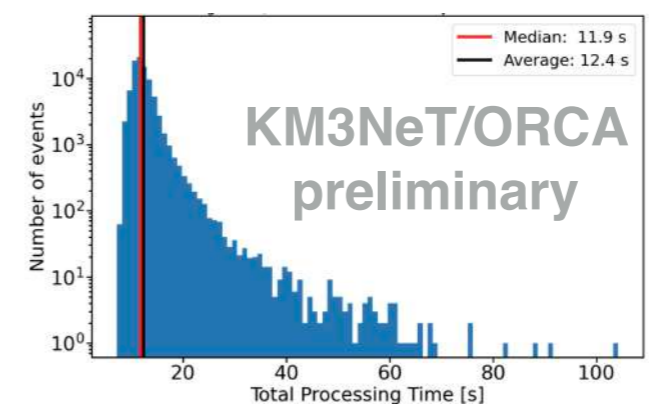
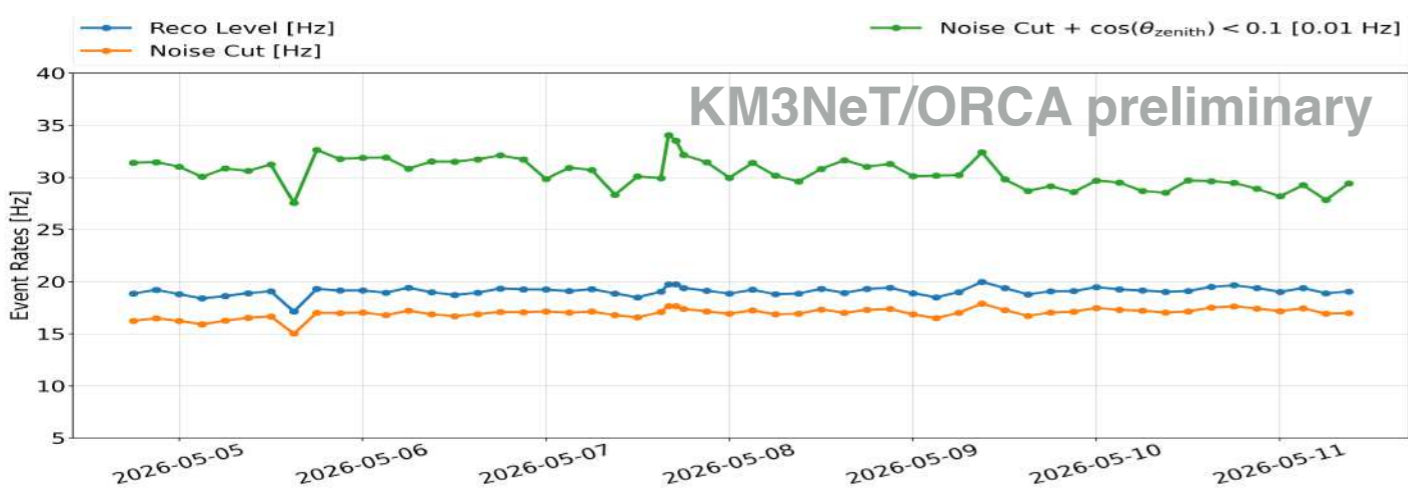


In the view of searching for correlation among  $\nu$  and MM signals (EM, GW), it is increasingly crucial to be able to identify (**reconstruct, classify & select**) cosmic neutrinos in real-time to allow **fast follow-up** for counterpart identification.

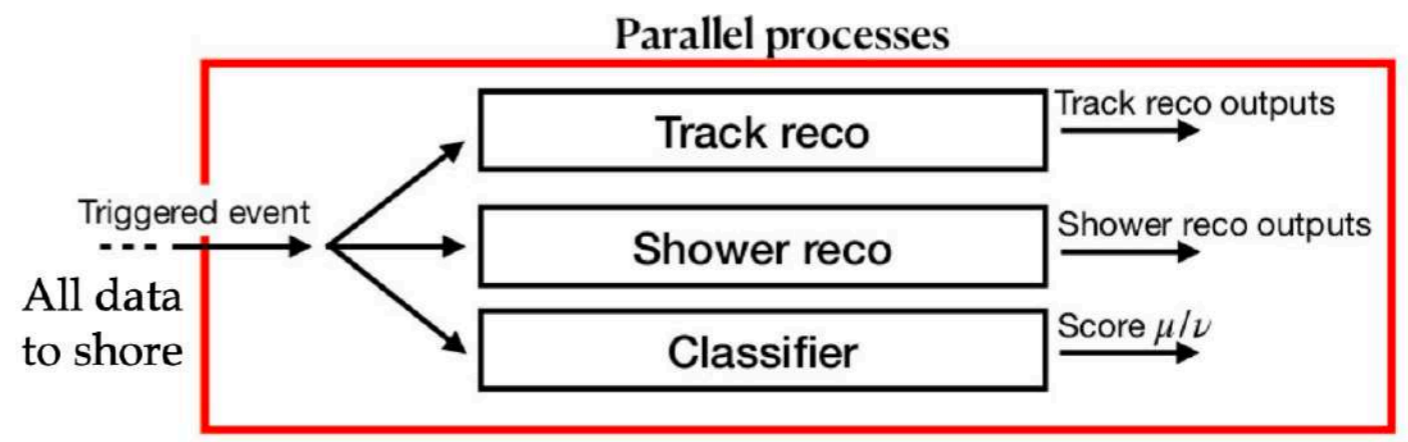
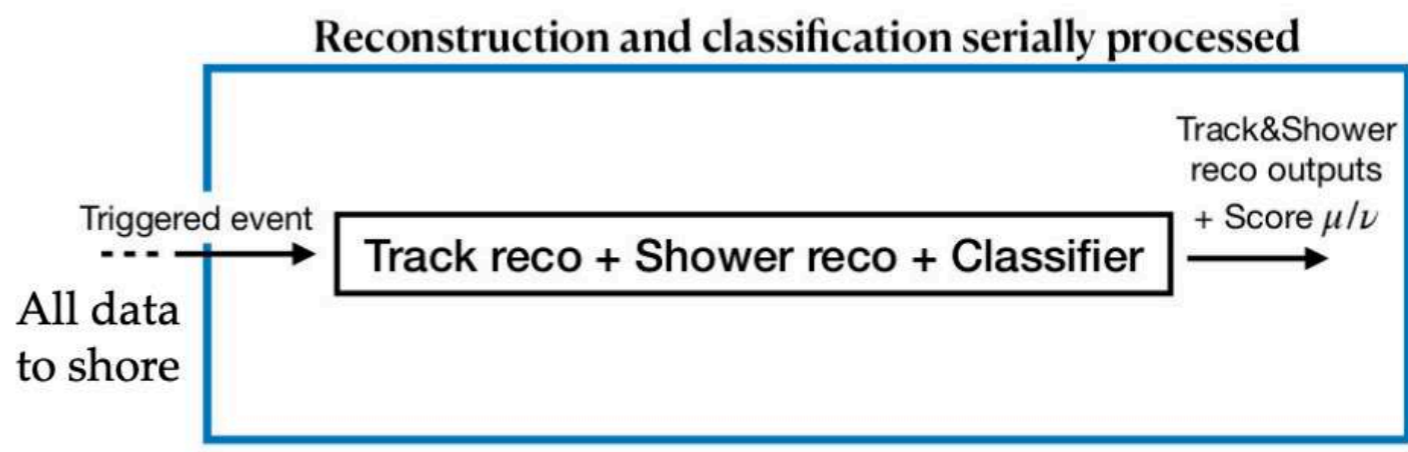
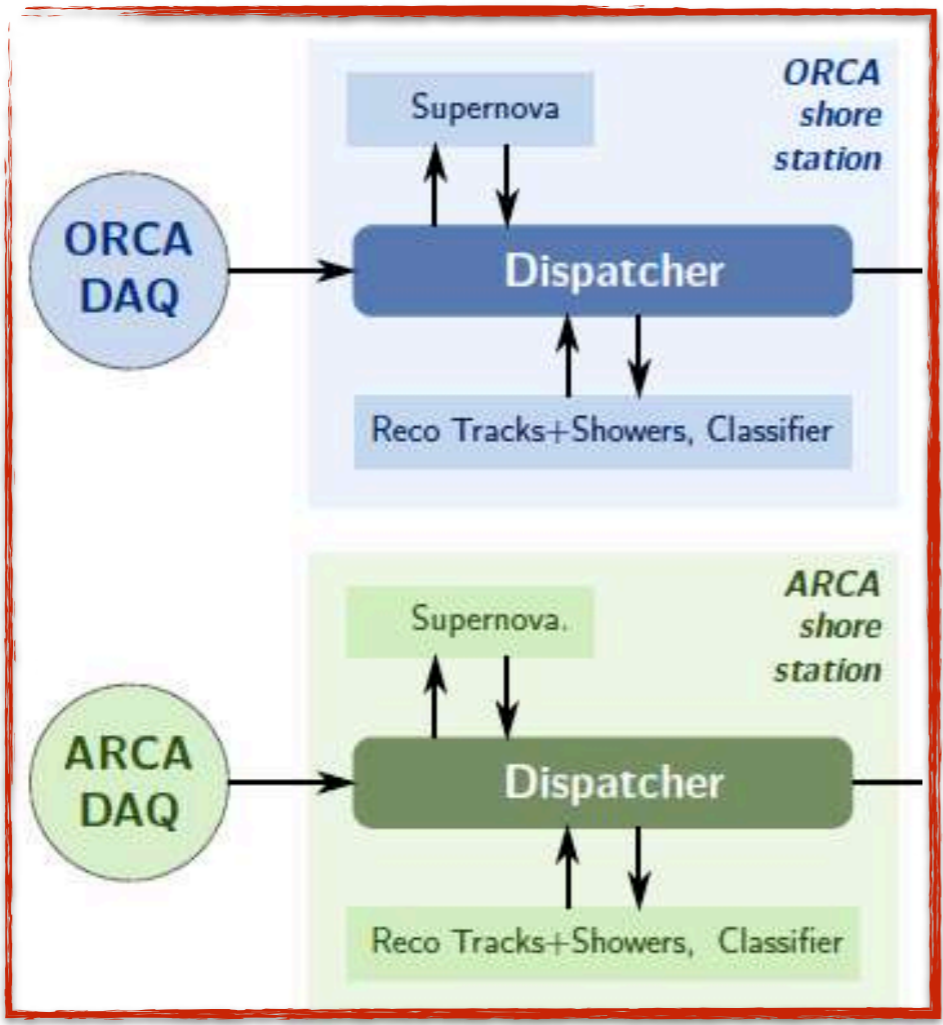
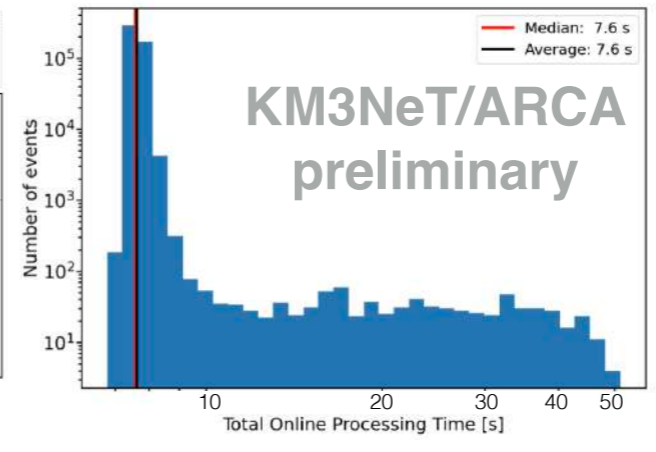
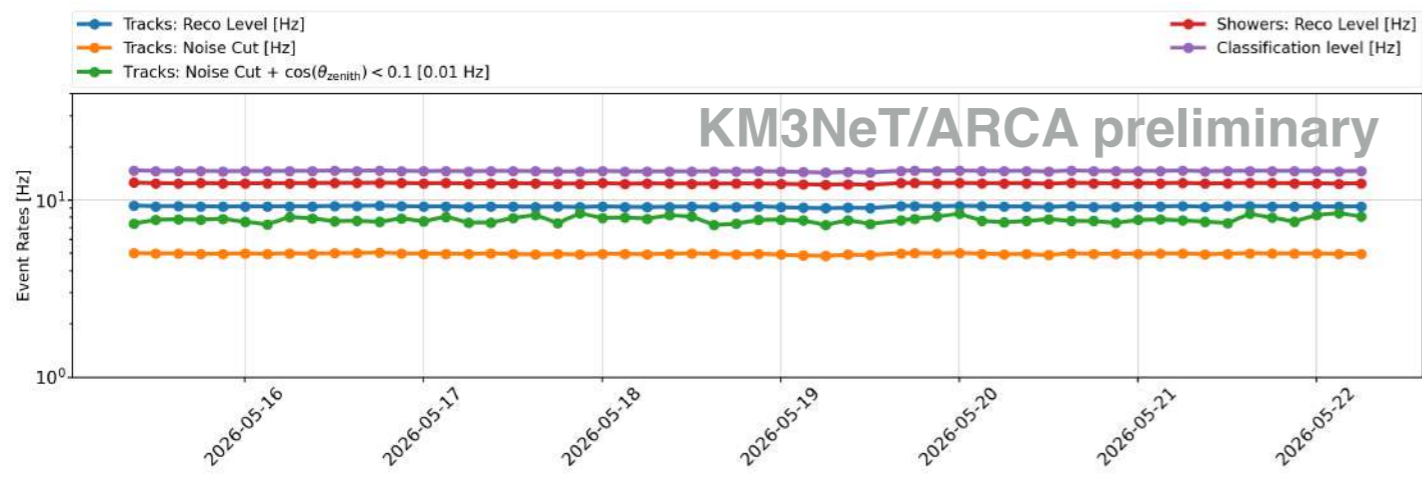
The **Real-Time Analysis (RTA)** program includes:

- Continuous **SN monitoring** (MeV)
- **Follow-up of external triggers** with KM3NeT data (>GeV)
- **Neutrino alert sending** (>GeV, HE, multiplets, ...)

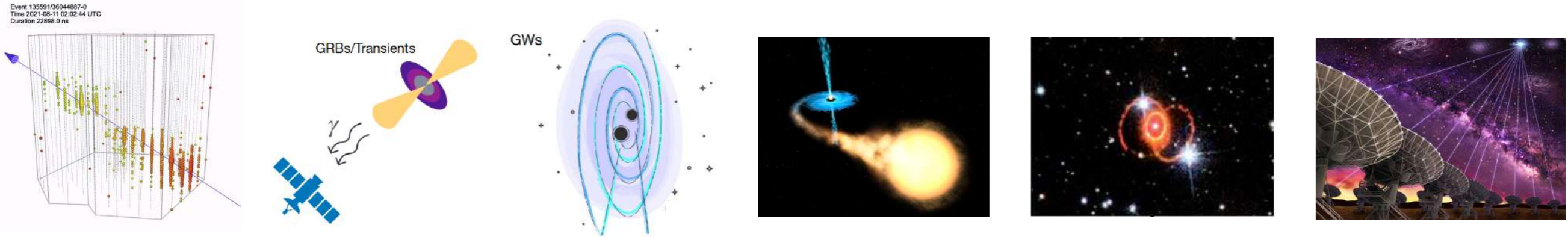




**+ analysis time  
→ KM3NeT  
can provide  
neutrino  
candidates  
within ~20  
seconds!**

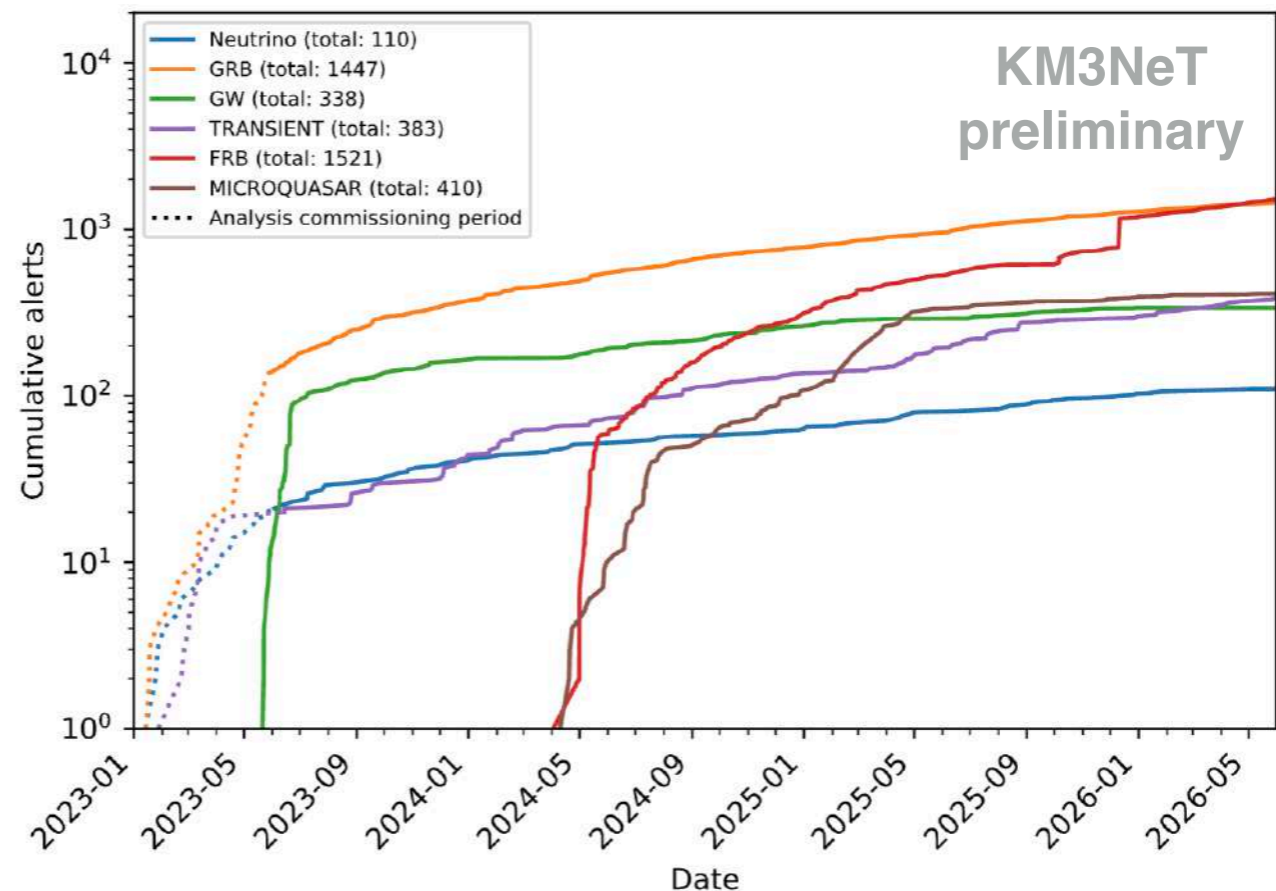


# KM3NeT realtime follow-up of external triggers

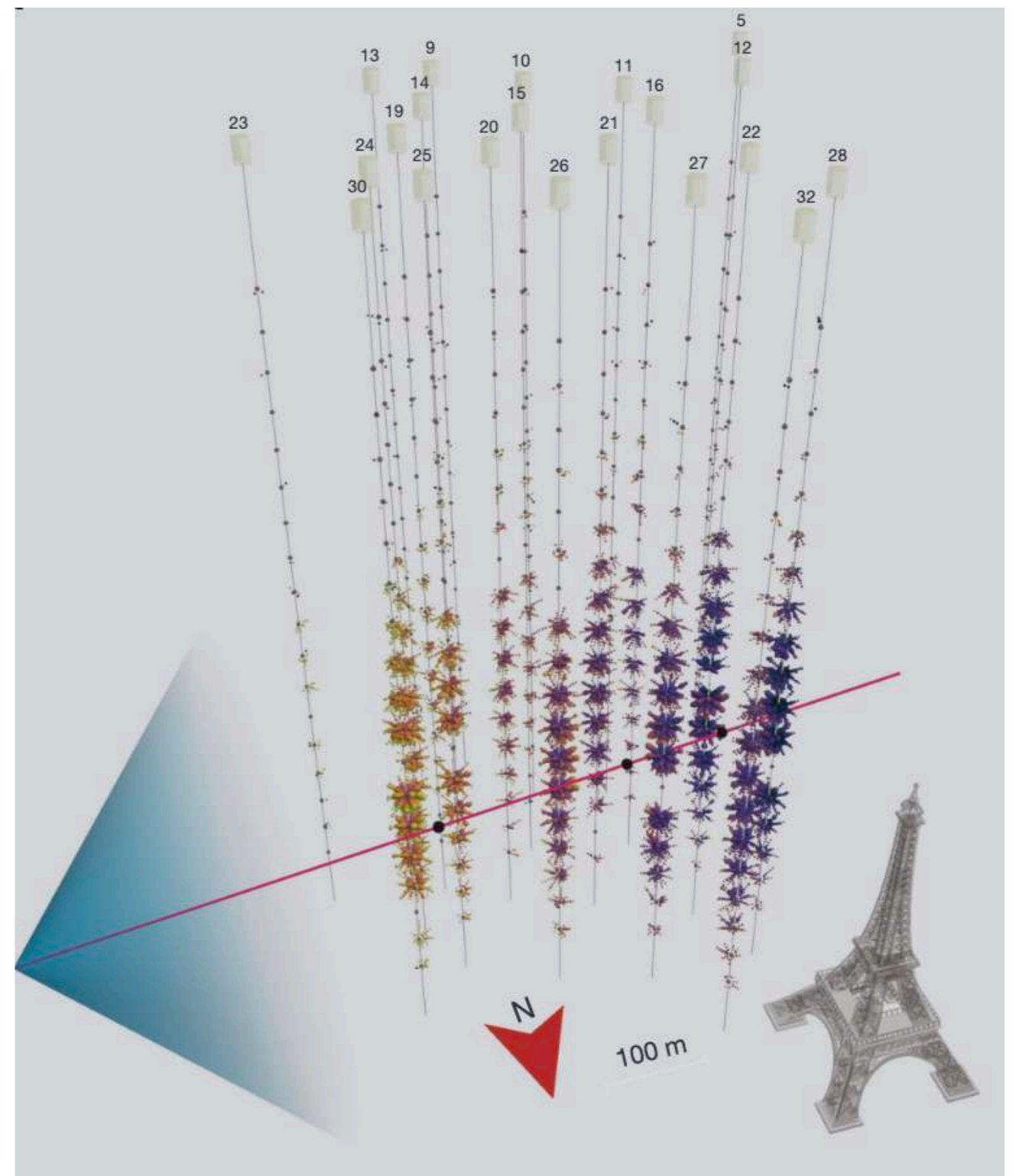


- External triggers received from several **brokers** (GCN, Chime, TNS, SNEWS)
- Each alert starts an **automated all-sky** analysis in **ARCA & ORCA**
- Several pipelines in place (IC  $\nu$ , GRBs/transients, GWs,  $\mu$ Qs, CCSNe, FRBs)
- Only **track-like events** used so far in coincident search
- **Iterative searches** over extended time, with updated information when available
- **Binned ON/OFF analysis** method for cut optimization and flux limit computation

GRBs	~1 per day
GWs	~1 per 2 days
Transients	~1 per 9 days
IC neutrinos	~1 per 2 weeks
FRBs	~1 per day
$\mu$ Quasars	~1 per 2 days



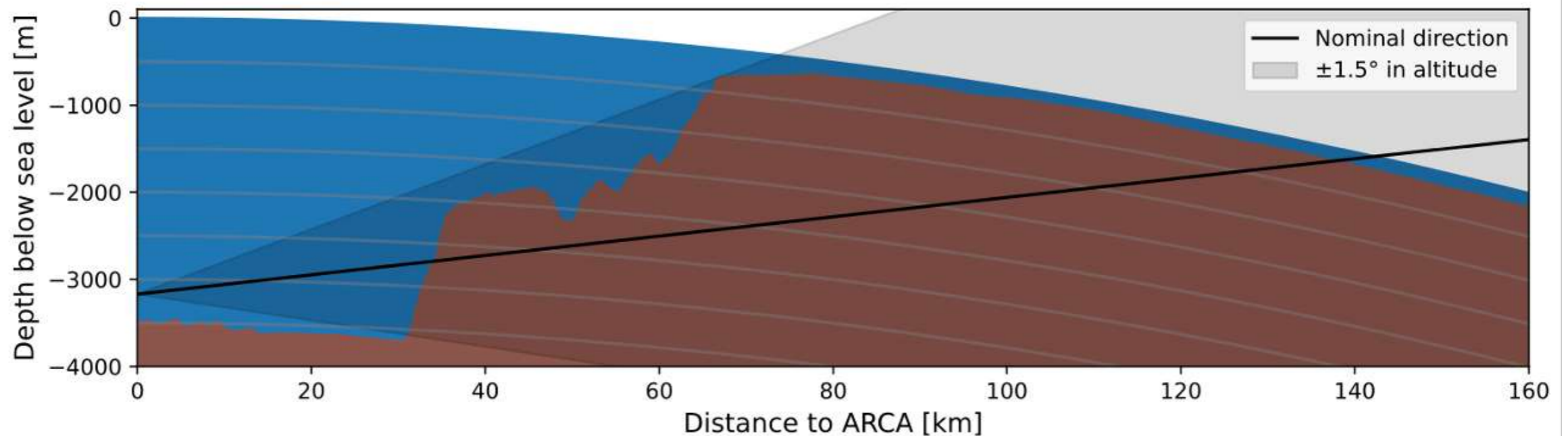
# KM3-230213A



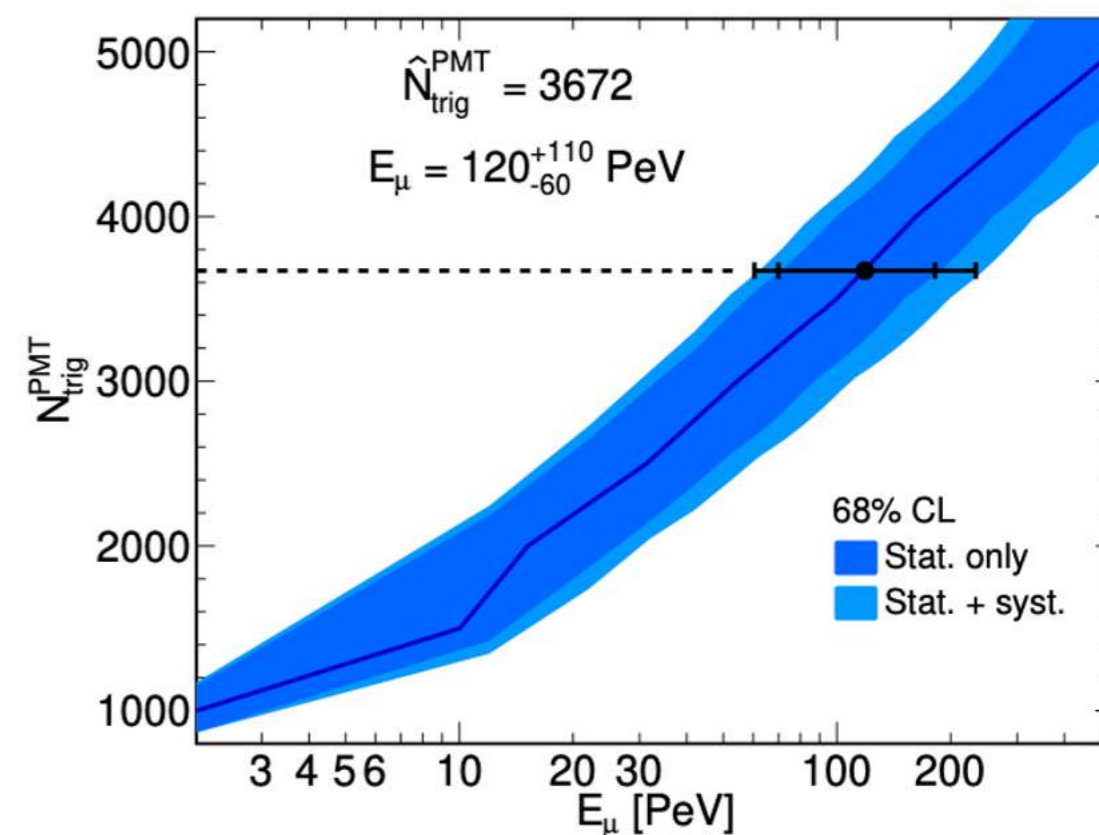
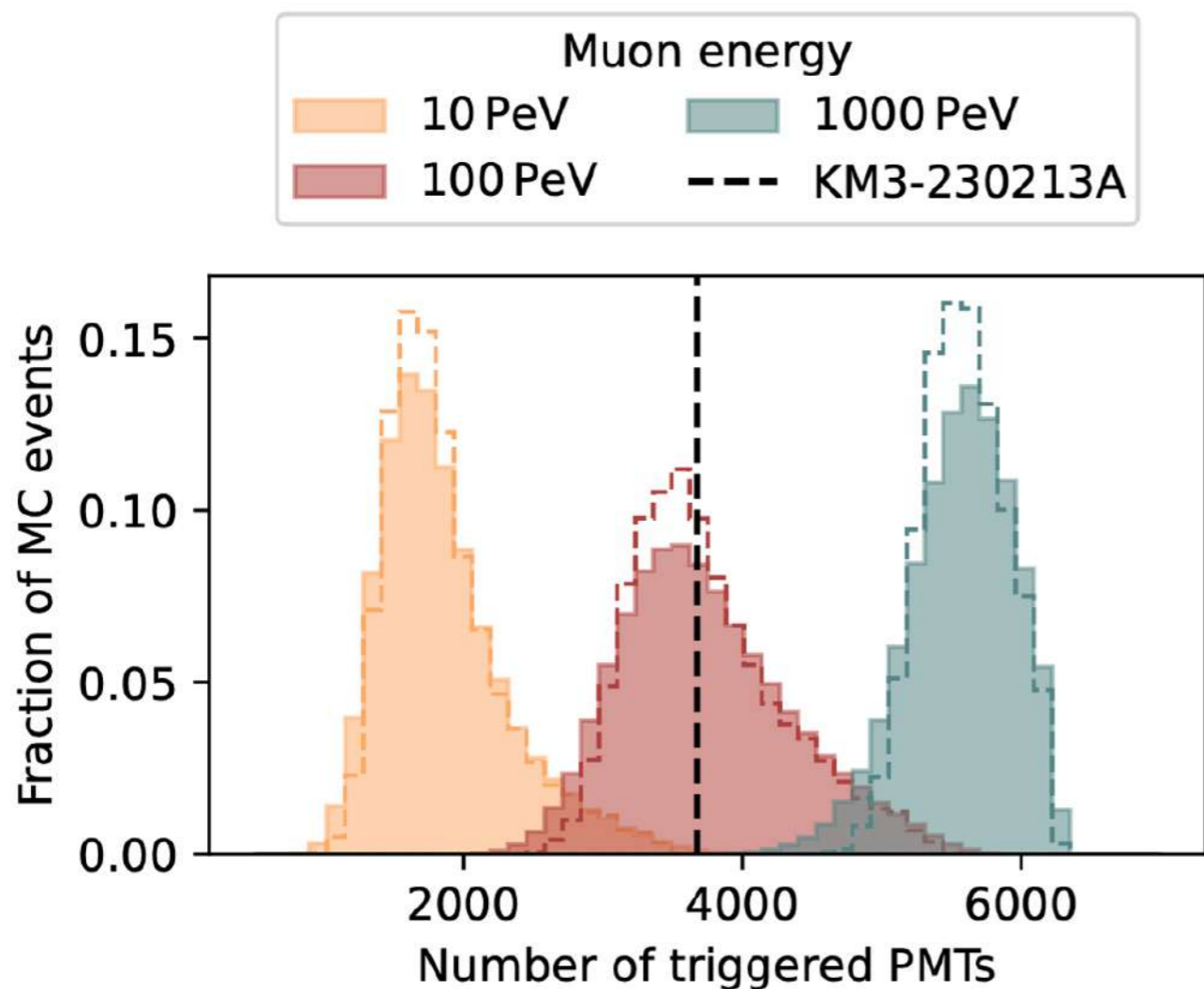
Public data set @ <https://zenodo.org/records/14860165>

# KM3-230213A: features

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



# KM3-230213A: energy reconstruction



**~35% of the detector was recording light**



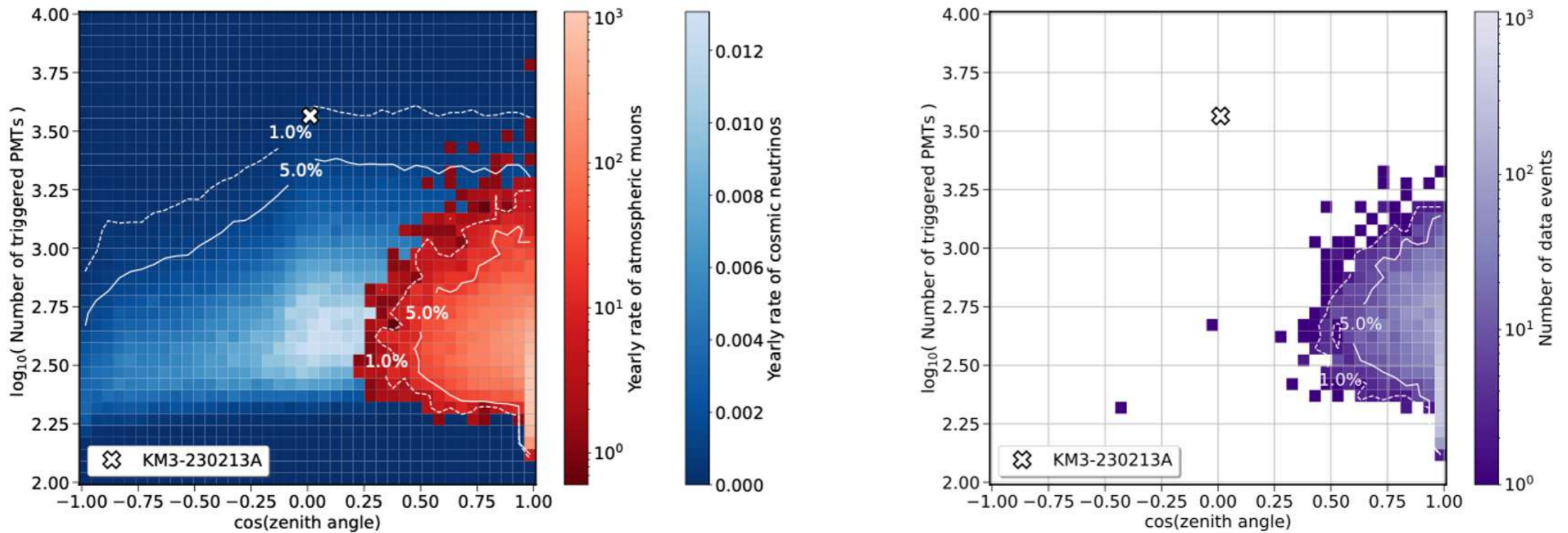
KM3NeT Coll., Nature 638 (2025) 8050

- Muon energy is inferred from the amount of light:
- The **parent neutrino energy** is estimated to be (assuming  $E^{-2}$  source flux):

$$E_{\mu} = 120^{+110}_{-60} \text{ PeV}$$

$$E_{\nu} = 220^{+570}_{-100} \text{ PeV}$$

# KM3-230213A



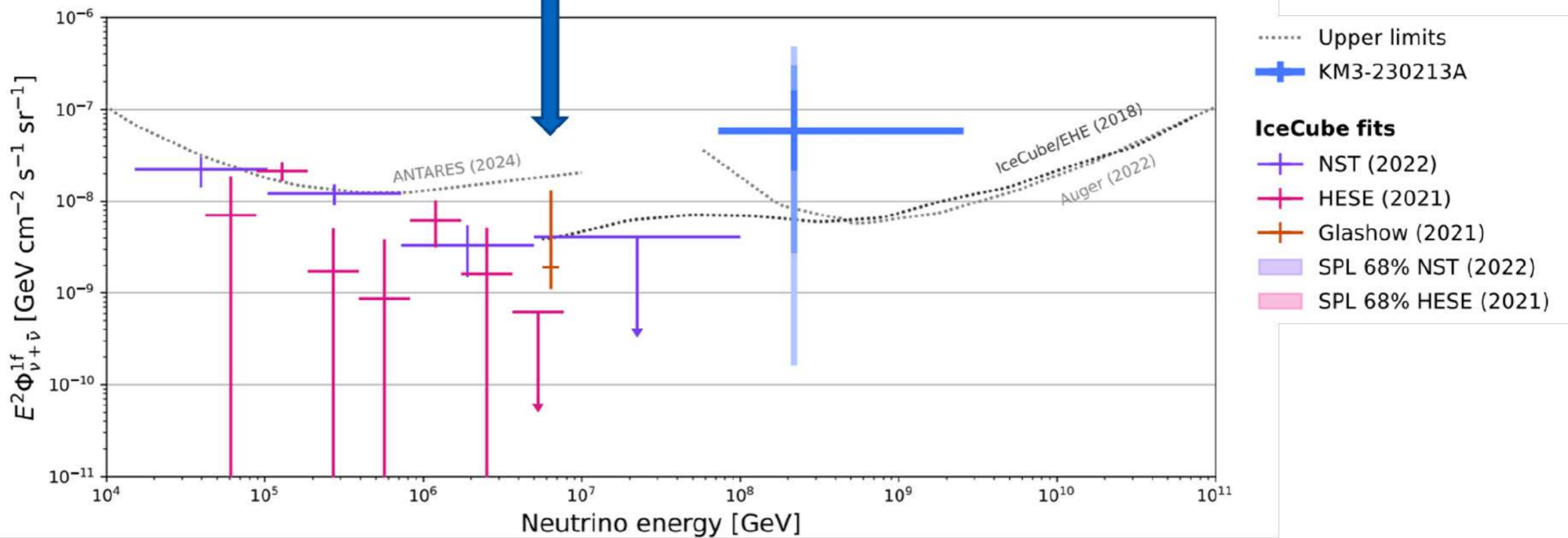
KM3NeT Coll., Nature 638 (2025) 8050

Assuming reconstructed energy and direction, we expect

- **Atmospheric muon contamination @ 100 (10) PeV:**
  - $\ll 10^{-10}$  ( $10^{-9}$ ) event/year within  $2\sigma$  of reconstructed direction
  - $\ll 10^{-4}$  event/year within  $5\sigma$  of reconstructed direction
- **Atmospheric neutrino rate > 100 PeV:**
  - $\ll (1-5) \times 10^{-5}$  event/year

# The most energetic neutrino ever probed

Previous highest energy neutrino

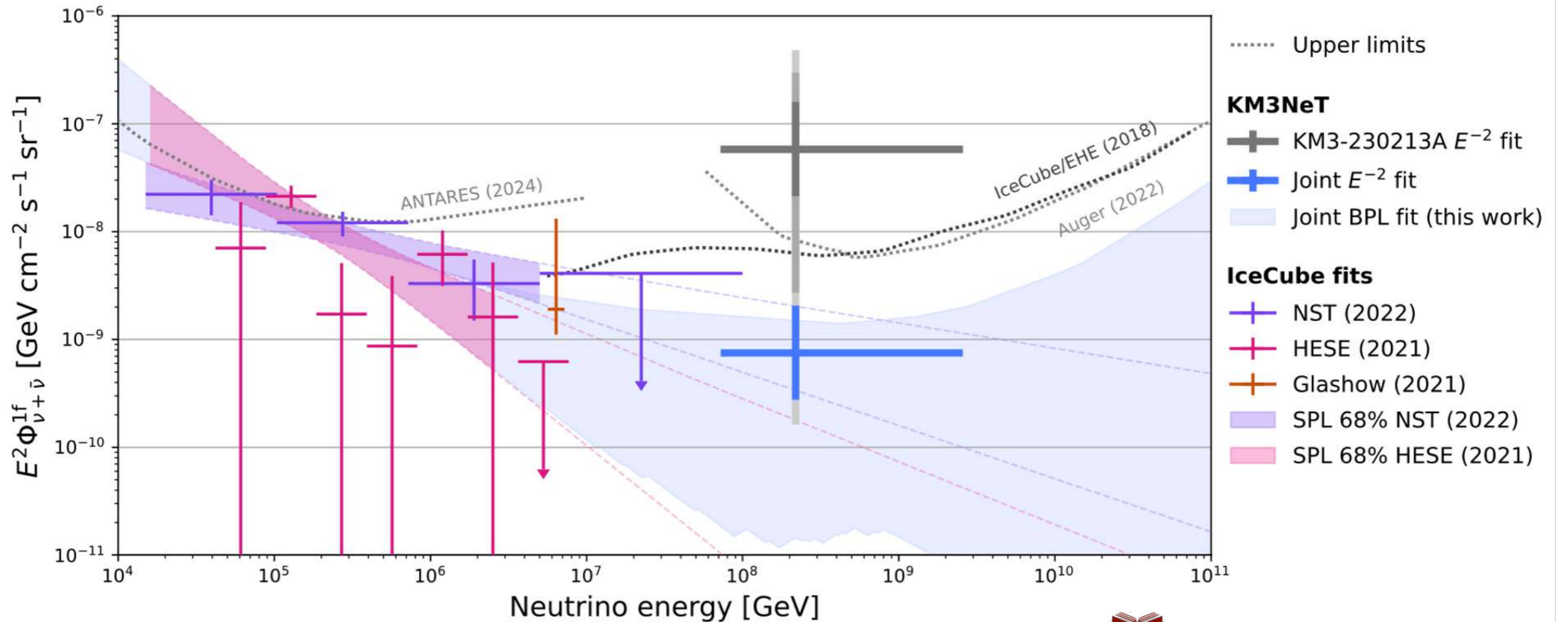


↑  
KM3-230213A

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




# A global fit to existing data




 KM3NeT Coll., PRvX 15 (2025) 1016A


Moderate tension with existing (null observations) datasets from PAO (18 yr) and IceCube (9yr EHE) \*

\*only relevant for steady UHE neutrino flux

 Adriani et al. [KM3NeT], Comm. Physics 8 (2025) 457

 Adriani et al. [KM3NeT], arXiv:2606.09986

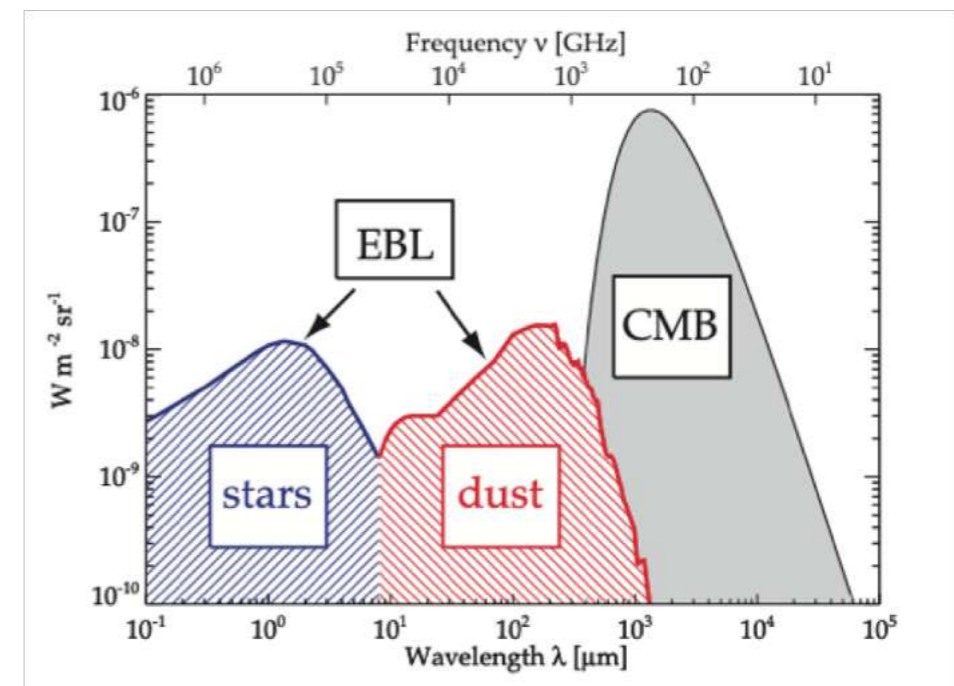
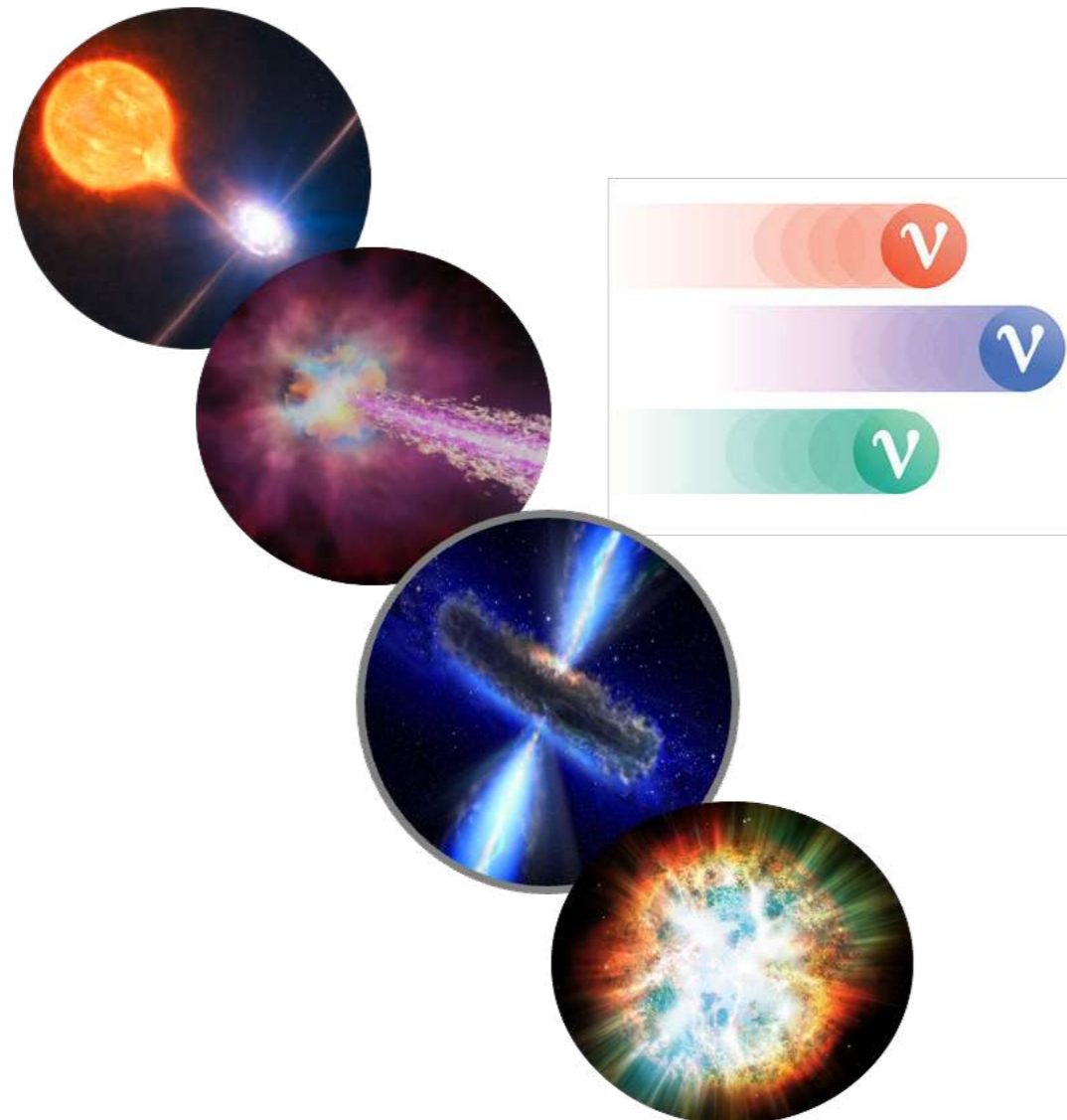
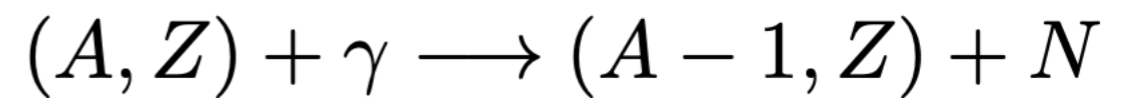
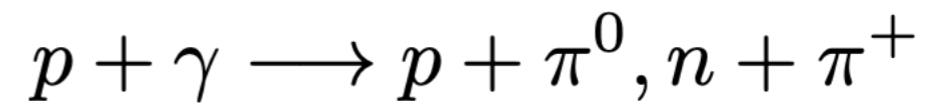
 Adriani et al. [KM3NeT], JCAP 03 (2026) 033

 Adriani et al. [KM3NeT], A&A (2026) & poster #154 by P. Myhr

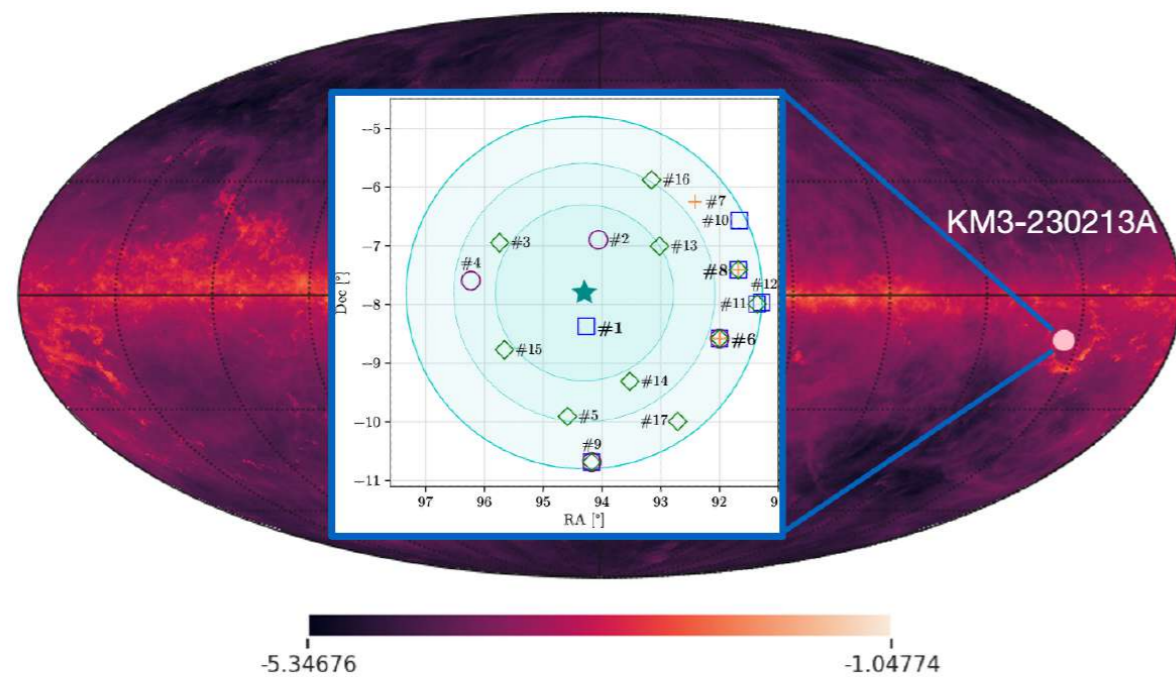
# Cosmic or cosmogenic?

**COSMIC** = in situ production at an extreme astrophysical accelerator

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

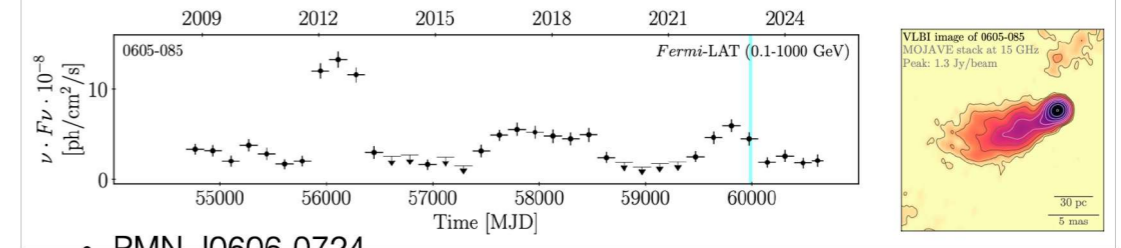


# The cosmic origin scenario

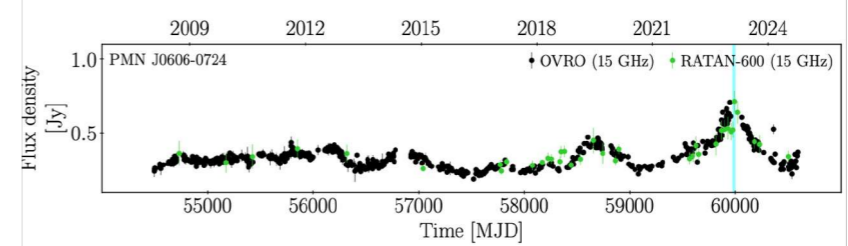


KM3NeT Coll., *Astronomical Journal* (2026) accepted, arXiv:2502.08484

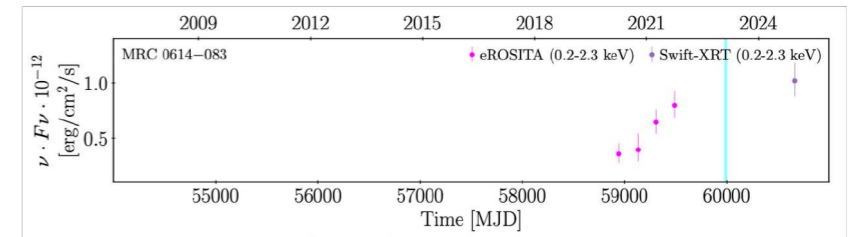
• 0605-085



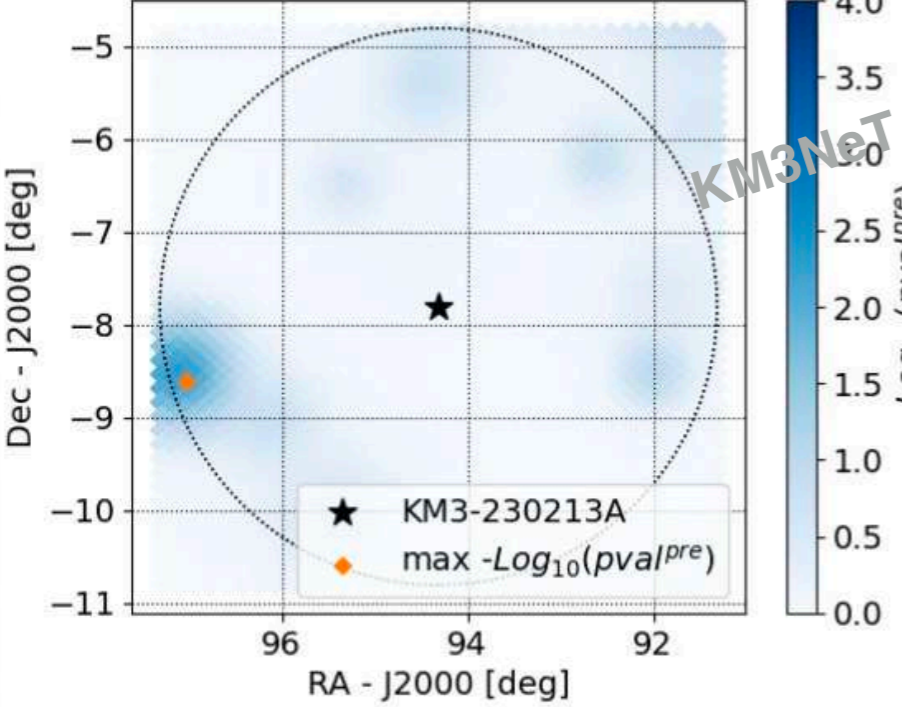
• PMN J0606-0724



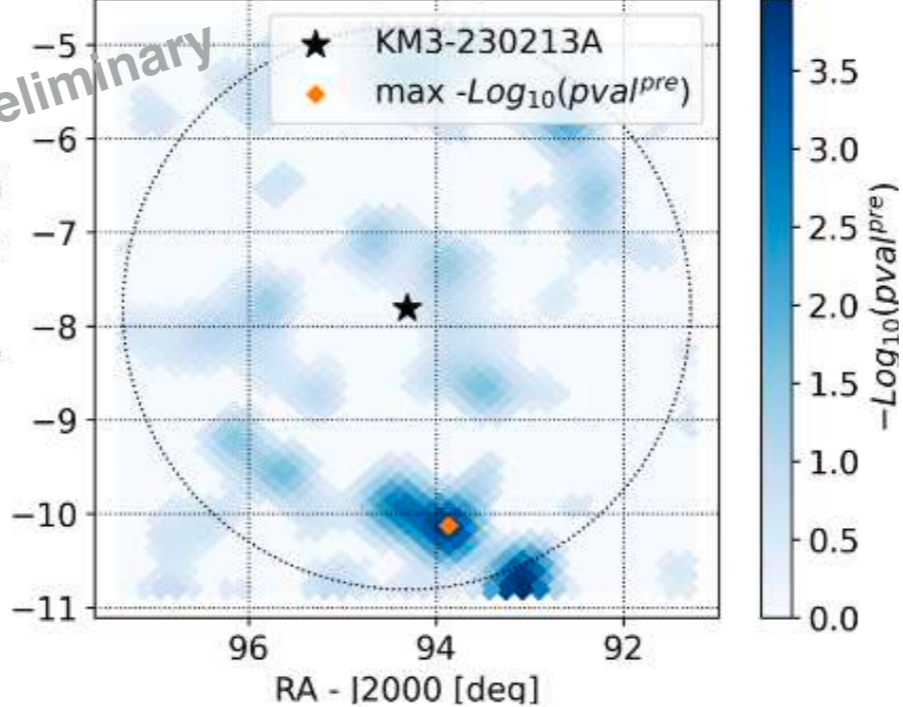
• MCR 0614-083



ANTARES (2007-2022) - PRELIMINARY



IceCube 10-year public data



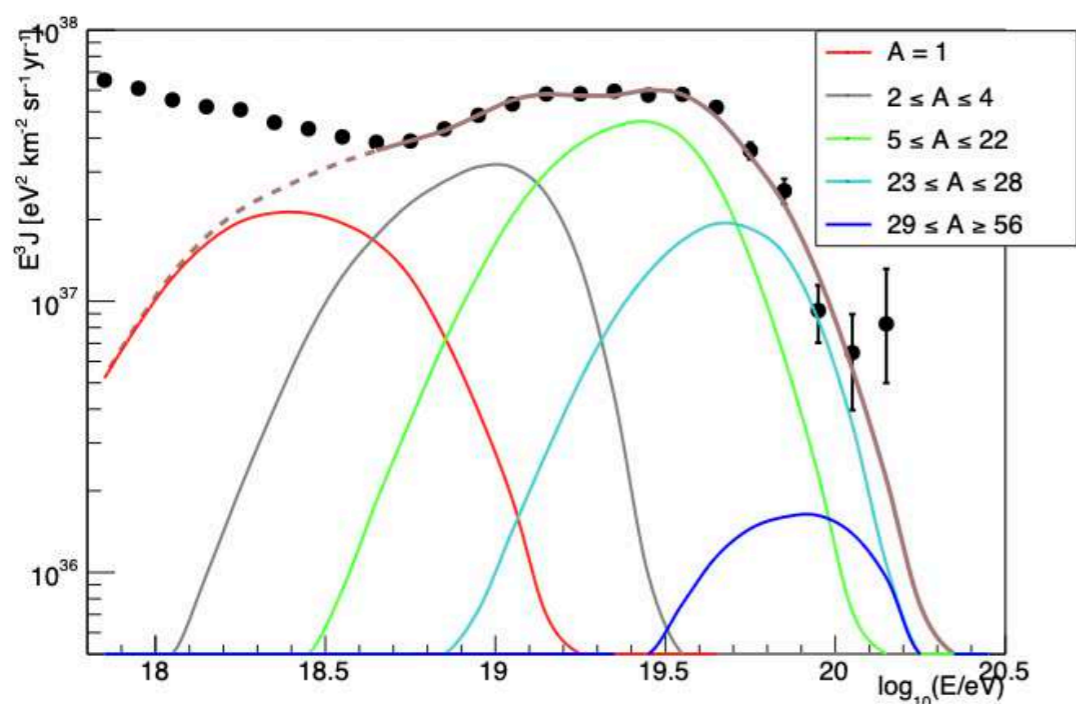
Upper limit on potential point-like source flux set to:

$$(E^2 \phi_\nu)^{90\%CL} \leq 1.2 \times 10^{-9} \text{ GeVcm}^{-2}\text{s}^{-1}$$

- KM3NeT Coll., *Nature* 638 (2025) 8050
- Del Rosso [KM3NeT Coll.], ICRC 2025

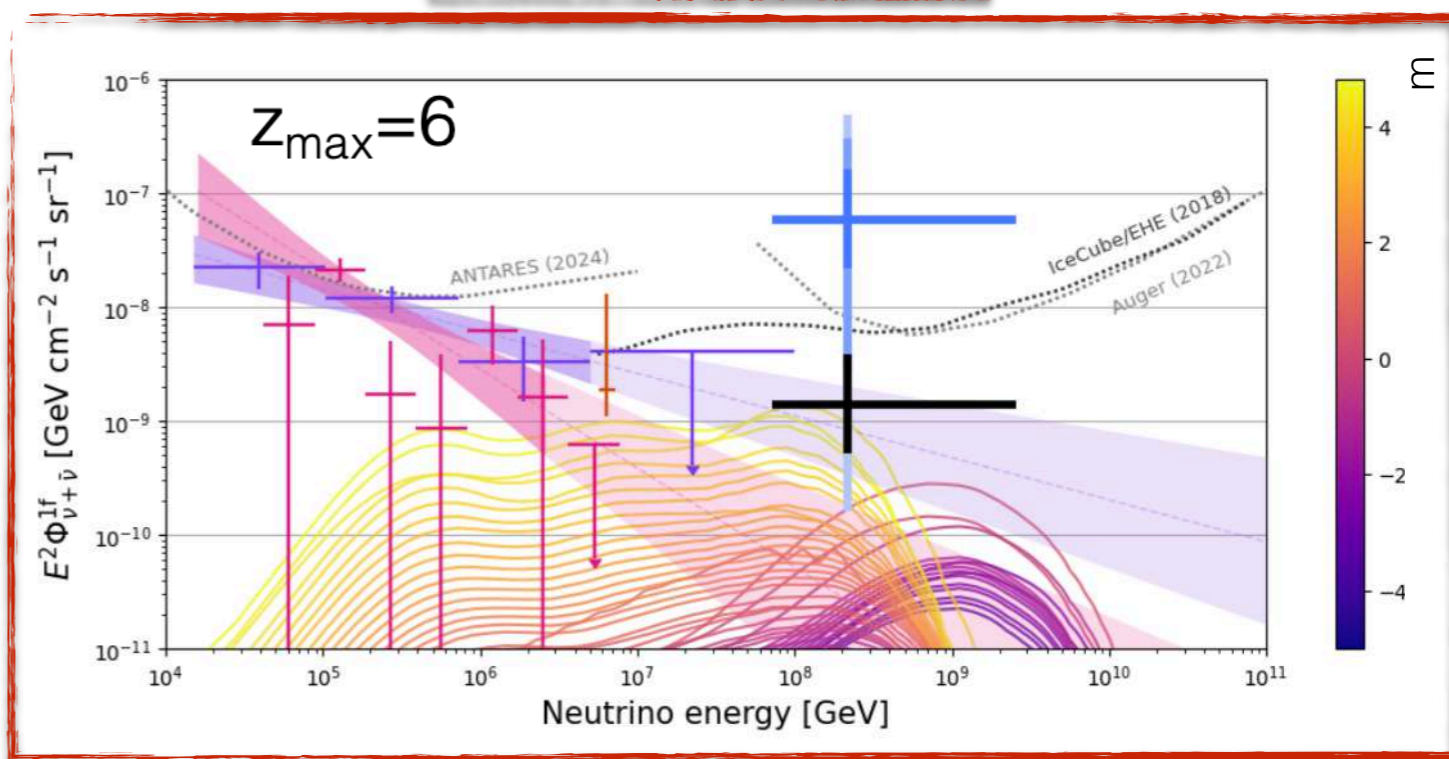
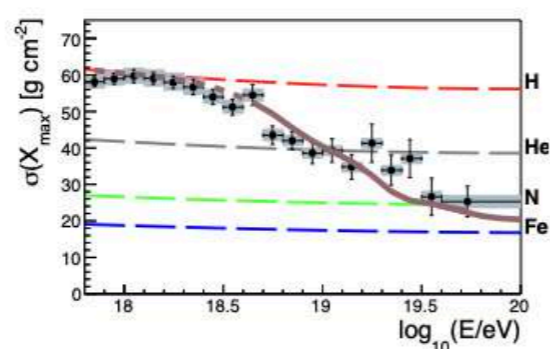
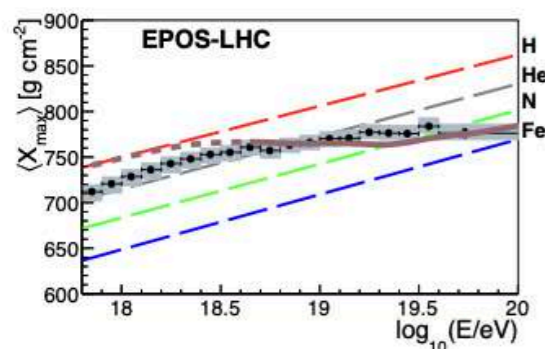
# The cosmogenic origin scenario

The Universe is opaque to electromagnetic radiation & UHECRs ( $E > 10^{19}$  eV) at  $z > 1$   $\longrightarrow$  **the majority of UHECR sources are unconstrained**



**Minimal** scenario (identical sources) fitting UHECR spectrum & composition above the ankle with hard UHECR injection and low-rigidity cut-off & few injected protons (mostly produced during propagation)

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



# Summary & conclusions

- **KM3NeT is** currently under construction while **taking data** in partial detector configurations (ARCA51 & ORCA38);
  - ORCA detector covering energies in GeV-TeV range;
  - ARCA detector covering energies  $>$ TeV;
  - Combined ARCA+ORCA detector at MeV energies;
  - Both detectors are rapidly growing.
- First astronomy results:
  - Point source and diffuse flux searches are in progress;
  - Analyses are being updated with more recent detector configurations;
  - Real-time multi-messenger program: follow-up searches regularly performed since 2023, neutrino alert sending system under finalization;
  - Detection of the first UHE neutrino, **KM3-230213A**, sets a new milestone in neutrino astronomy: increased statistics required to better characterize the landscape at such extreme energies.

**STAY TUNED FOR UPDATES!**

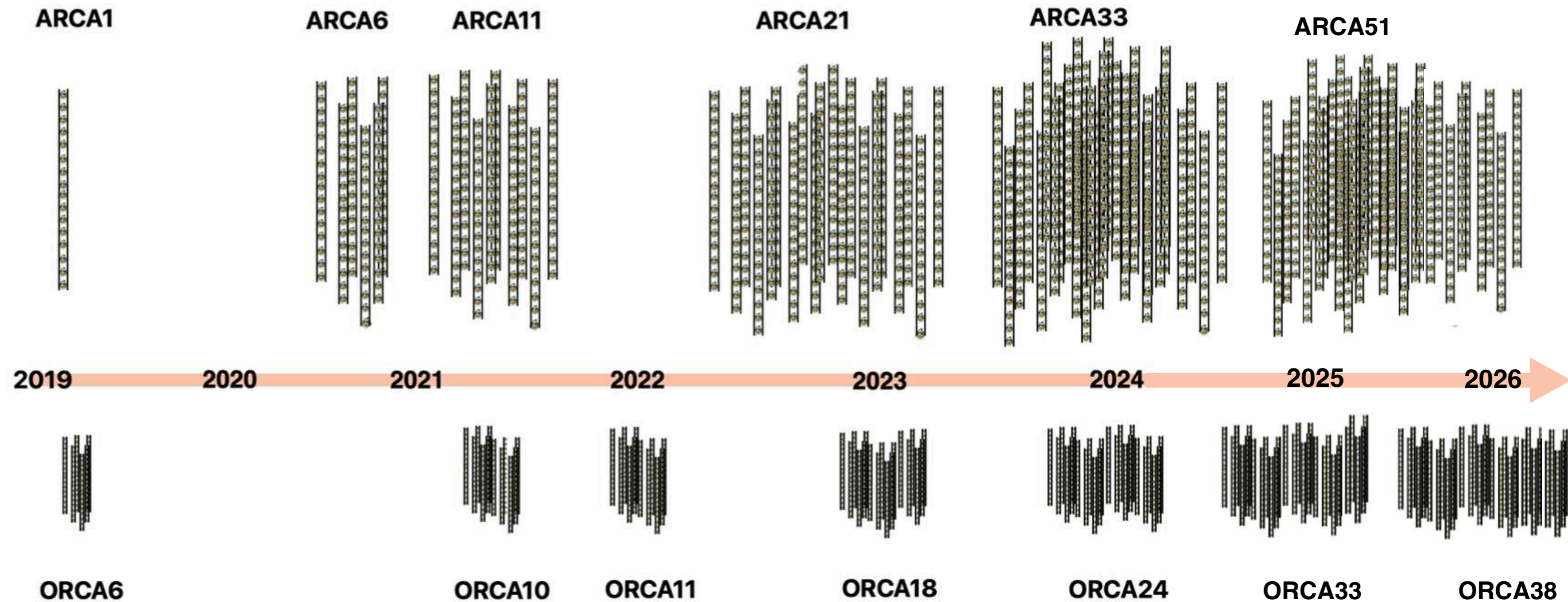


**Backup**

**NEUTRINO '26**

**International Conference on Neutrino Physics and Astrophysics**

# Current status of the KM3NeT detectors



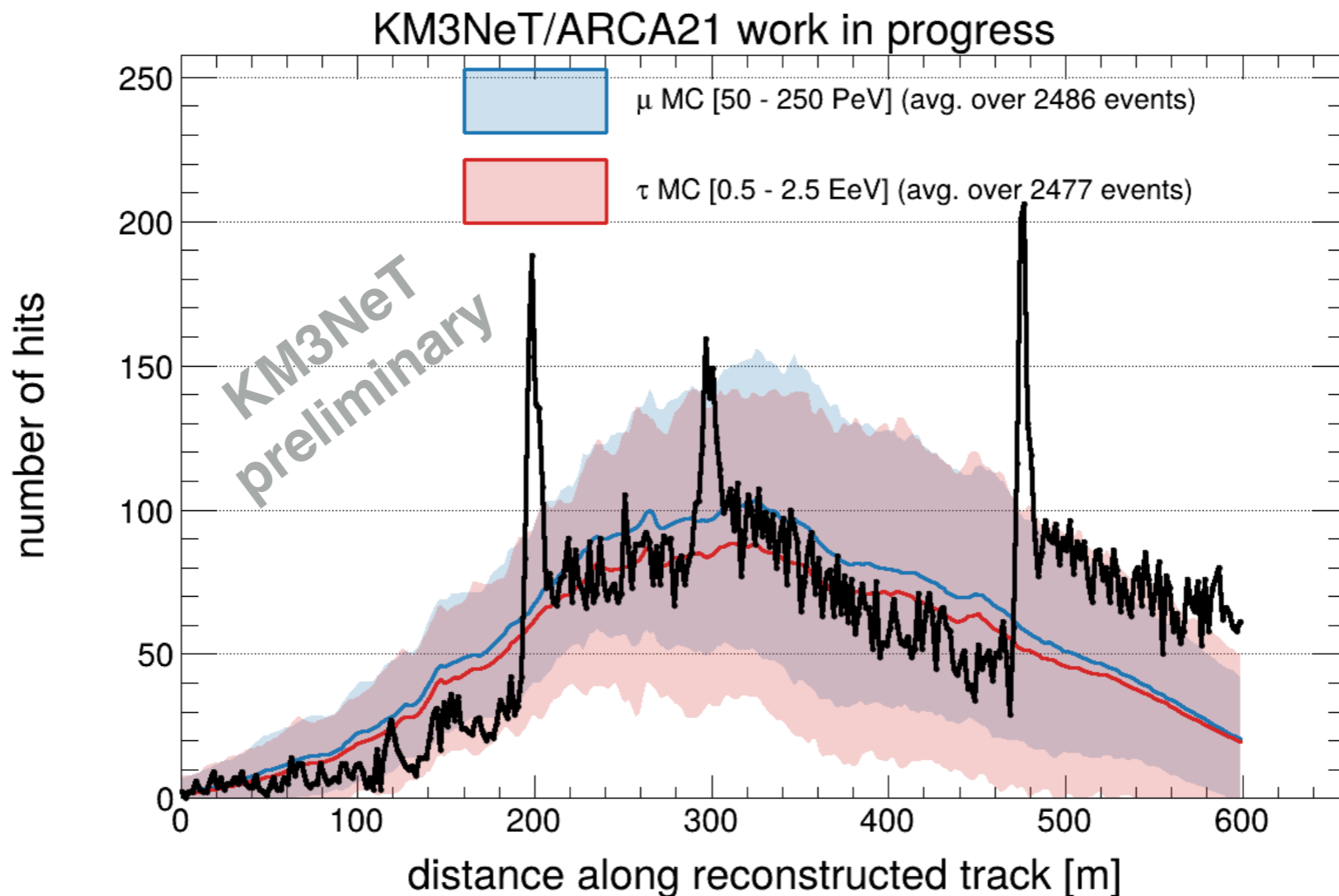
Further **sea campaigns** planned in next months

# KM3-230213A: $\mu$ or $\tau$ ?

- At extreme energies,  $\tau$  leptons propagate for km distances before decaying

$$L(E) = 49 \text{ m} \left( \frac{E_\tau}{1 \text{ PeV}} \right)$$

- The light profile of KM3-230213A track can be mimicked by a 17 times more energetic  $\tau$  lepton, though with a much less likely occurrence

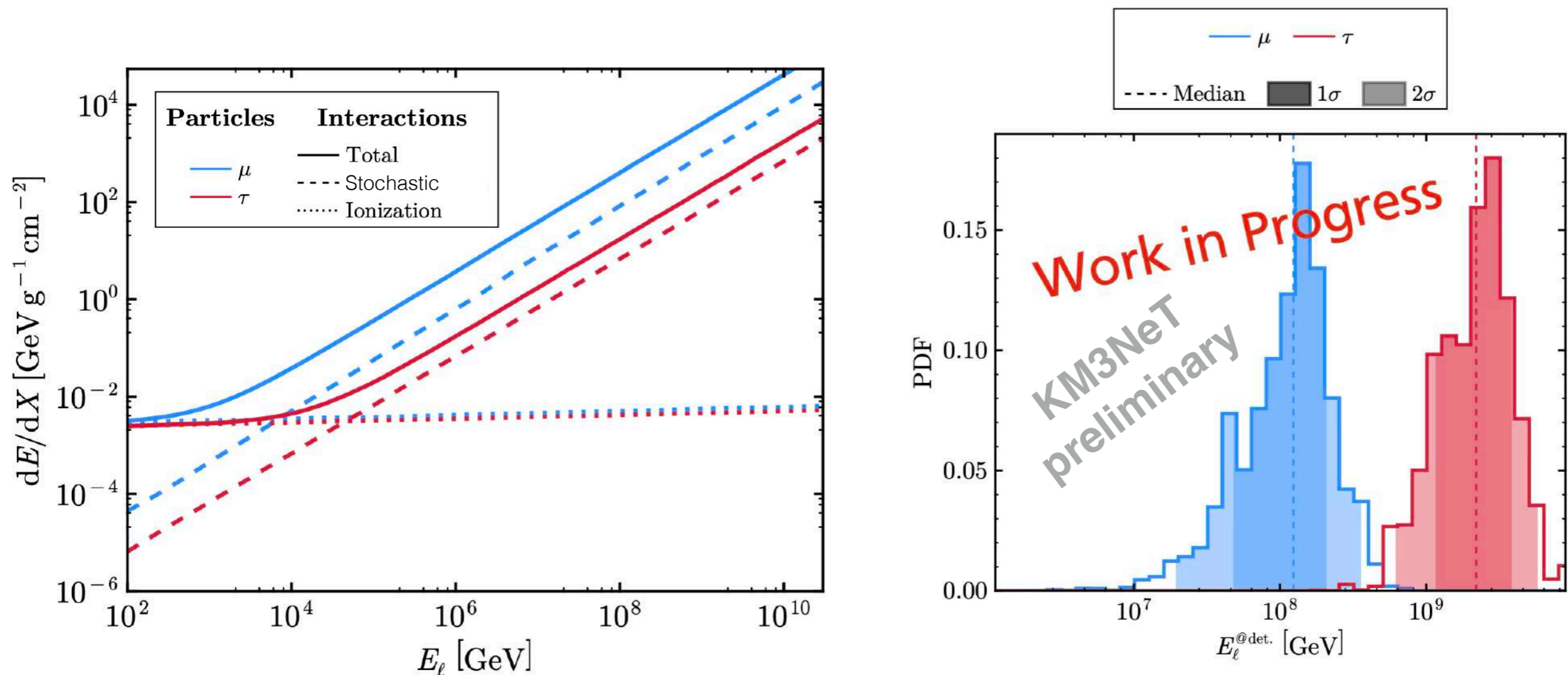


# KM3-230213A: $\mu$ or $\tau$ ?

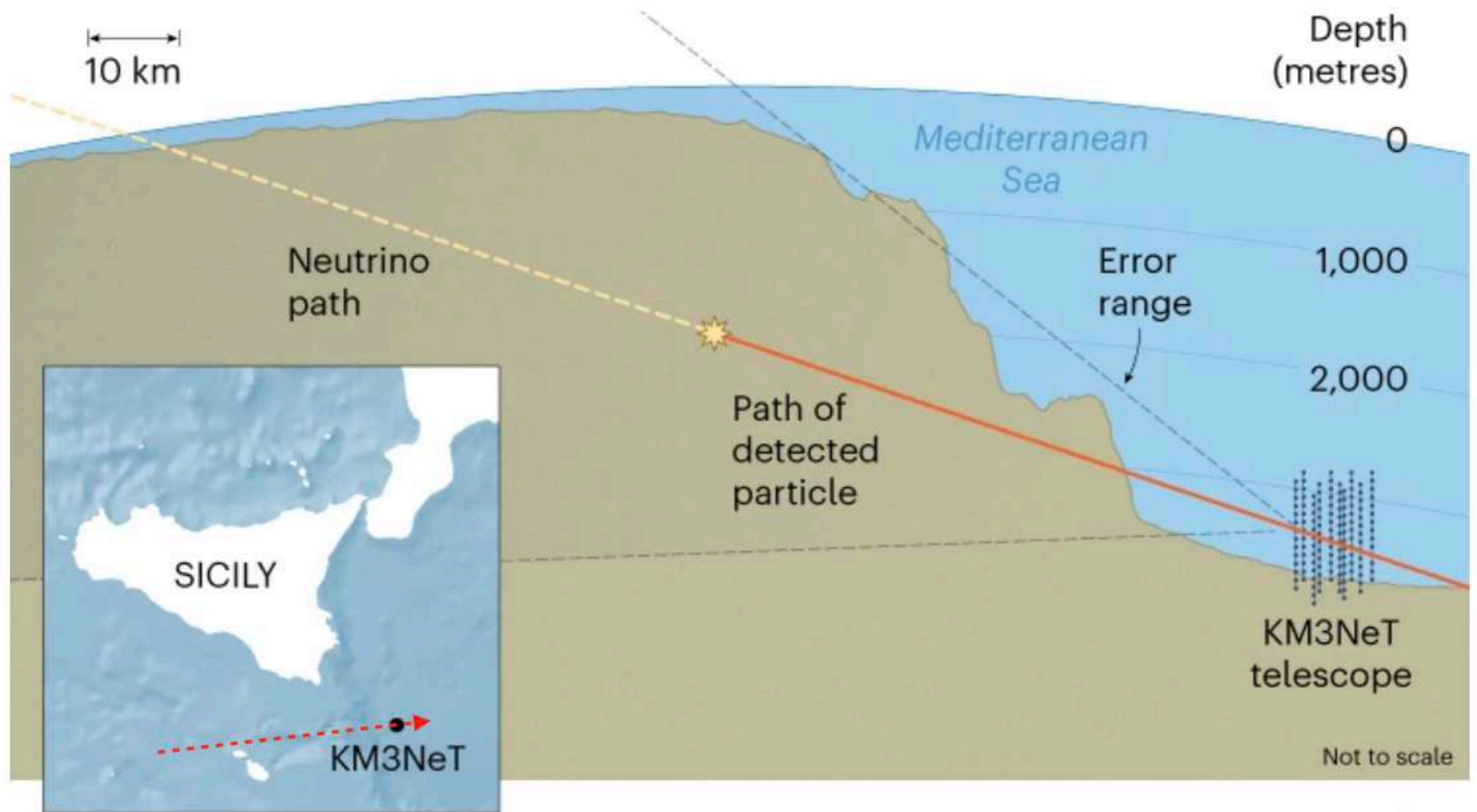
- At extreme energies,  $\tau$  leptons propagate for km distances before decaying

$$L(E) = 49 \text{ m} \left( \frac{E_\tau}{1 \text{ PeV}} \right)$$

- The light profile of KM3-230213A track can be mimicked by a 17 times more energetic  $\tau$  lepton, though with a much less likely occurrence

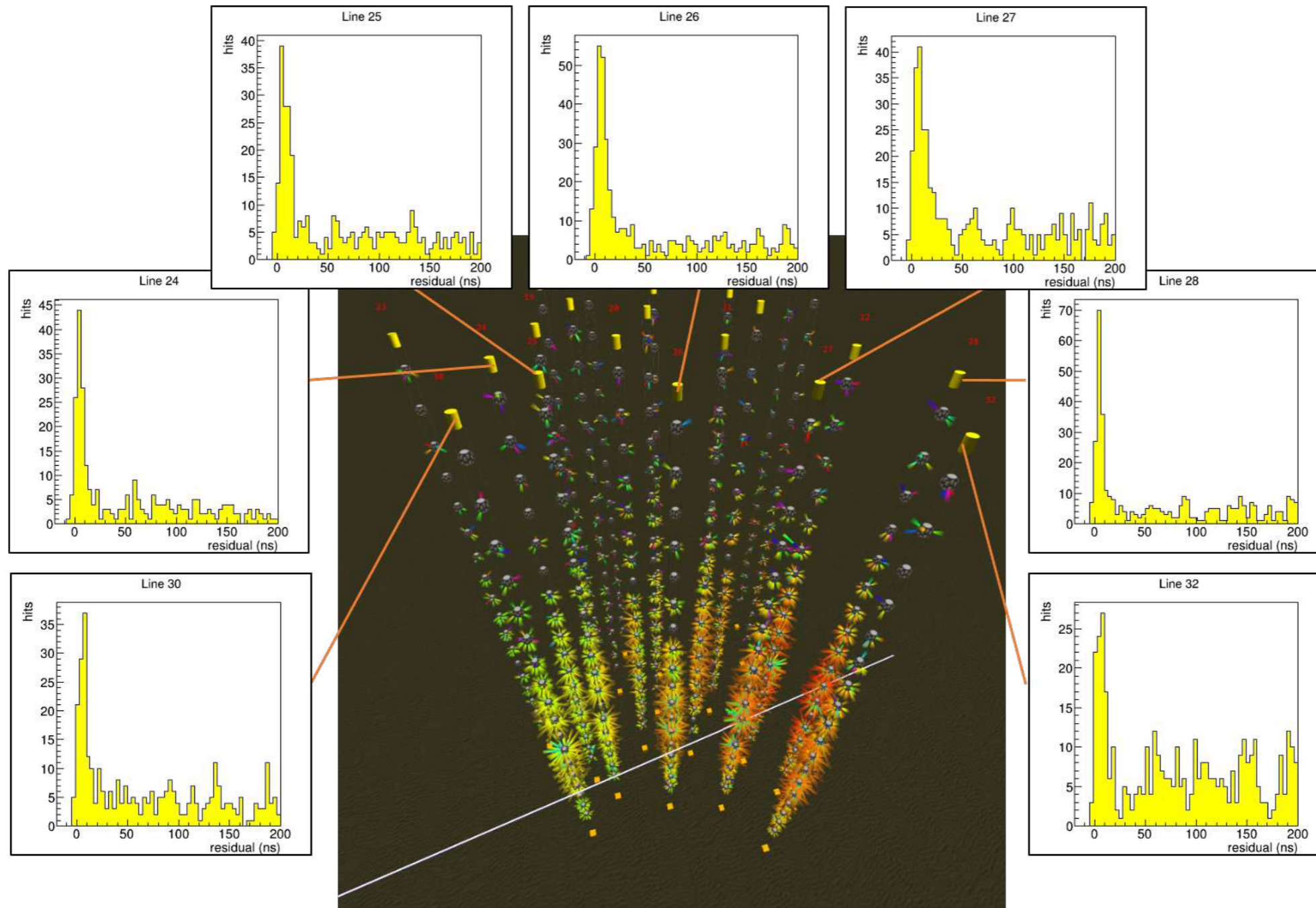


# The large shielding from Malta's shelf



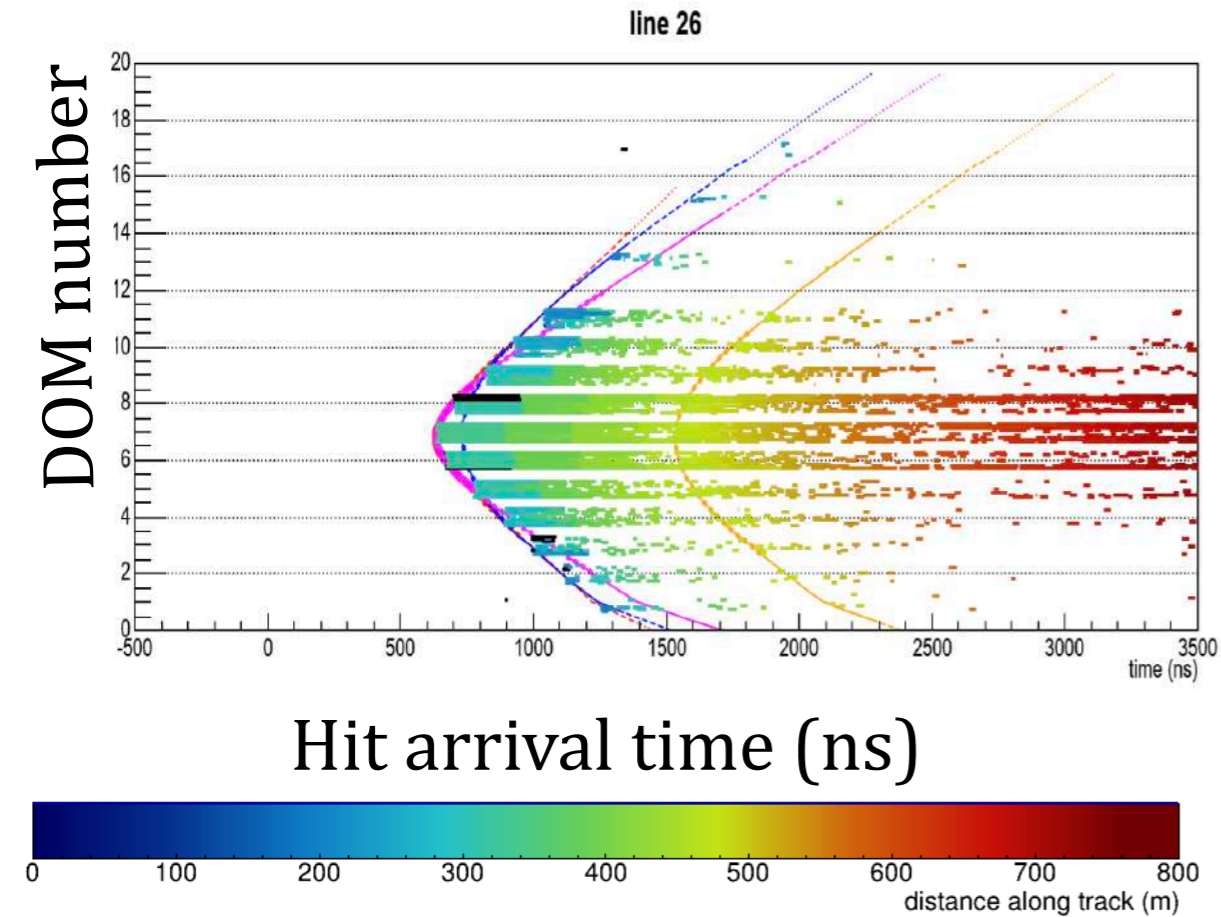
©nature

# A very well reconstructed muon track

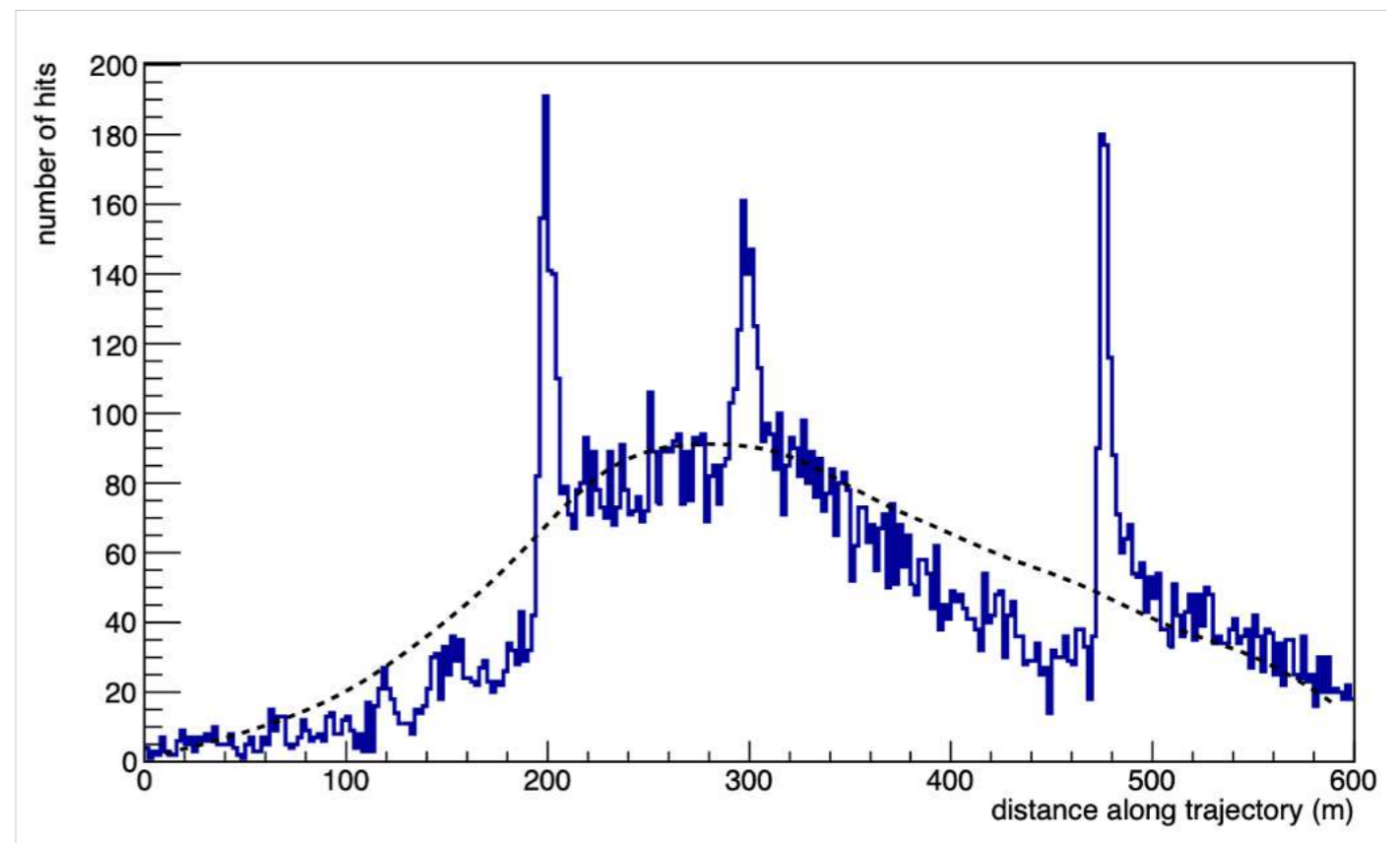
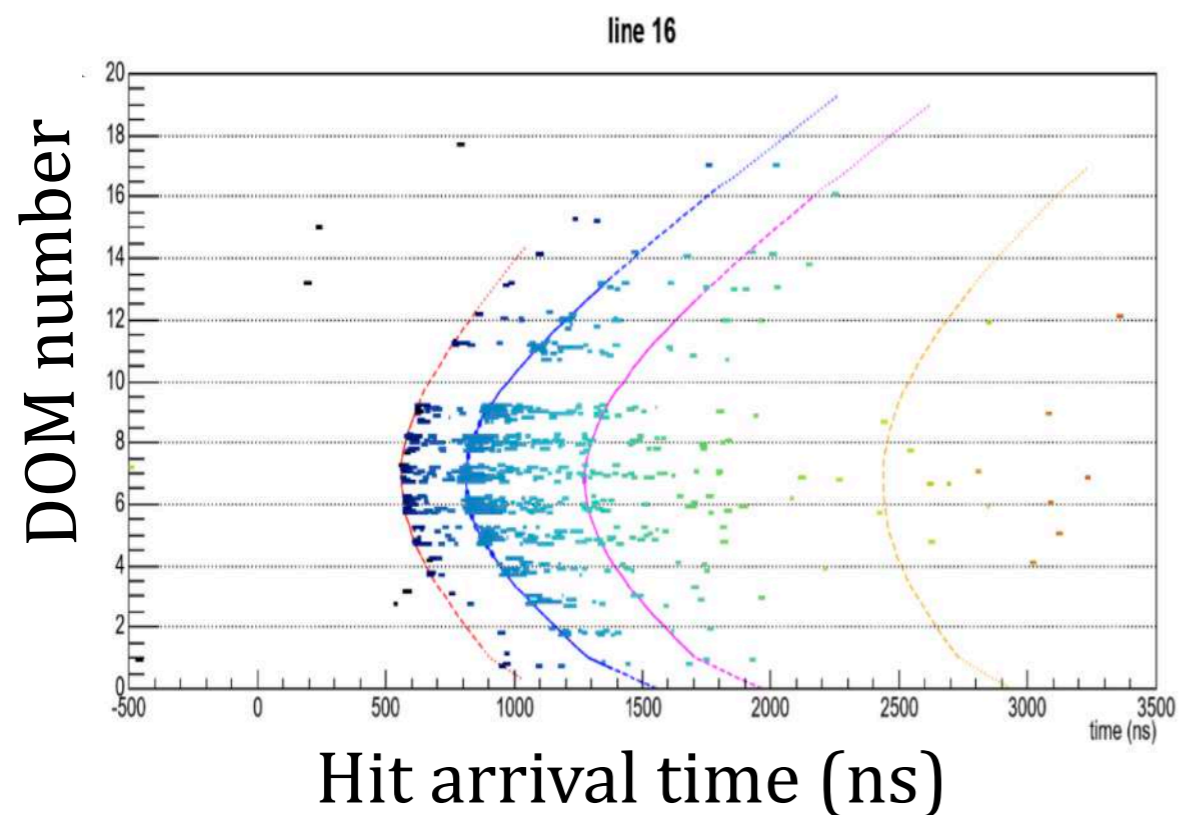


**Time residual distributions on different DUs**

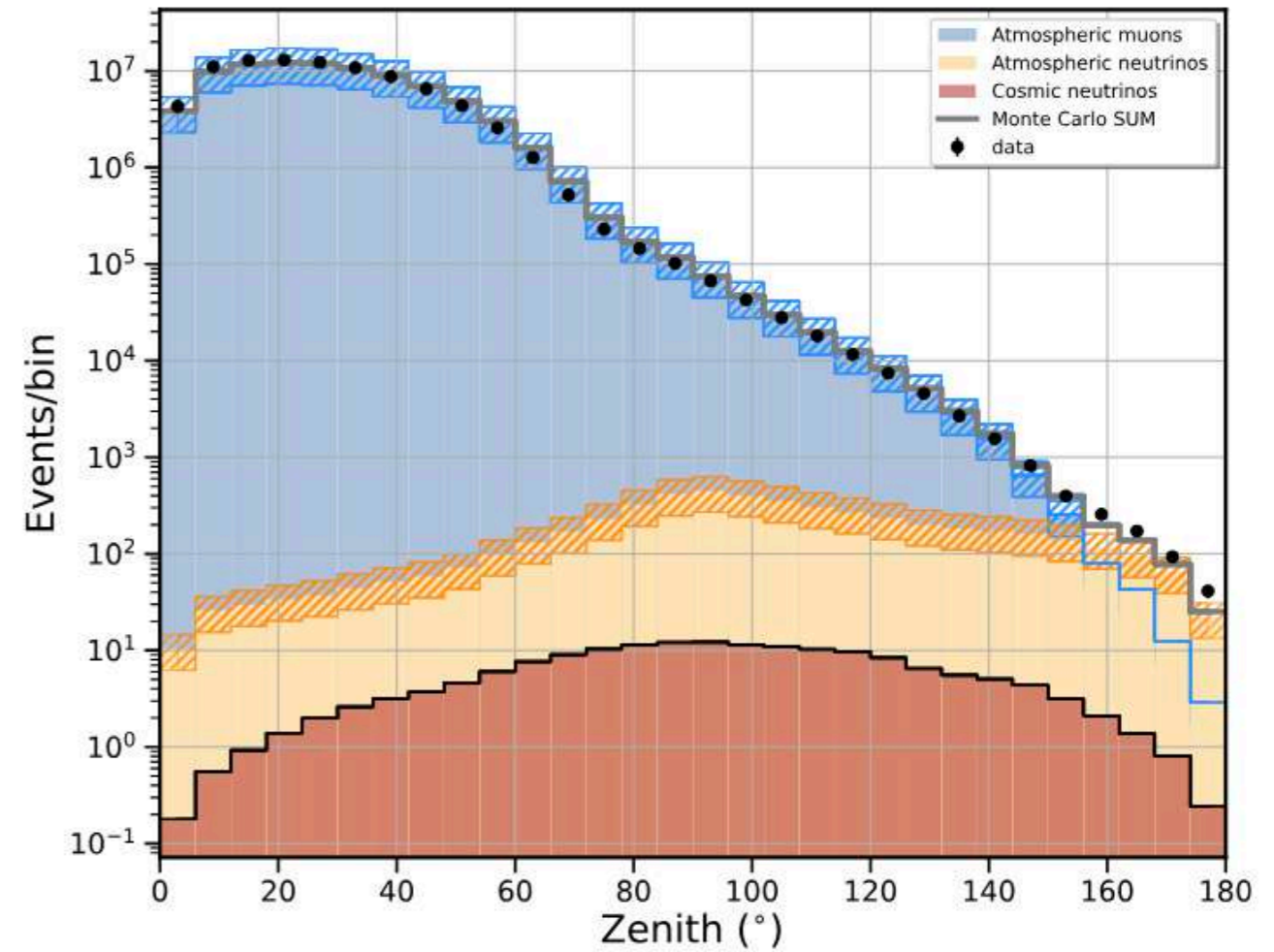
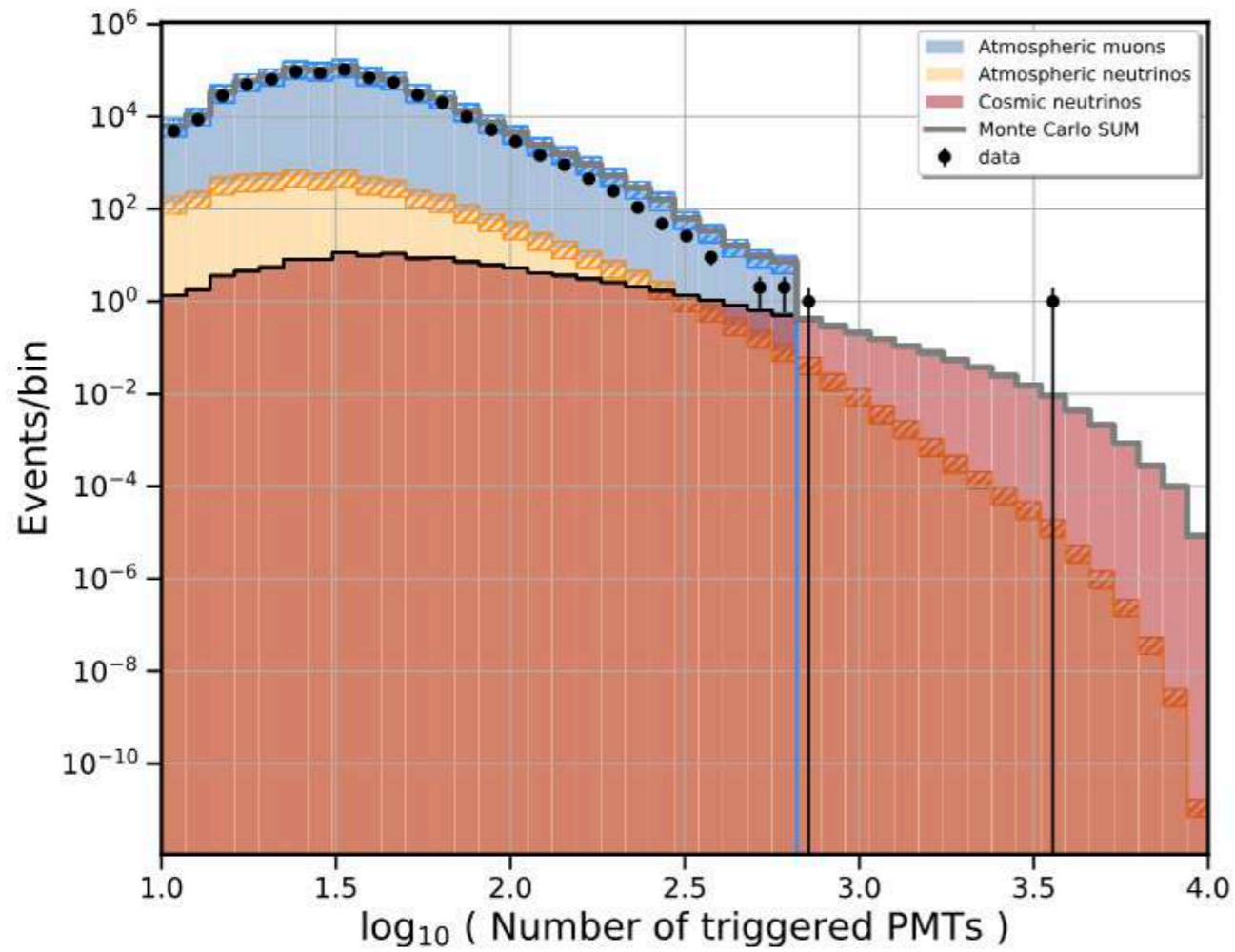
# KM3-230213A: direction



- 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



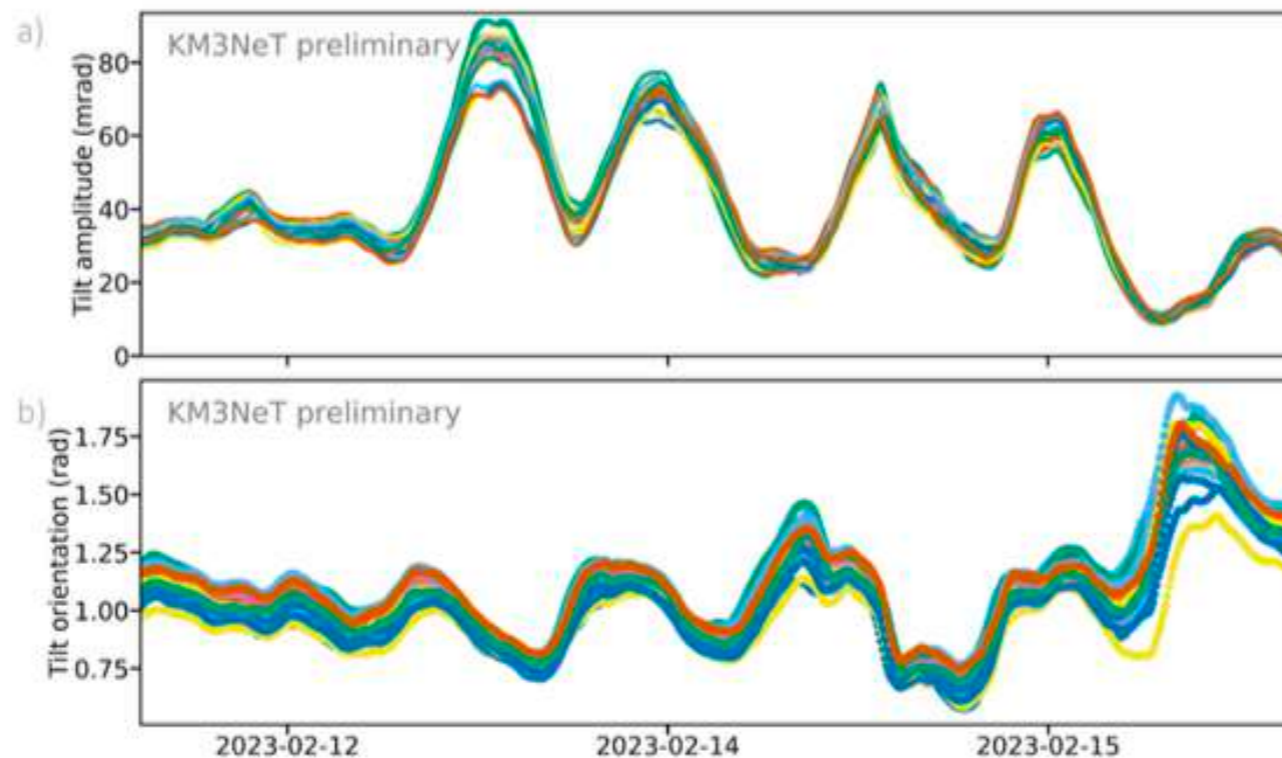
# Data/MC comparisons for ARCA21



KM3NeT Coll., Nature 638 (2025) 8050

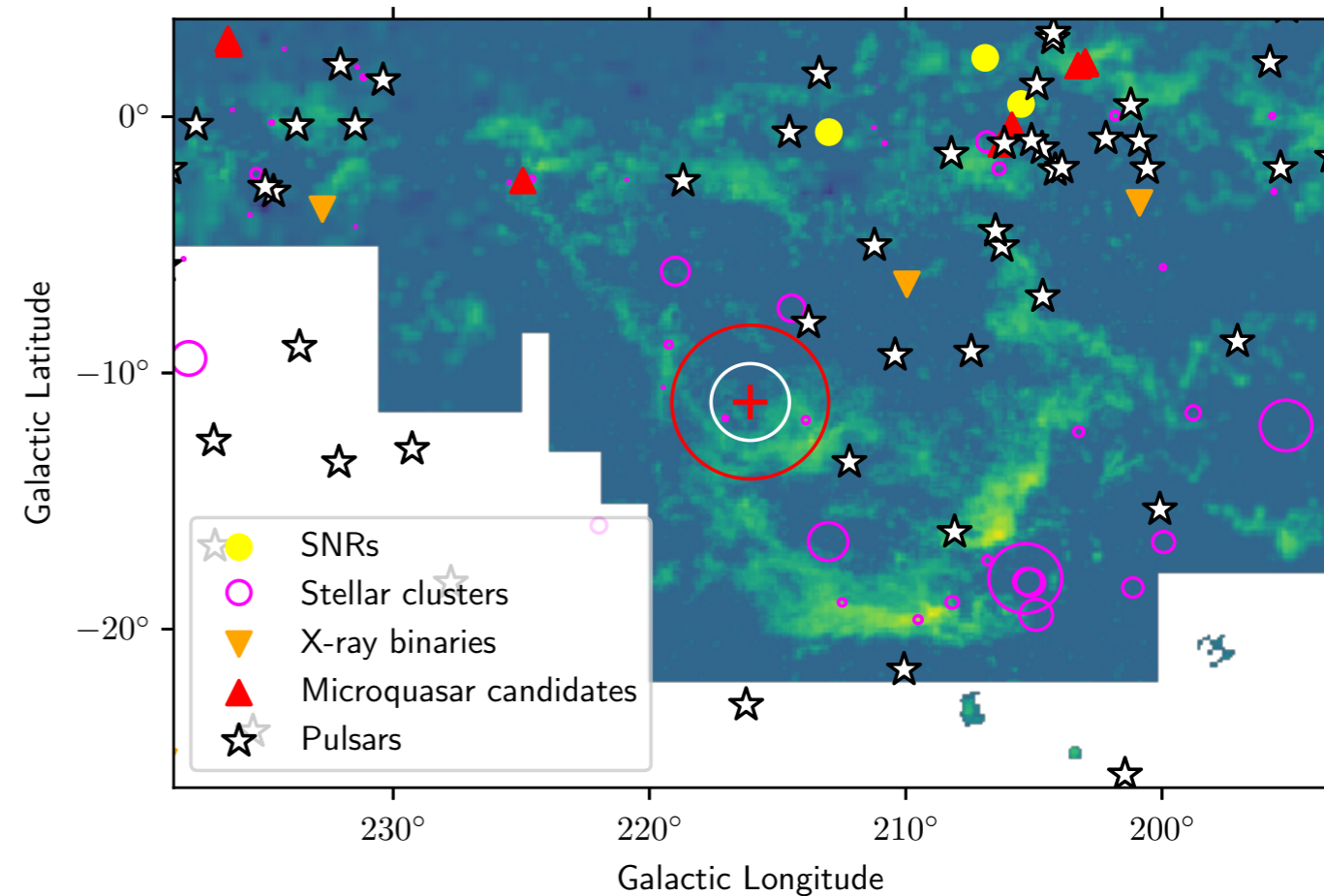
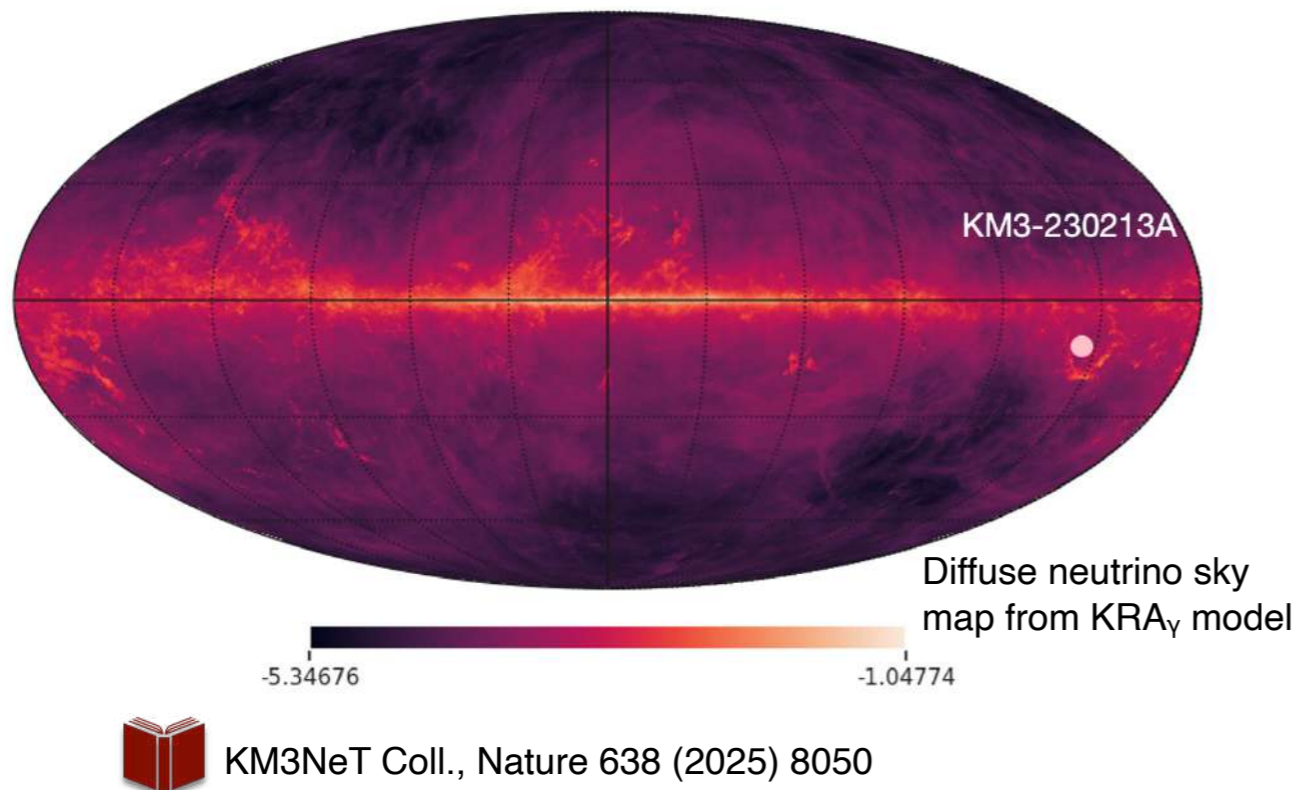
# KM3-230213A: direction reconstruction

- Dynamic position of the detector constrained using **acoustic system** (sensors in each DOM & emitters on the seabed)
- Absolute orientation of the detector is limited by the 10 m accuracy on emitter positions  $\longrightarrow$  **1° uncertainty per axis**
- Incoming sea campaign to improve on accuracy of emitter positions (<1 m) and **recalibration of data**



# Testing the Galactic origin

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



Potential nearby accelerators searched among:

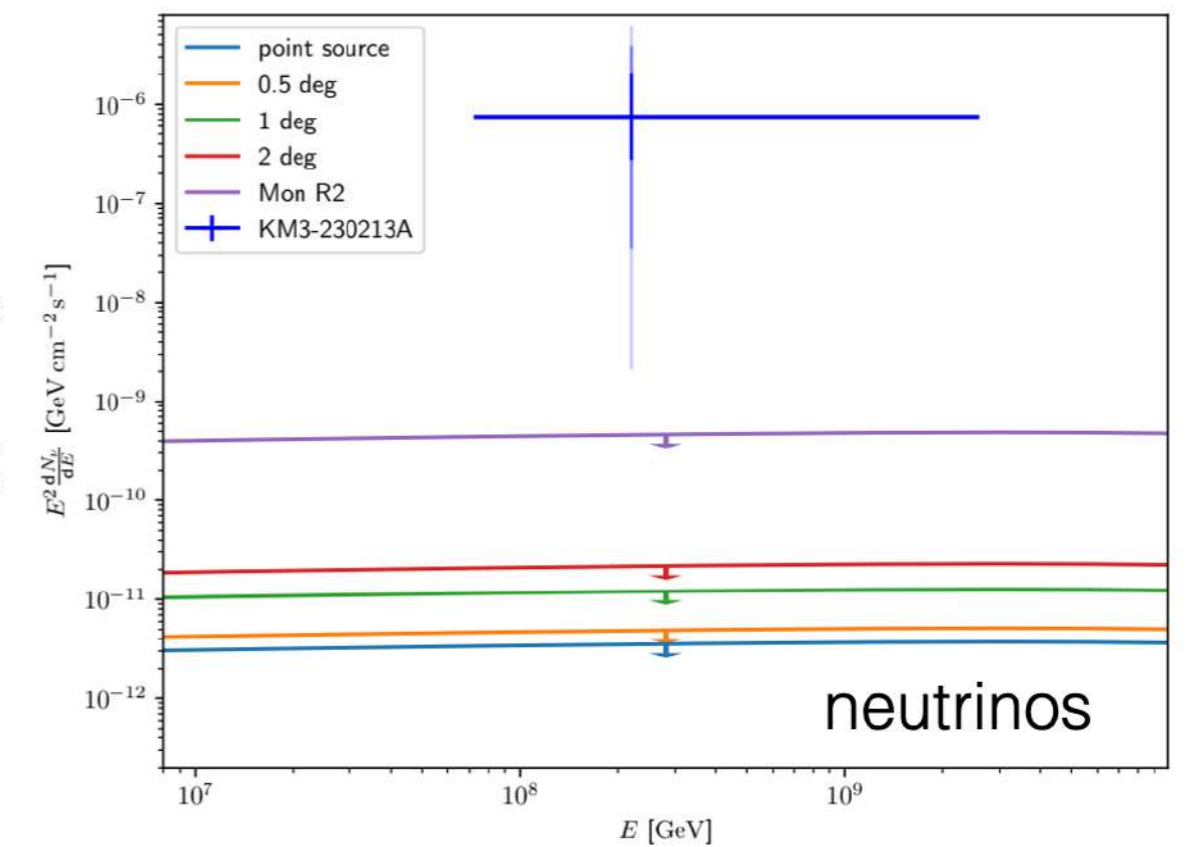
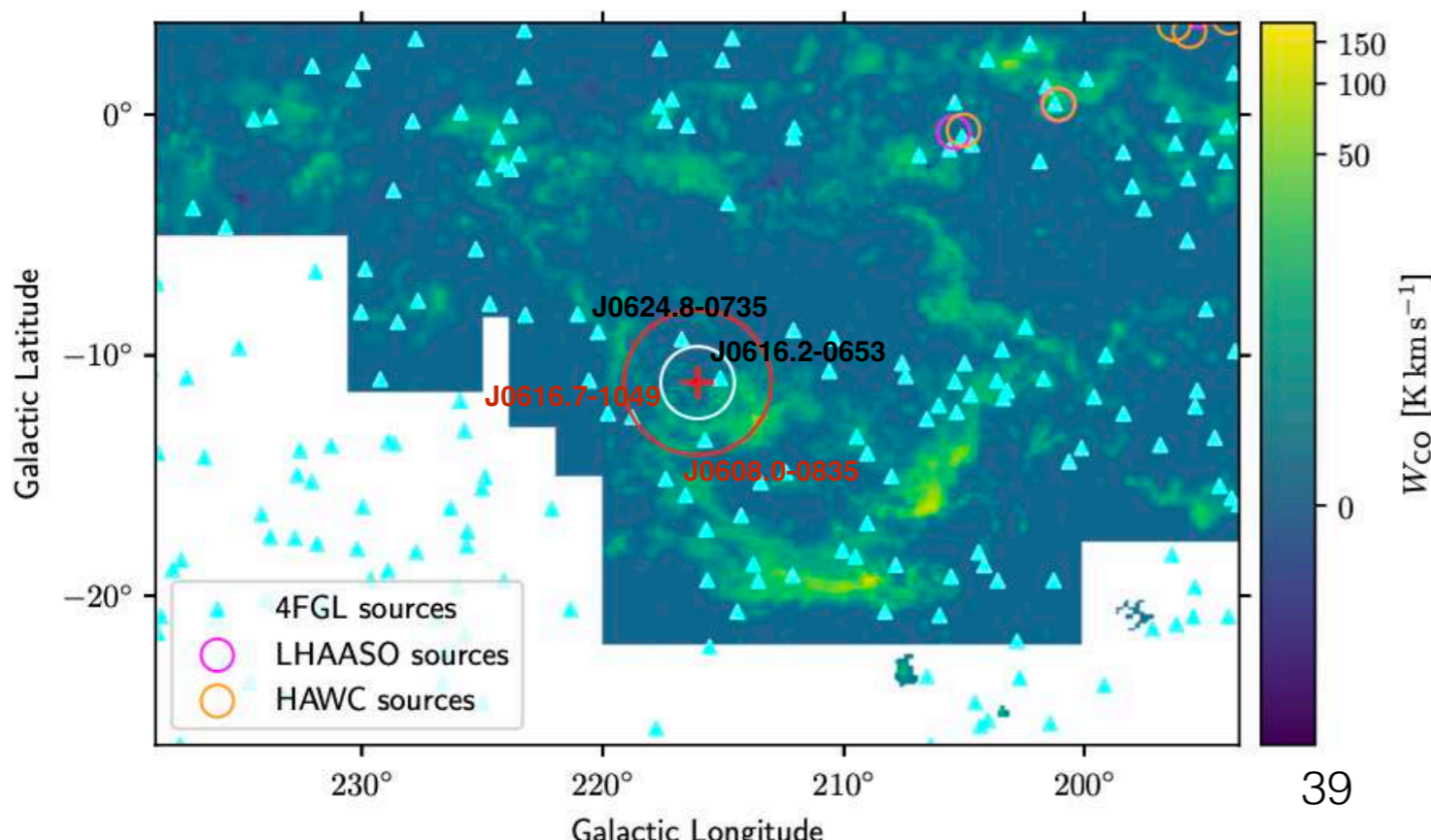
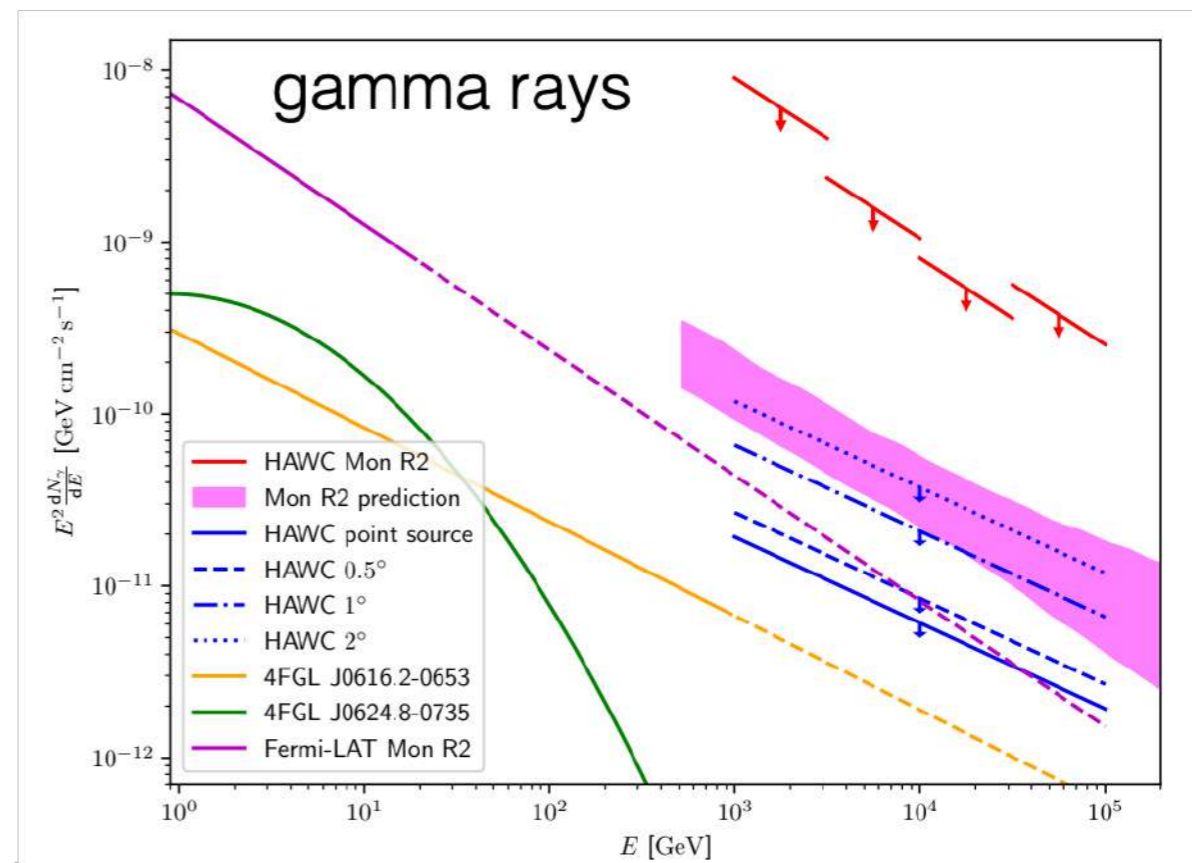
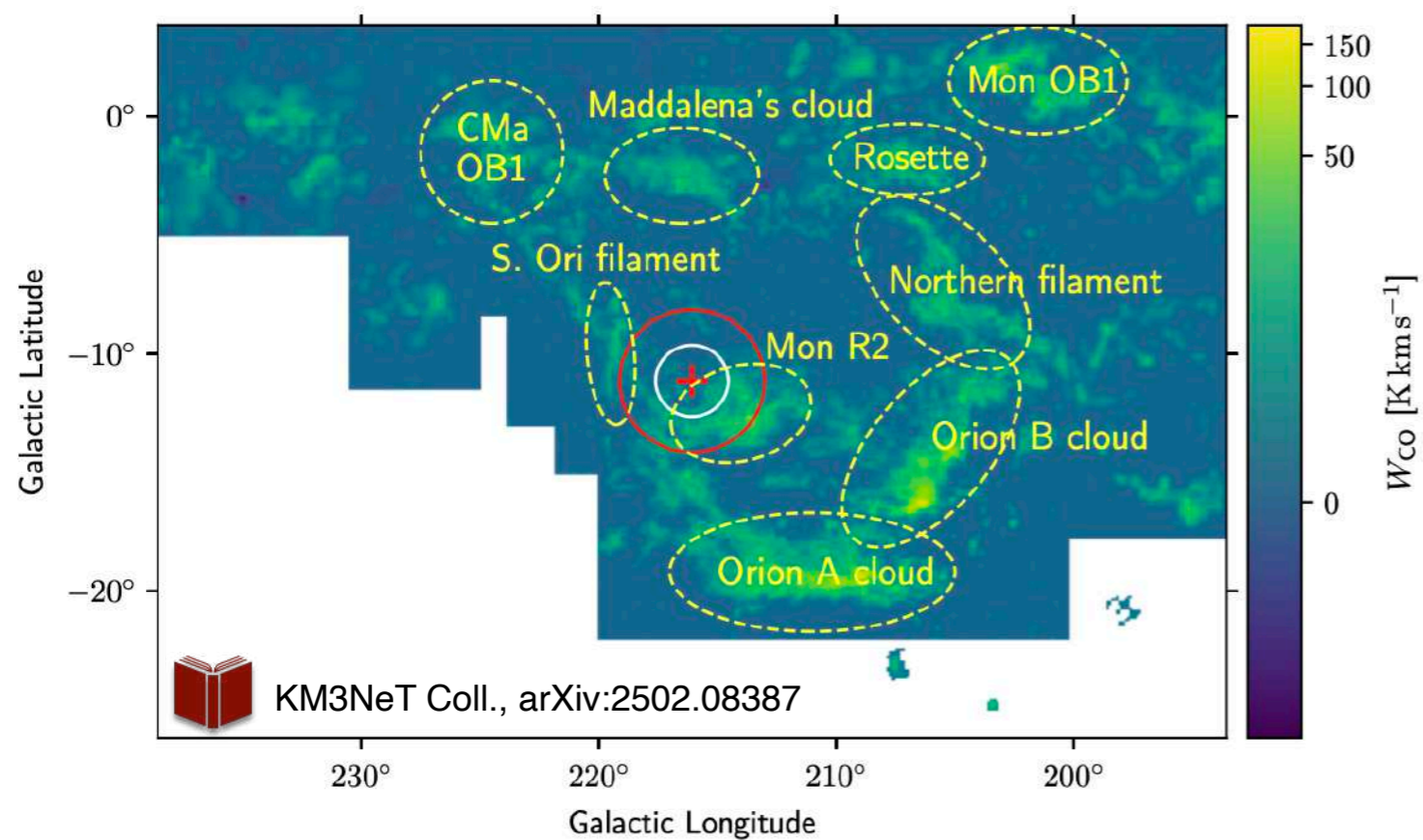
- SNRs (GreenCat)
- Young star clusters (Gaia DR2)
- X-ray binaries and  $\mu$ Qs (eRosita)
- Pulsars and PWNe (ATNF)
- Gamma-ray catalogs (4FGL, 3HWC, 1LHAASO)

No plausible counterparts found

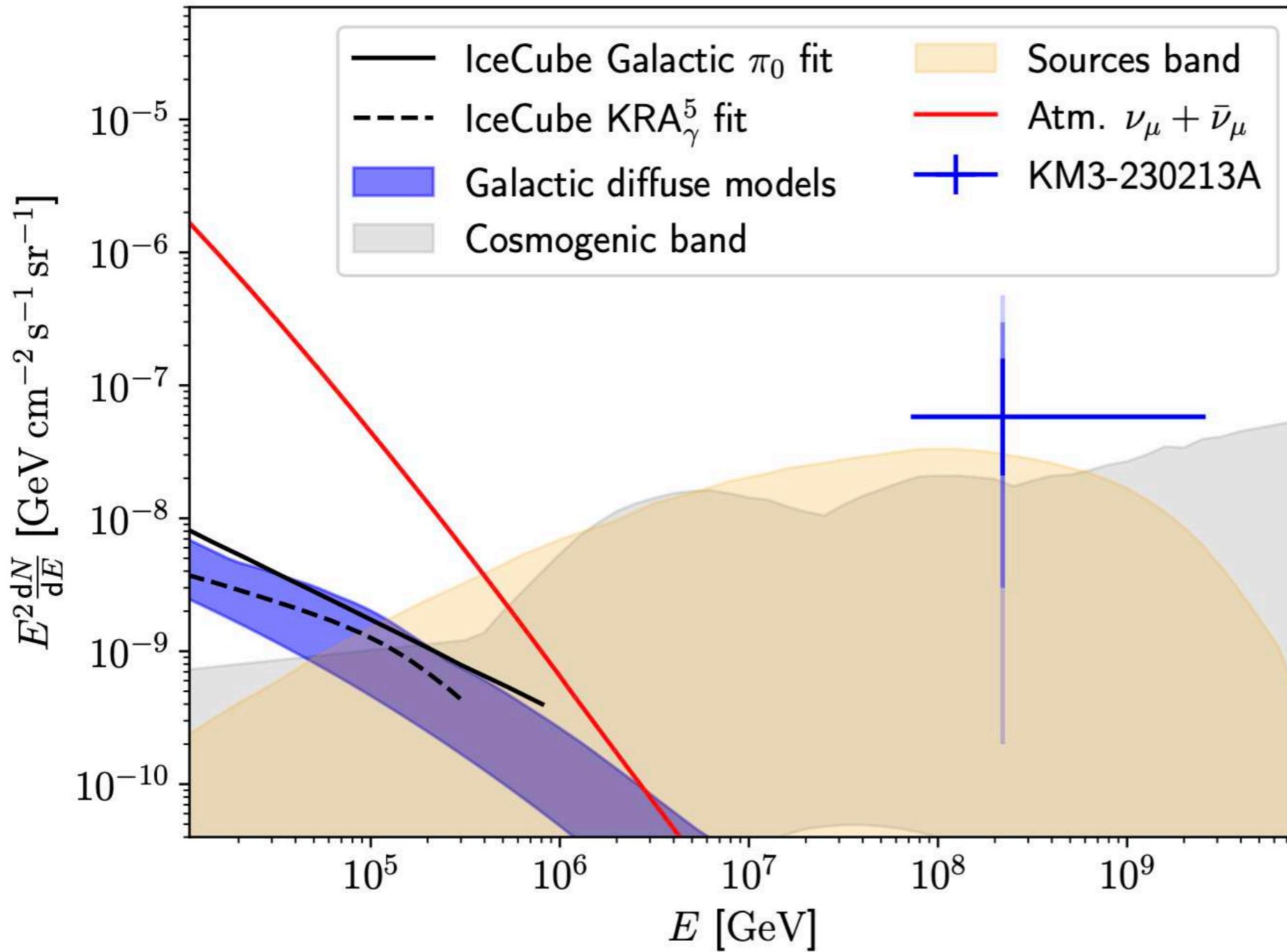


KM3NeT Coll., ApJ 1003 (2026) 157

# Hardly of Galactic nature



# Hardly of Galactic nature



Unlikely related to Galactic diffuse neutrino emission... even with the dense target of MonR2



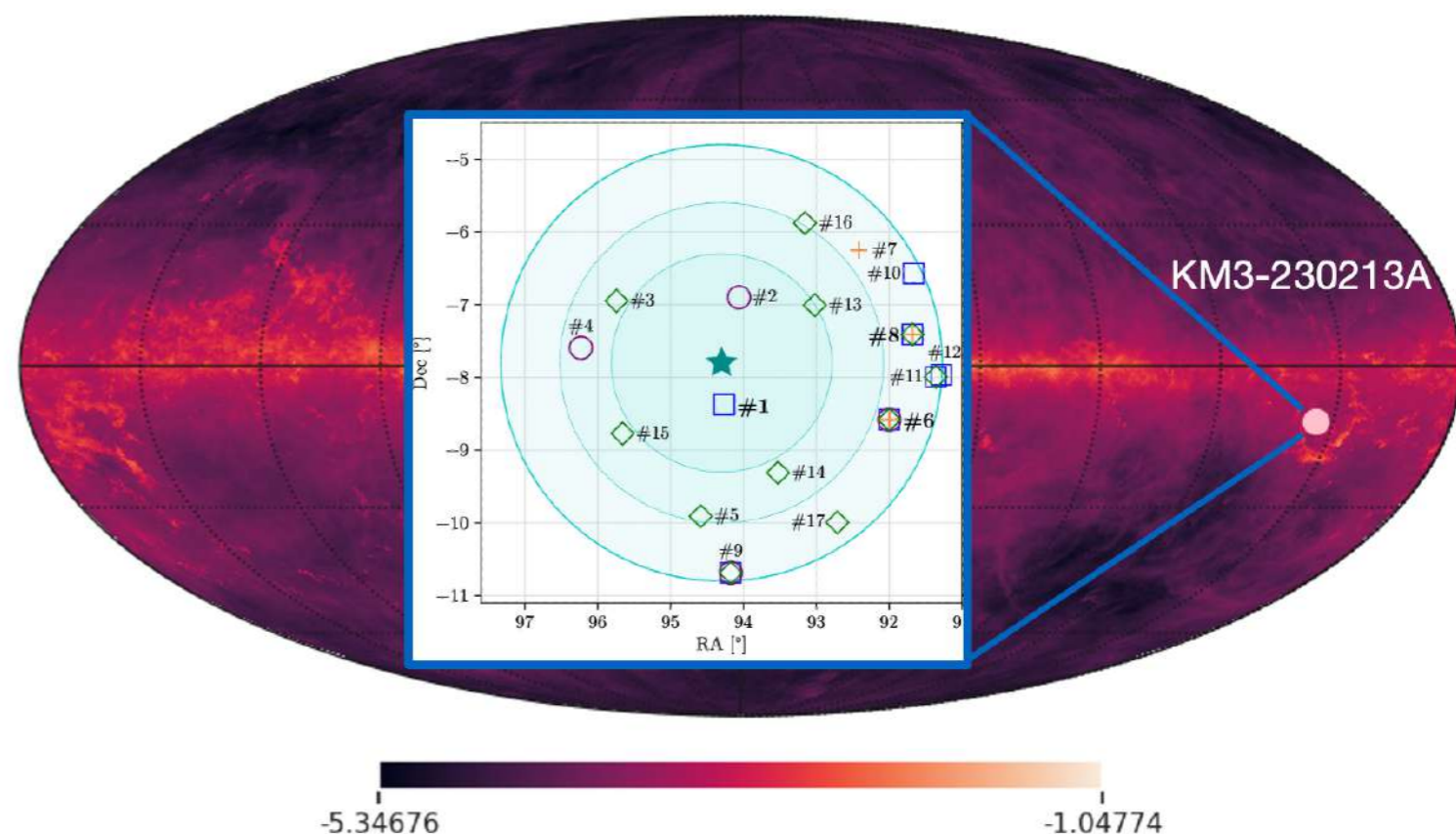
KM3NeT Coll., arXiv:2502.08387

# Testing the extra-galactic origin

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

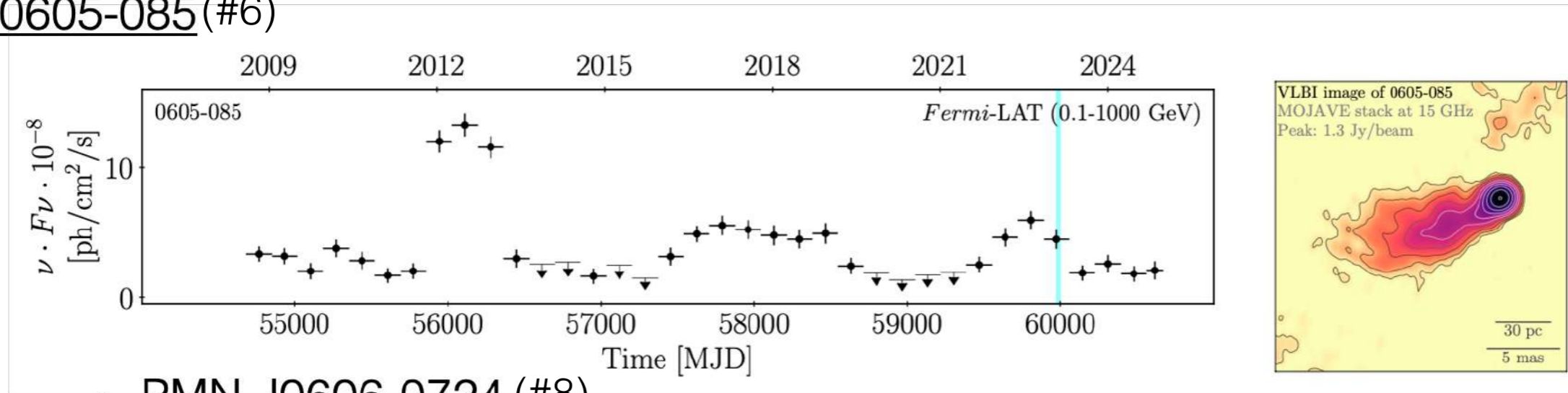
- Fermi 4FGL sources + TeVCat + 3HWC
- Optical transients (ZTF) + GCN, TNS and AT transients
- Blazars (radio VLBI/ALMA, infrared WISE/, optical ATLAS/CRTS/ZTF/Gaia, X rays SWIFT/Chandra/ROSAT/SVOM, gamma rays Fermi)

17 (2) blazars found in the  $3\sigma$  ( $1\sigma$ ) uncertainty region of  $3^\circ$  ( $1.5^\circ$ ) radius

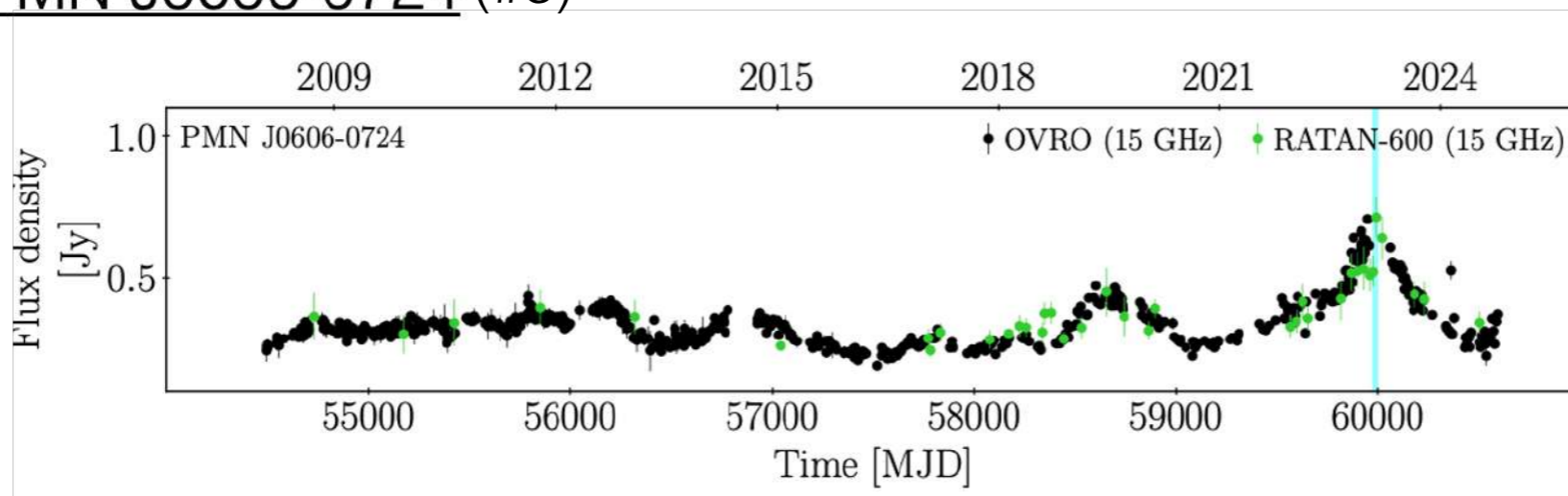


# Possible flaring blazar counterparts

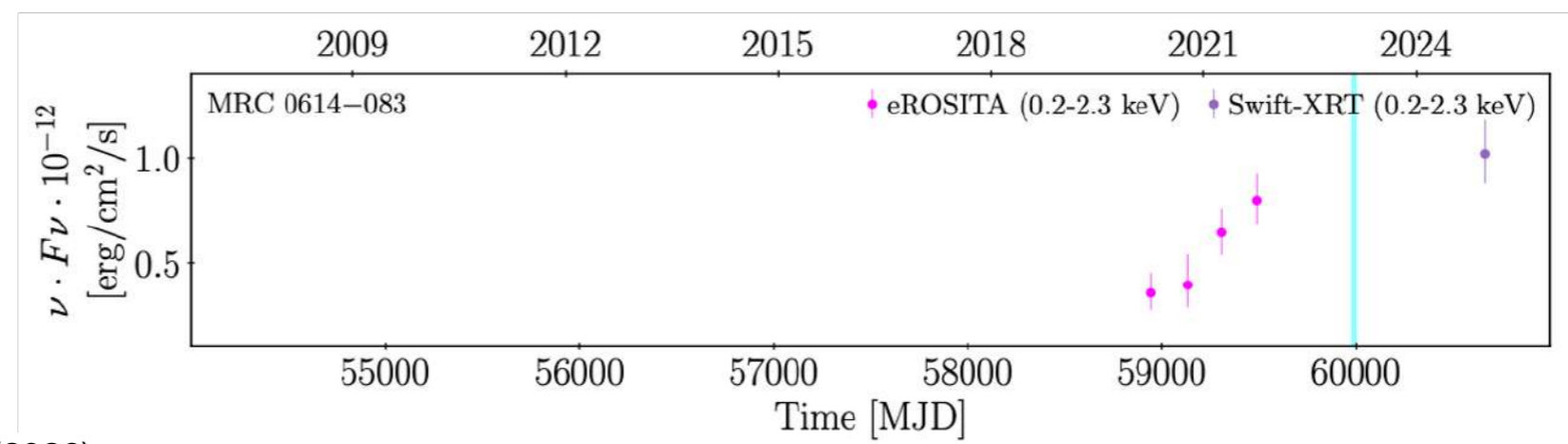
- 0605-085 (#6)



- PMN J0606-0724 (#8)



- MCR 0614-083 (#1)



No conclusive evidence

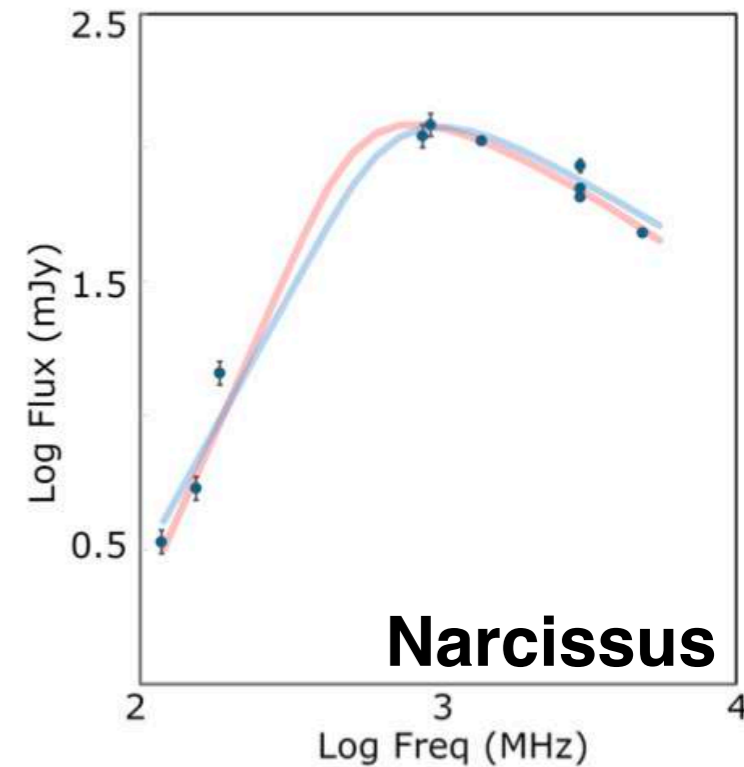
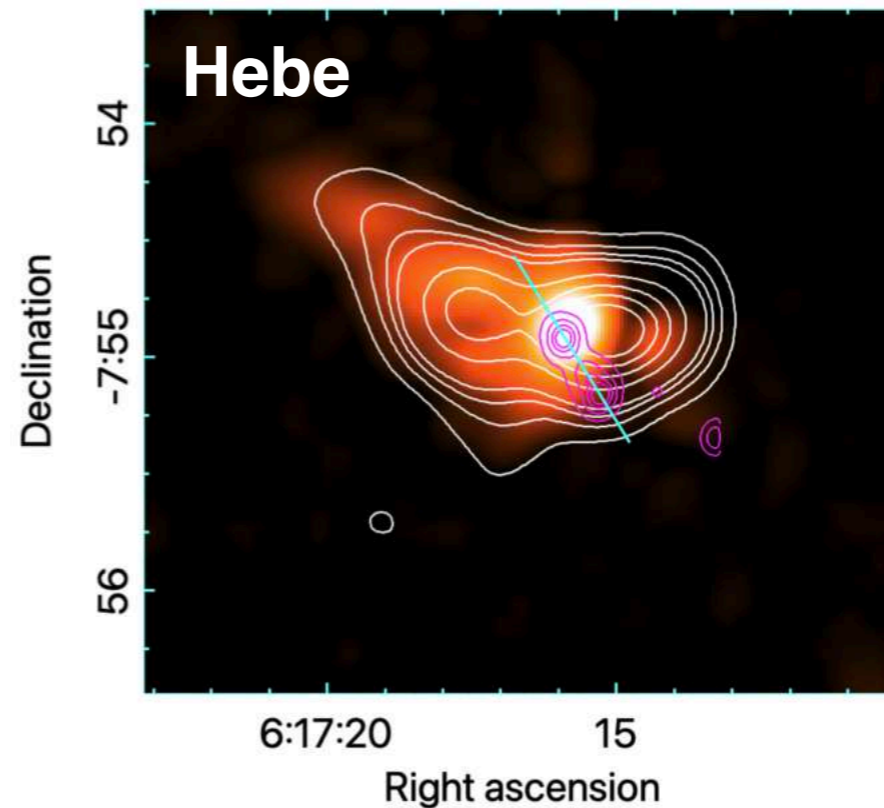
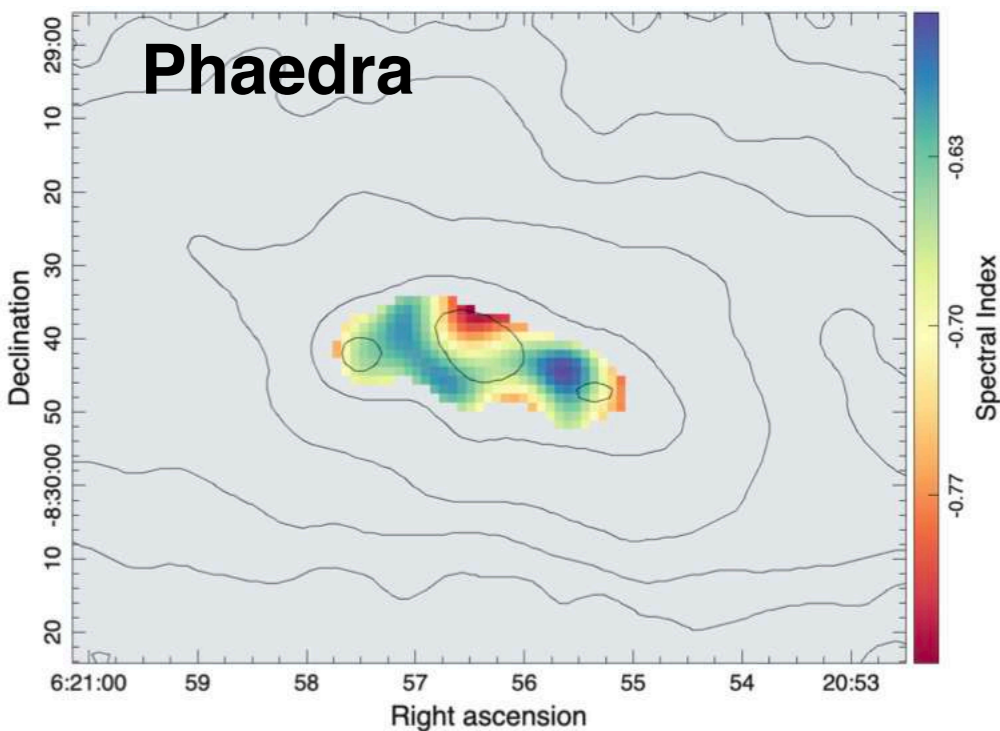


# KM3-230213A and non-blazar searches

- 3 non-blazar AGN identified in the KM3-230213A 68% search region via ASKAP/VLASS data
  - UGCA (aka Phaedra)
  - WISEA J061715.89–075455.4 (aka Hebe)
  - EMU J062248–072246 (aka Narcissus)

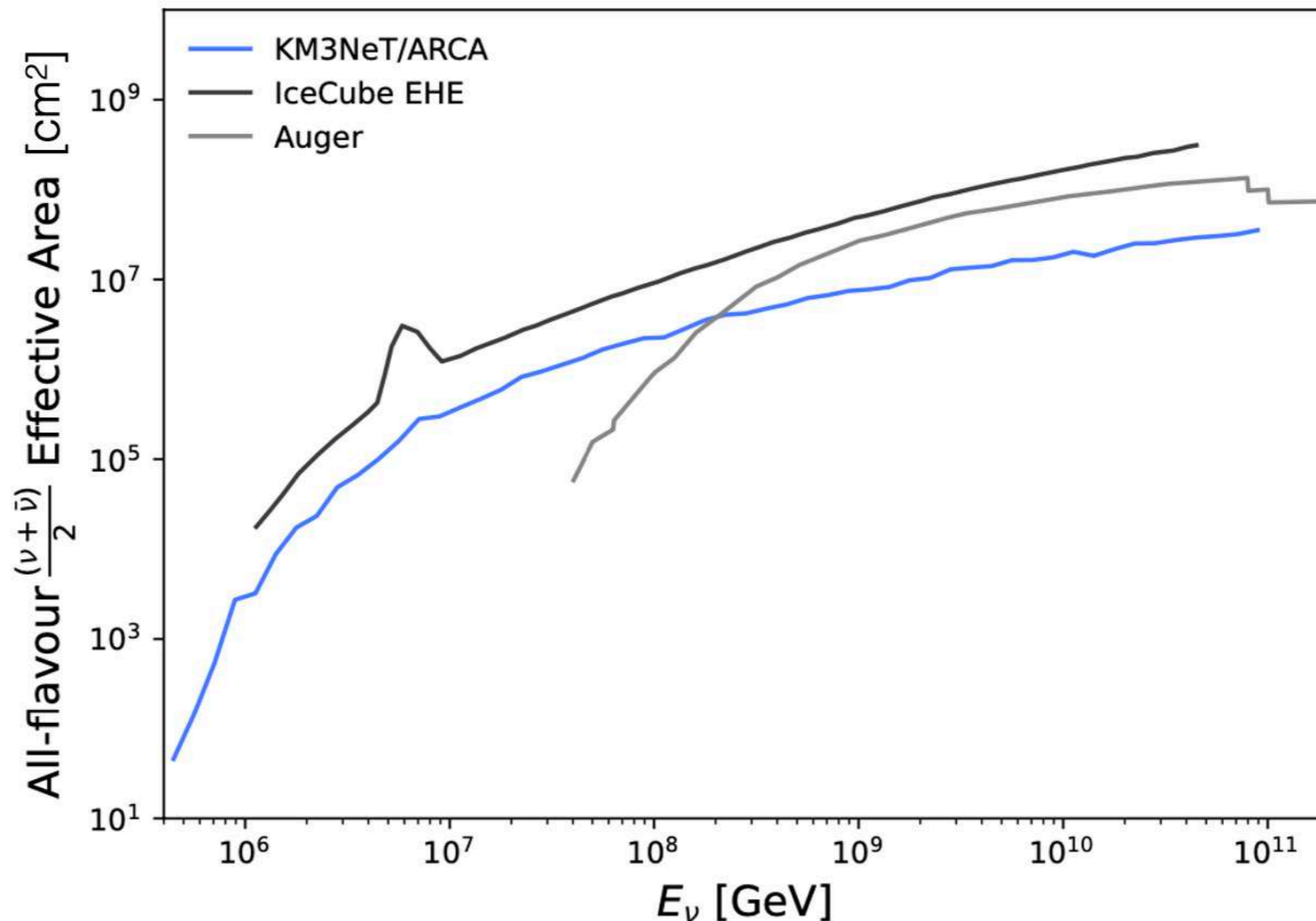


Filipovic et al., ApJL 984 (2025) 2

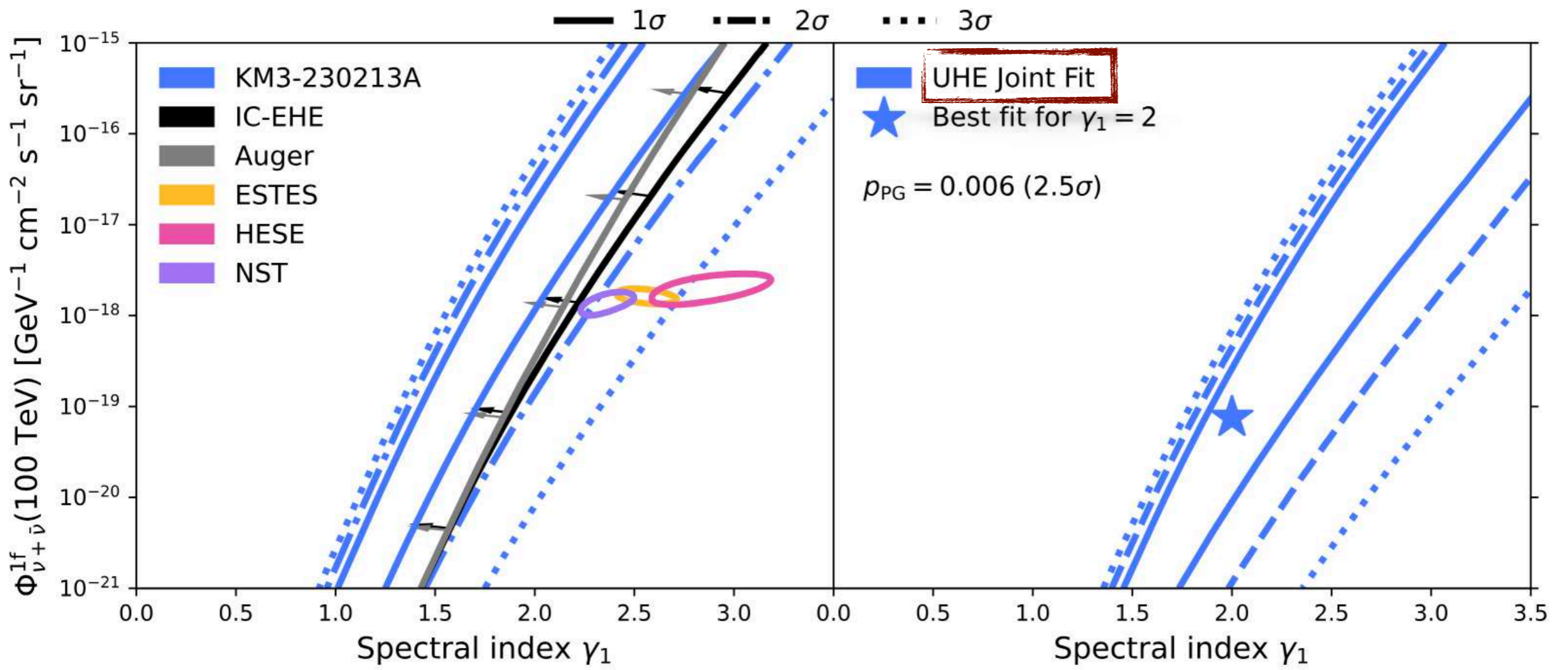


# A global fit to existing data

- Non-observations by IceCube & Auger place stringent constraints on the neutrino flux associated with KM3-230213A if this is associated to either a steady source or to cosmogenic origin



# A global fit to existing data




Single Power Law (SPL) scenario  
from TeV to multi-PeV

Adriani et al. [KM3NeT],  
JCAP 03 (2026) 033

# A global fit to existing data

		Samples <sup>a</sup>				Flux assumption		
		UHE			HE	$E^{-2}$	Simple Power Law	Broken Power Law
		K	I	A	I		SPL	BPL
HESE ESTES NST		✓	✓	✓	✗	$2.7\sigma/2.0\sigma$	<b><math>2.5\sigma/1.8\sigma</math></b>	...
		✓	✓	✓	H	...	$2.0\sigma/2.5\sigma$	$2.9\sigma/2.3\sigma$
		✓	✓	✓	E	...	$1.6\sigma/2.1\sigma$	$2.9\sigma/2.1\sigma$
		✓	✓	✓	N	...	$1.6\sigma/2.1\sigma$	$2.9\sigma/2.0\sigma$
		✓	✗	✗	H	...	$2.8\sigma/2.6\sigma$	...
		✓	✗	✗	E	...	$2.2\sigma/2.1\sigma$	...
		✓	✗	✗	N	...	$1.6\sigma/1.7\sigma$	...

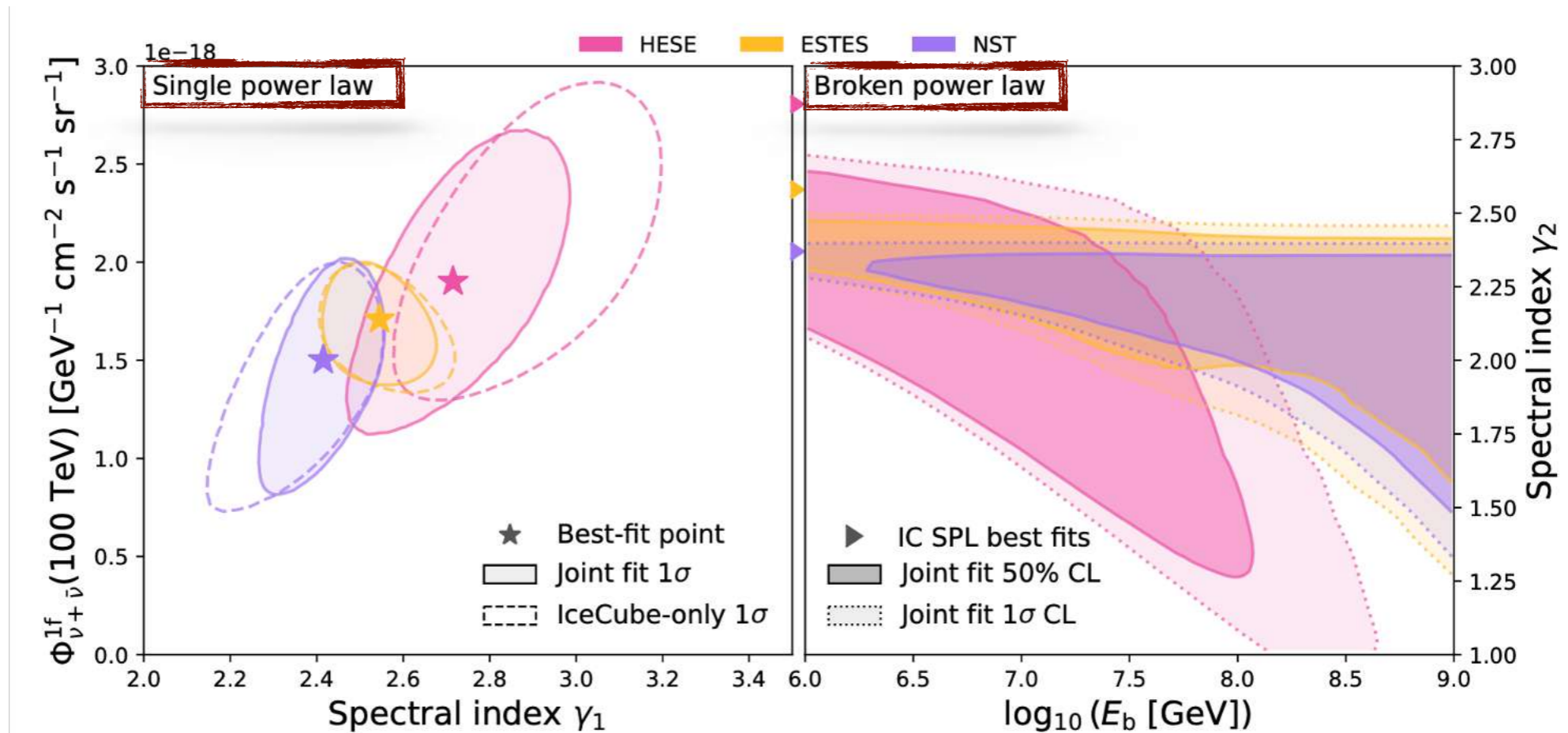
KM3NeT
Auger  
ICeCube

  
 frequentist/Bayesian

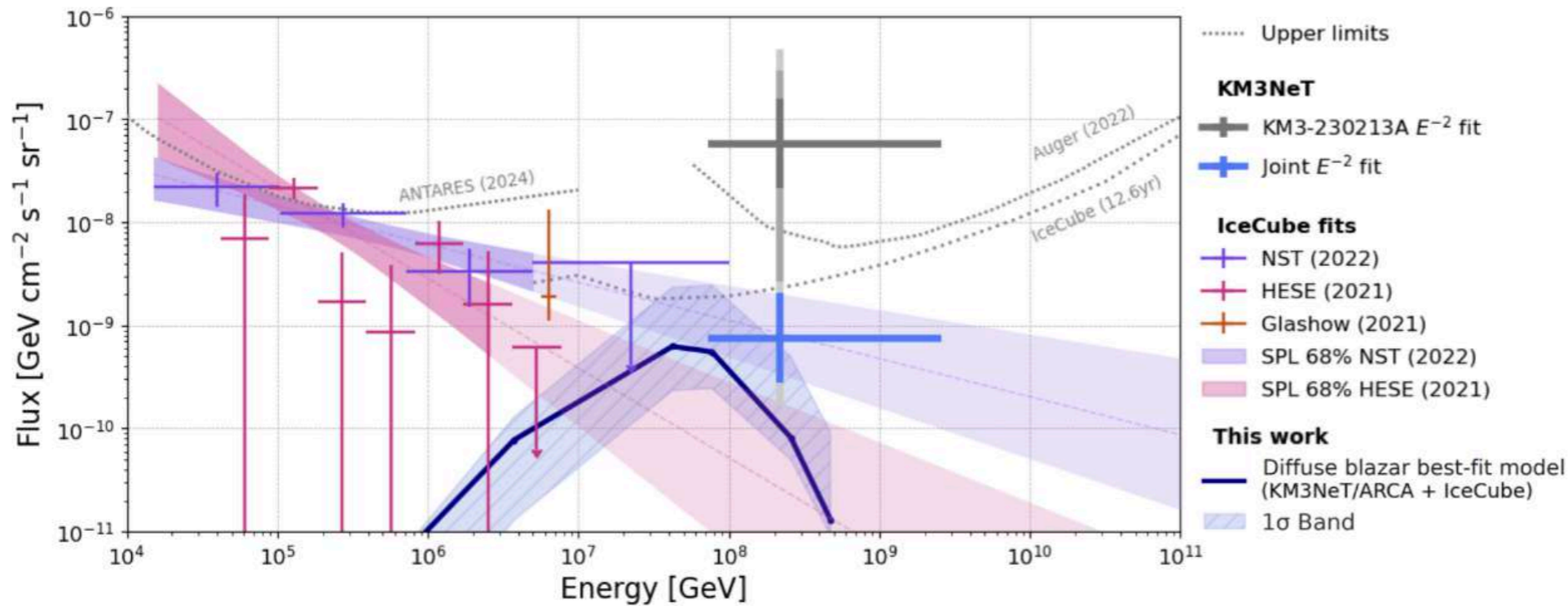
# Is there evidence of a new component?

- Both single (SPL) and broken power law (BPL) flux hypotheses tested across the entire astrophysical neutrino spectrum
- Three IceCube data samples below 10 PeV: HESE, ESTES, and NST
- No preference for BPL over SPL in the **global fit**

UHE Sample(s)	KM3-230213A			Global		
HE Sample	HESE	ESTES	NST	HESE	ESTES	NST
Bayes factor $\mathcal{B}$	27.0	8.7	3.9	1.2	0.6	0.3
LR p-value (%)	0.4	1.7	5.9	33	86	100



# Diffuse neutrinos from blazars and GRBs

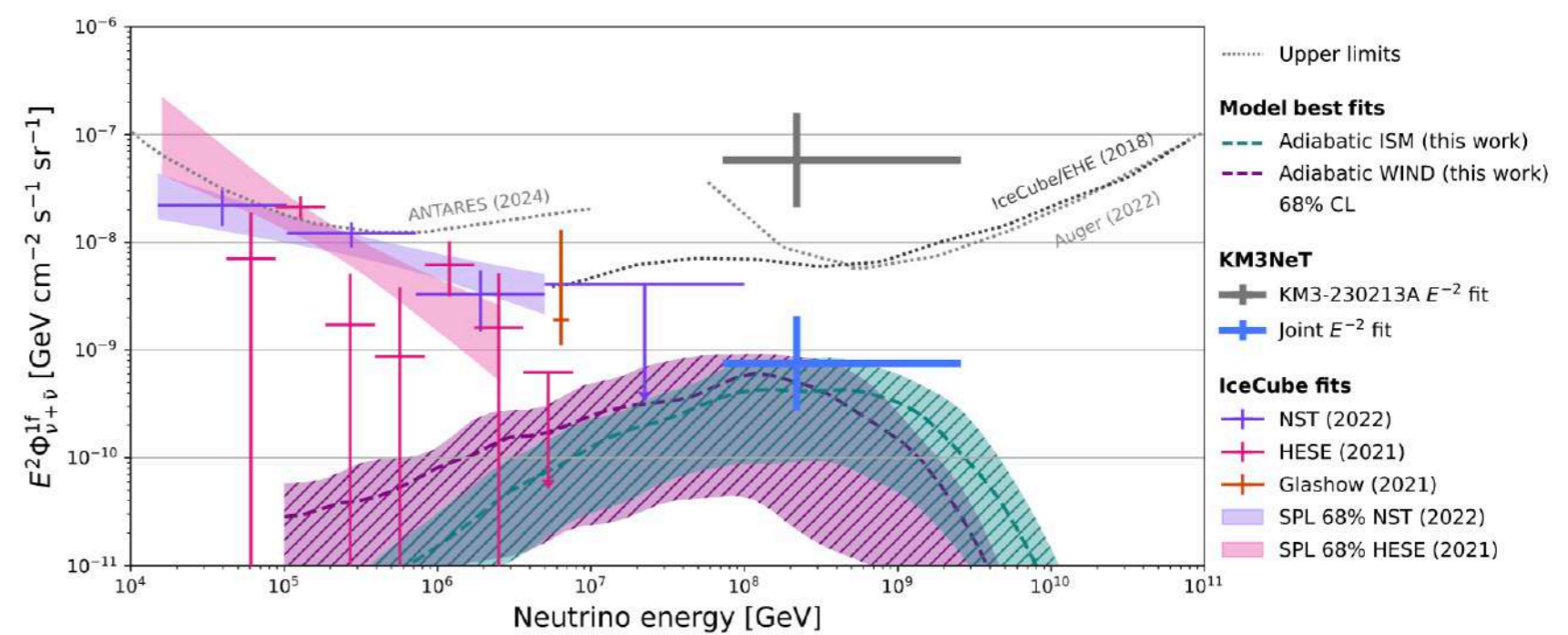


Blazar diffuse

Adriani et al. [KM3NeT], JCAP 03 (2026) 033

GRB afterglow

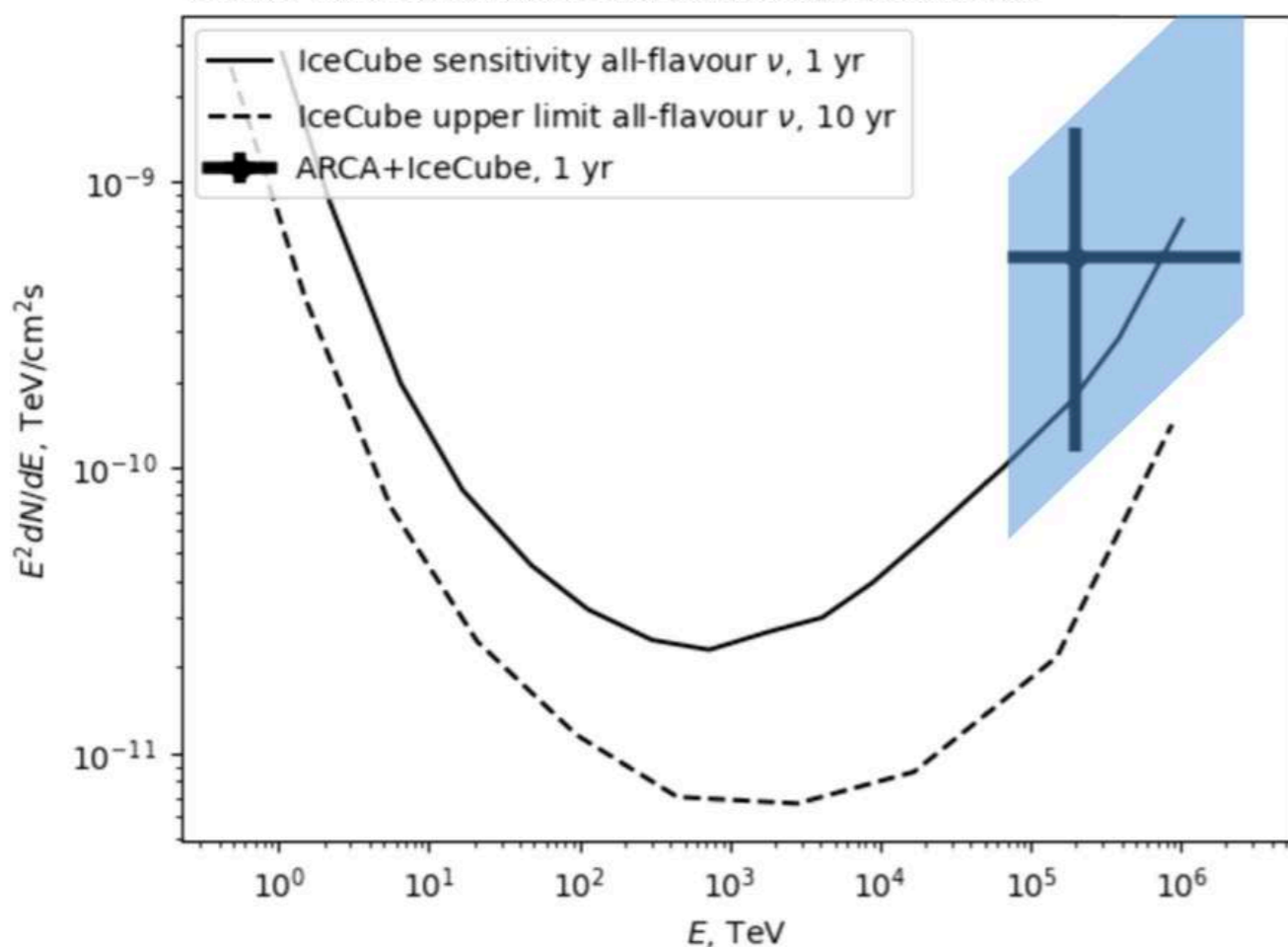
Adriani et al. [KM3NeT], A&A (2026) accepted



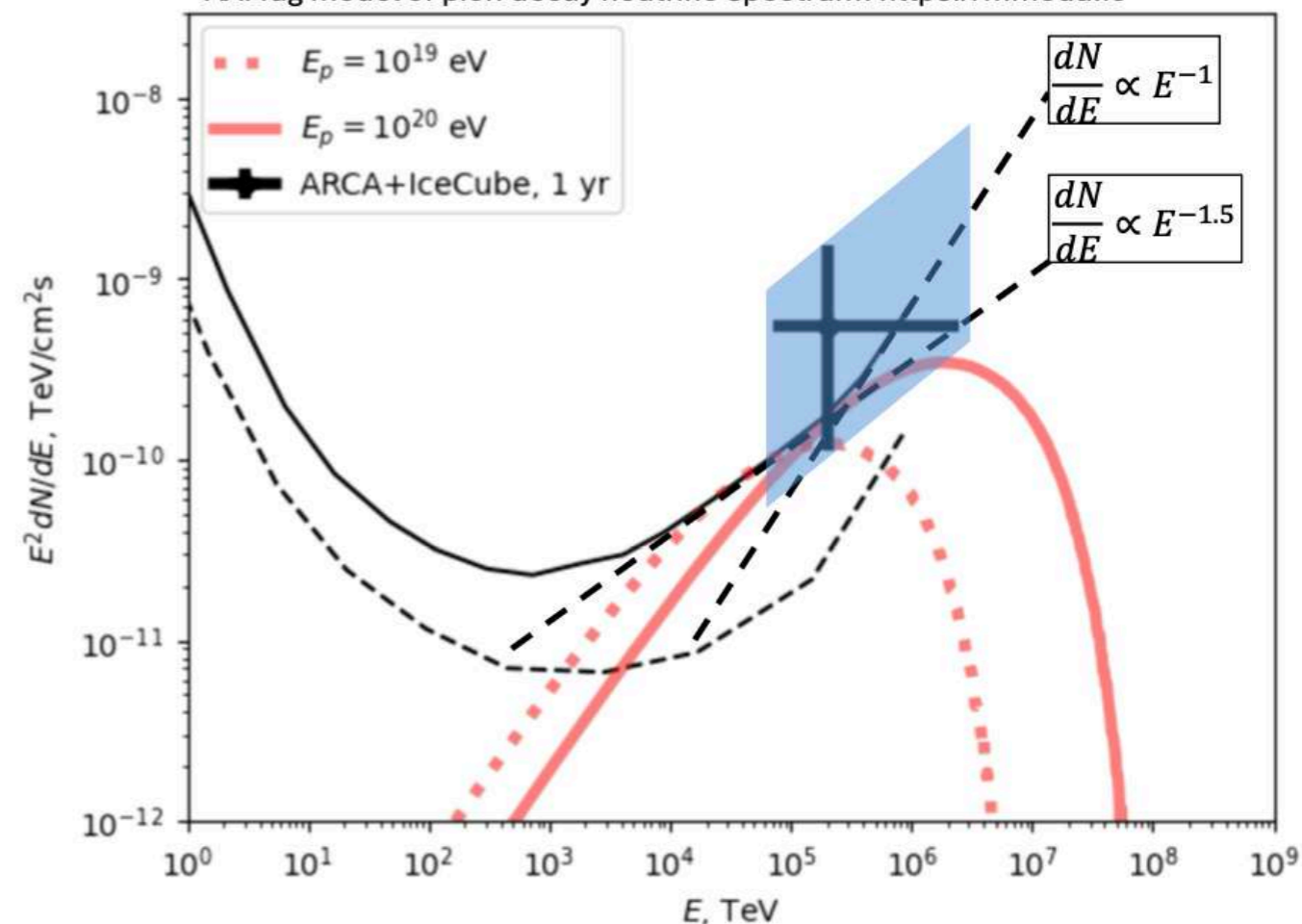
# An EG transient source?

- Flare with duration  $\mathbf{T < 2 \text{ yr}}$  compatible with IC non observation
- Particle injection spectrum must be **harder than  $E^{-2}$**  (either from monochromatic protons or as a result of py interactions off IR  $\gamma$ )
- Neutrino source fluence of  $10^{-2} \text{ erg/cm}^2$ , i.e.  $10^{50}$  (in  $1^\circ$ )- $10^{54} \text{ erg}$  @ 1 Gpc
- Suppressed, delayed & IGMF-deflected EM cascade emission ( $z > 0.1$ )
- Emissivity of these transient neutrino source class not extreme

IceCube public data analysis with SkyLLH: <https://mmoda.io>



AAFrag model of pion decay neutrino spectrum: <https://mmoda.io>



# Refined search for neutrino counterparts

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

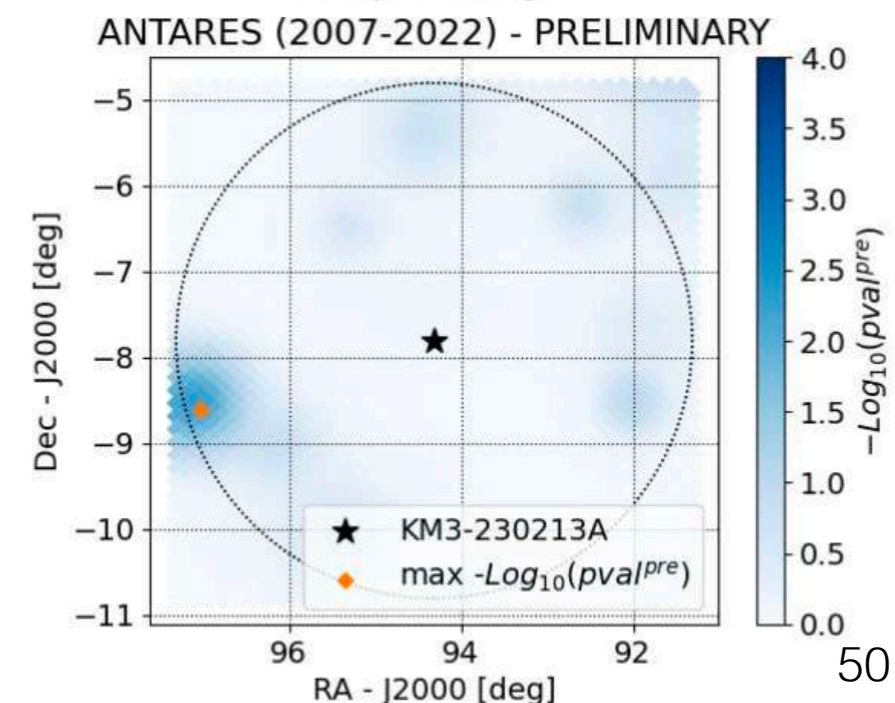
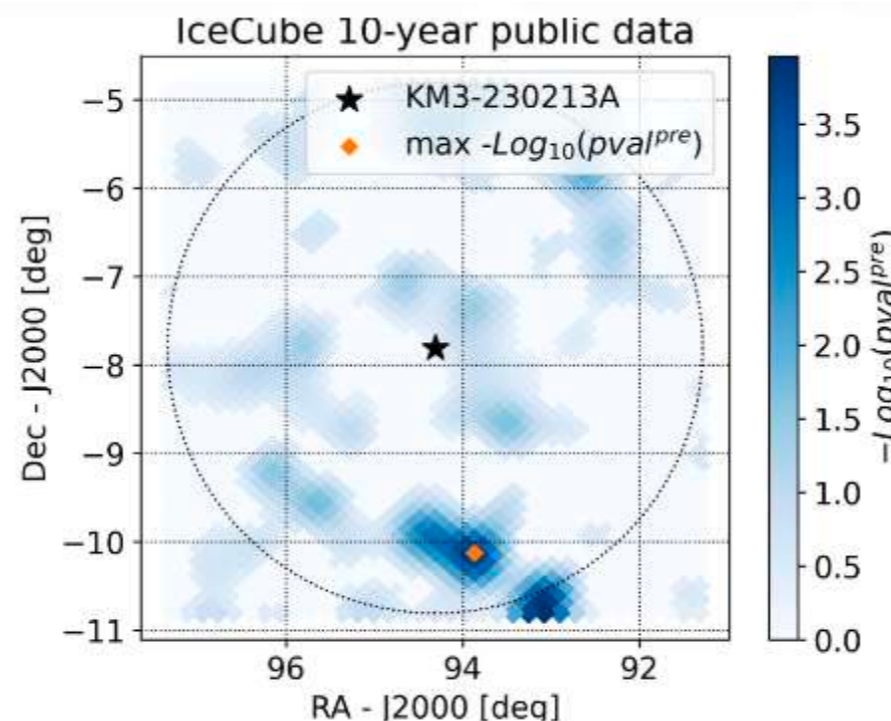
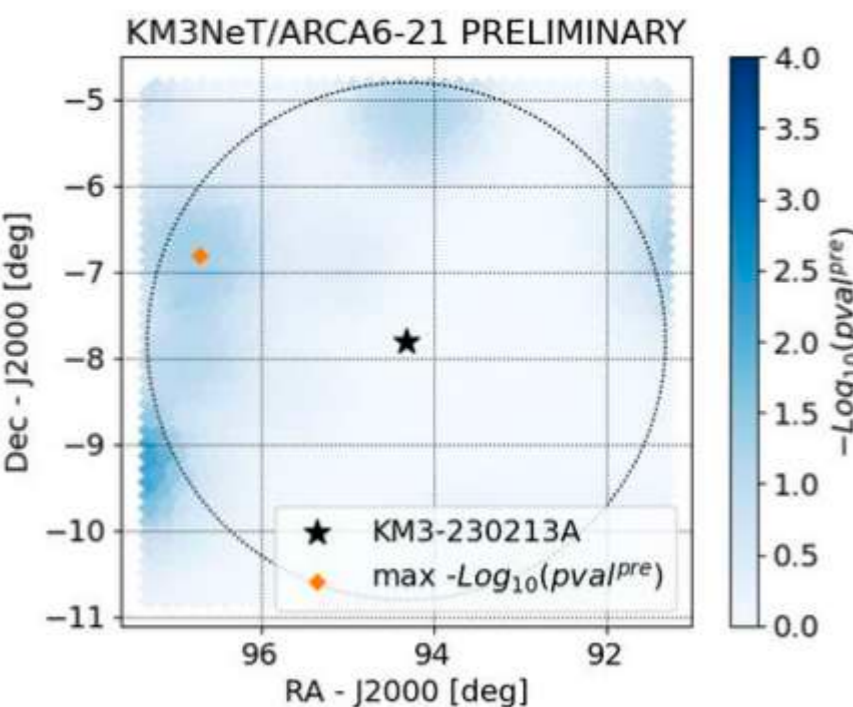
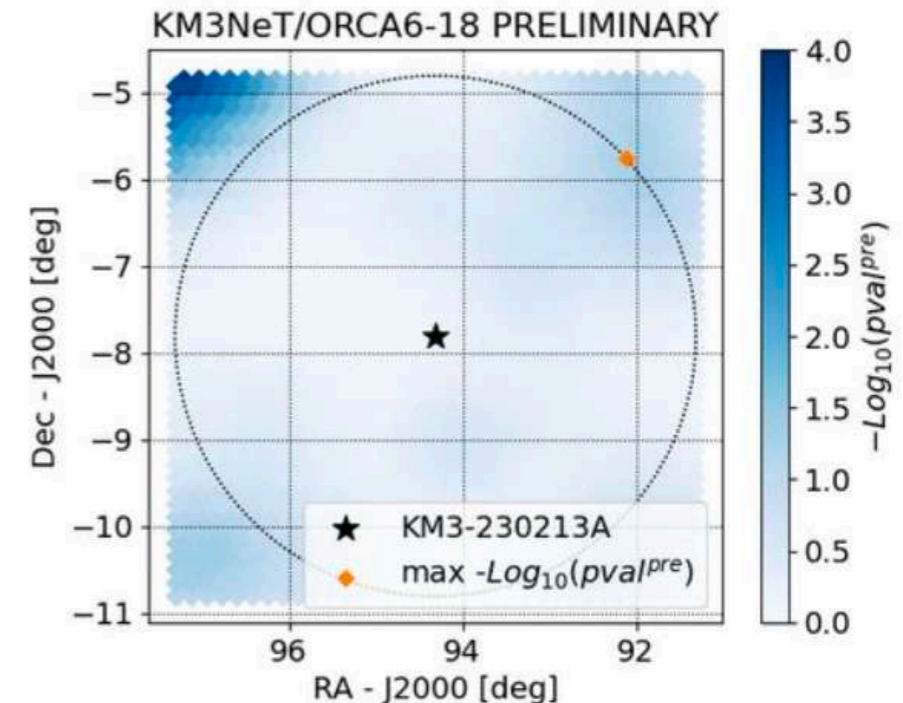
Upper limit on potential point-like source flux set to:

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



KM3NeT Coll., Nature 638 (2025) 8050

- Full ANTARES legacy dataset (tracks+showers)
- Offline KMeNeT/ORCA dataset
- **No significant excess at the coordinates of KM3-230213A**
  - 3°x3° scans largest excess in IceCube dataset (2.4° away from the UHE event, pre-trial  $p\text{-val} = 1.64 \times 10^{-4}$ , post-trial  $p\text{-val} = 0.07$ )



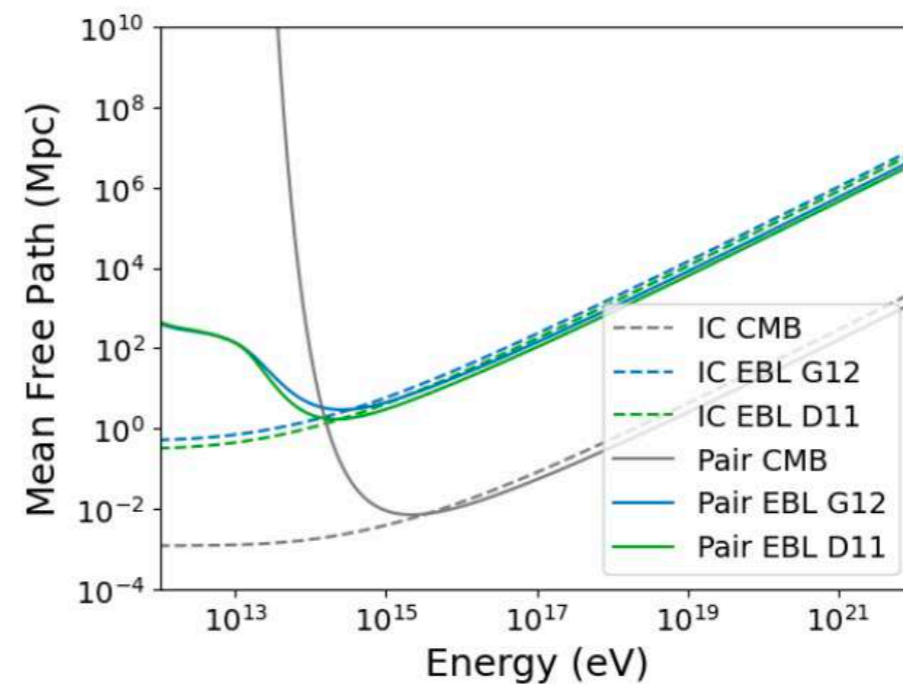
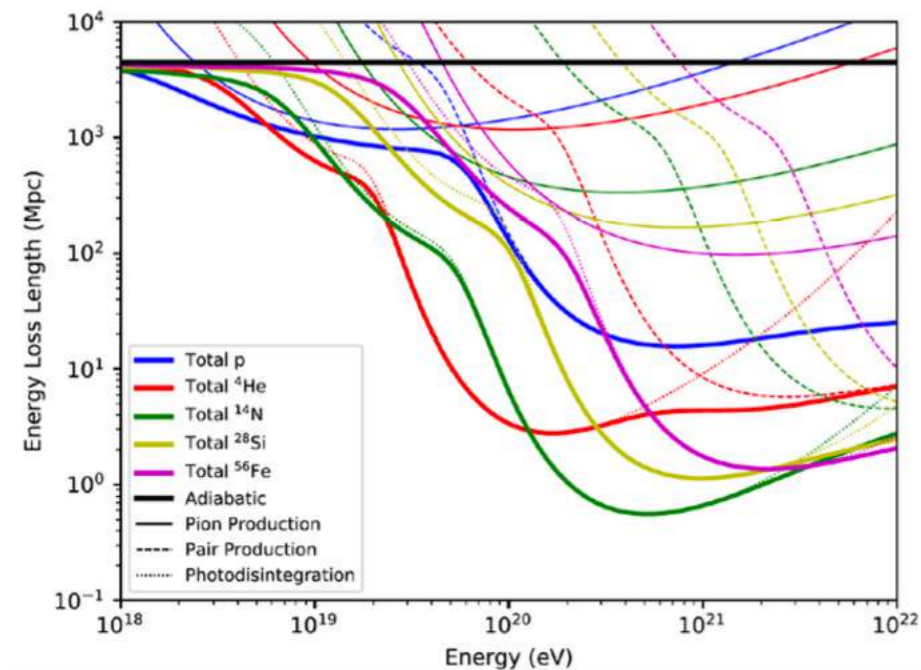
# Refined search for neutrino counterparts

Dataset				Method	
Detector	Type	Covered Period	Livetime [days]	Analysis Approach	Radius [deg]
ARCA6-21	offline	12/05/2021 - 11/09/2023	640	binned likelihood [5]	3
ORCA6-18	offline	11/02/2020 - 31/08/2023	1005	ON/OFF [13]	4
ORCA18-23	online	01/09/2023 - 29/07/2024	126	ON/OFF [13]	4
ANTARES	public	29/01/2007 - 31/12/2017	3125	unbinned likelihood [6]	3
IceCube	public	06/04/2008 - 08/07/2018	3577	unbinned likelihood [11, 12]	3
ANTARES*	legacy	29/01/2007 - 13/02/2022	4541	unbinned likelihood [9, 10]	3
ORCA6-18*	offline	11/02/2020 - 01/09/2023	1196	binned likelihood [8]	3

Datset	$p$ -value (pre-trial)	Flux Upper Limit [GeV <sup>-1</sup> cm <sup>-2</sup> s <sup>-1</sup> ]	(RA, $\delta$ ) [deg, deg]	Distance [deg]	$p$ -value (post-trial)
ARCA6-21	0.904	$1.8 \times 10^{-8}$	(94.3, -7.8)	0.0	-
	0.0492	$1.9 \times 10^{-8}$	(96.7, -6.8)	2.6	0.44
ORCA6-18	1.00	$2.1 \times 10^{-7}$	-	-	-
ORCA18-23	1.00	$2.3 \times 10^{-6}$	-	-	-
ORCA-combined	-	$2.0 \times 10^{-7}$	-	-	-
ANTARES	0.990	$1.1 \times 10^{-8}$	(94.3, -7.8)	0.0	-
	0.0116	$1.7 \times 10^{-8}$	(94.4, -5.3)	2.5	0.53
IceCube	0.471	$1.2 \times 10^{-9}$	(94.3, -7.8)	0.0	-
	$1.65 \times 10^{-4}$	$6.3 \times 10^{-9}$	(93.9, -10.1)	2.4	0.07
ANTARES*	0.870	$1.8 \times 10^{-9}$	(94.3, -7.8)	0.0	-
	$4.78 \times 10^{-3}$	$5.1 \times 10^{-9}$	(97.0, -8.6)	2.9	0.29
ORCA6-18*	0.670	$1.9 \times 10^{-7}$	(94.3, -7.8)	0.0	-
	0.053	$2.9 \times 10^{-7}$	(92.1, -5.7)	3.0	0.90

# Testing the cosmogenic origin

The Universe is opaque to electromagnetic radiation & UHECRs ( $E > 10^{19}$  eV) at  $z > 1$   $\longrightarrow$  **most of UHECR sources are unconstrained**



Cosmogenic neutrino fluxes depend on the UHECR injected spectrum (slope, maximum energy, mass composition) & source evolution:

$$q_A(E) = q_{0A} \left( \frac{E}{E_0} \right)^{-\gamma_A} \begin{cases} 1 & \text{if } E \leq E_{\max}^Z \\ \exp(1 - E/E_{\max}^Z) & \text{otherwise.} \end{cases}$$

$$S(z) \propto (1+z)^m \quad z_{\max} = 1, 6 \quad m = [-5, 5]$$

$$L(E, z) = S(z) \times Q_{\text{CR}}(E)$$

[ $A = 1, 4, 14, 28, 56$ ]

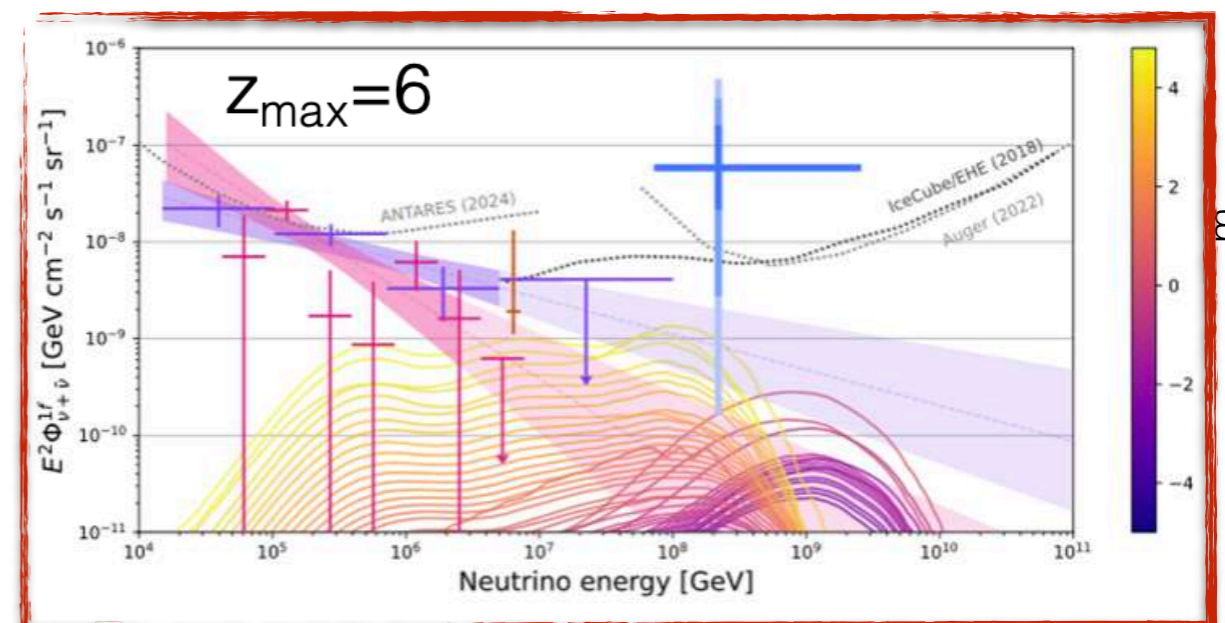
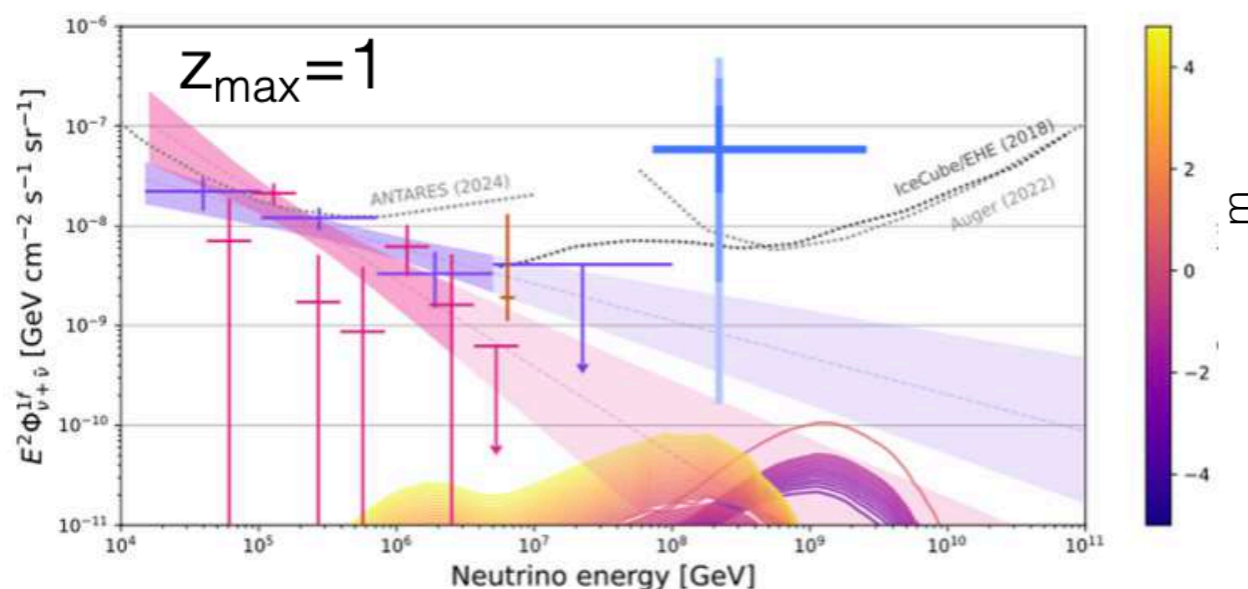
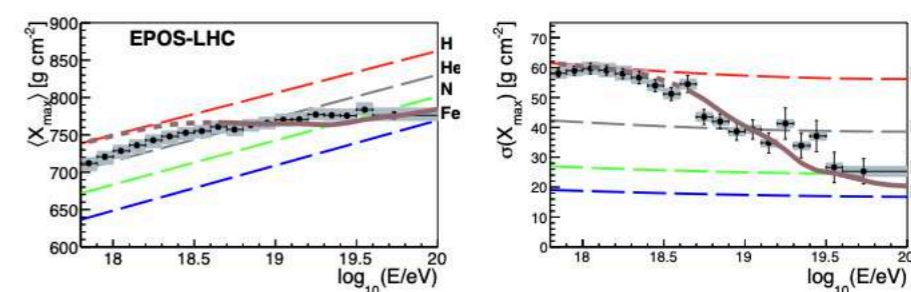
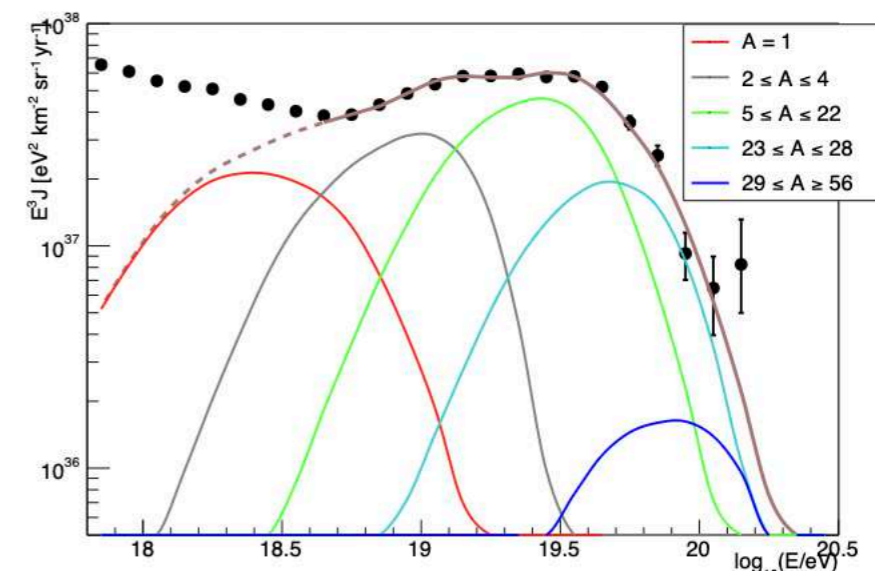


# Testing the cosmogenic origin

**Minimal** scenario (identical sources) fitting UHECR spectrum & composition above the ankle with:

- hard UHECR injection and low-rigidity cut-off
- few injected protons (mostly produced during propagation)

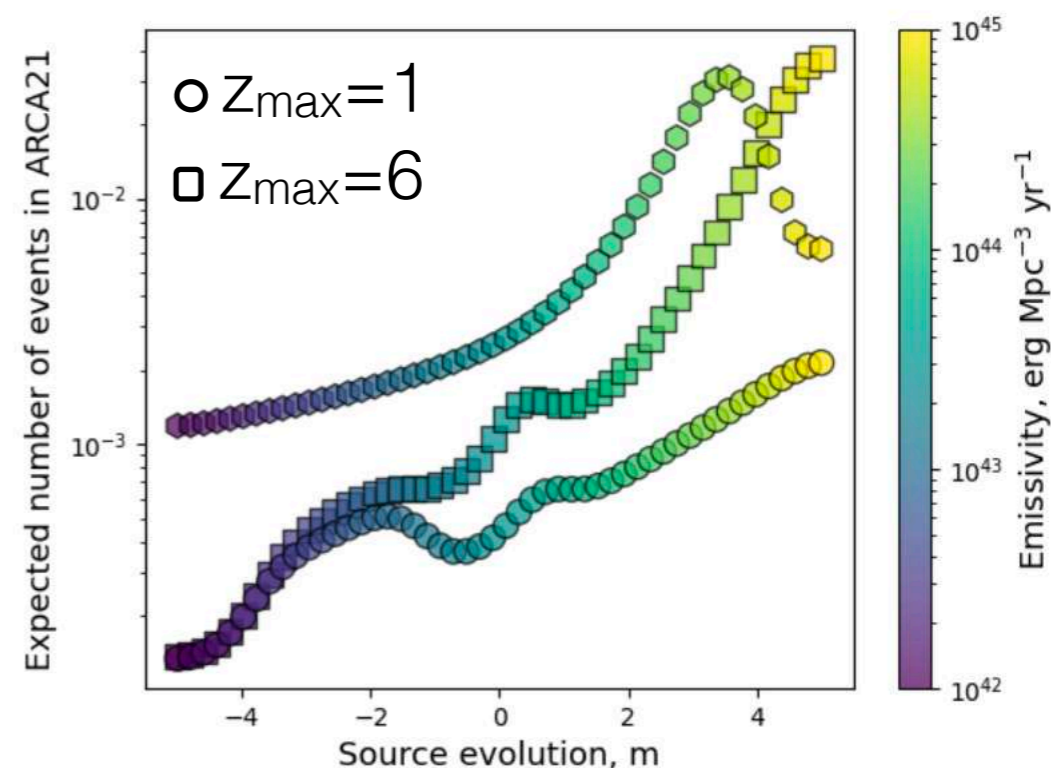
→ **Cosmogenic neutrino sources should extend up to  $z \sim 6$  with positive evolution**



# Testing the cosmogenic origin

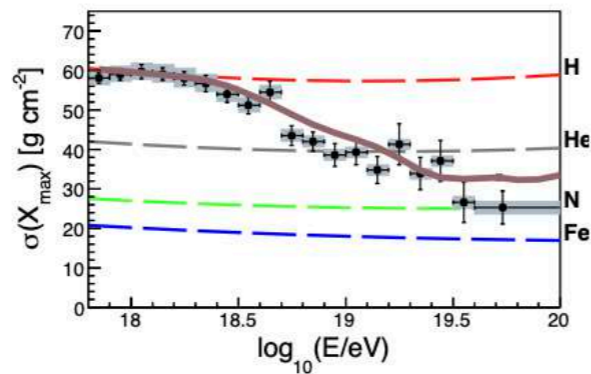
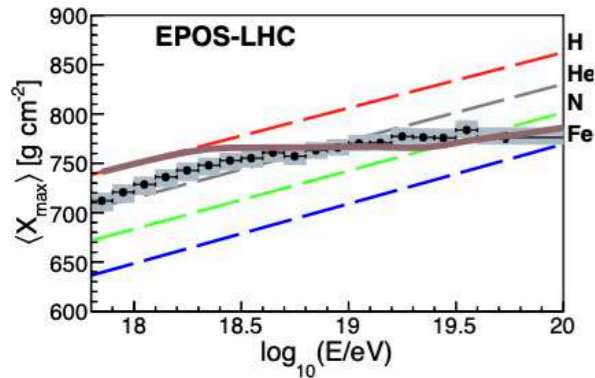
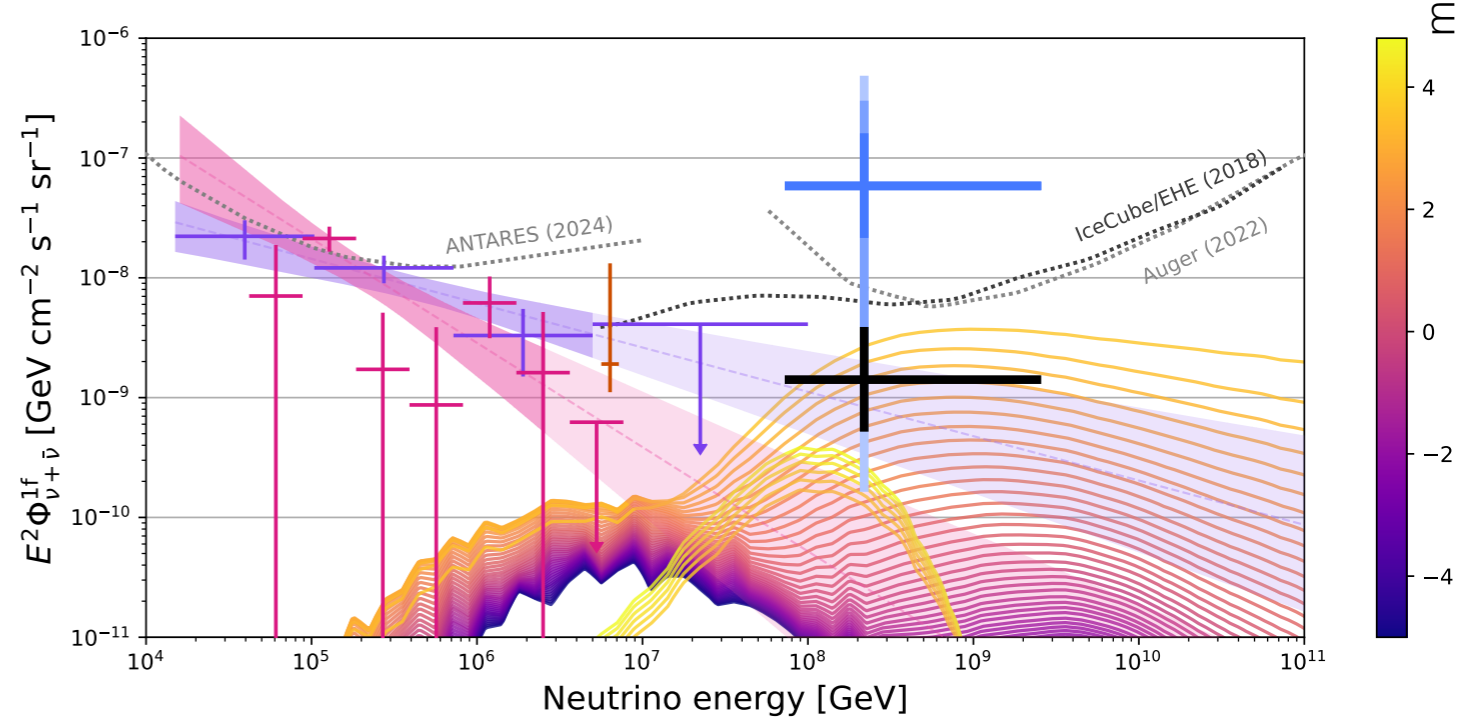
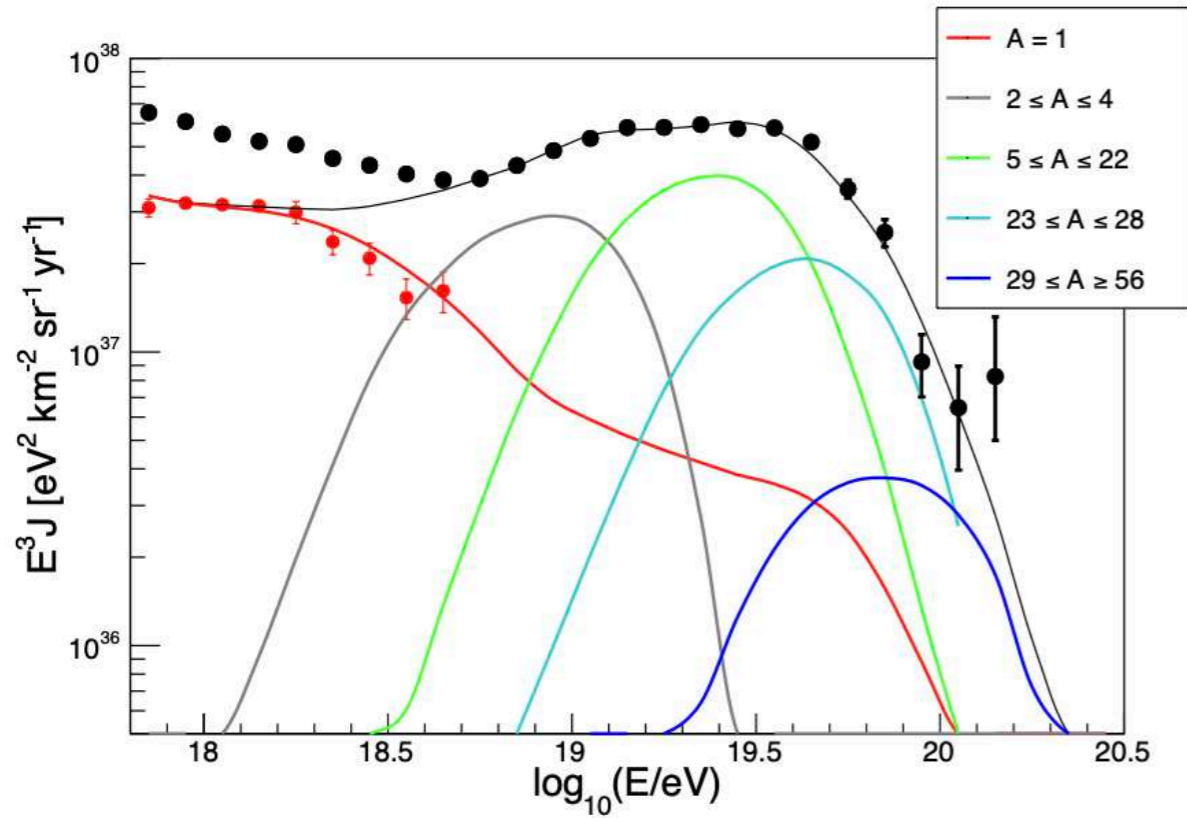
- **Negative source evolution** implies that the total flux is dominated by **nearby sources**  $\longrightarrow$  less room for photo-disintegration of heavy nuclei  $\longrightarrow$  the fit favors an intermediate-mass composition at the source, closely resembling the observed one.
- **Positive evolution** suggests that most **sources** are **farther away**, allowing for more photo-disintegration processes  $\longrightarrow$  heavier composition at the source, which becomes lighter at Earth due to interactions during propagation.

Event rate in ARCA21  
(335 days livetime)



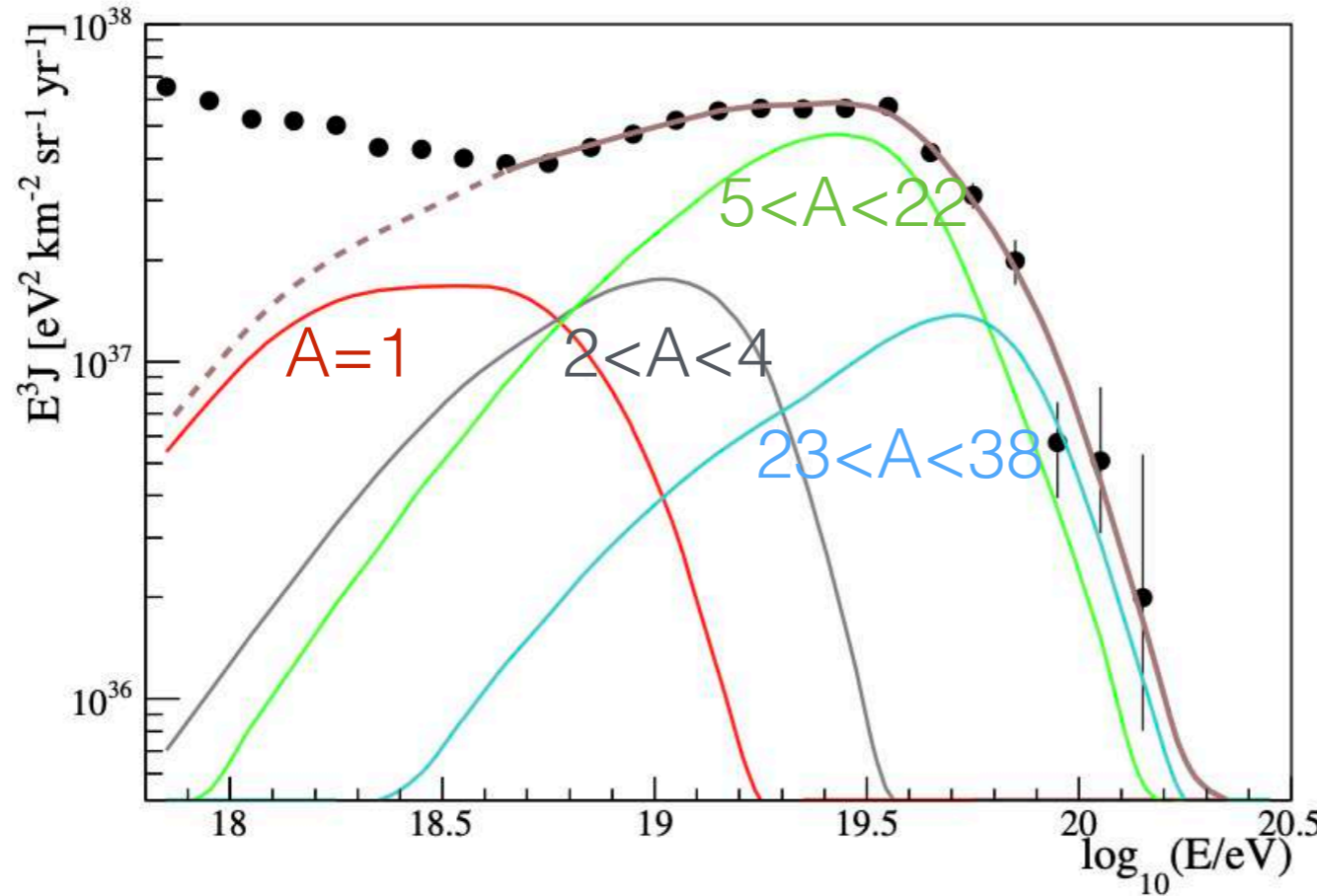
0.06 expected events in ARCA21  
livetime = 5.6% probability of  
observing the UHE event

# UHECR fit by KM3NeT with secondary sub-ankle protons



KM3NeT Coll., ApJL 984 (2025) L41

# UHECRs by Auger

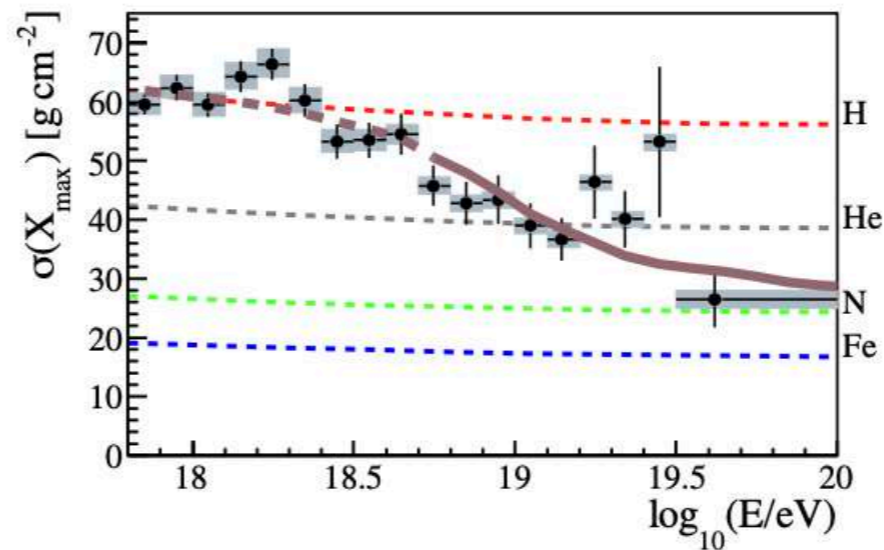
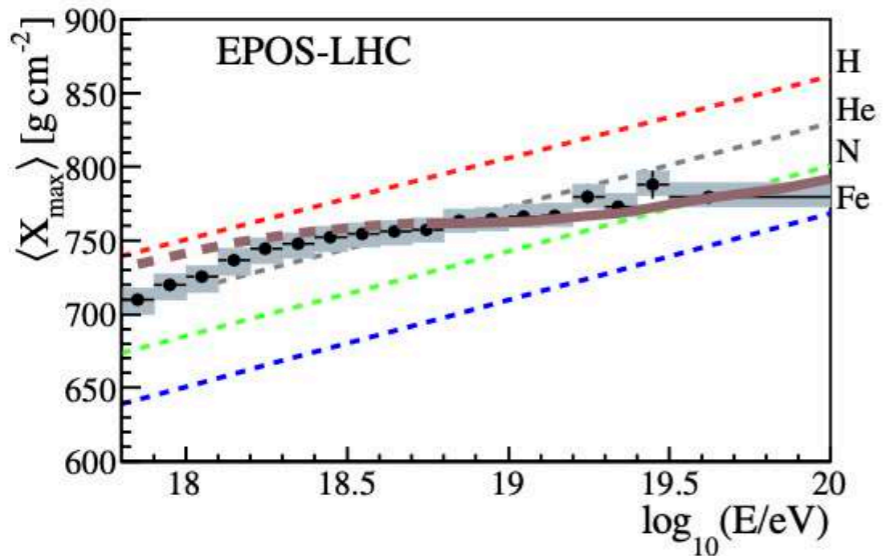


reference model	best fit	average	shortest 68% int.
$\gamma$	1.22	1.27	$1.20 \div 1.38$
$\log_{10}(R_{\text{cut}}/V)$	18.72	18.73	$18.69 \div 18.77$
$f_{\text{H}}(\%)$	6.4	15.1	$0.0 \div 18.9$
$f_{\text{He}}(\%)$	46.7	31.6	$18.9 \div 47.8$
$f_{\text{N}}(\%)$	37.5	42.1	$30.7 \div 51.7$
$f_{\text{Si}}(\%)$	9.4	11.2	$5.4 \div 14.6$
$\Delta X_{\text{max}}/\sigma_{\text{syst}}$	-0.63	-0.69	$-0.90 \div -0.48$
$\Delta E/\sigma_{\text{syst}}$	+0.00	+0.12	$-0.57 \div +0.54$

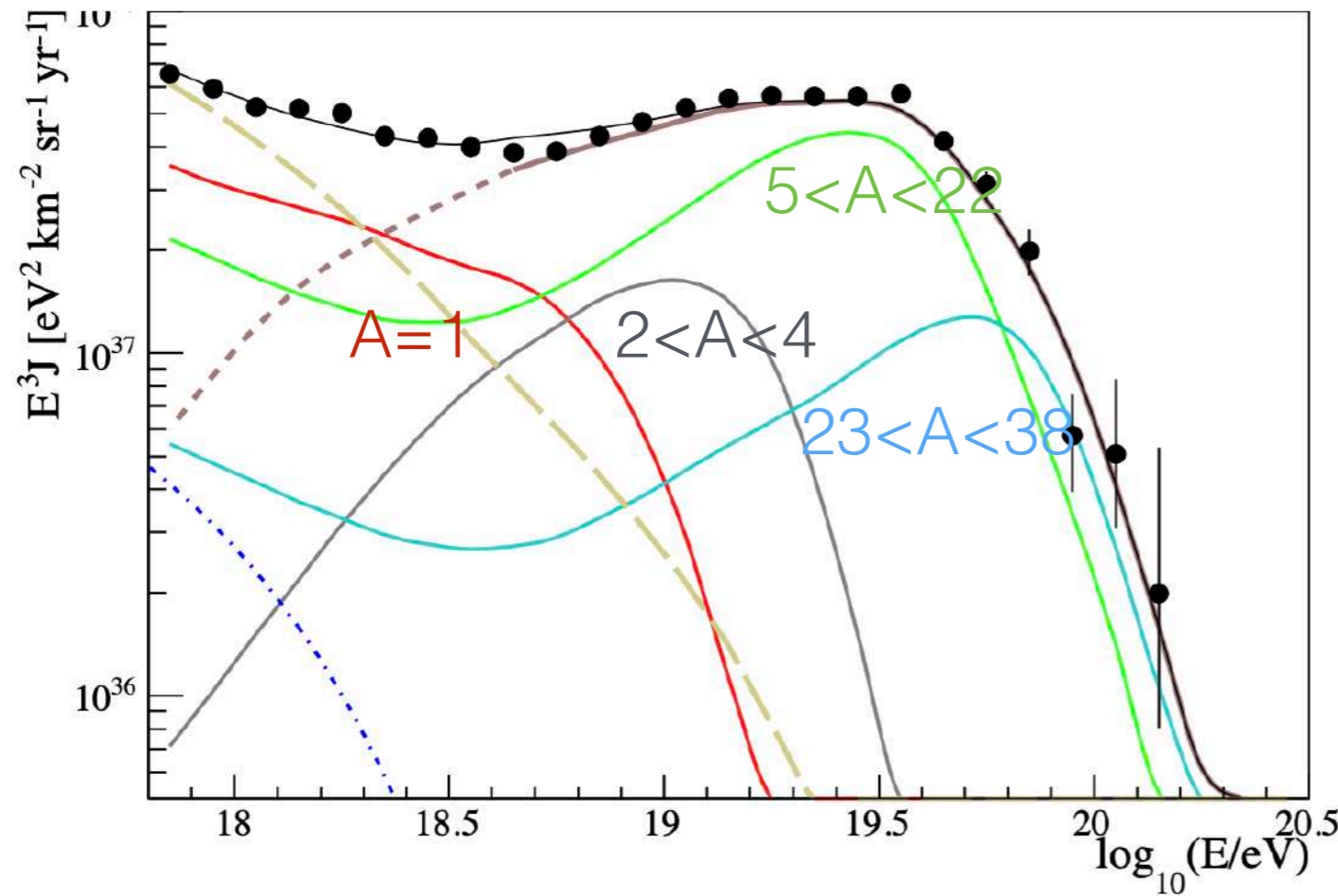


Auger Coll., JCAP 04 (2017) 038

- fit above the ankle



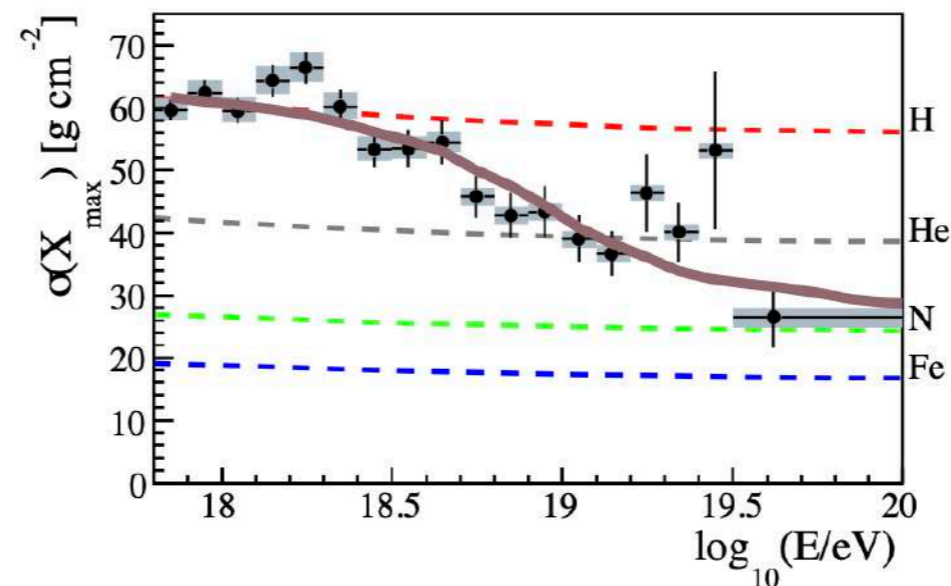
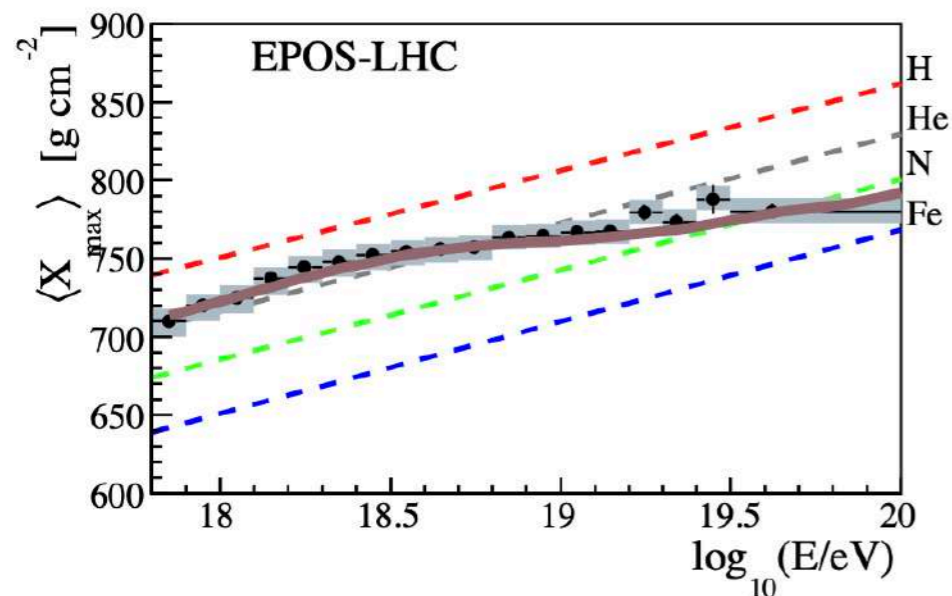
# UHECRs by Auger and the secondary sub-ankle component



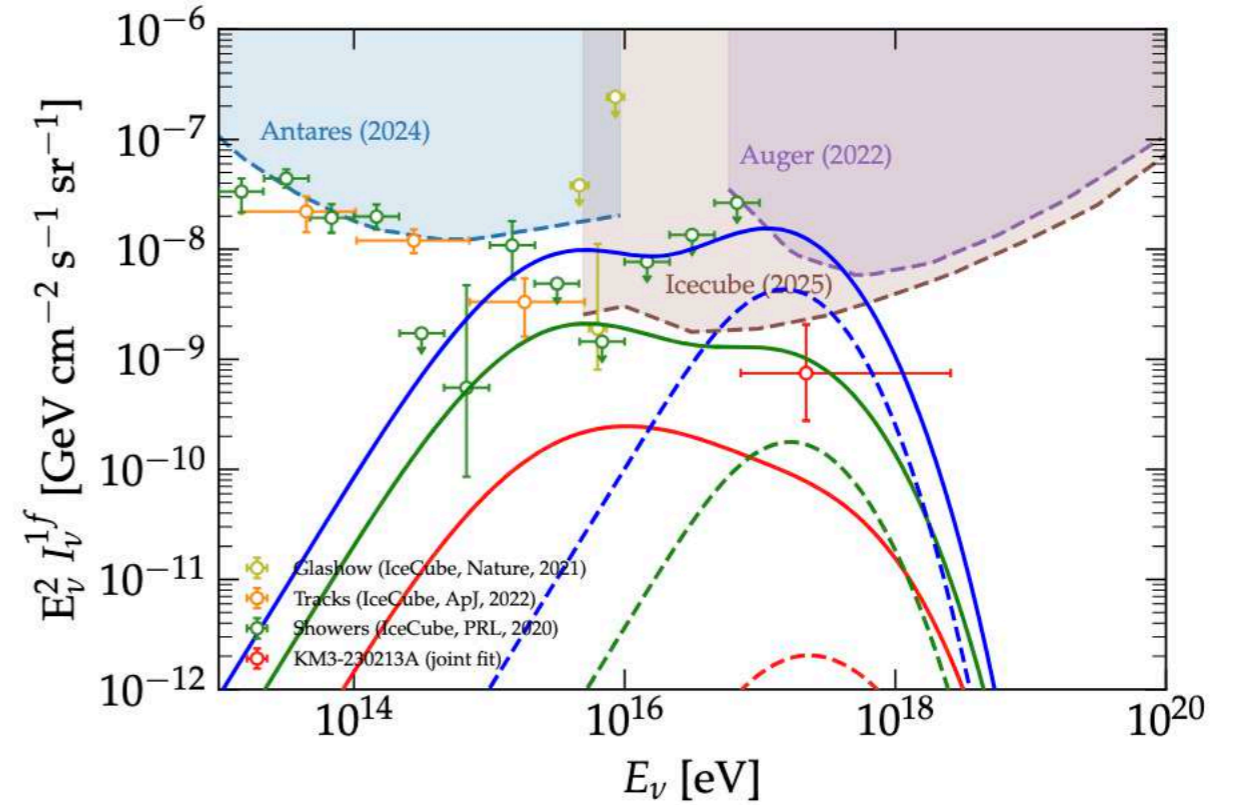
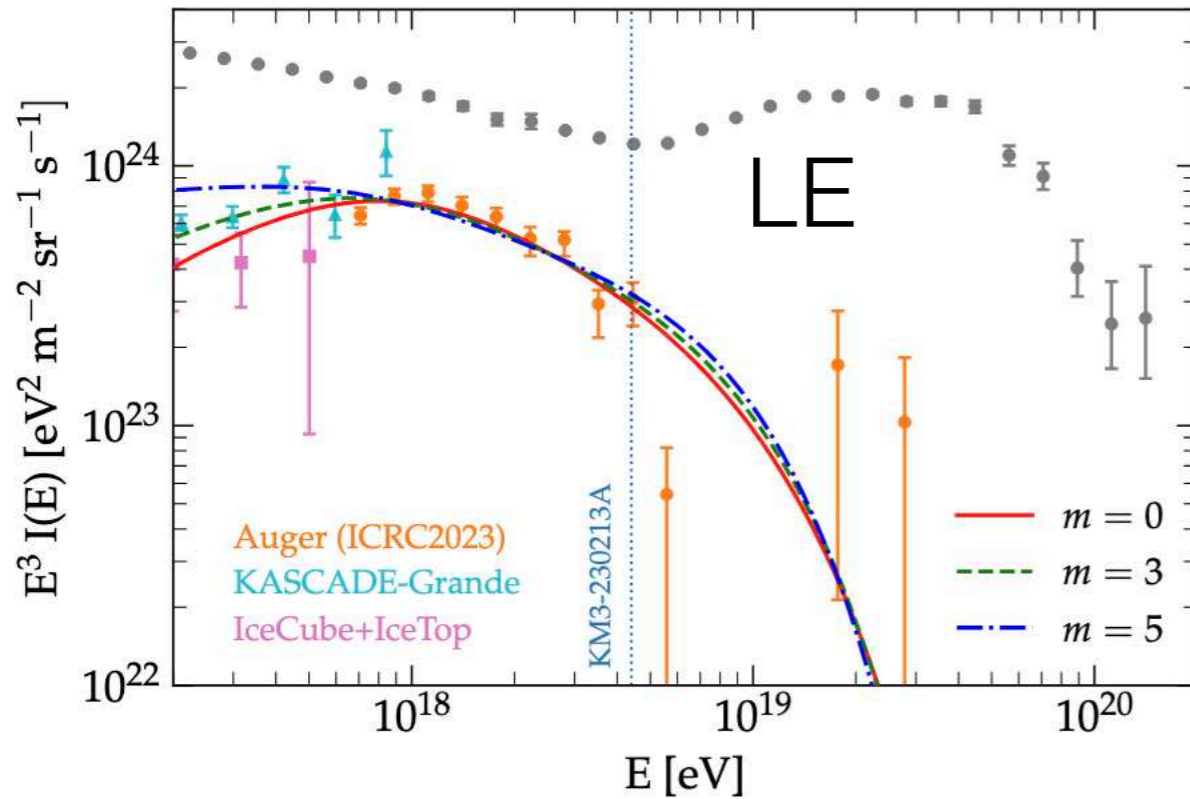
- spectral index  $\gamma = 3.6$
- rigidity cutoff  $\log_{10}(R_{\text{cut}}/V) = 18.4$
- a mix of  $\sim 56\%$  H,  $35\%$  N and  $9\%$  Si



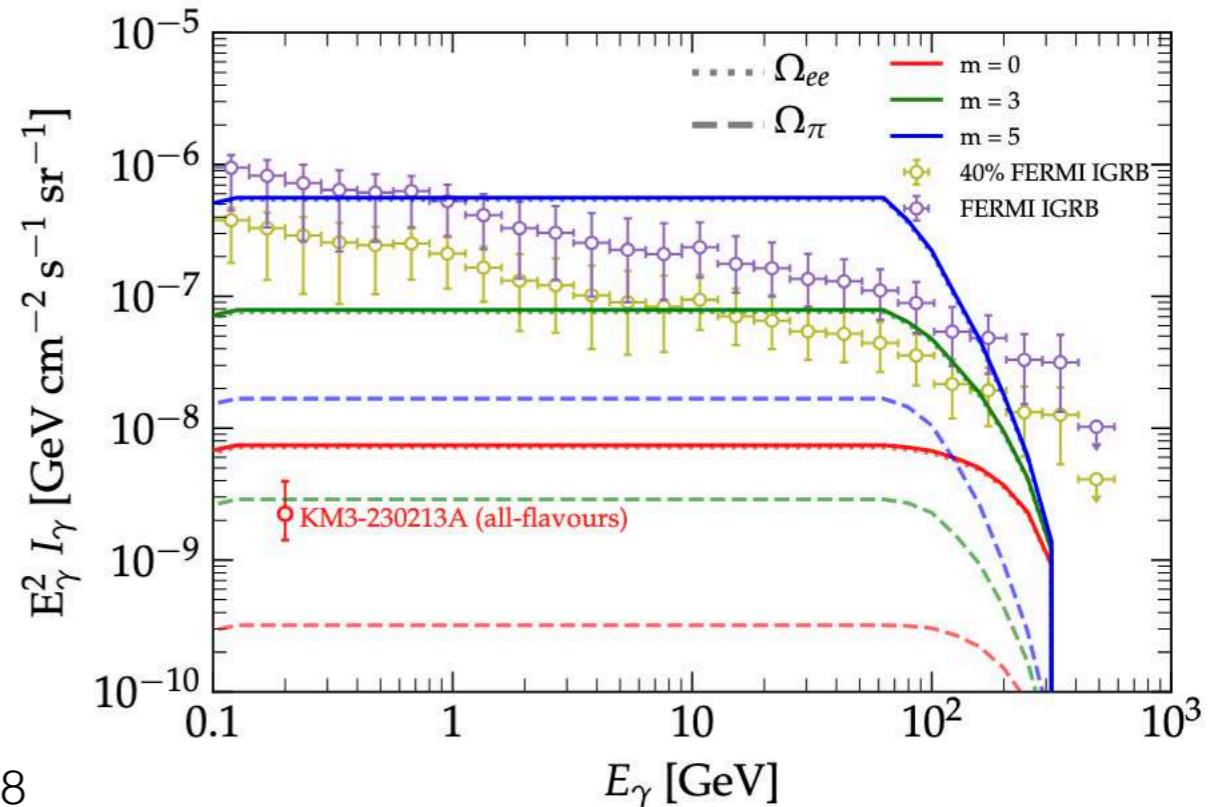
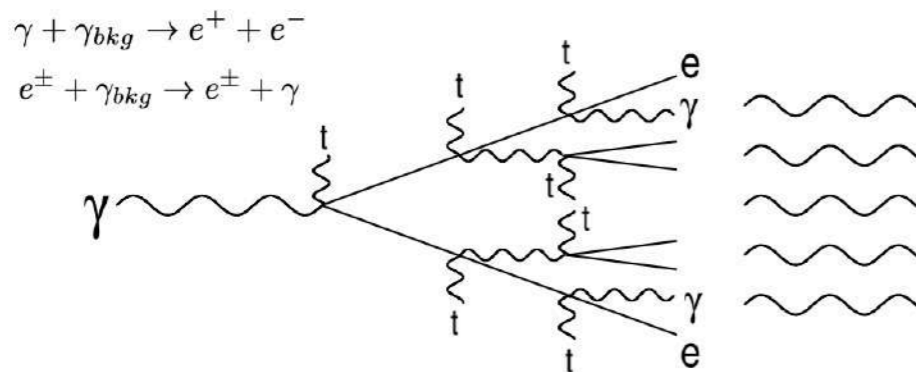
Auger Coll., JCAP 04 (2017) 038



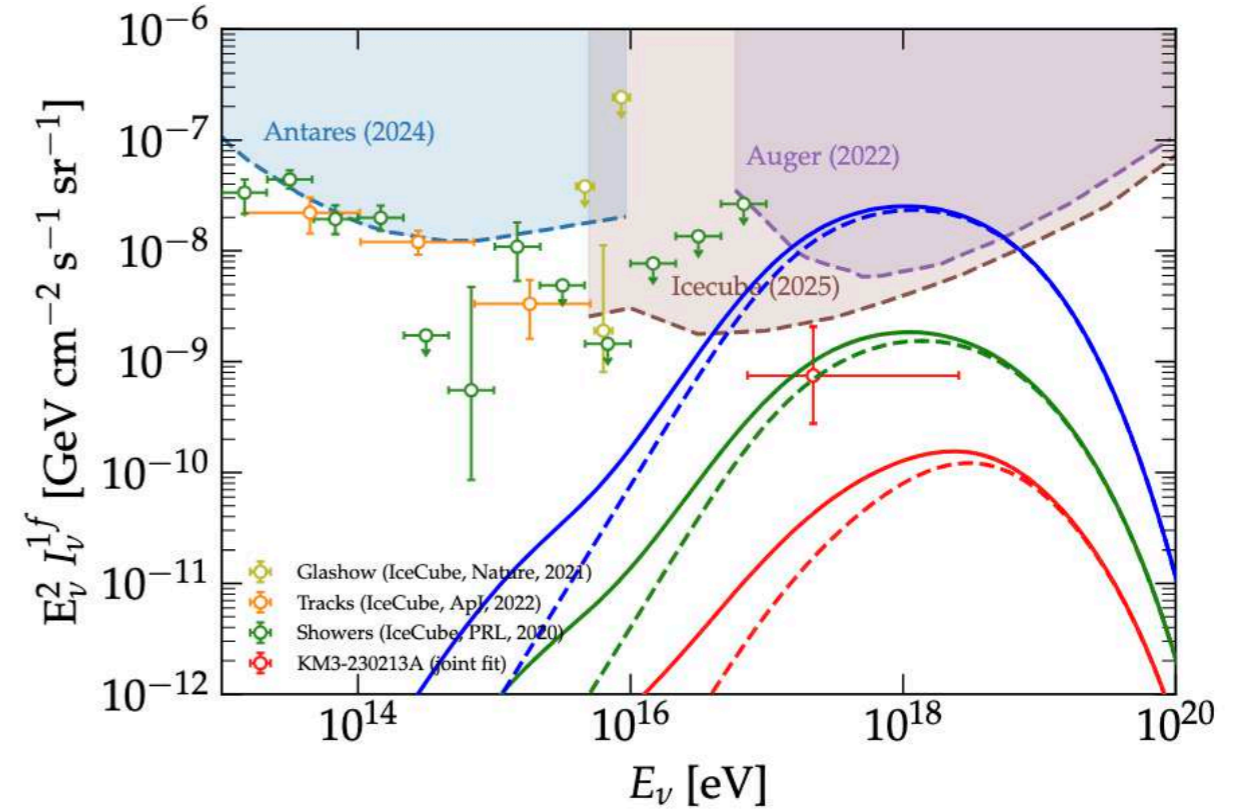
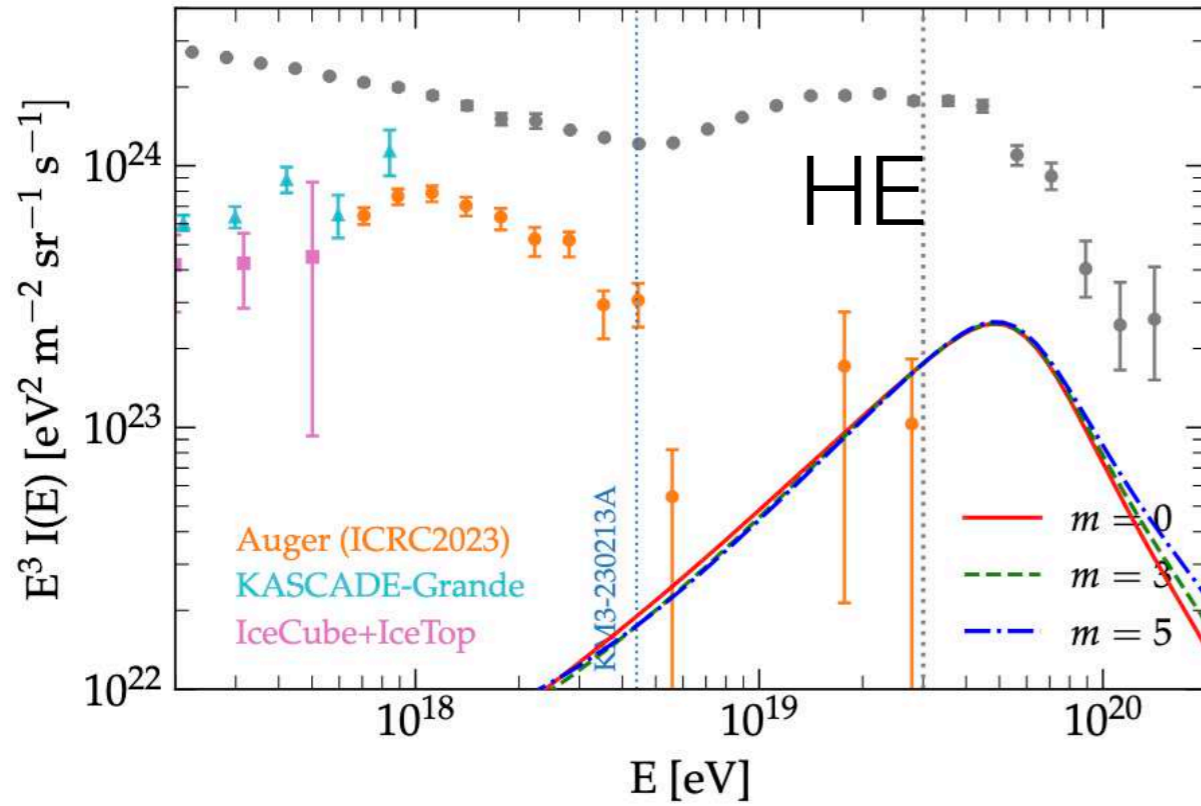
# Diffuse gamma-ray & neutrino constraints to cosmogenic UHECR fluxes



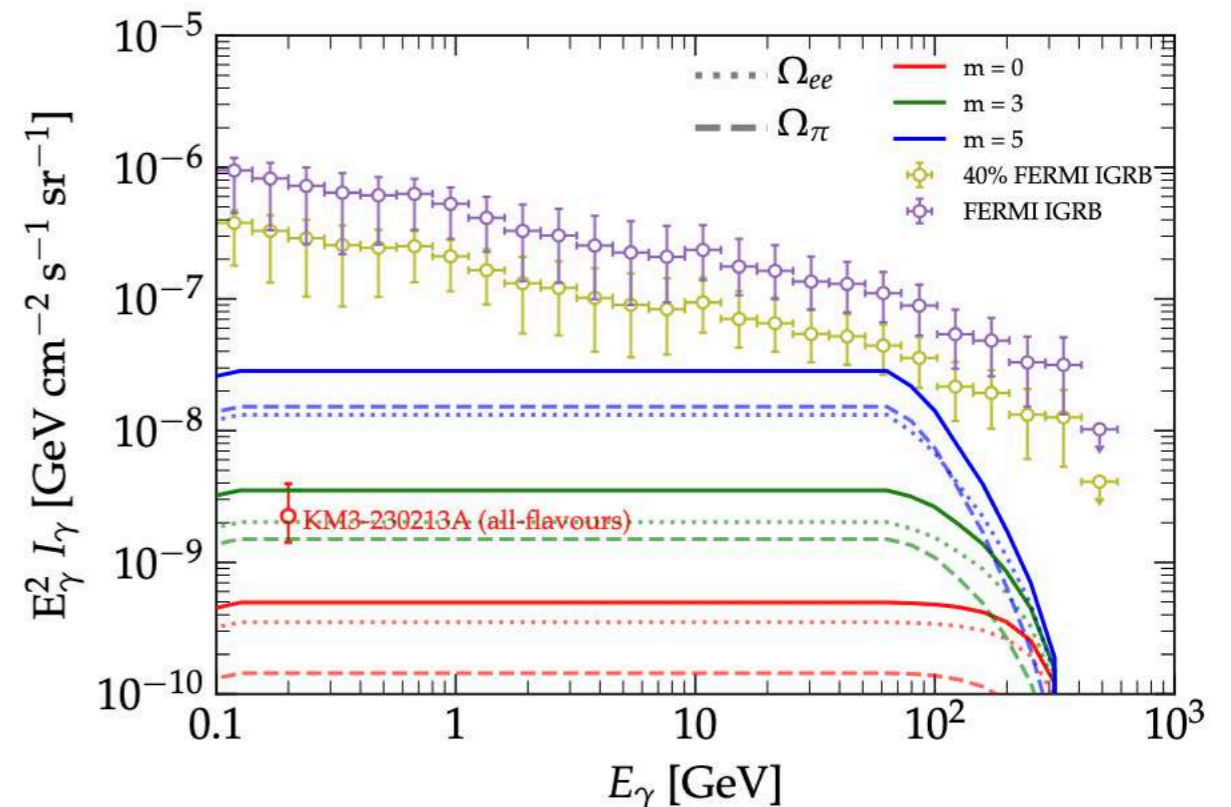
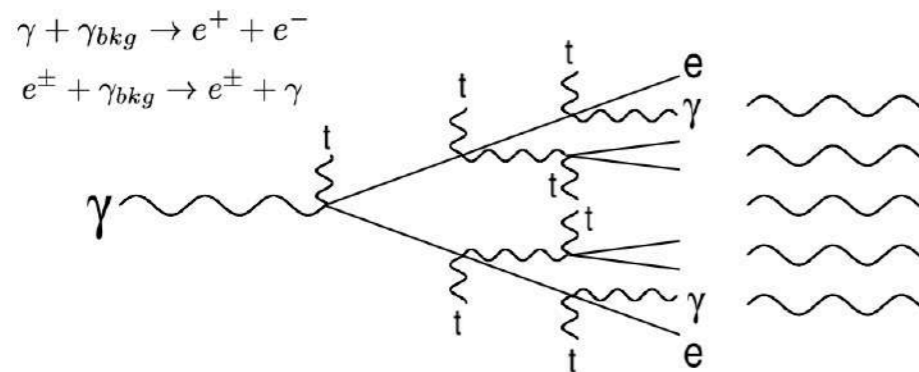
The diffuse EG gamma-ray flux is a very powerful observable to constrain the fraction of protons in UHECRs:



# Diffuse gamma-ray & neutrino constraints to cosmogenic UHECR fluxes



The diffuse EG gamma-ray flux is a very powerful observable to constrain the fraction of protons in UHECRs:



# Diffuse gamma-ray & neutrino constraints to cosmogenic UHECR fluxes

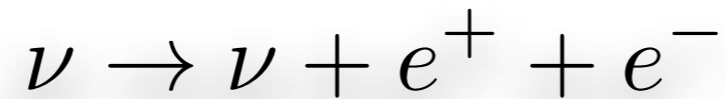
Table I. Parameter sets adopted for this analysis. From left to right, the columns report: the source redshift evolution parameter ( $m$ ), spectral index ( $\gamma$ ), maximum proton energy ( $E_{\max}$ ), total proton luminosity ( $L$ ), and the integrated contributions to the electromagnetic cascade energy density from proton pair production ( $\Omega_{\text{tot}}^{ee}$ ) and photopion interactions ( $\Omega_{\text{tot}}^{\pi}$ ). The upper and lower sections correspond to the low-energy (LE) and high-energy (HE) source populations, respectively.

	$m$	$\gamma$	$E_{\max} [10^{18} \text{ eV}]$	$L [10^{45} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}]$	$\Omega_{\text{tot}}^{ee} [\frac{\text{eV}}{\text{cm}^3}]$	$\Omega_{\text{tot}}^{\pi} [\frac{\text{eV}}{\text{cm}^3}]$
<b>LE</b>	0	2.5	6.0	2.68	$2.90 \times 10^{-9}$	$1.31 \times 10^{-10}$
	3	2.01	5.0	17.3	$3.09 \times 10^{-8}$	$1.17 \times 10^{-9}$
	5	1.4	4.0	0.24	$2.22 \times 10^{-7}$	$6.85 \times 10^{-9}$
<b>HE</b>	0	1.3	$10^2$	$1.59 \times 10^{-2}$	$1.47 \times 10^{-10}$	$6.02 \times 10^{-11}$
	3	1.0	$10^2$	$9.86 \times 10^{-3}$	$8.46 \times 10^{-10}$	$6.30 \times 10^{-10}$
	5	0.7	$10^2$	$6.86 \times 10^{-3}$	$5.52 \times 10^{-9}$	$6.37 \times 10^{-9}$



# World-leading constraints on LIV

- A superluminal neutrino would quickly lose energy via

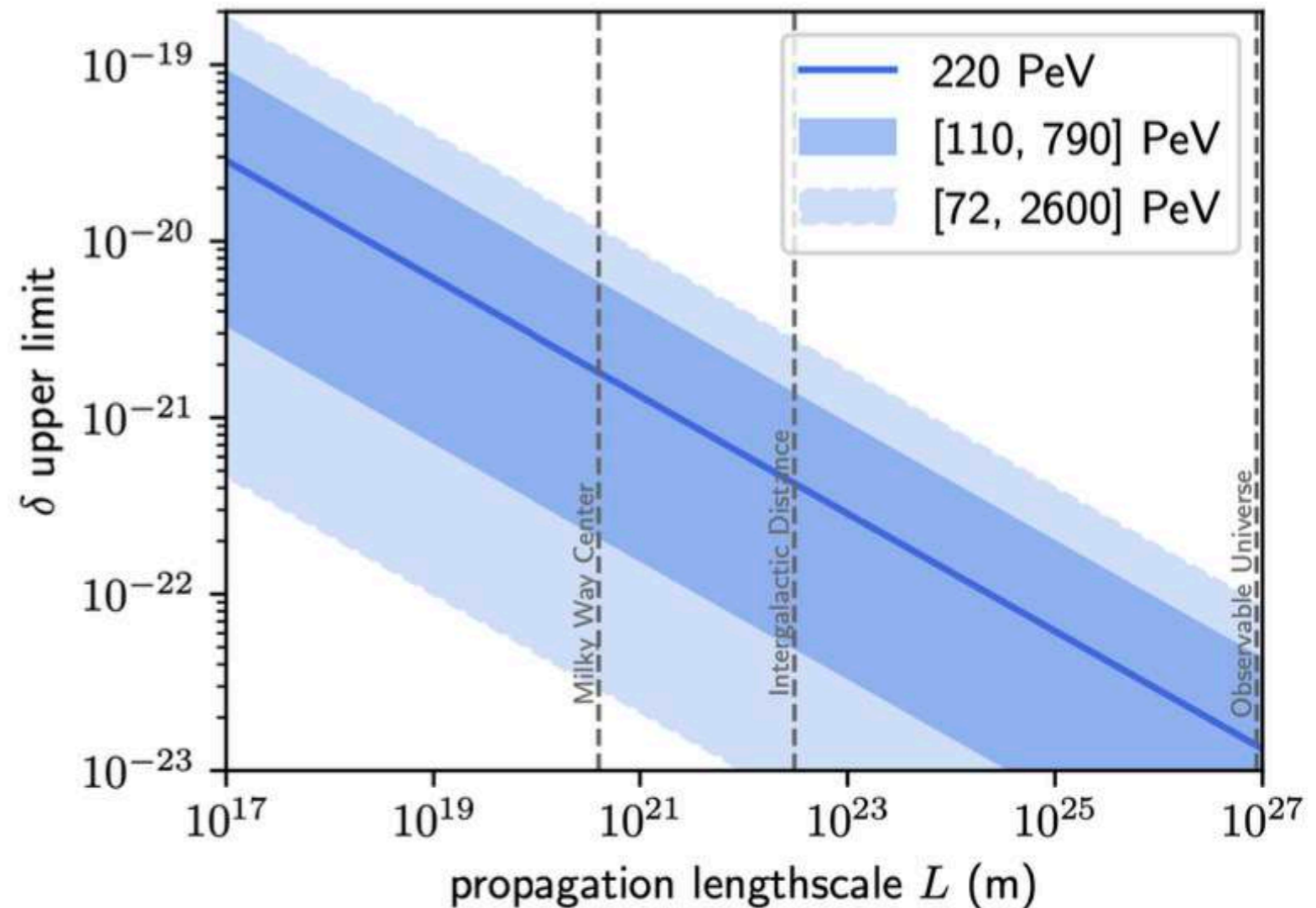


- Decay width given by

$$\Gamma \propto E^5 \delta^3$$

with  $\delta = c_\nu^2 - 1$

- KM3-230213A extreme energy places the stringent existing constraint



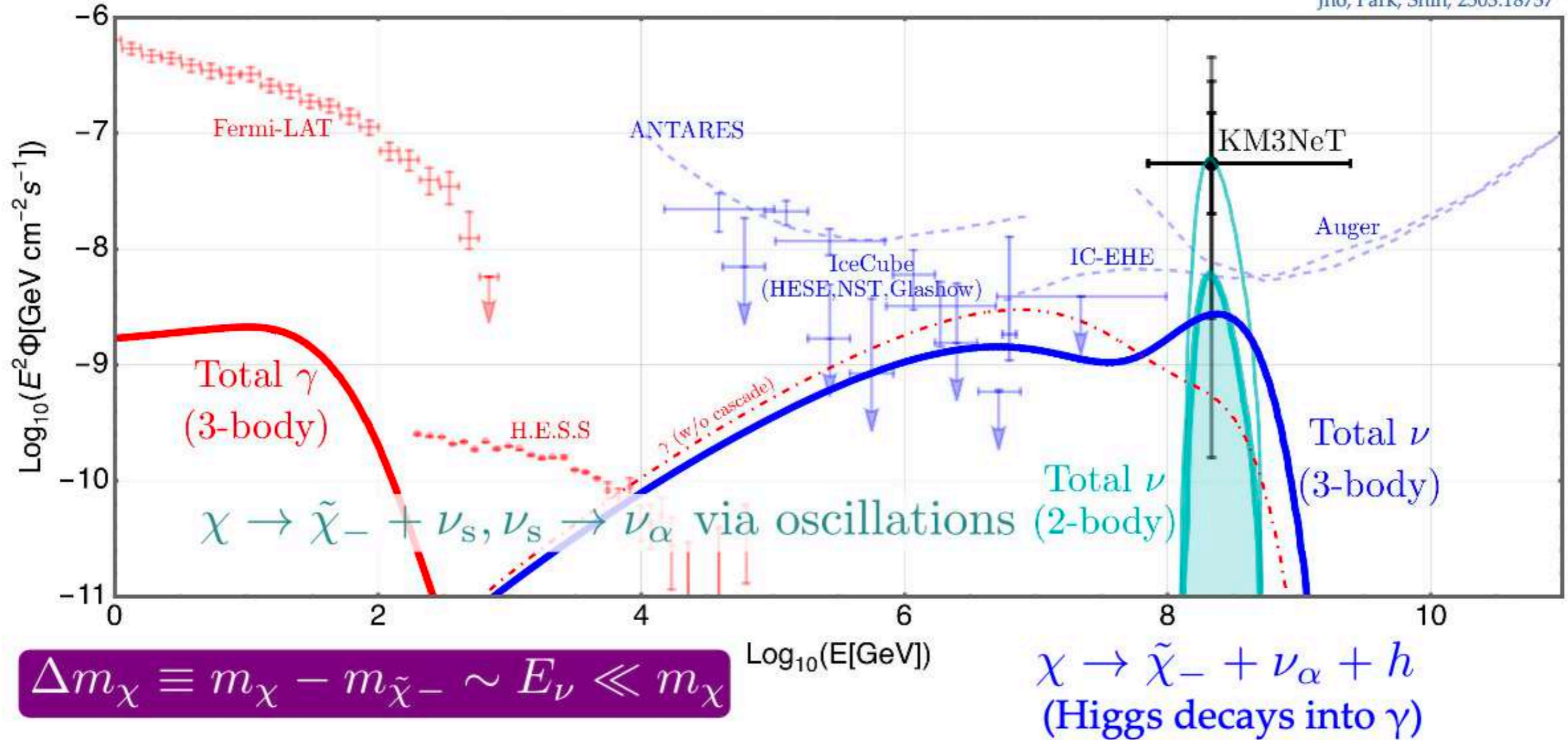
Method	Limit
IceCube atmospheric	$6.2 \times 10^{-11}$
IceCube NGC 1068	$1.5 \times 10^{-15}$
IceCube TXS 0506+056	$2.4 \times 10^{-18}$
Stecker et al. (Ref. [20])	$5.2 \times 10^{-21}$
KM3-230213A (conservative)	$1.8 \times 10^{-21}$
KM3-230213A (likely)	$4.2 \times 10^{-22}$



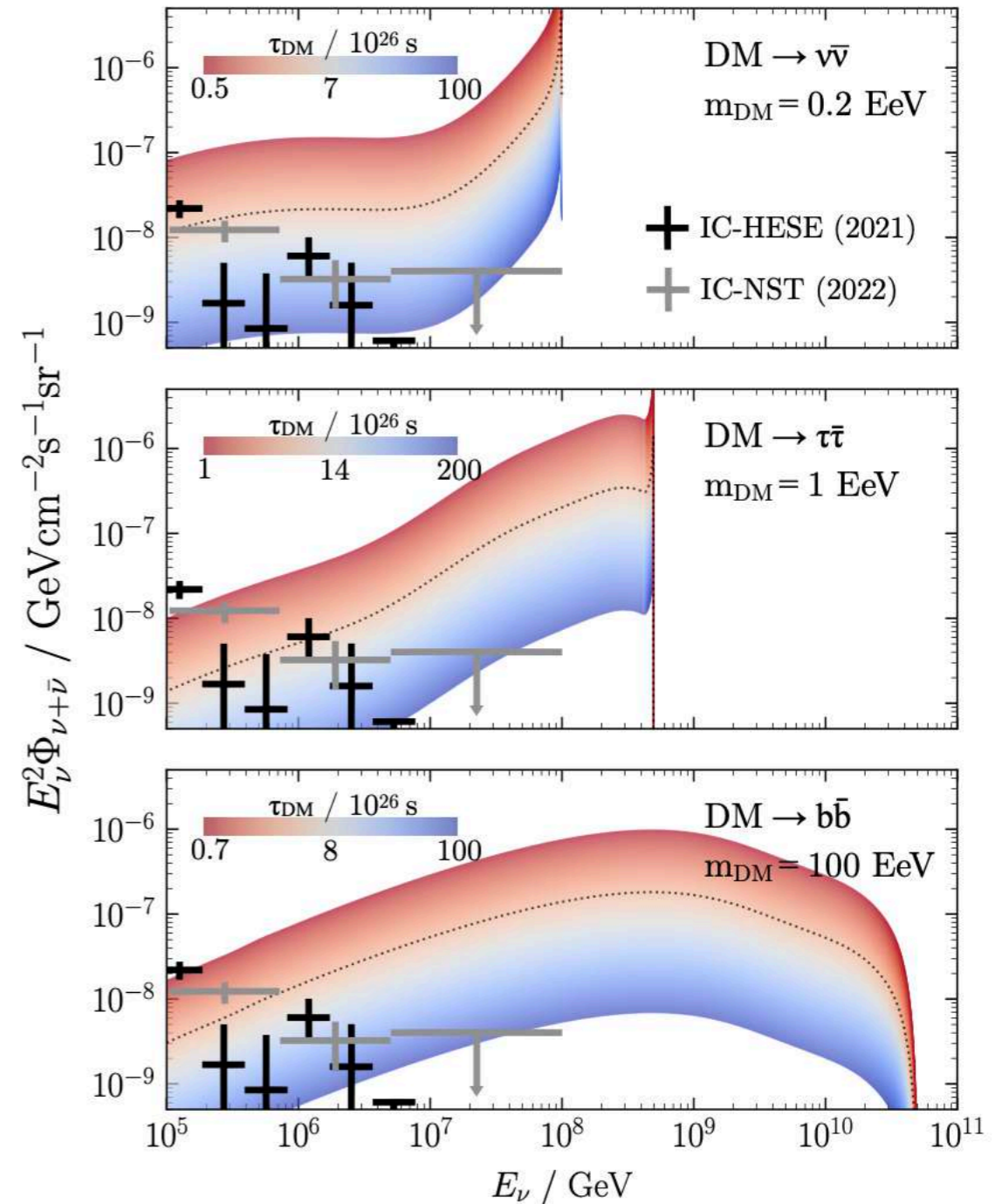
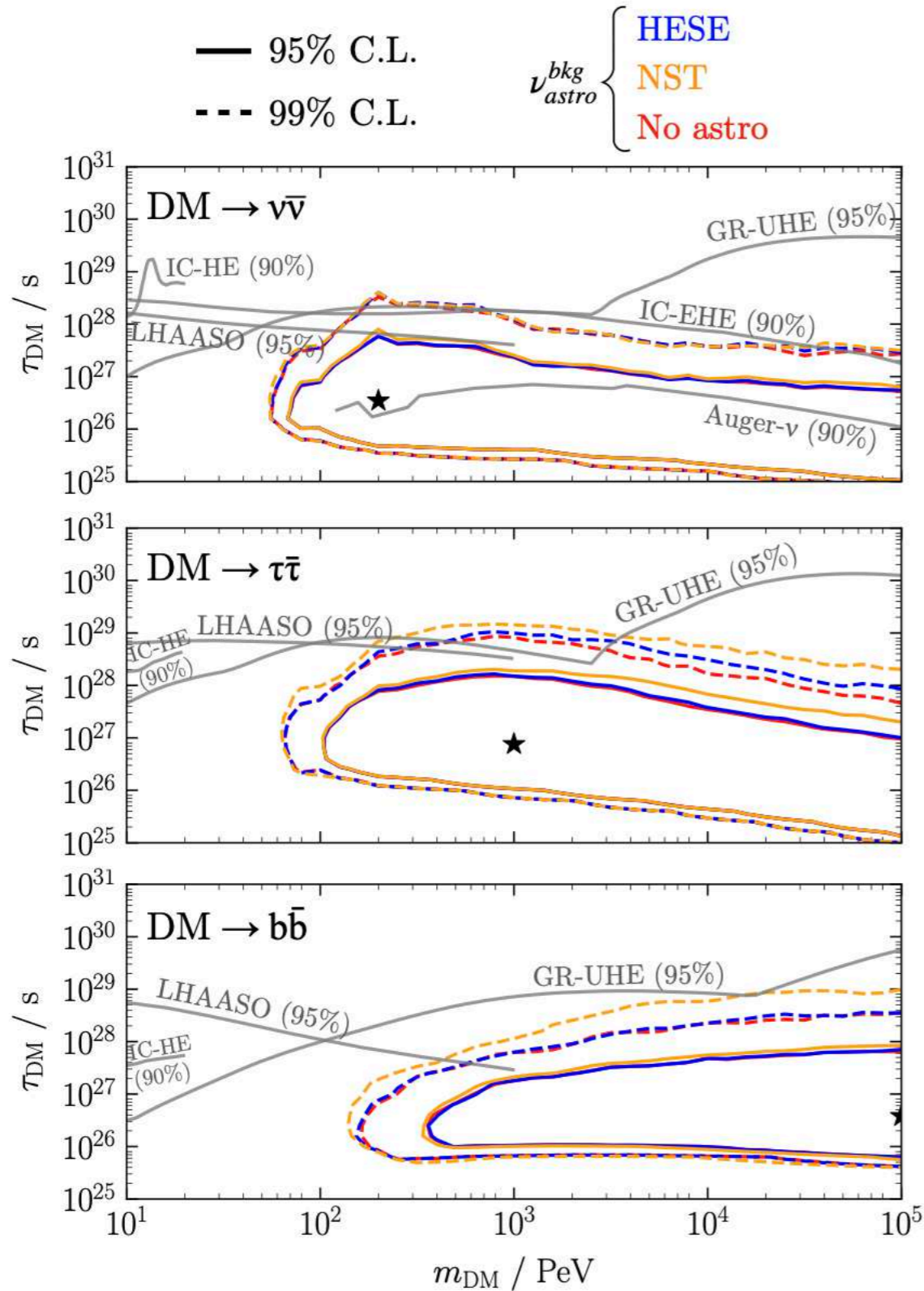
# BSM origin of KM3-230213A? Decay of heavy dark matter

Multi-component DM: heavy ( $\chi$ , unstable) & lighter ( $\tilde{\chi}_-$ , stable)

Jho, Park, Shin, 2503.18737



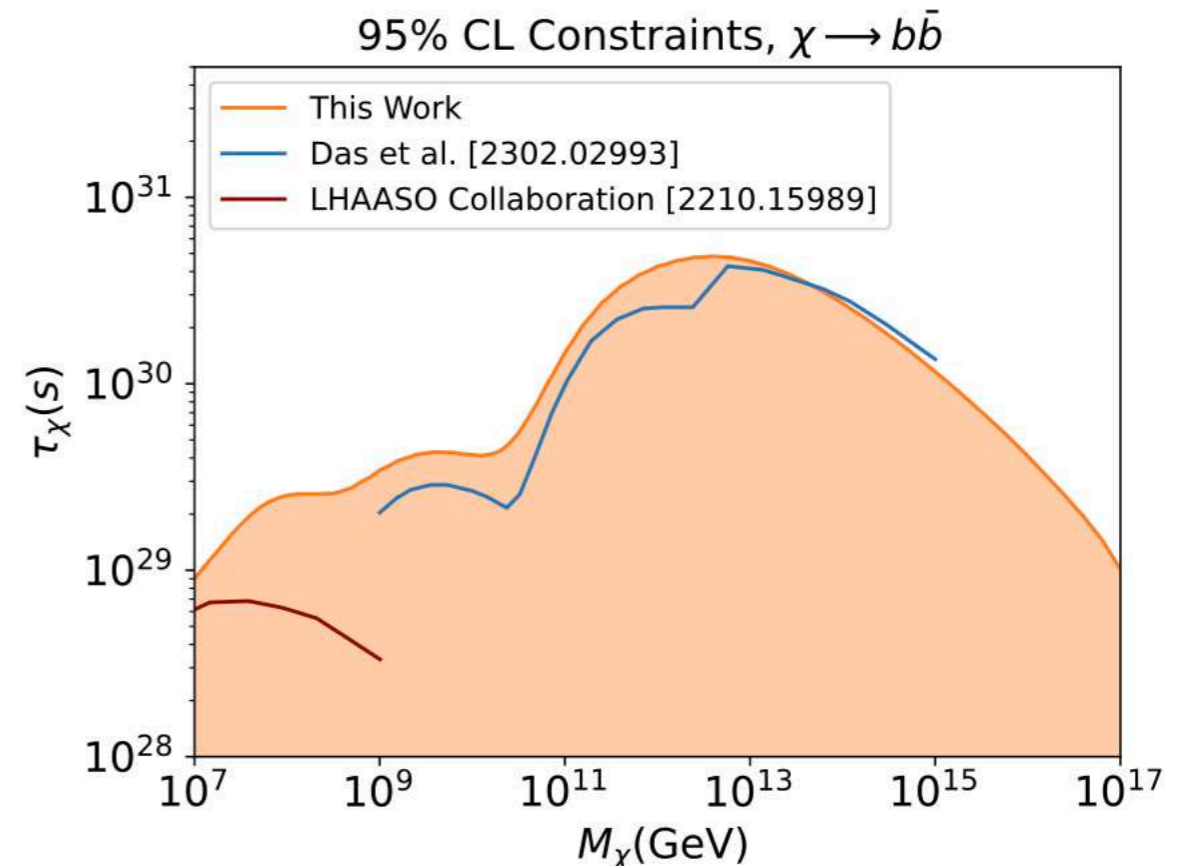
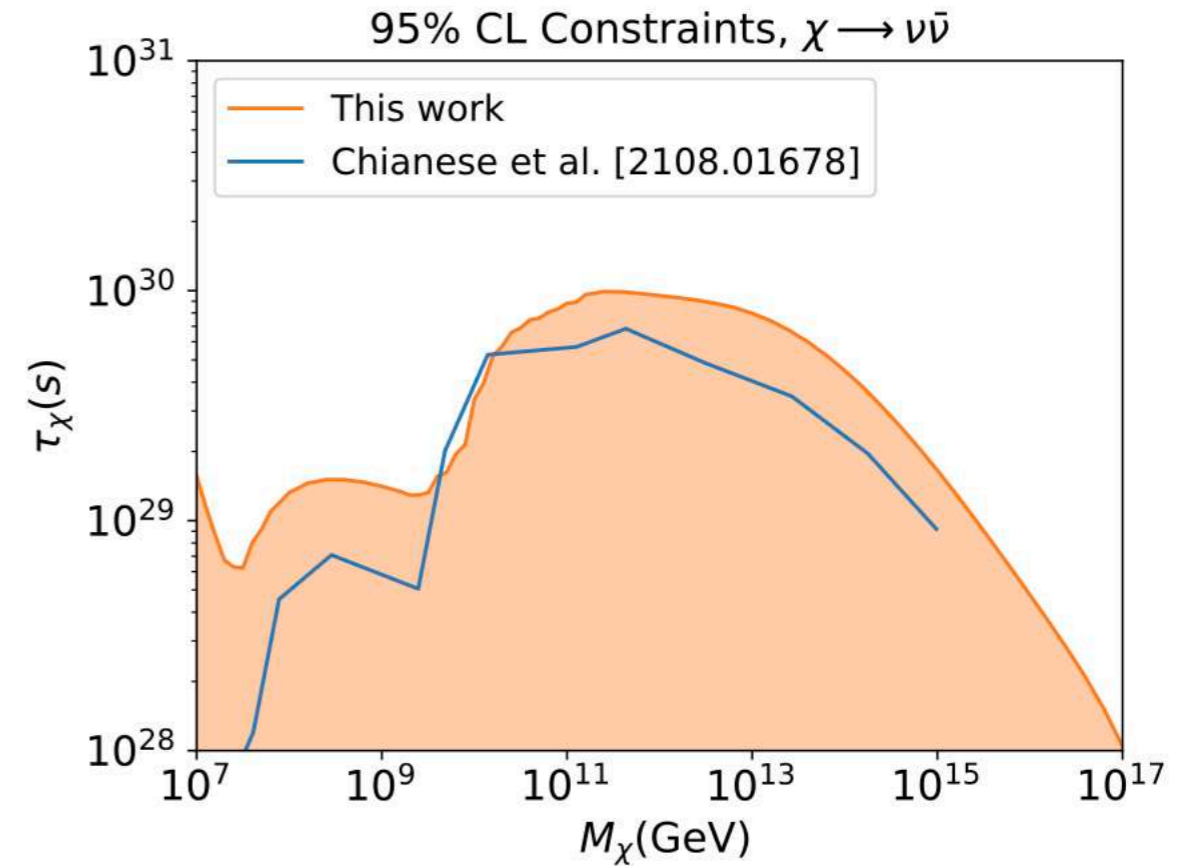
# Super-heavy dark matter constraints



# Super-heavy dark matter constraints

The possible DM origin of KM-230213A is linked to several constraints:

- its extreme energy requires a super-heavy ( $m_{\text{DM}} > 10^8 \text{ GeV}/c^2$ ) DM component
- its direction indicates, if originated in DM decay, the need for an extra-galactic component
- Multi-messenger constraints set a lower bound to its decay lifetime of  $\tau_{\text{DM}} > 5 \times 10^{29} - 10^{30} \text{ s}$



# **KM3NeT diffuse searches**

# Diffuse cosmic neutrino search

- ARCA full dataset (6-8-19-21) (640 days of livetime, up until Sept. 2023)
- **Upgoing track-like events** (KM3-230213A not in this sample), including BDT to further suppress mis-reconstructed atmospheric muons
- MonteCarlo driven background calculation
- MRF metrics for energy & BDT cut optimization
- 97% neutrino purity after cuts in ARCA19-21

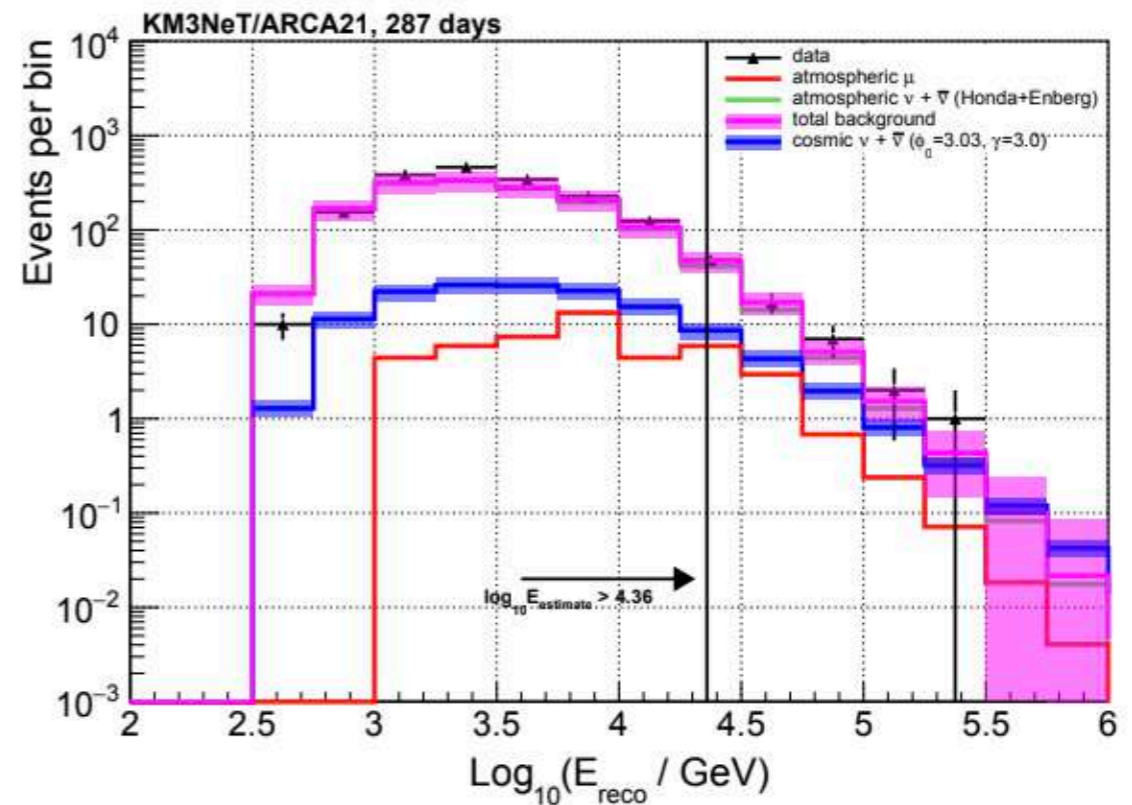
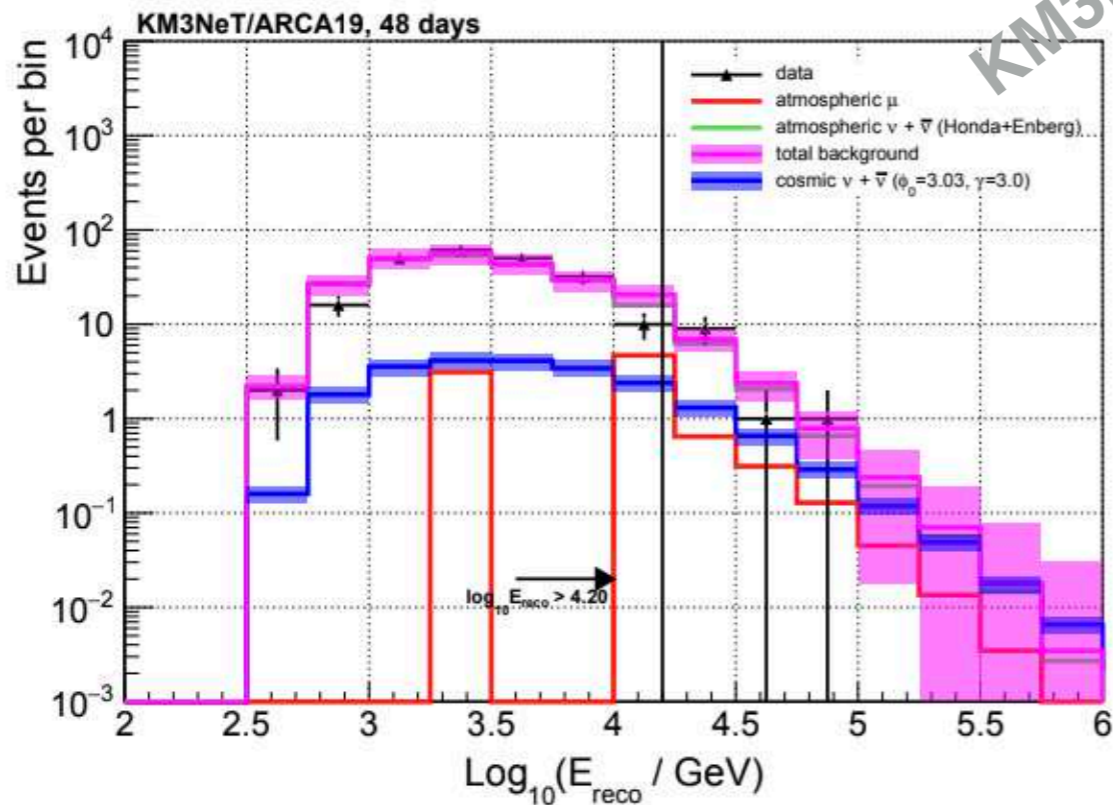
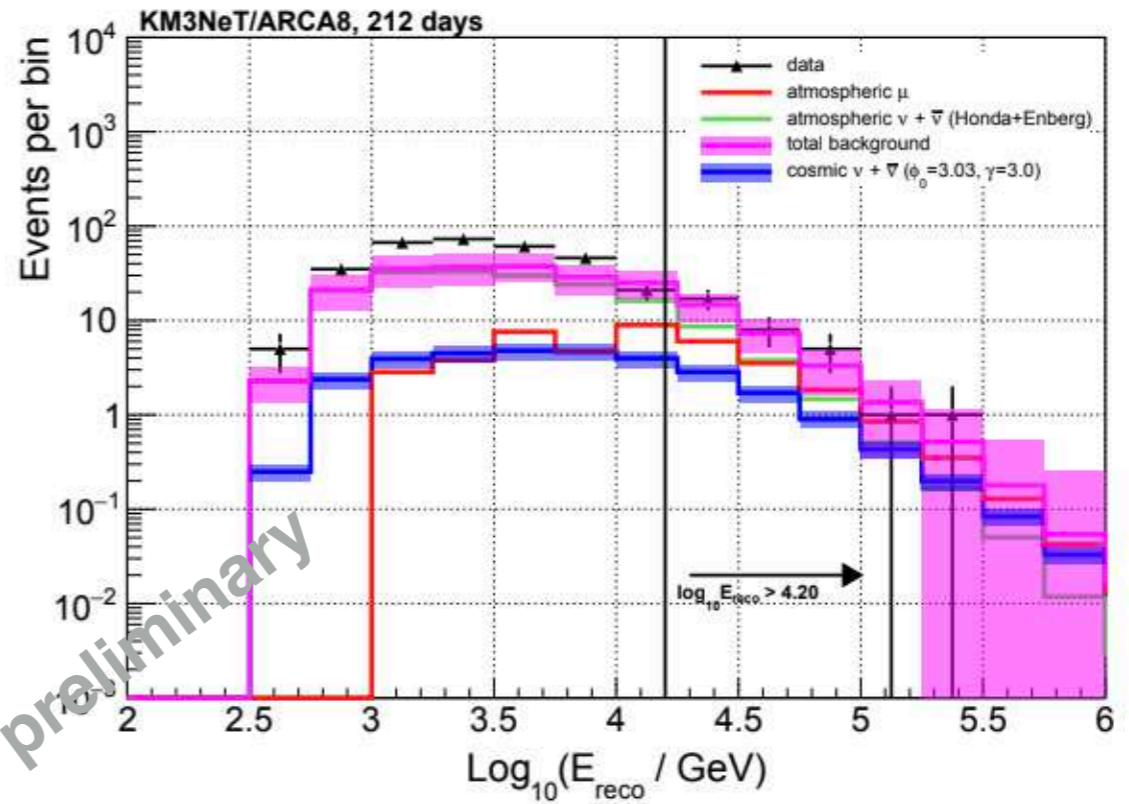
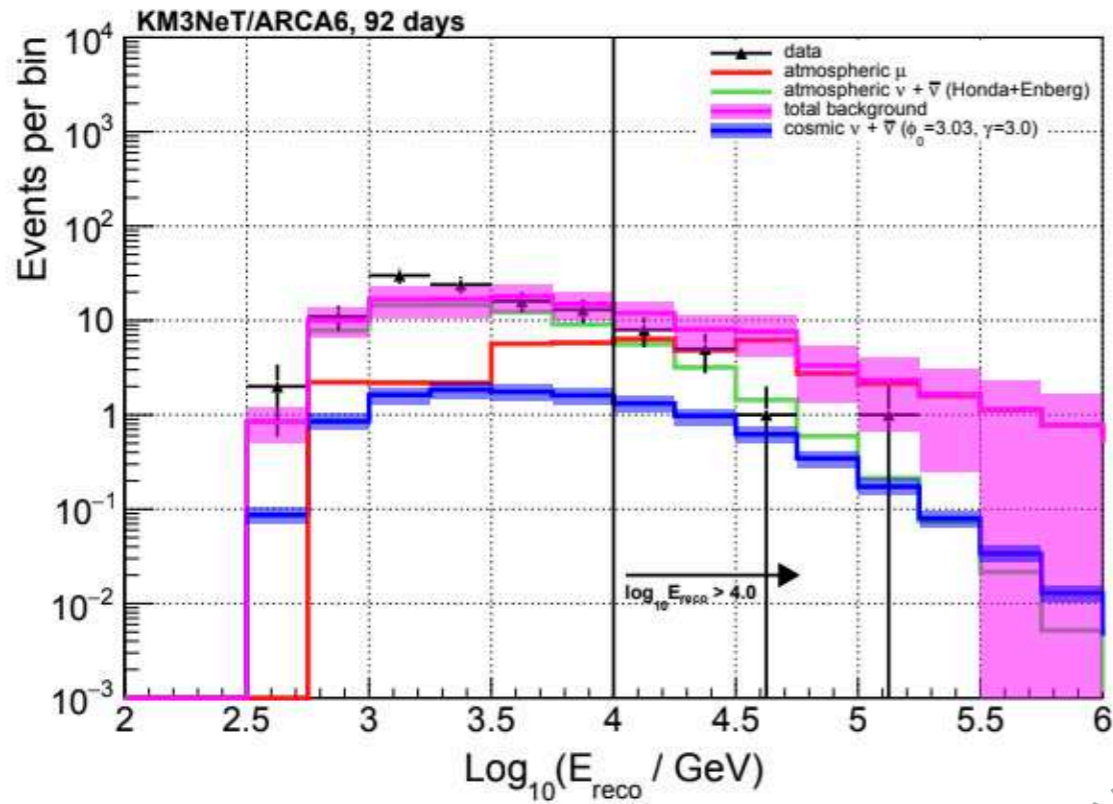
$$L(N; S(\gamma), B, \phi_0) = \prod \text{Poisson}(N_i, B_i + \phi_0 S_i(\gamma))$$

$$p(\phi_0, \gamma; N) = \int L(N; S(\gamma), B, \phi_0) \pi(B_i) \pi(S_i(\gamma)) \pi(\phi_0, \gamma) \prod_i dB_i dS_i(\gamma)$$

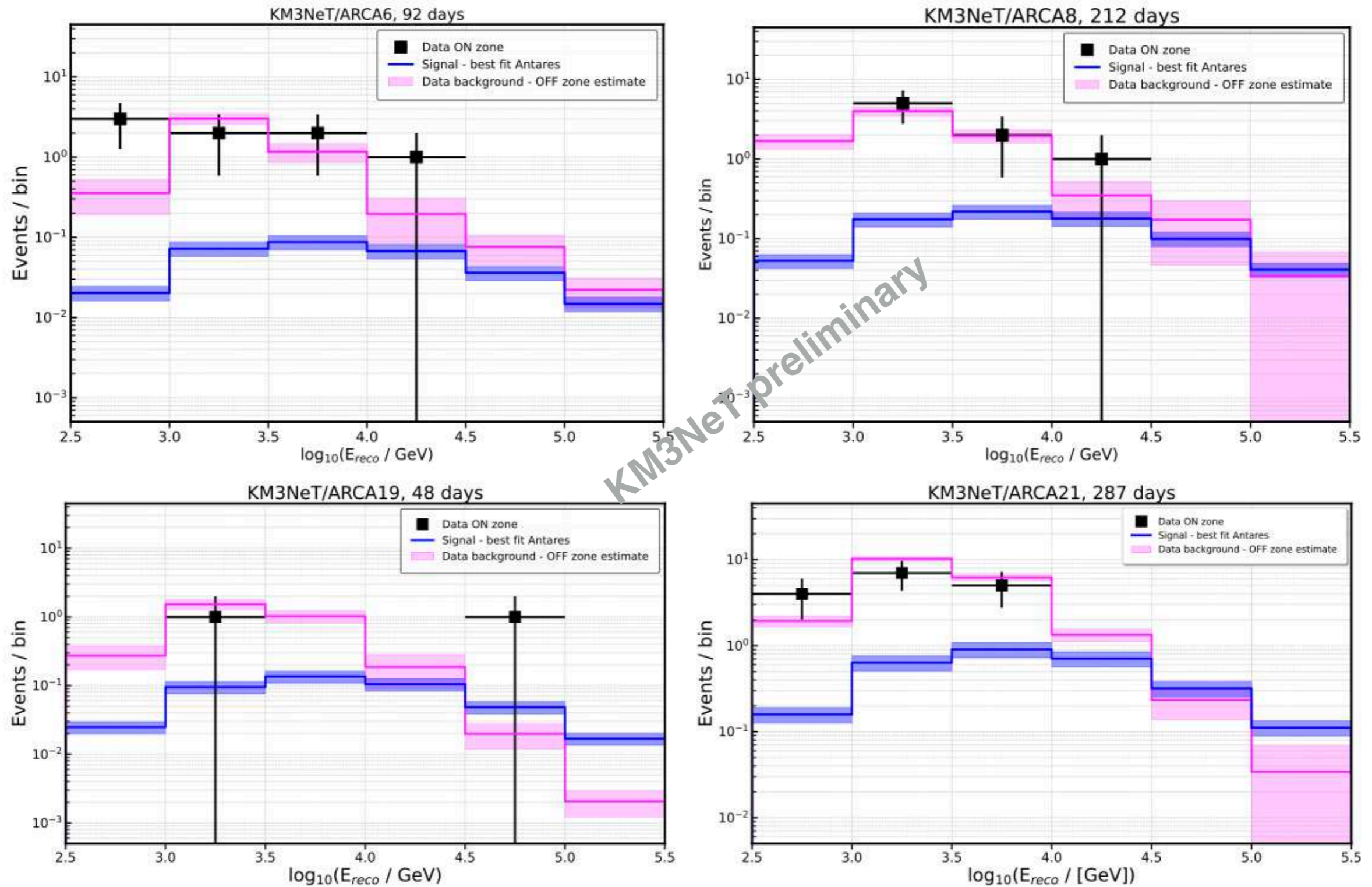
- Bayesian parameter fit with flat prior on expected signal flux
- Posterior probability marginalized over nuisance parameters, used to draw ULs, sensitivity & best fit values

Name	Period	Livetime (days)
ARCA6	May 2021 — September 2021	92.09
ARCA8	September 2021 — June 2022	212.26
ARCA19	July 2022 — September 2022	48.40
ARCA21	September 2022 — September 2023	287.39

# ARCA all-sky search results



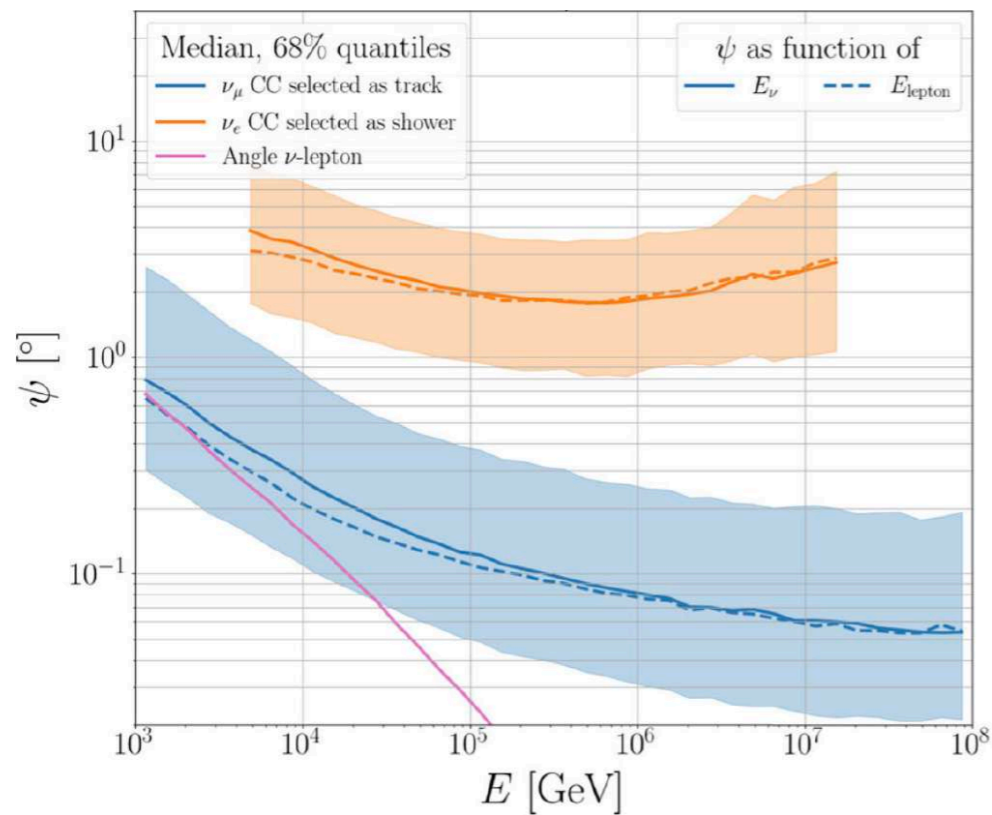
# ARCA Galactic Ridge analysis



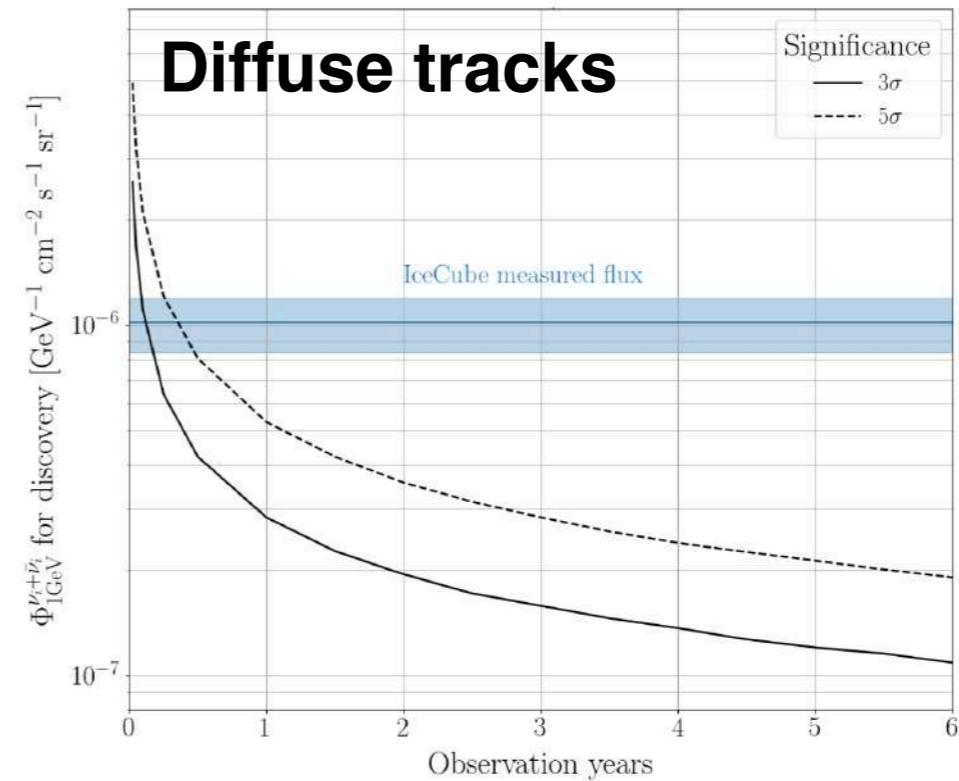
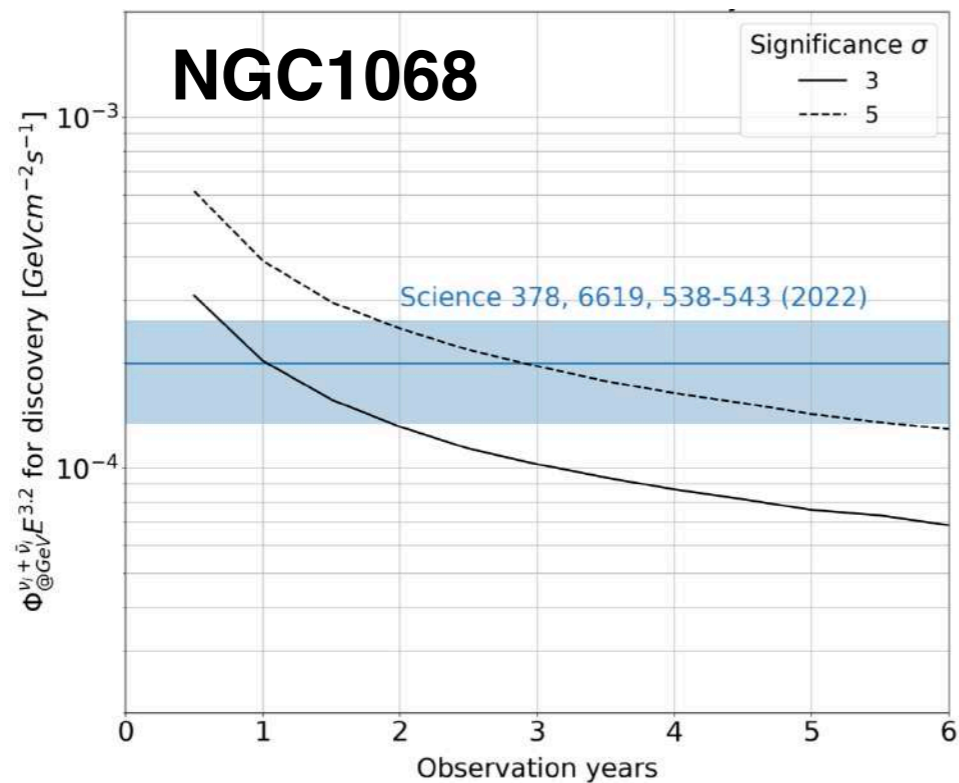
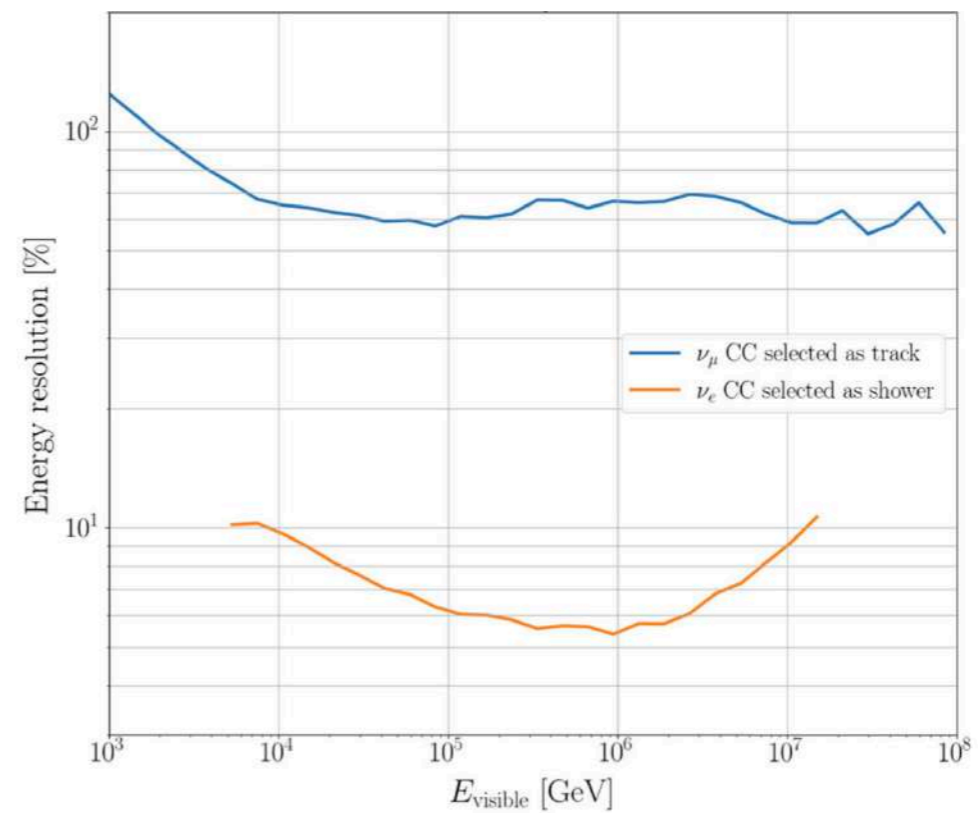
# **KM3NeT cosmic source searches**

# The KM3NeT/ARCA astronomical potential

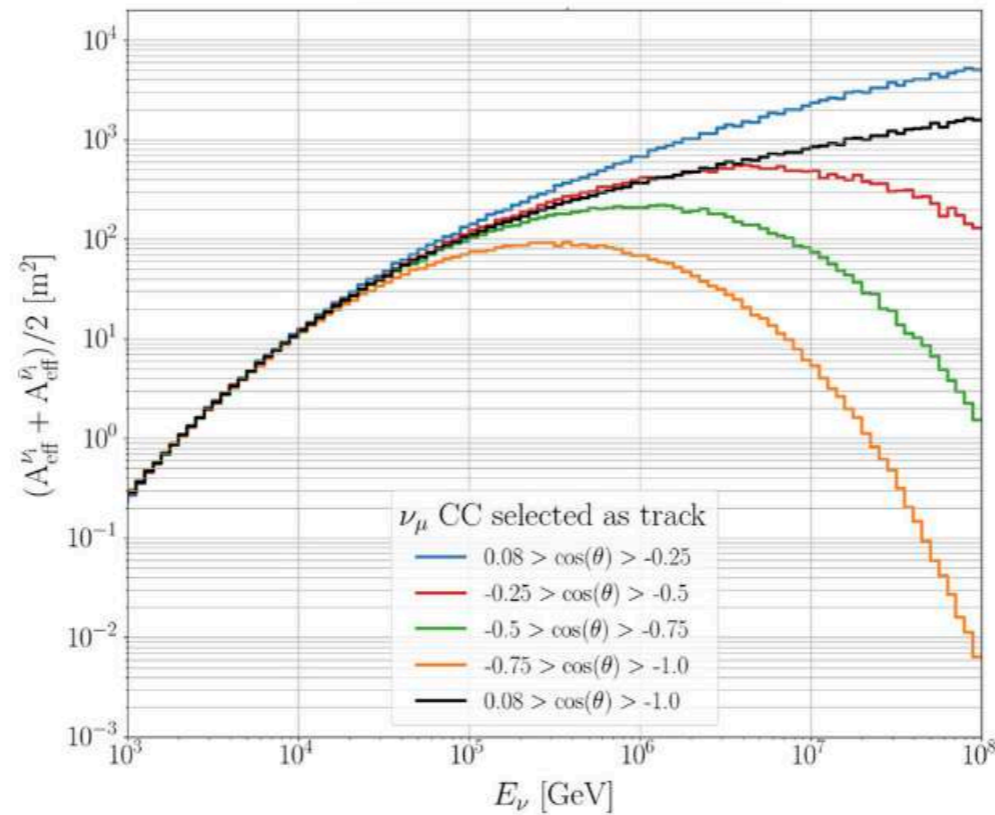
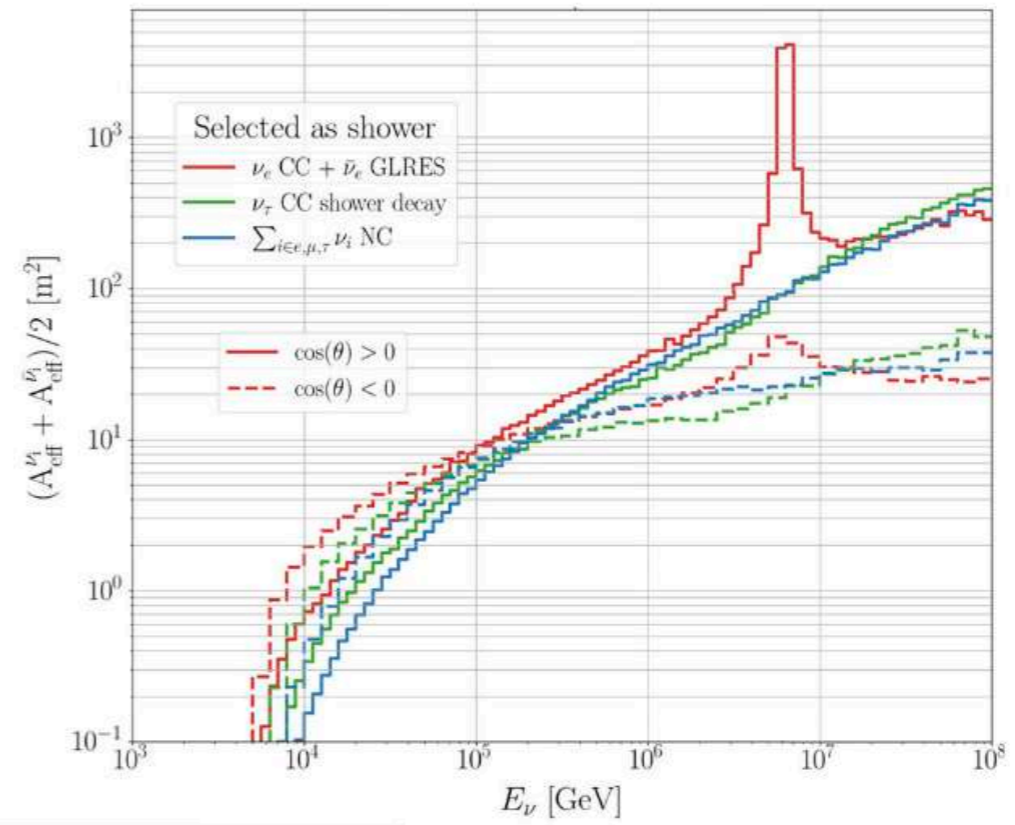
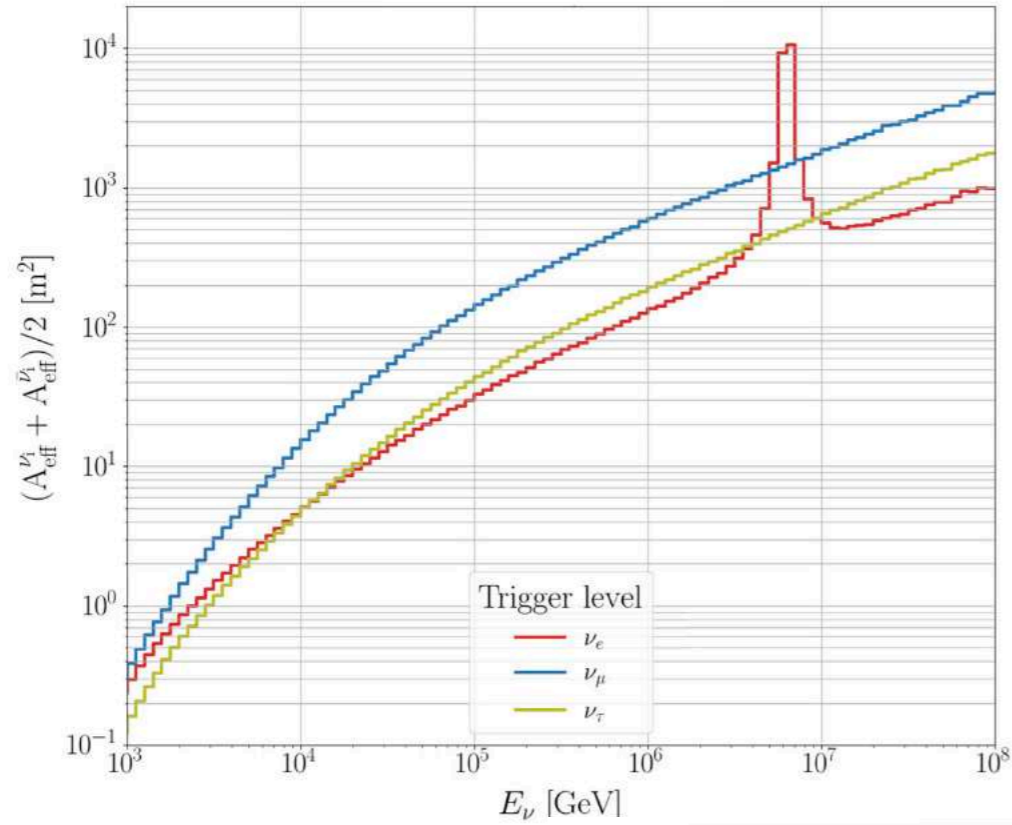
## Angular resolution



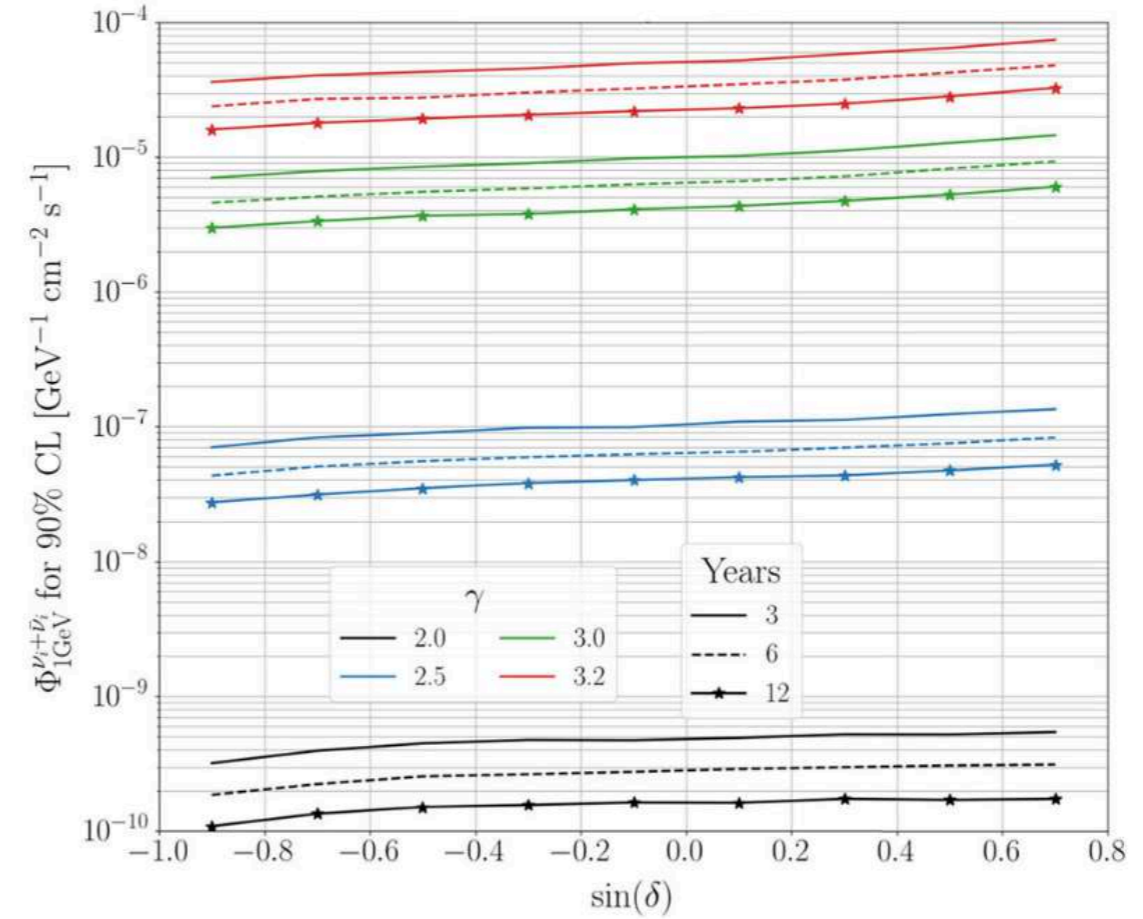
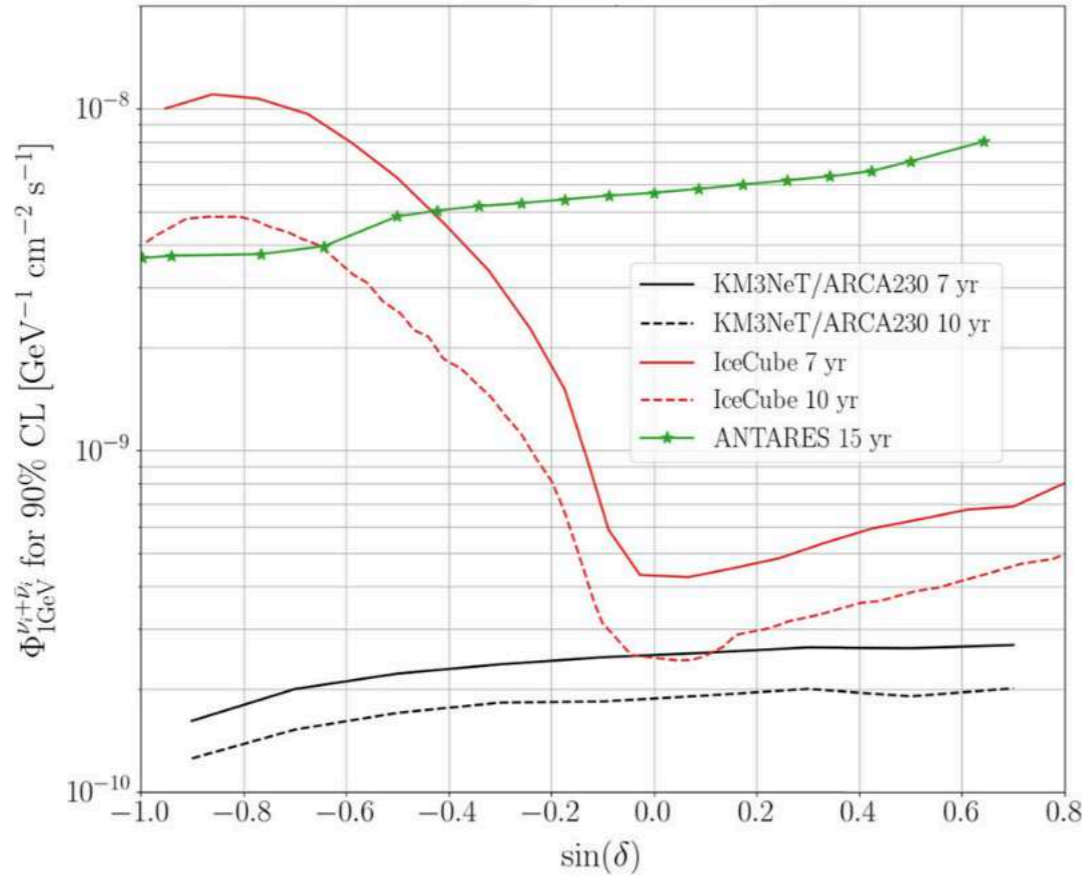
## ARCA energy resolution



# Full ARCA effective area for PS analysis



# Full ARCA point-like neutrino source sensitivity



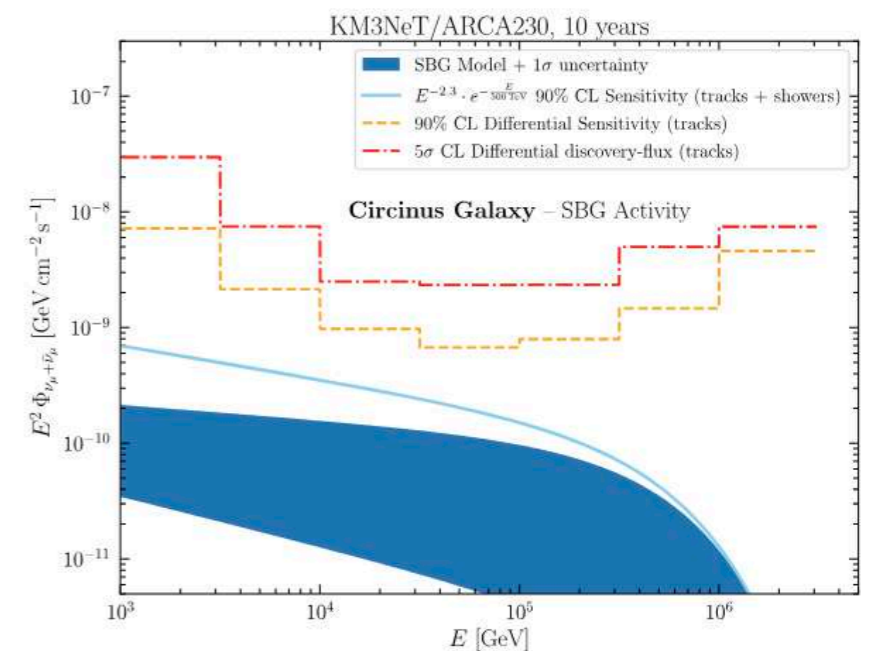
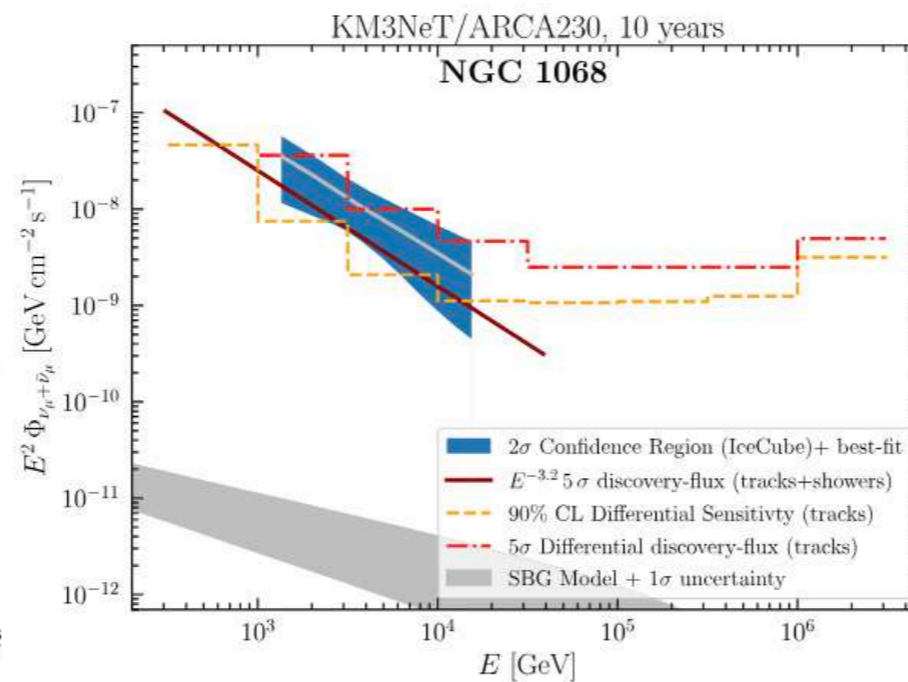
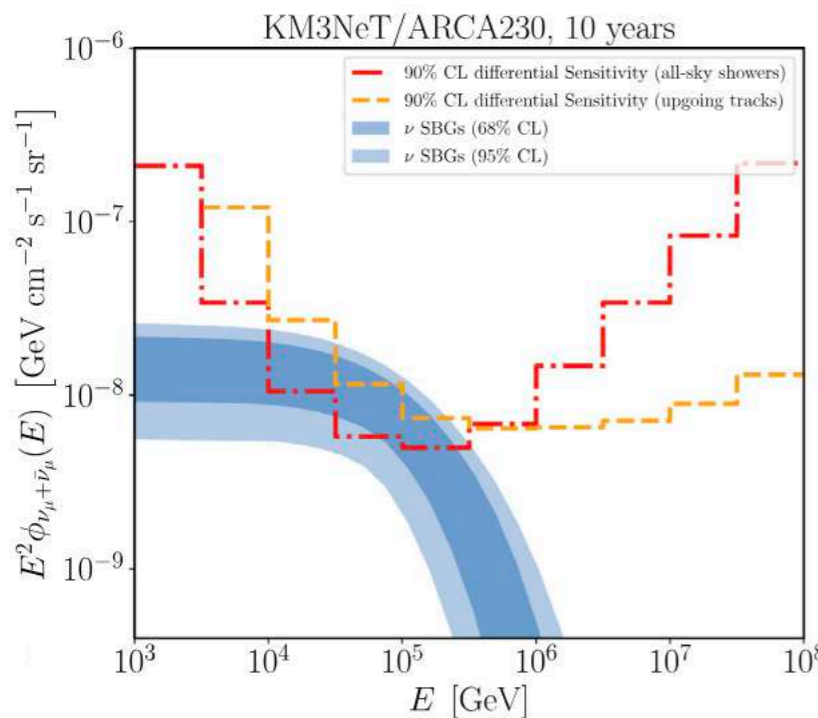
	Trigger [year <sup>-1</sup> ]	Track selection [year <sup>-1</sup> ]	Shower selection [year <sup>-1</sup> ]
Atmospheric $\mu$ (> 10 TeV)	$8.1 \times 10^7$	714	110
Atmospheric $\nu$	$1.9 \times 10^5$	$8.5 \times 10^4$	290
Cosmic $\nu$	730	220	60
Neutrino purity		99%	77%

$$\Phi^{\nu_i+\bar{\nu}_i} = 1.2 \times 10^{-8} \left( \frac{E_\nu}{\text{GeV}} \right)^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



# Starburst stacking analysis - full ARCA perspectives

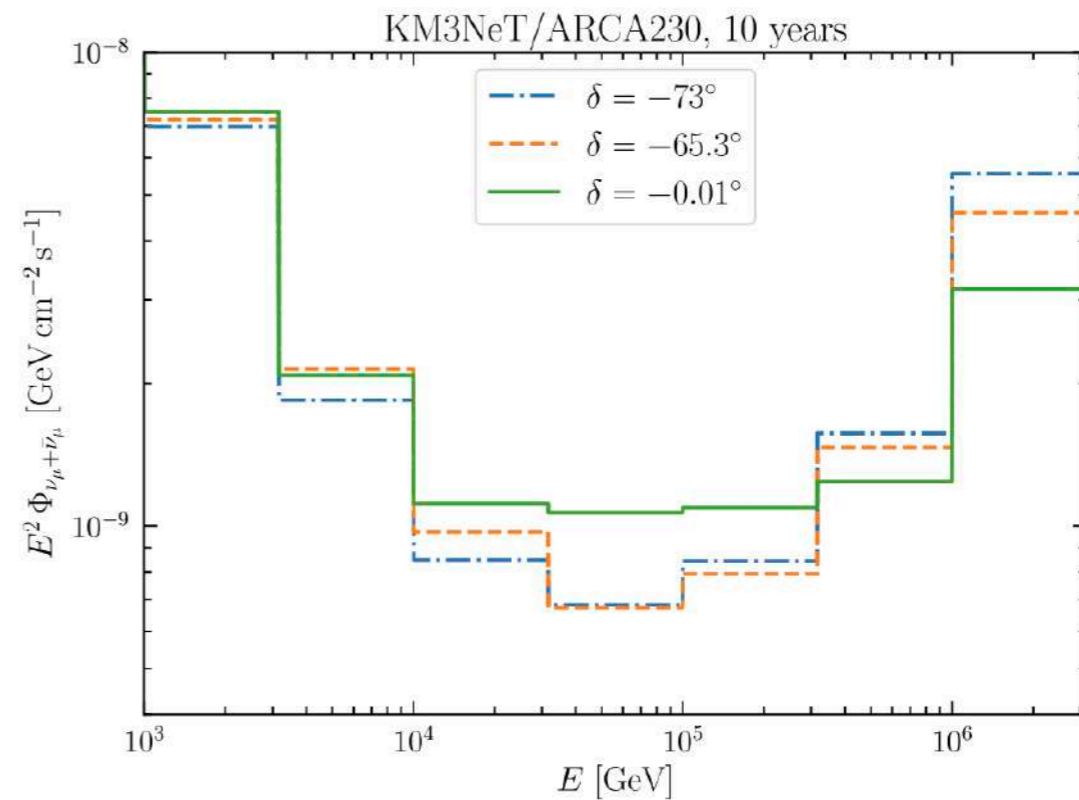
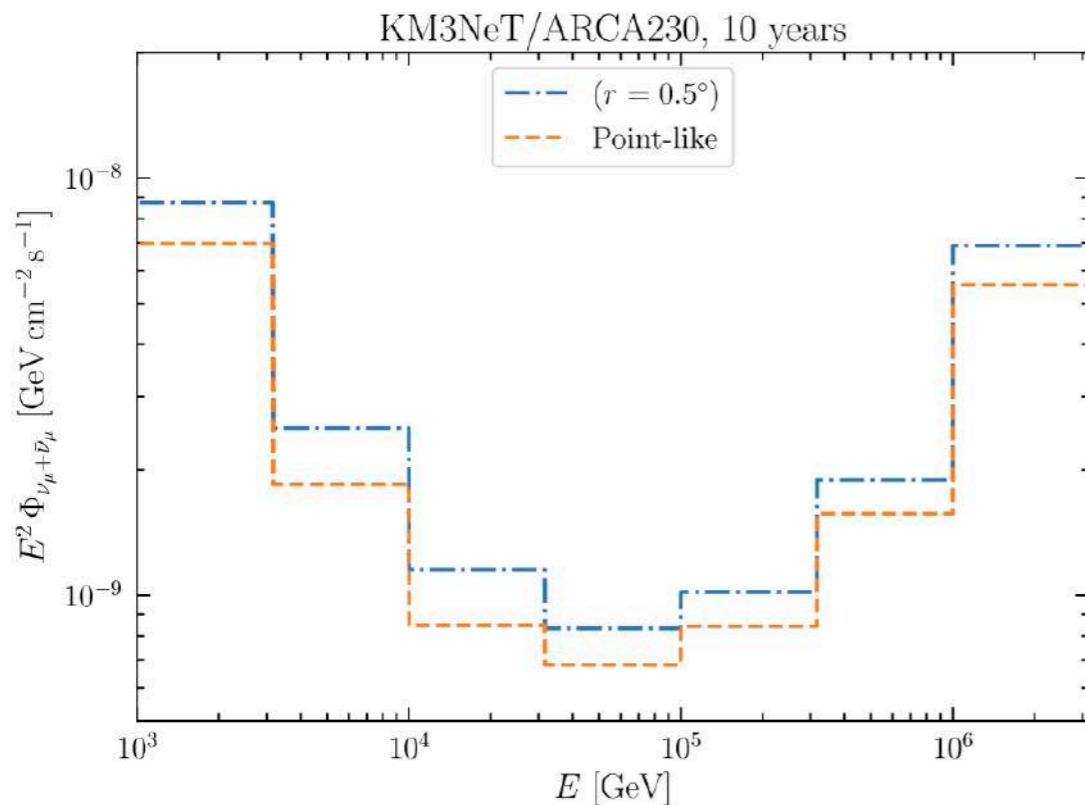
- Galaxies with intense star formation activity (hence SN rates)
- Full **ARCA230** MC simulations, **10 yr livetime**
- Upgoing track** selection with 99% sample purity & 90% efficiency
- All-sky shower** selection with 61% purity & 75% efficiency
- Both single source and diffuse contribution from SBGs.



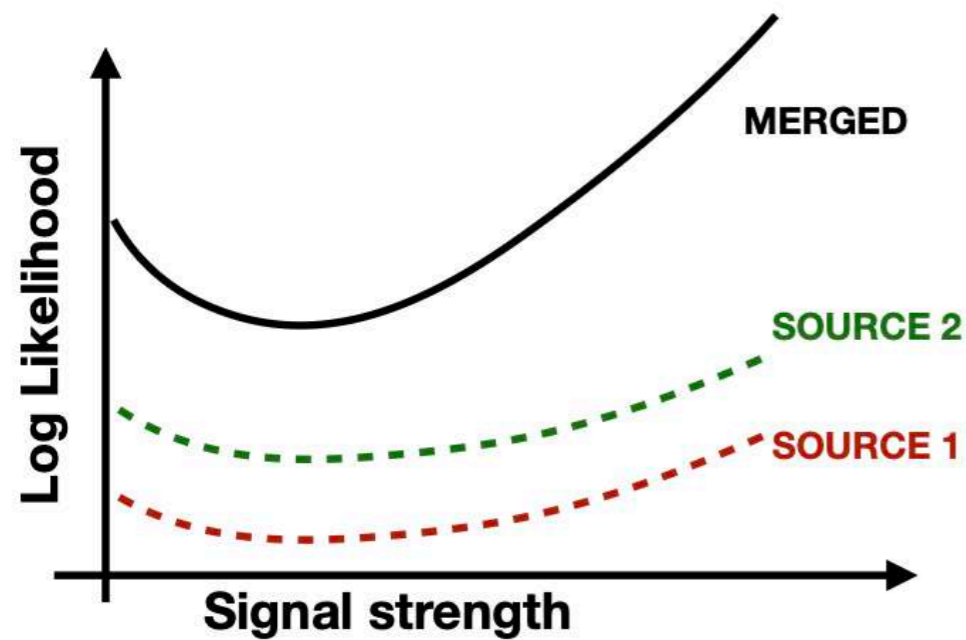
Aiello et al. [KM3NeT], Astropart. Phys. 162 (2024) 102990

# Starburst stacking analysis - full ARCA perspectives

- Galaxies with intense star formation activity (hence SN rates)
- Full **ARCA230** MC simulations, **10 yr livetime**
- **Upgoing track** selection with 99% sample purity & 90% efficiency
- **All-sky shower** selection with 61% purity & 75% efficiency
- Both single source and diffuse contribution from SBGs.



# (Stacking) Likelihood framework

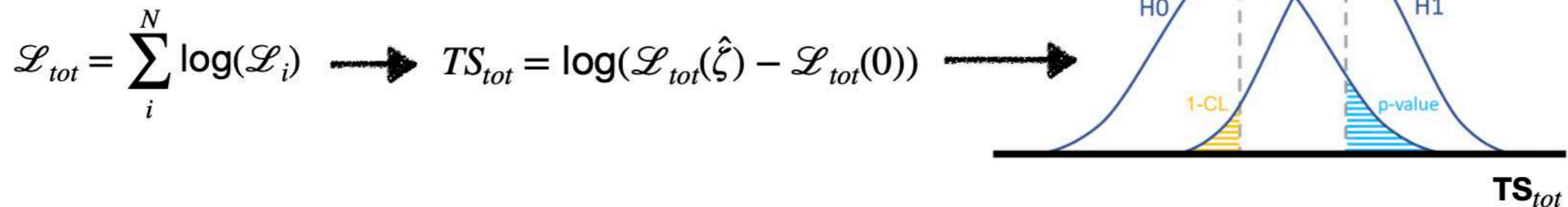


- For each of the  $N$  sources in the catalogue:
  - PDFs are distributions of expected signal ( $S_i$ ) and background ( $B_i$ )  $\rightarrow$  **energy ( $E_{rec}$ ) vs distance ( $\alpha$ ) to the source**
  - Binning:  $\log(E_{rec}/\text{GeV}) \in 1 - 8$  and  $\alpha[^\circ] \in 0 - 5$
  - Free parameter: **signal strength ( $\zeta$ )**

$$\log(\mathcal{L}) = \sum_{i \in \text{bins}} N_i \log(B_i + \zeta S_i) - B_i - \zeta S_i$$

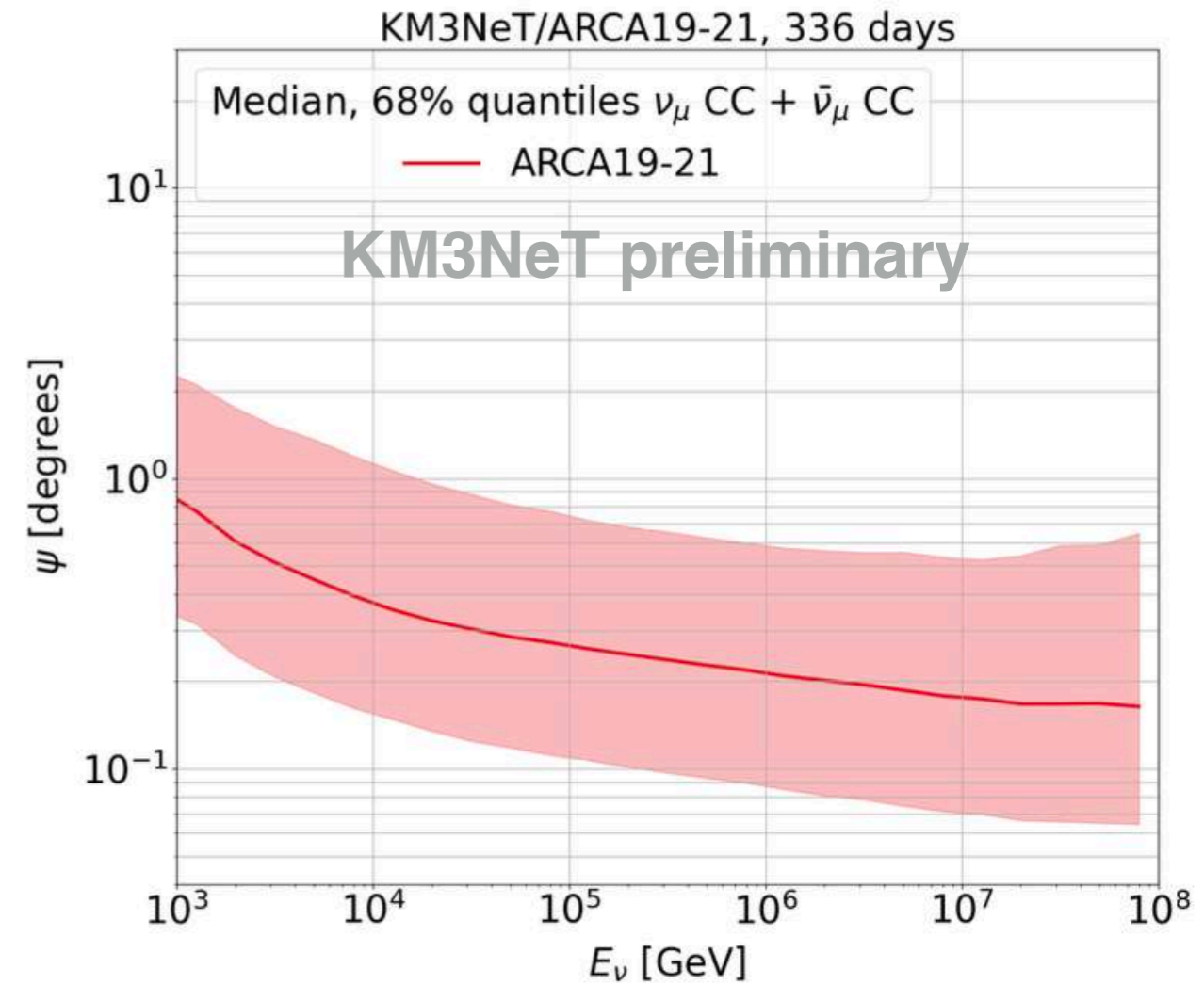
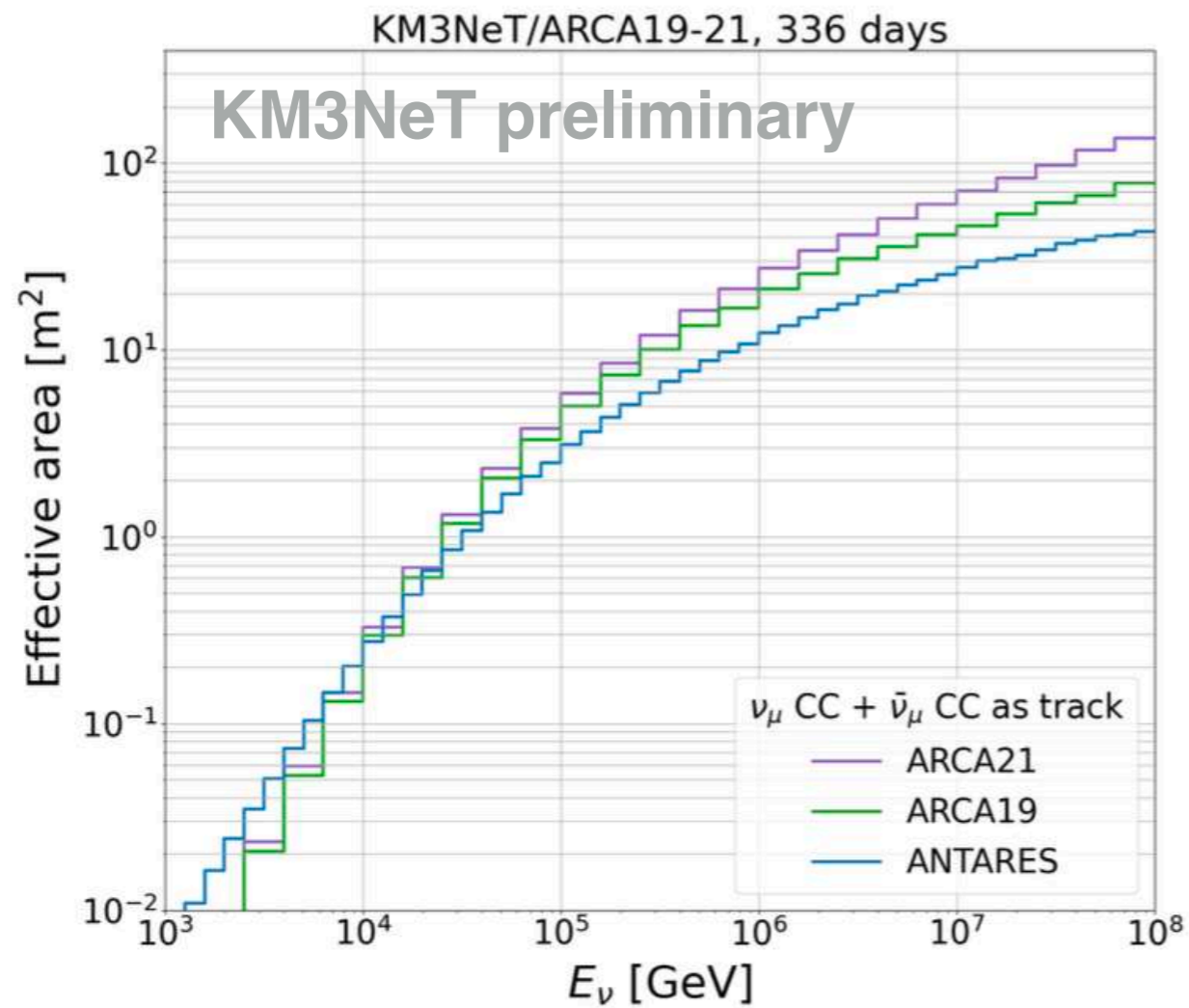
- - -  $\rightarrow$  Number of data events in bin  $i$

- Pseudo experiments varying signal strength
- **Build likelihood profile** for each source and merge them



p-value is represented by fraction of  $H_0$  PE with  $TS_{tot}$  above median of  $H_1$  PE

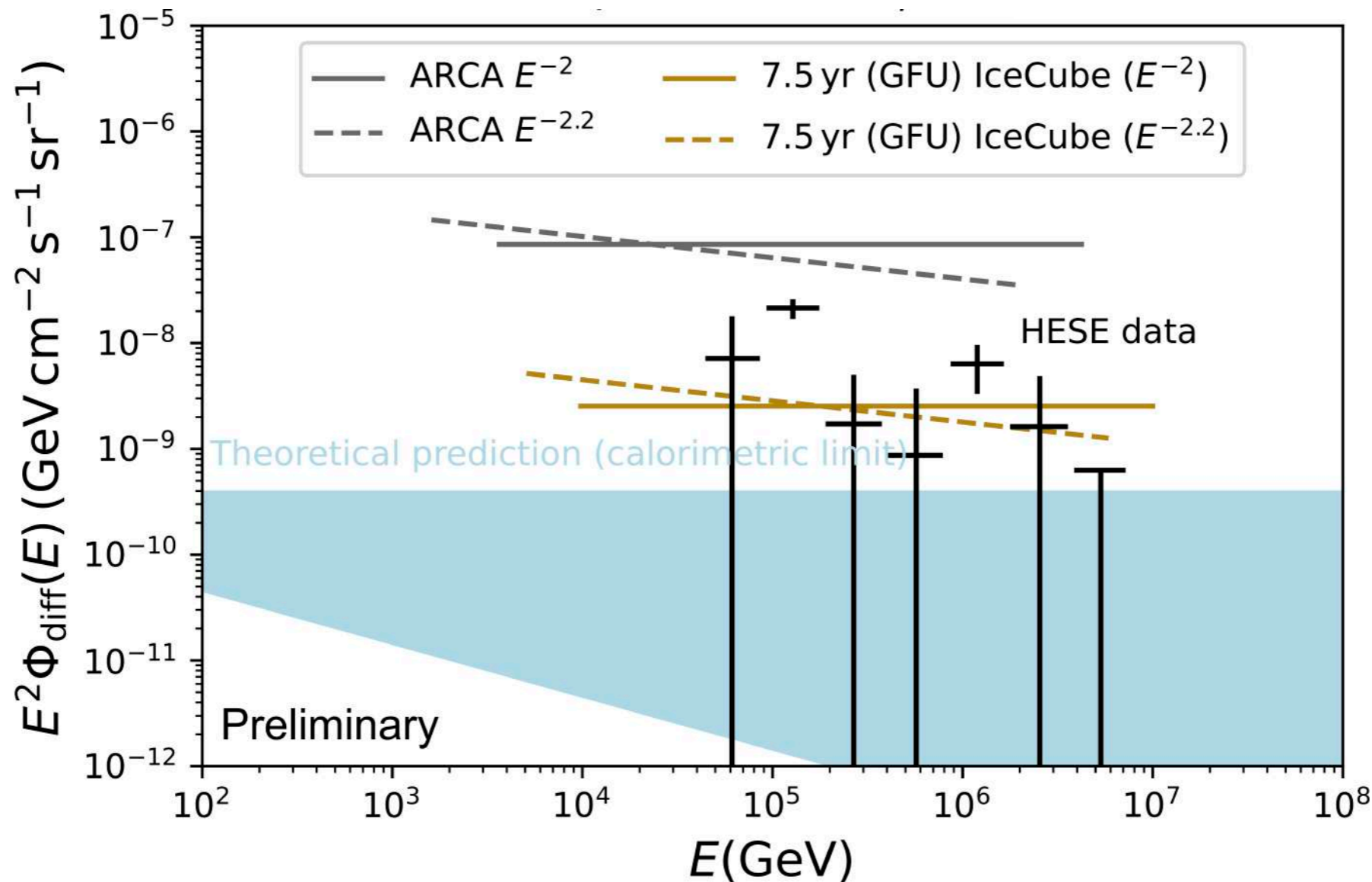
# ARCA19-21 stacking analyses



# Diffuse neutrinos from ULIRGs

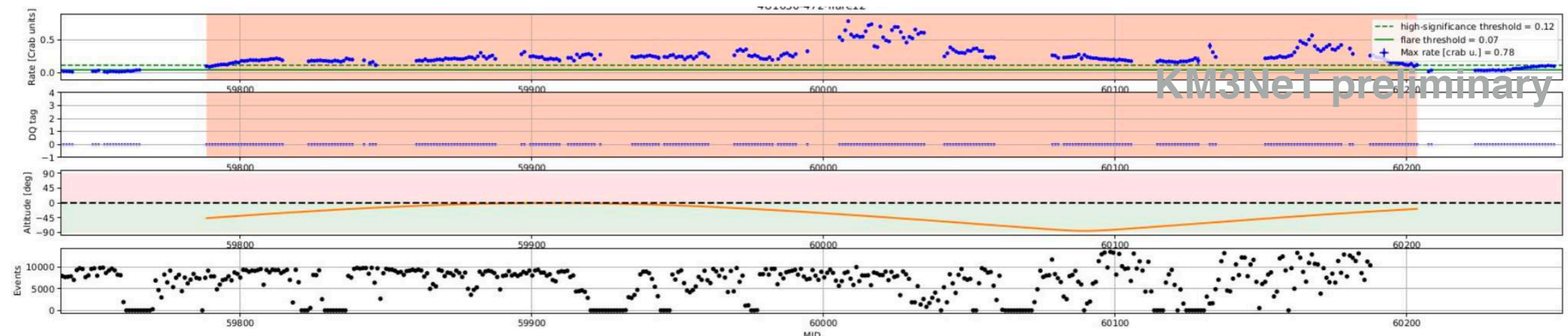
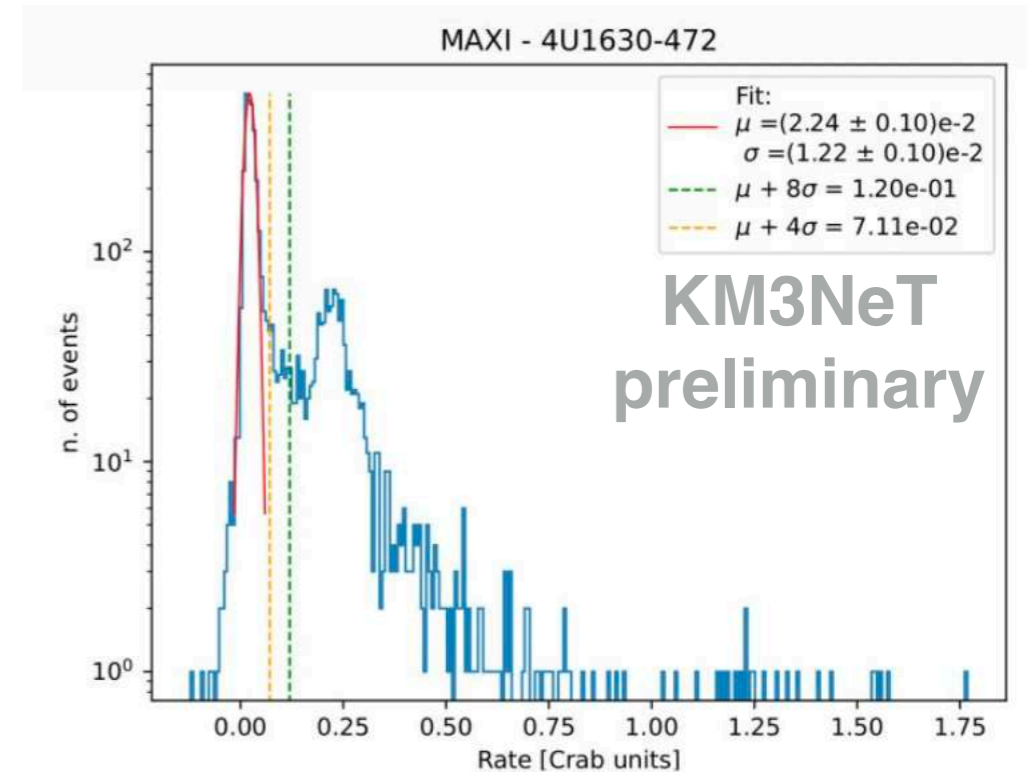
- Combined data from **ARCA19-21 (upgoing tracks only)**
- Extrapolation of ULIRGs with luminosity function

$$L(z) = \begin{cases} (1+z)^4 & z < 1 \\ \text{const} & 1 < z < 4 \end{cases}$$

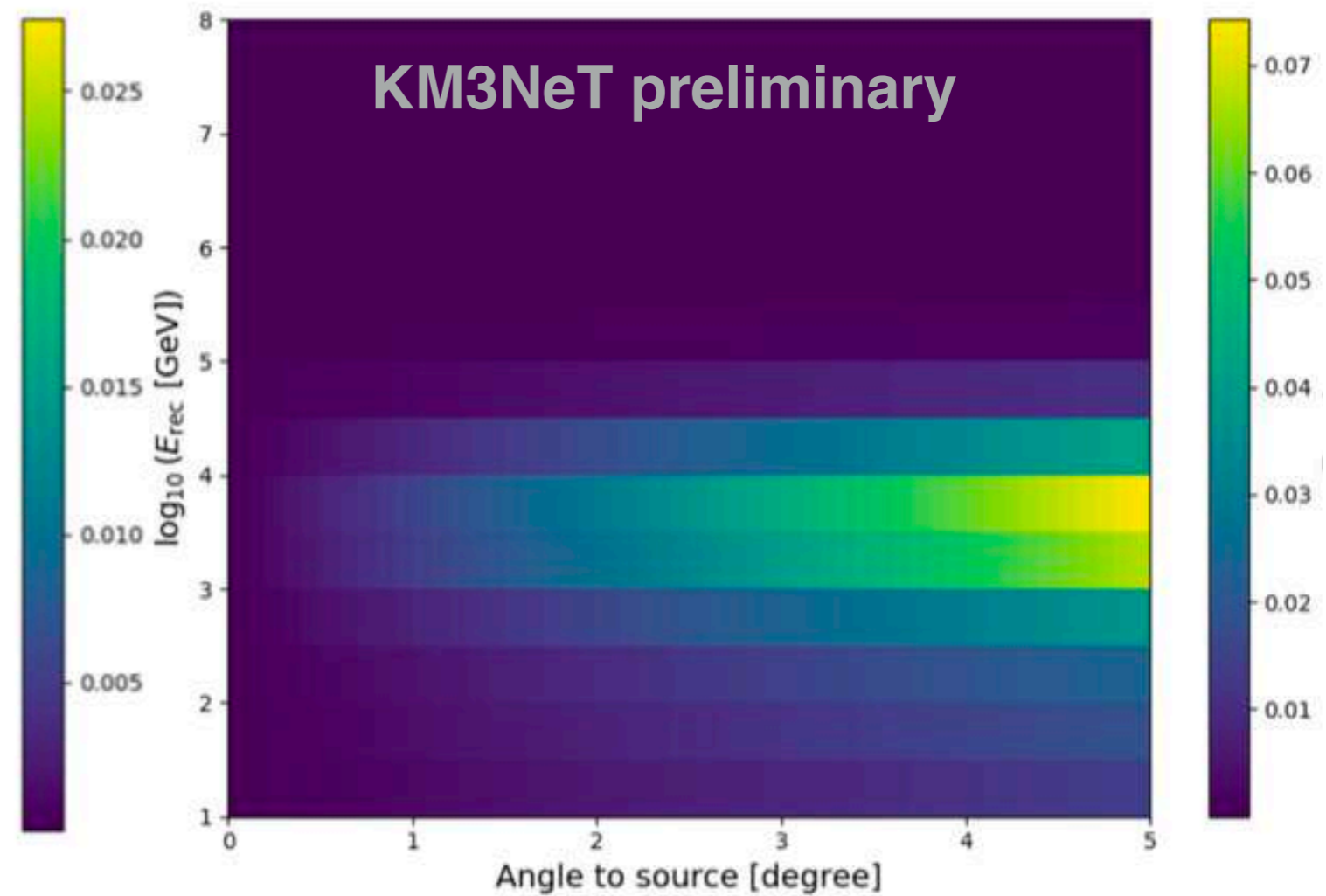
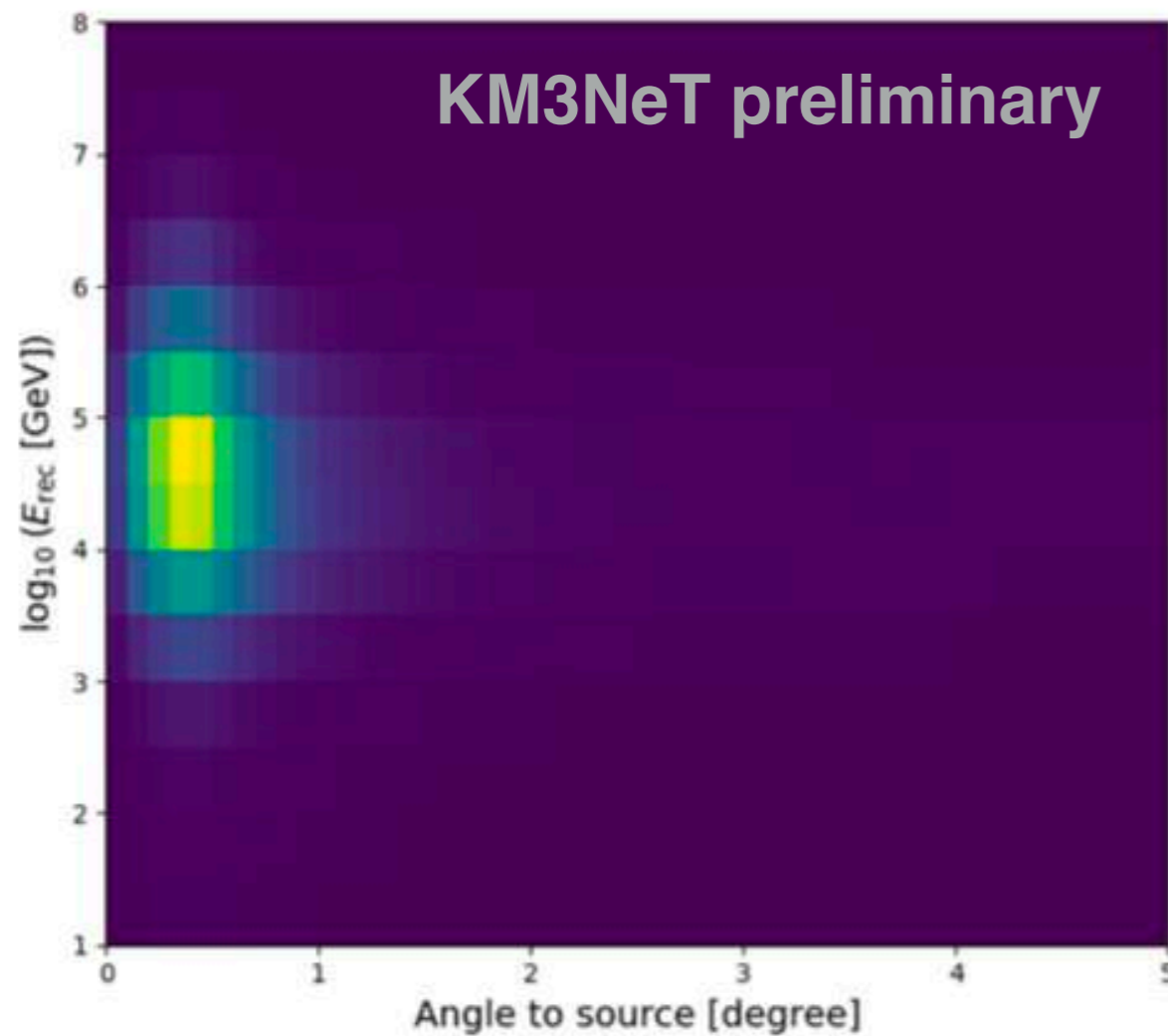


# KM3NeT $\mu$ quasar analysis

- ORCA6-18 & ARCA19-21 datasets
- Neutrino search in coincidence with X-ray flaring  $\mu$ quasars from MAXI (2-20 keV) & Swift/BAT catalogs (15-50 keV): 15 selected sources
- ON/OFF technique optimized to reach minimum MRF in BDT and angular cuts
- Non significant detection so far



# KM3NeT/ARCA point-like neutrino source search



Adriani et al. [KM3NeT], in prep.

# **The KM3NeT realtime program for multi- messenger analysis**

# KM3NeT realtime follow-up of external triggers

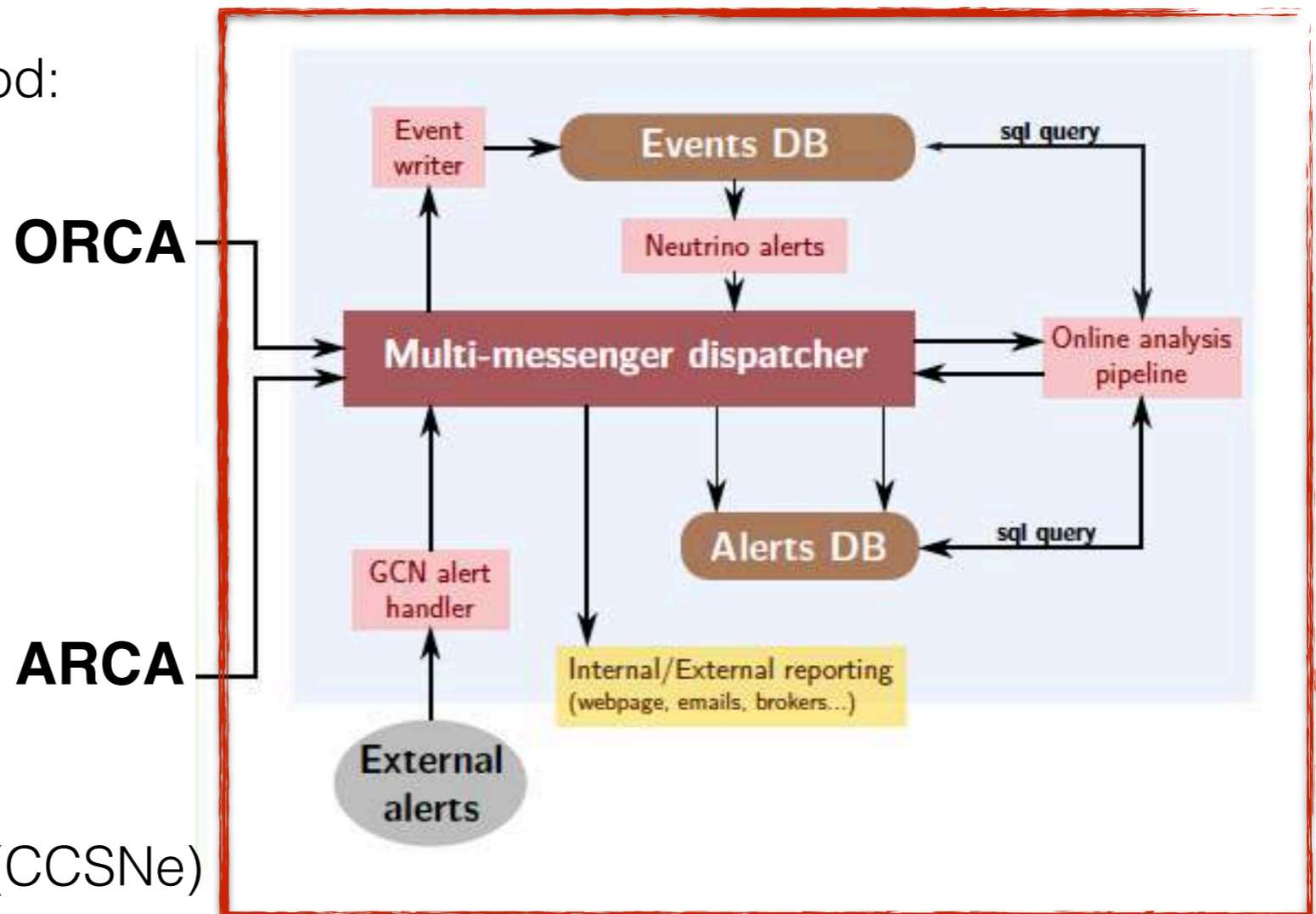
- External triggers received from 3 external **brokers** (GCN, Chime, TNS), 1 internal broker ( $\mu$ Quasar), SNEWS and HyperK
- Each alert starts an **automated all-sky** analysis in **ARCA & ORCA**
- Only **track-like events** used so far in coincident search (showers inclusion in progress)
- **Iterative searches** in extended time windows, profiting of updated information from instruments

- **Binned ON/OFF analysis** method:

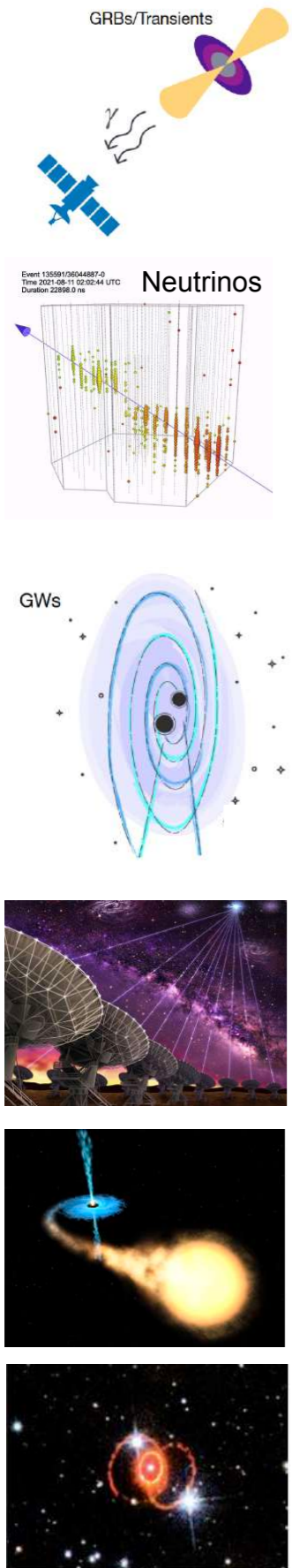
- background estimation
- cut optimization
- flux limit computation

- **Pipelines** currently in place:

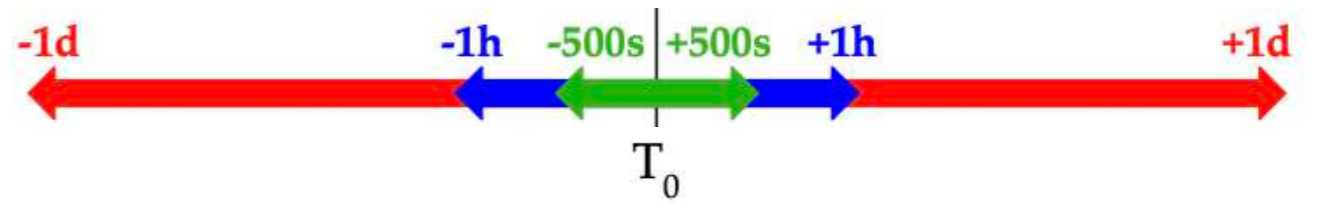
- Gamma Ray Bursts (GRBs)
- High-energy transients
- IceCube (IC) neutrinos
- Gravitational Waves (GWs)
- Fast Radio Bursts (FRBs)
- $\mu$ Quasars
- Core Collapse Supernovae (CCSNe)



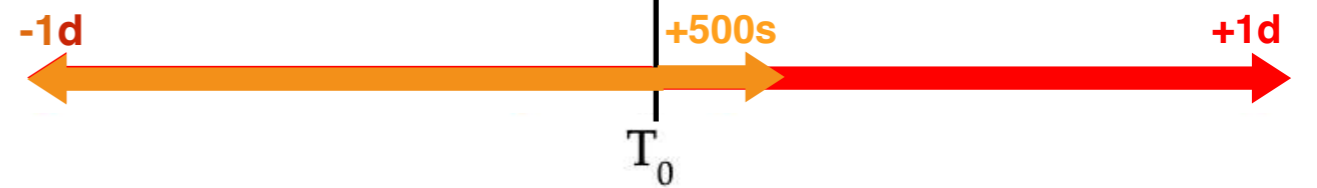
# Temporal windows for realtime follow ups



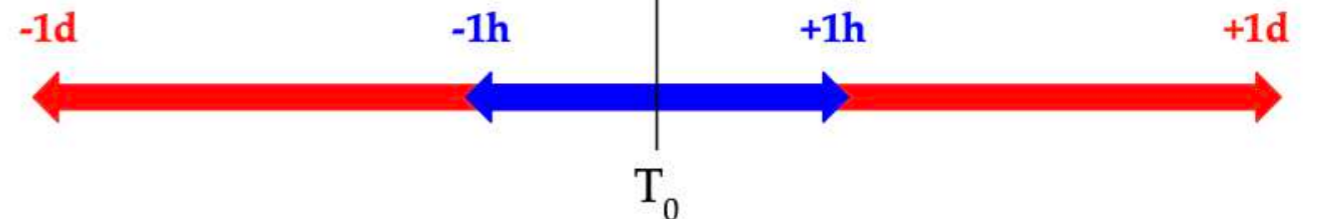
**GRBs**



**Transients**



**IC neutrinos**

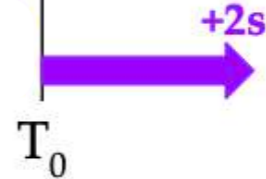


**GWs**

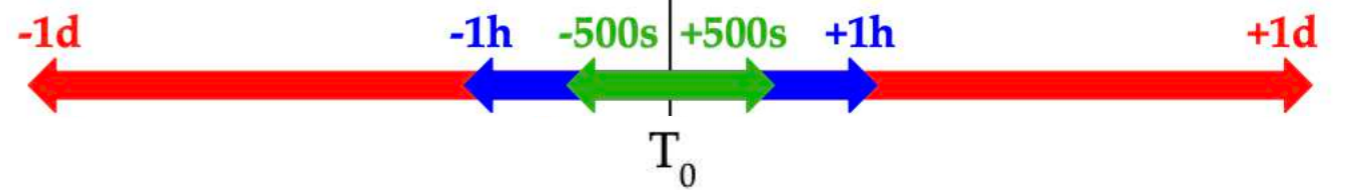
[HE analysis]



[MeV analysis]



**FRBs**

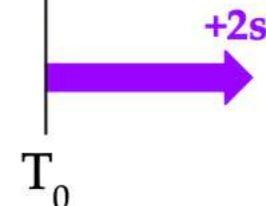


**μQuasars**



**CCSNe**

[MeV analysis]



# ON/OFF binned analysis



**ON region:** where signal is expected (including angular uncertainty & source error location)

→  $T_{\text{ON}}$  &  $\Omega_{\text{ON}}$

(multiple  $T_{\text{ON}}$  inspected depending on alert type)

**OFF region:** local zenith bands to compute the expected background spanning the ON region movement due to Earth's rotation

**p-value** determined by comparing the number of events in the ON region with expected background

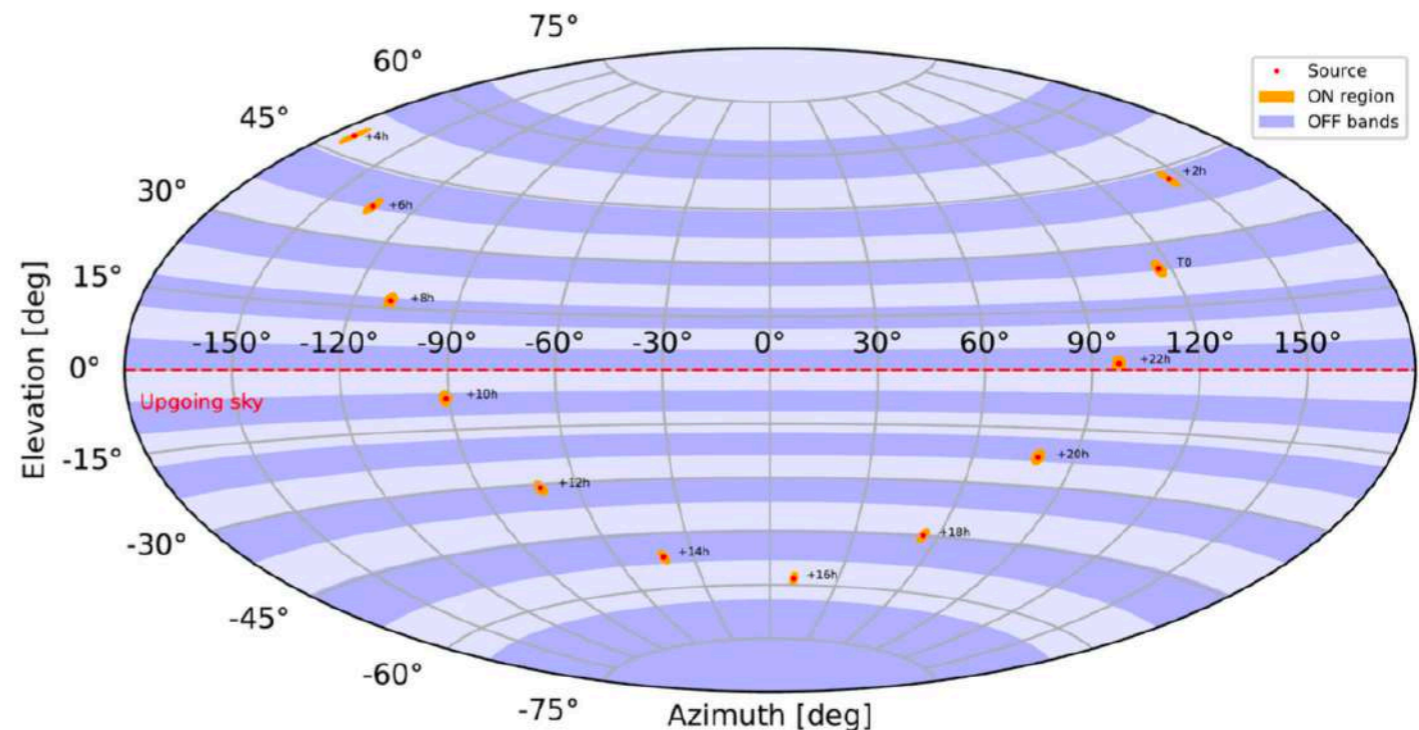
**Event selection:** pre-cuts + optimization cuts to achieve a target number of background event

Optimization criterion: m-sigma/n-events

1.  $n_{\text{BKG}} \leq \alpha$
2.  $\sigma(n_{\text{BKG}})/n_{\text{BKG}} < 30\%$
3.  $\sigma(n_{\text{OFF}}^i)/n_{\text{OFF}}^i < 50\%$

$$n_{\text{bkg}} = \sum_{i \in \text{bands}} \frac{T_{\text{ON}} \Omega_{\text{ON}}^i}{T_{\text{OFF}} \Omega_{\text{OFF}}^i} N_{\text{OFF}}^i$$

$T_{\text{ON}}$  : search time window, depending on the source type  
 $T_{\text{OFF}}$  : 2 weeks  
 $\Omega_{\text{ON}}^i$  : overlap between ON region and OFF region band  
 $\Omega_{\text{OFF}}^i$  : size of OFF region band  
 $N_{\text{OFF}}^i$  : number of events in OFF region band after selection



# Alert sending module



**GOAL:** To quickly identify potentially interesting neutrino events and alert the MM community within  $O(\text{min})$

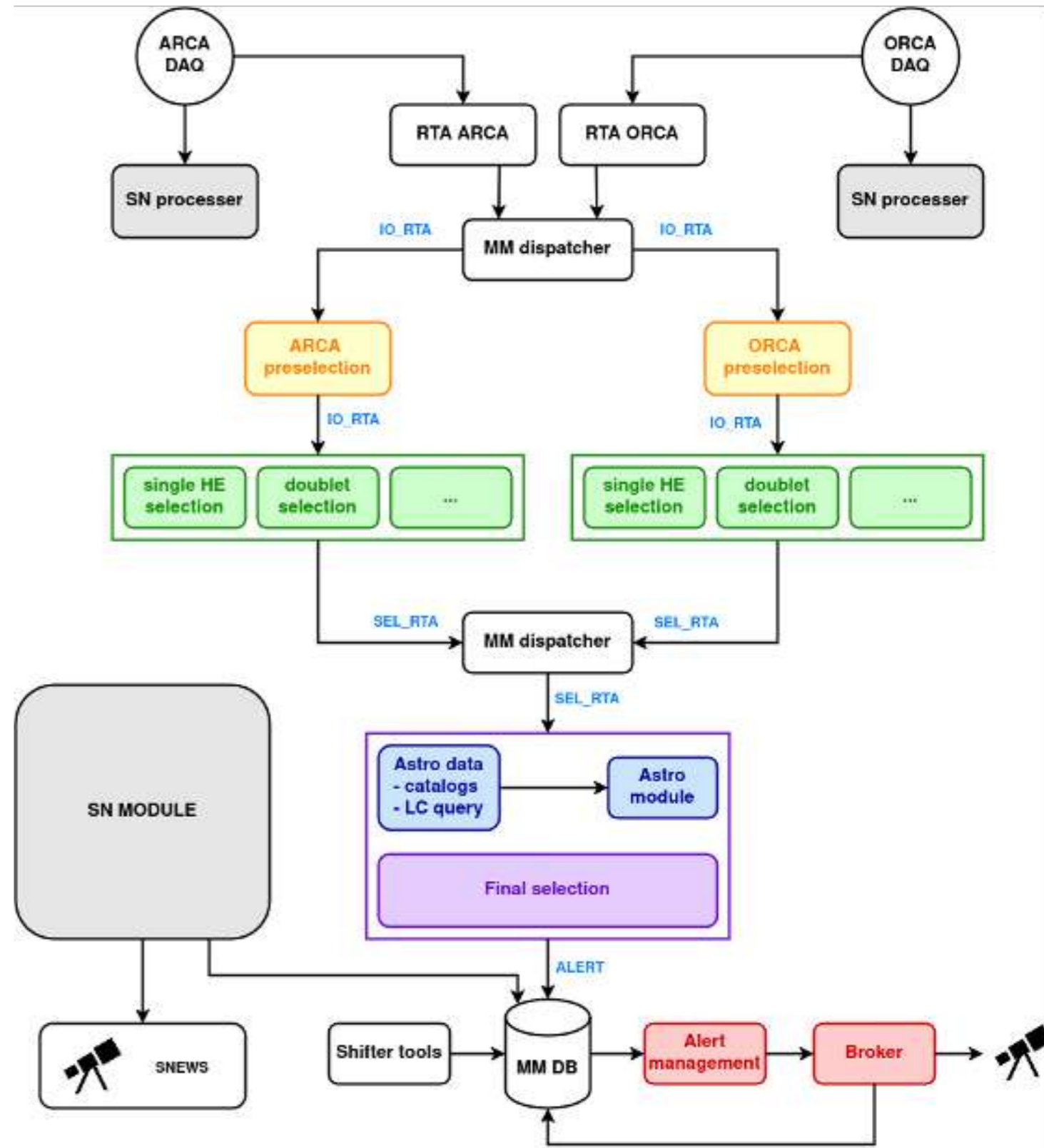
**INPUT:** Real-time reconstruction

## SELECTION PIPELINES:

- HE neutrinos
- Multiplets
- $O(10 \text{ selection/month})$

## ASTRO COUNTERPART SEARCH:

- Real-time access to source catalogs for spatial coincidence
- $O(1 \text{ alert/month})$



# Multiplet selection

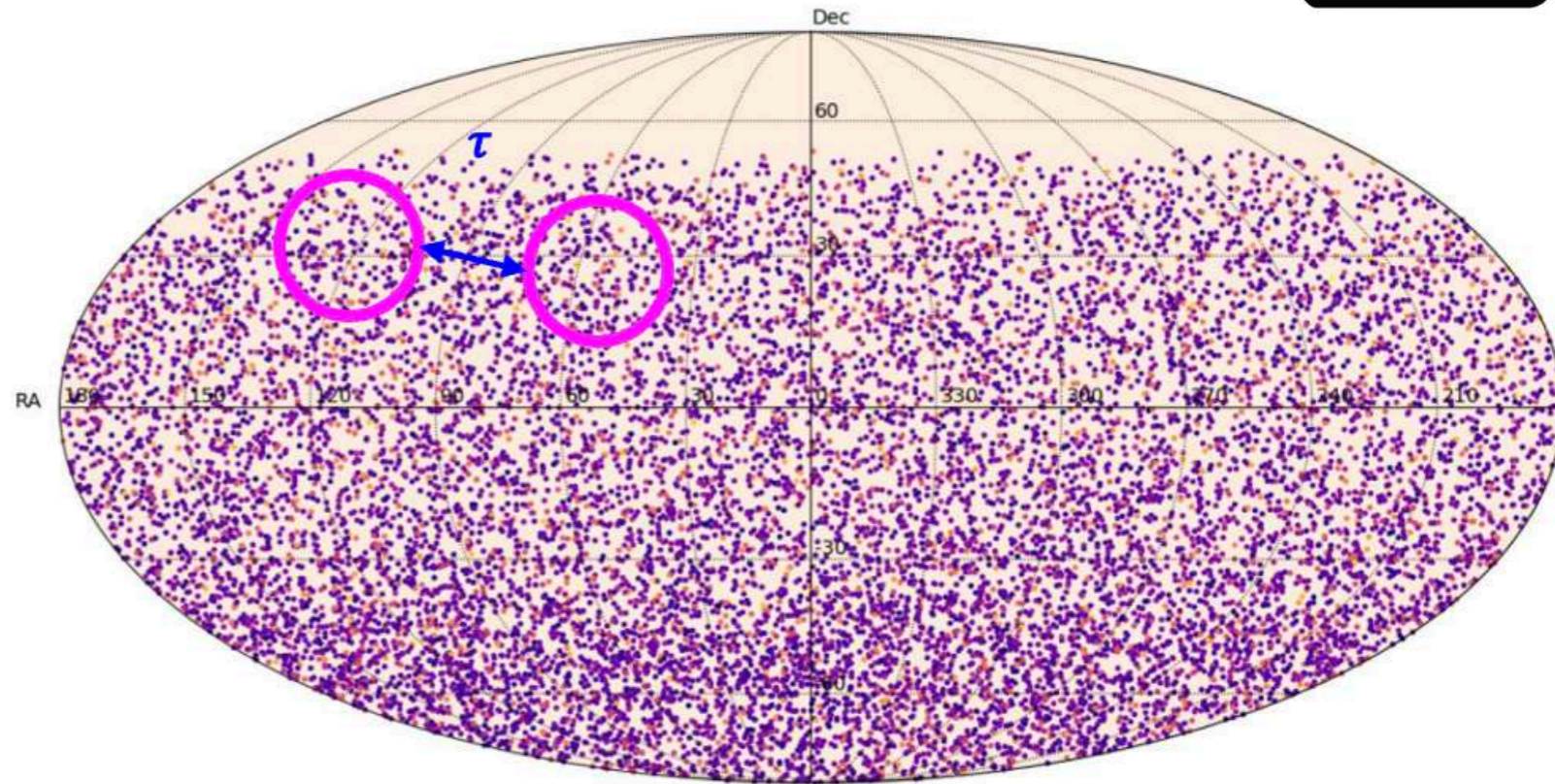


**MULTIPLLET:** More than one event with compatible sky localization and time of arrival

## TIME CORRELATION PROBABILITY:

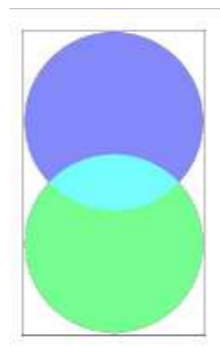
$$P(\Delta t \leq \tau | \lambda) = 1 - e^{-2\lambda\tau}$$

Two events in time interval  $\tau$   
Uniform event rate  $\lambda = N/\tau$



## SPACE CORRELATION PROBABILITY:

$$p_{loc} = 1 - \left( \frac{N_{comp}}{N_{use}} \times \left( 1 - \frac{N_{use}}{N_{tot}} \right) \right)$$



$N_{comp}$  = overlapping pixels (cyan)  
 $N_{use}$  = union pixels (purple, cyan, green)  
 $N_{tot}$  = total pixels in the sky

## COMBINED ALERT DIRECTION

$$\text{direction} = \frac{\sum_{i=1}^N \left( \frac{\text{dir}_i}{\sigma_i^2} \right)}{\sum_{i=1}^N \left( \frac{1}{\sigma_i^2} \right)}$$

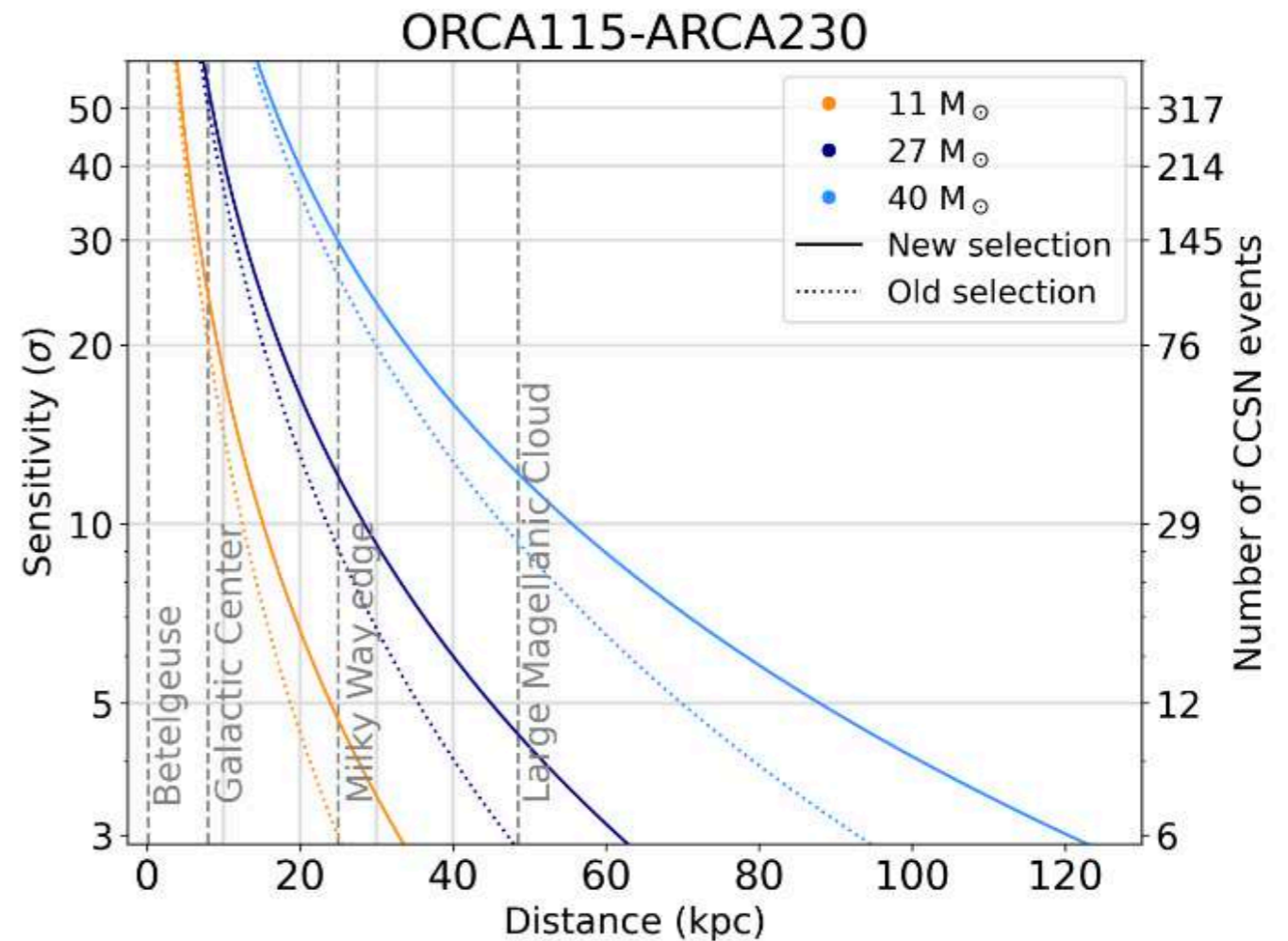
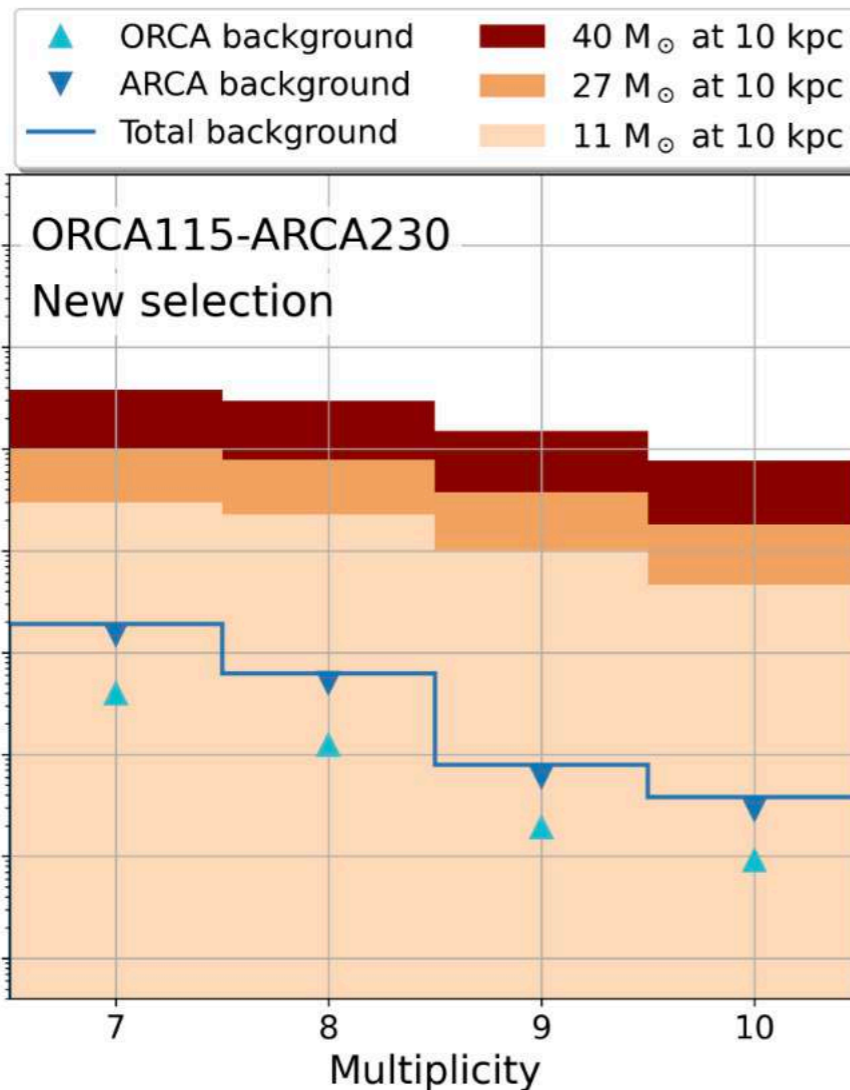
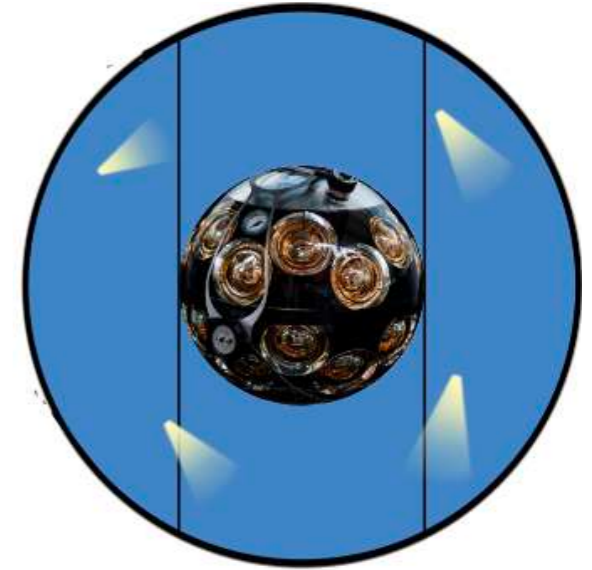
$$\text{err}(\text{direction}) = \frac{1}{\sqrt{\sum_{i=1}^N \frac{1}{\sigma_i^2}}}$$



# The KM3NeT multi-messenger program

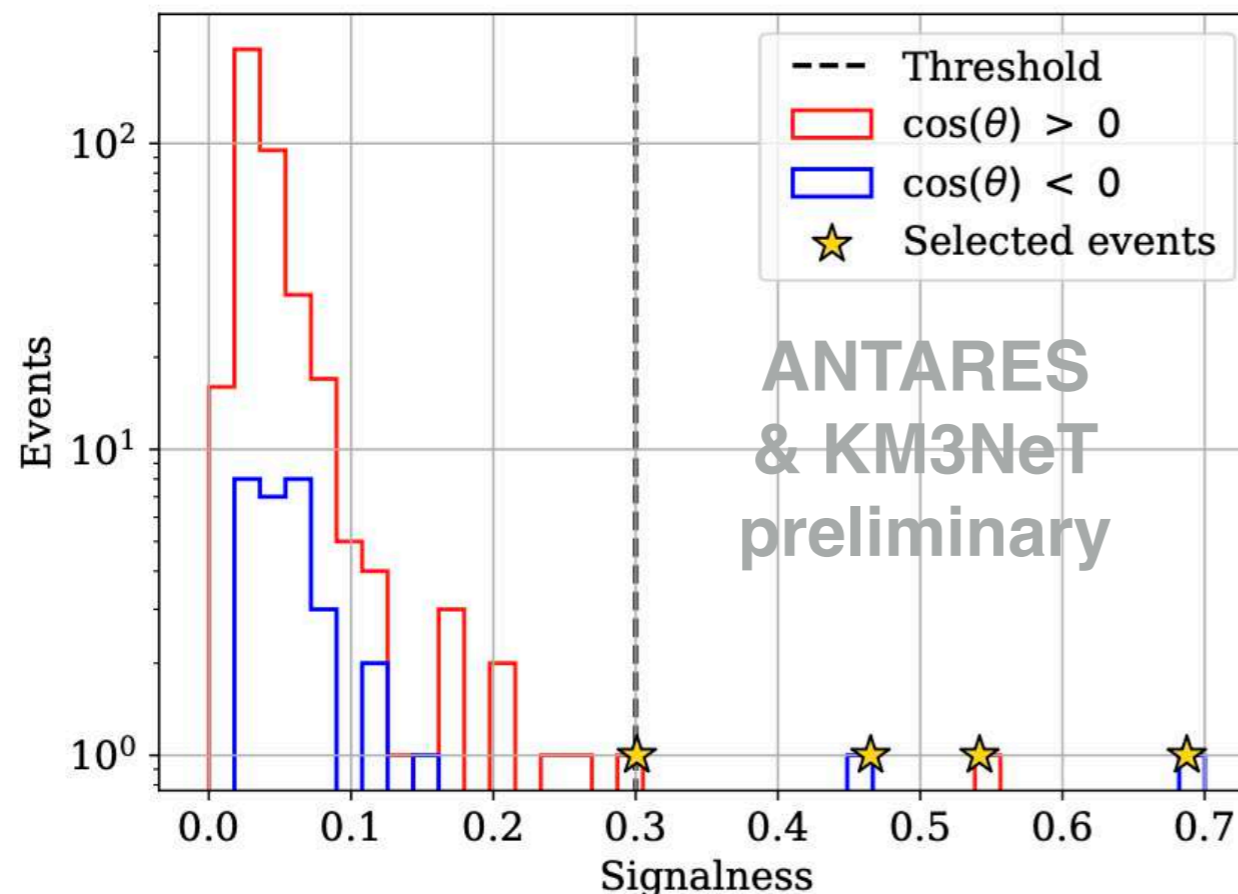
# Search for MeV neutrinos from CCSNe

- Neutrinos  $< 100$  MeV expected at massive stellar collapse
- Main interaction channels in water are IBD of electron antineutrinos with protons, ES on electrons and CC interaction with O nuclei
- Cherenkov signature detected as a **population of coincidences in single DOMs** = overall excess in detector



# MM analysis with GWs

- **ORCA6** (45.5 days livetime) + **ANTARES** (266 days livetime) **joint MM analysis** with GW data from **LVK run O3** (April 1<sup>st</sup> 2019-March 27<sup>th</sup> 2020)
- **Coherent unmodelled triggered search** looking for excess GW power in time-frequency domain based on **high-energy neutrino (HEN) tracks** ( $S > 0.3$ ), used to narrow sky location & set time window of the GW search
  - follow-up search with **X-pipeline**, exploring a broad range of GW waveforms (CBCs, CCSNe, ADIs, etc.), also used in FRB/GRB coincident searches
  - sub-threshold search with **PyCBC**, ranking pairs of GW/HENs with potential common origin



**NO significant detection**  
+  
**ongoing sub-threshold search**  
**with full a list**



# MM analysis with GWs and ORCA

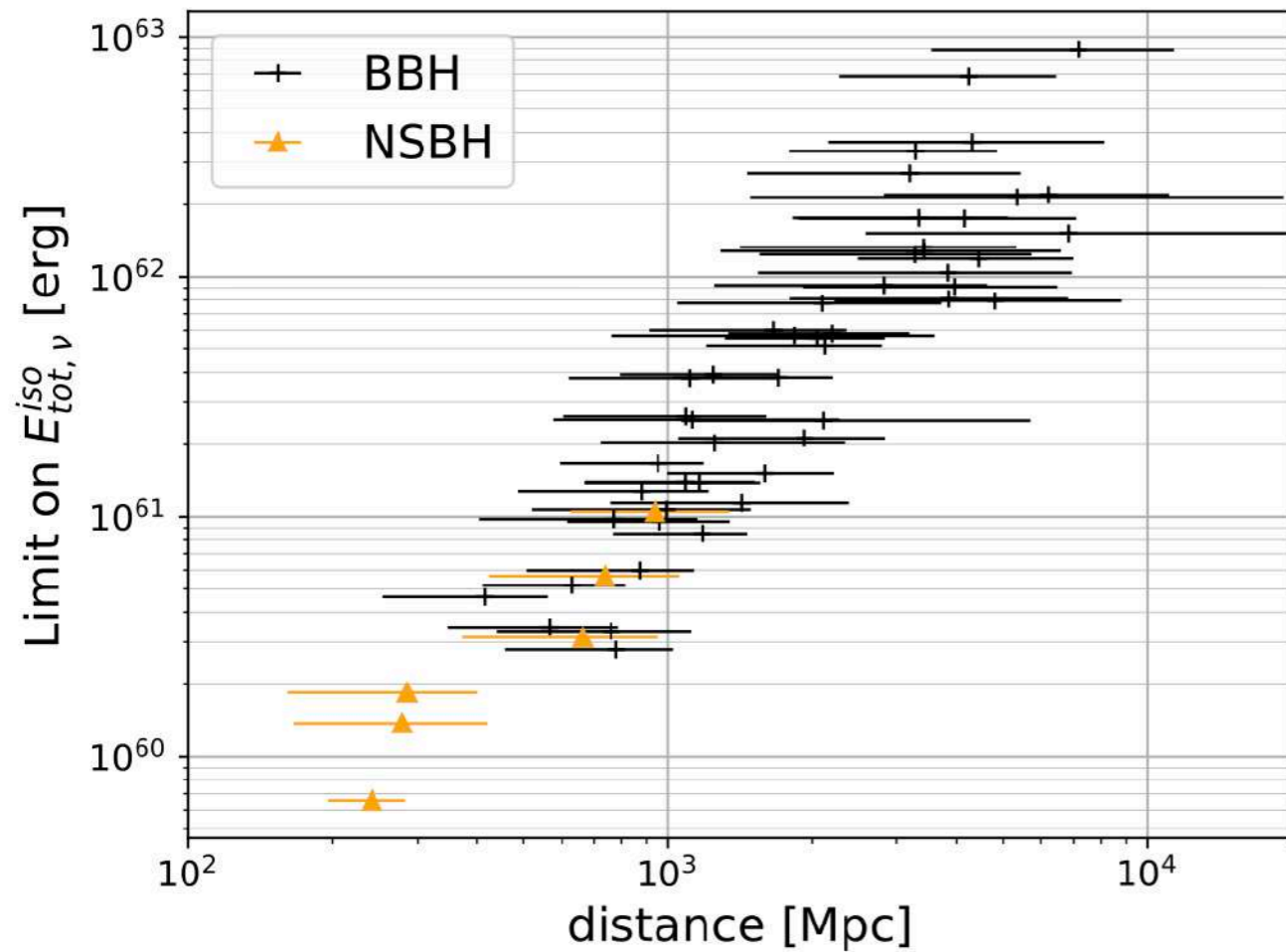
- Two **model-independent searches** performed with GW catalogs during O3: 39 detections in O3a (GWTC-2) + 8 more events (GWTC-2.1), 35 detections in O3b (GWTC-3) + NSBH candidate GW200105 162426 in O3b also included here
- **ORCA4** and **ORCA6** datasets exploited with:
  - **5-30 MeV (IBD) neutrinos**, similar to CCSN analysis (time coincidence in 2 s time window to minimize number of trials)
  - **GeV-TeV upgoing track**-like events (time coincidence in  $t_{\text{GW}}-500\text{s}$ ;  $t_{\text{GW}}+500\text{s}$  & space coincidence in the region containing 90% of the GW probability from sky map, extended for angular uncertainty of neutrino detector)
  - ON/OFF analysis with MRF minimization (BDT cut)



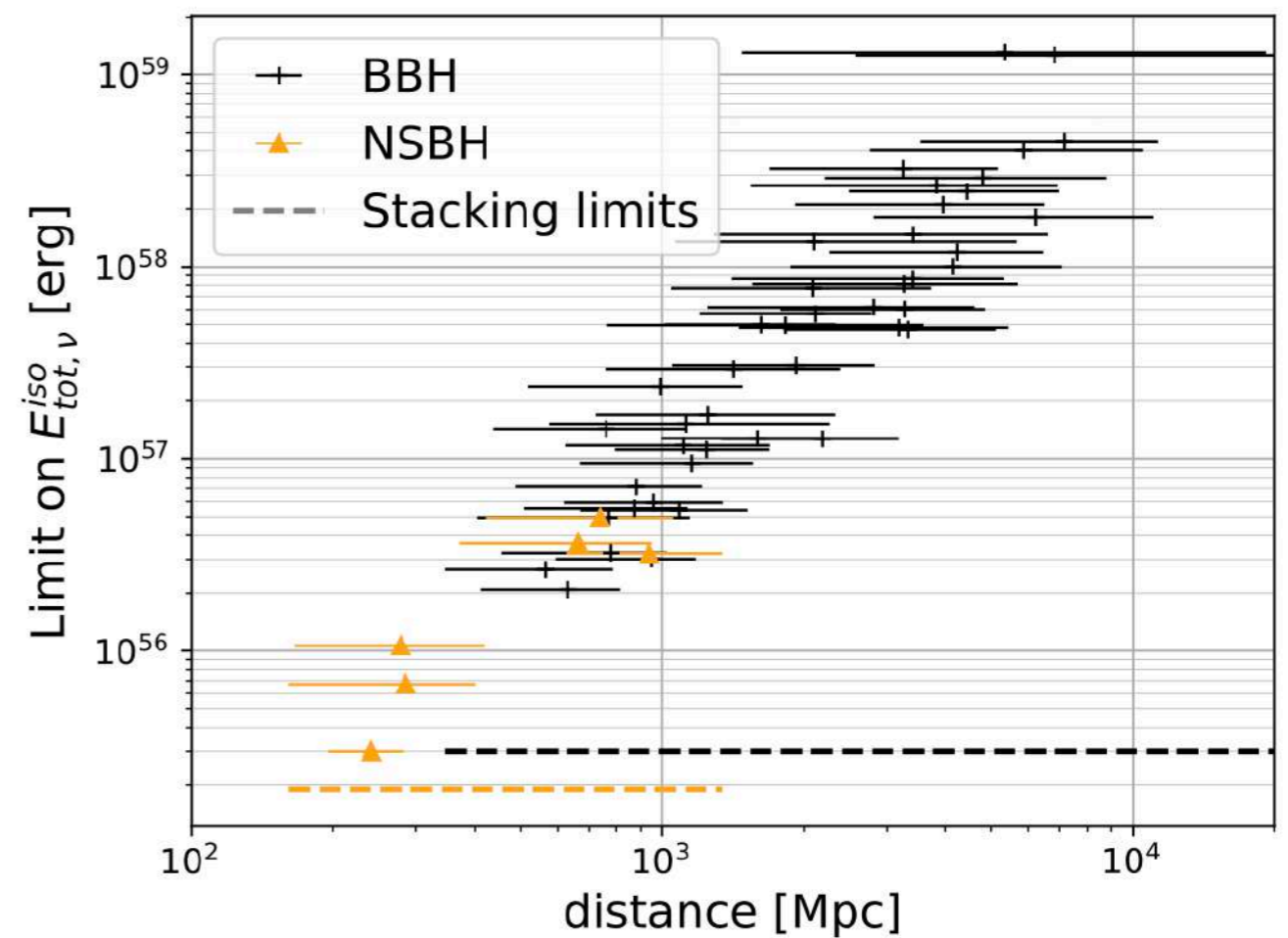
# MM analysis with GWs and ORCA

- No significant coincident detection
- Upper limits on neutrino isotropic energy release
- Stacking limits also derived in GeV-TeV analysis (visibility corrected)

## MeV analysis

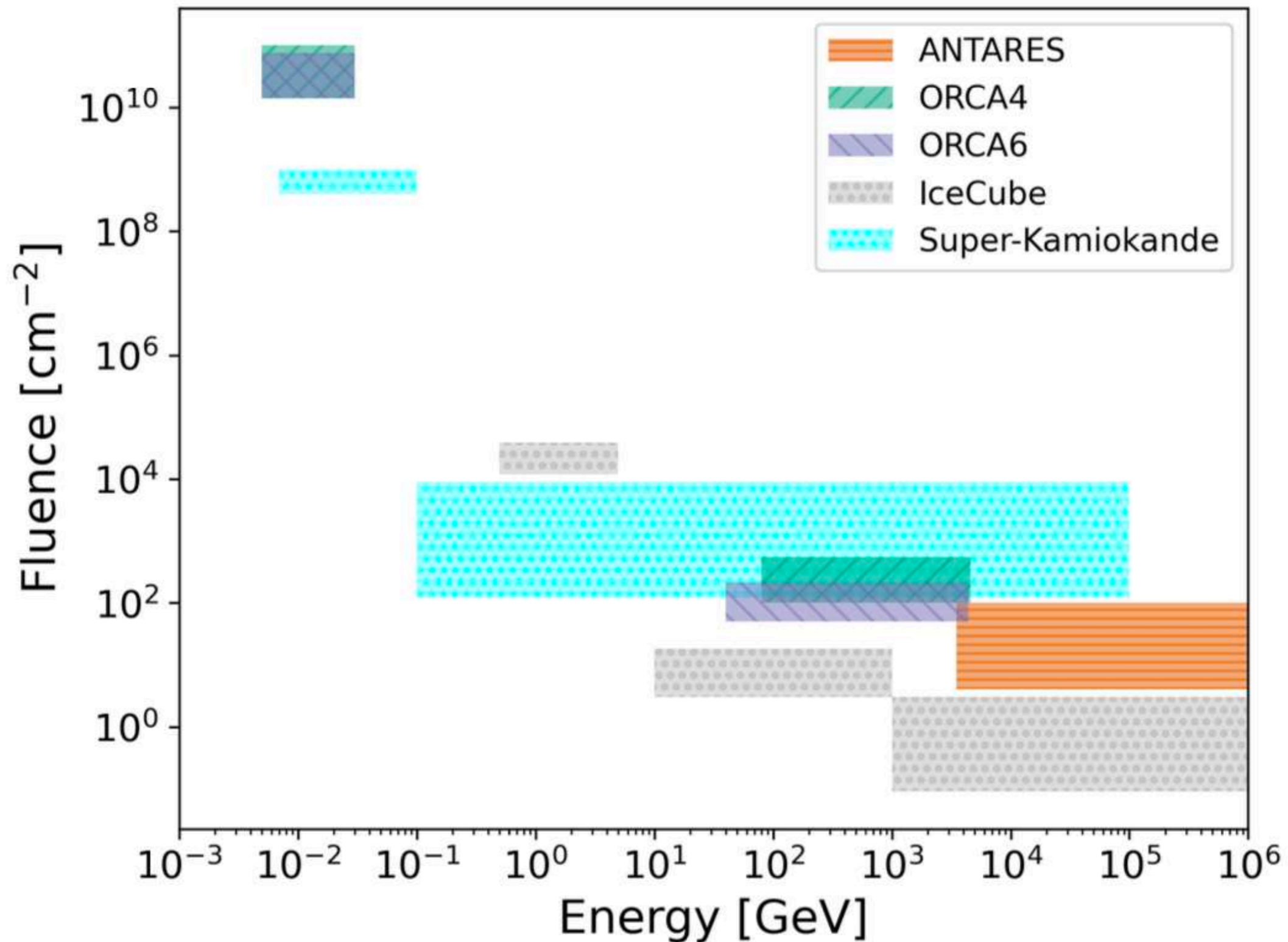


## GeV-TeV analysis



Aiello et al. [KM3NeT], JCAP 04 (2024) 026

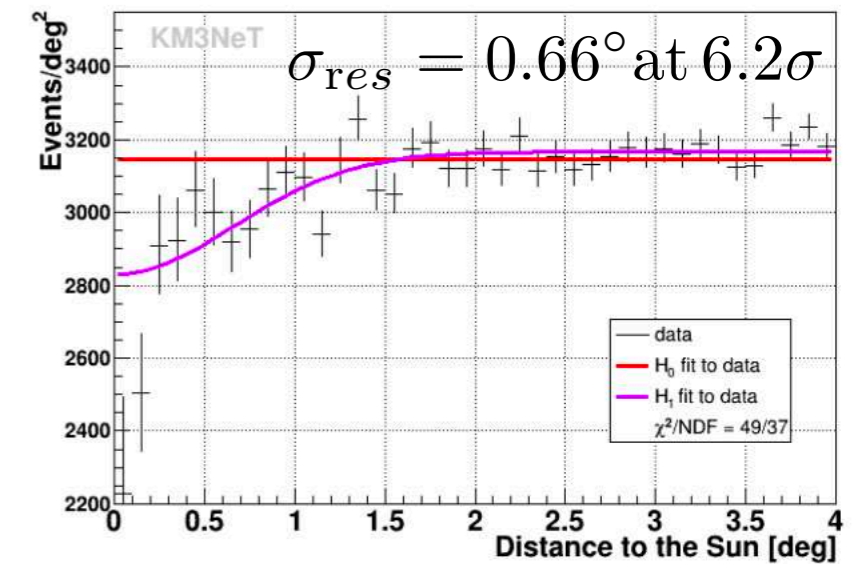
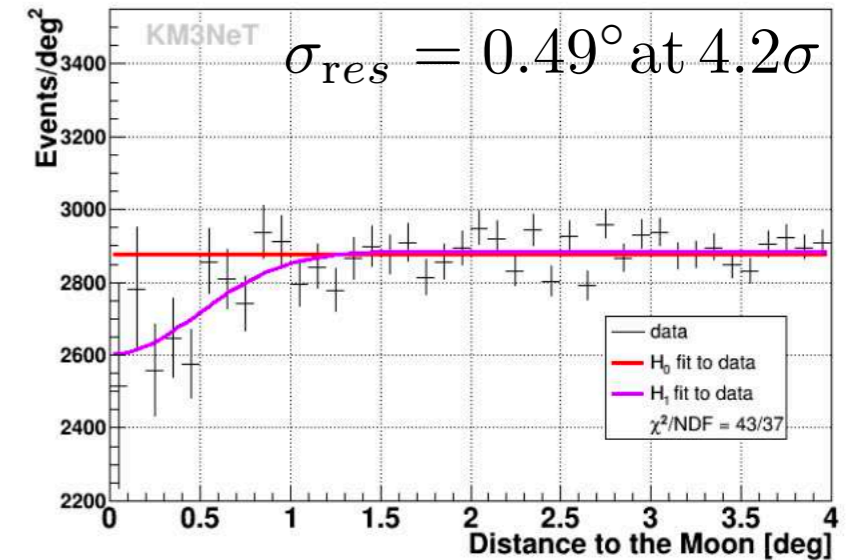
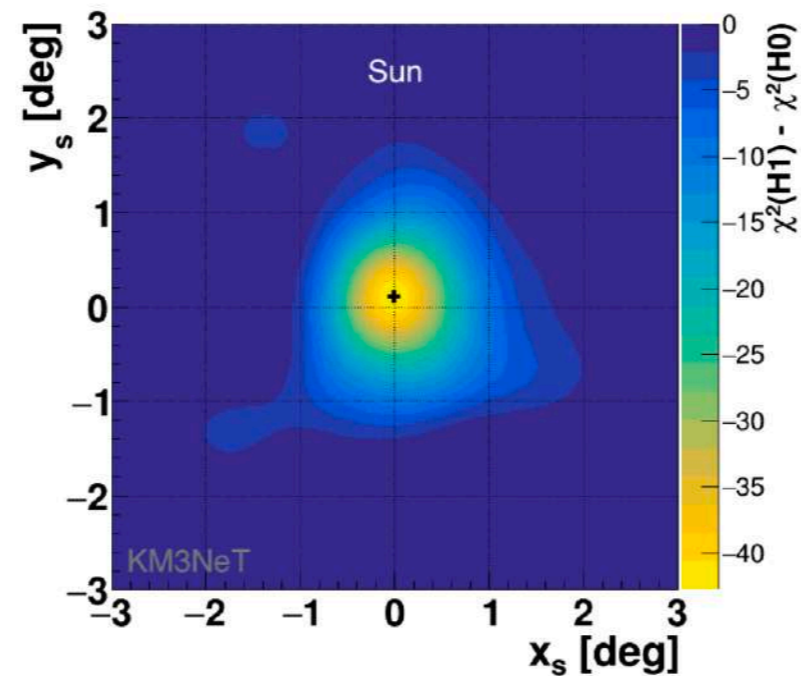
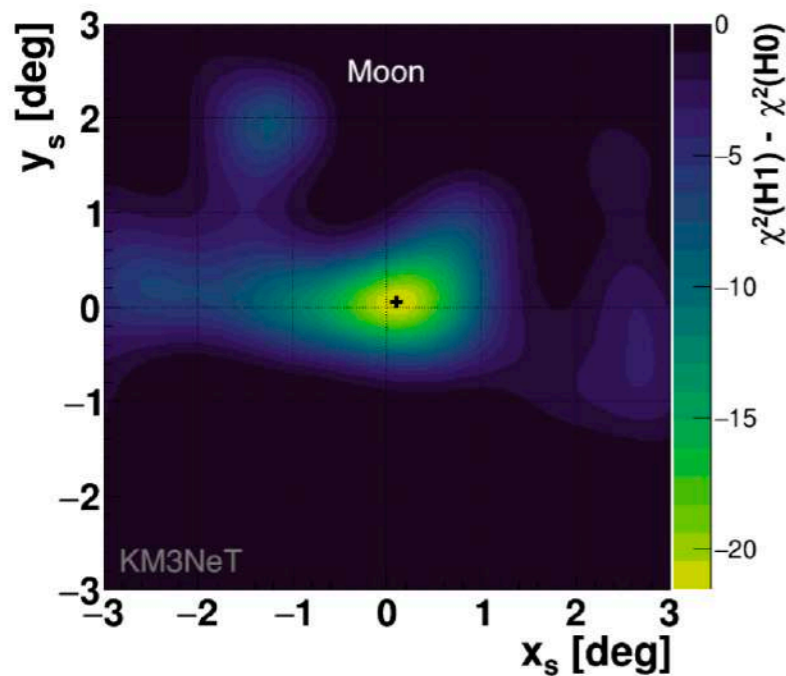
# MM analysis with GWs and ORCA



# Calibrations

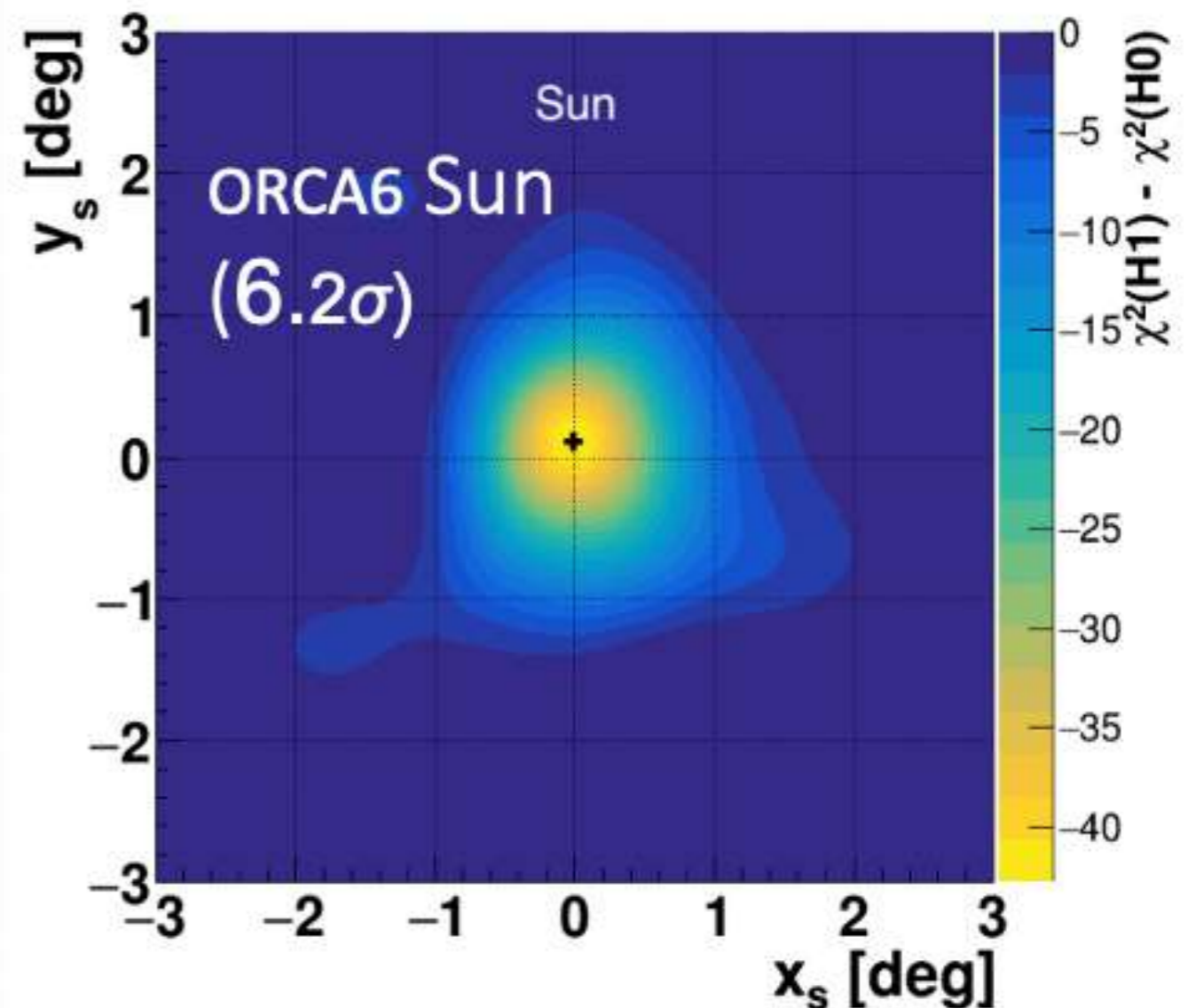
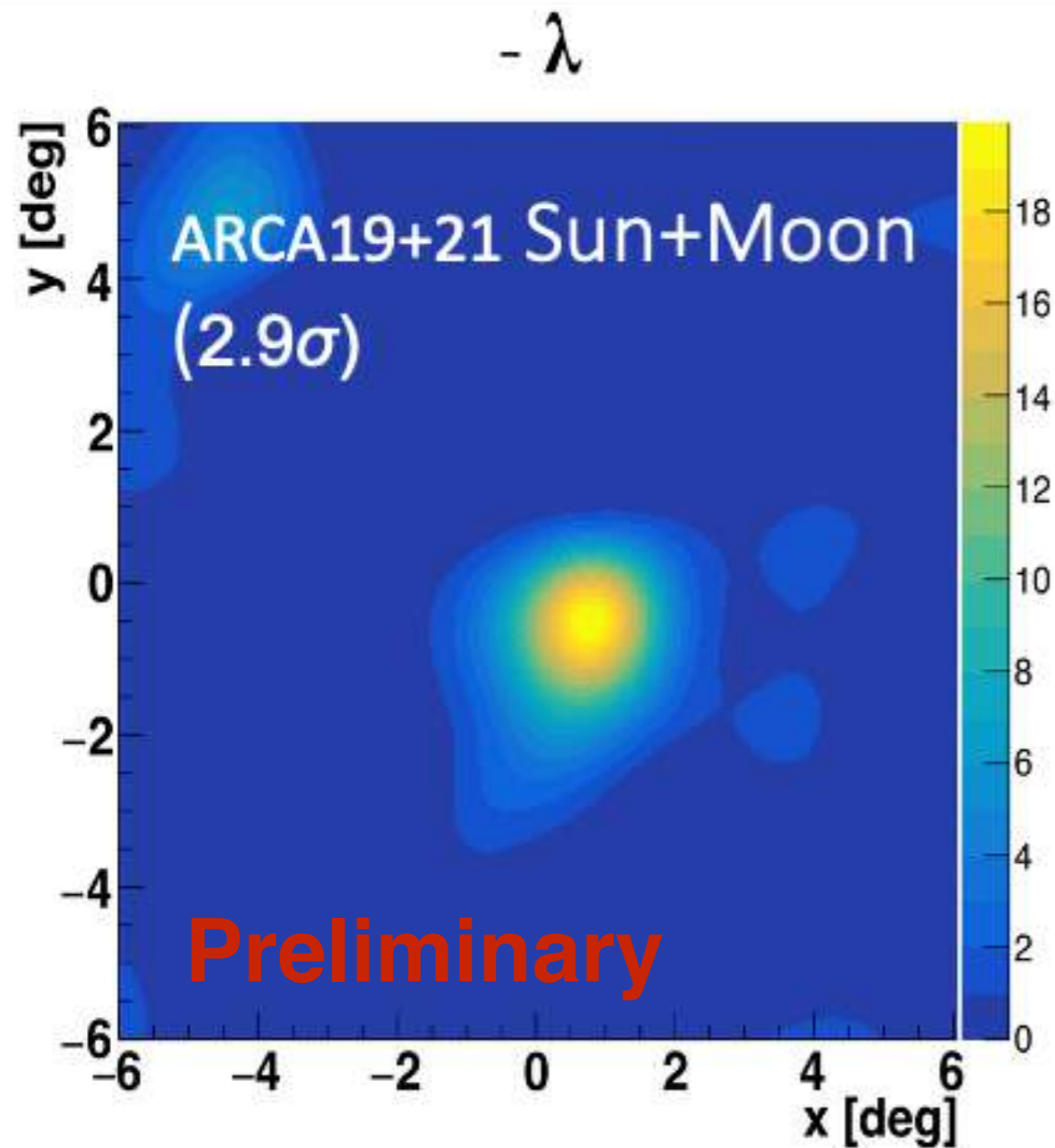
# ORCA Moon & Sun shadow analyses

- CR depletion from directions of astrophysical bodies
- Calibration tool for detector's pointing accuracy
- ORCA6 data set from 2020-2021 (499.3 days of livetime)

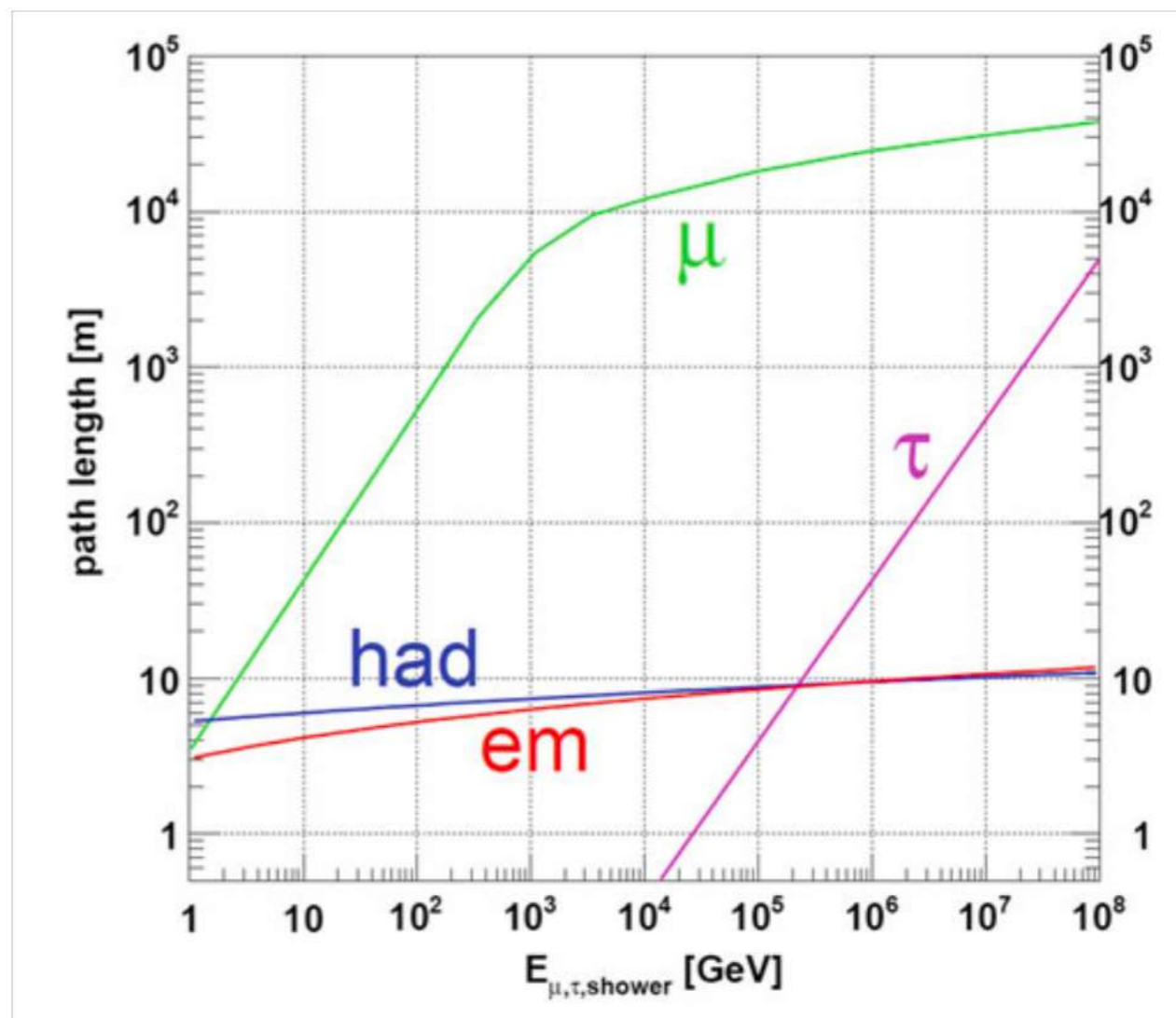
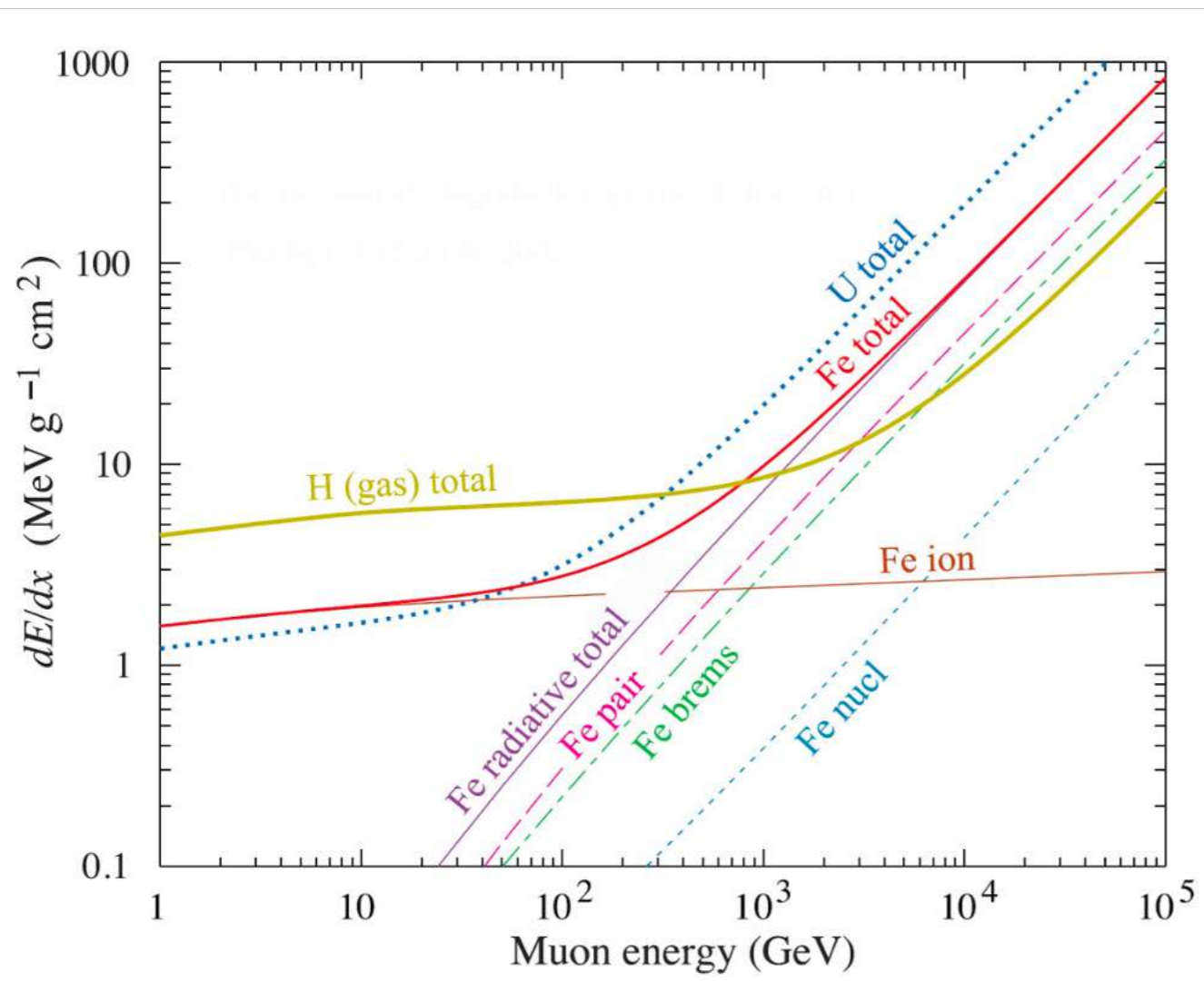


# KM3NeT pointing capabilities

- CR depletion from directions of astrophysical bodies
- Calibration tool for detector's pointing accuracy



# Muon energy losses



$$\frac{dE_\mu}{dX} = -\alpha - \beta E_\mu$$

$$\alpha \simeq 2 \text{ MeV g}^{-1} \text{ cm}^2$$

$$\beta = \beta_{\text{br}} + \beta_{\text{pair}} + \beta_{\text{ph}} \longrightarrow \beta \simeq 4 \times 10^{-6} \text{ g}^{-1} \text{ cm}^2$$

$$\langle E_\mu(X) \rangle = (E_\mu^0 + \epsilon_\mu) e^{-\beta X} - \epsilon_\mu$$

$$\epsilon_\mu = \alpha / \beta \simeq 500 \text{ GeV}$$

$$R(E_\mu^0) = \frac{1}{\beta} \ln\left(1 + \frac{E_\mu^0}{\epsilon_\mu}\right)$$

# Absorption and scattering: water vs ice

	acqua marina (Mar Mediterraneo) $\lambda = 473(375) \text{ nm}$	acqua (Lago di Baikal) $\lambda = 480 \text{ nm}$	ghiaccio (Polo Sud) $\lambda = 400 \text{ nm}$
$\lambda_a$	$60 \pm 10(26 \pm 3) \text{ m}$	$20 - 24 \text{ m}$	$110 \text{ m}$
$\lambda_s^{\text{eff}}$	$270 \pm 30(120 \pm 10) \text{ m}$	$200 - 400 \text{ m}$	$20 \text{ m}$

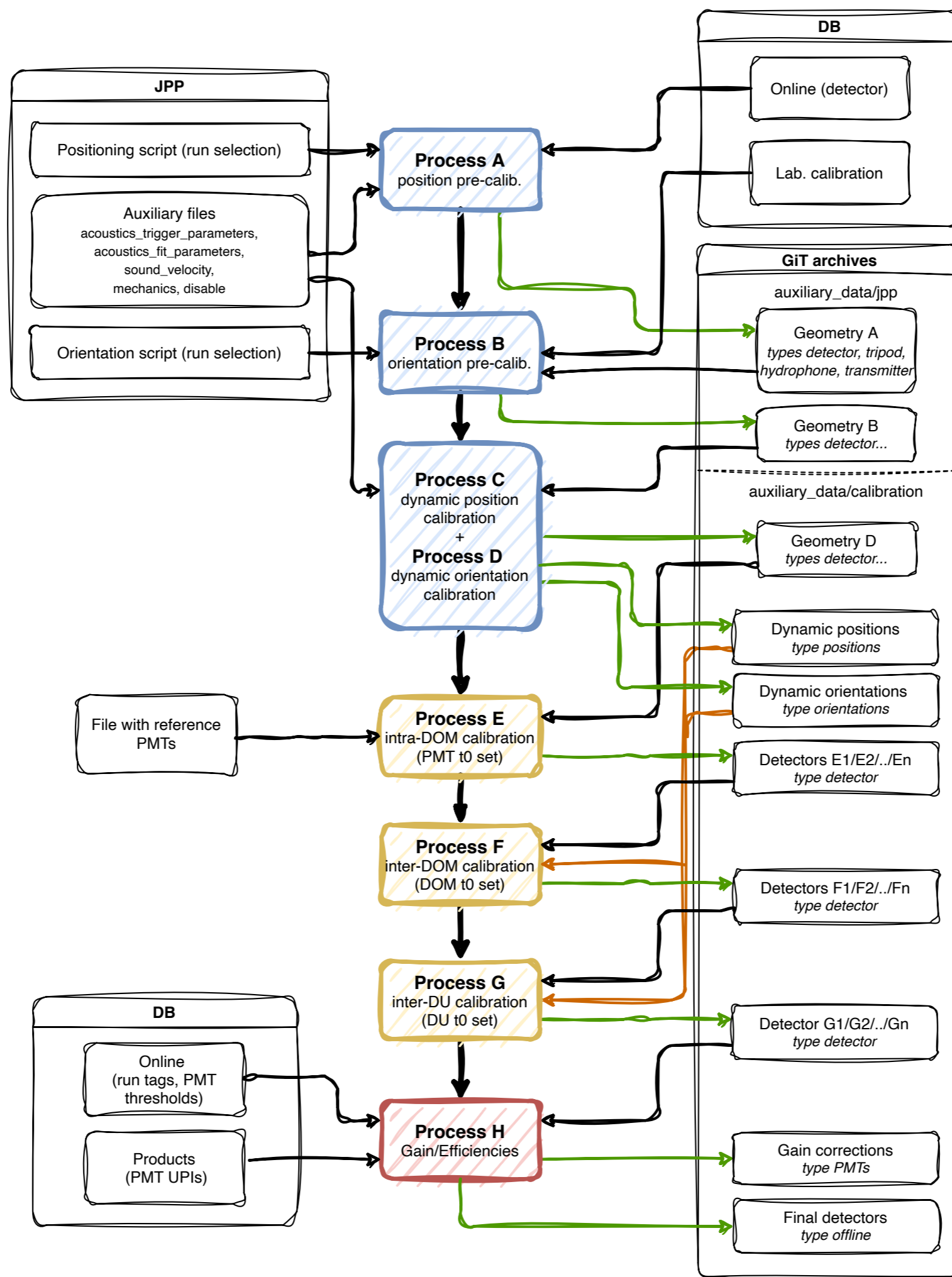
Tabella 3.2. Parametri della propagazione della luce in acqua e ghiaccio.



e



Gli elettroni prodotti nel primo processo, spesso, hanno energia sufficientemente elevata da indurre l'effetto Cherenkov, mentre nel processo di cattura dell'elettrone, il fotone nello stato finale viene prodotto con un'energia ( $E_\gamma = 1.46 \text{ MeV}$ ) che può facilmente portare alla produzione di elettroni con energie sopra la soglia di emissione di luce Cherenkov.



# Positioning calibrations

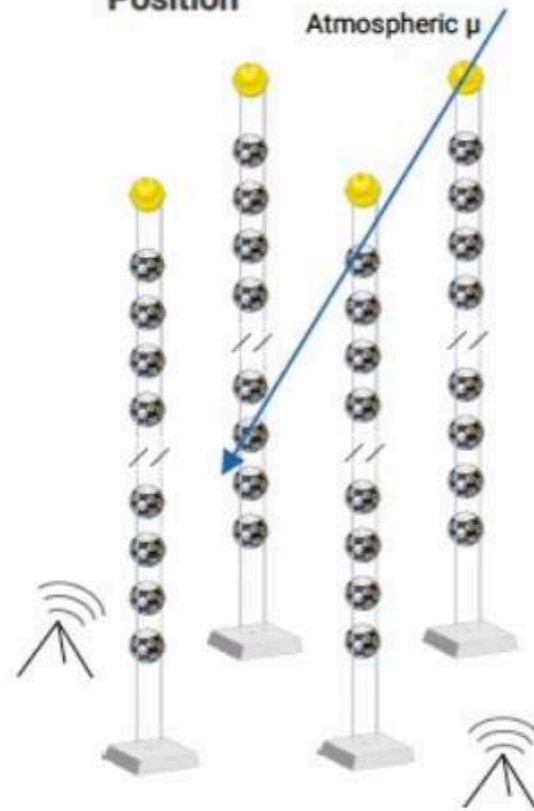
Lines move with the sea current. Needs dynamic position calibration

Orientation

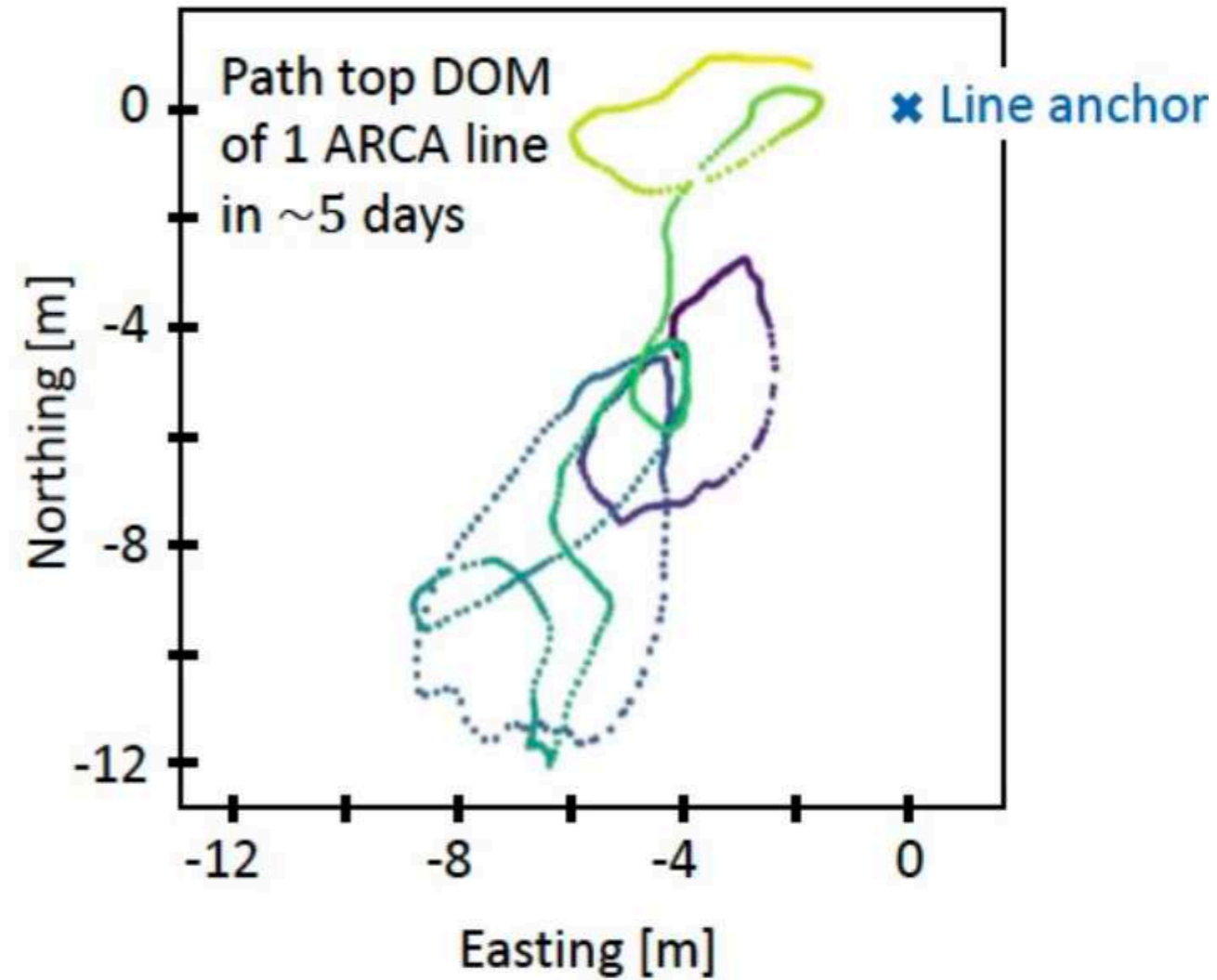


compass in DOMs

Position



acoustic emitters,  
hydrophones, piezo sensors

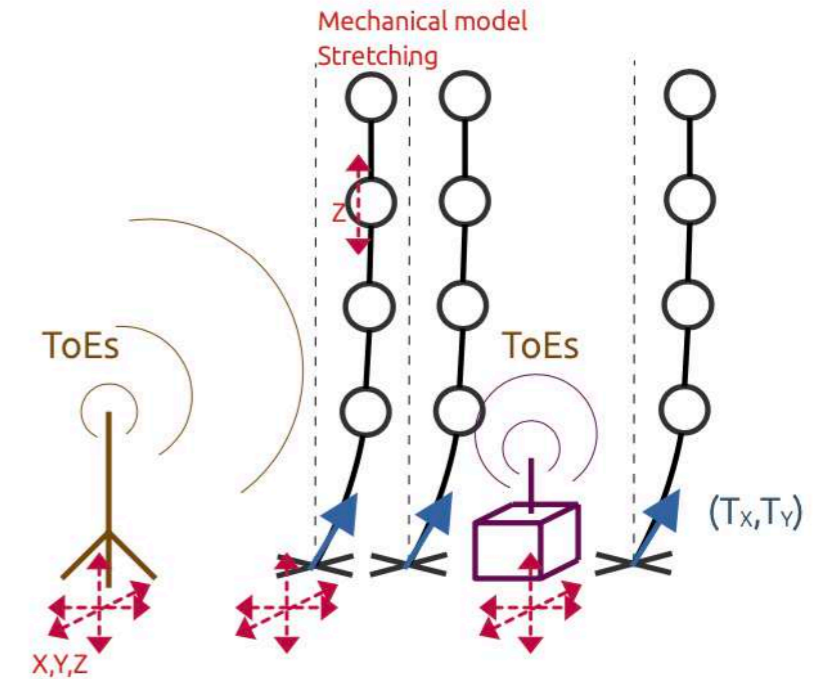


KM3NeT Coll., JINST 16 (2021) 09

# Positioning calibrations

## position $\longrightarrow$ acoustic data

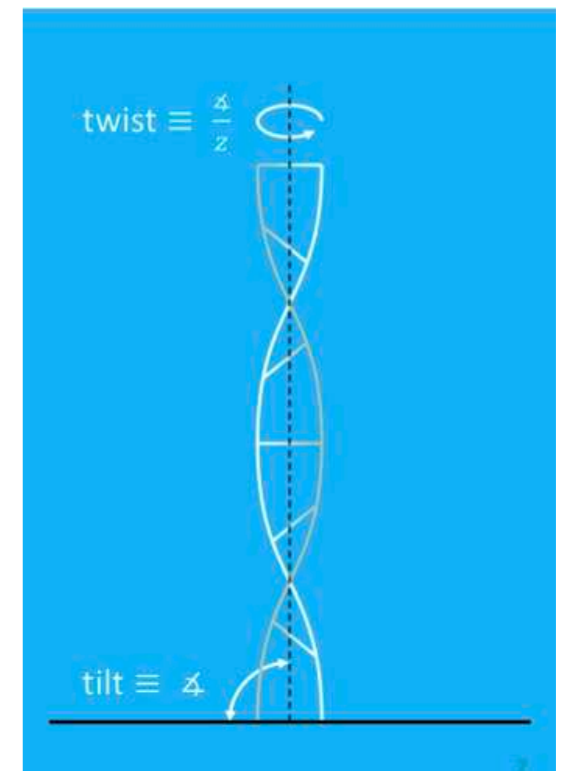
- emitters: autonomous beacons anchored to the seabed closely the detector
- receivers: hydrophones located at DU bases & piezo sensors glued in DOMs
- triangulation of acoustic signals to derive DOM positions, constrained by mechanical model of DUs



## orientation $\longrightarrow$ compass data

- attitude and heading reference system (AHRS), aka compass
- it is a set of accelerometers and magnetometers mounted on the electronics boards of each DOM

**Dynamic position and orientation systems updating every 10 minutes, with expected accuracies of  $< 20$  cm and a few degrees**

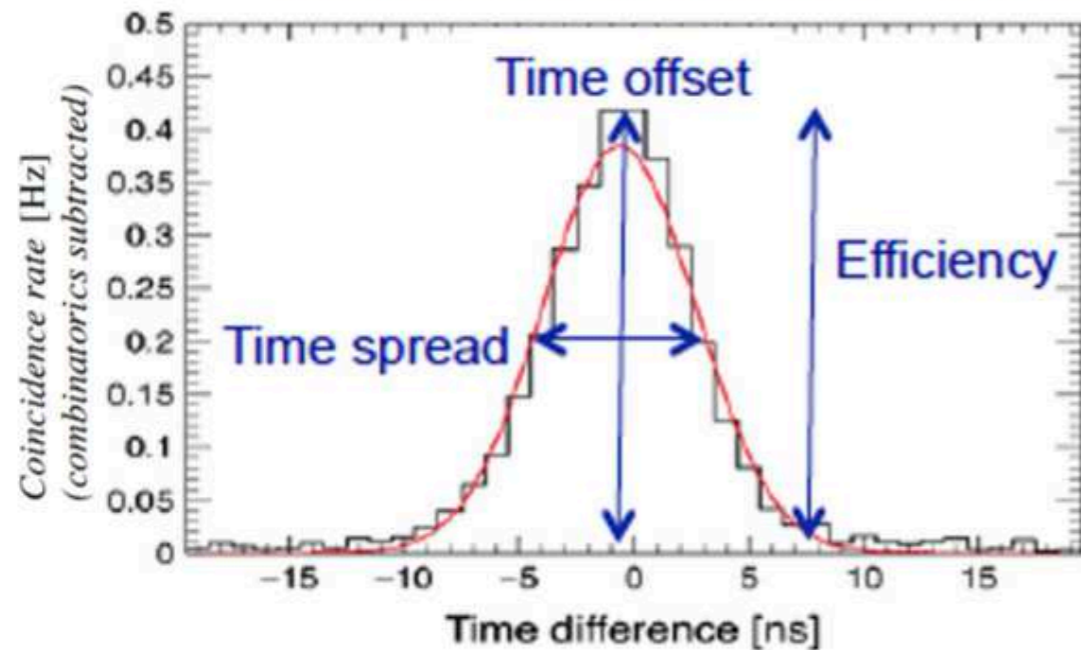


# Time calibrations

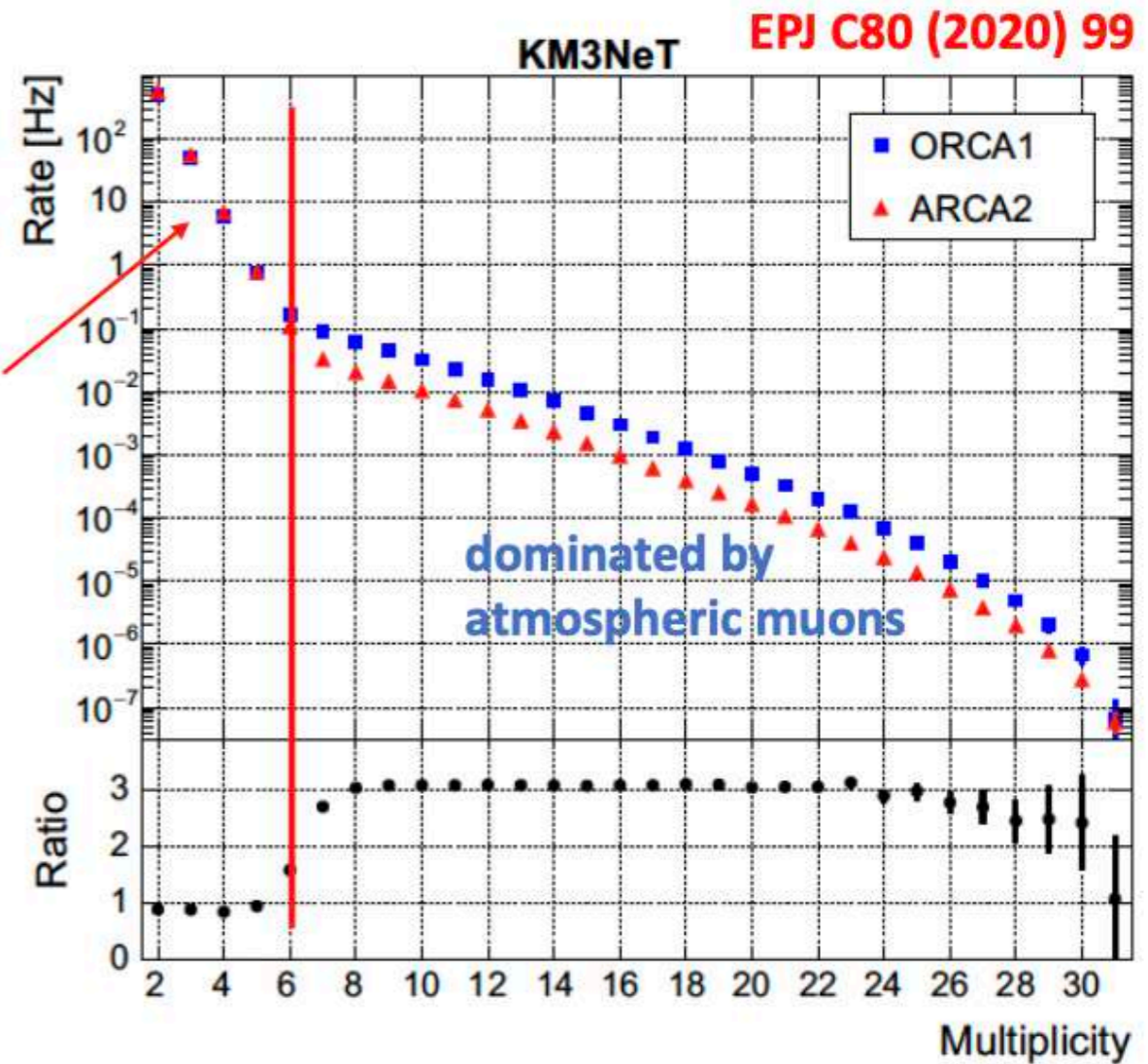


K40

information from PMT coincidences



dominated by  $^{40}\text{K}$



*Coincidence rate between PMTs on a DOM for one ORCA and one ARCA line, as a function of PMT multiplicity*

*Also: lab calibration of timing differences, LED flasher, timing from reconstructed tracks. Timing resolution better than 1 ns.*

# Time calibrations

## → optical data

- Intra DOM calibration (PMT t0 set)

**K40 fit to extract relative time shift between PMTs**

**T0 shift correction due to HV tuning (1-2 ns)**

**Requires a set of runs leading to the max # of active PMTs**

- Inter DOM calibration (DOM t0 set)

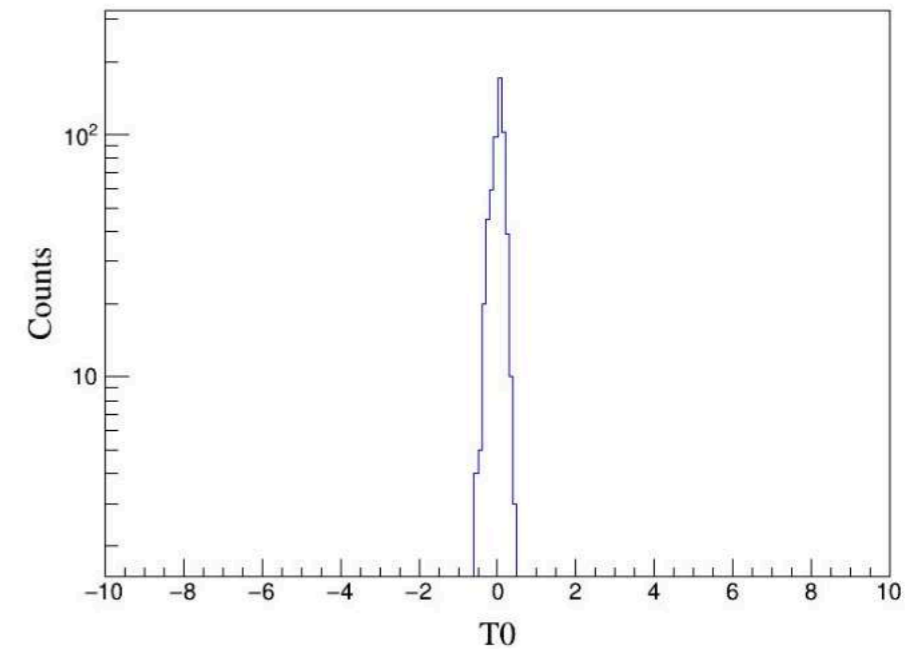
**Currently only performed in dark room before deployment**

**For the future, nanobeacon runs might be used for in-sea interDOM calibrations**

- Inter DU calibration (DU t0 set)

**Atmospheric muons used as the maximum likelihood in reconstruction algorithms is achieved for a detector as close as possible to reality**

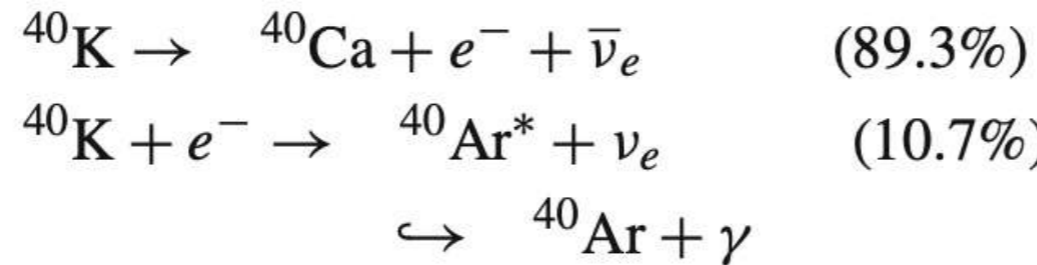
+ **master clock system** (onshore), providing common reference to all offshore electronics, via a network of optical fibers



# PMT efficiency calibrations

## → optical data

- Coincidence signals on adjacent PMTs is dominated by K40 decay



- Distribution of coincident hits is fitted:

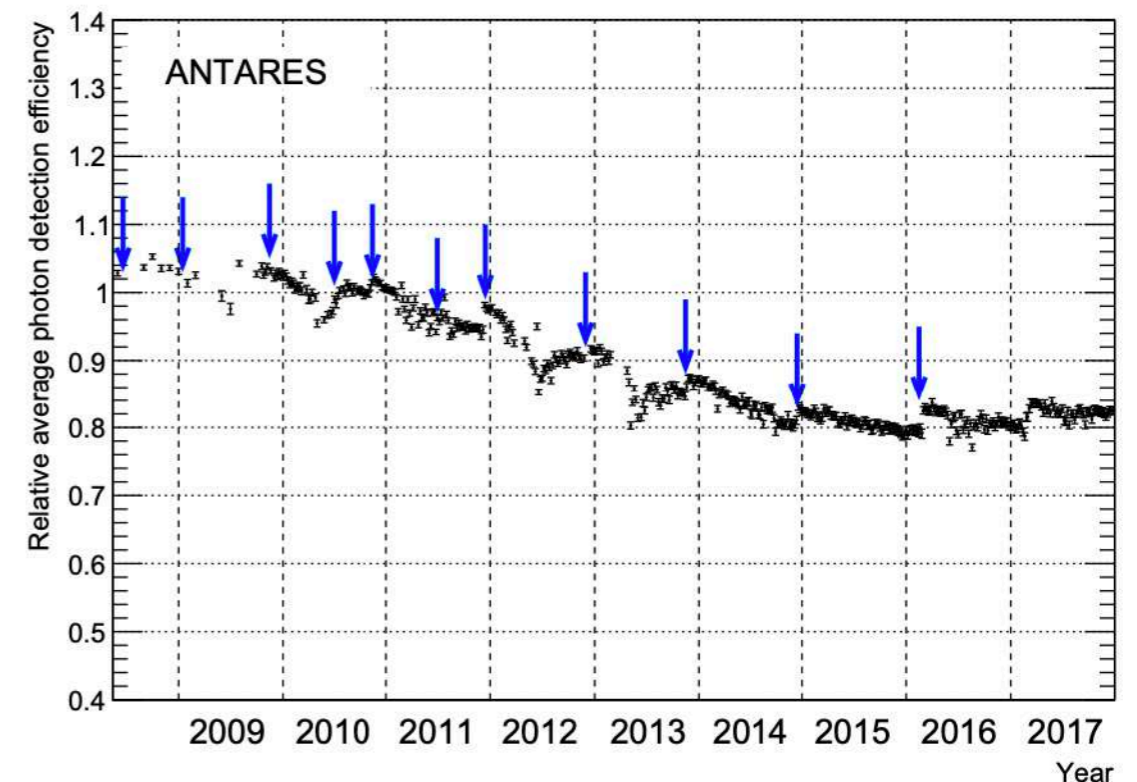
$$f(t) = p + a \cdot \exp\left(-\frac{(t - t_0)^2}{2\sigma^2}\right)$$

$$R = \frac{a \cdot \sigma \cdot \sqrt{2\pi}}{\Delta\tau} \longrightarrow \epsilon_i = \sqrt{\frac{1}{R_c^*} \frac{R_{ij} \cdot R_{ki}}{R_{jk}}}$$

- Measurements:

Gain, Gain spread, Efficiency

- Channels with bad response are masked (sedimentation, biofouling and exchange of deep sea water might affect efficiencies)



A. Albert et al. [ANTARES Coll.], EPJC 78 (2018) 699