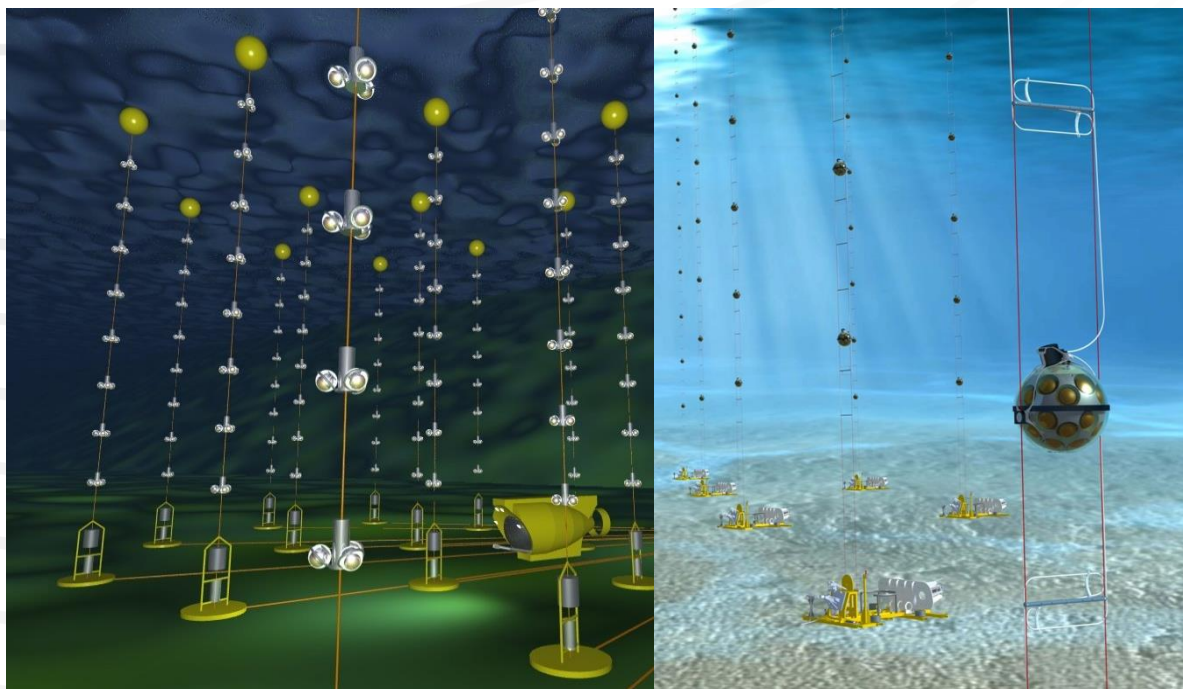




ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025



Combined KM3NeT/ARCA and ANTARES search for point-like neutrino emission



Barbara Caiffi

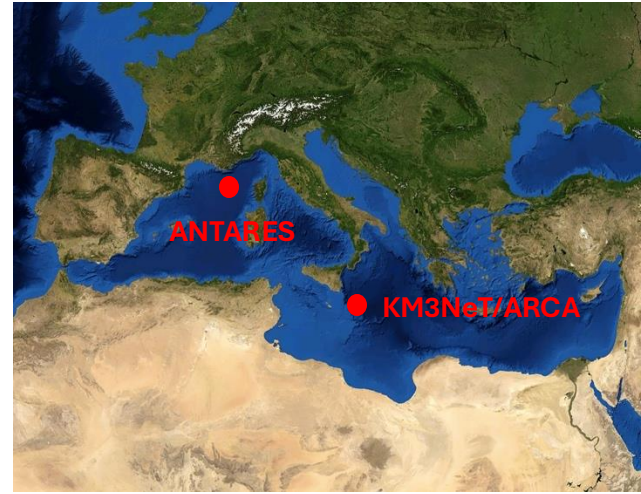
V. Kulikovskiy, S. Alves, J. Aublin, A. Heijboer, G. Illuminati, R. Muller, V. Parisi, M. Sanguineti, S. Zavatarelli

on behalf of the ANTARES and the KM3NeT collaborations

Outlook

- *ANTARES and KM3NeT/ARCA neutrino telescopes*
 - *Datasets and methods*
 - *Sensitivity and Discovery potential*
 - *Candidate search results*
 - *Conclusions and perspective*

Detectors: ANTARES and KM3NeT/ARCA



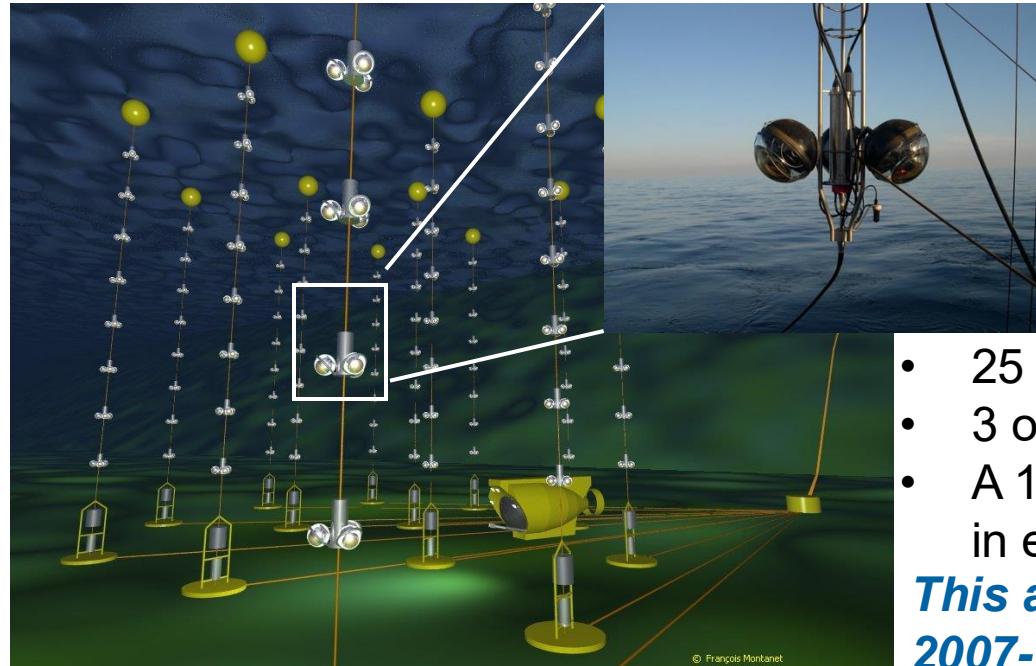
ANTARES

Operated for more than 15 years off the coast of Toulon (France), from 2007 to 2022. It consisted of 12 detection lines with:

- 25 storeys on each line
- 3 optical modules on each storey
- A 10" PhotoMultiplier Tube (PMT) in each optical module

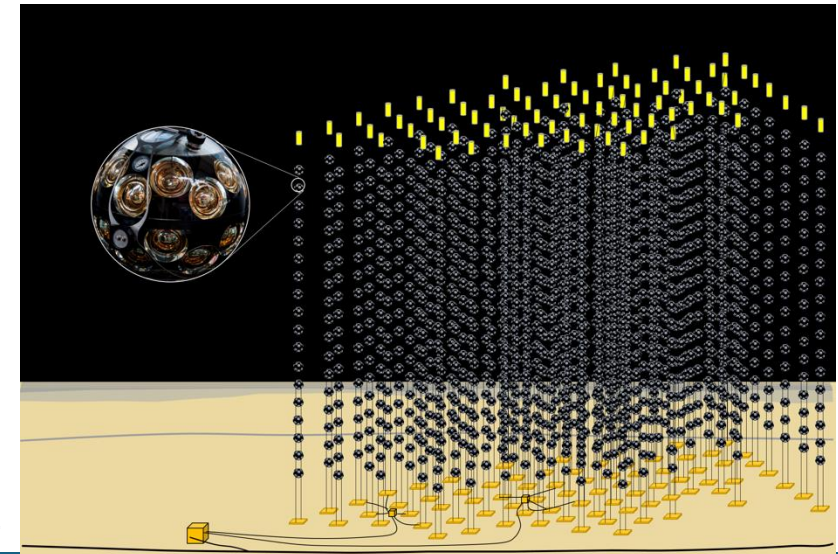
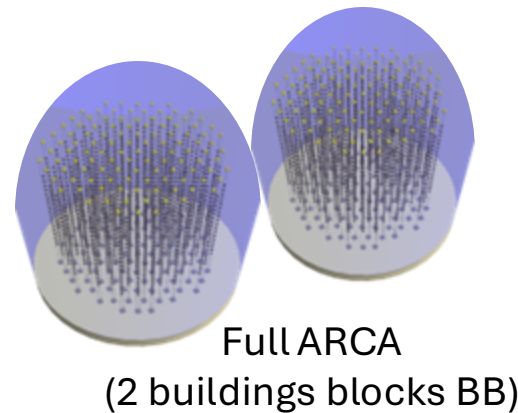
This analysis exploits the full 2007-2022 data (4541 days)

	ANTARES	ARCA
Effective Mass	10 Mt	1 Gt
Line length	350 m	650 m
Interline distance	70 m	90 m
Vertical spacing	14.5 m	36 m



KM3NeT/ARCA

- ARCA (Astroparticle Research with Cosmics in the Abyss) is a neutrino telescope under construction south of Sicily (Capo Passero)
- 2 Building Blocks (BB), each BB comprising 115 lines, 18 DOMs per line and 31 PMTs per DOM
- It is currently composed by 51 lines out of the 115 of the first complete BB



This analysis exploits ARCA6-21 configurations (640 days)

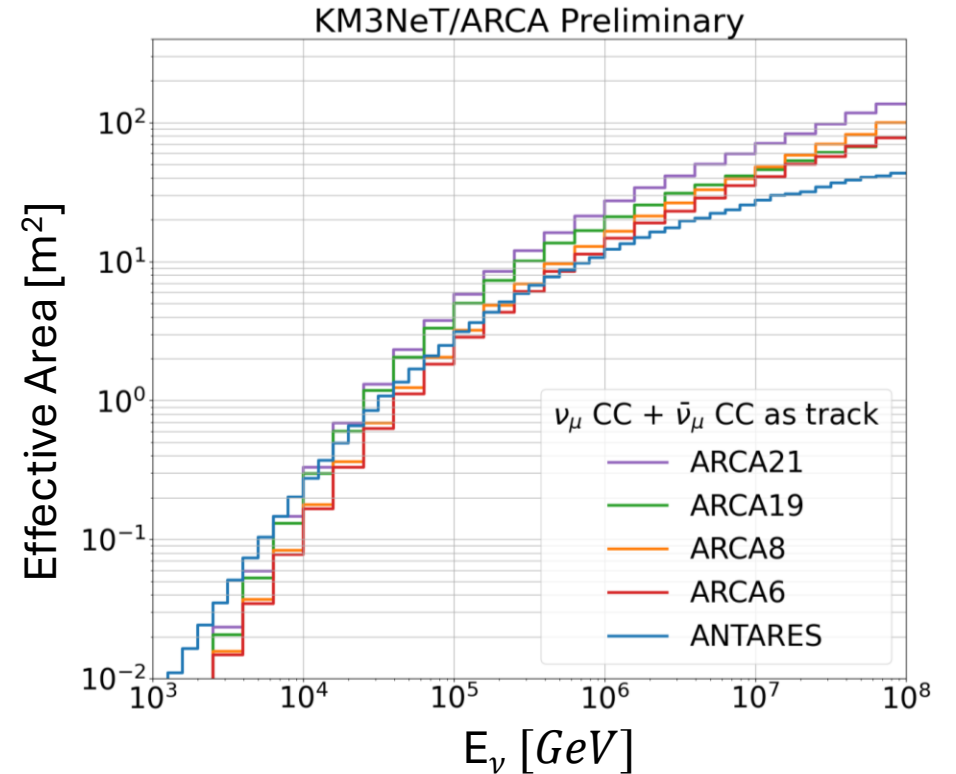
Combined point-like search

Why perform combined analysis?

- The data from about 2 year of ARCA6/8/19/21 is used in this analysis (640 days). Similar detector volume to that of ANTARES
- KM3NeT/ARCA has 33 lines deployed and the detector will continue to grow.
- In the next few years, KM3NeT/ARCA statistics will reach the ANTARES one and exceed it.

⇒ **Covenient timing to use combined searches.**

DATASET	LIVETIME [days]
ANTARES (tracks+showers) ^{[1][2]}	4541
KM3NET/ARCA 6 (only tracks) ^{[3][4]}	92.0
KM3NET/ARCA 8 (only tracks) ^{[3][4]}	212.3
KM3NET/ARCA 19 (only tracks) ^{[3][4]}	48.4
KM3NET/ARCA 21 (only tracks) ^{[3][4]}	287.4

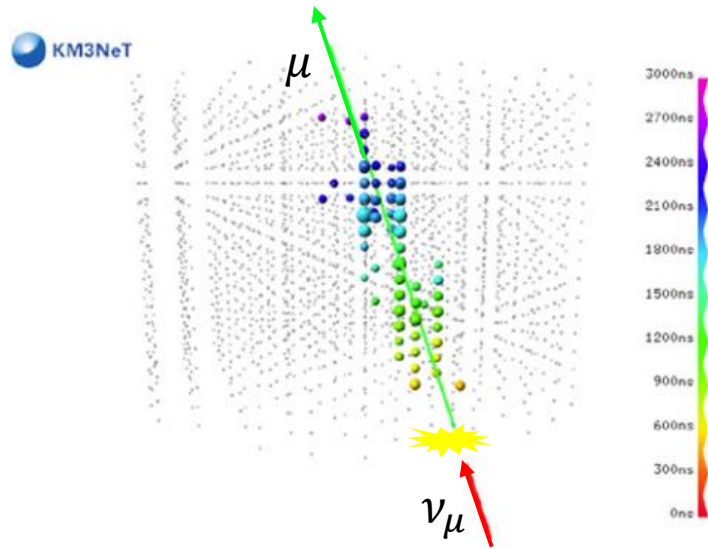


Data set: detector period with a dedicated event selection (track/showers etc).
Data sets do not overlap (no common events).

[1] ANTARES collaboration, "The ANTARES detector: Two decades of neutrino searches in the Mediterranean Sea" Physics Reports (2025)
 [2] F. Salesa « Searches for point-like and extended sources of cosmic neutrinos with the complete ANTARES dataset» Poster @ ICRC 2025
 [3] R. Muller «Time-integrated search for astrophysical neutrino emission with 2 years of KM3NeT/ARCA data», Poster @ Neutrino 2024
 [4] V. Parisi «Search for cosmic neutrino point sources and extended sources with 6-21 lines of KM3NeT/ARCA», Talk @ ICRC 2025

Event types

- **Track:** high energy μ travelling straight and far through water (mainly ν_{μ}^{CC} interactions);



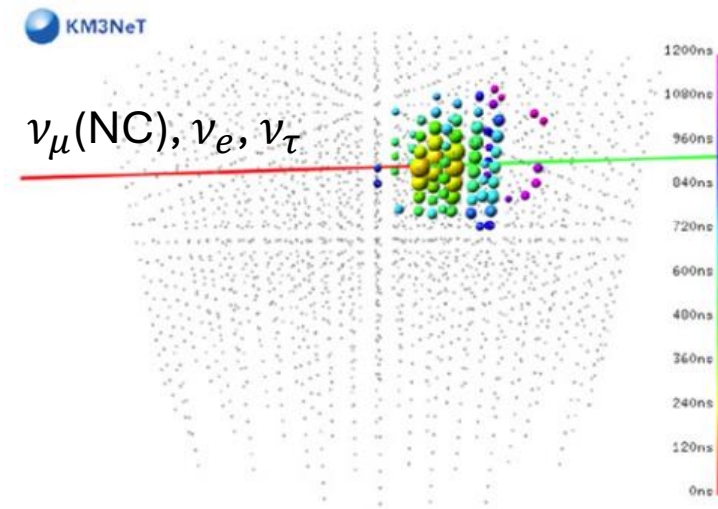
Angular resolution:

- ANTARES: $<0.4^{\circ}$ ($E > 10$ TeV)
- ARCA230: $<0.1^{\circ}$ ($E > 10$ TeV)

Energy resolution:

- ANTARES: <0.5 ($\log E_{\mu}$)
- ARCA230: $<27\%$ (E_{μ})

- **Shower:** electromagnetic/hadronic cascade (ν_e^{CC} and NC interactions).



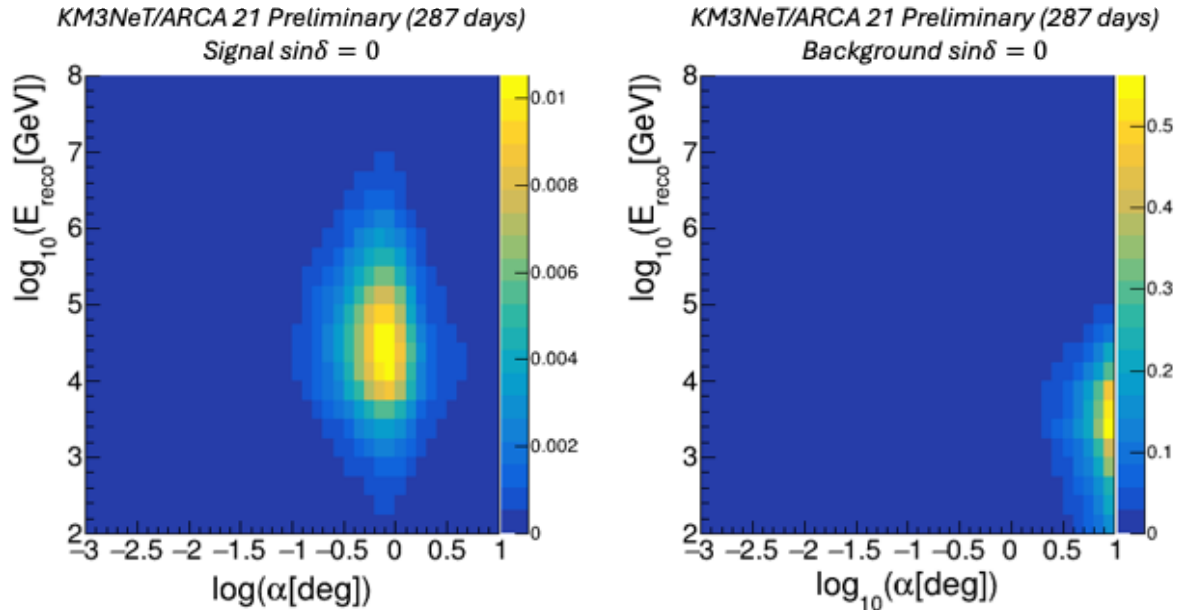
Angular resolution:

- ANTARES: $\sim 3^{\circ}$ ($E > 10$ TeV)
- ARCA(230): $\sim 2^{\circ}$ ($E > 10$ TeV)

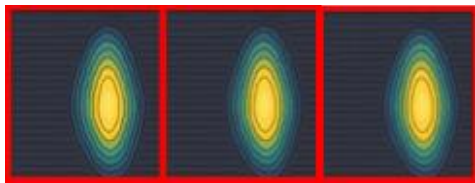
Energy resolution (E ν):

- ANTARES: $\sim 25\%$
- ARCA(230): $<5\%$

Binned likelihood framework

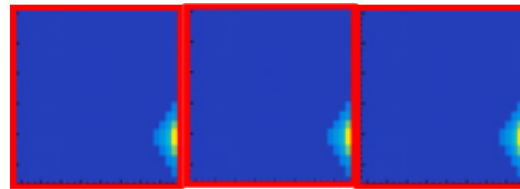


Combined signal histogram



$\times N_{\text{datasets}}$

Combined background histogram



$\times N_{\text{datasets}}$

The compatibility of the data with a point source hypothesis is quantified by filling a histograms of:

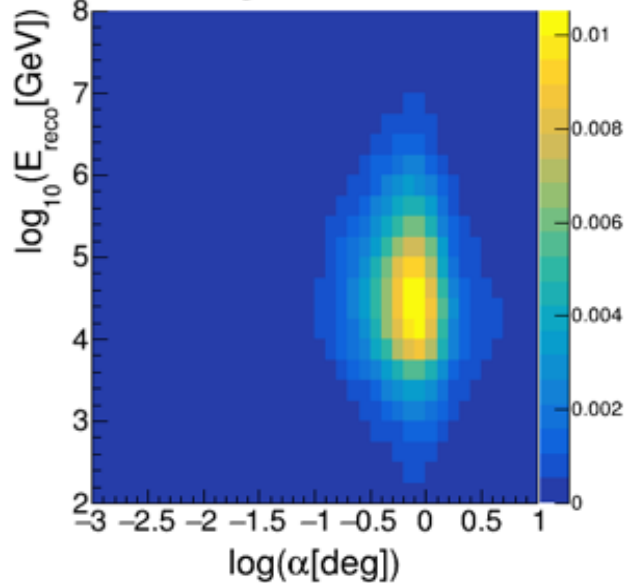
- $\log \alpha$: angular distance of the reconstructed events from the source centre
- $\log (E)$: event energy estimation
- $\log (\beta)$: angular error estimate (only for ANTARES-track dataset)

The combined signal and background histograms are constructed by concatenating the histograms of each dataset, each with its own custom N_{bins} .

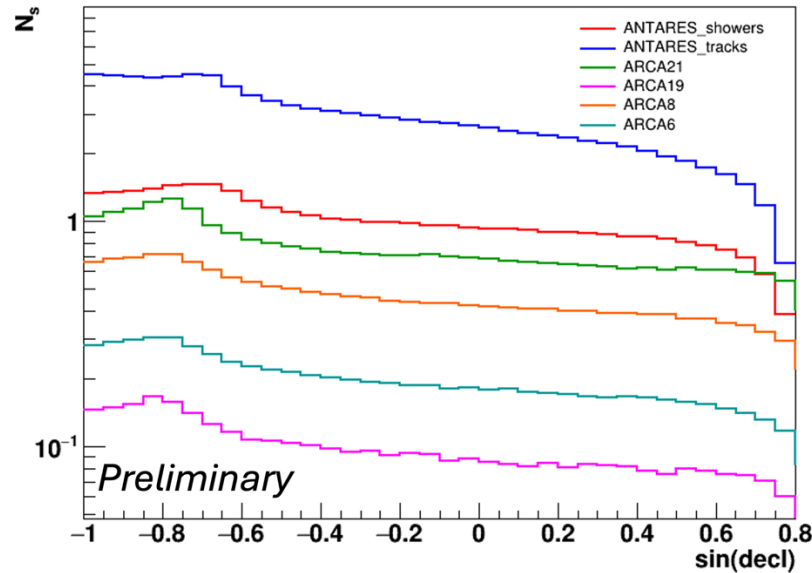
$$N_{\text{bins}} = \sum_i^{\text{dataset}} N_{\text{bins}}(i)$$

Binned likelihood ingredients: signal

KM3NeT/ARCA 21 Preliminary (287 days)
Signal $\sin\delta = 0$



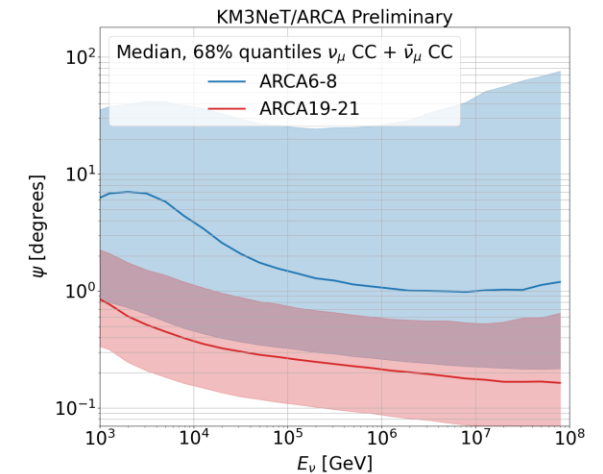
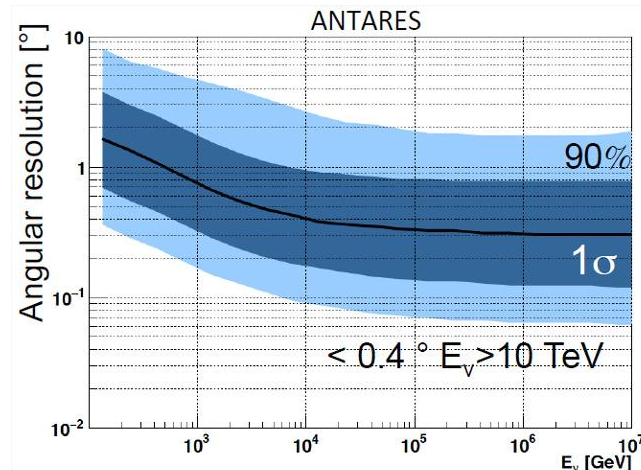
N_s for $\Phi = 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$



- $h_{\text{sig}}(\log\alpha, \log E)$ (or $h_{\text{sig}}(\log\alpha, \log E, \log\beta)$ for ANTARES tracks) collected in 0.2 bands in $\sin\delta$ from MC simulations, assuming $\phi(E) = 10^{-8} E^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1}$
- Signal expectation vs $\sin\delta$ with finer binning provide more accurate N_{sig} estimate at a given declination

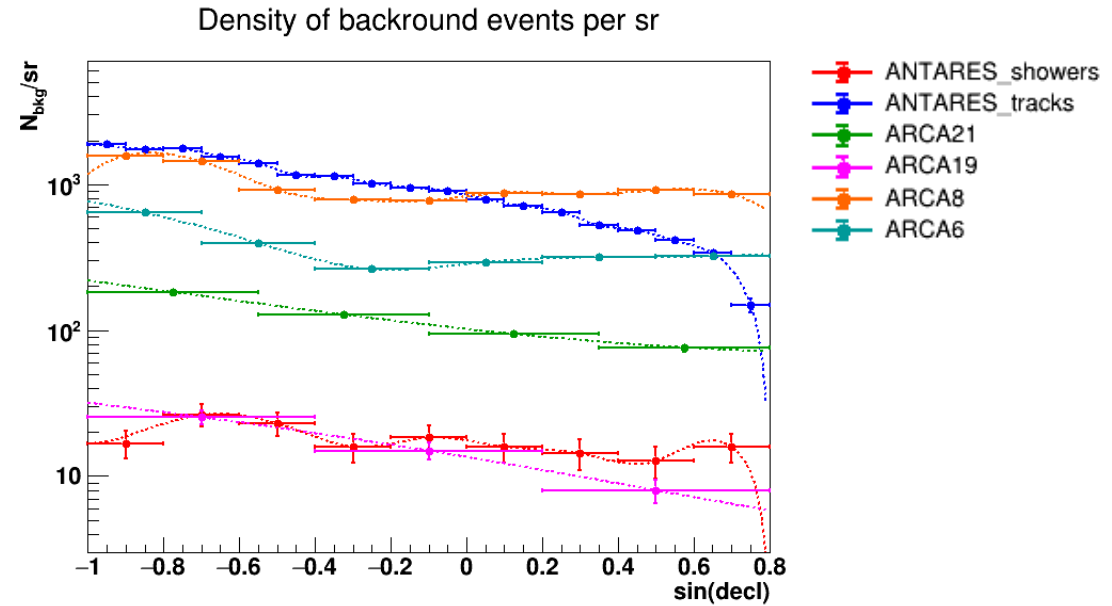
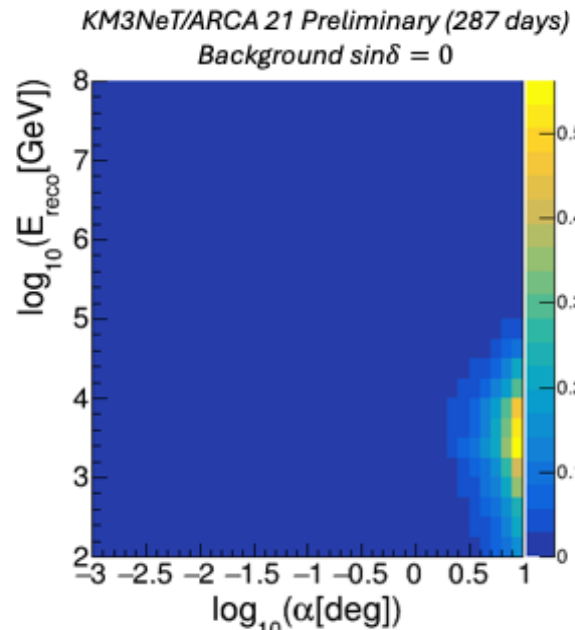
Median angular uncertainty above 100 TeV:

- < 2° ARCA6-8
- < 0.3° for ARCA19-21
- < 0.3° for ANTARES
- < 0.1° expected for the full detector (ARCA230^[*])



* KM3NeT Collaboration: "Astronomy potential of KM3NeT/ARCA." *The European Physical Journal C* 84.9 (2024): 885.

Binned likelihood ingredients: background



- $h_{bg}(\log\alpha, \log E)$ (or $h_{bg}(\log\alpha, \log E, \log\beta)$ for ANTARES tracks) collected in $\sin\delta$ bands from data, whose width depends on the available statistics (~ 500 events in each histogram)
- For candidate search, the declination bands are centred around the source position
- Background events vs $\sin\delta$ splines are produced from data and used to rescale h_{bg} to obtain a more accurate N_{bg} estimate at a given declination

DATASET	N° events	Sin δ band width
ANTARES (tracks)	11029	0.2
ANTARES (showers)	200	2
KM3NET/ARCA 6 (tracks)	4205	0.6
KM3NET/ARCA 8 (tracks)	11537	0.9
KM3NET/ARCA 19 (tracks)	182	2
KM3NET/ARCA 21 (tracks)	1361	0.9

Binned likelihood framework

Likelihood function

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

$\hat{\zeta}$: signal strength which parametrizes the flux intensity, was determined by maximizing $\log L$

Test statistics:

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

For each data set, we computed for each bin:

- Background expectation B_i (**data driven/MC**)
- Signal expectation S_i from a reference flux(**MC**)
- Number of events of data in: N_i

For a true value of the signal strength μ_{true} , pseudo- experiments can be generated by randomly drawing each N_i from a Poisson distribution with mean $B_i + \zeta_{true} S_i$.

The λ distributions are used to extract Neyman upper limits and p-values.

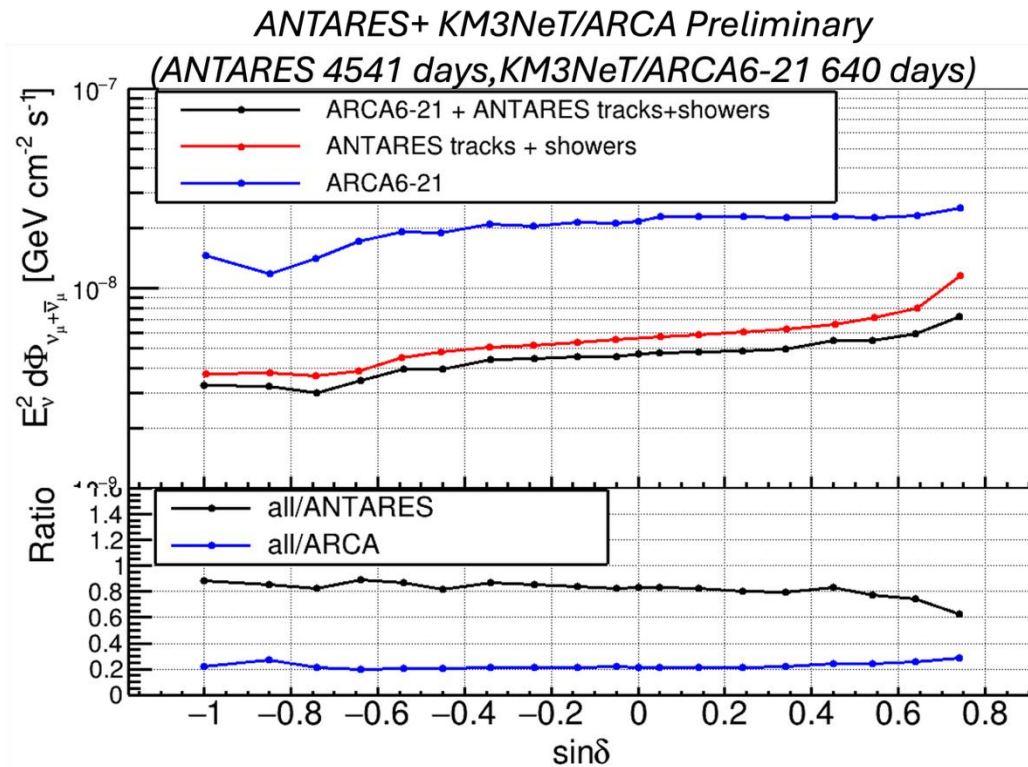
Sensitivity

$$\Phi_{90} = \zeta_{90} \Phi_0$$

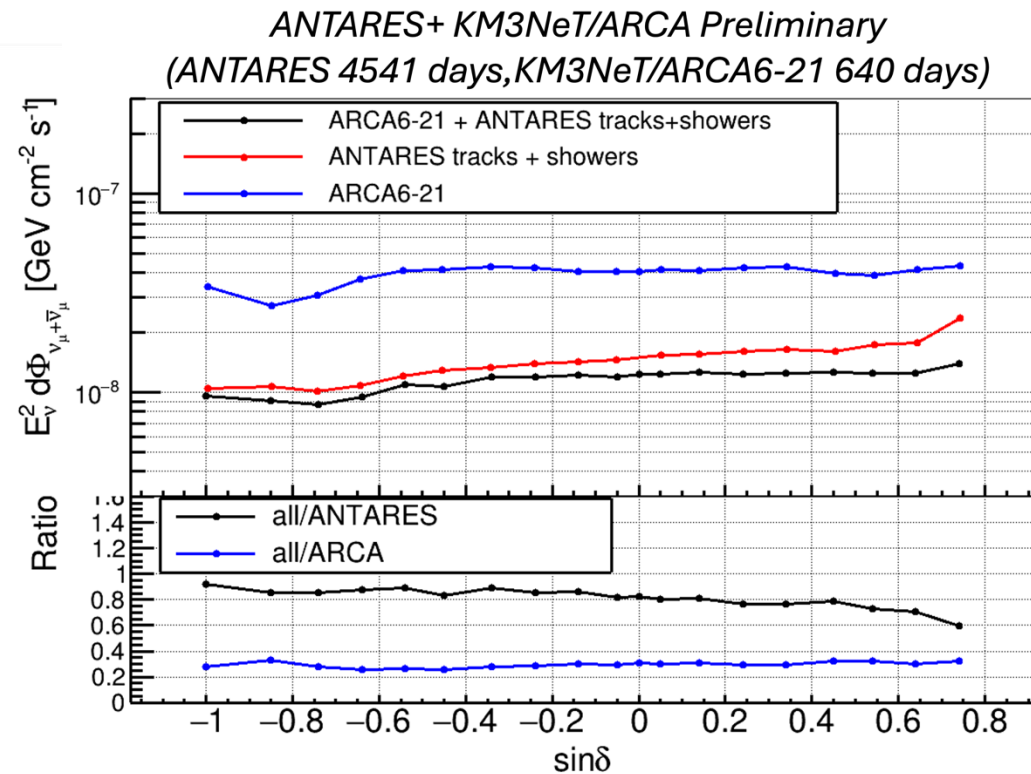
Discovery $\Phi_{5\sigma} = \zeta_{5\sigma} \Phi_0$

Combined sensitivity and discovery potential

Sensitivity 90% C.L.



Discovery 5 σ

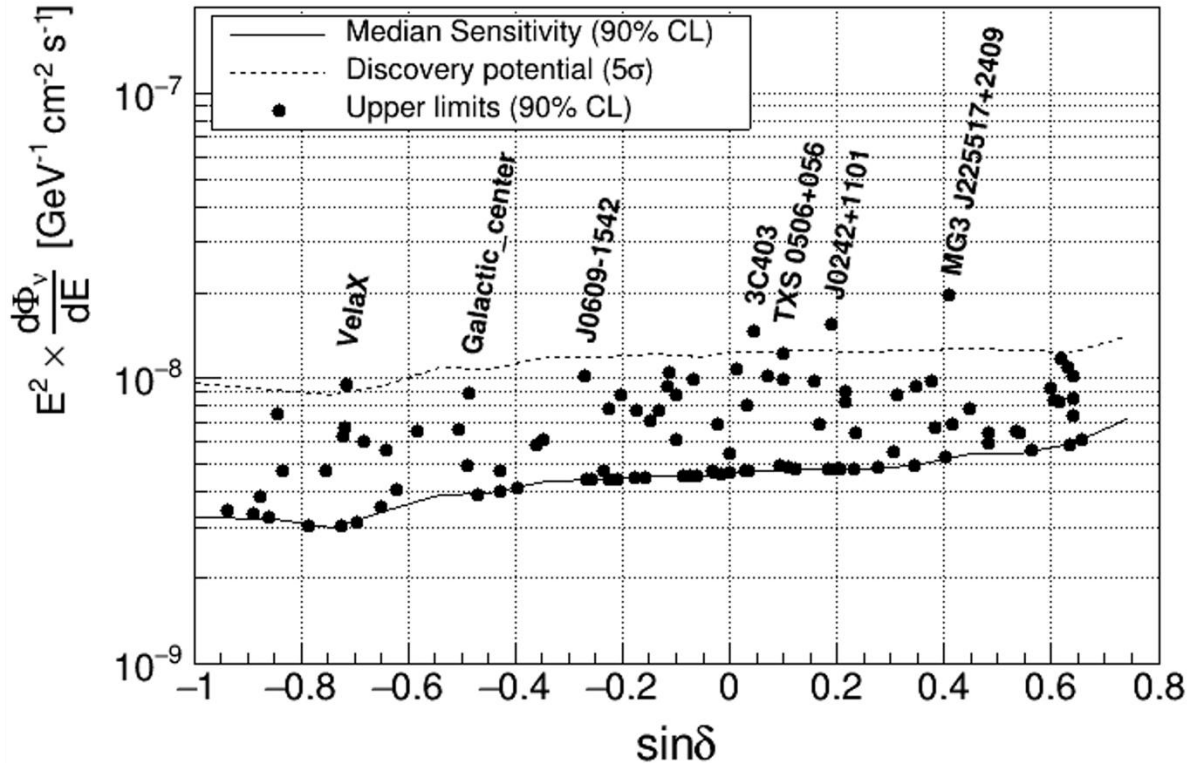


- ~20% improvement in sensitivity and discovery by adding the ARCA6-21 datasets to the ANTARES sample
- consistent with expectations based on the livetime of the two detectors (ANTARES: 4541 days, ARCA6-21: 640 days).

Results of candidate list search

ANTARES+ KM3NeT/ARCA Preliminary

(ANTARES 4541 days, KM3NeT/ARCA 6-21 640 days)



- 106 targeted sources, 87 point-like and 19 with extended Gaussian morphology

• Most significant source:

MG3 J225517+2409, γ ray blazar

➤ p-value(pre-trial)= $4 \cdot 10^{-5}$

➤ σ (pre-trial) = 3.94 (post-trial under evaluation)

Lowest p-value candidate in the standalone ANTARES analysis^[1]

➤ p-value (pre trial)= $2.4 \cdot 10^{-4}$, σ (pre trial)=3.5

$\phi_{90\%C.L.}$ (ANTARES)= $2.28 \cdot 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$

$\phi_{90\%C.L.}$ (ANTARES+KM3NET/ARCA)= $1.96 \cdot 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$

Most promising candidate in the ANTARES search with Fermi 3LAC catalogue with 1255 out of 1420 objects, in the field of view of ANTARES ^[2]

• Other significant candidates:

➤ **J0242+1101** (blazar), 3.12σ pre-trial

➤ **3C403** (radio-galaxy), 3.02σ pre-trial

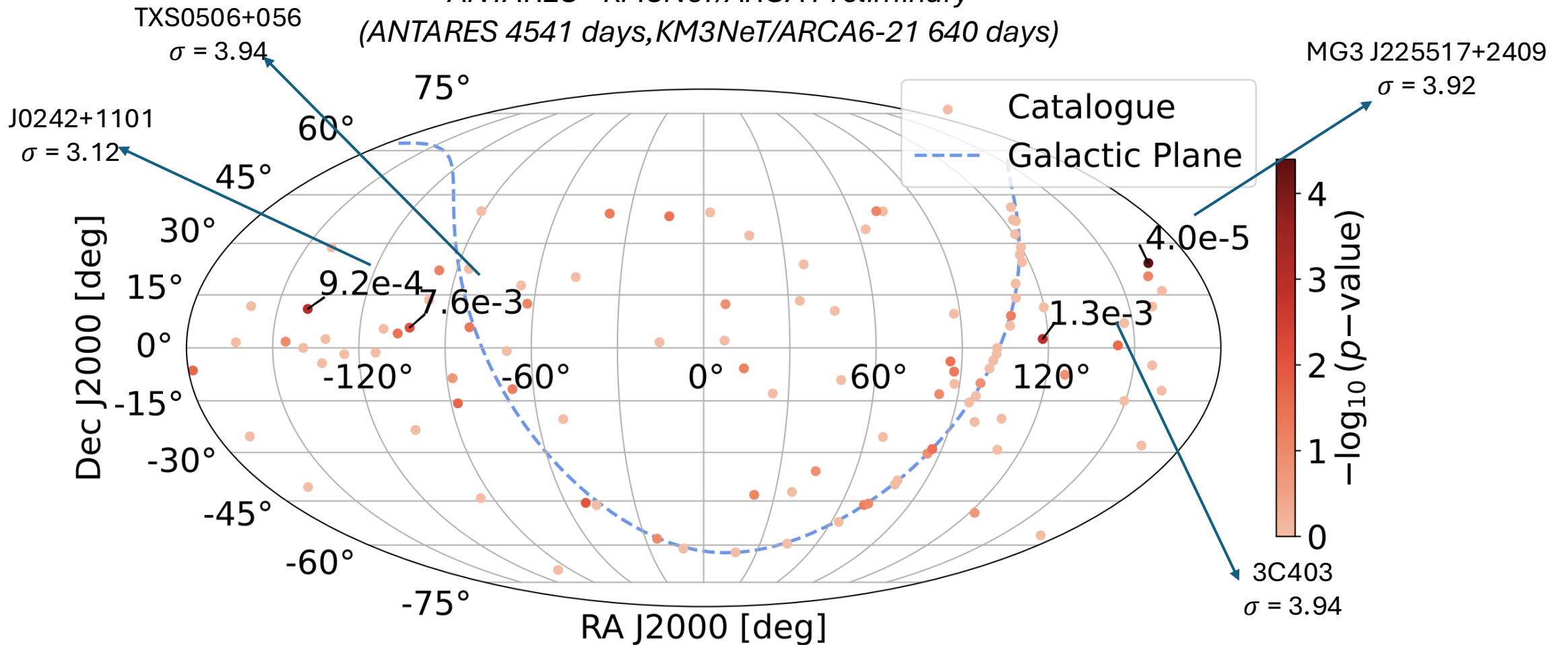
➤ **TXS0506+056** (blazar BL-LAC, IceCube-170922A), 2.43σ pre-trial

[1] ANTARES collaboration, "The ANTARES detector: Two decades of neutrino searches in the Mediterranean Sea» Physics Reports (2025)

[2] ANTARES collaboration «ANTARES Search for Point Sources of Neutrinos Using Astrophysical Catalogs: A Likelihood Analysis», 2021 *ApJ* **911** 48

Candidate skymap

ANTARES+ KM3NeT/ARCA Preliminary
(ANTARES 4541 days, KM3NeT/ARCA 6-21 640 days)



Skymap of the candidates, with $\log_{10}(p\text{-value})$ indicated by color. For sources with $\log_{10}(p\text{-value}) < -2$, the exact p -value is also displayed next to the source.

Best candidate skymaps

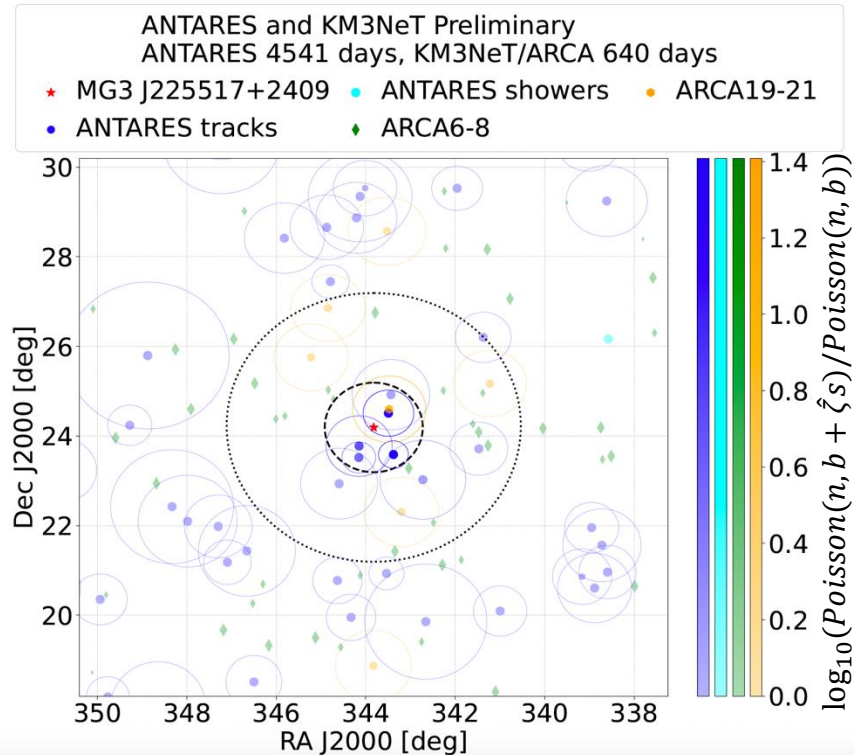
Skymap of the lowest p -value sources

Events opacity corresponds to:

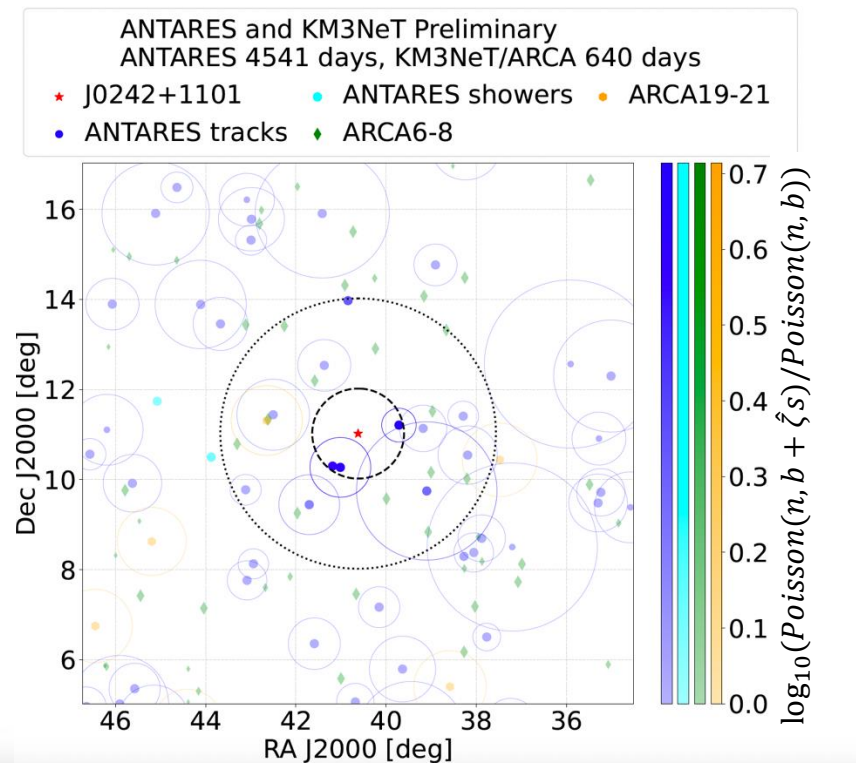
$$\log_{10} \left(\frac{\text{Poisson}(n, b + \hat{\zeta}s)}{\text{Poisson}(n, b)} \right)$$

- b : expected background events
- s : expected signal events for $\phi = 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$
- $\hat{\zeta}$: best-fit signal strength
- **Poisson($n, b + \hat{\zeta}s$)**: probability of this event being due to best signal and background
- **Poisson(n, b)**: probability of this event being due to background

MG3 J225517+2409



J0242+1101



- Error bands for events with >2 deg uncertainty are not shown (ARCA6/8 datasets).
- For MG3 J225517+2409, the ARCA 21 event with error box covering the source location strongly contributes to the combined event.
- For J0242+1101 there are no (new) ARCA events strongly contributing to the p -value

Conclusions & Perspective

- ❖ In this work, the framework for joint analysis has been developed. It features:
 - Binned analysis with different data sets: different detectors (ANTARES, ARCA...), different event selection (track-like, cascade-like...),
 - Inclusion of source morphology (extension with Gaussian, disk, etc..)
- ❖ Using ARCA6-21 helps to improve ANTARES standalone analysis by ~20%.
- ❖ A list of 106 sources was considered, finding that the most significant ones are: γ ray blazar **MG3 J225517+2409** (3.94σ pre-trial), blazar **J0242+1101** (3.12σ pre-trial) and radio galaxy **3C403** (3.02σ pre-trial) . This is in agreement with the ANTARES standalone point sources search
- ❖ Major gain in the next years respect to the standalone analyses is expected
- ❖ Don't miss stand-alone KM3NeT/ARCA and ANTARES analysis at this conference:
 - F. Salesa on behalf of ANTARES collaboration « **Searches for point-like and extended sources of cosmic neutrinos with the complete ANTARES dataset**» Poster
 - V. Parisi on behalf of KM3NeT collaboration «**Search for cosmic neutrino point sources and extended sources with 6-21 lines of KM3NeT/ARCA**» NU session, 23 Jul 2025, 16:20
 - I. Del Rosso on behalf of KM3NeT collaboration « **Extending KM3NeT's Point-Source Searches to Lower Energies with KM3NeT/ORCA** » NU session, 22 Jul 2025, 13:35

Thanks for the attention!

