Combined diffuse and point source search with KM3NeT/ARCA and ANTARES neutrino telescopes

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Abstract

In recent years, the multi-messenger approach in Astrophysics has become a real game changer for better understanding the still unclear phenomena in our Universe. **Neutrino telescopes** can play a key role in highlighting the hadronic component of such phenomena by testing the known γ-ray sources. In this contribution, we report on the results of the combined analyses of the data collected by two neutrino telescopes located at abyssal sites in the Mediterranean Sea, **ANTARES** and **KM3NeT/ARCA**. Searches are performed for both a point source and a diffuse emission of cosmic neutrinos.

KM3NeT/ARCA

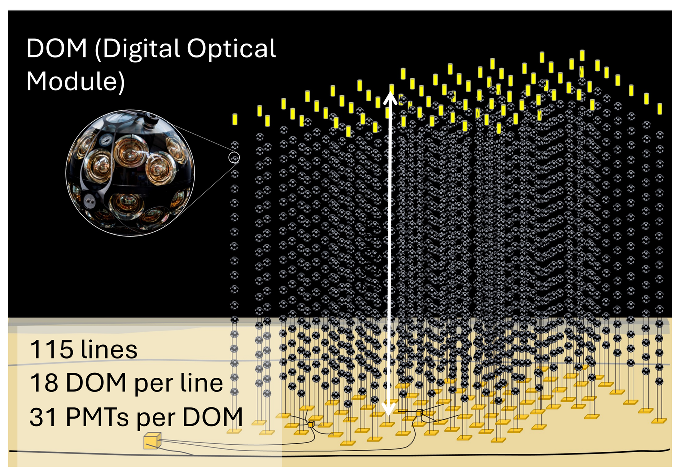

Fig.1: KM3NeT/ARCA neutrino telescope

KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) is a neutrino telescope under construction south of Sicily (Capopassero), currently composed by 28 lines out of the 115 of the first complete building block.

ANTARES

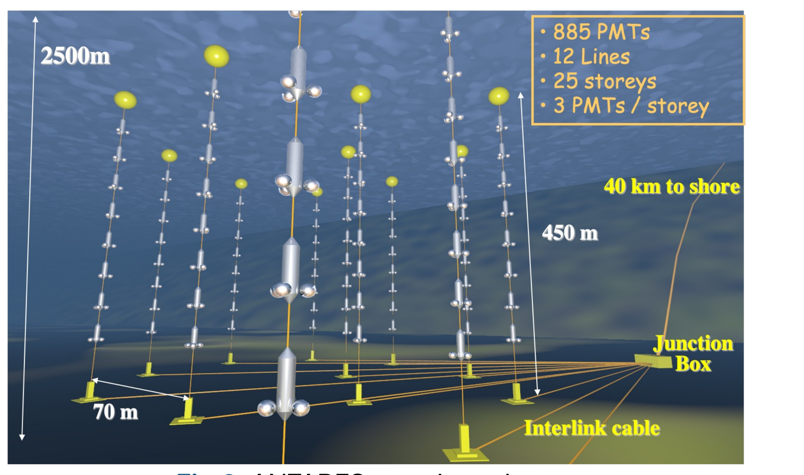

Fig.2: ANTARES neutrino telescope

ANTARES was a neutrino detector that operated for more than 15 years off the coast of Toulon (France), from 2008 to 2022.
It consisted of 12 lines, each equipped with 25 storeys with 3 PMTs.

Event topology

- **Tracks**: high energy μ travelling straight and far through water (ν_μ^{CC} interactions). Good pointing resolution.
- **Shower**: electromagnetic/hadronic shower (NC and ν_e^{CC} interactions). Good energy resolution.

Point source search analysis framework

- The datasets considered in this analysis refer to the whole ANTARES data taking period (from 2008 to 2022) and the KM3NeT/ARCA data taking period covering from 2021 to 2023, characterized by 4 subsets with respectively 6, 8, 19 and 21 lines (see more details in Tab.1). For ANTARES, both track and shower selections are considered and treated as separate datasets, while for KM3NeT/ARCA only track selection is used in this analysis.
- For each data period, Instrument Response Functions are produced, which fully characterize the detector in terms of effective area, angular and energy resolution (see Fig.3).

Dataset	Livetime [days]
ANTARES [1]	4541
KM3NeT/ARCA 6 [2]	92
KM3NeT/ARCA 8 [2]	210
KM3NeT/ARCA 19 [2]	53
KM3NeT/ARCA 21 [2]	70

Tab.1: Datasets considered in this analysis with corresponding livetime. The number next to KM3NeT/ARCA is the number of lines available during the dataset.

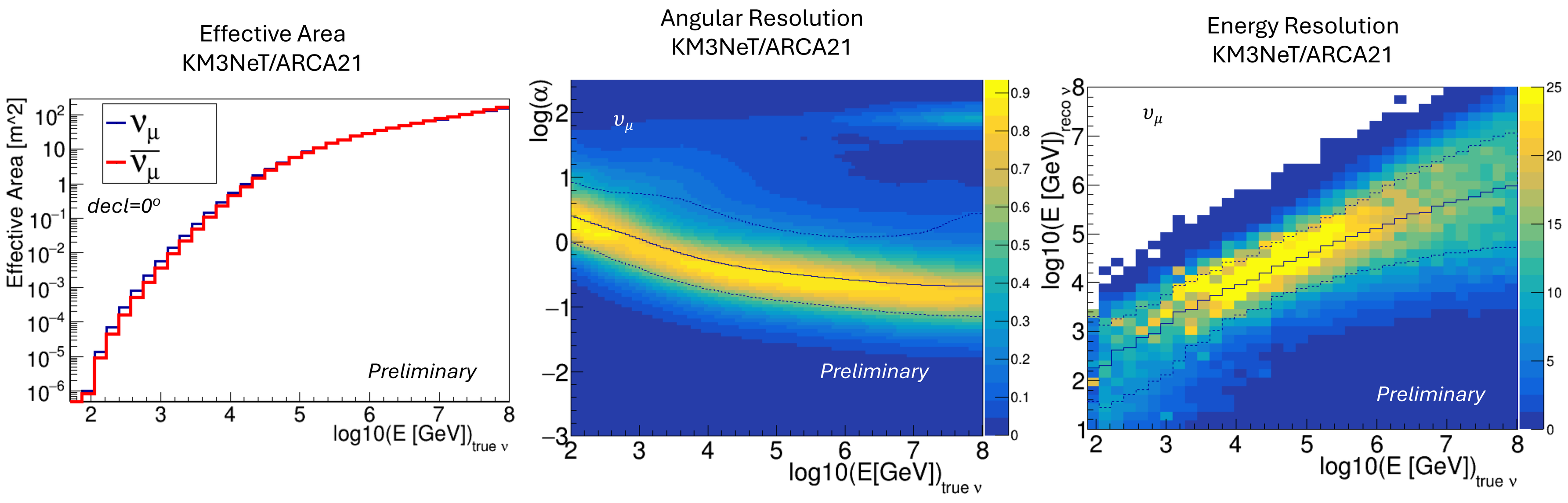

Fig.3: Effective area (left), angular resolution (center) and energy resolution (right) for the KM3NeT/ARCA21 dataset

- The analysis is performed using a **binned likelihood** defined as:

$$\log L = \sum_{bins} N_i log(-B_i - \mu S_i) - (B_i + \mu S_i)$$

$$B_i = n \times F(logE) \times G(sin\delta)$$

For ANTARES (shower selection), KM3NeT/ARCA 19 and KM3NeT/ARCA 21

$$B_i = n \times KDE(sin\delta, logE)$$

For ANTARES (track selection), KM3NeT/ARCA 6 and KM3NeT/ARCA 8

$$S_i = \sum_{E_{true}} \mathrm{rate}(decl, E_{true}) \times f_\alpha(E_{true}, \alpha_{min}, \alpha_{max}) \times f_E(E_{true}, decl, E_{rec,min}, E_{rec,max})$$

FROM EFFECTIVE AREA — *FROM ANGULAR RESOLUTION* — *FROM ENERGY RESOLUTION*

- B_i → background expectation, data-driven scrambled in RA, reconstructed energy and declination independent factorization if low statistics, 2D functions following KDE[3] approach if enough statistics (Fig.4)
- S_i → signal expectation, from Instrument Response Functions
- μ → signal strength, which parametrizes the flux intensity
- N_i → number of events of data in bin *i*

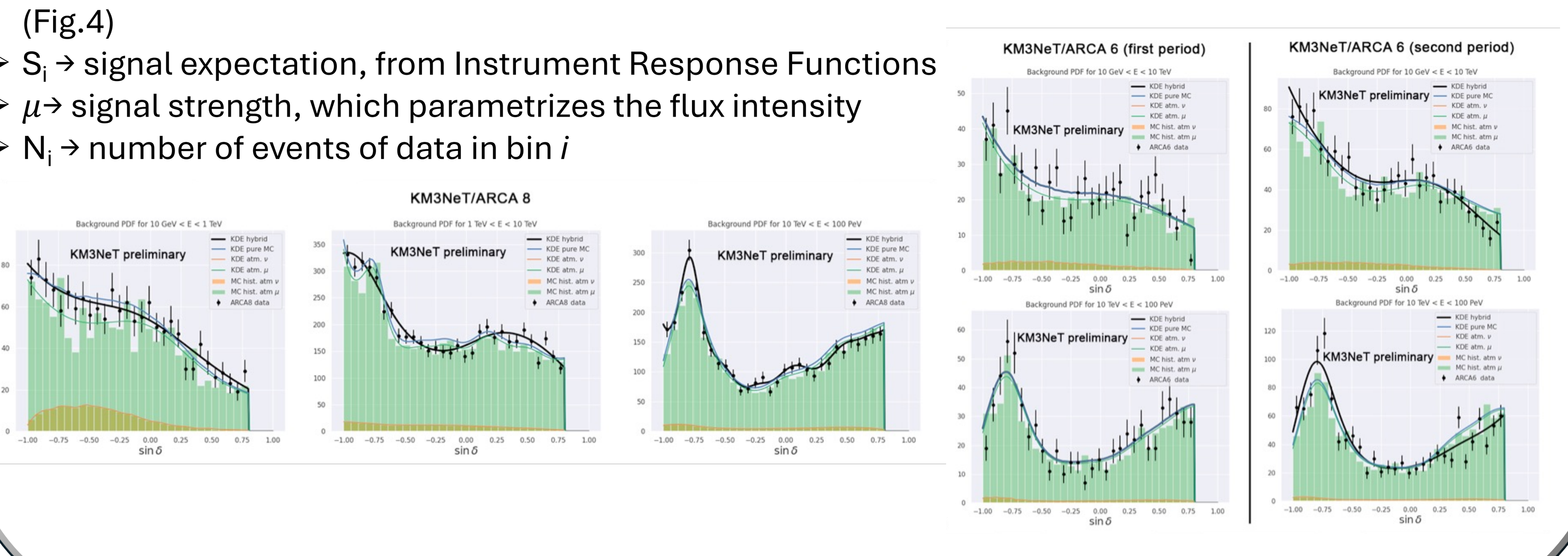

Fig.4: KDE functions vs sinδ for KM3NeT/ARCA6 and KM3NeT/ARCA8

Point source search results

The compatibility of the data with a point source hypothesis is quantified by filling a histogram of α (angular distance of the reconstructed event from the source center) and $\log_{10}$(E) (event energy estimation) with the events (see Fig.5). For a given dataset, $\hat{\mu}$ is determined by maximizing $\log L$:

TEST STATISTIC

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

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 $B_i + \mu_{true} S_i$.
The λ distributions are used to extract Neyman upper limits and p-values. The sensitivity, S_{90}, is defined as the median upper limit on S for 90% C.L. which is converted to the flux as follows:

$$\text{Sensitivity} \quad \Phi_{90} = \frac{S_{90}}{S}\Phi_0$$

Systematics used in this analysis:

- Signal efficiency (30% ARCA, 15% ANTARES)
- Angular resolution (0.5° ARCA, 0.15° ANTARES)

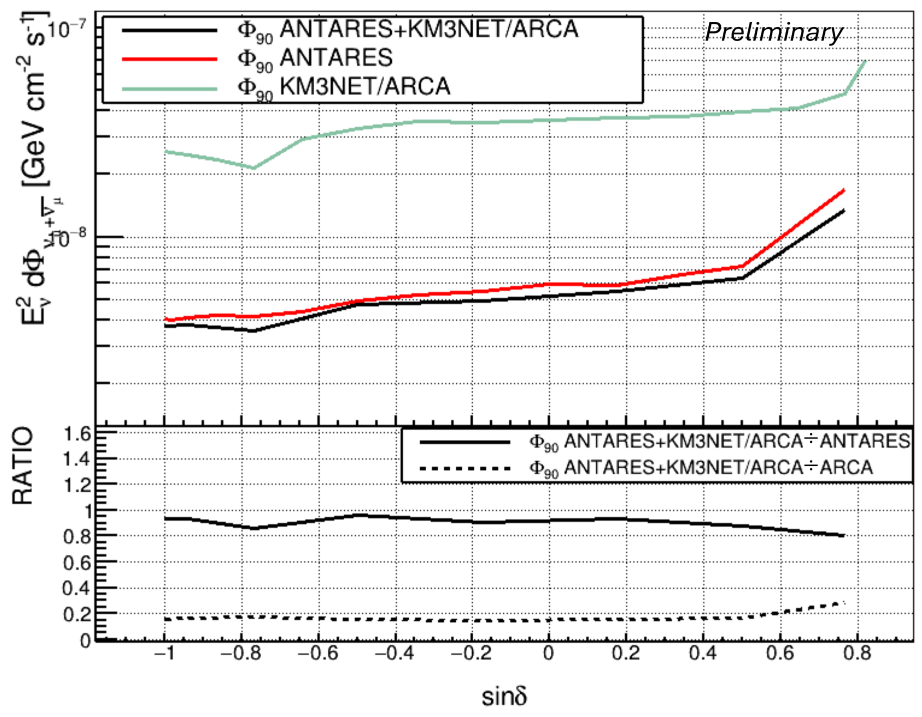

Fig.6: Top: sensitivity fluxes of ANTARES, KM3NeT/ARCA and of the combination of the two neutrino telescopes. Bottom: Ratio of combined sensitivity over ANTARES and over KM3NeT/ARCA

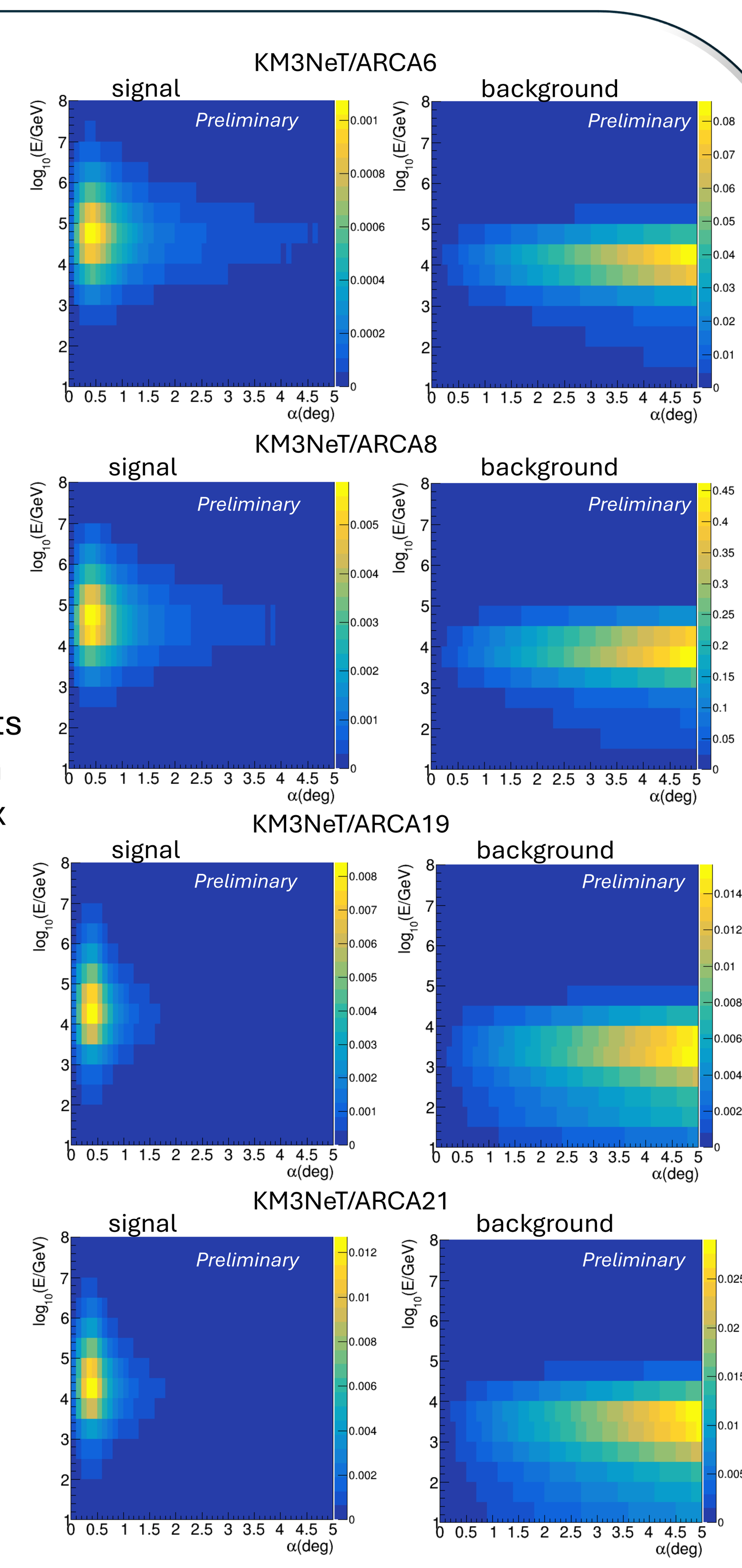

Fig.5: Signal (left) and background (right) distributions as a function of reconstructed energy and reconstructed distance to the source center for some the datasets considered in this analysis

Adding KM3NeT/ARCA datasets, the sensitivity of ANTARES improves by about 10%, as expected from the relative data-taking livetime.

Diffuse Flux Search Framework and Results

The combination of the 15-years ANTARES and of the ARCA tracks data samples has also been studied in the search for a diffuse flux of cosmic neutrinos. Three high-purity event samples have been defined with ANTARES data: tracks, showers, and low-energy showers. The combined analysis of these samples is also presented in this conference [4]. A binned likelihood function is defined as:

$$\mathcal{L}\left(N_i, S_i^{(\gamma)}, B_i, \phi_{\rm astro}\right) = \prod_k \prod_{i=1}^{N_{\rm bins}^k} \mathcal{P}(N_i, B_i + \phi_{\rm astro} S_i^{(\gamma)})$$

- The Poisson probability *P* of observing N_i events in the i-th bin of data is computed assuming an expected event rate in that bin from simulations, B_i being the background and S_i a power-law cosmic template with normalisation ϕ_{astro} and spectral index γ. The product runs over all the bins of the reconstructed energy distributions, for each of the *k* samples in the analysis.
- Systematic uncertainties are included as Gaussian priors on the background (30% σ) and signal (20% σ) in a Bayesian analysis to determine the parameters of interest ϕ_{astro} and γ, for which a flat prior is assumed.
- Pseudo-experiments are run to determine the sensitivity of this analysis. Preliminary results from the combination of the ANTARES samples with the ARCA21 sample are shown in Fig. 7.

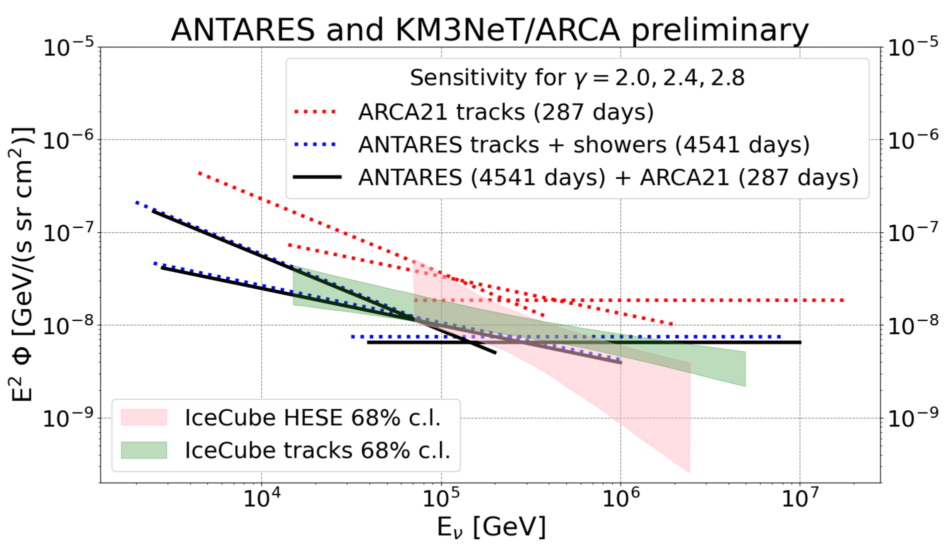

Fig.7: Sensitivity of the ARCA21 tracks data sample (red dotted lines), of the ANTARES tracks and showers combined samples (blue dotted line), and their combination (black solid lines) for three power-law hypotheses compared to the measurements of the diffuse flux obtained by the IceCube collaboration (shaded areas)

Conclusions and next steps

- An analysis framework used to combine different KM3NeT/ARCA periods[2] was extended to include the data from the ANTARES neutrino telescope.
- Combining the ANTARES and KM3NeT/ARCA datasets, the sensitivity improved by 10% w.r.t. ANTARES alone. The first KM3NeT/ARCA building block (115 lines) is foreseen by the end of 2026, so KM3NeT will rapidly grow in the near future. Stay tuned!

References:

[1] Searches for Point-like Sources of Cosmic Neutrinos with 15 Years of ANTARES Data, 10.22323/1.444.1128
[2] Search for cosmic neutrino point sources and extended sources with 6-21 lines of KM3NeT/ARCA, https://doi.org/10.22323/1.444.1018
[3] SUFTware https://suftware.readthedocs.io/en/latest/index.html
[4] L.A. Fusco, Constraints on the diffuse cosmic neutrino flux from the ANTARES neutrino telescope (Poster ID 537)