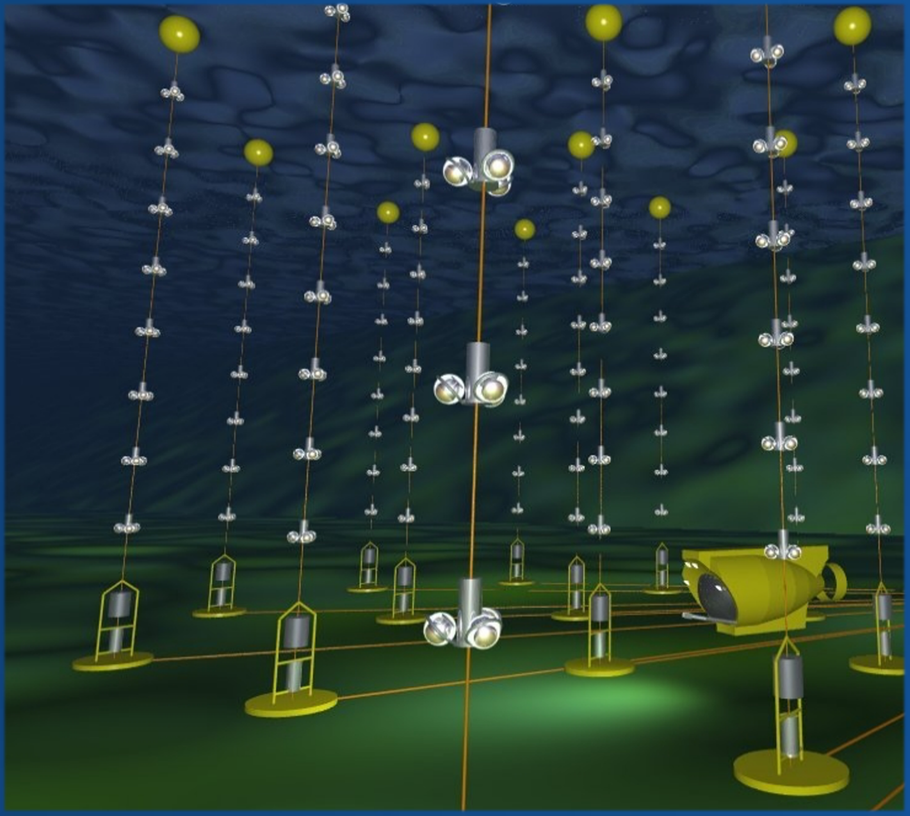

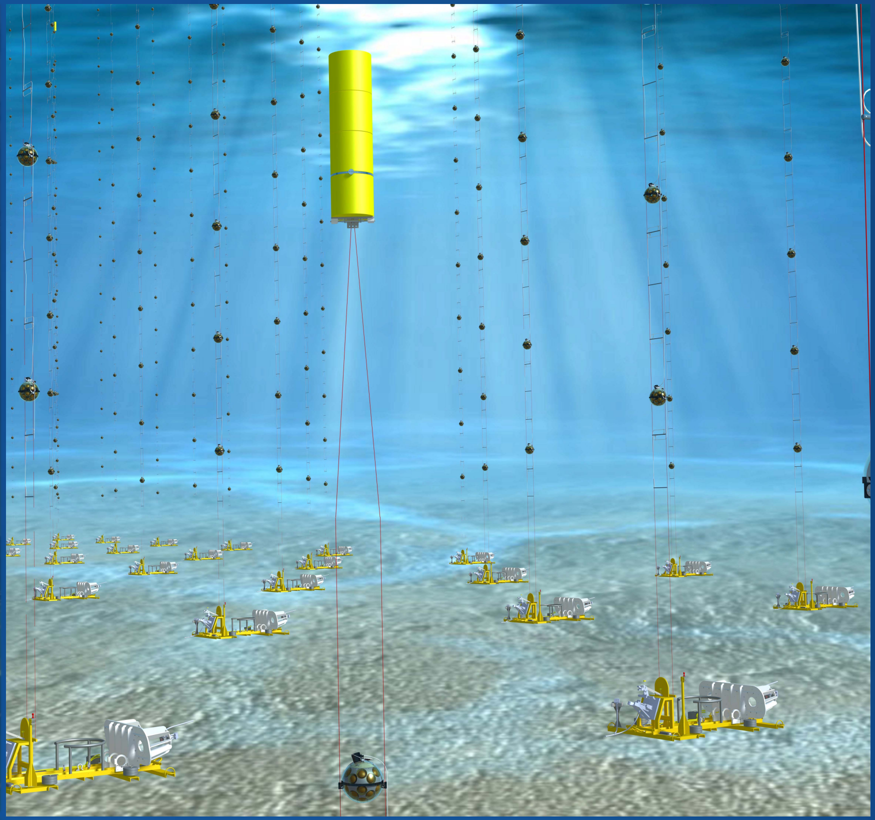

The search for point-like neutrino sources with ANTARES and KM3NeT/ARCA telescopes

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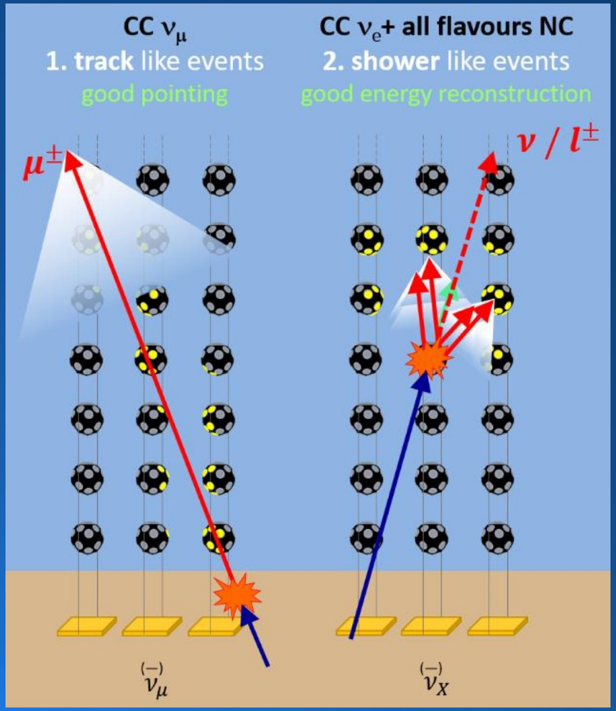
on behalf of the KM3NeT and ANTARES collaborations

Combined point-like search

In this contribution, we report about the results of a new **combined** analyses of the data collected by two neutrino telescopes located at abyssal sites in the Mediterranean Sea, ANTARES (depth~ 2475 m) and KM3NeT/ARCA (depth ~3500 m). Separate analysis frameworks already developed*.



- Data set: a specific detector period with a particular event selection (track/shower).

Data sets do not overlap (no common events).

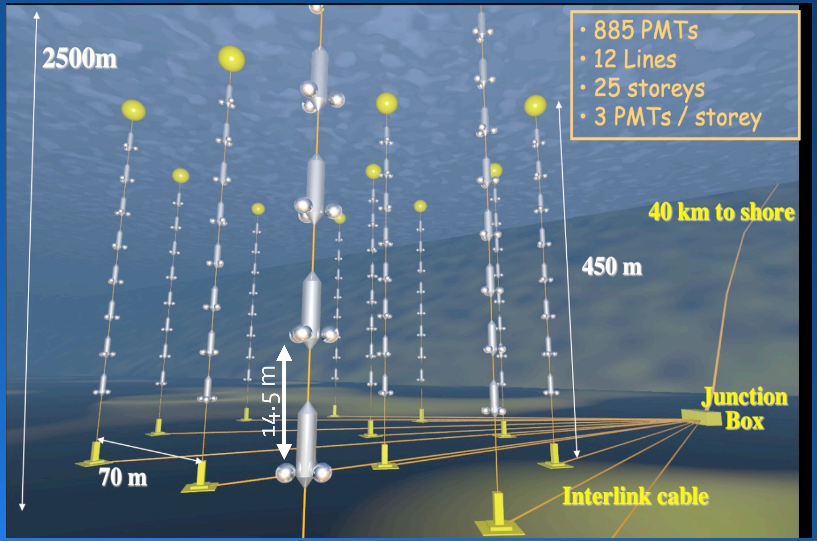
- Track: muons from ν_μ^{CC} interactions and ν_τ^{CC} interactions where the τ decays into a muon (branching ratio ~ 17%),
- Shower: hadronic showers from all-flavour neutrino NC interactions, electromagnetic showers from ν_e^{CC} interactions and ν_τ^{CC} interactions where the τ decays either into an electron or into hadrons (branching ratio ~ 83%).

*PoS(ICRC2023)1128, https://doi.org/10.22323/1.444.1128, PoS(ICRC2023)1018, https://doi.org/10.22323/1.444.1018

ANTARES

- ANTARES was a neutrino detector that operated 40 km off-shore of Toulon (France), at a depth of 2475 m from 2007 to 2022 (15 years). 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
- It was switched off in February 2022

- This analysis exploits the full 2007-2022 data (4541 days)* and events classified both as tracks and as showers



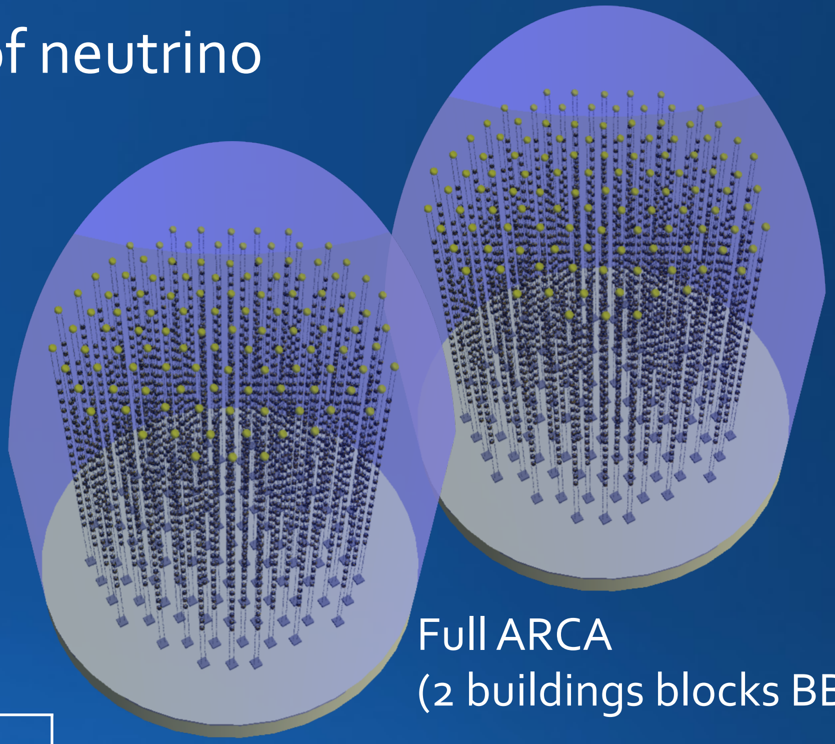
*PoS(ICRC2023)1128, https://doi.org/10.22323/1.444.1128

KM3NeT/ARCA telescope

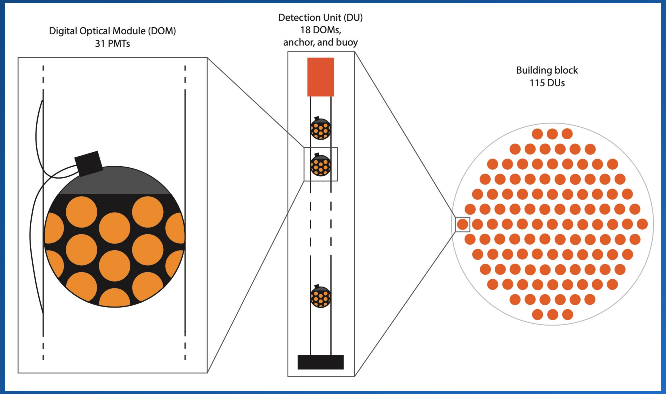
KM3NeT collaboration is installing a next generation of neutrino detectors in the deep sea.

ARCA (**A**stroparticle **R**esearch with **C**osmics in the **A**byss) is a neutrino telescope under construction south of Sicily (Capopassero), with two Building Block (BB); each BB will count 115 lines, 18 DOMs per line and 31 PMTs per DOM

It is currently composed of 28 lines out of the 115 of the first complete building block



Full ARCA
(2 buildings blocks BB)



Eur. Phys. J. C **84**, 885 (2024).
https://doi.org/10.1140/epjc/s10052-024-13137-2

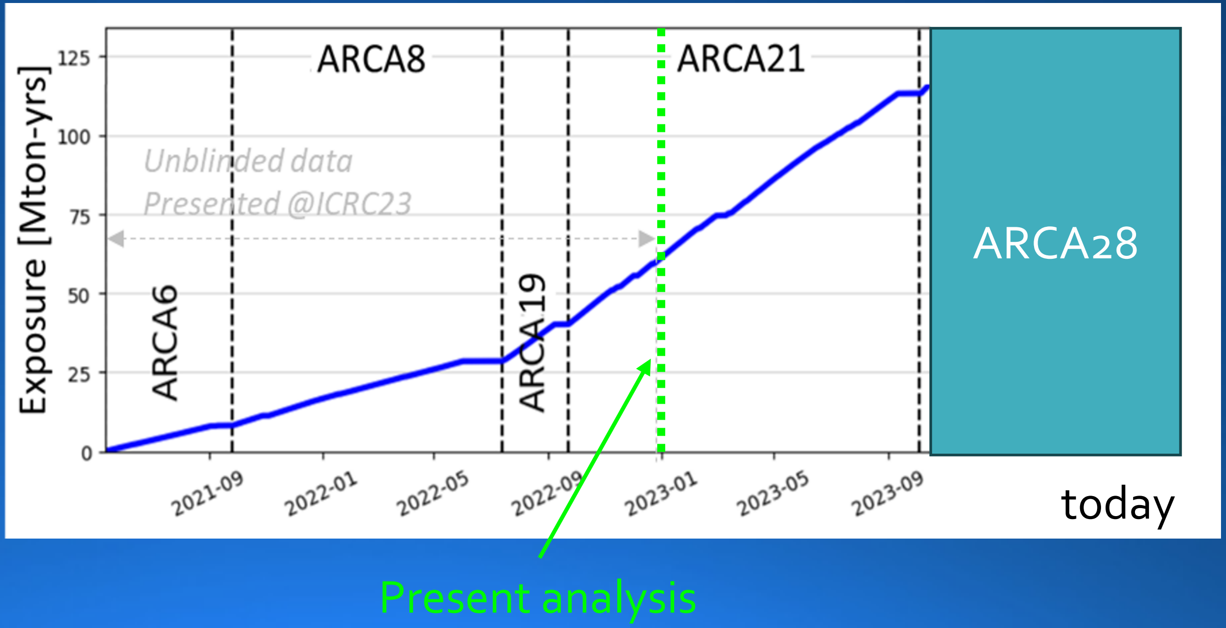
	ANTARES	ARCA
Effective Mass	10 Mt	1 Gt
Line length	350 m	650 m
Interline distance	70 m	90 m
Vertical spacing	14.5 m	36 m

← Factor 100!!

KM3NeT/ARCA : Data-sets

The data sets considered in this analysis refer to the KM3NeT/ARCA data taking period covering from May 2021 to Dec. 2022* (424 days), characterized by 4 subsets with respectively 6, 8, 19 and 21 lines . Only track events were considered (up to now)

DATASET	LIVETIME [days]
ANTARES	4541
KM3NET/ARCA 6	92
KM3NET/ARCA 8	210
KM3NET/ARCA 19	52
KM3NET/ARCA 21	70

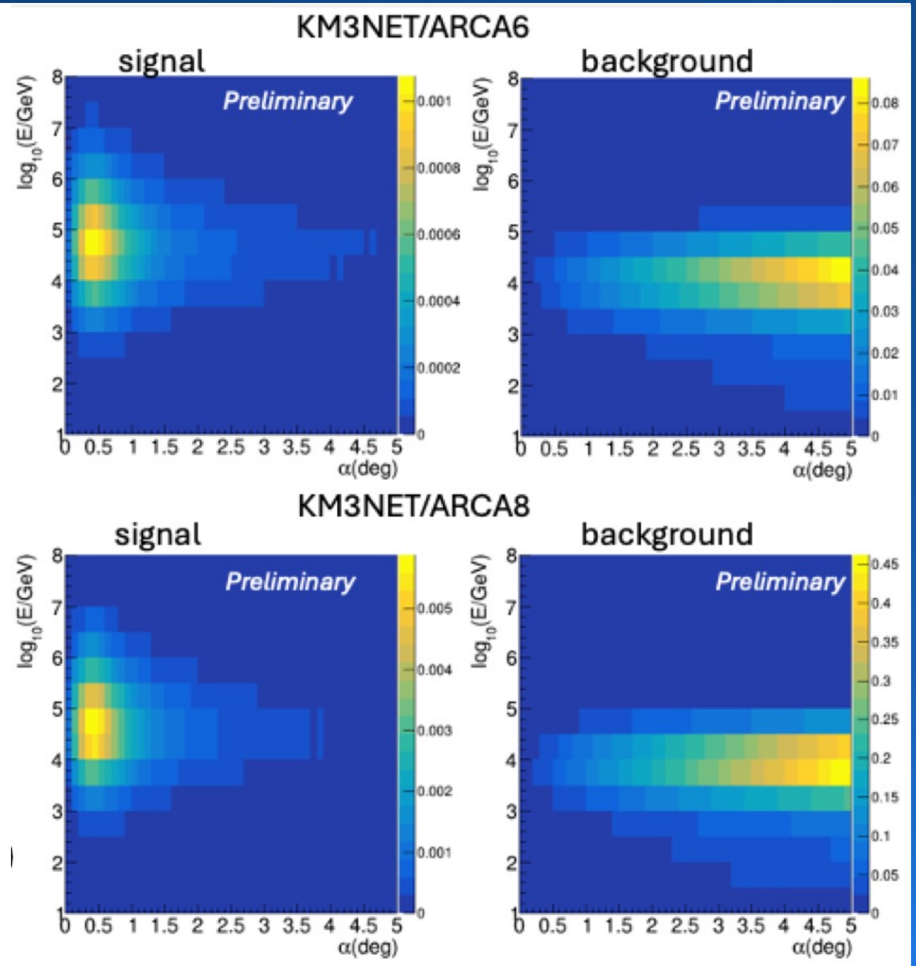


*PoS(ICRC2023)1018, https://doi.org/10.22323/1.444.1018

Point search analysis framework: binned likelihood

KM3NeT/ARCA6 (92 days) preliminary

KM3NeT/ARCA8 (210 days) preliminary



distributions are for sin(decl)=0

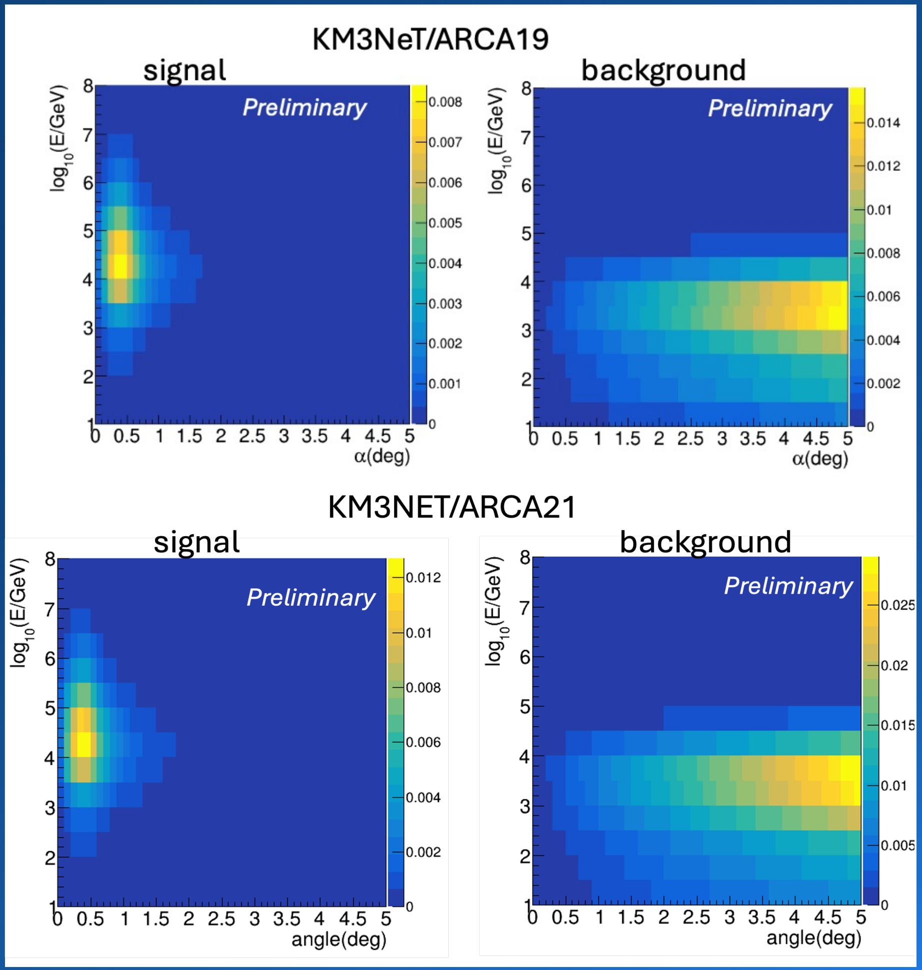
The compatibility of the data with a point source hypothesis is quantified by filling a 2D histogram of:

- α (angular distance of the reconstructed events from the source center) and
- log10(E) (event energy estimation)

Point search analysis framework: binned likelihood

KM3NeT/ARCA19 (52 days) preliminary

KM3NeT/ARCA21 (70 days) preliminary



distributions are for sin(decl)=0

- For each data set, we computed:
  - Signal expectation (**MC**) *S*,
  - Background expectation (**data driven, MC**) *B*,
  - Number of events of data in bin i : *N*,

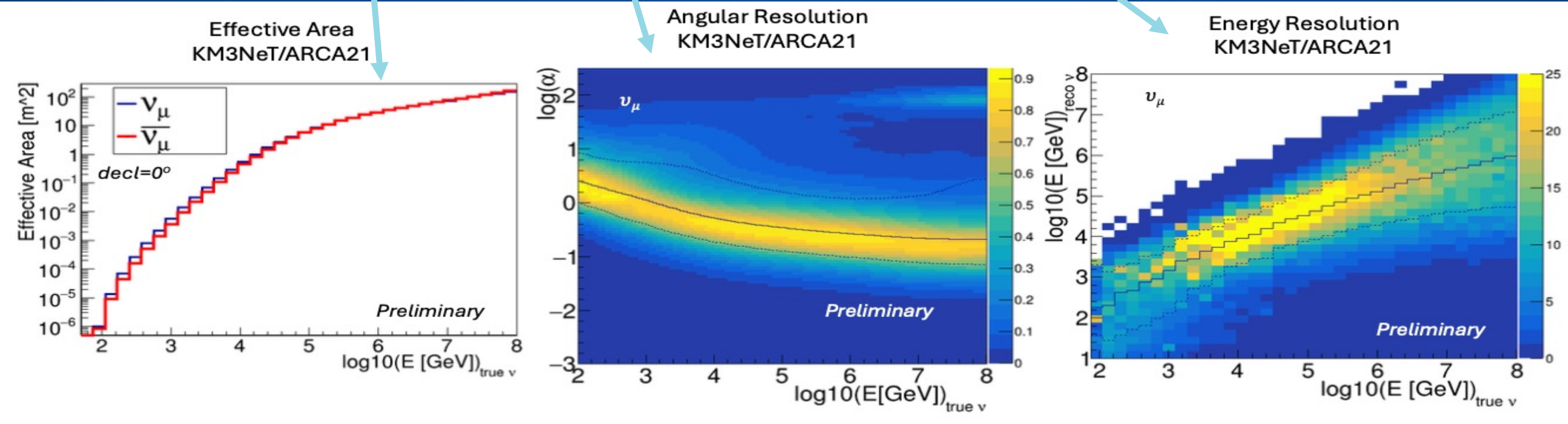
The signal strength μ (which parametrize the flux intensity) was determined by maximizing a binned likelihood:

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

Signal estimation : MC

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

ARCA21

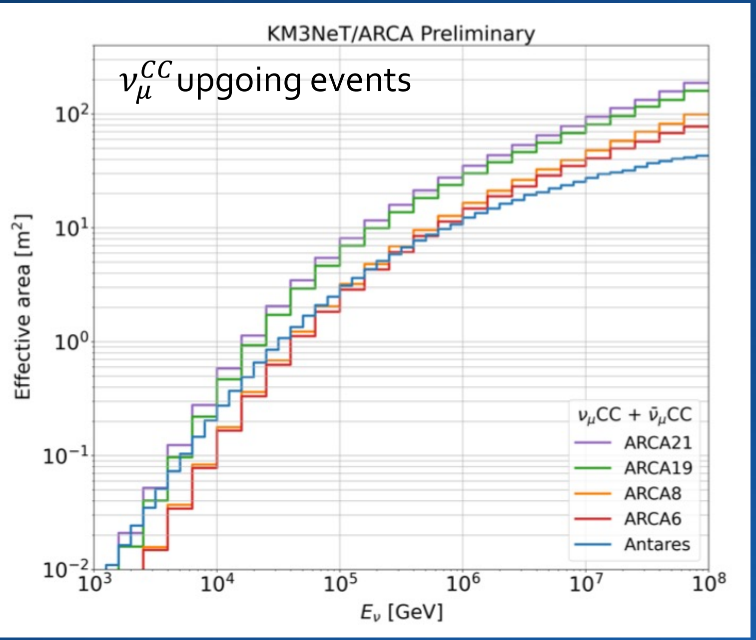


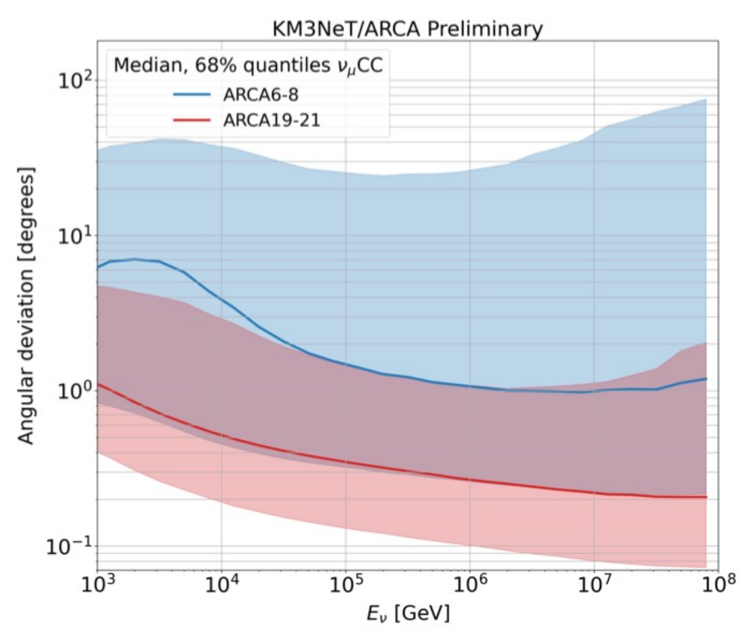
From MC - Instrumented Response Functions (IRF's):

- ➢ Effective area vs E_ν^{true} and zenith^{true}/declination^{true}
- ➢PSF (Point Spread Function): event fraction vs E_ν^{true} and α (distance of the reco event direction to the true source centre)
- ➢Energy resolution: event fraction vs E_ν^{true}, E_ν^{reco} and zenith^{true}/declination^{true}

Antares & KM3NeT ARCA6-21 : comparison

*PoS(ICRC2023)1018, https://doi.org/10.22323/1.444.1018
PoS(ICRC2019)920, https://doi.org/10.22323/1.444.1128





The plot and table are based on simulation produced alongside the data until December '22

Energy integrated median angular resolution (ν_μ^{CC}) :

Antares	0.4°	(E_ν> 100 TeV)
ARCA6	2.11°	
ARCA8	1.56°	
ARCA19-21	0.37°	

The full KM3NeT/ARCA230 detector will achieve < 0.1° for E_{ν_μ} > 30 TeV

Background estimation

Data-driven approach : from data scrambled in RA ➔ histograms of reconstructed energy and declination distributions

- If low statistics : independent factorization

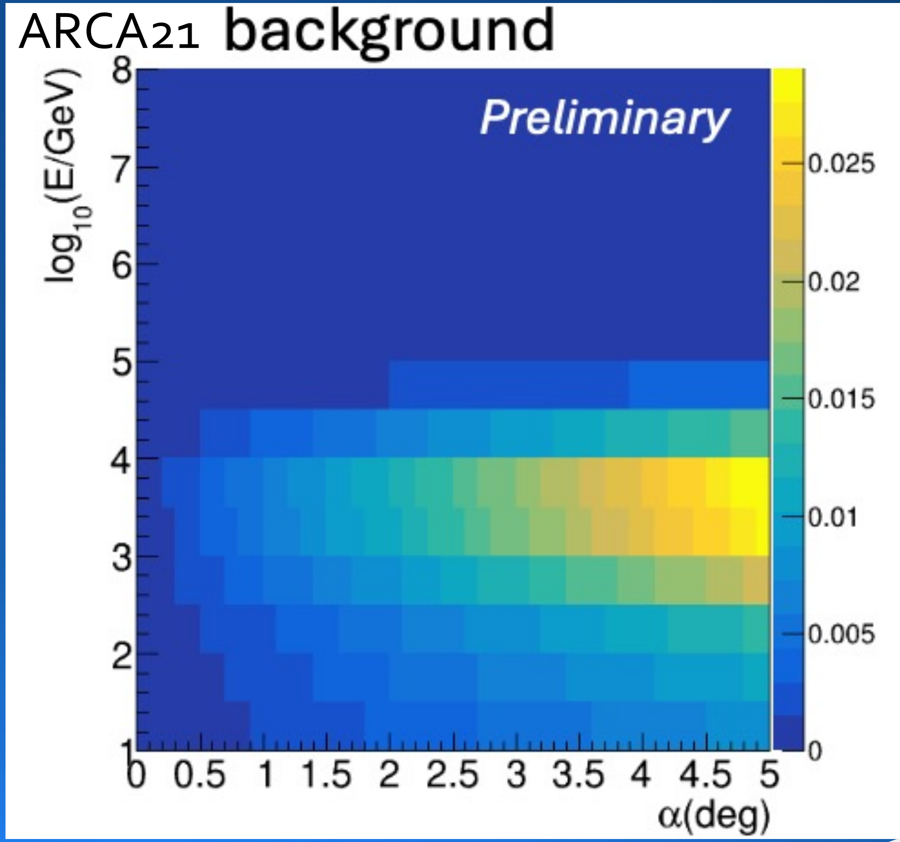
For ANTARES (showers), KM3NET/ARCA 19 and KM3NET/ARCA 21 (n. events< 1000) :

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

- If high statistics : KDE approach

For ANTARES (tracks), KM3NET/ARCA 6 and KM3NET/ARCA 8

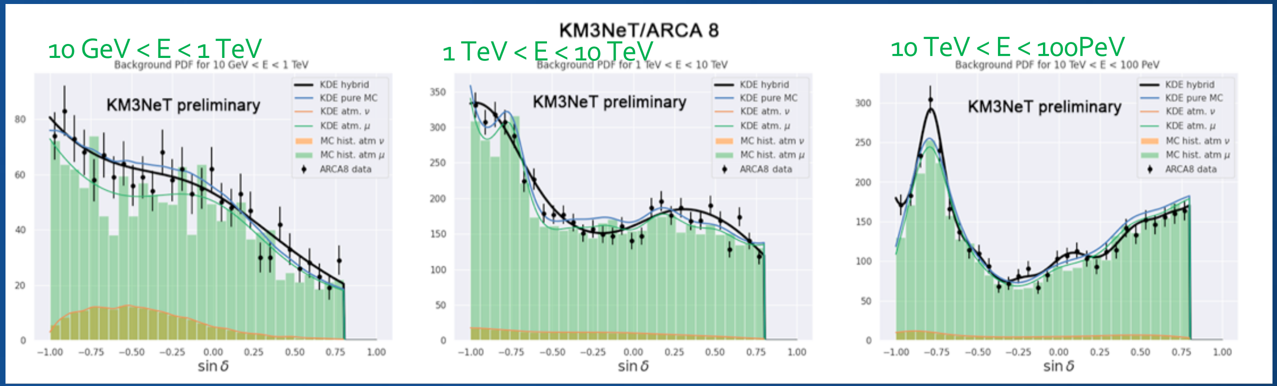
$$B_i = N_i \times KDE(sin\delta, logE)$$

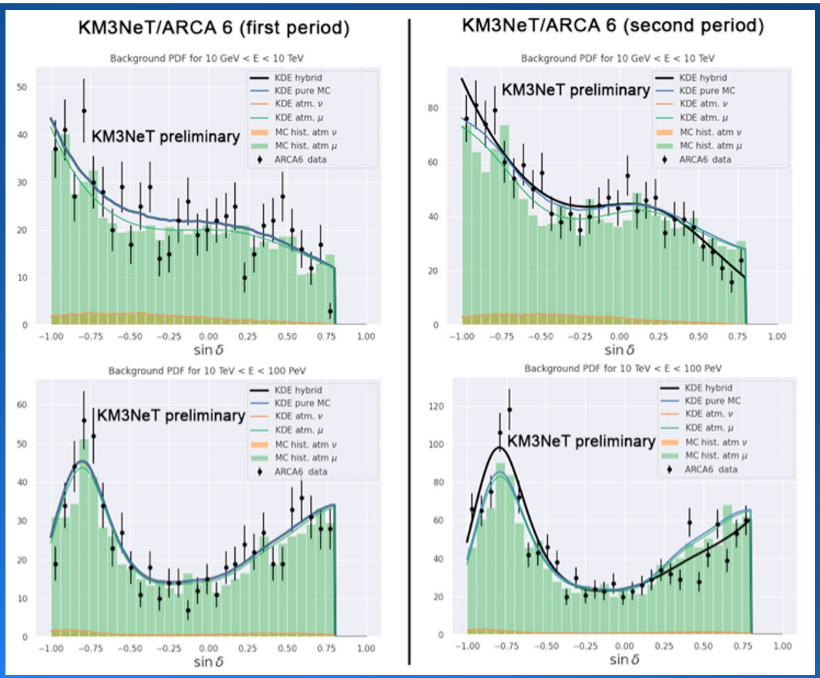


Background estimation: KDE

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

- Event distribution in declination varies with energy → 2D parametrisations are more accurate!
- Kernel Density Evaluation approach using SUFTware, following Galactic plane analysis @ ICRC2023.
    - Python implementations of Bayesian Field Theory algorithms for low-dimensional statistical inference
- Splitting dataset in energy on bins with at least 1000 events (in data or MC). Fitting data (if 1000 events are available) or MC.





SUFTware
https://suftware.readthedocs.io/en/latest/index.html

Sensitivity estimation

- Evaluated from pseudo-experiments :
- For a true value of the signal strength μ_{true}, pseudo- experiments can be generated by randomly generating each N_i from a Poisson distribution with mean $B_i + \mu_{true} S_i$.
- H0 (background only), and H1 (signal + background) models are built from the signal and background expectations

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

Statistics test:

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

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:

Sensitivity

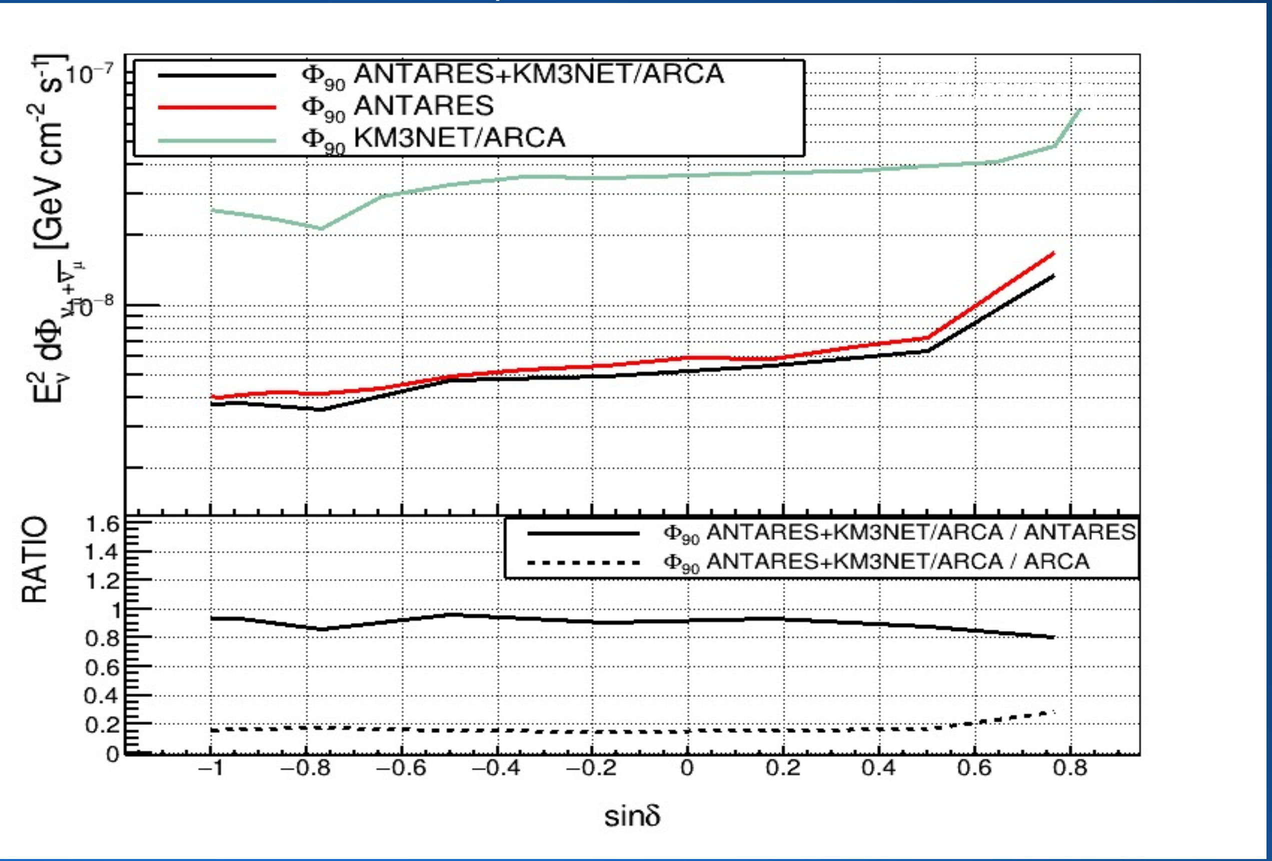
$$\phi_{90} = \frac{S_{90}}{S} \phi_0$$

$$\begin{cases} \phi_{\nu_i + \bar{\nu}_i} = \phi_0 \left(\frac{E}{1GeV} \right)^{-2} \\ \phi_0 = \frac{1}{10^4} \frac{1}{GeV\ m^2 s} \end{cases}$$

Combined sensitivity

- ARCA6-21 (424 days) dataset sensitivity is ~20% of the joint analysis.
- By adding ARCA 6/8/19/21 to ANTARES dataset, the sensitivity improves by 10% as expected from the relative statistics.
- This will rapidly improve with the upcoming data sets

Bottom:
Ratio of combined sensitivity over ANTARES and over KM3NeT/ARCA

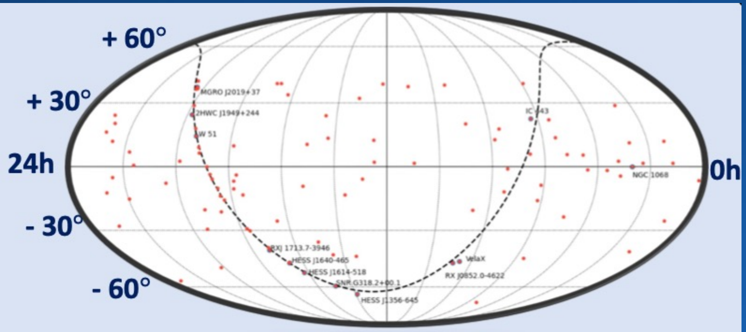


Systematics used in the analysis:
Signal efficiency (30% ARCA, 15% ANTARES)
Angular resolution (0.5^0 ARCA, 0.15^0 ANTARES)

Search for cosmic neutrino point sources with 6-21 lines of KM3NeT/ARCA

Sensitivity studies performed also for ARCA6 - 8 - 19 - 21 up to Dec. 2022 (424 days) with unblinded data*

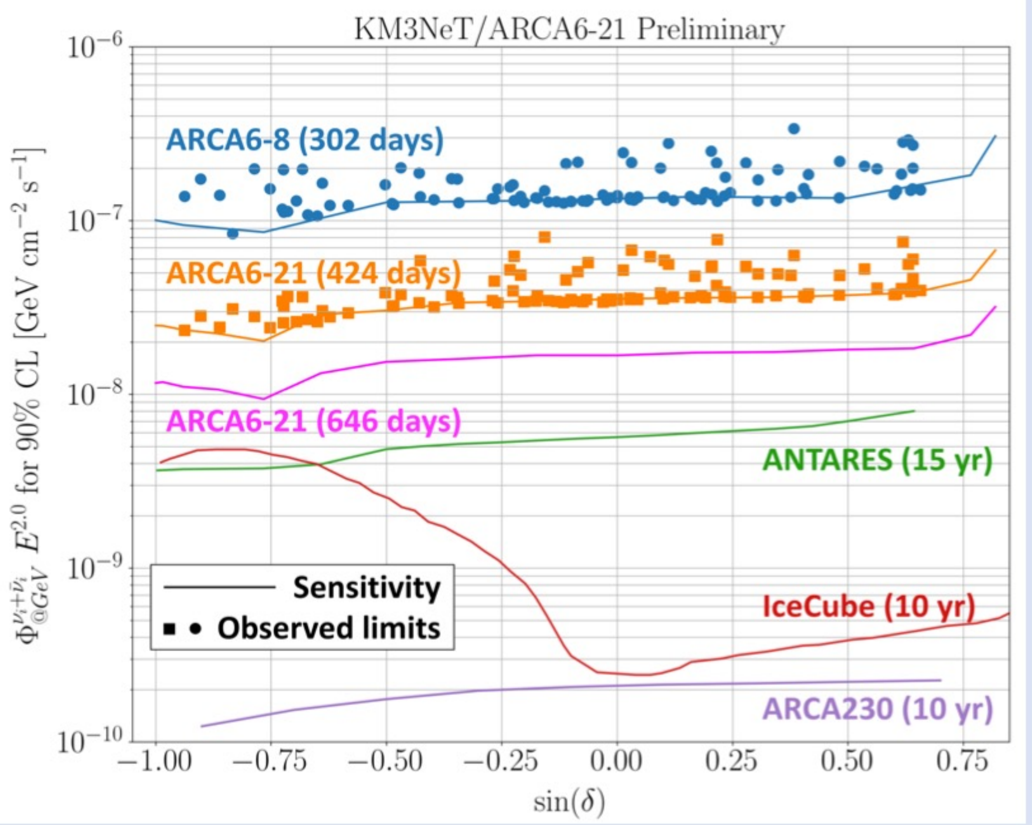
101 candidate sources have been probed*:
among them 12 sources are spatially extended in the sky. For these sources the detector point spread function is modified with a Gaussian or disk-like smearing around the source center in line with the source size



For the ARCA6-21 (424 days) unblinded dataset, the lowest pre-trial p- value (0.011) was found for the AGN J1512-0905 at at RA = 228.21°, $\delta = -9.10°$, for $\gamma = 2.0$

No significant excess found

Sensitivities on the flux for the individual candidates assuming an E^{-2} energy spectrum⁺:



*PoS(ICRC2023)1018, https://doi.org/10.22323/1.444.1018
⁺M. Spurio poster @ Neutrino24

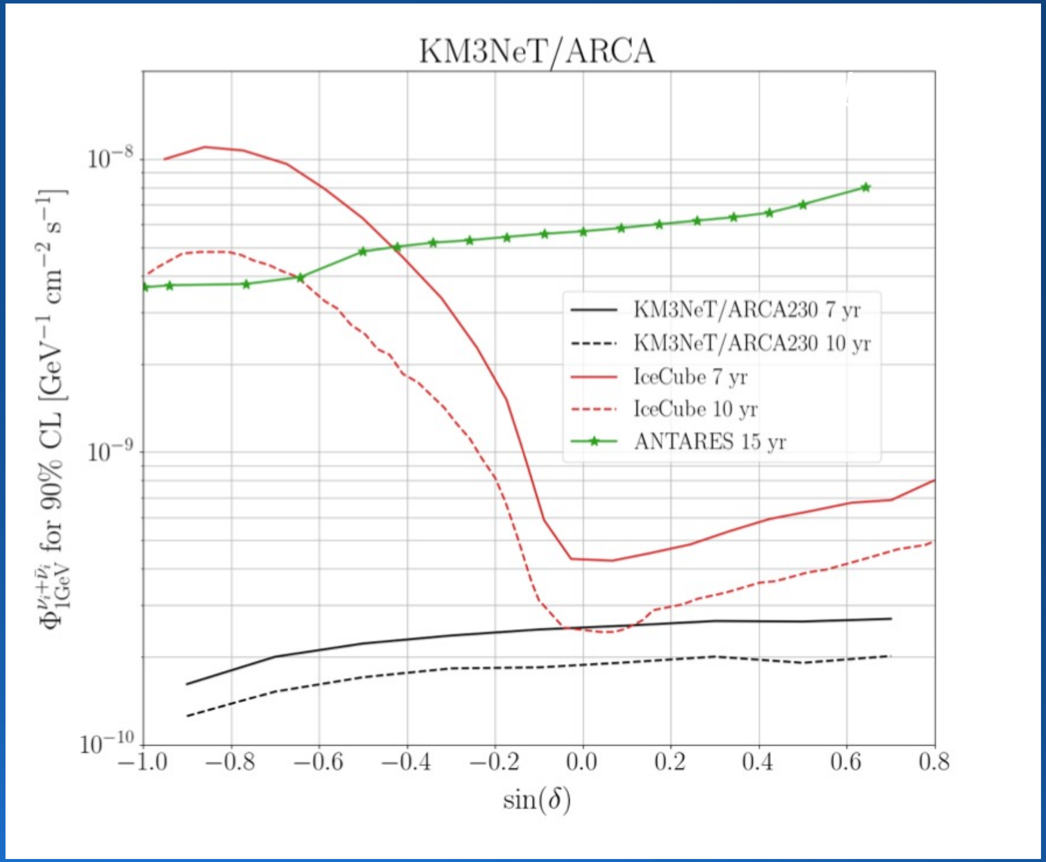
Future sensitivity

- ARCA230 : two building blocks

- The sensitivity of ARCA surpasses that of IceCube in the Southern Sky (sin(δ) < 0) due to visibility, i.e. the proportion of time a source is below the horizon, favouring ARCA in the Northern Hemisphere to study the Southern Sky.

- In the Northern Sky (sin(δ) > 0), the enhanced performance of ARCA is attributed to its angular resolution.

Channels: Tracks + showers



KM3NeT Collaboration., Astronomy potential of KM3NeT/ARCA. *Eur. Phys. J. C* **84**, 885 (2024). https://doi.org/10.1140/epjc/s10052-024-13137-2

Conclusions and outlook

- The binned likelihood framework used for the ARCA 6/8/19/21 analysis has been expanded to incorporate data from the ANTARES neutrino telescope. Completing ARCA21 dataset analysis is in progress (287 days).
- Currently, ANTARES contributes most significantly, but combining with KM3NET/ARCA the performance enhances by 10%.
- Extensive cross-checks with the official ANTARES analysis are ongoing, data unblinding is expected in the next months.
- Large improvement in sensitivity is expected in the next year: ARCA28 from Sept 2023, ARCA47 (?) from November 2024, indicating rapid growth for KM3NET in the near future!

Conclusions and outlook

- The binned likelihood framework used for the 6/8/19/21 analysis has been expanded to incorporate data from the ANTARES lescope. Completing ARCA21 dataset analysis is in progress (287 days).
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- Extensive ficial ANTARES analysis are ongoing, data unblinding is expected in t
- Large improve n sensitivity is expected in the next year: + 9 months of ARCA21, then ARCA28 from Sept 2023 + ARCA47 (?) from November 2024, the first KM3NeT/ARCA building block (consisting of 115 lines) is expected by the end of 2026, indicating rapid growth for KM3NET in the near future!

Thank you!!

ANTARES

INFN GENOVA

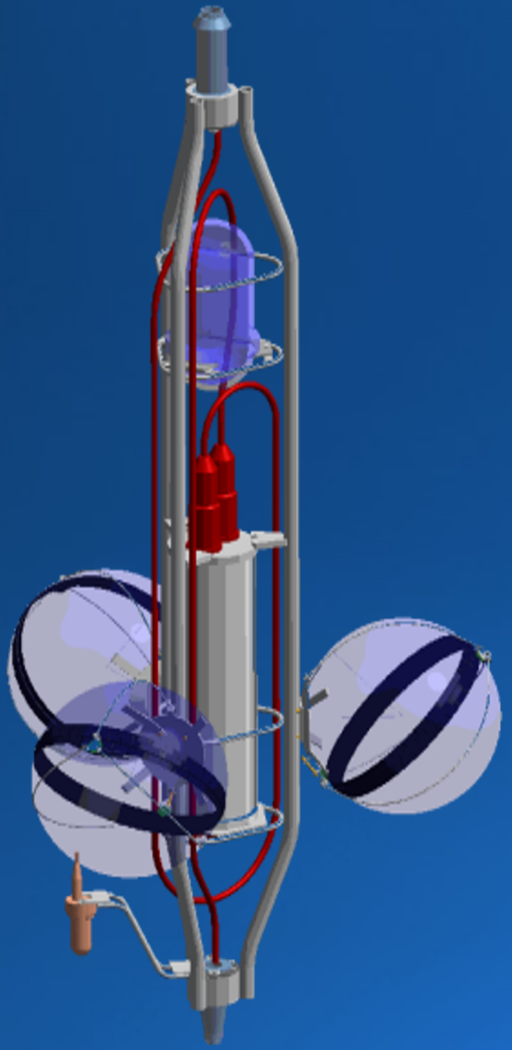
KM3NeT

Backup

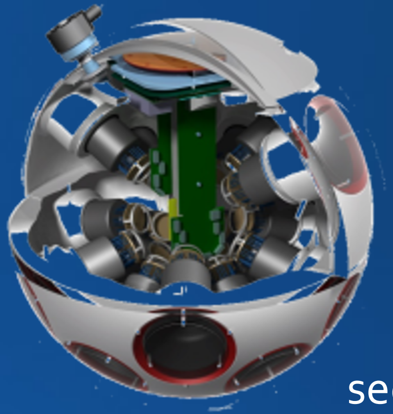
The 101 analysed candidates (ARCA) are:

LMC N132D, HESS J1356-645 , SNR G318.2+00.1, IC-hotspot South hemisphere, HESS J1614-518, PKS 2005-489, HESS J1640-465, RX J0852.0-4622, HESS J1641-463, VelaX , PKS 0537-441, CentaurusA, PKS 1424-418, J0106-4034, RX J1713.7-3946, CTB 37A, PKS 1454-354, HESS J1741-302, J1924-2914, Galactic center, J2258-2758, J1625-2527, NGC 253, J0457-2324, J1833-210A, J0836-2016, J1911-2006, J0609-1542, SNR G015.4+00.1, J2158-1501, LHAASO J1825-1326 , QSO 1730-130, J1337-1257, J2246-1206, PKS 0727-11, TXS 1749-101, HESS J1828-099, J1512-0905, J0607-0834, QSO 2022-077, RS Ophiuchi, J0006-0623, 3C279, LHAASO J1839-0545 , J2225-0457, 4FGL J0307.8-0419, PKS 1741-038, LHAASO J1843-0338 , J0339-0146, J0423-0120, J0725-0054, LHAASO J1849-0003 , NGC 1068, J2136+0041, J1058+0133, J0108+0135, PKS 0215+015, J1229+0203, TXS 0310+022, 3C403, CGCG 420-01, J0433+0521, TXS 0506+056, HESS J0632+057, LHAASO J1908+0621 , PKS 2145+067, W 49B, OT 081, PKS 1502+106, J0242+1101, J2232+1143, J0121+1149, J1230+1223, J0750+1231, PKS 1413+135, J0530+1331, W 51, J2253+1608, PKS 0735+178, LHAASO J1929+1745 , J0854+2006, RGB J2243+203, LHAASO J0534+2202 , IC 443, PKS 1424+240, MG3 J225517+2409, 2HWC J1949+244, LHAASO J1956+2845 , J0237+2848, J1310+3220, J1613+3412, LHAASO J2018+3651 , J2015+3710, MGRO J2019+37, Mkn 421, J0927+3902, NGC 4151, Mkn 501, J1642+3948, J0555+3948, LHAASO J2032+41025.

Optical modules comparison



3*10″ PMTs -> 31*3″ PMTs
same sensitive area
+ compactness
+ wider angle of view
+ directional information
+ cost reduction



see L. Morales-Gallegos talk