# Investigating Neutrino Emission from Gamma-Ray (Galactic) Sources with KM3NeT/ARCA

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  - how to modelize the neutrino signal from a source using the gamma-ray observations.
- The KM3NeT/ARCA detector:
  - how to detect high energy astrophysical neutrino.
- Point-like (extended) source search:
  - how to analyse data to search for neutrino signal (binned likelihood method).
- Results and conclusions

# Introduction

Neutrino sources are **cosmic ray accelerators**.
The two main mechanisms of high-energy neutrino production are:

1)when cosmic rays interact with matter (**hadro-nuclear interactions**):

$$p + p \rightarrow p + n + \pi^+$$
$$\rightarrow p + p + \pi^0$$
$$p + n \rightarrow p + p + \pi^0$$
$$\rightarrow p + p + \pi^-$$

2) when cosmic rays interact with photons (**photo-hadronic interactions**):

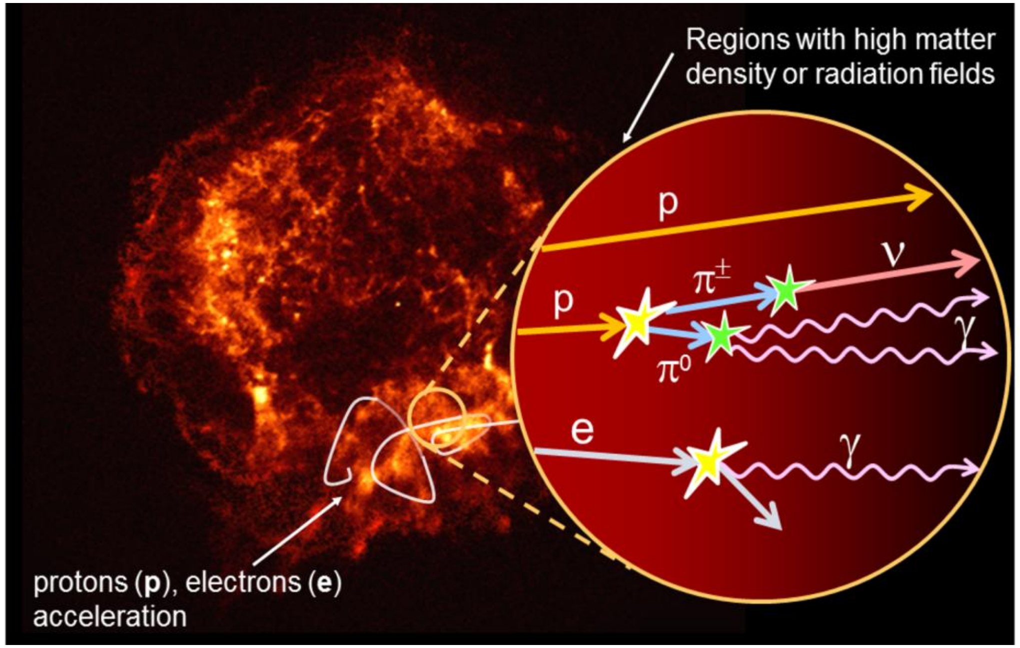
$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$

Neutrinos are produced in the decay of the charged pions:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$
$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} \qquad \mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$$

While the neutral pions decay into γ-rays: $\pi^0 \rightarrow \gamma + \gamma$

Such high energy gamma-rays could be detected by high altitude gamma observatories like HAWC or LHAASO, while the neutrino component could be studied by neutrino telescopes as KM3NeT.



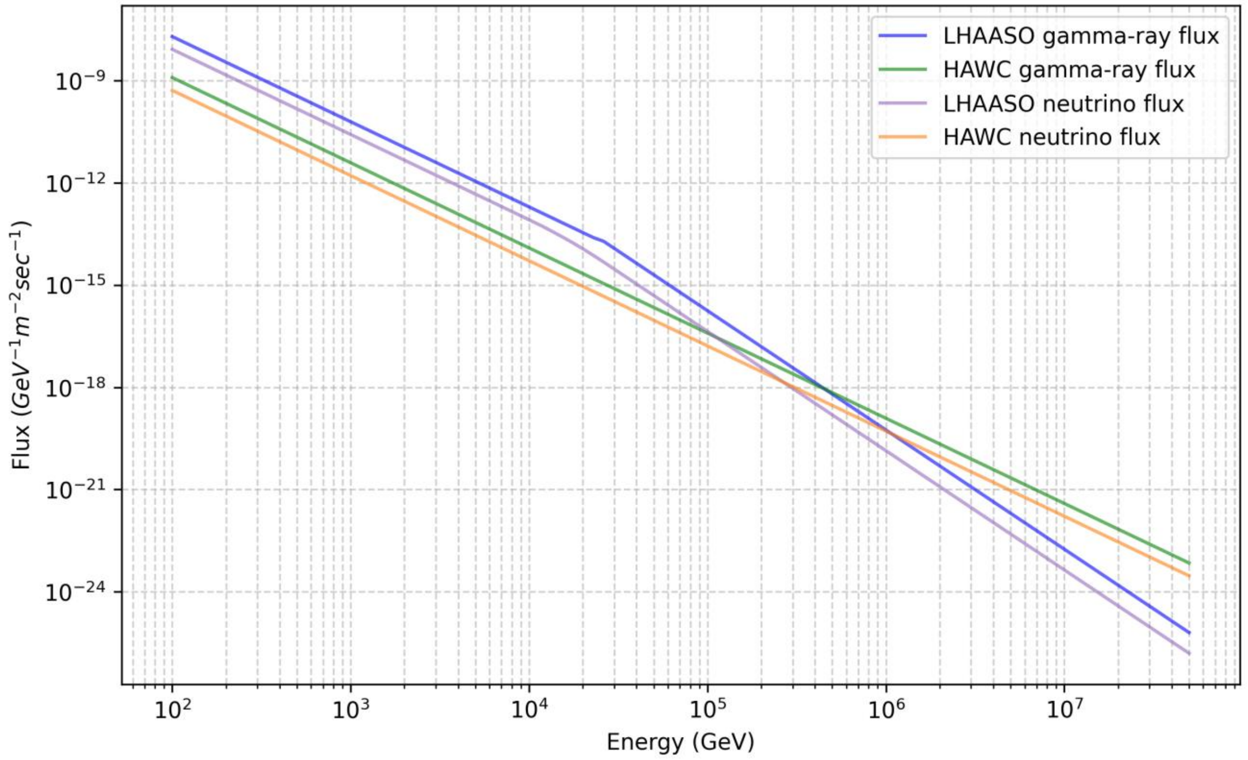
# Gamma-rays Neutrino connection

- In **Villante-Vissani (2008)***, it is developed a model to estimate the neutrino flux from astrophysical sources, using the measured gamma-ray flux. in case of p-p collisions.

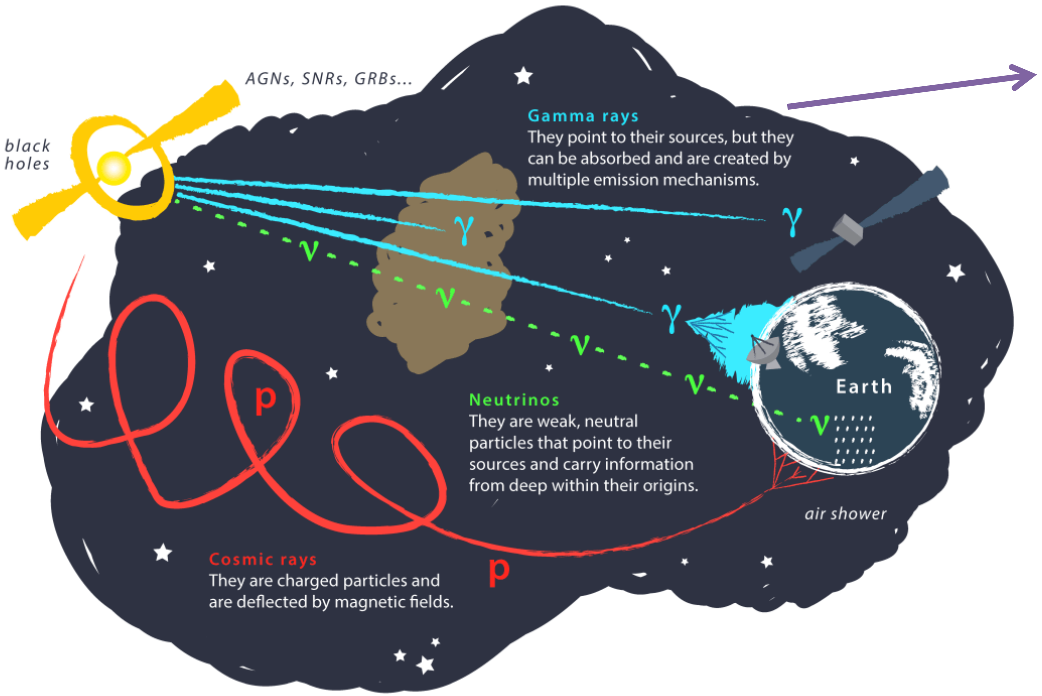
- Such model assumed a full hadronic scenario (p-p collisions).

- The model was later refined by **Mascaretti-Vissani(2019)**** through the inclusion of the most recent neutrino oscillation parameters

$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} \Phi_\gamma(E_\gamma) K_{\nu\gamma}(\frac{E_\nu}{E_\gamma})$$



# Gamma-rays absorption




Villante-Vissani model can be modified to take into account gamma-ray absorption dued to pair-production mechanism

$$\gamma_{src} + \gamma_{cmb/isrf} \rightarrow e^{+} + e^{-}$$

$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} \Phi_\gamma^{src}(E_\gamma) K_{\nu\gamma}\left(\frac{E_\nu}{E_\gamma}\right)$$

$$\Phi_\gamma^{obs}(E_\gamma) = \Phi_\gamma^{src}(E_\gamma)$$

$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} \frac{\Phi_\gamma^{obs}(E_\gamma)}{e^{-\tau}} K_{\nu\gamma}\left(\frac{E_\nu}{E_\gamma}\right)$$

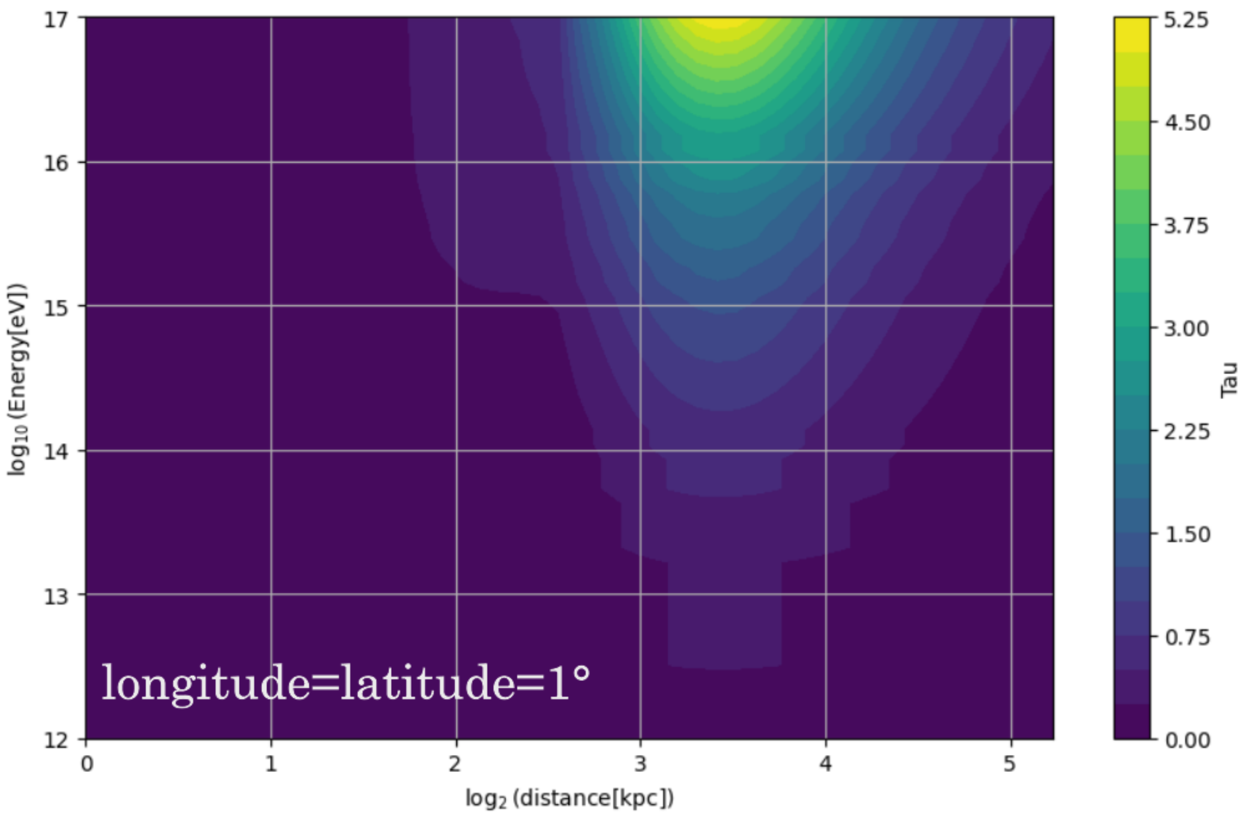
$$\Phi_\gamma^{obs}(E_\gamma) = \Phi_\gamma^{src}(E_\gamma) \times e^{-\tau}$$

# Absorption Factor Parameterization

$e^{-\tau} \rightarrow \tau = \tau(\mathrm{E}, \delta, \mathrm{RA}, \mathrm{D})$

E = energy
δ = declination
RA = Right Ascension
D =Distance

- The **optical depth τ** for pair production mechanism dued to the interaction with photon from **Cosmic Micro-wave Background** or from the **Inter Stellar Radiation Field** .
- It could be parameterized as done by **Lipari-Vernetto (2016)** as a function of the source position and distance.

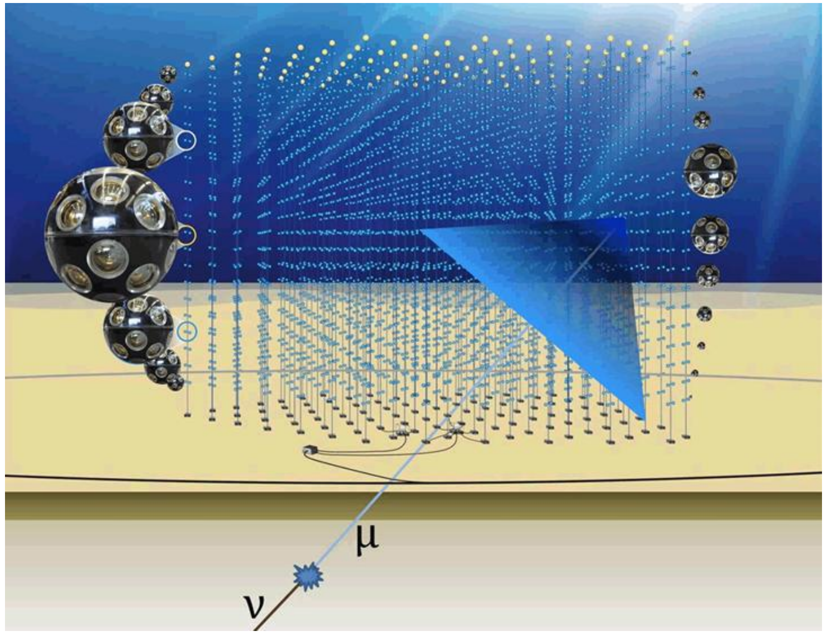





*P.Lipari S.Vernetto Phys. Rev. D 94, 063009 (2016)

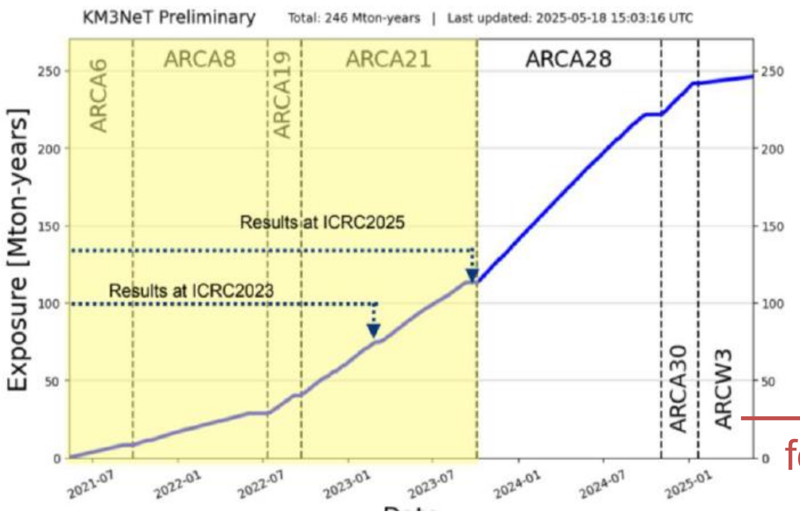
# KM3NeT Network

Location = Mediterranean Sea
It will consits of building blocks of 115 strings each, with 18 Digital Optical Modules per string. In every DOM, are located 31 Photo-multipliers (PMT)



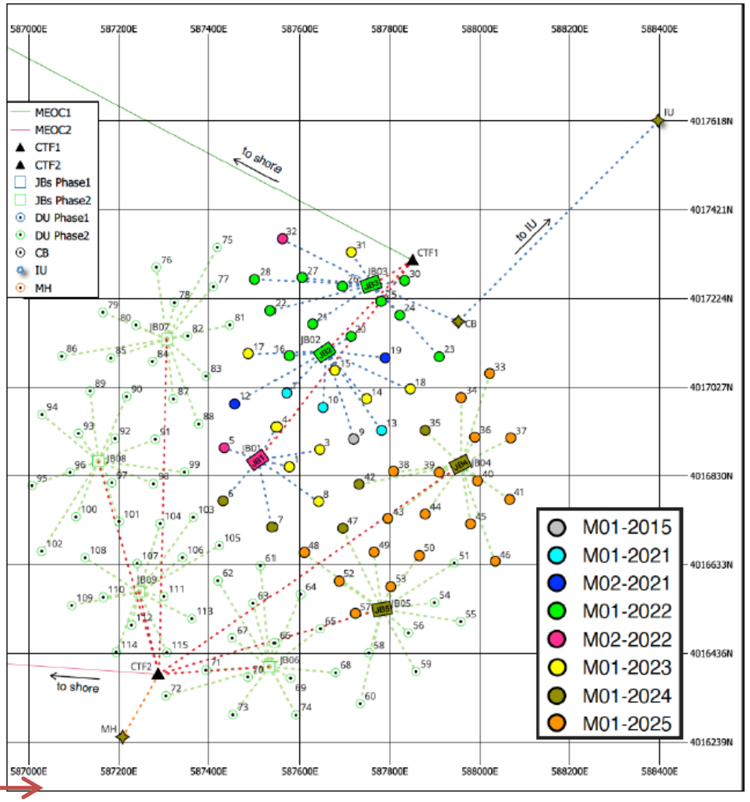

**KM3NeT/ARCA**

- 2 BBs for neutrino astronomy (located near Capo Passero, Italy).
- Vertical distance between OMs of 36 m, lateral distance between adjacent strings of 90 m.
- Neutrino energy range TeV-PeV

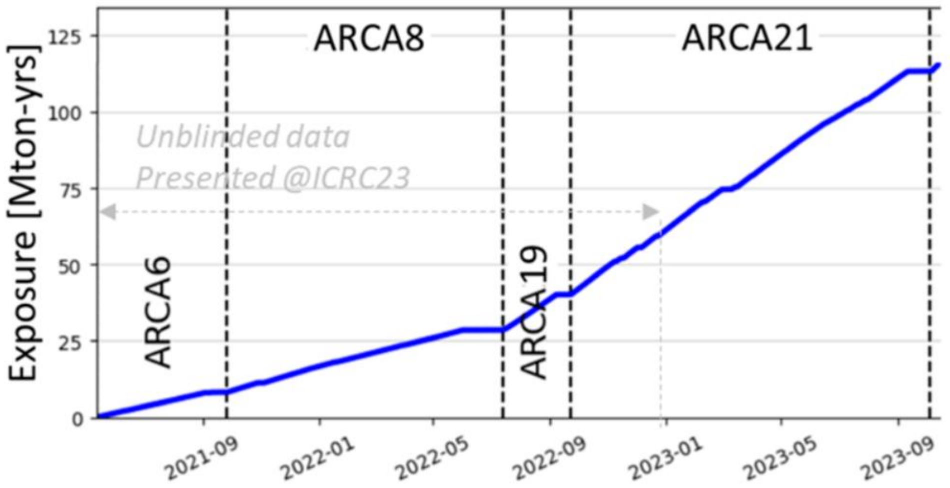



footprint

## KM3NeT/ARCA51



# Data sample and Event selection

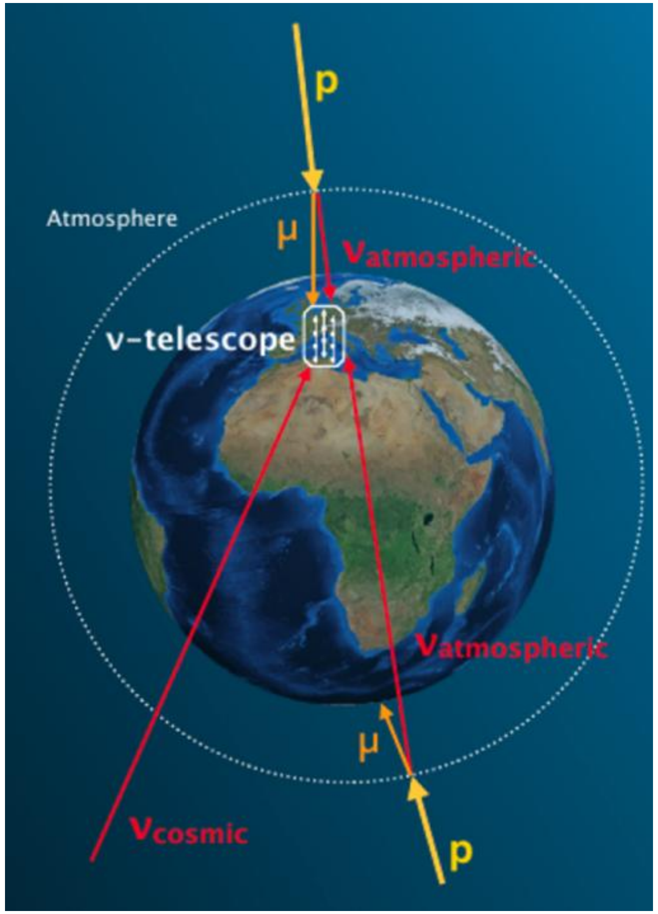



Only track-like events

In total, 640 days of data

Detector lifetimes:

- ARCA6 → 7949520.0 sec → 92 days
- ARCA8 → 18346400.0 sec → 212 days
- ARCA19 → 4181527.4 sec → 48 days
- ARCA21 → 24830910.5 sec → 287 days




Signal definition: A cosmic neutrino with an outgoing muon reconstructed better than 1°.

Event selection criteria:

1. select horizontal/up-going tracks,
2. select event with high number of hits used in the reconstruction,
3. select events with good fit quality (based on the likelihood of the reconstruction).

Additional selection criteria for the dominant ARCA19-21 sample:

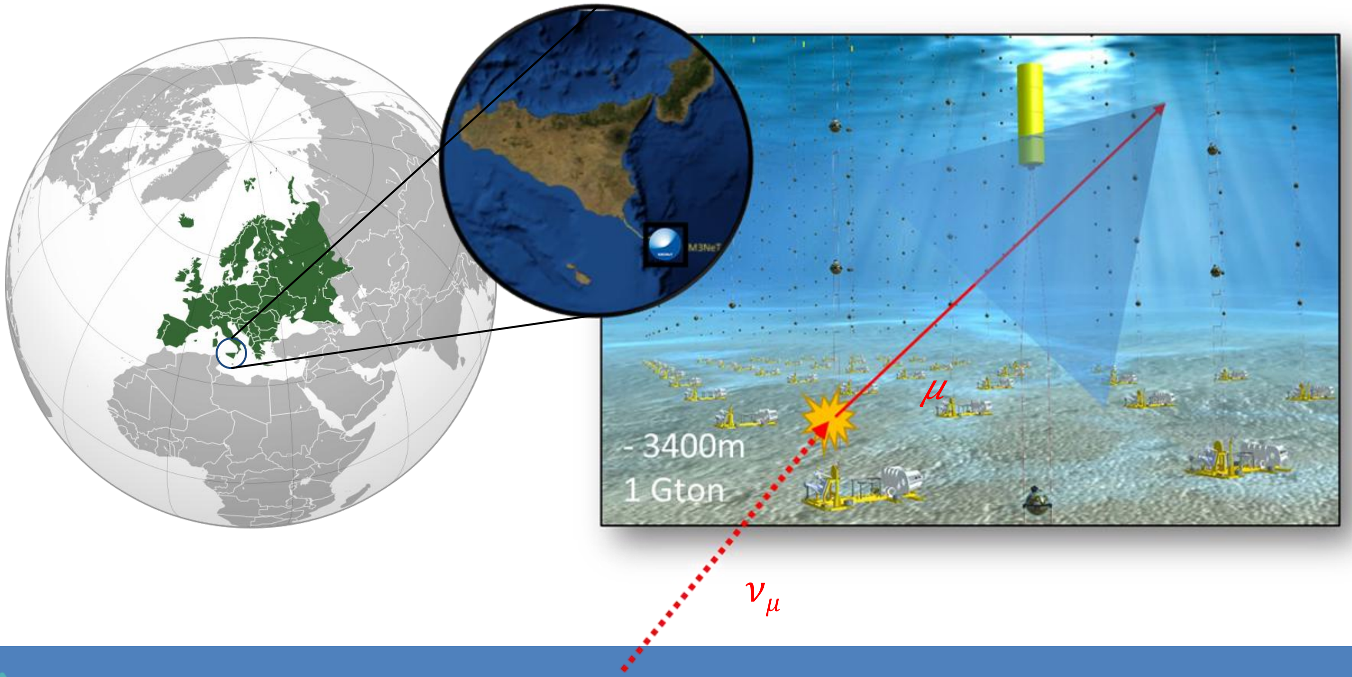
1. select events with long track length,
2. select events estimated to have a small error in its reconstructed direction,
3. boosted decision tree.

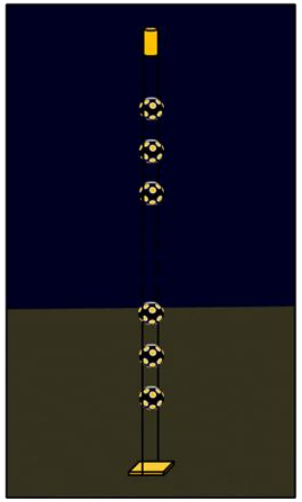
Background estimation: made with scrambled data.

Very High Energy event KM3-230213A* removed from data sample.

# Full ARCA detector prospects

- The ARCA230 performance can be studied using the most updated simultaion*.
- Theoretical methods are used to modelize the signal.
- For this work, only track-like events are considered.

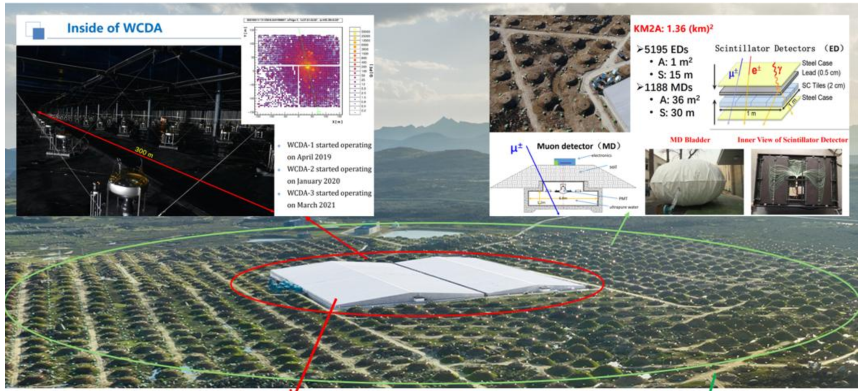


*T. van Eeden Eur. Phys. J. C 84, 885 (2024)

# Candidate sources

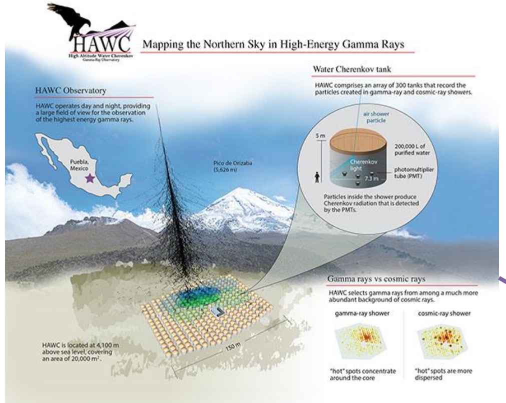
- 26 sources selected from the first LHAASO catalogue*.
- 6 sources selected from the third HAWC catalogue**.




$$\Phi_\gamma(E) = \begin{cases} N_{\rm WCDA}\left(\frac{E}{3TeV}\right)^{-\Gamma_{\rm WCDA}} \cdot \frac{10^{-13}}{TeV\cdot cm^2\cdot sec}, & E < 25TeV \\ N_{\rm KM2A}\left(\frac{E}{50TeV}\right)^{-\Gamma_{\rm KM2A}} \cdot \frac{10^{-16}}{TeV\cdot cm^2\cdot sec}, & E > 25TeV \end{cases}$$

| # | Source Name | RA (°) | Decl (°) | Association (°) |
|---|---|---|---|---|
| 1 | 1LHAASOJ1809-1918u | 272.38 | -19.3 | HESSJ1809-193(0.24) |
| 2 | 1LHAASOJ1814-1719u* | 273.27 | -17.89 | 2HWCJ1814-173(0.16) |
| 3 | 1LHAASOJ1825-1418 | 276.25 | -14 | HESSJ1825-137(0.56) |
| 4 | 1LHAASOJ1825-1337u | 276.45 | -13.63 | HESSJ1825-137(0.15) |
| 5 | 1LHAASOJ1825-1256u | 276.44 | -12.94 | HESSJ1826-130(0.14) |
| 6 | 1LHAASOJ1813-1245 | 273.36 | -12.75 | HESSJ1813-126(0.07) |
| 7 | 1LHAASOJ1831-1007u* | 277.81 | -9.83 | HESSJ1831-098(0.25) |
| 8 | 1LHAASOJ1834-0831 | 278.44 | -8.38 | HESSJ1834-087(0.24) |
| 9 | 1LHAASOJ1837-0654u | 279.31 | -6.86 | HESSJ1837-069(0.05) |
| 10 | 1LHAASOJ1839-0548u | 279.79 | -5.81 | LHAASOJ1839-0545(0.17) |
| 11 | 1LHAASOJ1841-0519 | 280.21 | -5.23 | HESSJ1841-055(0.25) |
| 12 | 1LHAASOJ1843-0335u | 280.91 | -3.6 | HESSJ1843-033(0.06) |
| 13 | 1LHAASOJ1848-0153u | 282.02 | -1.78 | HESSJ1848-018(0.11) |
| 14 | 1LHAASOJ1850-0004u* | 282.89 | -0.07 | HESSJ1852-000(0.36) |
| 15 | 1LHAASOJ1852+0050u* | 283.10 | 0.84 | 2HWCJ1852+013*(0.55) |
| 16 | 1LHAASOJ1857+0203u | 284.38 | 2.06 | HESSJ1858+020(0.21) |
| 17 | 1LHAASOJ1910+0516* | 287.55 | 5.28 | SS433w1(0.26) |
| 18 | 1LHAASOJ1908+0615u | 287.05 | 6.26 | MGROJ1908+06(0.07) |
| 19 | 1LHAASOJ1912+1014u | 288.38 | 10.5 | HESSJ1912+101(0.10) |
| 20 | 1LHAASOJ1914+1150u | 288.73 | 11.84 | 2HWCJ1914+117*(0.13) |
| 21 | 1LHAASOJ0703+1405 | 105.83 | 14.1 | HWCJ0700+143(0.72) |
| 22 | 1LHAASOJ1922+140 | 290.73 | 14.11 | W51(0.13) |
| 23 | 1LHAASOJ0634+1741u | 98.57 | 17.69 | Geminga(0.54) |
| 24 | 1LHAASOJ0534+2200u | 83.61 | 22.036 | Crab(0.01) |
| 25 | 1LHAASOJ0542+2311u | 85.71 | 23.2 | HAWCJ0543+233(0.21) |
| 26 | 1LHAASOJ0622+3754 | 95.5 | 37.9 | LHAASOJ0621+3755(0.03) |

**Table 1:** List of selected sources from the LHAASO catalogue [2]; for each source, the coordinates (right ascension RA and declination Decl) are reported as well as the estimated extension/width and the associated source (with the distance)




$$\Phi_\gamma(E) = N_0 \left(\frac{E}{7\,\rm TeV}\right)^{-\Gamma}$$

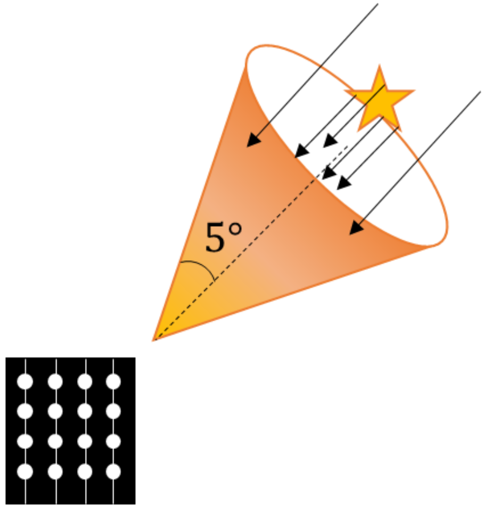
| # | Source Name | RA (°) | Decl (°) | Association |
|---|---|---|---|---|
| 1 | 3HWCJ1757-240 | 269.30 | -24.09 | HESSJ1800-240B |
| 2 | 3HWCJ1803-211 | 270.97 | -21.18 | HESSJ1804-216 |
| 3 | 3HWCJ1849+001 | 282.35 | 0.15 | IGRJ18490-0000 |
| 4 | 3HWCJ1857+027 | 284.33 | 2.80 | HESSJ1857+026 |
| 5 | 3HWCJ0634+067 | 98.66 | 6.73 | HAWCJ0635+070 |
| 6 | 3HWCJ0617+224 | 94.39 | 22.47 | IC443 |

**Table 2:** List of selected sources from the 3rd HAWC catalogue [1]; for each source, the coordinates (right ascension RA and declination Decl) are reported as well as the estimated extension/width and the associated source (with the distance).

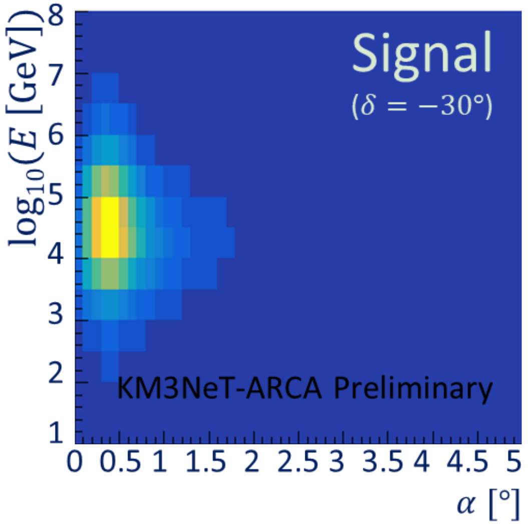
*LHAASO coll. ApJ Supplement Series, 271 (2024) 25 **HAWC coll. (2020) ApJ 905 76

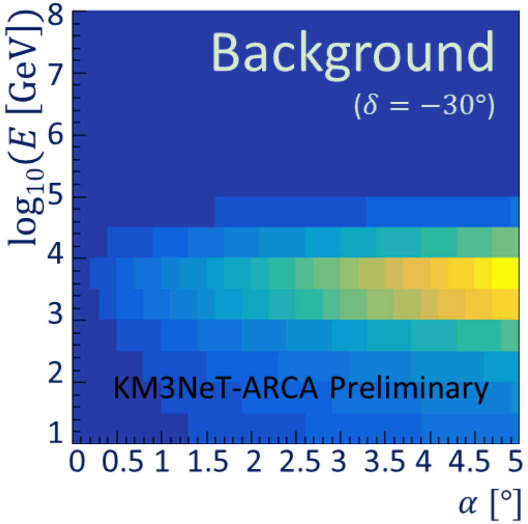
# The analysis

A **binned analysis** is performed for **each candidate sources**. It is checked in a **5 degree** cone around each source whether the **position**, and **energy** distributions are in line with a cosmic neutrino excess. The **log-likelihood** is the Poisson probability of the bin-contents.




KM3NeT/ARCA6-21




$$\lambda = \mathrm{Log}\, L(\xi = \hat{\xi}) - \mathrm{Log}\, L(\xi = 0)$$

$$\mathrm{Log}\, L(\xi) = \sum_{i \in bins} N_i\, \mathrm{Log}(B_i + \xi S_i) - B_i - \xi S_i$$

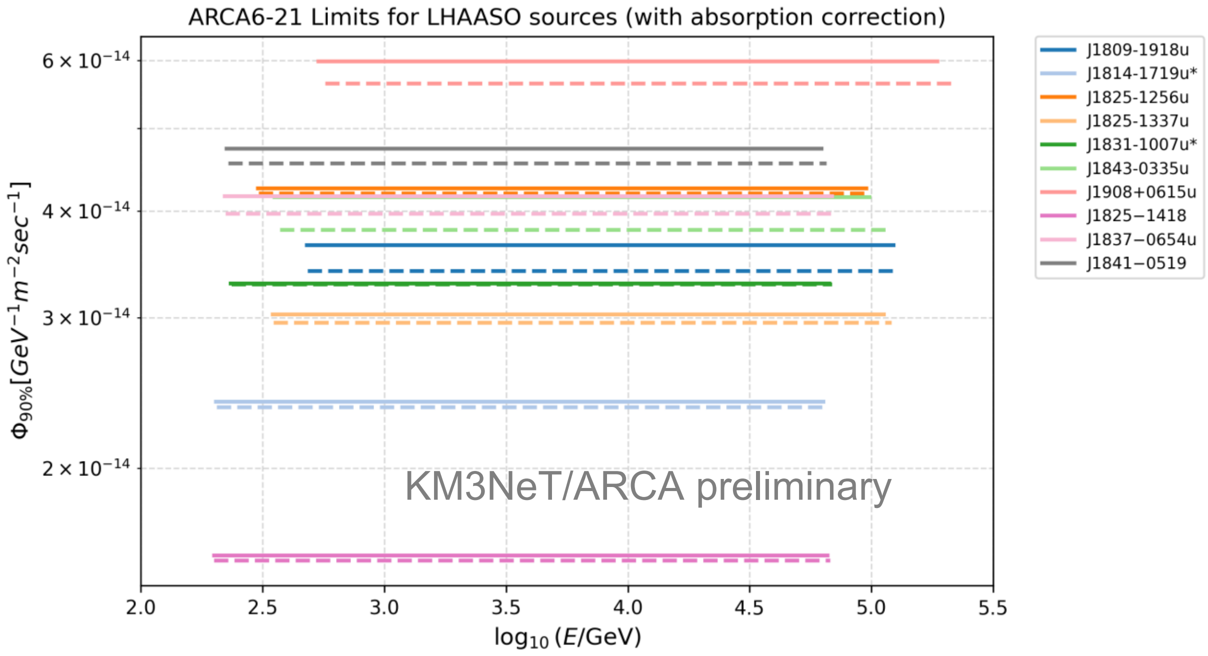
$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} \Phi_\gamma^{src}(E_\gamma) K_{\nu\gamma}\left(\frac{E_\nu}{E_\gamma}\right)$$
$$\Phi_\gamma^{obs}(E_\gamma) = \Phi_\gamma^{src}(E_\gamma)$$

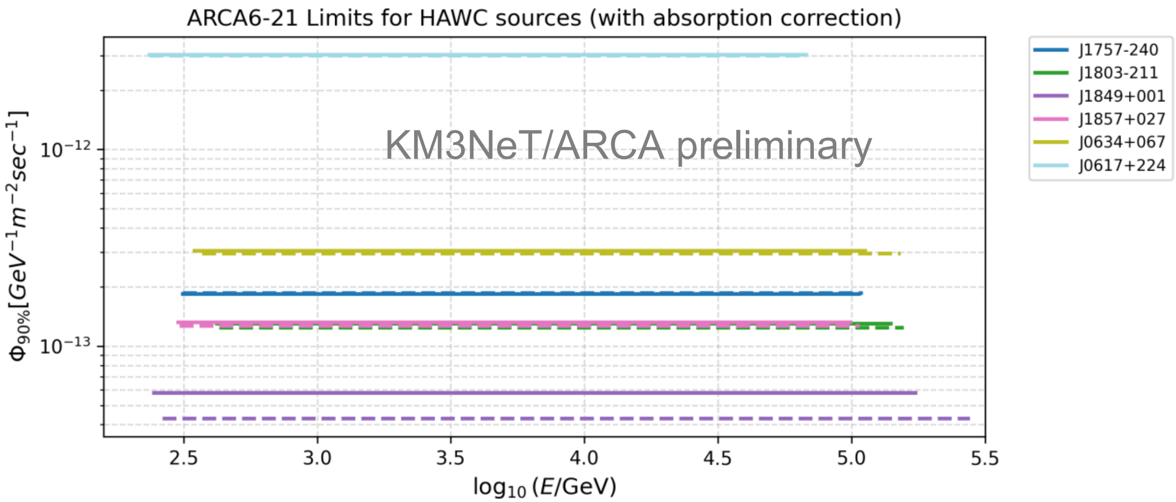
$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} \frac{\Phi_\gamma^{obs}(E_\gamma)}{e^{-\tau}} K_{\nu\gamma}\left(\frac{E_\nu}{E_\gamma}\right)$$
$$\Phi_\gamma^{obs}(E_\gamma) = \Phi_\gamma^{src}(E_\gamma) \times e^{-\tau}$$

# Results:

**Using KM3NeT/ARCA6-21 DATA , no significant signal evidence** is found. The flux **upper limits** are computed as the **energy range** where 90% of the signal is expected:

- With/without absorption correction (dashed/continuous lines).
- 10 sources from the LHAASO catalogue with the best upper limits, the best 3 are **J1825-1418, J1814-1719u*** and **J1825-1337**.
- The best 3 HAWC sources: **J1849+001, J1857+027** and **J1803-211**.
- “Taking into account gamma-ray absorption” could have an impact of 25% for some of the sources.

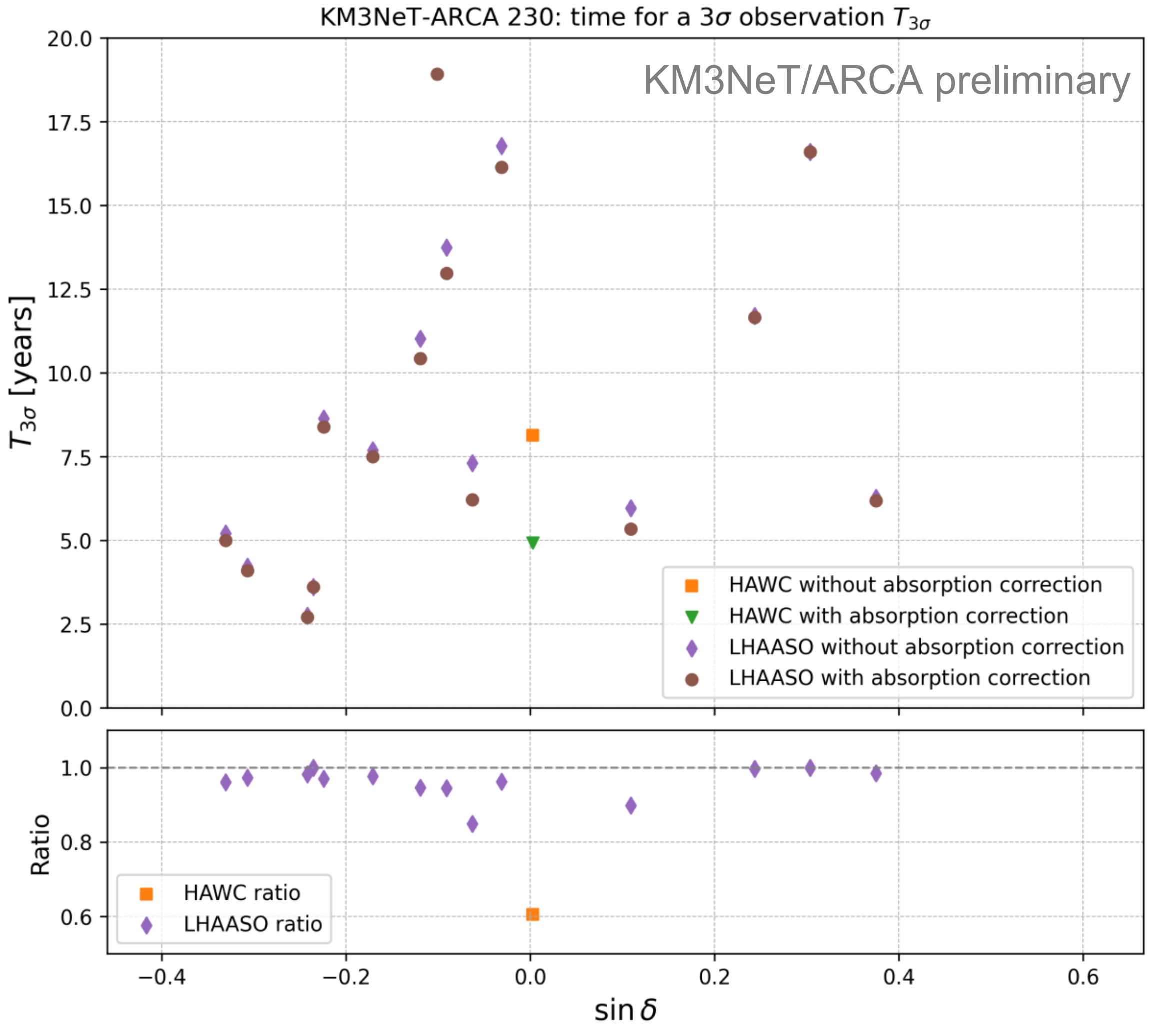


# Results:

**The KM3NeT/ARCA230 Performance**: time to make a 3 sigma significant observation is computed for the full detector.

- For **5 sources**, a 3σ observation could be made in **5 years**, taking into account absorption
- For **10 sources**, a 3σ observation could be made in **10 years**, taking into account absorption.
- For **16 sources,** a 3σ observation could be made in **20 years**, taking into account absorption.



# Conclusions

Gamma-ray observation are used to modelize the neutrino signal from galactic sources

Search in the available data: In the point source search **no significant neutrino source** was found among the list of 32 checked candidate sources. Upper limits are then computed

- The best 3 sources from the LHAASO catalogue: **J1825-1418, J1814-1719u*** and **J1825-1337**.
- The best 3 sources from the HAWC catalogue: **J1849+001, J1857+027** and **J1803-211**.

Complete detector prospects: in the future KM3NeT/ARCA230 would be able to make significant observation for many of the considered sources.

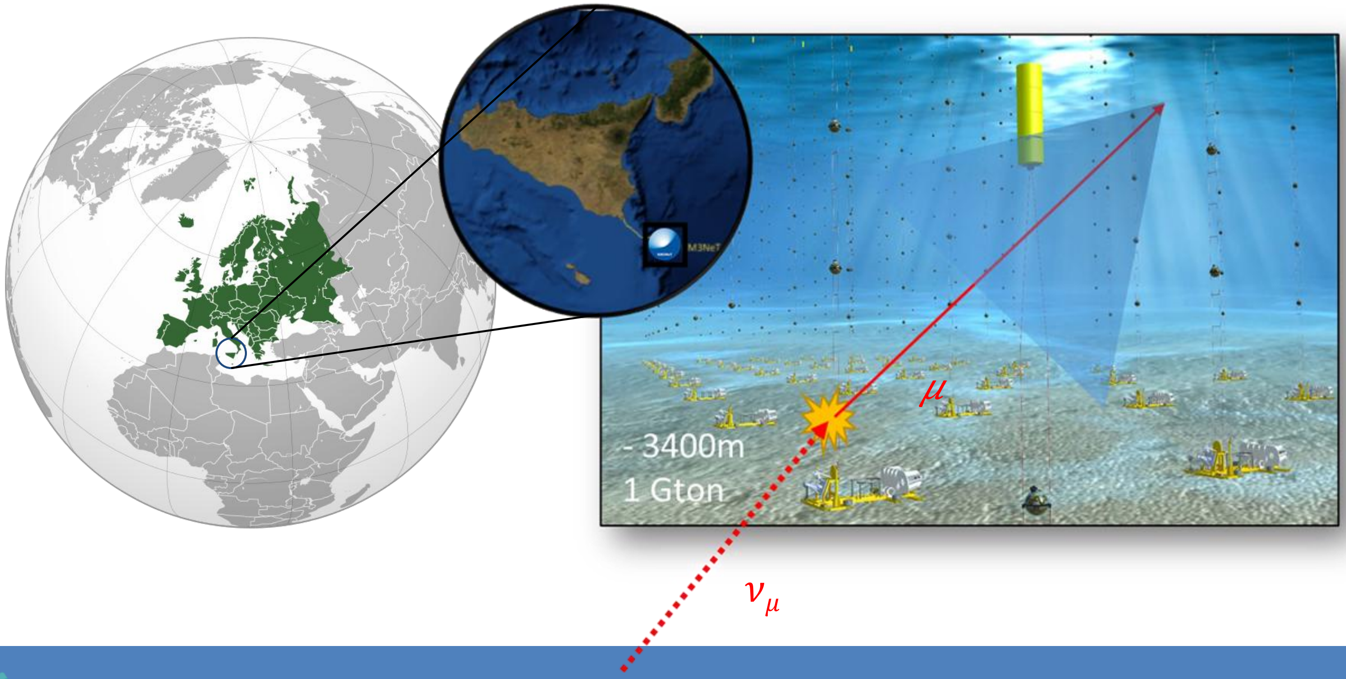
**With the rapid growth of KM3NeT/ARCA, and data of sept 2023-today still to be included in the analysis, the results are expected to significantly improve in the near future.**

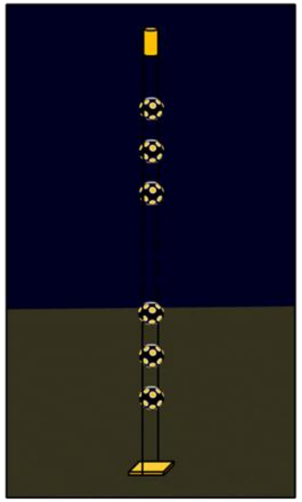
Thanks for the attention.

# Backup Slides

# The KM3NeT/ARCA detector

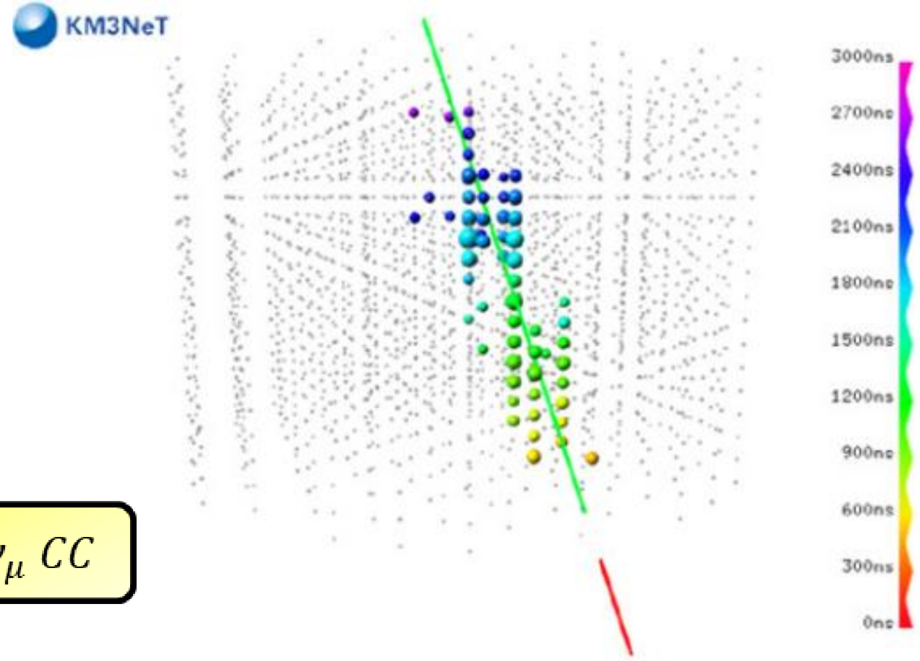
KM[3] Neutrino Telescope / Astroparticle Research with Cosmics in the Abyss is a **neutrino observatory**, currently being built at the bottom of the Mediterranean Sea. It can do **multi-flavour** astronomy ($\nu_e$, $\nu_\mu$, $\nu_\tau$), will have **sub-degree** angular resolution, is sensitive in a **large energy range** [MeV - PeV], and can probe many **different type of $\nu$-sources**. Its location in the Northern hemisphere provides a **good view of the Galactic Region**.



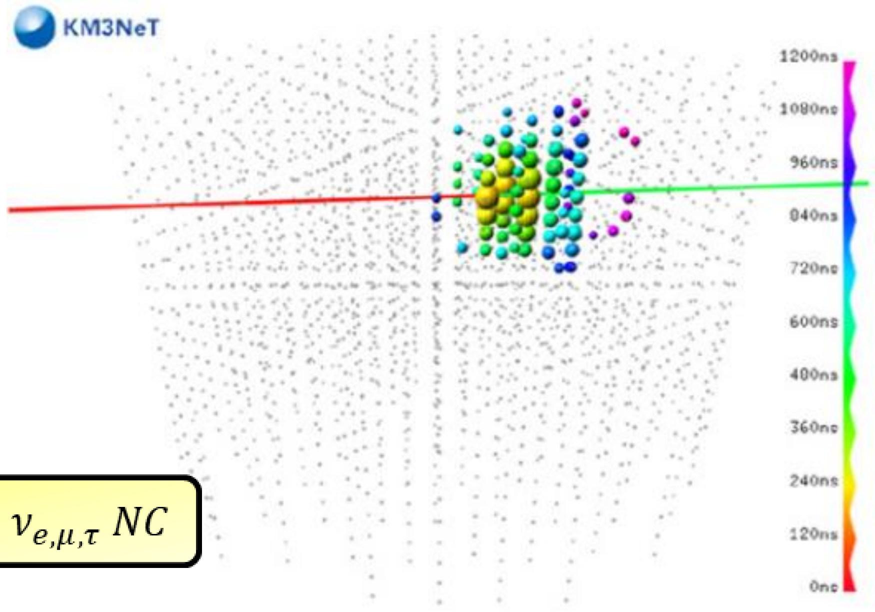
# Event Topology in a Neutrino Telescope:

## Track-like




$\nu_\mu$ $CC$

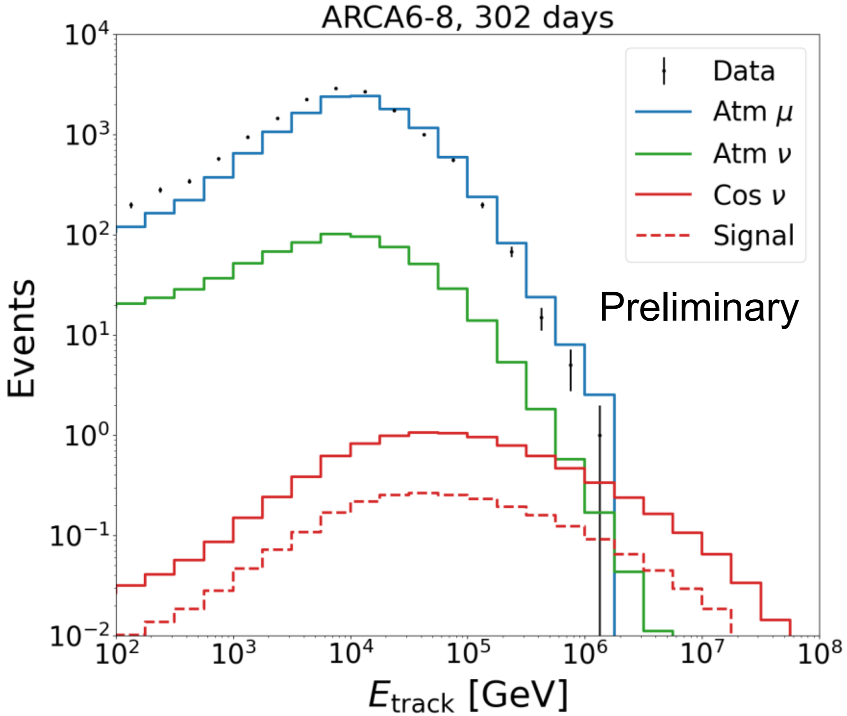
## Shower-like




$\nu_e$ $CC$ and $\nu_{e,\mu,\tau}$ $NC$

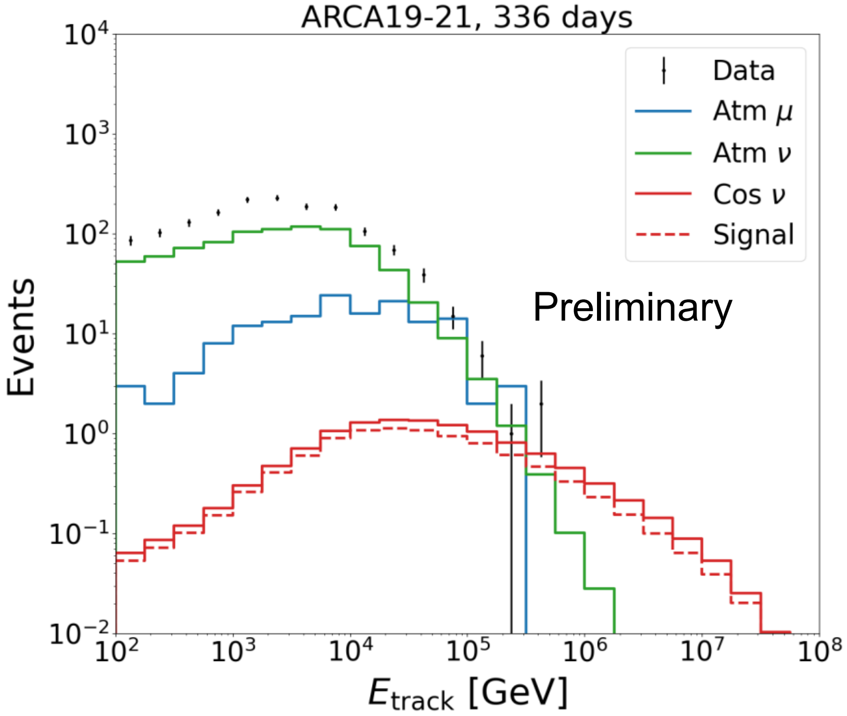
# Data sample after event selection

Data are taken with 6 - 21 lines, between May 2021 and Sept. 2023. After event selection, the **dominant ARCA19-21 data sample** has a muon contamination of 15%. A cosmic neutrino flux of $\phi_{\nu+\bar{\nu}} = 1.2 \cdot 10^{-4} (E_\nu / \text{GeV})^2$ per flavour yields **21.4 cosmic neutrino events** in the full ARCA6-21 sample, of which 12.1 contain a **muon** and are reconstructed



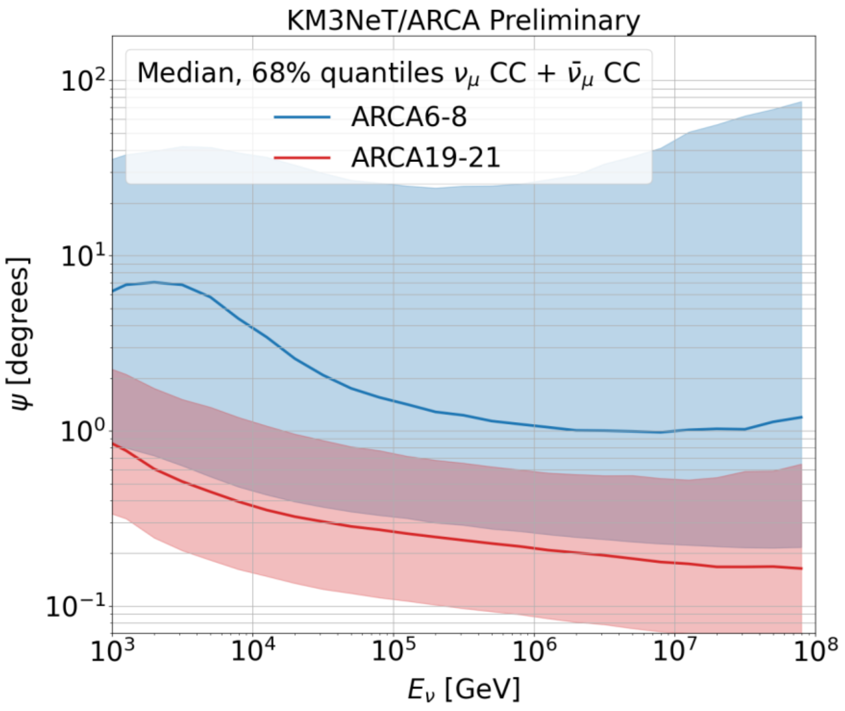

| KM3NeT dataset | Nº events |
|---|---|
| ARCA 6 | 4205 |
| ARCA 8 | 11537 |
| ARCA 19 | 182 |
| ARCA 21 | 1361* |

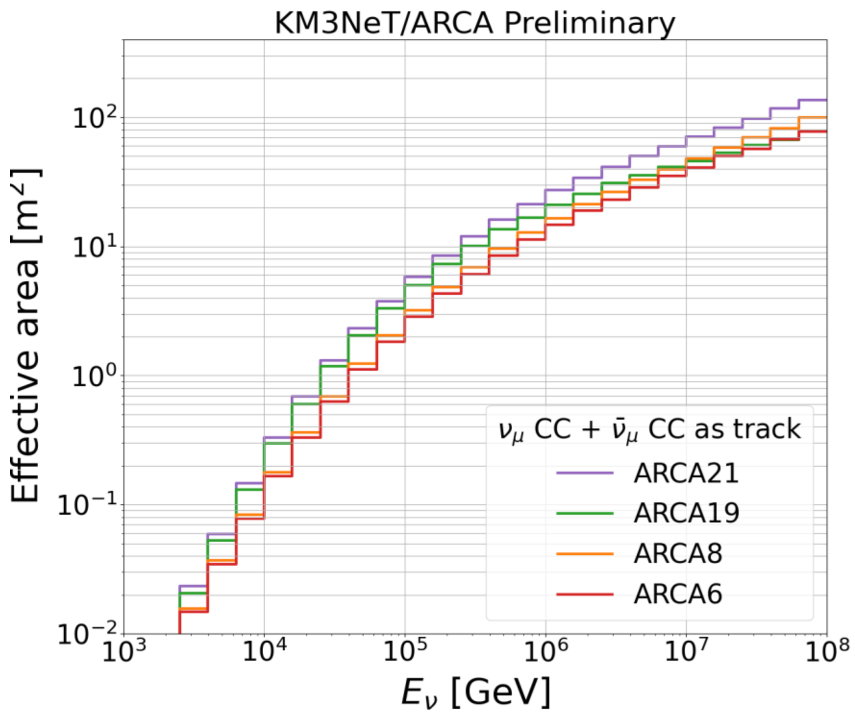
** KM3-230213A removed*



# Detector performance

The **median angular uncertainty** for ARCA6-8 is < 2° above 100 TeV, this improved significantly to < 0.3° for ARCA19-21, and is expected to improve further down to < 0.1° for the full detector (ARCA230[*])



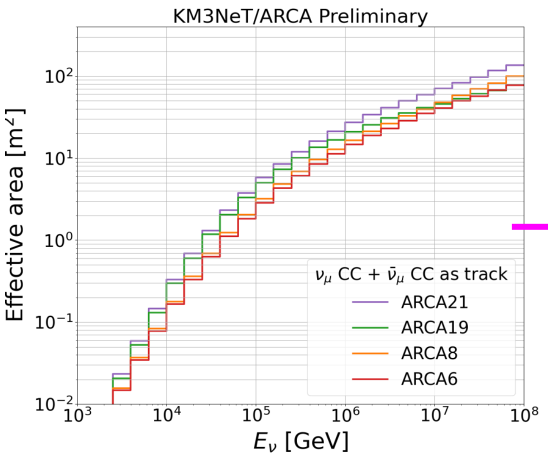



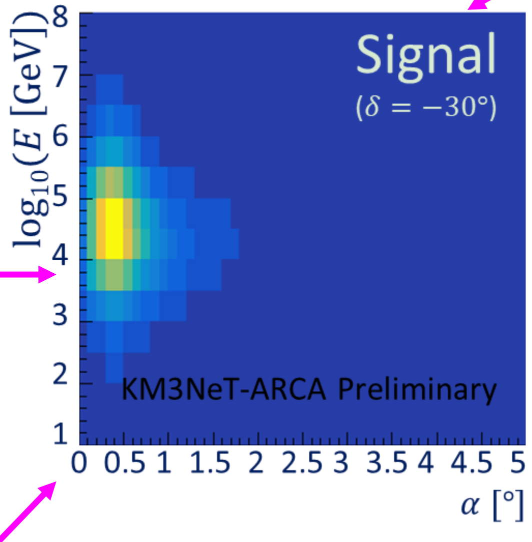


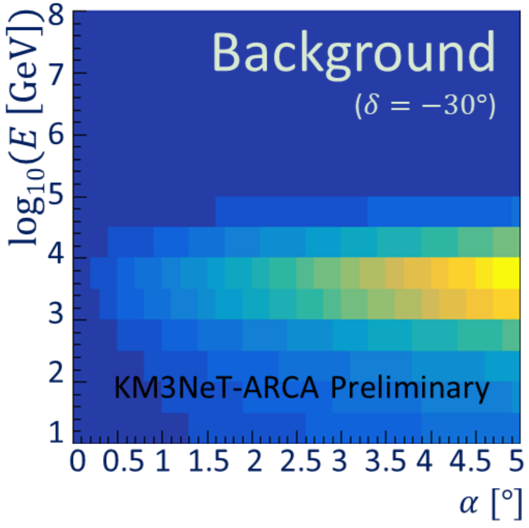
* KM3NeT Collaboration: "Astronomy potential of KM3NeT/ARCA." The European Physical Journal C 84.9 (2024): 885.

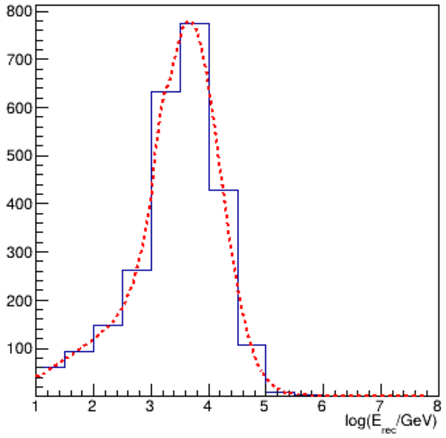
# Binned Likelihood: basic idea

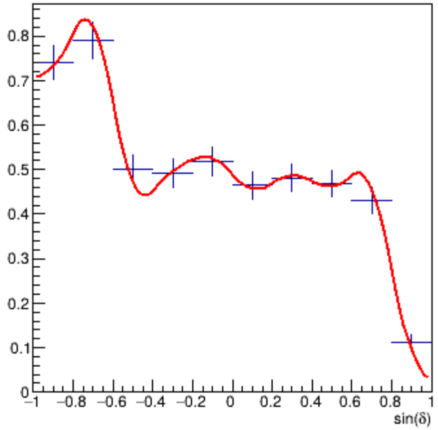
$$\text{Log}\, L(\xi) = \sum_{i \in bins} N_i\, \text{Log}(B_i + \xi S_i) - B_i - \xi S_i$$




$$\Phi_{\nu+\bar{\nu}} \propto E^{-\gamma}$$

$\gamma = 2.0$
$\gamma = 2.5$
$\gamma = 3.2$