



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

Vittorio Parisi

vparisi@ge.infn.it



Barbara Caiffi

barbara.caiffi@ge.infn.it



Vladimir Kulikovskiy

adimir.kulikovskiy@ge.infn.it



Francisco Salesa Greus

Paco.Salesa@ific.uv.es



Matteo Sanguineti

Matteo.Sanguineti@ge.infn.it



List of Contents:

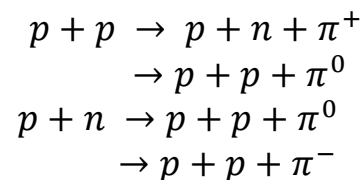
- High Energy Gamma rays Neutrinos Connection:
 - how to modelize the neutrino signal from a source using the gamma-ray observations.
- The KM3NeT/ARCA detector:
 - how to detect high energy astrophysical neutrino.
- Point-like (extended) source search:
 - how to analyse data to search for neutrino signal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

Introduction

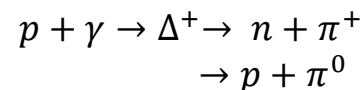
Neutrino sources are **cosmic ray accelerators**.

The two main mechanisms of high-energy neutrino production are:

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



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

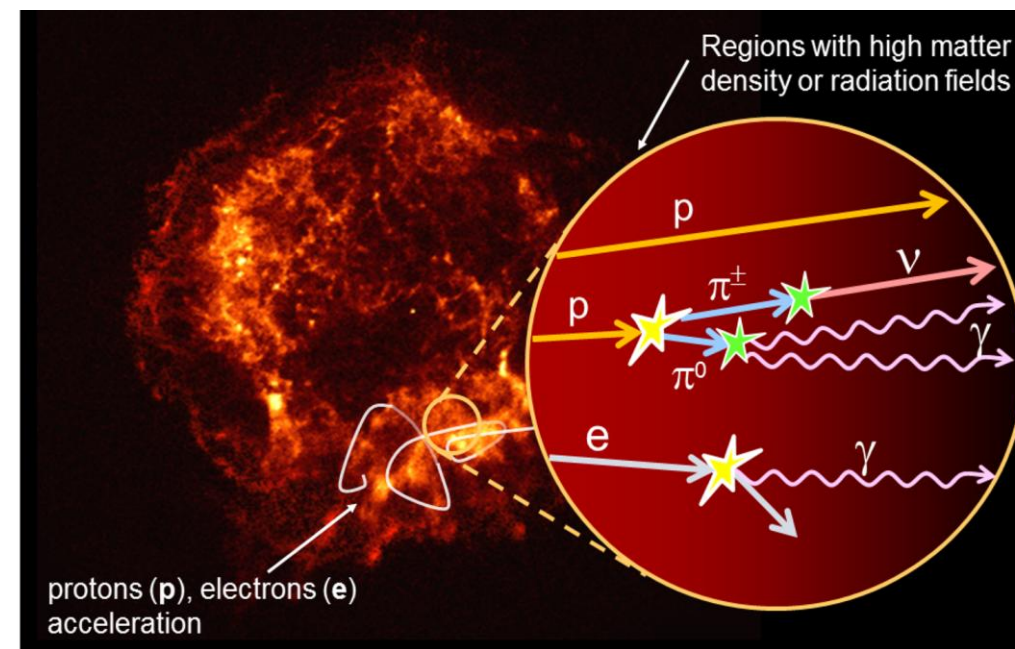


Neutrinos are produced in the decay of the charged pions:



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

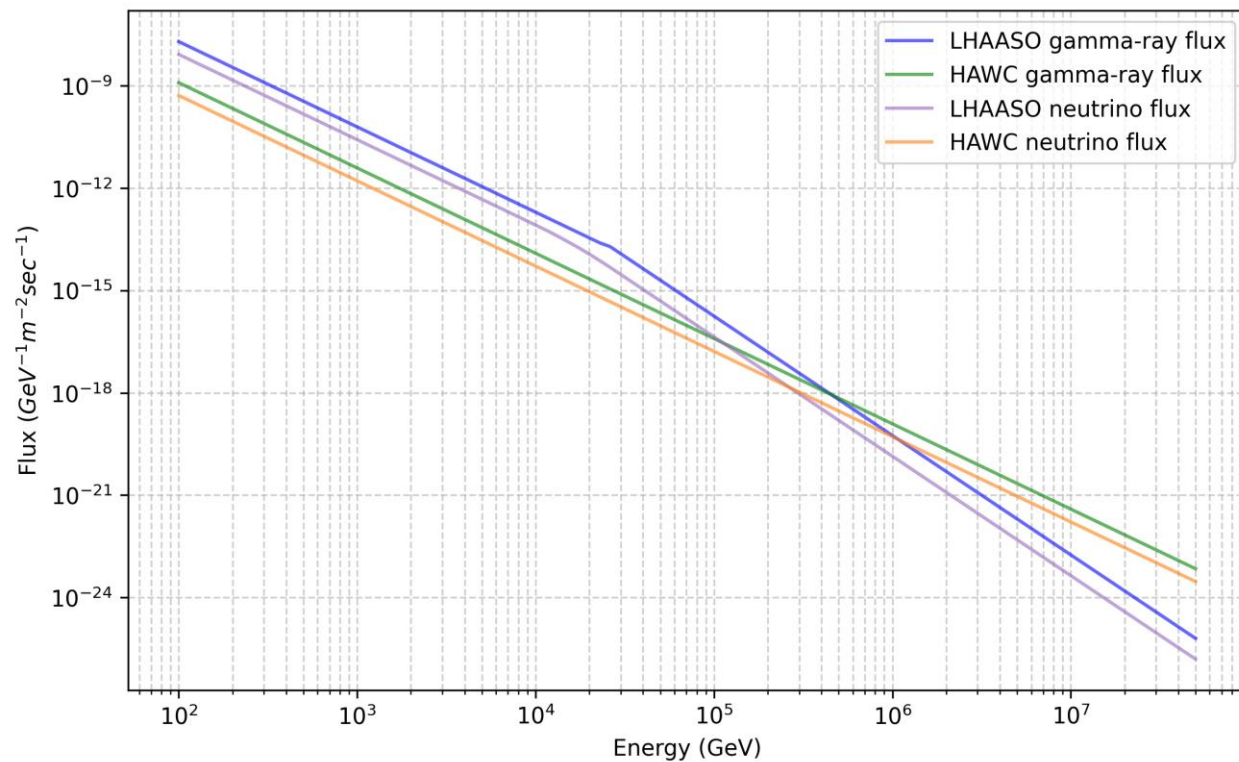
Such high energy gamma-rays could be detected by high altitude gamma observatories like HAWC or LHAASO, while the neutrino component could be studied by neutrino telescopes as KM3NeT.



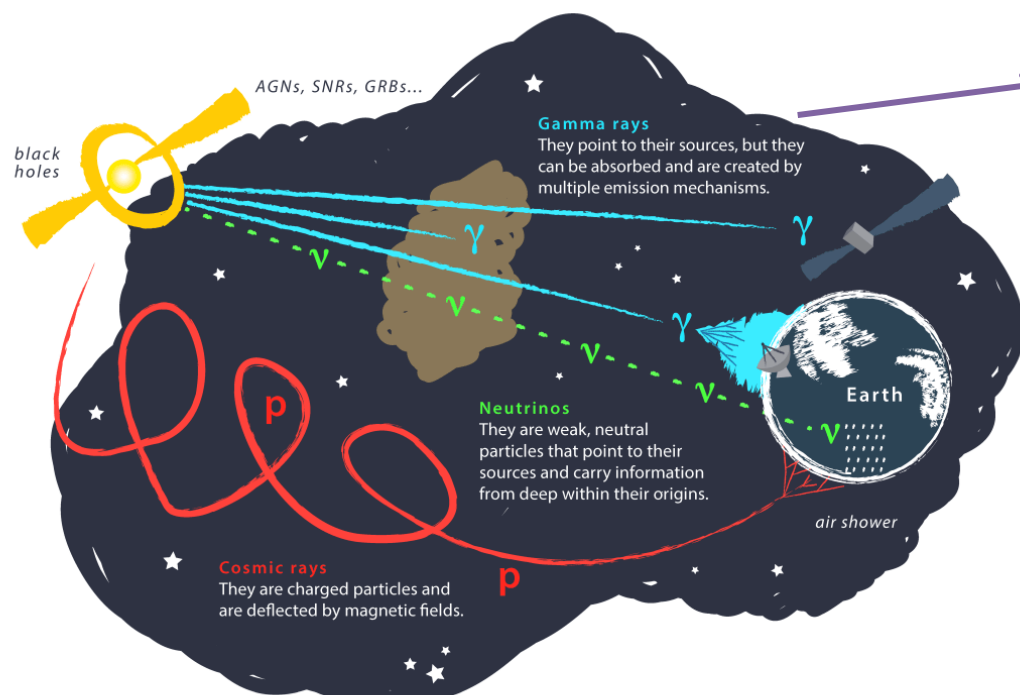
Gamma-rays Neutrino connection

- 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

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



Gamma-rays absorption



Villante-Vissani model can be modified to take into account gamma-ray absorption due 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

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

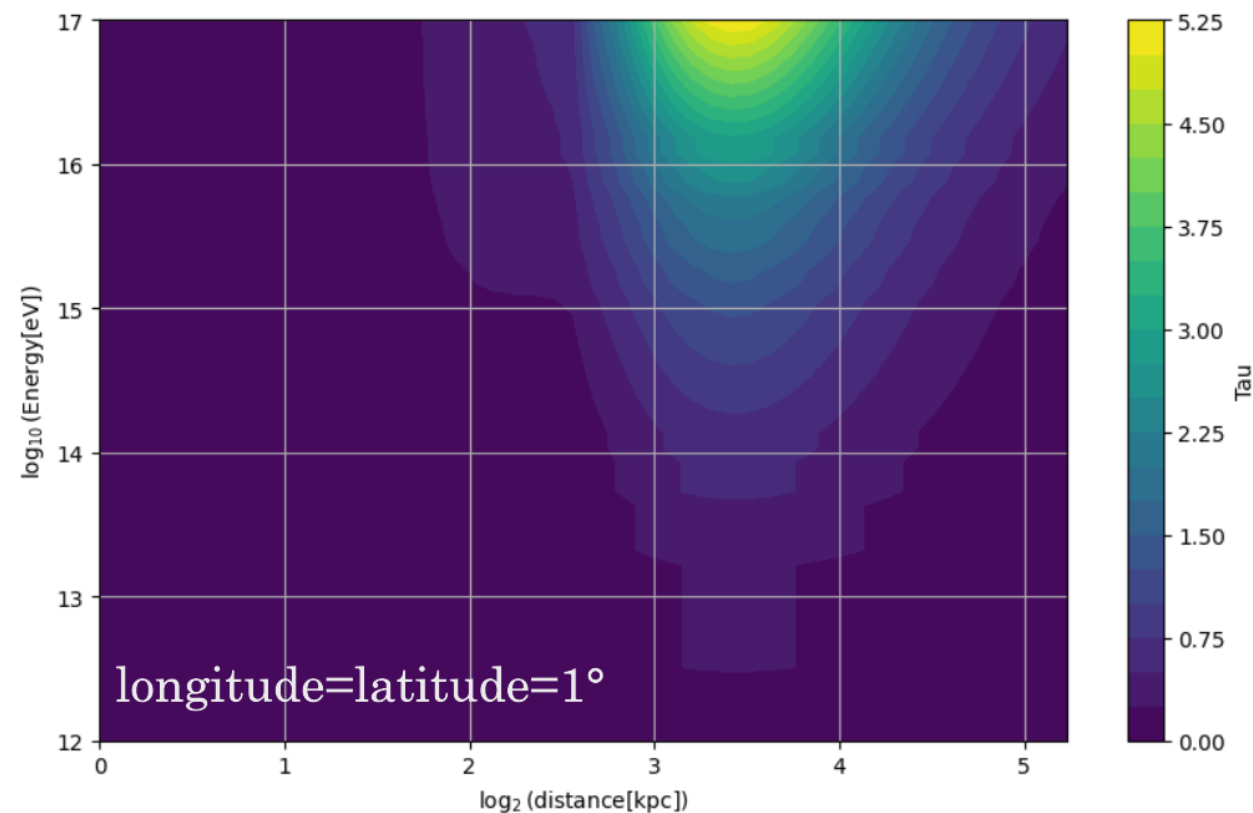
E = energy

δ = declination

RA = Right Ascension

D = Distance

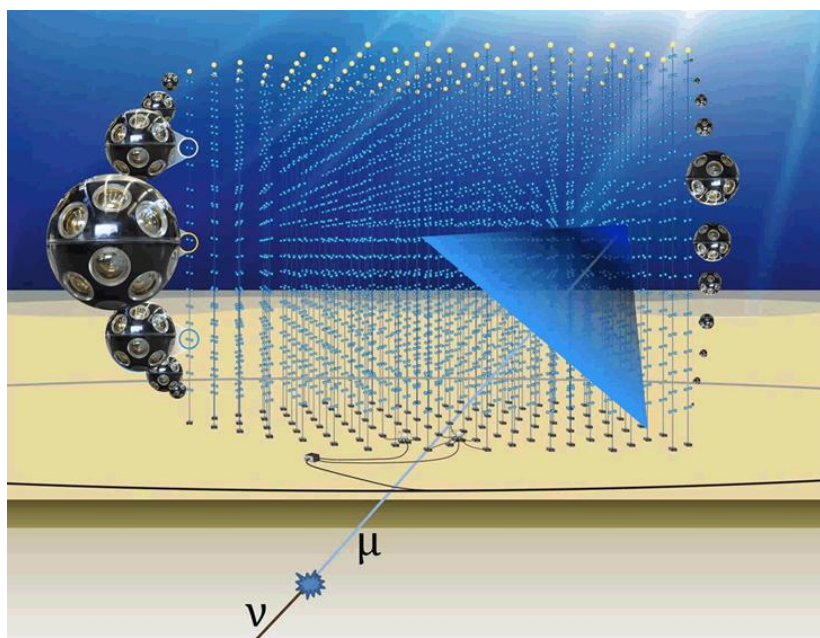
- The **optical depth** τ for pair production mechanism due to the interaction with photon from **Cosmic Microwave Background** or from the **Inter Stellar Radiation Field**.
- It could be parameterized as done by **Lipari-Vernetto (2016)** as a function of the source position and distance.



KM3NeT Network

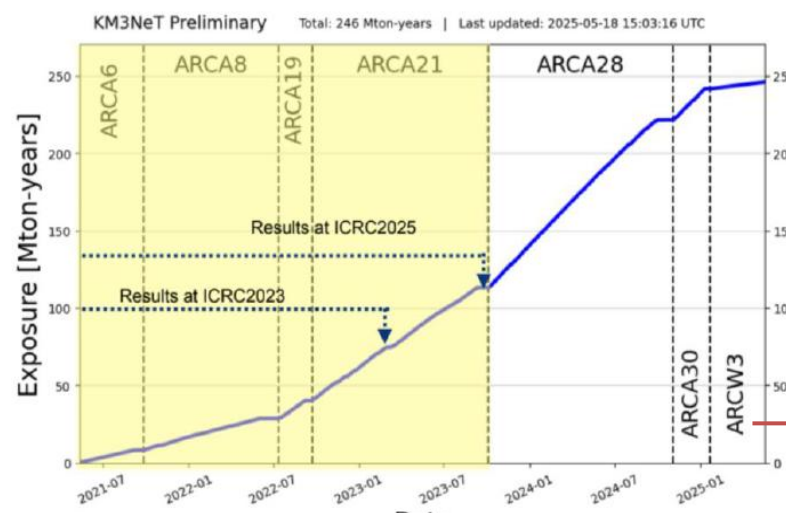
Location = Mediterranean Sea

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

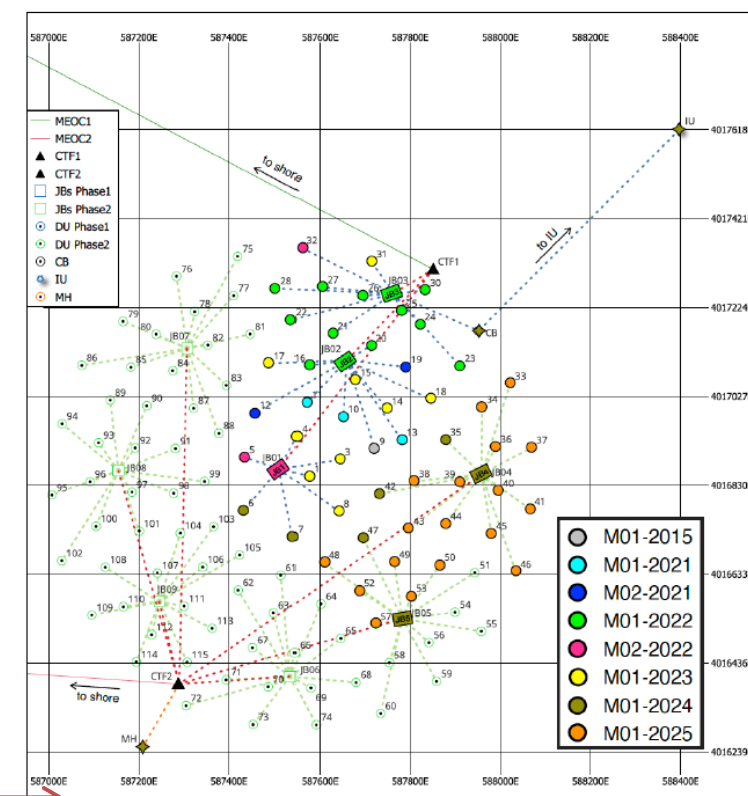


KM3NeT/ARCA

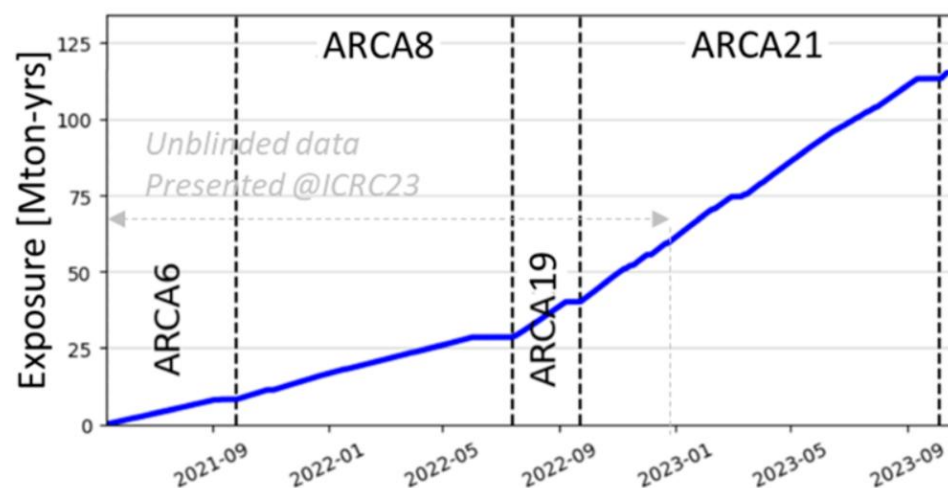
- 2 BBs for neutrino astronomy (located near Capo Passero, Italy).
- Vertical distance between OMs of 36 m, lateral distance between adjacent strings of 90 m.
- Neutrino energy range TeV-PeV



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:

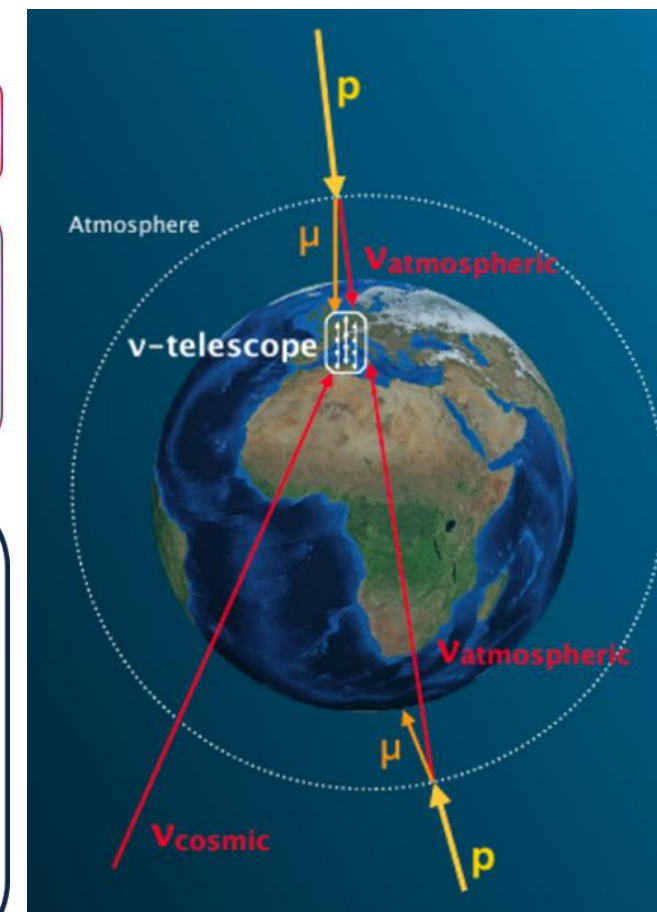
1. select horizontal/up-going tracks,
2. select event with high number of hits used in the reconstruction,
3. select events with good fit quality (based on the likelihood of the reconstruction).

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.

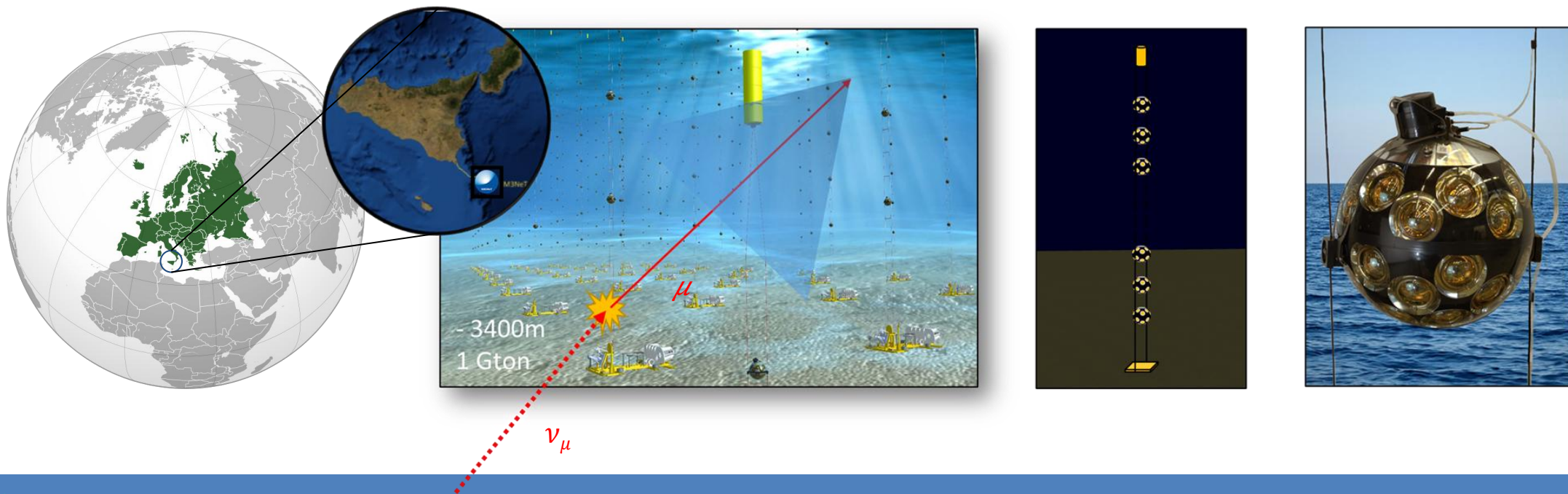
Background estimation: made with scrambled data.

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



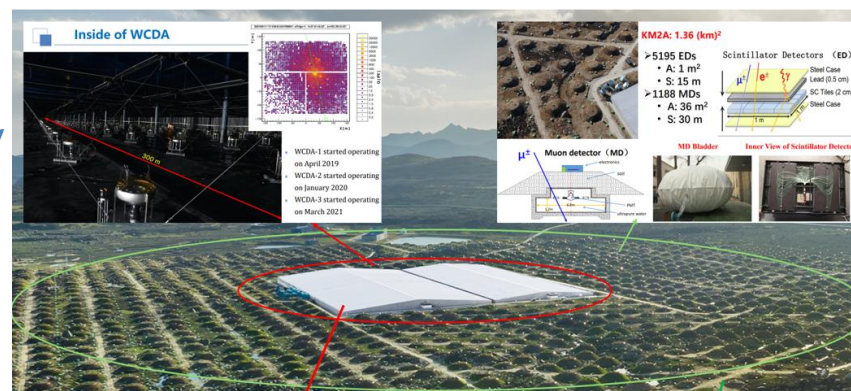
Full ARCA detector prospects

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

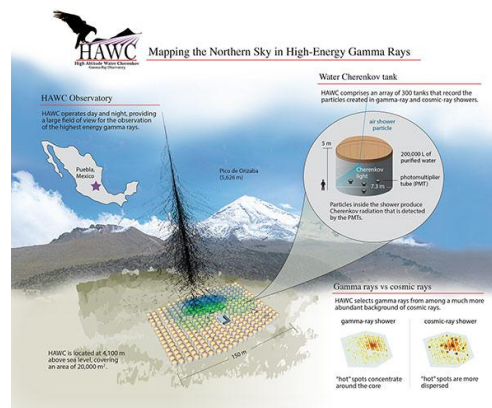


Candidate sources

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



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



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

#	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)

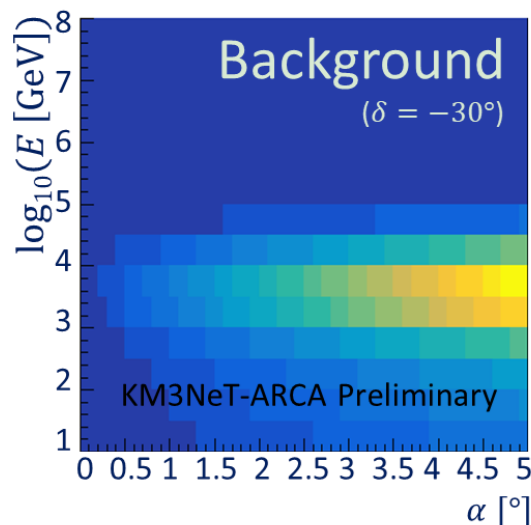
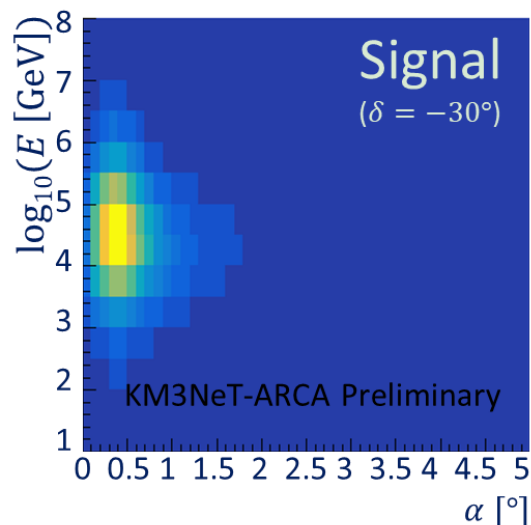
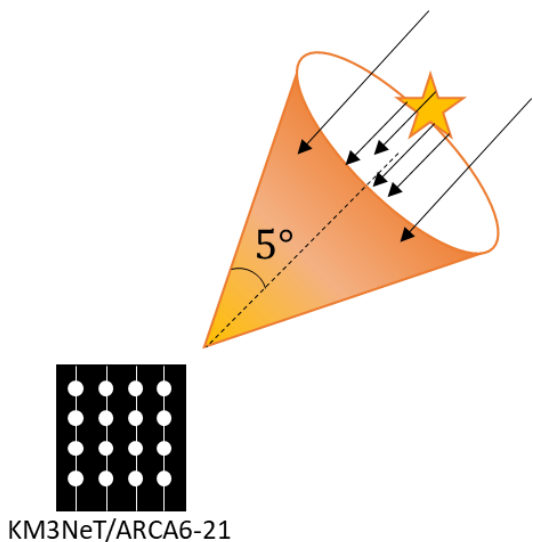
Table 1: List of selected sources from the LHAASO catalogue [2]; for each source, the coordinates (right ascension RA and declination Decl) are reported as well as the estimated extension/width and the associated source (with the distance)

#	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).

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.



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

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

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

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

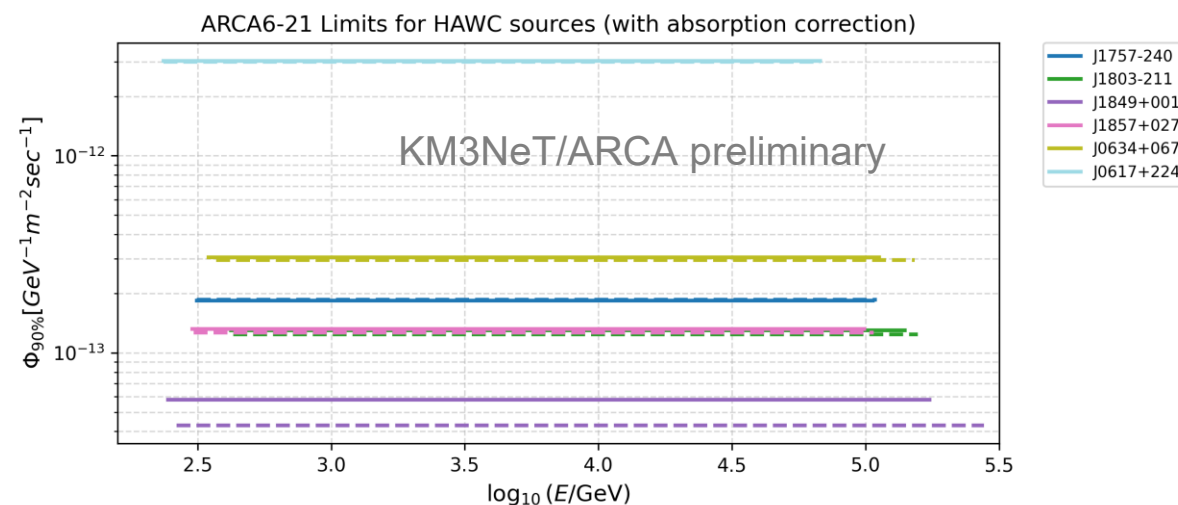
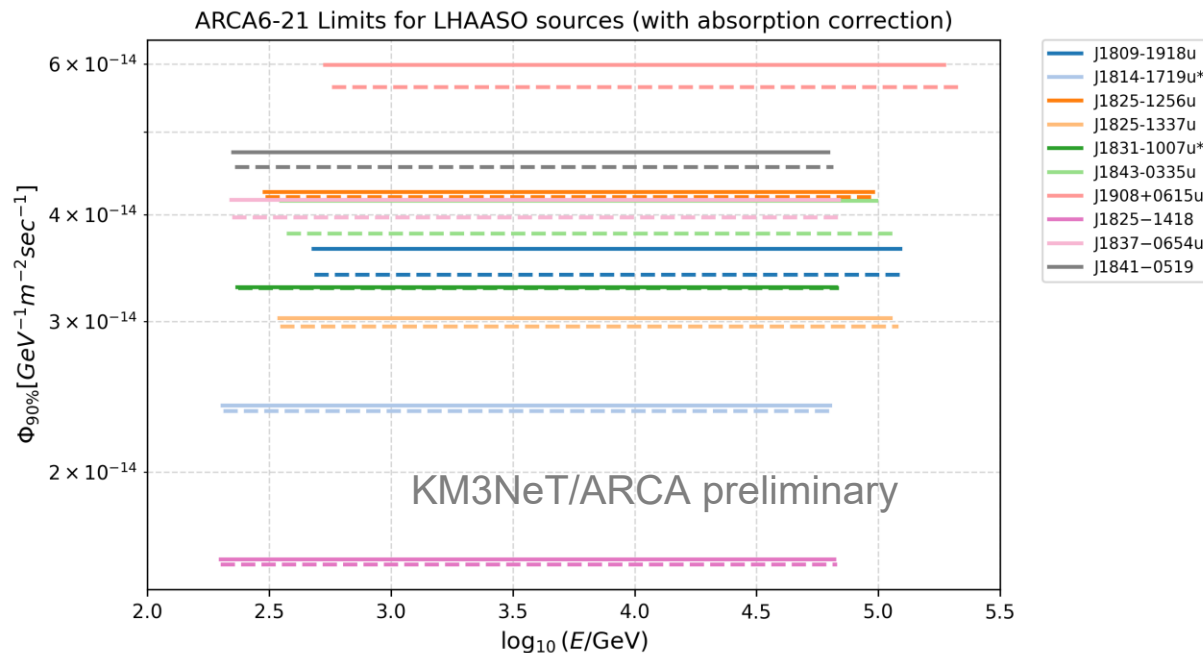
$$\Phi_\nu(E_\nu) = \int \frac{dE_\gamma}{E_\gamma} \frac{\Phi_\gamma^{\text{obs}}(E_\gamma)}{e^{-\tau}} K_{\nu\gamma}\left(\frac{E_\nu}{E_\gamma}\right)$$

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

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:

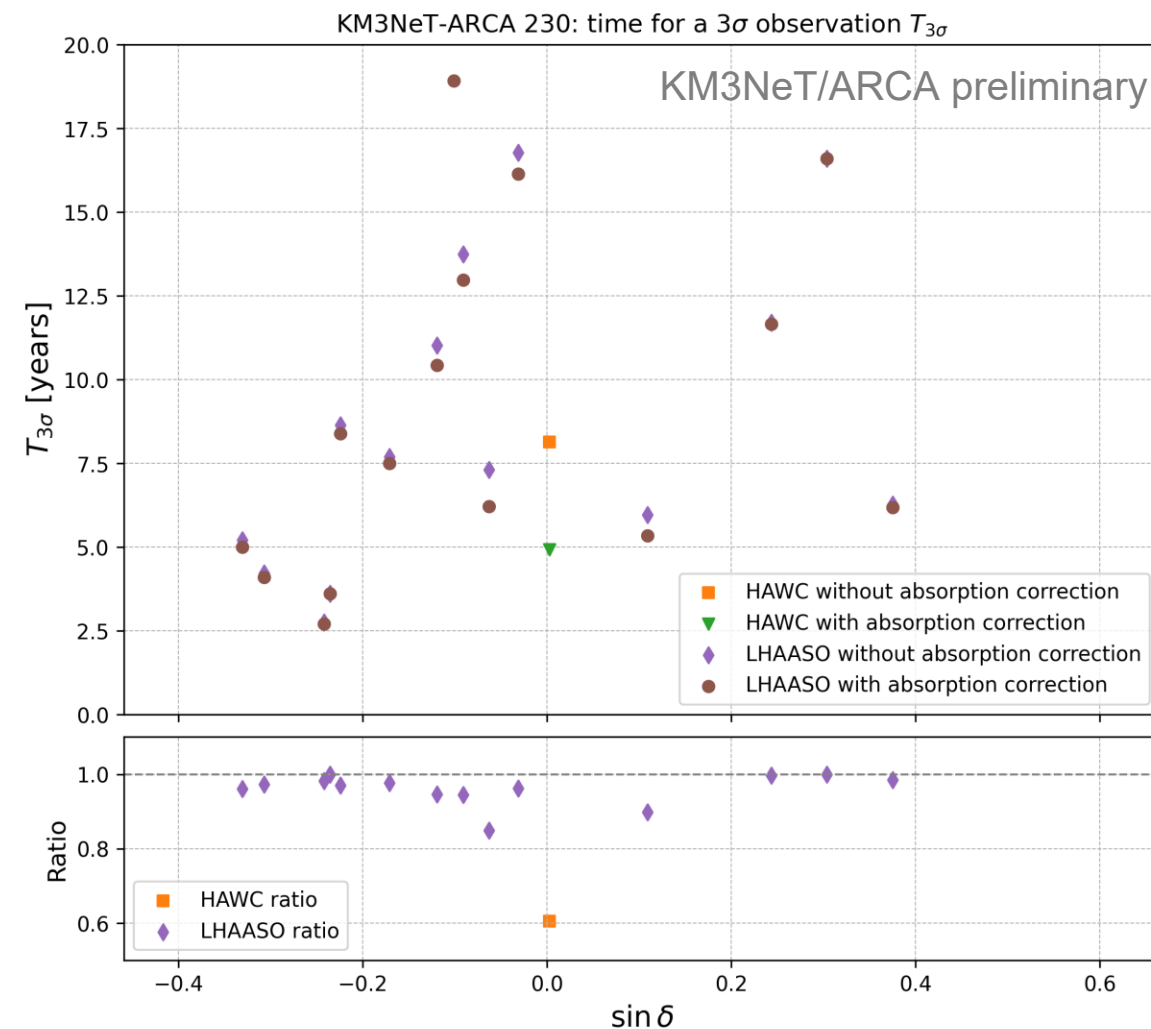
- With/without absorption correction (dashed/continuous lines).
- 10 sources from the LHAASO catalogue with the best upper limits, the best 3 are **J1825-1418**, **J1814-1719u*** and **J1825-1337**.
- The best 3 HAWC sources: **J1849+001**, **J1857+027** and **J1803-211**.
- “Taking into account gamma-ray absorption” have an impact of 10% for many of the sources and of 25 % for 3HWCJ1849+001.



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.

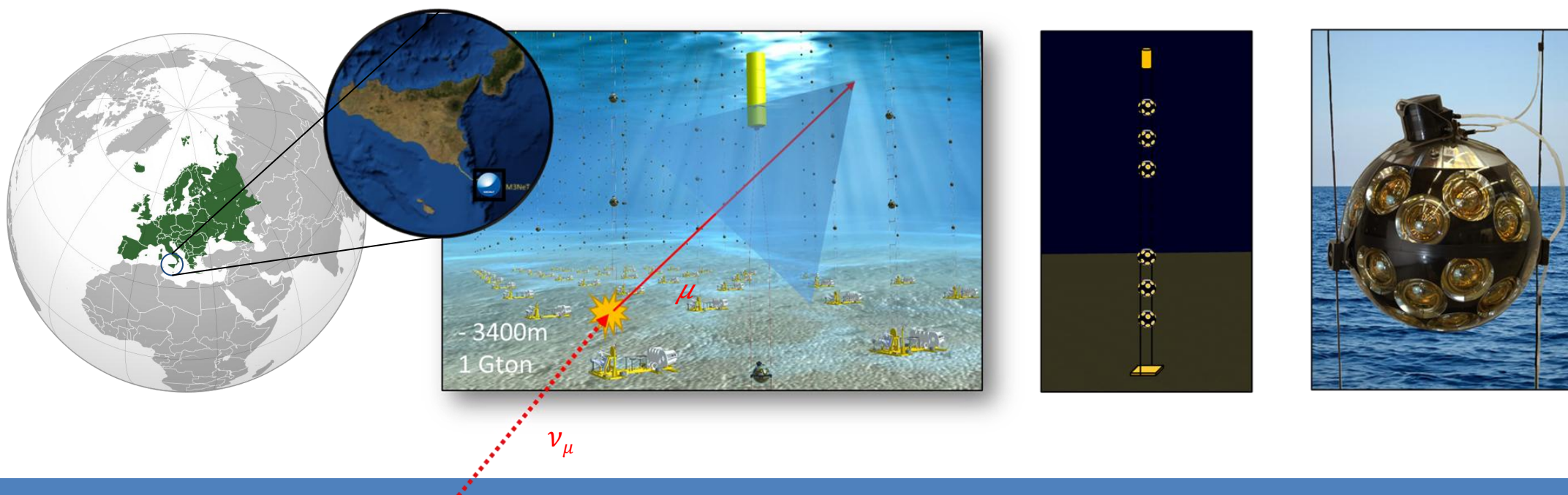
With the rapid growth of KM3NeT/ARCA, and data of sept 2023-today still to be included in the analysis, the results are expected to significantly improve in the near future.

Thanks for the
attention.

Backup Slides

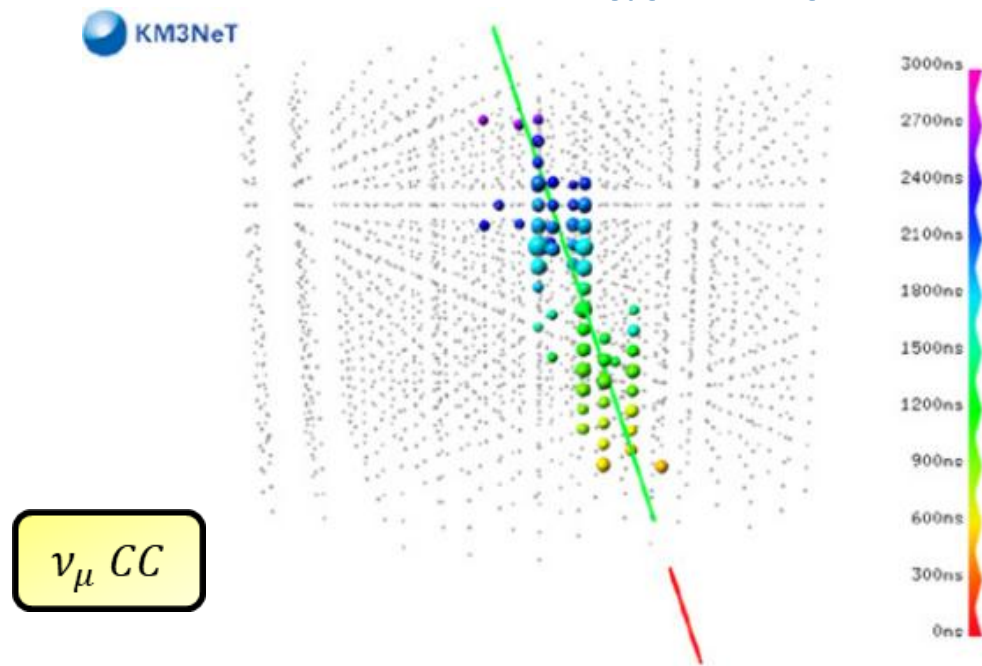
The KM3NeT/ARCA detector

KM³ 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 (ν_e , ν_μ , ν_τ), will have **sub-degree** angular resolution, is sensitive in a **large energy range** [MeV - PeV], and can probe many **different type of ν -sources**. Its location in the Northern hemisphere provides a **good view of the Galactic Region**.

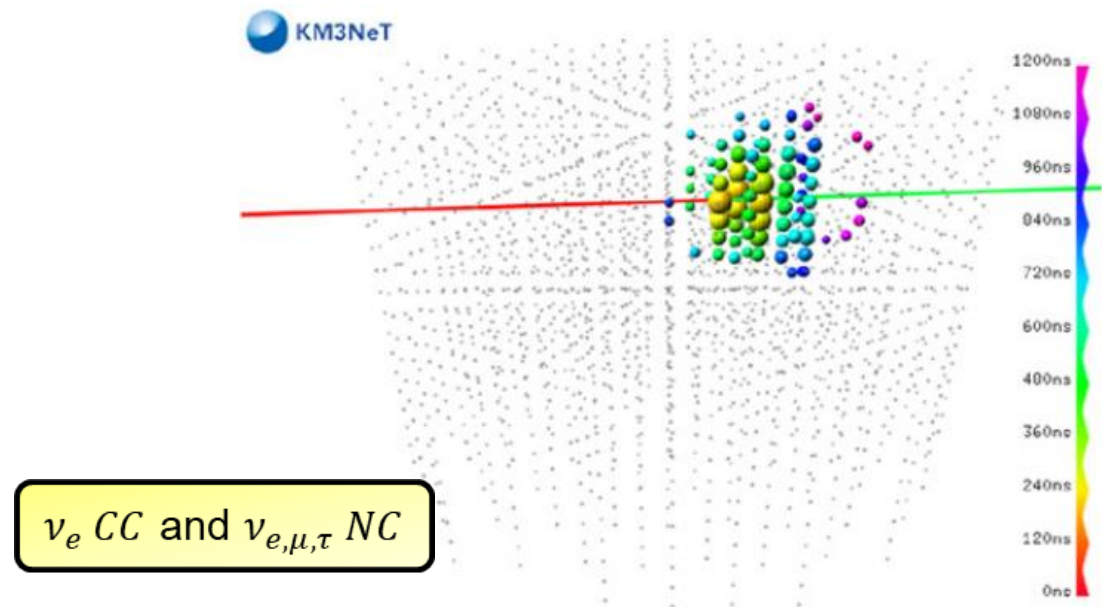


Event Topology in a Neutrino Telescope:

Track-like

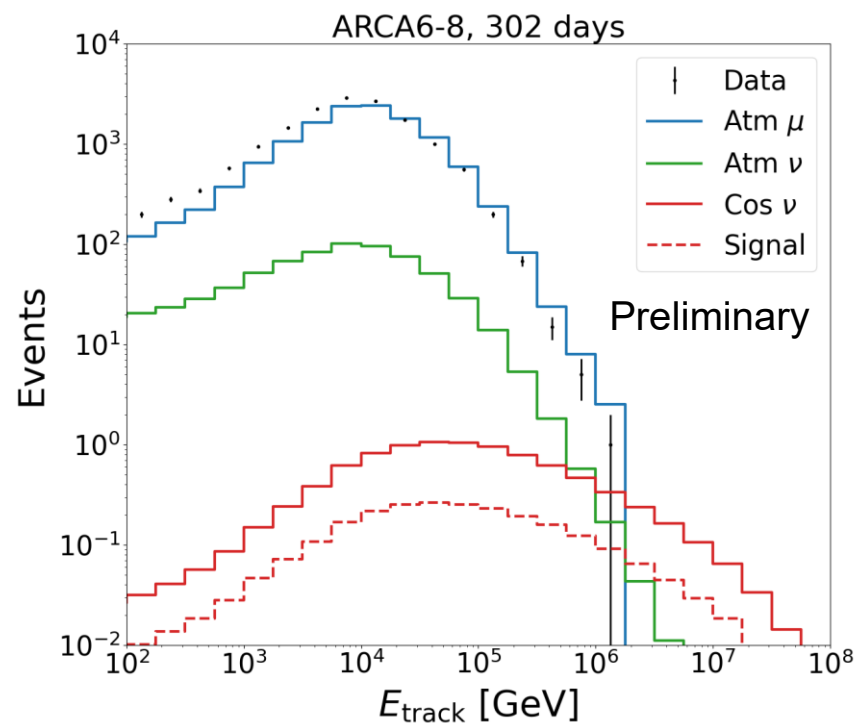


Shower-like



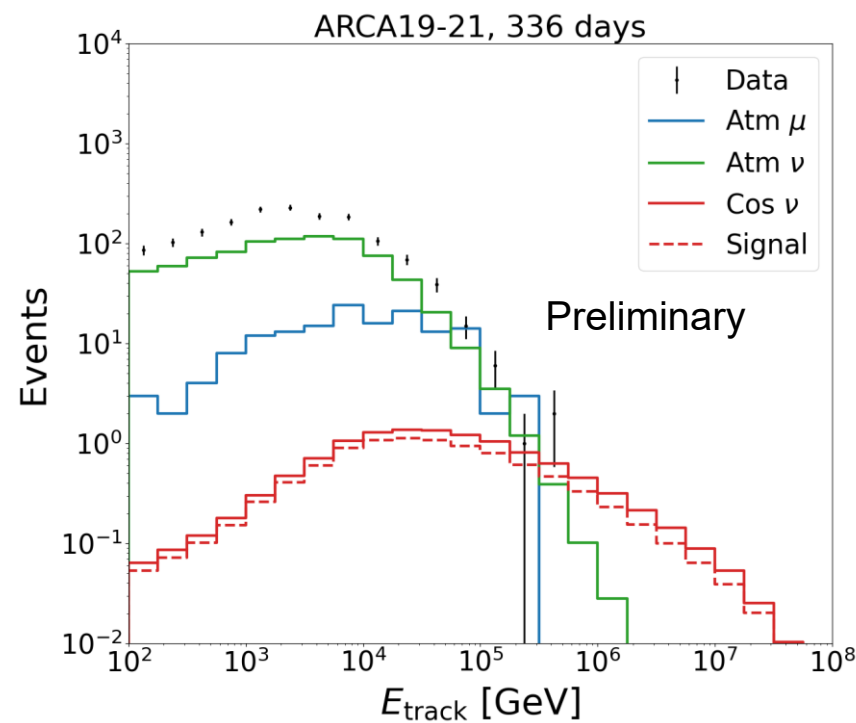
Data sample after event selection

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



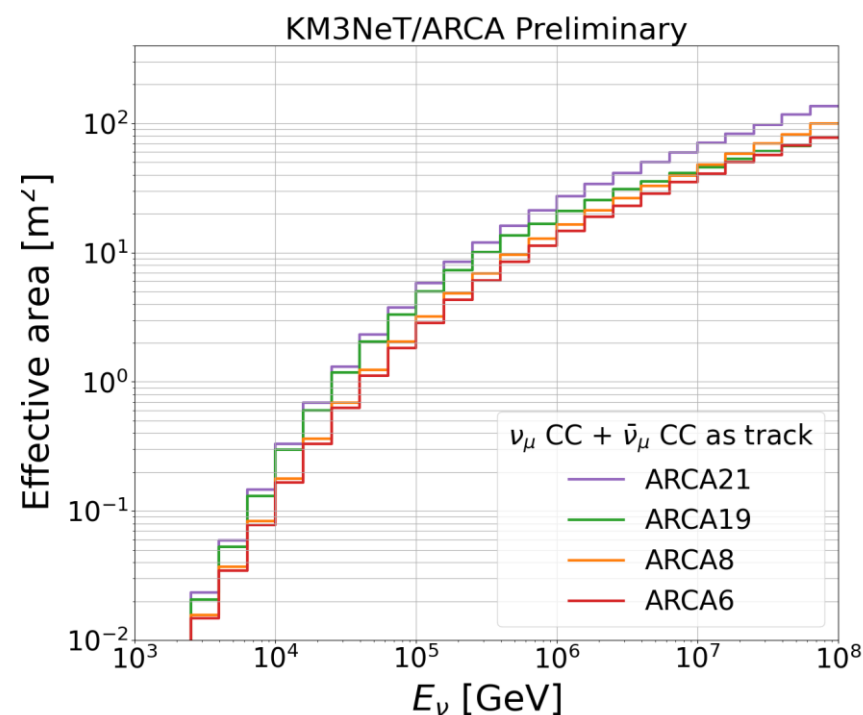
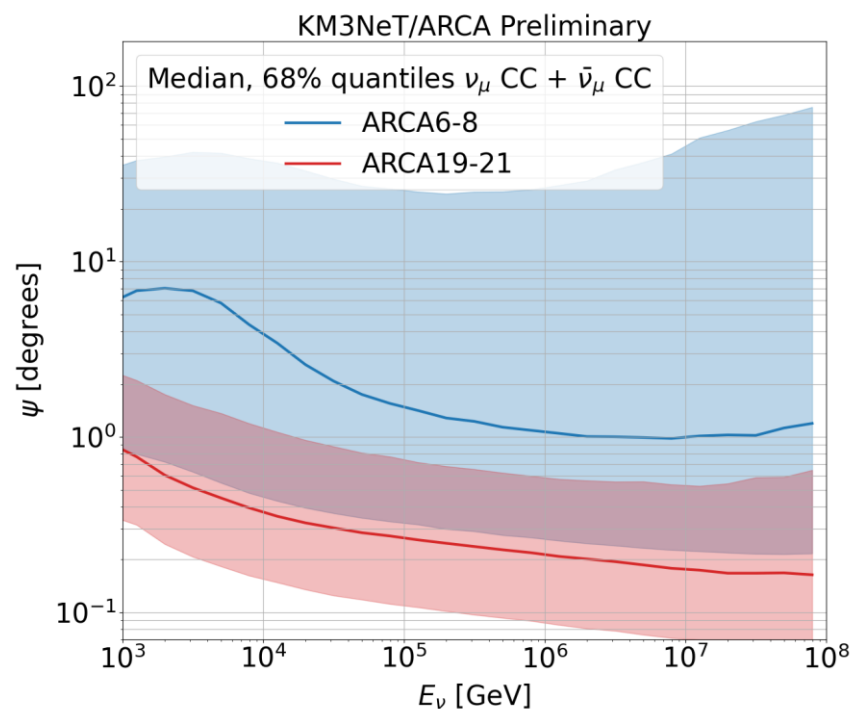
KM3NeT dataset	N° events
ARCA 6	4205
ARCA 8	11537
ARCA 19	182
ARCA 21	1361*

* KM3-230213A removed



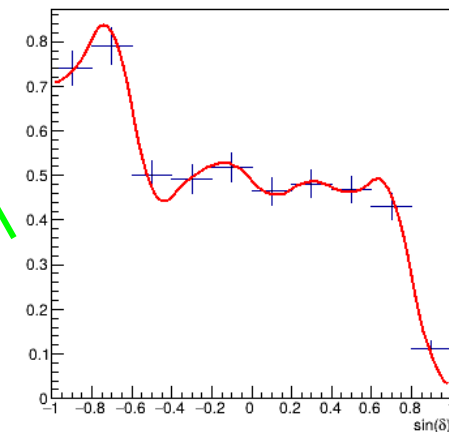
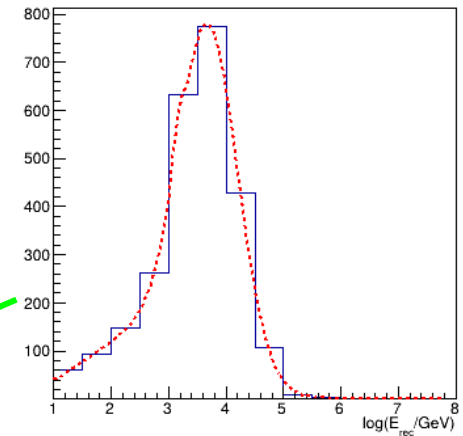
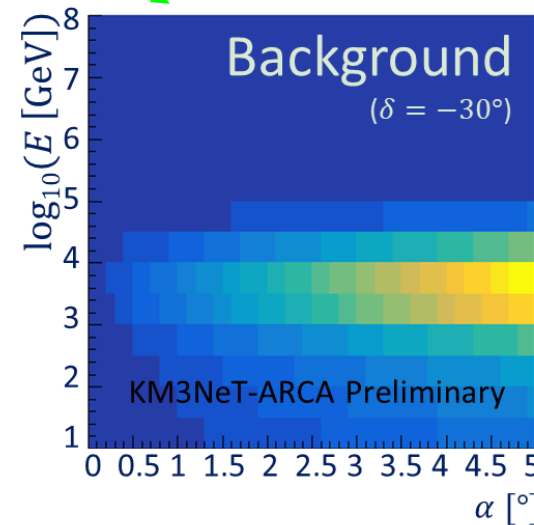
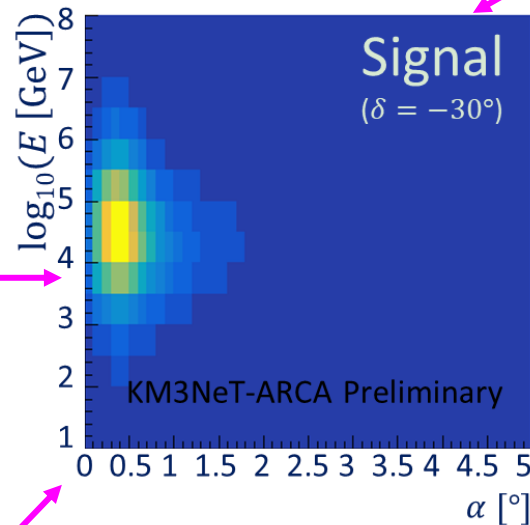
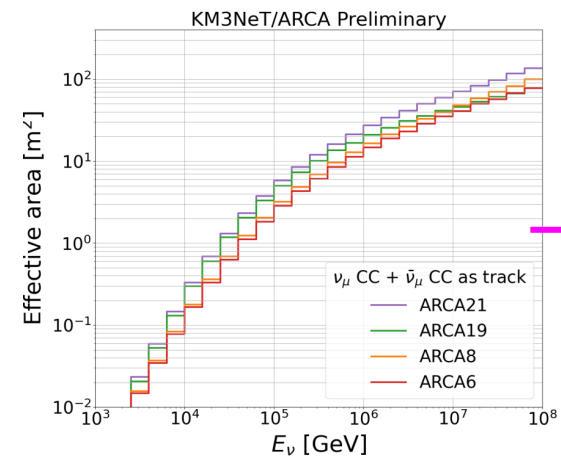
Detector performance

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



Binned Likelihood: basic idea

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



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

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