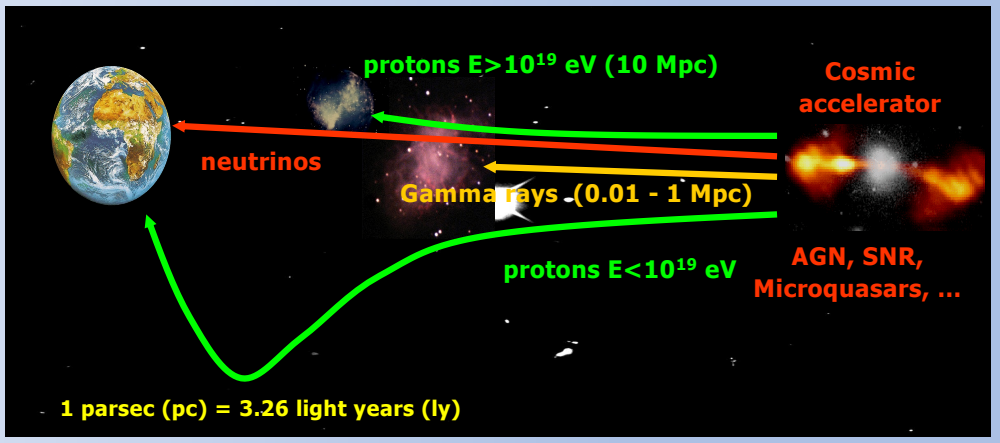
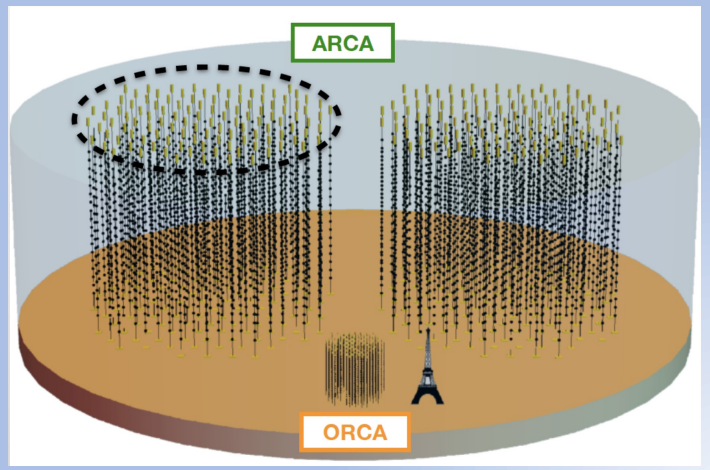
KM3NeT (ARCA & ORCA) status and recent results

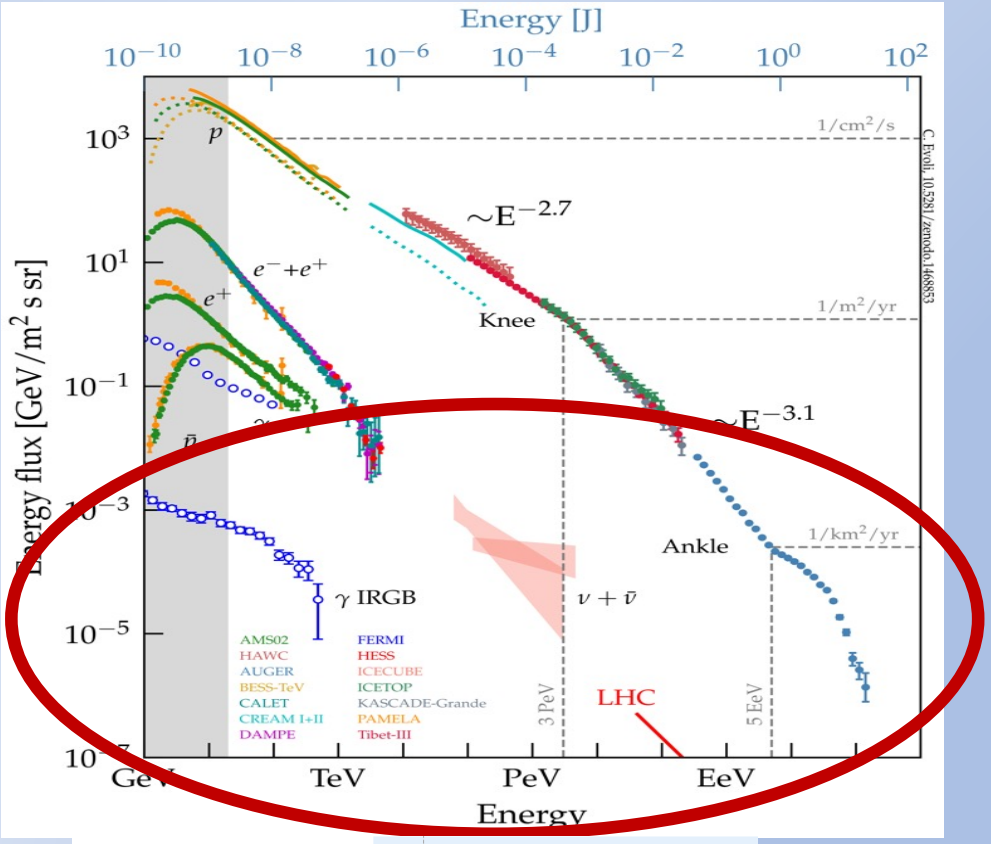
Antonio Capone

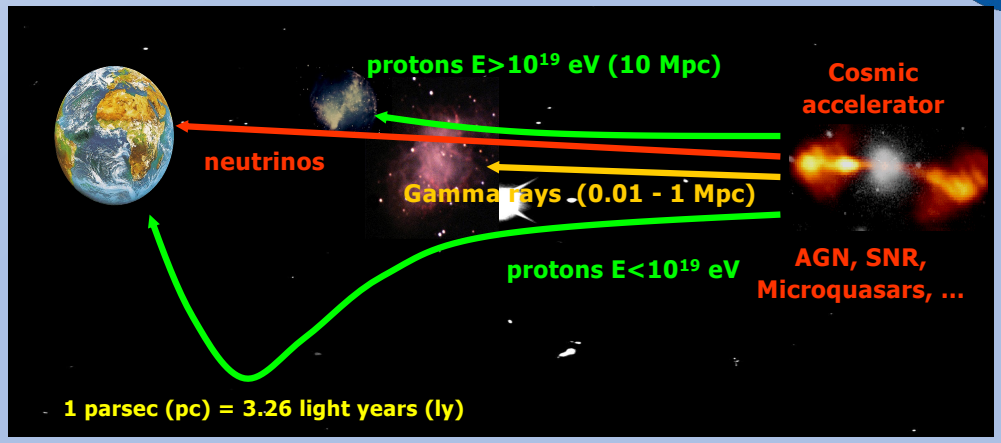
on behalf of KM3NeT Collaboration

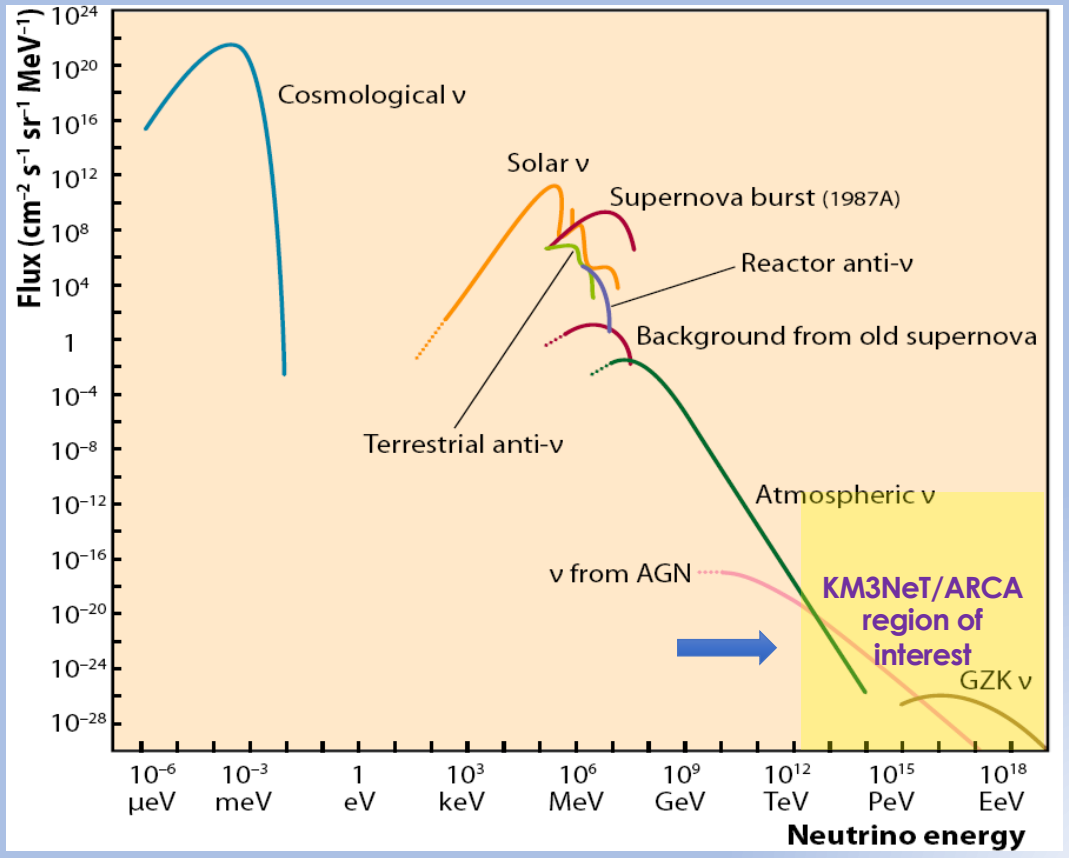




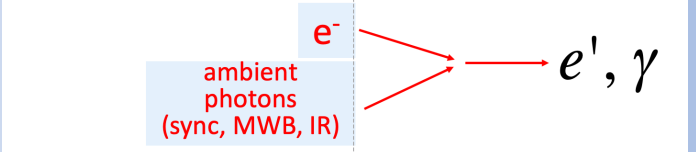
Motivations for High Energy Neutrino Astrophysics



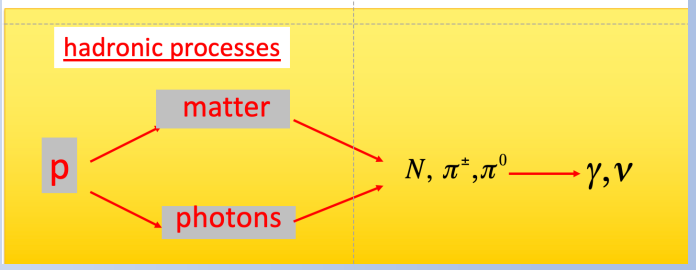




leptonic process — Inverse Compton scattering



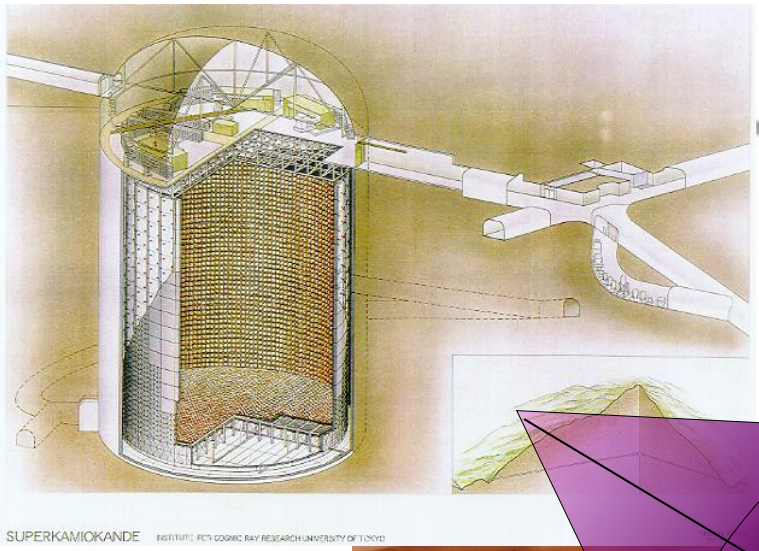
hadronic processes



Detecting neutrinos in H_2O

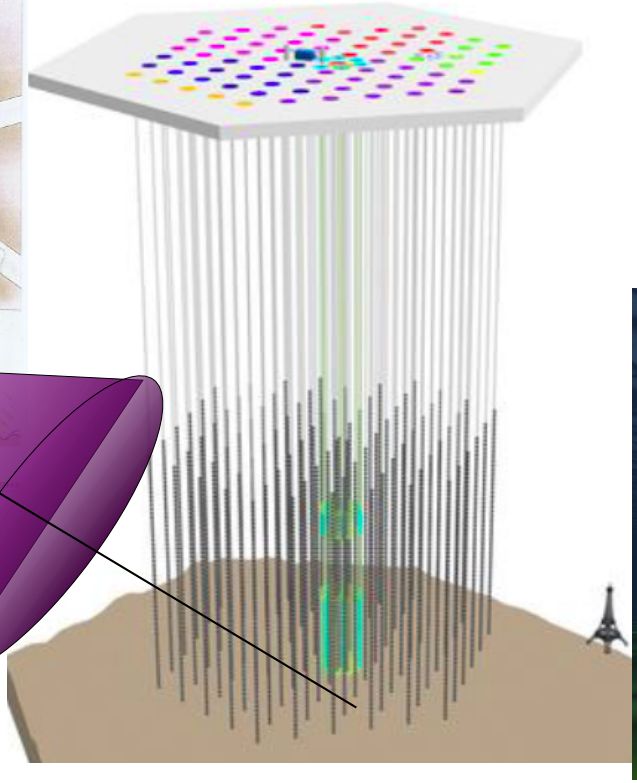
Proposed by Greisen, Reines, Markov in 1960

- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA

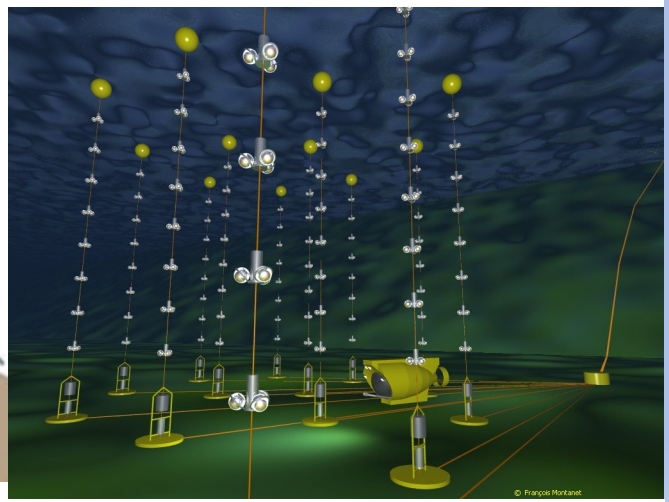


Super-K

SNO



IceCube, Gen2

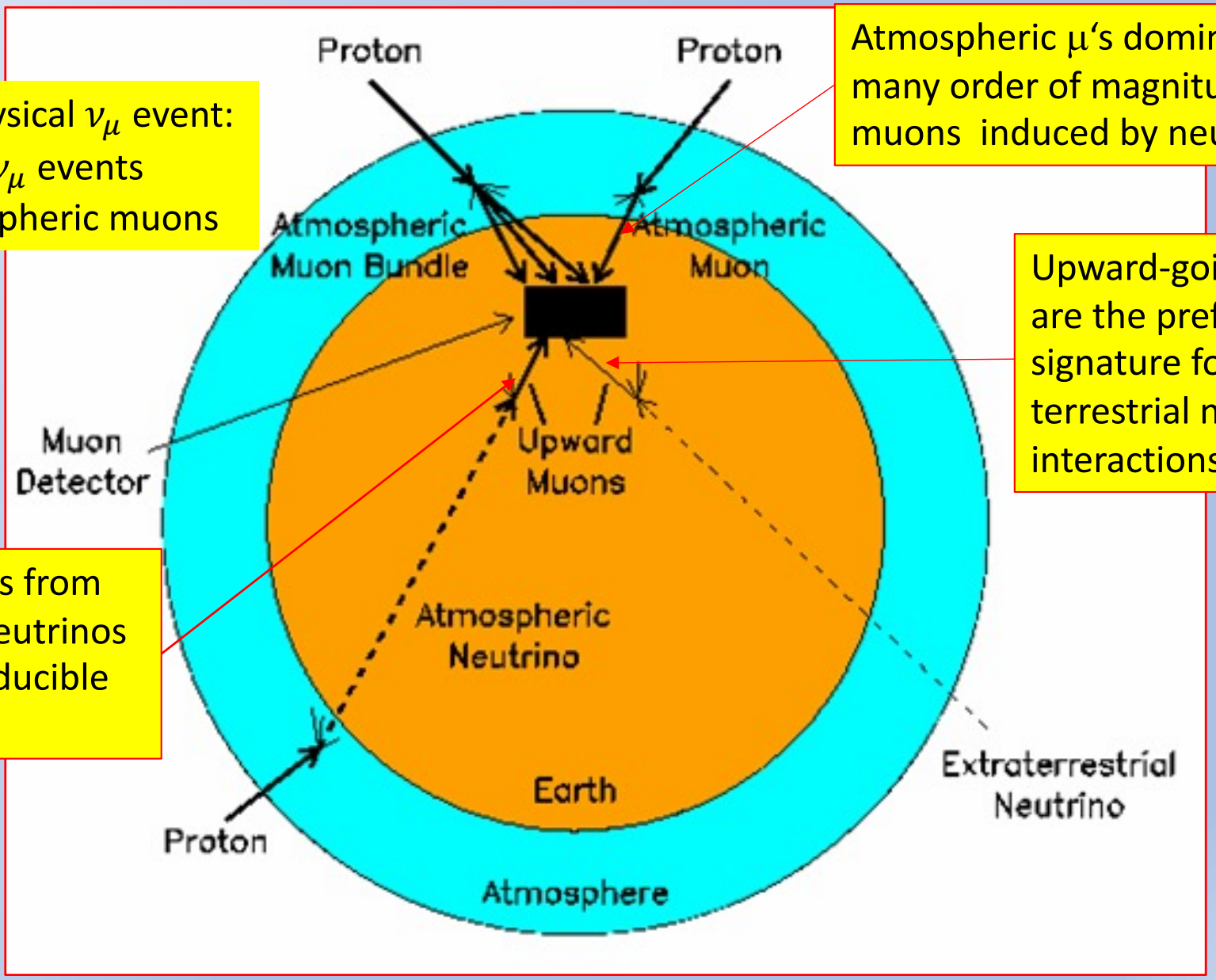


ANTARES, KM3NeT

Neutrinos must interact to be detected: use water as target and Cherenkov radiator, use PMT as detectors

Neutrino Telescopes: signal and background

- for 1 astrophysical ν_μ event:
→ ~ 100 atm. ν_μ events
→ ~ 10^8 atmospheric muons



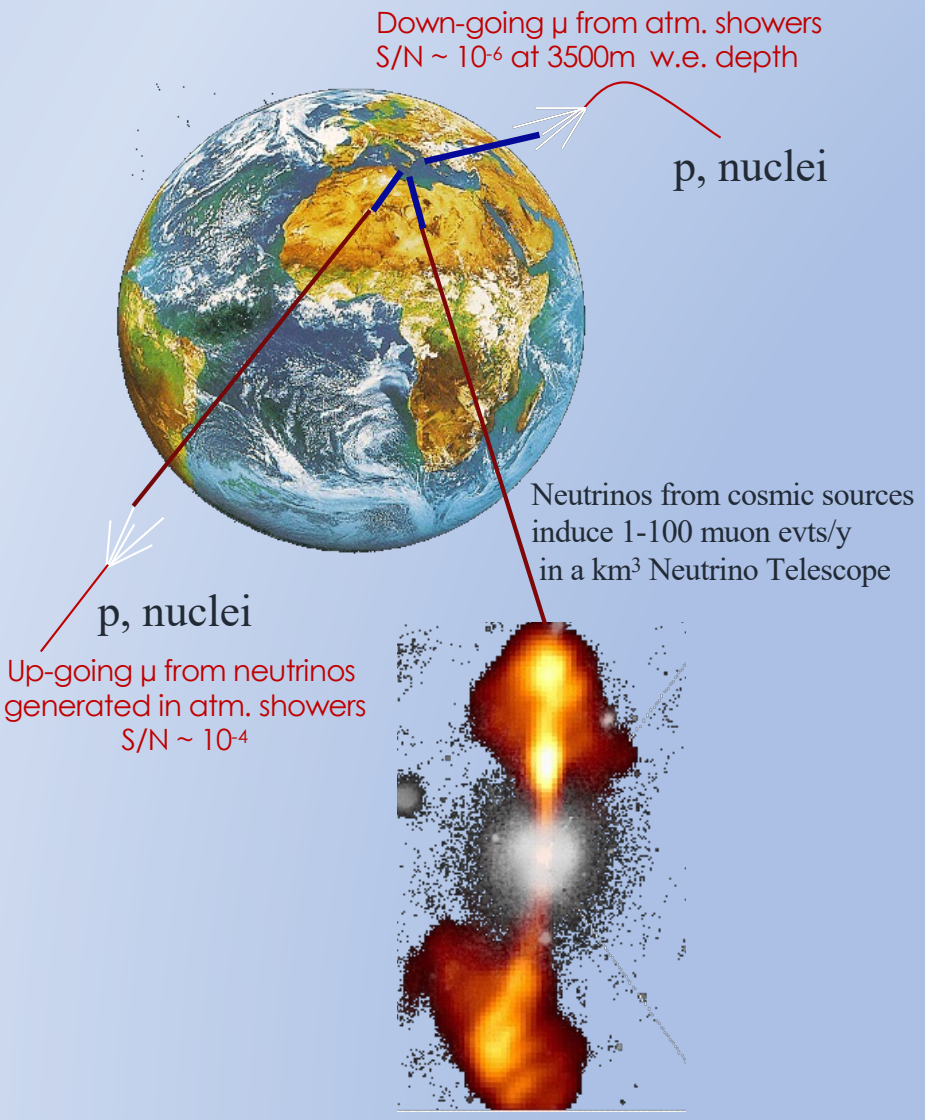
Atmospheric μ's dominate by many order of magnitude the muons induced by neutrinos

Upward-going particles are the preferred signature for extra-terrestrial neutrino interactions

Upgoing muons from atmospheric neutrinos represent irreducible background

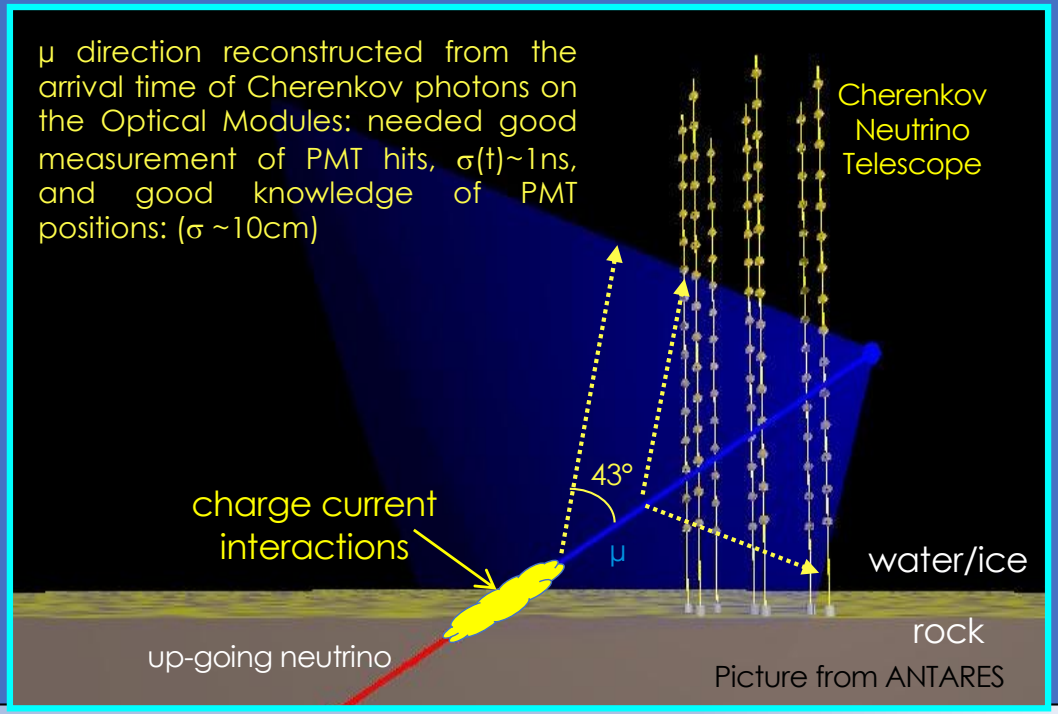
Cherenkov ν Telescope: Detection principle

Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater

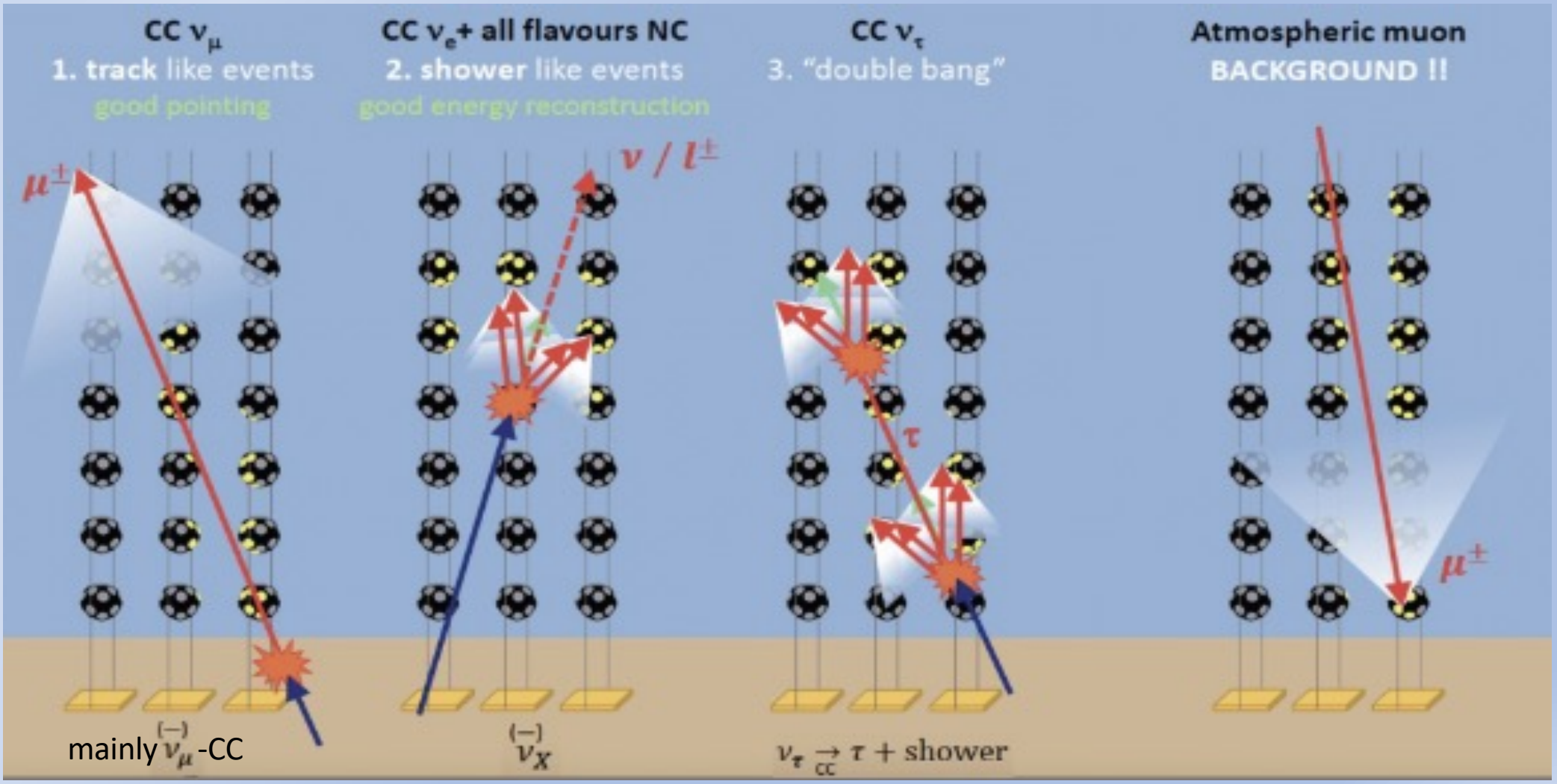


- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>10 TeV
- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

$$For\ E_\nu \geq 1TeV \rightarrow\ \theta_{\mu\nu} \sim \frac{0.7^0}{\sqrt{E_\nu[TeV]}}$$



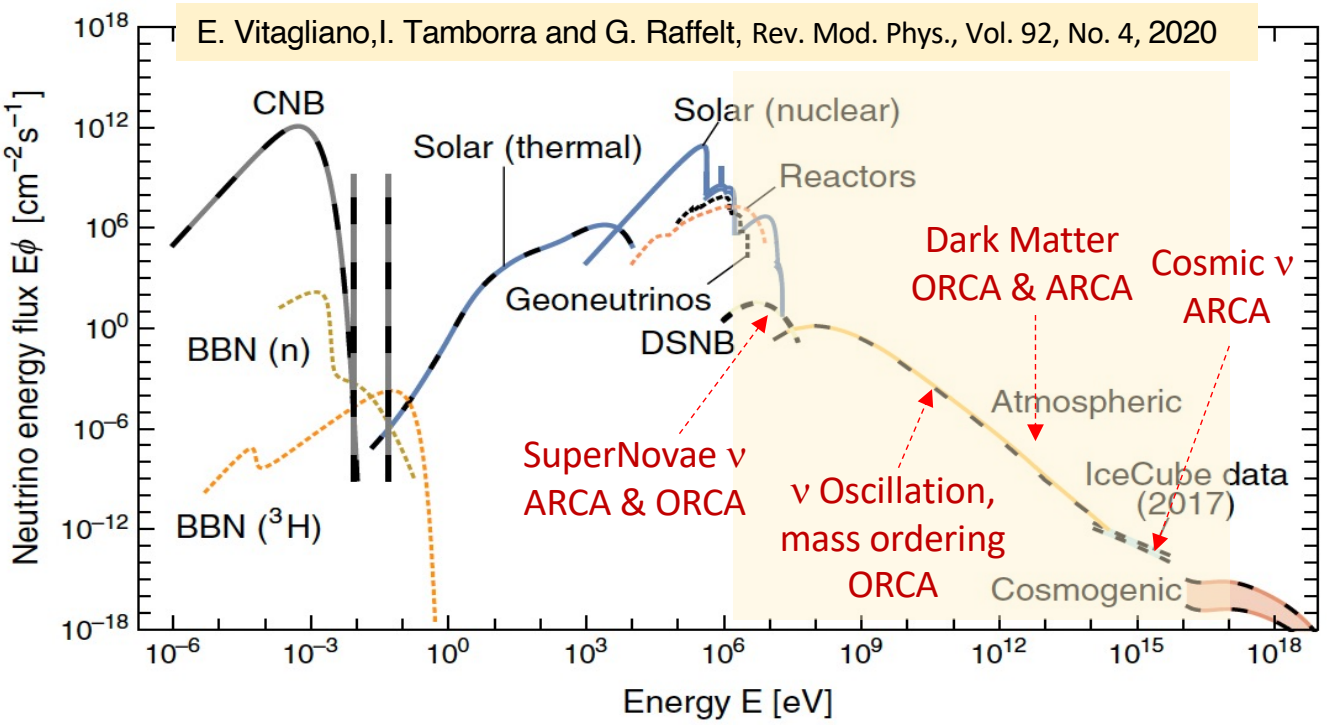
Neutrino interactions and event types

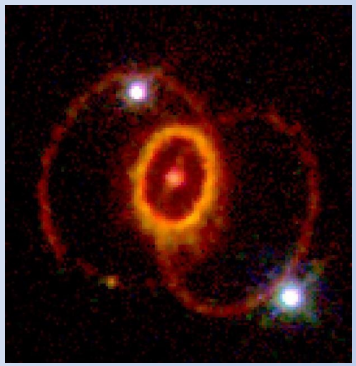


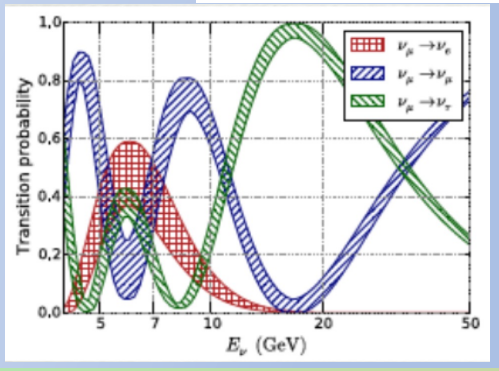
Tracks → good angular resolution: $\leq 0.1^0$ for E_ν >100 TeV - Energy resolution ~ factor 2

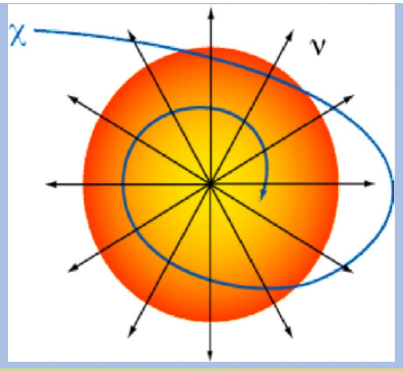
Showers → angular resolution: $\leq 2^0$ for E_ν >100 TeV - Energy resolution ~6%

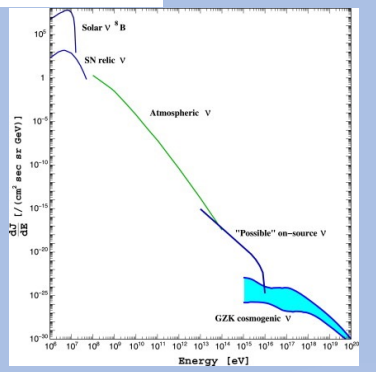
Cherenkov ν Telescope: science goals





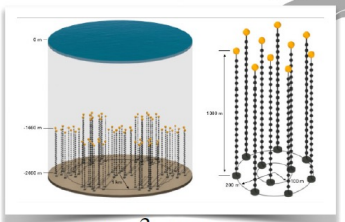






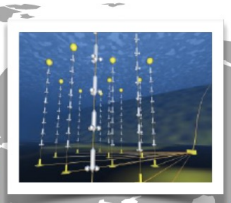
CC –SN ν	ν Oscillations	Indirect D.M search	Astroph. Sources	GZK ν, …
MeV	$10 < E_\nu < 100$ GeV	GeV $< E_\nu <$ 100 GeV	TeV $< E_\nu <$ EeV	> EeV
- ν from SN	- ν Oscillations	- D. M. search	– ν from extra-	U.H.E. C.R.
	- ν Hierarchy	- Monopoles	terrestrial sources	nature and
	- Sterile ν	- Nuclearites	- Hadronic-leptonic ?	propagation

High Energy ν Telescopes world map



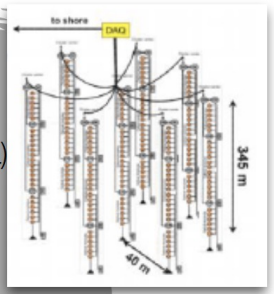
1 km^3, R&D

P-ONE (Canada)



ANTARES
>0.01 km^3, 2008-2022

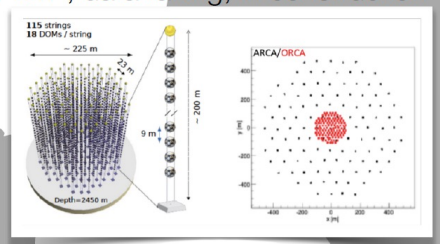
Baikal/GVD (Russia)
1 km^3, in construction



KM3NeT-ORCA (France)

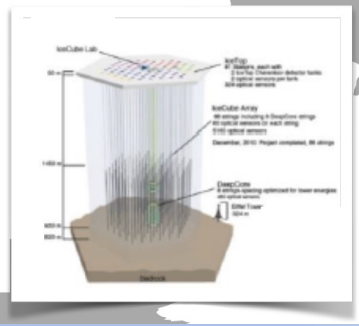
KM3NeT-ARCA (Sicily, Italy)

>1 km^3, data taking, in construction



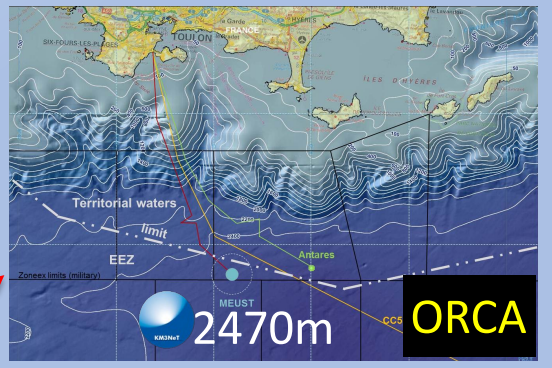
IceCube
(South Pole)
1 km^3, 2011-data taking

IceCube-Gen2
(South Pole)
10 km^3, R&D



KM3NeT the future of ν astronomy in the Mediterranean

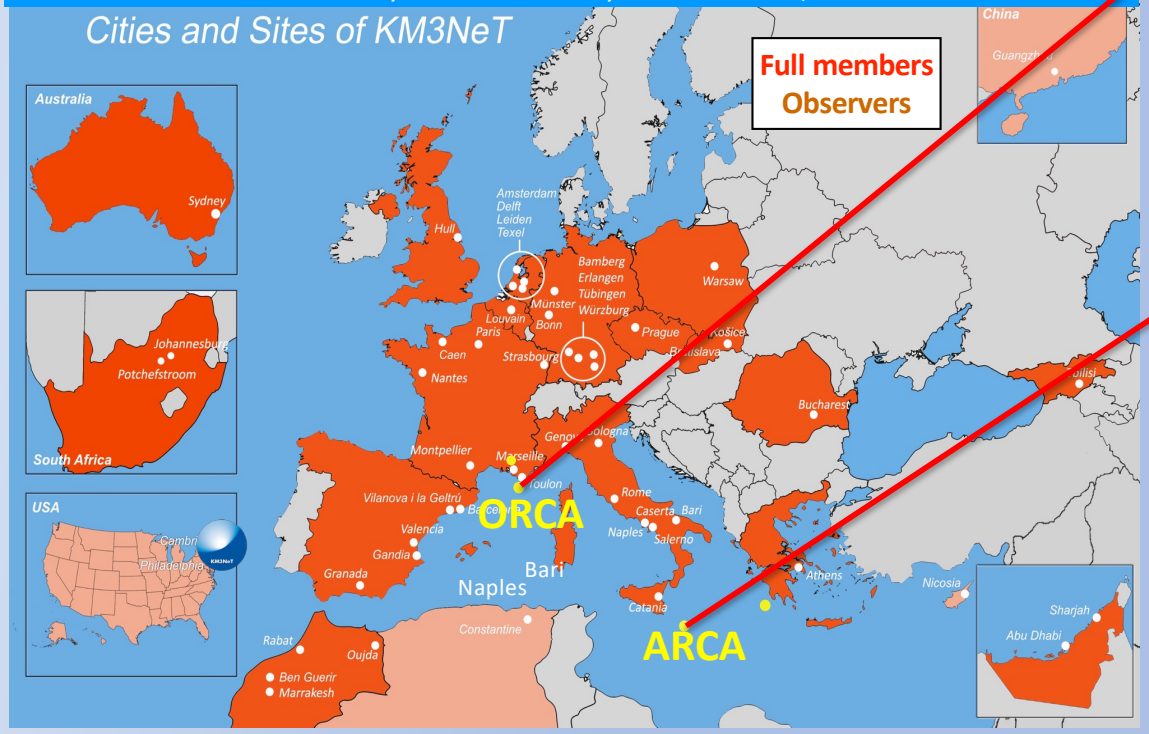
- Multi-site, deep-sea neutrino telescope
- Selected by ESFRI roadmap
- Single collaboration, Single technology

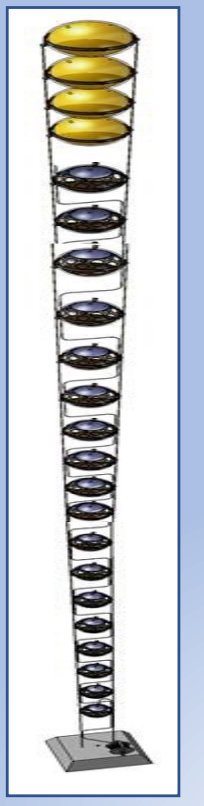


Oscillation Research
with Cosmics In the Abyss

Astroparticle Research
with Cosmics In the Abyss

>250 scientists, 63 institutes, 22 countries, 5 continents





~ 700 or 200 m

KM3NeT 2.0: Letter of Intent
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

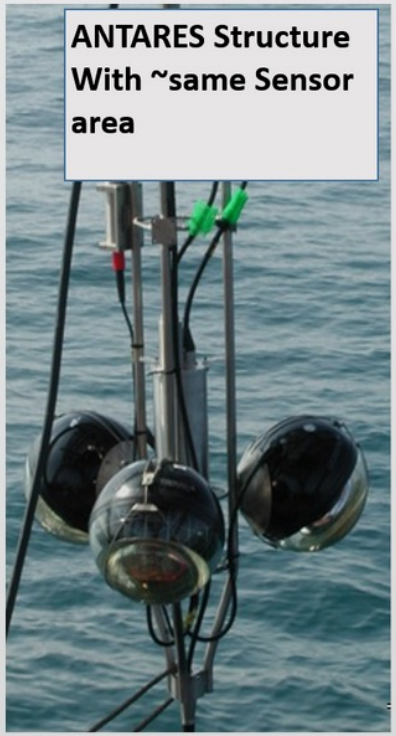
Connection nodes of
european multidisciplinary seafloor & water column observatory
emso

KM3NeT basic elements:

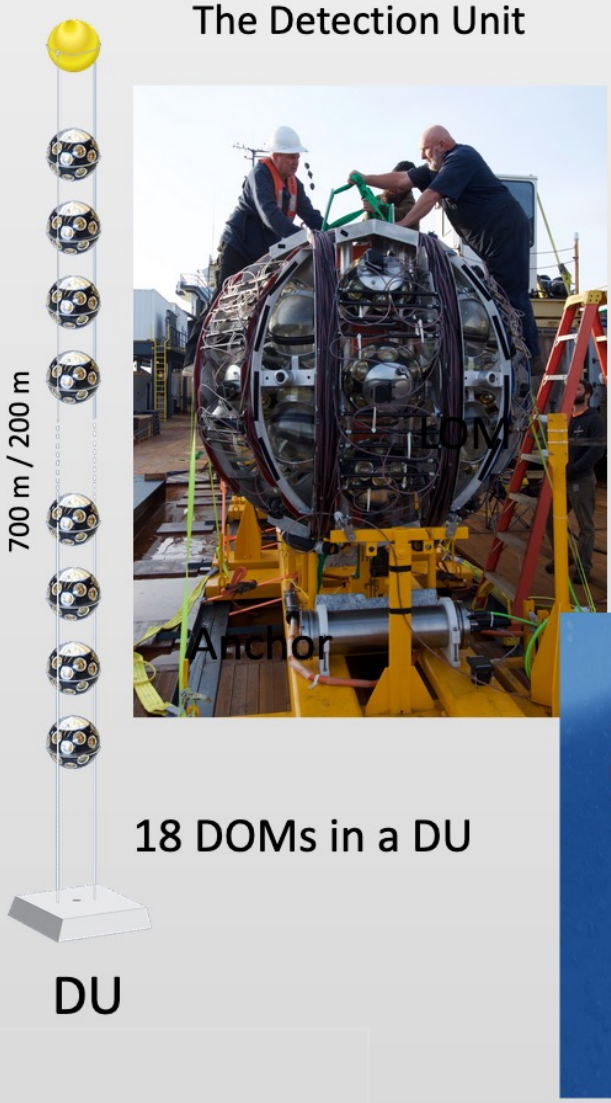
The Digital Optical Module

Multi-PMT DOM

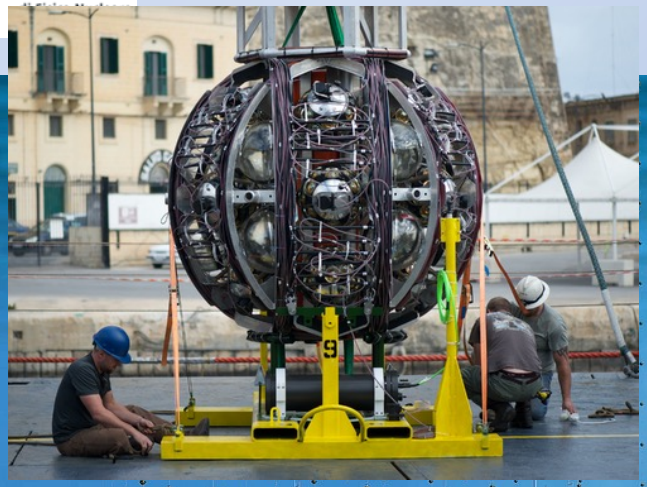
- 31 PMTs
- Cost effective sensor Area
- Photon counting
- Directional sensitivity



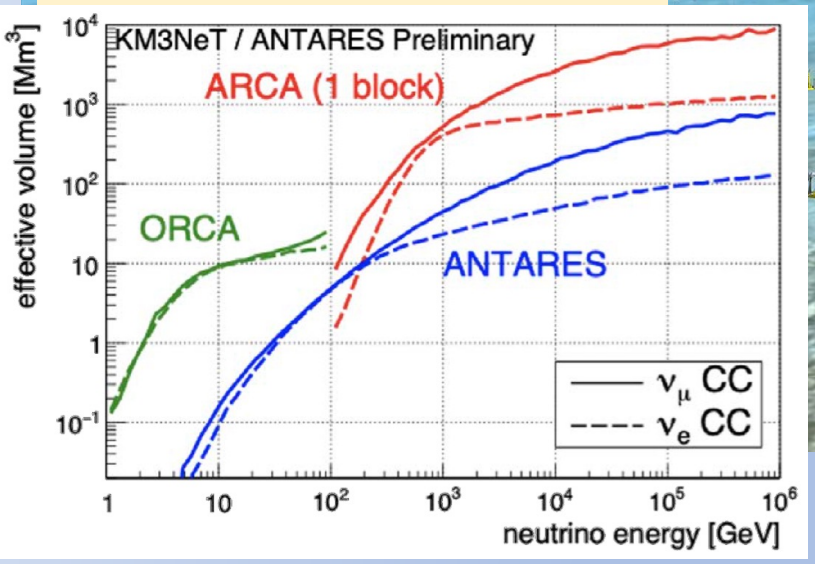
The Detection Unit

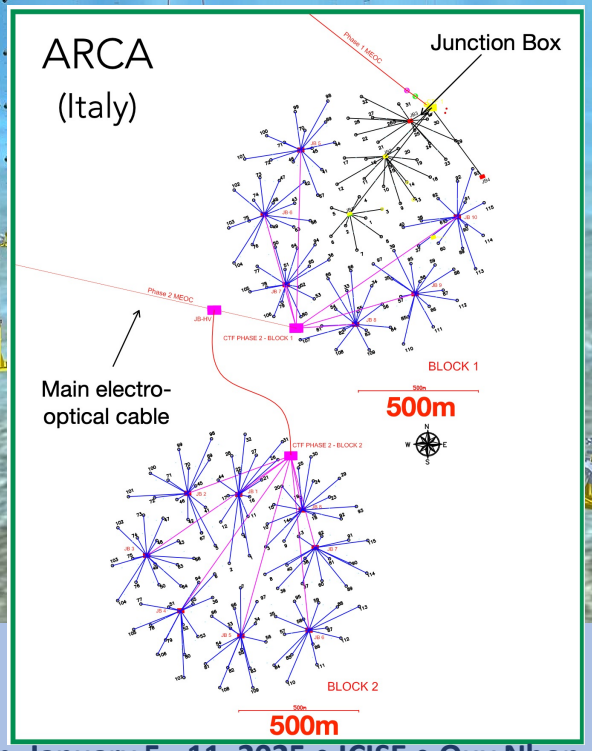


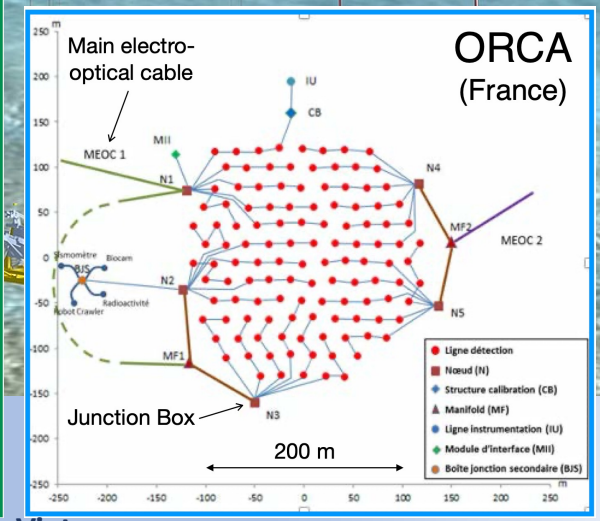
ORCA and ARCA schematic view



- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable





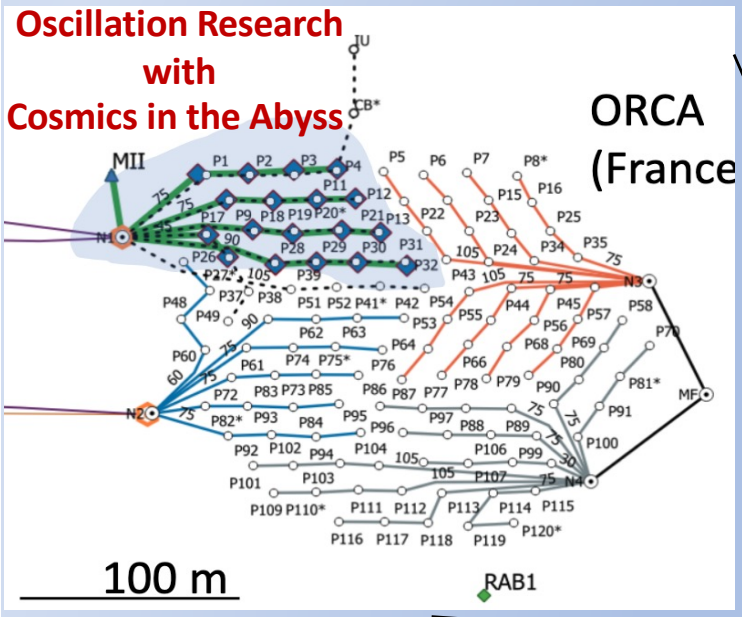


KM3NeT and deep-Sea infrastructure construction status

ORCA Current status:
- First node completed ! (Oct. 2024)
- 24 DUs operating (20% full detector)

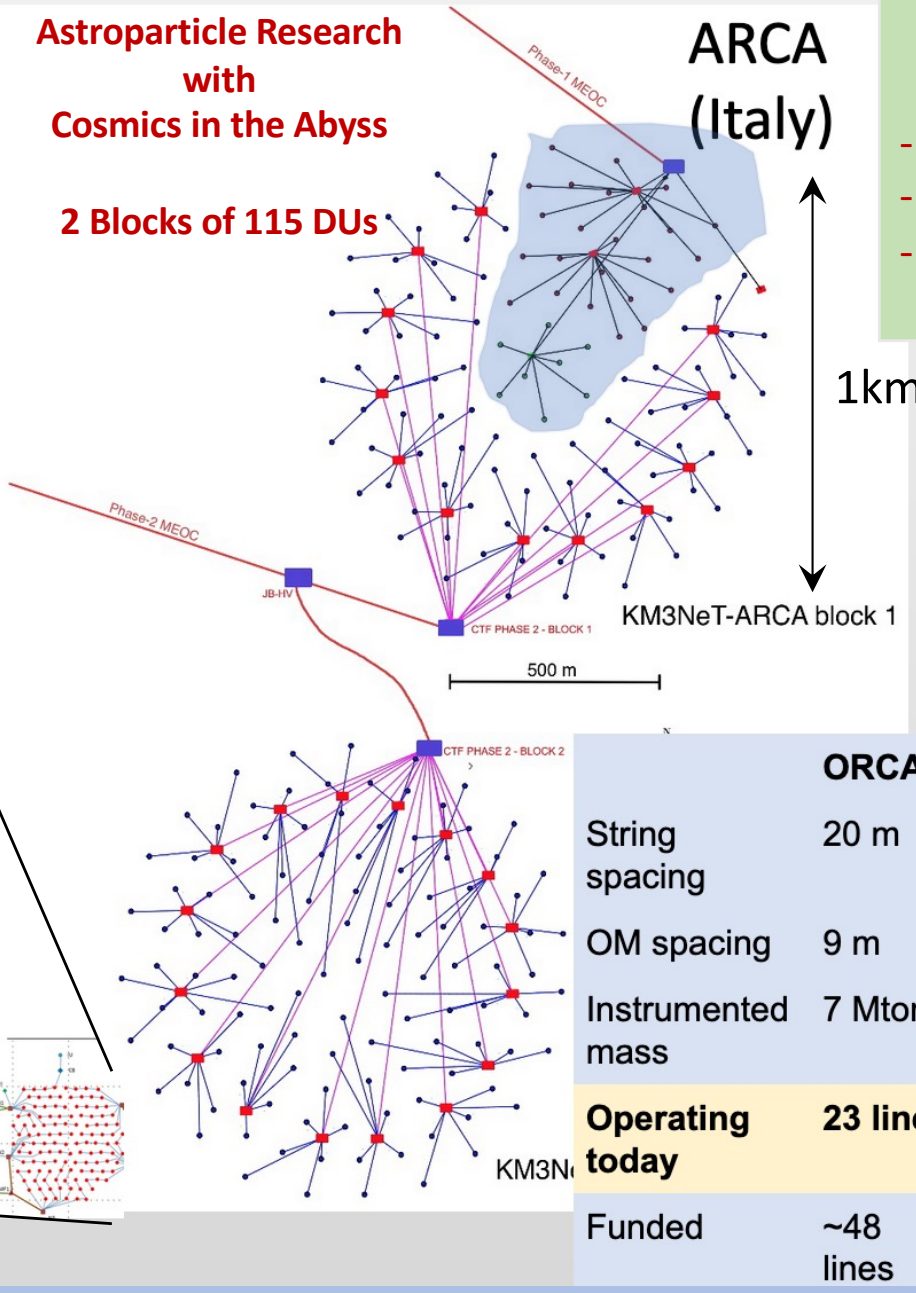
One block of 115 DUs

Oscillation Research with Cosmics in the Abyss



Astroparticle Research with Cosmics in the Abyss

2 Blocks of 115 DUs



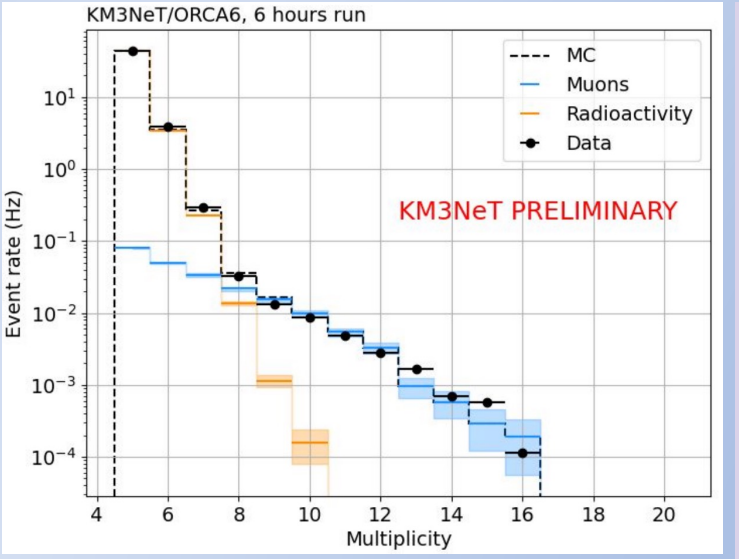
ARCA Current status:
- 2 long cables
- 3 Junction Boxes
- 28 DUs operating

	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	7 Mton	500*2 Mton
Operating today	**23 lines**	**28 lines**
Funded	~48 lines	~130 lines

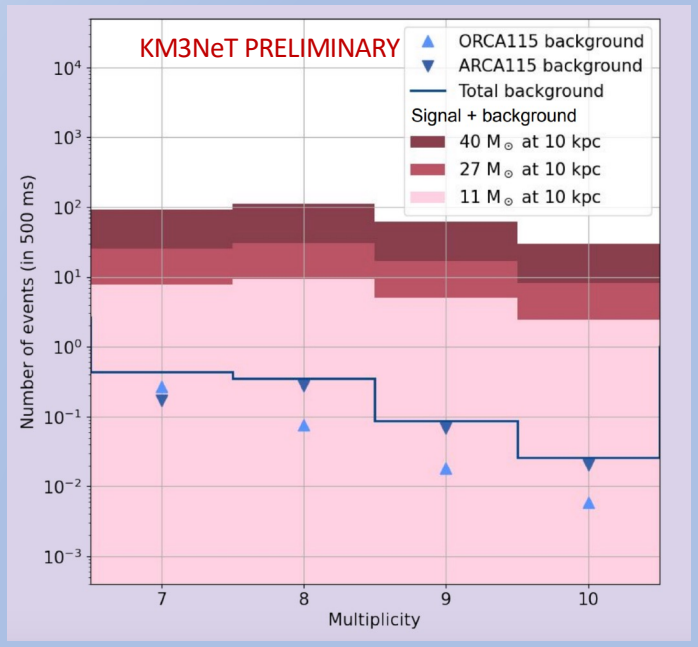
ORCA & ARCA: search for ν from SuperNova

The intense flux of neutrinos from the Supernova explosion will increase the PMT's rate, then the PMTs multiplicity in the DOMs. Each DOM can be considered a single detector

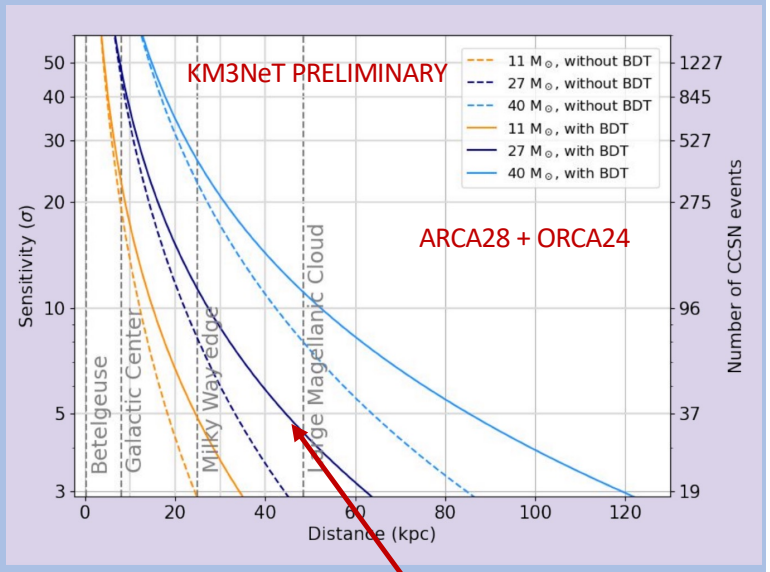
PMTs multiplicity plot



Background and signal: detection is possible



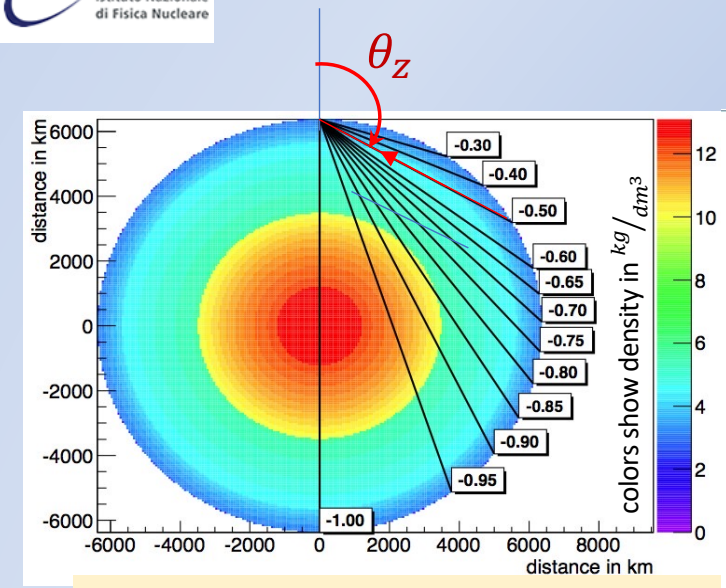
Detection significance as function of SN distance and mass



> 5σ detection by ARCA+ORCA for 27$M_\odot$ at <50kpc distance

KM3NeT has already implemented a Core-Collapse SN on-line alert system
KM3NeT part of the SuperNova Early Warning System (SNEWS)

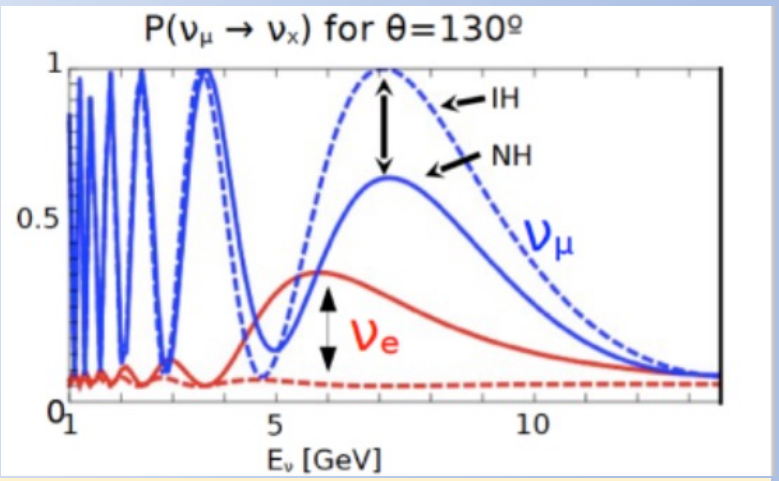
ν oscillation and ν mass order with ORCA



Event measurements

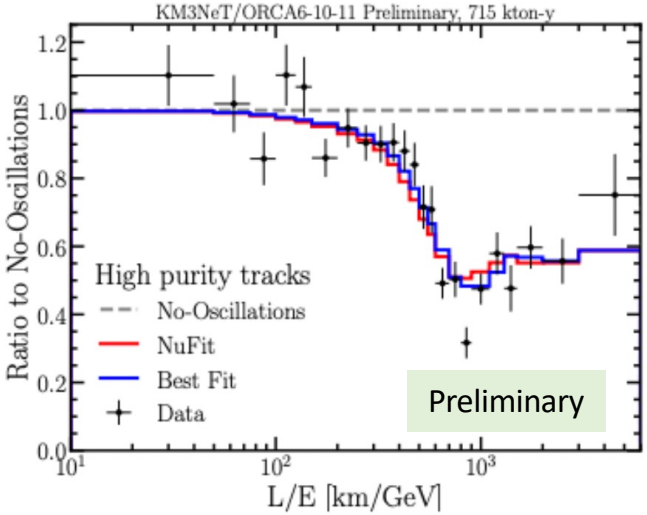
→ θ_z → path into the Earth L

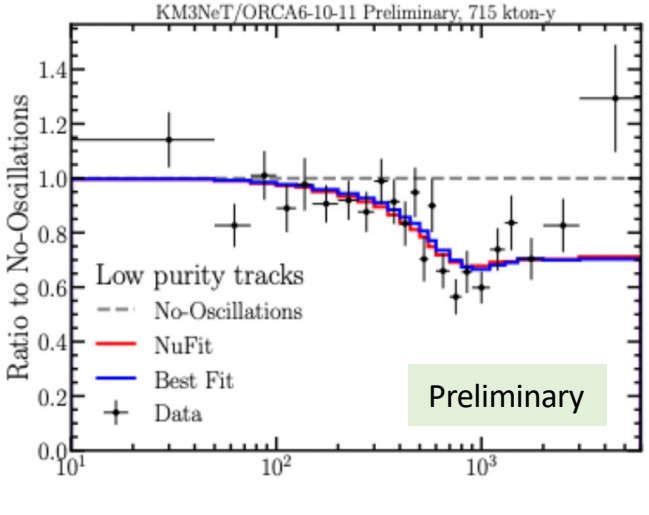
→ E_ν → evaluate **L/ E_ν**



$(\sim 5 \leq E_\nu \leq \sim 15)\ GeV$

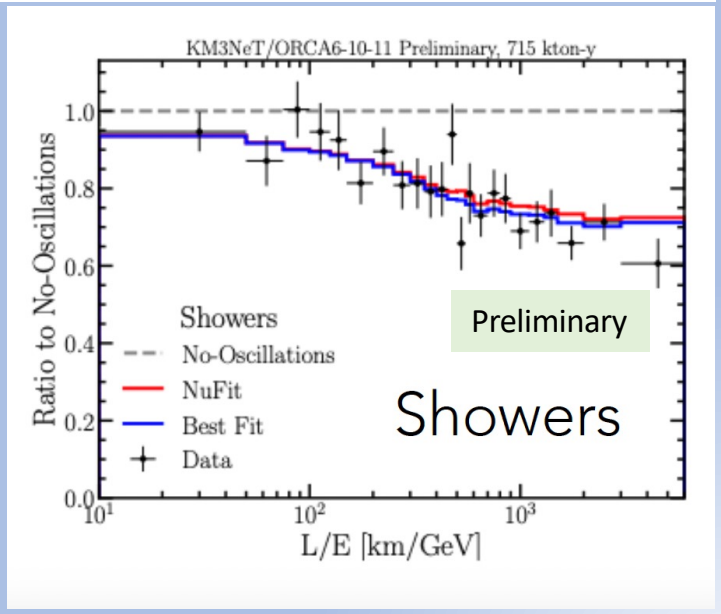
Tracks



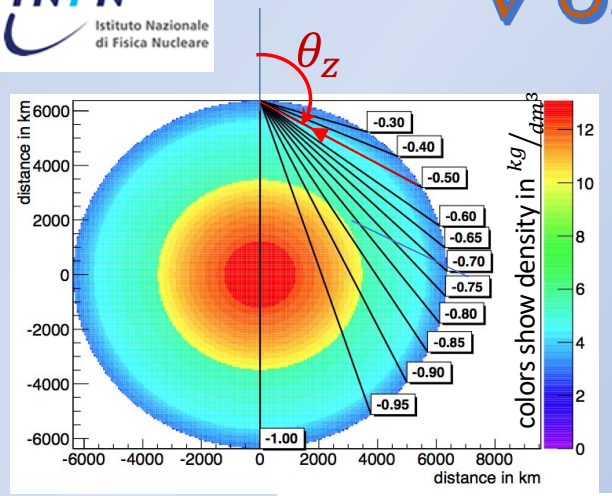


Neutrino oscillation clearly Indicated both in track and shower events

Data collected with ORCA 6 – 7 -11 Dus (715 kto/y) Preliminary Results

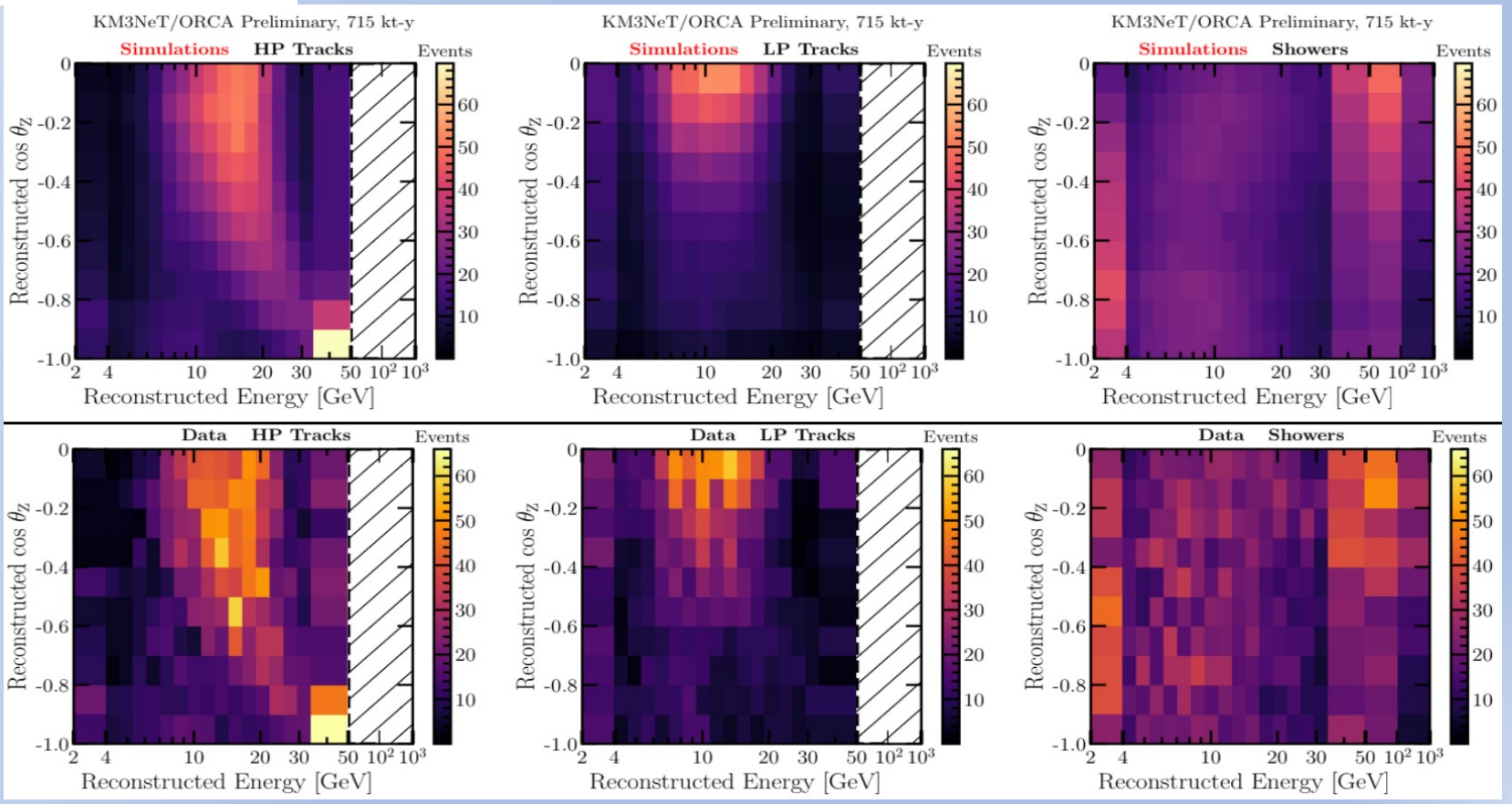


ν oscillation patterns in ORCA.



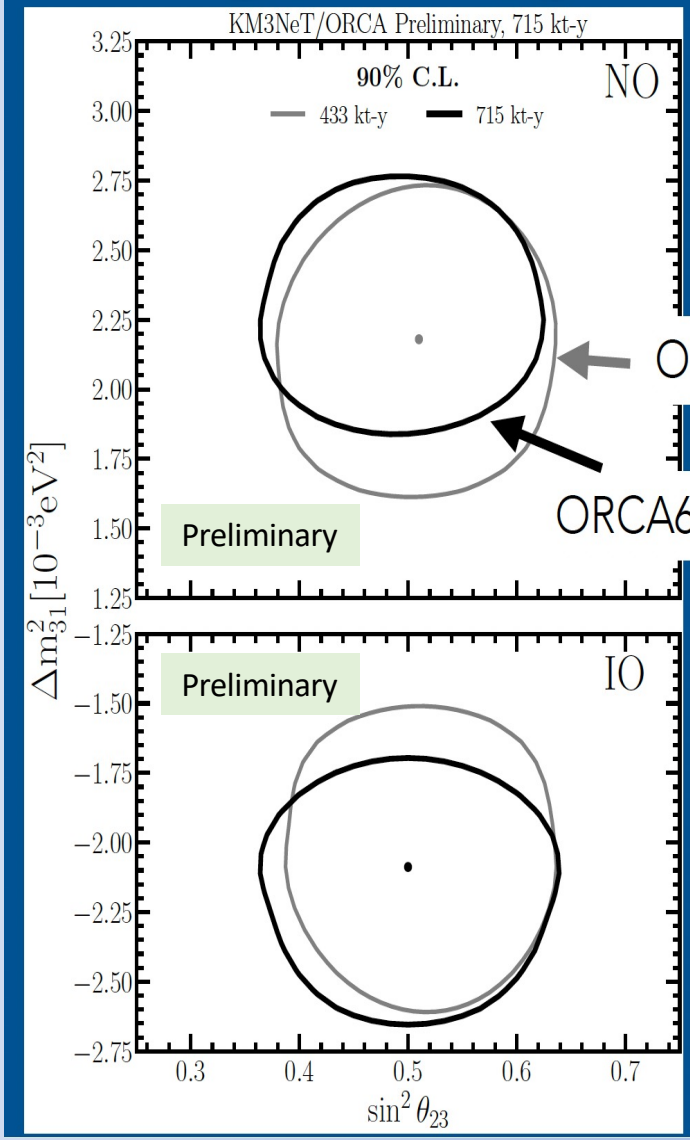
Simulations versus data for:

- Tracks (High and low precision reconstruction)
- Showers



ν oscillation and ν mass order with ORCA

Δm^2_{32} vs $\sin^2\theta_{23}$



Same kind analysis as for ICRC2023 increased the exposure

👇

From 433kt-yr to 715 kt-yr

ORCA6 👉 433 kton-yr

ORCA6-10-11 👉 715 kton-yr

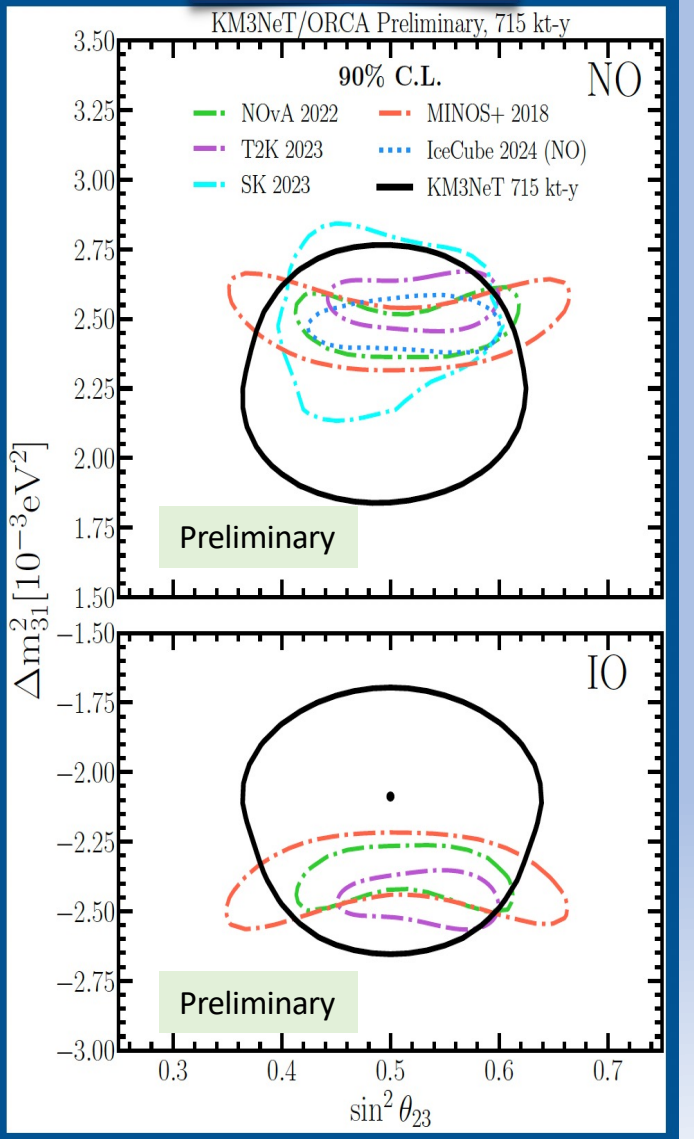
$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\mathrm{eV}^2, & \mathrm{IO} \\ [2.10, 2.37] \times 10^{-3}\mathrm{eV}^2, & \mathrm{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$

KM3NeT/ORCA competitive

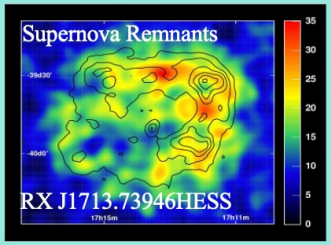
Δm^2_{32} vs $\sin^2\theta_{23}$

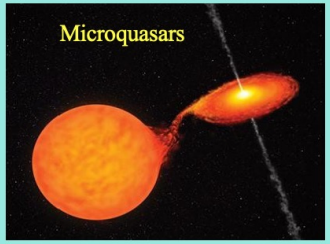


KM3NeT/ARCA ν main science goals

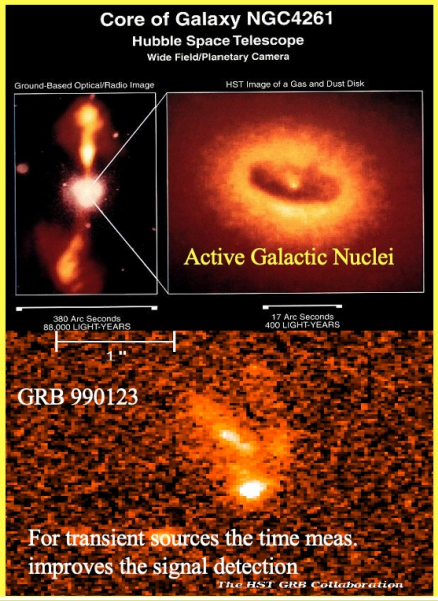
Search for point-like cosmic Neutrino Sources

Galactic





Extragalactic



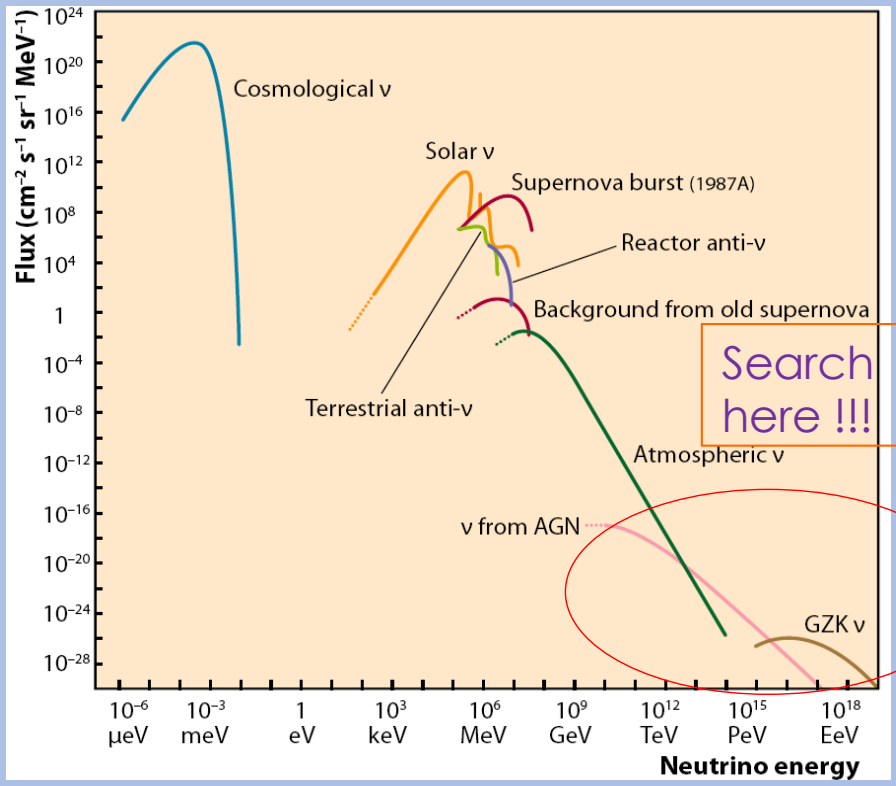
- Their identification requires a detector with accurate angular reconstruction

$$\sigma(\vartheta) \leq 0.5^\circ \text{ for } E_\nu \geq 1 TeV$$

- Their identification requires a detector with **accurate angular reconstruction**
- Search for sources from catalogue
- Auto-correlation search

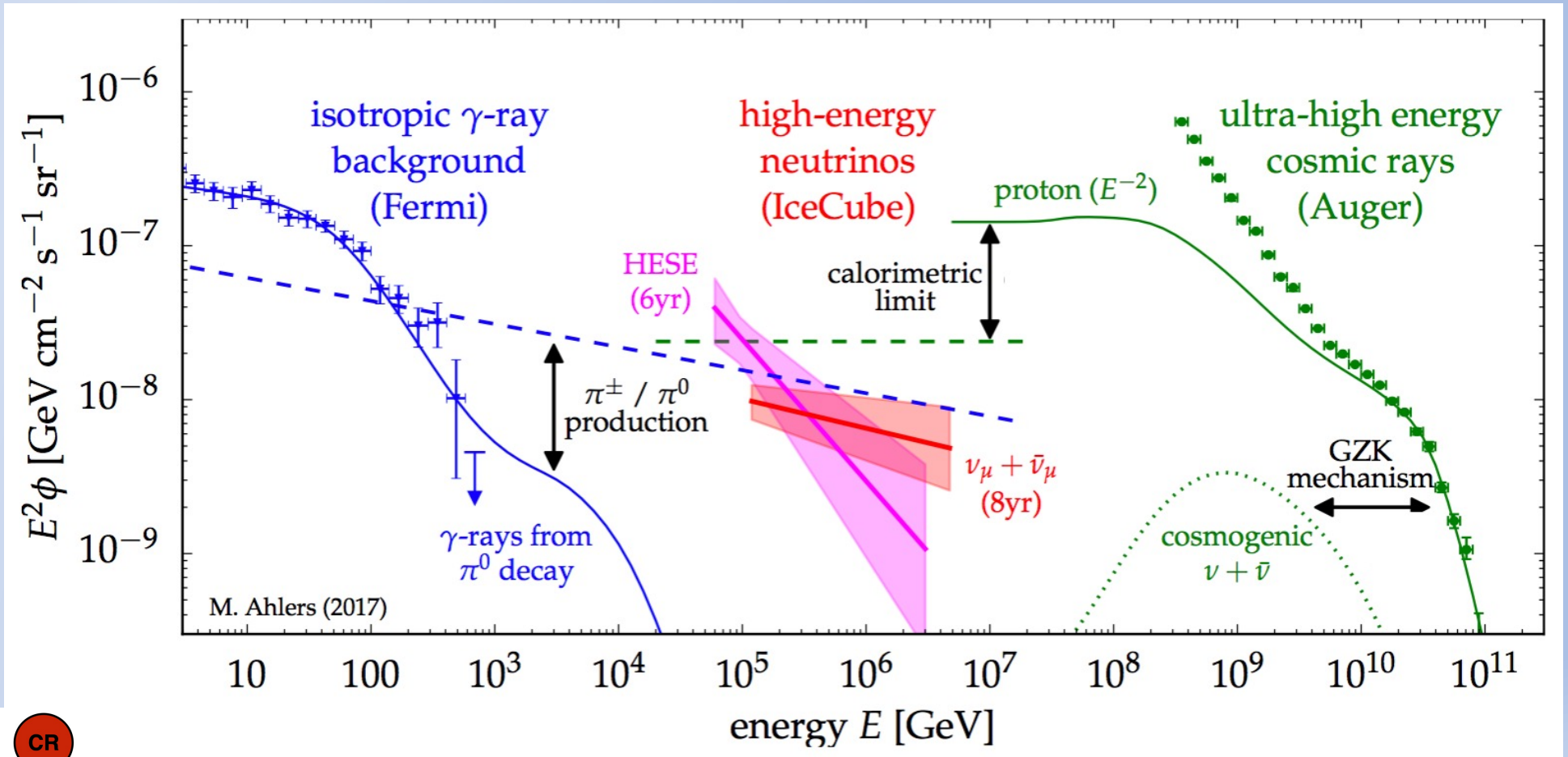
Their identification out of the more intense background of atmospheric neutrinos (and μ) is possible at very high energies (E_μ >> TeV) and requires **good energy reconstruction.**

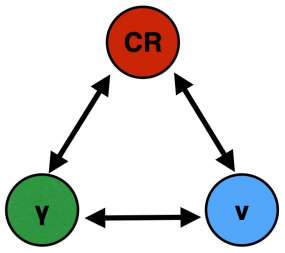
Search for Diffuse flux of Cosmic Neutrinos



- Neutrinos from:
  - Unresolved AGN
  - "Z-bursts"
  - "GZK like" proton-CMB interactions
- Top-Down models ν
- ….

The "diffuse" ν-γ-CR fluxes connection



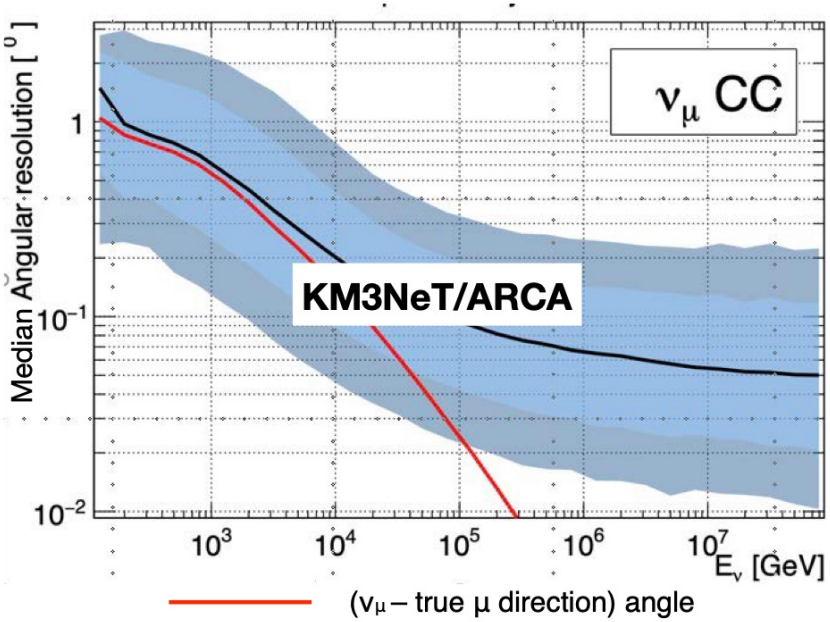


ARCA Reconstruction Performances

Track-like and shower-like events

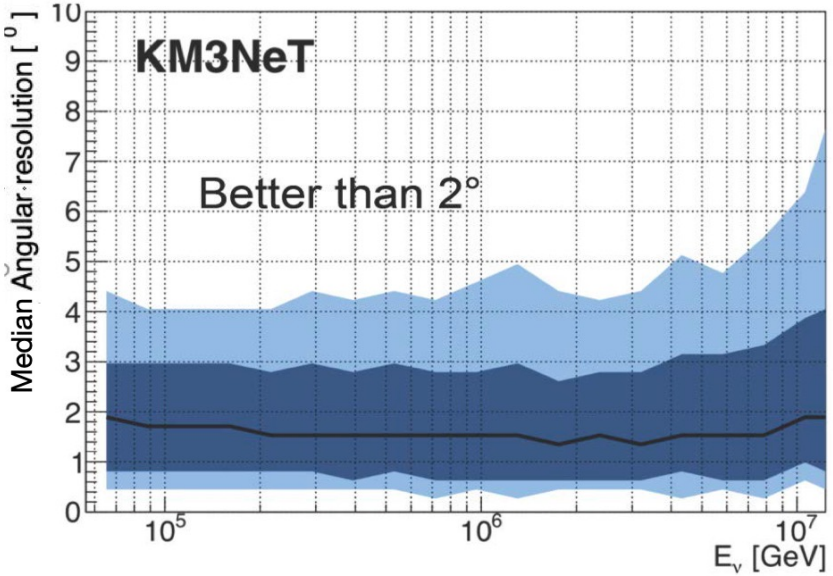
Tracks (ν_μ CC) ideal tool for astronomy

- **Ang. Resol. < 0.2°** above 10 TeV
- **Energy Resol. ~ 0.27** in $\log_{10}(E_{reco}/E_\mu)$ (10 TeV < E_μ < 10 PeV)



Shower (ν_x NC + ν_e CC) contained events

- **Ang. Resol. < 2°** above 50 TeV
- **Energy Resol. < 5%**



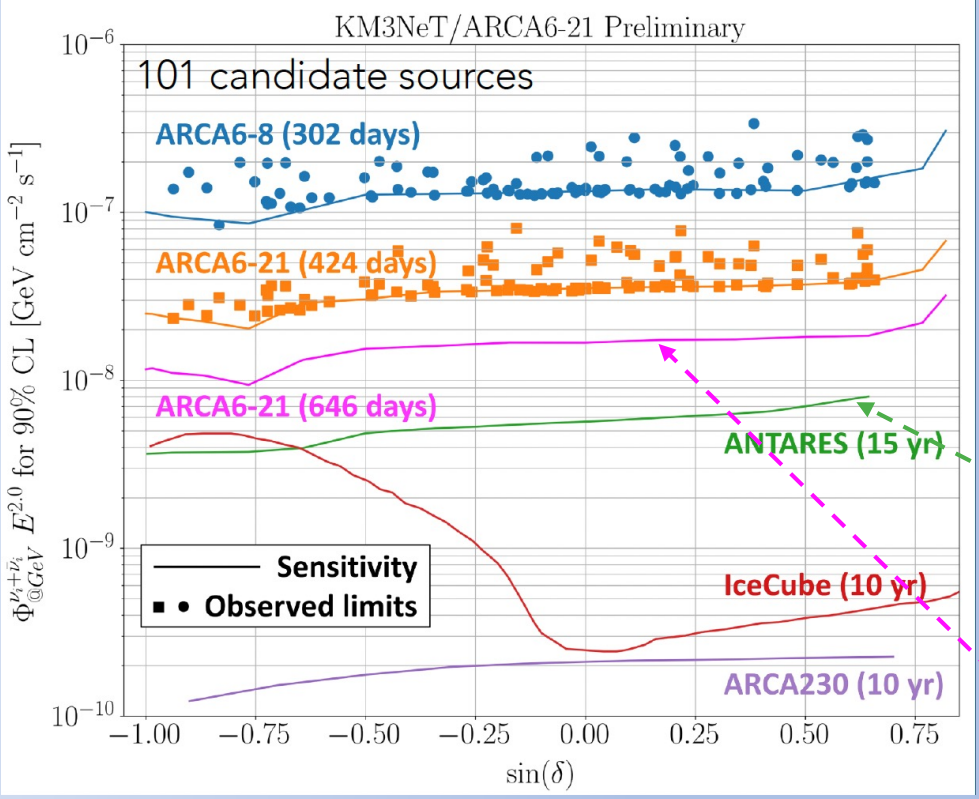
KM3NeT vs IceCube:

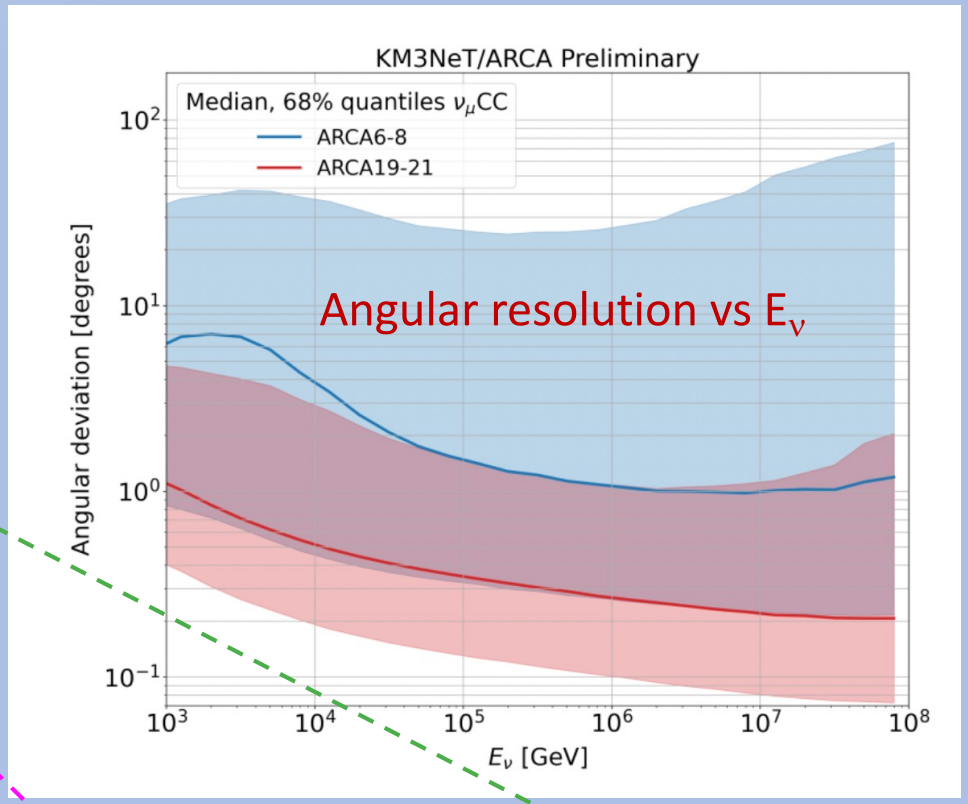
Con: ^{40}K background, bioluminescence, need for real-time positioning, deep-sea operations

Pro: ^{40}K calibration, better view of the galactic center, no bubbles/dust —> better angular resolution

KM3NeT/ARCA ν main science goals

Search for point-like cosmic Neutrino Sources



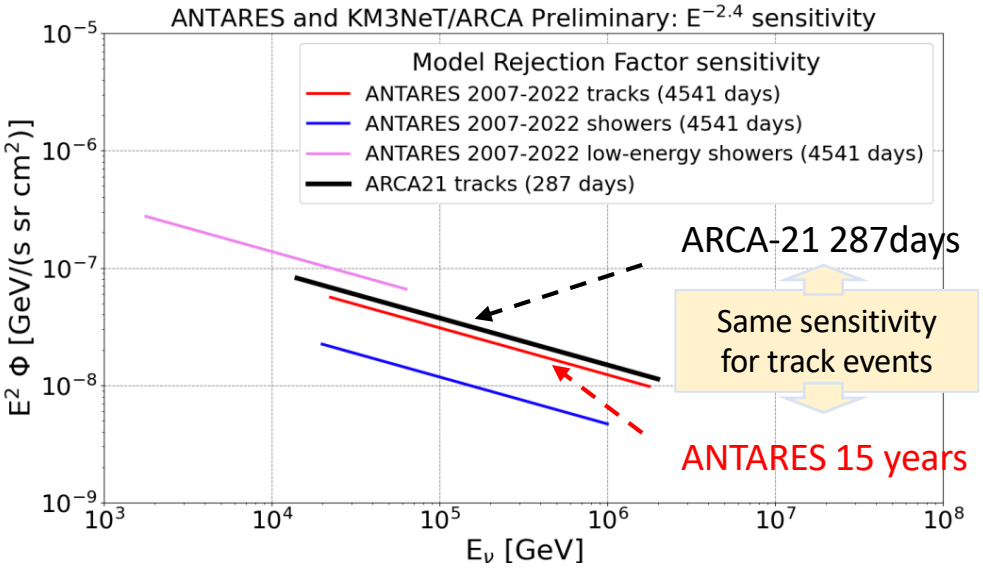


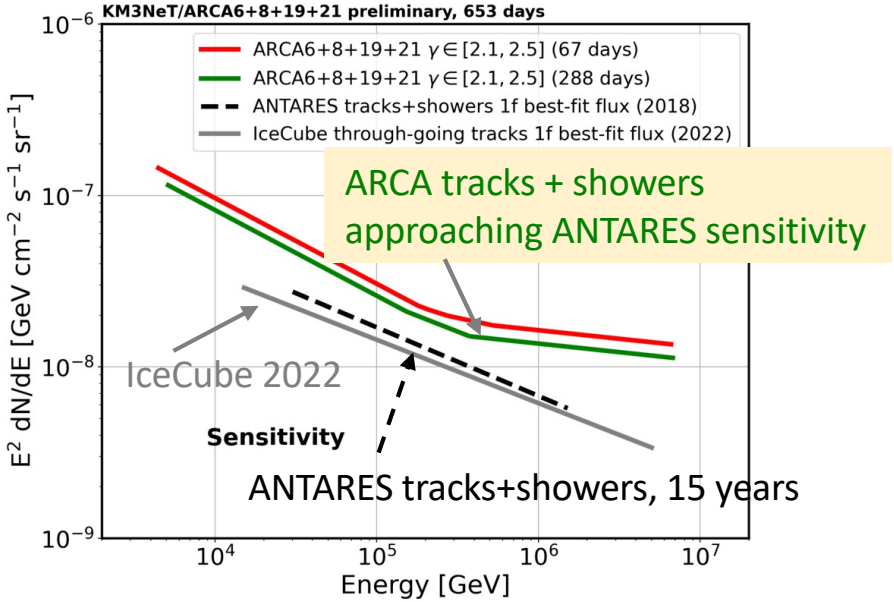
ARCA-21 data only partially (< Dec. 2022) analysed.
Soon full period results released.
ARCA-28 data from Sept.2023 will be added.
Deployment/operation of > 20 lines during 2025.

KM3NeT/ARCA upper limits close to ANTARES 15yr ones.
Joint ARCA-ANTARES search for point-like sources ongoing.
Results expected soon.

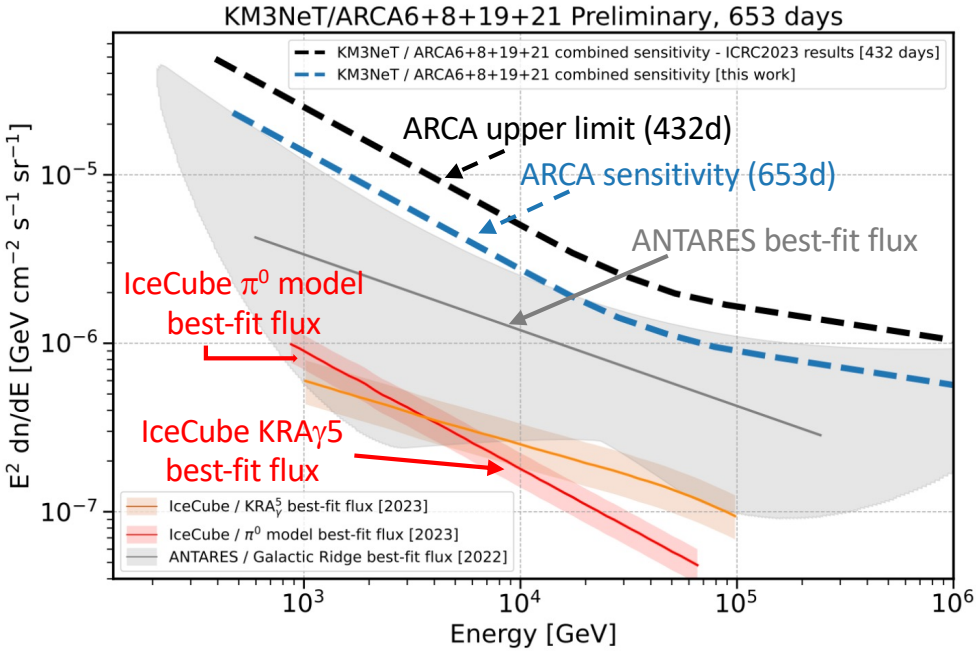
KM3NeT/ARCA search for diffuse sources of cosmic ν

Searching for ν from the full sky





Searching for ν from the galactic plane

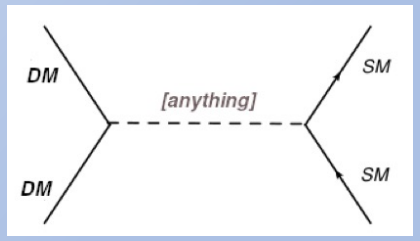


ARCA6 + ARCA8 + ARCA19 + ARCA21 (< Dec. 2022) data
KM3NeT/ARCA preliminary results

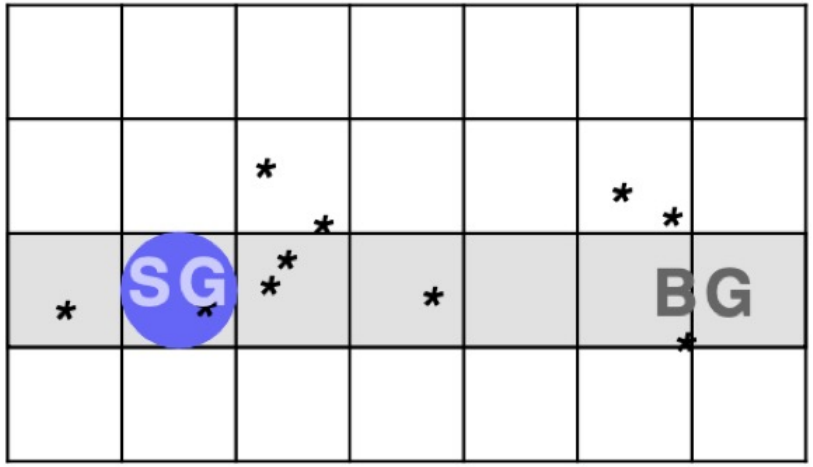
on-off zone analysis:
- $|l| < 31^0$ and $|b| < 5^0$ for ARCA6 & ARCA8
- $|l| < 31^0$ and $|b| < 4^0$ for ARCA19 & ARCA21

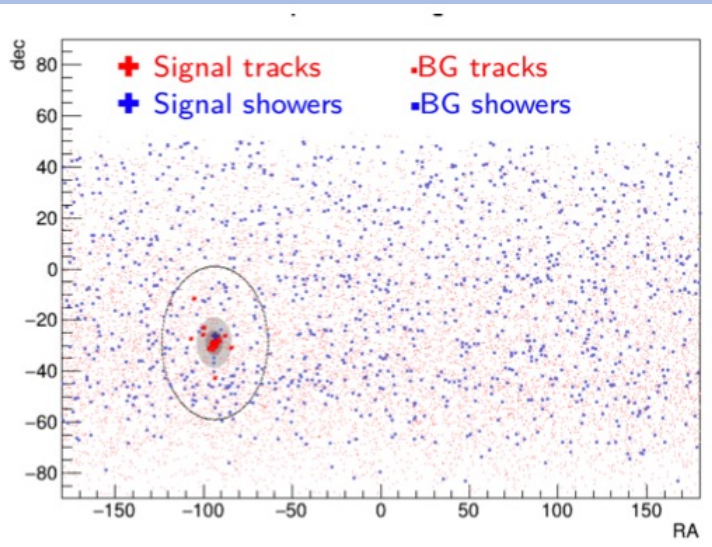
… not only neutrino astrophysics…

Indirect search for Dark Matter evidences in the Galactic Center



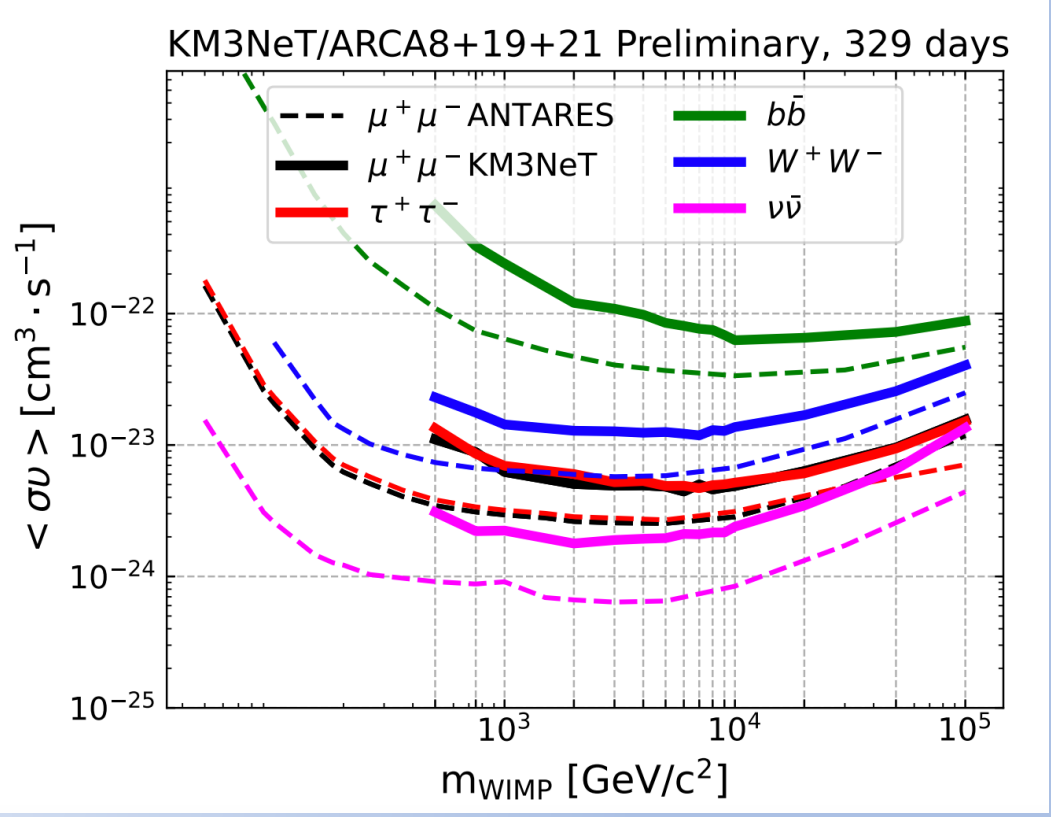
Signal: neutrino events from the GC region originated in Dark-Matter pair-annihilation process
Background: neutrinos from off-GC zones
Signal and **Background** events characterised by arrival direction and energy distributions
Number of signal events from binned or unbinned maximum likelihood analysis .

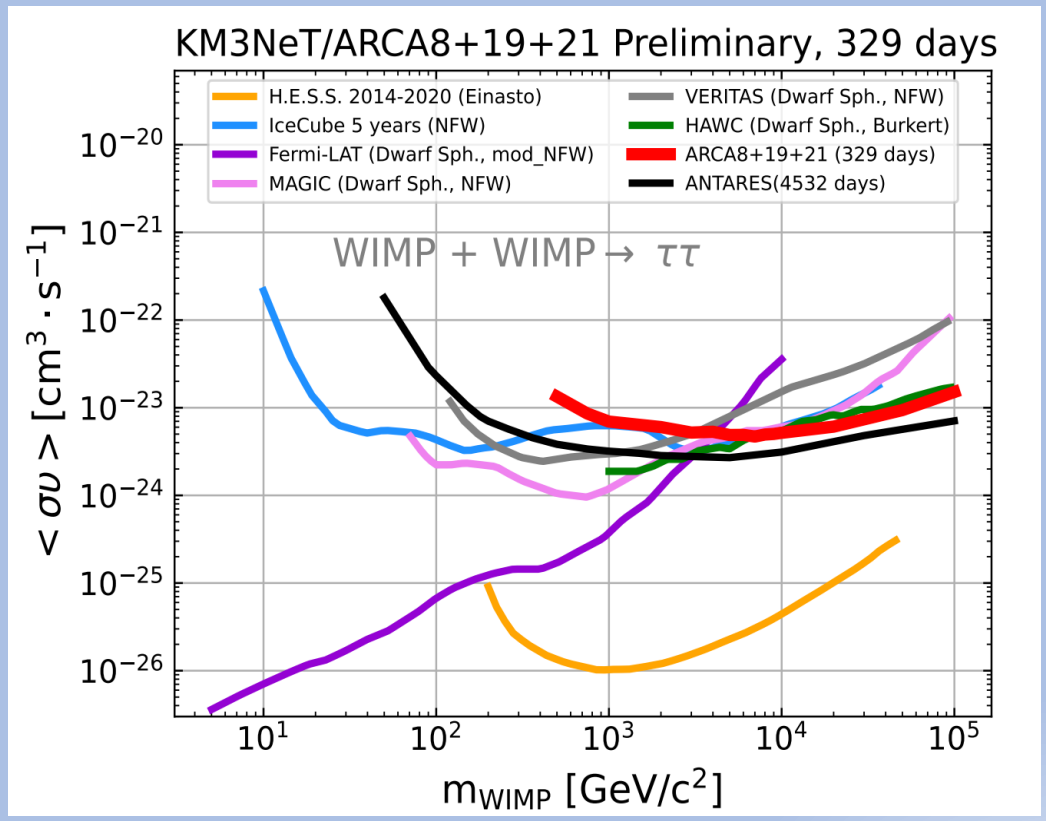




… not only neutrino astrophysics…

Indirect search for Dark Matter evidences in the Galactic Center

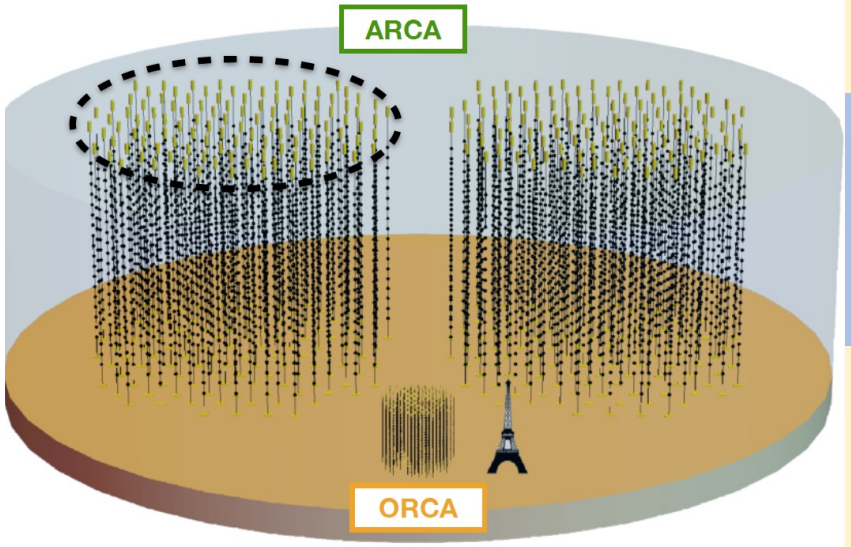




KM3NeT quickly reaching the ANTARES limits

KM3NeT & Multi-Messenger program

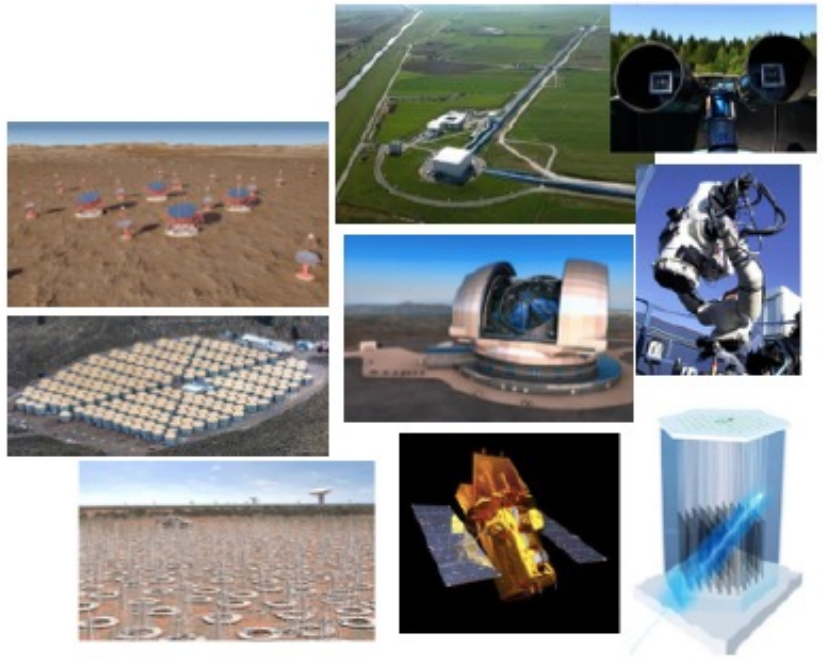
At ARCA/ORCA shore stations Real-Time Analysis & alerts communication



Send neutrino alerts to external communities

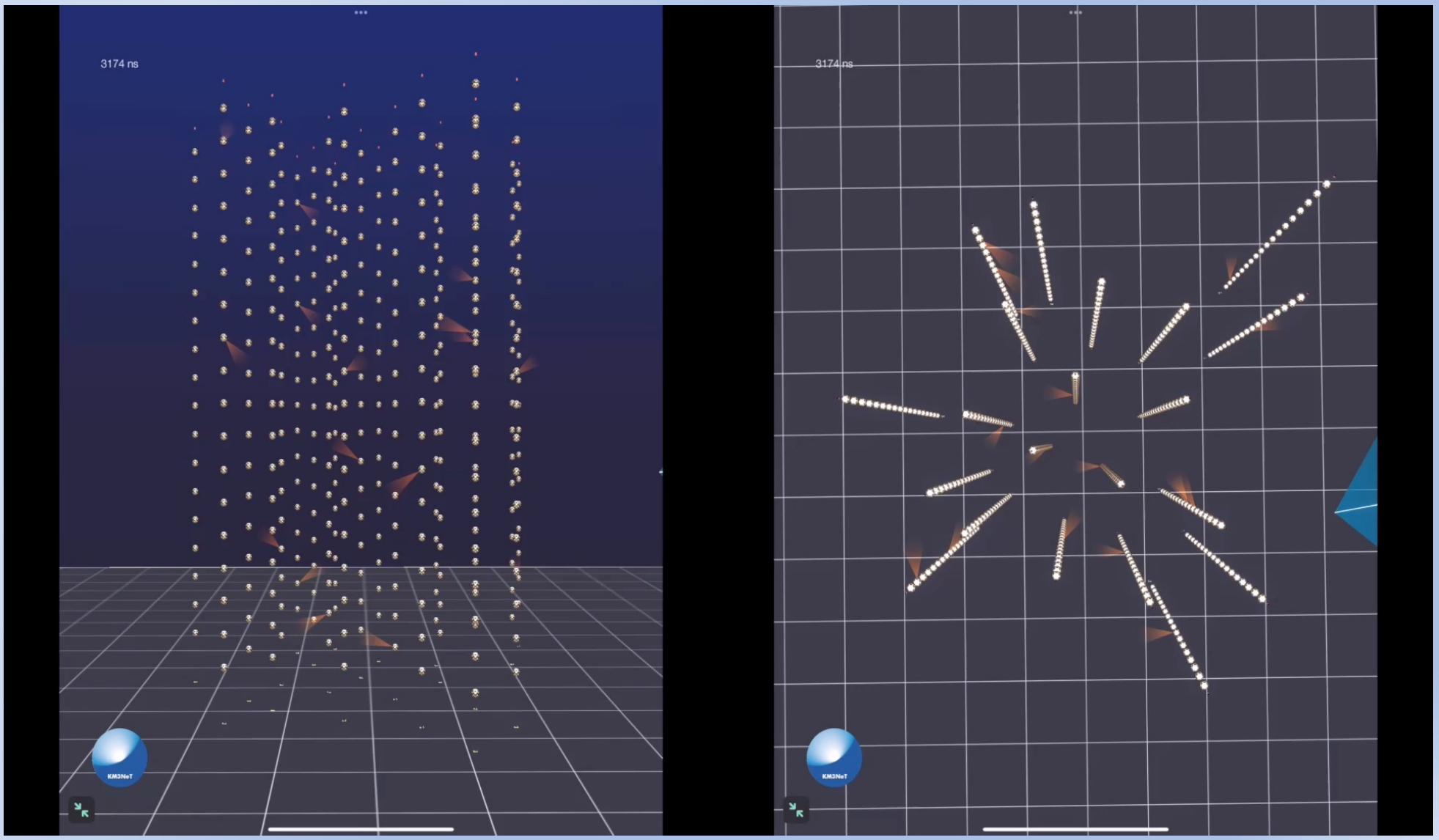
Receive alerts from external communities
➢ On-line analysis and follow-up

EM/MM external communities



Receiving alert system operative since November 2022 in ARCA and ORCA.
Sending High-energy neutrino alert system ~ finalised

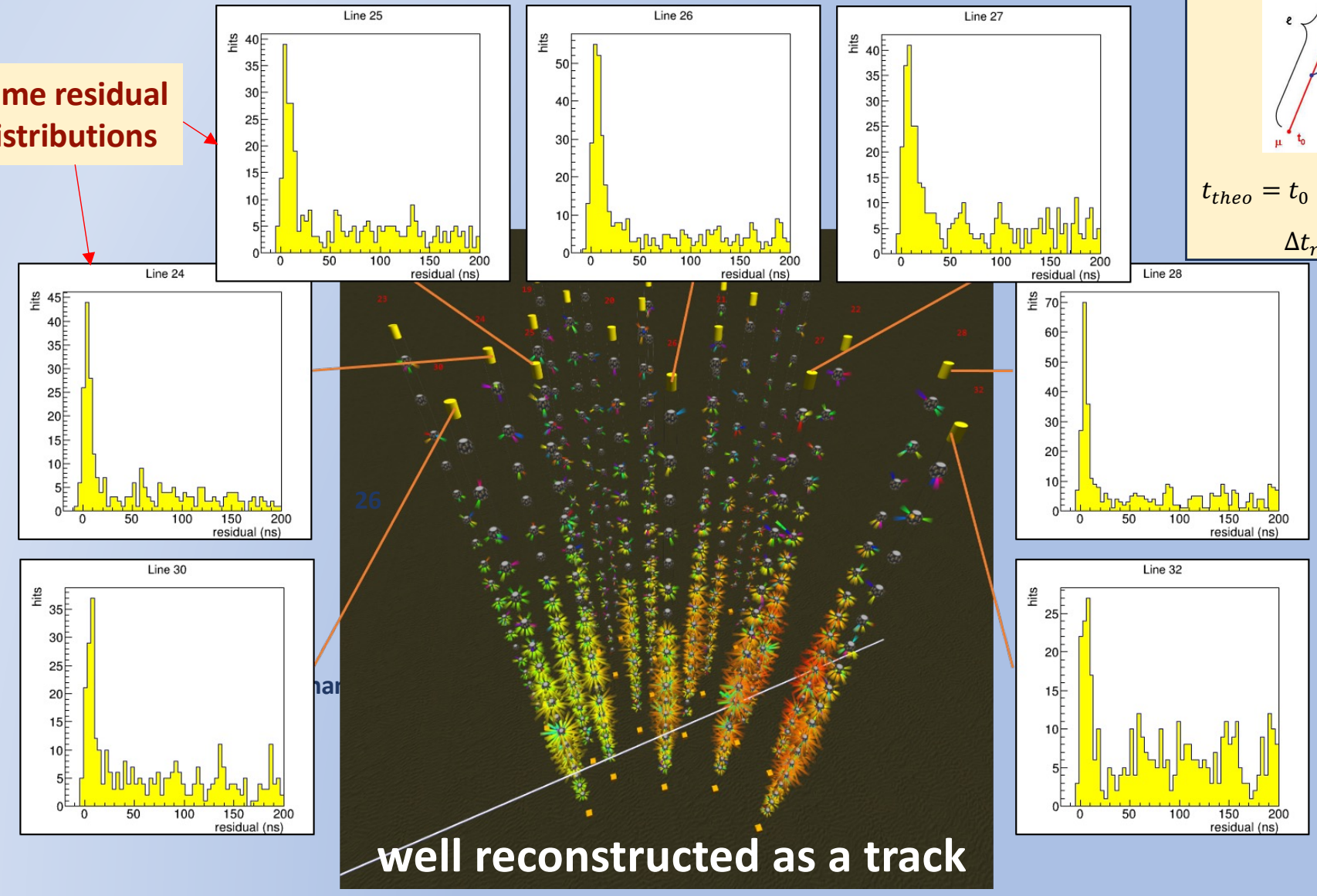
Very High Energy cosmic ν detected in ARCA21

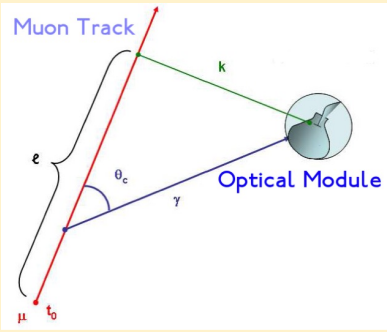


Very High Energy cosmic ν detected in ARCA21

February 2023

Time residual distributions

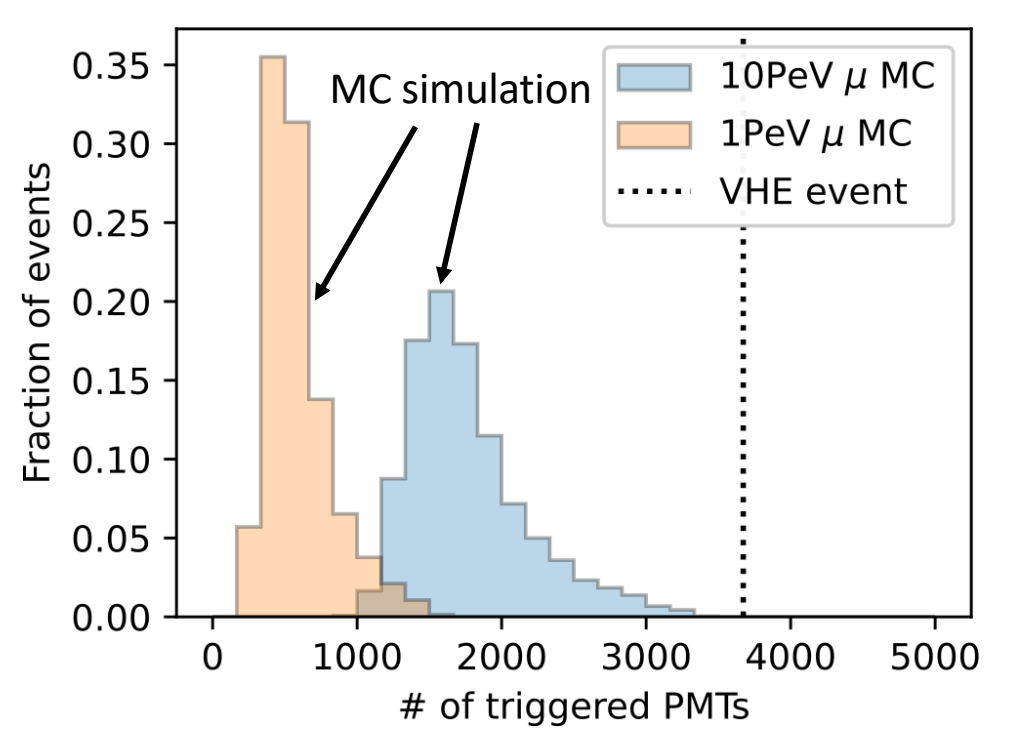


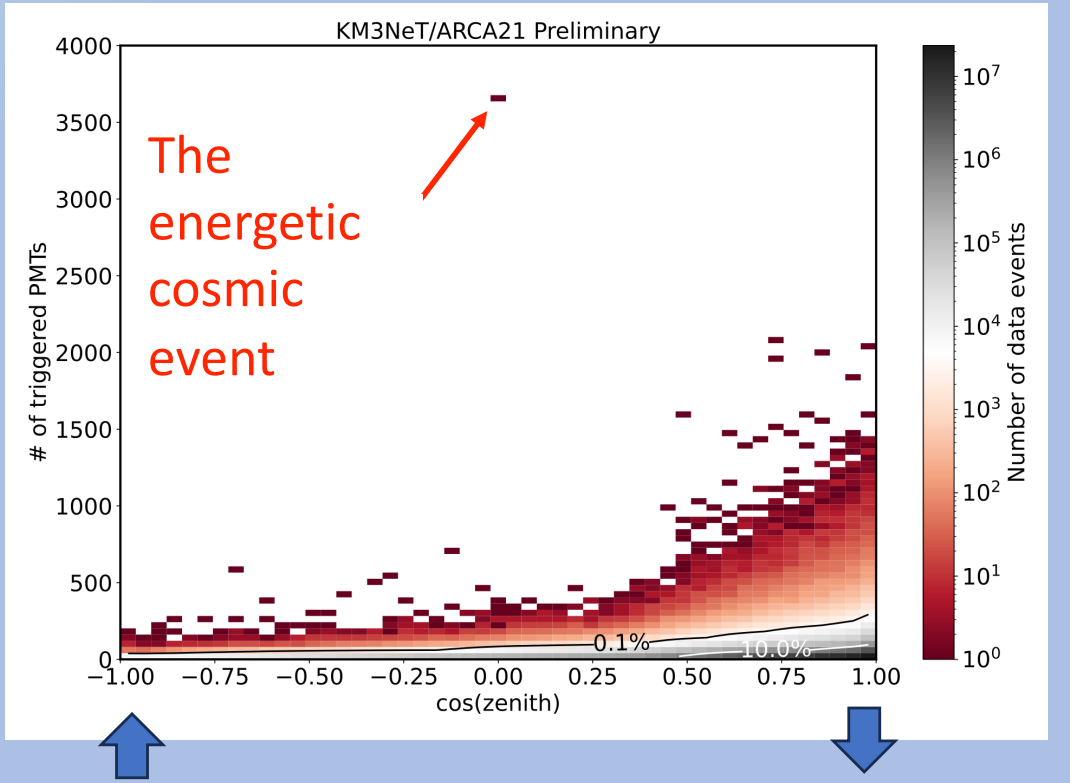


$$t_{theo} = t_0 + \frac{1}{c}\left(l - \frac{k}{tan\theta_c}\right) + \frac{1}{v_g}\left(\frac{k}{sin\theta_c}\right)$$

$$\Delta t_{residual} = t_{theo} - t_{exp}$$

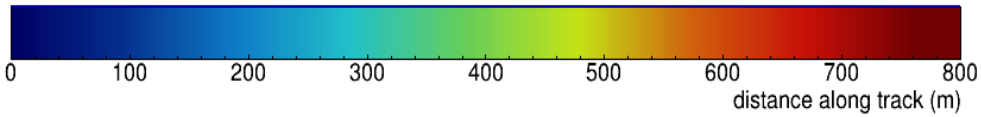
Very High Energy cosmic ν detected in ARCA21



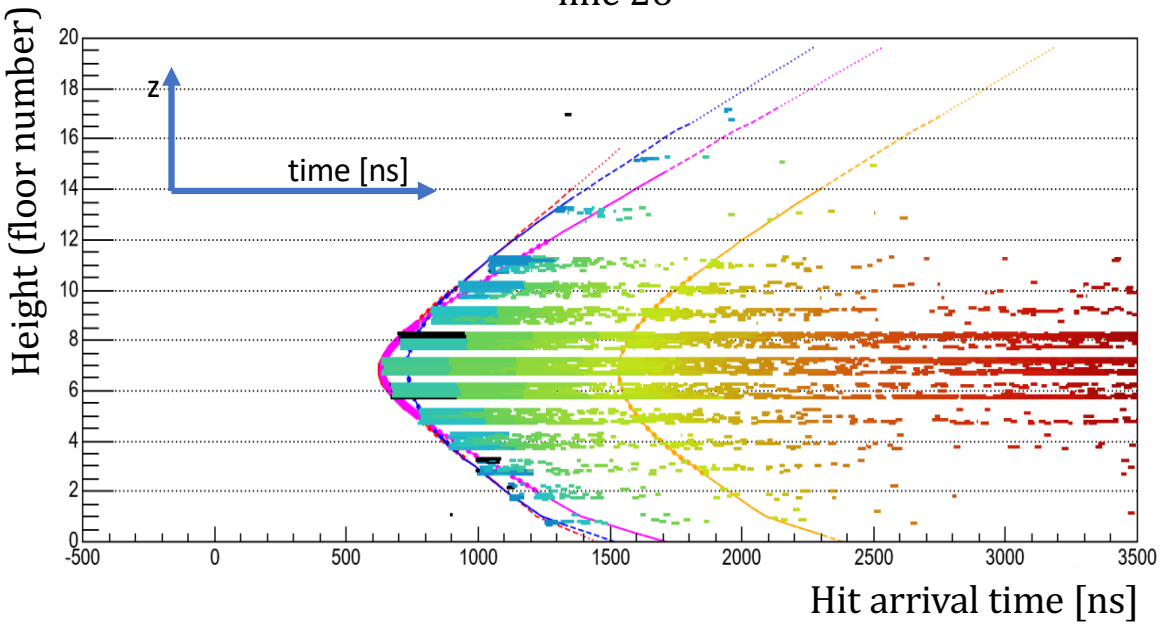


Horizontal event (1° above the horizon) with energy above 10 PeV
Huge amount of light detected ⇛ 35% of all PMTs were triggered

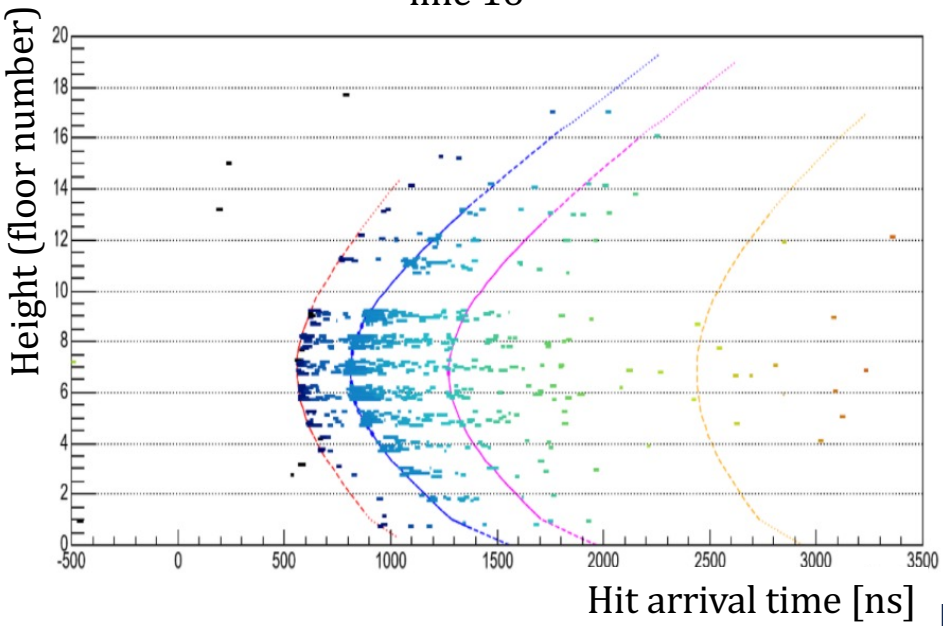
Very High Energy cosmic ν detected in ARCA21



line 26



line 16

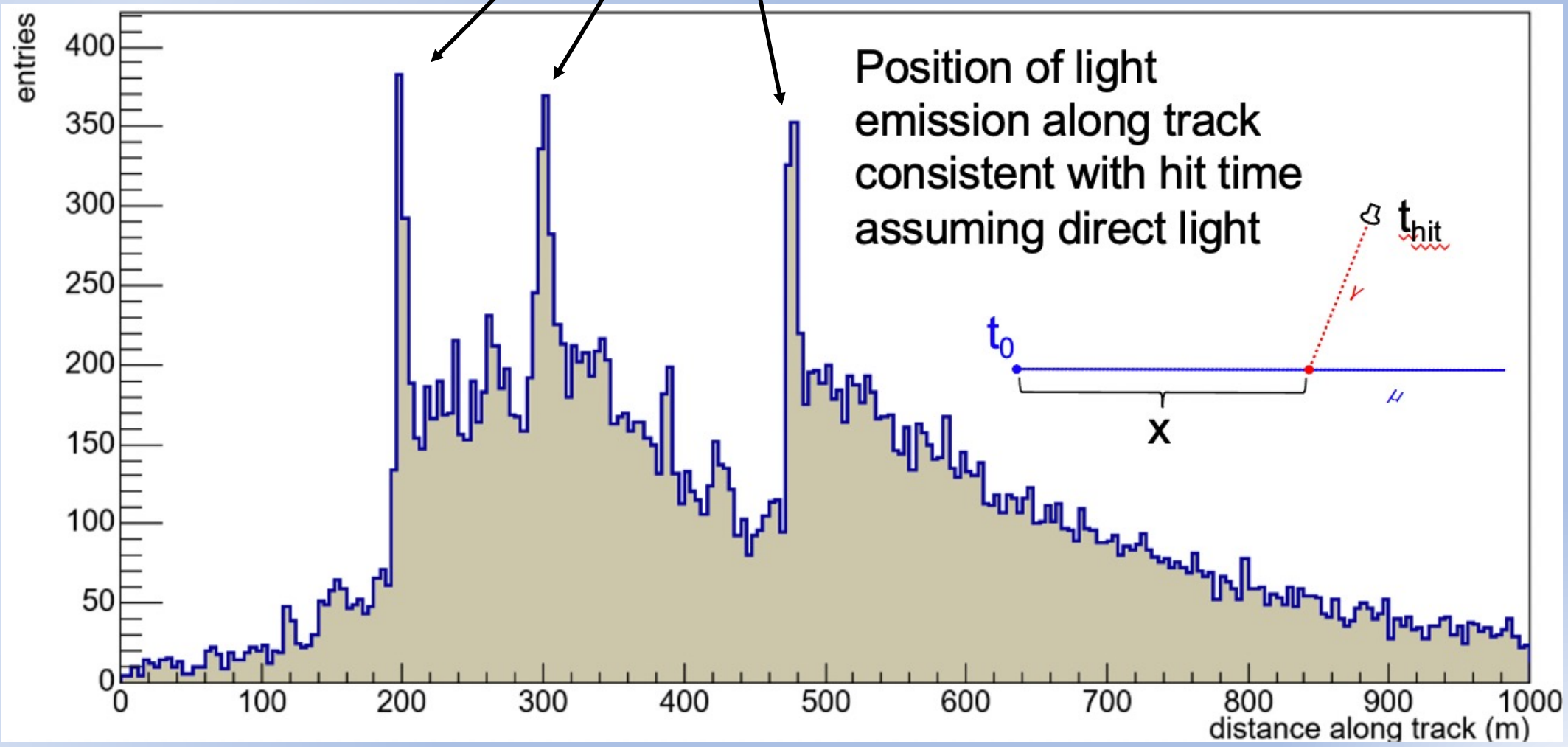


Hit times are fully consistent with photons from Cherenkov emission

A muon track and three showers detected

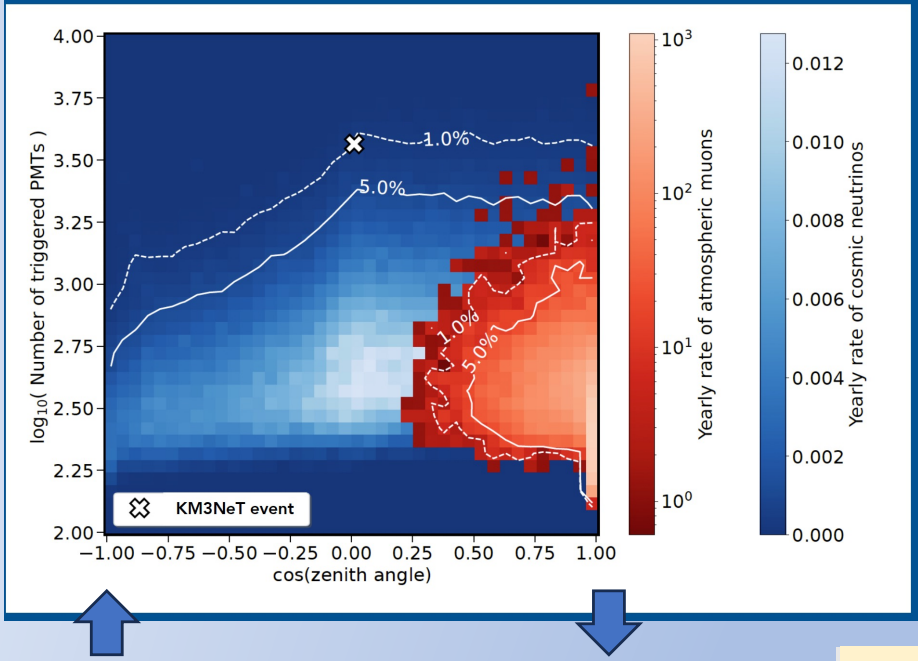
Very High Energy cosmic ν detected in ARCA21

Hit times consistent with the emission from three points along the track



Very High Energy cosmic ν detected in ARCA21

Is it background ?

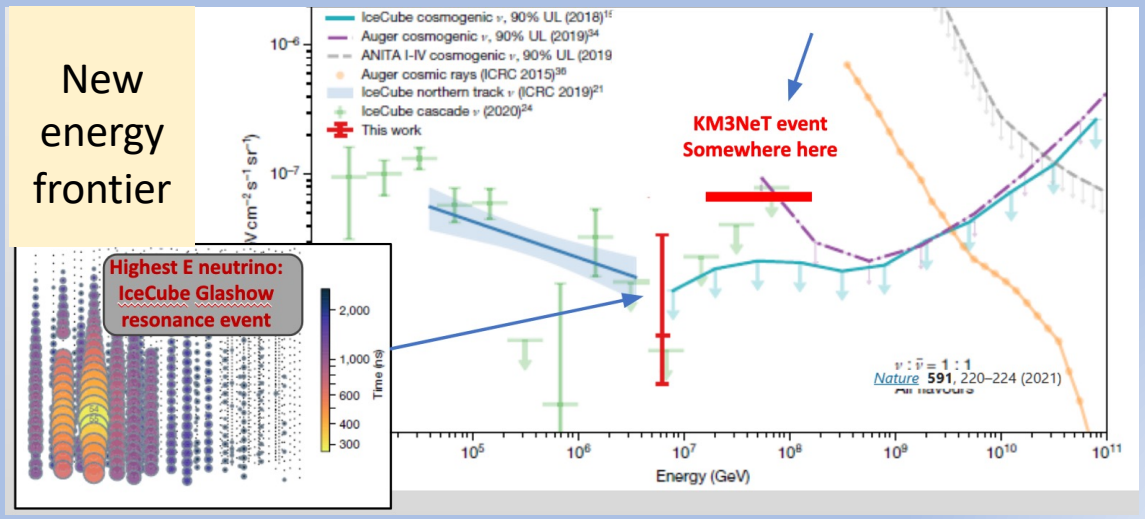


Given the detected energy and direction the expected rate of atmospheric muon reaching the detector is very low

- The amount of material traversed along the event direction is >100km of water equivalent (uncertainties included)

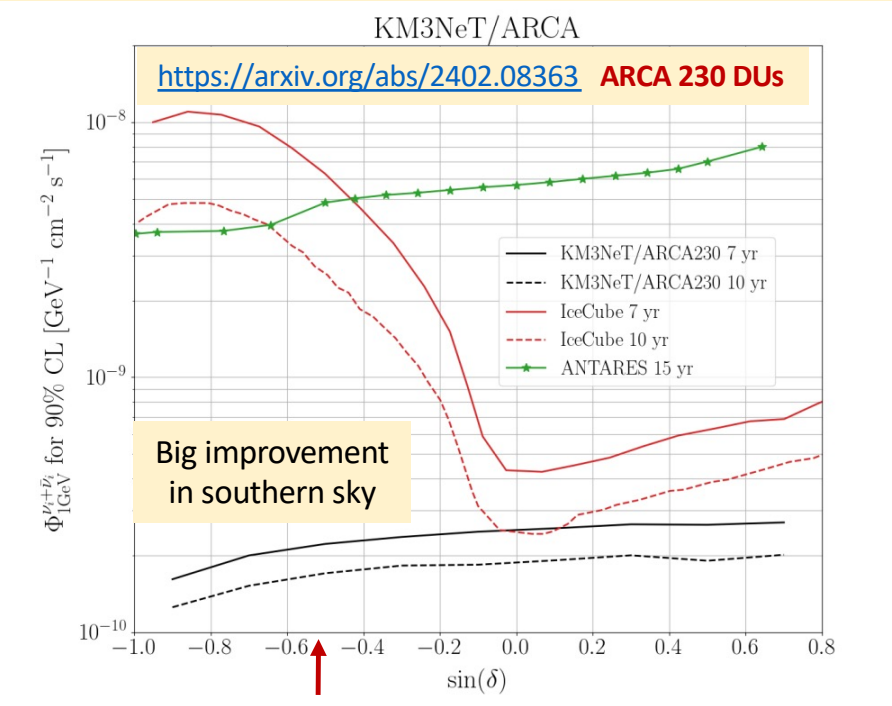
At this energies the expected rate of an atmospheric neutrino (prompt component) is about 10^{-5} events per year

New energy frontier



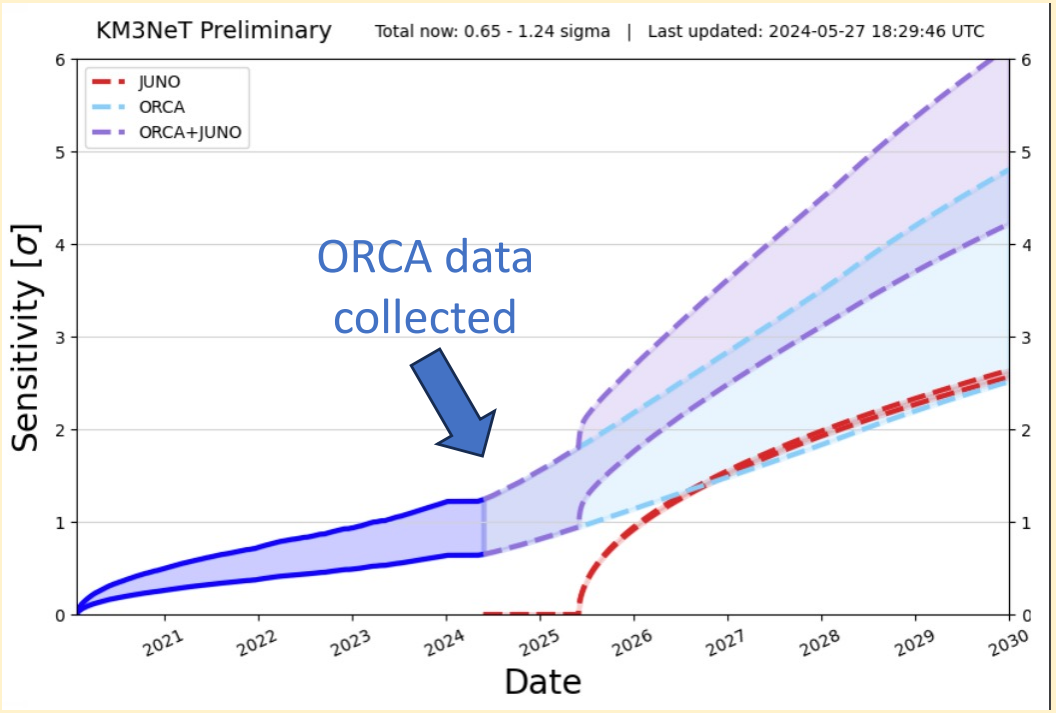
KM3NeT Perspectives

ARCA – sensitivity for point-like sources



GC declination

ORCA - neutrino mass ordering



5σ can be reached in the next 5-6 years if combined with Juno

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

- **ANTARES decommissioning**
- **ARCA 28 ORCA 24**
- **ARCA and ORCA completion**

Summary

KM3NeT infrastructure hosting two detectors built with same technology:

- ARCA at present 28 DUs deployed and tacking data (in few months > 50 Dus)
- ORCA at present 24 DUs deployed and tacking data

Construction plans: detector completion by end 2028

ARCA:

- sensitivities already close to the ANTARES 15 years ones
- Big improvement for the observation of southern sky

ORCA

- already competitive results for neutrino oscillation studies
- Neutrino mass hierarchy one of the main goals

An exceptional Very High Energy event observed: a horizontal cosmic neutrino carrying an energy > 10 PeV: crossing the UHE frontier