

# Neutrino astronomy

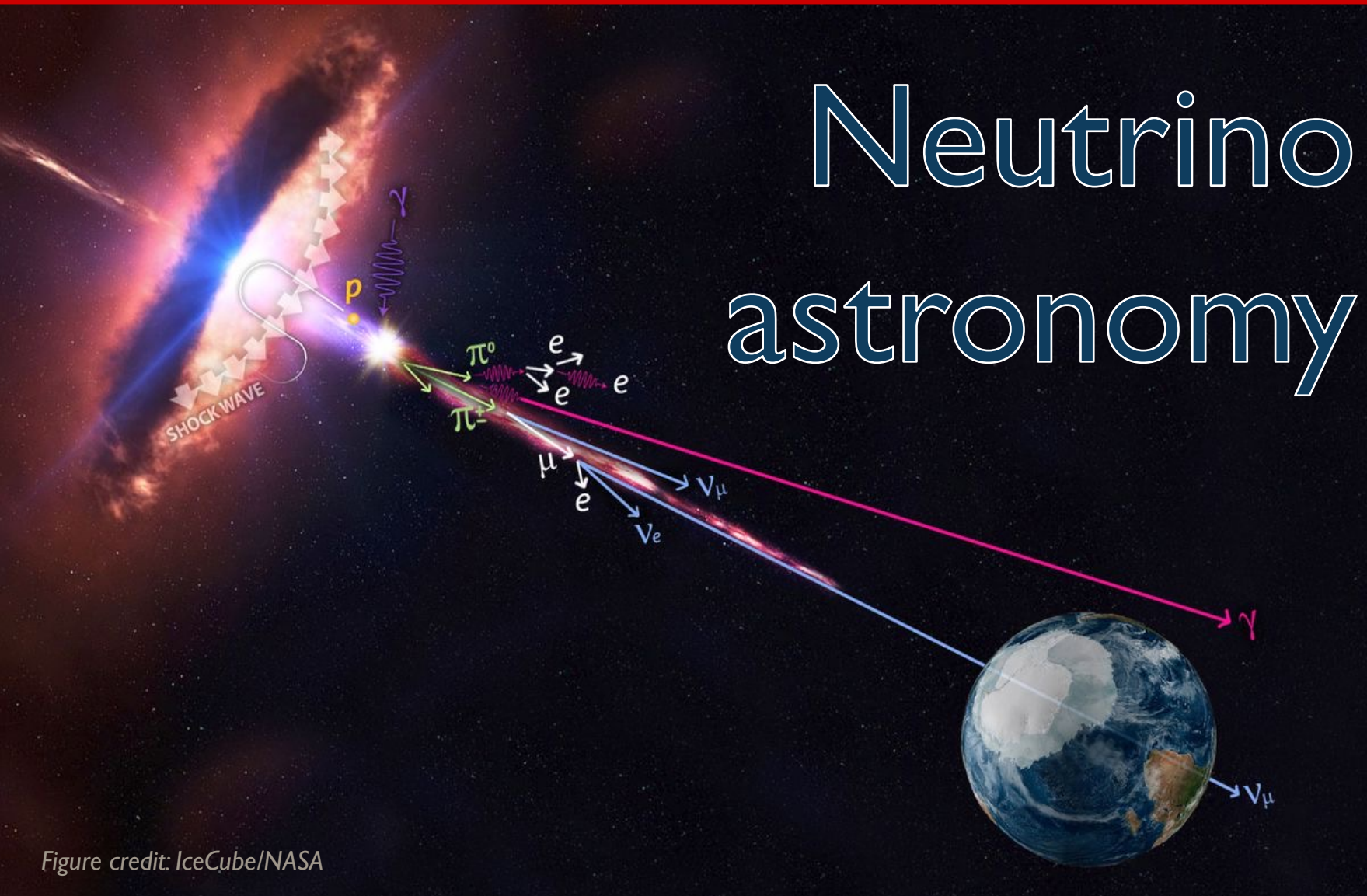
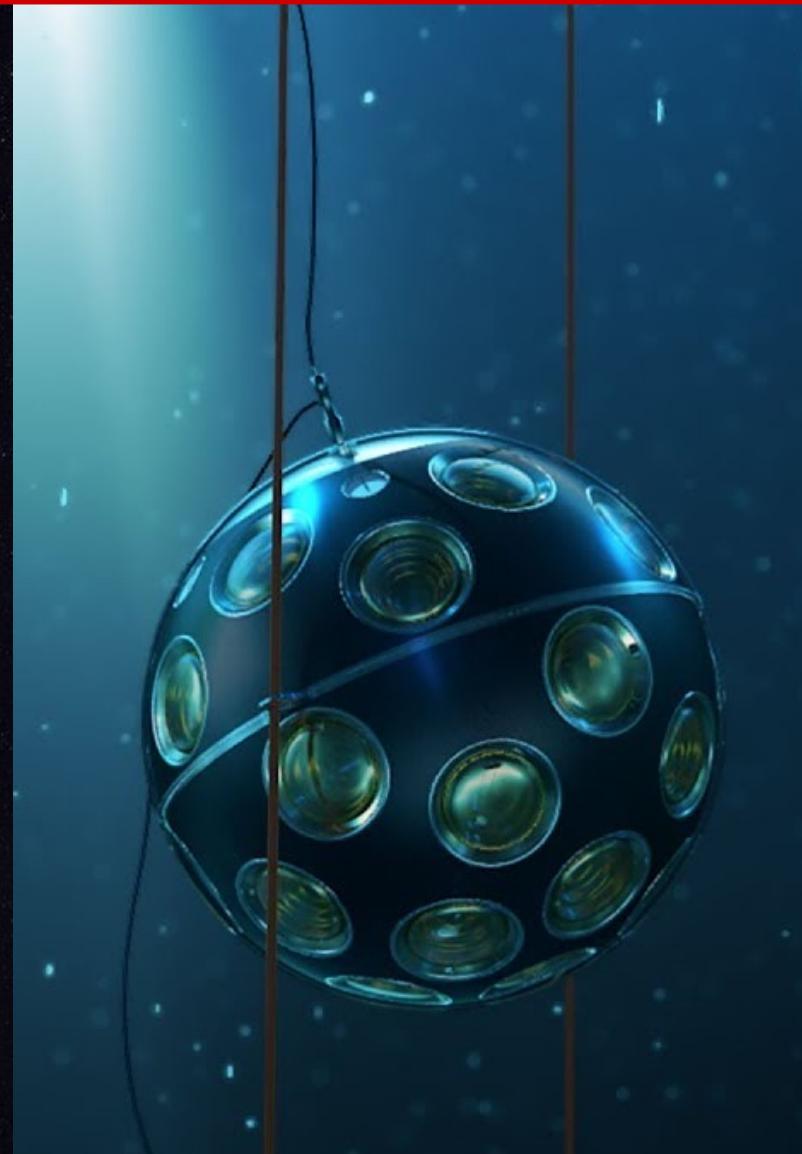
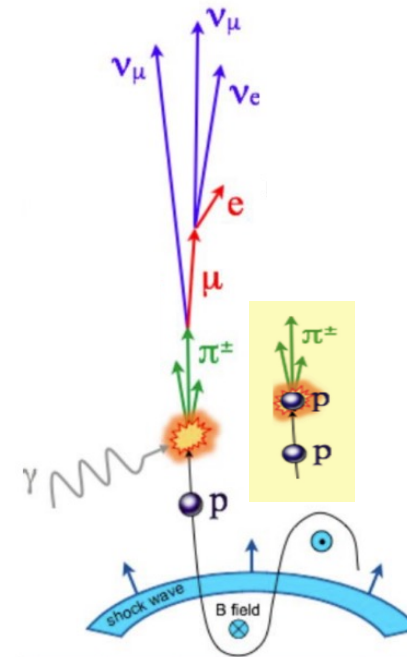
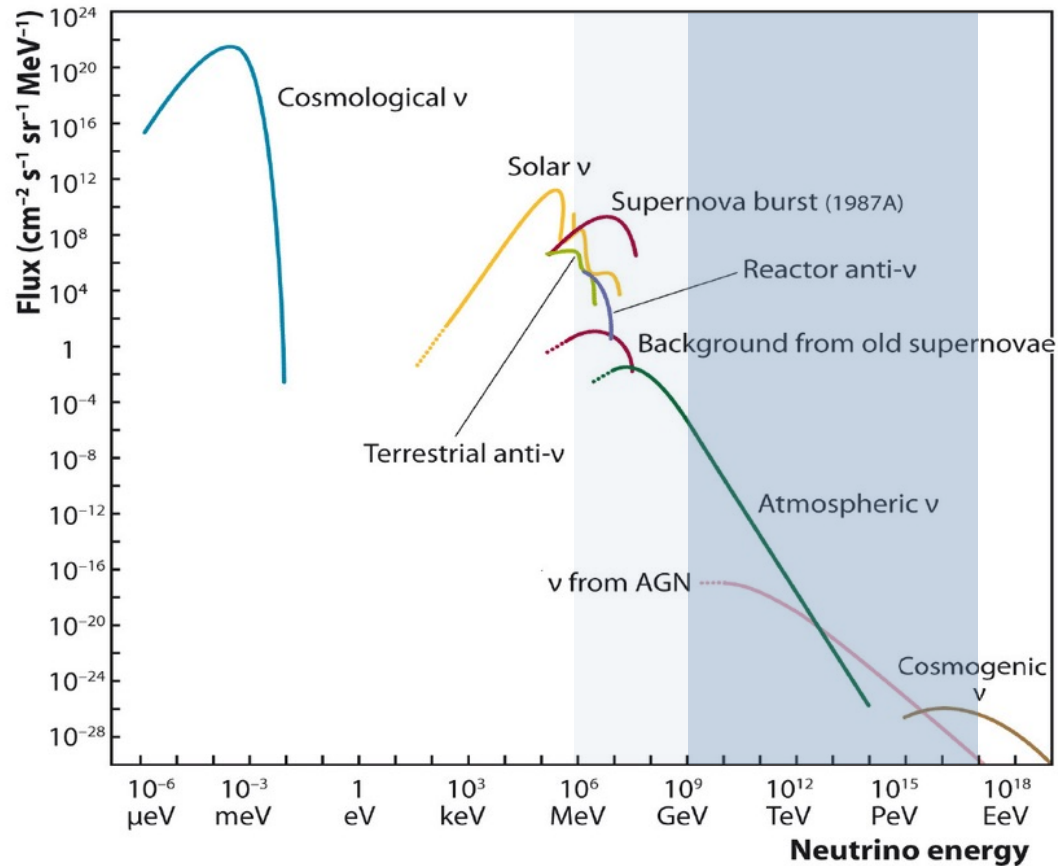


Figure credit: IceCube/NASA



# High-energy astrophysical neutrinos



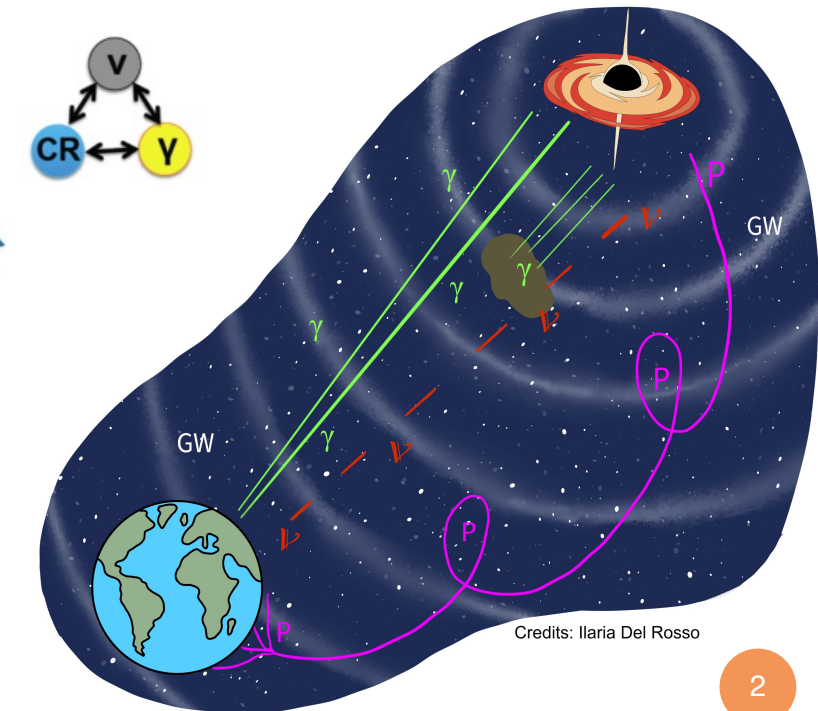
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \quad \text{at the source}$$

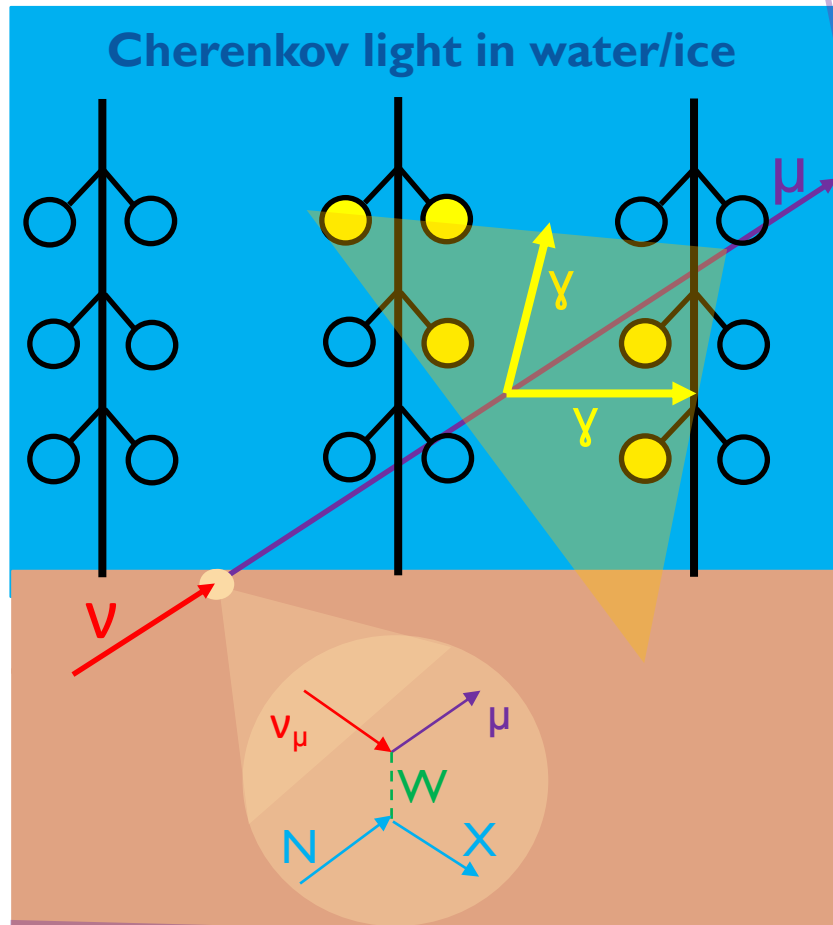
$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \quad \text{at Earth}$$



Credits: Ilaria Del Rosso

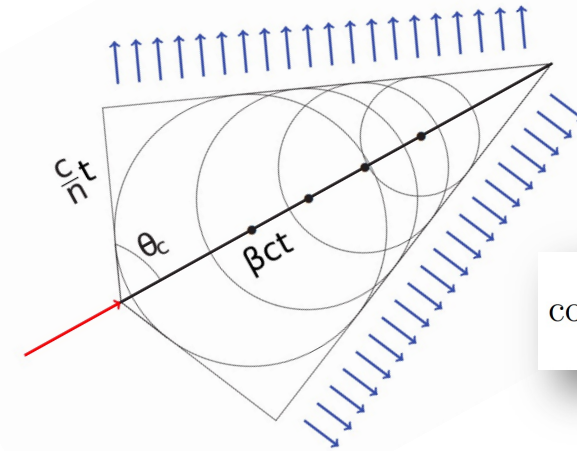


# High-energy neutrino detection



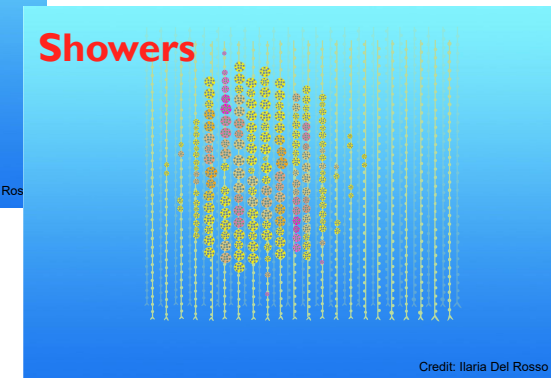
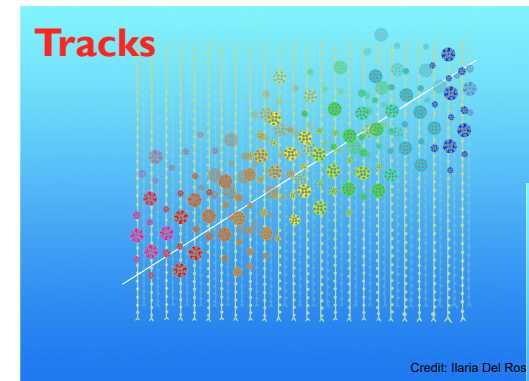
**Cherenkov radiation**  
detected by **arrays of PMTs**

Position, time and charge  
used to reconstruct  
**direction and energy**



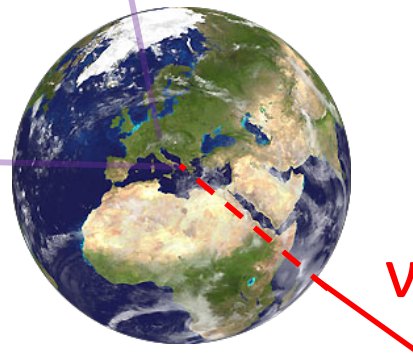
$$\cos \theta_C = \frac{1}{\beta n}$$

**Two main event signatures** →



Either **CC** or **NC**  
**interaction** with a  
nucleon **N**

**CC:**  $\nu_\ell + N \rightarrow \ell + X$   
**NC:**  $\nu_\ell + N \rightarrow \nu_\ell + X$



# High-energy neutrino telescopes today

## Decommisioned:

- **ANTARES** ( $\ll 1 \text{ km}^3$ )



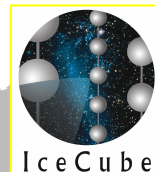
## Operating in full configuration:

- **IceCube** ( $1 \text{ km}^3$ )



## Under construction:

- **KM3NeT** (foreseen:  $1 \text{ km}^3$  )
- **Baikal GVD** (foreseen:  $> 1 \text{ km}^3$  )





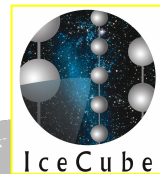
# Future neutrino telescope landscape



**HUNT**  
**NEON**

**In planning phase:**

- **IceCube Gen2**
- **P-ONE**
- **HUNT**
- **NEON**
- **TRIDENT**

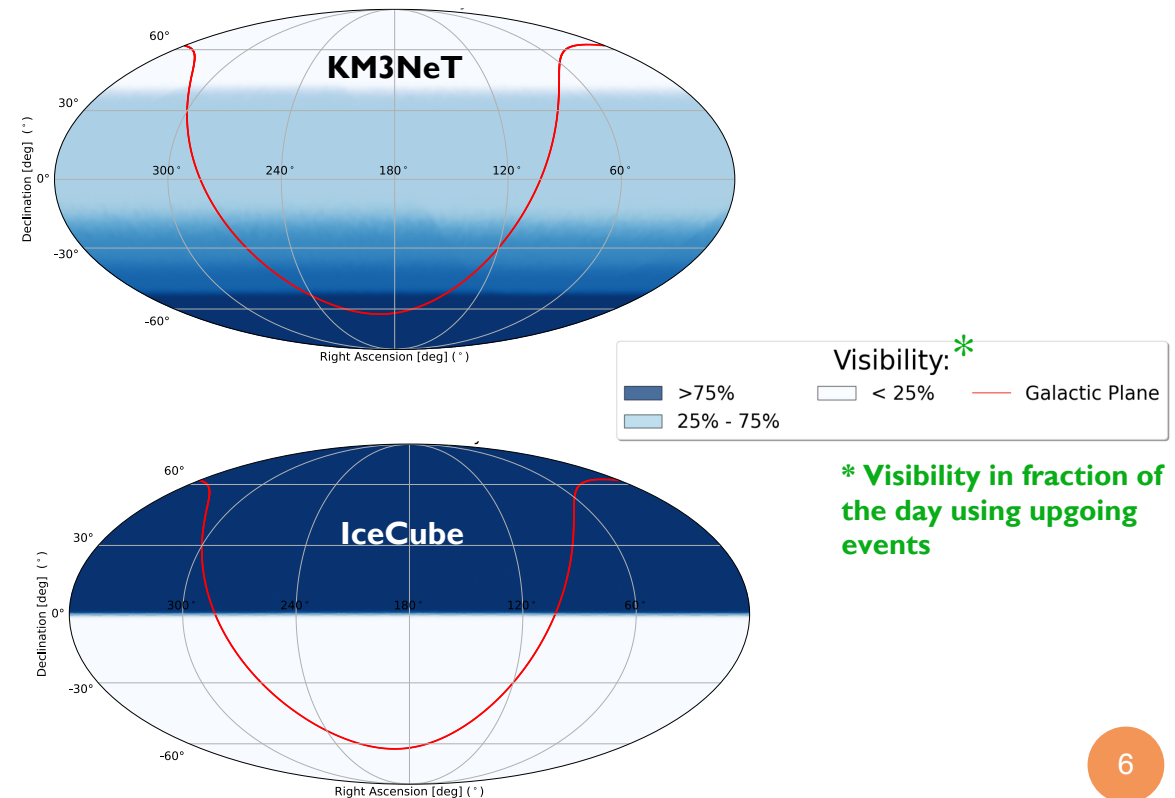
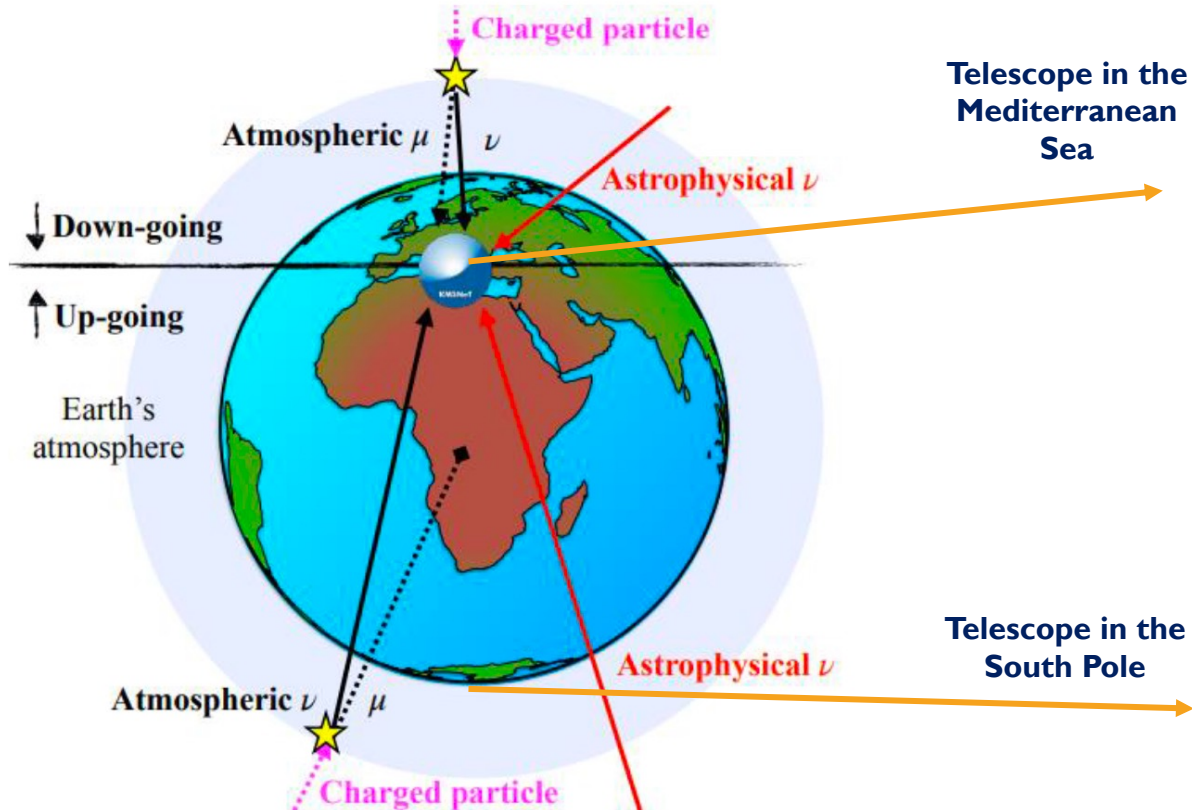


# Complementarity of $\nu$ telescopes

Neutrino telescopes **FoV: Full Sky**  
**BUT**

Depending on telescope location, **different sky regions correspond to different:**

- Background contamination (atmospheric muons are only down-going)
- Accessible energy range (Earth absorbs **VHE** neutrinos)

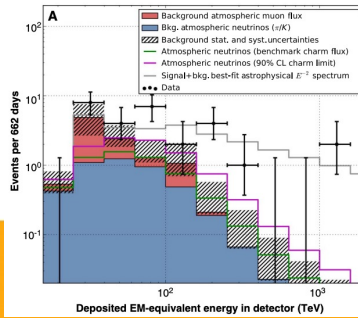


# Neutrino astronomy: a young field



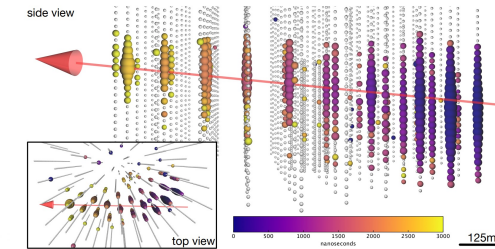
**4 $\sigma$  evidence for high-energy cosmic neutrinos by IceCube**

**2013**



Later confirmed at  $>5\sigma$  with more statistics, different IceCube samples, and by Baikal-GVD ( $3\sigma$ )  
ANTARES confirms spectral features at low energies

**3 $\sigma$  association between IceCube alert and flaring blazar TXS 0506+056**



**ANTARES:**

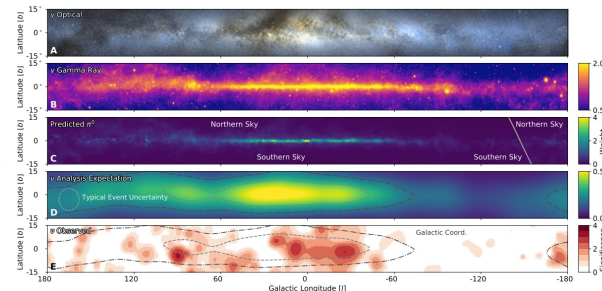
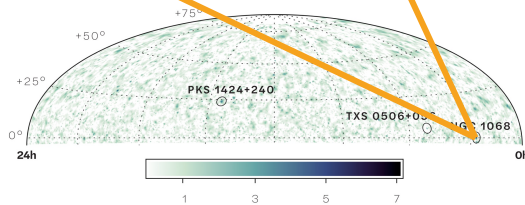
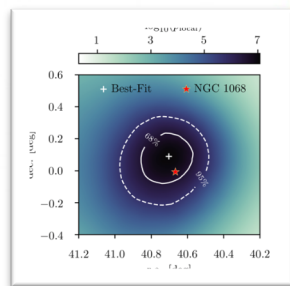
- 2.4 $\sigma$  (steady flux)
- ANTARES-IceCube overlapping neutrino flare (0.5% chance probability)

**$>4\sigma$  evidence for neutrino emission from active Galaxy NGC 1068 seen by IceCube**

**2022**

**4.5 $\sigma$  observation of neutrinos from the Galactic plane by IceCube**  
ANTARES: 2.2 $\sigma$

**2023**



**2025**

**Observation of a 220 PeV neutrino by KM3NeT**



# Neutrinos and radio-bright AGNs

THE ASTROPHYSICAL JOURNAL, 894:101 (13pp), 2020 May 10  
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ApJ 894 (2020) 101

<https://doi.org/10.3847/1538-4357/ab86bd>

Observational Evidence for the Origin of High-energy Neutrinos in Parsec-scale Nuclei of Radio-bright Active Galaxies

Alexander Plavin<sup>1,2</sup>, Yuri Y. Kovalev<sup>1,2,3</sup>, Yuri A. Kovalev<sup>1</sup>, and Sergey Troitsky<sup>4</sup>  
<sup>1</sup> Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia; alexander@plav.in

THE ASTROPHYSICAL JOURNAL, 908:157 (10pp), 2021 February 20  
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ApJ 908 (2021) 157

<https://doi.org/10.3847/1538-4357/abc6b8>

Directional Association of TeV to PeV Astrophysical Neutrinos with Radio Blazars

A. V. Plavin<sup>1,2</sup>, Y. Y. Kovalev<sup>1,2,3</sup>, Yu. A. Kovalev<sup>1</sup>, and S. V. Troitsky<sup>4</sup>  
<sup>1</sup> Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia; alexander@plav.in

<sup>2</sup> Moscow MNRAS 523, 1799–1808 (2023)  
<sup>3</sup> Max Advance Access publication 2023 May 16  
<sup>4</sup> Institute for Nuclear Research Received 2020 Sept

MNRAS 523 (2023) 1799

<https://doi.org/10.1093/mnras/stad1467>

Growing evidence for high-energy neutrinos originating in radio blazars

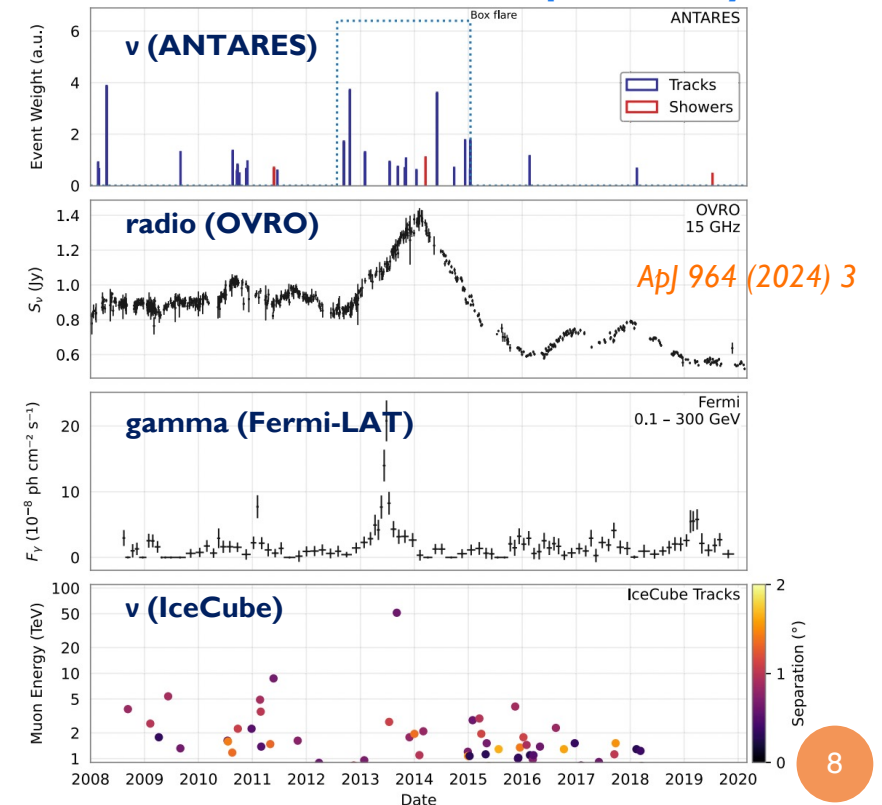
A. V. Plavin<sup>1,\*</sup>, Y. Y. Kovalev<sup>1,2,3</sup>, Yu. A. Kovalev<sup>1</sup> and S. V. Troitsky<sup>4,5</sup>

<sup>1</sup> Lebedev Physical Institute of the Russian Academy of Sciences, Leninsky prospekt 53, 119991 Moscow, Russia  
<sup>2</sup> Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany  
<sup>3</sup> Moscow Institute of Physics and Technology, Institutskiy per. 9, 141700 Dolgoprudny, Russia  
<sup>4</sup> Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary prospect 7a, 117312 Moscow, Russia  
<sup>5</sup> Physics Department, Lomonosov Moscow State University, 1-2 Leninskie Gory, Moscow 119991, Russia

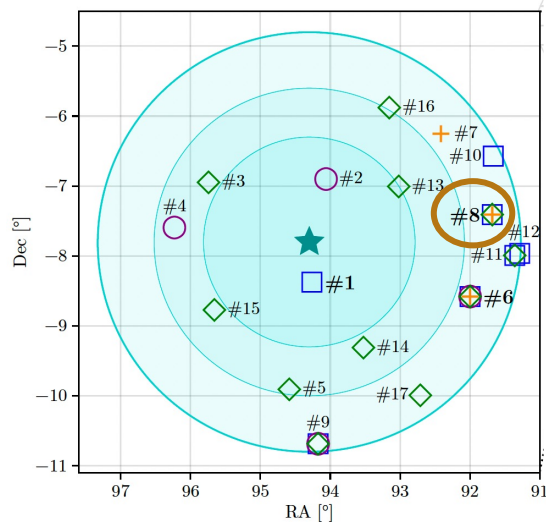
**IceCube neutrinos – AGNs from RFC**

AGNs coincident with neutrinos have typically stronger parsec-scale cores (higher VLBI flux density) than rest of the sample (**0.2% chance probability**)

**ANTARES  $\nu$  flare and J0242+1101**  
**0.5% chance probability**

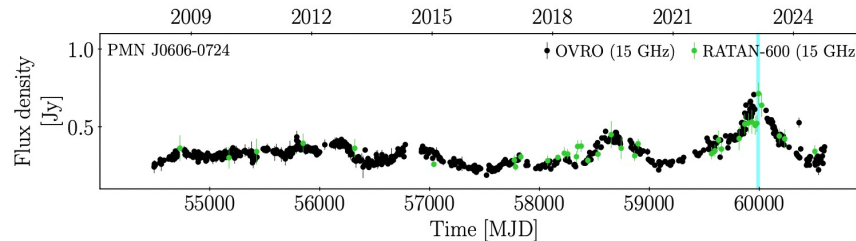


**No correlation found by IceCube with refined information (2023 ApJ 954 75) mitigates these findings**



**KM3-231213A and PMN J0606-0724**

[arXiv:2502.08484](https://arxiv.org/abs/2502.08484) [astro-ph.HE]



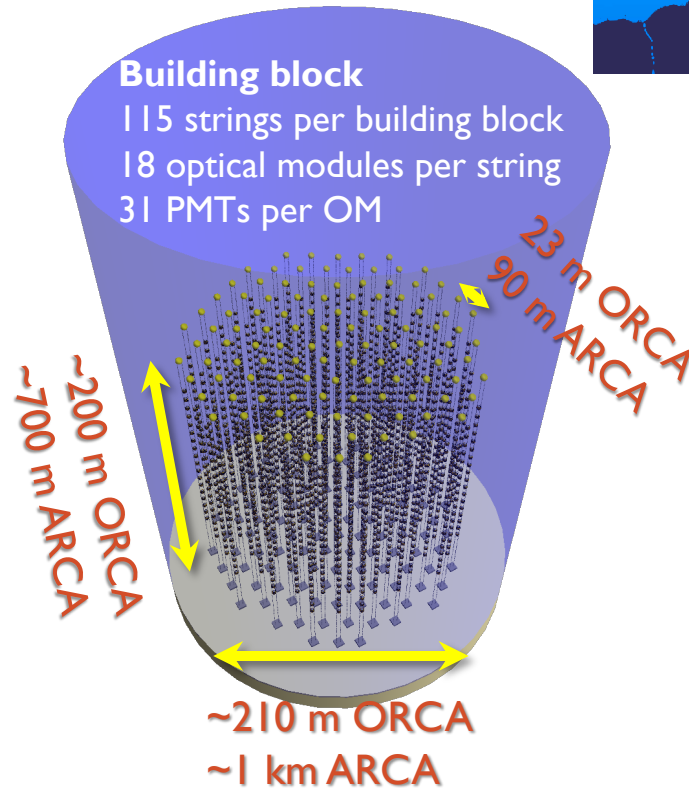
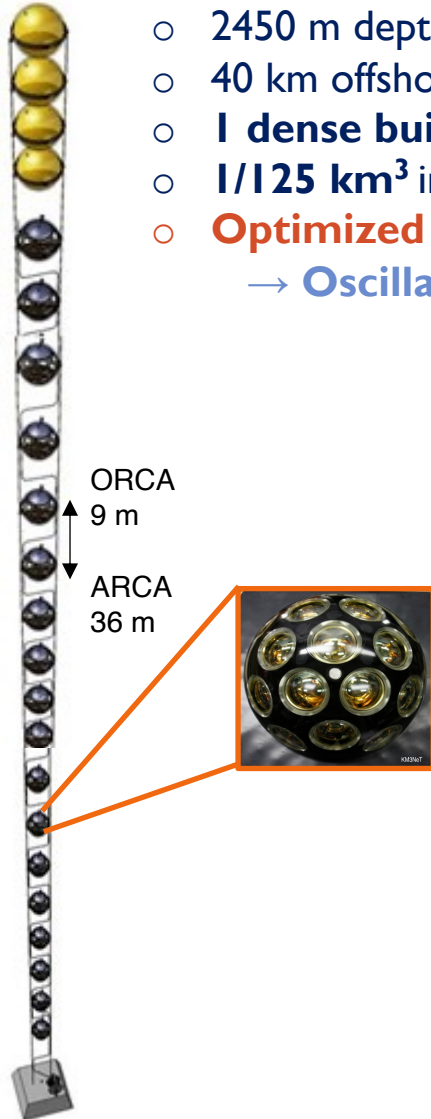
Time difference of five days between KM3-231213A arrival time and peak of highest radio flare  
→ **0.26% pre-trial chance probability**

# KM3NeT

KM3NeT-Collab, [Letter of intent for KM3NeT 2.0](#),  
J. Phys. G: Nucl. Part. Phys. 43 084001

## KM3NeT/ORCA

- **33 lines operating**, 115 lines foreseen
- 2450 m depth in the Mediterranean Sea
- 40 km offshore from Toulon
- **1 dense building block**
- **1/125 km<sup>3</sup>** instrumented volume
- **Optimized for GeV energies**  
→ **Oscillations, mass hierarchy**

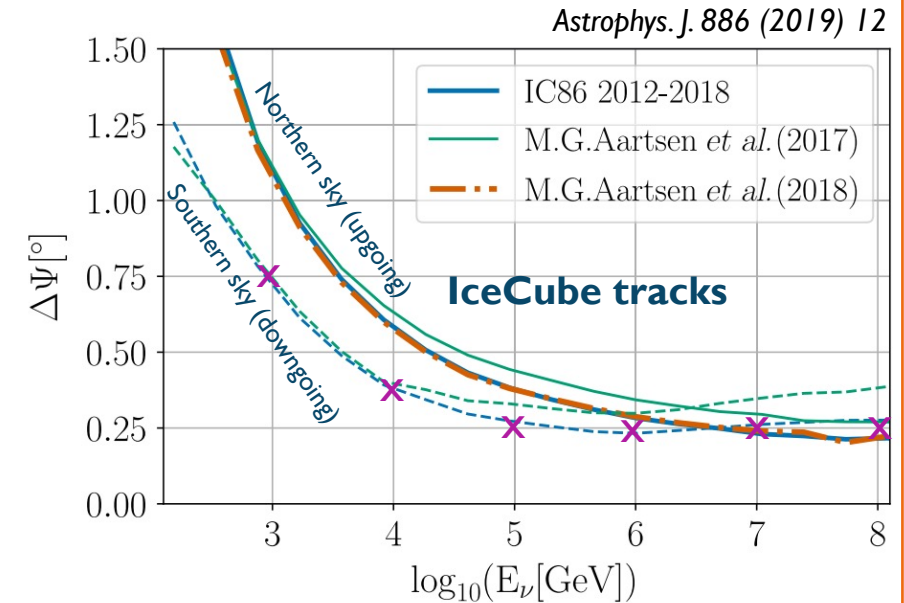
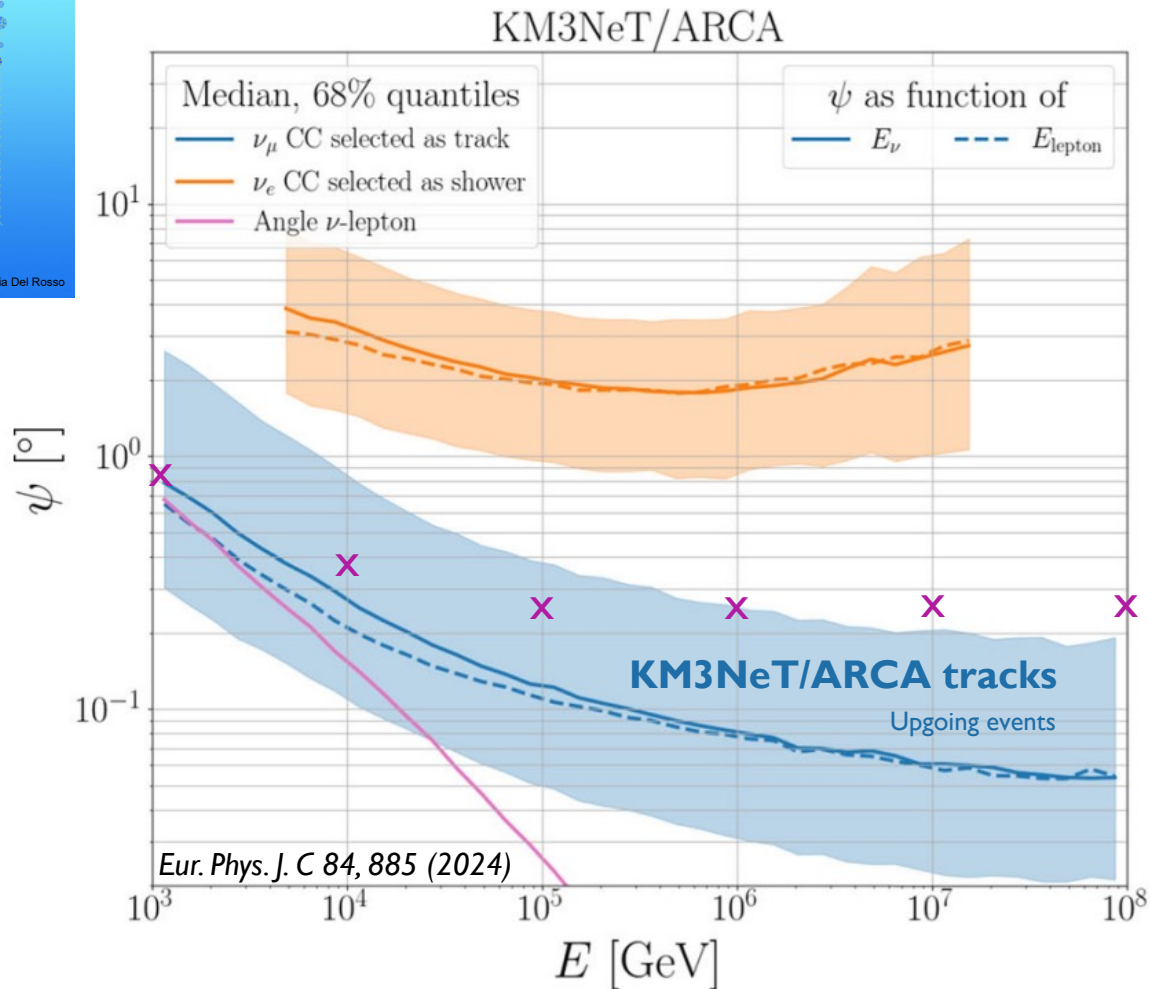
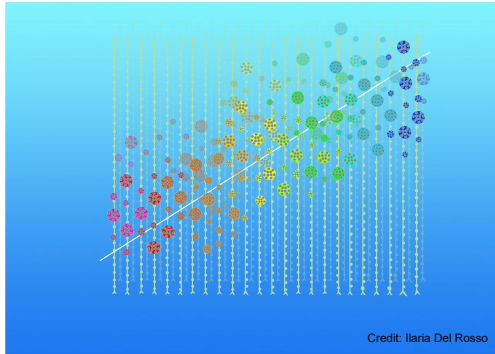


## KM3NeT/ARCA

- **51 lines operating**, 230 lines foreseen
- 3500 m depth in the Mediterranean Sea
- 100 km offshore from Sicily
- **2 sparse building blocks**
- **1 km<sup>3</sup>** instrumented volume
- **Optimized for > 1-10 TeV energies**  
→ **High-energy neutrino astronomy**

# Superior angular resolution of KM3NeT

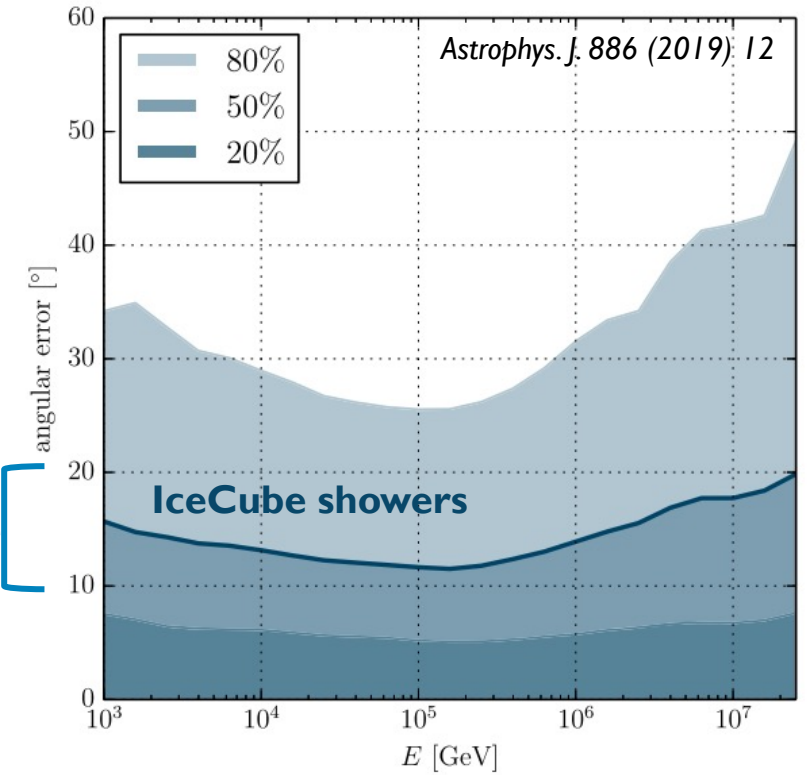
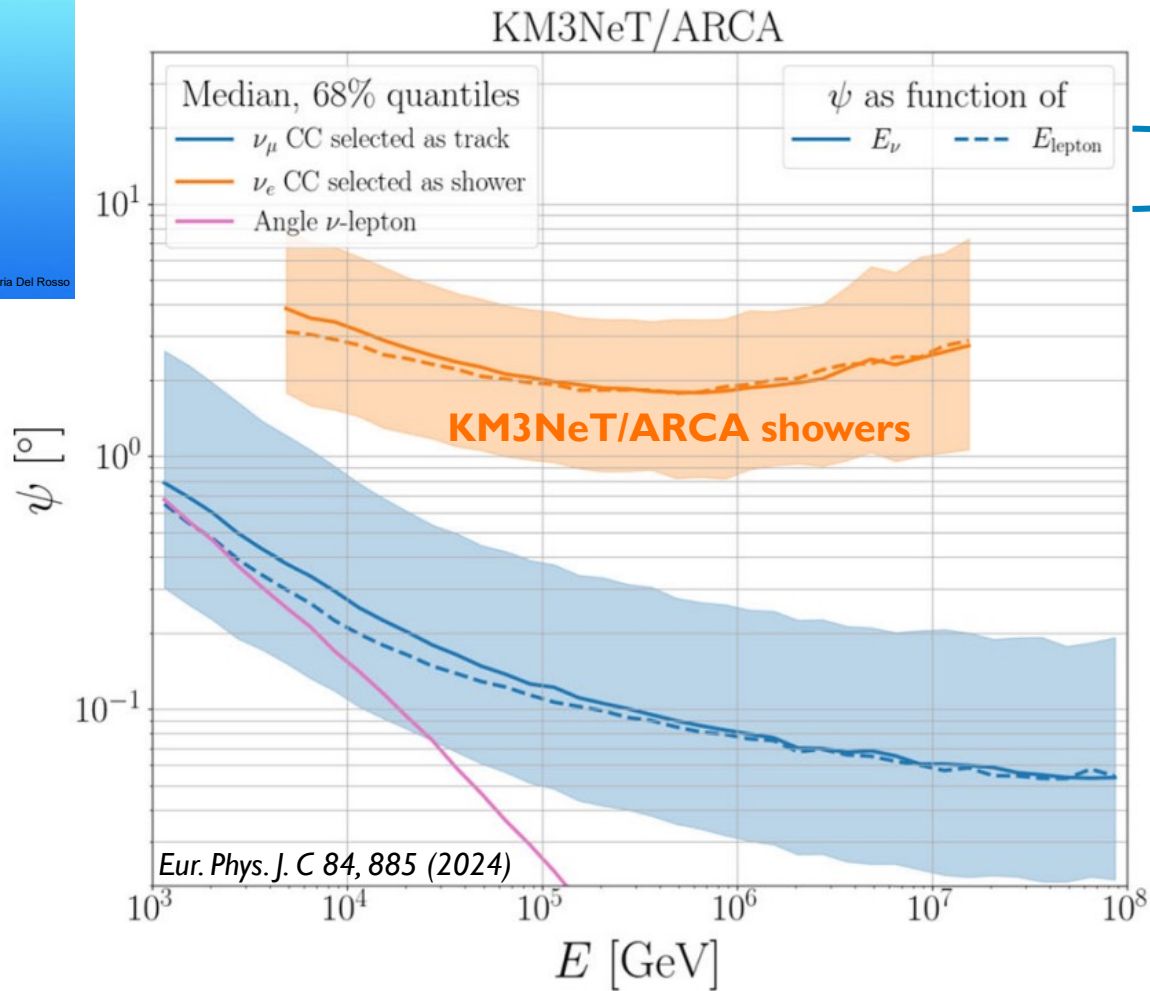
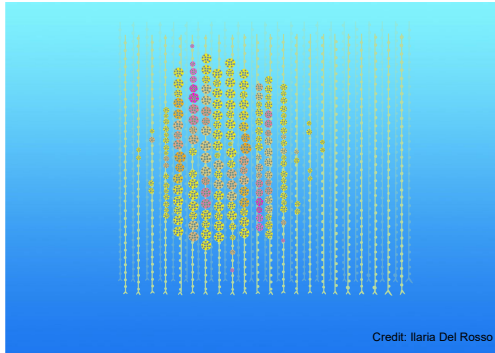
## Track channel



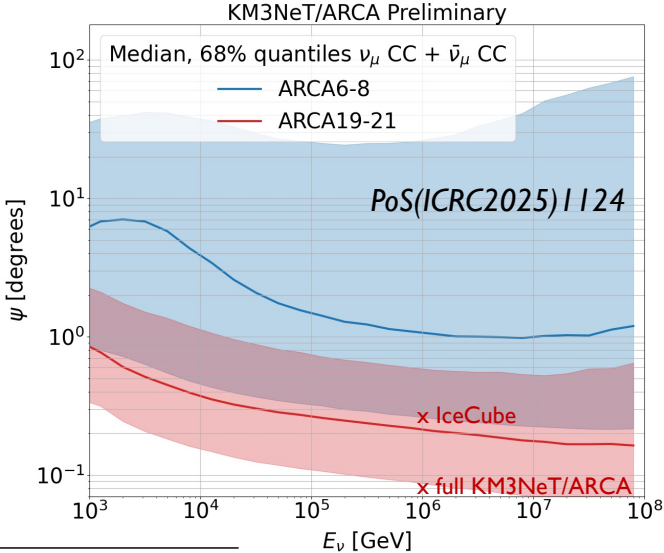


# Superior angular resolution of KM3NeT

## Shower channel

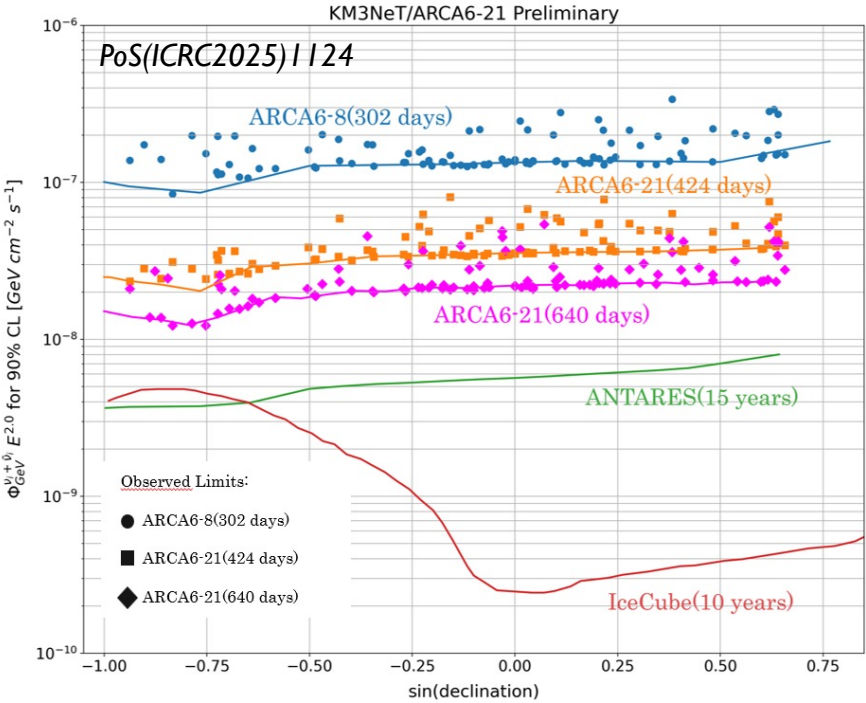


# Point-like sources: results and prospects

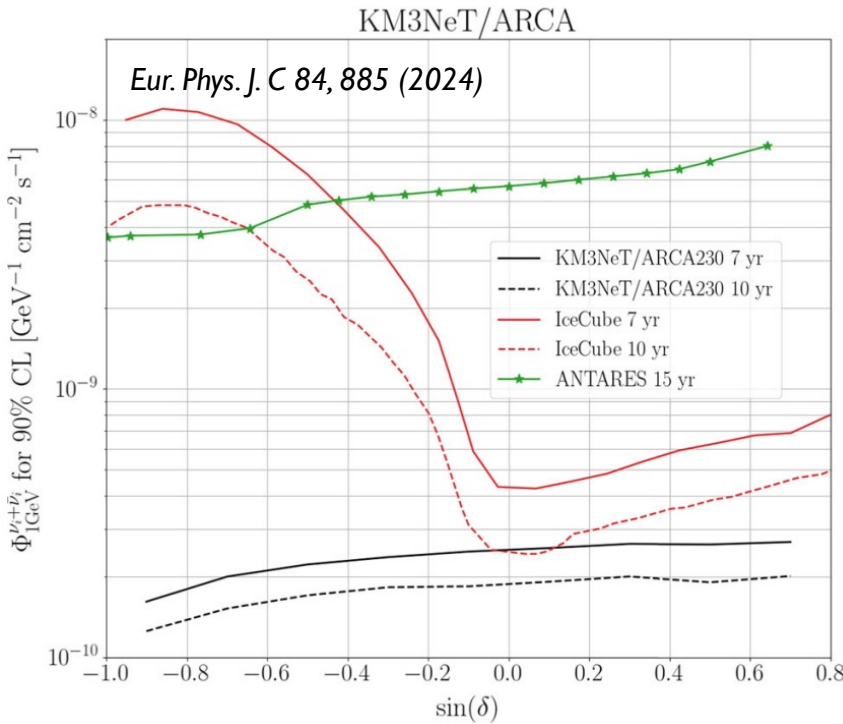


KM3NeT dataset	Median resolution
ARCA 6	1.97°
ARCA 8	1.47°
ARCA 19	0.28°
ARCA 21	0.27°
ARCA6-21 total	0.4°

## Results with current KM3NeT/ARCA

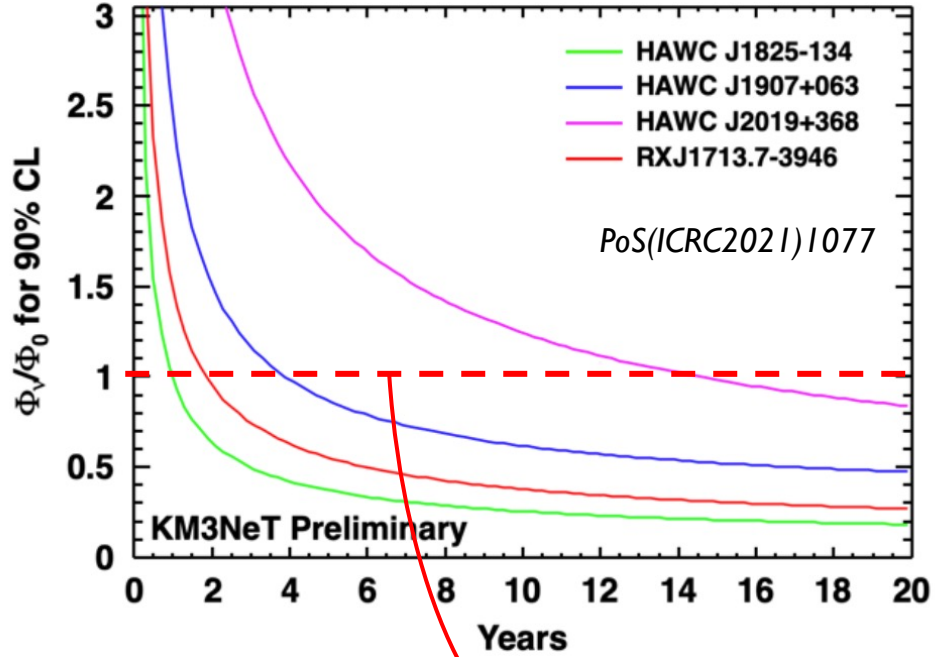


## Prospects with complete KM3NeT/ARCA

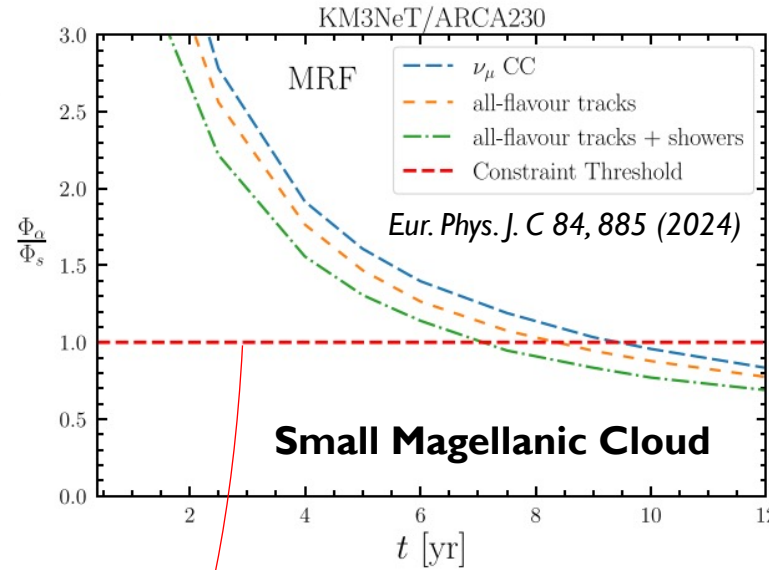


# KM3NeT clear visibility of Southern Sky

## Galactic sources



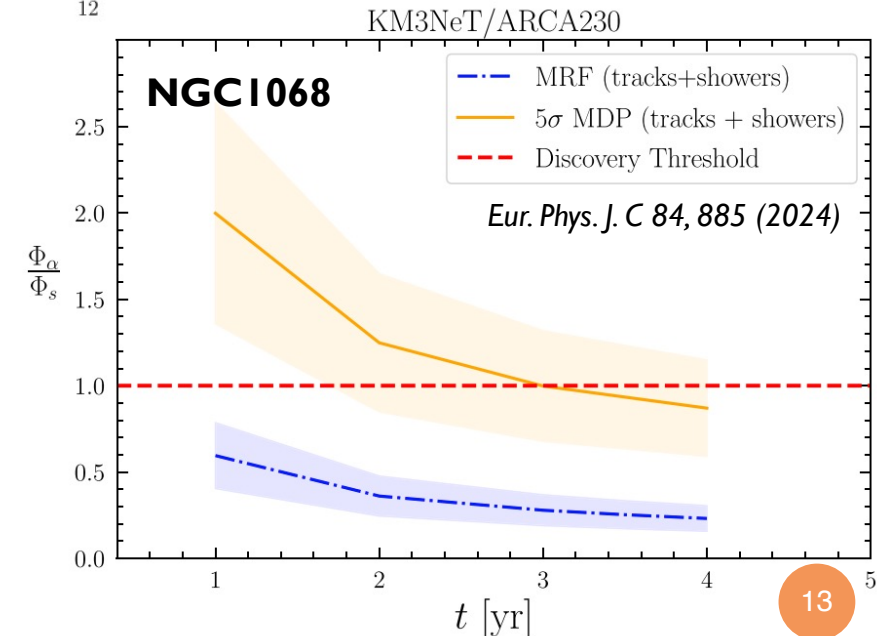
Sensitivity at expected neutrino flux level  
(assuming 100% hadronic emission)  
reached in a few years of operation with  
KM3NeT/ARCA230



Small Magellanic Cloud

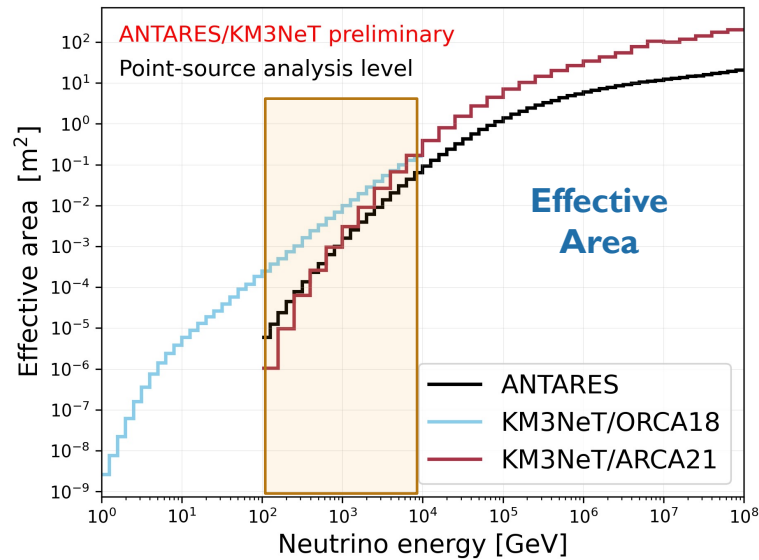
## Extra-galactic sources: case of starburst galaxies

NGC1068 will be observed at  
5 $\sigma$  CL in 3 years of operation  
with KM3NeT/ ARCA230

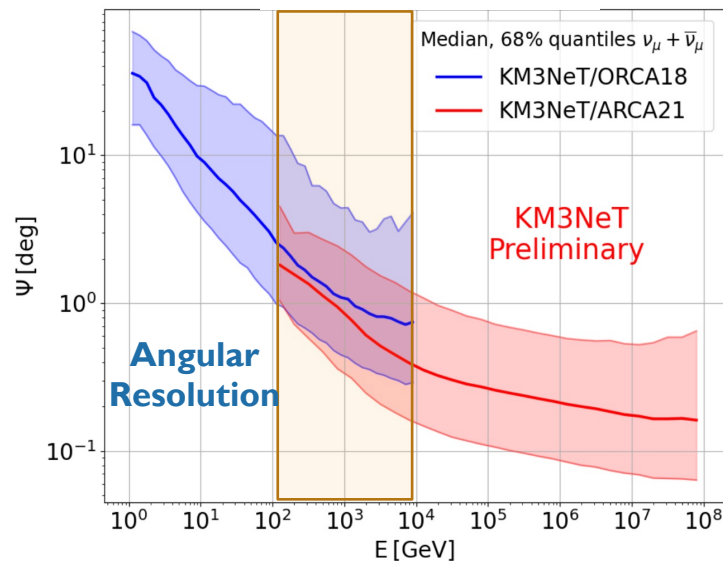
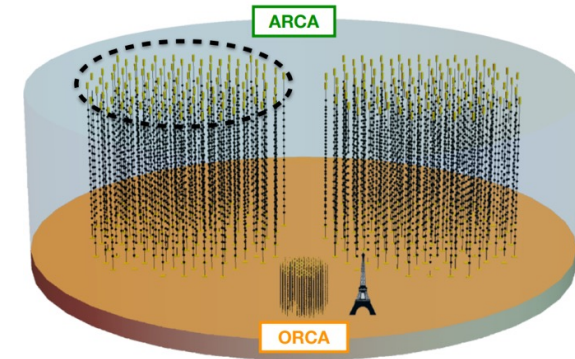




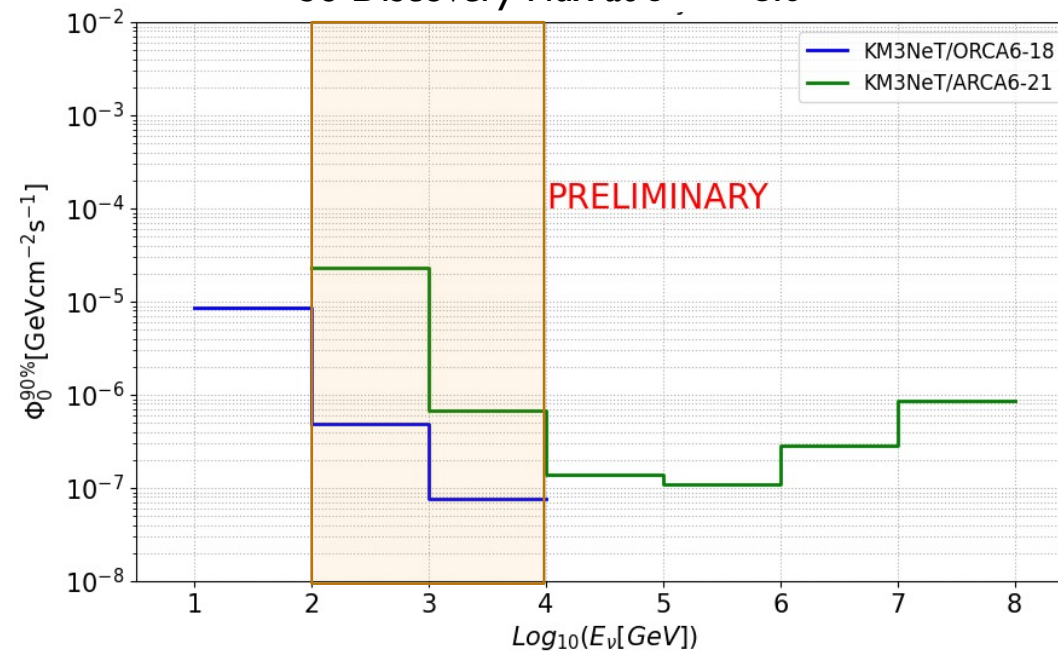
# Extended energy range of KM3NeT



KM3NeT/ORCA provides good performances in the **100 GeV - 10 TeV** range, effectively **extending the energy reach of KM3NeT**



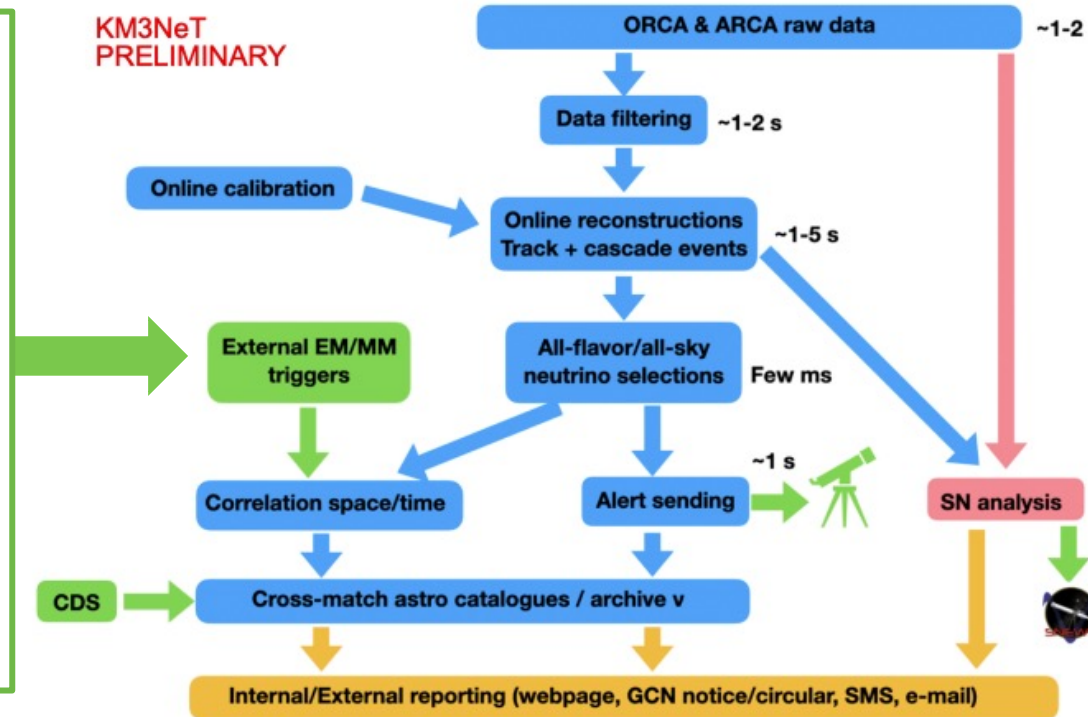
$3\sigma$  Discovery Flux at  $\delta = -8.0^\circ$



# Astronomy in real time

## GCN notices:

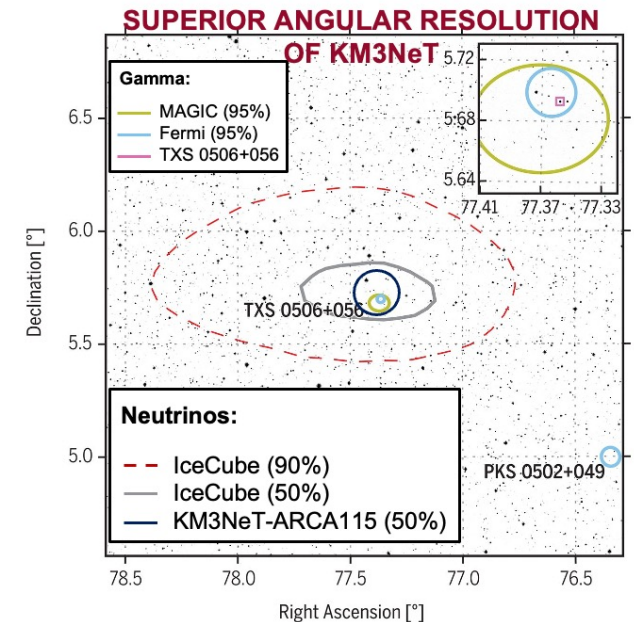
- INTEGRAL (GRB)
- FERM\_GB (GRB/Transient/Undef)
- FERMI\_LAT (Transient)
- SWIFT\_BAT\_GRB (GRB/Transient/Undef)
- SWIFT\_XRT (GRB/Transient/Undef)
- SWIFT\_BAT\_TRAN (Transient)
- MAXI (Transient)
- HAWC (Transient)
- IceCube (Neutrino)
- LVK (GW)
- SNEWS (CCSN)
- SK\_SN (CCSN)
- Chime online notices (FRB)
- TNS catalog updates (FRB)
- $\mu$ Quasar (Micro-quasar)



Real-time architecture: PoS(ICRC2025)1115

Follow-up of external triggers: PoS(ICRC2025)1038

Neutrino alerts: PoS(ICRC2025)920



## Follow-up of external triggers:

- Automatic search for spatial+time correlations
- Fully operational since July 2023
- No significant association so far

## Finalizing KM3NeT neutrino alert streams:

- Single exceptional events
- Multiplets (two or more events in spatial+time correlation)
- Subthreshold events with an astrophysical counterpart



**Strengthening links with the MM community to enable effective real-time follow-ups**

# Conclusions

- **Neutrino astronomy:** a young field and a new messenger for astrophysics
- **Feasibility proven:** a diffuse neutrino flux (Galactic + extragalactic) is established
- **Open problem:** the sources remain largely unidentified
- To identify them we need:
  - 1) Large instrumented volume
  - 2) Wide energy range
  - 3) Excellent angular resolution
  - 4) Multi-messenger/wavelength synergies

**KM3NeT delivers 1–3 and is actively developing 4  $\Rightarrow$  key instrument for source discovery and leading actor in multi-messenger astronomy**