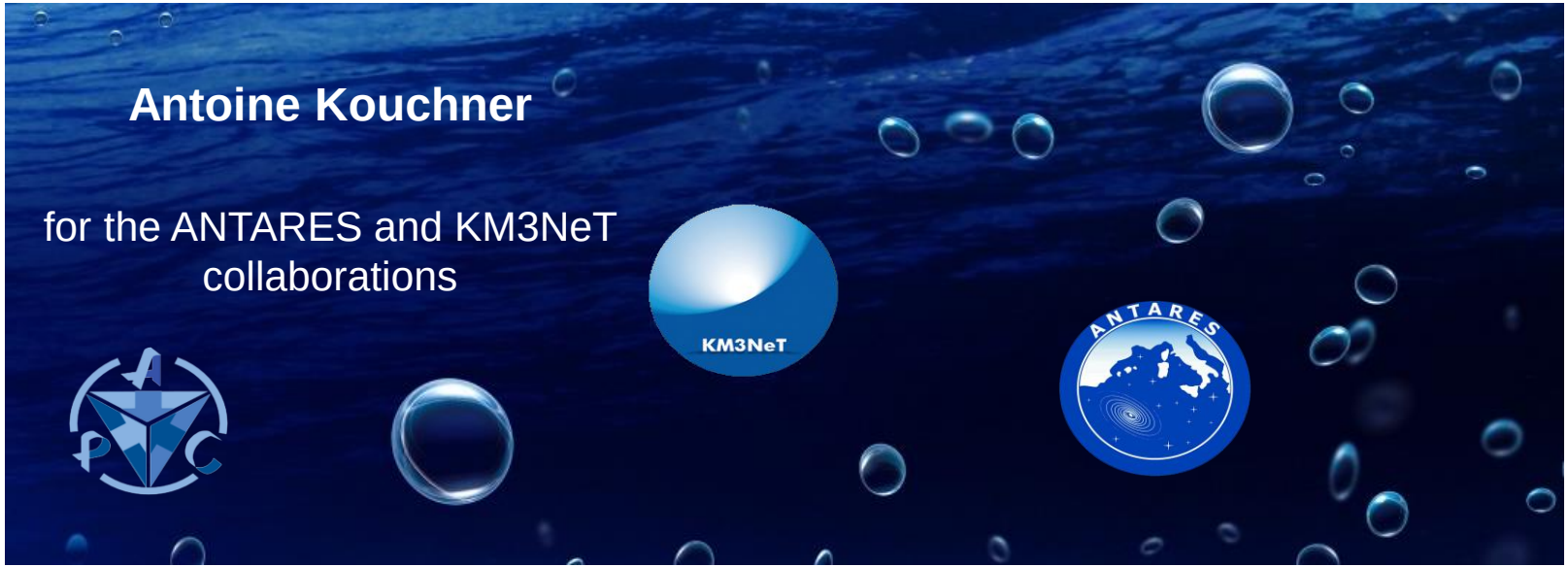
https://antares.in2p3.fr https://www.km3net.org

# From ANTARES to KM3NeT: The Adventure of Neutrino Detection in the Mediterranean Sea



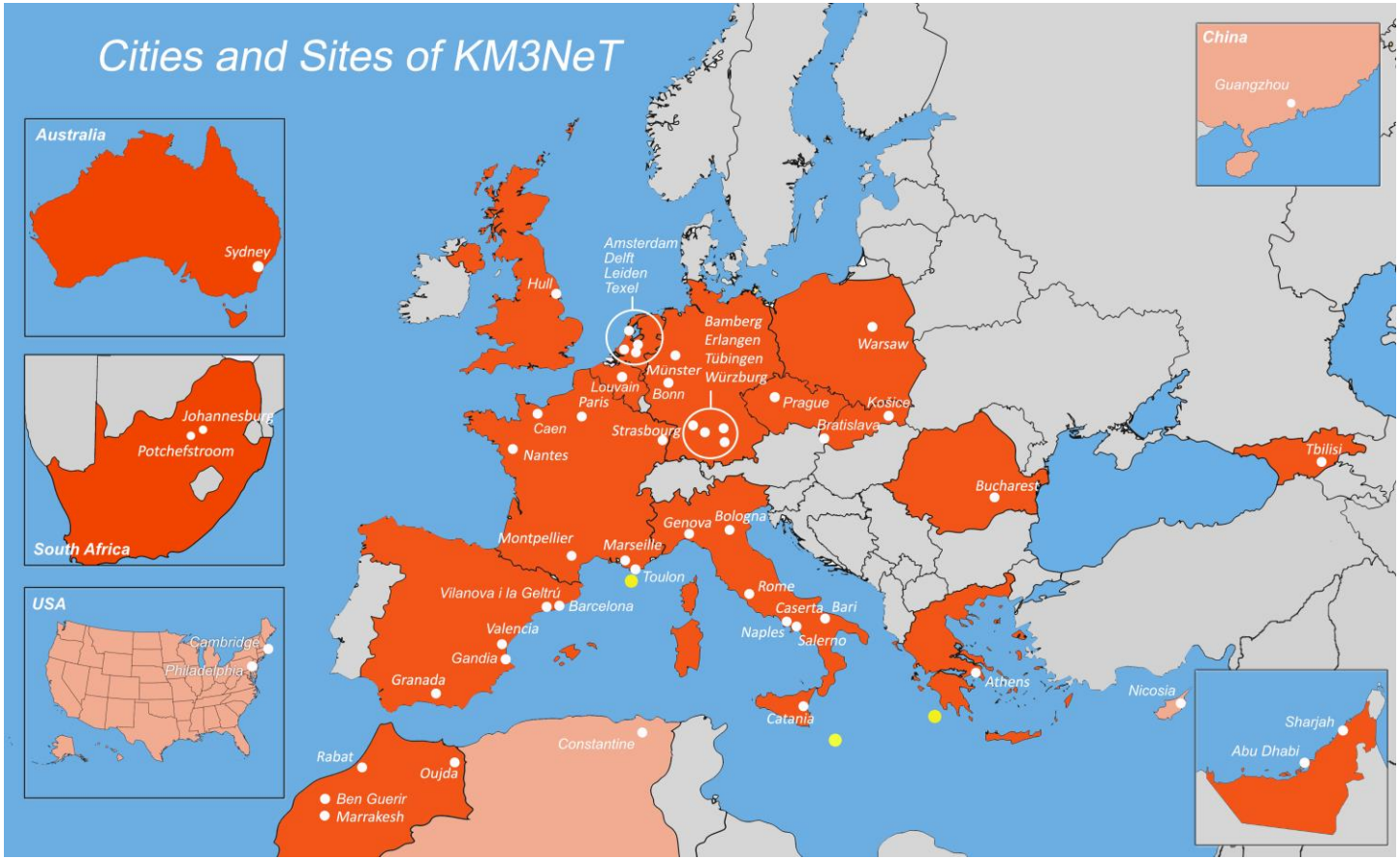

HAESA 2024, October 2 - 4 Wits Rural Facility, South Africa

# ANTARES and KM3NeT Collaborations



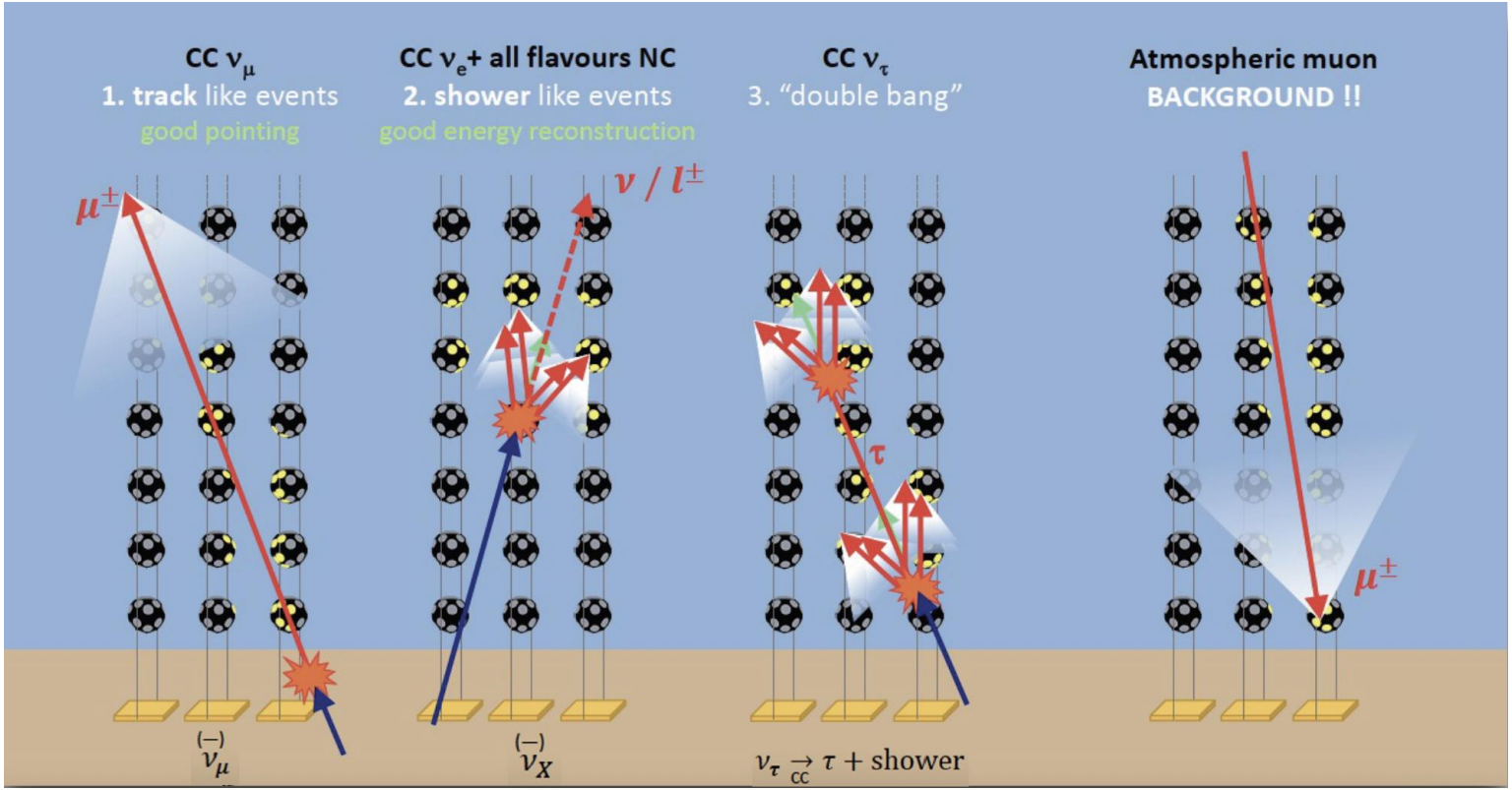
## ANTARES Collaboration

Paris
Marseille
Clermont-Ferrand
Strasbourg
Nice
Oujda
Rabat
Valence
Amsterdam
Leyde
Rome
Gênes
Bologne
Catane
Pise
Naples
Bari
Erlangen
Wurtzbourg
Bamberg
Bucarest
Bentley



# Detection Principle in a nutshell






Deep-sea waters offer long effective scattering length – Homogeneous medium

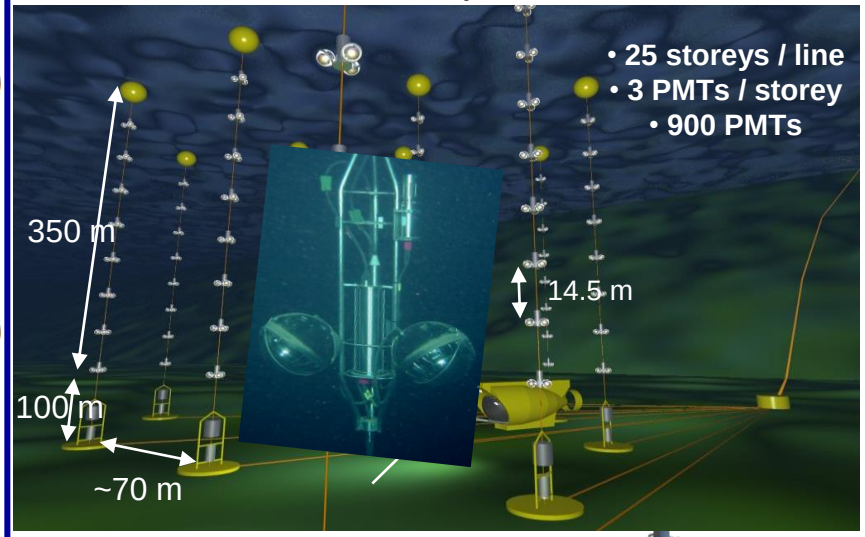
→ Tracks: median ang. res. can drop below 0.1° above 100 TeV, factor 2 energy estimate

→ Showers : median angular resolution can reach 1° at 100 TeV, 10% energy resolution

# Mediterranean Detectors



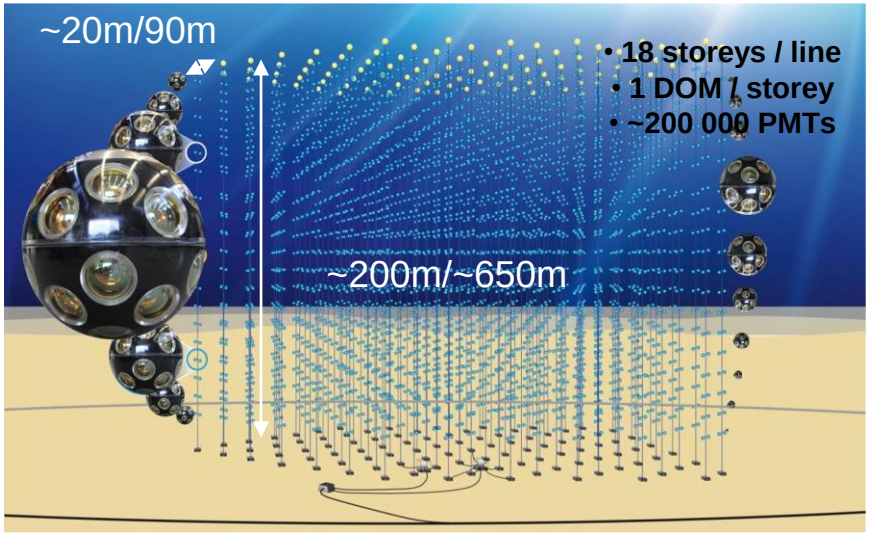
## ANTARES complete 2008 - 2022



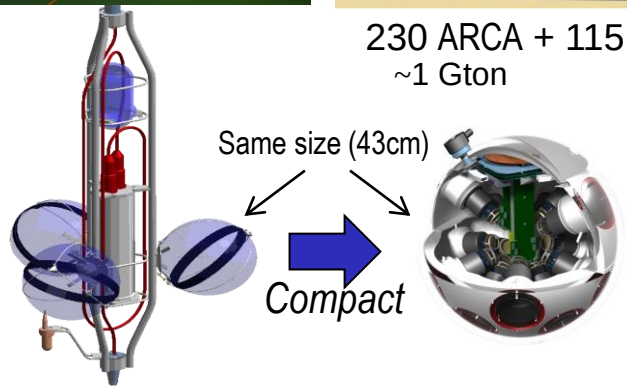

~10 Mton
12 lines First Generation
First line in 2006

📖 NIM A 656 (2011)

## KM3NeT Under Construction




230 ARCA + 115 ORCA lines New Generation
~1 Gton ~7 Mton




- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt Antares

# The ANTARES Endeavor

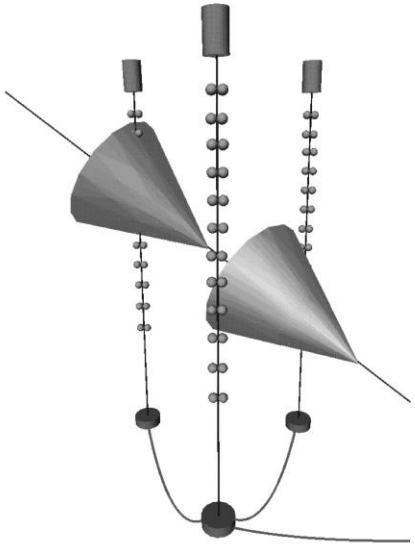


CPPM-97-02
DAPNIA-97-03
IFIC-97-35
OUNP-97-06

**ANTARES**

Astronomy with a Neutrino Telescope and Abyss environmental RESearch

**TOWARDS A LARGE SCALE HIGH ENERGY COSMIC NEUTRINO UNDERSEA DETECTOR**

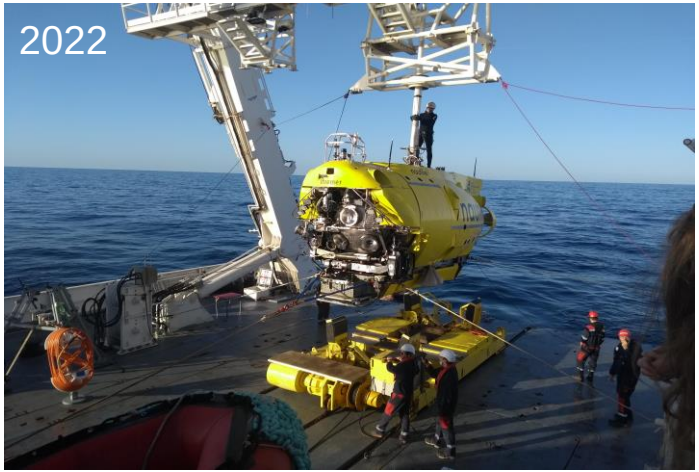


**PROPOSAL – May 1997**



# ANTARES 2001-2022




2001 2002 2003 2004 2005 2006 2007 2008… 2016 …2022

- 2001: Main Electro-Optical Cable
- 2002: Junction Box
- 2003: Prototype Sector line
- 2005: Mini Instrumentation Line with OMs
- 2006: First line
- 2008…: Completion
- 2016: Running (almost) without common fund
- …2022: End of data taking Recovery

# ANTARES: A key step towards KM3NeT



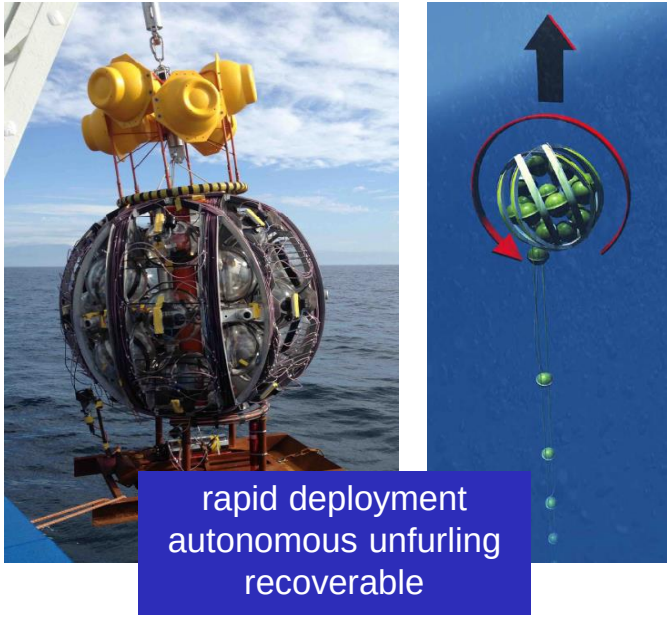
## News item on ANTARES (new) web site, published on June 23rd, 2022

*The recovery of the PPM-DOM, the first prototype of the future KM3NeT DOMs, still in good shape. This marks the passage to the next generation – KM3NeT.*

ANTARES is now history, long live KM3NeT !

# KM3NeT Construction

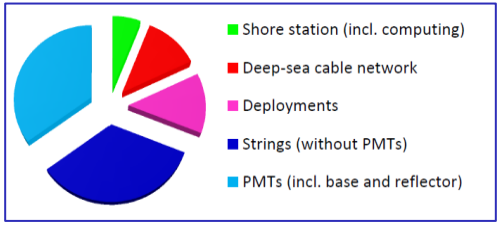




rapid deployment
autonomous unfurling
recoverable

https://www.youtube.com/watch?v=tR8jwgG6uzk

- 28 (23) strings deployed in ARCA (ORCA)
- ANTARES' online acceptance overcome (> ×3 )
- Data taking on the fly
- **Total KM3NeT cost: 320 M€**




APPEC

Flagship Experiment

ARCA 47 DUs
ORCA 28 DUs

2020 2021 2022 2023 2024 2025 2026 2027 2028 2029

**ANTARES decommissioning**

**ANTARES legacy papers**

**ORCA & ARCA completions**

# Physics Studies

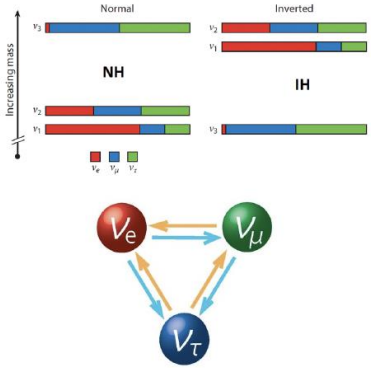
Supernovae Explosion

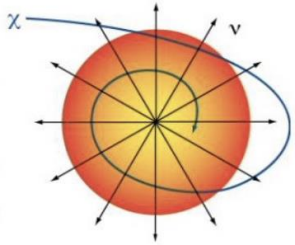
Neutrino Physics

Dark Matter & Exotic searches

Cosmic neutrinos Multi-messenger program

MeV GeV TeV PeV




(See backup)

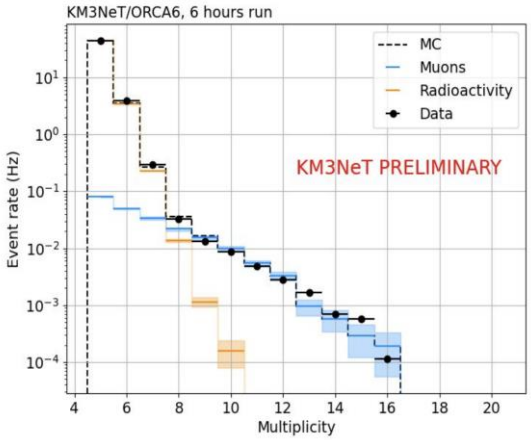
KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

# Supernova Physics

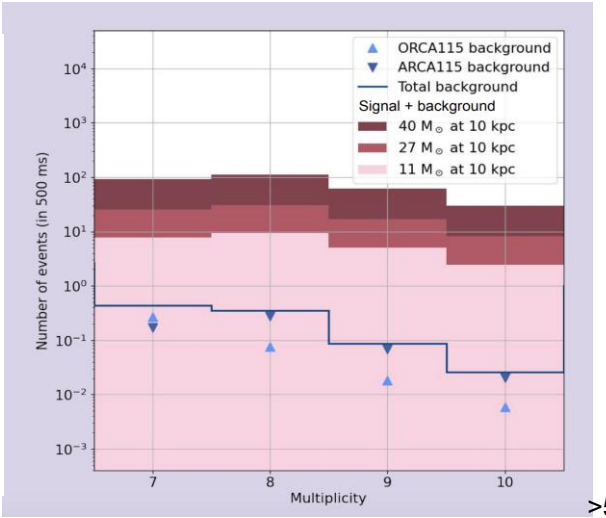
## A DOM as a single detector

## Muon background rejection improved

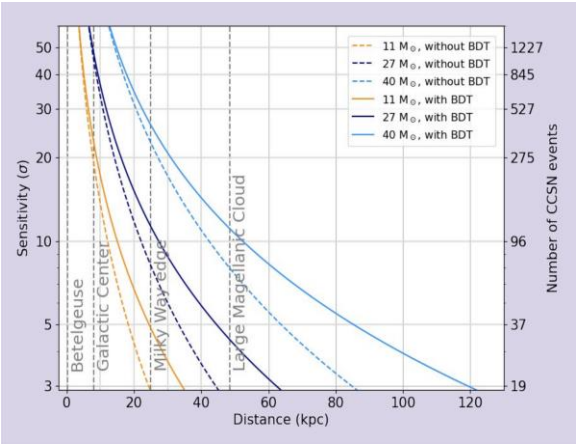
PMT multiplicity plot




Signal expected above background




Significance
ARCA28+ORCA24




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

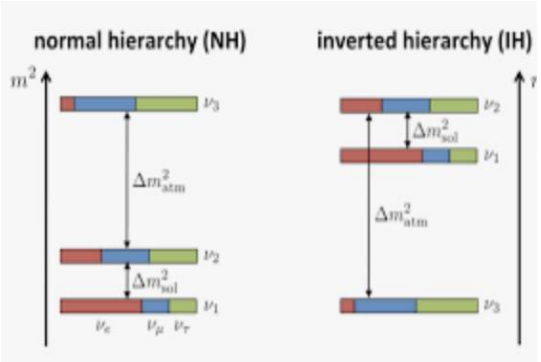
An on-line alert system for CCSN already implemented
Integrated in SNEWS

# Neutrino Oscillations

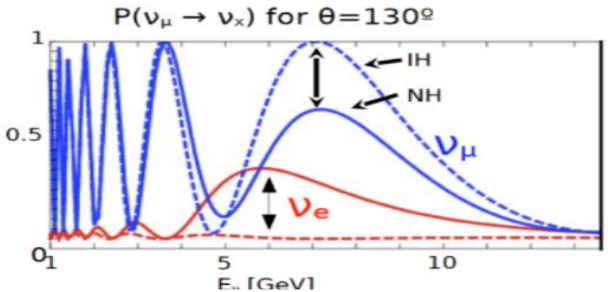


Neutrino Mass Ordering measuring atmospheric neutrinos crossing the Earth

Baseline from 50 to 12800 km

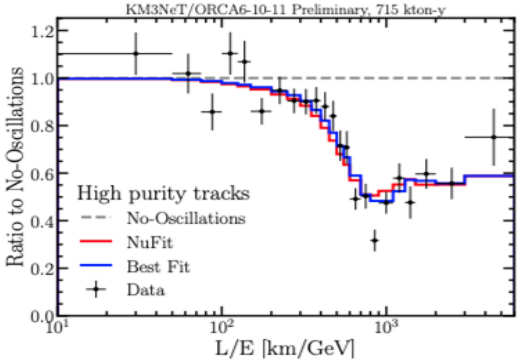


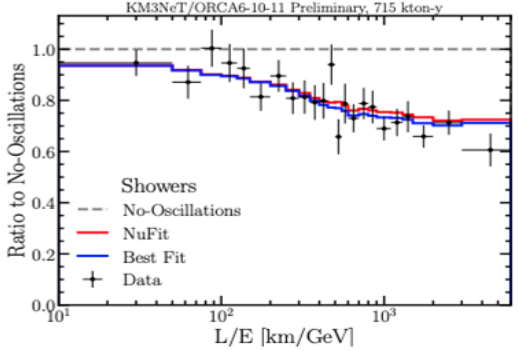

Energy range of interest 5-15 GeV

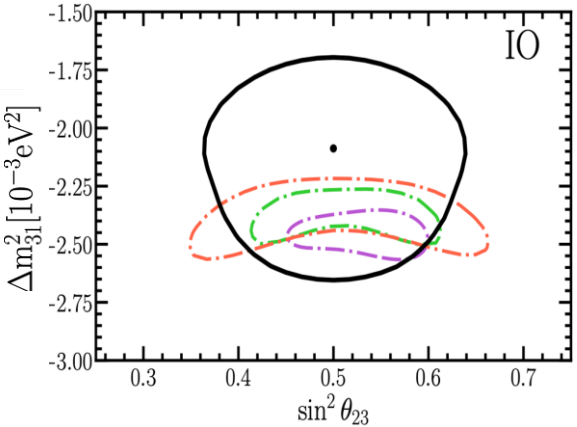


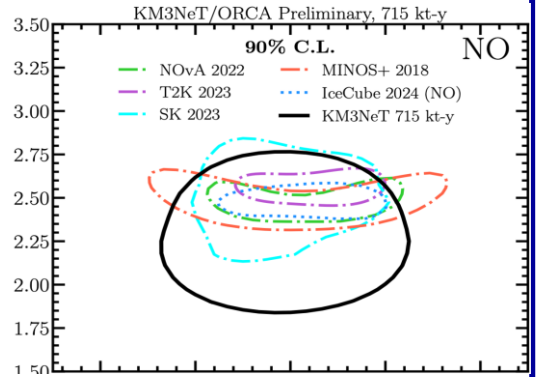

ORCA6-10-11 data

Oscillations clearly seen both in track and shower events



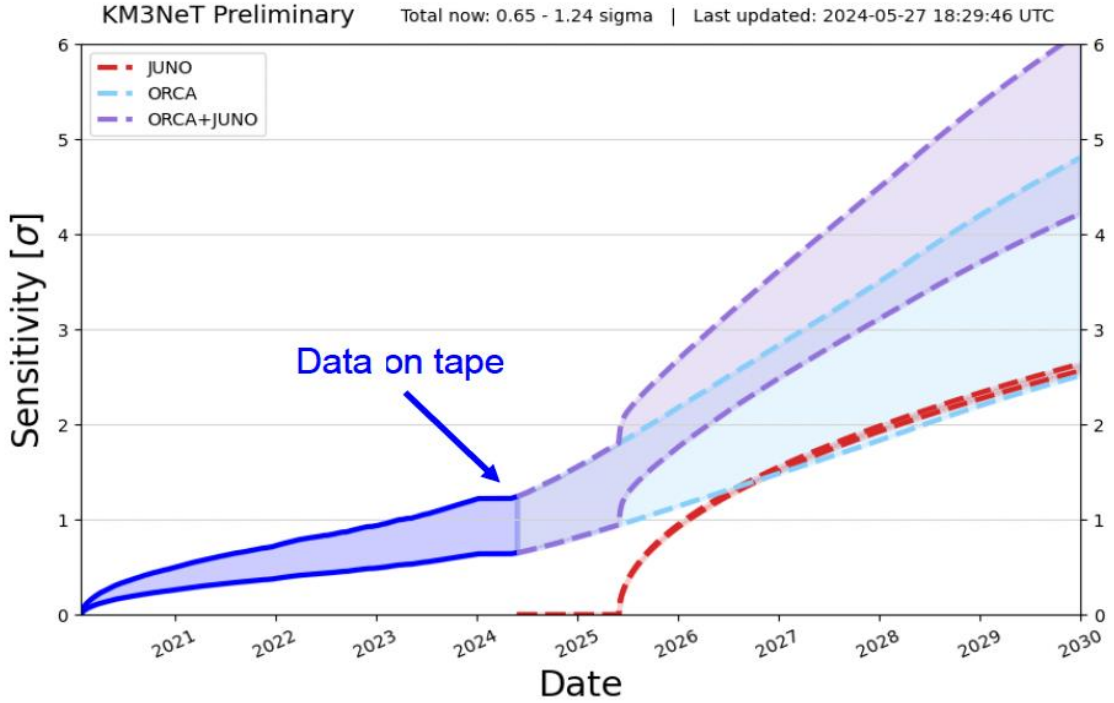



# Neutrino Mass Ordering



Predictions based on the current construction plan.




→ Exploiting synergies with reactor experiments can boost the measurement

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

J. High Energ. Phys. 2022, 55 (2022)

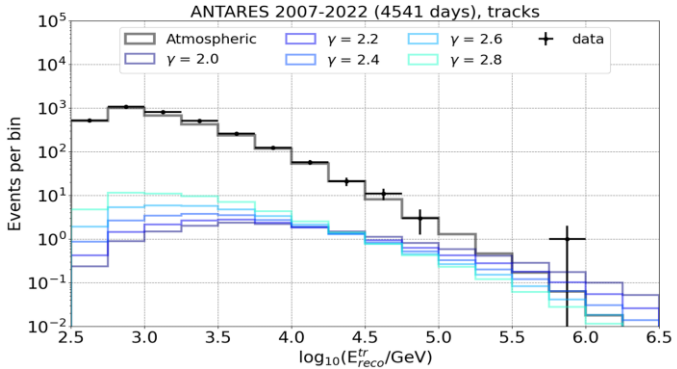
Eur. Phys. J. C 82, 26 (2022)

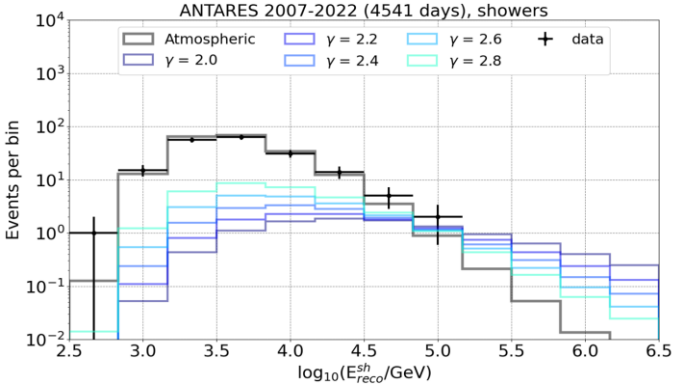
# Antares Final Diffuse Flux Search



ANTARES data from 2007 to 2022 (4541 days) All-sky / All-flavor neutrino search

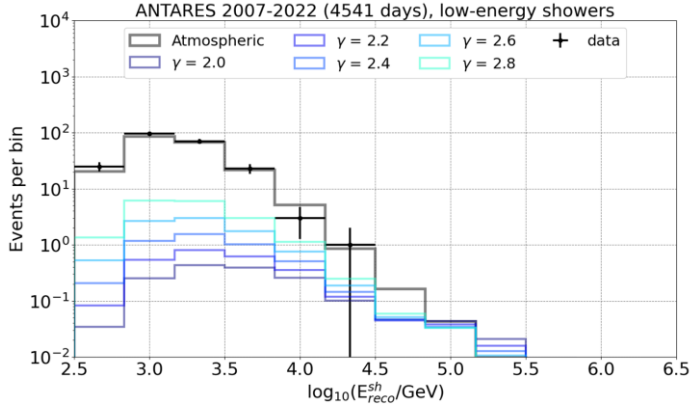
- Selection cuts optimized with Model Rejection Factor procedure (spectral index $\Gamma$ = 2.5)
- Look for excess above a given energy threshold




Three high-purity samples (Tracks, Showers, LE showers)

Showers provide most of the sensitivity




arXiv:2407.00328

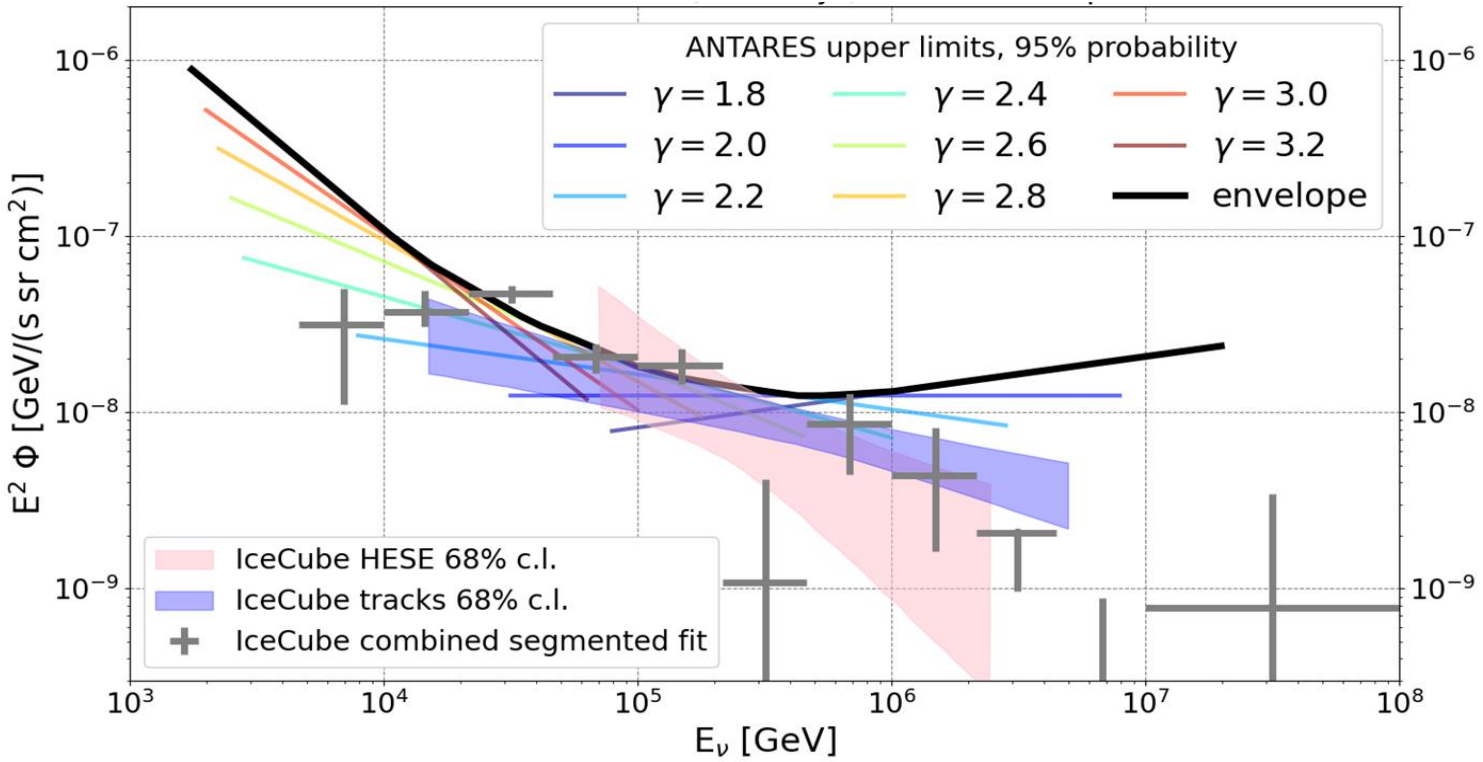
No significant excess of events is observed

# Antares Final Diffuse Flux Search



ANTARES data from 2007 to 2022 (4541 days) All-sky / All-flavor neutrino search

- Upper limits can be extracted from the non-observation of a clear signal
- Mostly relevant below 100 TeV



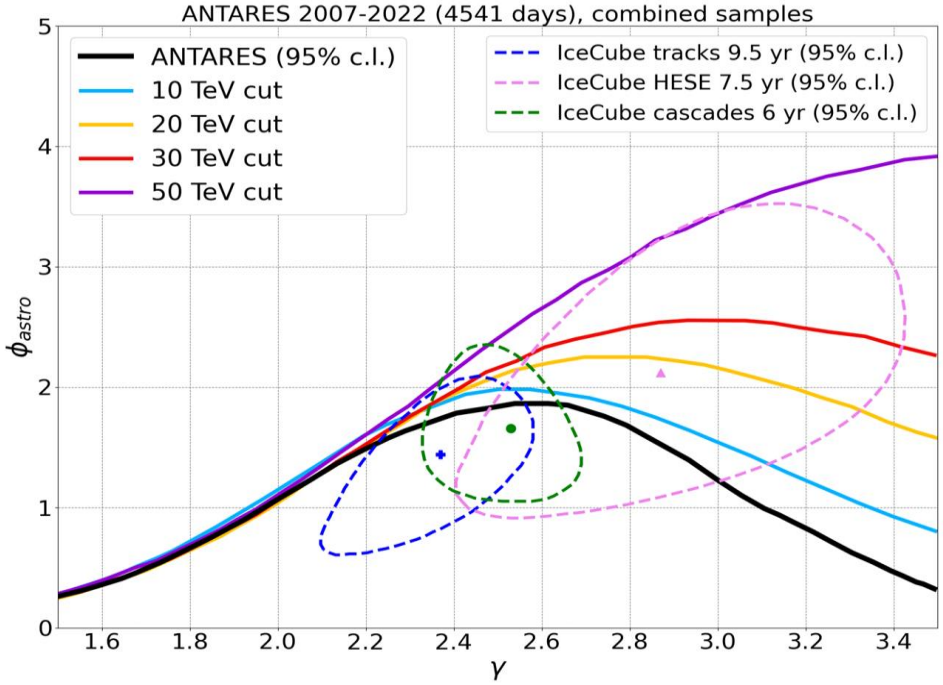

arXiv:2407.00328

# Antares Final Diffuse Flux Search



ANTARES sensitivity optimal in the 10-50 TeV range

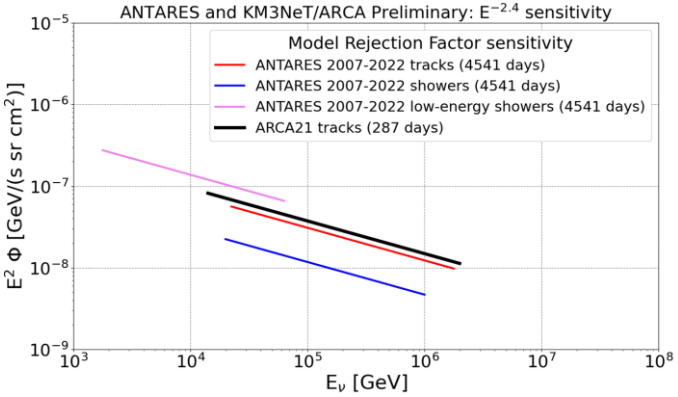
- Study hypothesis of single unbroken power-law at low energies
- Soft spectra fits of the IceCube signal become admissible (2 σ) only with spectral break

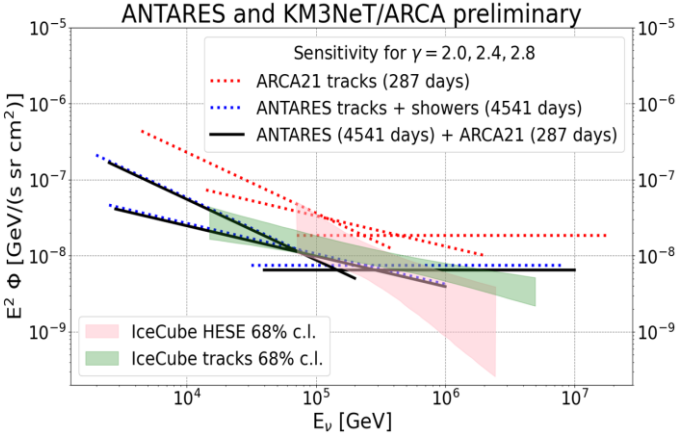



Legacy paper:
JCAP 08 (2024) 038

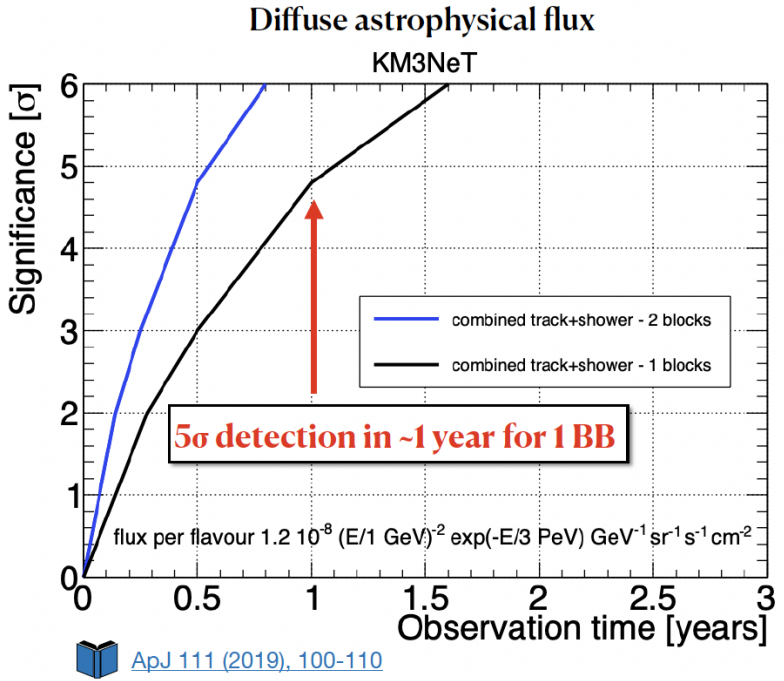
# Diffuse flux – Towards a confirmation of IC

## ANTARES and ARCA21 (tracks) : first combination



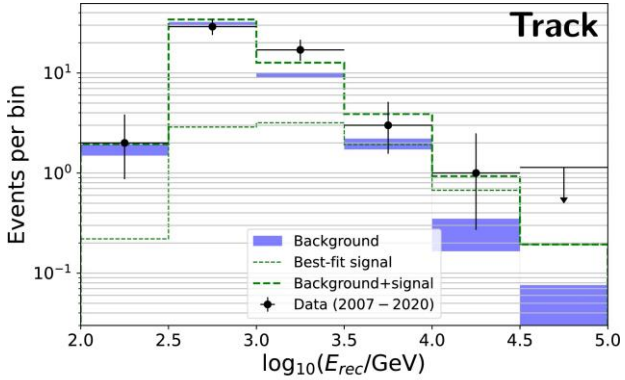

## Independent confirmation with KM3NeT

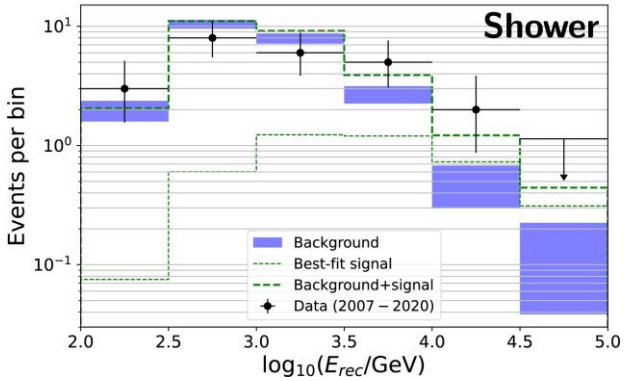


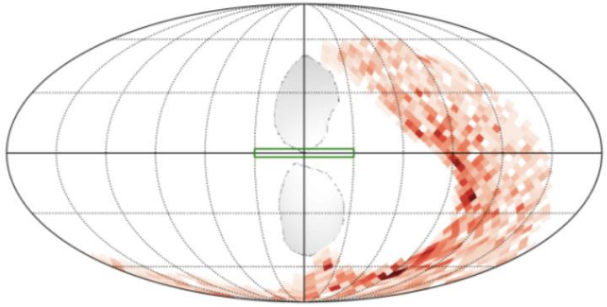

ApJ 111 (2019), 100-110

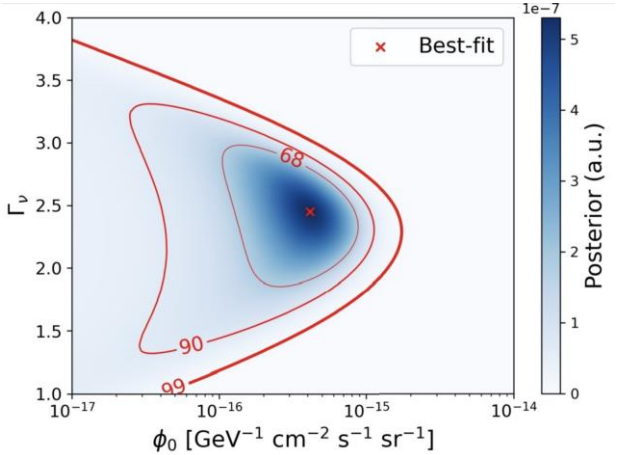
# Search for Diffuse Galactic Emission

More robust analyses: background measured from OFF regions of same local acceptance





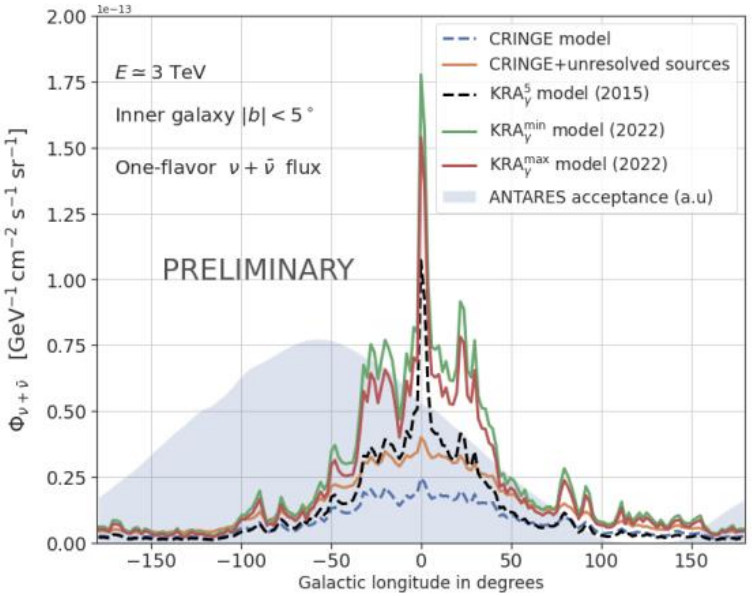

📖 Phys. Lett. B 841 (2023) 137951

96% C.L. hint of a galactic signal – Compatible with IceCube

# Search for Diffuse Galactic Emission



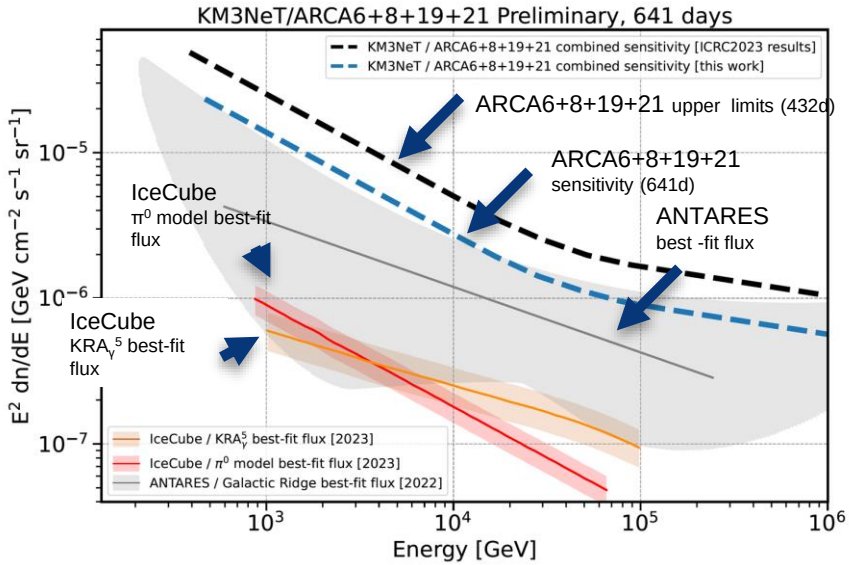
Comparison with template studies
(full sky not trivial)




**KM3NeT** On-Off zone analysis

$|l| < 31°$ and $|b| < 5°$ for KM3NeT/ARCA6-8 and
$|l| < 31°$ and $|b| < 4°$ for KM3NeT/ARCA19-21

ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

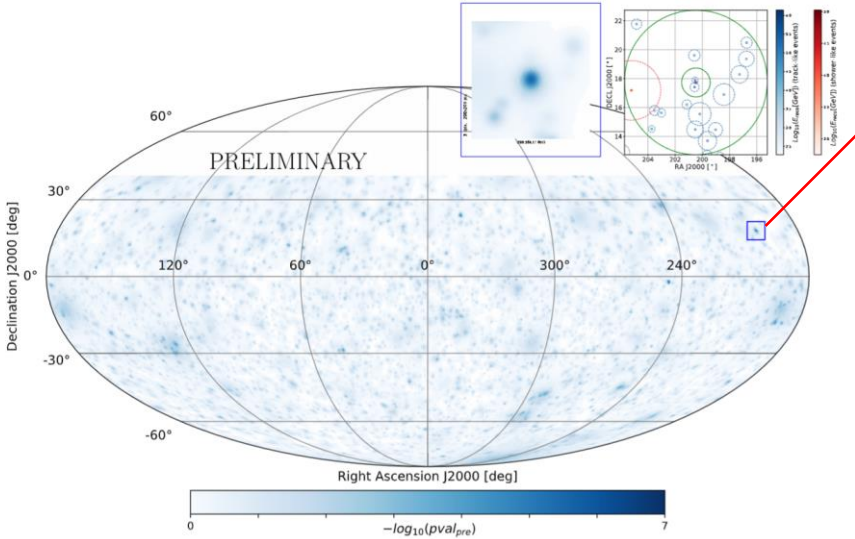



Next : identify sources with KM3NeT

A. Neronov, et al, Phys. Rev. D 108, 103044 (2023)

# Search for Point Sources

ANTARES 2007-2022 sample: 11029 tracks and 200 showers

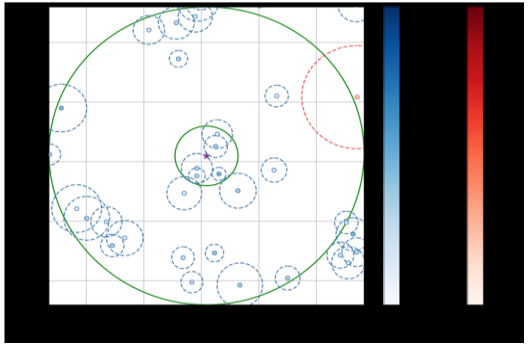


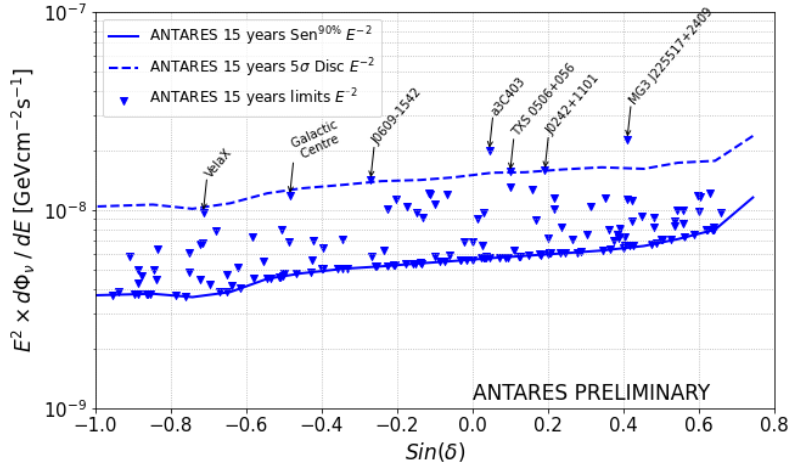

Hottest spot ($\delta$, RA) = (17.7, 200.5)
Pre(post)-trial significance 4.5$\sigma$ (0.29$\sigma$)

World best limit on the Southern sky below hundreds of TeV.

## Candidate-list search

Most significant:
MG3 J225517+2409
Pre(post)-trial
3.6$\sigma$ (1.8$\sigma$)

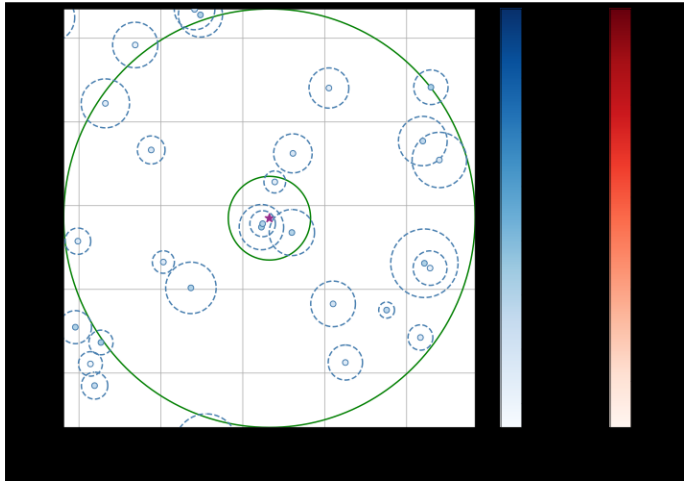




# Search for Point Sources

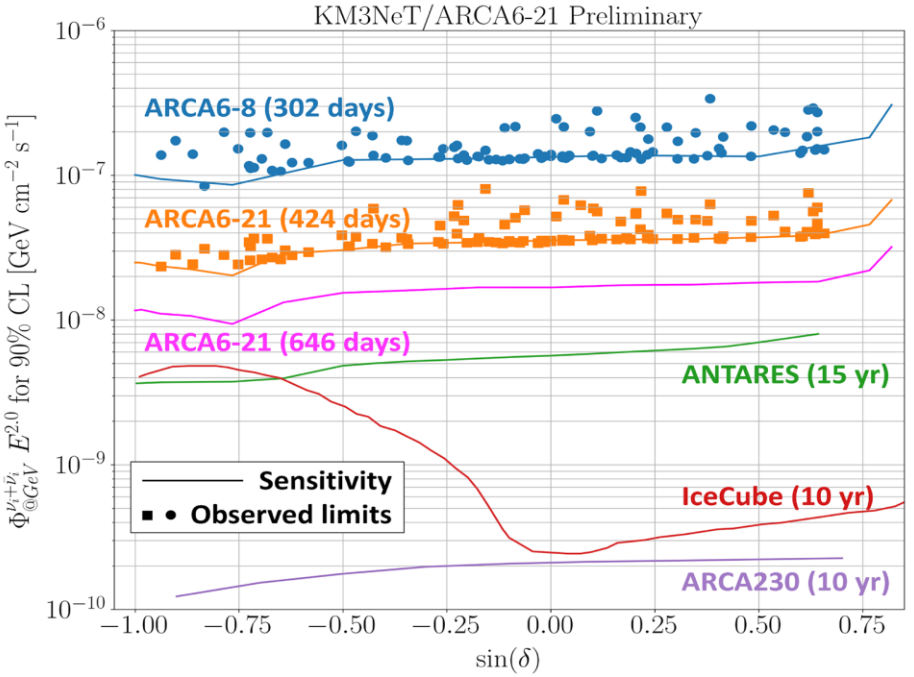
## Remarkable sources

- TXS 0506+056 p-value 0.007 $n_{signal}$ = 2.2



- 3C403 (3.3σ)
- J0242+1101 (2.1σ)
- J0609-1542 (2.3σ)
- Galactic Centre (2.1σ)

- No signal seen from NGC1068 (as expected)



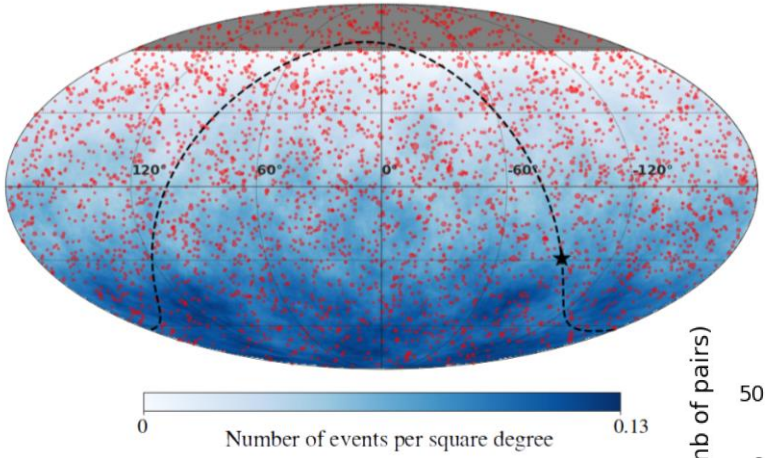

Improved sensitivity (for equivalent exposure) & sky coverage wrt IceCube

☞ *PoS(ICRC2023)1018 & 1075*

Large improvement is expected in the next year:
+ ARCA28 from sept 2023 + ARCA48 from sept 2024

# Catalog-based Searches



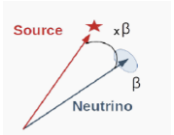


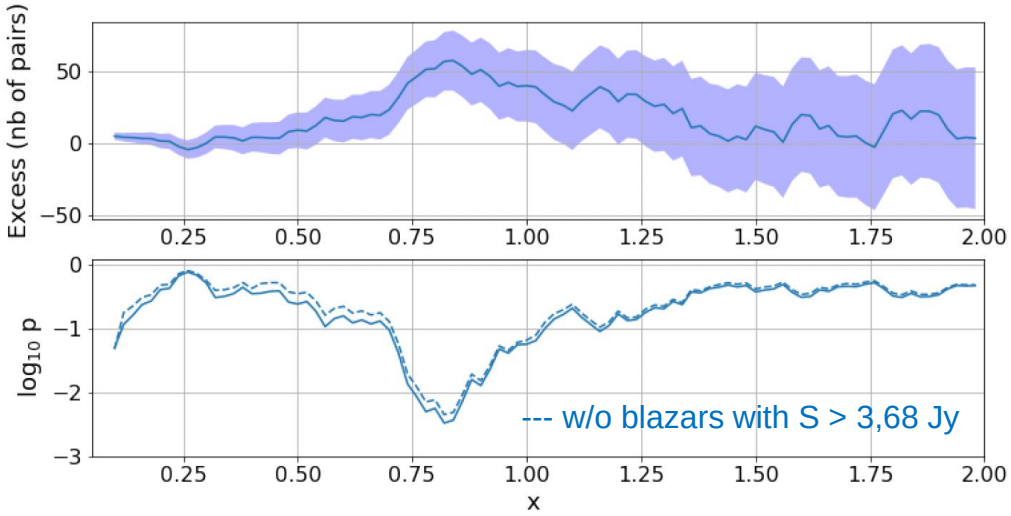

*VLBI blazars (red dots)*
📖 *Plavin et al., Astrophys. J. 908 no. 2, (2021) 527 157*

ANTARES between January 29, 2007 and February 29, 2020 (3845 day live time)
📖 Astrophys.J. 964 (2024) 1, 3

**Simple counting analysis**

- Count the nb of neutrino-blazar pairs at less than x$\beta$
- Angular uncertainty estimate $\beta$ is multiplied by x for possible systematics
- Scan on the values of x to search for the most significant excess




Only accounting for a 1D scan in x gives post-trial p-value = 0.03 (2.2 σ)

📖 A. Albert *et al* 2024 *ApJ* **964** 3

# The multi-messenger program

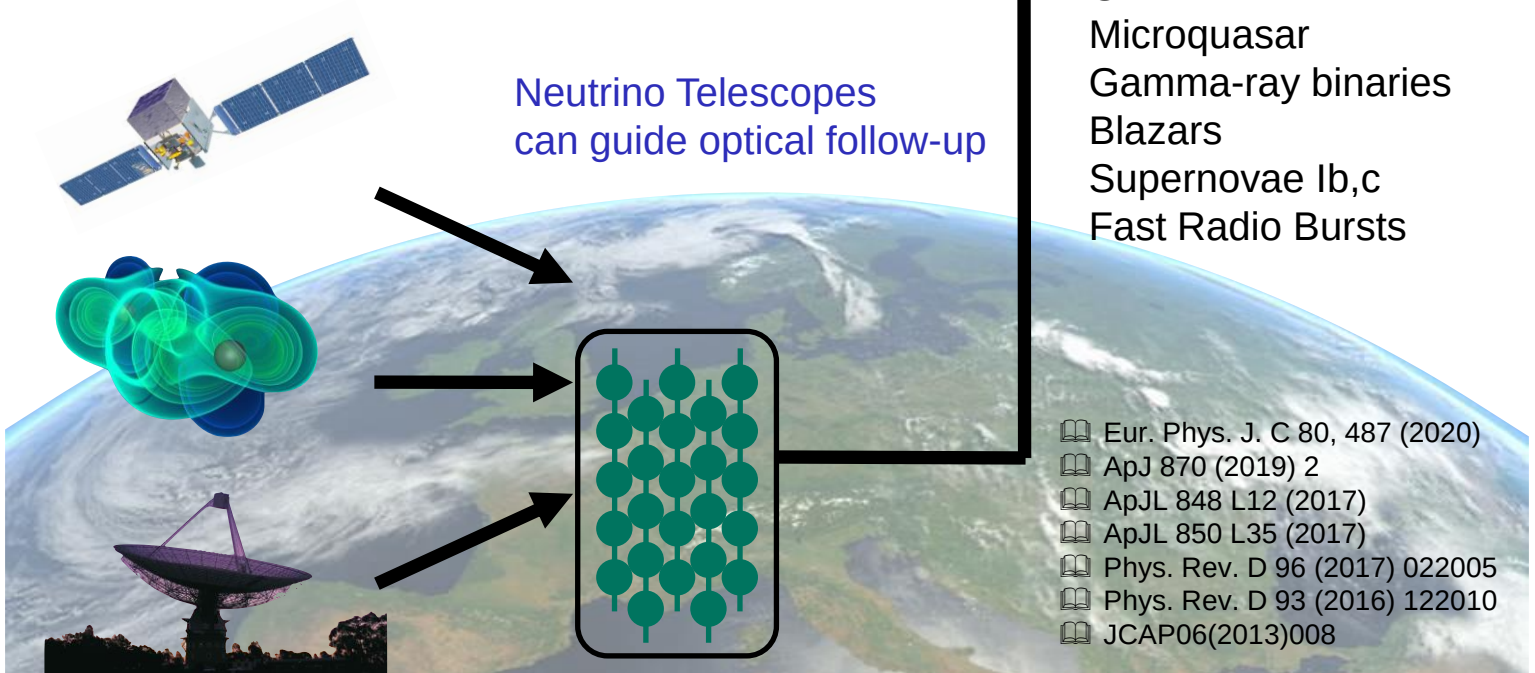
📖 Legacy paper:
A. Albert et al., JCAP 08 (2023) 072

1ST APPROACH:

**Time dependent searches**

GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts

Neutrino Telescopes
can guide optical follow-up



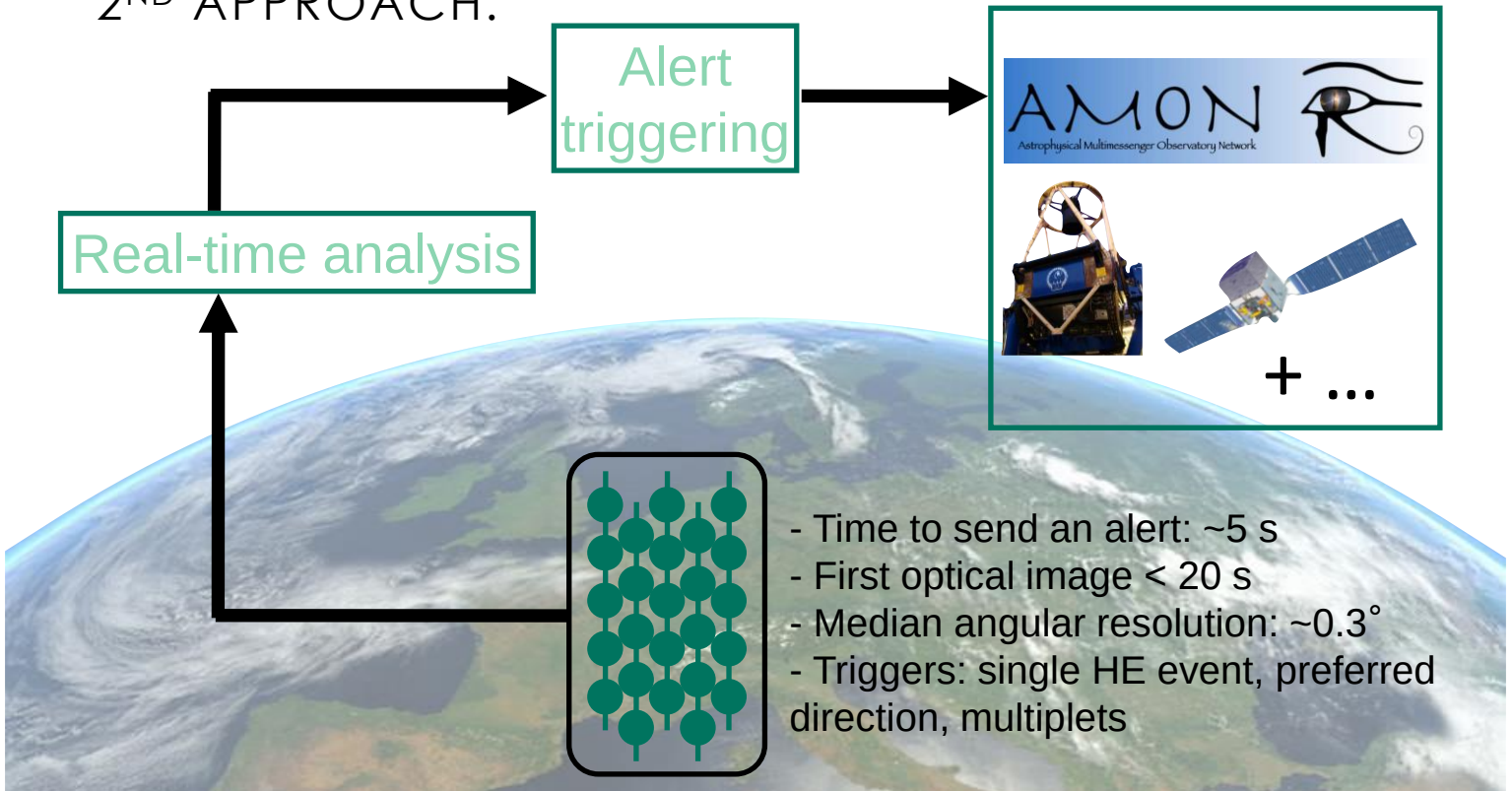
📖 Eur. Phys. J. C 80, 487 (2020)
📖 ApJ 870 (2019) 2
📖 ApJL 848 L12 (2017)
📖 ApJL 850 L35 (2017)
📖 Phys. Rev. D 96 (2017) 022005
📖 Phys. Rev. D 93 (2016) 122010
📖 JCAP06(2013)008

# The multi-messenger program: TATOO

Telescope-Antares Target of Opportunity

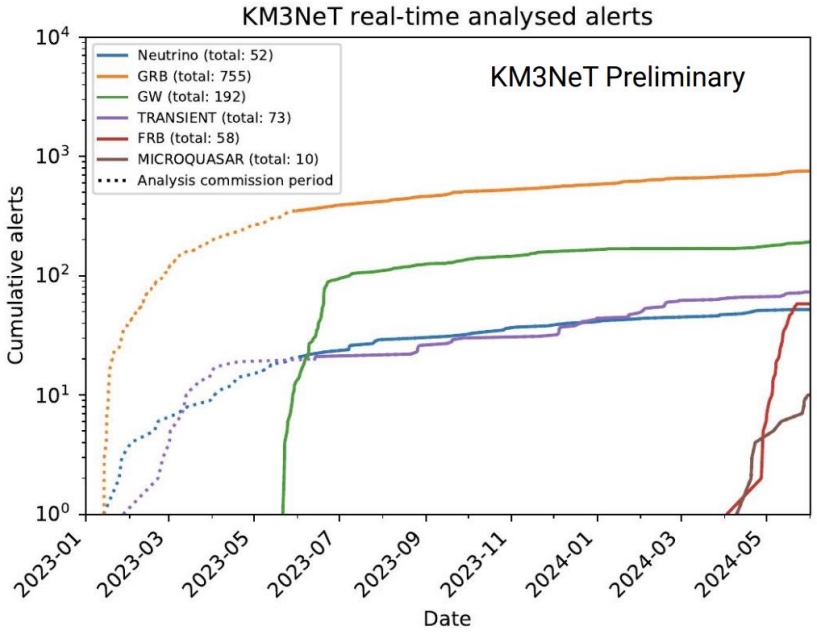
📖 Legacy paper :
A. Albert et al., JCAP 09 (2024) 042

## 2ND APPROACH:




- Time to send an alert: ~5 s
- First optical image < 20 s
- Median angular resolution: ~0.3°
- Triggers: single HE event, preferred direction, multiplets

# KM3NeT taking up the torch online



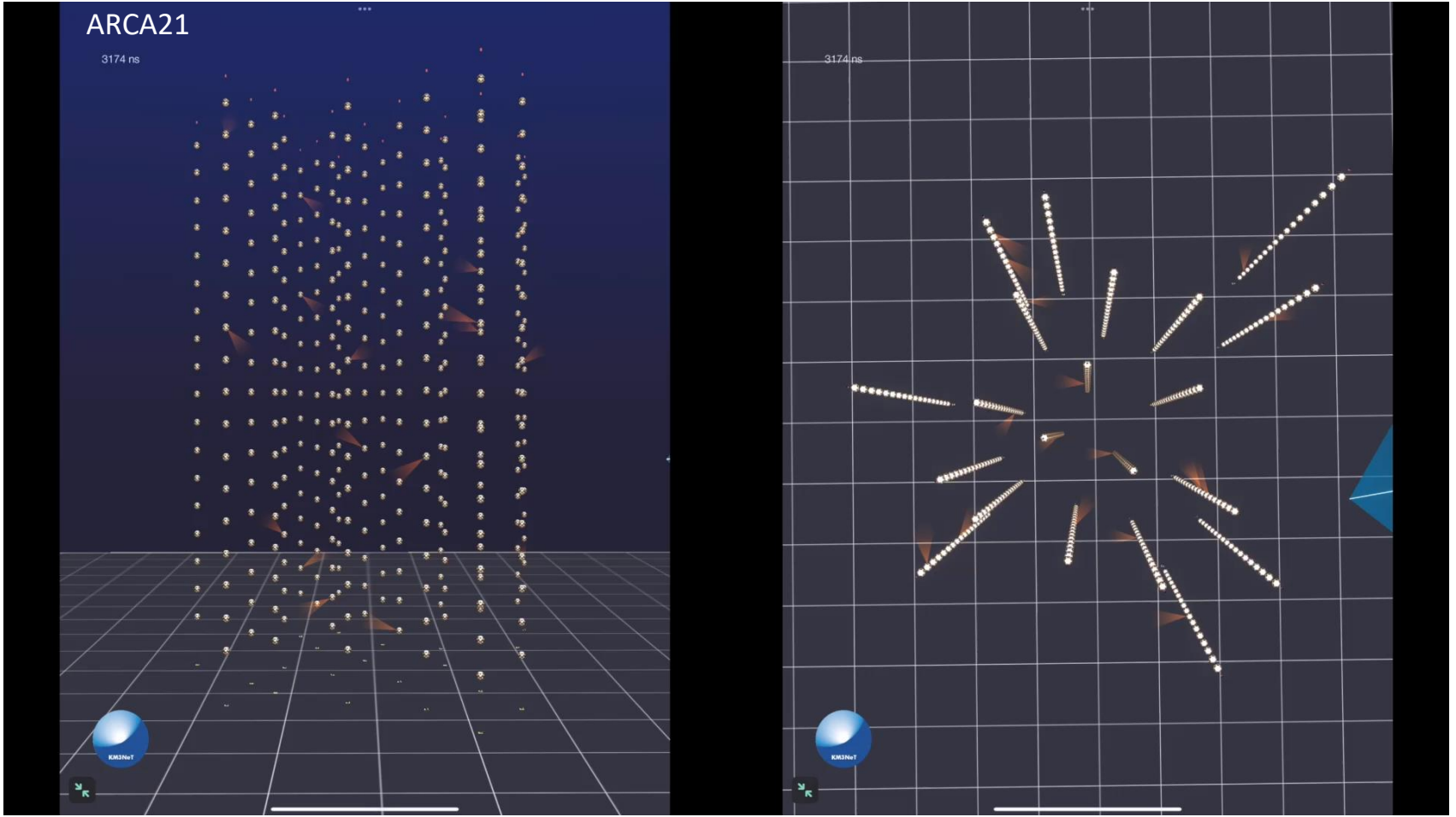


Several thousands of alerts received and analyzed in real time

☞ so far no significant excess found in any of the observed alerts

# The Highest Energetic Neutrino Event ?

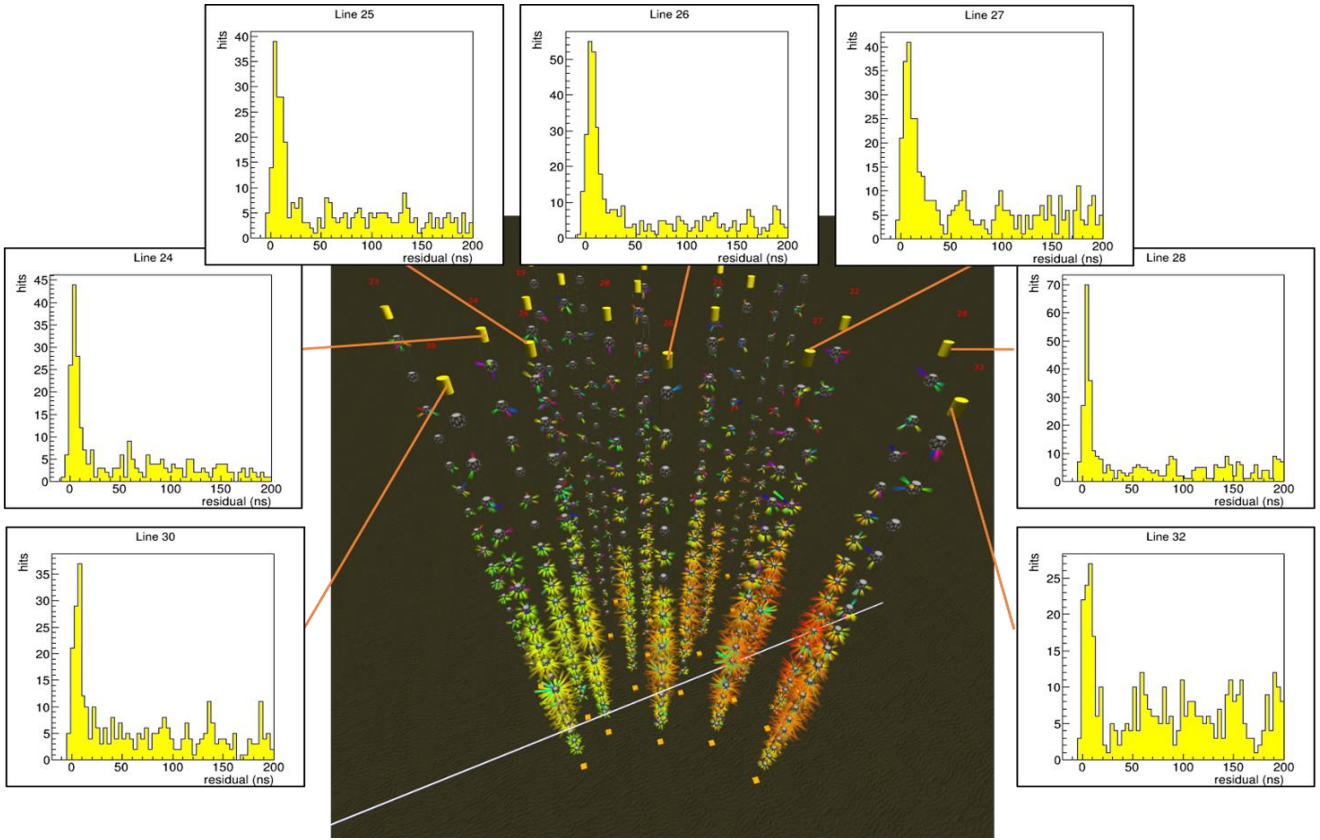




# The Highest Energetic Neutrino Event ?

The event is well reconstructed as a track (cf. time residuals)

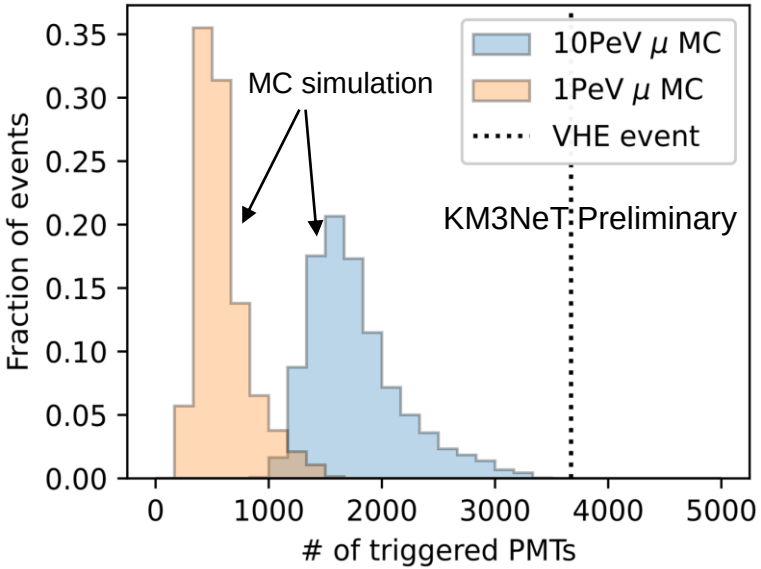
1° above the horizon

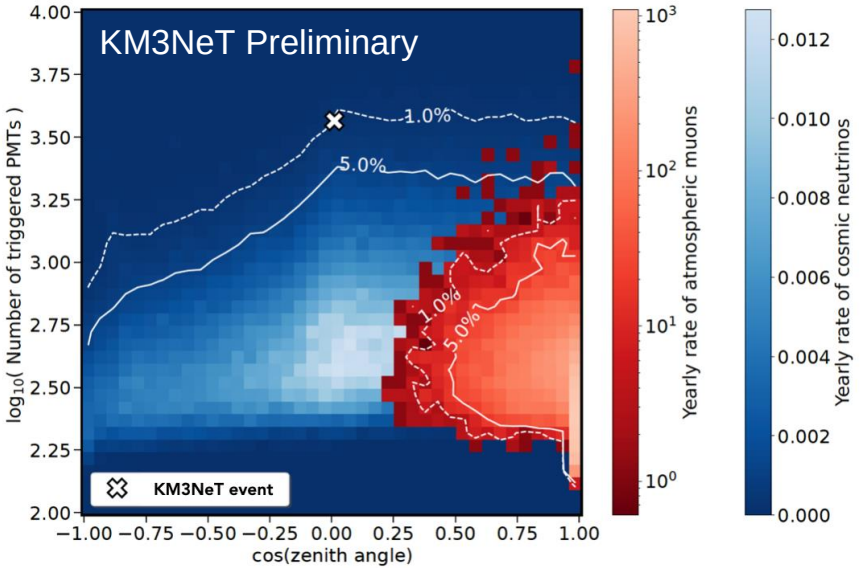


# The Highest Energetic Neutrino Event ?

## With a deposited energy above 10 PeV !

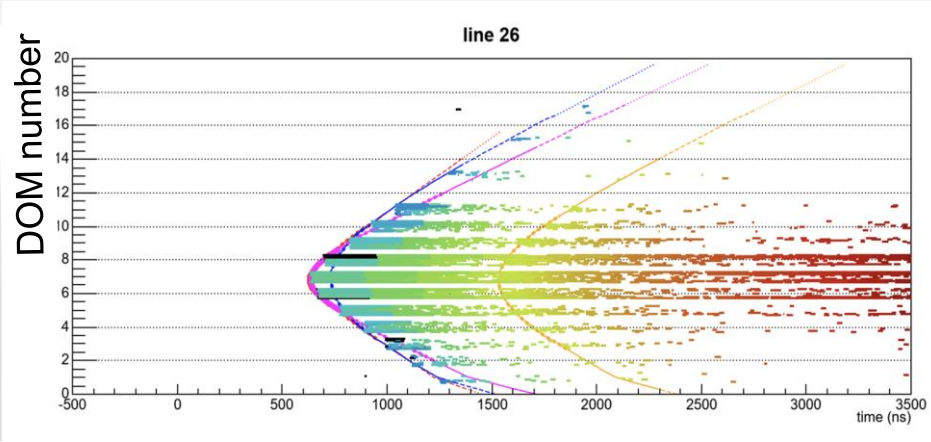
Huge amount of light detected 👉 35% of the total number of PMTs were triggered



# The Highest Energetic Neutrino Event ?

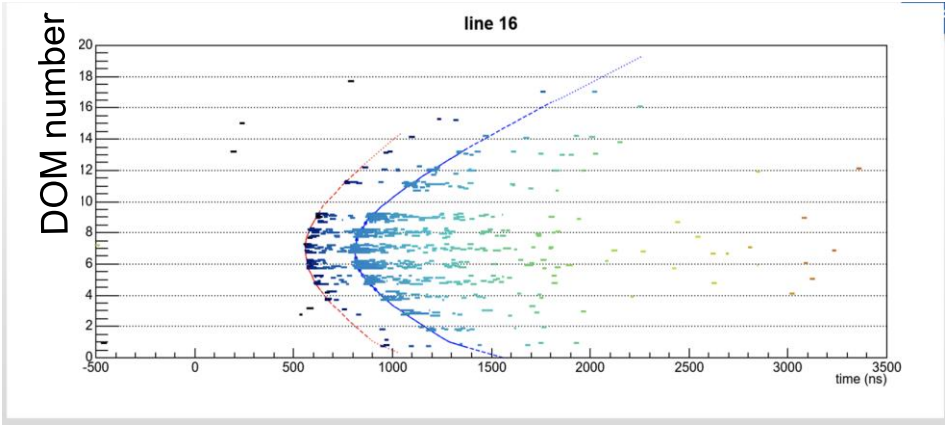





From the track and shower reconstructions

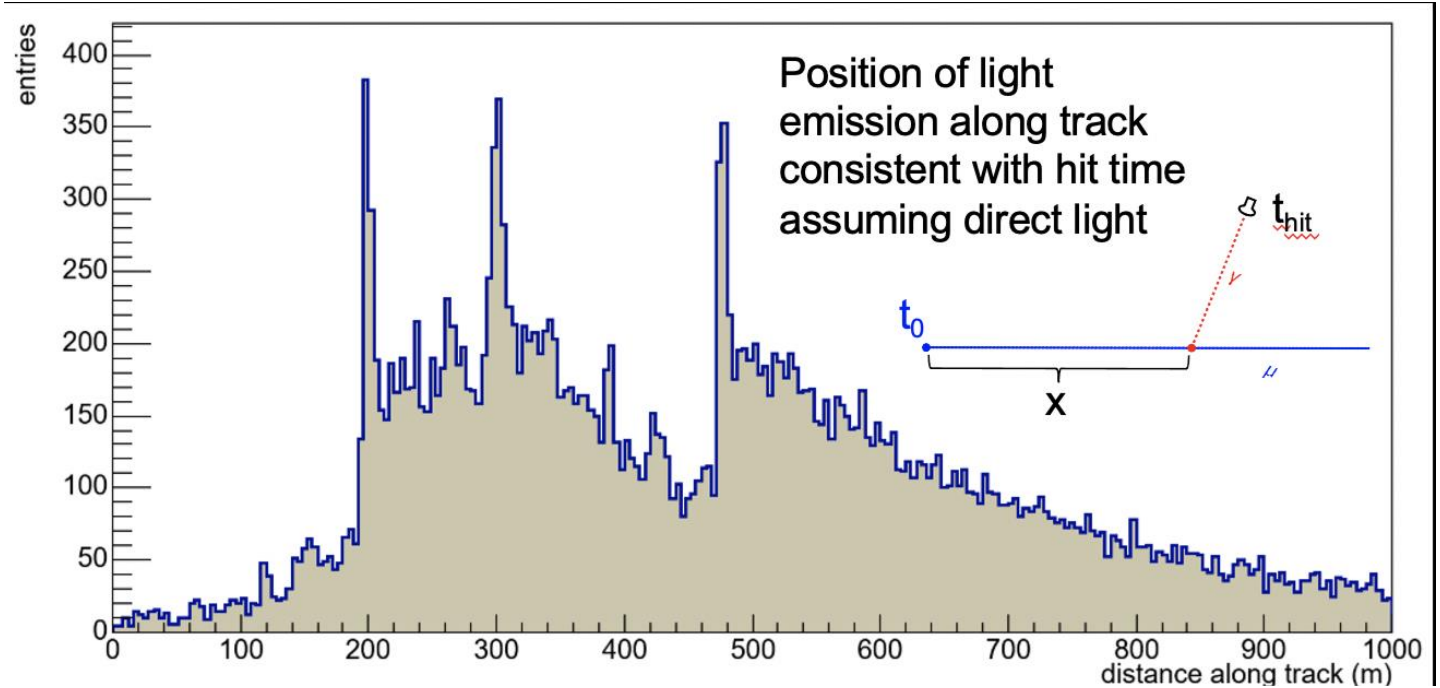
A muon track and three showers detected

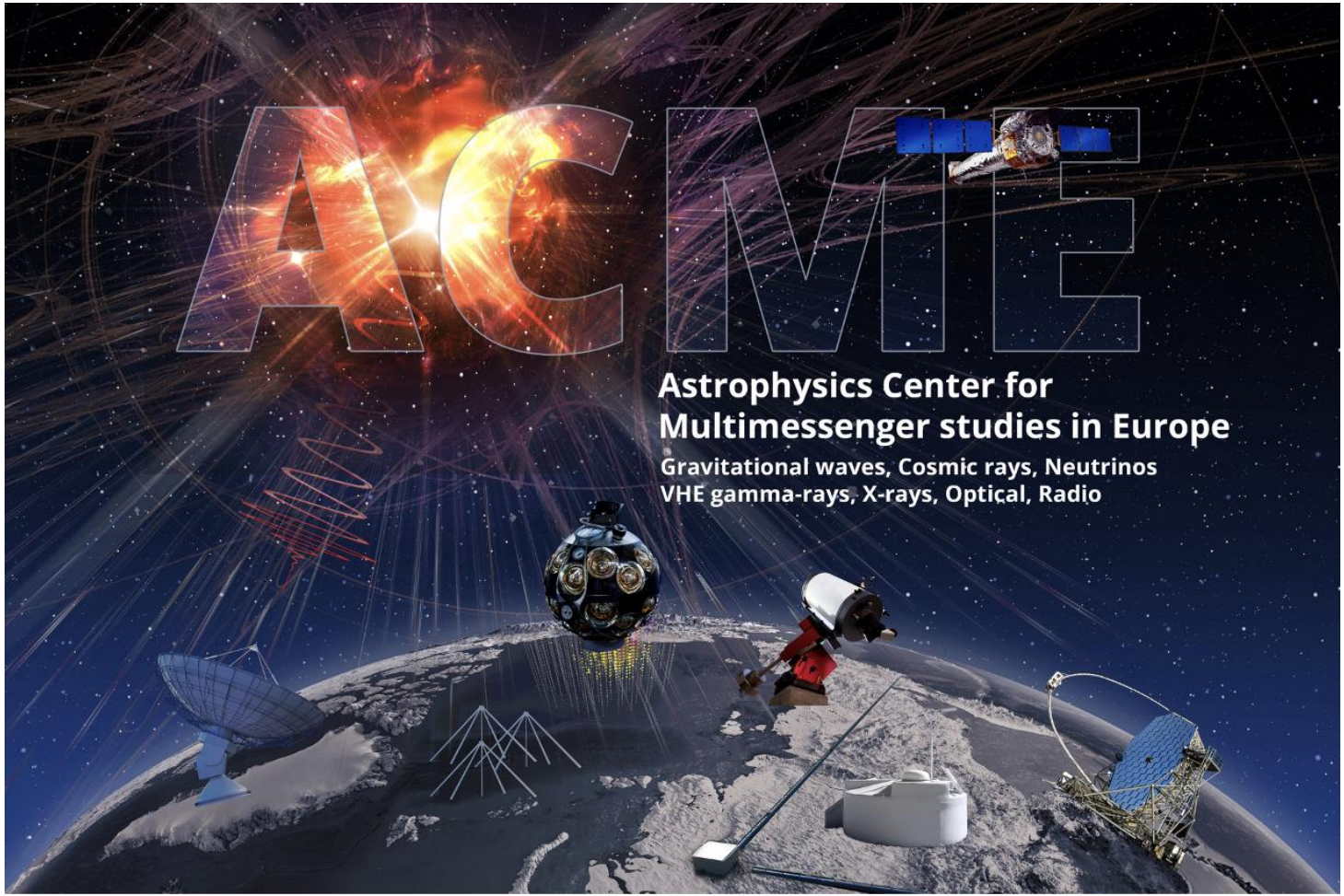
Hit times are fully consistent with photons from Cherenkov emission



# The Highest Energetic Neutrino Event ?

Hit times consistent with the emission from three points along the track 👉 stochastic light emission






**An answer to the Horizon Europe 2023 call for Research Infrastructures**

# Astrophysics Centre for Multimessenger studies in Europe

**Objective**: ACME is set up to realize an ambitious coordinated European-wide optimization of the accessibility and cohesion between multiple leading RI, offering access to instruments, data and expertise, focused on the new science of multi-messenger astrophysics.

**Funded under**
Research infrastructures

**Total cost**
€ 14 499 999,34

**EU contribution**
€ 14 499 999,25

**Coordinated by**
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
France

**Coordinator:** Prof. Antoine Kouchner – APC Laboratory (CNRS/Université Paris Cité)

Funded by the European Union

*Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or of the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.*

# Astrophysics Centre for Multimessenger studies in Europe

**Consortium:** 40 partners, 15 countries, over 30 research infrastructures (observatories and detectors, cyberinfrastructures and expertise centers) from Astronomy and Astroparticle domains, covering GW, Gamma & X-rays, neutrinos, CR, radio, optical.

**Suppported by:**

AstroParticle Physics European Consortium APPEC

A planning and advisory Network for European astronomy ASTRONET

The ACME project coordinator **Prof. Antoine Kouchner** (CNRS/Université Paris Cité), and co-coordinator **Paolo D'Avanzo** (INAF), represent each community to ensure balance and drive cross-domain collaboration.

Funded by the European Union

*Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or of the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.*

# Astrophysics Centre for Multimessenger studies in Europe

**Objectives:** The Astronomy and Astroparticle physics research infrastructures involved in this proposal will lay the foundations for building a new ecosystem for a deepened, stronger and long-term vision collaboration with the aim to:

1. implement the **European roadmaps'** recommendations and act as a pathfinder to broaden, improve and align the accesses to the respective RI services and data
2. provide a harmonized **transnational and virtual access** to world-class RIs
3. develop **centers of expertise**
4. improve the **science data products** management
5. develop and improve interoperable **cyberinfrastructures** for alert sending and better manage **coordinated observations**
6. provide **training** for a new generation of scientists and engineers
7. open the astrophysics data sets to other disciplines and increase **citizen engagement** in scientific research

**7 Work Packages (WP)** corresponding to the objectives above

ACME objectives are to implement the Astroparticle Physics European Consortium's (APPEC) and the Planning and Advisory Network for European Astronomy's (ASTRONET) roadmaps' recommendations

https://www.appec.org/roadmap/ https://www.astronet-eu.org/?page_id=521

Funded by the European Union

*Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or of the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.*

# Astrophysics Centre for Multimessenger studies in Europe
# Kick-Off meeting September 16-17, 2024

Now hiring a technical coordinator part time on SVOM (GRBs)

https://emploi.cnrs.fr/Offres/CDD/UMR7164-KEVVEL-029/Default.aspx

# Summary

- **ANTARES**: first undersea Cherenkov detector
  - Excellent angular resolution, view of Southern sky, competitive sensitivities
  - Constraints on the origin of the IceCube signal
  - Hint of a Galactic neutrino diffuse emission
  - A rejuvenated web page is online
  - Last results and legacy program by mid-2025.

- **KM3NeT**: phased approach to next-generation neutrino telescope by 2028
  - Deployment of detection units on good pace.
  - Instantaneous sensitivity exceeds that of ANTARES
  - **Likely detection of the most energetic cosmic muon neutrino**
  - **ORCA and ARCA combine a rich neutrino physics and astrophysics scientific scope, from MeV to PeV energies, in addition to a unique multidisciplinary program.**

- **ANTARES and KM3NeT are both part of the novel ACME endeavor**

# Indirect search for Dark Matter (GC)



Improved results with respect to 🕮JCAP 10 (2015) 068

$$\frac{d\phi_\nu^{ann.}}{dE} = \underbrace{\frac{\delta}{4\pi}\frac{\langle\sigma v\rangle}{m_{DM}^2}\frac{dN_\nu}{dE}}_{\text{Particle physics}} \underbrace{\int_{res.} d\Omega \int_{l.o.s} \rho_{DM}^2(r) dl}_{\text{Astrophysics}}$$

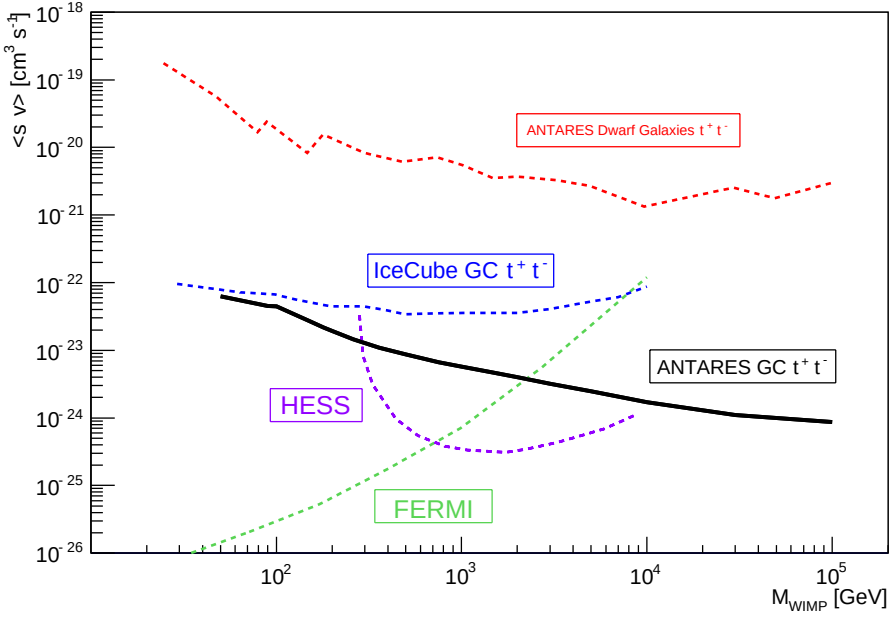
Results depend on density profile

## New !

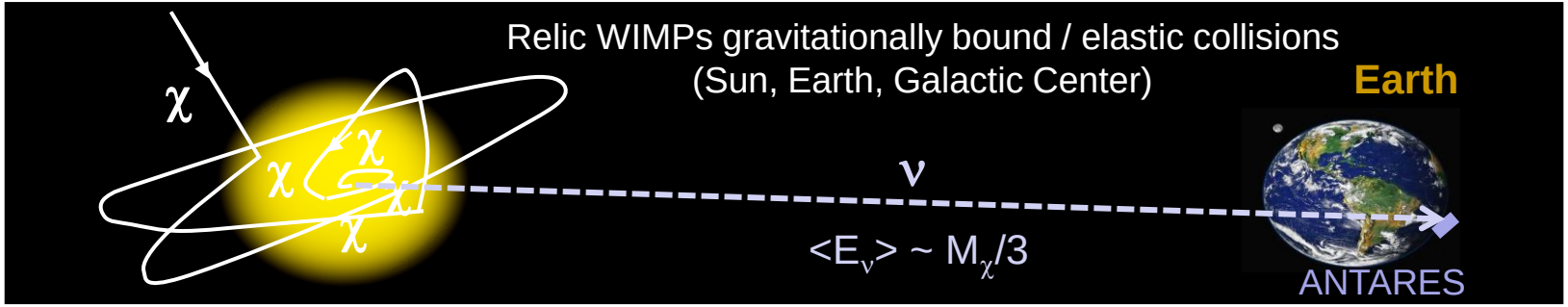
- 2007 – 2013 dataset
- Track channel only
- Single and multi-line events
- Extended likelihood function
- New Dark Matter density profile NFW (same parameters as IceCube)

- Best limit from a Neutrino Telescope

- Also limits from the Earth [P4.005]



# Indirect Search for Dark Matter



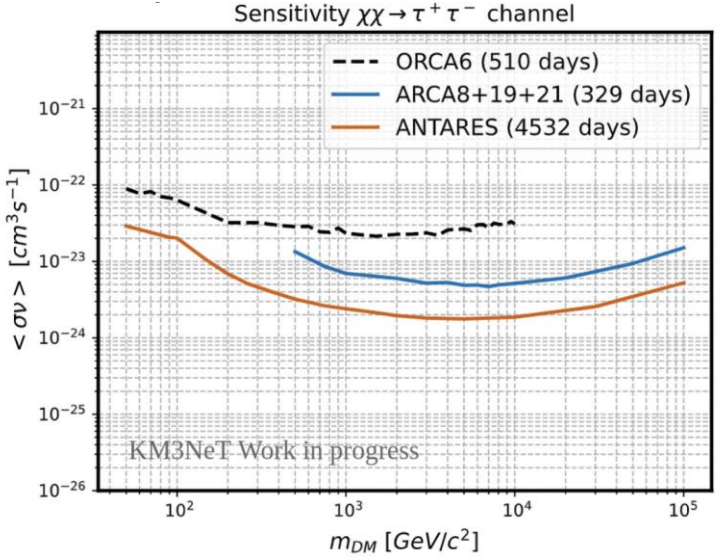

📖 **Earth**
Physics of the Dark Universe, 16 (2017) 41–48

📖 **Sun**
Phys.Lett. B759 2016
JCAP 05 (2016) 016
JCAP11 (2013) 032

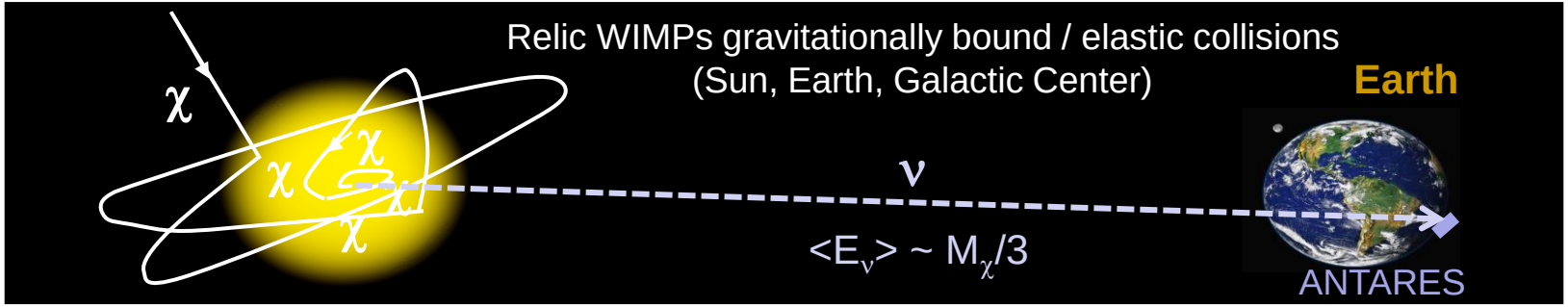
📖 **Galactic Center**
JCAP 06 (2022) 06, 028 (secluded DM)
Phys. Lett. B 805 135439 (2020).
Phys. Rev. D 102, 082002 (2020)
Phys. Let. B 769 (2017) 249
JCAP 10 (2015) 068

*Improvement expected with single line reconstruction*
☞ *PoS(ICRC2023)1443*

Full ANTARES (4532.16 days) & ARCA8+19+21 (328 days)



# Indirect Search for Dark Matter




📖 Earth
Physics of the Dark Universe, 16 (2017) 41–48

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Phys.Lett. B759 2016
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📖 Galactic Center
JCAP 06 (2022) 06, 028 (secluded DM)
Phys. Lett. B 805 135439 (2020).
Phys. Rev. D 102, 082002 (2020)
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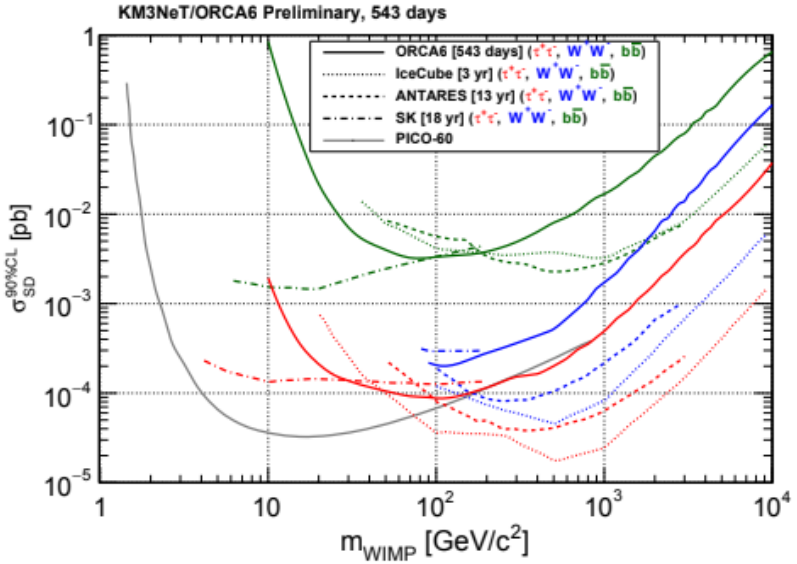


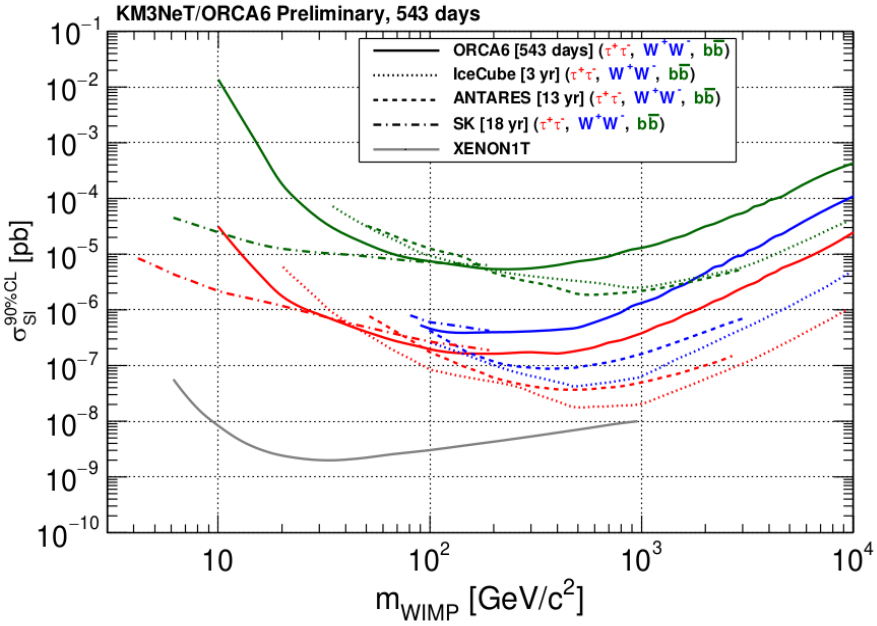

ORCA offers better sensitivity to low WIMP masses

Final ANTARES limits being produced

☞ PoS(ICRC2023)1406,

# Example of Indirect Search for Dark Matter





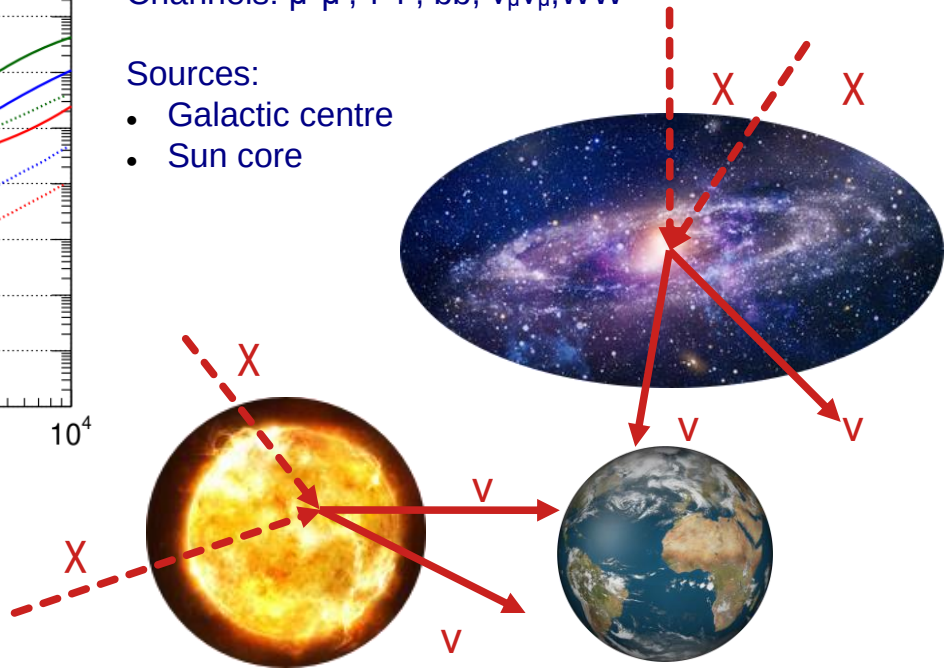

Search for WIMPs annihilating

Mass range: 300 GeV/$c^2$ ÷ 100 TeV/$c^2$

Channels: $\mu^+\mu^-$, $\tau^+\tau^-$, bb, $\nu_\mu\nu_\mu$,WW

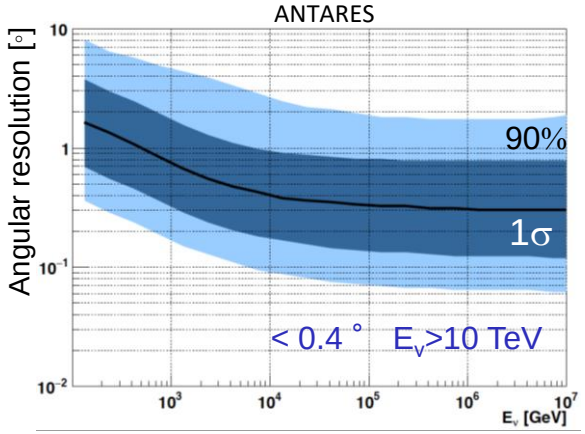
Sources:

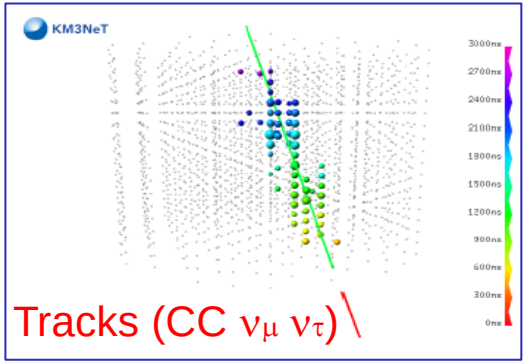
- Galactic centre
- Sun core



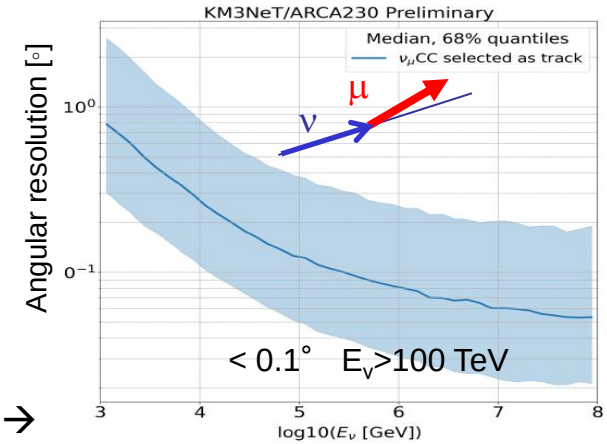
# Reconstruction Performances



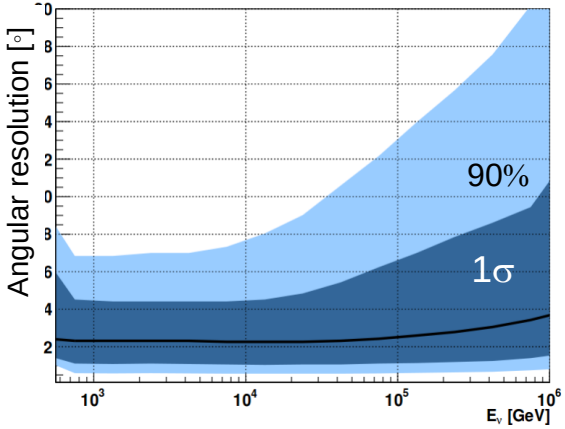


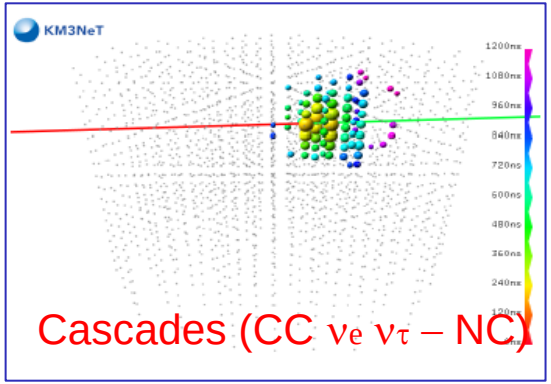




←0.35 Log(Eμ) Resolution 0.27→

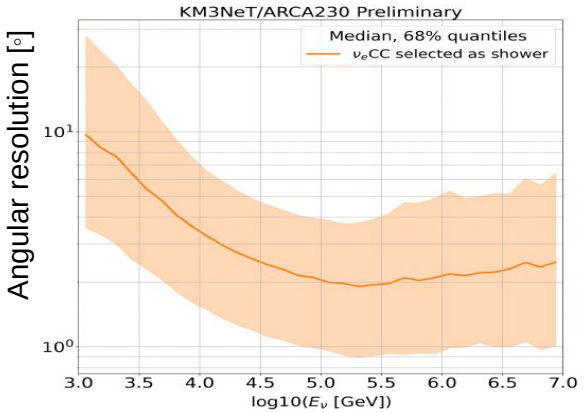



☞ *PoS(ICRC2023) 1074*




←10% Energy Resolution 5%→

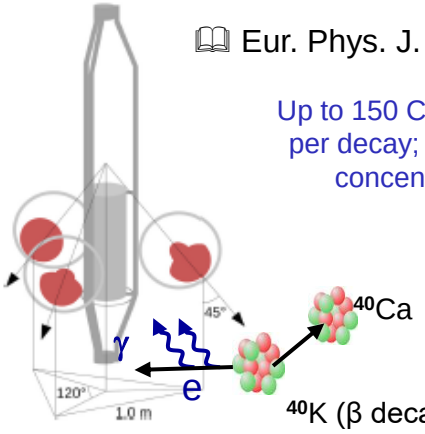


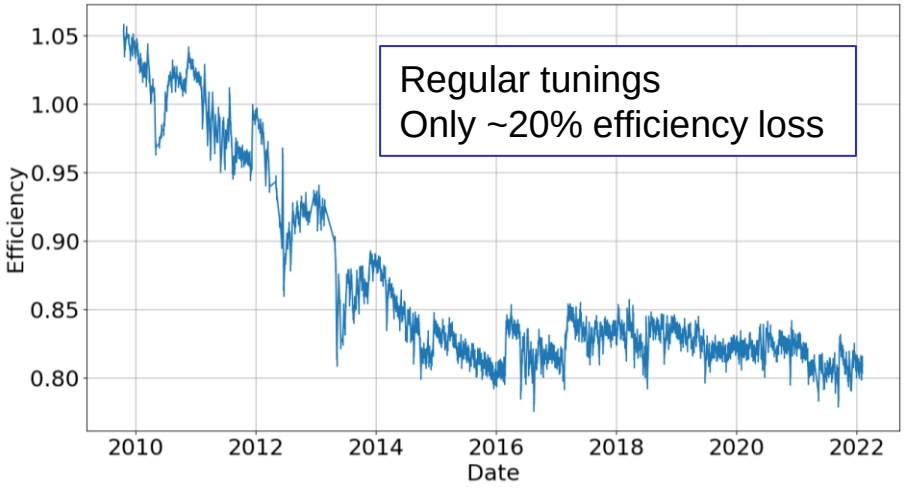
# Calibration procedures & monitoring



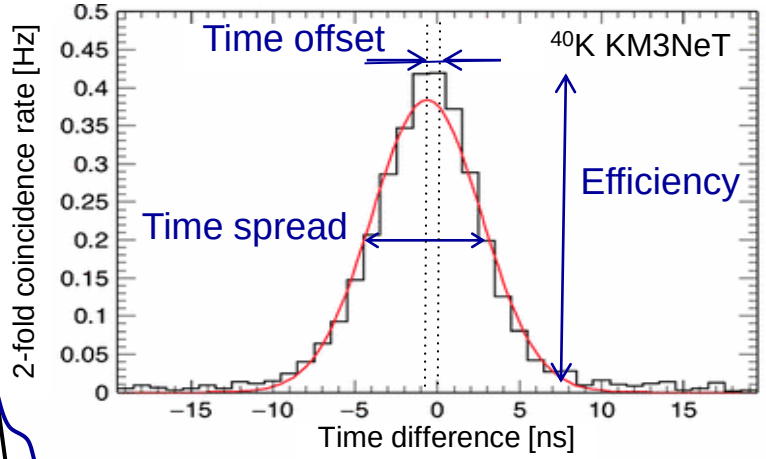
Eur. Phys. J. C (2018) 78: 669

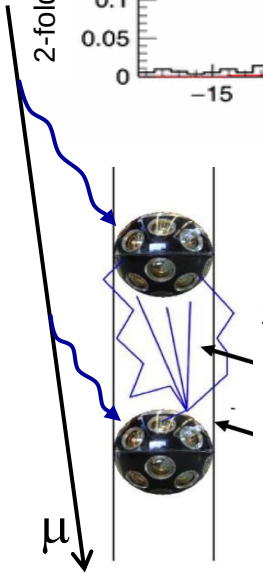
Up to 150 Cherenkov γ per decay; stable $^{40}$K concentration




Regular tunings
Only ~20% efficiency loss




## Complemented by:

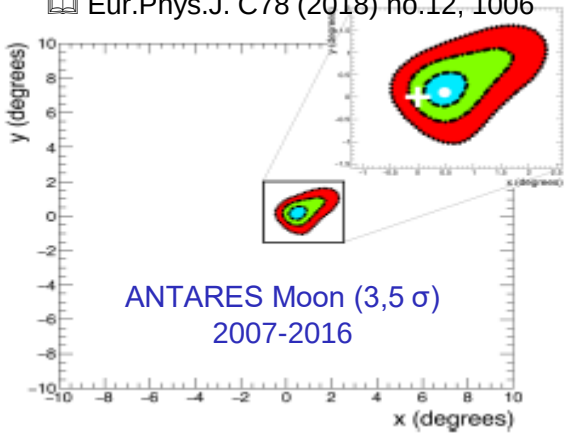
- Scattered photons
- Direct photons
- Nanobeacon

Cross-calibration with muons

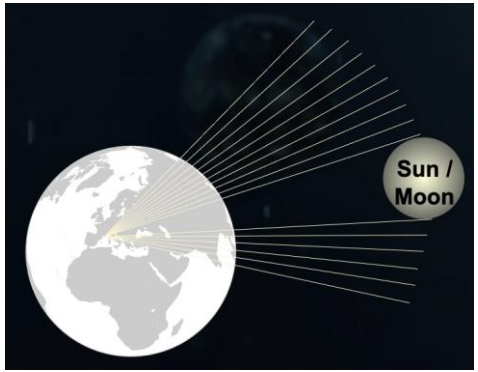
# Absolute Pointing

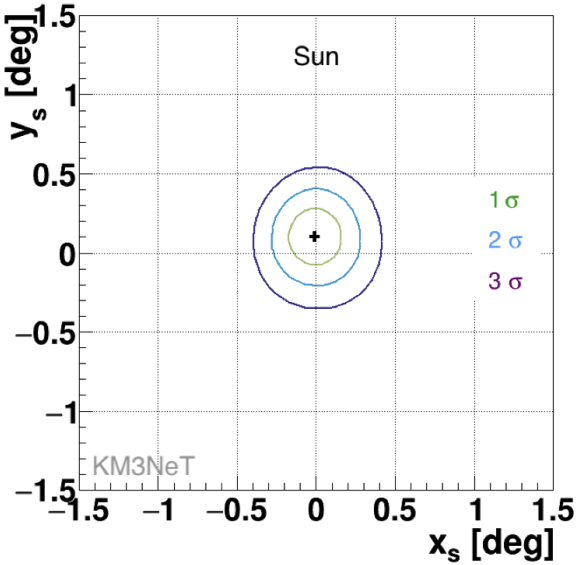


📖 Eur.Phys.J. C78 (2018) no.12, 1006

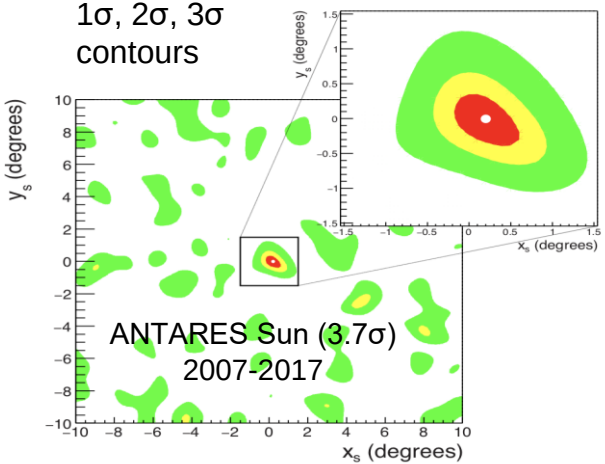



ANTARES Moon (3,5 σ)
2007-2016




1σ, 2σ, 3σ contours




ANTARES Sun (3.7σ)
2007-2017

📖 Phys. Rev. D 102, 122007 (2020)

| ORCA6 (500 days) | Sun | Moon |
|---|---|---|
| Statistical Significance | 6.2 σ | 4.2 σ |
| Resolution | 0.65° ± 0.13° | 0.49° ± 0.15° |

📖 S. Aiello et al., Eur. Phys. J. C 83, 344 (2023)

# Multidisciplinary Observatories


📖 Deep-Sea Research I 58 (2011) 875–884
*Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean*

📖 PLoS ONE 8 (7) 2013
*Deep-sea bioluminescence blooms after dense water formation at the ocean surface*

📖 Ocean Dynamics, April 2014, 64, 4, 507-517
*High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean*

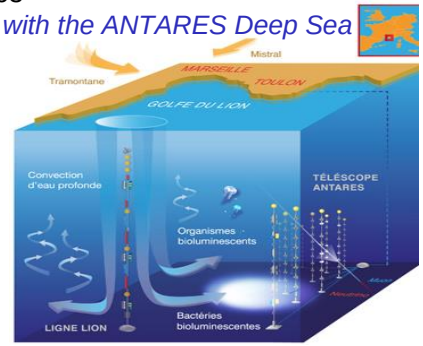
📖 J of Geophysical Research: Oceans, 122, 3, 2017
*Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection*

📖 Sci. Rep. 7 (2017) 45517
*Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope*

📖 https://arxiv.org/abs/2107.08063
*Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope*


+ Citizen science

REINFORCE
REsearch INFrastructures FOR Citizens in Europe




## A dedicated program on French KM3NeT Site

Oceanography
Biology

Seismology
Bioacoustics…