A decade of neutrino searches in the sea

First ANTARES Legacy Results

- The ANTARES detector
  - Construction and dismantling
  - Detection Principle
  - Performances
- Scientific Results
  - Earth and Sea science
  - Particle Physics
  - High-Energy Astrophysics
- The ACME Challenge

Antoine Kouchner

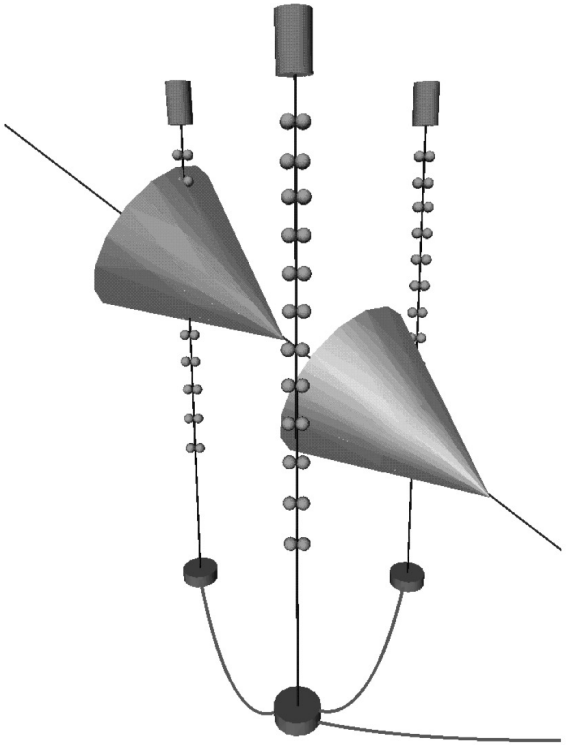
The first deep-sea Neutrino Telescope

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

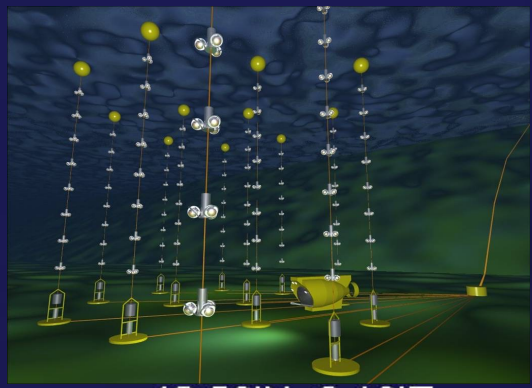


PROPOSAL – May 1997

Toulon

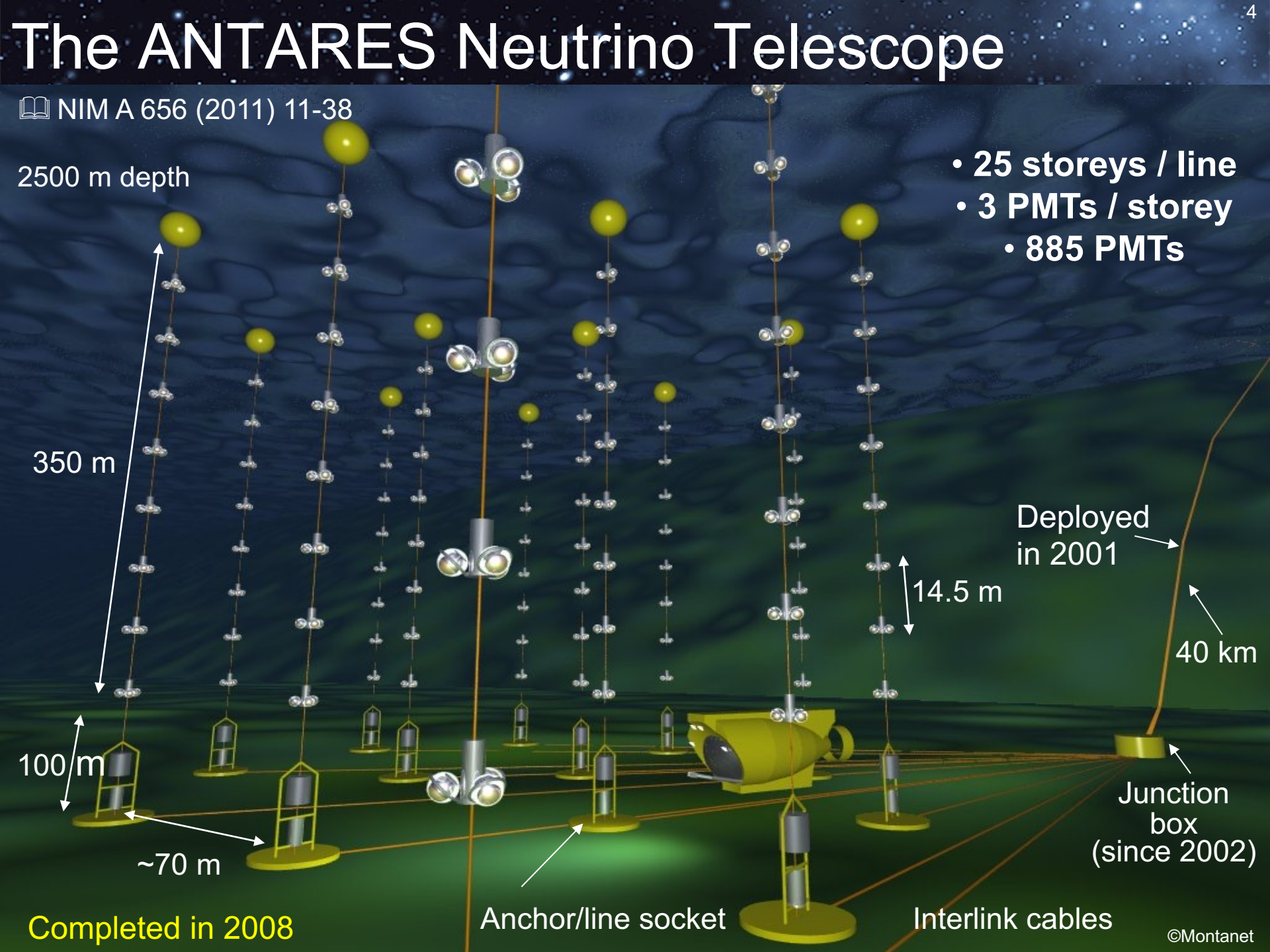
Institute Michel Pacha

Antares

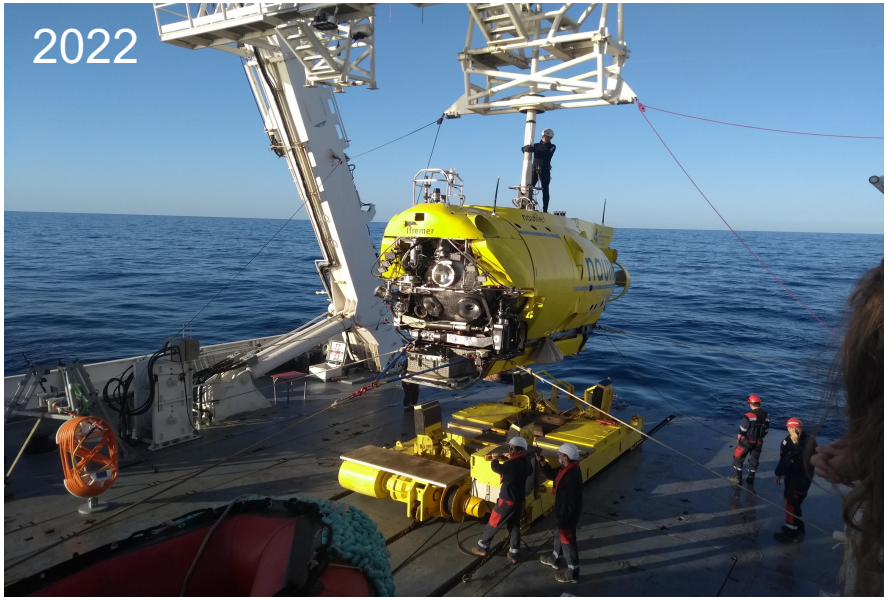


42 50'N, 6 10'E

The ANTARES Neutrino Telescope



ANTARES 2001-2022



2001 Main Electro-Optical Cable
2002 Junction box
2003 Prototype Sector Line
2005 Mini Instrumentation Line with OMs
2006 First complete detector line
2008 Detector with 12 lines completed
2016 Running (almost) without common funds
2022 Data taking terminated & Recovery

Recovery completed

Recovery completed

ANTARES : A key step towards KM3NeT

ANTARES is now fully dismantled...

[Published June 23rd, 2022]

The disconnection of the interlink cables between the junction box and the line anchors, carried out with the manned Nautile submarine on 12/02/2022, defined the end of data taking of the ANTARES detector.

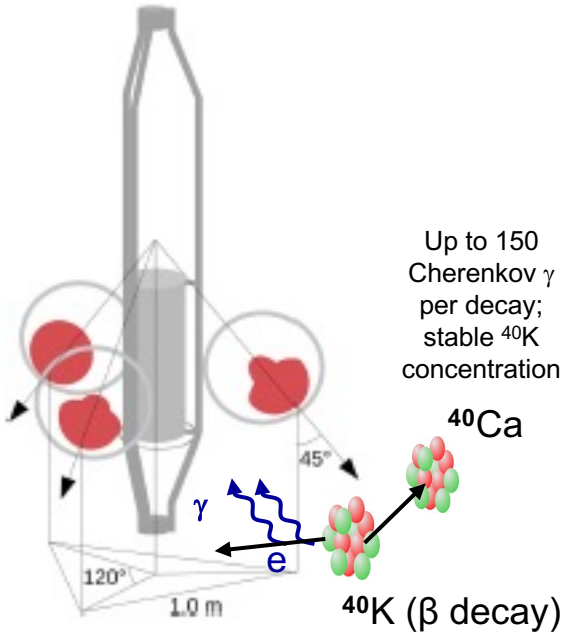
As a natural follow-up step, two dismantling campaigns took place in May and June 2022. The Castor02 ship from Foselev Marine and the Janus-II ship with its ROV Apache from SAAS - the work horses used for the majority of ANTARES and KM3Net/ORCA campaigns - had been in operation. During these two operations all active detector elements have been recovered and brought to shore. Only the junction box will remain in place until a forthcoming KM3NeT campaign to reroute the main electro-optical cable from the ANTARES to the KM3NeT/ORCA site.

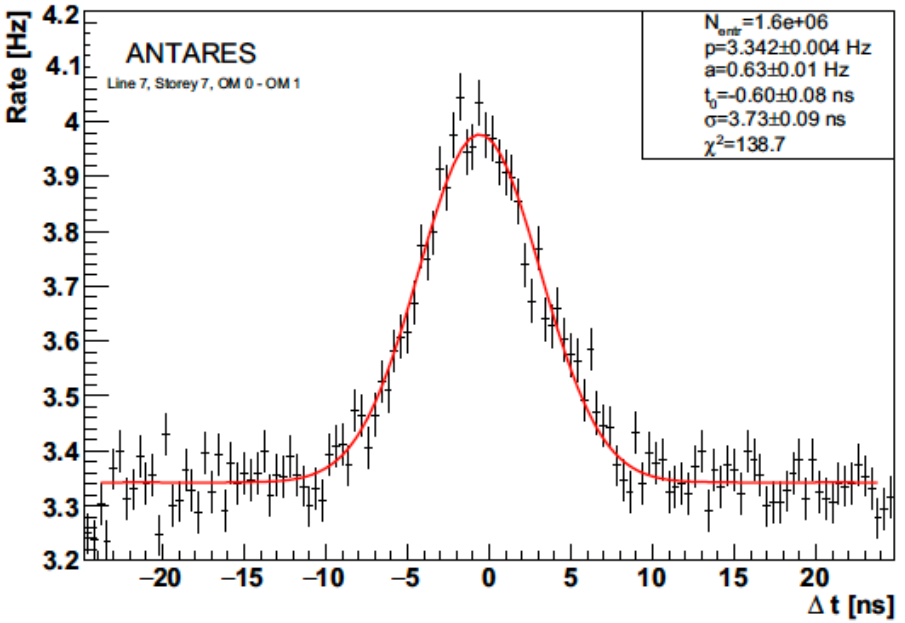
One of the last recovered elements was the PPM-DOM (see Figure below), the first prototype of the future KM3NeT DOMs, installed in 2013 and still in good shape. Some of the ANTARES equipment, notably the optical modules with their photomultipliers, might be used in future science projects. Other parts will be recycled or used in exhibitions or other outreach projects to illustrate the success of this first-generation deep-sea neutrino telescope.

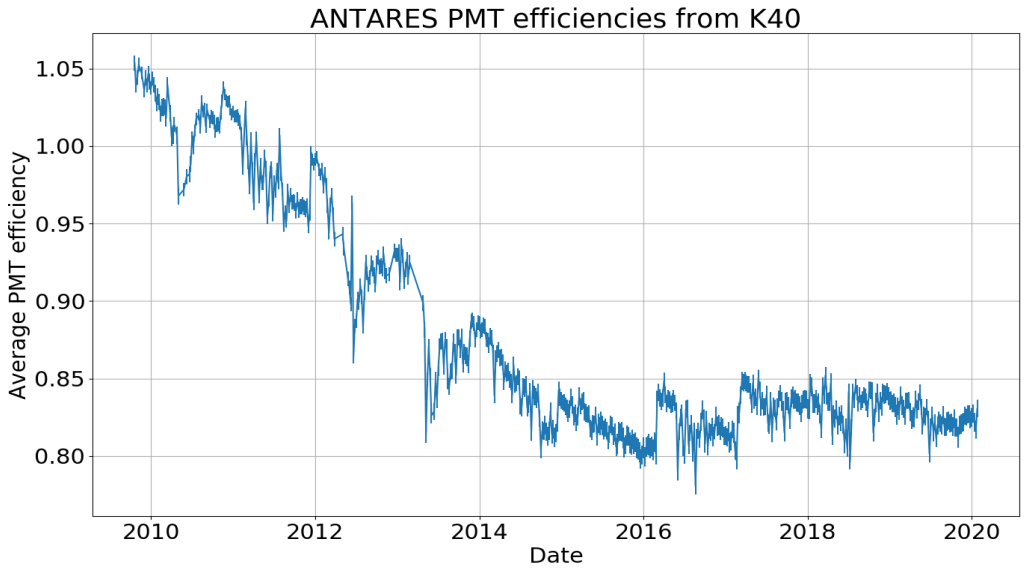
The recovery of the PPM-DOM, the first prototype of the future KM3NeT DOMs, still in good shape. This marks the passage to the next generation - KM3NeT.

ANTARES is now history, long live KM3NeT !

^{40}K (long-term) monitoring







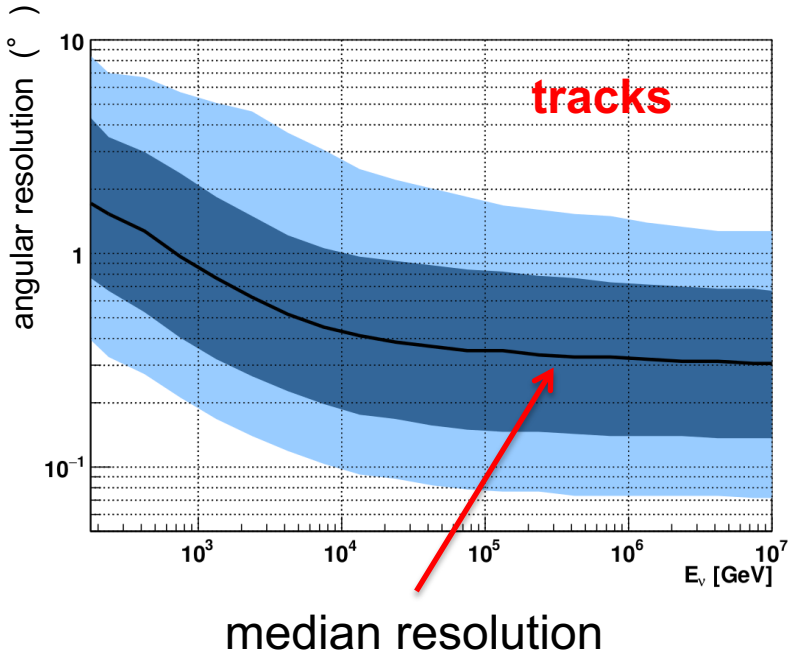
Regular tunings
Only ~20% efficiency loss

^{40}K powerful calibration tool

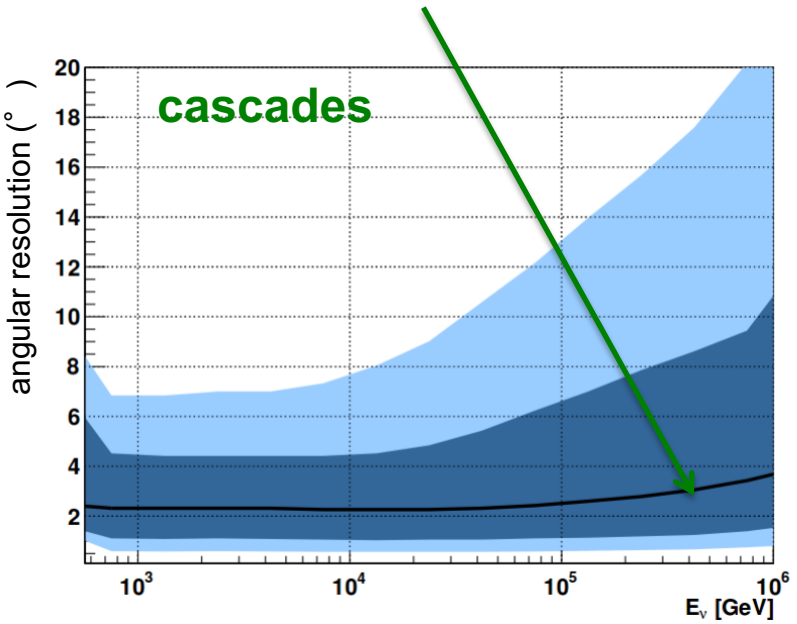
Eur. Phys. J. C (2018) 78: 669

Reconstruction performances

- Upgoing track events (ν_μCC)
- Angular resolution <0.4° for E_ν>10 TeV
- 90% purity
- Energy resolution of about a factor 2



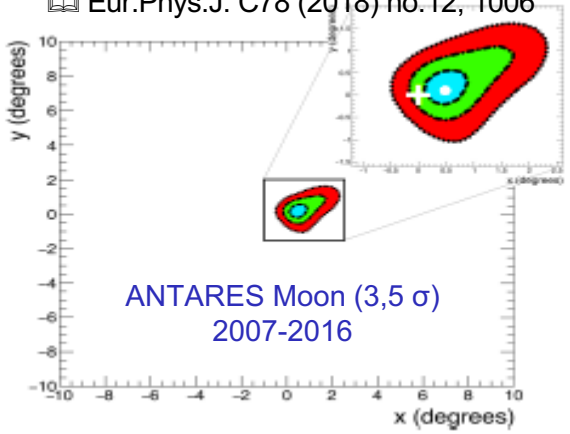
- Upgoing cascade events (ν_e / ν_τ CC, NC)
- Angular resolution < 3°
- Energy resolution for ν_eCC better than 10%

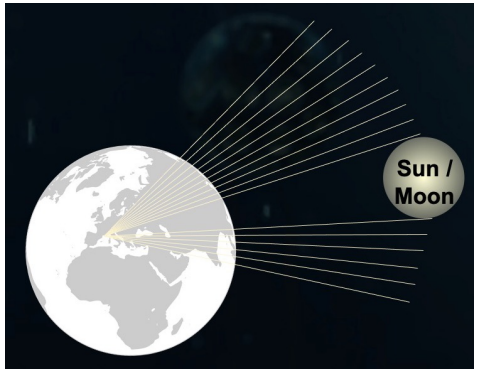


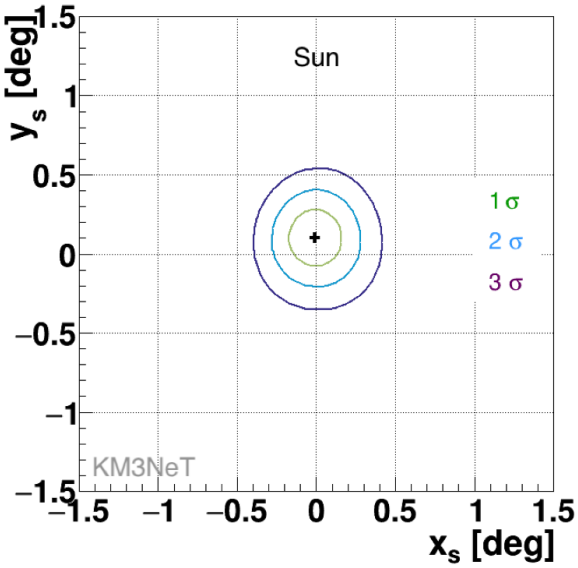
📖 ANTARES Monte Carlo, JCAP01 (2021) 064

Absolute Pointing

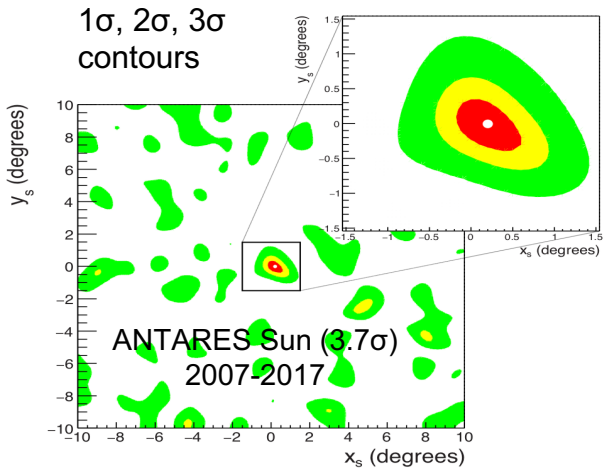
📖 Eur.Phys.J. C78 (2018) no.12, 1006







1σ, 2σ, 3σ contours



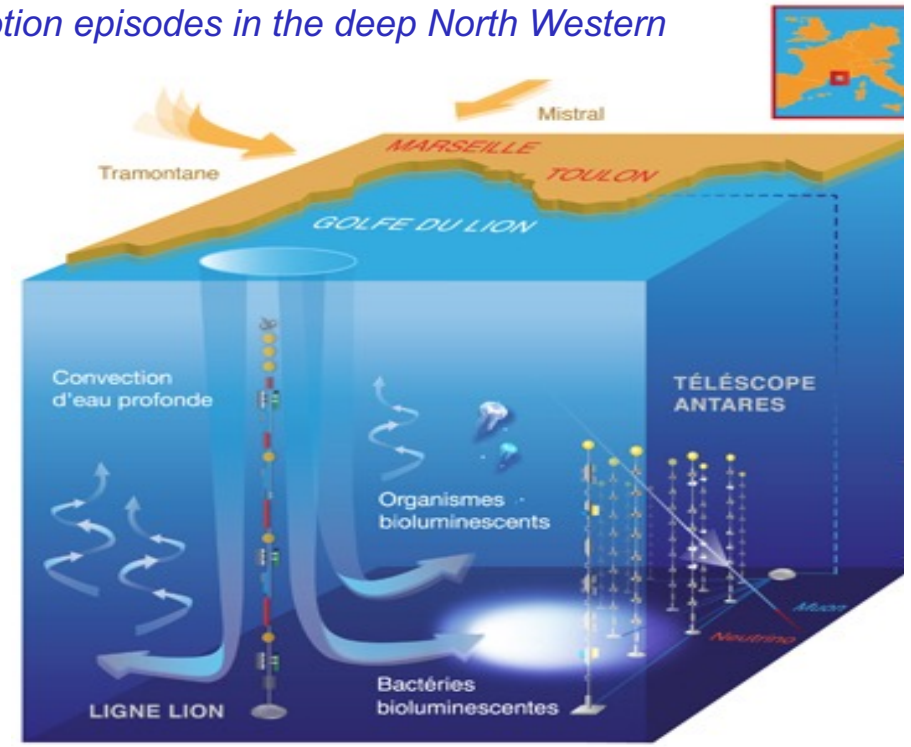
📖 Phys. Rev. D 102, 122007 (2020)

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)

A multidisciplinary observatory

📖 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

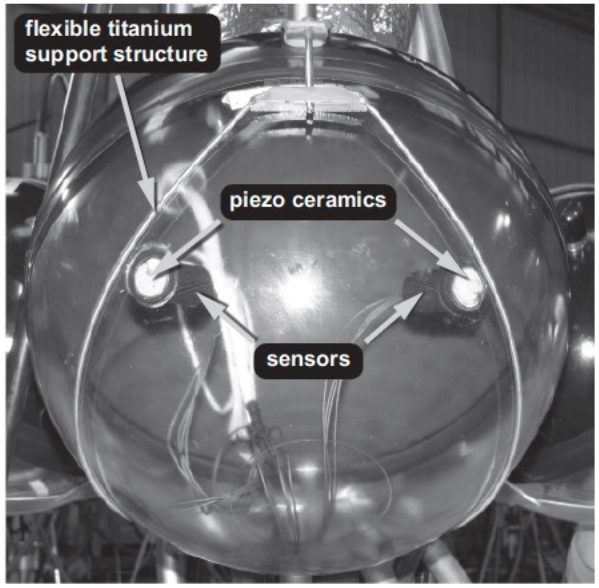
📖 *Sci. Rep. 7 (2017) 45517*
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

📖 Limnology and Oceanography: Methods, October 2023
Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope

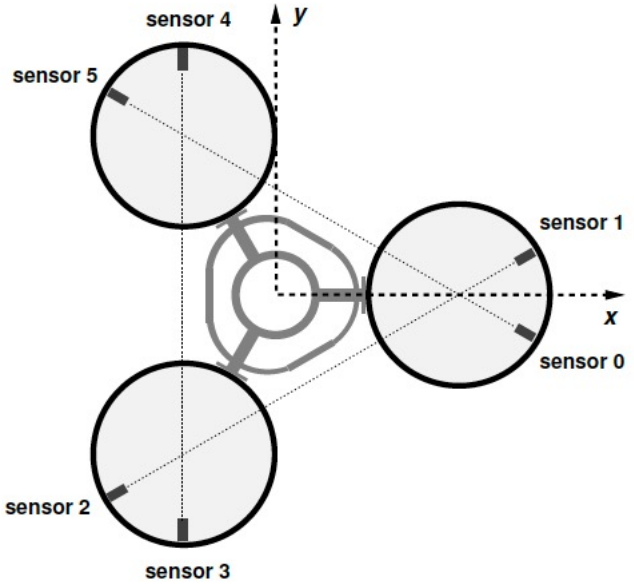
Piezzo results

📖 https://arxiv.org/abs/2405.07230 - To Appear In Experimental Astronomy

Acoustic Positioning for Deep Sea Neutrino Telescopes with a System of Piezo Sensors Integrated into Glass Spheres



(a)



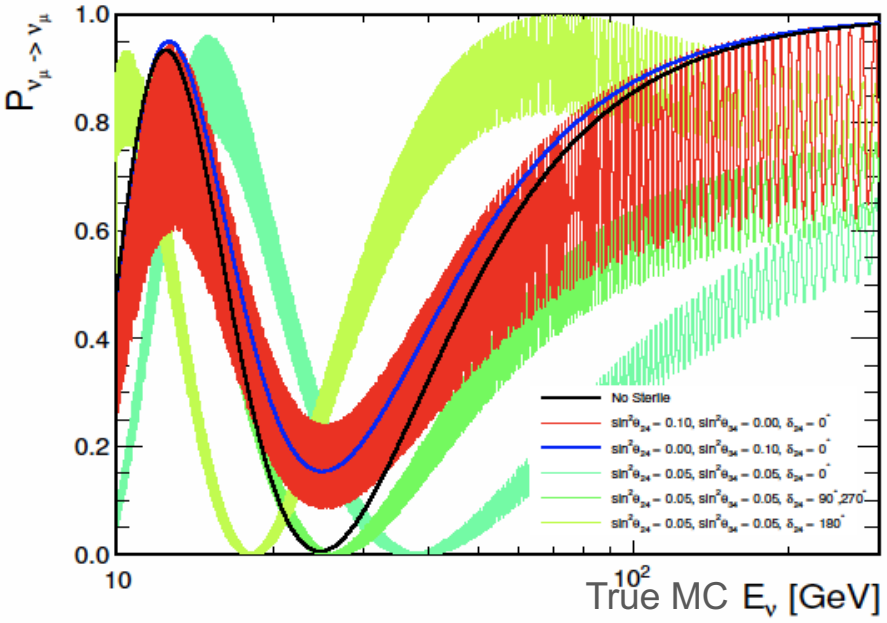
(b)

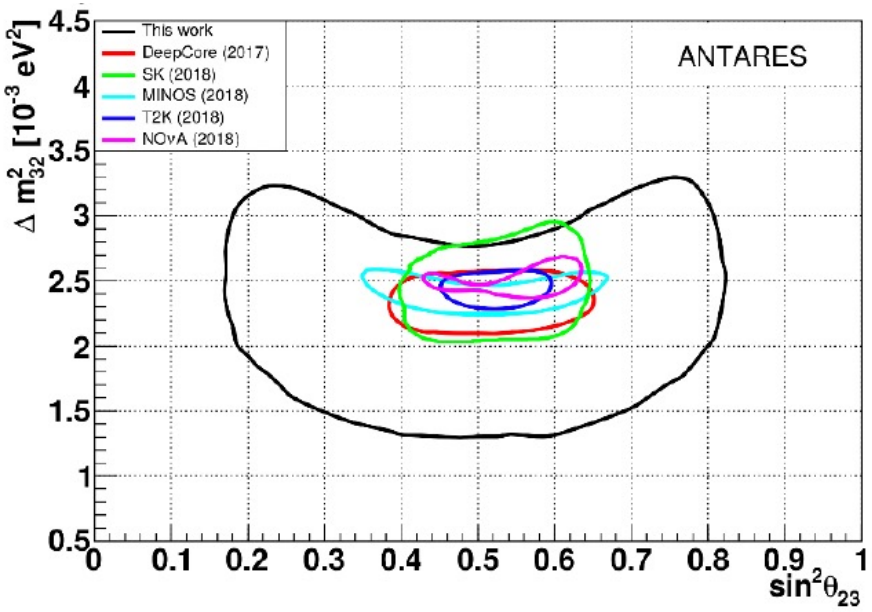
Two waves propagating through the glass sphere are found as a result of the excitation by the waves in the water which can be qualitatively associated with symmetric and anti-symmetric Lamb-like waves of zero-th order: a fast (early) one with ve ~ 5mm/μs and a slow (late) one with v_l ~ 2mm/μs. Accounting for the propagation of the emitter signals through the glass sphere improves the results of the position calibration of the acoustic modules.

→ KM3NeT.

Latest Oscillation Studies

For illustration: Vertical Upgoing





📖 J. High Energ. Phys. (2019) 2019: 113

- Data from (2007-2016) sample - 2830 days of lifetime
- 7710 events selected, two reconstruction procedures
- Track channel only, E_{reco} from muon range
- A binned likelihood fit (Poisson stat.) is performed in two dimensions ($\log_{10}(E_{reco})$, $\cos\theta_{reco}$)
- Sample soon public

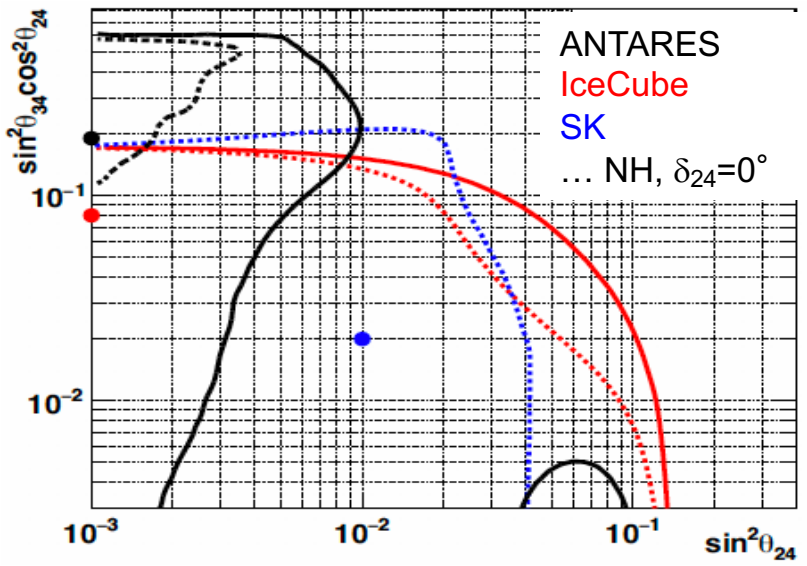
No-oscillation hypothesis excluded at 4.6σ

Latest Oscillation Studies Sterile & NSI

- (3+1) sterile neutrino models $\Delta m^2_{41} > 0.5\ eV^2$
- Tight complementary information to eV-scale sterile neutrino searches

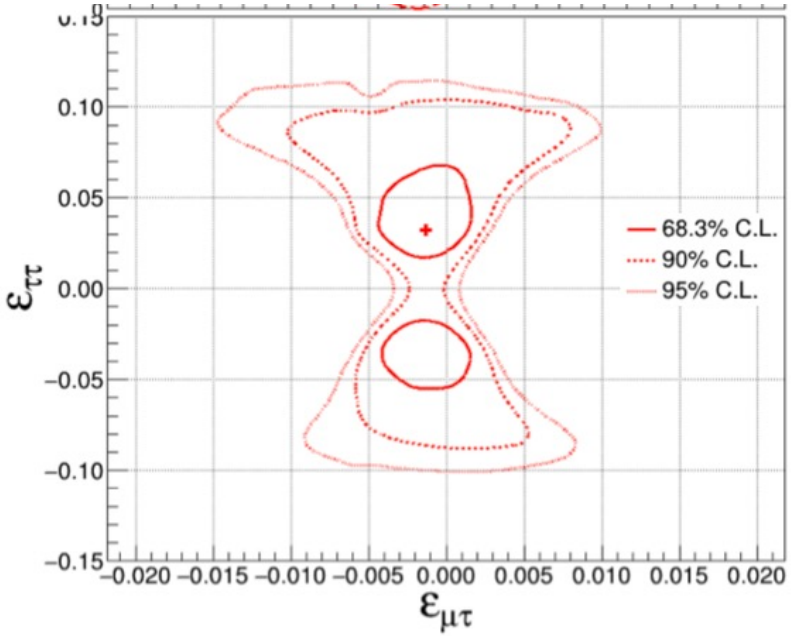
Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.

📖 J. High Energ. Phys. (2019) 2019: 113



- Non-standard interaction signature in neutrino oscillation patterns are detectable
- Mild hint for non-standard interactions observed in 10 years of ANTARES data Ruled out by IC
- The non-NSI hypothesis is disfavoured with a significance of 1.7σ (1.6σ) for the normal (inverted) mass ordering scenario.

📖 J. High Energ. Phys. 2022, 48 (2022)

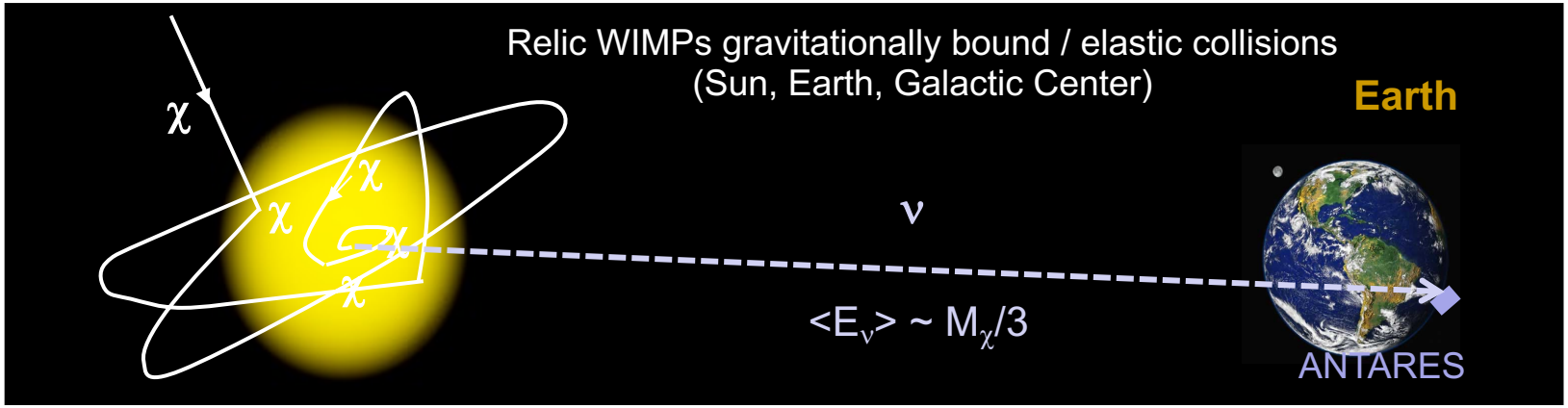


Available data sets

Four data sets are available :

- Point sources search using 2007-2010 data ;
- Point sources search using 2007-2012 data.
- Point sources search using 2007-2017 data.
- **Latest Data Release :** Searches for non-standard neutrino interactions using 2007-2016 data.

Indirect Search for Dark Matter



📖 Earth

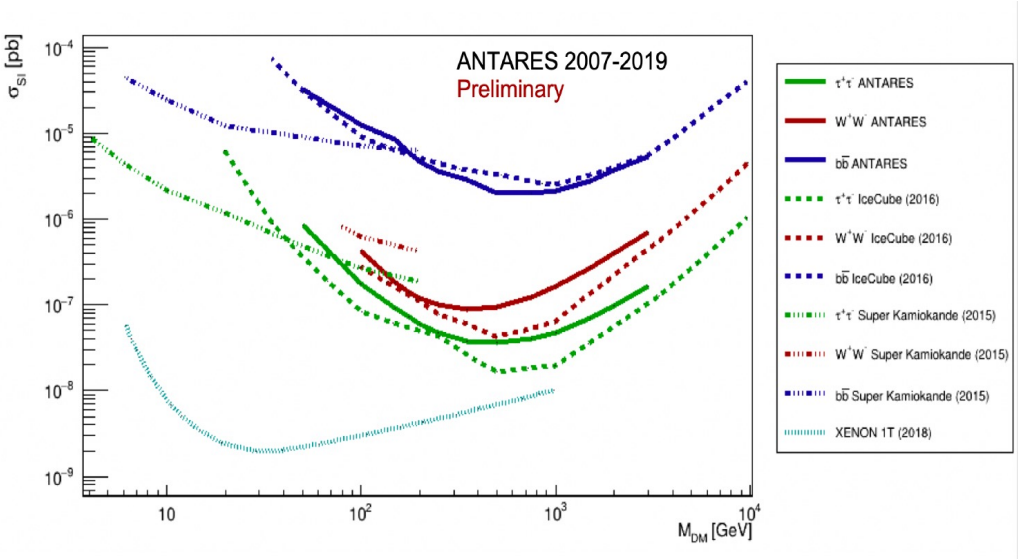
Physics of the Dark Universe, 16 (2017) 41–48

📖 Sun

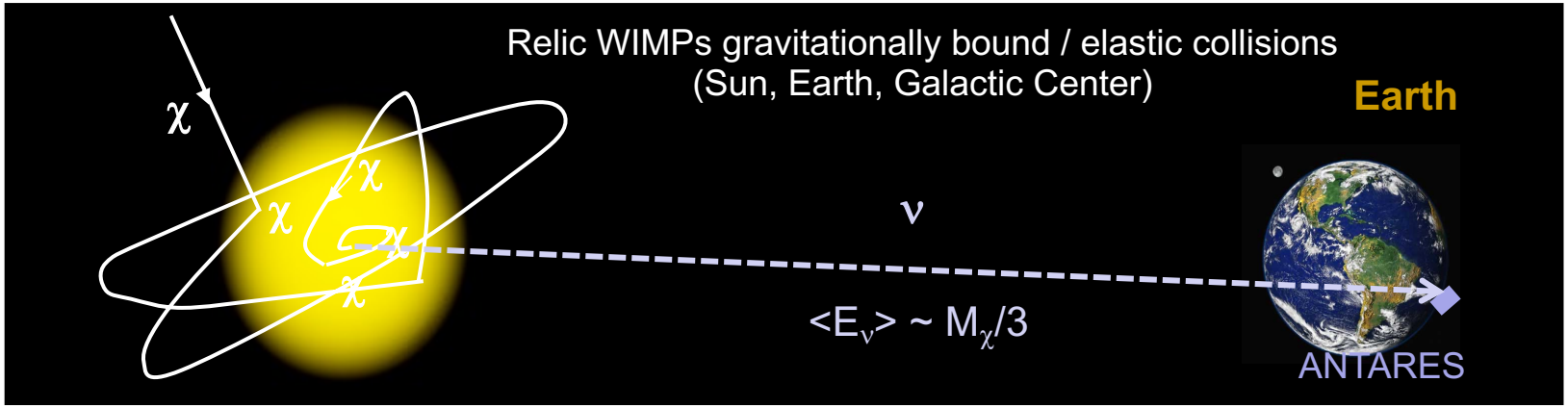
Phys.Lett. B759 2016
JCAP 05 (2016) 016
JCAP11 (2013) 032

📖 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



Indirect Search for Dark Matter



📖 Earth

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

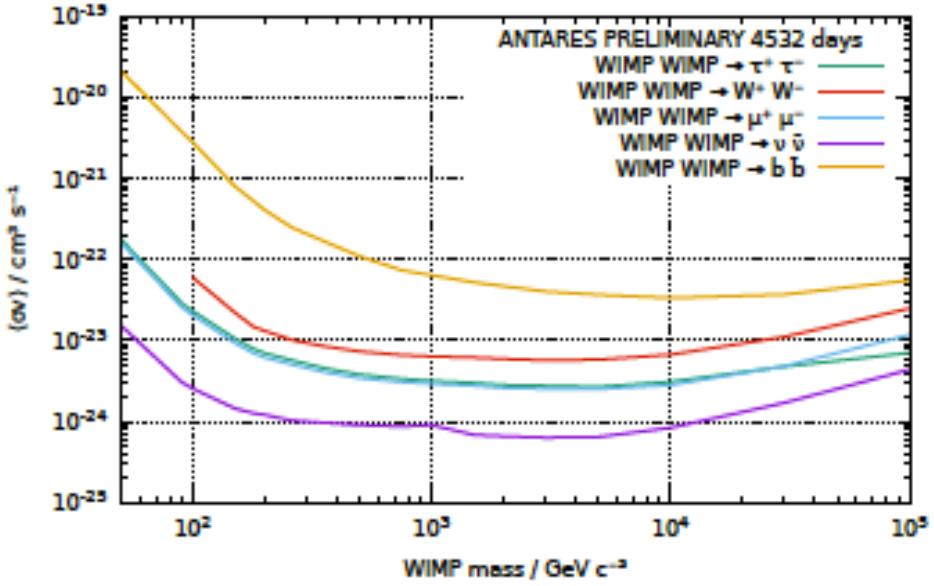
The data set covers an effective livetime of 4532.16 days, and includes both tracks and showers.

📖 Sun

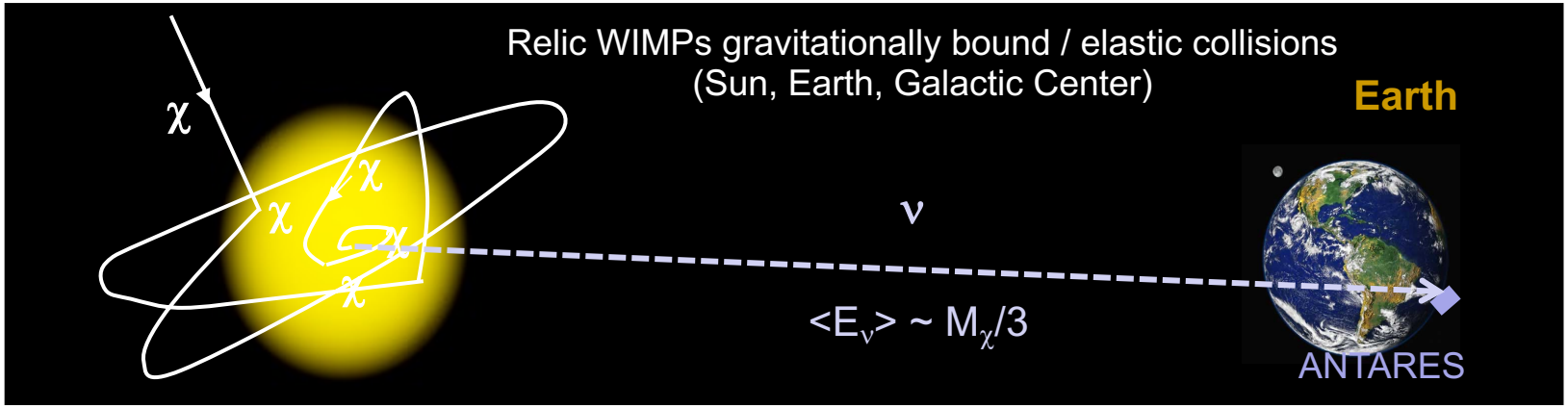
Phys.Lett. B759 2016
JCAP 05 (2016) 016
JCAP11 (2013) 032

📖 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



Indirect Search for Dark Matter



📖 Earth

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

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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

Competitive limits !

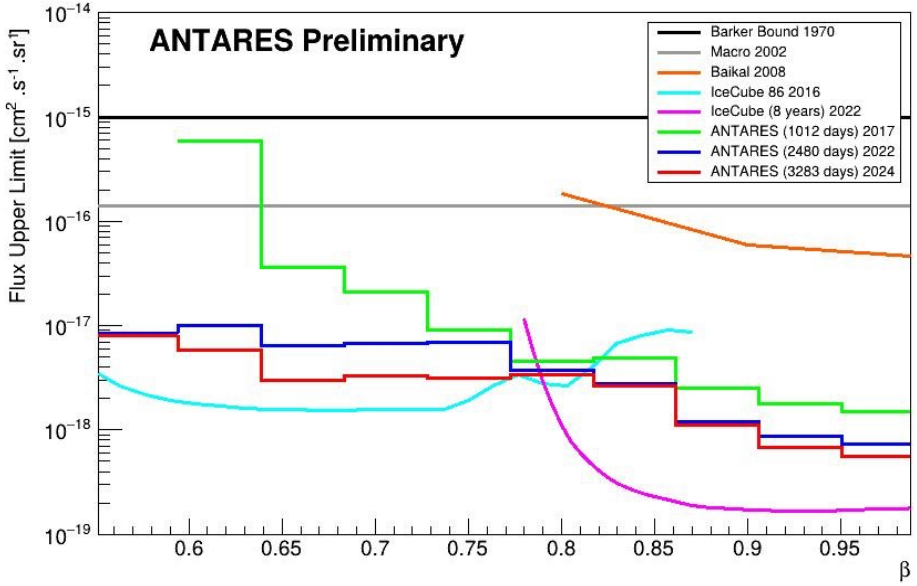
All final studies will include showers and tracks

Results from the Sun to be soon unblinded

Search for Exotic Physics with ANTARES

Monopoles

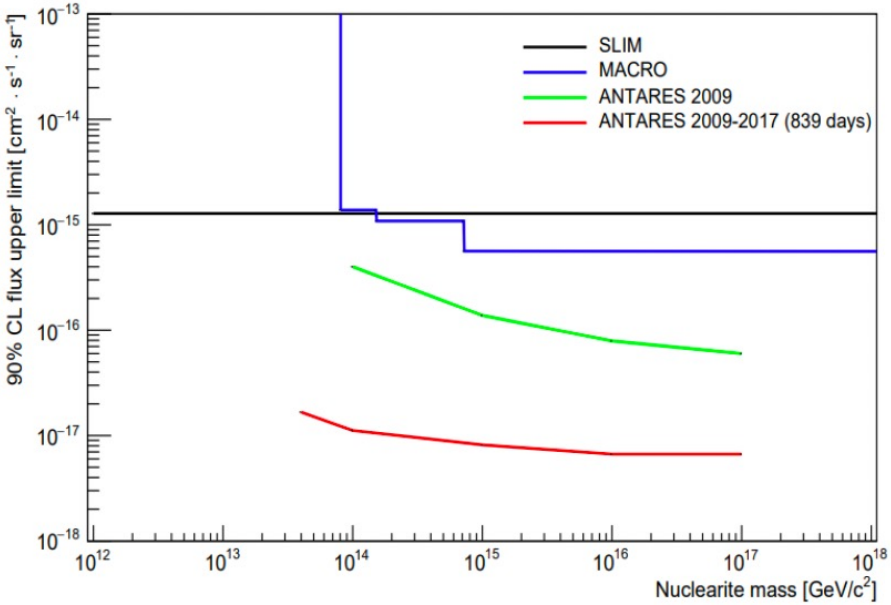
Magnetic monopoles
Kasama, Yang and Goldhaber model
Adapted reco for slow moving particles



📖 JHEAp, Volume 34, 2022, Pages 1-8
📖 Final results (shown) in prep

Nuclearites

Nuclearites of strange quark matter
Down going flux with Galactic velocities
according to de Rújula & Glashow model



📖 JCAP01 (2023) 012
Updated study on-going

Vlad Popa (1956-2024)

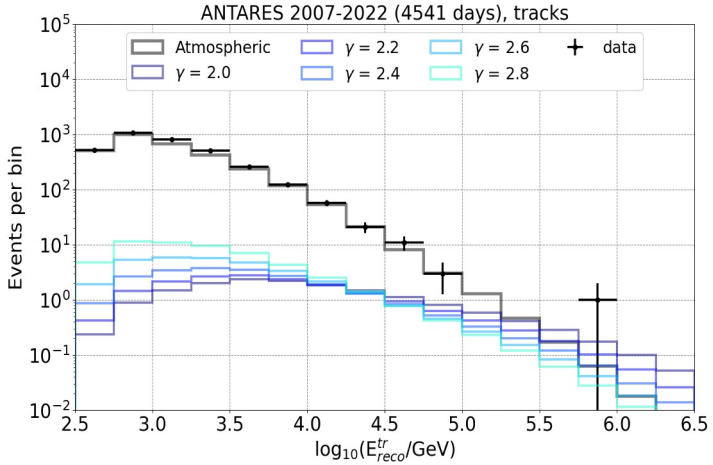
V.P. contributed to the simulations concerning the possible signals produced by light and relativistic magnetic monopoles in the ANTARES detector. He also studied the light yield of slow intermediate mass nuclearites in water, aiming to simulate the signal characteristic for such particles in ANTARES and to design an off-line "trigger" for an experimental search. V.P. developped a complete Monte Carlo simulation of nuclearite detection in ANTARES and in the inclusion in the “event filter" of a procedure intended to identify possible candidates. V .P . made preliminary estimations on the sensitivity of ANTARES to possible violation of the Lorentz invariance effects to be searched using the atmospheric neutrino data.

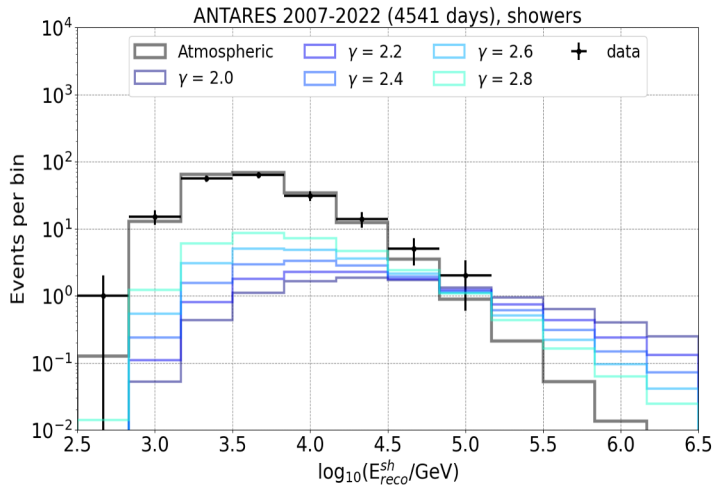
V.P. has been a member of the ANTARES Institution Board (as a representative of I.S.S. Bucharest), September 2006.

Antares Final Diffuse Flux Search

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

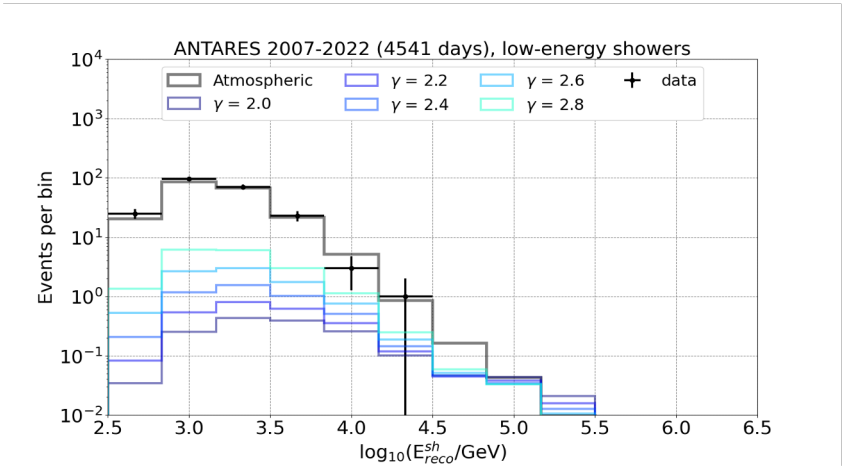
- Selection cuts optimized with Model Rejection Factor procedure (spectral index Γ = 2.5)
- Look for excess above a given energy threshold





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

Showers provide most of the sensitivity



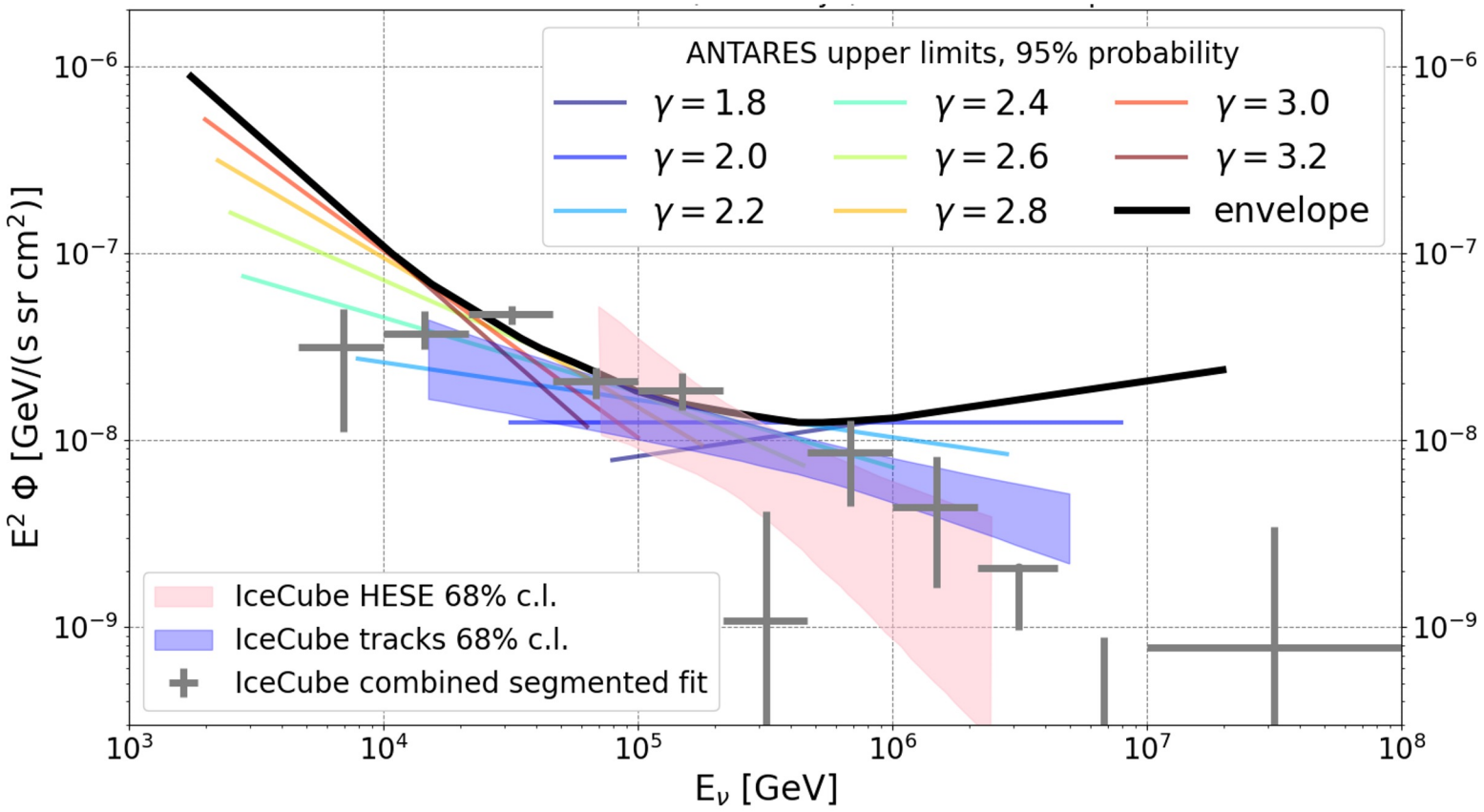
JCAP 08 (2024) 038

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

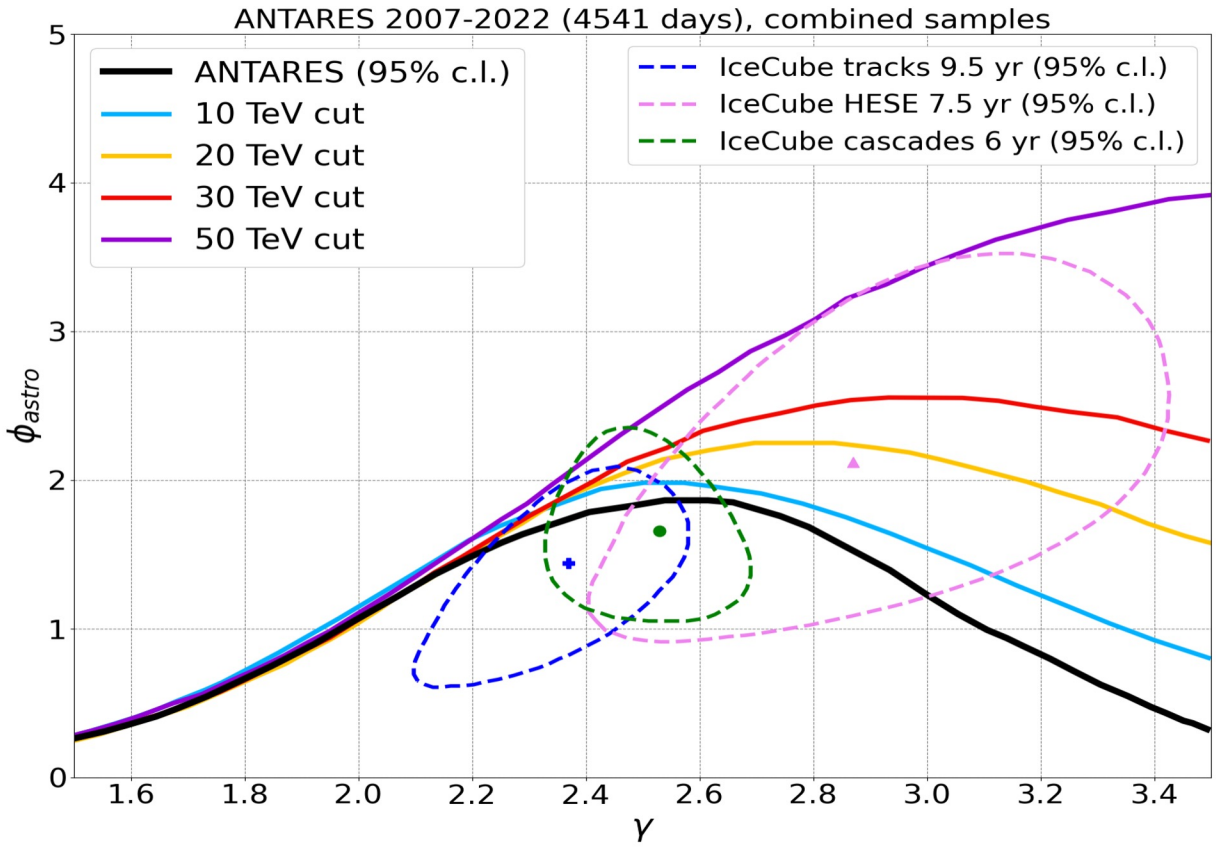


JCAP 08 (2024) 038

Antares Final Diffuse Flux Search

ANTARES sensitivity optimal in the 10-50 TeV range

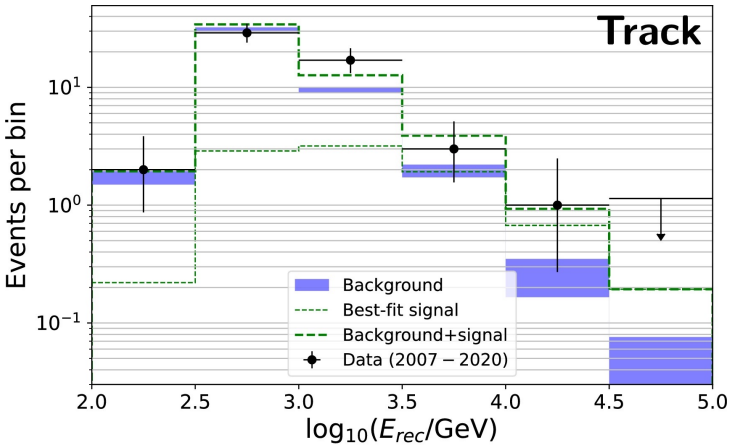
- Study hypothesis of single unbroken power-law at low energies
- Soft spectra fits of the IceCube signal become admissible (2 σ) only with spectral break

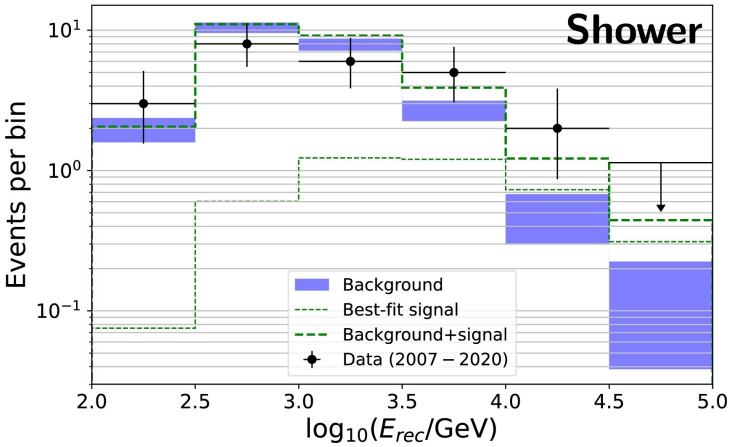


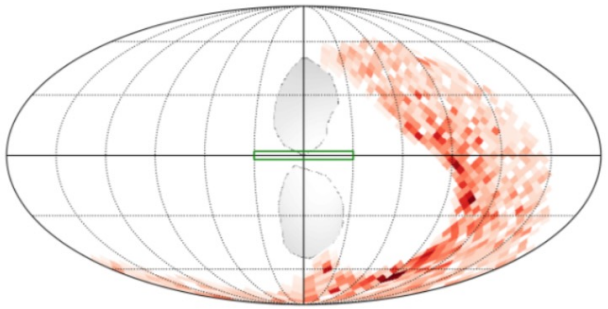
JCAP 08 (2024) 038

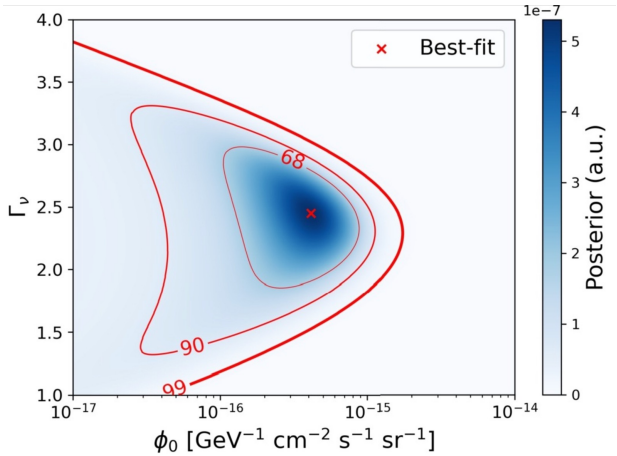
Search for Diffuse Galactic Emission

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







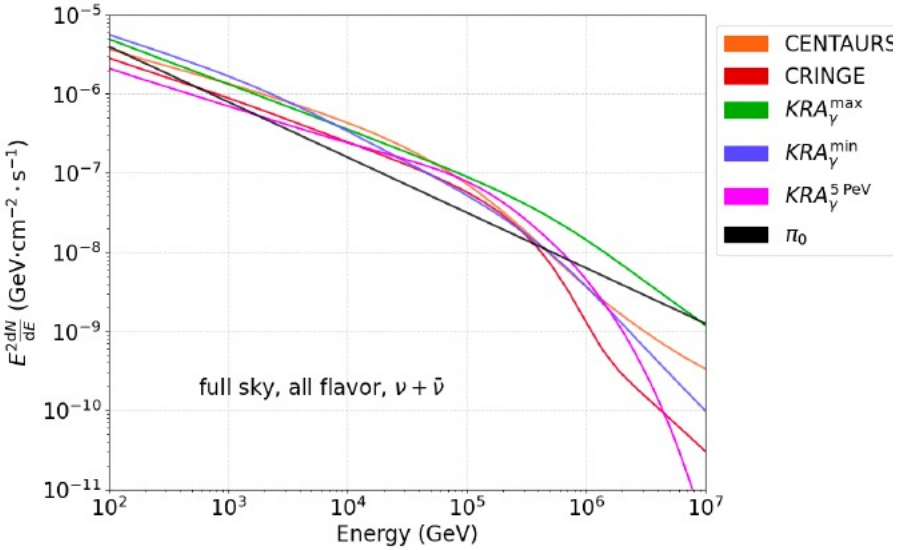


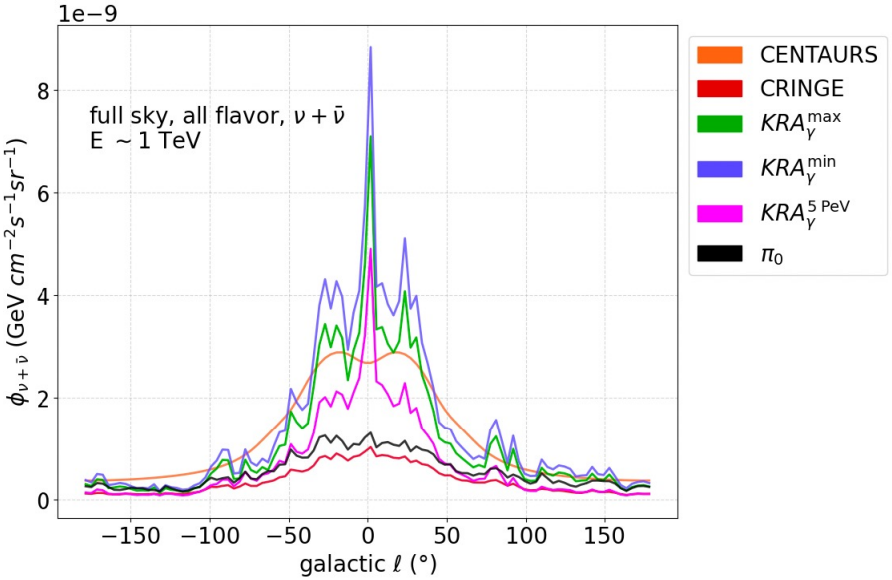
96% C.L. hint of a galactic signal – Compatible with IceCube

📖 Phys. Lett. B 841 (2023) 137951

Search for Diffuse Galactic Emission

Template based analyses





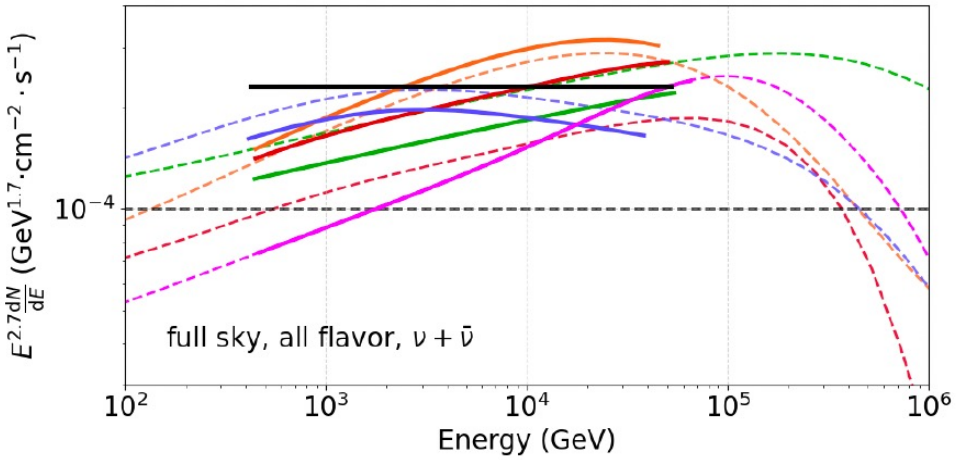
Same Data set as for the all sky diffuse
→ median angular resolution below 4° shower-like events and below 0.4° for track-like events.

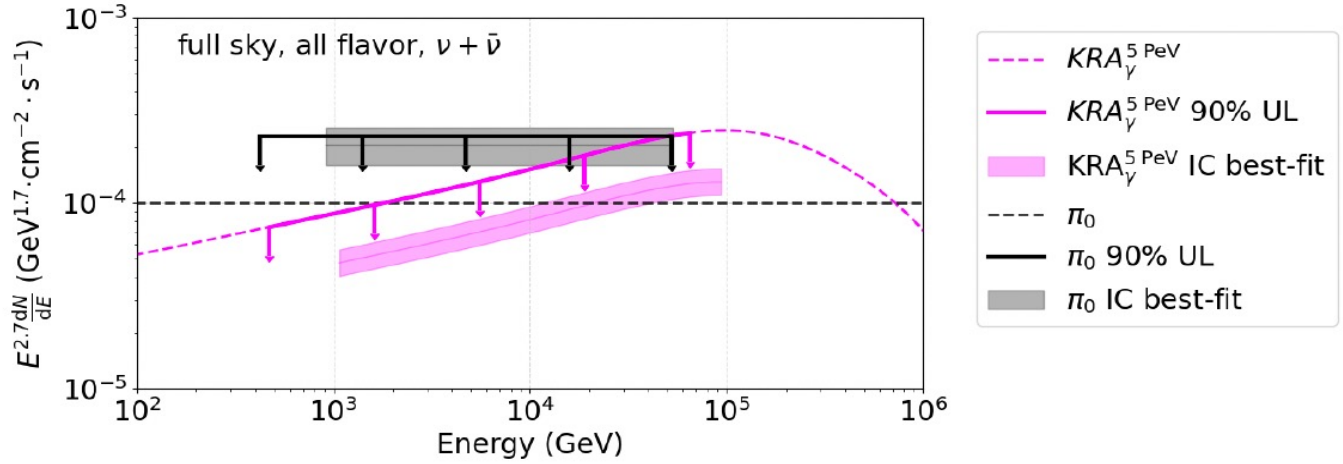
Specificities of the study
- Model dependent
- All flavors
- Energy bins

Publication on-going

Search for Diffuse Galactic Emission

Template based analyses

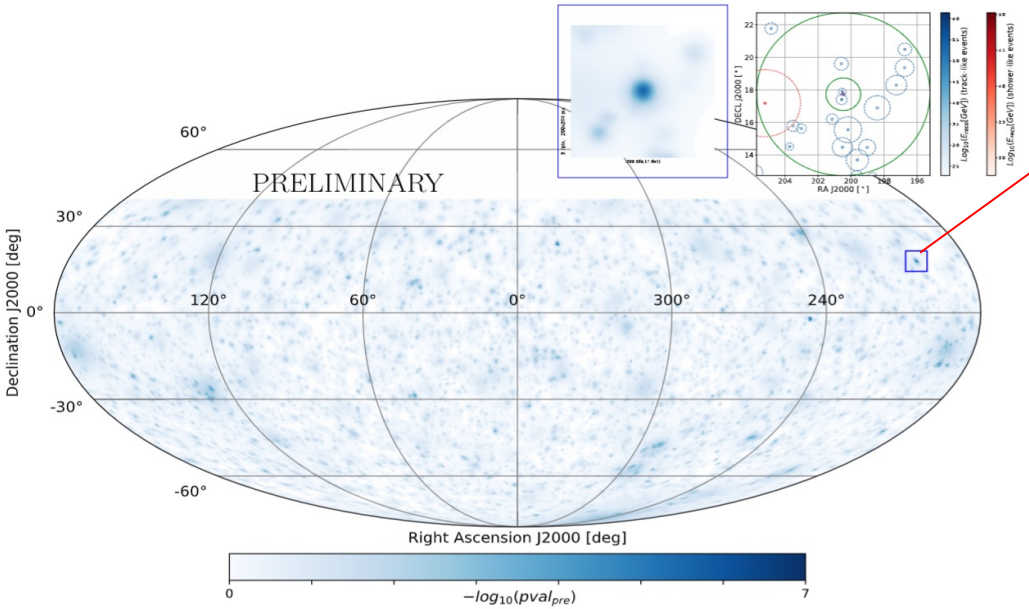




Small tension with IC best fit π^0 model : combined study in the pipeline

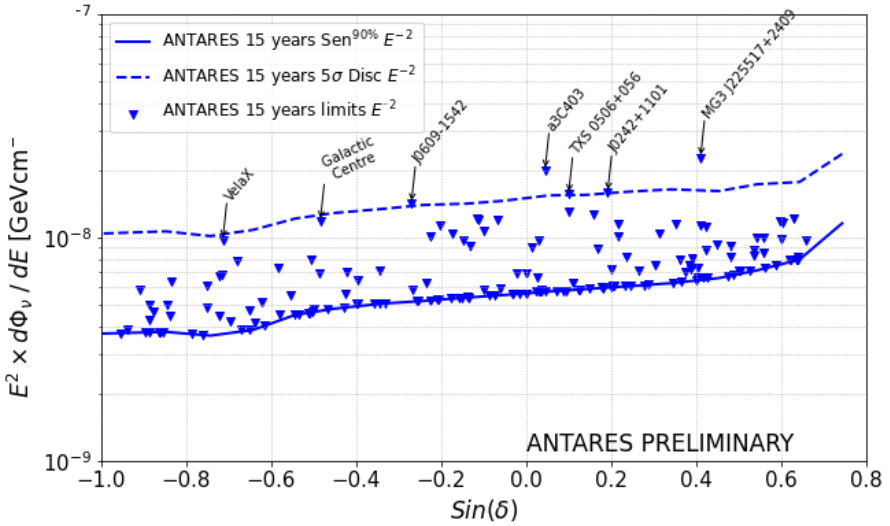
Search for Point Sources

ANTARES 2007-2022 sample: 11029 tracks and 200 showers



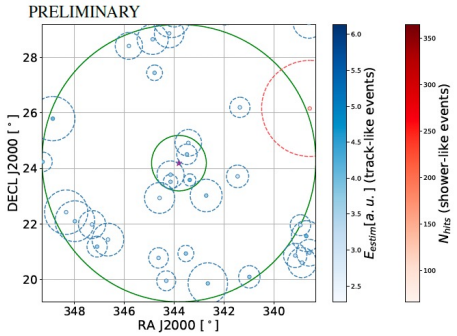
Hottest spot (δ, RA) = (17.7, 200.5)
Pre(post)-trial significance 4.5σ (0.29σ)

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



Candidate-list search

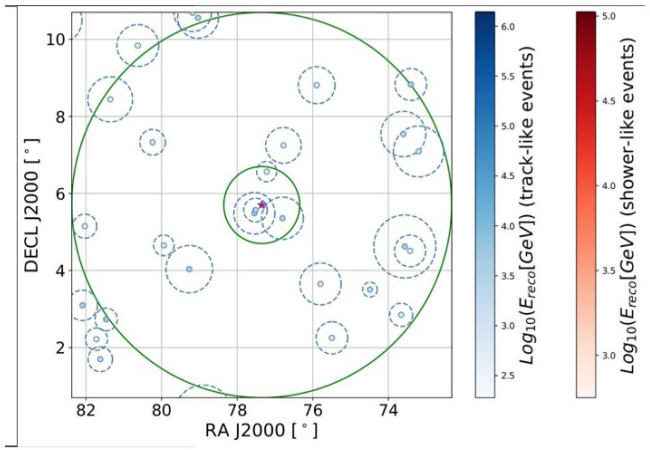
Most significant:
MG3 J225517+2409
Pre(post)-trial
3.5σ (1.8σ)



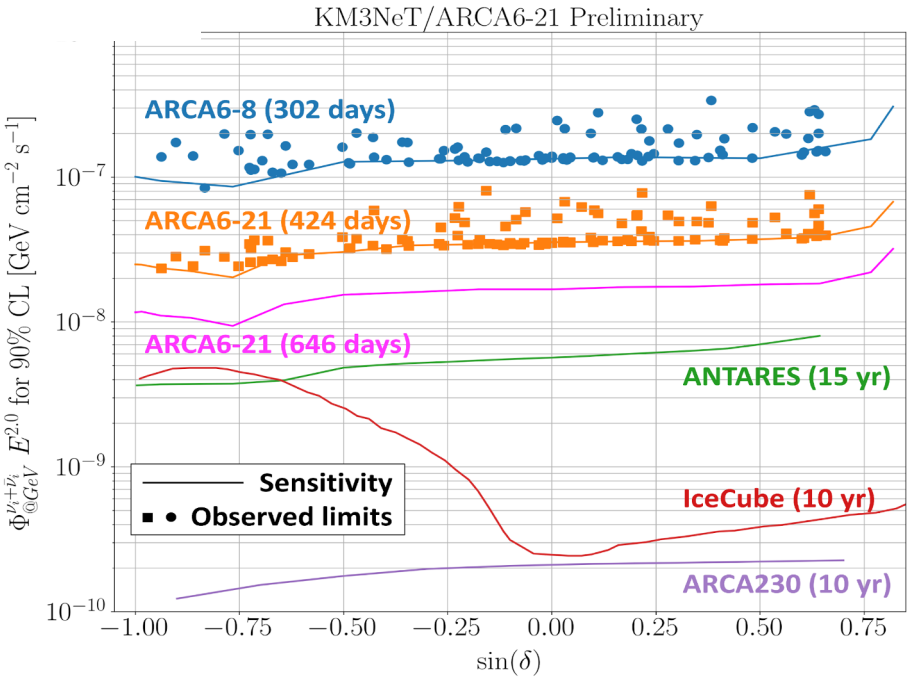
Search for Point Sources

Remarkable sources

- TXS 0506+056 n_{signal} = 2.23 (2.43 σ pre-trial)



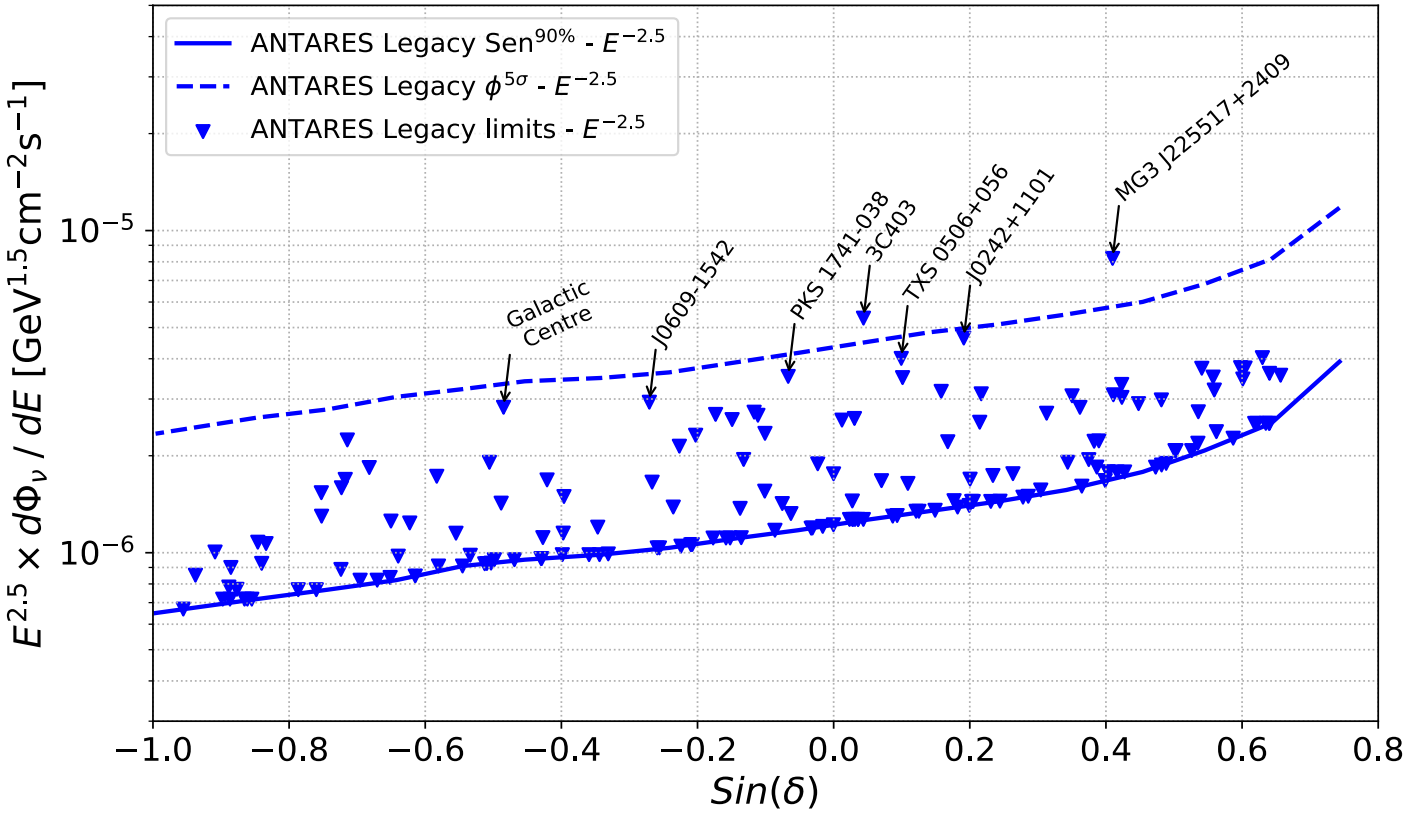
Name	(Ra, dec)[°]	size [°]	ns	-Log(p-value)	σ	$\Phi^{90\%}$ [10e-8]
MG3 J225517+2409	(343.82, 24.19)	-	3.97	3.63	3.49	2.27
3C403	(298.07, 2.51)	-	2.47	3.31	3.30	2.00
J0609-1542	(92.42, -15.71)	-	1.21	2.14	2.44	1.41
J0242+1101	(40.62, 11.02)	-	3.66	2.13	2.43	1.58
TXS 0506+056	(77.35, 5.7)	-	2.23	2.12	2.43	1.56
Galactic Center	(266.42, -29.01)	-	2.06	1.76	2.11	1.19
Vela X	(128.75, -45.6)	0.56	2.76	1.56	1.92	9.73



Search for Point Sources : soft spectra

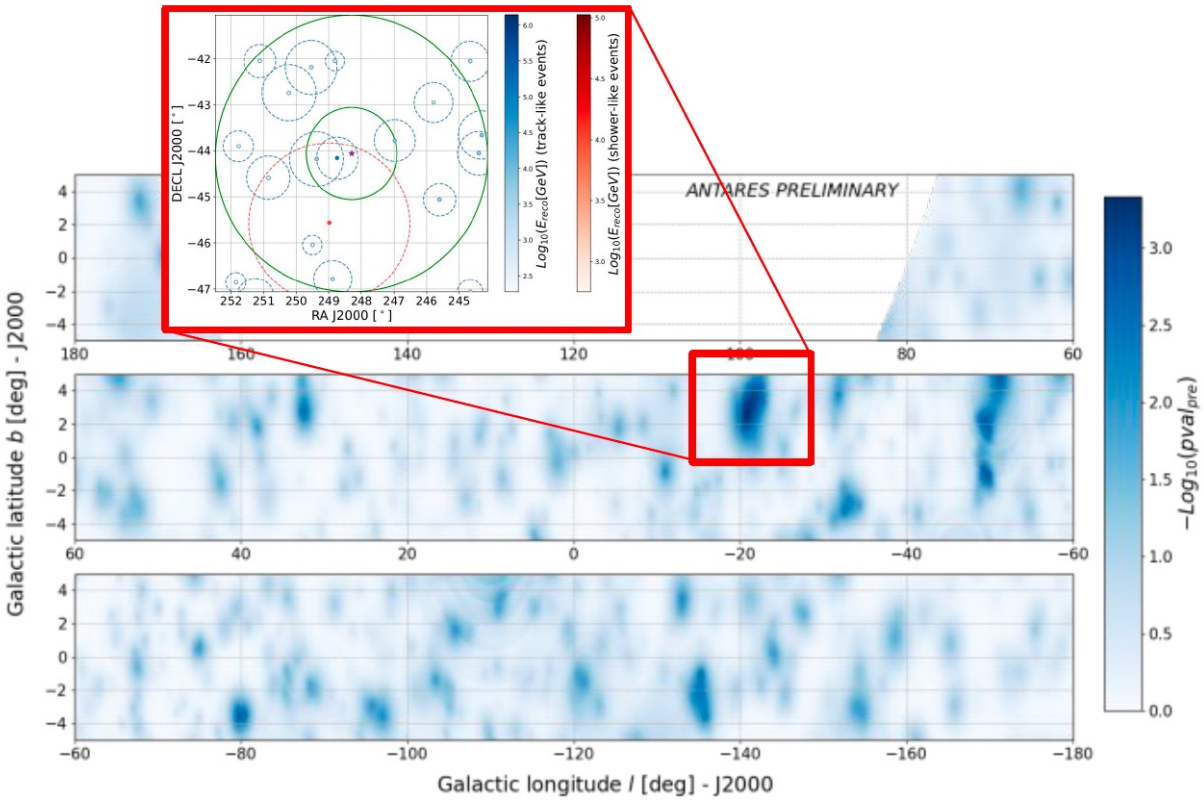
NGC1068 : spectrum of E^{-3} and the IC normalization, n_signal ~ 1 event expected.
→ n_fit = 0.78 with p-value = 0.22 and $\phi_{90\%} = 1.92 \cdot 10^{-10}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$,
which is a factor 2 over the IC flux.

The sensitivities and discoveries, UL results for 2.5 spectrum :



Search for Point Sources

Scan of the Galactic Plane (Point-like + extension up to 2°)



More significant spot found for an extension of **1 degree**.

$n^{Fit} = 3.5$

ICRS: (248.30°, -44.06°)
Gal: (339.27°, 2.59°)

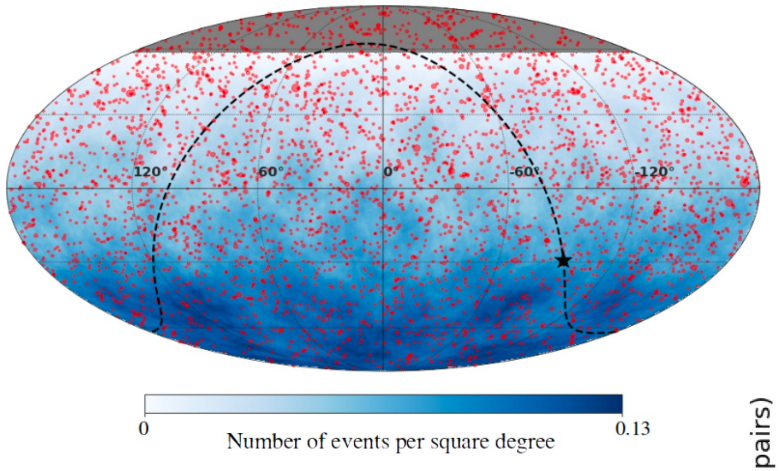
$p\text{-val}^{pre} = 4.65e\text{-}4$
$p\text{-val}^{pos} = 0.60$

Still a trial correction for the number of extensions tested (4) must be applied.

No source association done yet

Paper in prep. as well as untriggered all-sky search

Catalog-based searches

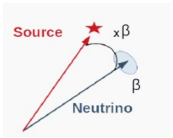


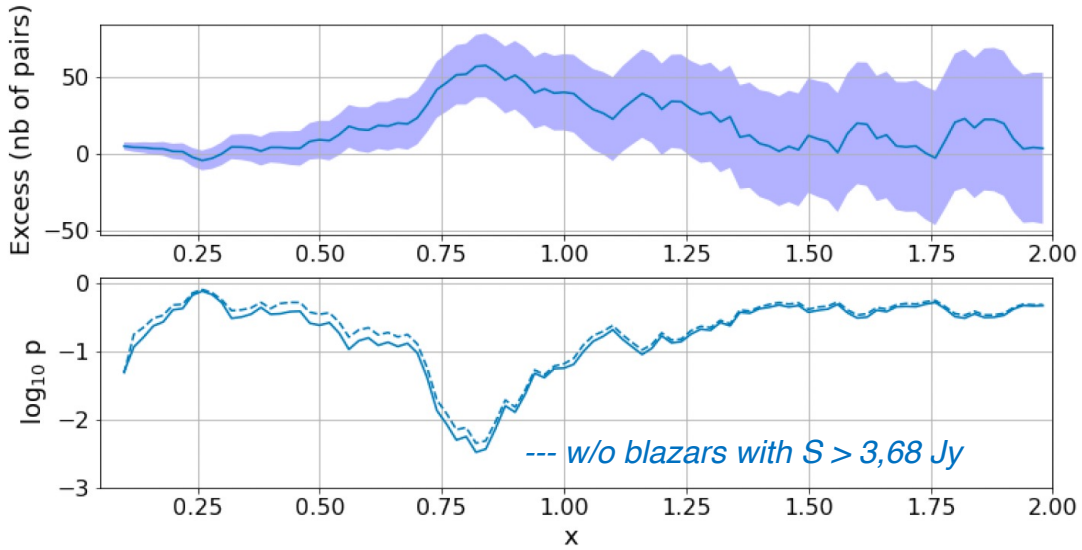
VLBI blazars (red dots)
📖 *Plavin et al., Astrophys. J. 908 no. 2, (2021) 527 157*

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 xβ
- Angular uncertainty estimate β 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

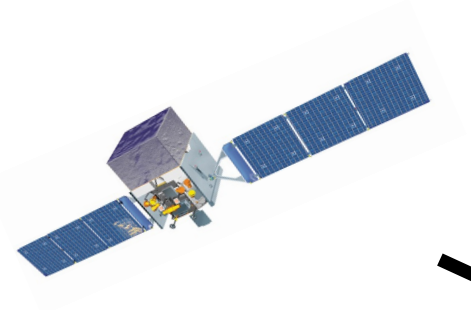
The multi-messenger program

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

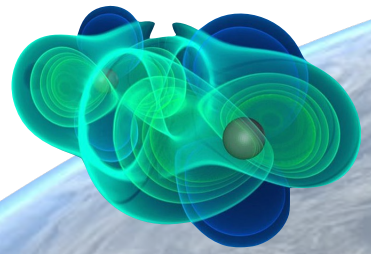
1ST APPROACH:

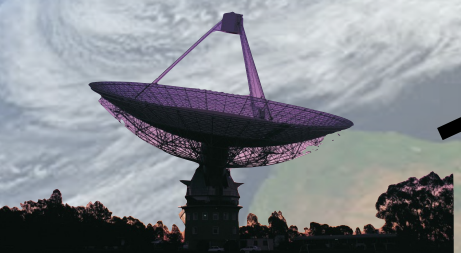
Time dependent searches

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



NT can guide optical follow-up



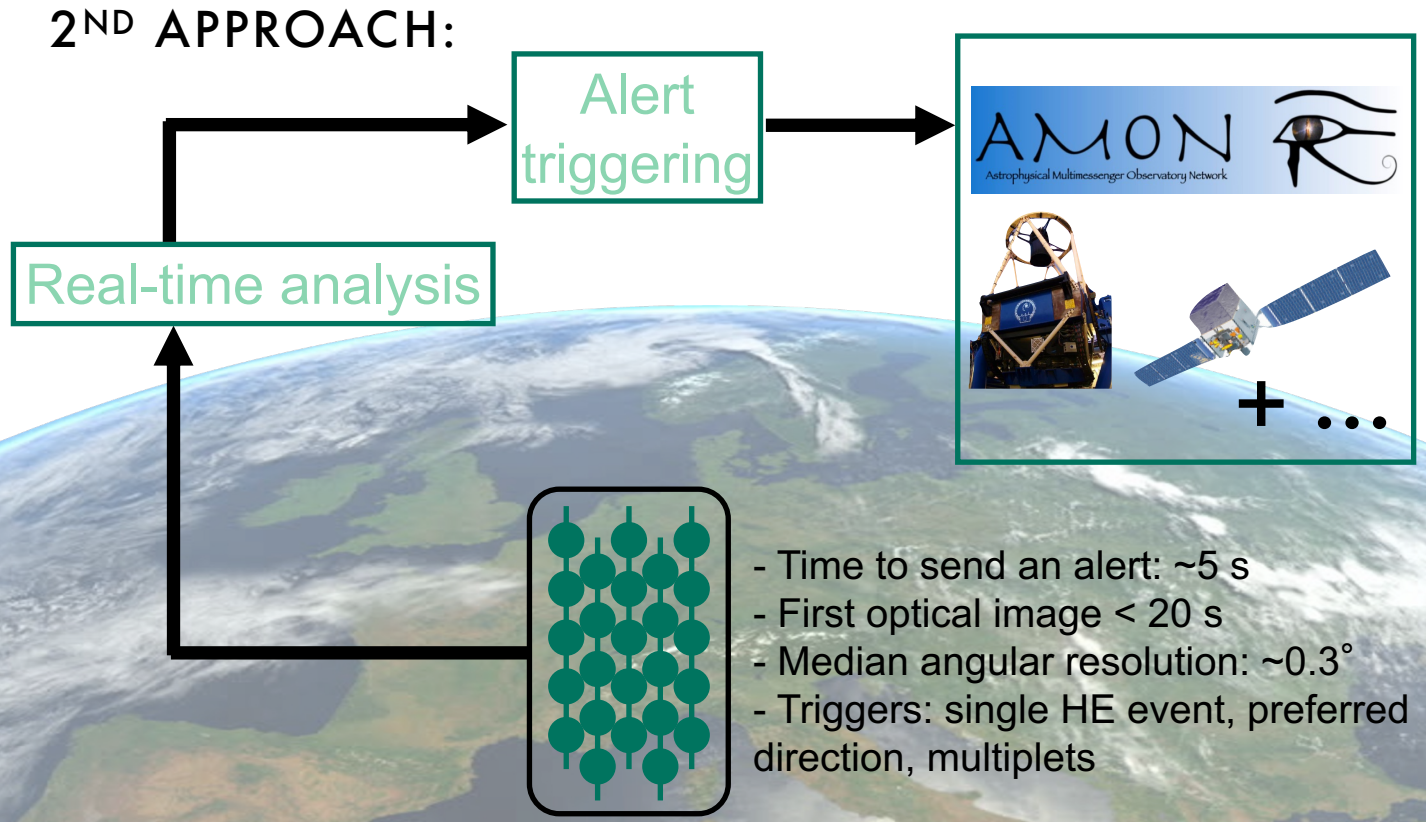


📖 Eur. Phys. J. C 80, 487 (2020)
📖 ApJ 870 (2019) 2
📖 ApJL 848 L12 (2017)
📖 ApJL 850 L35 (2017)
📖 Phys. Rev. D 96 (2017) 022005
📖 Phys. Rev. D 93 (2016) 122010
📖 JCAP06(2013)008

The multi-messenger program

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

Telescope-Antares Target of Opportunity



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

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.

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

Funded by the European Union

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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

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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

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ACME – Work Packages

WP1 Coordination & Management
A. Kouchner (Coord.), P. d'Avanzo (Co-coord.), J. Epas (PM), M Lamoureux (Tech. C)

WP2 Transnational Access for Multi-messenger and time-domain Astrophysics
Rob Beswick, Damien Dornic, Izabela Rottmann

WP3 Provision of scientific expertise for multi-messenger observations
WP leaders: Marica Branchesi, Zsolt Paragi

WP4 Provision of improved access to near-real time and archival multi- messenger data
WP leaders: Andrii Neronov, Lukasz Wyrzykowski

WP5 Improved coordination for real-time detection of transient events and low-latency alert management
WP leaders: Fabian Schüssler, Marek Kowalski

WP6 Training for scientists and engineers
WP leaders: Natalie Webb, Heidi Korhonen

WP7 ACME for environment and society
WP leaders: Gwenhaël De Wasseige, Stephen Serjeant

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

https://acme-grav-waves.sciencesconf.org

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MEETING DESCRIPTION

The first ACME workshop

The gravitational wave sky and complementary observations

Toulouse, France

7th-11th April 2025

Summary

Thanks for your attention !

- **ANTARES was the first and largest NT in the Mediterranean Sea.**

A multi disciplinary observatory (associated sciences).

More than a proof of feasibility.

- **Competitive physics results & intriguing hints**
- **Constraints on neutrinos as seen by IceCube.**
- **Extensive multi-messenger program.**
- **Joint studies with several partners.**
- **About 100 papers published & 100 PhD students**
- **ANTARES data will be made available also within the ACME initiative.**