A decade of neutrino searches in the sea

The ANTARES Adventure (>2 decades)

- The ANTARES detector
  - Construction and dismantling
  - Detection Principle
  - Performances
- Scientific Results
  - Earth and Sea science
  - Particle Physics
  - High-Energy Astrophysics
- Passing the baton → A. Heijboer

Antoine Kouchner

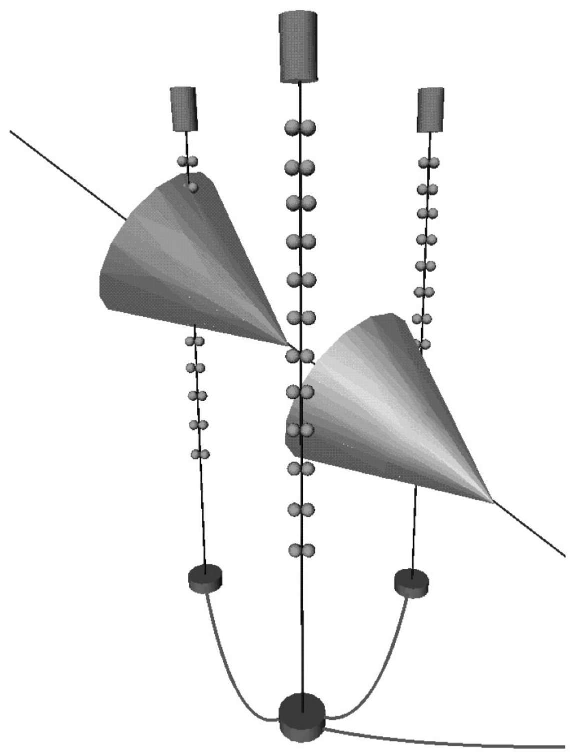
The first deep-sea Neutrino Telescope

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

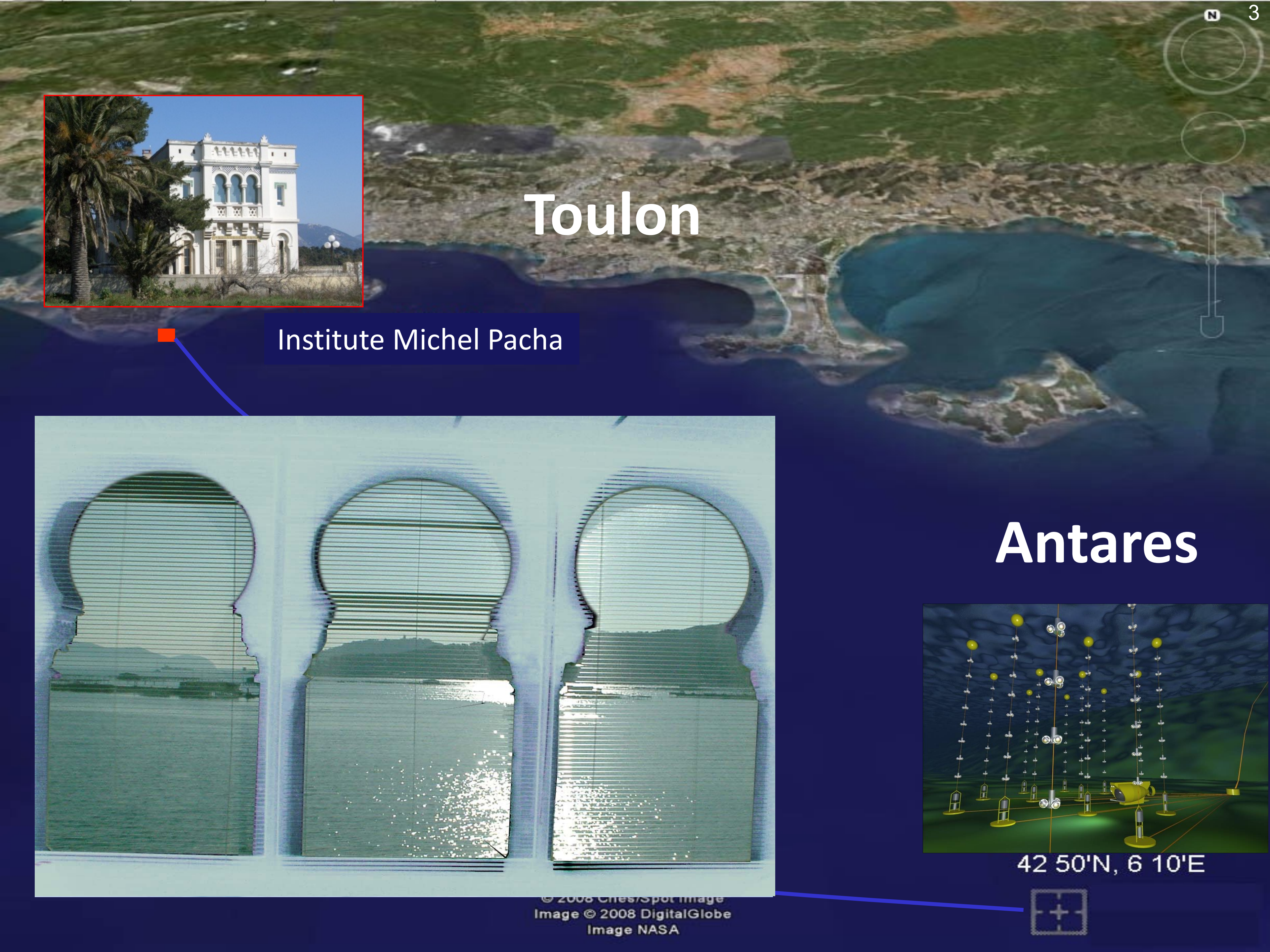
ANTARES

Astronomy with a Neutrino Telescope and Abyss environmental RESearch

TOWARDS A LARGE SCALE HIGH ENERGY COSMIC NEUTRINO UNDERSEA DETECTOR

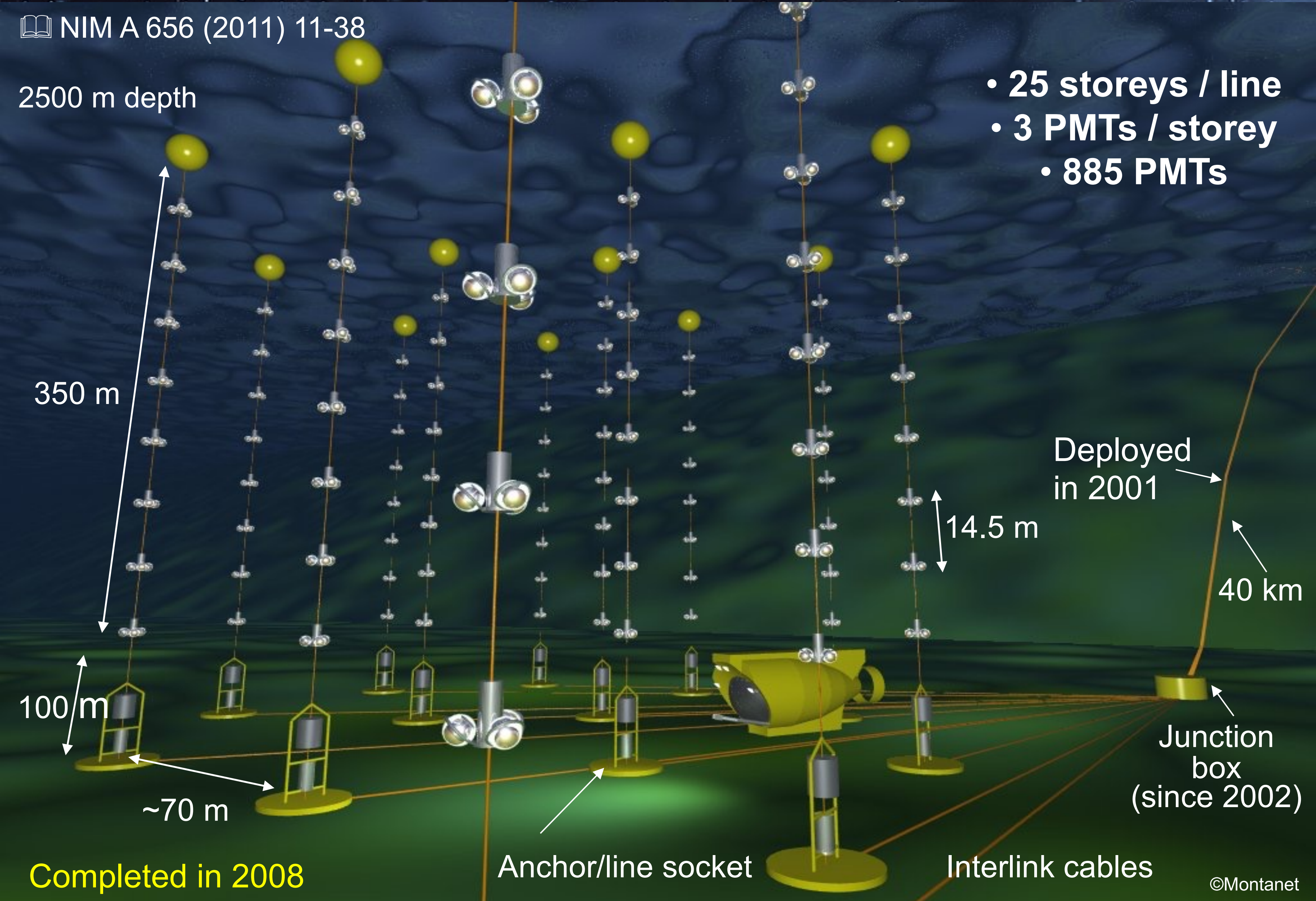


PROPOSAL – May 1997

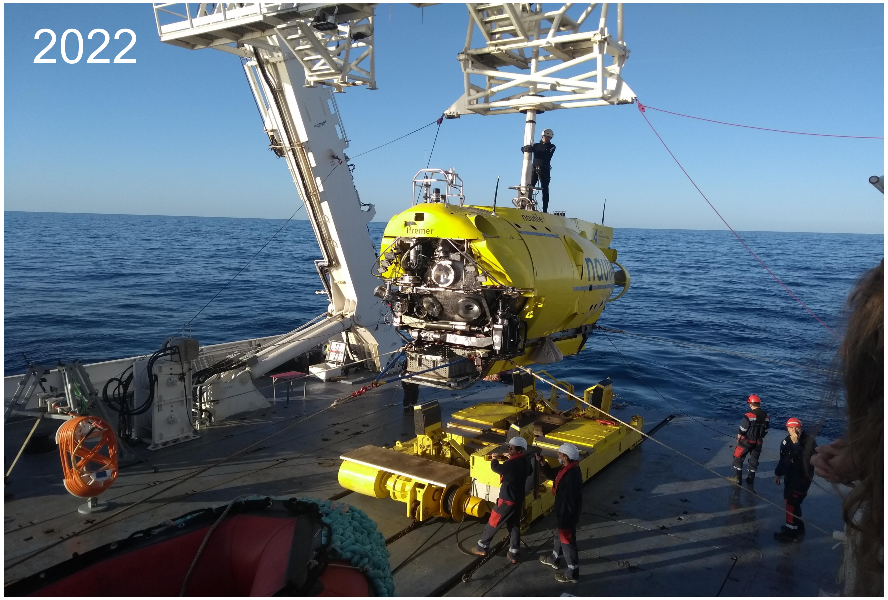

Toulon
Institute Michel Pacha
Antares
42 50'N, 6 10'E
Image © 2008 DigitalGlobe
Image NASA

The ANTARES Neutrino Telescope

NIM A 656 (2011) 11-38



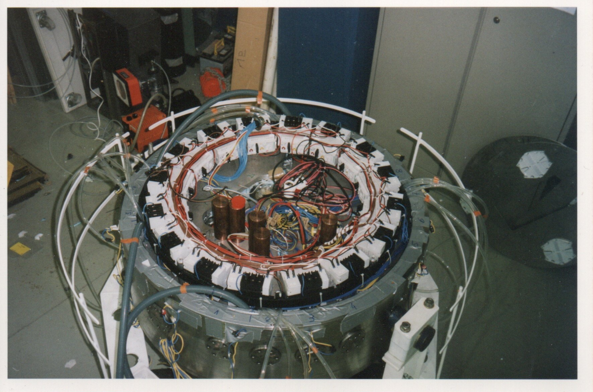
ANTARES 2001-2022

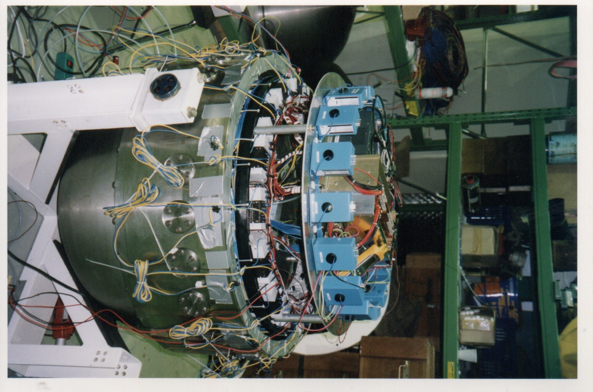


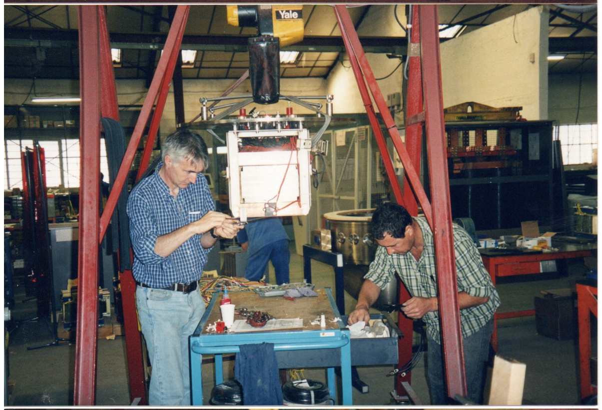
2001 Main Electro-Optical Cable
2002 Junction box
2003 Prototype Sector Line
2005 Mini Instrumentation Line with OMs
2006 First complete detector line
2008 Detector with 12 lines completed
2016 Running (almost) without common funds
2022 Data taking terminated & Recovery

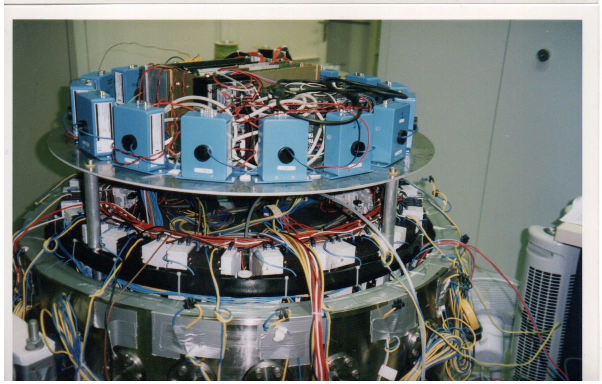
Main Electro-Optical Cable - 2001

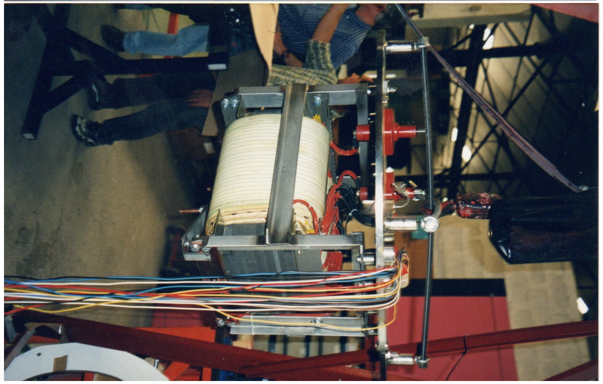
Junction Box 2002 – Construction

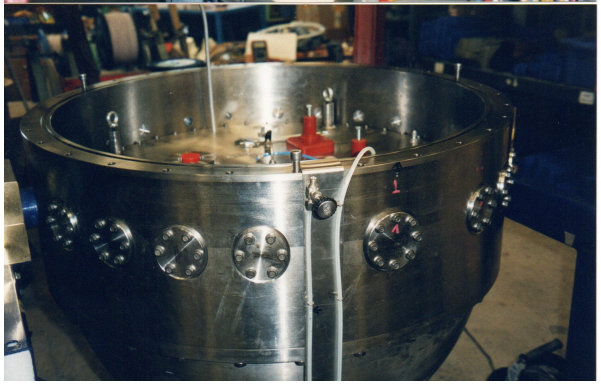




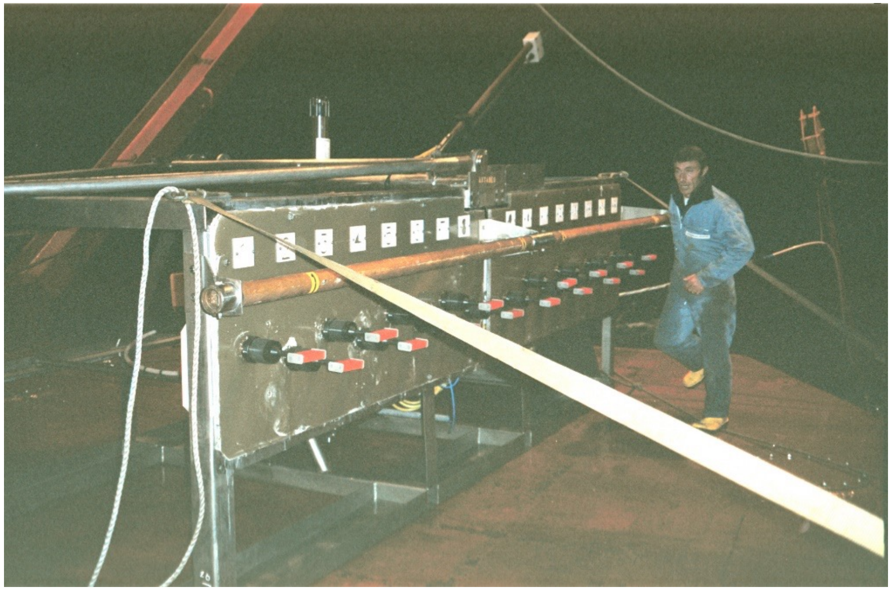


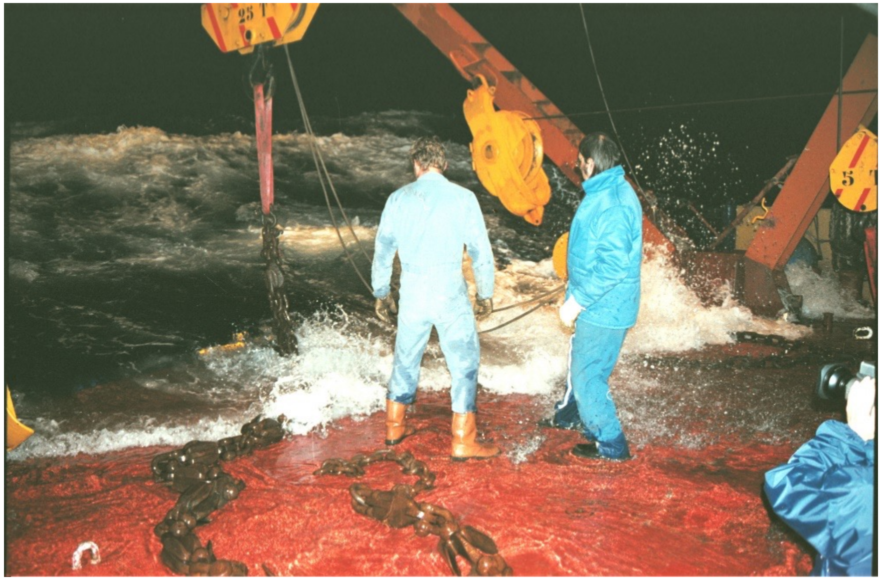






Junction Box 2002 – Deployment





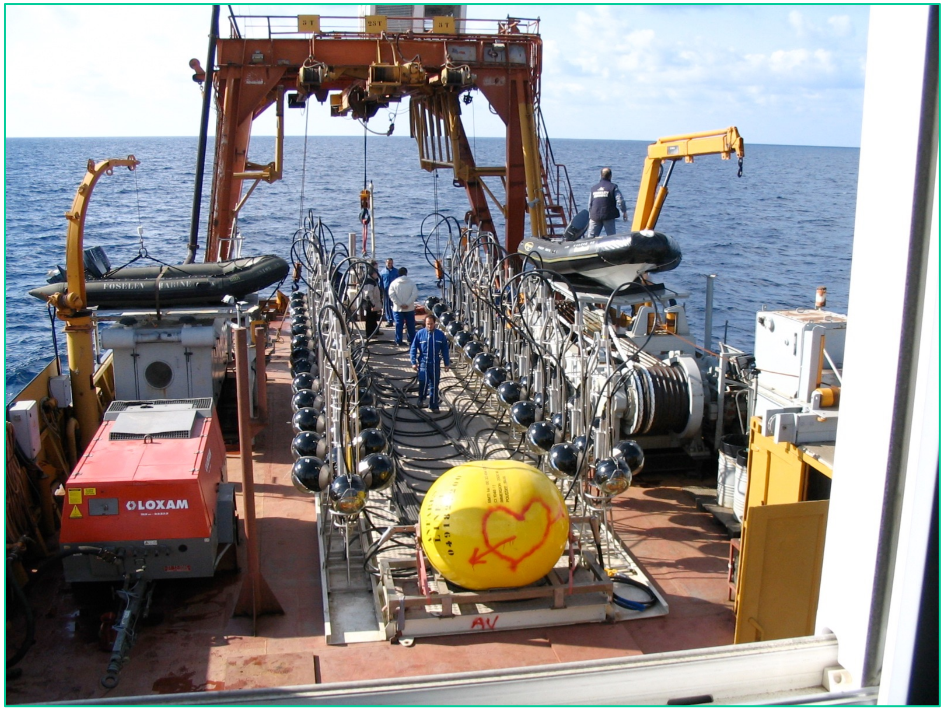
Junction Box 2002

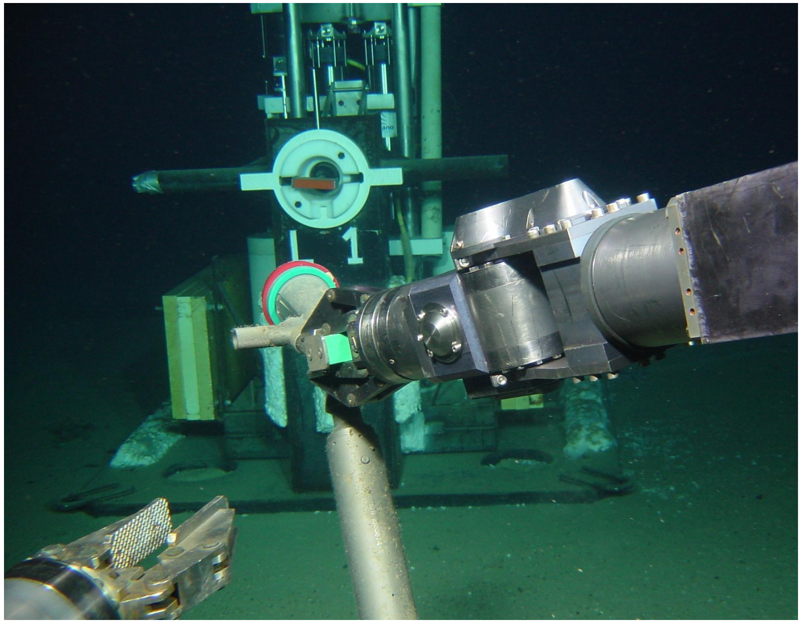
Worked reliably for 20 years
No failure, no repair needed
Waiting for recovery and potential second life?

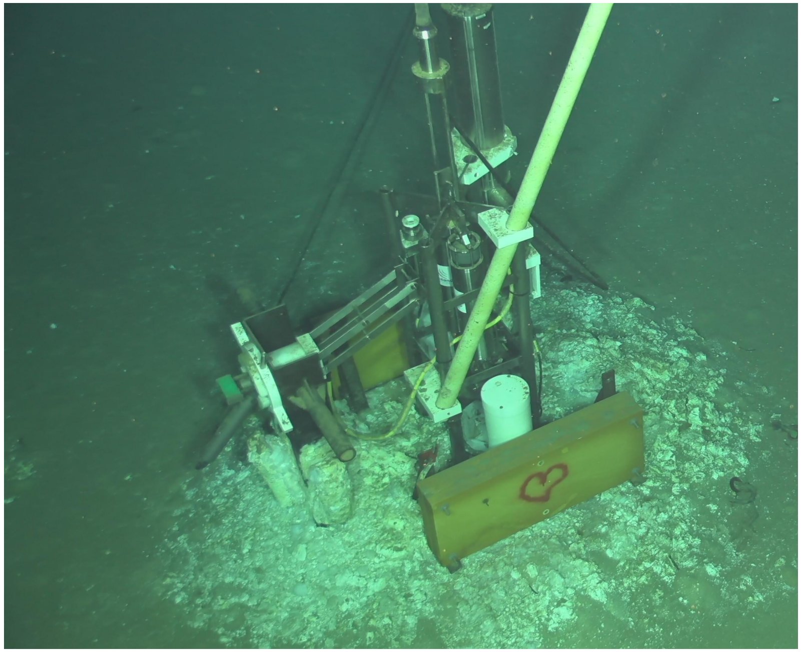
First complete detector line - 2006

First complete detector line – 2006 - 2022

Deployment 14/02/2006
Connection March 2006
Disconnection February 2022





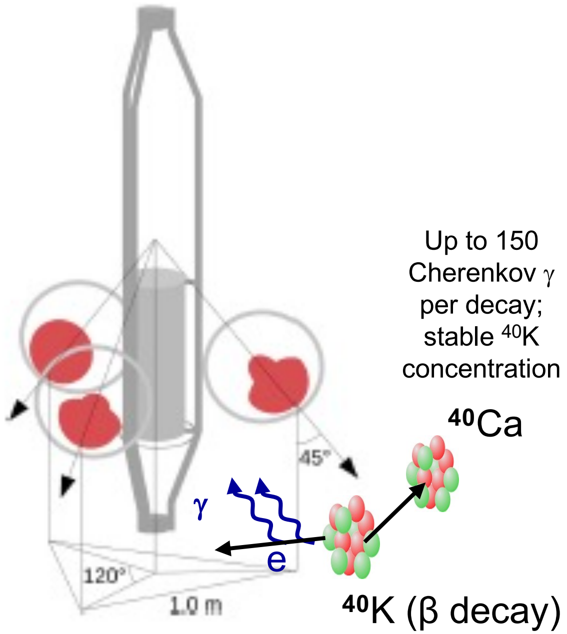


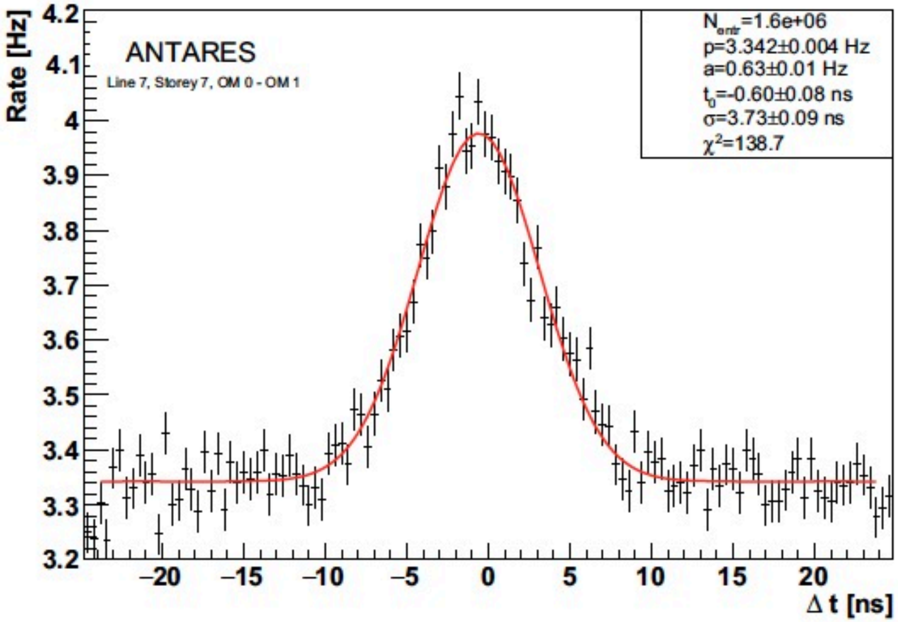
Recovery completed

Recovery completed

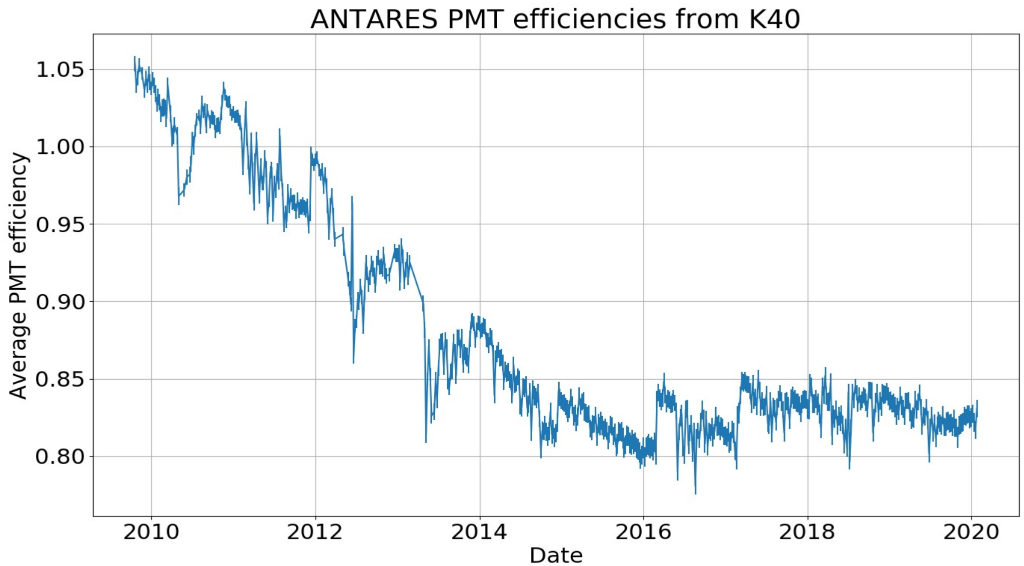
Including Line 1, 16 years after…

^{40}K (long-term) monitoring





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



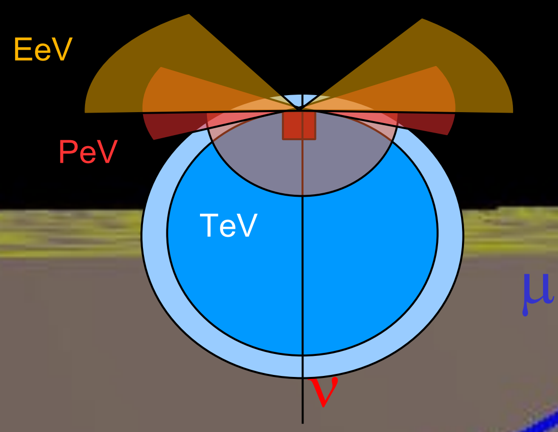
Regular tunings
Only ~20% efficiency loss

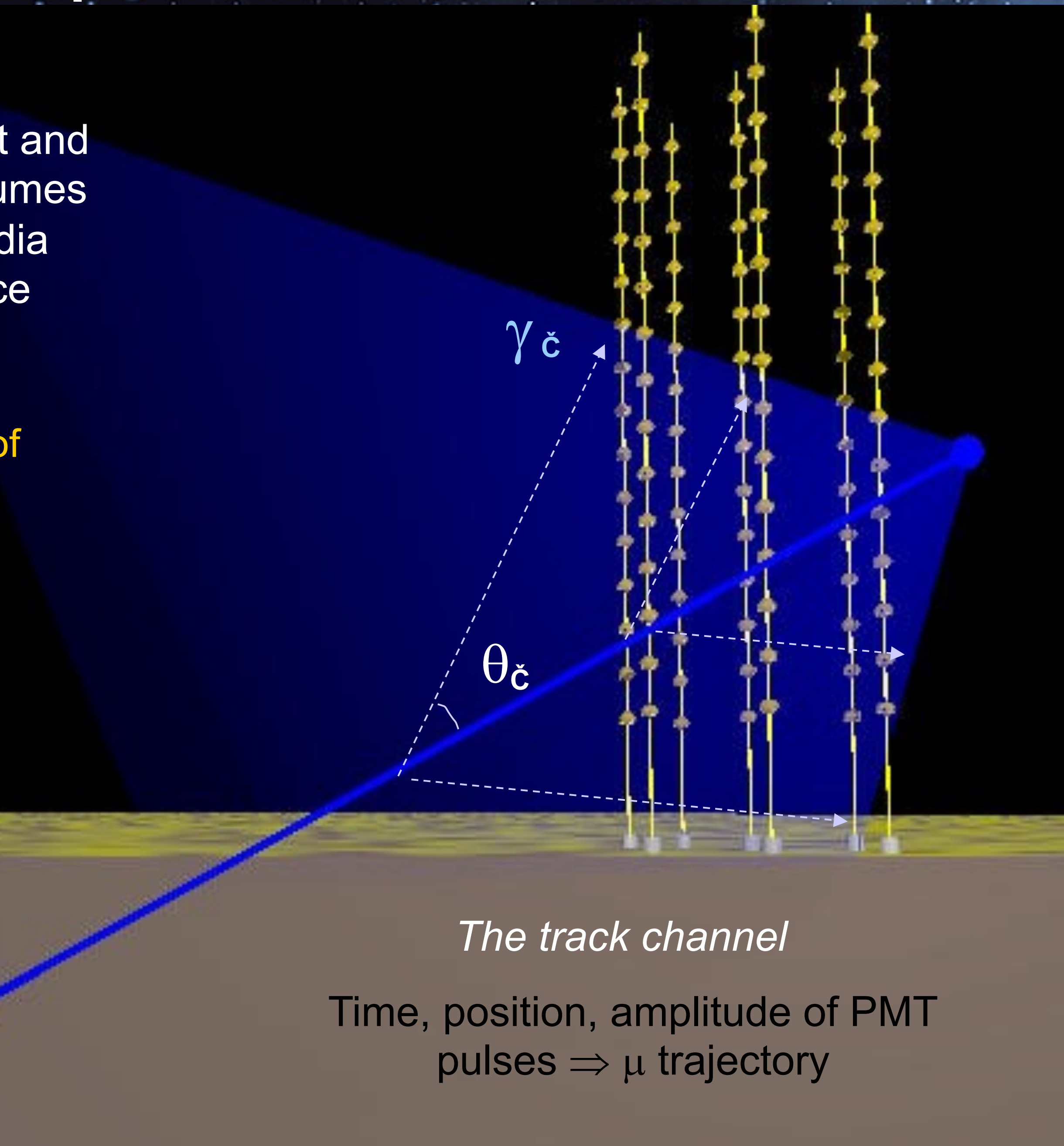
^{40}K powerful calibration tool

Detection Principles: Cherenkov

Natural radiators are low cost and allow huge instrumented volumes in dark but transparent media
→ Deep lake, seawater, ice

Detection of Cherenkov light induced by the travel of relativistic muons with a 3D array of PMTs



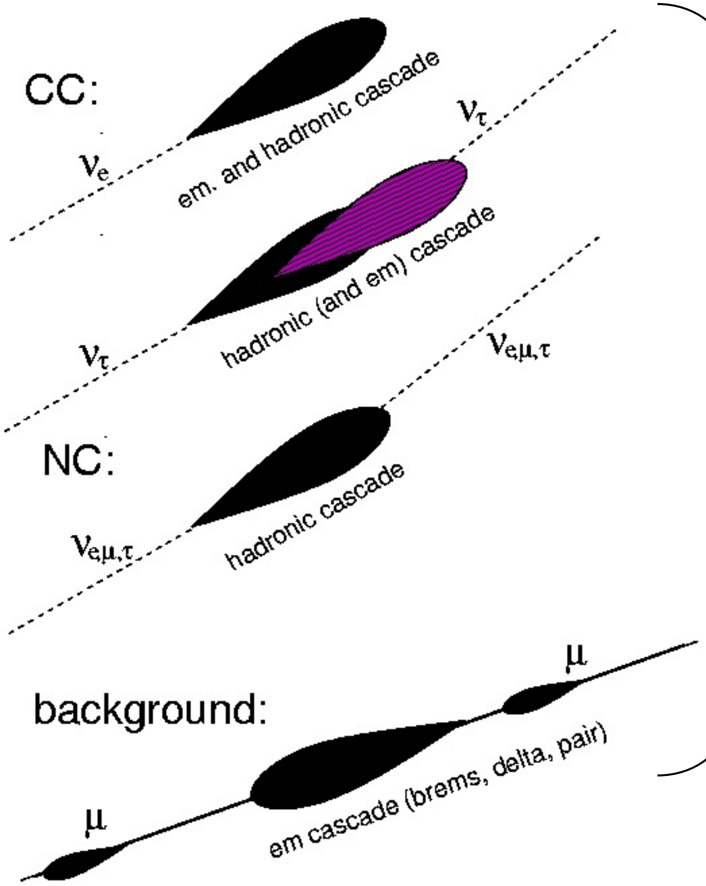


The track channel

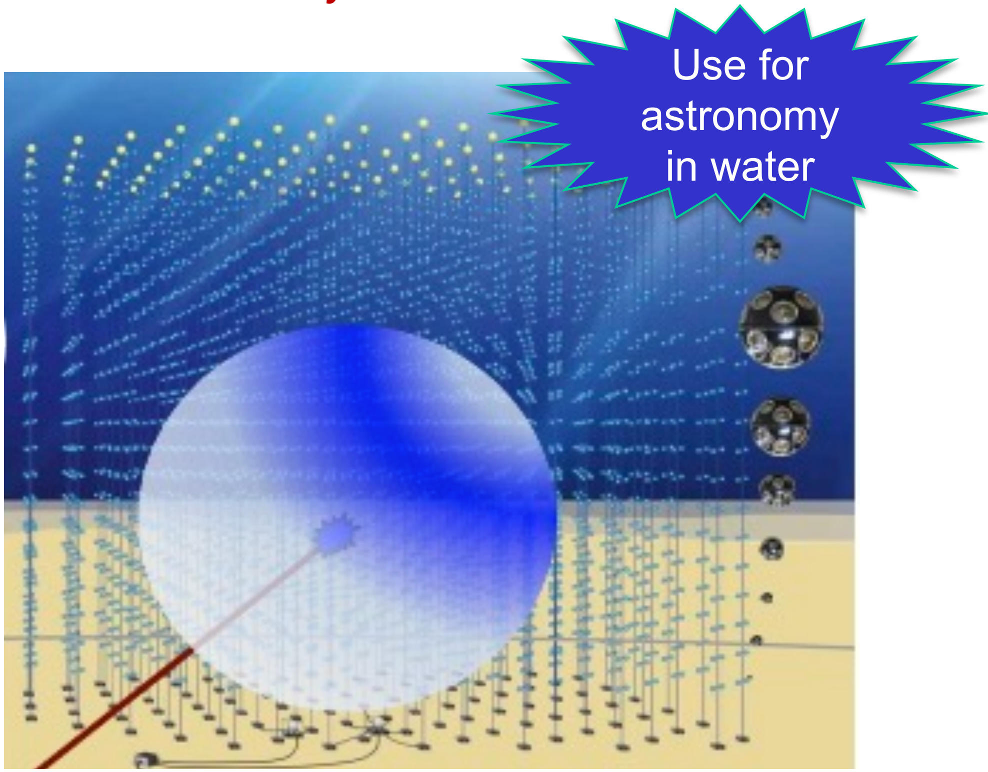
Time, position, amplitude of PMT pulses ⇒ μ trajectory

Cascade topology

$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ at source $\xrightarrow{oscillation}$ $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ at Earth !



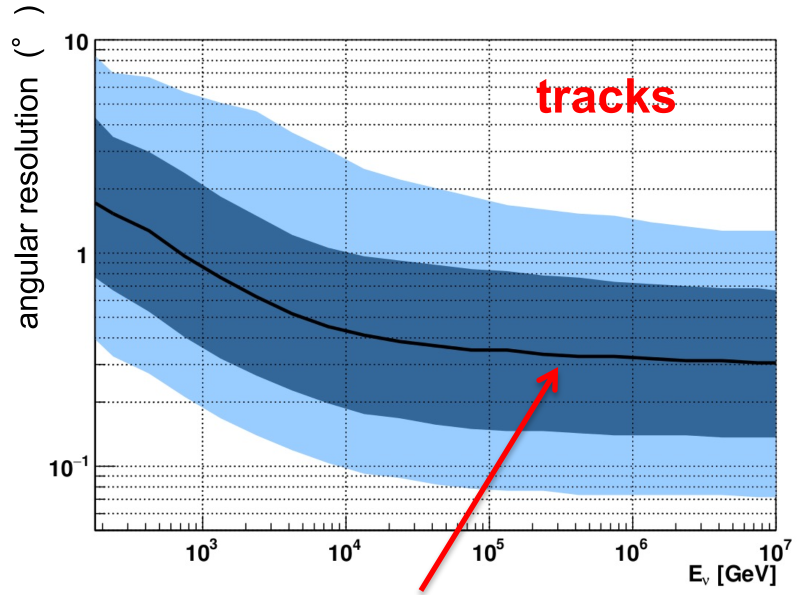
IceCube discovery channel



→ Provides sensitivity to all neutrino flavours – Increases overall sensitivity

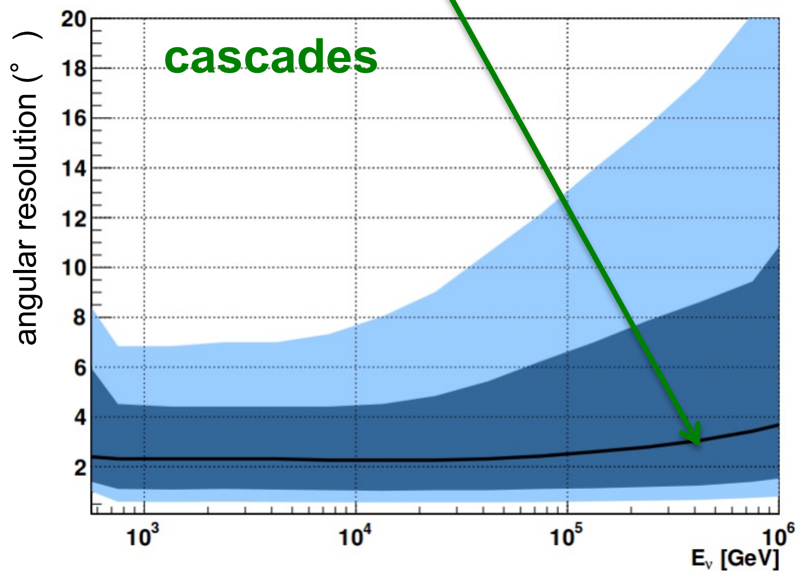
Reconstruction performances

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



median resolution

- 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

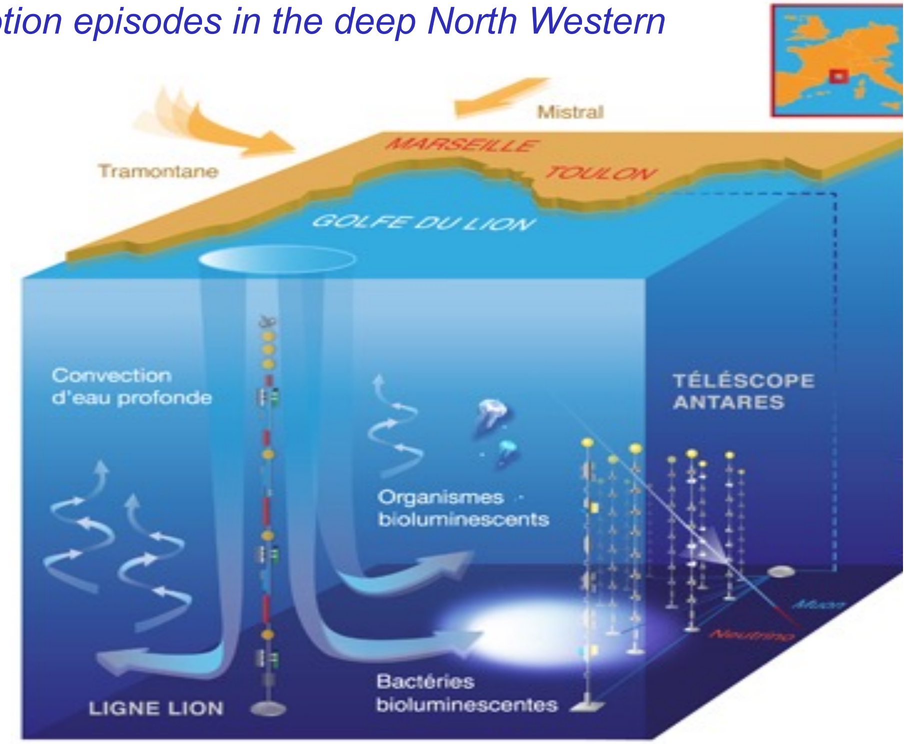
A multidisciplinary observatory

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

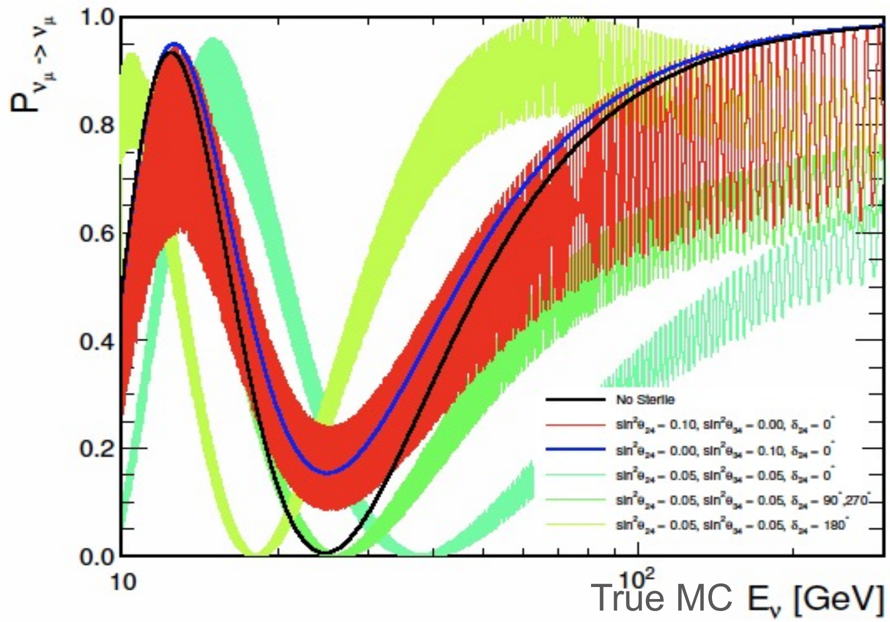


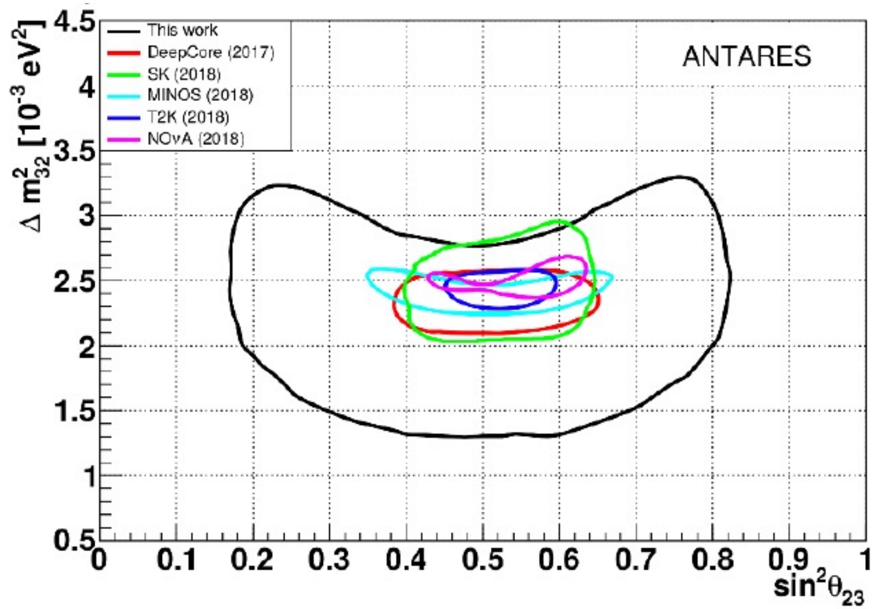
Sci. Rep. 7 (2017) 45517
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

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

Updated 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

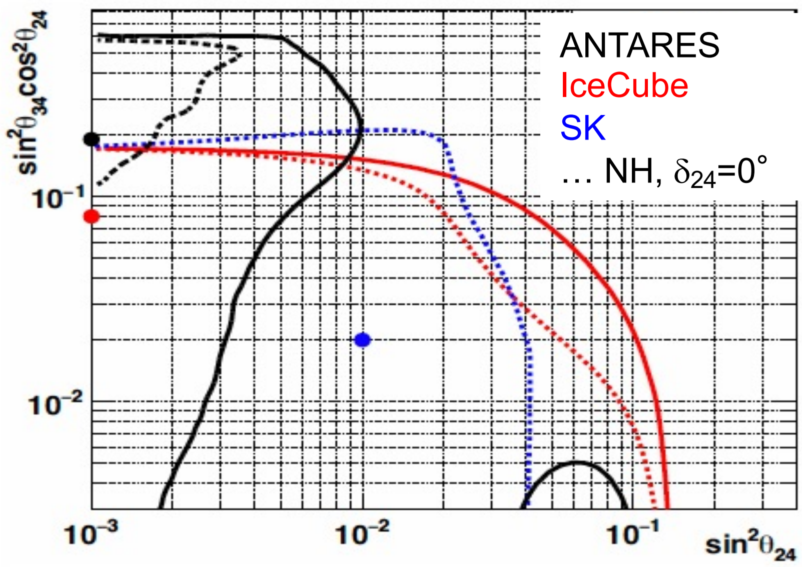
No-oscillation hypothesis excluded at 4.6σ

Updated 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

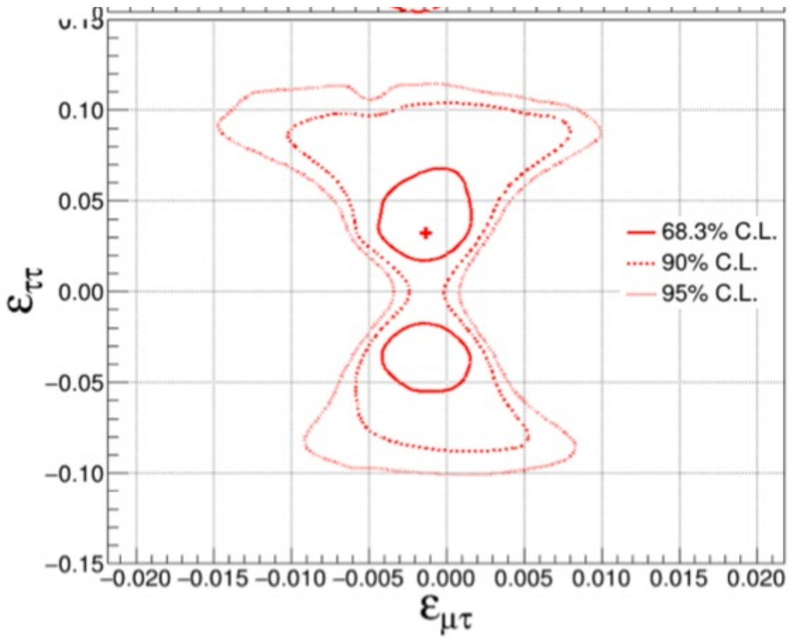
Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.

📖 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)



Updated Oscillation Studies Sterile & NSI

- (3+1) s
- Tight c
  sterile r

Our resu
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J. High E

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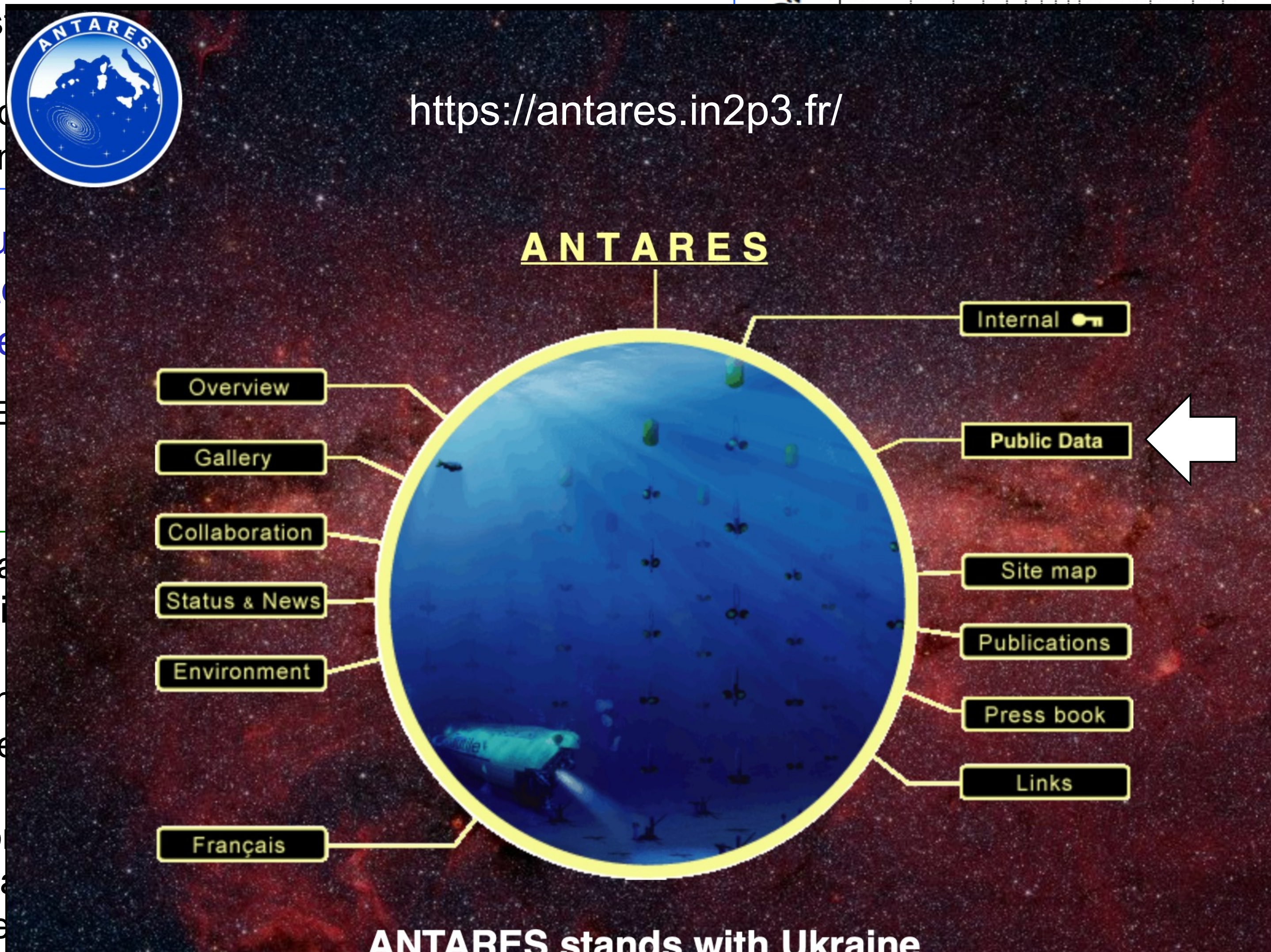
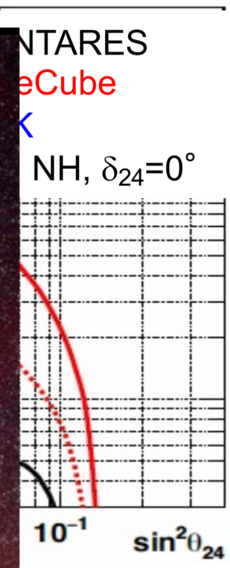
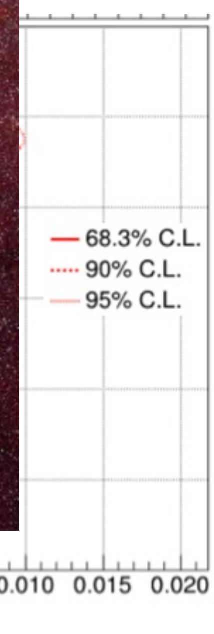
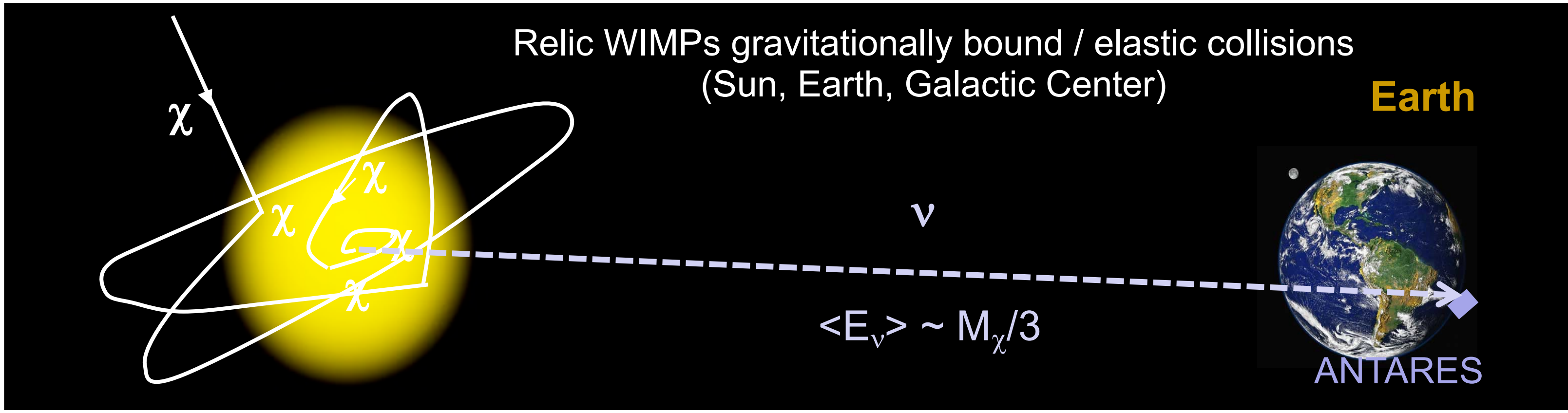






J. High Energ. Phys. 2022, 48 (2022)

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

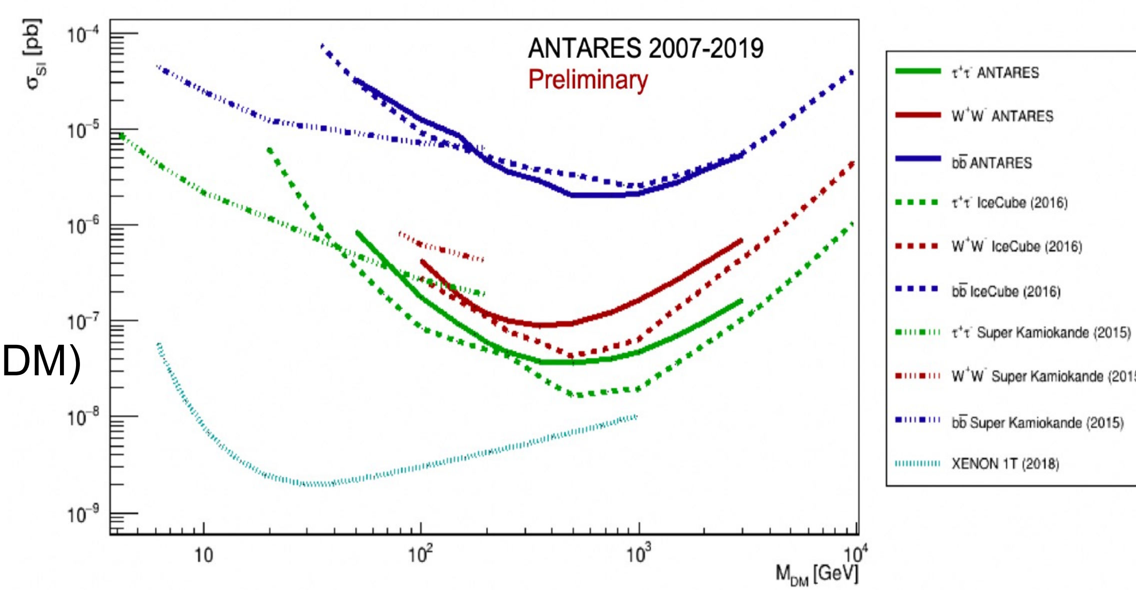
JCAP 06 (2022) 06, 028 (secluded DM)

Phys. Lett. B 805 135439 (2020)

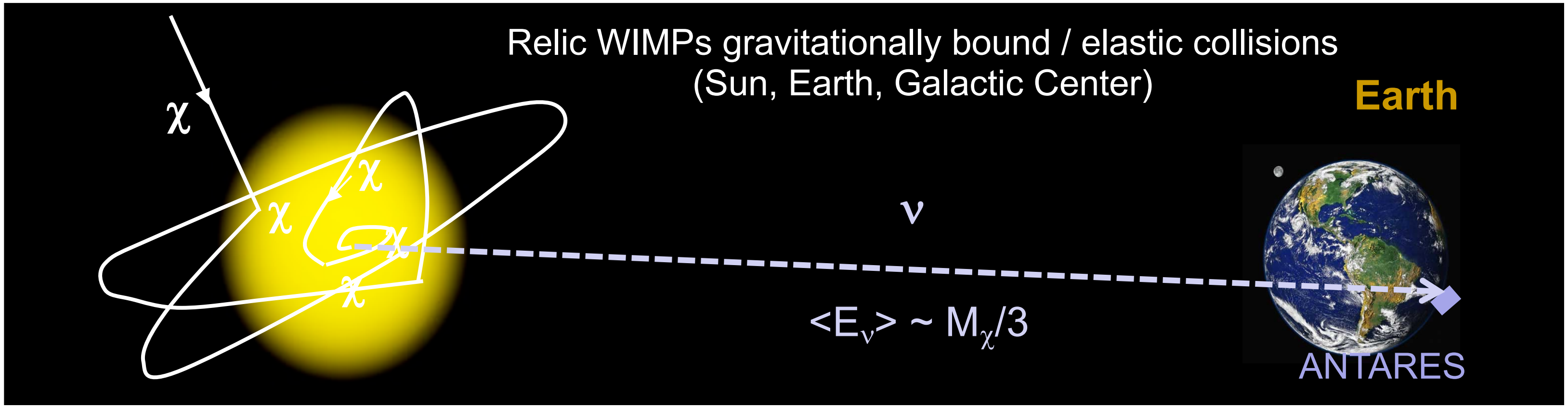
Phys. Rev. D 102, 082002 (2020)

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

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Phys.Lett. B759 2016
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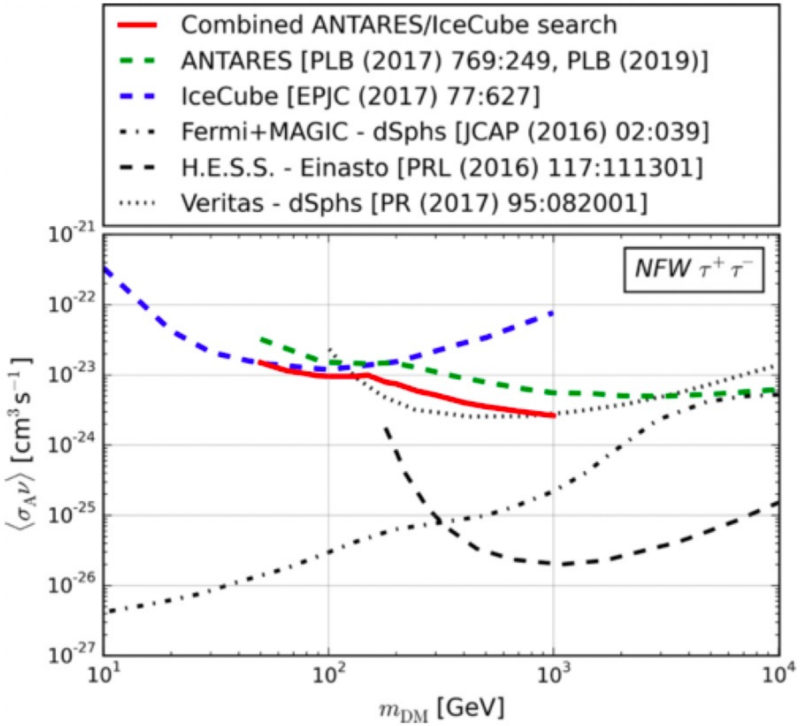
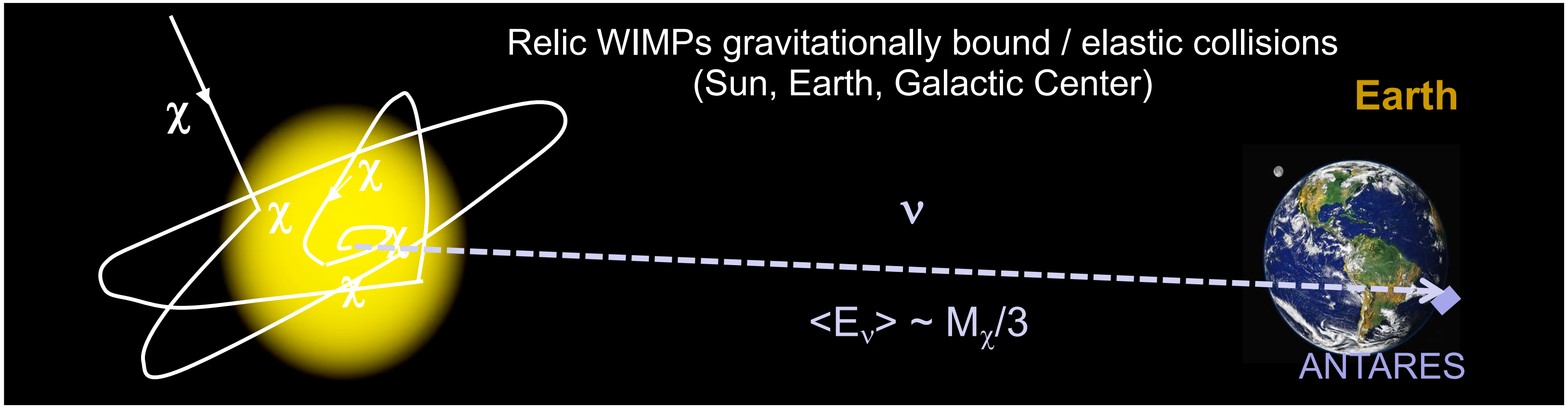
JCAP 06 (2022) 06, 028 (secluded DM)
Phys. Lett. B 805 135439 (2020).
Phys. Rev. D 102, 082002 (2020)
Phys. Let. B 769 (2017) 249
JCAP 10 (2015) 068



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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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 !

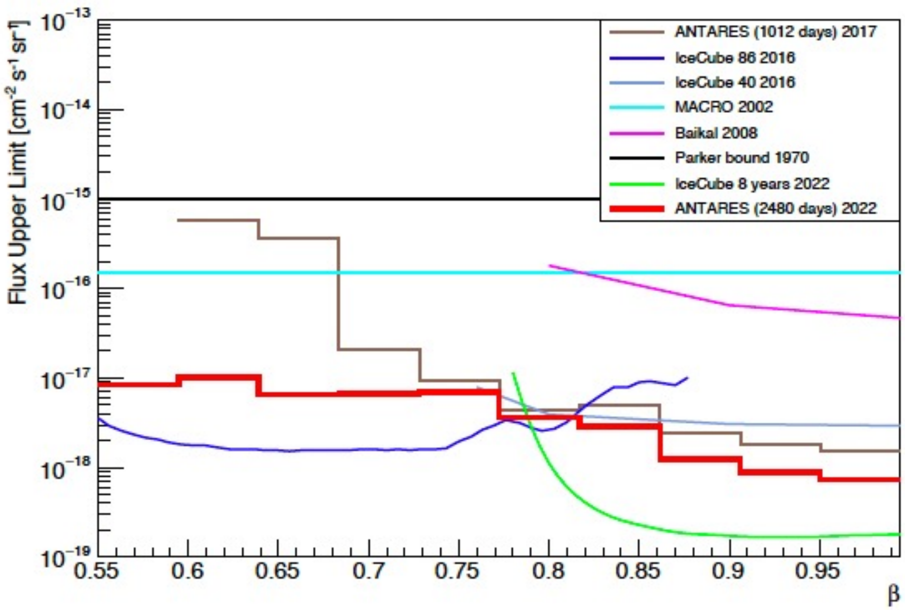
Our analyses do not include showers (all flavors) yet

Improvements ahead

Search for Exotic Physics with ANTARES

Monopoles

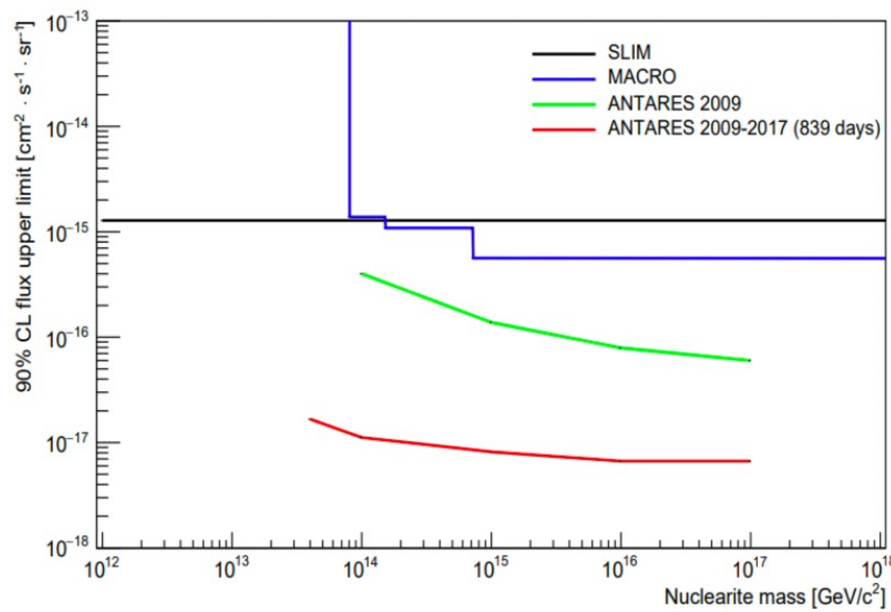
Magnetic monopoles
Kasama, Yang and Goldhaber model
Adapted reco for slow moving particles



JHEAp, Volume 34, 2022, Pages 1-8

Nuclearites

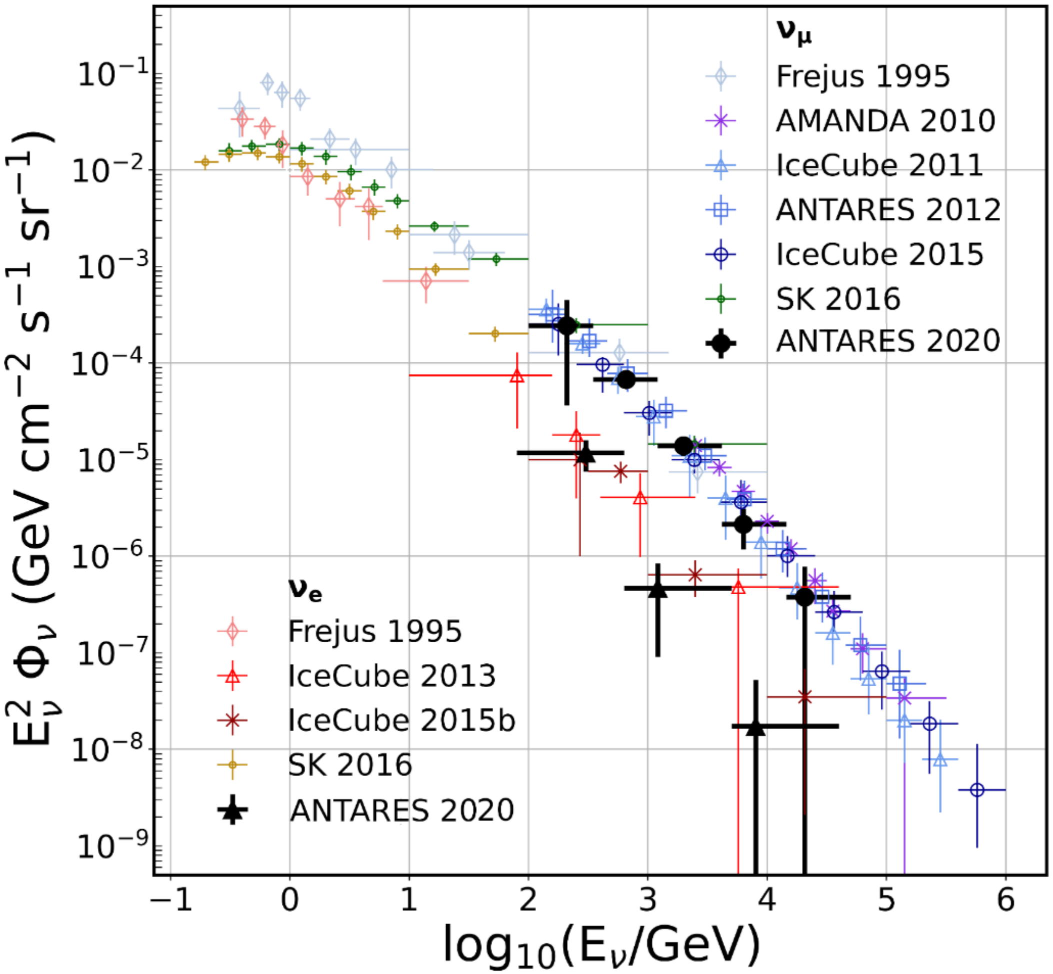
Nuclearites of strange quark matter
Down going flux with Galactic velocities
according to de Rújula & Glashow model



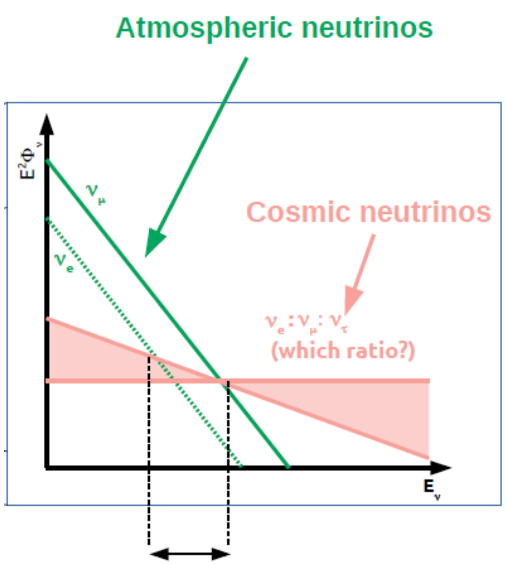
https://arxiv.org/pdf/2208.11689.pdf.

The atmospheric neutrino background

📖 EPJ 73: 2606 (2013)
📖 PLB 816: 136228 (2021)



- Atmospheric ν_μ and ν_e energy spectra can be measured
  - energy estimation
  - detector systematics



Atm./Cosmic transition: 30-200 TeV

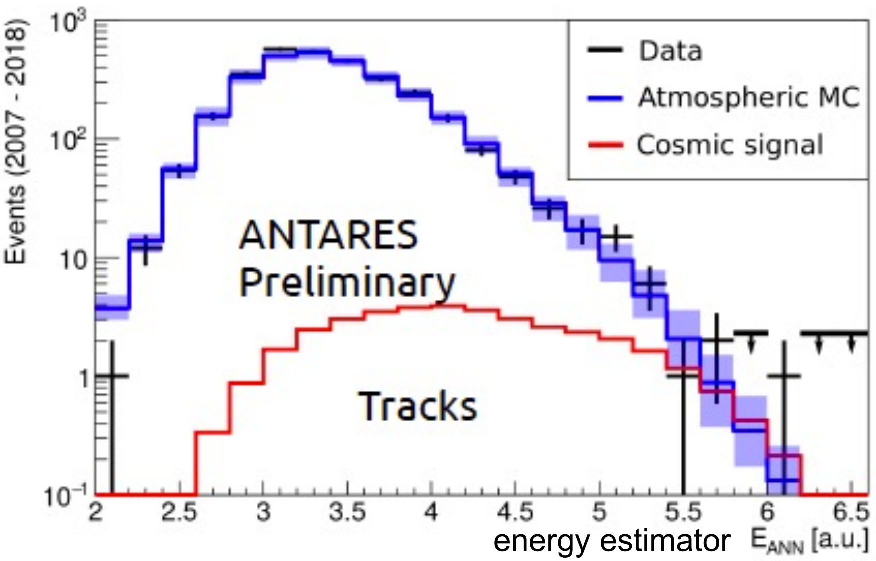
Diffuse flux

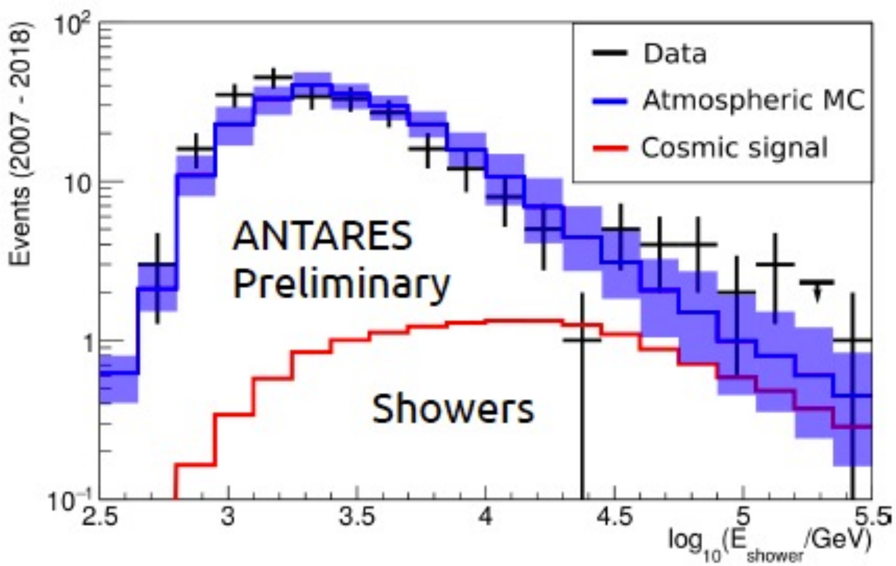
📖 https://pos.sissa.it/358/891/pdf (ICRC 19)

Updated data sample @ ICRC2019: 2007-2015 (2450 days) → 2007-2018 (3330 days)

All-sky / All-flavor neutrino search

- Selection cuts optimized with MRF procedure (assumed spectral index $\Gamma = 2.5$)
- Look for excess above a given E_{th}
- Combine track & shower samples





Data: 50 events (27 tracks + 23 showers)

Background expectation (atm. flux, incl. prompt) :

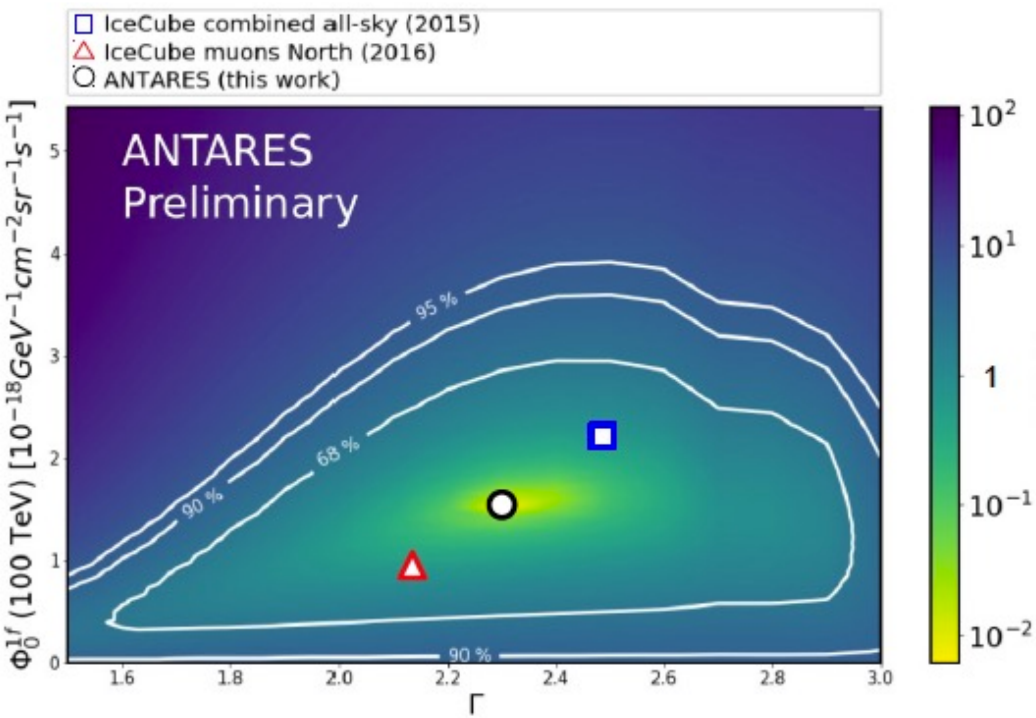
36.1 ± 8.7 (19.9 tracks and 16.2 showers) – stat. + syst.

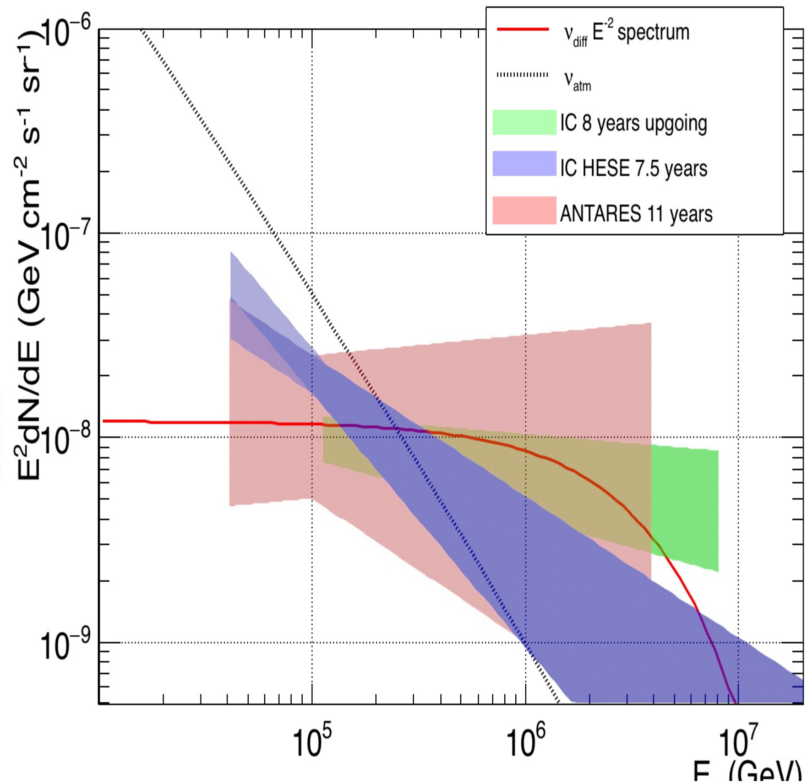
Results not really constraining… but fully compatible with IceCube

Diffuse flux – Towards a confirmation of IC ?

Combined (tracks+showers) likelihood fitting:

Cosmic: $$\Phi_{100\ \mathrm{TeV}} = (1.5 \pm 1.0) \times 10^{-18}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$
$$\Gamma = 2.3 \pm 0.4$$

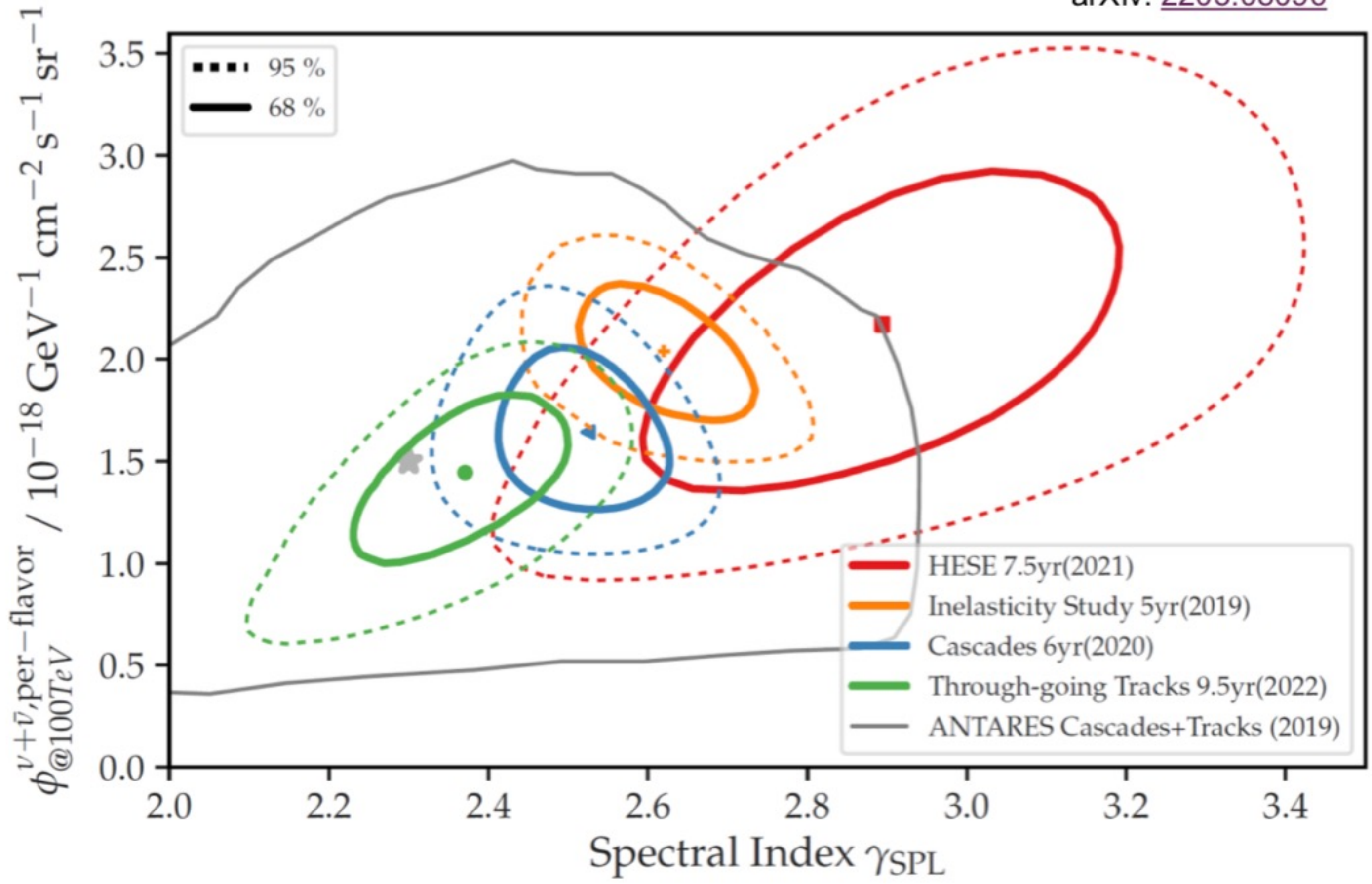




Results not really constraining… but fully compatible with IceCube

Diffuse flux – Single Power low

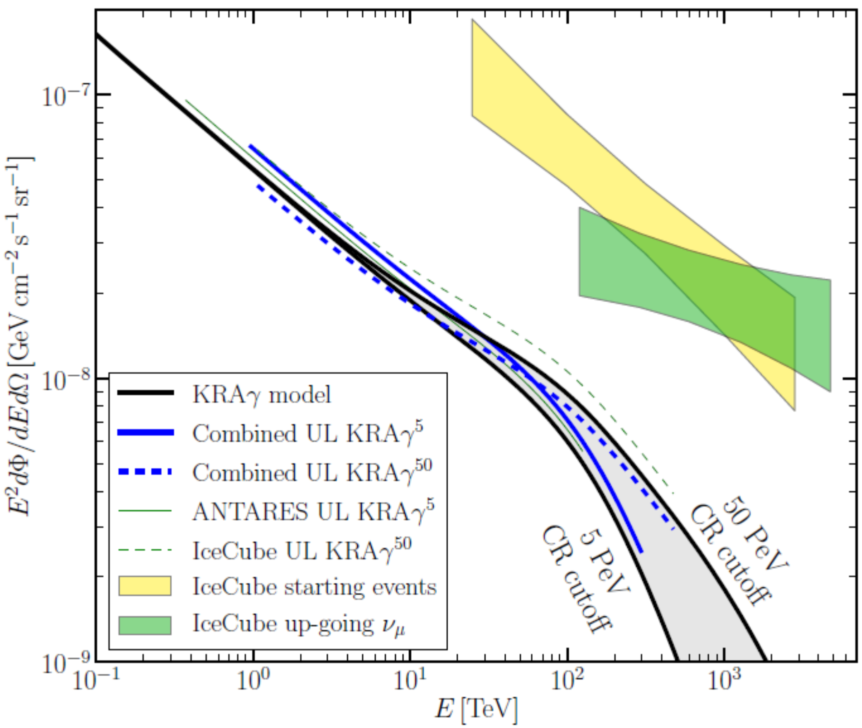
arXiv: 2203.08096



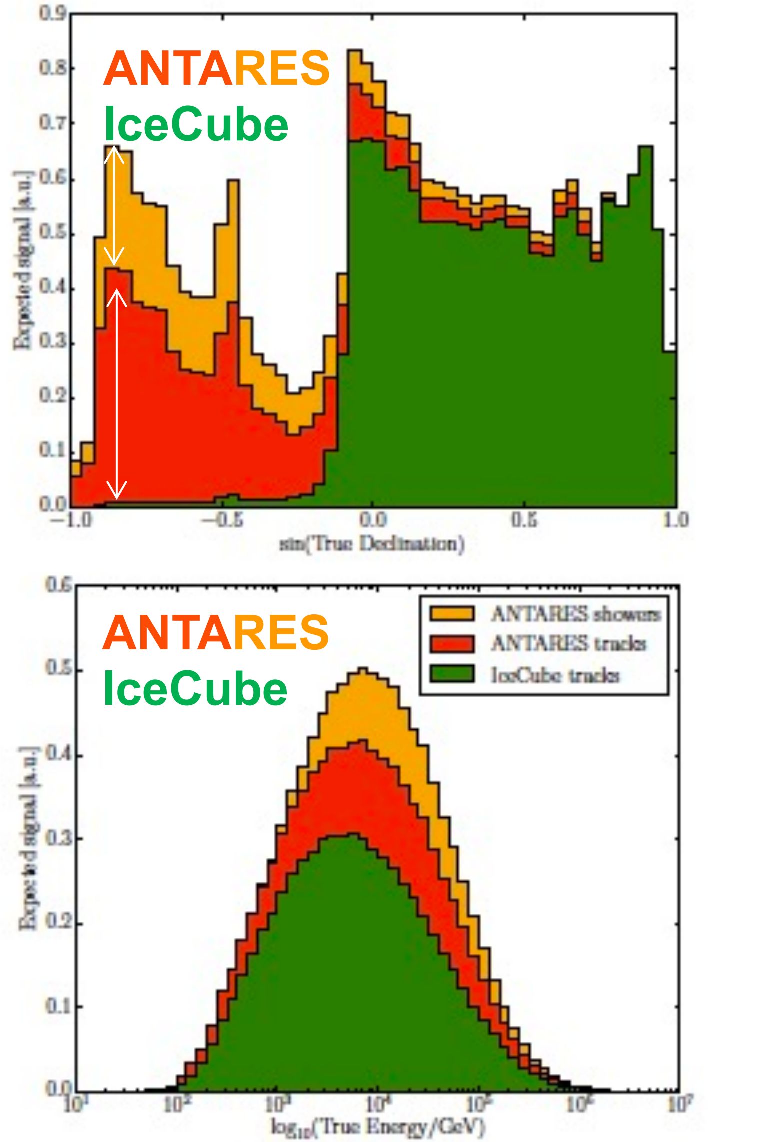
Results not really constraining… but fully compatible with IceCube

Search for diffuse flux from Galactic ridge

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRAγ model (5-50 PeV cutoff)



Stacked expected signal vs. δ (top) and energy (bottom). Colors relative contribution to the sensitivity

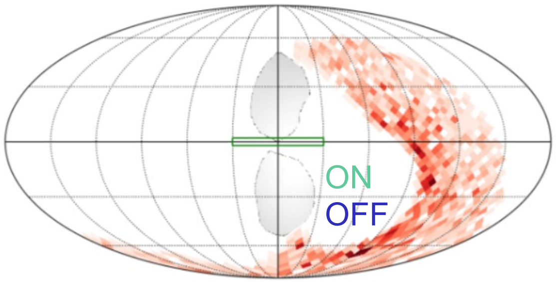


Result: total flux contribution of **diffuse Galactic neutrino** emission <9% *of the total diffuse IC astrophysical signal* (E_ν> 30 TeV)
Updates ongoing…

📖 Phys. Rev. D 96, 062001 (2017)
📖 ApJL 868, L20 (2018)

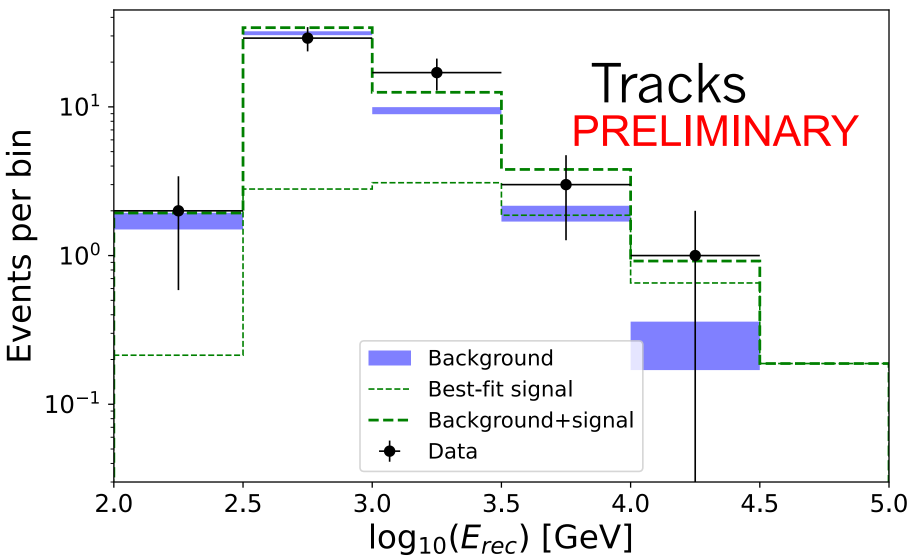
Hint in latest ANTARES Search !

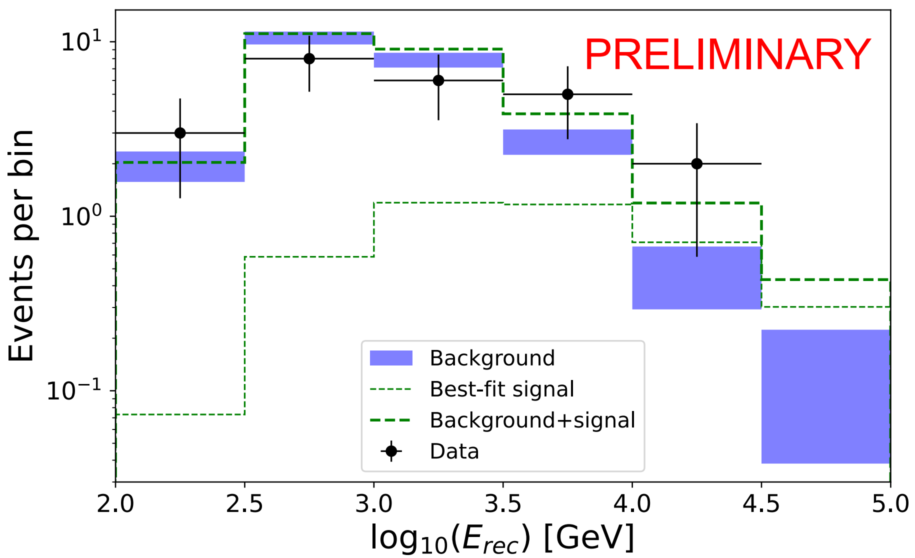
PRELIMINARY



- **Data period:** 2007–2020
- **Events:** tracks + showers, using existing diffuse neutrino selections
- **Signal hypothesis:** looking for signal in the region $|\ell| < 30^\circ$ and $|b| < 2^\circ$ assuming a simple power-law

$$\frac{dN}{dE\,dt\,d\Omega} = \phi_0 \times \left(\frac{E}{40\ \text{TeV}}\right)^{-\gamma} \text{ in } [\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}]$$





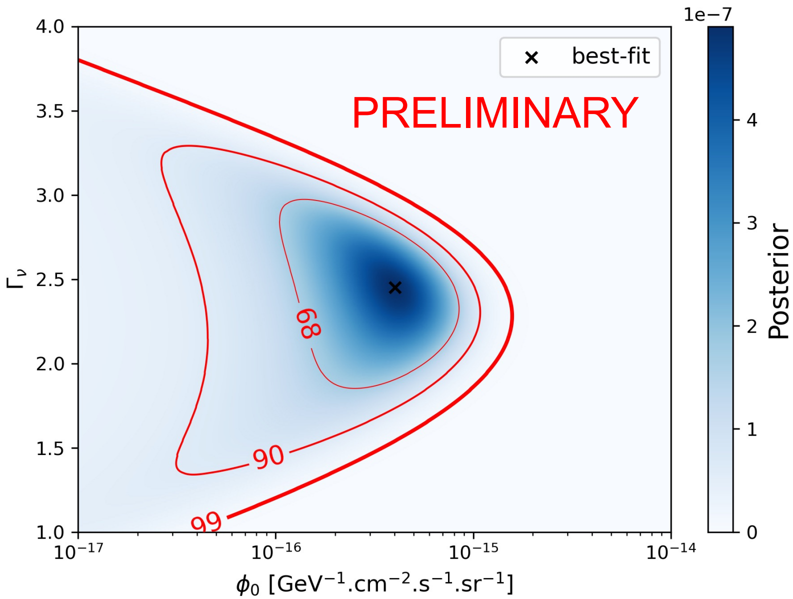
Hint in latest ANTARES Search !

M. Lamoureux's poster

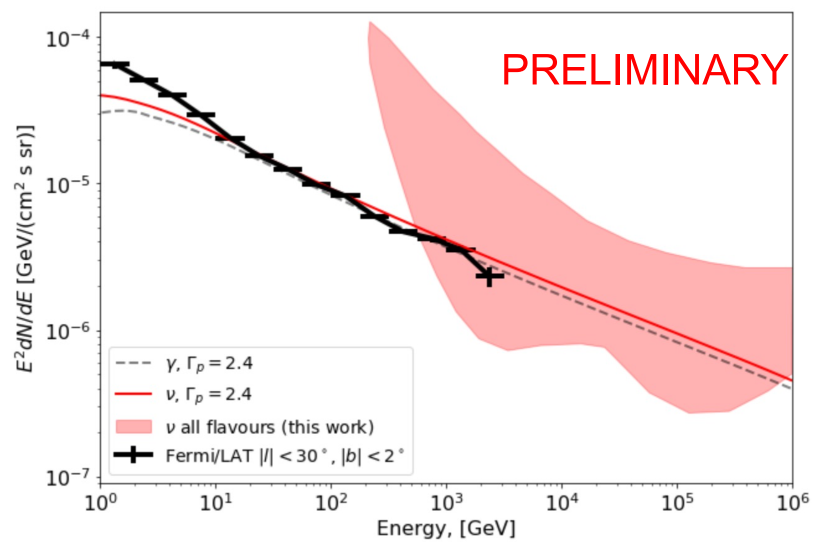
PRELIMINARY

- **Data period:** 2007–2020
- **Events:** tracks + showers, using existing diffuse neutrino selections
- **Signal hypothesis:** looking for signal in the region $|\ell| < 30^\circ$ and $|b| < 2^\circ$ assuming a simple power-law

$$\frac{dN}{dE\,dt\,d\Omega} = \phi_0 \times \left(\frac{E}{40\ \mathrm{TeV}}\right)^{-\gamma} \quad \text{in } [\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}] \quad \text{per flavor}$$

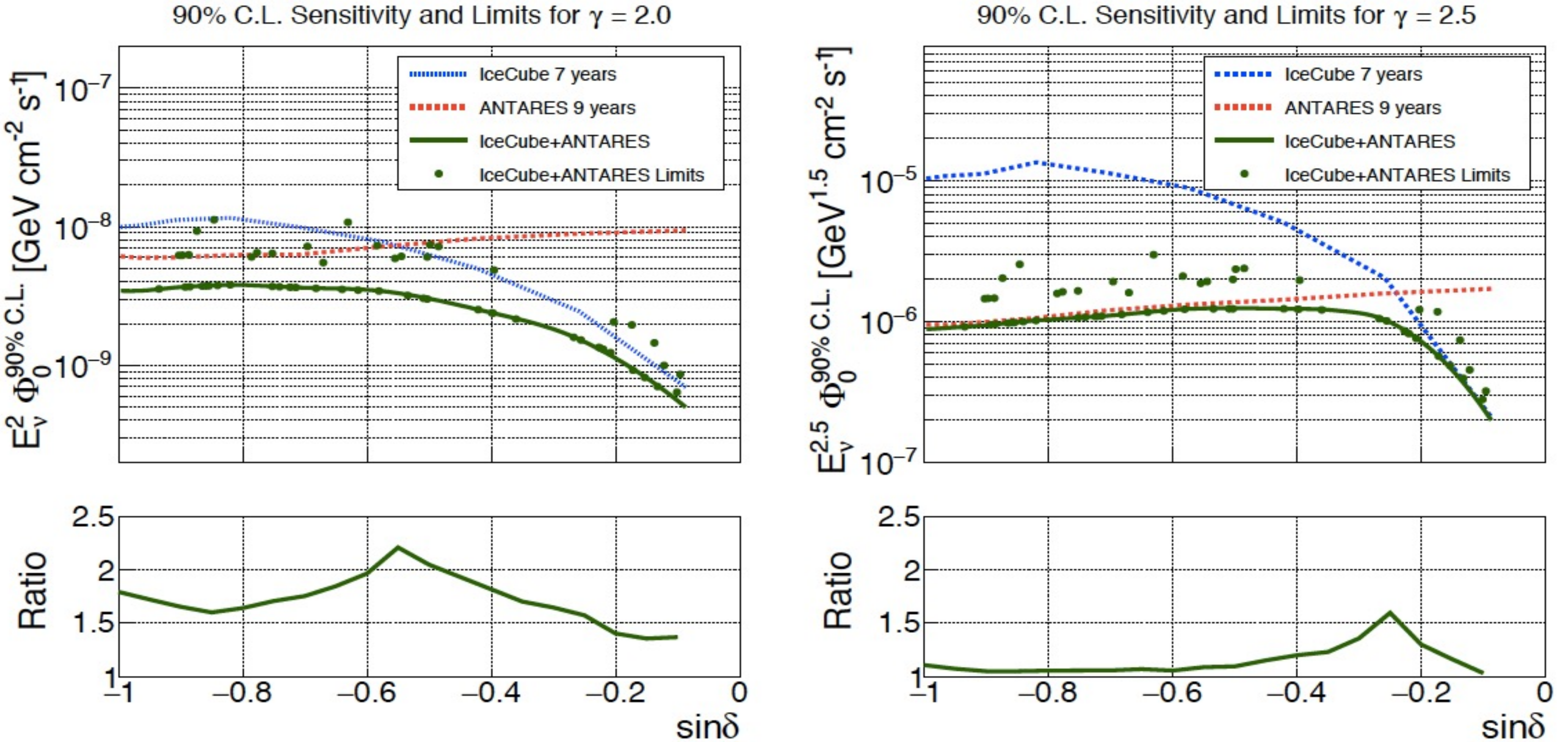


Best-fit: γ =2.45, ϕ_0(40 TeV)=4.0e-16



Combined ANTARES-IceCube PS search

ANTARES 2007-2015 and the IC40, IC59, IC79, IC86 samples for the Southern Hemisphere



Significant improvement of limits especially for hard energy spectra
Best limits on neutrino point source emission in Southern Hemisphere

ANTARES data set is public : see https://antares.in2p3.fr

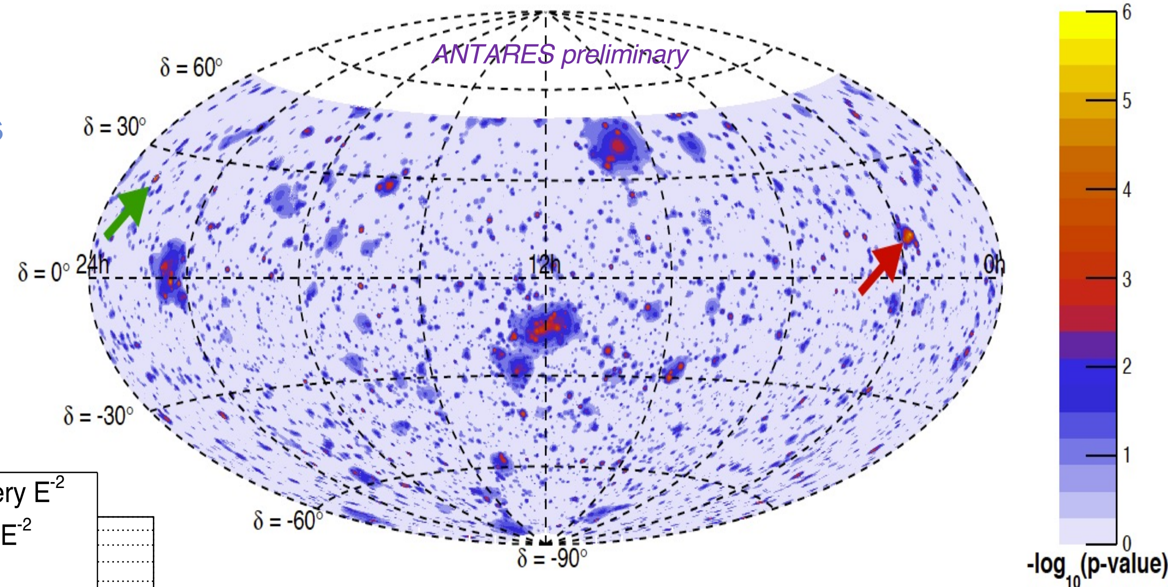
📖 The Astrophysical Journal 892 (2020) 2

Latest ANTARES search – All flavours !

Data set:

Period: from Jan 2007 to Feb 2020
Livetime: 3845 days
Events: 10162 tracks and **225 showers**

Full-sky search

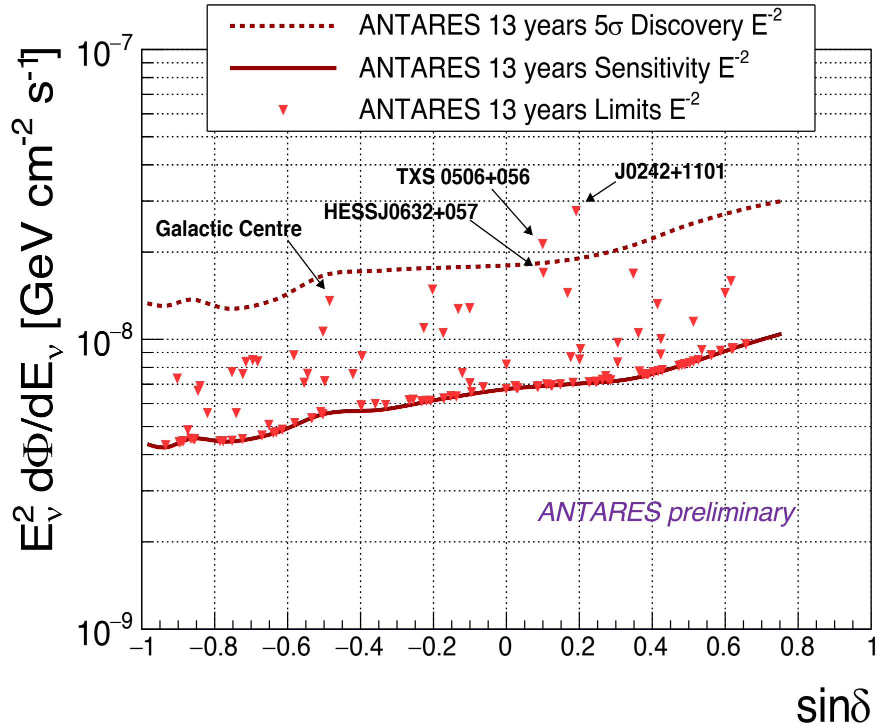


Full-sky hottest spot
pre-trial p-value: of 6.8 × 10^{-6} (4.3σ)
post-trial p-value: of 48%

📖 PRD 96, 082001 (2017)
📖 PoS(ICRC2021)1161

Candidate-list search:

121 investigated sources



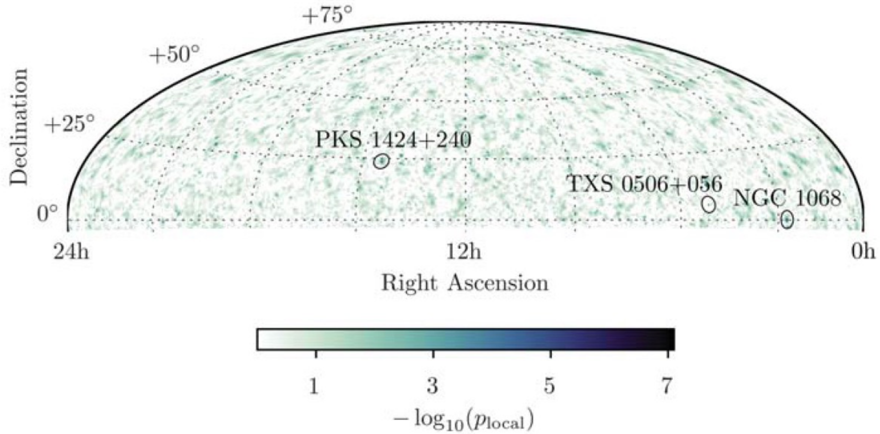
Most significant source:
J0242+1101
pre-trial significance: 3.8σ
post-trial significance: 2.4σ

Latest IceCube results !

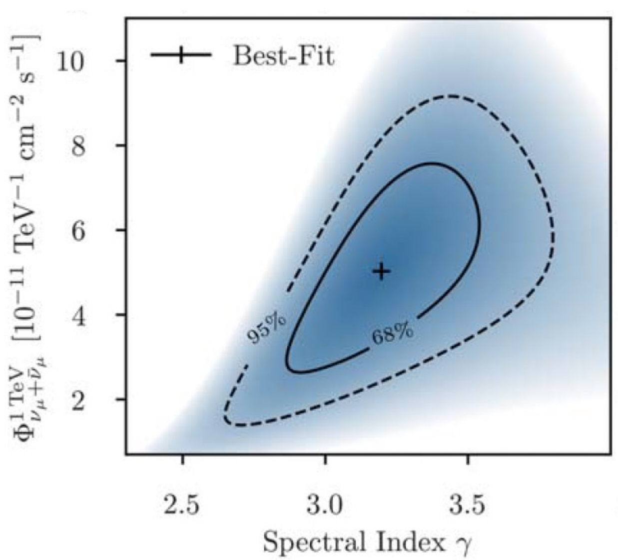
NEUTRINO ASTROPHYSICS

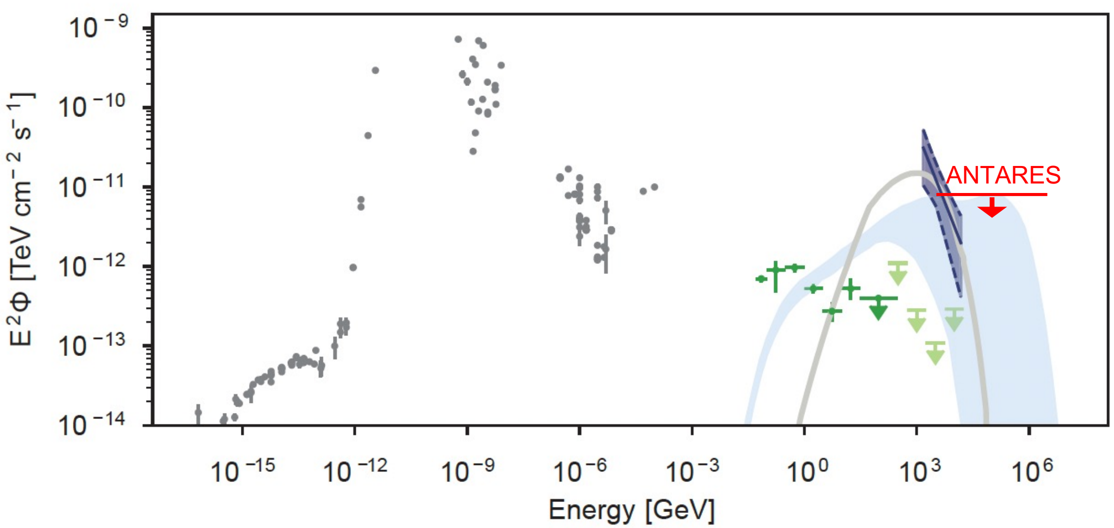
Evidence for neutrino emission from the nearby active galaxy NGC 1068

SCIENCE, 4 NOVEMBER 2022 • VOL 378 ISSUE 6619



Mean number of signal events is 79^{+22}_{-20}





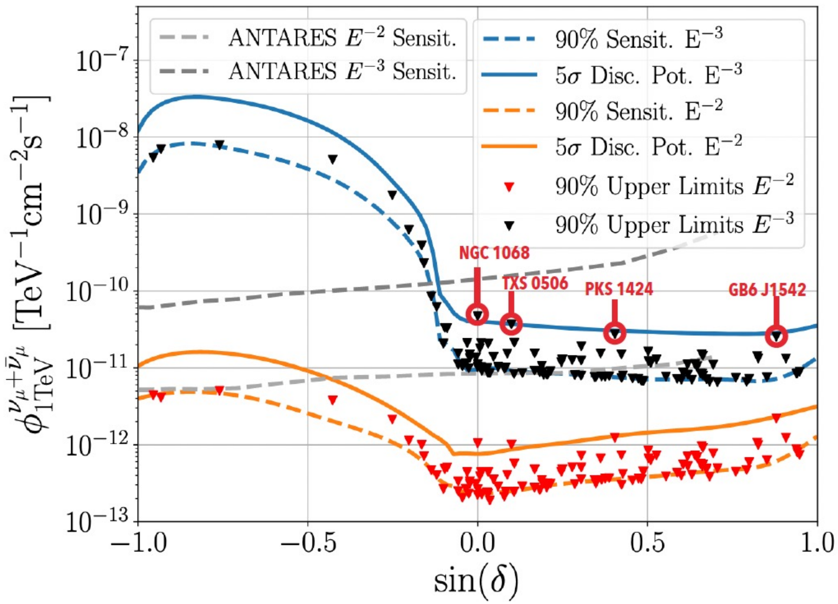
https://antares.in2p3.fr/News/news_Antares_NGC1068.html

Latest IceCube results !

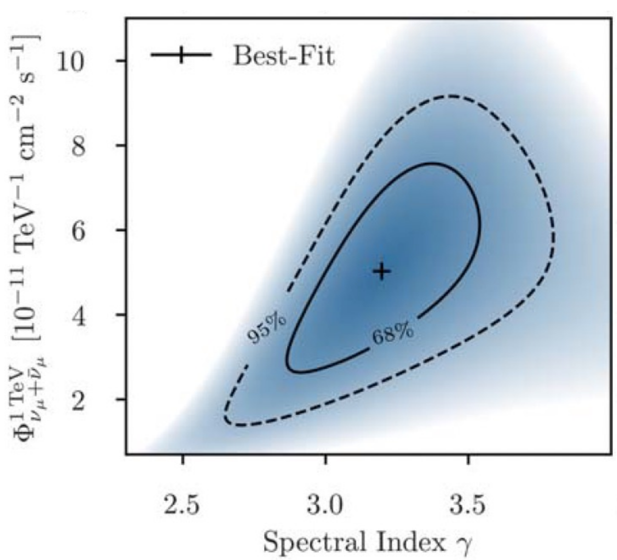
NEUTRINO ASTROPHYSICS

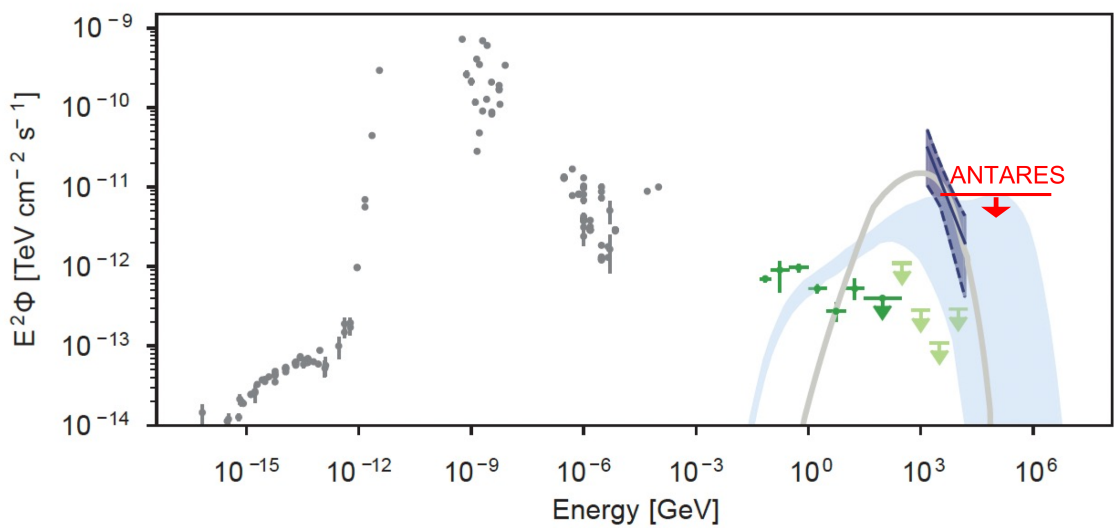
Evidence for neutrino emission from the nearby active galaxy NGC 1068

SCIENCE, 4 NOVEMBER 2022 • VOL 378 ISSUE 6619



Mean number of signal events is 79^{+22}_{-20}





https://antares.in2p3.fr/News/news_Antares_NGC1068.html

Catalog-based searches

📖 A. Albert et al. 2021 ApJ 911 48

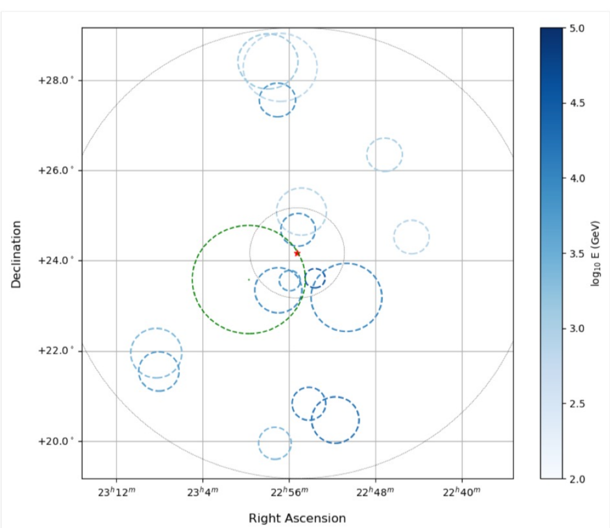
Likelihood based stacking approach

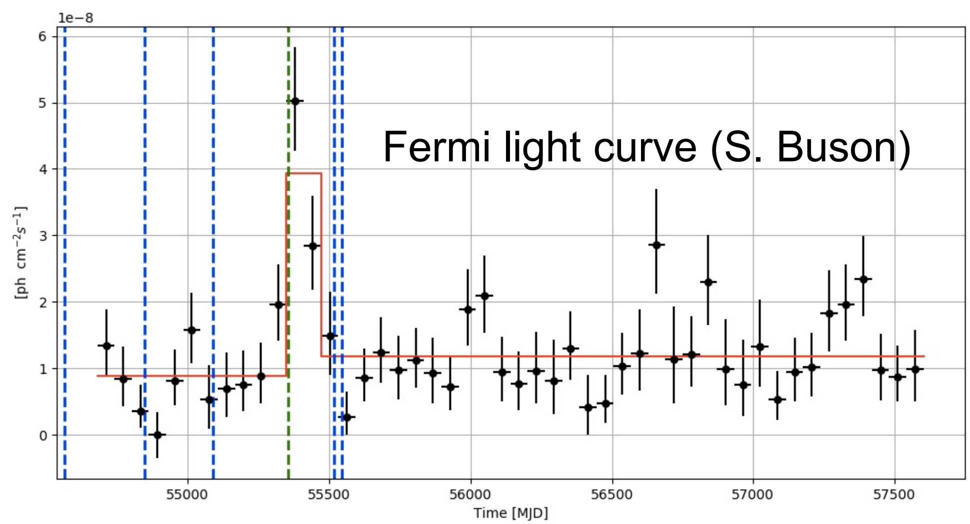
CATALOG	PRE-TRIAL	POST-TRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSRQ	0.57	0.97	
Fermi 3LAC BL Lacs	**0.088**	**0.64**	**MG3J225517+2409**
Radio-galaxies	**4.8 10^{-3}**	**0.10**	**3C403**
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IC HE tracks	0.05	0.49	

0.10 → 1.6 σ

Mild excess seen for radio galaxies

Blazar MG3 J225517+2409
ANTARES & IceCube tracks





Space-time association: ANTARES -> **2.3σ** & IceCube track -> **2.6σ**

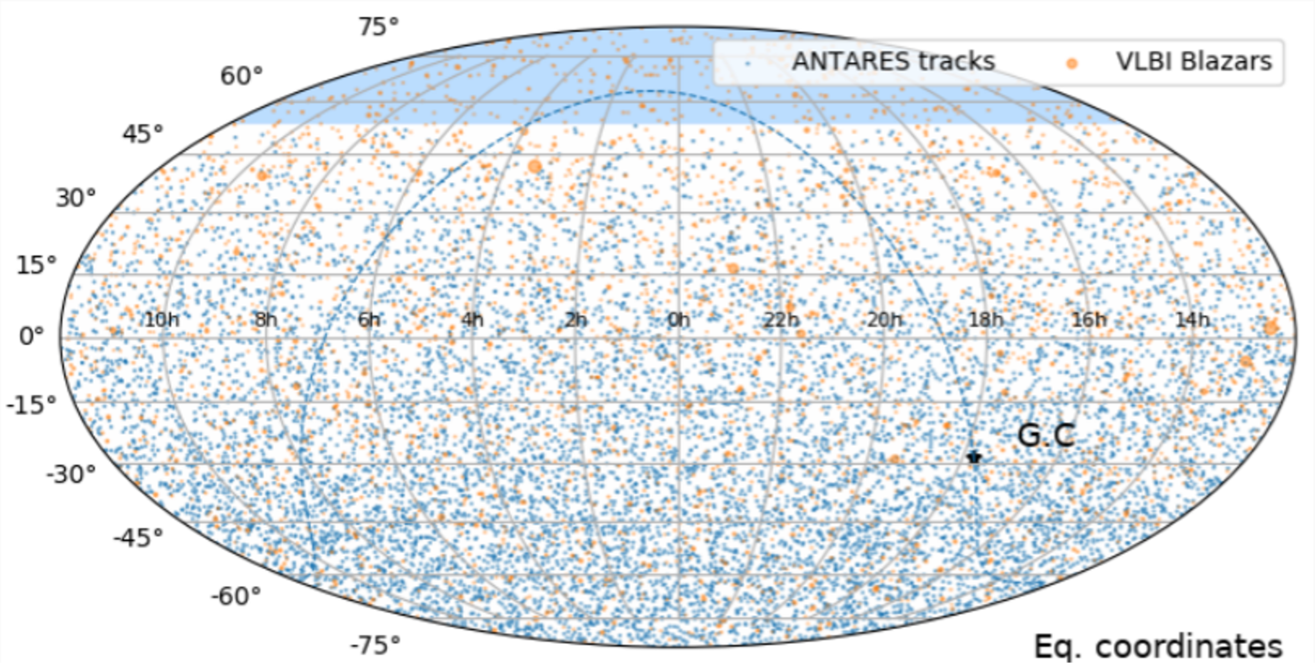
Sensitivity to association to VLBI catalog

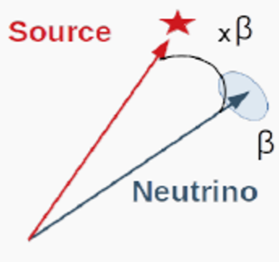
📖 A. V. Plavin *et al* 2021 *ApJ* **908** 157

Ongoing search for correlation between neutrino candidates and radio blazars seen in VLBI data (3411 objects)

Simple counting analysis

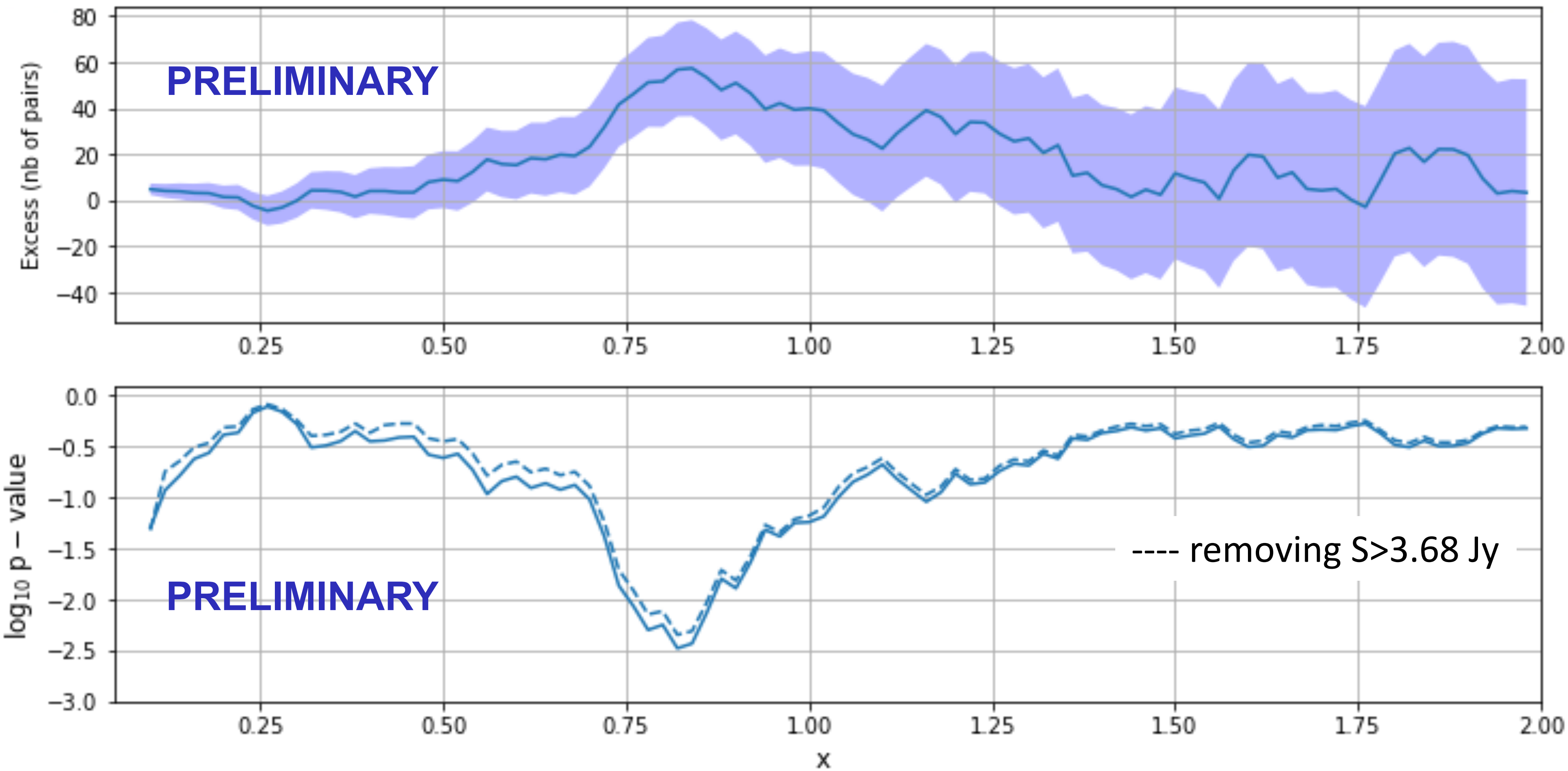
- Count the nb of neutrino-blazar pairs at less than xβ
- Angular uncertainty estimate β is multiplied by x for possible systematics
- Scan on the values of x to search for the most significant excess





Sensitivity to association to VLBI catalog

Single counting approach



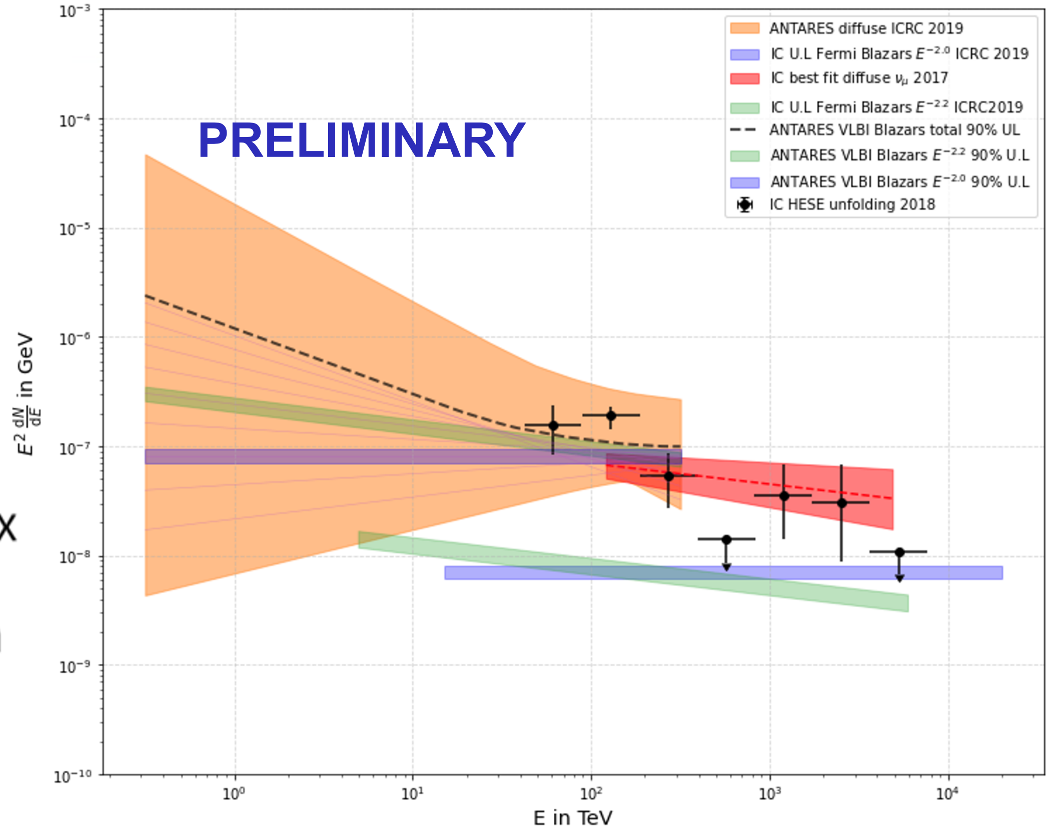
Only accounting for a 1D scan in x gives $P_1(1D) = 0.03$ ($2.2\ \sigma$) – Not significant

Sensitivity to association to VLBI catalog

Stacked likelihood approach

- Computation for several spectral indexes (pure power law)
- New background angular pdf made E-dependent

- New p-values slightly better
- Largest excess of 2.2σ for $E^{-2.3}$ with flux weight
- Computation of 90 % U.L as a function of spectral index

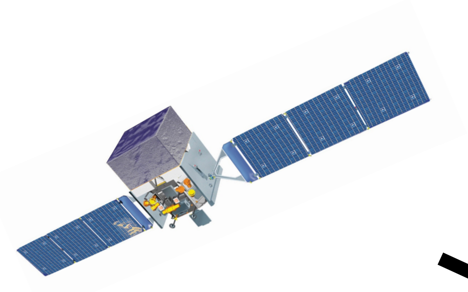


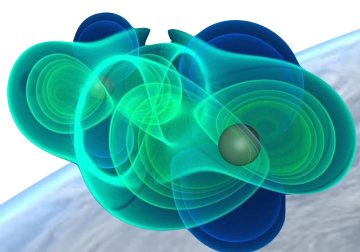
Consistent 2.2 σ excess – Not significant, not constraining the origin of IC events
But worth being followed-up…

The multi-messenger program

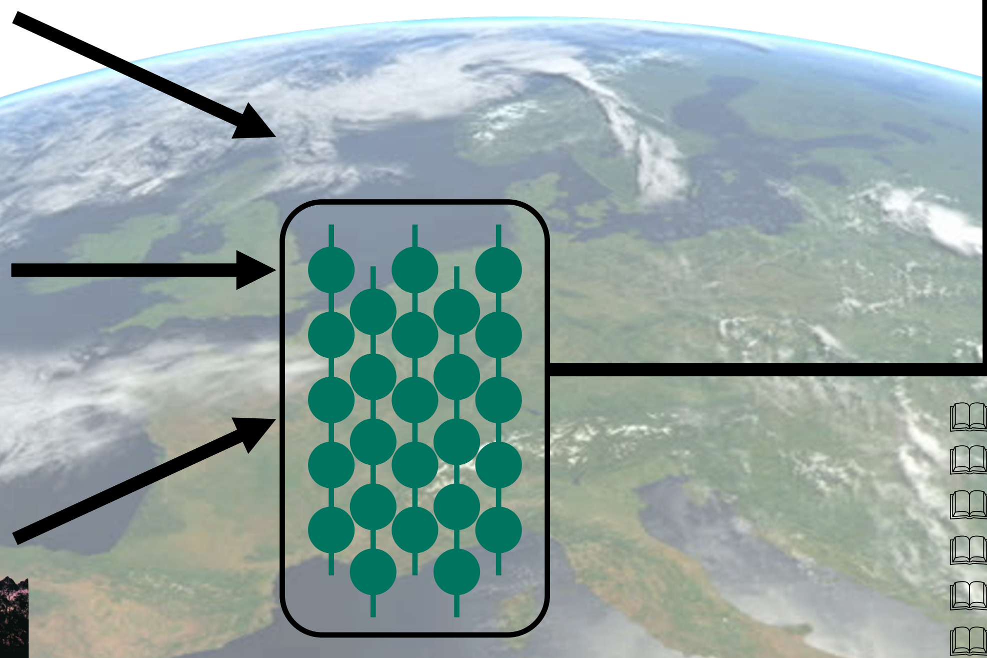
1ST APPROACH:

Time dependent searches





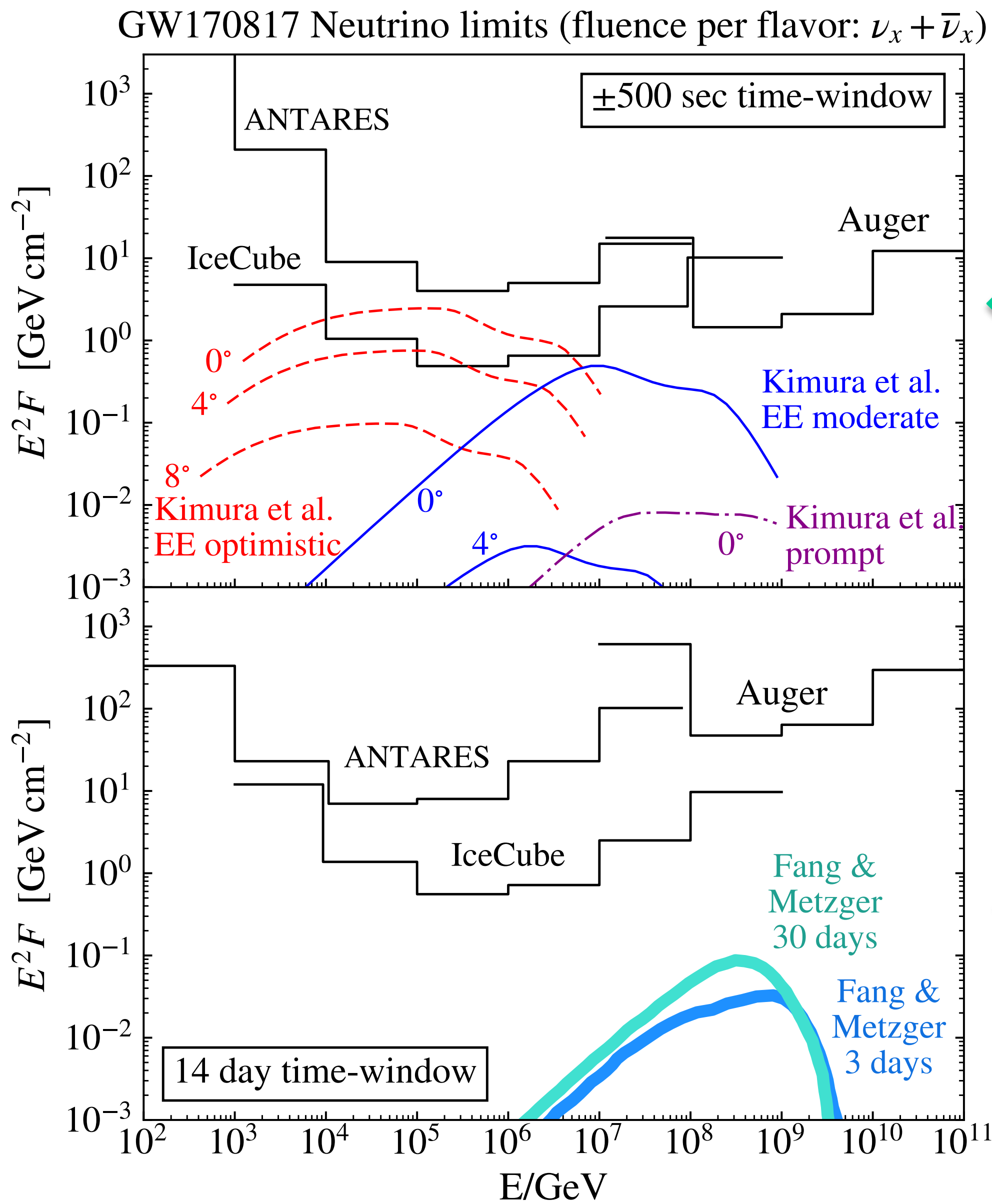
NT can guide optical follow-up



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

📖 Eur. Phys. J. C 80, 487 (2020
📖 ApJ 870 (2019) 2
📖 ApJL 848 L12 (2017)
📖 ApJL 850 L35 (2017)
📖 Phys. Rev. D 96 (2017) 02200
📖 Phys. Rev. D 93 (2016) 12201

Neutrino Follow-up of GW170817



📖 ANTARES, IceCube, Pierre Auger, LIGO Scientific and Virgo Collaborations ApJL 850 L35 (2017)

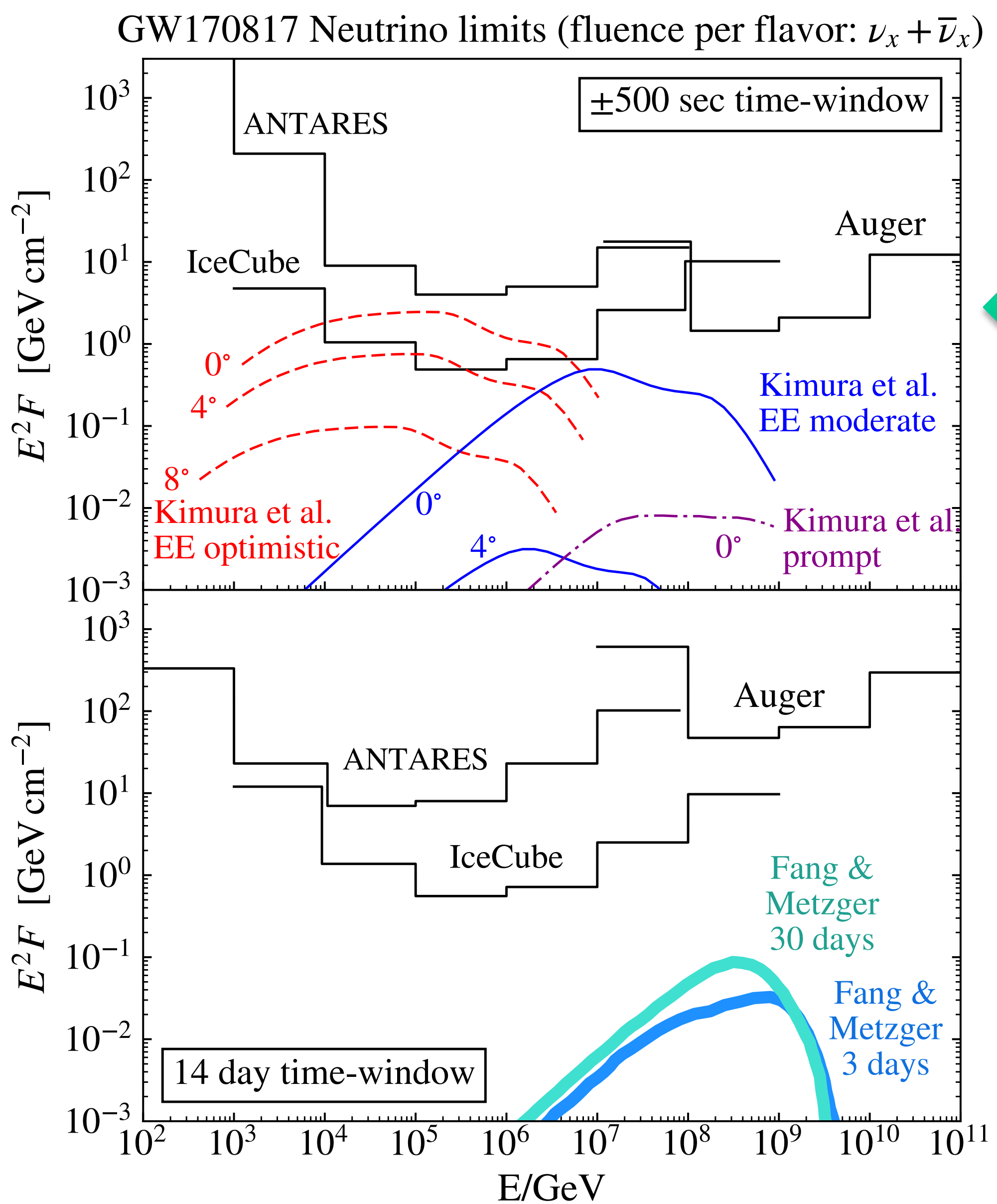
Non-detection consistent with expectation from short GRB observed at large off-axis angle

Model prediction:
Kimura et al. ApJL 848, L4

No detection during extended time period of 14 days after the GRB

Model prediction:
Fang, K., & Metzger, B. D. 2017, arXiv:1707.04263

Neutrino Follow-up of GW170817



ANTARES, IceCube, Pierre Auger, LIGO Scientific and Virgo Collaborations ApJL 850 L35 (2017)

Non-detection consistent with expectation from short GRB observed at large off-axis angle

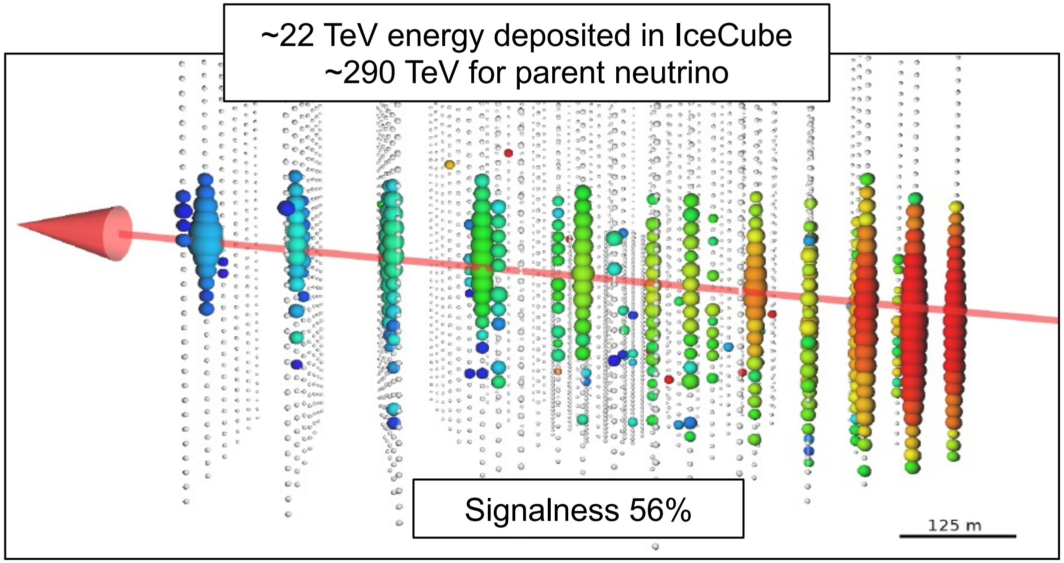
Model prediction:
Kimura et al. ApJL 848, L4

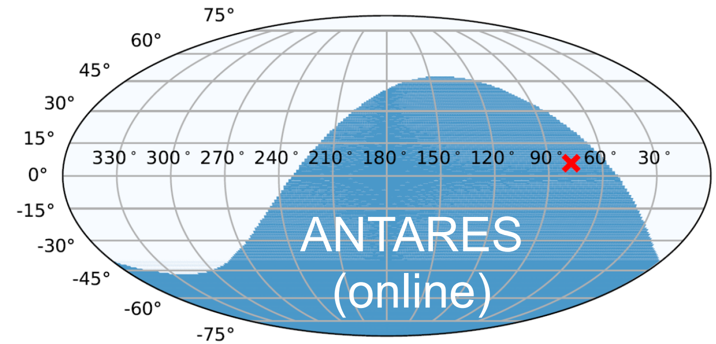
Other follow-ups of GW signals

- 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

→ no counterparts

Follow-up of ICECUBE-170922





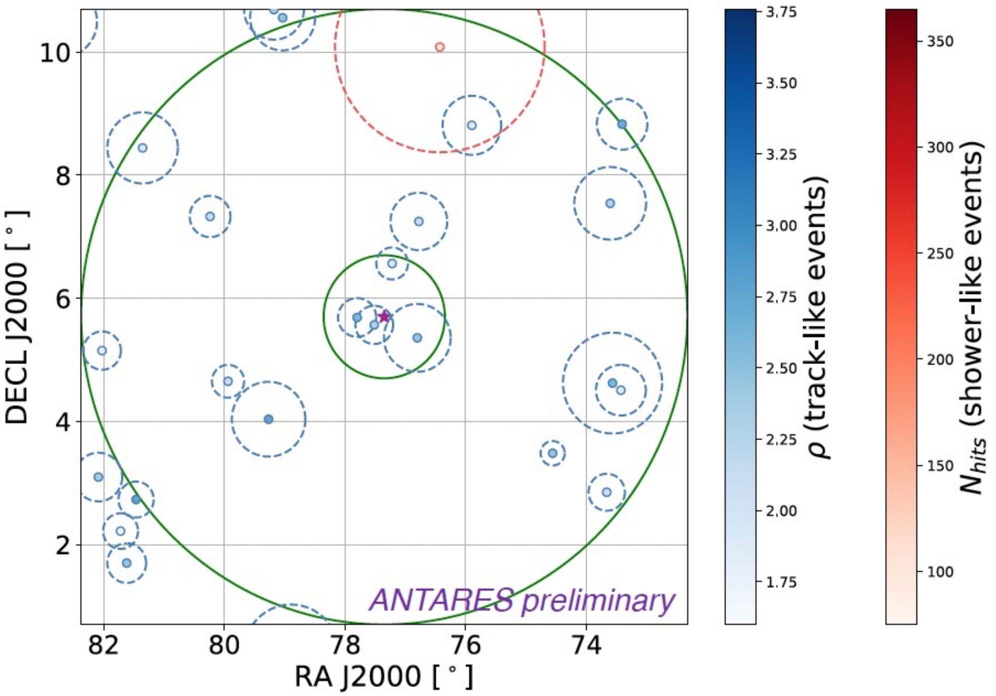
- "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IC170922A"
  - ~3 σ neutrino-gamma coincidence
- "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IC170922A alert"
  - First 7 years (excluding 170922A): 2.1 σ
  - Neutrino flare in late 2014 – early 2015: 3.5 σ

Search for neutrinos from TXS 0506+056

ANTARES Time integrated search

- Same method as PS study 2007-2017

- Expected background (3136 days) :
  - 0.23/deg² for track-like
  - 0.005/deg² for shower-like events
- # of events fitted the likelihood signal function for the source: μ_{sig} **= 1.03**
- **Pre-trial p-value of 3.4%** (post-trial 87%)



- Updated 2007-2020, recalibrated

- 4 events within 1° μ_{sig} **= 2. 9**
- Pre-trial: 2.9σ (1-sided)

- Soon, yet another update
- Time sequence under investigation

📖 ApJL 863, L2 (2018) update at ICRC 2021

The multi-messenger program: TAToO

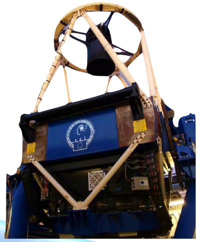
Telescope-Antares Target of Opportunity

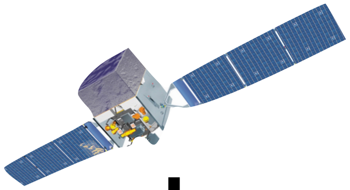
2ND APPROACH:

Alert triggering

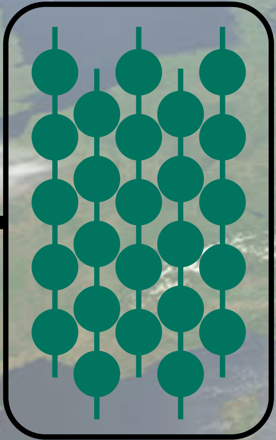
Real-time analysis

AMON
Astrophysical Multimessenger Observatory Network





+ ...



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

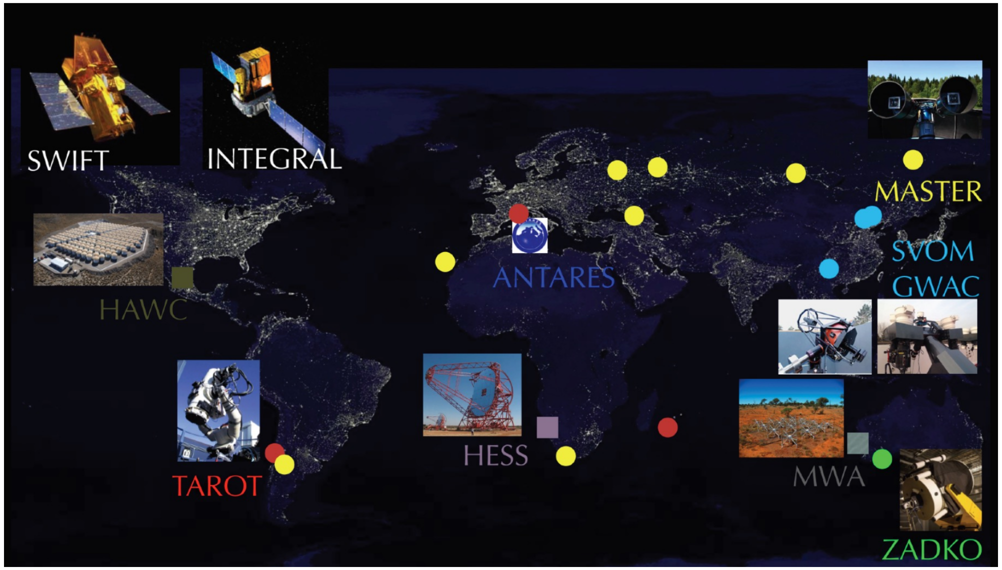
TATOO and the transients

📖 MNRAS, 48 (2019) 1
📖 ApJ, 886:98 (2019)

Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA (12/yr)	TAROT ZADKO MASTER (GWAC) (30/yr)	Swift (6/yr) Integral	Fermi (offline)	HESS (2/yr) HAWC (offline)

Triggers:

- Doublet of neutrinos (<3°, <15 min): ~0.04 events/yr
- Single neutrino with direction close to local galaxies:
  ~1 TeV, ~10 events/ yr
- Single HE neutrinos: ~5 TeV, 20 events/ yr
- Single VHE neutrinos: ~30 TeV, ~3-4 events/ yr



Performances:

- Time to send an alert: ~5 s
- Median angular resolution: ~ 0.4°

Sent neutrino alerts (2009-2021)

322 to robotic telescopes
+26 to Swift
+15 to INTEGRAL
+20 to MWA
+2 to HESS

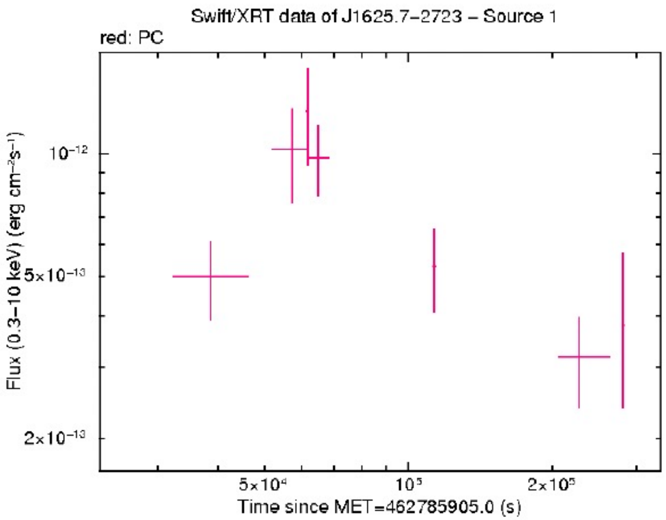
Follow-up efficiencies: ~70% (X-ray / optical) + ~20% (radio)

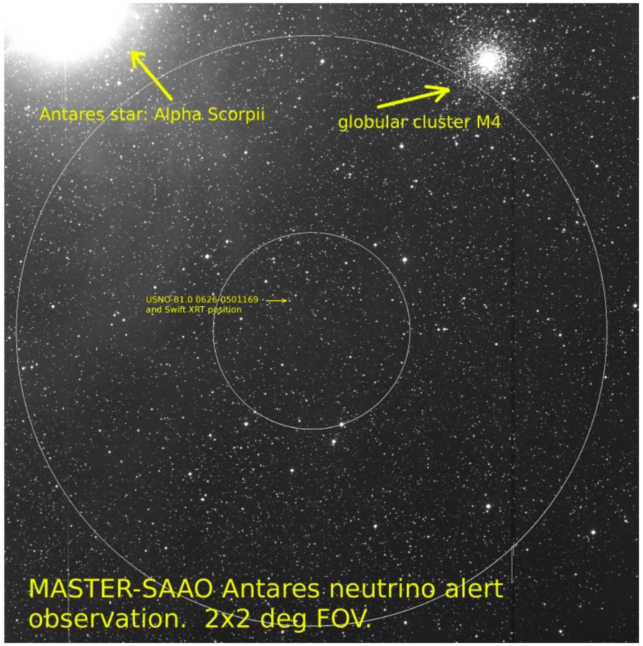
ANT150901

In September 2015, ANTARES has issued a neutrino alert and during the follow-up, a potential transient counterpart was identified by Swift and MASTER.

- The associated neutrino had an energy of about 87 TeV with a 1 σ range of 24 - 316 TeV
- This source location at 0.11 deg from neutrino

A multi-wavelength follow-up campaign allowed to identify the class of this source resulting in a fortuitous association with the neutrino. ☹
→ A young accreting G-K star, undergoing a flaring episode (X-ray emission). Probably associated to Rho Ophiuchi star forming region.





Multifrequency observations:
15 ATEL + 6 GCN

📖 D. Dornic et al. "ANTARES neutrino detection and possible Swift X-ray counterpart". In: The Astronomer's Telegram 7987 (Sept. 2015), p. 1.

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.

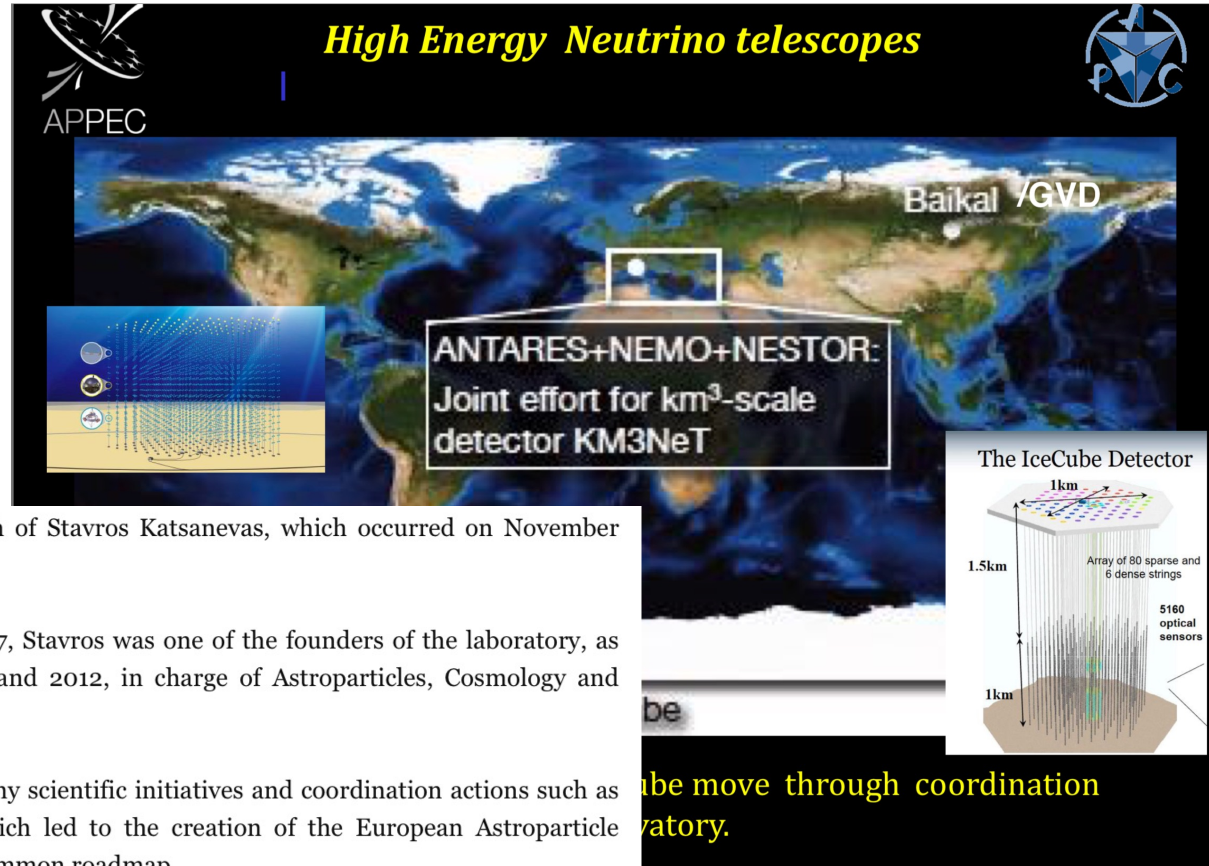
One of the last recovered elements was the PPM-DOM (see Figure below), the first prototype of the future KM3NeT DOMs, installed in 2013 and still in good shape. Some of the ANTARES equipment, notably the optical modules with their photomultipliers, might be used in future science projects. Other parts 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 !

Stavros Katsanevas (1953 - 2022)

https://apc.u-paris.fr/



The APC laboratory is deeply saddened by the death of Stavros Katsanevas, which occurred on November 27, 2022.

Before heading the laboratory between 2014 and 2017, Stavros was one of the founders of the laboratory, as Deputy Scientific Director of IN2P3 between 2002 and 2012, in charge of Astroparticles, Cosmology and Neutrino Physics.

At the forefront, Stavros has been at the origin of many scientific initiatives and coordination actions such as the European programmes ILIAS and ASPERA, which led to the creation of the European Astroparticle Consortium (APPEC) aiming at the elaboration of a common roadmap.

With his open-mindedness, he favoured all bridges: between Earth sciences and Universe sciences, between Art and Science, between science and society.

Stavros passed away as he was finishing his mandate as director of the European Gravitation Observatory (EGO) and preparing his return to the APC laboratory as Professor Emeritus, determined to conquer the moon to detect gravitational waves.

Stavros leaves us with a legacy of vision and passion.

Tribute to Stavros' career in APC website.

Summary

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

  A multi disciplinary observatory (associated sciences).

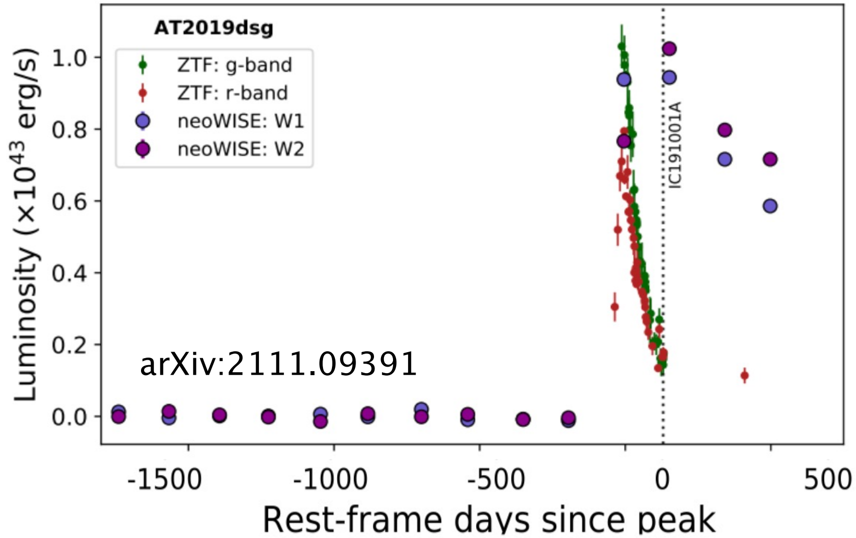
  More than a proof of feasibility.

- 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
- QUITE AN ADVENTURE ! But only the beginning …

Join us in KM3NeT for the next decade !

Search for ν counterparts to TDE events

IC191001A & AT2019 dsg



Soon after IC191001A, the tidal disruption event (TDE) AT2019dsg, observed by the Zwicky Transient Facility, was indicated as the most likely counterpart of the IceCube track.

R. Stein, *et al.*, *Nature Astronomy* 5, 510 (2021).

The probability of finding any coincident radio-emitting tidal disruption event by chance is 0.5%, while the probability of finding one as bright in bolometric energy flux as AT2019dsg is 0.2%.

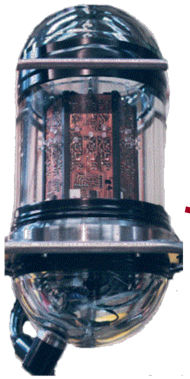
At least another association reported : IC200530A & AT2019fdr

No significant counterpart in ANTARES

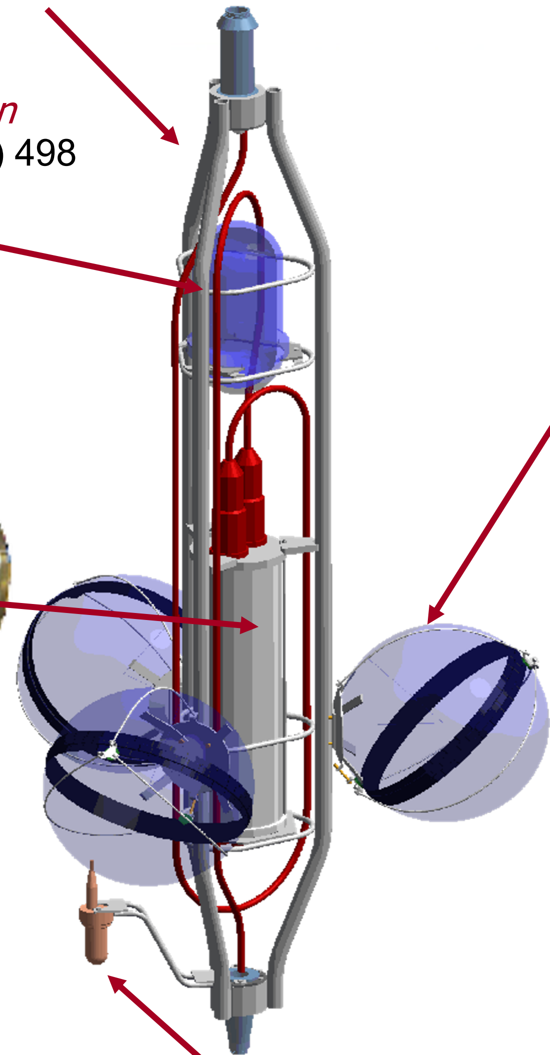
🕮 2021 ApJ 920 50

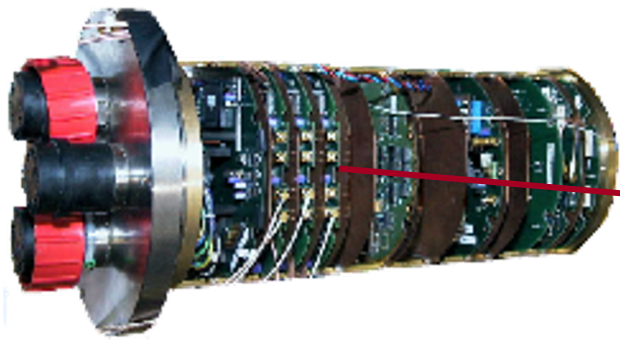
Basic neutrino detector element: storey

Titanium frame: *support structure*

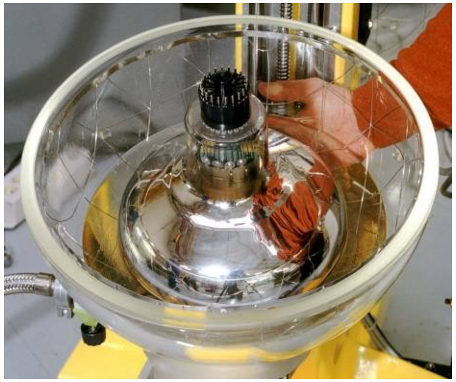


Optical Beacon
with blue LEDs:
timing calibration
NIM A578 (2007) 498





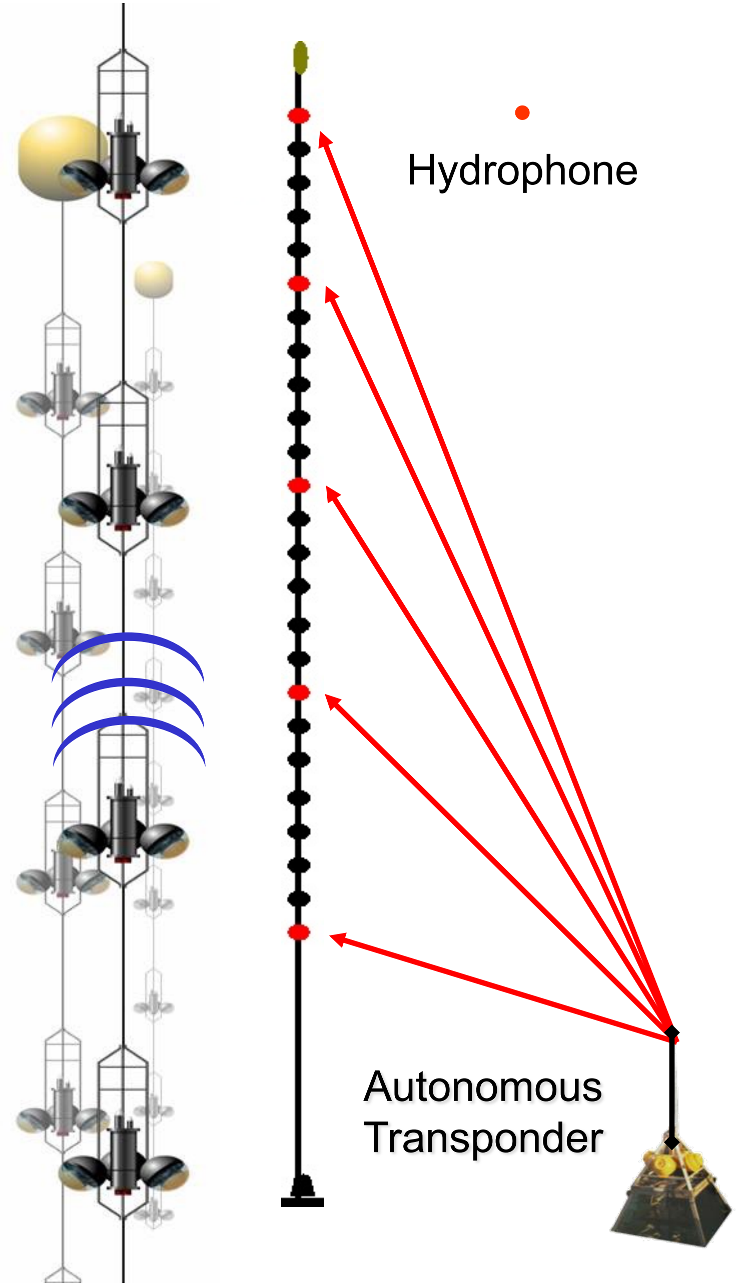
Local Control Module (Ti):
Front-end ASIC, DAQ/SC, DWDM,
Clock, tilt/compass, power distribution…
NIMA 622 (2010) 59-73

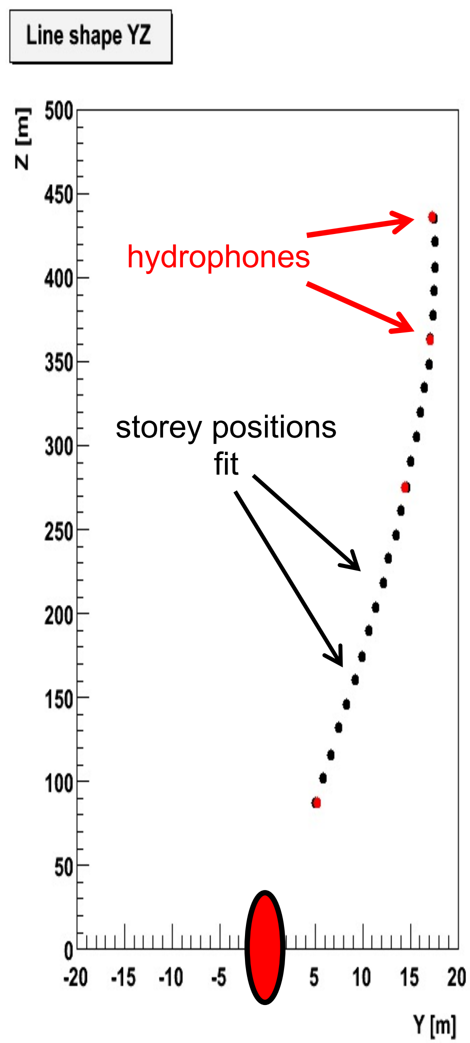


Optical Module:
10” Hamamatsu PMT in 17” glass sphere
photon detection
NIM A484 (2002) 369
NIM A555 (2005) 132

Hydrophone:
acoustic positioning
JINST 7 T08002

Detector Calibration



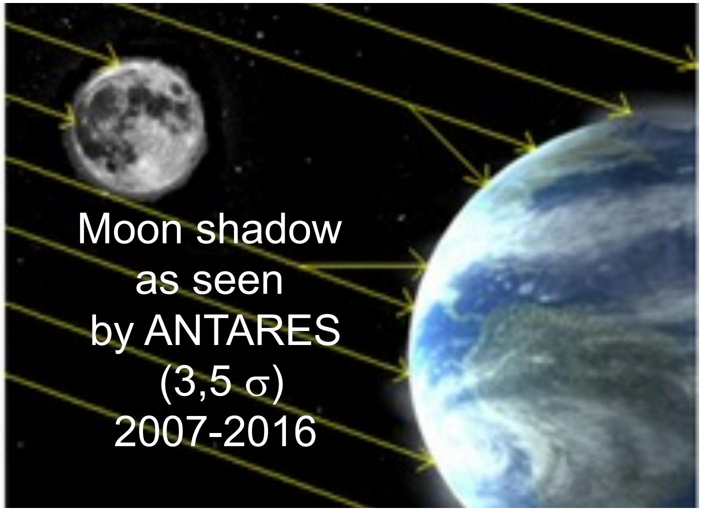


Led/laser beacons
Intense light:
PMT TTS
negligible

Timing resolution of electronics ~ 0.5 ns

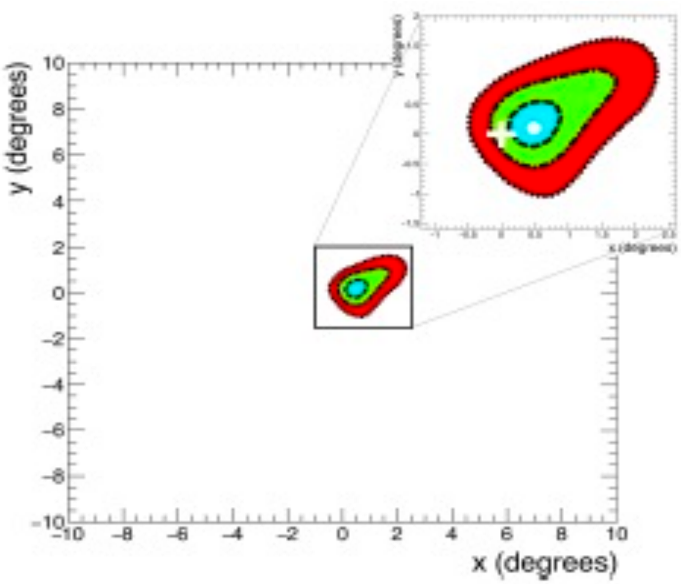
Positioning resolution < 10 cm

Absolute Pointing – Consistent with expectation

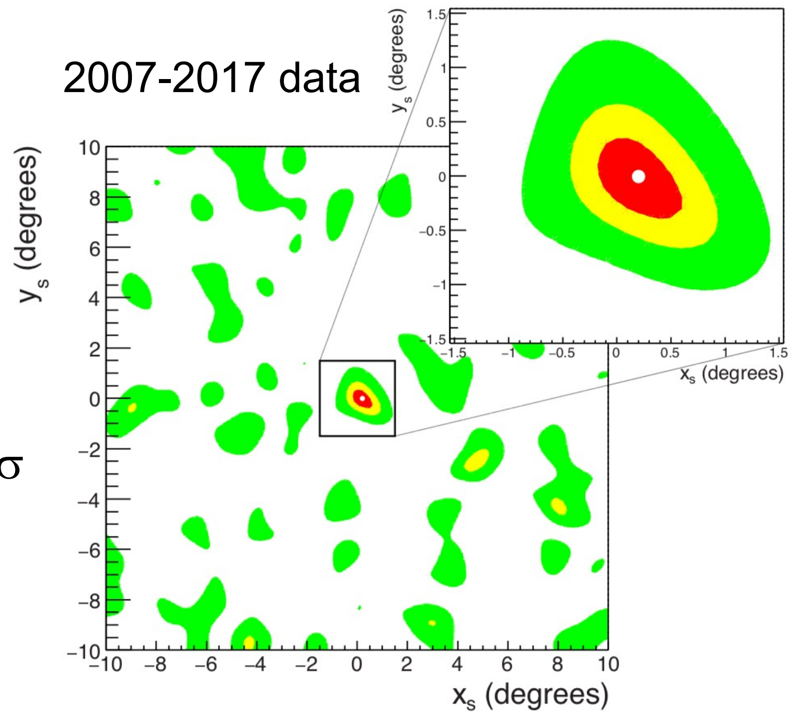


The Sun shadow is also observed with a statistical significance of 3.7σ, and an angular resolution of 0.59° ± 0.10° for downward-going muons.

2007-2017 data



1σ, 2σ, 3σ contours



📖 Eur.Phys.J. C78 (2018) no.12, 1006

📖 Phys. Rev. D 102, 122007 (2020)