The ANTARES adventure

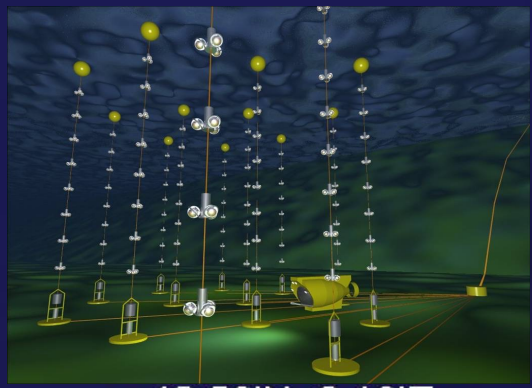
- The ANTARES detector
  - Construction and dismantling
  - Detection Principle
  - Calibration and performances
- Scientific Results
  - Earth and Sea science
  - Particle Physics
  - High-Energy Astrophysics
- Passing the baton

Antoine Kouchner
for the ANTARES Collaboration

Toulon

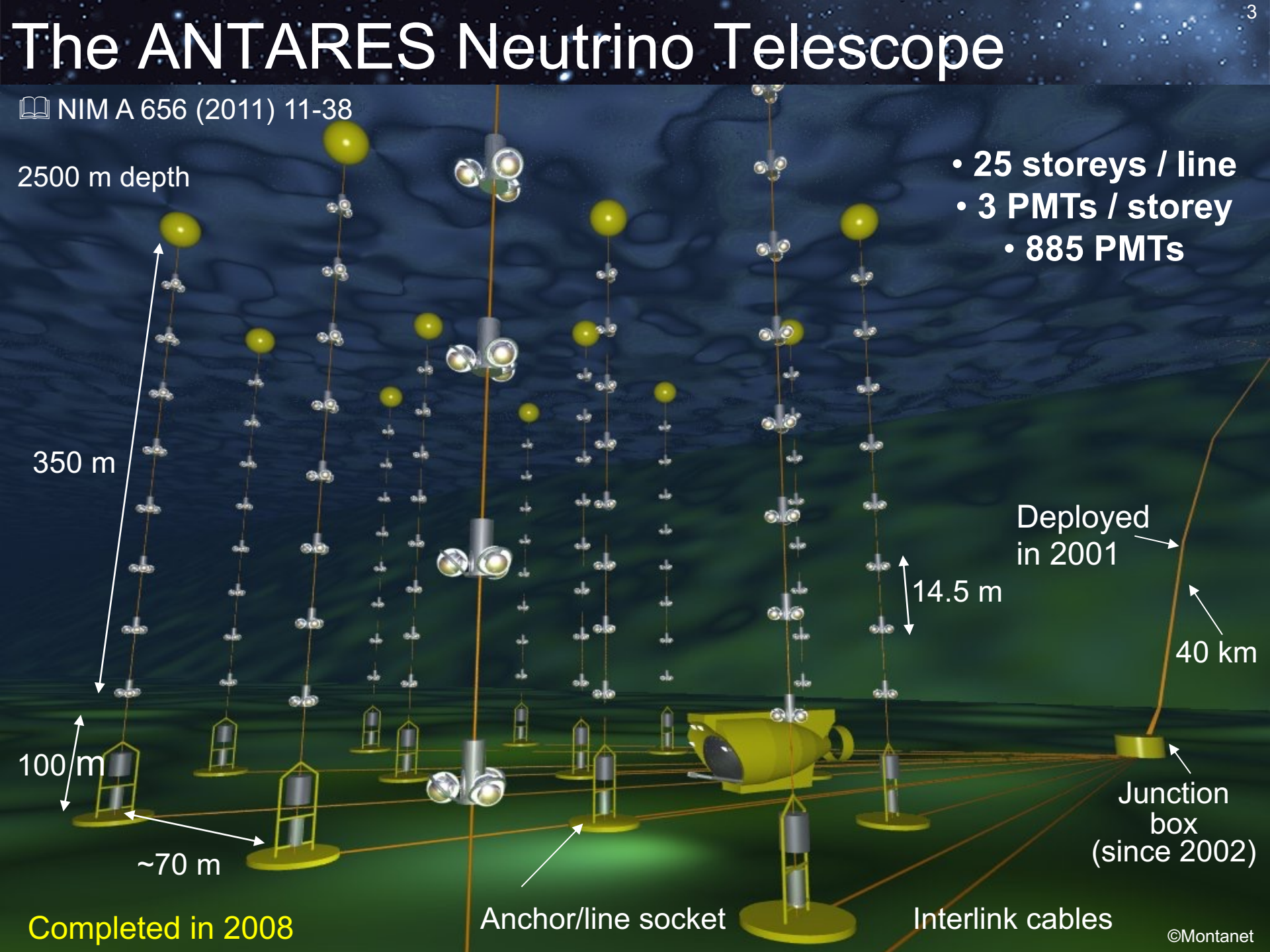
Institute Michel Pacha

Antares



42 50'N, 6 10'E

The ANTARES Neutrino Telescope

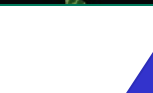


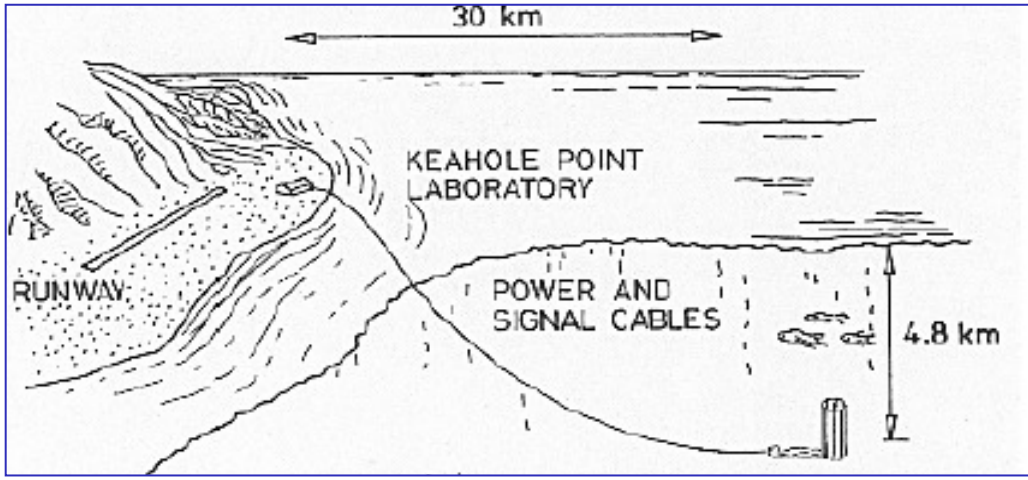
Why the Deep Sea ?

As early as the mid-70's yearly workshops about
Deep Underwater Muon And Neutrino Detector

December 1993: deployment of first string and connection to junction box. Failure after several hours

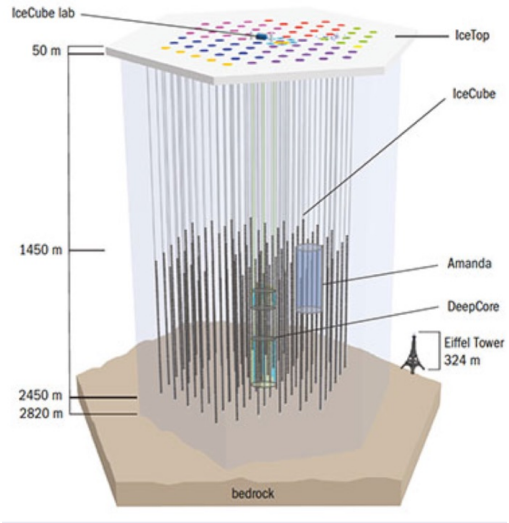
1995: DUMAND project is terminated



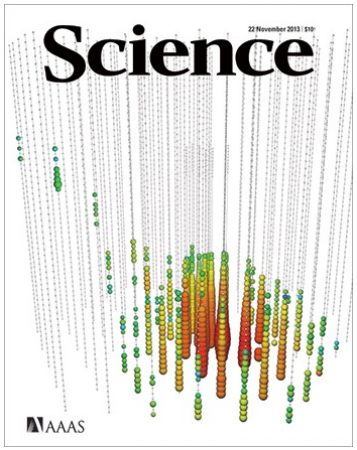


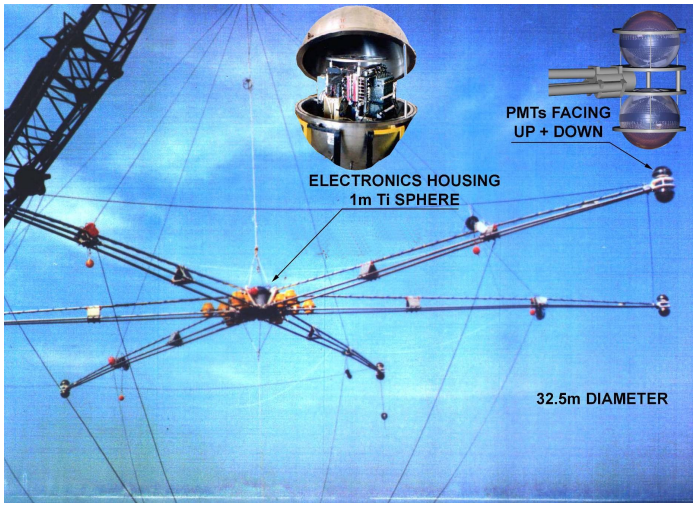
Ice

Sea



IceCube





Nestor

Why the Mediterranean Sea?

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites: 2500→5000m

  Shielding from downgoing muons

- Logistically attractive

  Close to shore (deployment / repair)

- Complementarity to IceCube South Pole

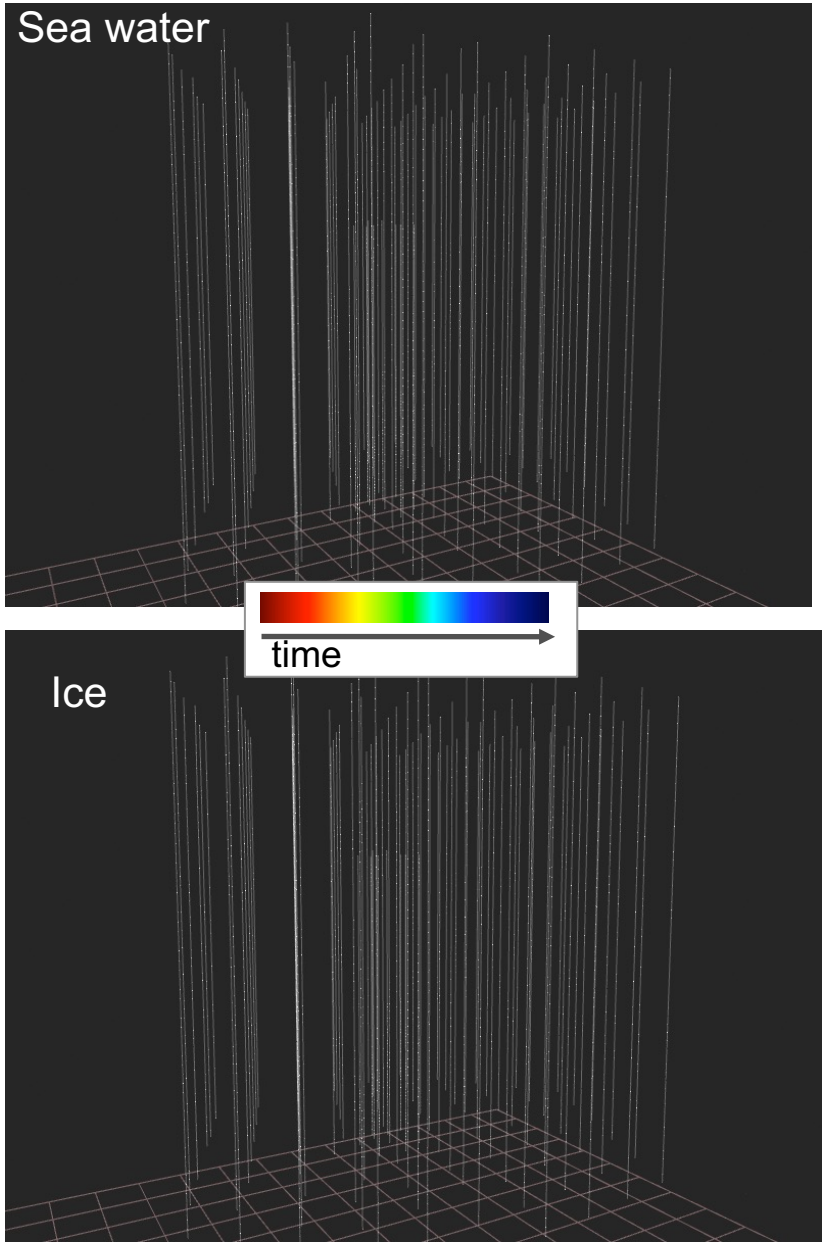
  Excellent view of Galaxy

- Mild Latitude

  On/off studies → Background control

- K40 optical background

  Useful calibration, but requires causality filters



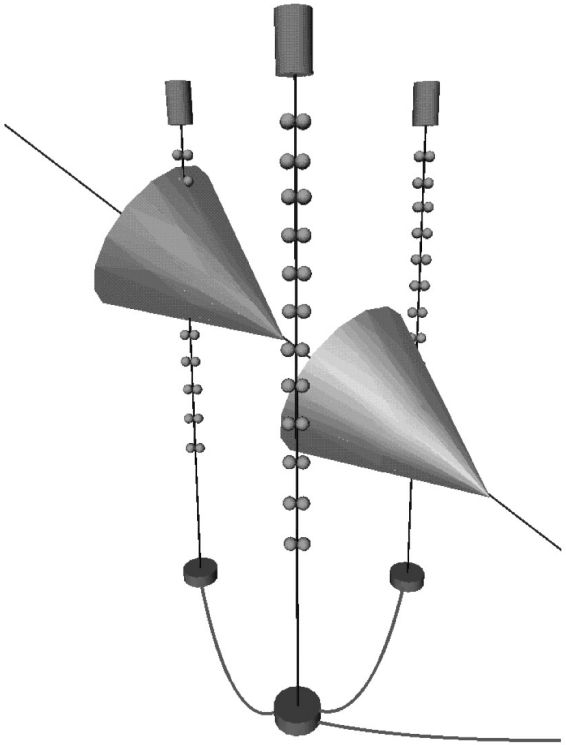
The first deep-sea Neutrino Telescope

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

ANTARES

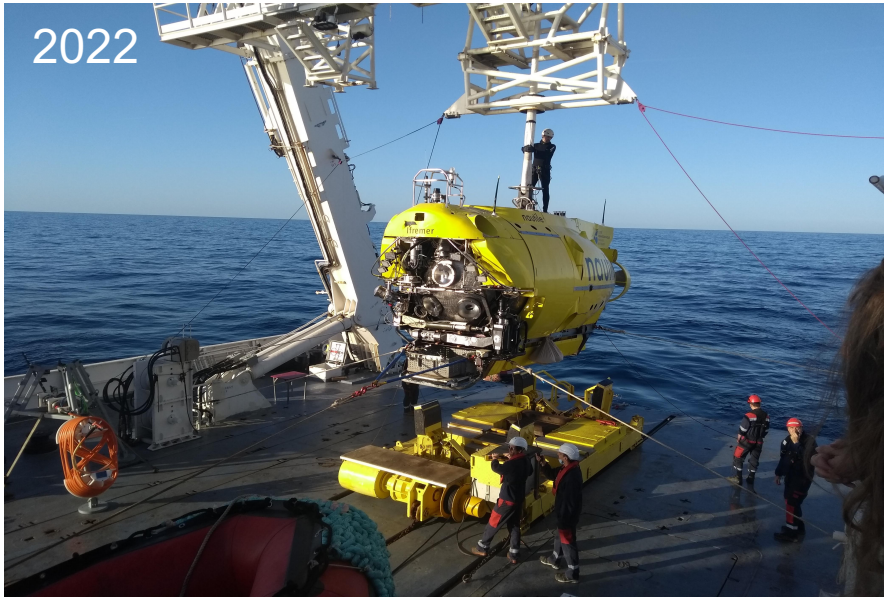
Astronomy with a Neutrino Telescope and Abyss environmental RESearch

TOWARDS A LARGE SCALE HIGH ENERGY COSMIC NEUTRINO UNDERSEA DETECTOR



PROPOSAL – May 1997

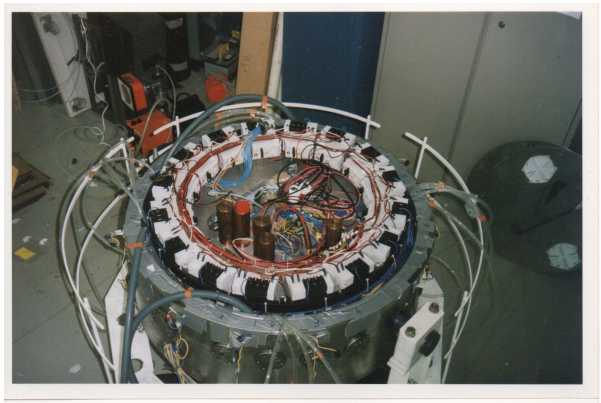
ANTARES 2001-2022

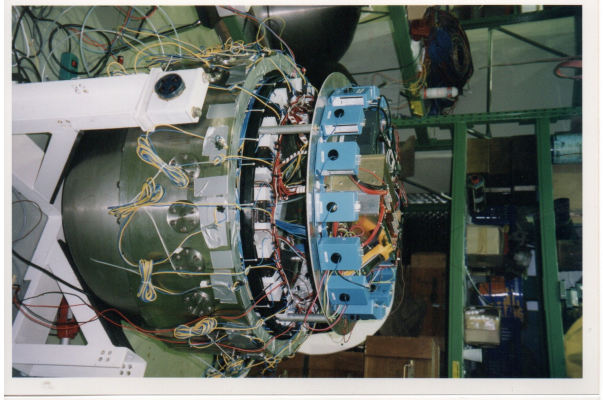


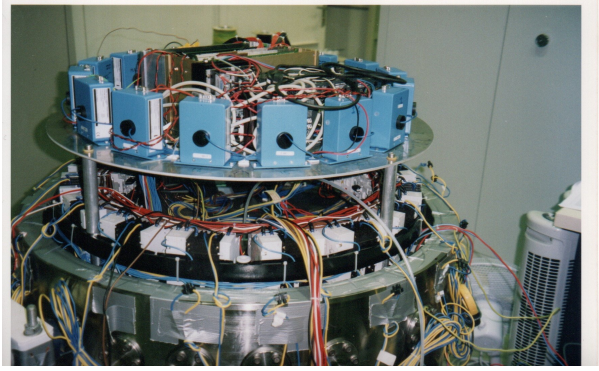
2001 Main Electro-Optical Cable
2002 Junction box
2003 Prototype Sector Line
2005 Mini Instrumentation Line with OMs
2006 First complete detector line
2008 Detector with 12 lines completed
2016 Running (almost) without common funds
2022 Data taking terminated

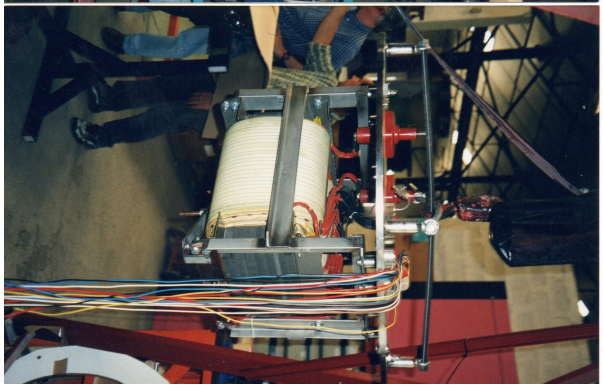
Main Electro-Optical Cable - 2001

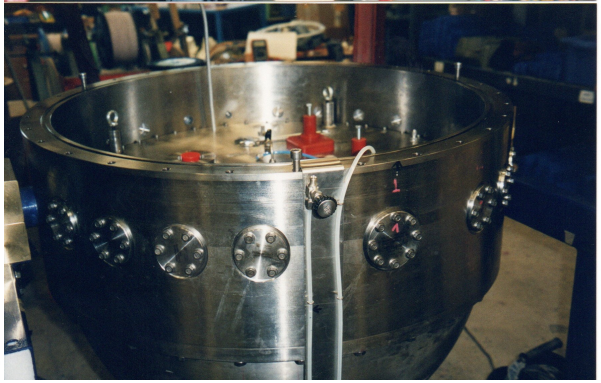
Junction Box 2002 – Construction



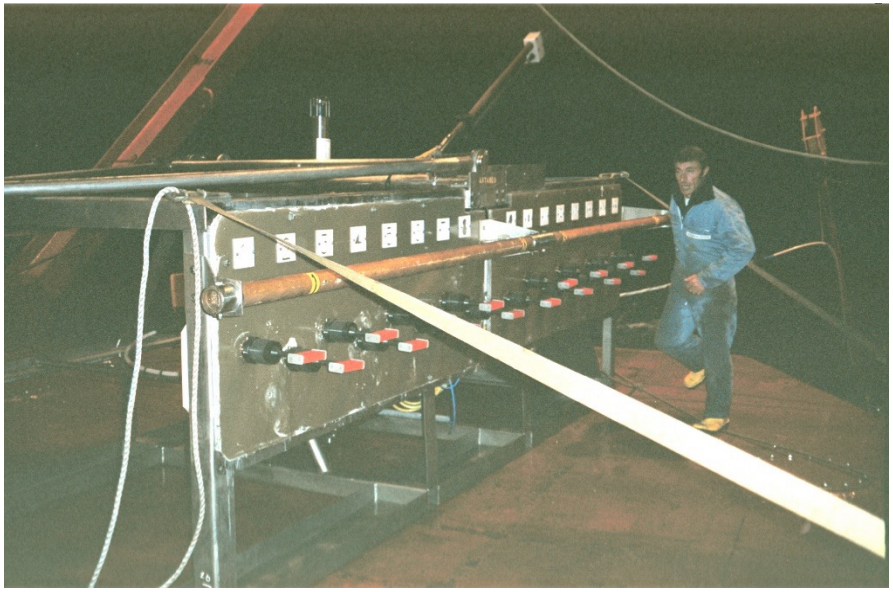


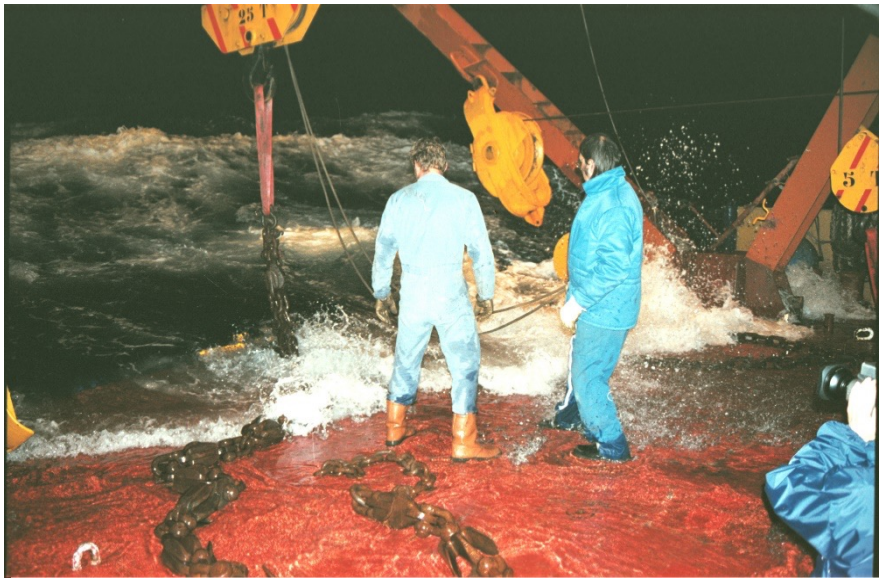






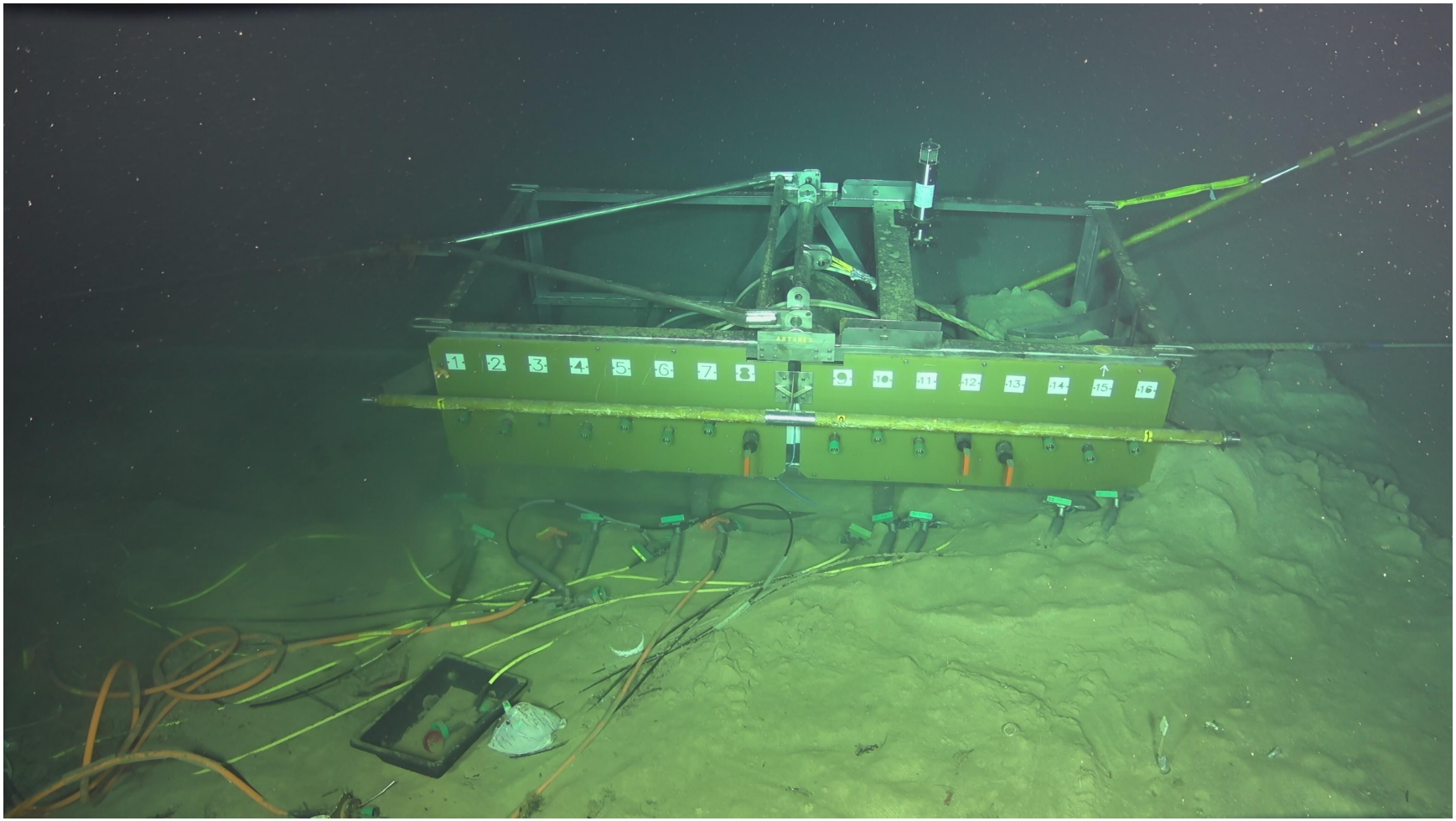
Junction Box 2002 – Deployment





Junction Box 2002

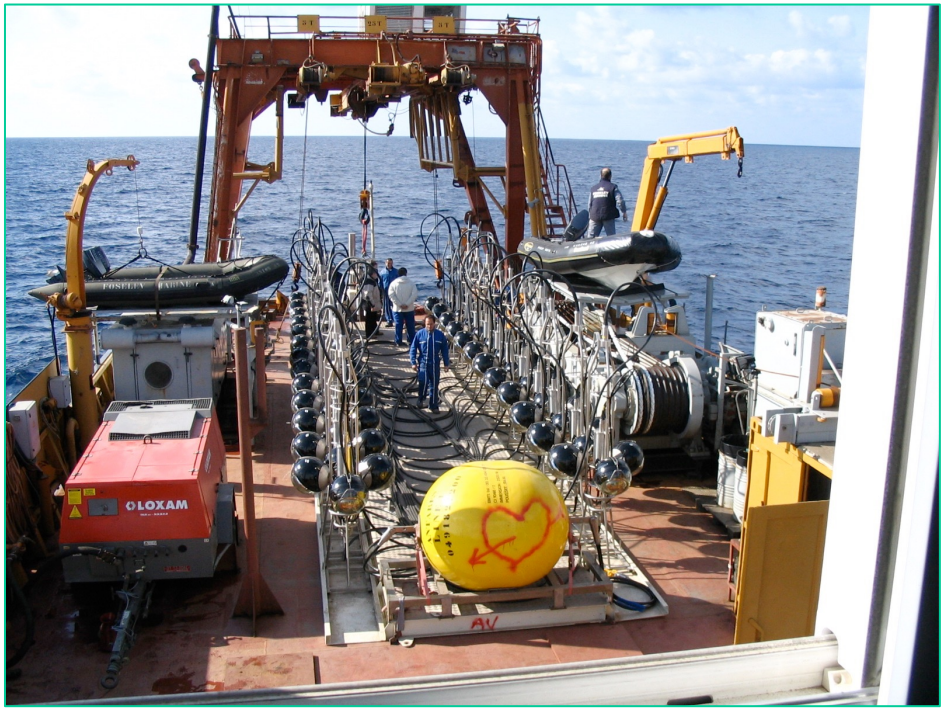
Worked reliably for 20 years
No failure, no repair needed
Waiting for recovery and potential second life?

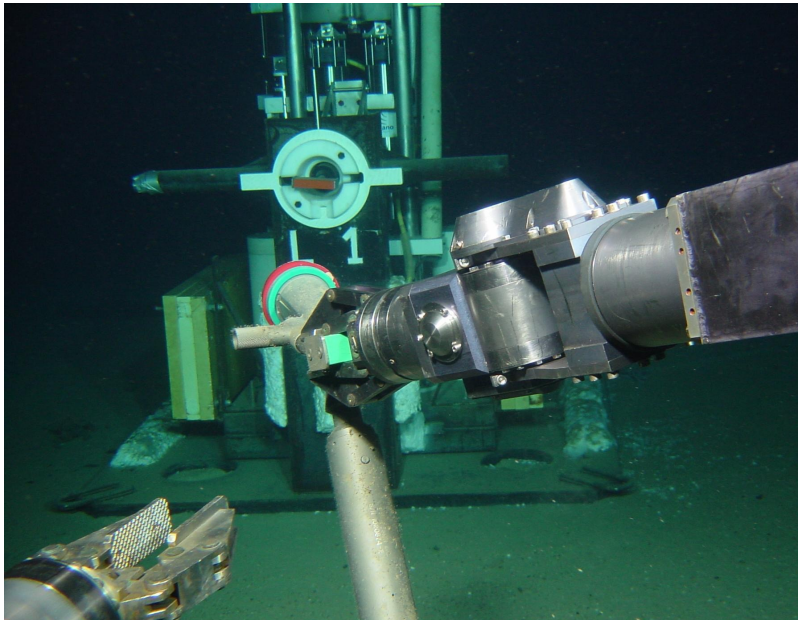


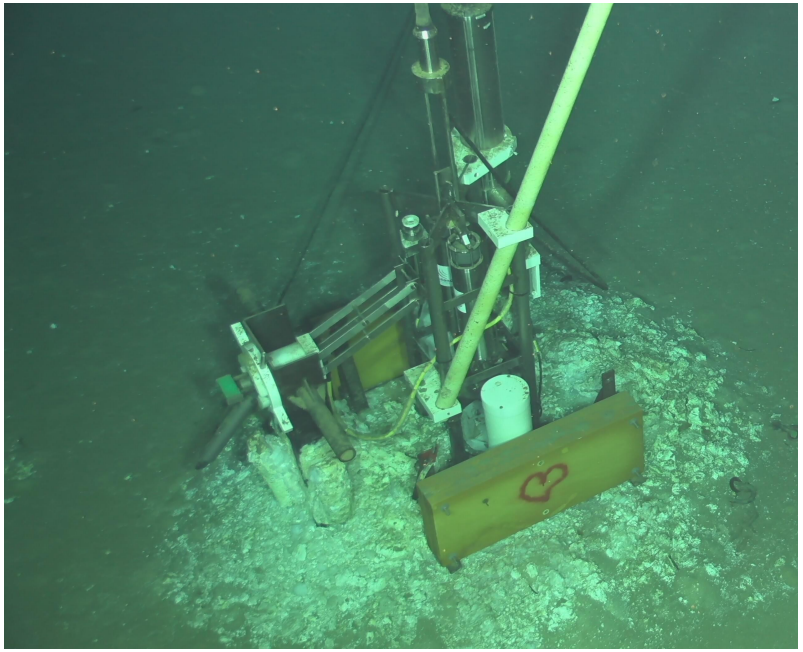
First complete detector line - 2006

First complete detector line – 2006 - 2022

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



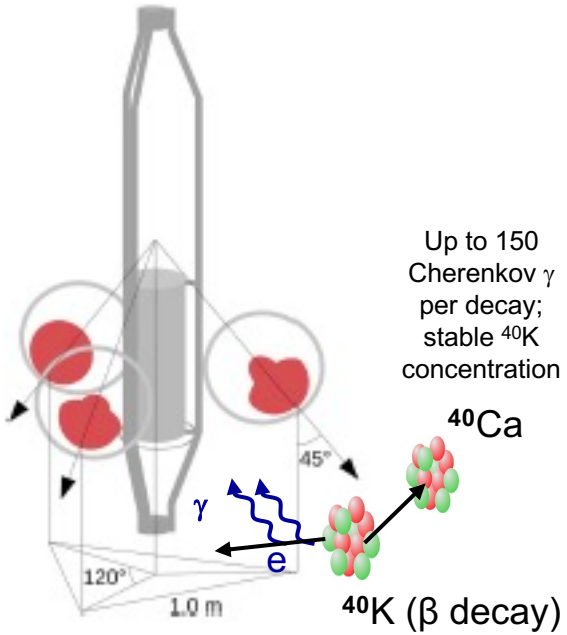


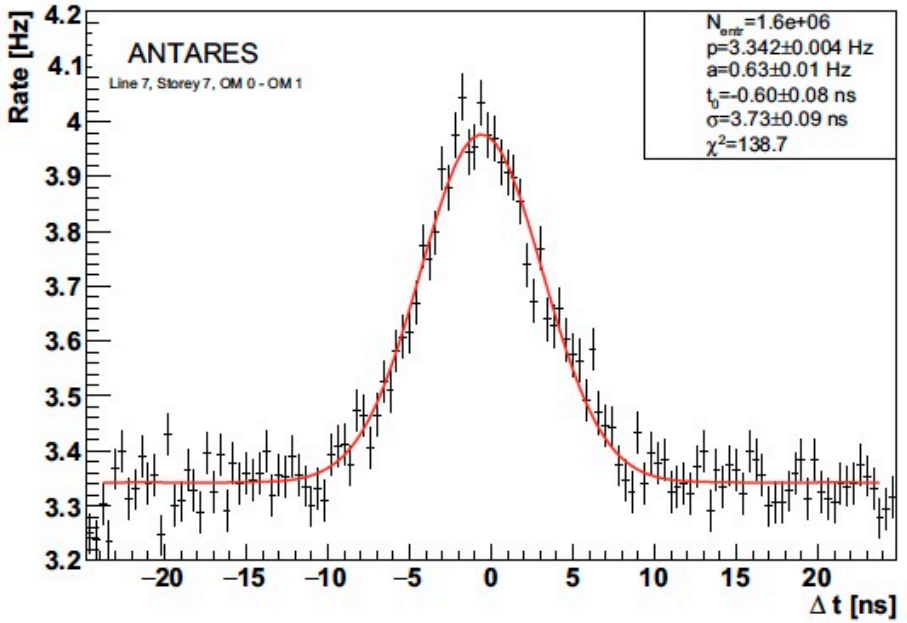


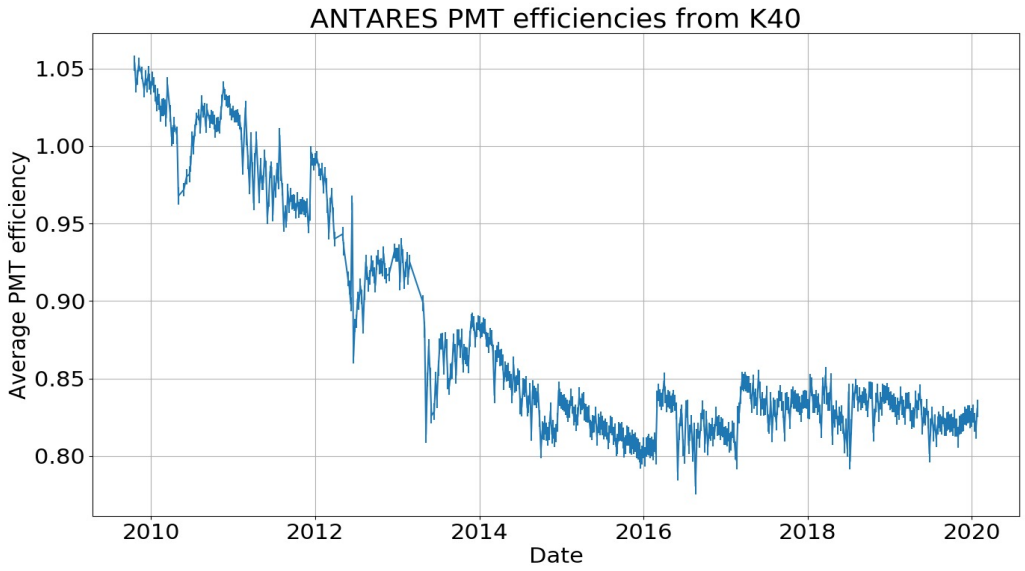
First part of recovery completed (6 lines)

Including Line 1, 16 years after…

^{40}K (long-term) monitoring







Regular tunings
Only ~20% efficiency loss

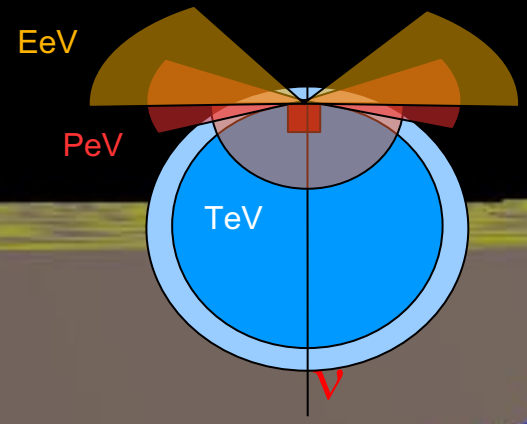
^{40}K powerful calibration tool

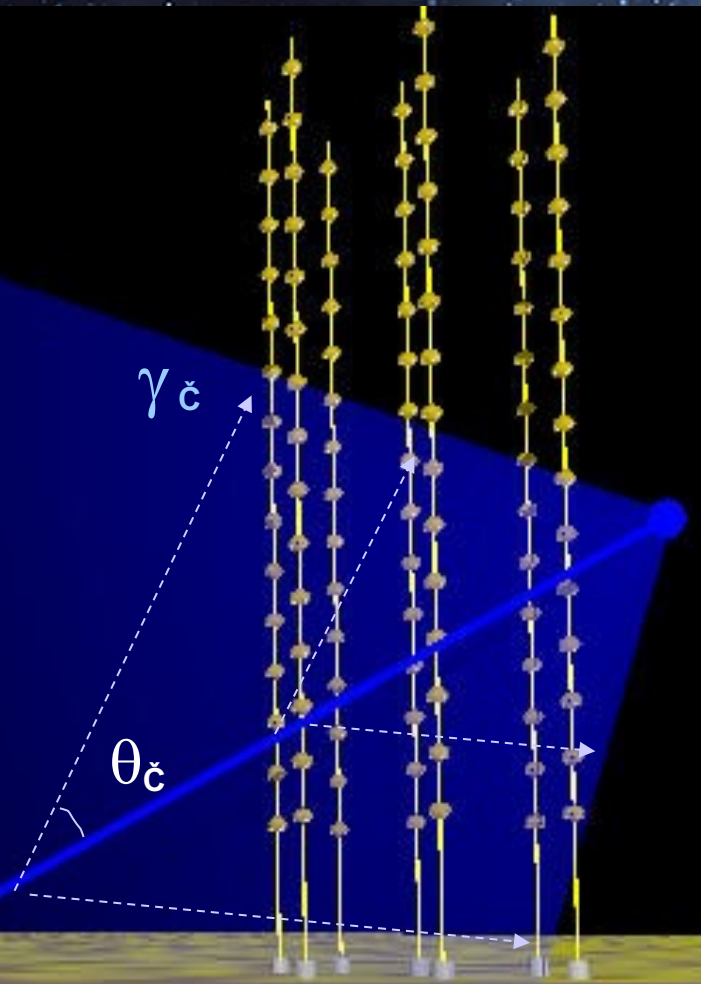
Eur. Phys. J. C (2018) 78: 669

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



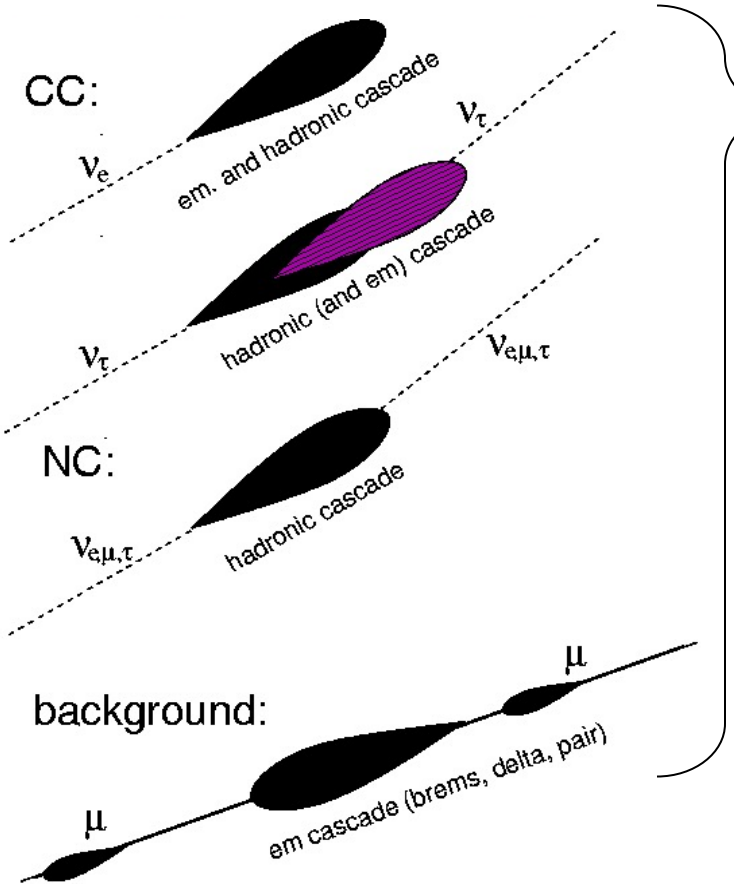


The track channel

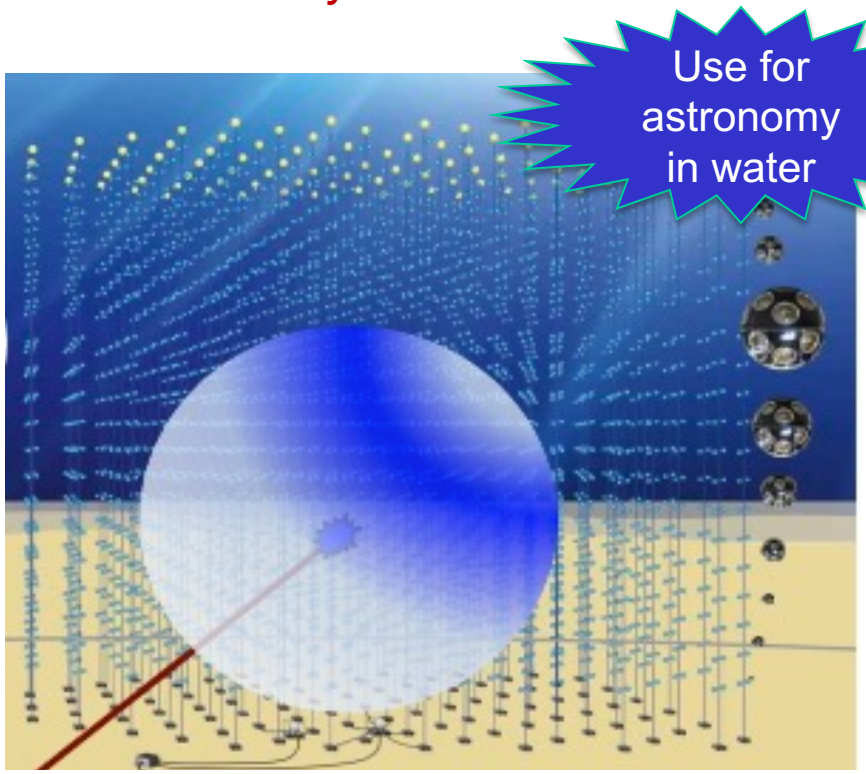
Time, position, amplitude of PMT pulses ⇒ μ trajectory

Cascade topology

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



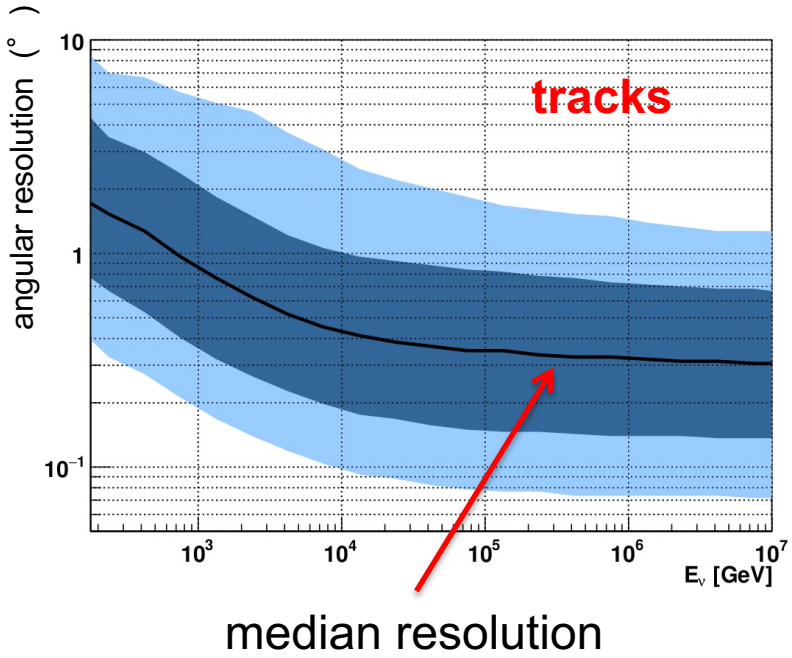
IceCube discovery channel



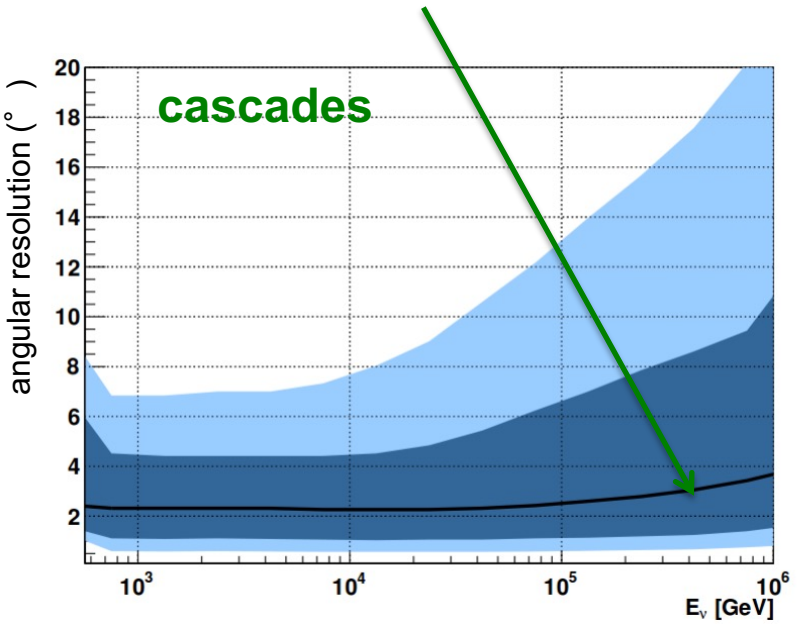
→ Provides sensitivity to all neutrino flavours – Increases overall sensitivity

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

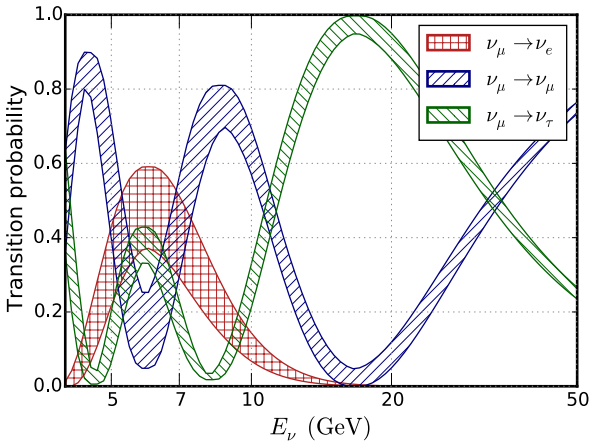


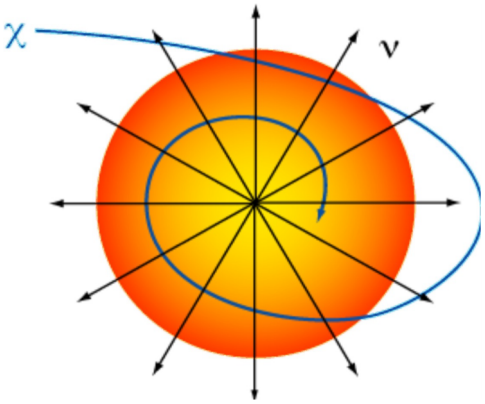
- Upgoing cascade events (ν_e / ν_τ CC, NC)
- Angular resolution < 3°
- Energy resolution for ν_eCC better than 10%

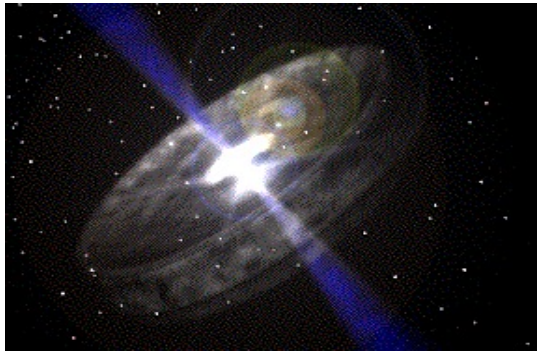


📖 ANTARES Monte Carlo, JCAP01 (2021) 064

Science scope







Low Energy
> 10 GeV

Medium Energy
10 GeV < E_ν < 10 TeV

High Energy
E_ν > 1 TeV

E

ν Oscillations

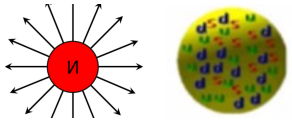
Dark matter search

Talk by Adrian Saina

ν from extra-terrestrial sources

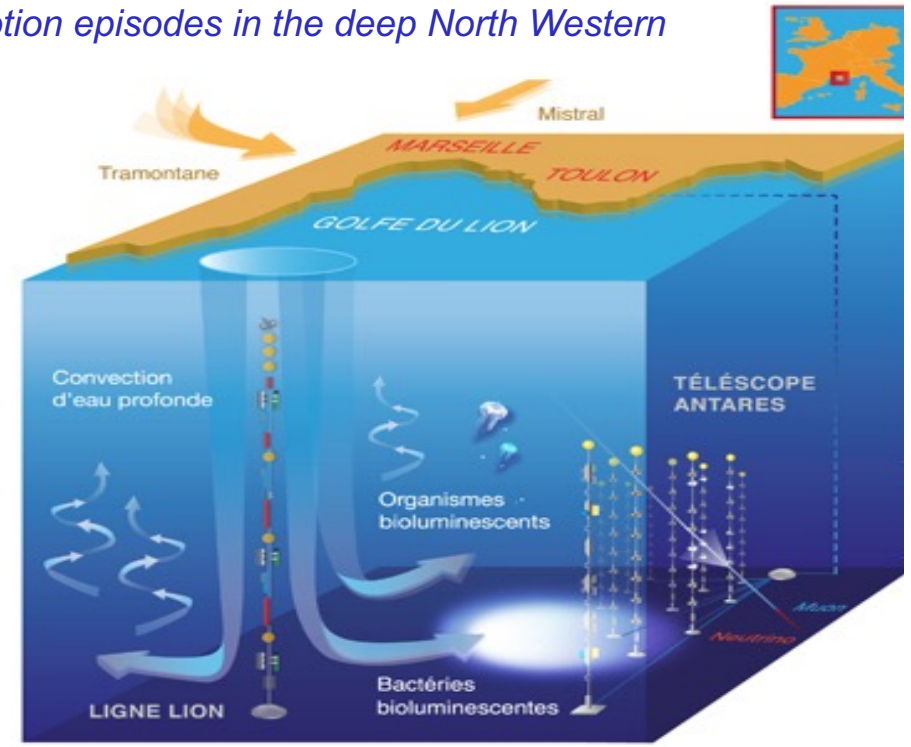
Origin and production mechanism of high-energy Cosmic-rays

+ Exotic searches



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

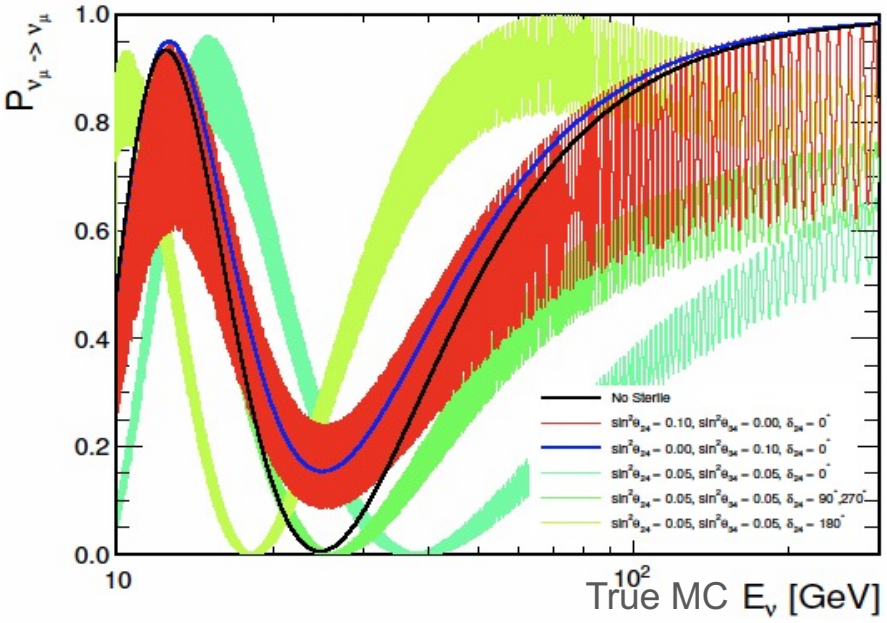
📖 *J of Geophysical Research: Oceans, 122, 3, 2017*
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

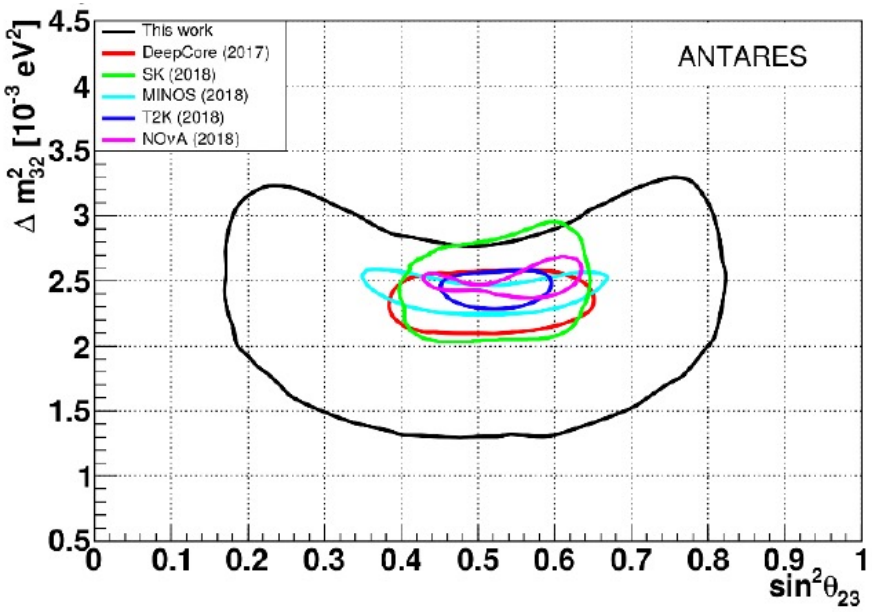
📖 *Sci. Rep. 7 (2017) 45517*
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

📖 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 ($\log_{10}(E_{reco})$, $\cos\theta_{23}^{reco}$)
- Sample soon public

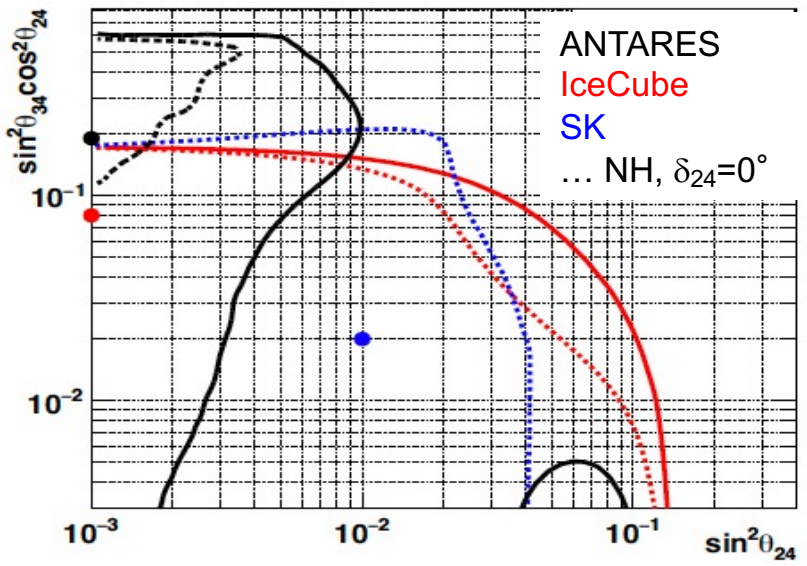
No-oscillation hypothesis excluded at 4.6σ

Updated Oscillation Studies Sterile & NSI

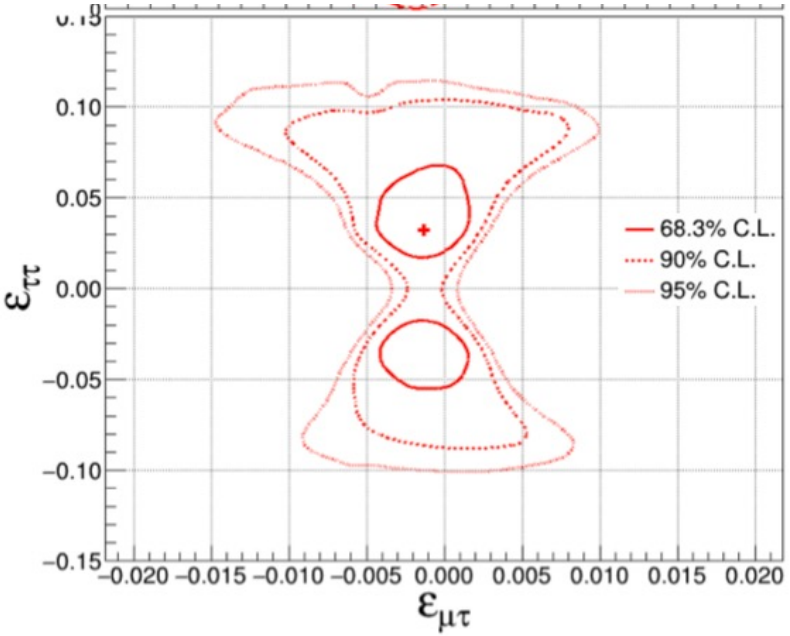
- (3+1) sterile neutrino models $\Delta m^2_{41} > 0.5\ eV^2$
- Tight complementary information to eV-scale sterile neutrino searches

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

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

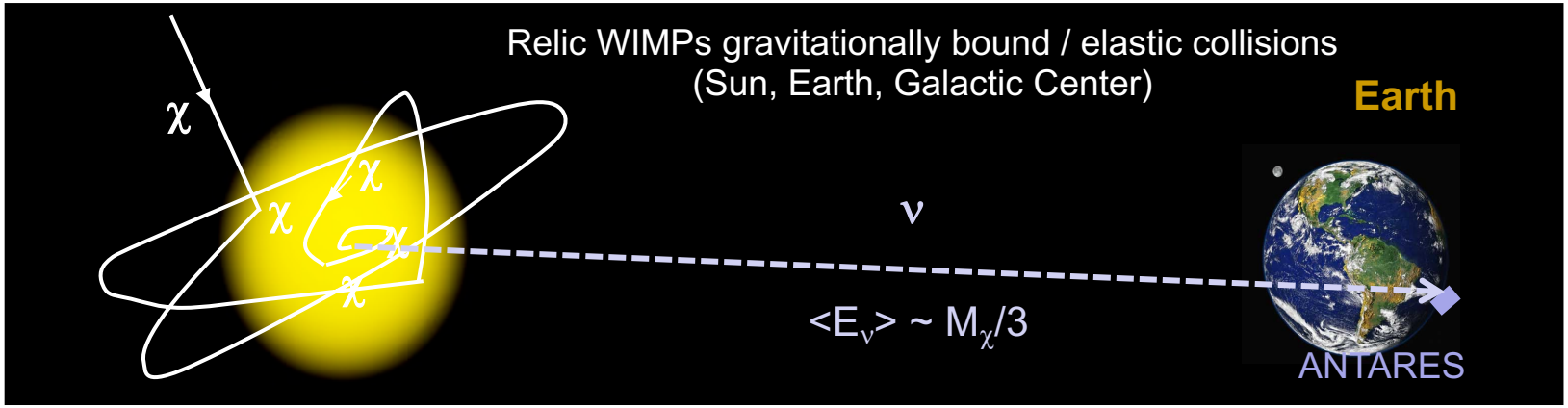


- Non-standard interaction signature in neutrino oscillation patterns are detectable
- Mild hint for non-standard interactions observed in 10 years of ANTARES data
- The non-NSI hypothesis is disfavoured with a significance of 1.7σ (1.6σ) for the normal (inverted) mass ordering scenario.



📖 http://arxiv.org/abs/2112.14517

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

arXiv:2203.06029
Phys. Lett. B 805 135439 (2020).
Phys. Rev. D 102, 082002 (2020)
Phys. Let. B 769 (2017) 249
JCAP 10 (2015) 068

Talk by Adrian Saina

Competitive limits !

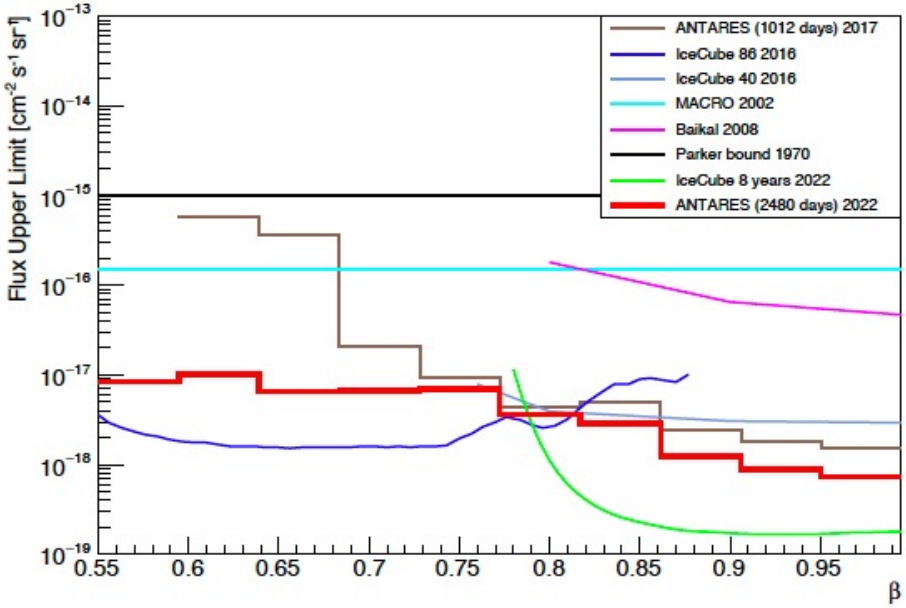
Our analyses do not include showers (all flavors) yet

Improvements ahead

Search for Exotic Physics with ANTARES

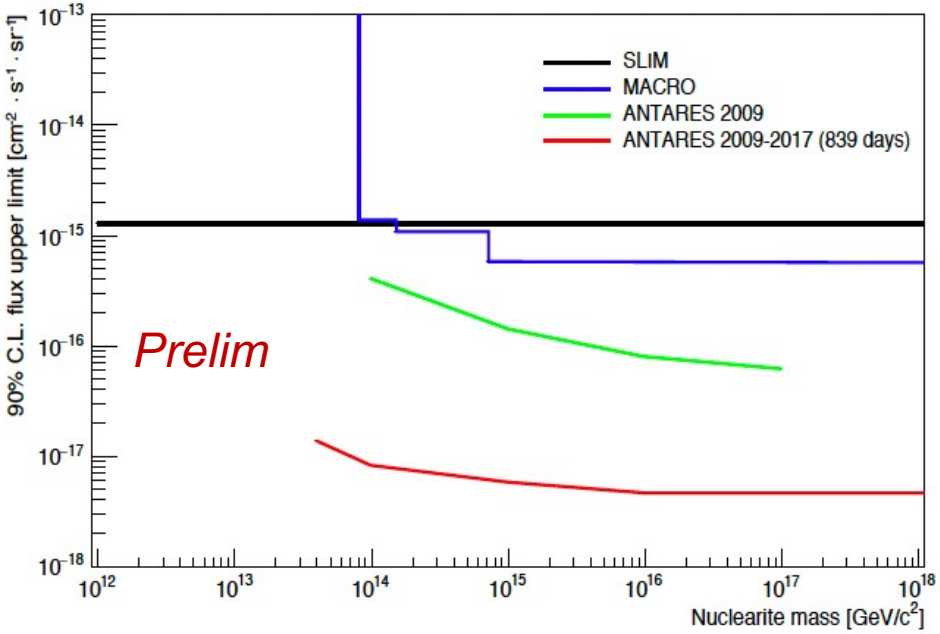
Monopoles

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



Nuclearites

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



📖 JHEAp, Volume 34, 2022, Pages 1-8

10 year sample

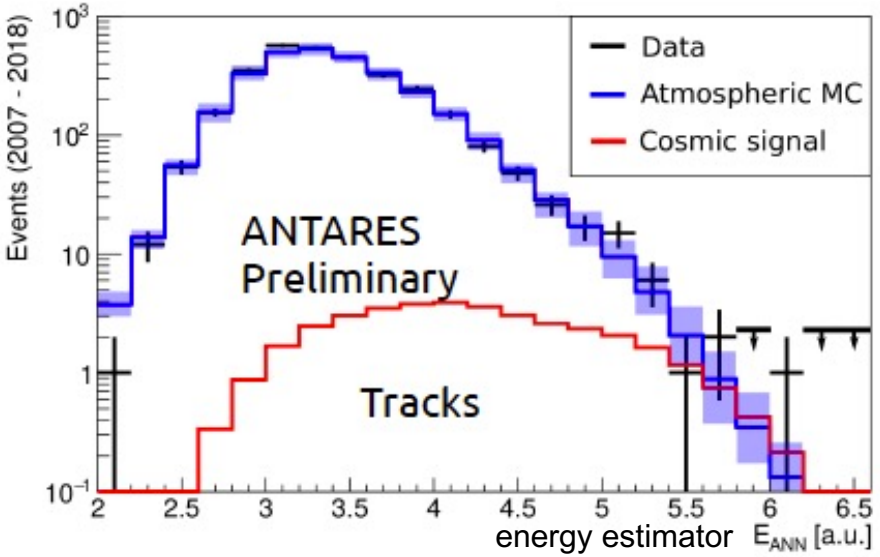
Diffuse flux

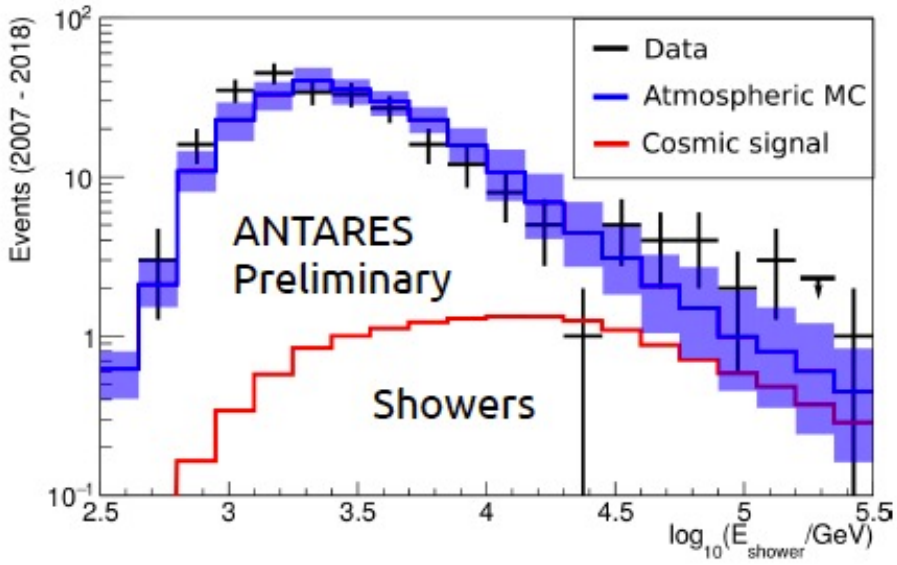
https://pos.sissa.it/358/891/pdf (ICRC 19)

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.

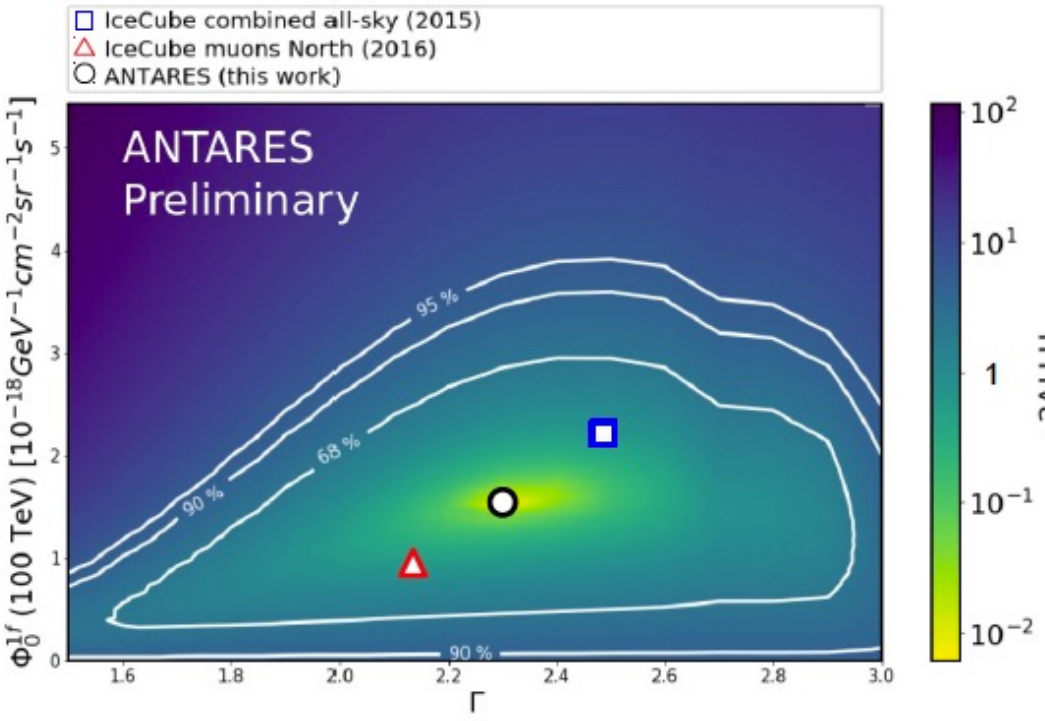
Results not really constraining… but fully compatible with IceCube

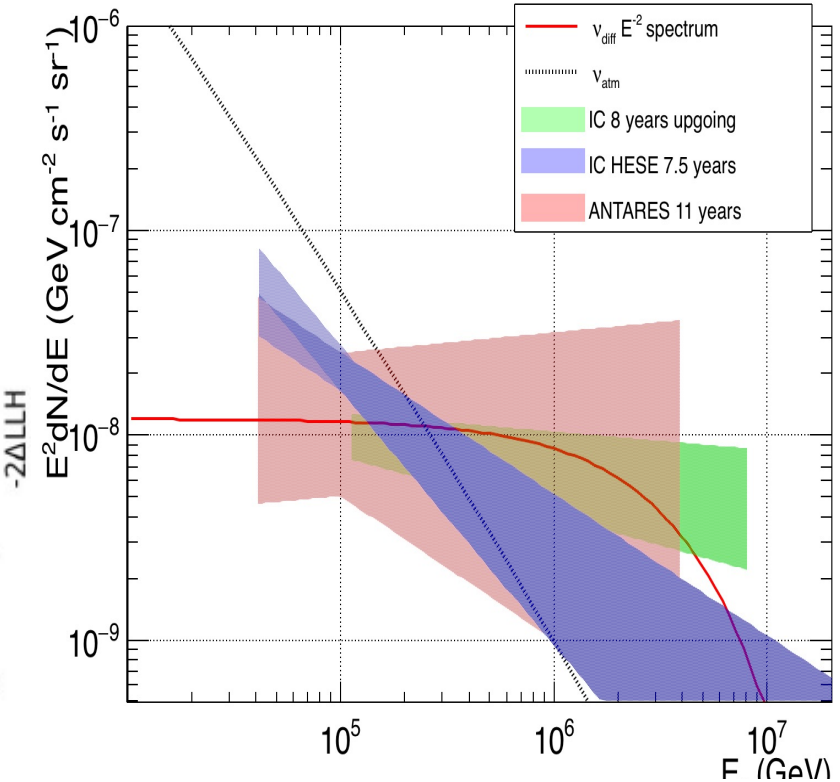
Diffuse flux – Towards a confirmation of IC ?

Combined (tracks+showers) likelihood fitting:

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

$\Gamma = 2.3 \pm 0.4$

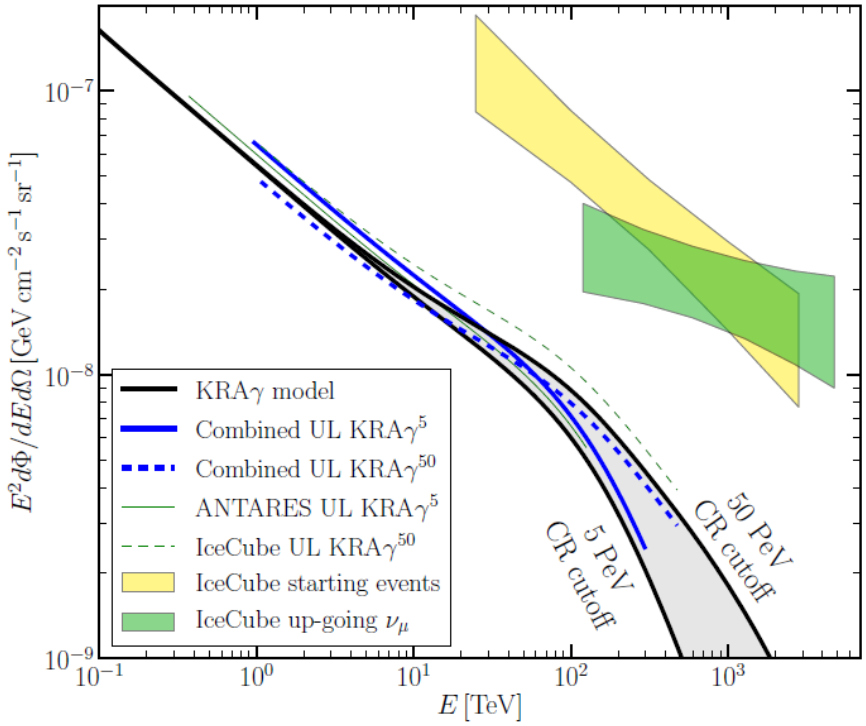




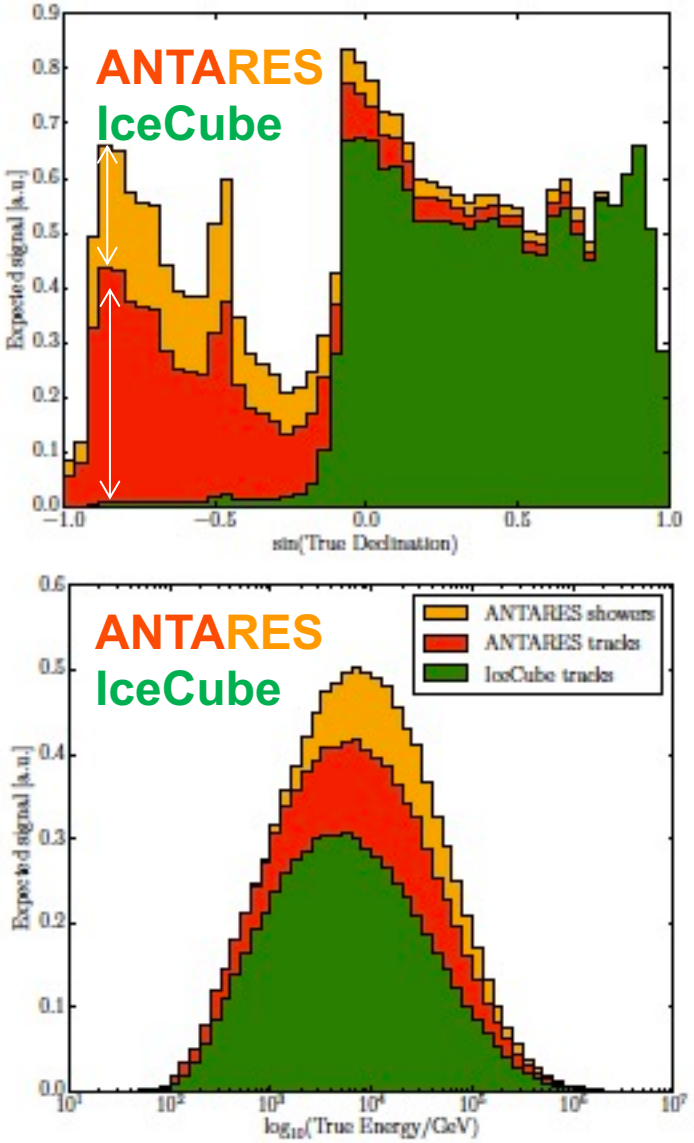
Results not really constraining… but fully compatible with IceCube

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

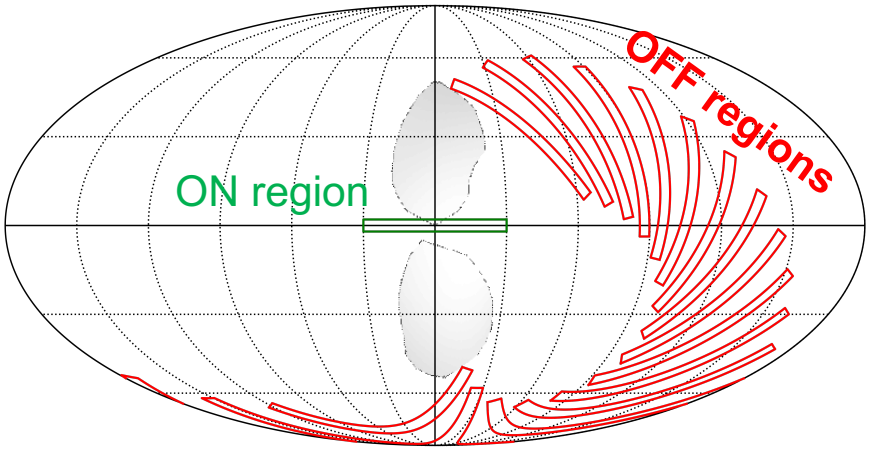


Result: total flux contribution of **diffuse Galactic neutrino** emission <9% *of the total diffuse IC astrophysical signal (E_ν>* 30 TeV)
Updates ongoing…

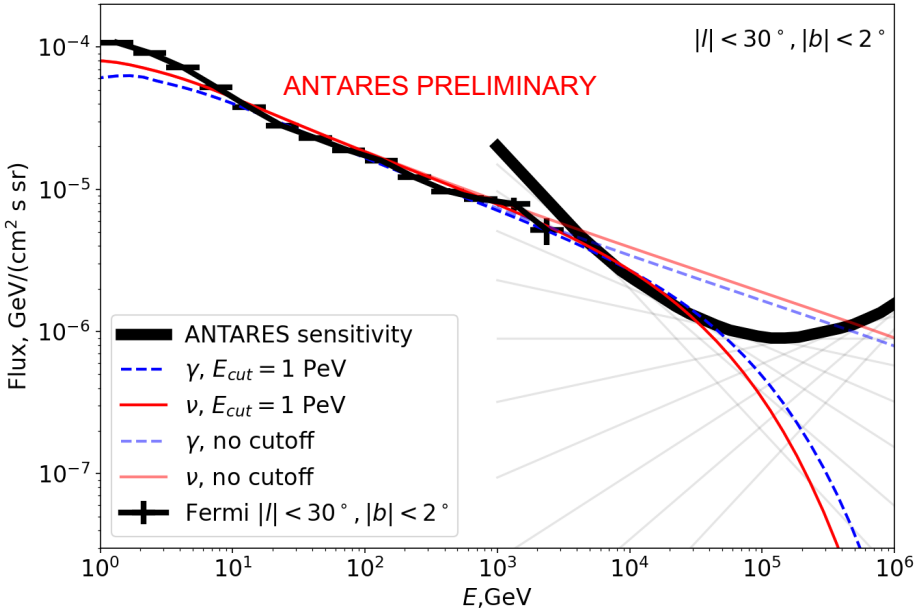
📖 Phys. Rev. D 96, 062001 (2017)
📖 ApJL 868, L20 (2018)

Simpler ON/OFF approach

Galactic ridge region definition:
$|l| < l_{ridge} \approx 30\text{-}40°$ and $|b| < b_{ridge} \approx 2\text{-}3°$



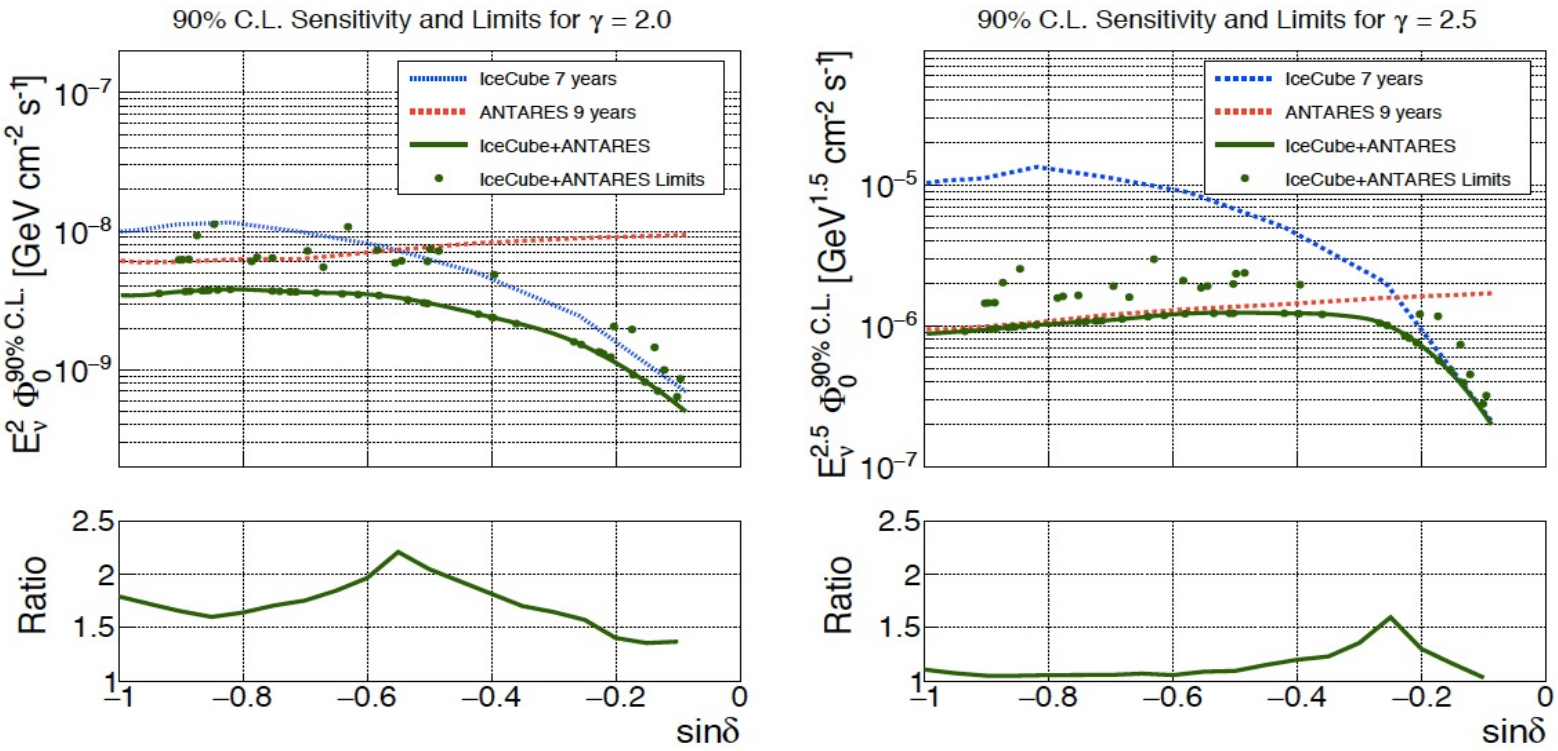
Robust background estimate



Using the full ANTARES dataset, we expect to see evidence for a neutrino signal from the Ridge if the spectrum of cosmic rays has a harder slope, as suggested by gamma-ray data, and if it does not have a cut-off below 1 PeV.

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

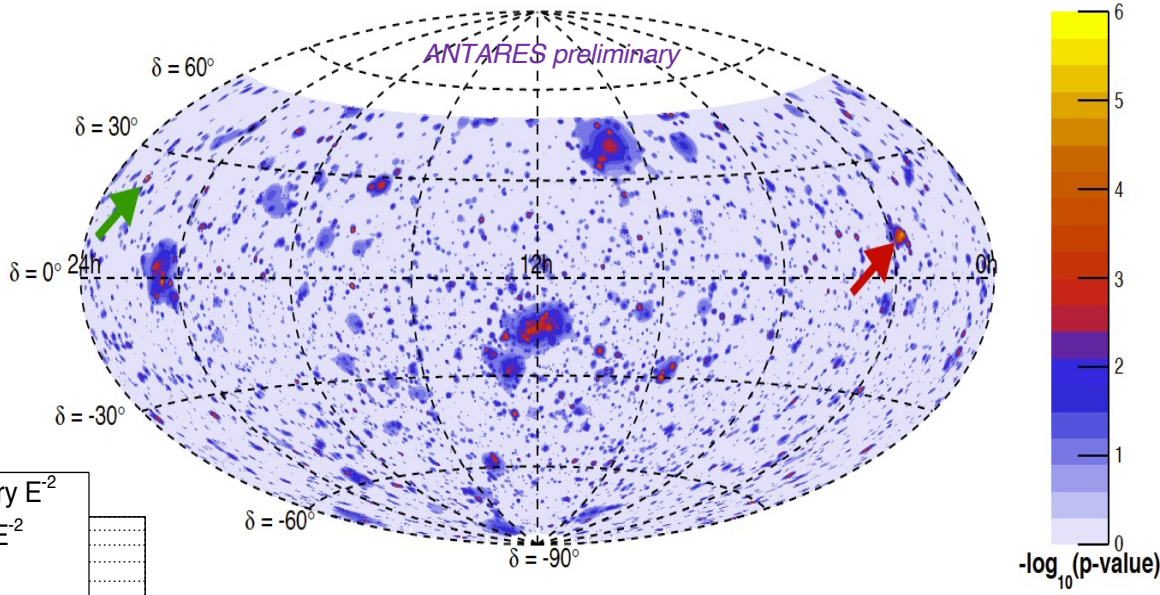
📖 The Astrophysical Journal 892 (2020) 2

Latest PS search – All flavours !

Data set:

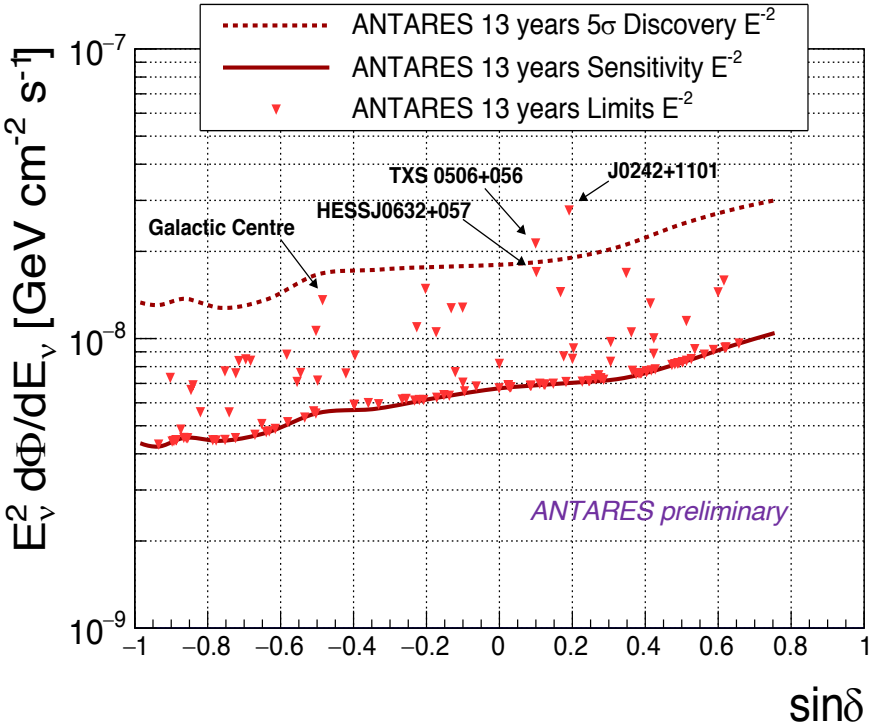
Period: from Jan 2007 to Feb 2020
Livetime: 3845 days
Events: **10162 tracks** and **225 showers**

Full-sky search



Candidate-list search:

121 investigated sources



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

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

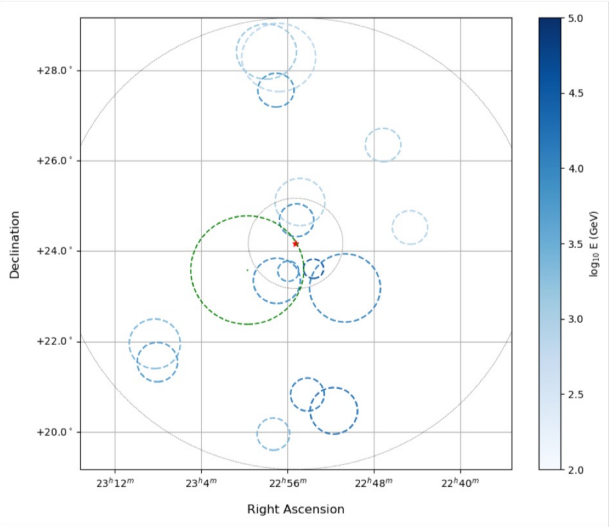
Catalog-based searches

📖 A. Albert et al. 2021 ApJ 911 48

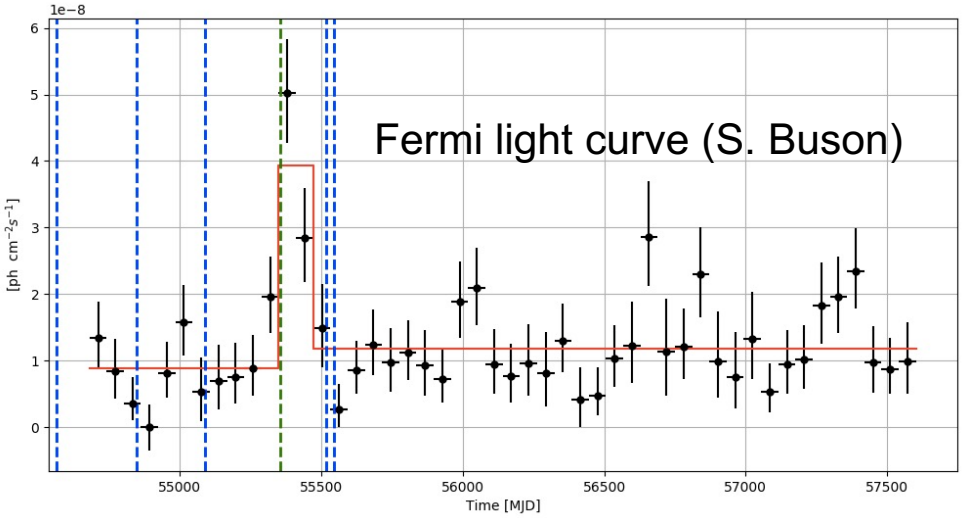
Likelihood based stacking approach

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	1.6 σ
IC HE tracks	0.05	0.49	

Blazar MG3 J225517+2409
ANTARES & IceCube tracks



Mild excess seen for radio galaxies

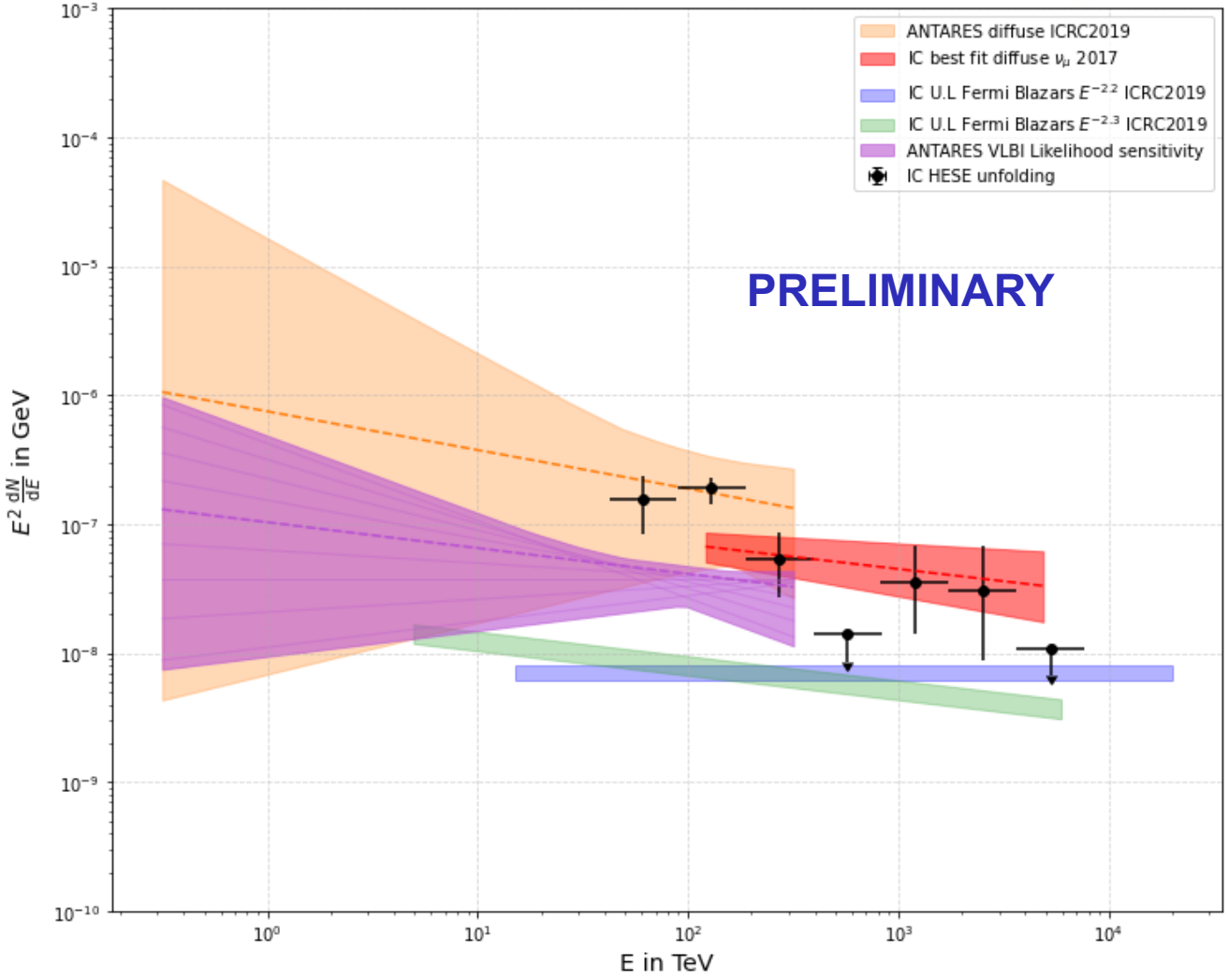


Space-time association: ANTARES -> **2.3σ** & IceCube track -> **2.6σ**

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)



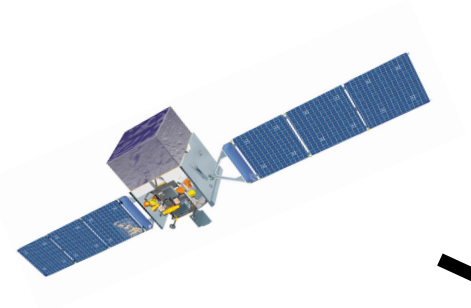
The multi-messenger program

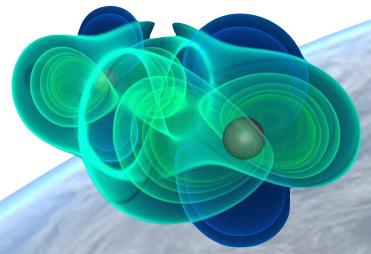
1ST APPROACH:

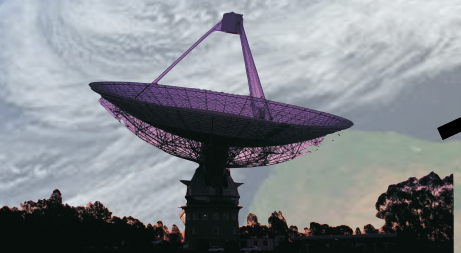
Time dependent searches

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

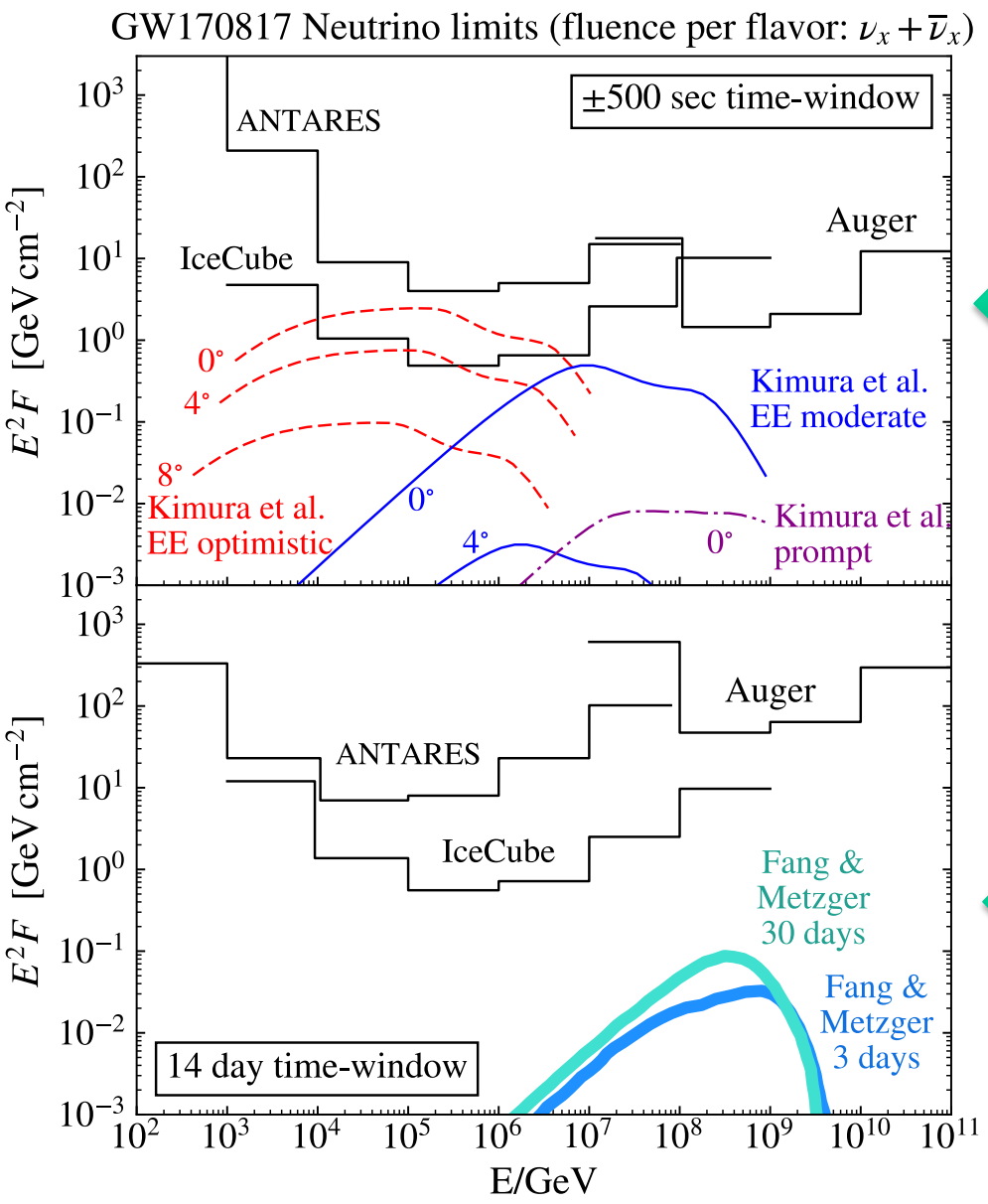
NT can guide optical follow-up







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

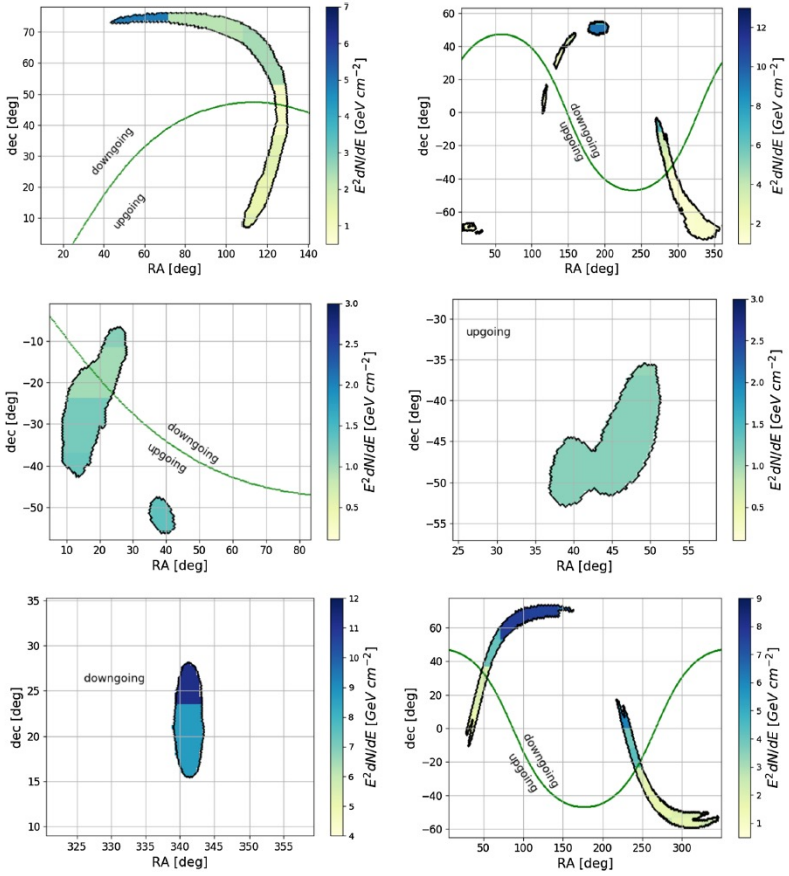
Model prediction:
Kimura et al. ApJL 848, L4

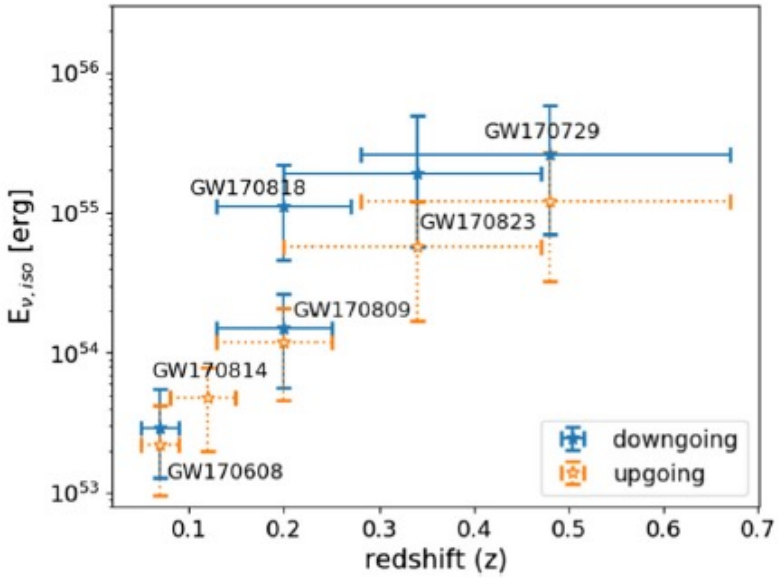
No detection during extended time period of 14 days after the GRB

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

Follow-up of Gravitational Waves (O2)

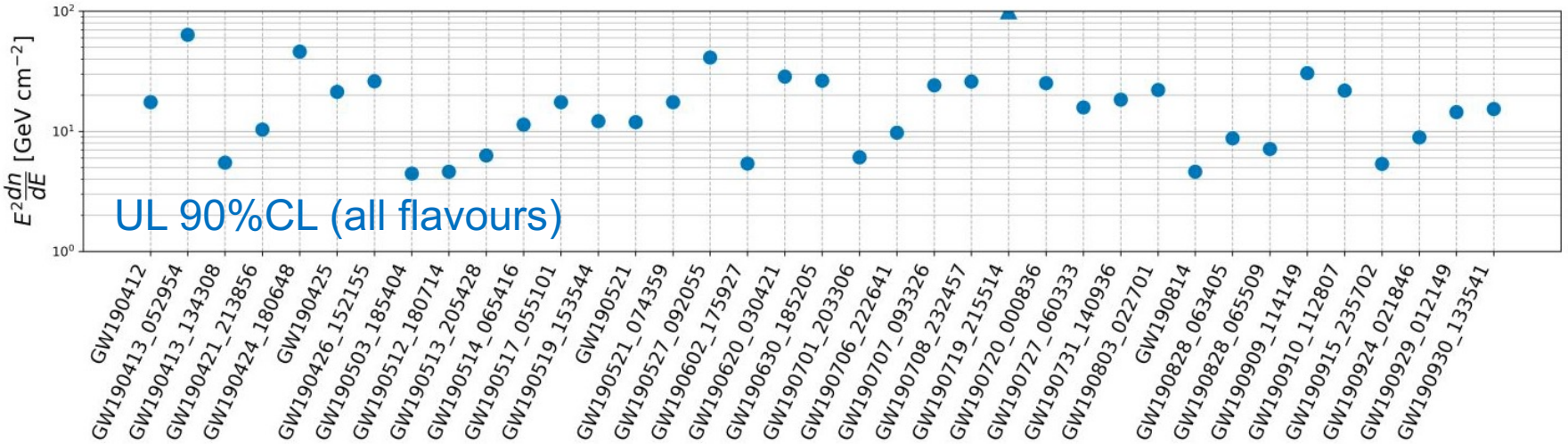
- Online alerts followed. Results from counterpart searches after 24hr through GCN
- Refined offline searches (fully calibrated sample): No events found → limits set.
- Latest O2 BBH: Constraints on fluence and $E_{\nu,iso}$ for BBH



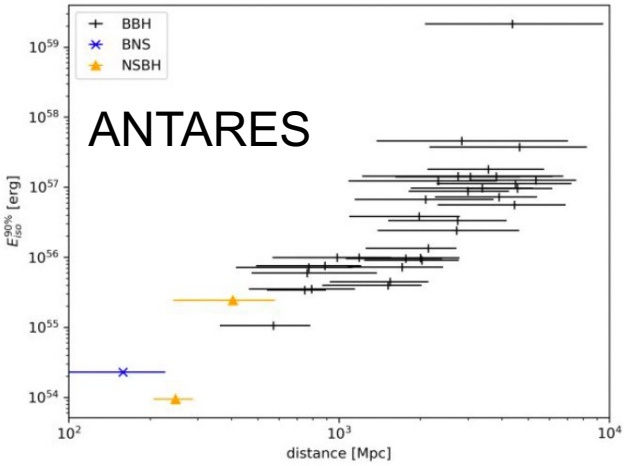


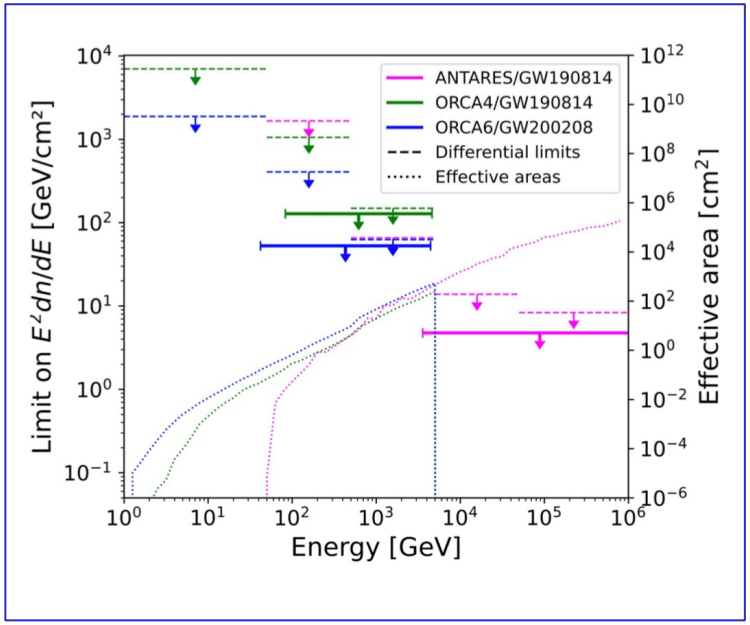
- Eur. Phys. J. C 80, 487 (2020)
- ApJ 870 (2019) 2
- ApJL 848 L12 (2017)
- ApJL 850 L35 (2017)
- Phys. Rev. D 96 (2017) 022005
- Phys. Rev. D 93 (2016) 122010
- JCAP06(2013)008

Follow-up of Gravitational Waves (O3)



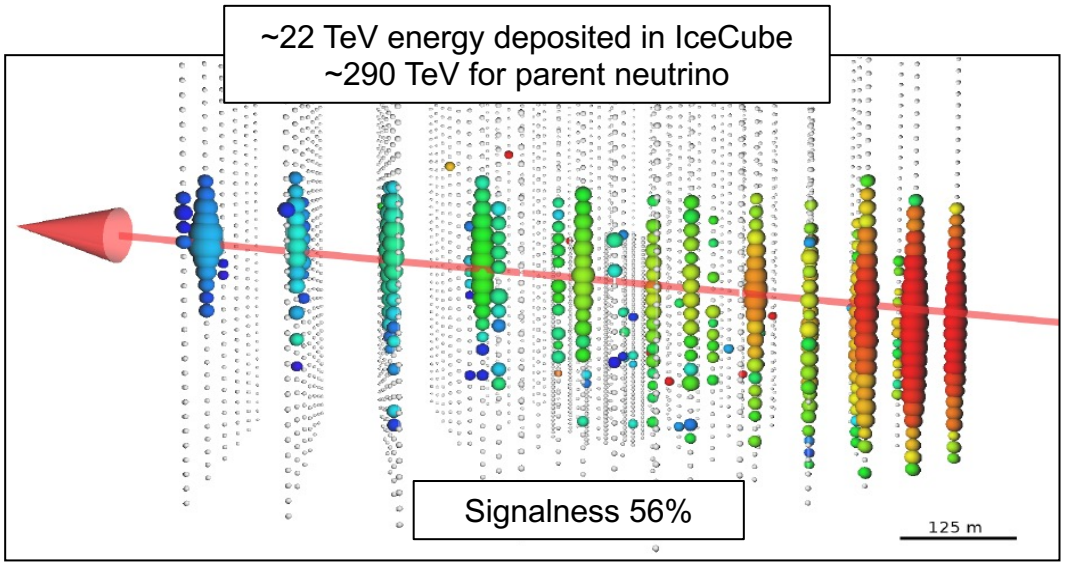
UL on total E in n 90%CL (all flavours)

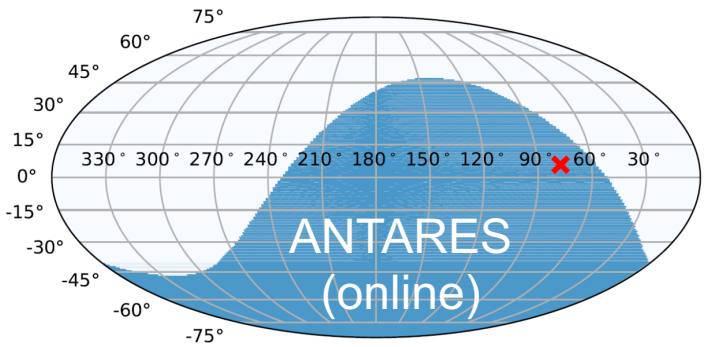




And ORCA for some cases !

Follow-up of ICECUBE-170922





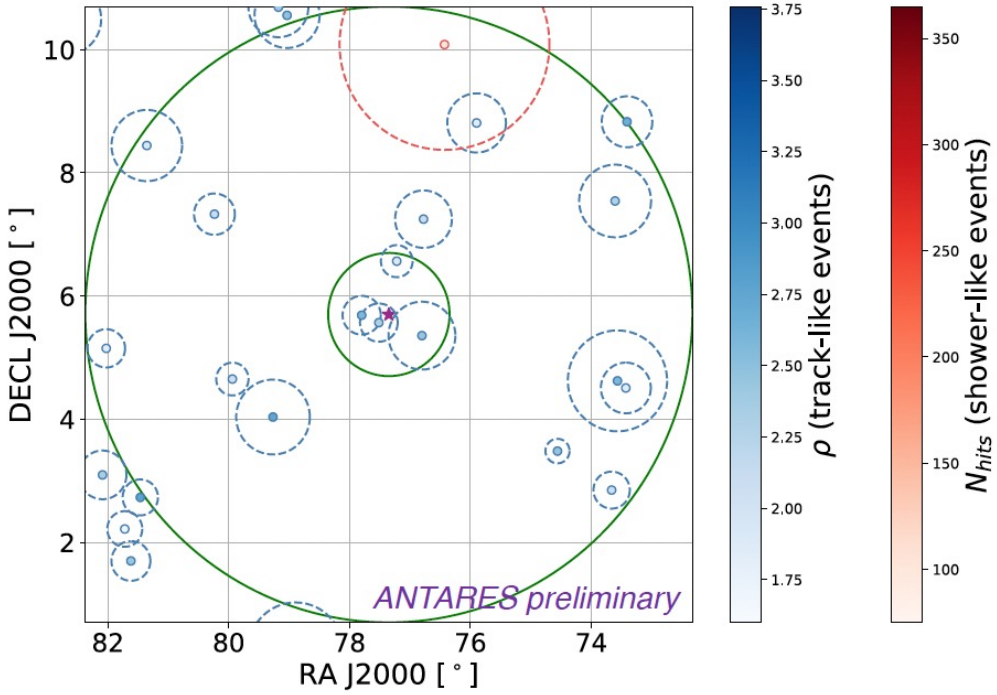
- "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IC170922A"
  - ~3 σ neutrino-gamma coincidence
- "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IC170922A alert"
  - First 7 years (excluding 170922A): 2.1 σ
  - Neutrino flare in late 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/deg^2 for track-like
  - 0.005/deg^2 for shower-like events
- # of events fitted the likelihood signal function for the source: $\mu_{sig} = 1.03$
- **Pre-trial p-value of 3.4%** (post-trial 87%)



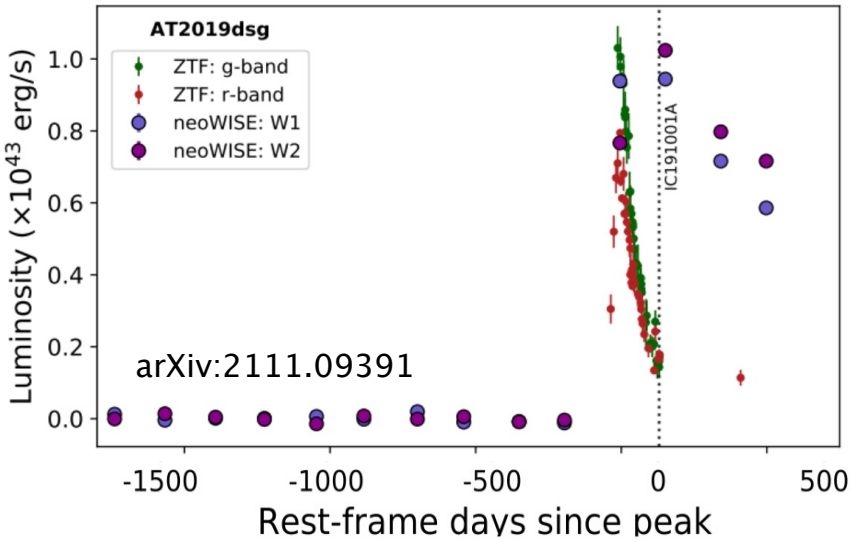
- Updated 2007-2020, recalibrated
- 4 events within 1° $\mu_{sig} = 2.9$
- Pre-trial: 2.9σ (1-sided)

- Soon, yet another update
- Time sequence under investigation

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

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

The multi-messenger program: TAToO

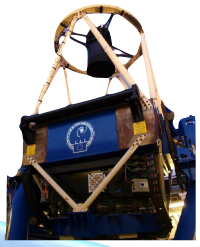
Telescope-Antares Target of Opportunity

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

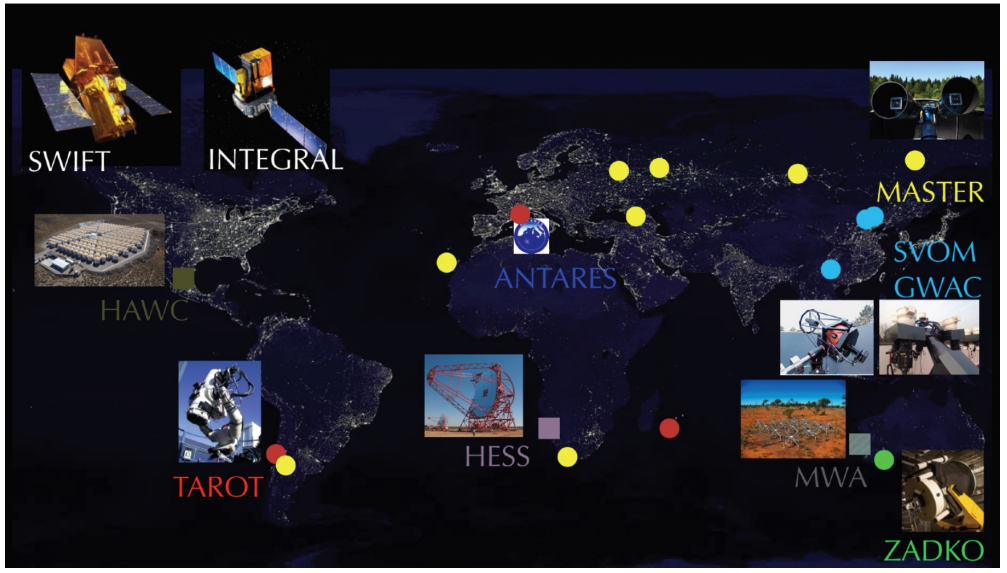
TATOO and the transients

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
+12 to INTEGRAL

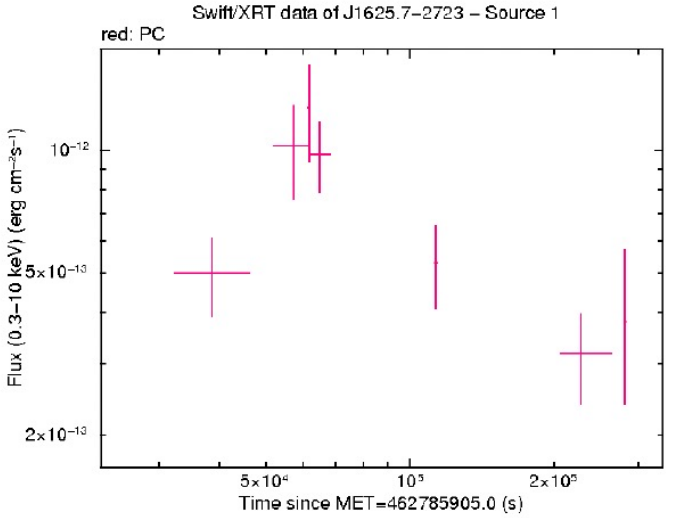
+~25 to MWA
+2 to HESS

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

ANT150901

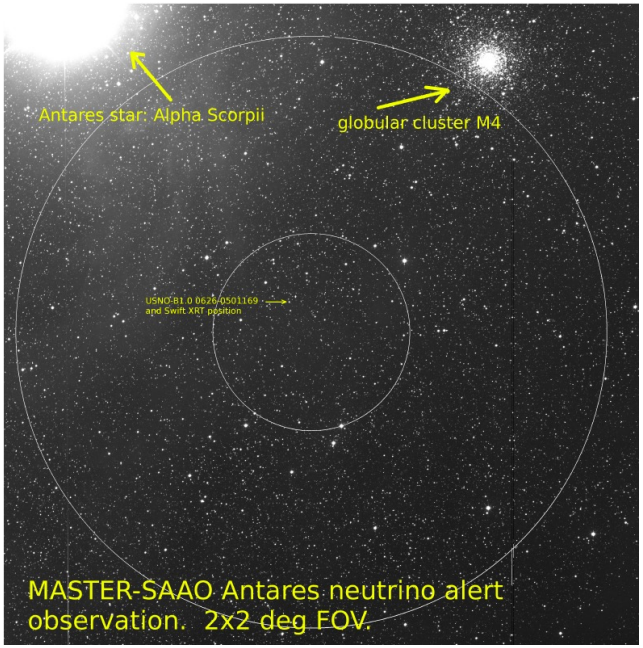
In September 2015, ANTARES has issued a neutrino alert and during the follow-up, a potential transient counterpart was identified by Swift and MASTER.

- 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



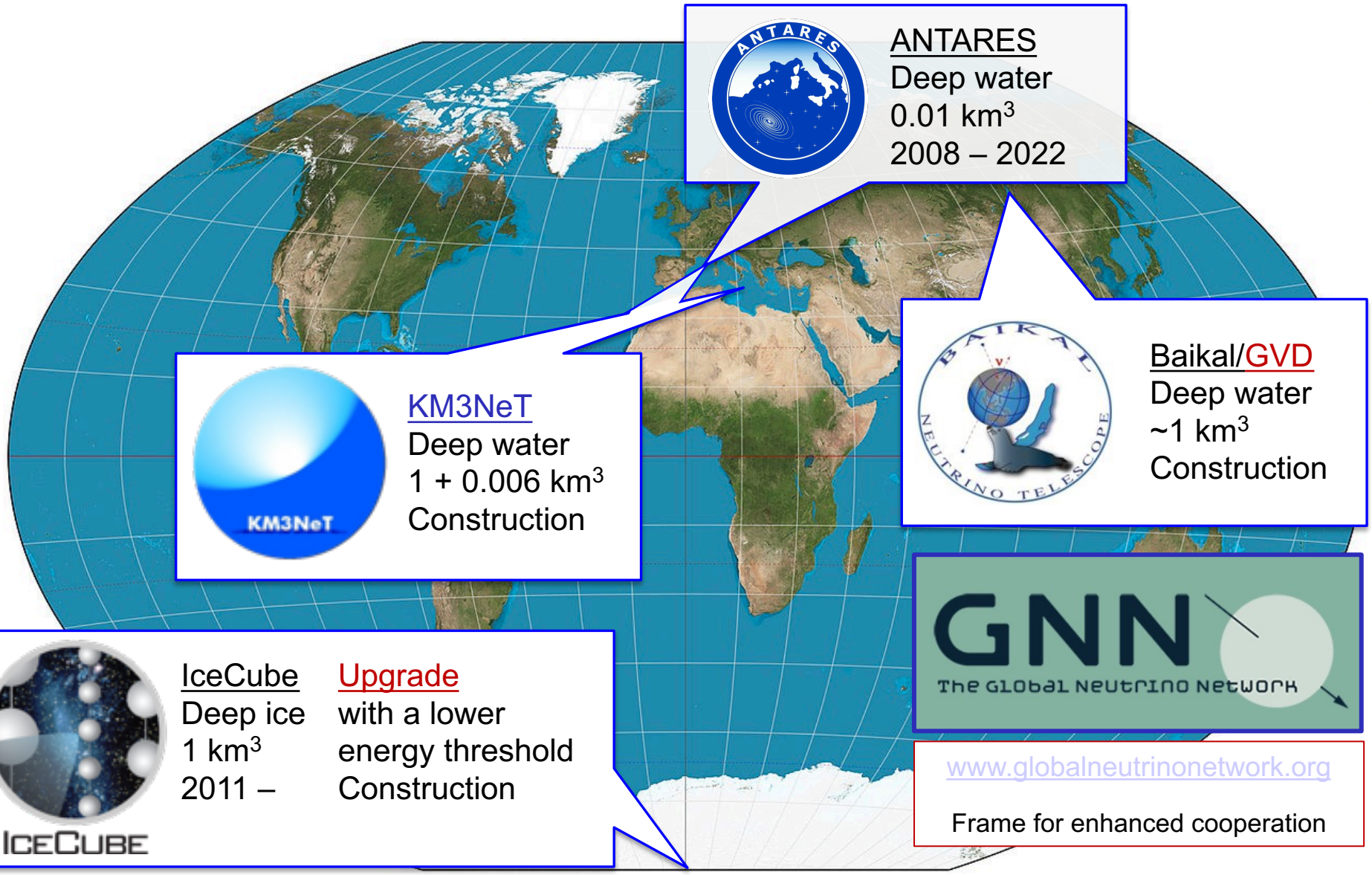
A multi-wavelength follow-up campaign allowed to identify the class of this source resulting in a fortuitous association with the neutrino. ☹
→ A young accreting G-K star, undergoing a flaring episode (X-ray emission). Probably associated to Rho Ophiuchi star forming region.

Multifrequency observations:
16 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.

The neutrino telescope world map 2020



ANTARES
Deep water
0.01 km^3
2008 – 2022

KM3NeT
Deep water
1 + 0.006 km^3
Construction

Baikal/GVD
Deep water
~1 km^3
Construction

IceCube
Deep ice
1 km^3
2011 –

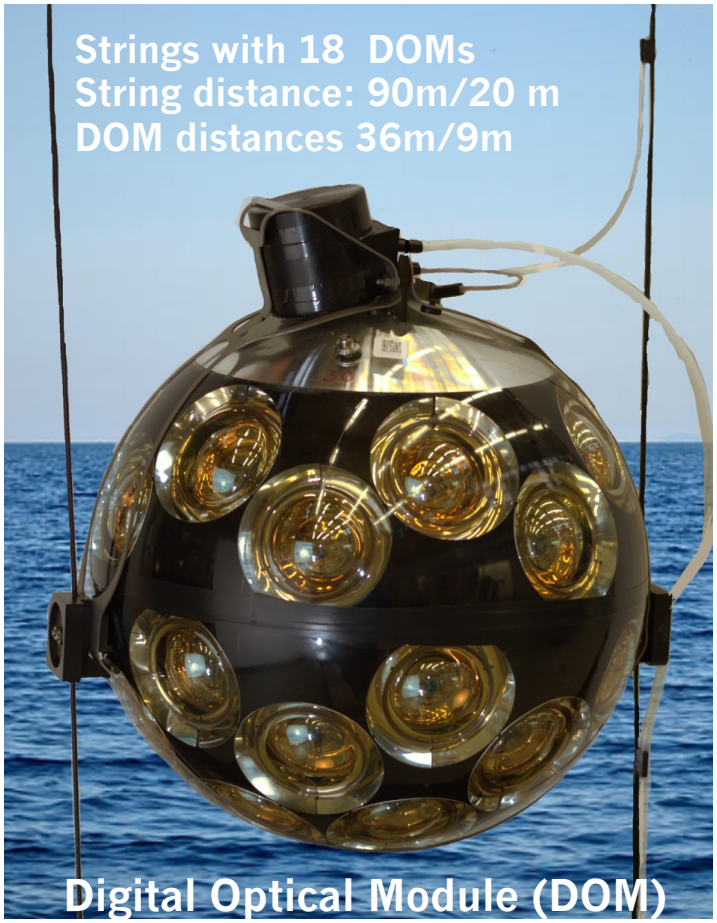
Upgrade
with a lower
energy threshold
Construction

GNN
The Global Neutrino Network

www.globalneutrinonetwork.org

Frame for enhanced cooperation

KM3NeT, successor of ANTARES



- 31 PMTs in one sphere
- 3 x cathode area wrt ANTARES OM
- Single photon counting
- Directional information
- Inspiring design for IceCube-Gen 2

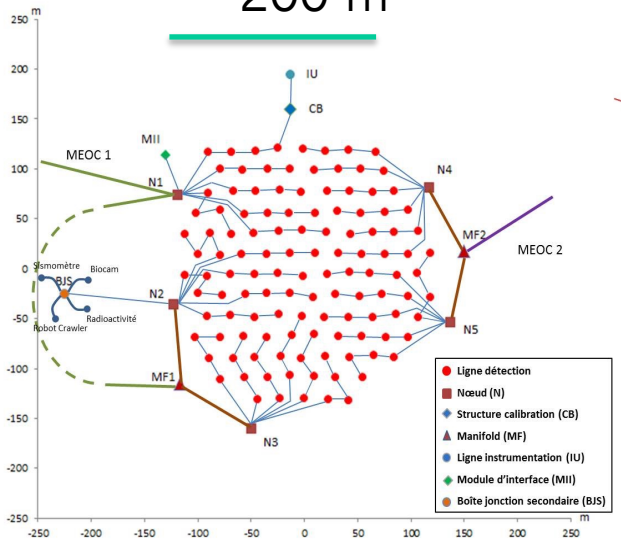
KM3NeT ARCA/ORCA

Astrophysics/**O**scillation **R**esearch
with **C**osmics in the **A**byss

ARCA: 3.5km depth, 100km from Capo Passero (Sicily)
Focus: Cosmic Neutrino Sources
large, sparse grid -> high energy
ORCA: 2.5 km depth, 40km from Toulon (France)
Focus: Atmospheric neutrino oscillations
small, dense grid -> low energy

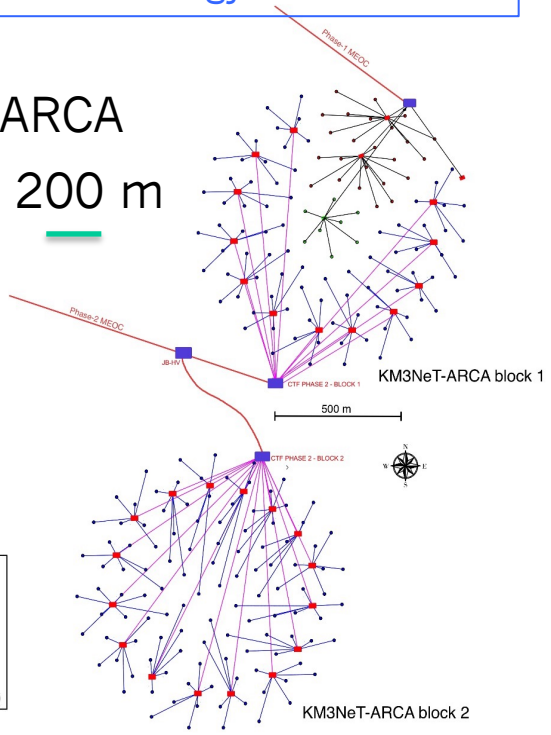
ORCA

200 m

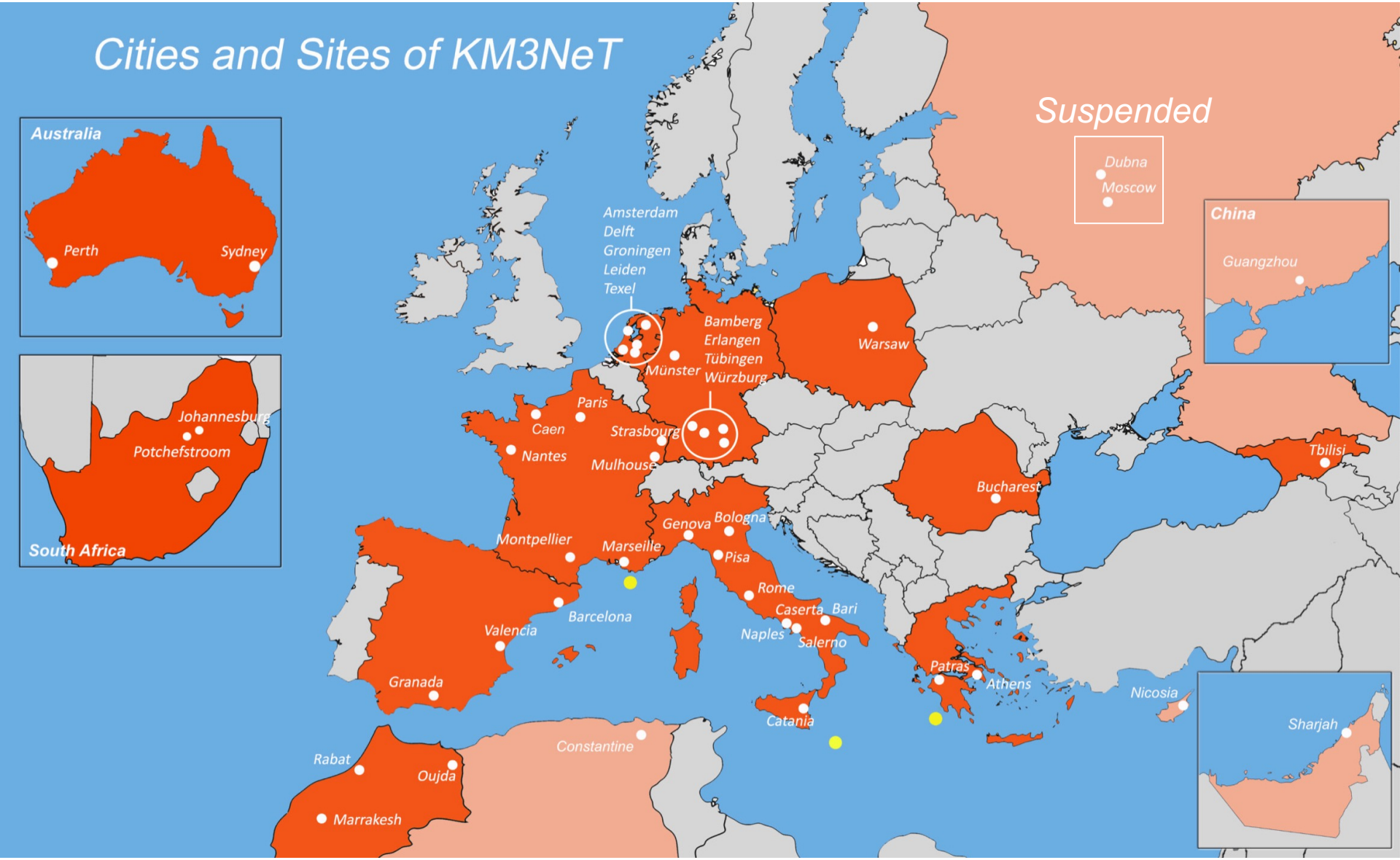


ARCA

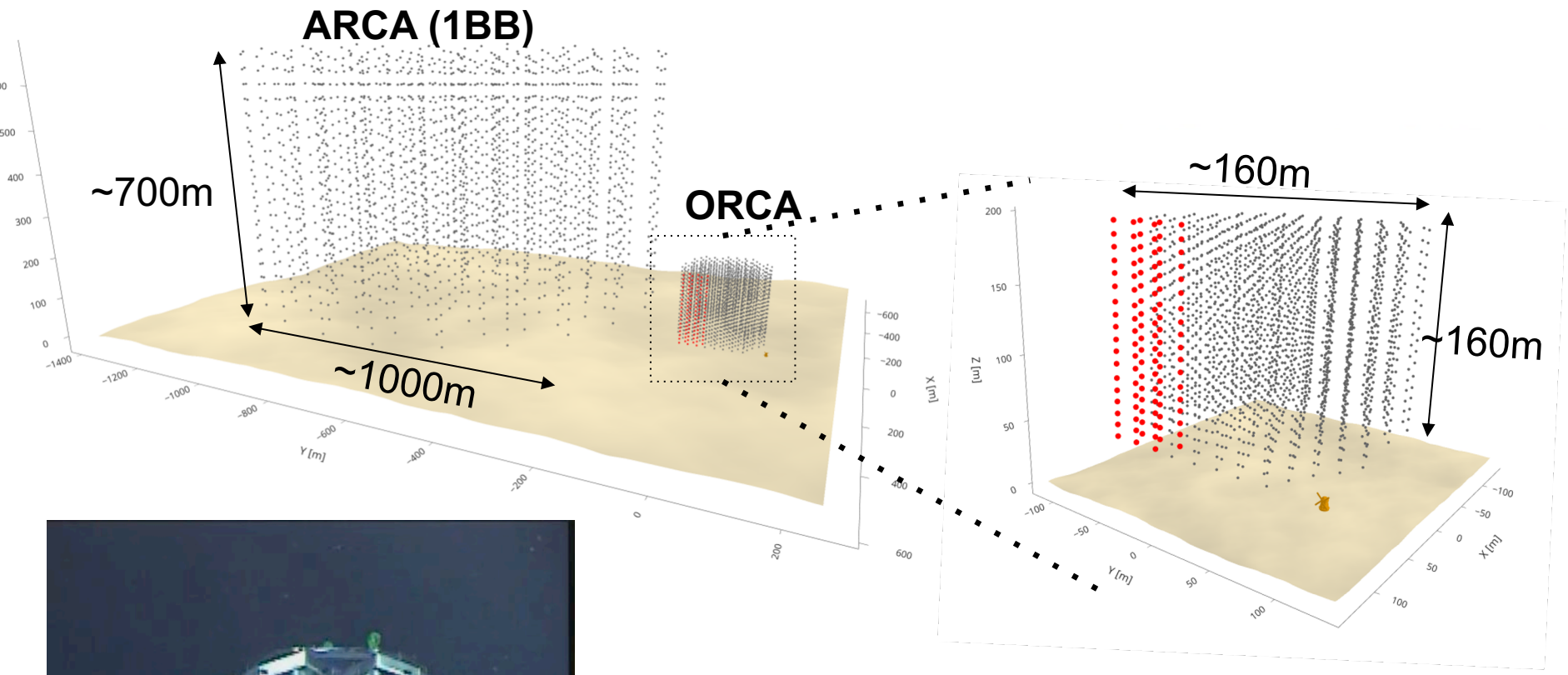
200 m

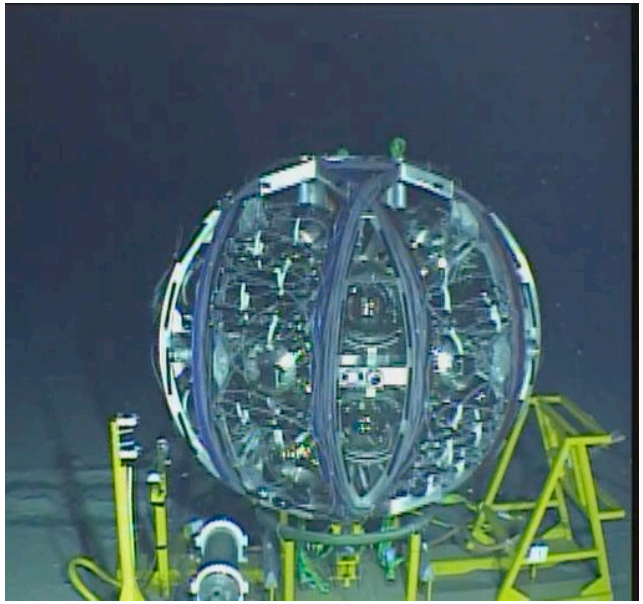


KM3NeT, successor of ANTARES



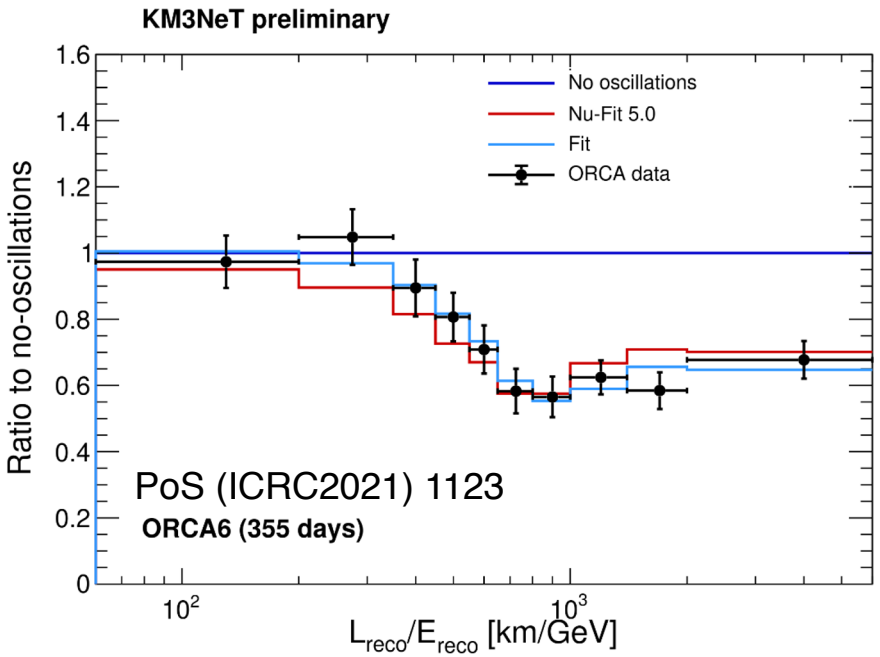
KM3NeT ramping up



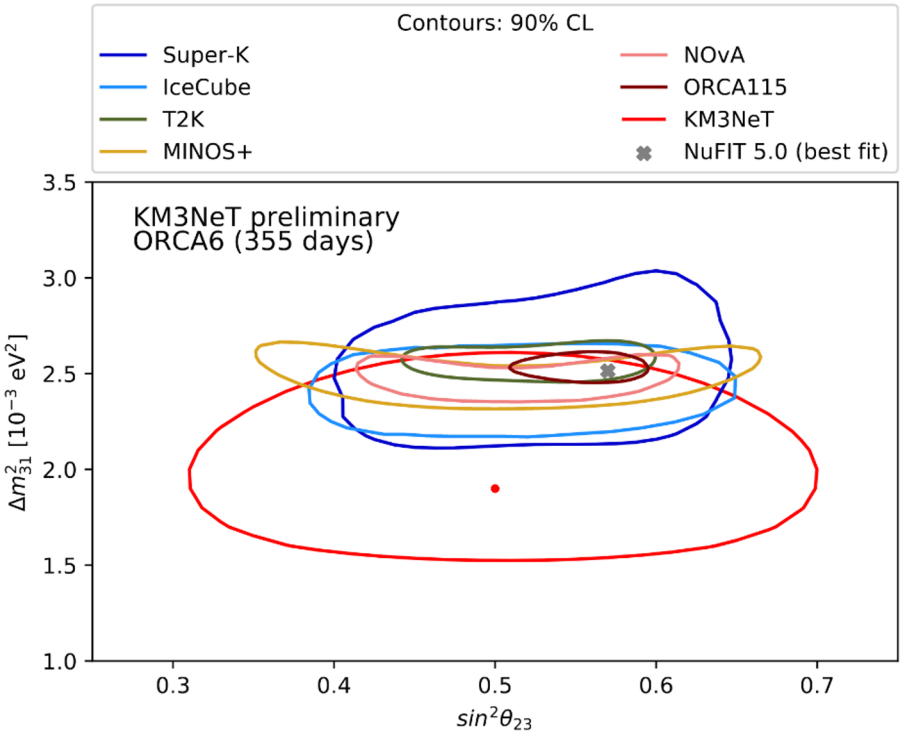


Compacting allows for several deployments at once
Unfurling from sea bed

Oscillation studies

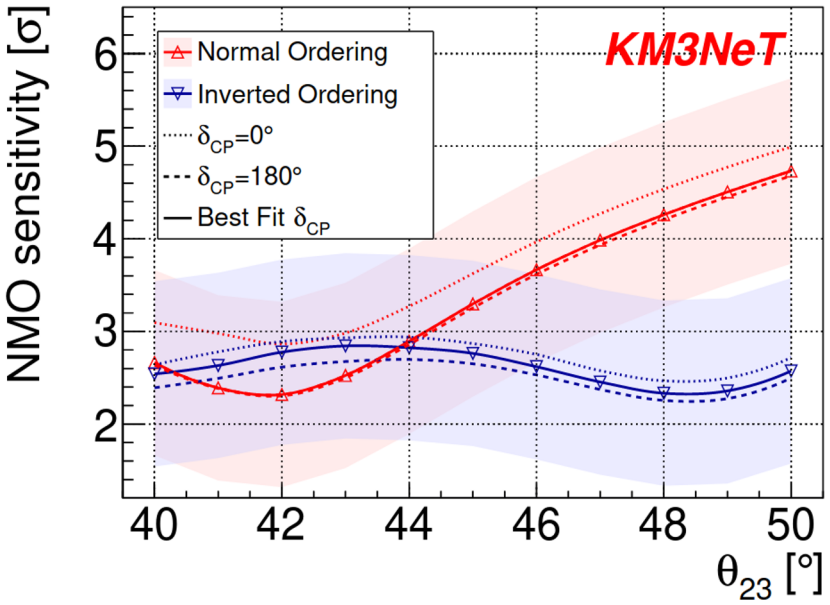


Strong oscillation signal with only 6 DU

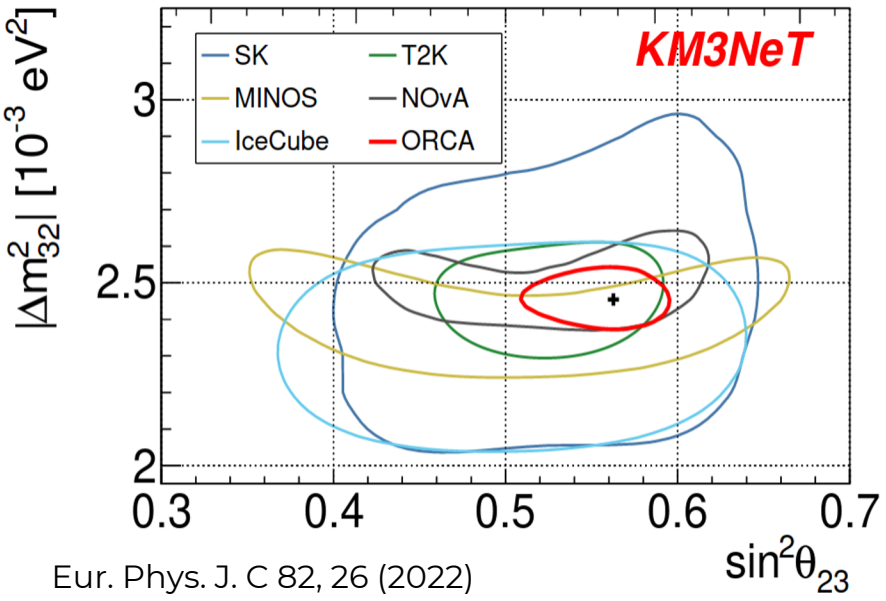


Data has a preference to oscillation of 5.9σ

Prospects for the Mass Ordering



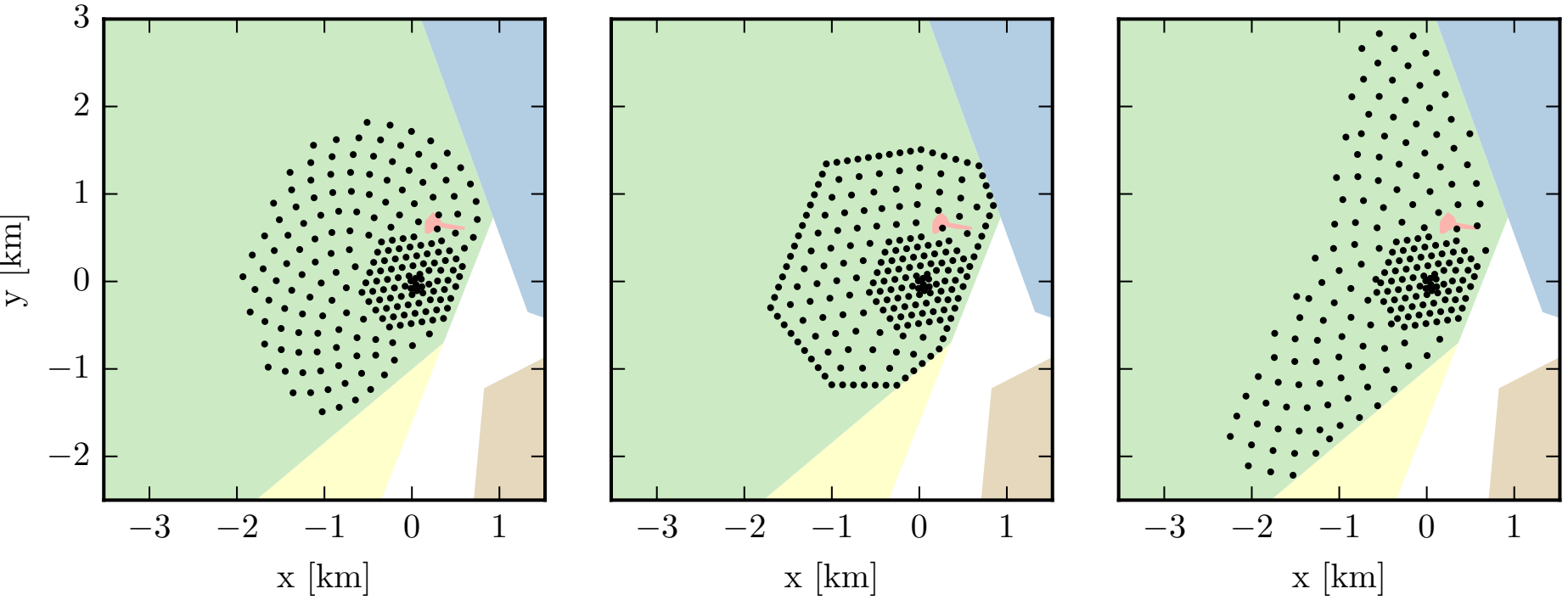
Expected results for 3 years exposure, full detector.



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

Competitive sensitivity to Δm^2_{32}, θ_{23}

IceCube-Gen2: the next generation

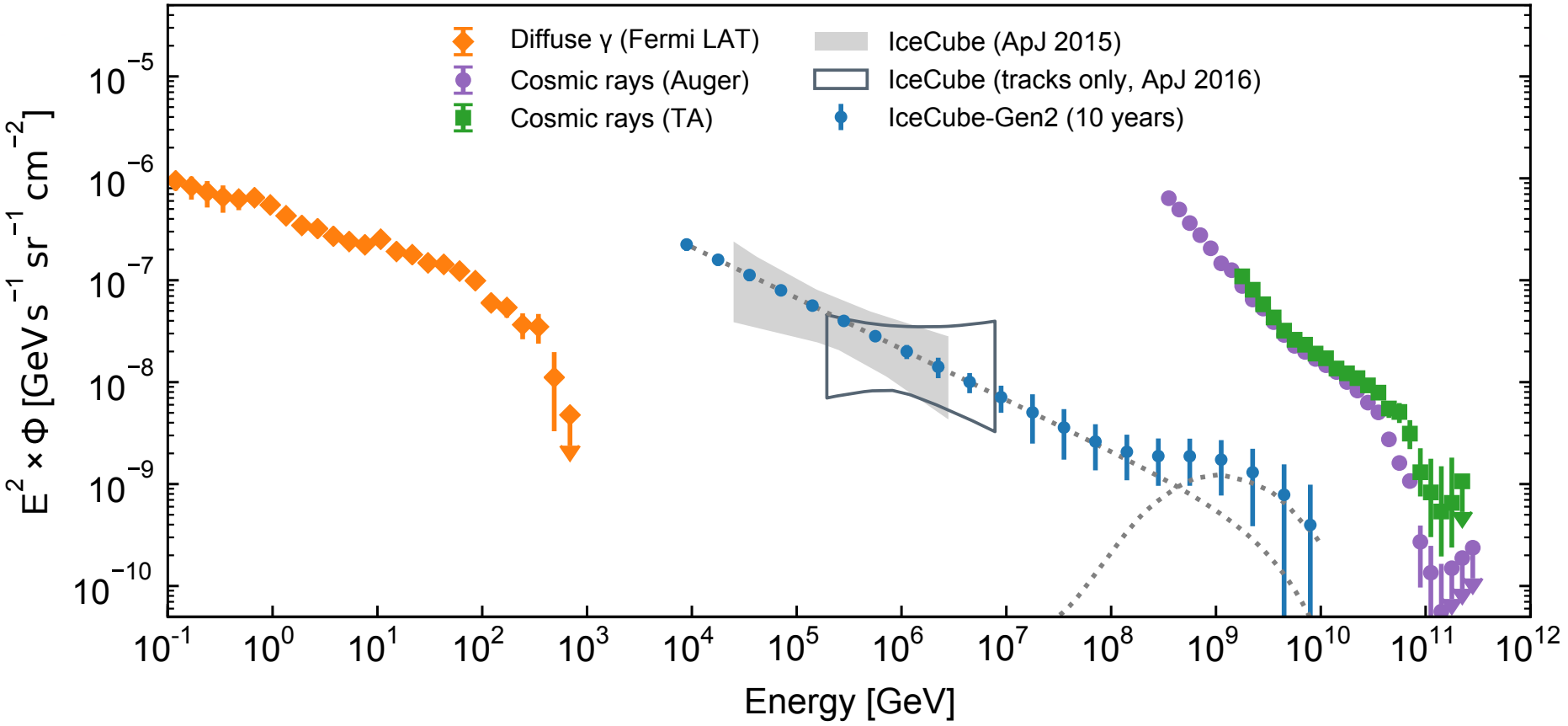


- High energy extension: Instrument ~10 km^3 (sparsely with ~120 new strings) to increase sensitivity to high energy (0.1-10 PeV) muon and cascade events
- Surface array for increased southern sky sensitivity and cosmic-ray physics
- Identify neutrino sources and study them with multiple messengers
- Dense inner core for neutrino physics including mass hierarchy
- Radio antenna array for 10^{18} eV neutrinos

Positively supported in decal survey

IceCube, 1412.5106 (LOI)
IceCube, 1510.05228 (ICRC)
IceCube, 2008.04323 (white paper)

IceCube-Gen2: the next generation



"IceCube-Gen2: The Window to the Extreme Universe"
J. Phys. G: Nucl. Part. Phys. 48 060501 (2021)

Summary

Thanks for your attention !

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

  A multi disciplinary observatory (associated sciences).

- 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 endeavor !