Overview of ANTARES, the first undersea neutrino telescope

Marco Circella, INFN Bari - for the ANTARES Collaboration

- The ANTARES apparatus
  - Construction and dismantling
  - Detection Principle
  - Calibration and performance
- Scientific Results
  - Earth and Sea science
  - Particle Physics
  - High-Energy Astrophysics
- Passing the baton to KM3NeT

The concept of Cherenkov neutrino telescopes

- Photomultipliers (PMTs) collecting Cherenkov photons due to relativistic charged particles from ν – interactions
- Particle direction reconstructed using time & position of optical sensors

First attempt in mid ‘70s:
Deep **U**nderwater **M**uon **A**nd **N**eutrino **D**etector **Project** (https://www.phys.hawaii.edu/~dumand/dumacomp.html)
about 4800 m under the Hawaiian sea

DUMAND-II Progress Report

R. J. Wilkes, for
The DUMAND Collaboration :
C.M. Alexander[4], T. Aoki[11], U. Berson[1], P. Bosetti[1], J. Bolesta[4], P.E. Boynton[14], H. Bradner[9], U. Camerini[15], S.T. Dye[3], E. Gergin[3], P.W. Gorham[4], P.K.F. Grieder[2], W. Grogan[15], H. Hanada[10], D. Harris[4], T. Hayashino[10], E. Hazen[3], M. Ito[10], M. Jaworski[11], M. Jenko[3], H. Kawamoto[10], T. Kitamura[7], K. Kobayakawa[6], S. Kondo[4], P. Koske[5], J.G. Learned[4], C. Ley[1], J.J. Lord[14], R. Lord[14], T. Lozic[3], R. March[15], T. Matsumoto[10], S. Matsuno[4], A. Mavretic[3], L. McCourry[14], M. Mignard[4], K. Miller[13], P. Minkowski[2], R. Mitiguy[4], K. Mitsui[11], S. Narita[10], D. Nicklaus[15], Y. Ohashi[11], A. Okada[11], D. Orlov[3], V.Z. Peterson[4], A. Roberts[4], M. Sakuda[12], V.J. Stenger[4], H. Suzuki[10], S. Tanaka[10], S. Uehara[12], C. Wiebusch[1], G. Wilkins[4], M. Webster[13], R.J. Wilkes[14], G. Wurm[1], A. Yamaguchi[10], I. Yamamoto[8], K.K. Young[14]

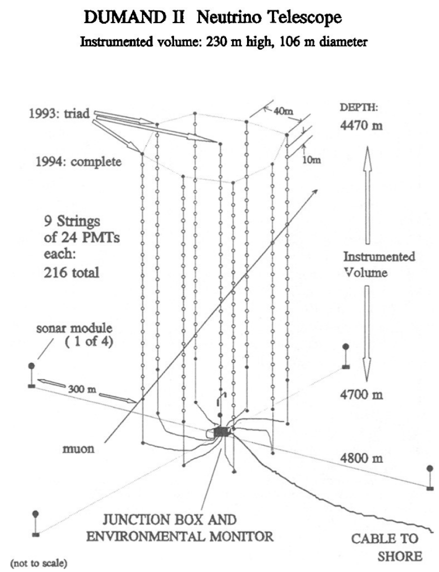
1) Technische Hochschule Aachen, Germany; 2) University of Bern, Switzerland; 3) Boston University, USA; 4) University of Hawaii, USA; 5) University of Kiel, Germany; 6) Kobe University, Japan; 7) Kinki University, Japan; 8) Okayama Science University, Japan; 9) Scripps Institution of Oceanography, USA; 10) Tohoku University, Japan; 11) ICRR, University of Tokyo, Japan; 12) NLHEP, Tsukuba, Japan; 13) Vanderbilt University, USA; 14) University of Washington, USA; 15) University of Wisconsin, USA.

Abstract

The design, scientific goals, and capabilities of the DUMAND II detector system are described. Construction was authorized by DOE in 1990, and construction of various detector subsystems is under way. Current plans include deployment of the shore cable, junction box and three strings of optical detector modules in 1993, with expansion to the full 9-string configuration about one year later.

ISVHECRI 1992

640 DUMAND-II Progress Report



DUMAND Project canceled in 1996

ANTARES accepted the challenge! It was the first neutrino telescope to be operated in the deep sea

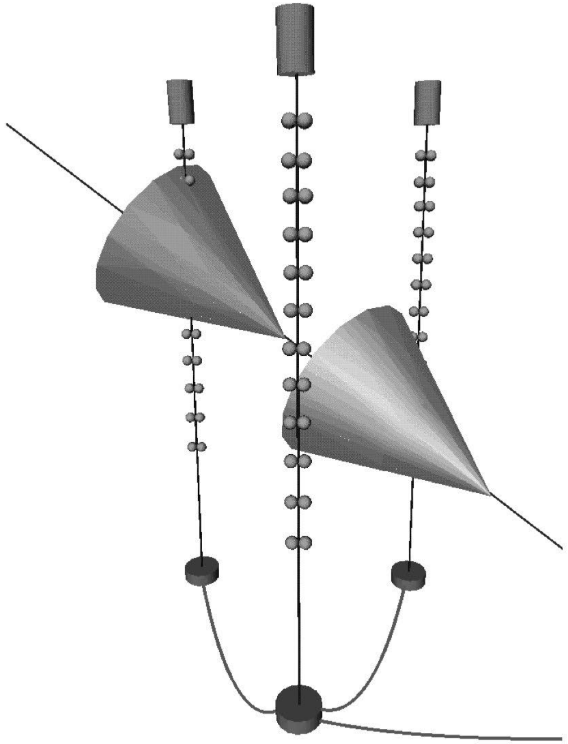
The first deep-sea Neutrino Telescope

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

Complete description in: NIM A 656 (2011) 11-38

Nuclear Instruments and Methods in Physics Research A 656 (2011) 11–38

Contents lists available at ScienceDirect

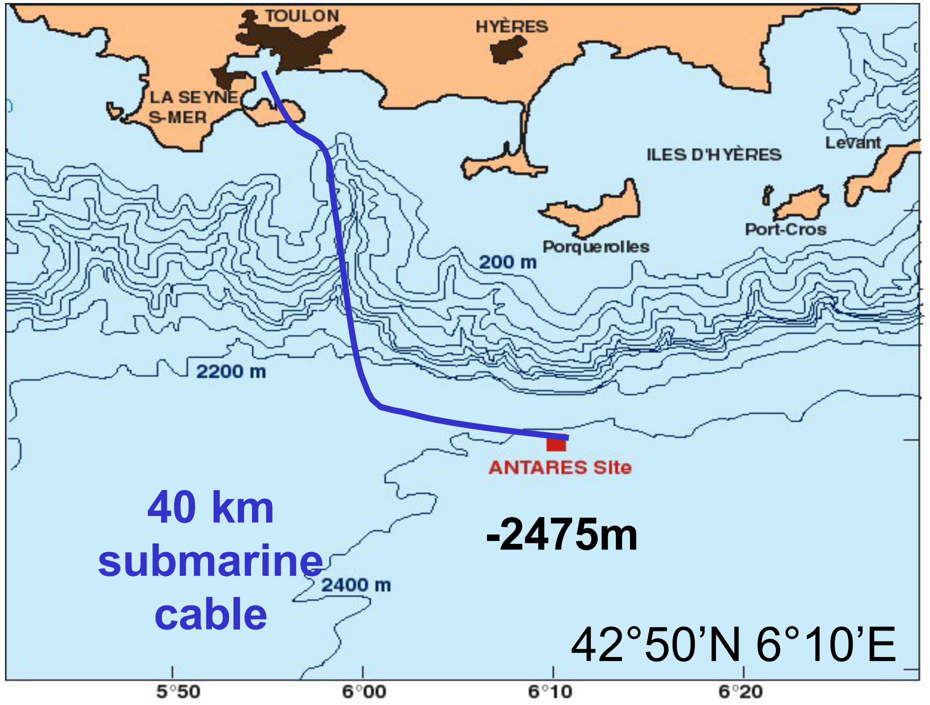
Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ANTARES: The first undersea neutrino telescope ☆

M. Ageron[a], J.A. Aguilar[b], I. Al Samarai[a], A. Albert[c], F. Ameli[d], M. André[e], M. Anghinolfi[f], G. Anton[g], S. Anvar[h], M. Ardid[i], K. Arnaud[a], E. Aslanides[a], A.C. Assis Jesus[j], T. Astraatmadja[j,1], J.-J. Aubert[a], R. Auer[g], E. Barbarito[k], B. Baret[l], S. Basa[m], M. Bazzotti[n,o], Y. Becherini[p], J. Beltramelli[h], A. Bersani[f], V. Bertin[a], S. Beurthey[a], S. Biagi[n,o], C. Bigongiari[b], M. Billault[a], R. Blaes[c], C. Bogazzi[j], N. de Botton[p], M. Bou-Cabo[i], B. Boudahef[q], M.C. Bouwhuis[j], A.M. Brown[a], J. Brunner[a,2], J. Busto[a], L. Caillat[a], A. Calzas[a], F. Camarena[i], A. Capone[d,r], L. Caponetto[s], C. Cârloganu[t], G. Carminati[n,o], E. Carmona[b], J. Carr[a], P.H. Carton[h], B. Cassano[k], E. Castorina[q,u], S. Cecchini[o], A. Ceres[k], Th. Chaleil[h], Ph. Charvis[v], P. Chauchot[w], T. Chiarusi[o], M. Circella[k,*], C. Compère[w], R. Coniglione[x], X. Coppolani[h], A. Cosquer[a], H. Costantini[f], N. Cottini[p], P. Coyle[a], S. Cuneo[f], C. Curtil[a], C. D'Amato[x], G. Damy[w], R. van Dantzig[j], G. De Bonis[d,r], G. Decock[h], M.P. Decowski[j], I. Dekeyser[y], E. Delagnes[h], F. Desages-Ardellier[h], A. Deschamps[v], J.-J. Destelle[a], F. Di Maria[g], B. Dinkespiler[a], C. Distefano[x], J.-L. Dominique[h], C. Donzaud[l,p,z], D. Dornic[a,b], Q. Dorosti[aa], J.-F. Drogou[ab], D. Drouhin[c], F. Druillole[h], D. Durand[h], R. Durand[h], T. Eberl[g], U. Emanuele[b], J.J. Engelen[j], J.-P. Ernenwein[a], S. Escoffier[a], E. Falchini[q,u], S. Favard[a], F. Fehr[g], F. Feinstein[a,p], M. Ferri[i], S. Ferry[p], C. Fiorello[k], V. Flaminio[q,u], F. Folger[g], U. Fritsch[g], J.-L. Fuda[y], S. Galatá[a], S. Galeotti[q,u], P. Gay[t], F. Gensolen[a], G. Giacomelli[n,o], C. Gojak[a], J.P. Gómez-González[b], Ph. Goret[ac], K. Graf[g], G. Guillard[ad], G. Halladjian[a], G. Hallewell[a], H. van Haren[ae], B. Hartmann[g], A.J. Heijboer[j], E. Heine[j], Y. Hello[v], S. Henry[a], J.J. Hernández-Rey[b], B. Herold[g], J. Hößl[g], J. Hogenbirk[j], C.C. Hsu[j], J.R. Hubbard[p], M. Jaquet[a], M. Jaspers[j,af], M. de Jong[j,1], D. Jourde[h], M. Kadler[ag], N. Kalantar-Nayestanaki[aa], O. Kalekin[g], A. Kappes[g], T. Karg[g,3], S. Karkar[a], M. Karolak[h], U. Katz[g], P. Keller[a], P. Kestener[h], E. Kok[j], H. Kok[j], P. Kooijman[j,af,ah], C. Kopper[g], A. Kouchner[p,l], W. Kretschmer[g], A. Kruijer[j], S. Kuch[g], V. Kulikovskiy[f,ai], D. Lachartre[h], H. Lafoux[p], P. Lagier[a], R. Lahmann[g], C. Lahonde-Hamdoun[h], P. Lamare[h], G. Lambard[a], J.-C. Languillat[h], G. Larosa[i], J. Lavalle[a], Y. Le Guen[w], H. Le Provost[h], A. LeVanSuu[a], D. Lefèvre[y], T. Legou[a], G. Lelaizant[a], C. Lévéque[ab], G. Lim[j,af], D. Lo Presti[aj], H. Loehner[aa], S. Loucatos[p], F. Louis[h], F. Lucarelli[d,r], V. Lyashuk[ak], P. Magnier[h], S. Mangano[b], A. Marcel[h],

The ANTARES site

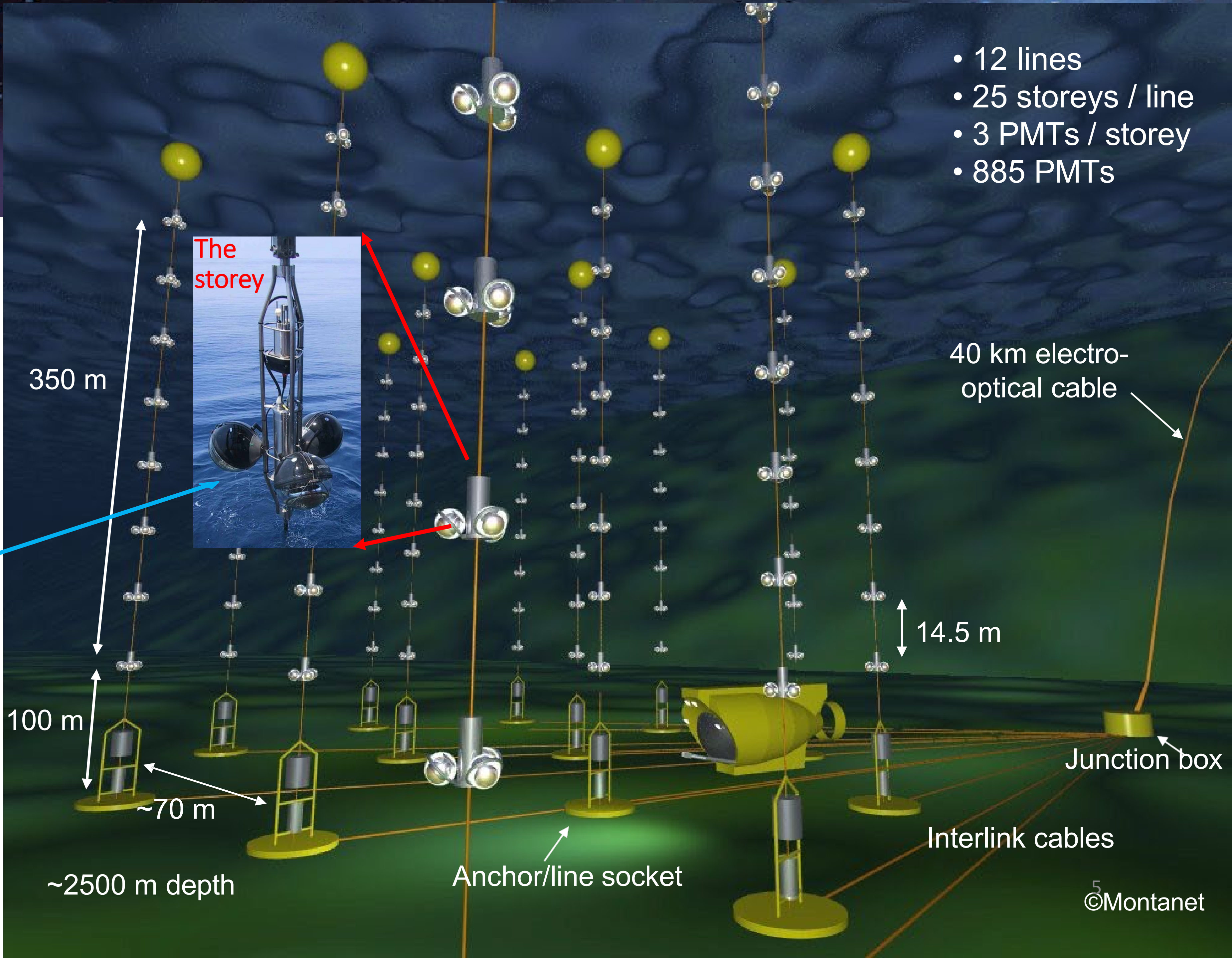


The apparatus

NIM A 656 (2011) 11

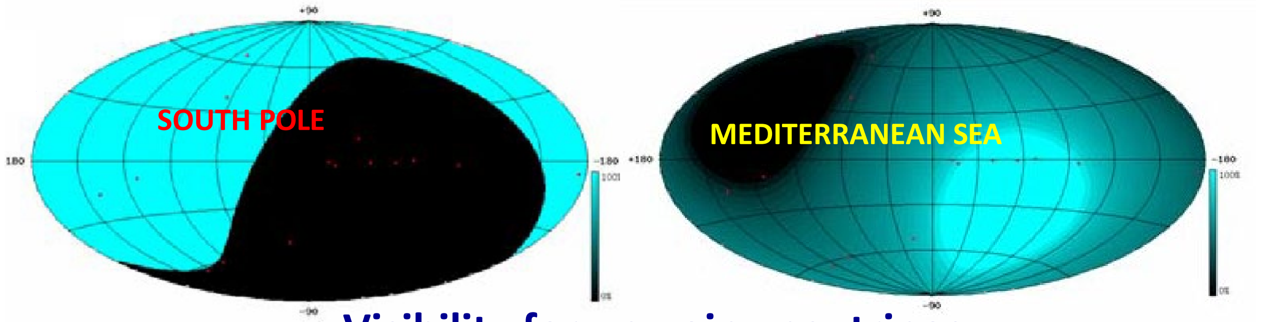
The Optical Module

NIM A 484 (2002) 369



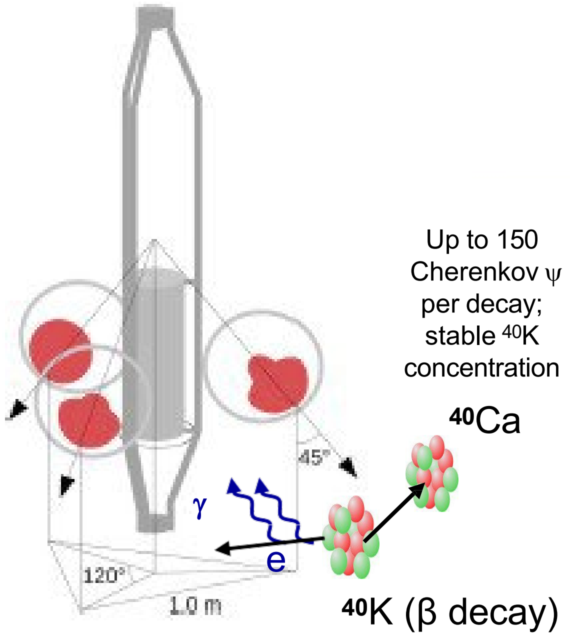
Why the Mediterranean Sea?

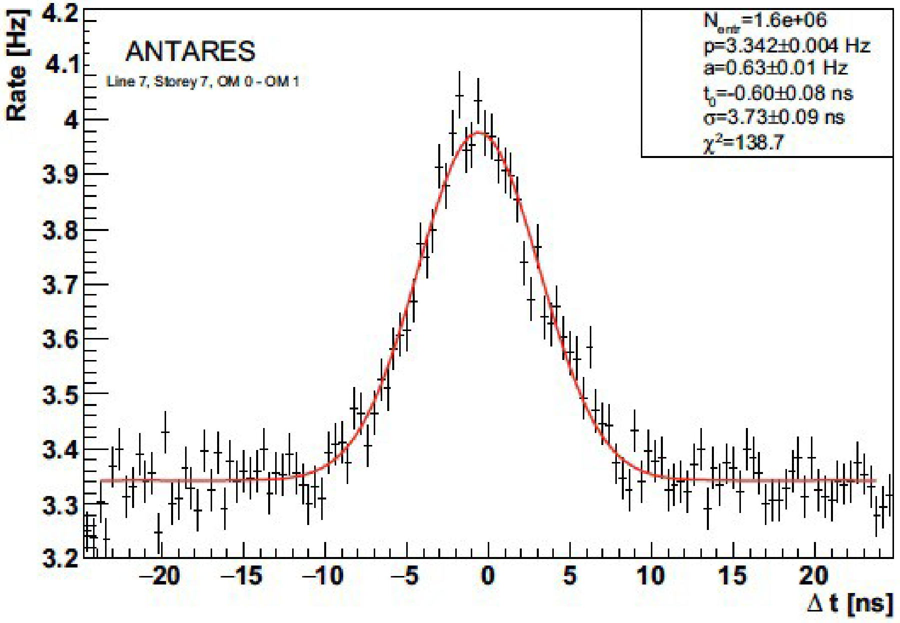
- Long (homogeneous) scattering length — Good pointing accuracy
- Deep: 2500 m at the ANTARES site — Shielding from downgoing muons
- Logistically attractive — Close to shore (deployment / repair)
- Mid Latitude — Excellent view of Galaxy; Complementarity with IceCube; On/off studies ➔ Background control
- K40 optical background — Useful calibration

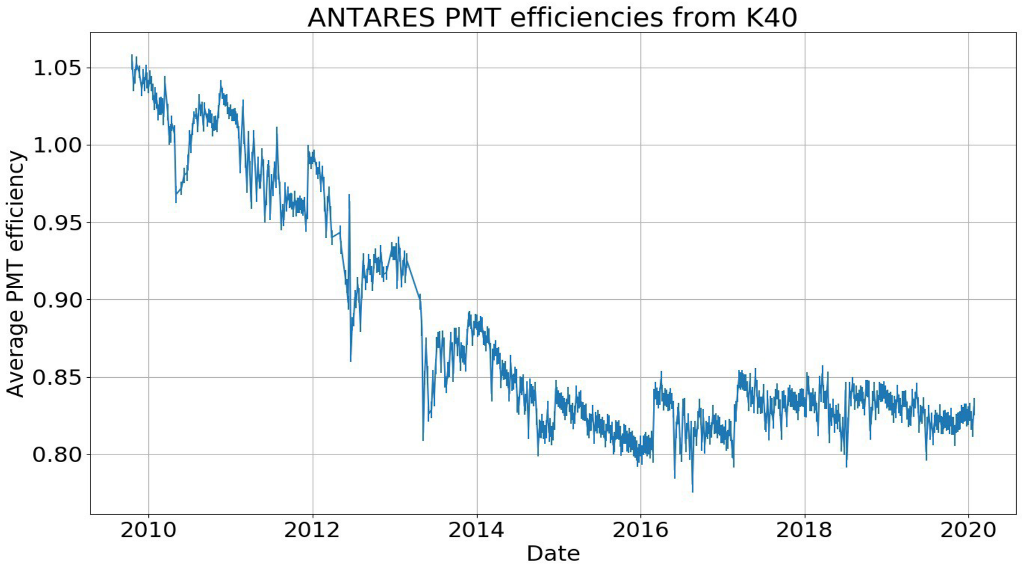


Visibility for up-going neutrinos

^{40}K (long-term) monitoring







^{40}K powerful calibration tool

Regular tunings

Only ~20% efficiency loss

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

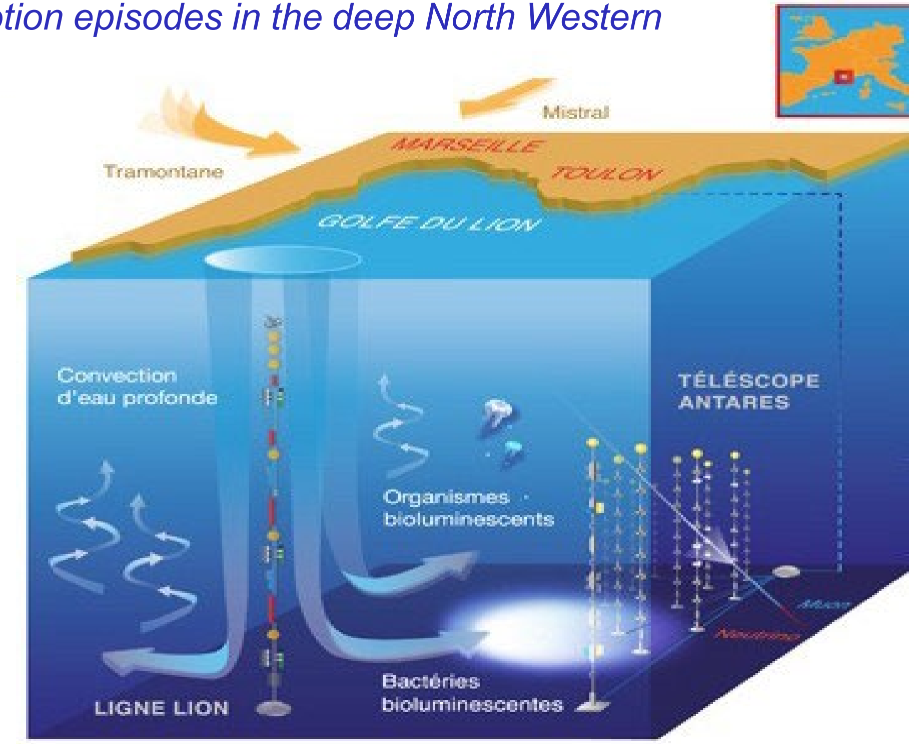
A multidisciplinary observatory

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



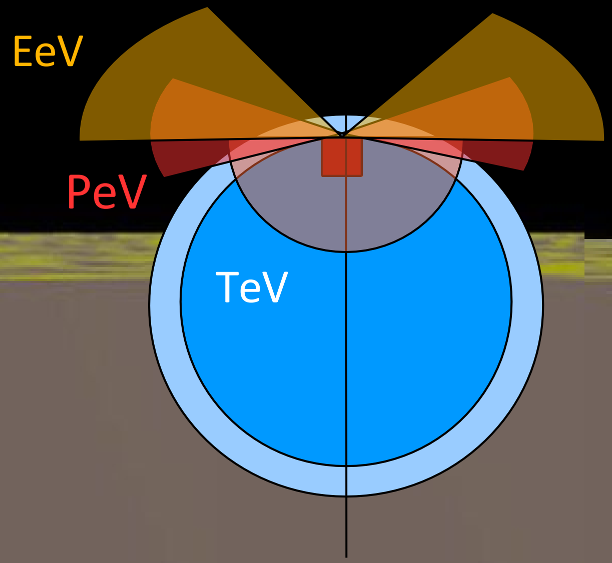
Sci. Rep. 7 (2017) 45517
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

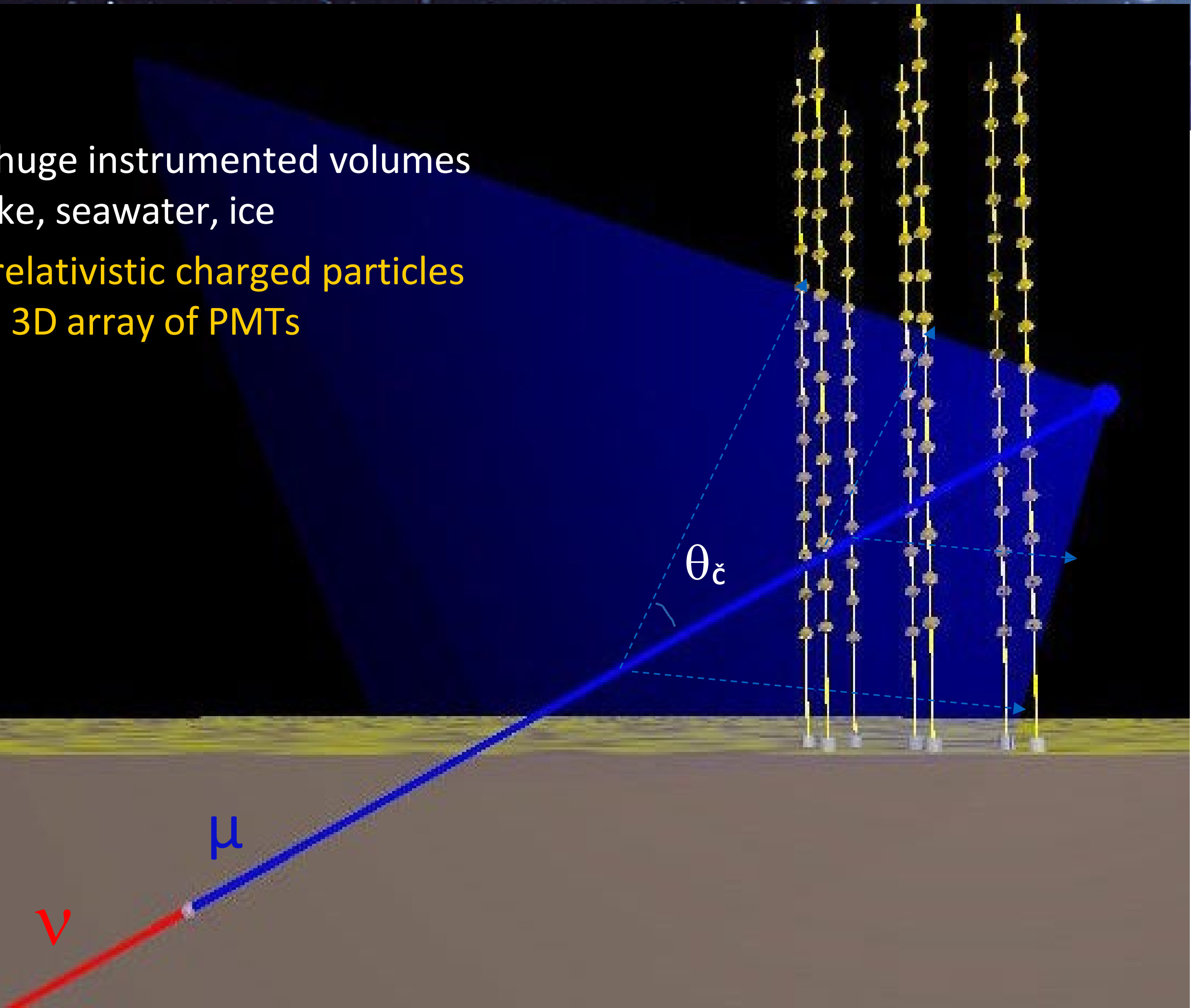
https://arxiv.org/abs/2107.08063
Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope

ν detection principle

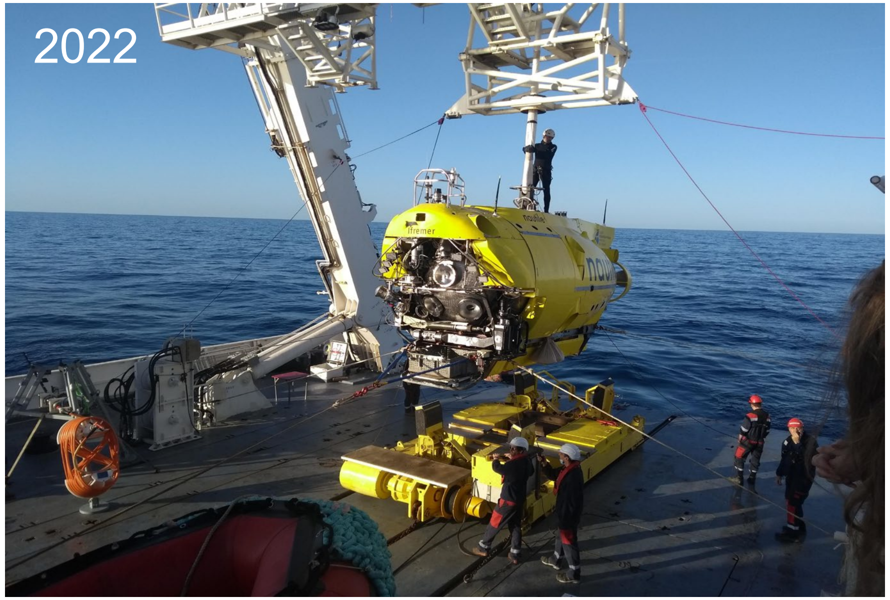
Natural radiators are low cost and allow huge instrumented volumes in dark but transparent media ➔Deep lake, seawater, ice

Detection of Cherenkov light induced by relativistic charged particles produced in neutrino interactions using a 3D array of PMTs

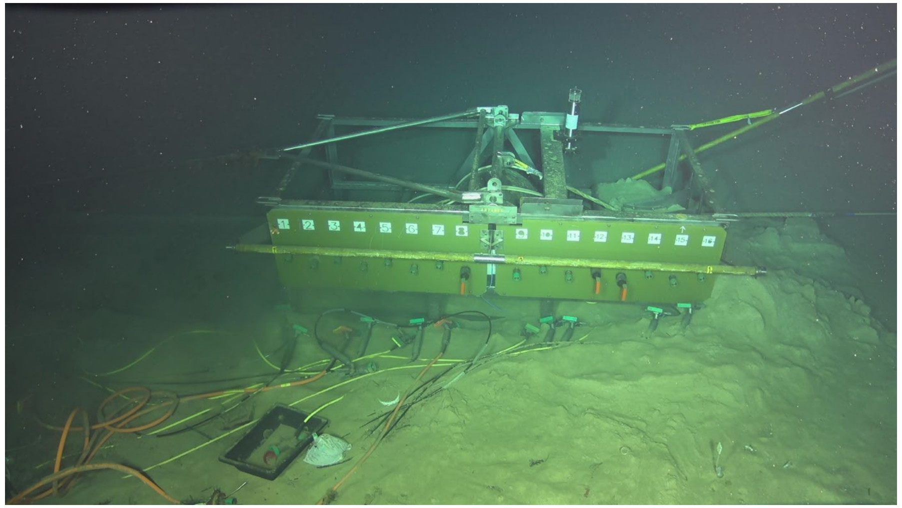




ANTARES 2001-2022

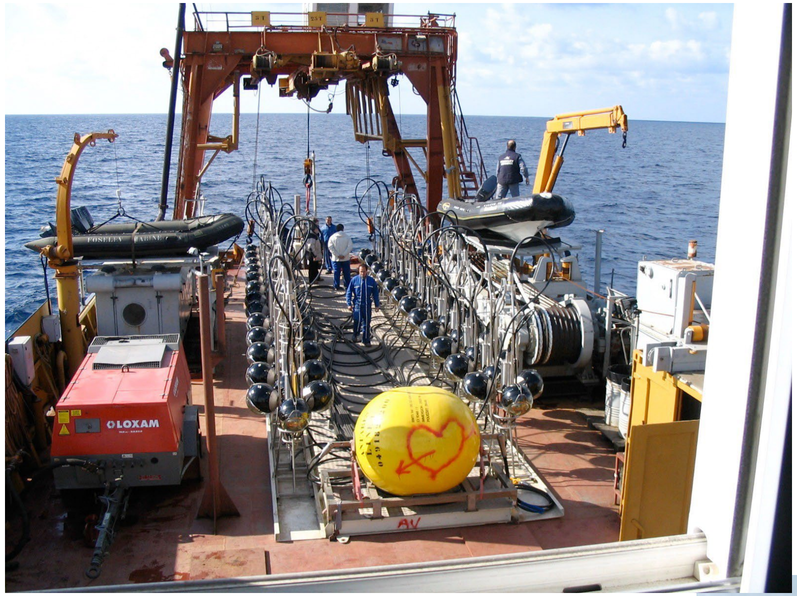


2001 Main Electro-Optical Cable
2002 Junction box
2003-2005 Prototype Lines
2006 First complete detector line
2008 Detector with 12 lines completed
2016 Running (almost) without common funds
2022 Data taking terminated

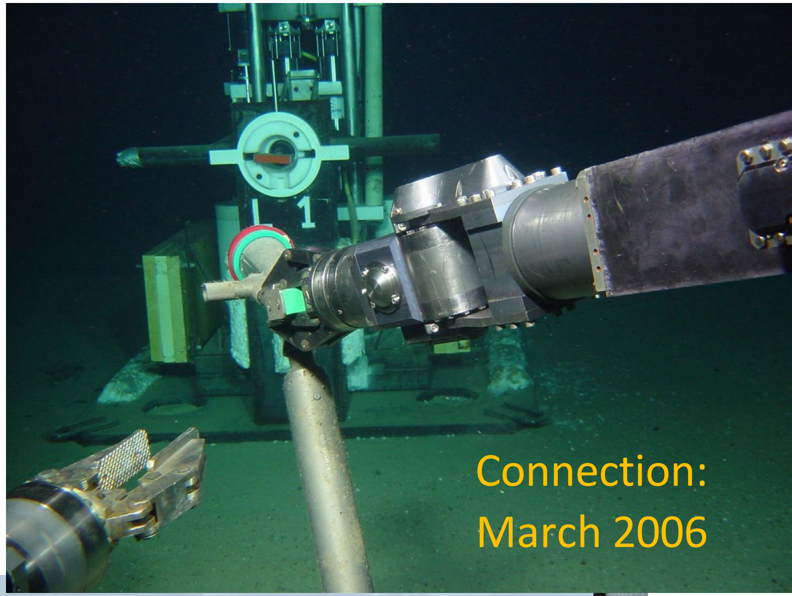


The ANTARES Junction Box:
no failure in 20 years!

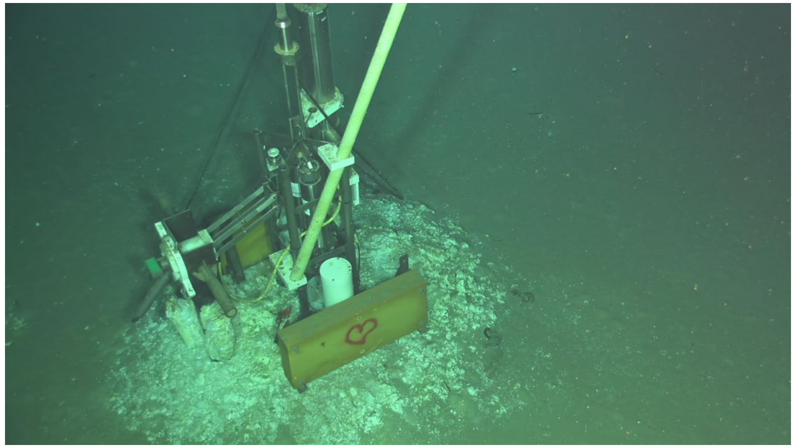
ANTARES: the first detection line



Deployment: 14 Feb. 2006



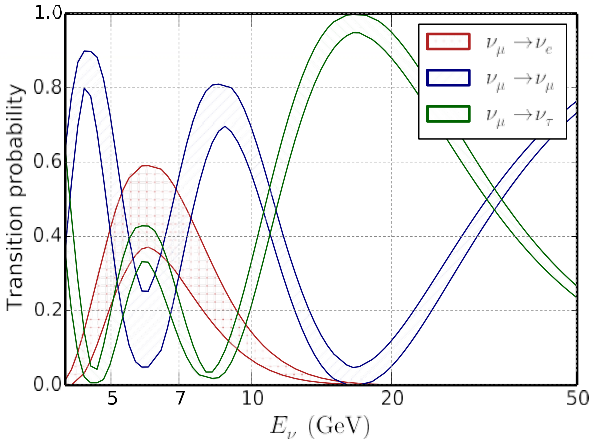
Connection:
March 2006

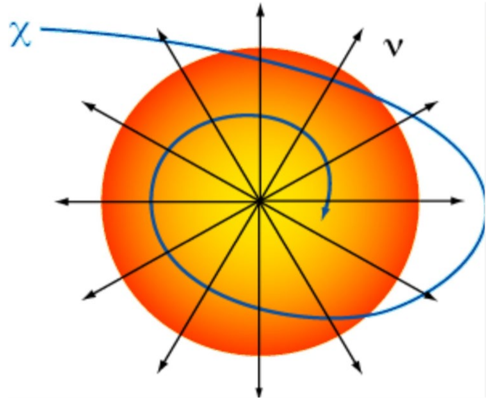


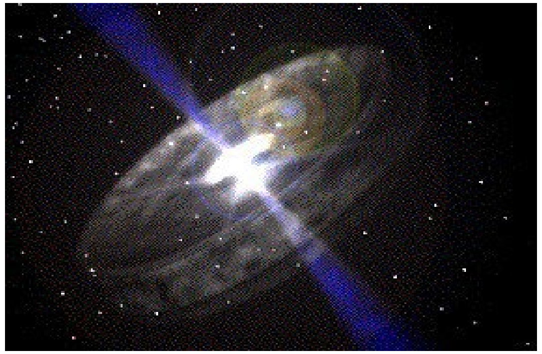
Disconnection after 16 years

Recovered optical modules available
for new experimental programs

Science scope







Low Energy
> 10 GeV

Medium Energy
10 GeV < E_ν < 10 TeV

High Energy
E_ν > 1 TeV

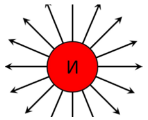
E

ν Oscillations

Dark matter search

ν from extra-terrestrial sources

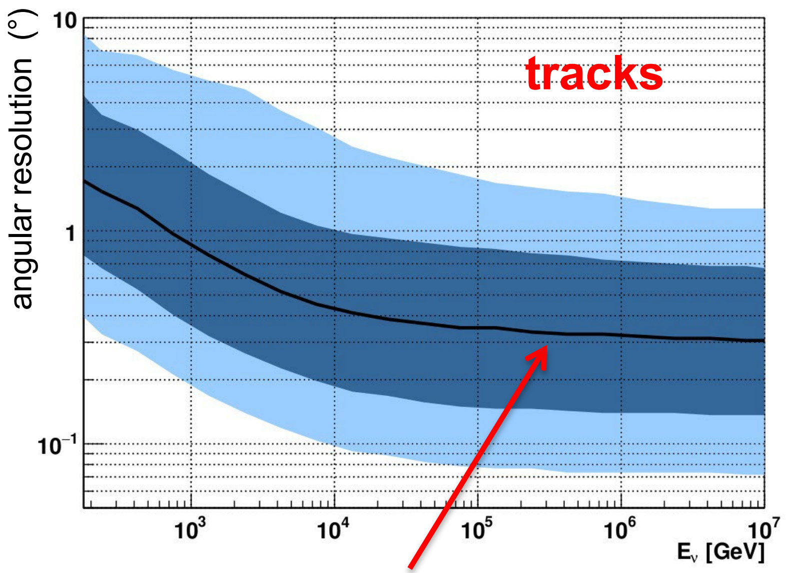
+ Exotic searches



Origin and production mechanism
of high-energy cosmic-rays

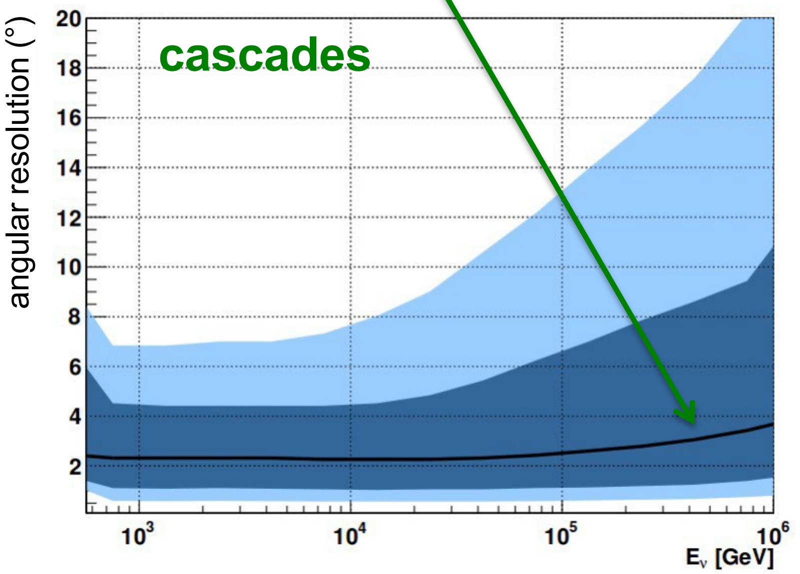
Reconstruction performance

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



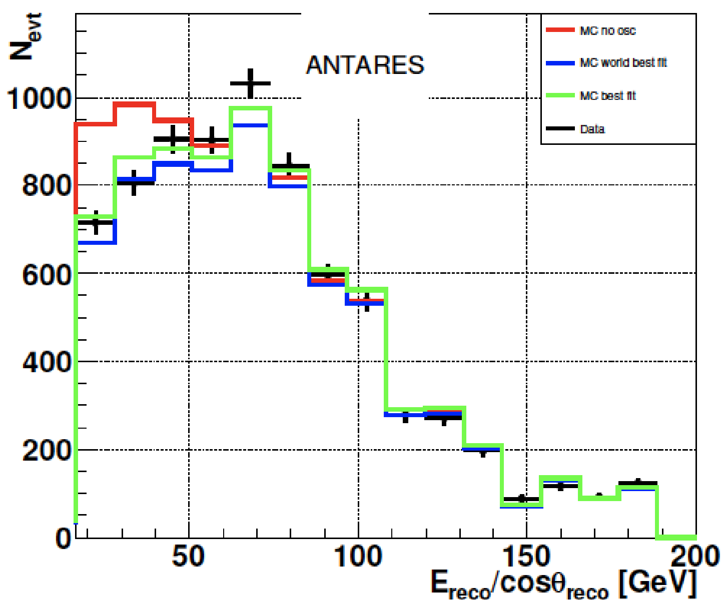
median resolution

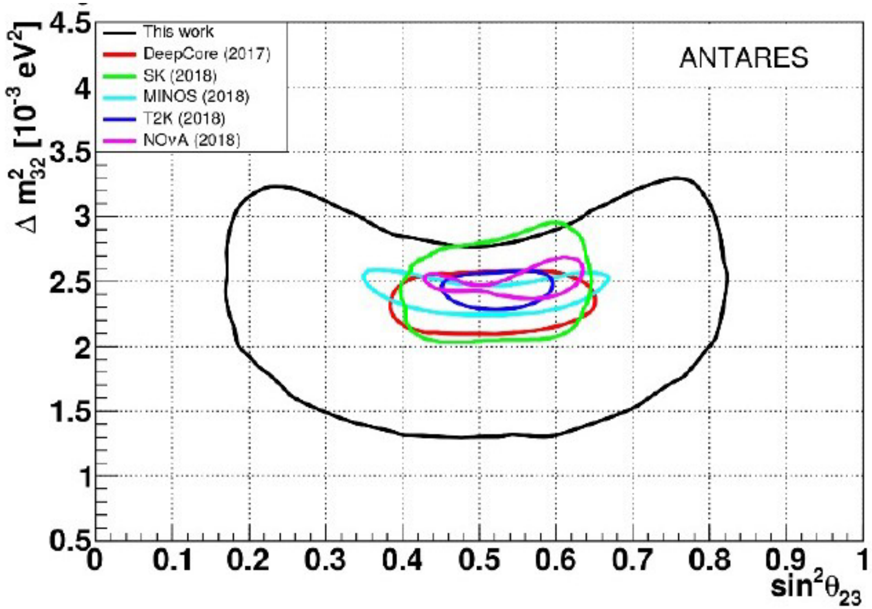
- Upgoing cascade events (ν_e / ν_τ CC, NC)
- Angular resolution < 3°
- Energy resolution for ν_e CC better than 10%



ANTARES Monte Carlo, JCAP01 (2021) 064

Oscillation Studies





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 ($\log_{10}(E_{reco})$, $\cos\theta^{reco}_{23}$)
- Data sample available (check the ANTARES website)

No-oscillation hypothesis excluded at 4.6 σ

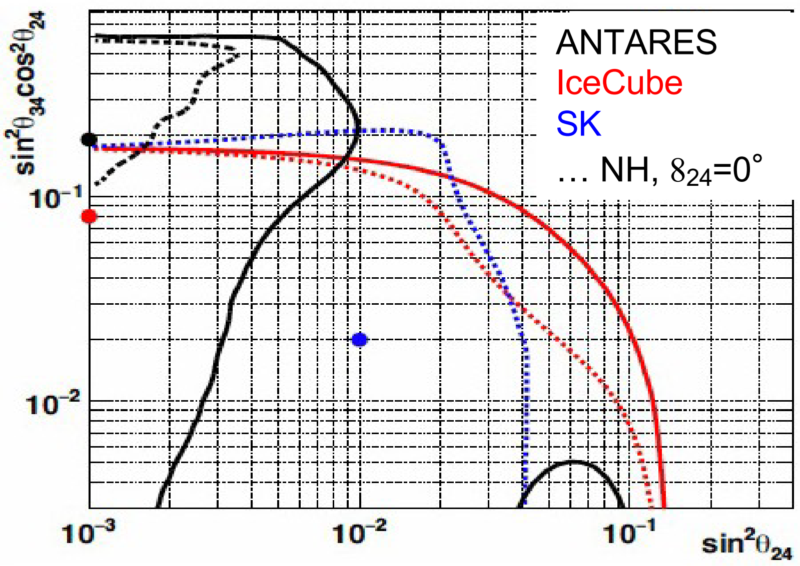
Additional Oscillation Studies

Sterile & NSI

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

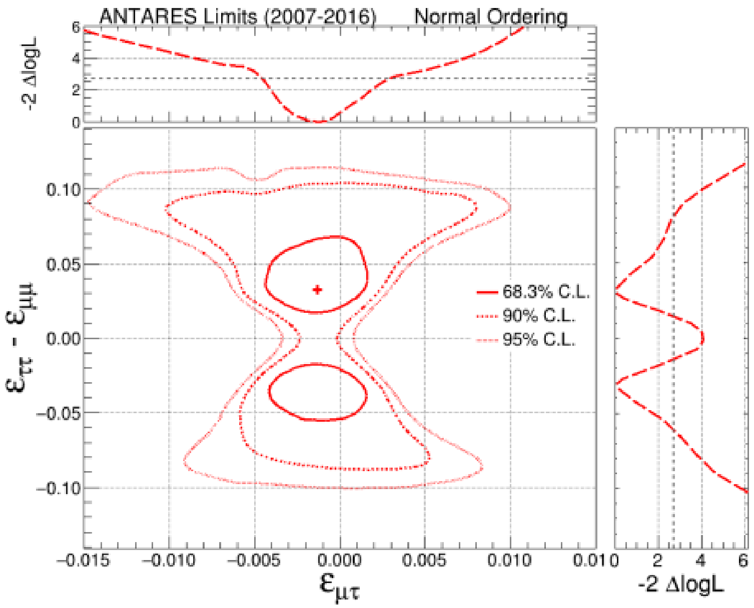
Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.

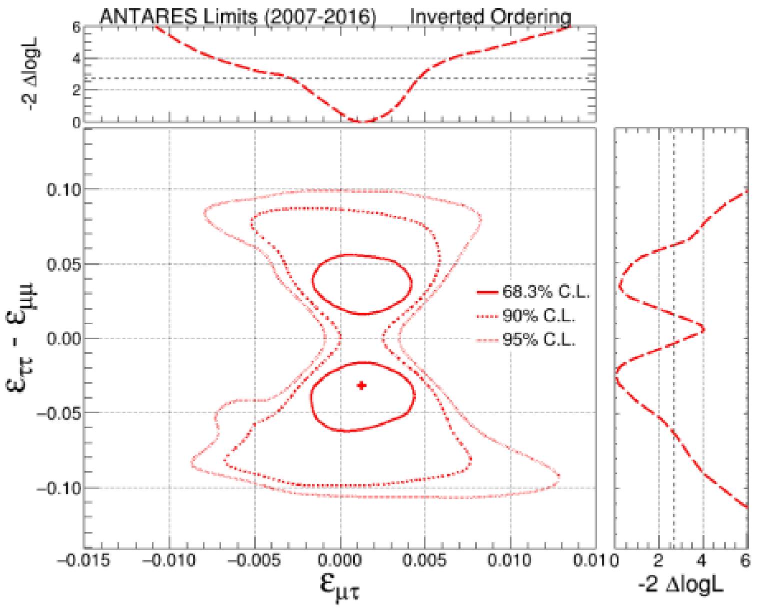
J. High Energ. Phys. (2019) 2019: 113



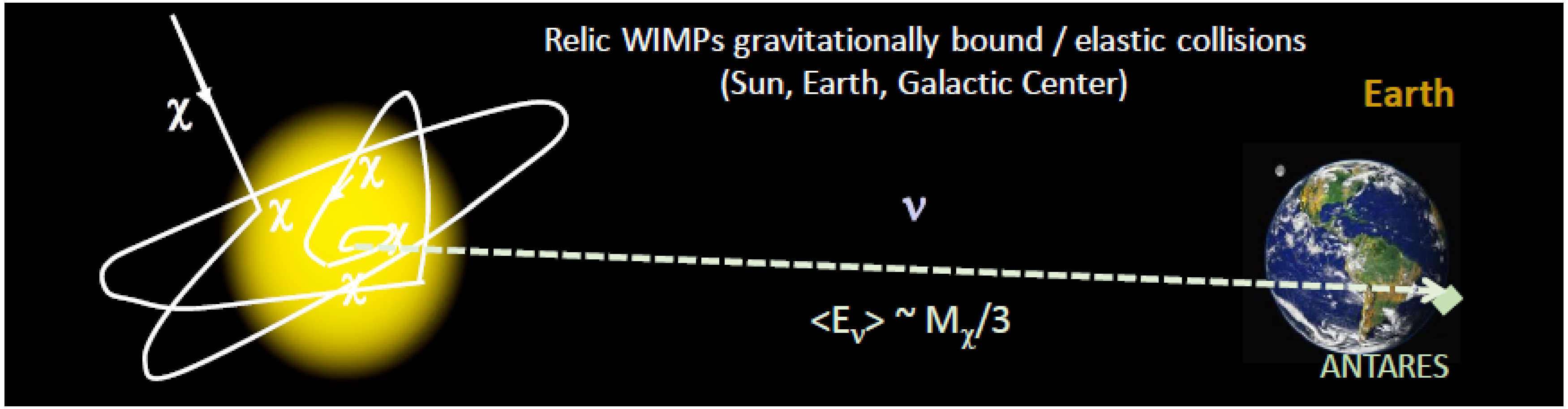
- Non-standard interaction signature in neutrino oscillation patterns are detectable
- Mild hint for non-standard interactions observed in 10 years of ANTARES data
- The non-NSI hypothesis is disfavoured with a significance of 1.7 σ (1.6 σ) for the normal (inverted) mass ordering scenario.

J. High Energy Phys. (2022) 7: 48





Indirect Search for Dark Matter



Competitive limits !

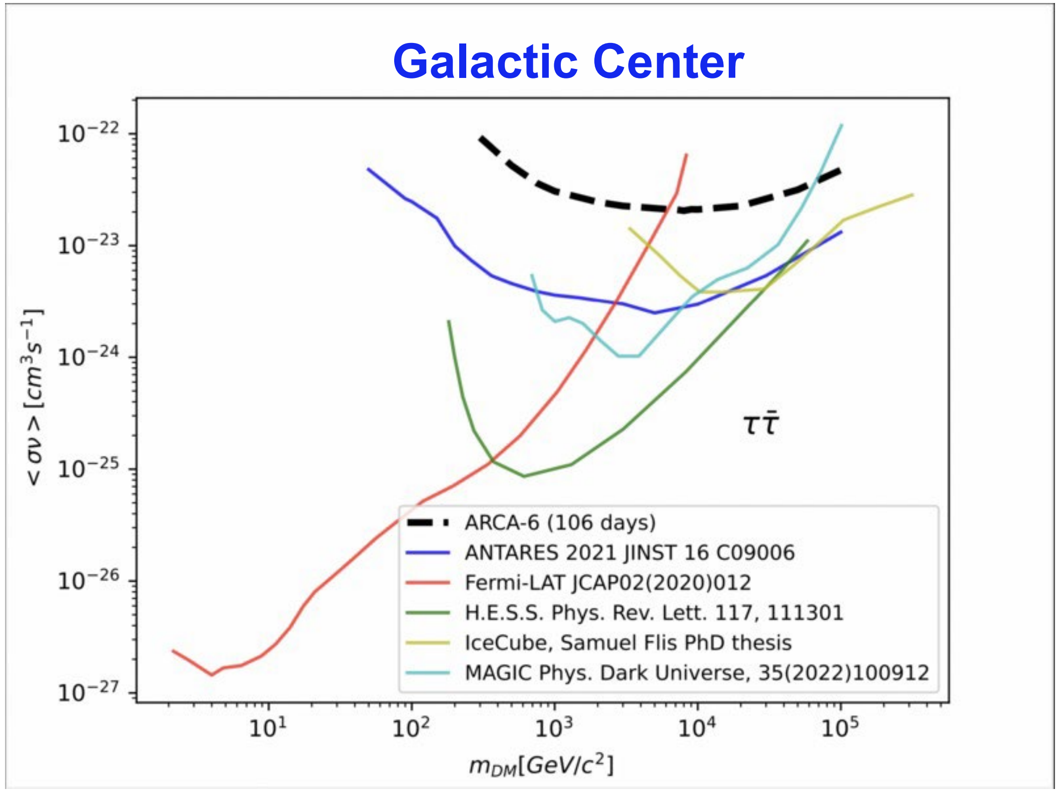
Our analyses do not include showers (all flavors) yet

Improvements ahead

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

Sun
Phys. Lett. B759 (2016) 69
JCAP 05 (2016) 016
JCAP11 (2013) 032

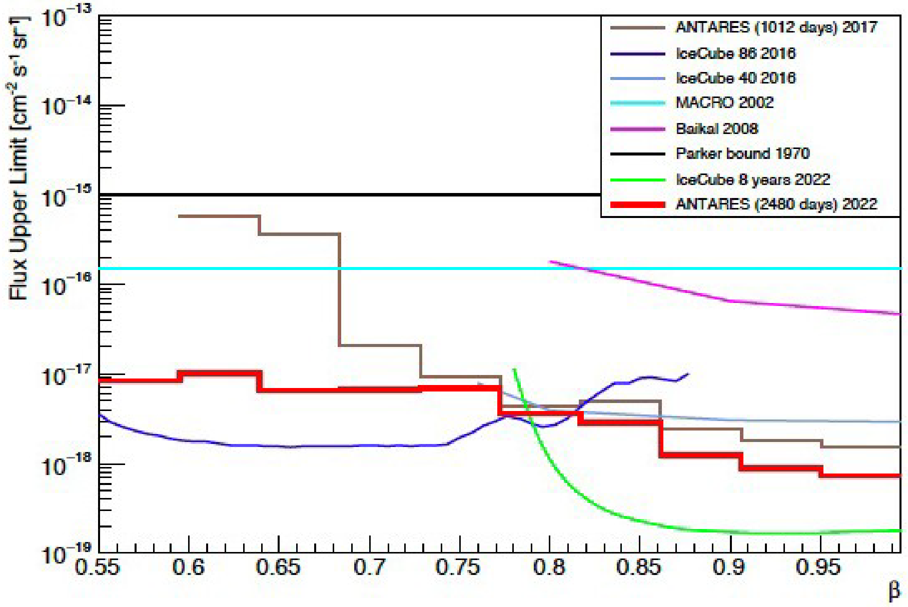
Galactic Center
JCAP 06 (2022) 028 (secluded DM)
Phys. Lett. B 805 (2020) 135439 .
Phys. Rev. D 102 (2020) 082002 (with IceCube)
Phys. Let. B 769 (2017) 249
JCAP 10 (2015) 068



Search for Exotic Physics with ANTARES

Monopoles

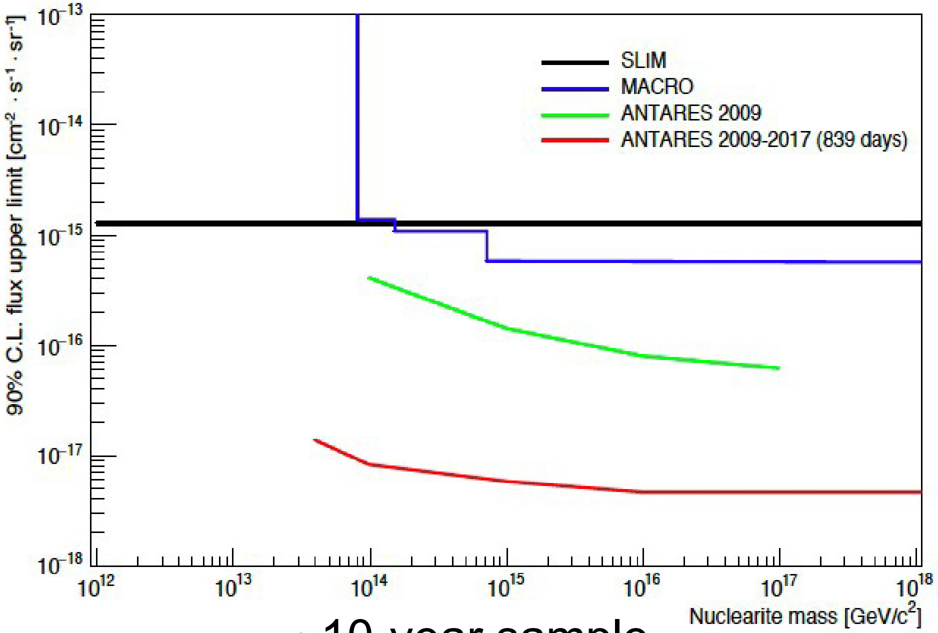
Magnetic monopoles
Kasama, Yang and Goldhaber model
Adapted reco for slow moving particles



JHEAP 34 (2022) 1-8

Nuclearites

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



~10-year sample

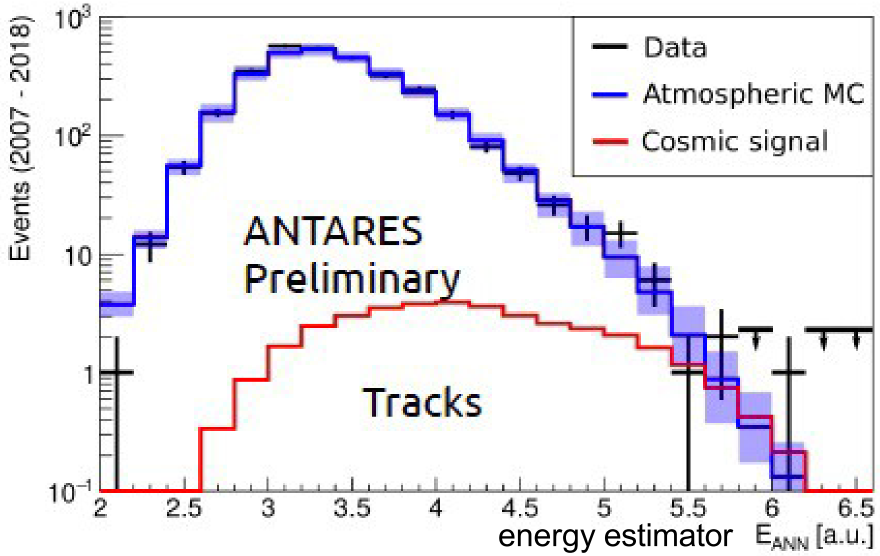
JCAP 01 (2023) 012

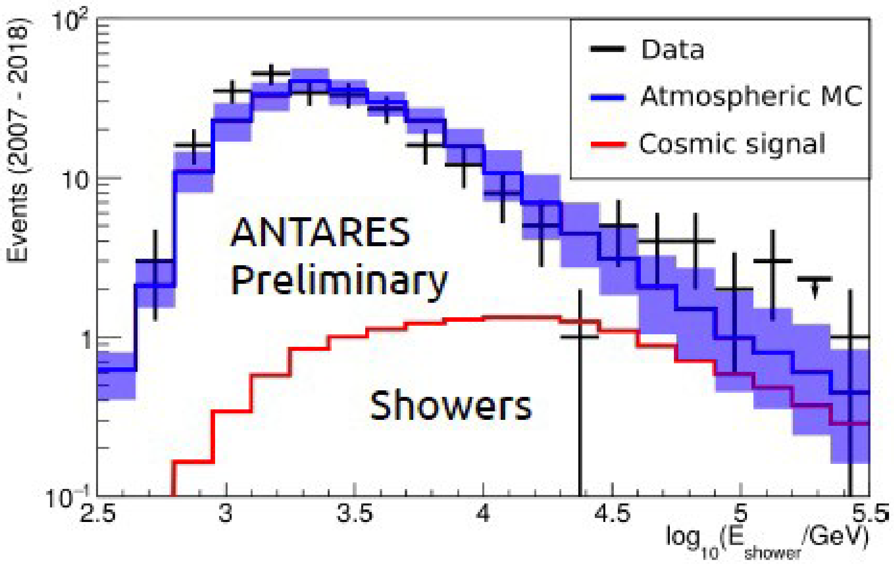
Diffuse ν flux

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

All-sky / All-flavor neutrino search, 2007-2018 (3330 days)

- 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)

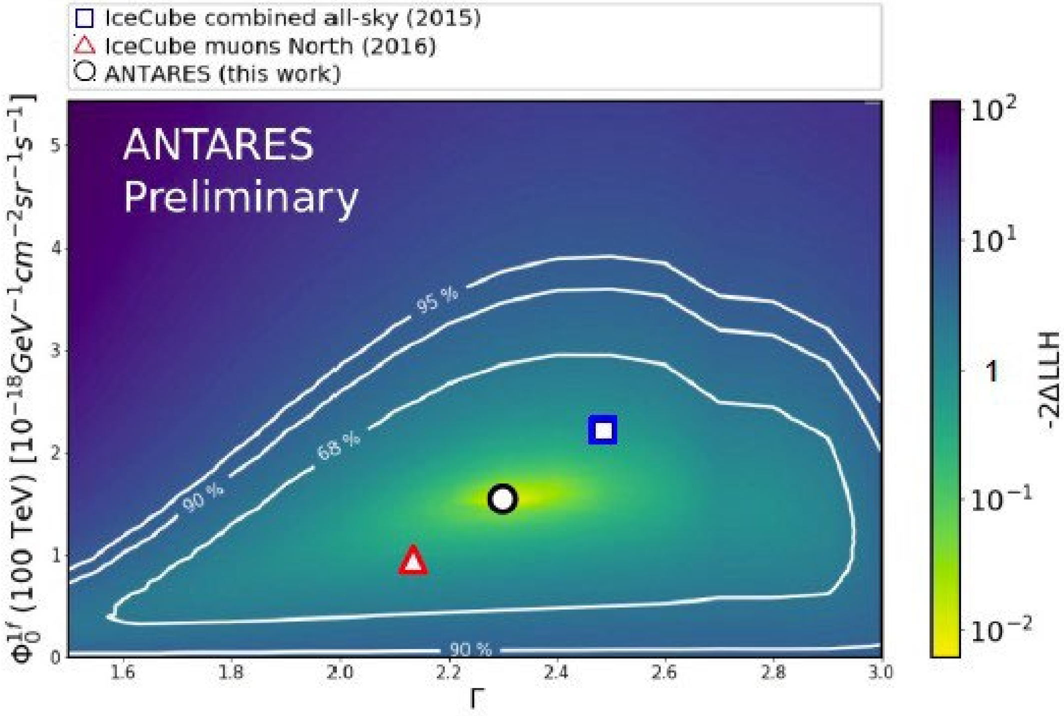
Background expectation (atm. flux, incl. prompt) :
36.1 ± 8.7 (19.9 tracks and 16.2 showers)
1.8 σ excess

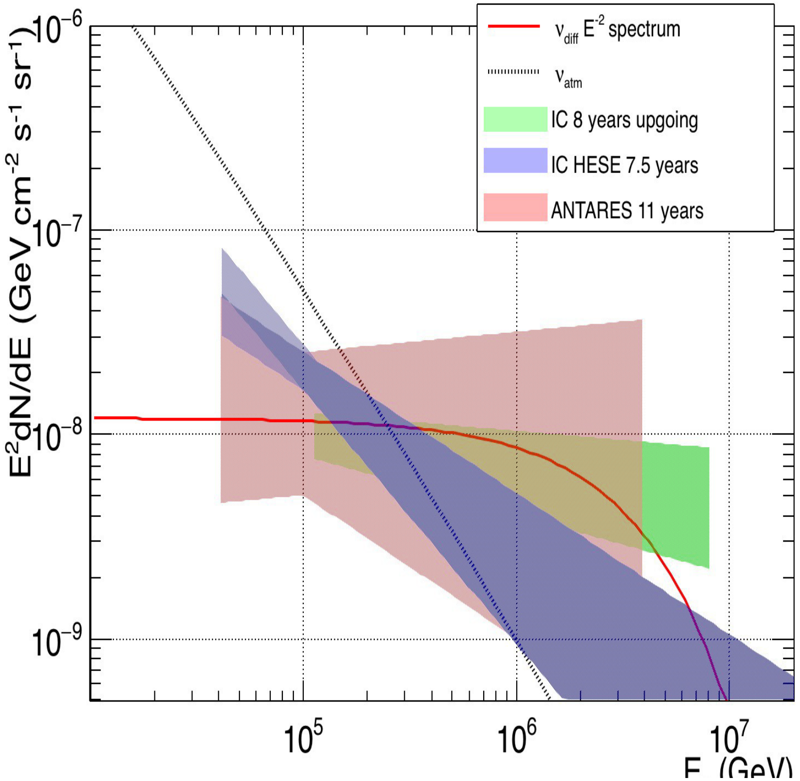
Results not really constraining… but fully compatible with IceCube

Diffuse ν flux – Towards a confirmation of IC?

Combined (tracks+showers) likelihood fitting:

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



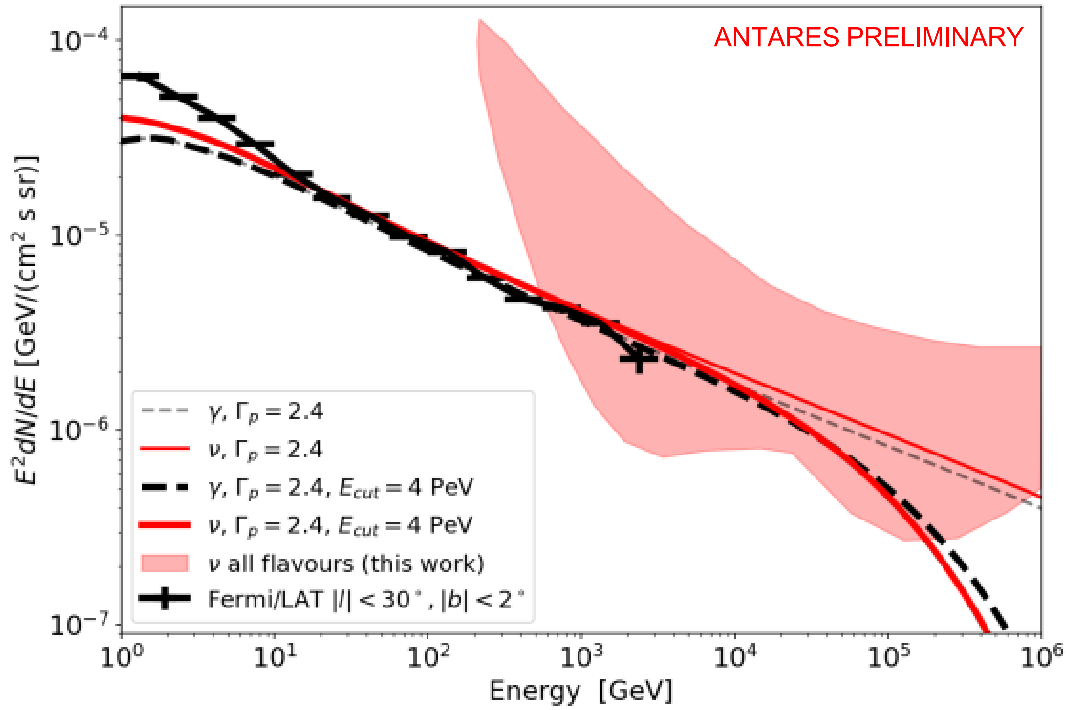


Results not really constraining… but fully compatible with IceCube

Hint for a neutrino emission from the Galactic ridge

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

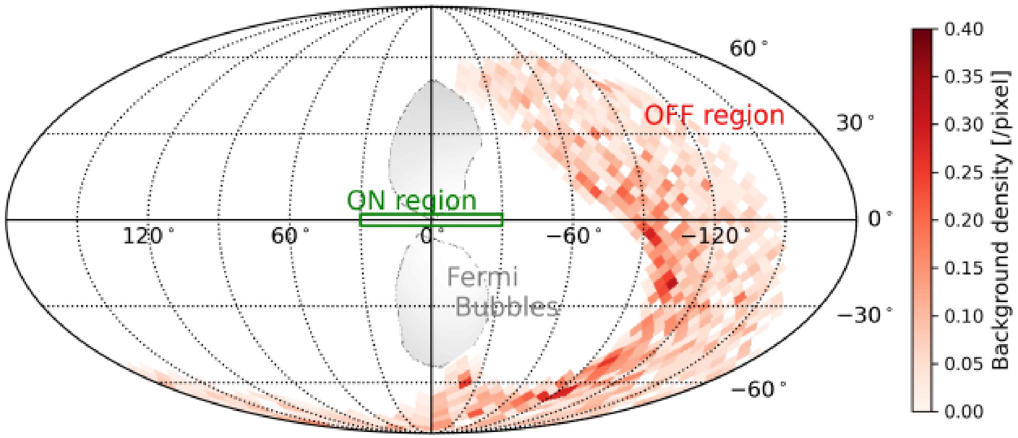
Phys. Lett. B 760 (2016) 143-148
https://arxiv.org/abs/2212.11876



Models computed with AAFrag

Such flux is consistent with the expected neutrino signal if the bulk of the observed γ-ray flux from the Galactic Ridge originates from interactions of cosmic ray protons and nuclei with a power-law spectrum extending well into the PeV energy range.

Robust background estimate



Latest improvements:

- Data sample: 2007-2020
- Tracks and cascades included
- Event selection optimized for region: $|l| < 30°$ and $|b| < 2°$

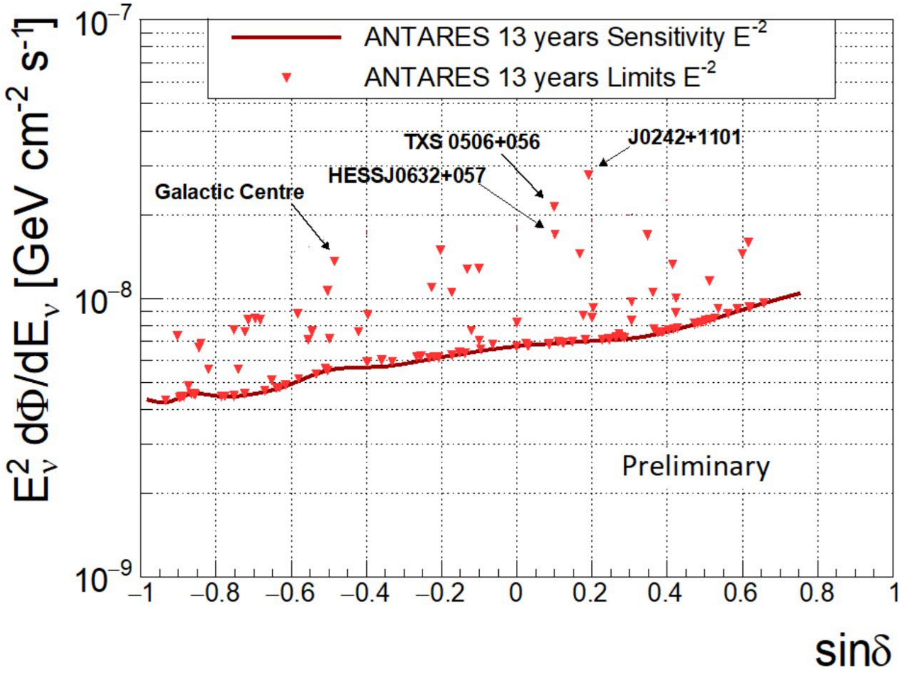
Latest PS search – All flavours

Data set:

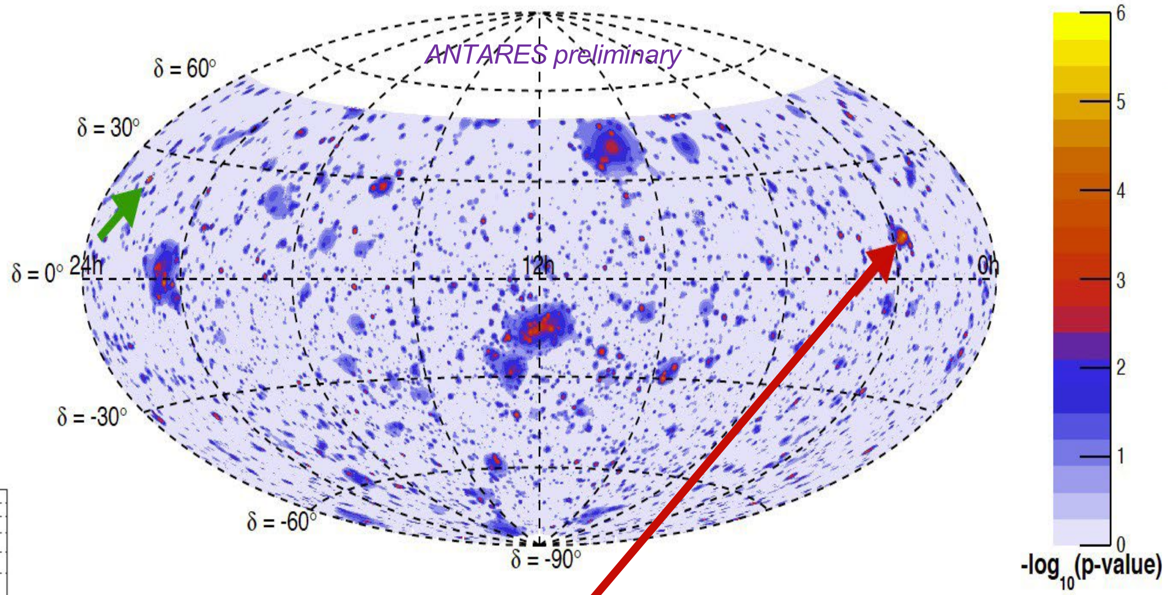
Period: from Jan 2007 to Feb 2020
Livetime: 3845 days
Events: 10162 tracks and **225 showers**

Candidate-list search:

121 investigated sources



Full-sky search

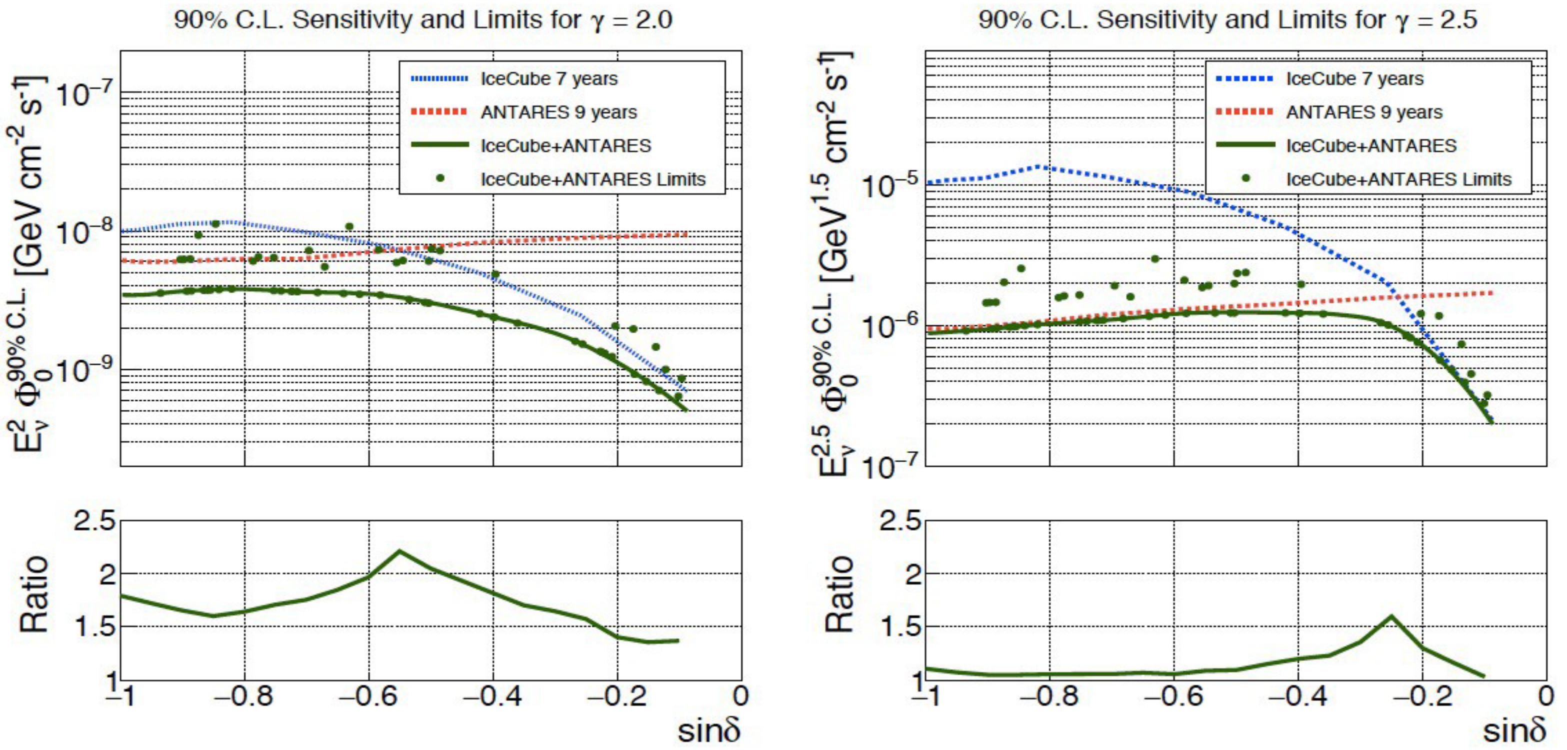


Full-sky hotspot (α,δ) = (39.6°, 11.1°)
pre-trial p-value: of 6.8 × 10^{-6} (4.3 σ)
post-trial p-value: of 48%
Within 1 degree from J0242+1101

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

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

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The multi-messenger program

Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA	TAROT ZADKO MASTER GWAC	Swift INTEGRAL	Fermi	HESS HAWC

What triggers an alert:
- Doublet of neutrinos (~0.04 events/yr)
- Single neutrino with direction close to local galaxies (~1 TeV, ~10 events/ yr)
- Single HE neutrinos:
  - HE (~5 TeV, 20 events/ yr)
  - VHE (~30 TeV, ~3-4 events/ yr)

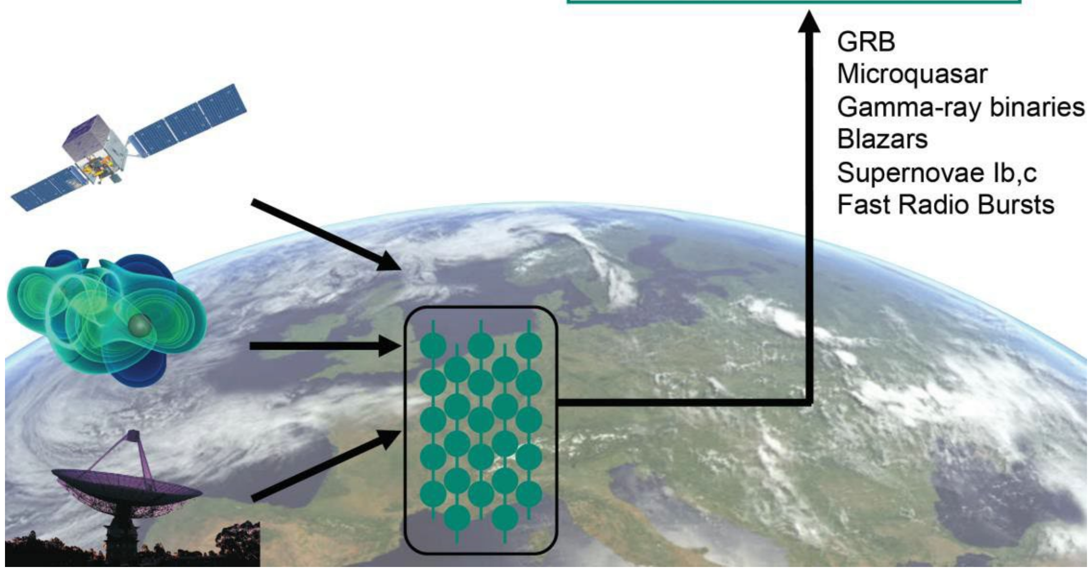
Performances:
- **Time to send an alert: ~5 s**
- **Median angular resolution: ~ 0.4°**

electromagnetic

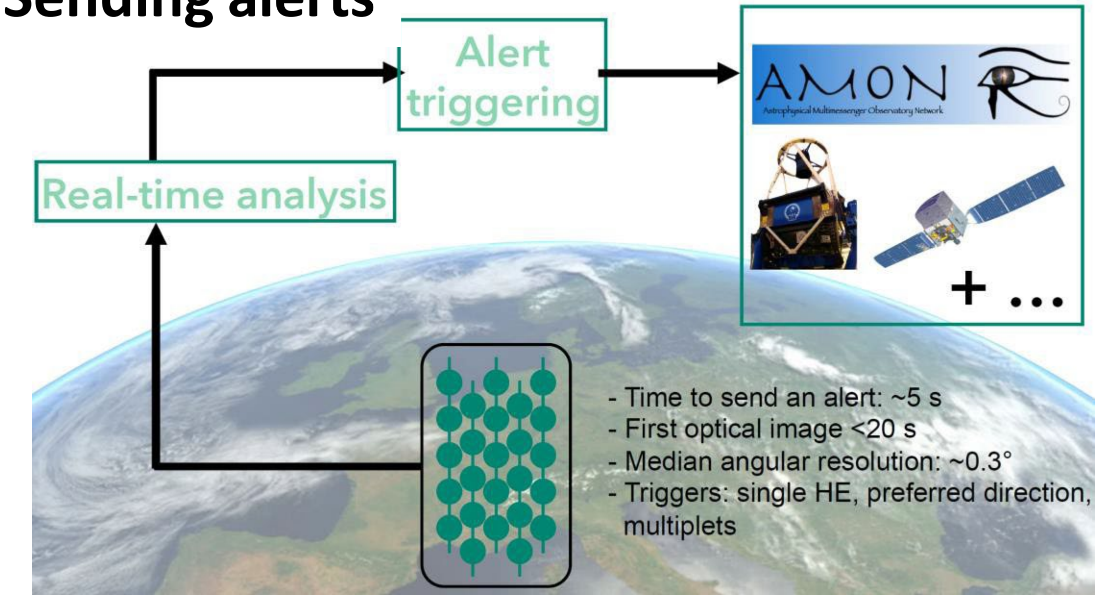
+ LIGO VIRGO, PIERRE AUGER OBSERVATORY, ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Alert system (**TAToO**: Telescopes and Antares Target of Opportunity)
active since 2009
APP 35 (2012) 530

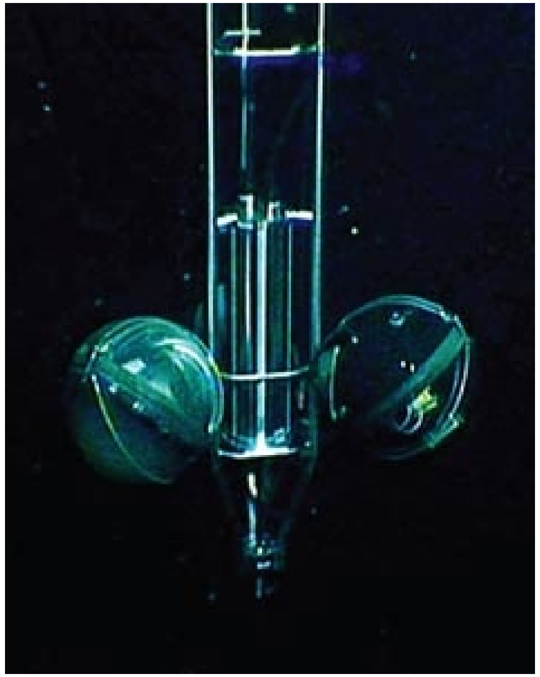
Receiving alerts



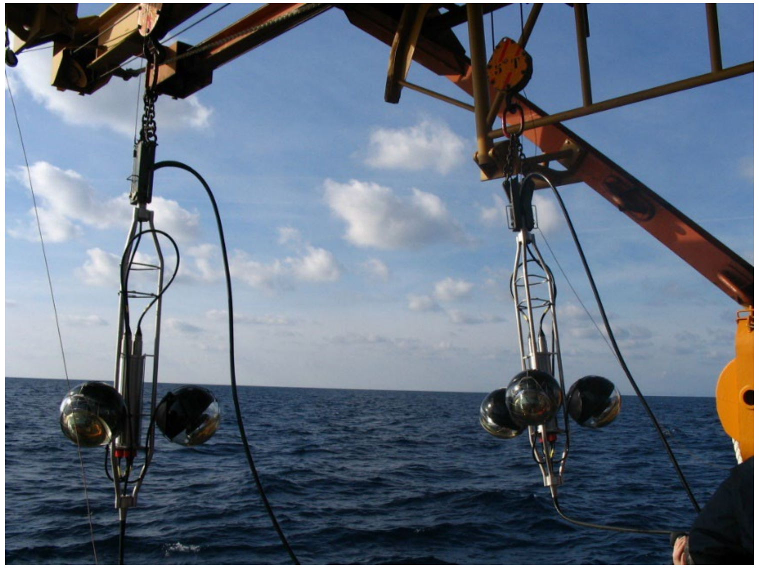
Sending alerts

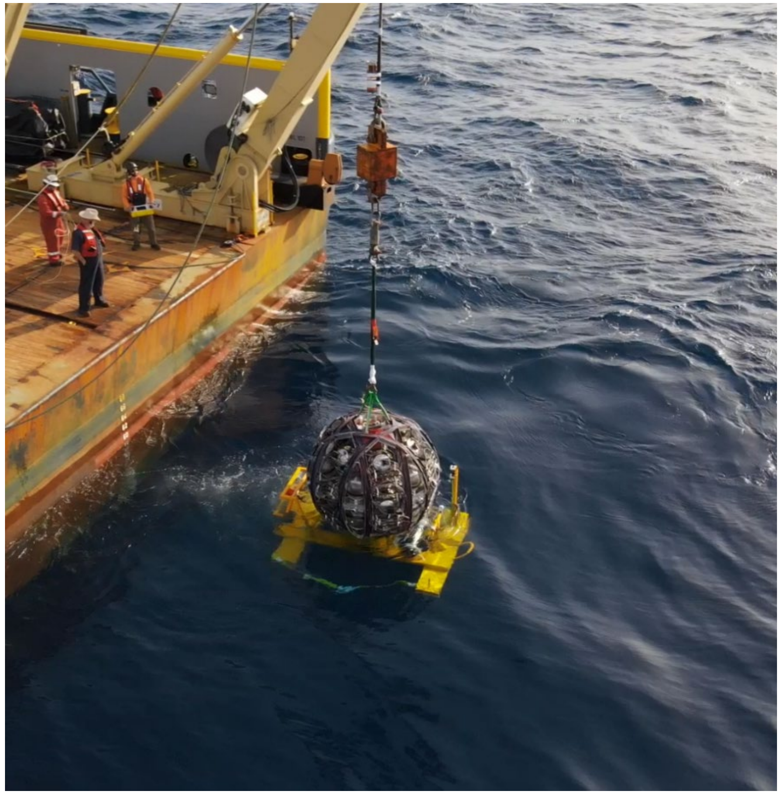


From ANTARES to KM3NeT



ANTARES:
- Storeys with triplets of optical modules (OMs) and electronics container
- One 10" PMT in each OM





Innovative deployment technique in KM3NeT, with detection line furled on a spherical launcher vehicle

KM3NeT:
- 31 3" PMTs in one 17" sphere (DOM)
- 3x cathode area w.r.t. an ANTARES OM
- Single photon counting
- Directional information

JINST 17 (2022) P0703

(See Sonia El Hedri's presentation on KM3NeT!)

KM3NeT blooming on ANTARES...

The first optical module of KM3NeT ever operated in the sea

At installation time on the instrumentation line of ANTARES in spring 2013...

...and at recovery in spring 2022

Summary

► ANTARES has been the first undersea neutrino telescope

► Fundamental lesson learned from ANTARES: undersea Cherenkov technique is feasible and reliable for long time data taking!

► Multi-disciplinary observatory (Earth and sea sciences)

► Competitive physics results & intriguing hints

► Constraints on neutrinos as seen by IceCube

► Extensive multi-messenger program

► Joint studies with several partners

QUITE AN ADVENTURE! To be continued...