The ANTARES neutrino telescope

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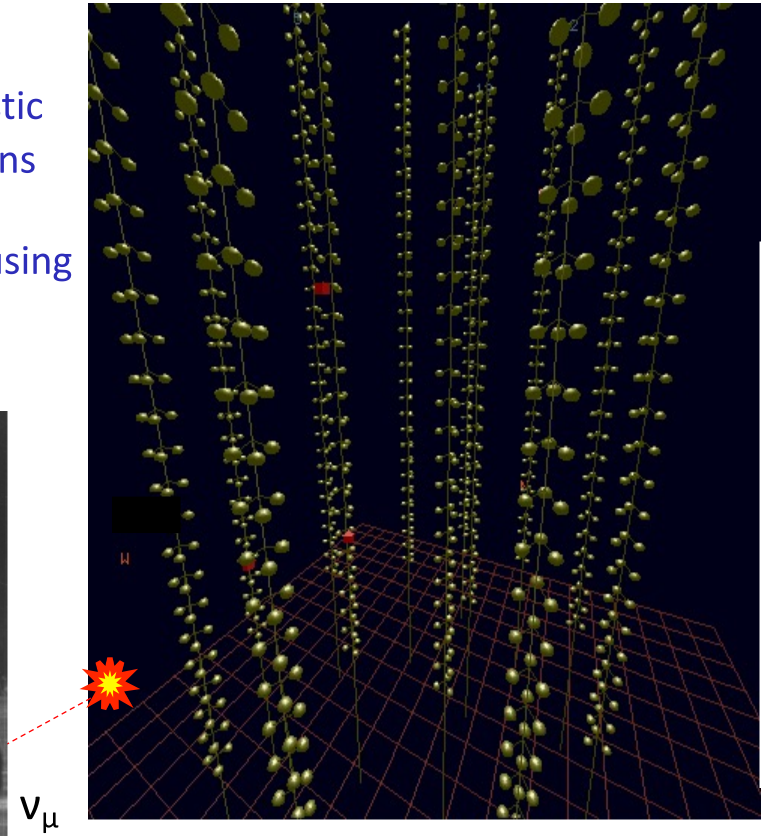
on behalf of the ANTARES Collaboration

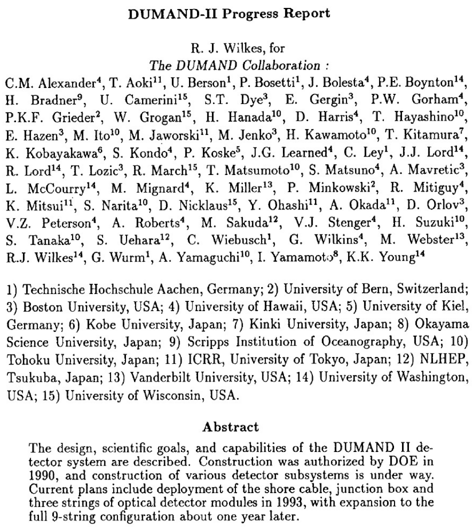
Rome, 6- 9 September 2022

The concept of Cherenkov neutrino telescopes

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



First tentative in water 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 sea - Hawaii island



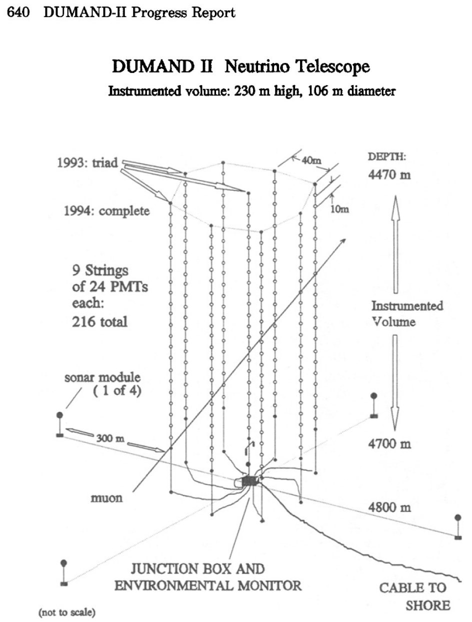
DUMAND-II Progress Report

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

DUMAND Project canceled in 1996 because of technological problems

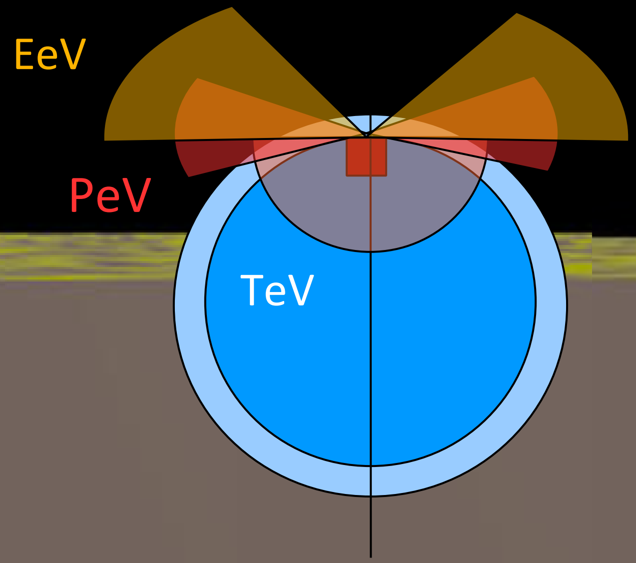
Precursor of the present neutrino telescopes, under water and ice

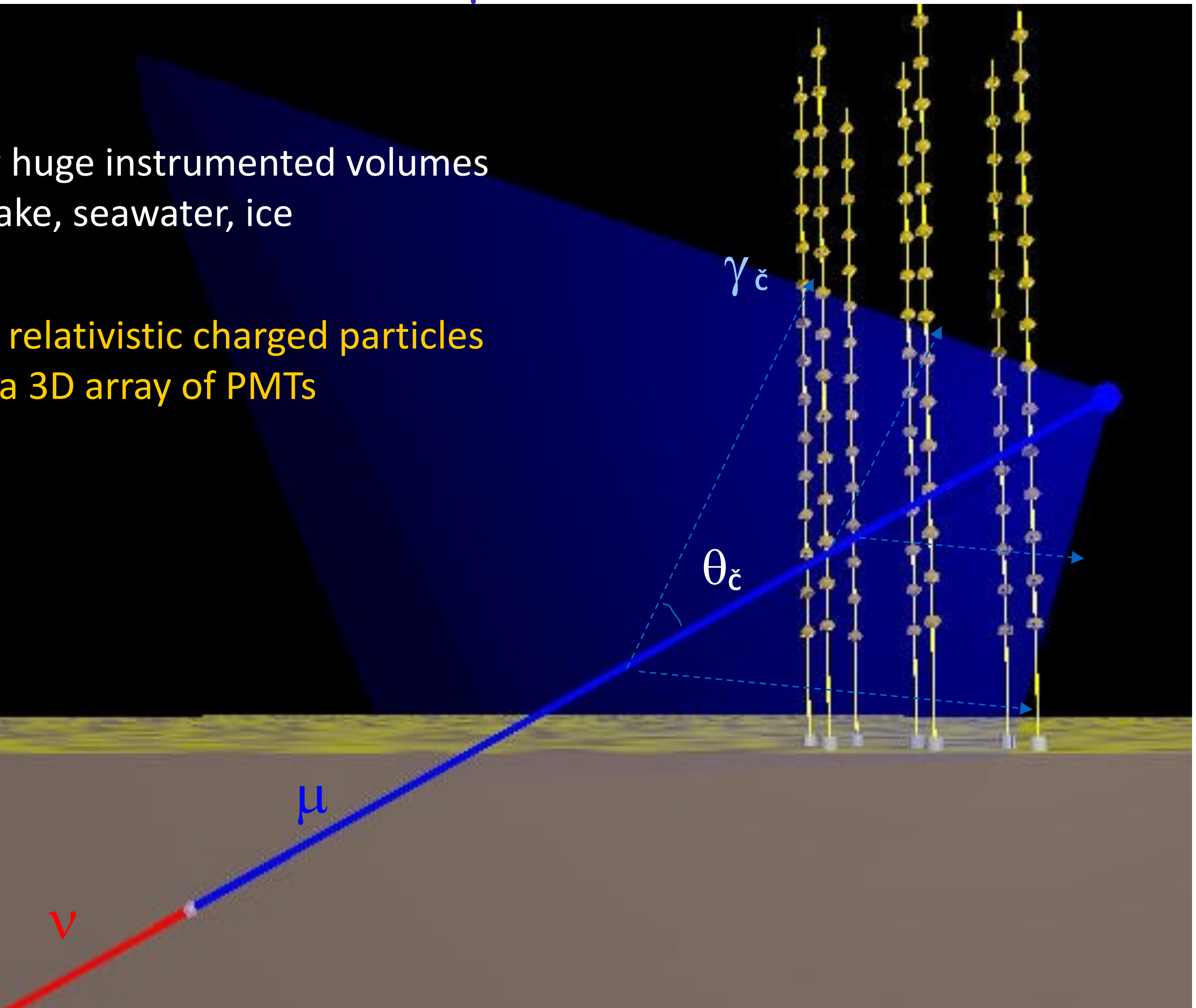
ANTARES accepted the challenge - the present and the future undersea neutrino telescopes shall exploit the ANTARES experience

Detection principle: muon tracks (CCν_μ)+ cascades (NC+ν_e)

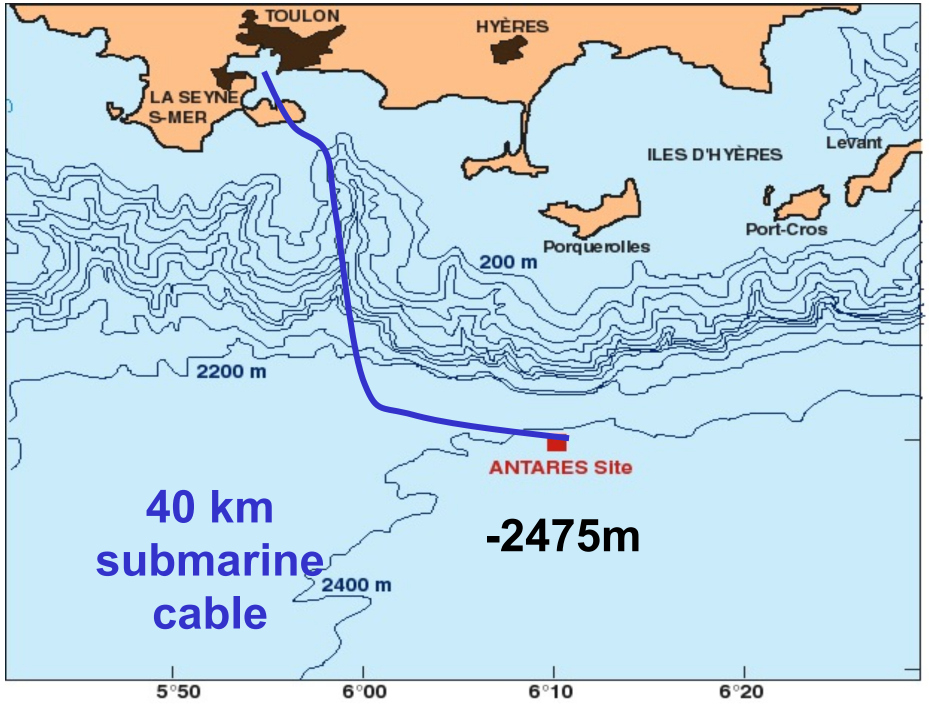
Natural radiators are low cost and allow huge instrumented volumes in dark but transparent media →Deep lake, seawater, ice

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





The ANTARES site

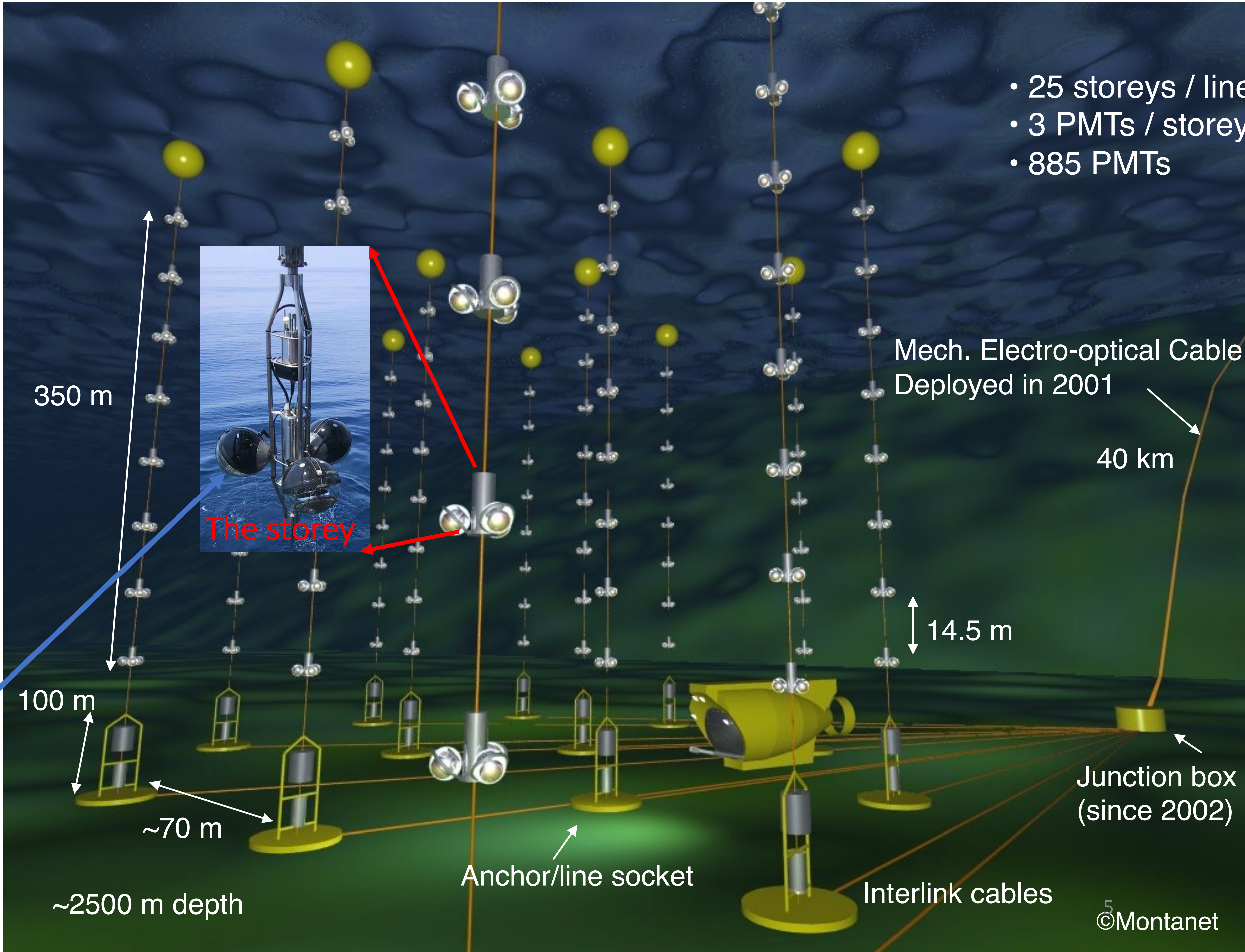


The ANTARES detector

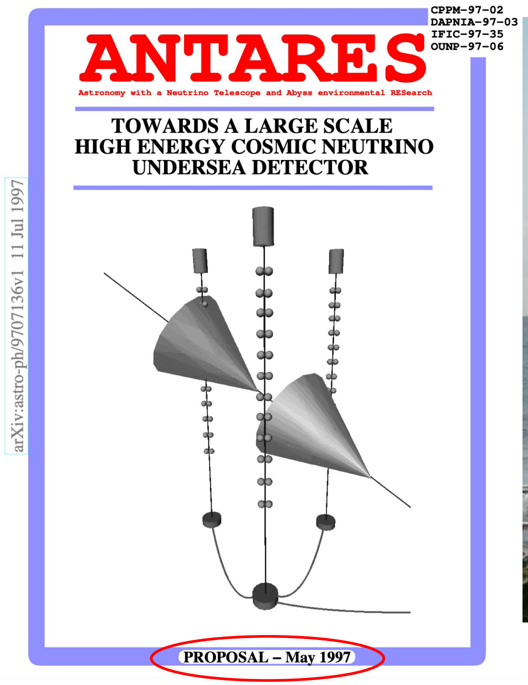
NIM A 656 (2011) 11

The Optical Module

NIM A 484 (2002) 369



ANTARES 2001-2022



2001 Main Electro-Optical Cable deposition

2002 Junction Box deployment:
no repair, no failure in 20 years

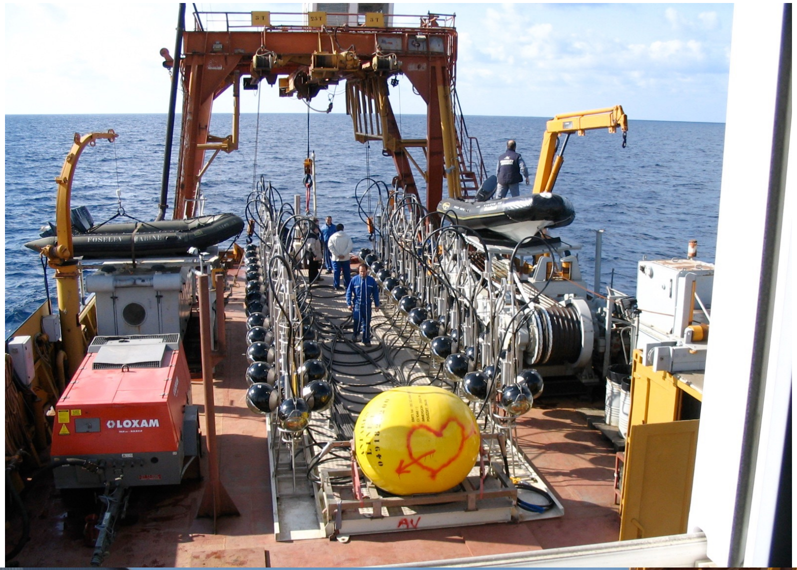
1997 Proposal
2001 Main Electro-Optical Cable deposition
2002 Junction box deployment
2003 Prototype Sector Line - First data
2005 Mini Instrumentation Line with OMs - environmental data
2006 First complete detector line
2008 Detector with 12 lines completed - complete configuration
2016 Running (almost) without common funds

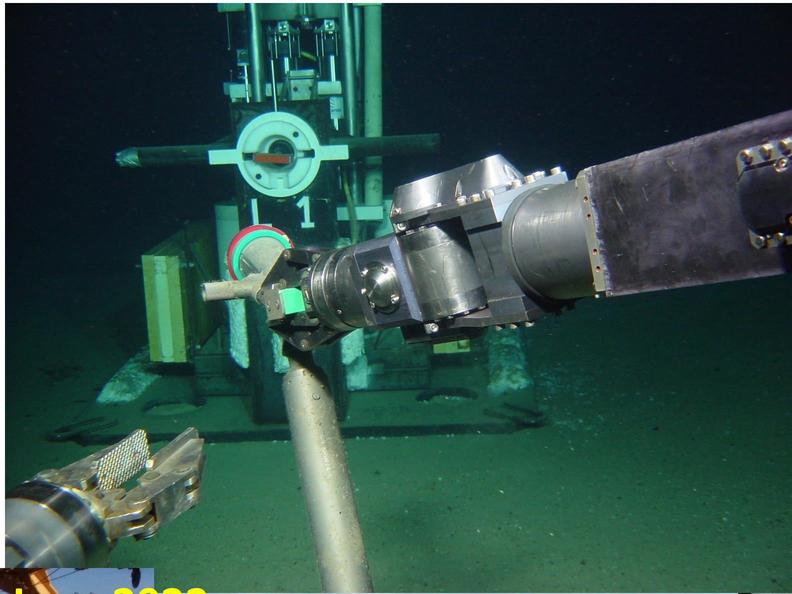
February 2022 Data taking terminated

First detector line

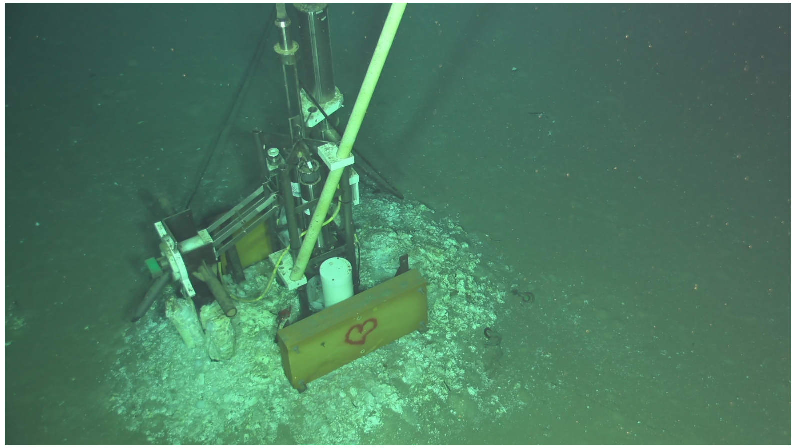
Deployment
14/02/2006

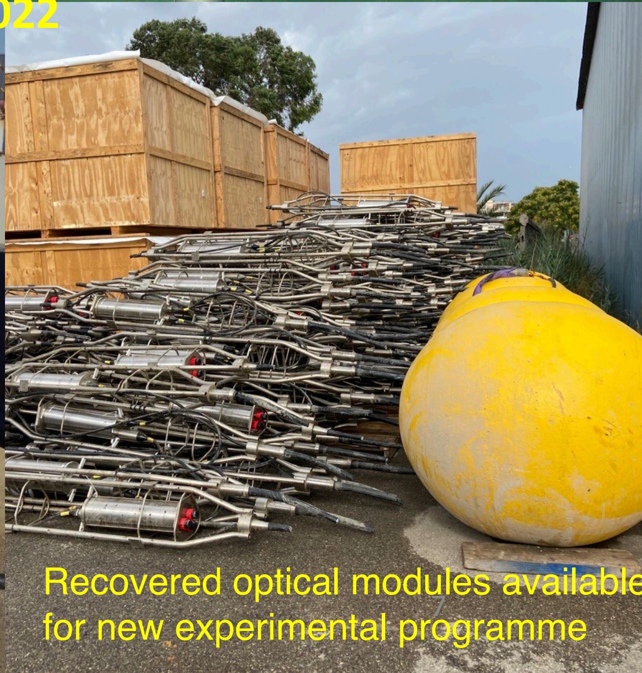
Connection
march 2006



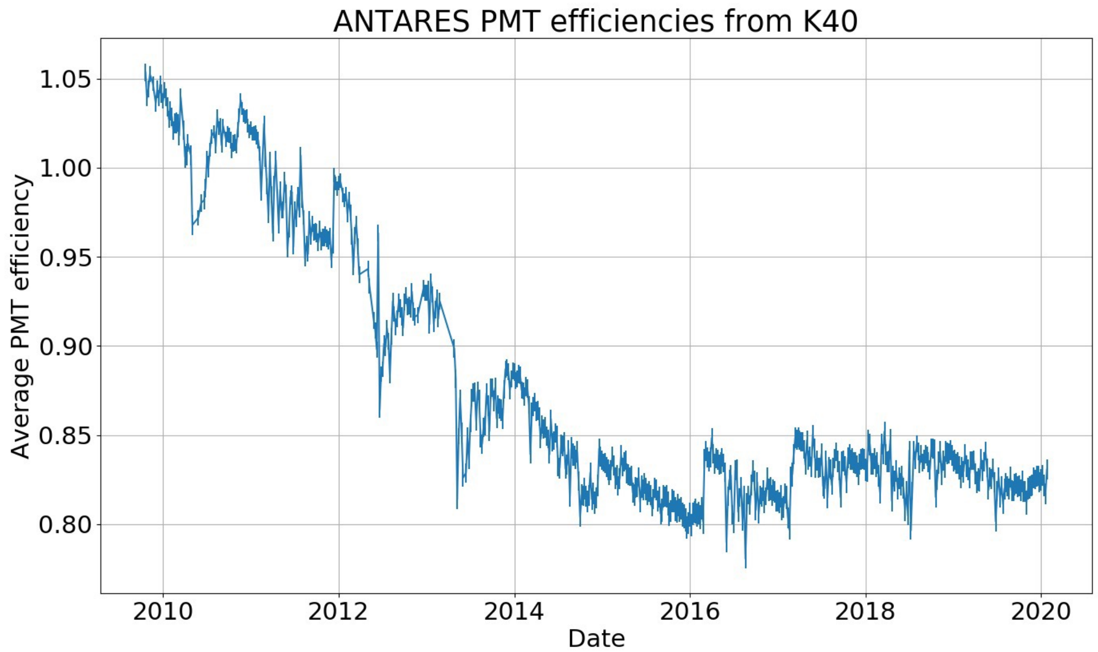


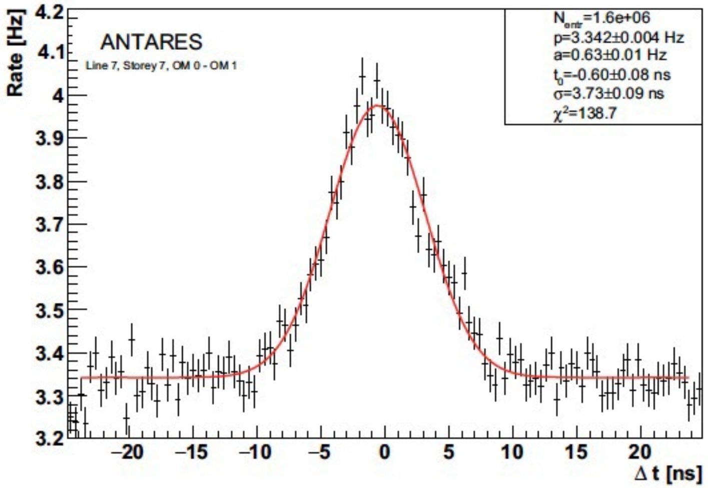
Disconnection after 16 years





^{40}K (long-term) monitoring of PMT efficiency





Example of the detected hit time differences, Δt, between two adjacent OMs

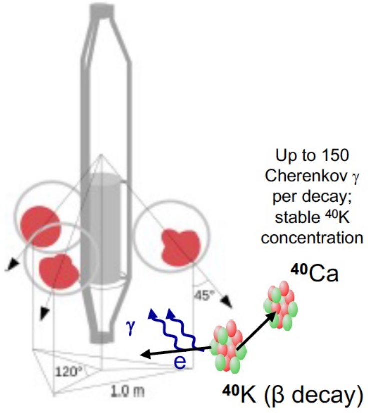
Regular tunings

Only ~20% efficiency loss

Extremely stable data acquisition

^{40}K powerful calibration tool

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

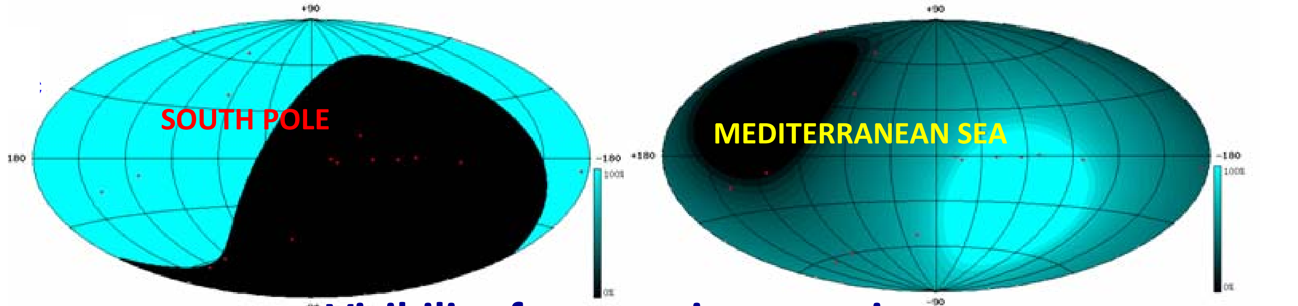


$$
\begin{aligned}
{}^{40}\mathrm{K} \rightarrow \quad & {}^{40}\mathrm{Ca} + e^- + \overline{\nu}_e && (89.3\%) \\
{}^{40}\mathrm{K} + e^- \rightarrow \quad & {}^{40}\mathrm{Ar}^* + \nu_e && (10.7\%) \\
\hookrightarrow \quad & {}^{40}\mathrm{Ar} + \gamma &&
\end{aligned}
$$

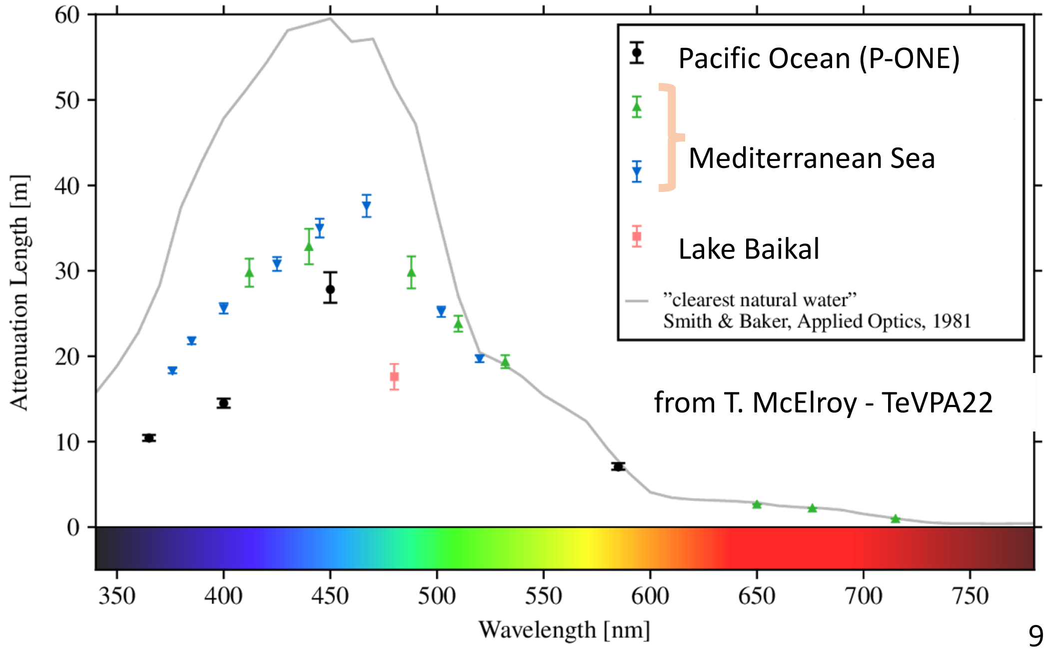
electrons above Cherenkov threshold

Why the Mediterranean Sea

- excellent water optical properties → excellent reconstruction performance
- angular resolution
  - **tracks: ~0.4° [< 0.1 ° KM3NeT] @ 10TeV; (IceCube : 0.3° @ >100 TeV)**
  - **showers: ~4° [2° KM3NeT] @10 TeV ; (IceCube: 10° @ > 100 TeV)**
- Visibility of the Galactic region ➔ ~ 70 % for the Galactic Centre
- Investigation of the IceCube diffuse flux from another point of view



Visibility for up-going neutrinos

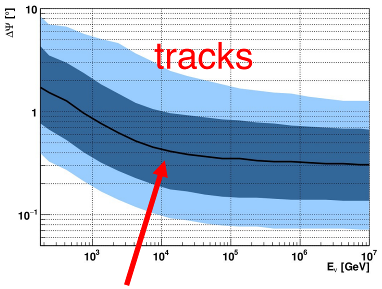


from T. McElroy - TeVPA22

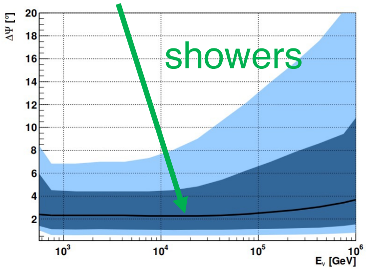
Event topologies - reconstruction performances

track channel = the golden channel for source identification

- Upgoing track events (νμCC)
- Angular resolution <0.4° for Eν>10 TeV
- 90% purity
- Energy resolution ~ factor 2

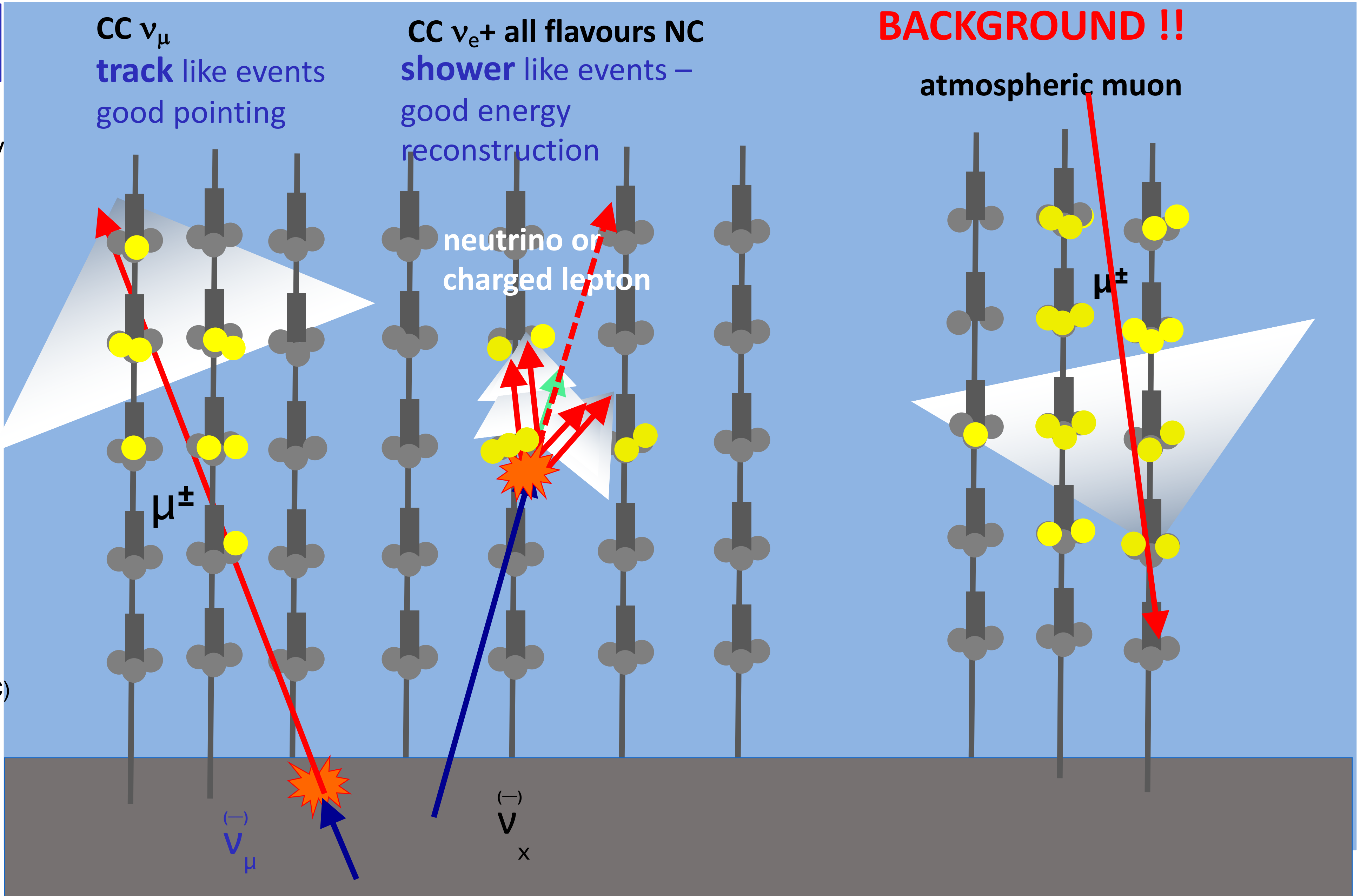


median resolution



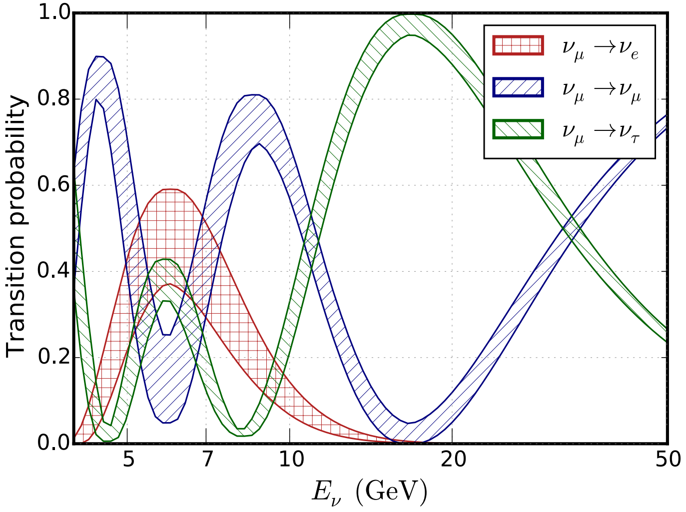
- Upgoing shower events (ve / vt CC, NC)
- Angular resolution < 4°
- Energy resolution for better than 10%

shower channel = good energy resolution
(IceCube discovery channel)

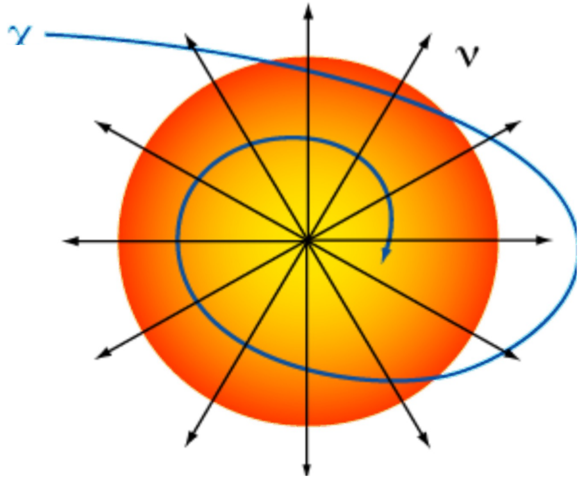


Science with ANTARES

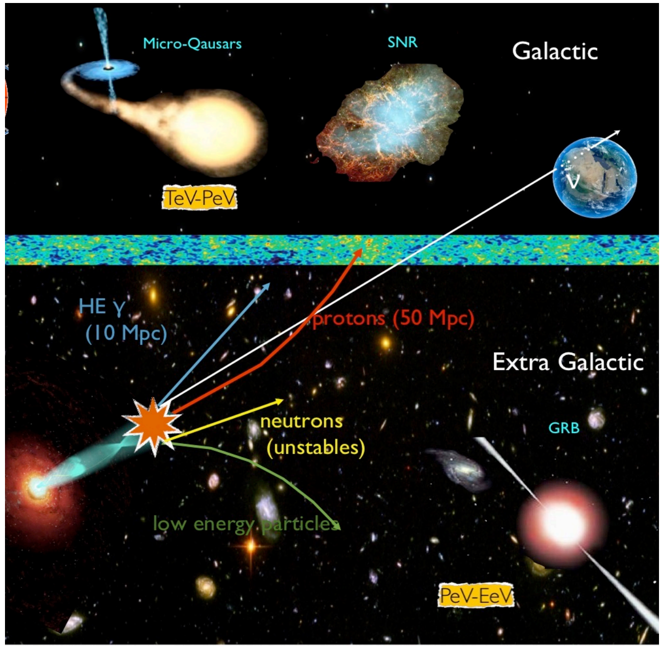
Neutrinos: undeflected and unabsorbed → perfect probes



Low Energy
> 10 GeV



Medium Energy
10 GeV < E_ν < 10 TeV



Galactic → Extragalactic
High Energy, E_ν > TeV → PeV

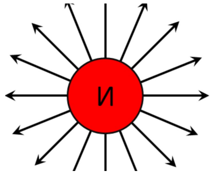
Energy

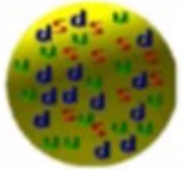
Dark matter search

ν from cosmic sources
origin and production
mechanism of HE CRs

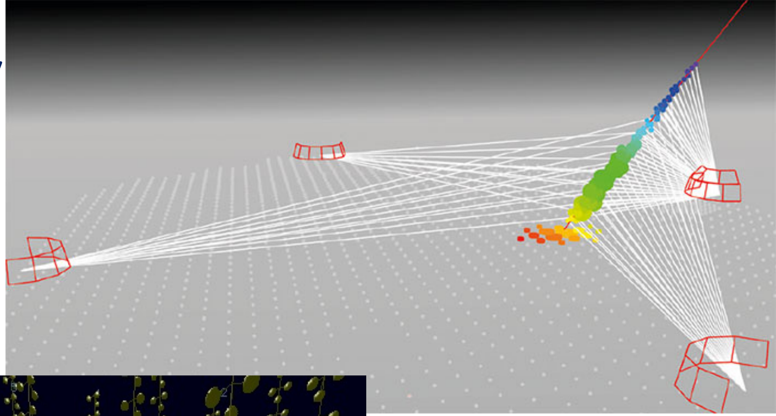
ν Oscillations

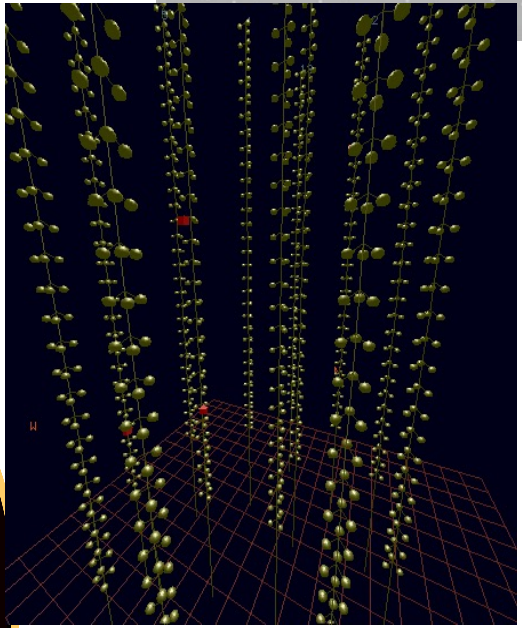
+ Exotic searches - Nuclearites, Magnetic monopoles...

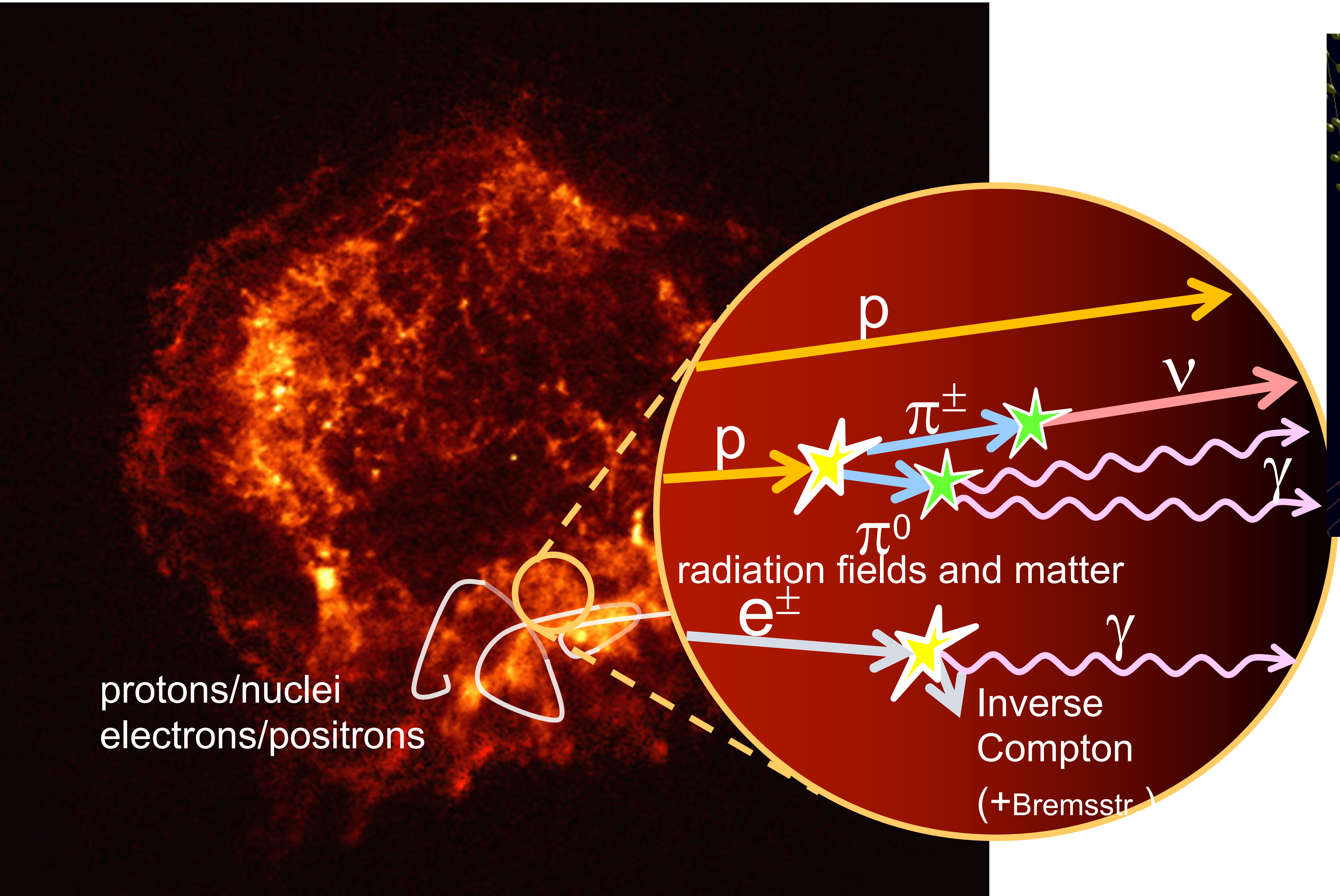


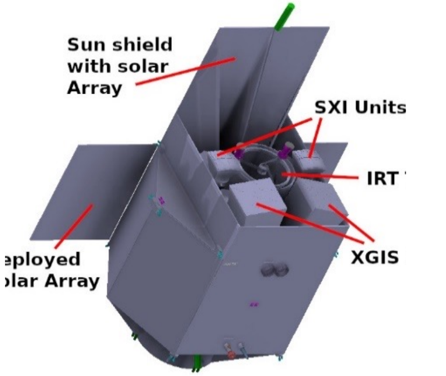


ν, CRs, γs and multimessenger astronomy

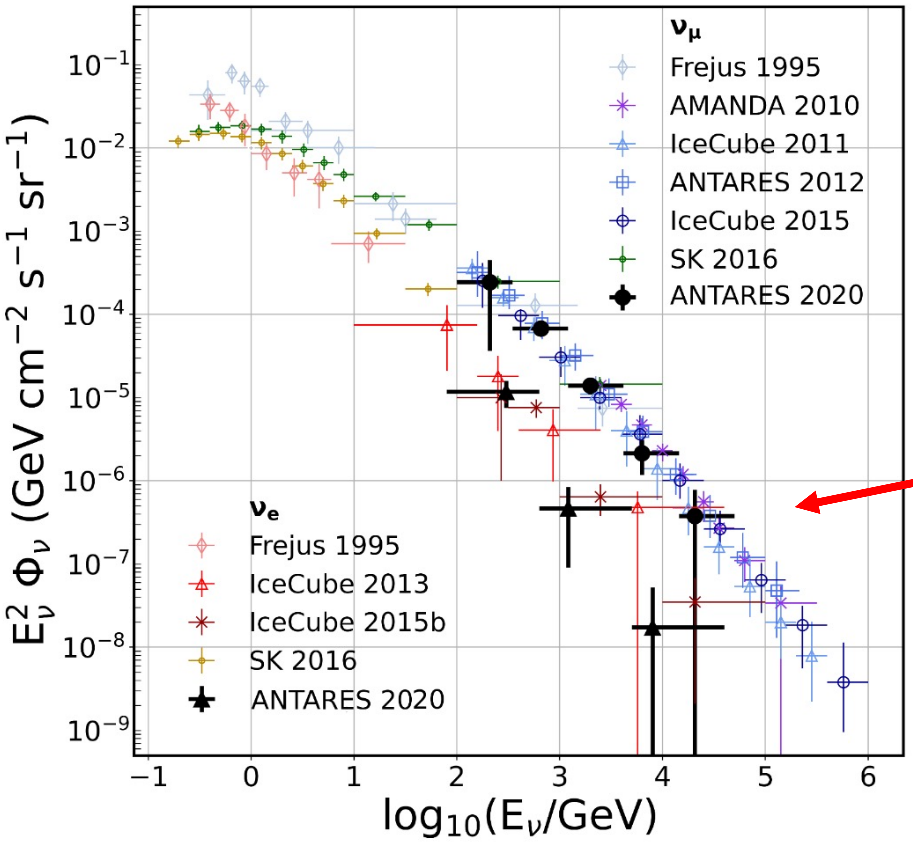


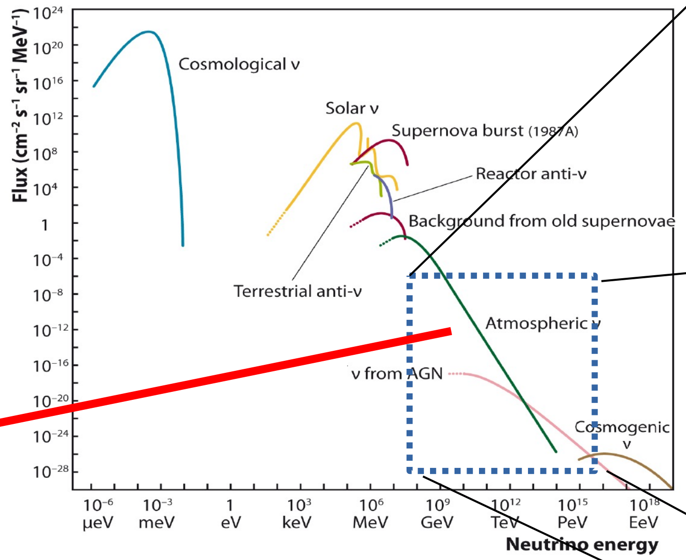


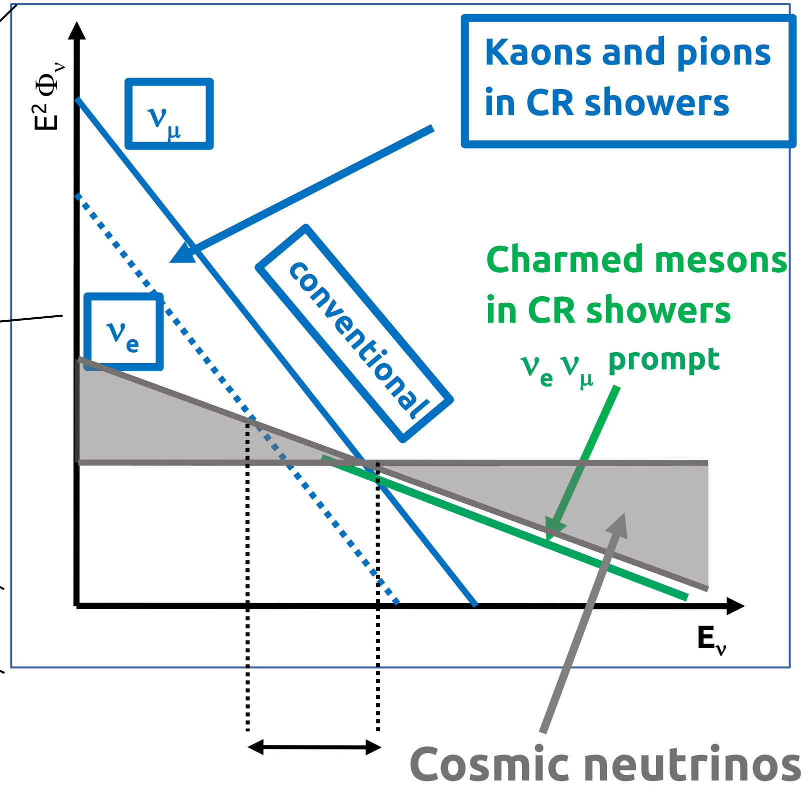




Atmospheric neutrino background







Atmos-to-Cosmic transition
30-200 TeV

measured using an energy estimator
accounting for detector systematics

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

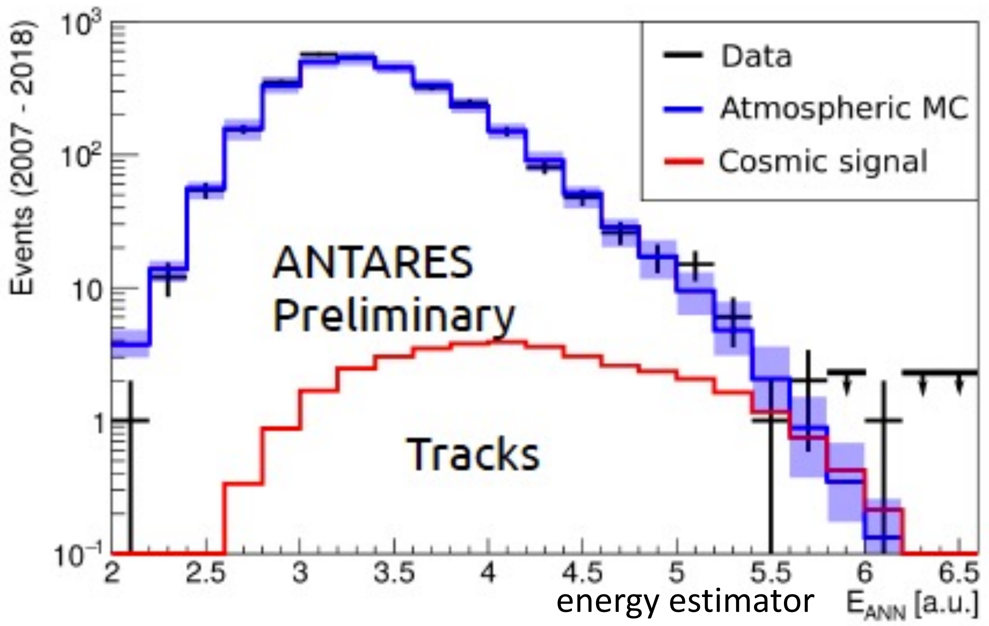
Diffuse flux of cosmic neutrinos in ANTARES

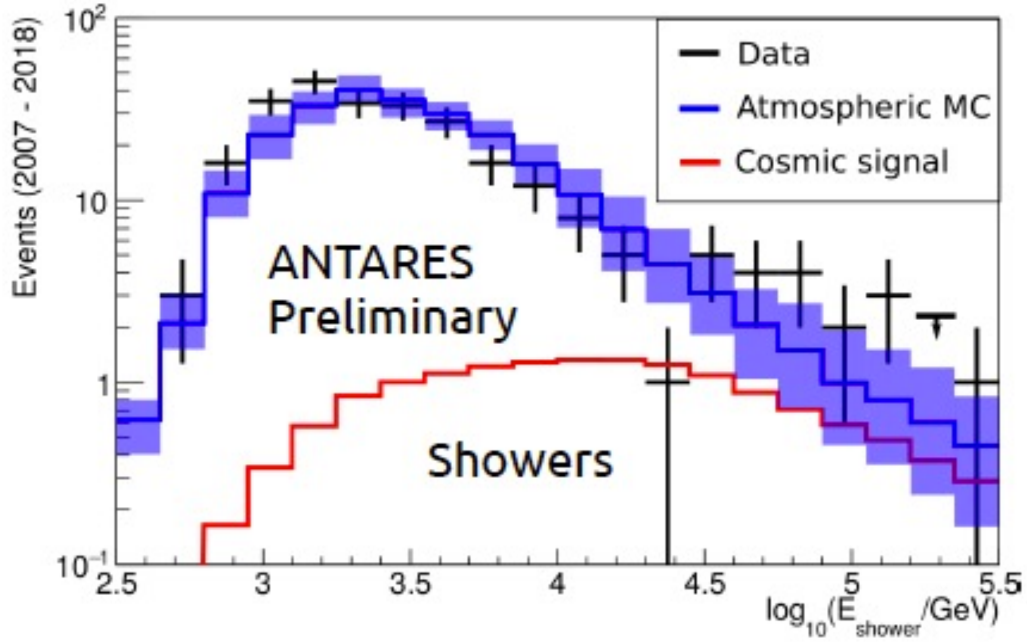
📖 Ap.J.Lett. 853 (2018) 1, L7
📖 https://pos.sissa.it/358/891/pdf -(ICRC 19)

Search for an excess of high-energy events w.r.t atmospheric neutrinos

- Selection cuts optimized with MRF procedure (assumed spectral index Γ=2.5)
- Look for event excess above a given E_{th} both for track & shower samples
- Data with E> E_{th} : **50 events (27 tracks + 23 showers)**
- Background with E> E_{th} (atm. Flux=HONDA + Enberg): **36.1 ± 8.7 (19.9 tracks +16.2 showers)**
- → **1.8σ excess** of events with E> E_{th}, assumed as cosmic flux (red histogram)

DATA sample 2007-2018



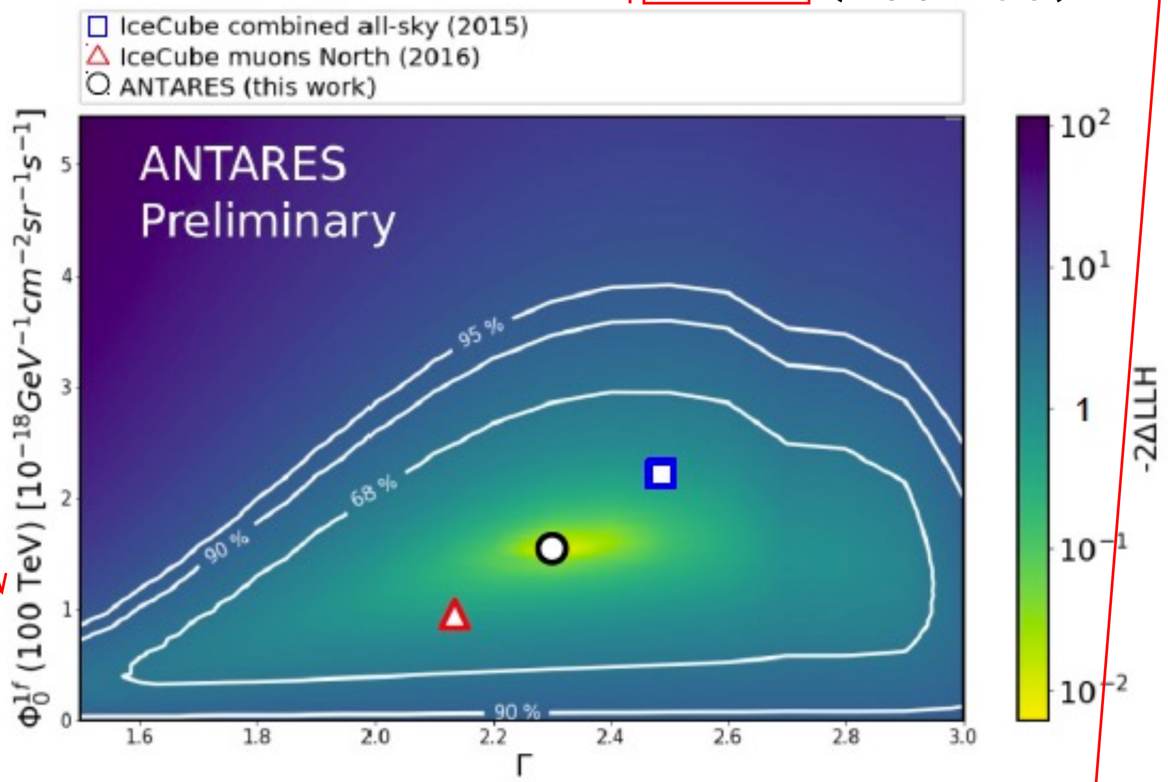


Diffuse flux of cosmic neutrinos in ANTARES

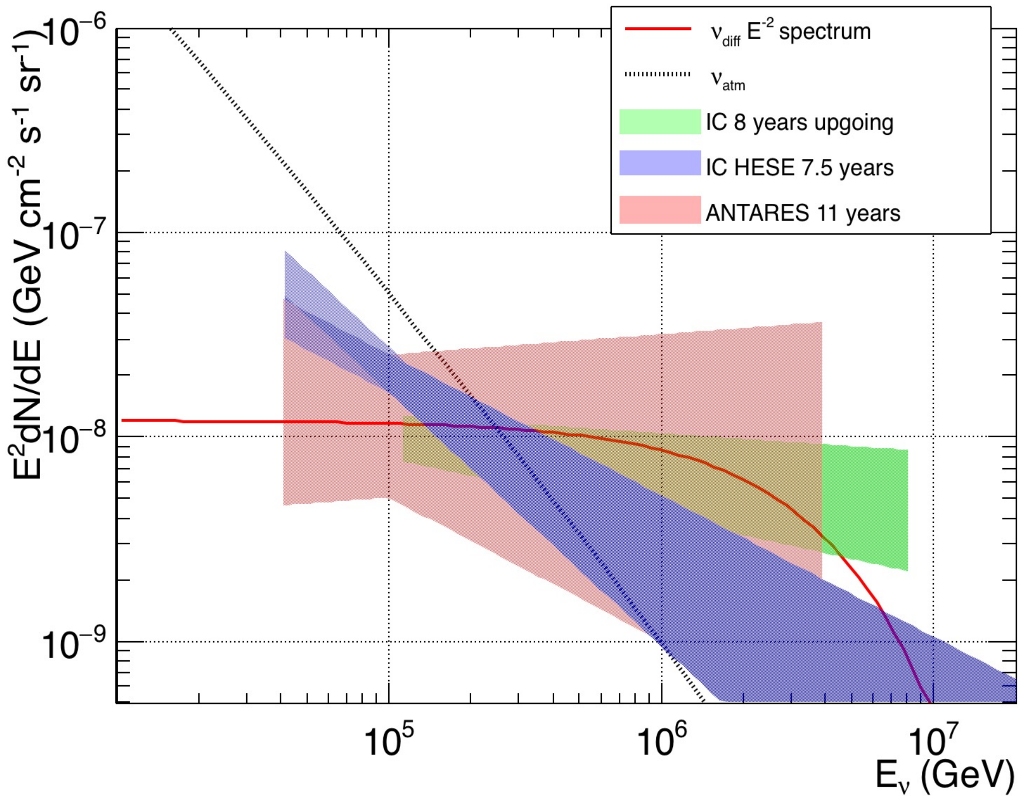
📖 Ap.J.Lett. 853 (2018) 1, L7
📖 https://pos.sissa.it/358/891/pdf -(ICRC 19)

Cosmic: Combined (tracks+showers) likelihood fitting:

$$\Phi_{100\text{ TeV}} = \Phi_0 \left(\frac{E}{100\text{ TeV}}\right)^{\Gamma}$$



Results not really constraining… but fully compatible with IceCube

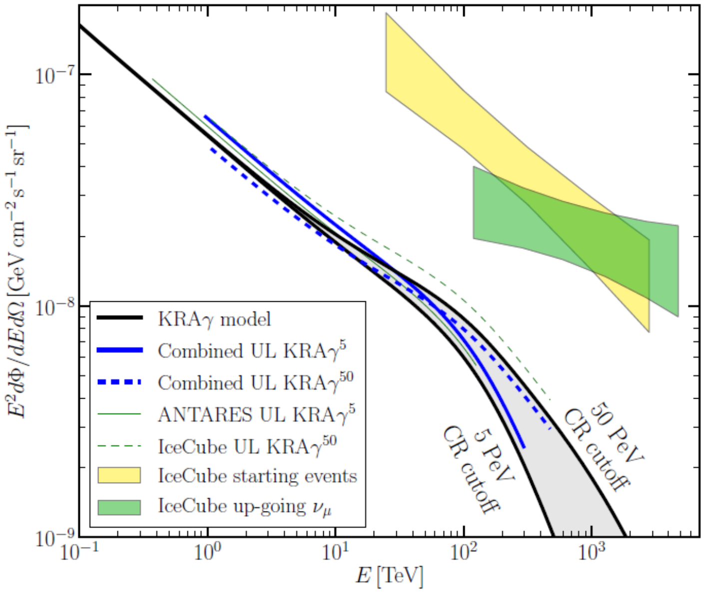


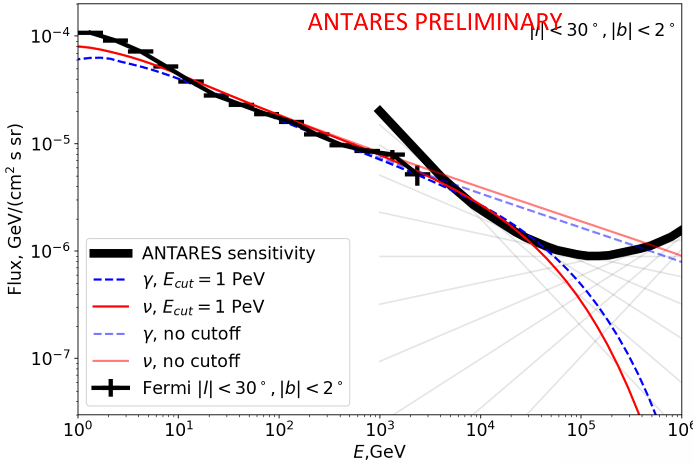
Flux from the Galactic ridge

📖 PLB 760 (2016) 143
📖 Phys. Rev. D 96, 062001 (2017)
📖 ApJL 868, L20 (2018)

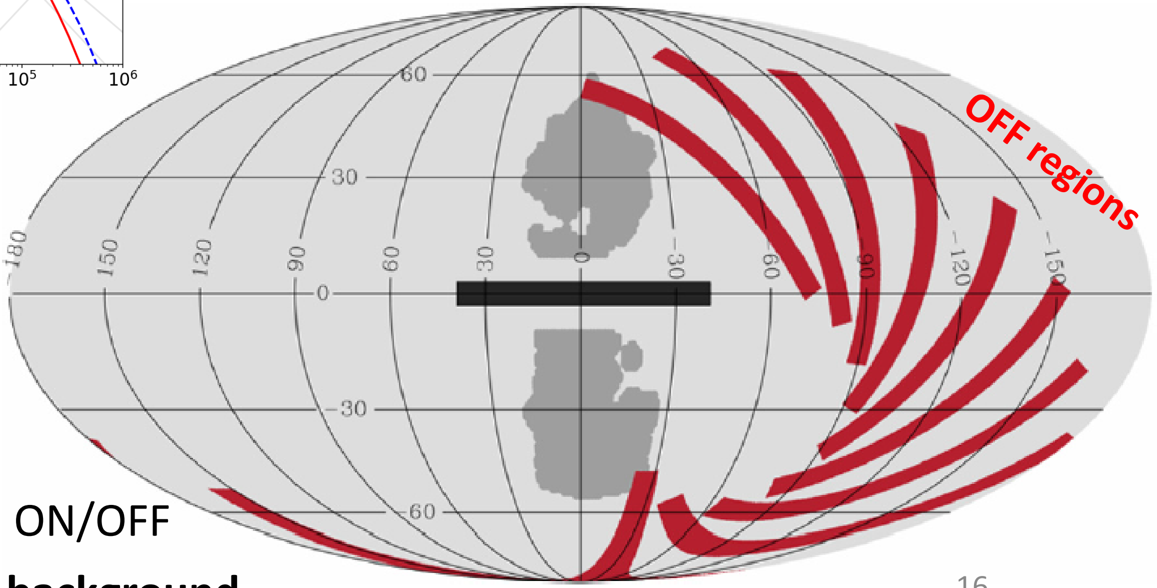
- neutrino signal expected from the Galactic Ridge (gamma-ray data)
- ν flux related to the primary CRs spectrum, if no cut-off below 1 PeV in CR flux
- Analysis in 2016 (7 y data 2007-2013) gives limits close to expectation without cutoff

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





Using the full ANTARES dataset, a sensitivity below the extrapolated gamma-ray is expected



- Combined analysis ANTARES- IceCube
- at most 10% of the all-sky diffuse flux detected by IceCube can be of Galactic origin

simple approach ON/OFF

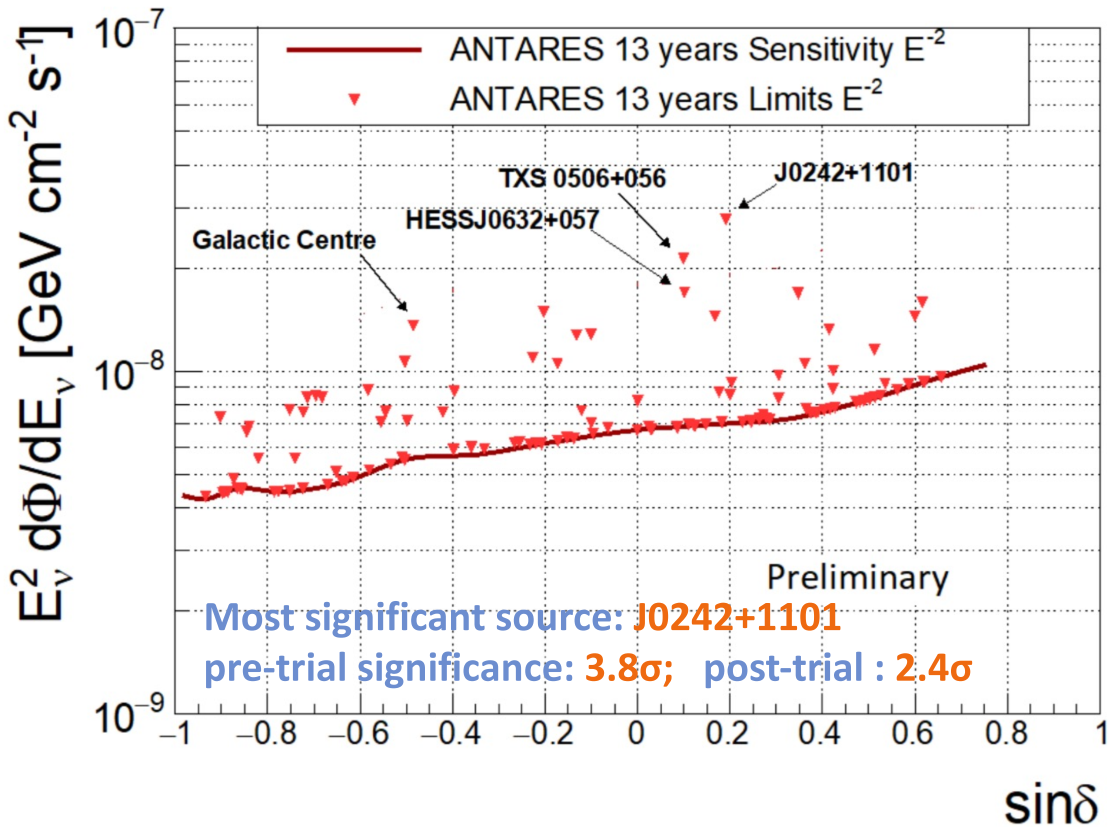
NO evidence above background

Search for cosmic sources: tracks+cascades

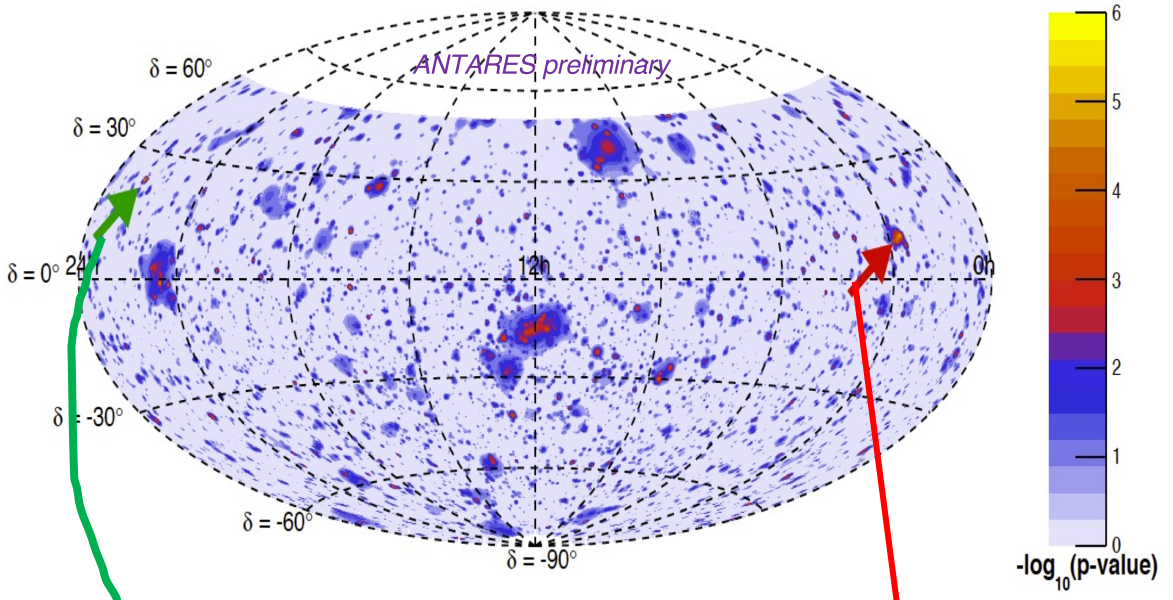
PRD 96, 082001 (2017)
PoS(ICRC2021)1161

Data set 13 year (from Jan 2007 to Feb 2020); Livetime: 3845 days
Search for an excess of events from a particular sky direction

Using a pre-definite candidate-list search:
121 investigated sources



With a unbinned full-sky search



2nd most significant cluster:
RA=343.8°δ=+23.5°
Pre-trial: 4.2 σ
Close to blazar MG3 J225517+2409

Full-sky hotspot (α,δ) = (39.6°, 11.1°)
pre-trial p-value: (4.3σ) (48% post)
Within 1 degree from J0242+1101

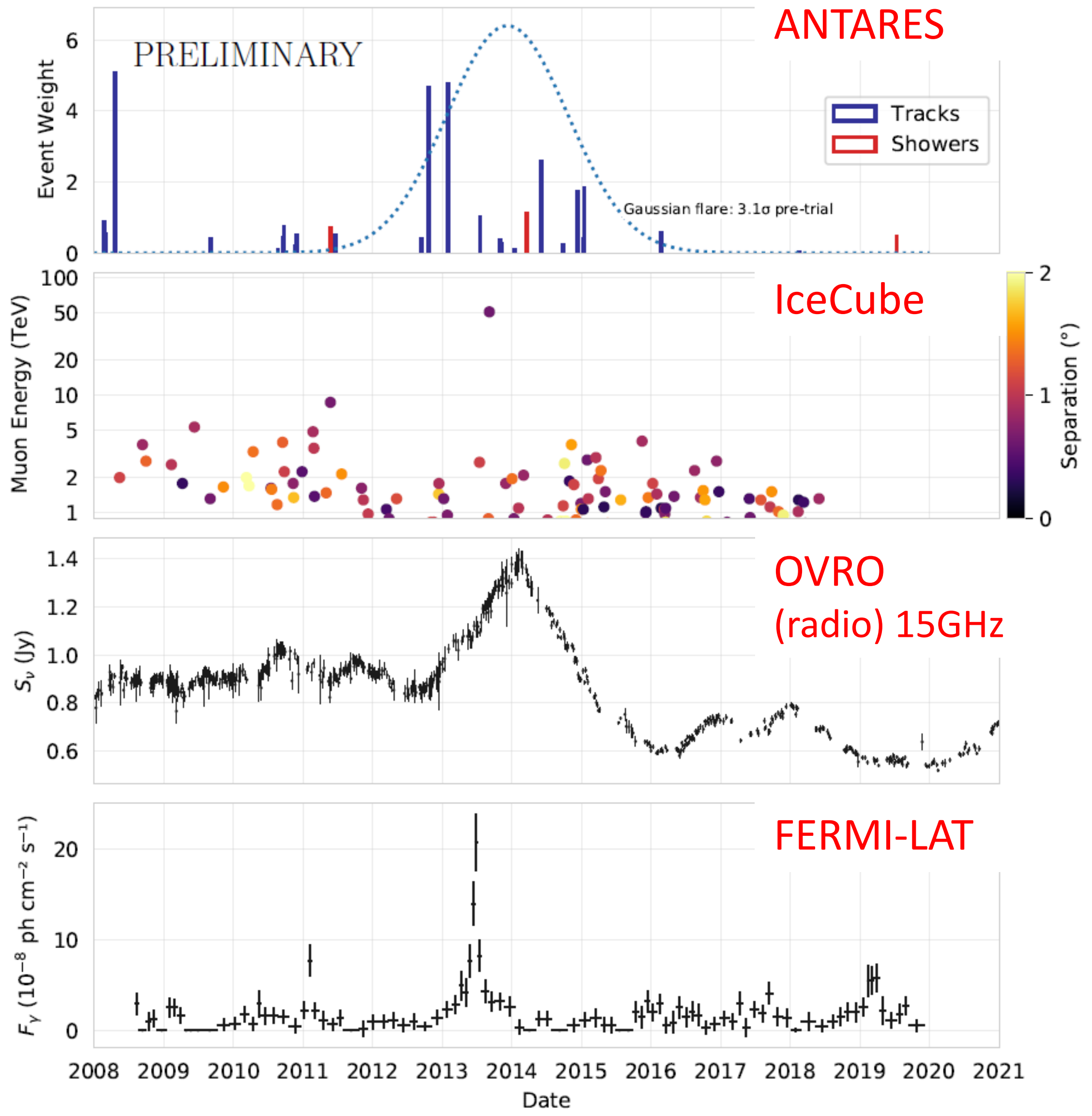
Notable case of J0242+1101 (PKS0239+108)

PoS(ICRC2021)972

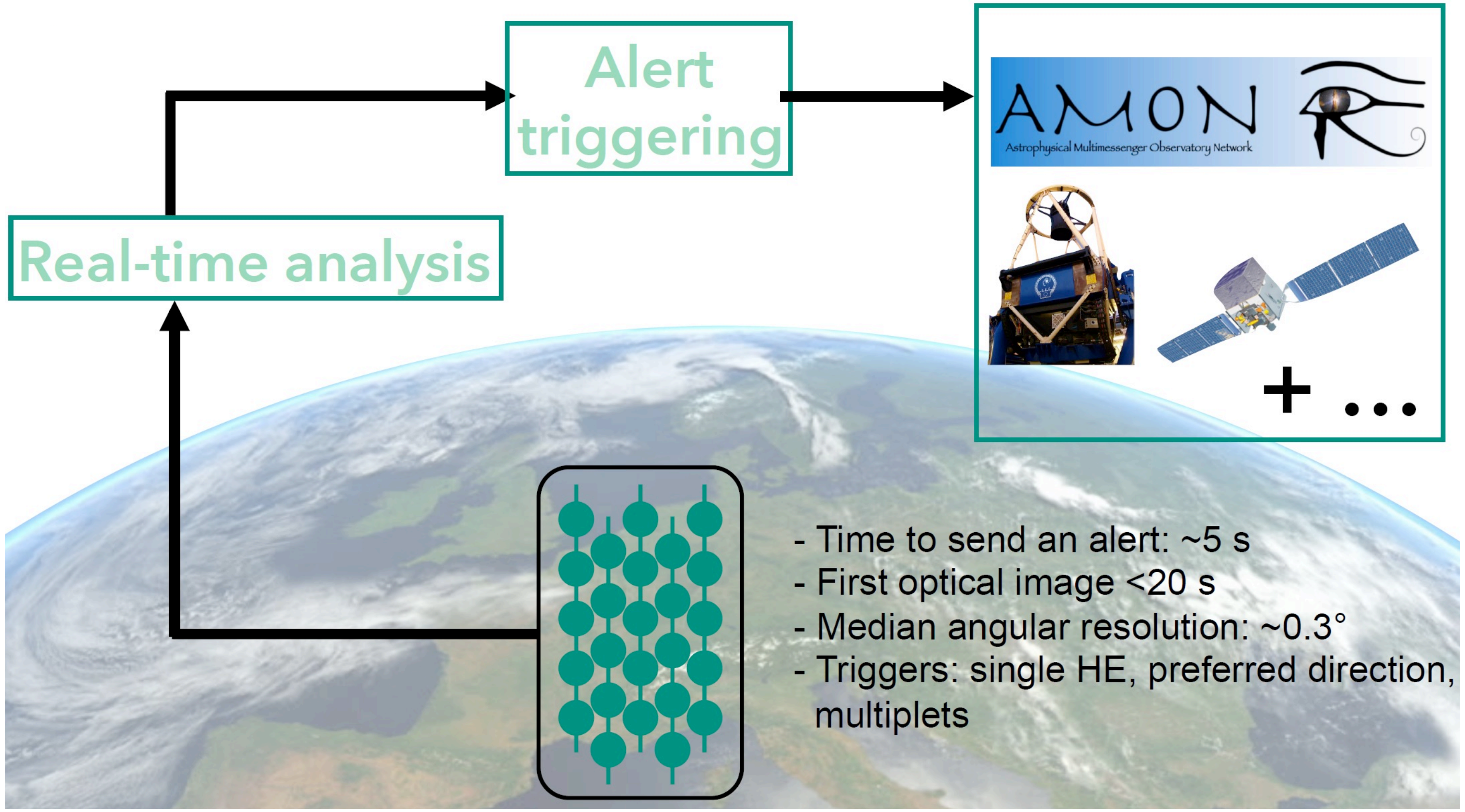
Intriguing overlap in time of the flaring emission in radio, γ-ray and neutrino found from the direction of the blazar **J0242+1101** studied from **2008 to 2021**.

- First panel: weighted time distribution of the ANTARES tracks (showers) within 5^o(10^o) from J0242+1101 and best-fit Gaussian time profile.
- Second panel: weighted time distribution of the Ice-Cube tracks closer to J0242+1101 than 50% angular error. Weight=energy of each event. The color scale indicates the event angular distance from the source.
- Third panel: OVRO (Owens Valley Radio Observatory) radio light-curve @15 GHz for J0242+1101.
- Fourth panel: adaptive binned γ-ray light-curve obtained from Fermi LAT data for J0242+1101.

Chance probability of the multi-messenger association under study.



Multi-messenger approaches - **sending alerts**

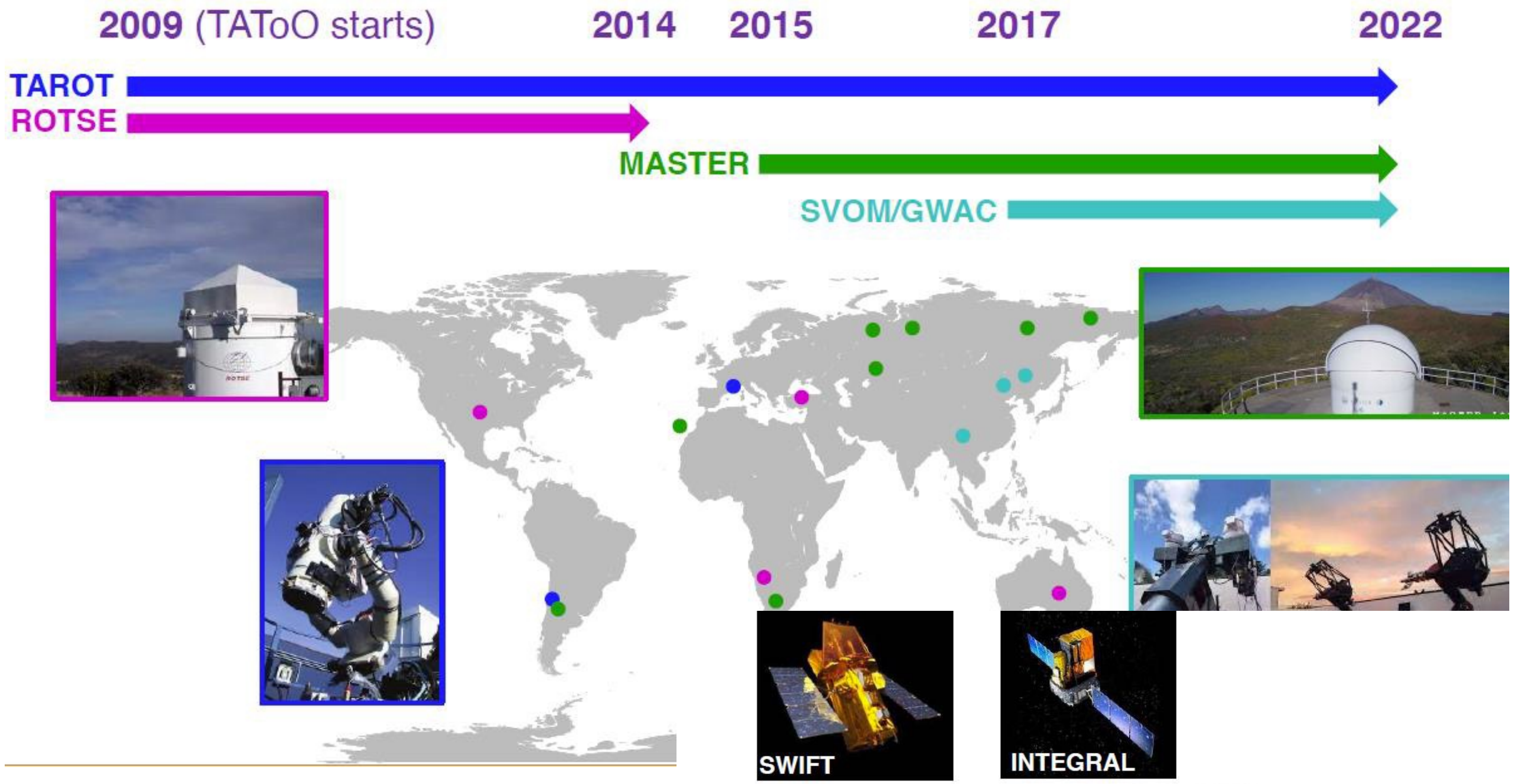


Alert system (**TAToO**: Telescopes and Antares Target of Opportunity) active since 2009
📖APP 35 (2012) 530

What triggers an alert:

- **High energy (HE):** single neutrino with energy ≥ 5 TeV. Rate: ~1/month
- **Very high energy (VHE):** single neutrino with energy ≥ 30 TeV. Rate: ~3-5/year
- **Directional trigger:** single neutrino from the direction (≤ 0.4°) of a local galaxy (≤ 20 Mpc). Introduced to increase the chance to detect a local CCSN. Rate: ~1/month
- **Doublet trigger**: at least two neutrinos coming from close directions (≤ 3°) within a predefined timewindow (15 min). **No doublet trigger ever**

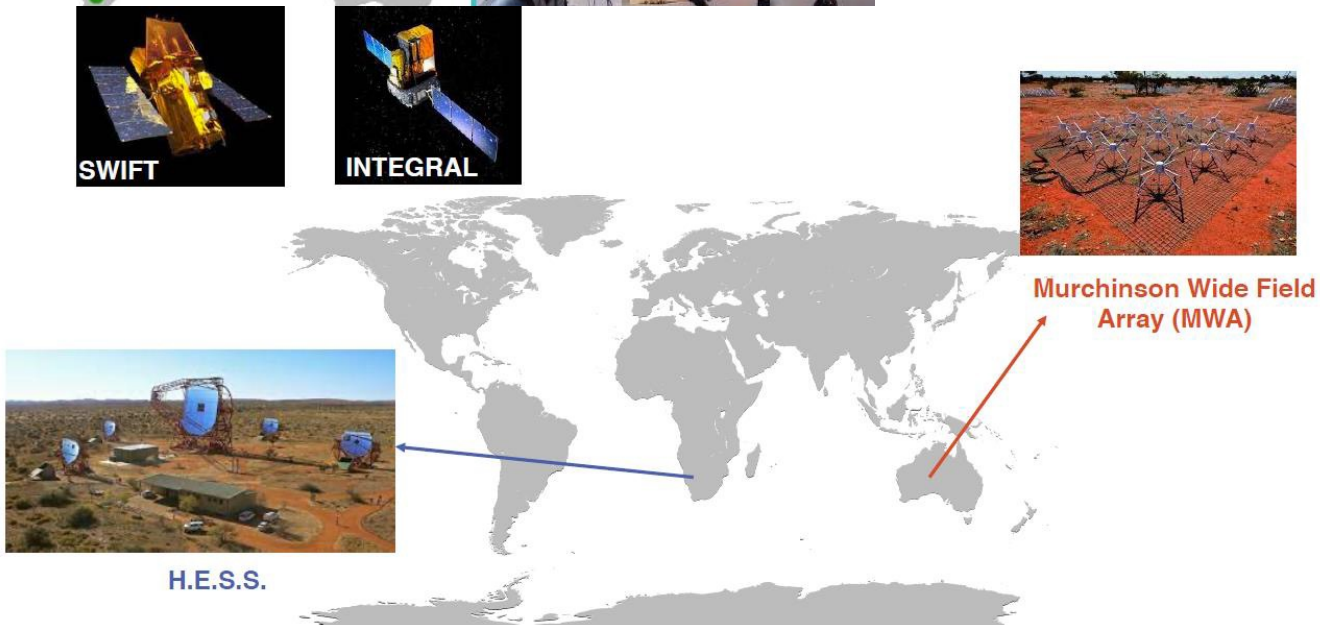
Multi-messenger approaches - **sending alerts**



📖 paper in preparation on results

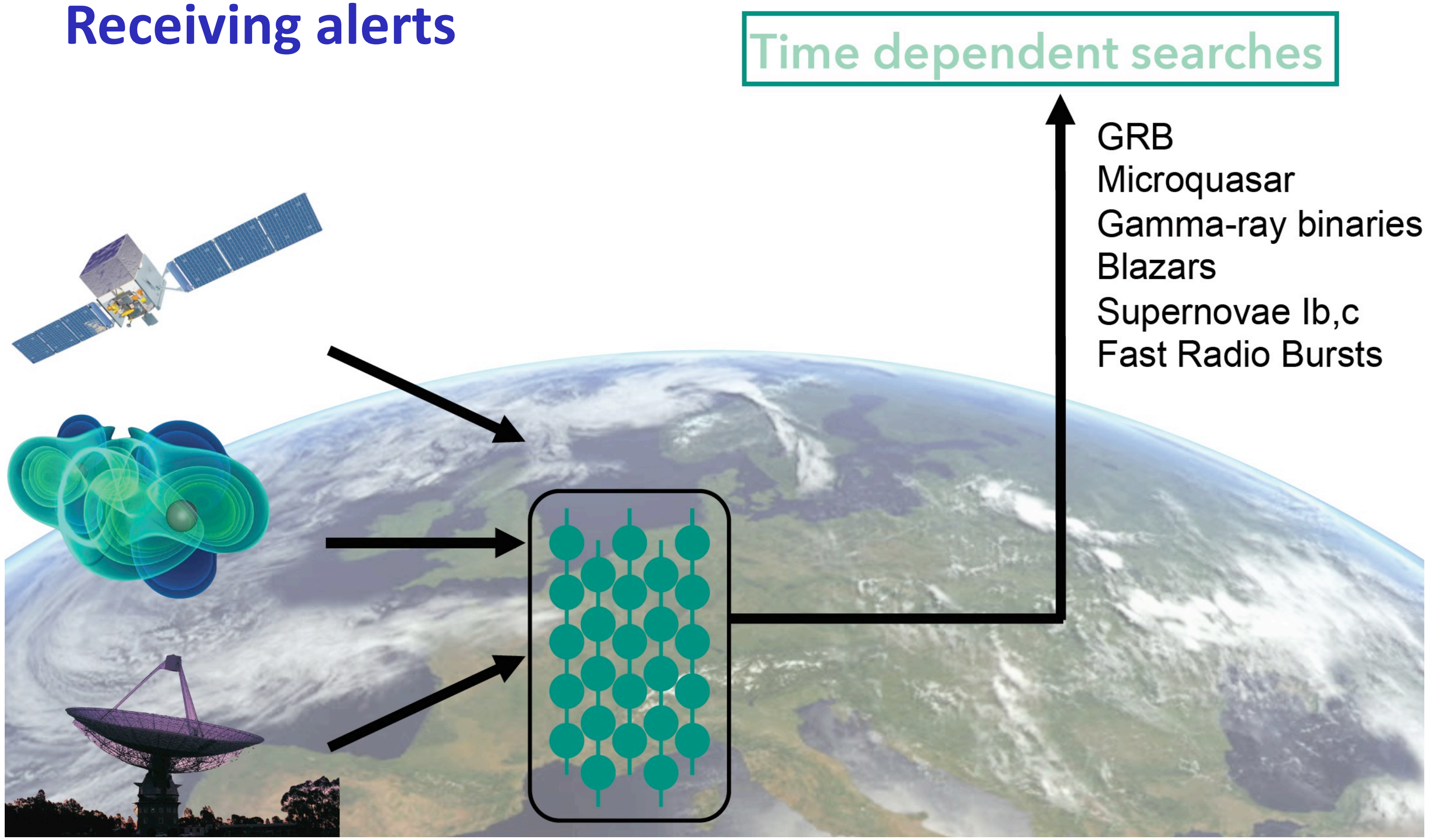
Optical telescopes

Radio, x-ray and gamma-ray telescopes



Multi-messenger approaches - **receiving alerts**

Receiving alerts



Follow-up of IceCube neutrinos:

- 115 IceCube events received, 37 analyzed (7 HESE, 3 EHE, 10 gold and 17 bronze)
- No ANTARES candidates compatible with any of the IceCube alerts
- 90% confidence level upper limits on the neutrino fluence

Dedicated offline follow-up of IC events:

TXS0506+056 (📖 **ApJL863 (2018) 2, L30**)
AT2019dsg and AT2019fdr (📖 **ApJ920 (2021) 1, 50**)
HESE and EHE events (📖 **ApJ. 879 (2019)2, 108**)

Follow-up of LIGO/Virgo GWs

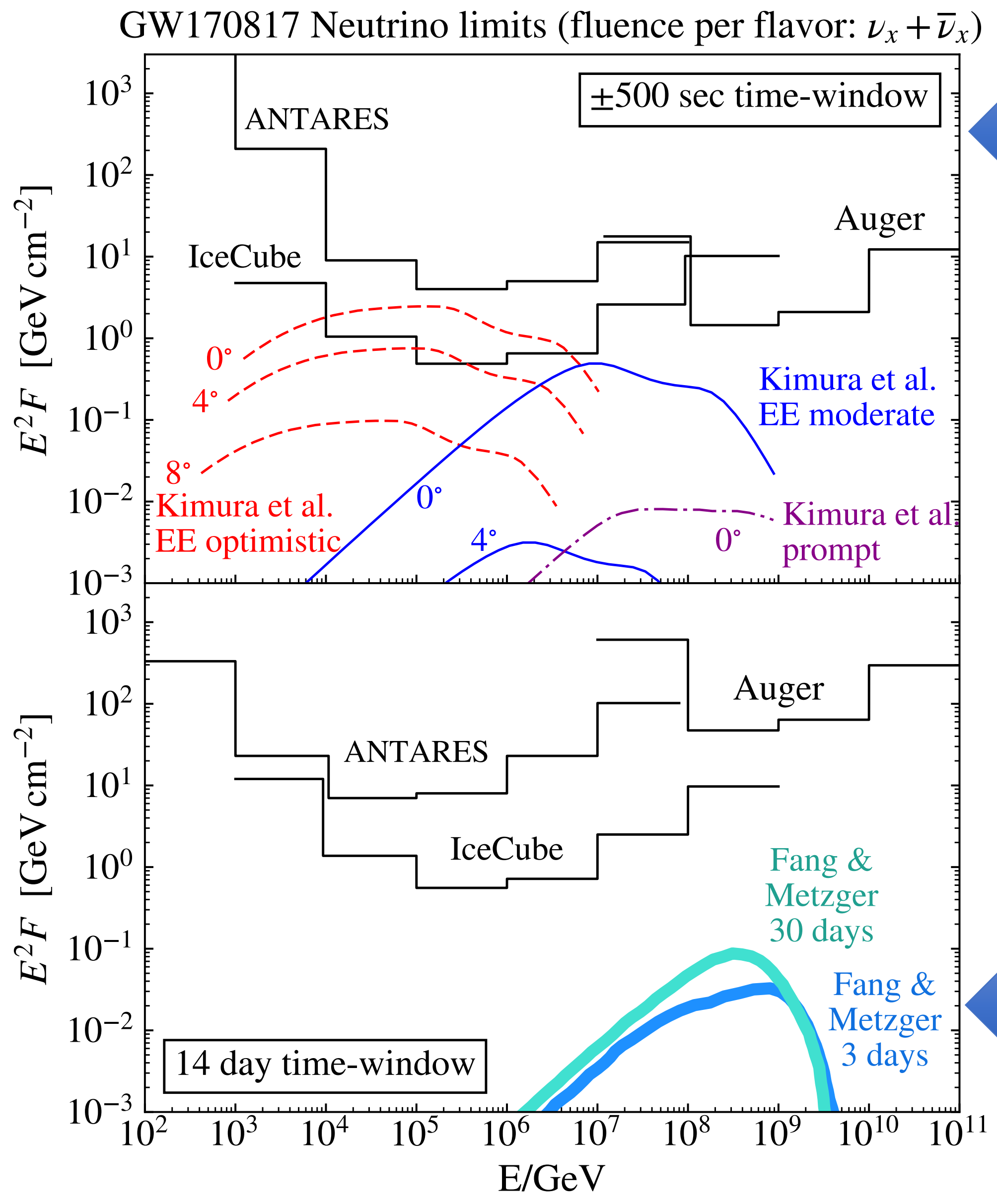
No candidates associated with GWs

Follow-up of Fermi-GBM and Swift GRBs

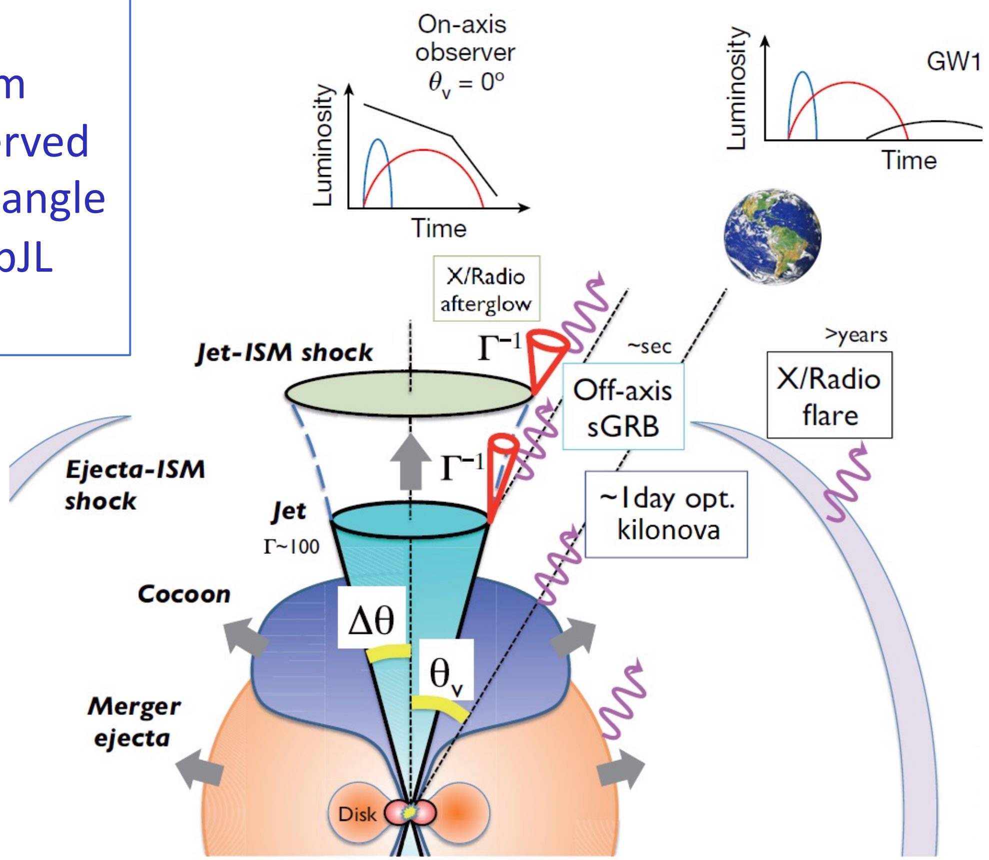
Follow-up of HAWC alerts

Neutrino Follow-up of GW170817

📖 ANTARES, IceCube, Pierre Auger, LIGO/Virgo. ApJL 850 L35 (2017)

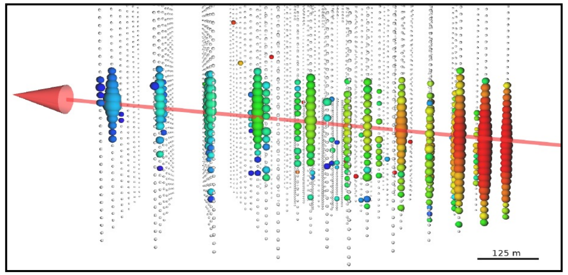


Non-detection consistent with expectation from short GRB observed at large off-axis angle (Kimura et al. ApJL 848, L4)



No detection during extended time period of 14 days after the GRB)Fang, K., & Metzger, B. D. 2017, arXiv:1707.04263)

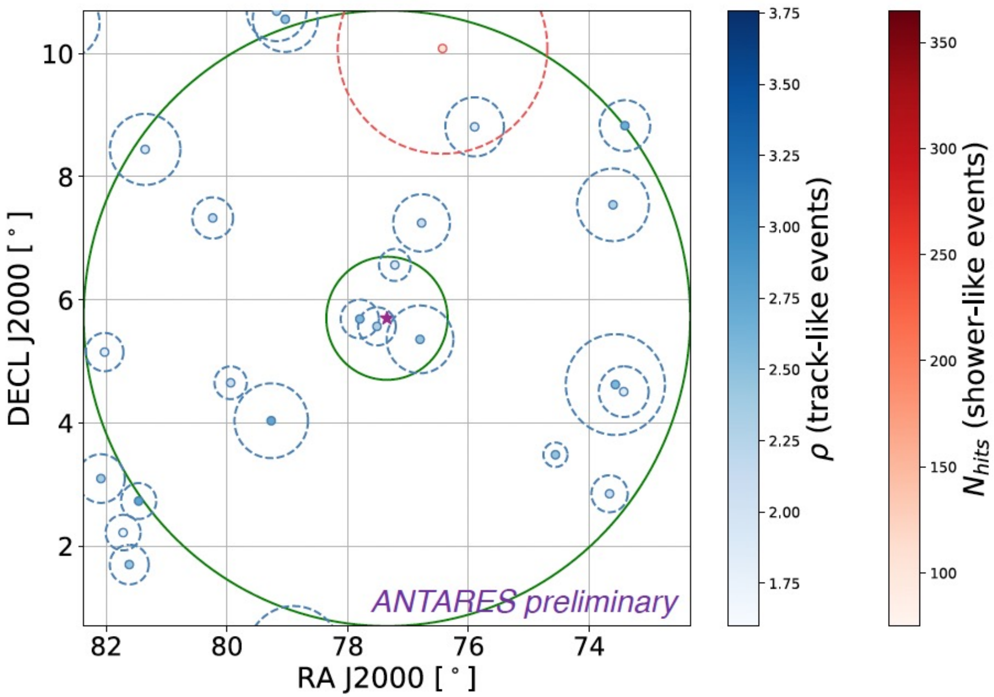
ANTARES Follow-up of ICECUBE-170922

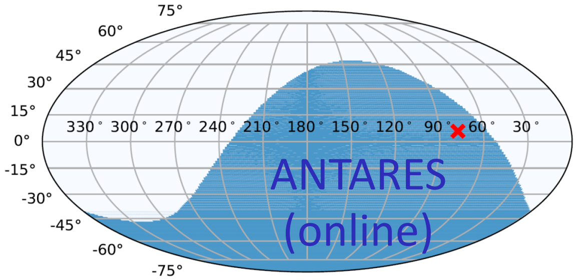


ANTARES Time integrated search

- ○ Same method as PS study 2007-2017 applied to the TXS 0506+056 source, potentially associated to the IC event

- 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: μ_{sig} **= 1.03**
- **Pre-trial p-value of 3.4%** (post-trial 87%)

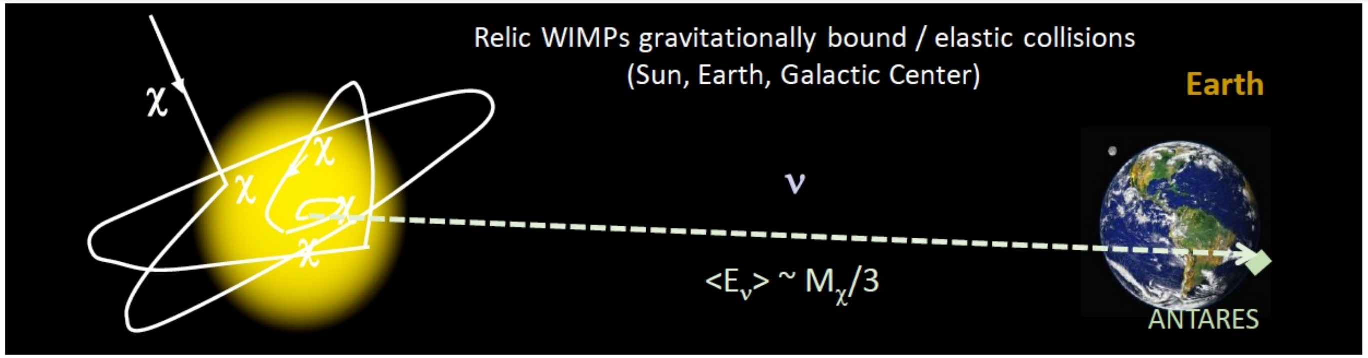




- ○ **Updated 2007-2020, after recalibration**
- 4 events within 1° μ_{sig} **= 2. 9**
- Pre-trial: 2.9σ (1-sided)

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

Indirect search for Dark Matter



Earth
Physics of the Dark Universe, 16 (2017) 41
Sun
Phys.Lett. B759 (2016) 69
JCAP 05 (2016) 016
JCAP11 (2013) 032

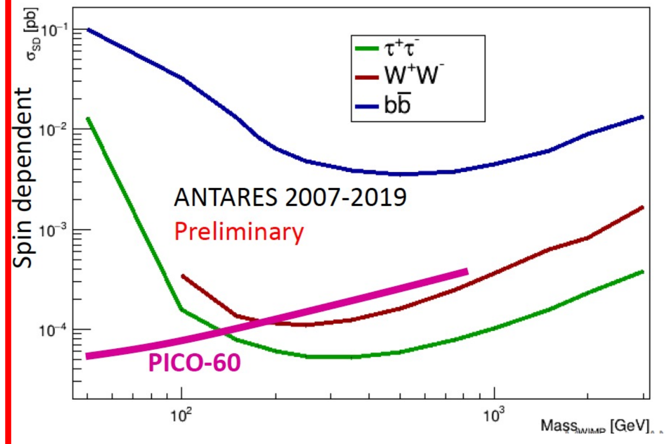
Galactic Center
JCAP 10 (2015) 068
Phys. Lett. B 769 (2017) 249
Phys. Rev. D 102 (2020) 082002 (with IceCube)
JCAP06 (2022) 028 (secludedDM)
Phys. Lett. B 805 (2020) 135439

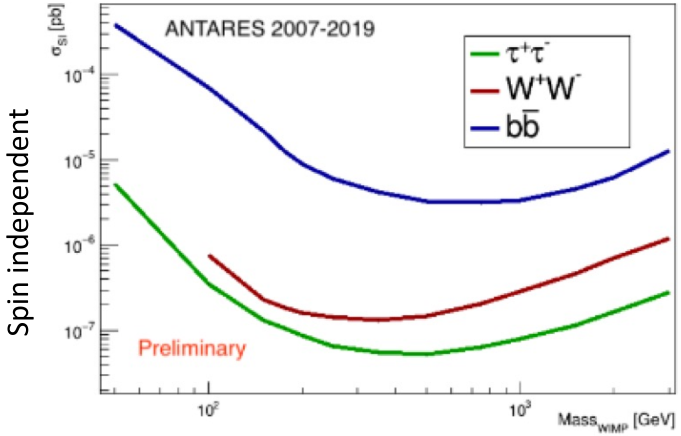
Neutrino telescopes are very versatile and good for different search channels

Search for an excess of neutrinos - as final product of annihilation - from the core of astrophysical objects were WIMPS could have accumulated

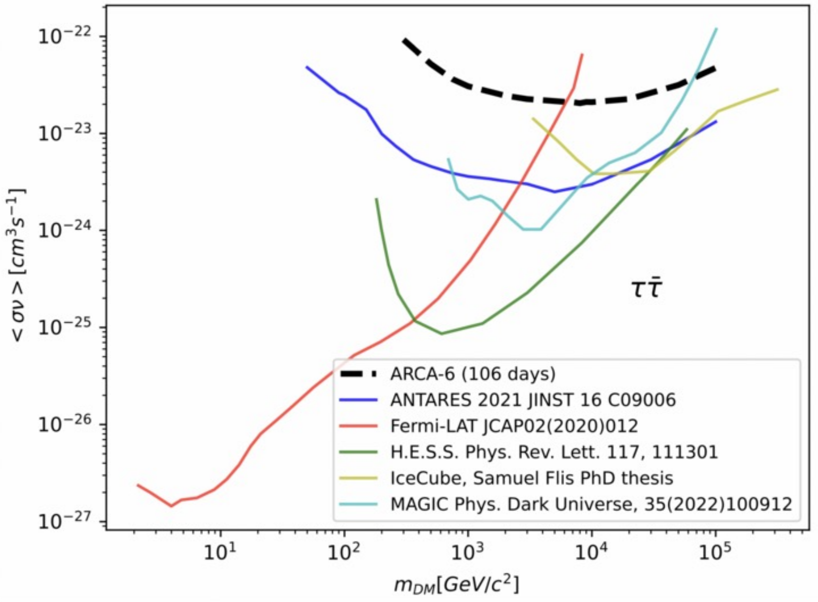
The Sun

- equilibrium between capture and annihilation
- The Sun has known isotopic abundance ⇒sensitive to WIMP-nucleon cross section for spin-dependent and spin-independent case (odd or even atomic number)
- Competitive limits to direct experiment for spin-dependent





Galactic Center



data 2007 - 2020 compatible with background

ν - oscillation studies

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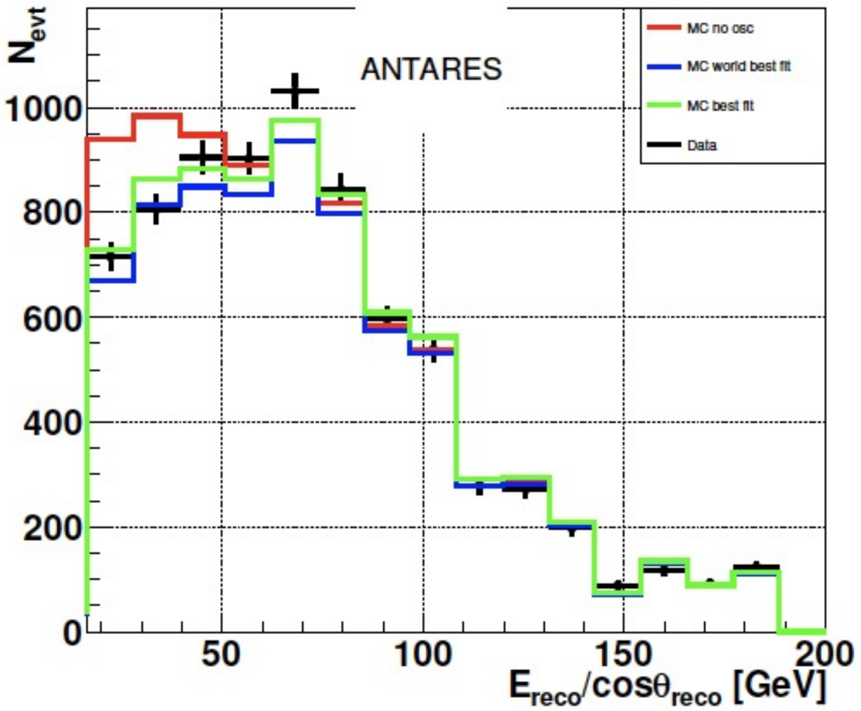
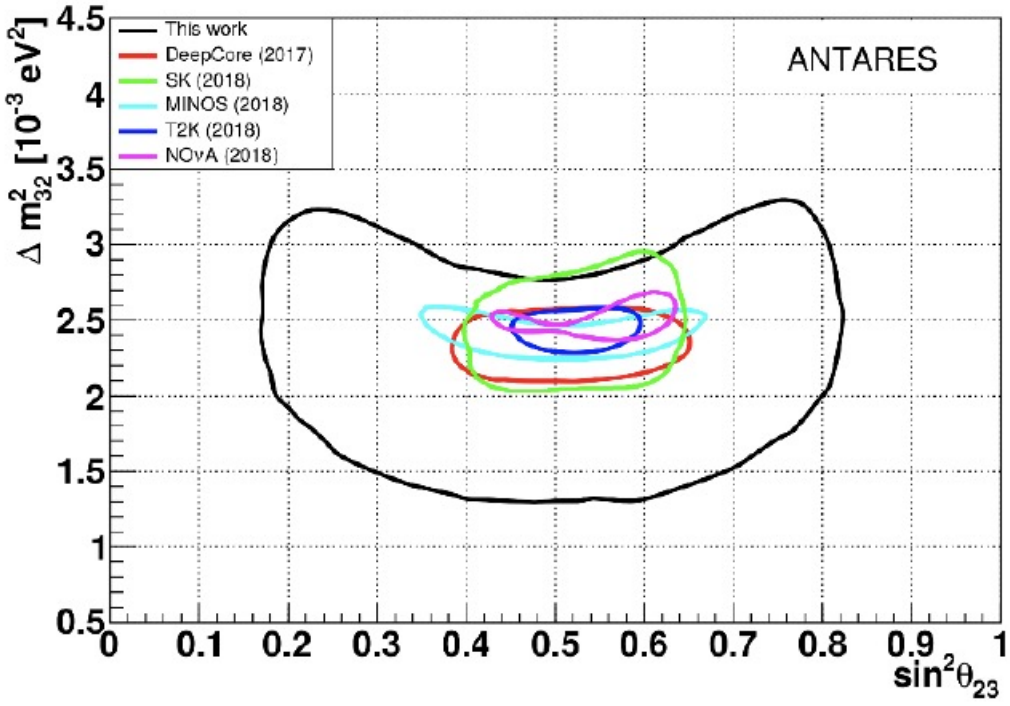
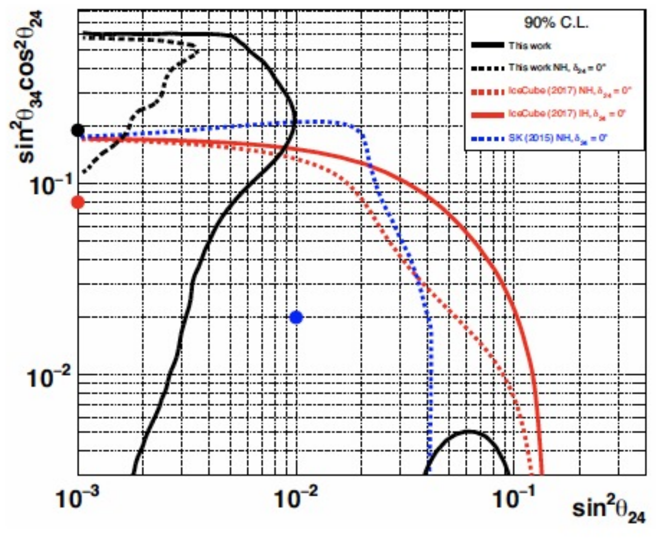
- Data sample (2007-2016) → 2830 days of lifetime
- 7710 events selected, two reconstruction procedures
- Track channel only, E_{reco} from muon range
- Binned likelihood fit (Poisson stat.) performed in two dimensions ($\log_{10}(E_{reco})$, $\cos\theta_{reco}$)
- Sample soon public

No-oscillation hypothesis excluded at 4.6σ





Beyond the SM: sterile neutrinos and NSI



The same data sample used for oscillation studies allowed to investigate the existence of sterile neutrinos and Non-Standard Interaction signature.

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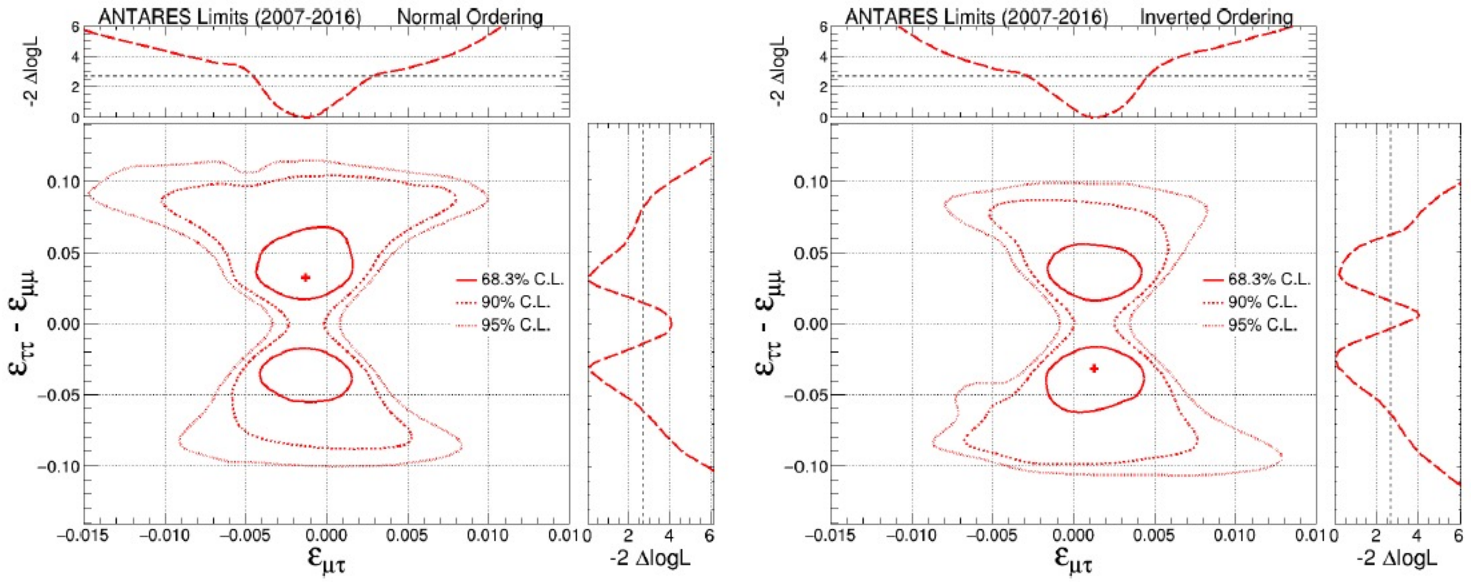
- (3+1) sterile neutrino models $\Delta m^2_{41} > 0.5$ eV^2
- Tight complementary information to eV-scale sterile neutrino searches
- Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.



- Non-standard interactions signature in neutrino oscillation patterns detectable
- A log-likelihood ratio test of the dimensionless coefficients $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ does not provide clear evidence of deviations from standard interactions.
- The non-NSI hypothesis is disfavouredwith a significance of 1.7σ (1.6σ) for the normal (inverted) mass ordering scenario.

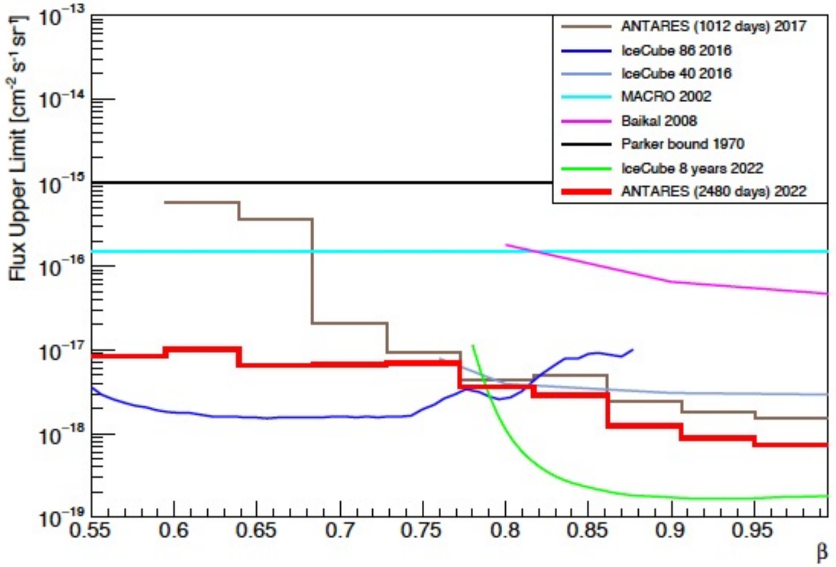
J. High Energ. Phys. 07(2022) 048

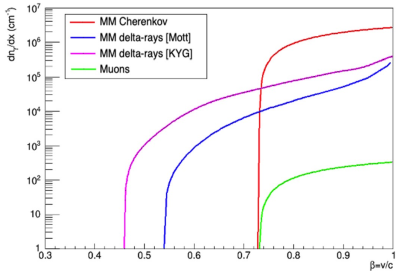
Exotic particles: Magnetic Monopoles and Nuclearites

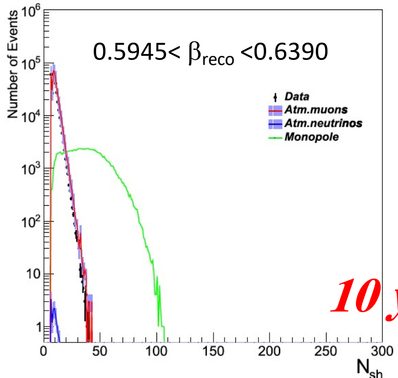
Magnetic Monopoles

JHEAp 34 (2022) 1

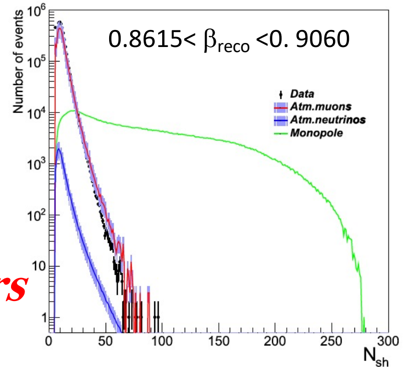
- Search for fast MM with Dirac magnetic charge
- Kasama, Yang and Goldhaber model - improved description of MM cross section ➔ increased light production
- better atmospheric muon rejection







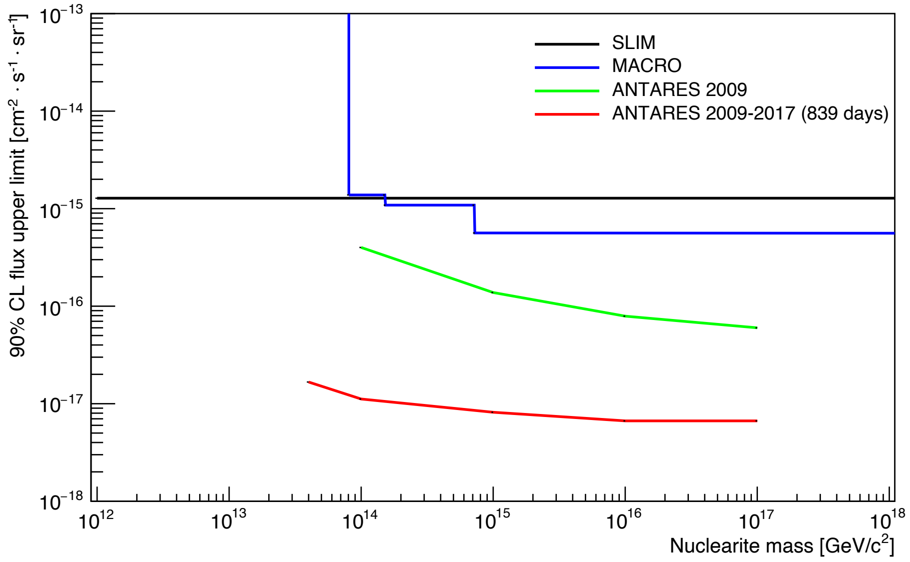
10 yrs



Nuclearites (Strange Quark Matter)

- Down going flux with Galactic velocities ($v/c=10^{-3}$)
- dE/dx according to de Rujula& Glashow model
- Nuclearite mass 4×10^{13}GeV/c^2<M_N <10^{17} GeV/c^2
- No Cherenkov emission - Visible photons from black body radiation

arXiv:2208.11689



ANTARES: 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

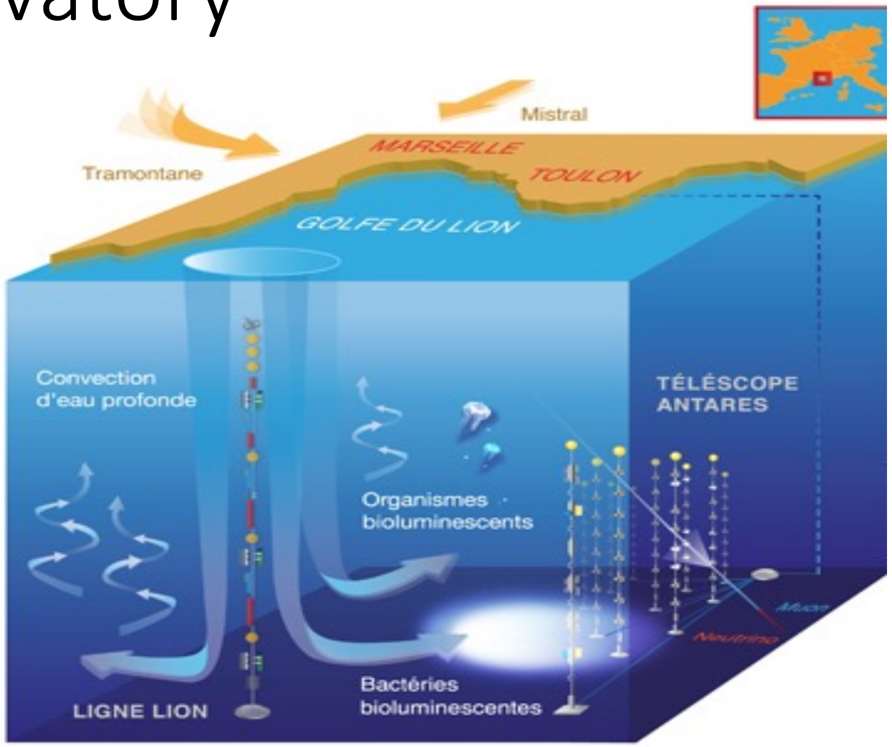
📖 Ocean Dynamics, April 2014, 64, 4, 507-517
High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

📖 *Journal of Geophysical Research: Oceans, Vol 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

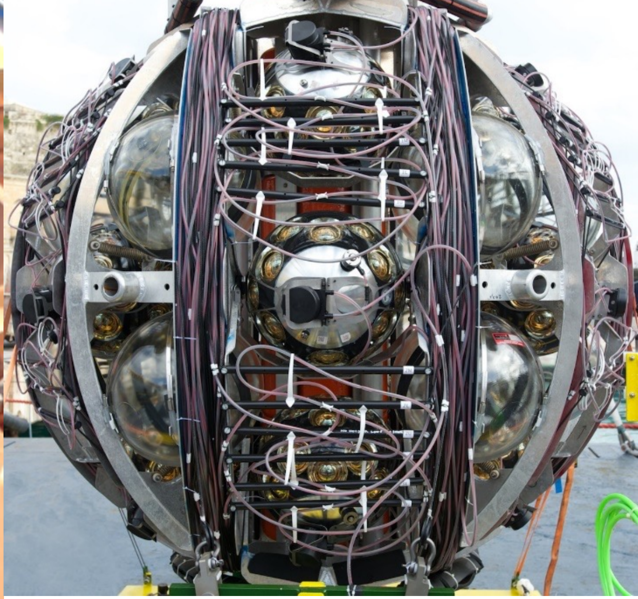
📖 A new paper on pressure measurements at the sea bottom in preparation

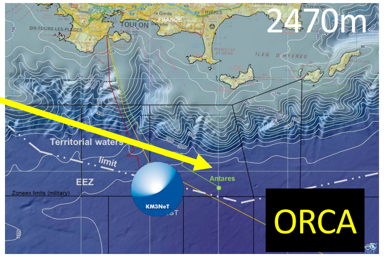


ANTARES → KM3NeT

- ANTARES was the first and largest NT in the Mediterranean Sea.
- 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 (electromagnetic+ GWs + Cosmic Rays + Neutrinos).
- About 100 papers published & 100 PhD.

- AN EXCITING ADVENTURE ! To be continued...





Oscillation **R**esearch
with **C**osmics In the **A**byss

Astroparticle **R**esearch
with **C**osmics in the **A**byss

Paris - June 2008