The ANTARES neutrino telescope

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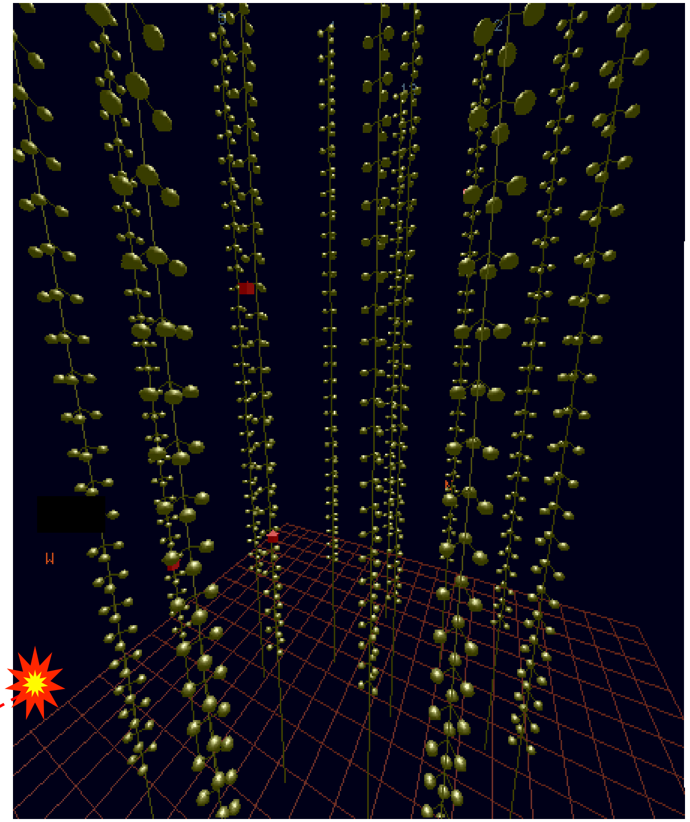
XII International Conference on New Frontiers in Physics - Crete, 10-23 July 2023

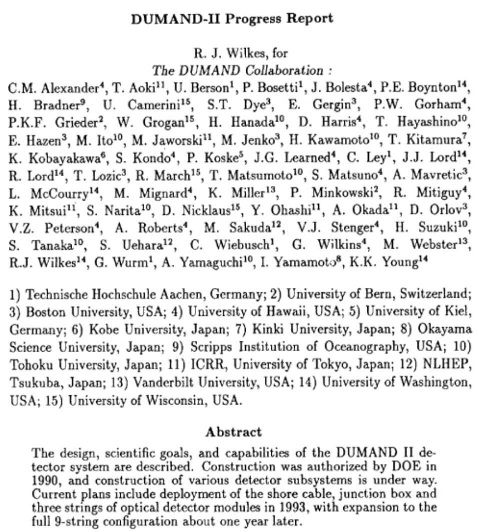
The concept of Cherenkov neutrino telescopes

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

ν_μ



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



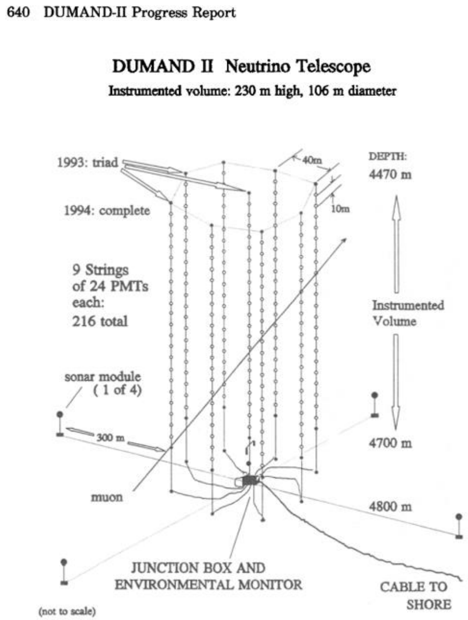
DUMAND-II Progress Report

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

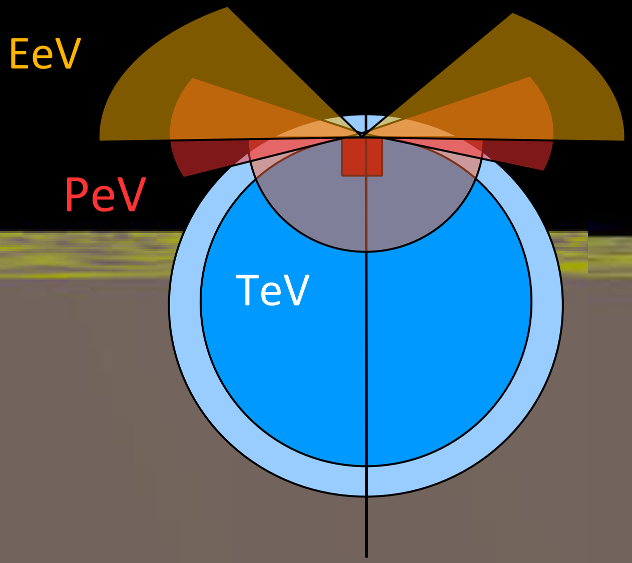
Precursor of the present neutrino telescopes, under water and ice

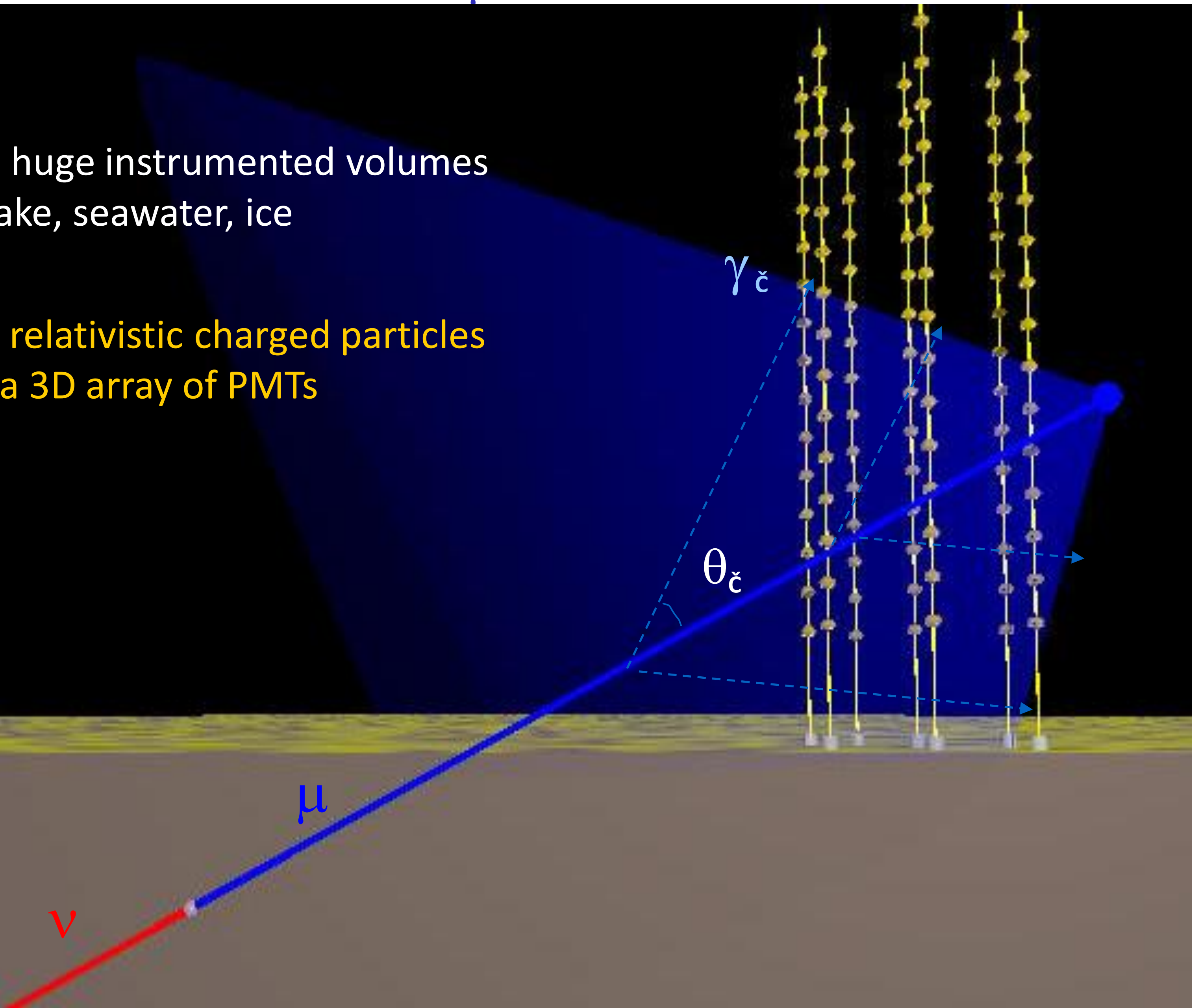
ANTARES accepted the challenge - the present and the future undersea neutrino telescopes shall exploit the ANTARES experience

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

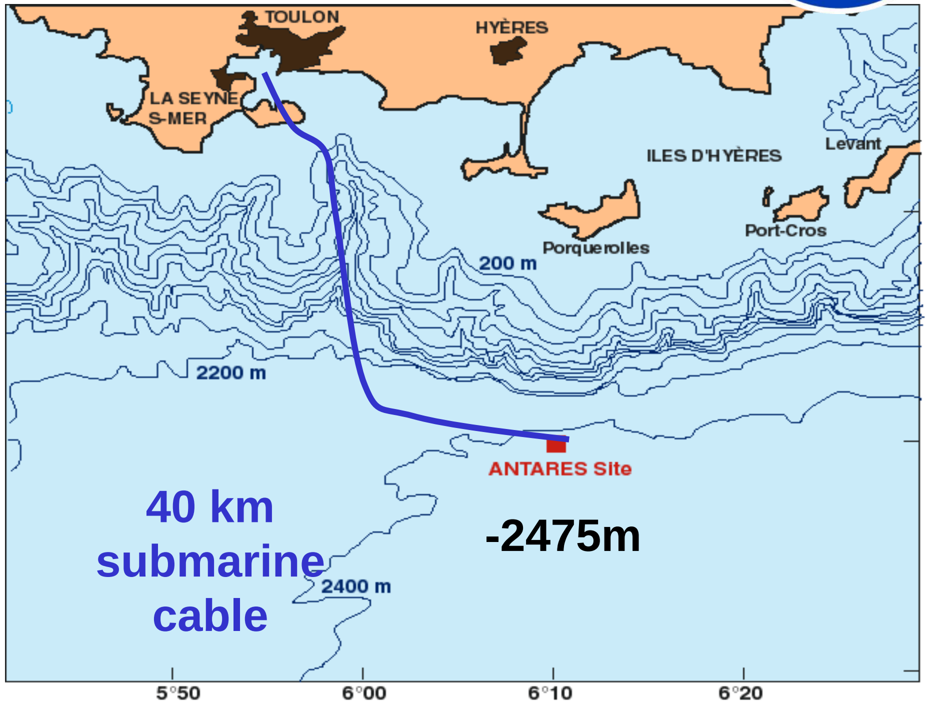
Natural radiators are low cost and allow huge instrumented volumes in dark but transparent media →Deep lake, seawater, ice

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





The ANTARES site

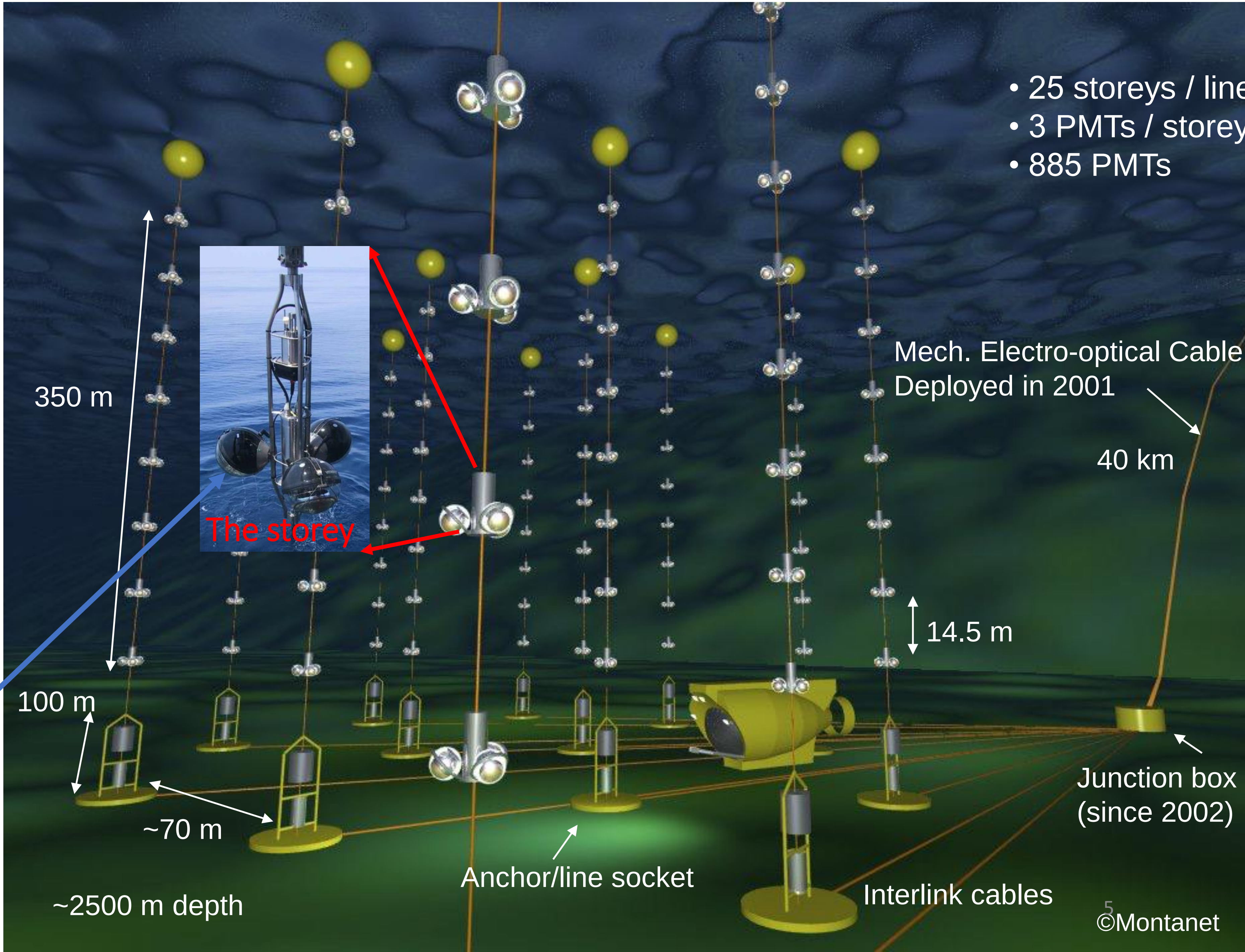


The ANTARES detector

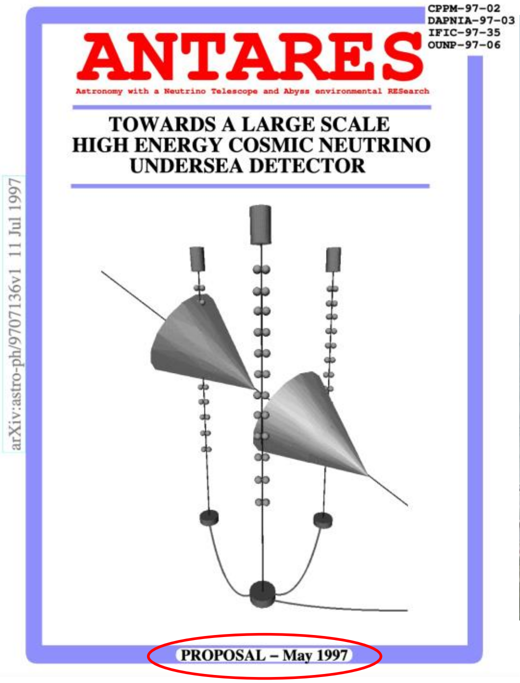
NIM A 656 (2011) 11

The Optical Module

NIM A 484 (2002) 369



ANTARES 2001-2022


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

arXiv:astro-ph/9707136v1 11 Jul 1997

ANTARES

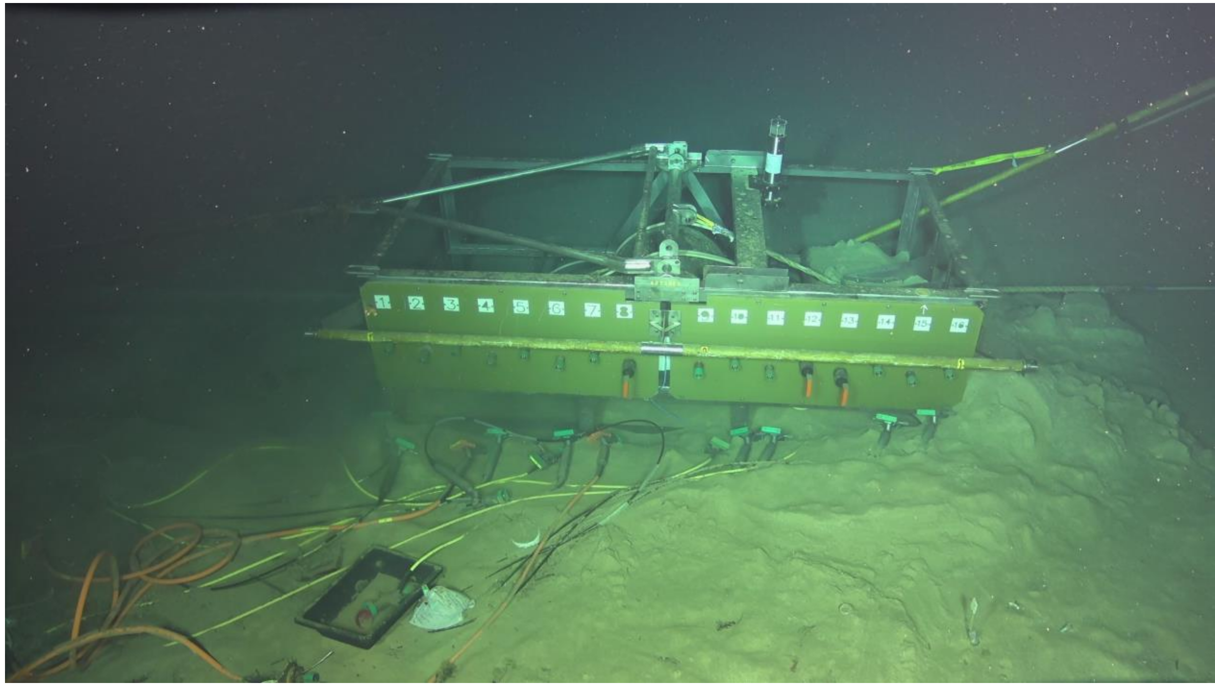
Astronomy with a Neutrino Telescope and Abyss environmental RESearch

TOWARDS A LARGE SCALE
HIGH ENERGY COSMIC NEUTRINO
UNDERSEA DETECTOR

PROPOSAL – May 1997

2001 Main Electro-Optical Cable deposition

2002 Junction Box deployment:
no failure in 20 years



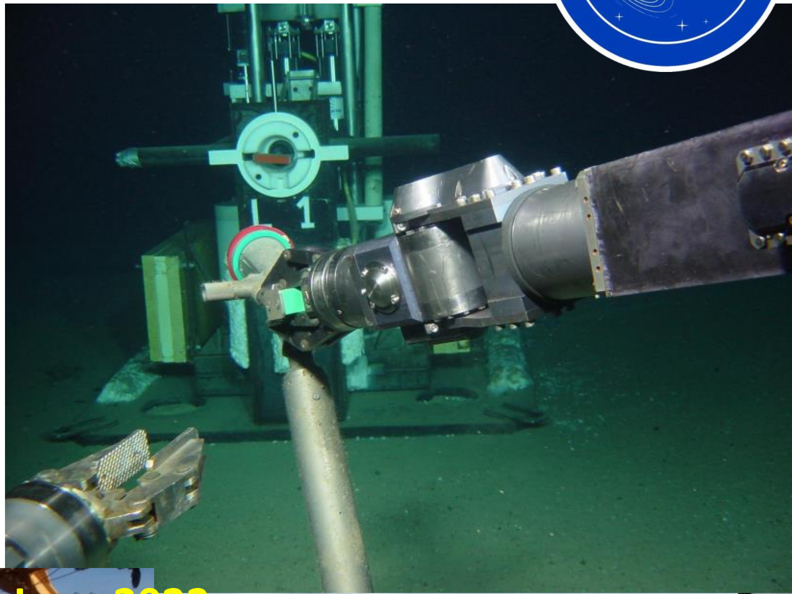
1997 Proposal
2001 Main Electro-Optical Cable deposition
2002 Junction box deployment
2003 Prototype Sector Line - First data
2005 Mini Instrumentation Line with OMs - environmental data
2006 First complete detector line
2008 Detector with 12 lines completed - complete configuration
2016 Running (almost)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

February 2022 Data taking terminated

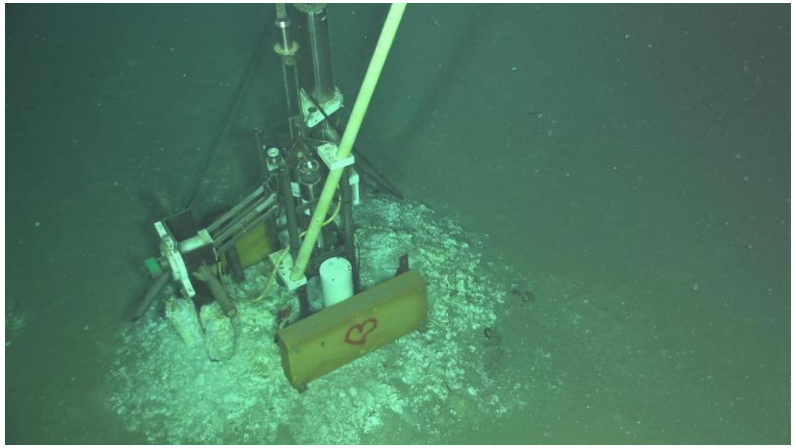
First detector line

Deployment
14/02/2006

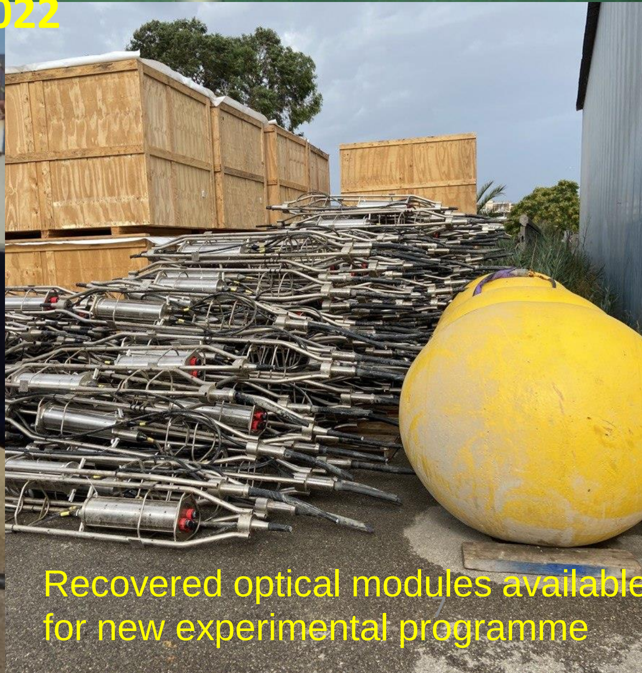
Connection
march 2006



Disconnection after 16 years

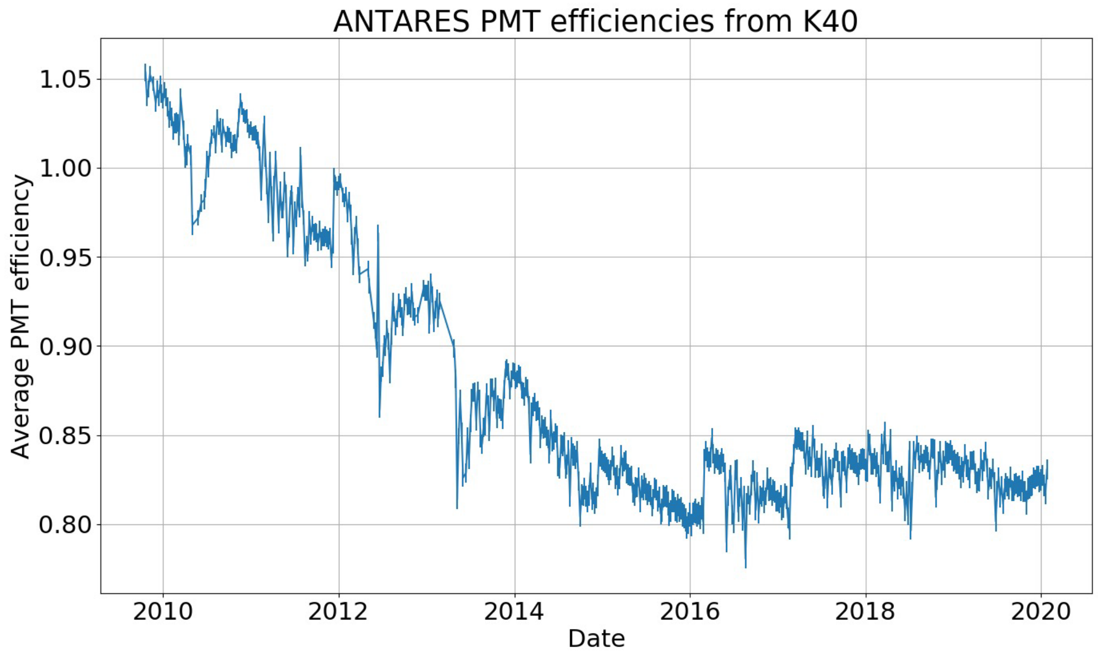


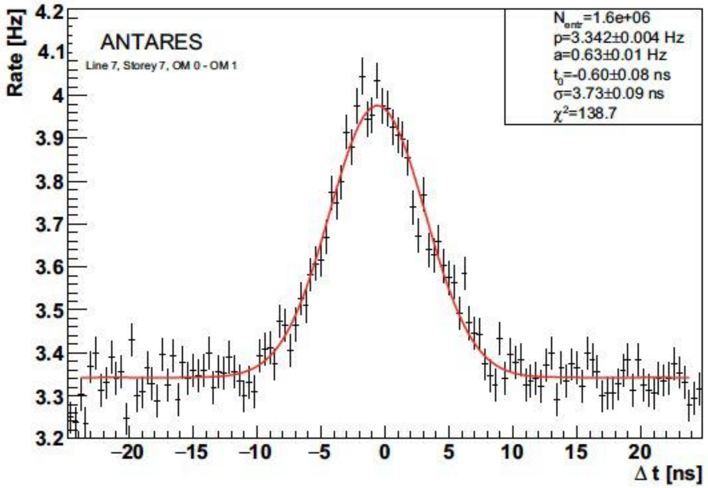
On shore, June 2022



Recovered optical modules available
for new experimental programme

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





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

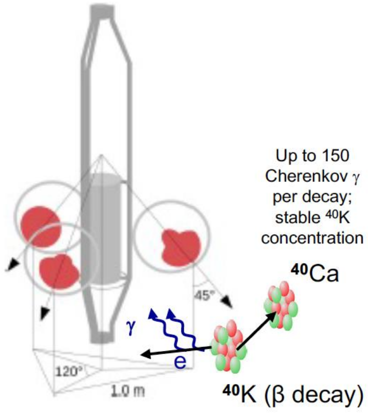
Regular tunings

Only ~20% efficiency loss

Extremely stable data acquisition

^{40}K powerful calibration tool

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



$$^{40}\mathrm{K} \rightarrow \; ^{40}\mathrm{Ca} + e^- + \overline{\nu}_e \qquad (89.3\%)$$

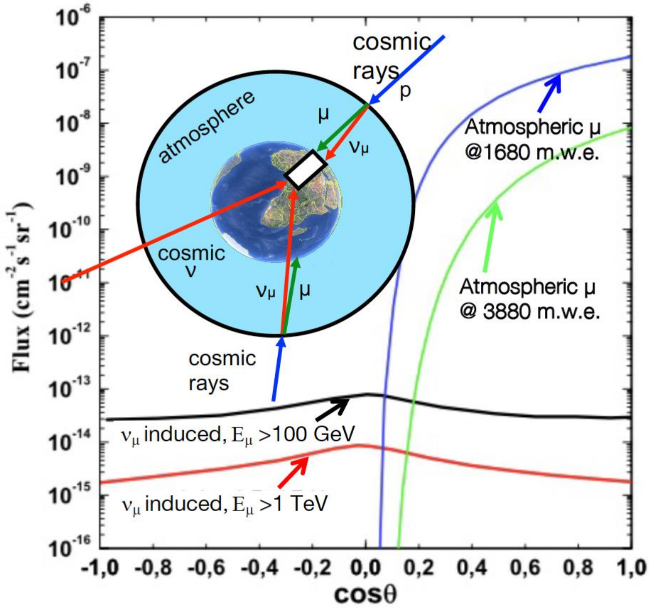
$$^{40}\mathrm{K} + e^- \rightarrow \; ^{40}\mathrm{Ar}^* + \nu_e \qquad (10.7\%)$$

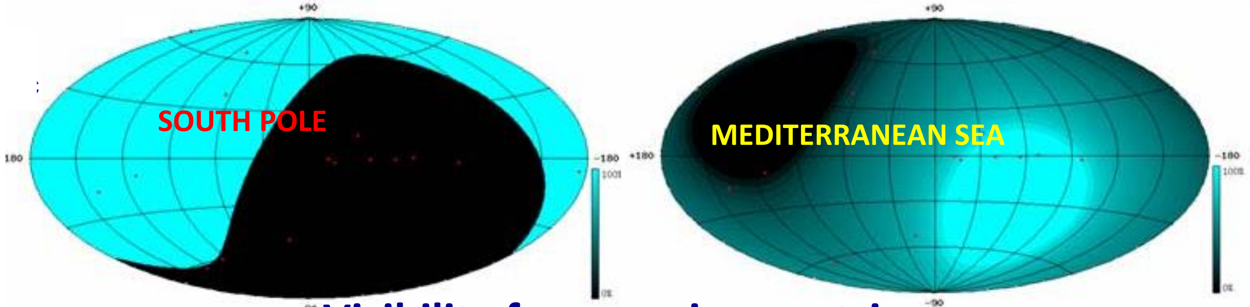
$$\hookrightarrow \; ^{40}\mathrm{Ar} + \gamma$$

electrons above Cherenkov threshold

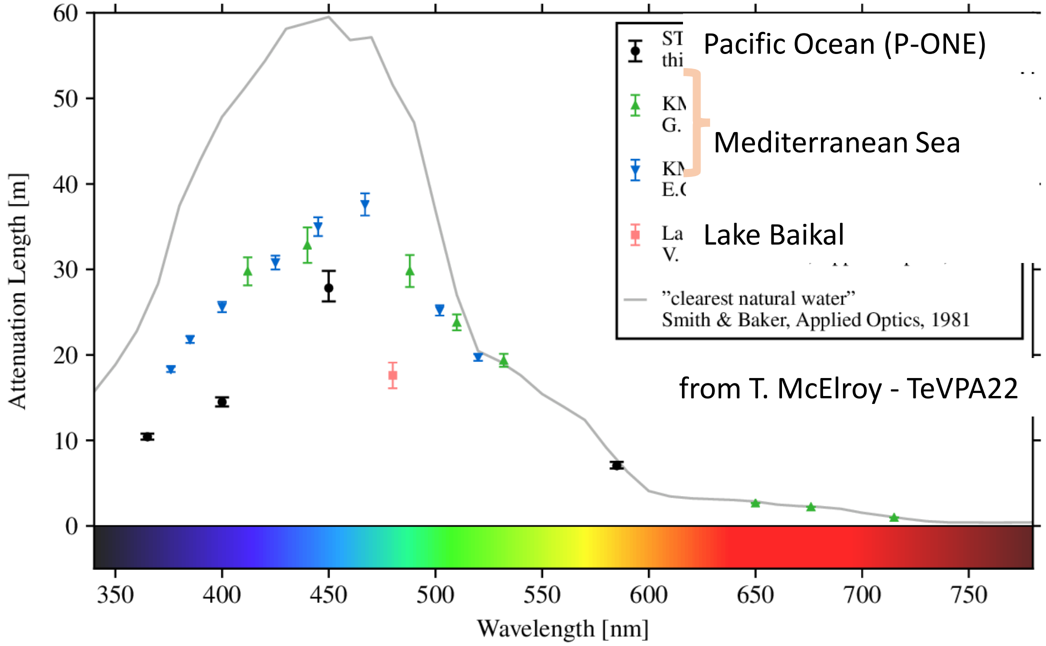
Why the Mediterranean Sea

- 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

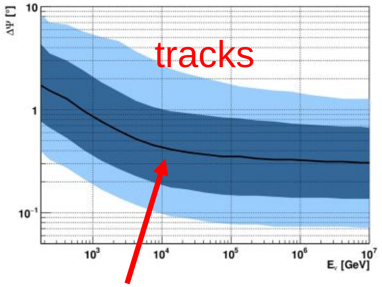


from T. McElroy - TeVPA22

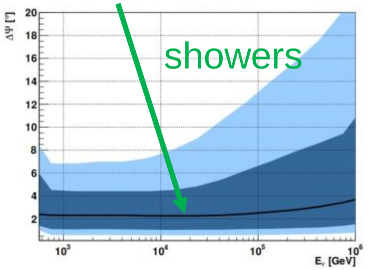
Event topologies - reconstruction performances

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

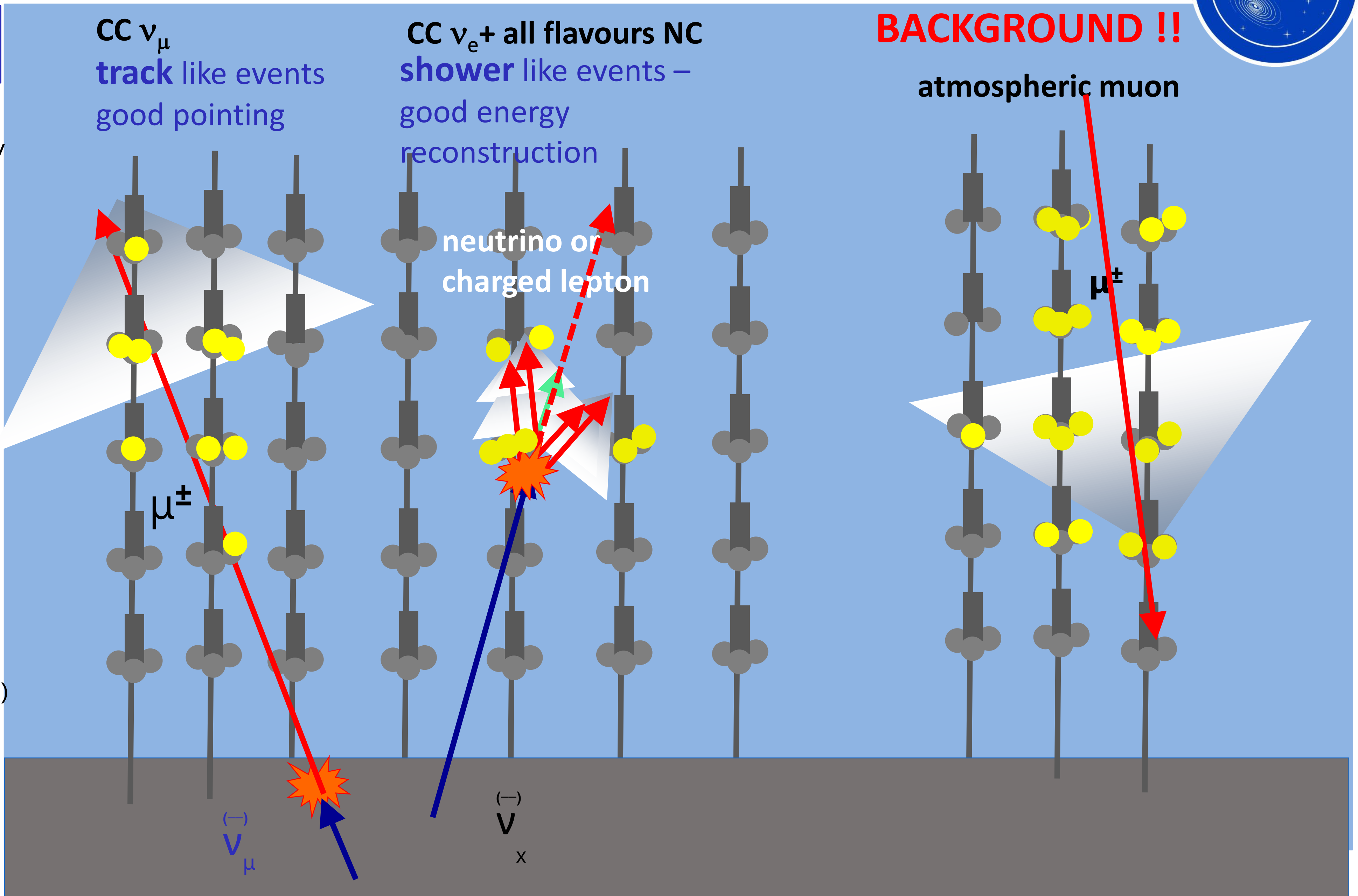


median resolution



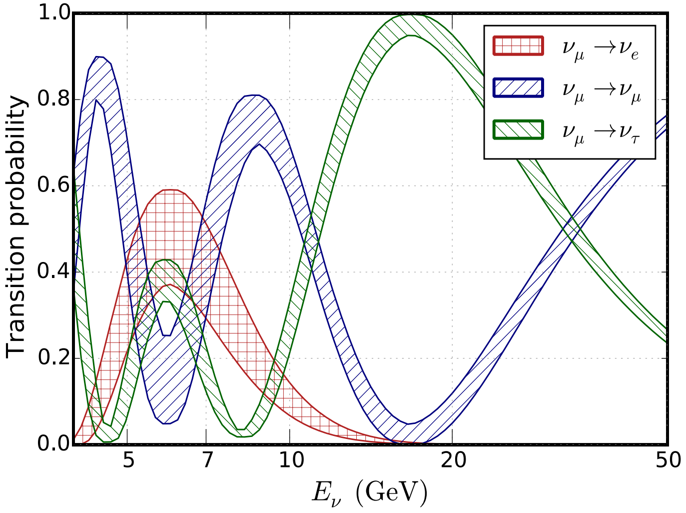
- Upgoing shower events (ve / vt CC, NC)
- Angular resolution < 4°
- Energy resolution for better than 10%

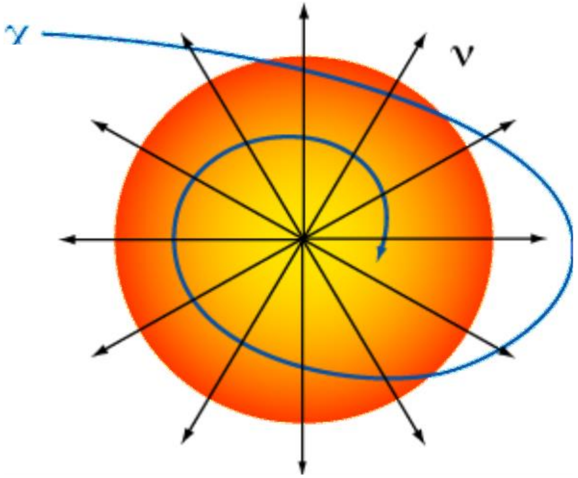
shower channel = good energy resolution
(IceCube discovery channel)

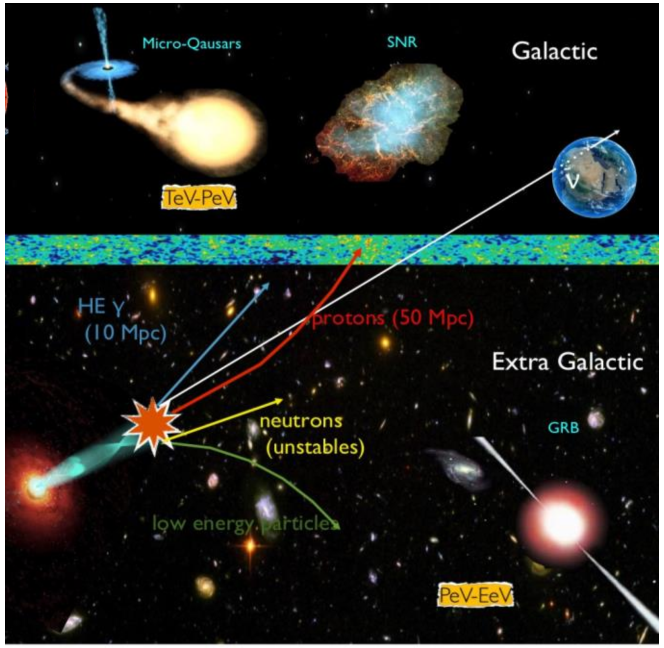


Science with ANTARES

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

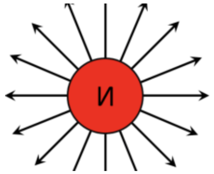
Energy

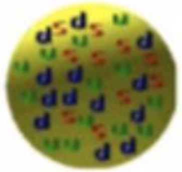
ν Oscillations

Dark matter search

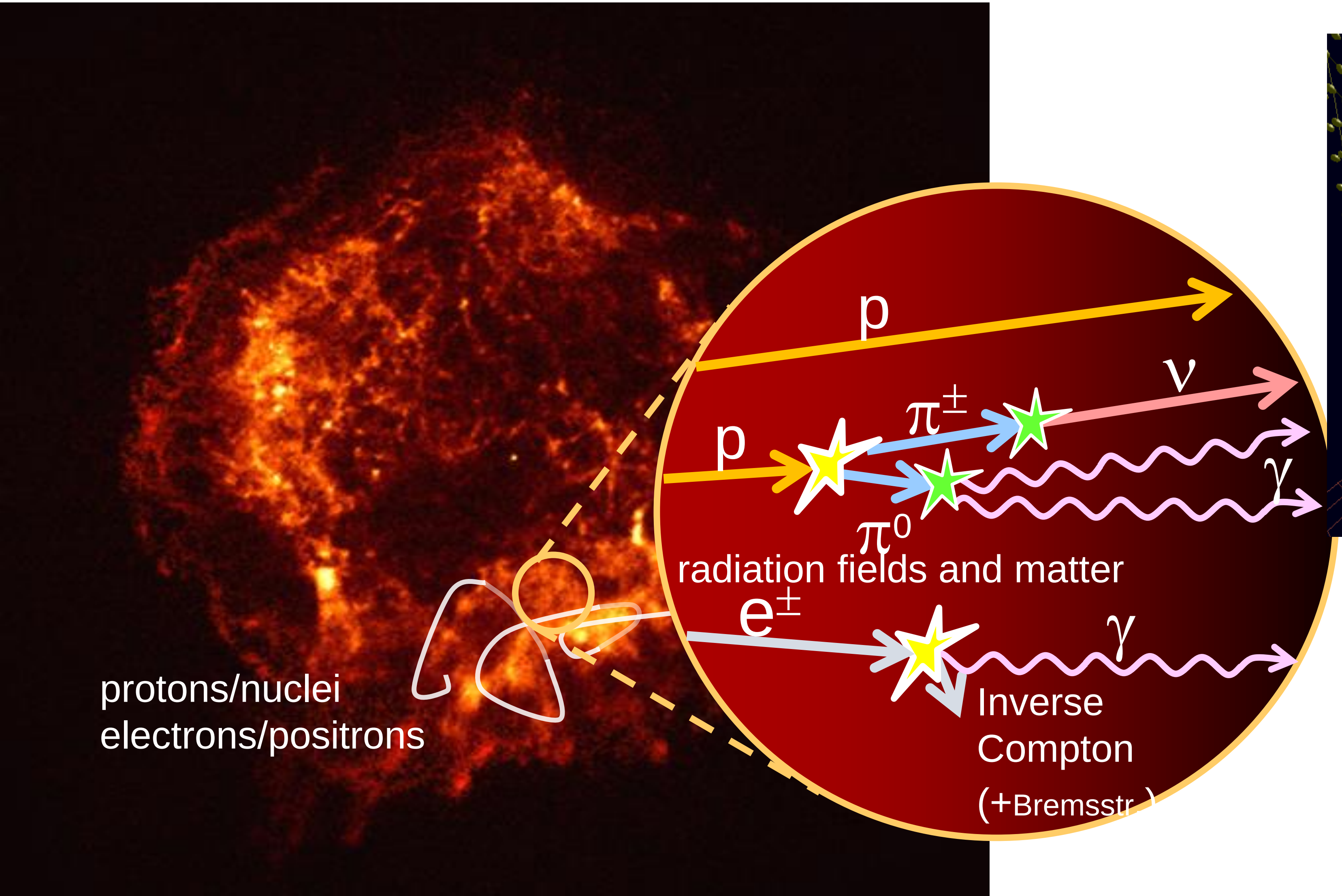
ν from cosmic sources
origin and production
mechanism of HE CRs

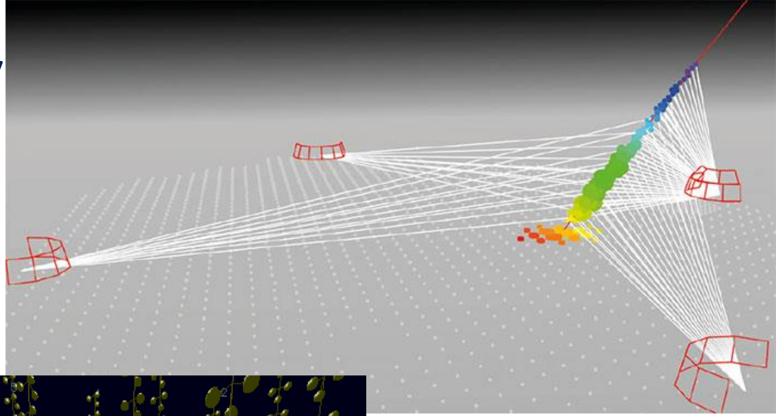
+ Exotic searches - Nuclearites, Magnetic monopoles...

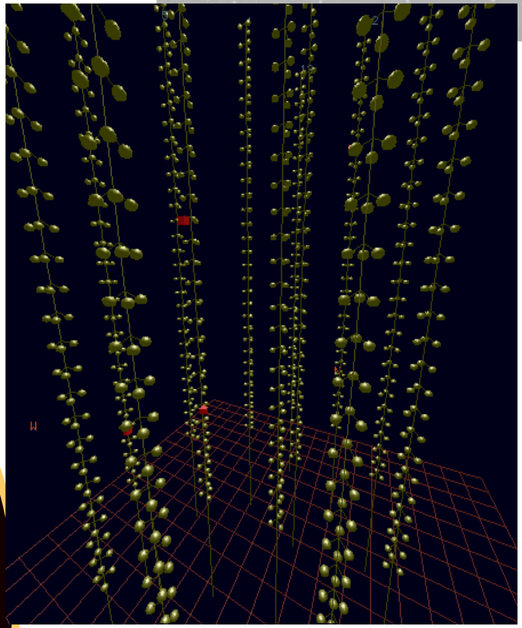


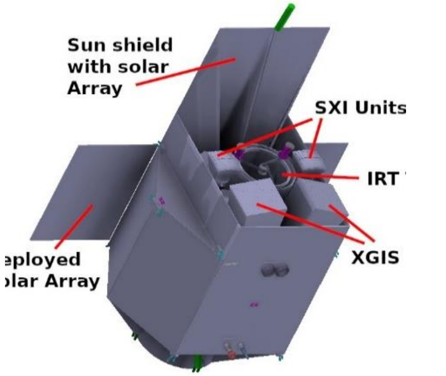


ν, CRs, γs and multimessenger astronomy

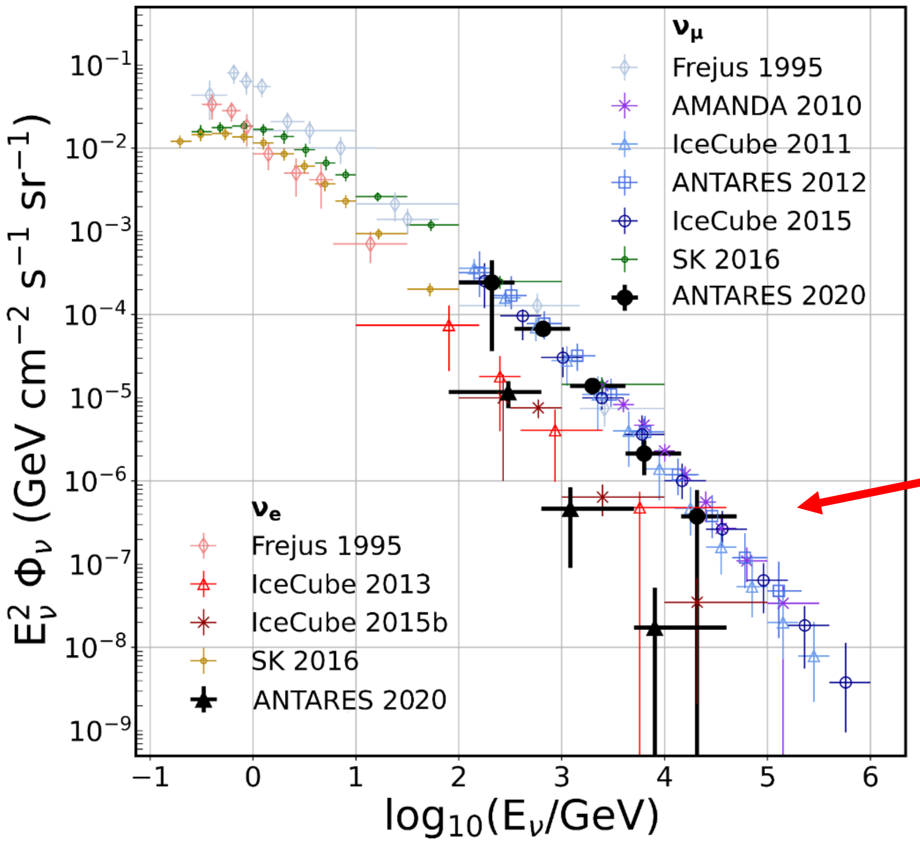


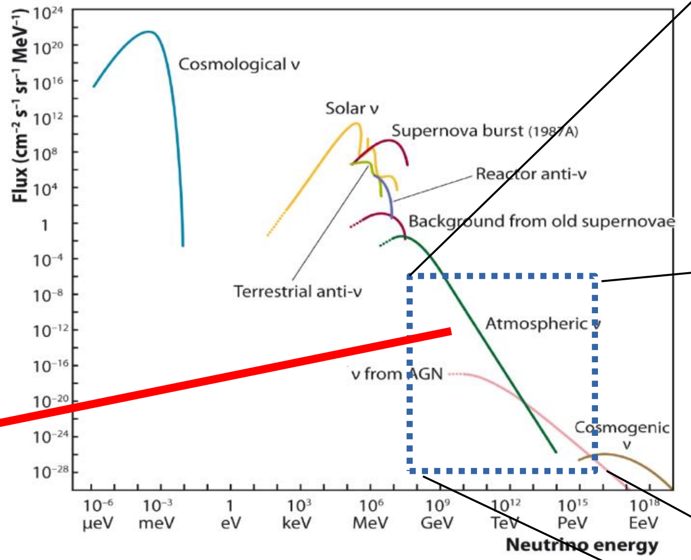


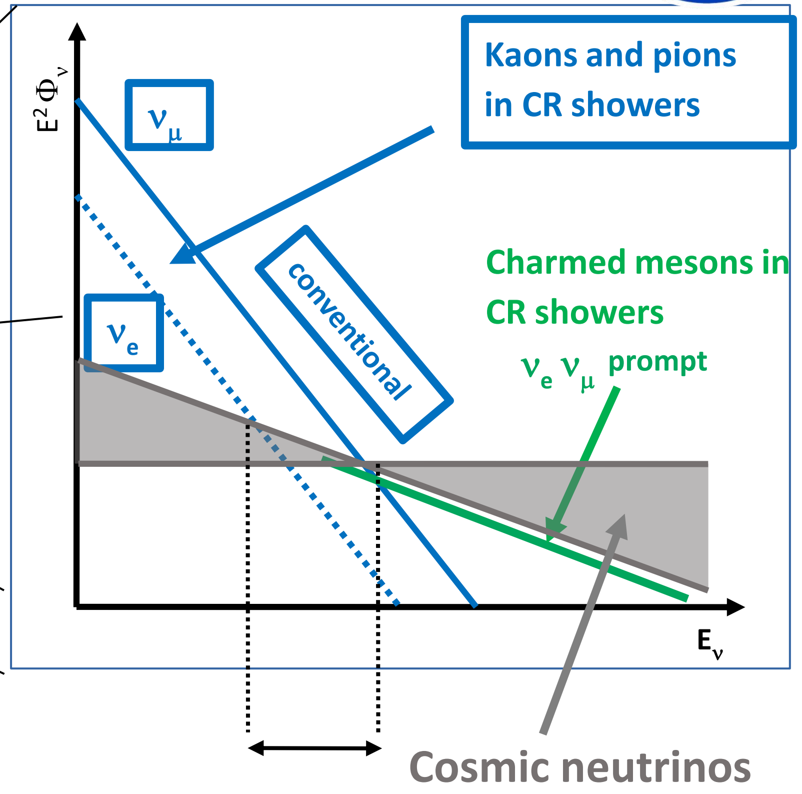




Atmospheric neutrino background







Atmos-to-Cosmic transition
30-200 TeV

measured using an energy estimator
accounting for detector systematics

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

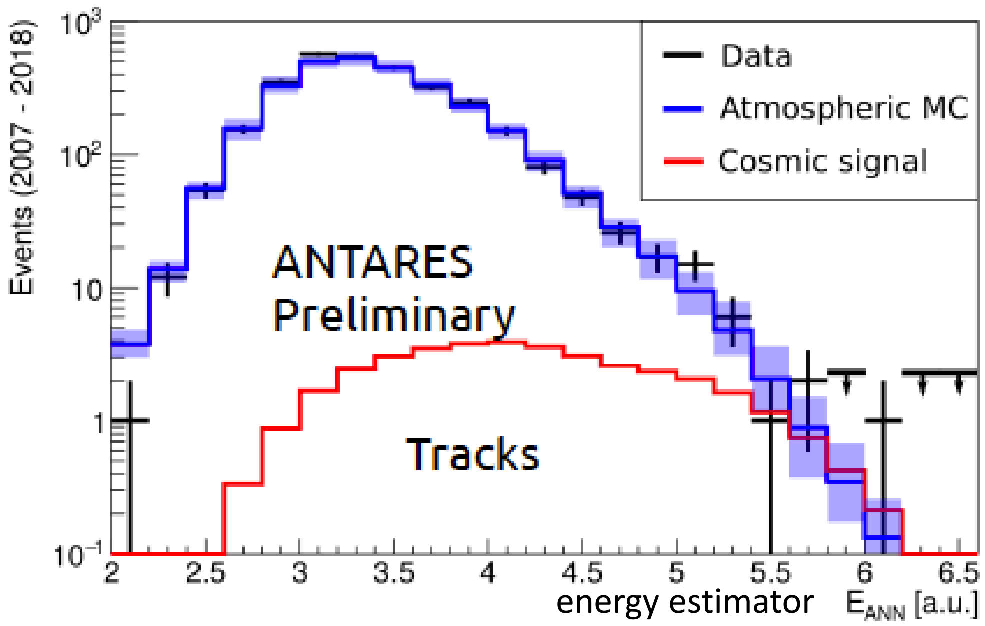
Diffuse flux of cosmic neutrinos in ANTARES

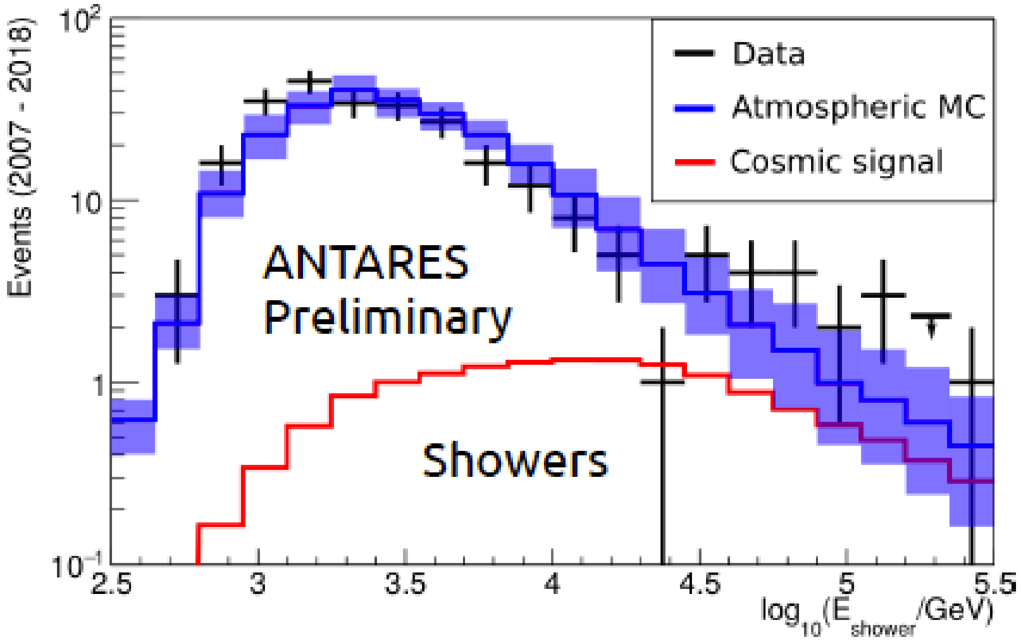
📖 Ap.J.Lett. 853 (2018) 1, L7
📖 https://pos.sissa.it/358/891/pdf -(ICRC 19)

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





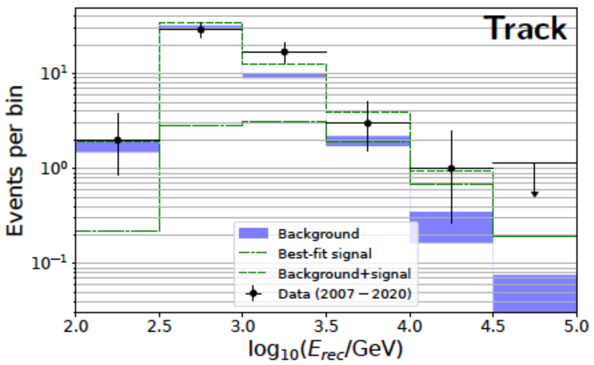
Flux from the Galactic ridge - new analysis ON/OFF

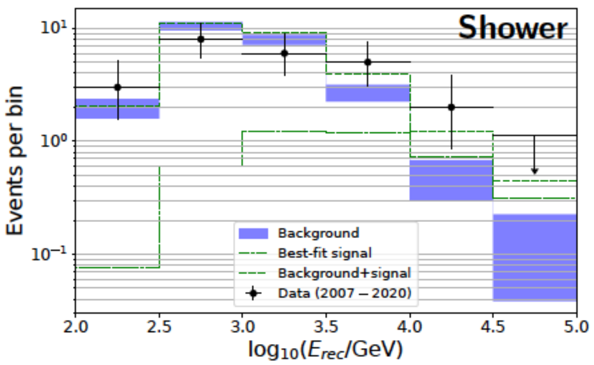
previous analyses
- PLB 760 (2016) 143
- Phys. Rev. D 96, 062001 (2017)
- ApJL 868, L20 (2018)

- neutrino signal expected from the Galactic Ridge (gamma-ray data)
- Cosmic ray interactions → π^o → γ $\pi^{\pm}$ → ν
- extension of a previous analysis ----

  Data period: 2007–2013 → 2007–2020
- sample of events: tracks-only → tracks + showers

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

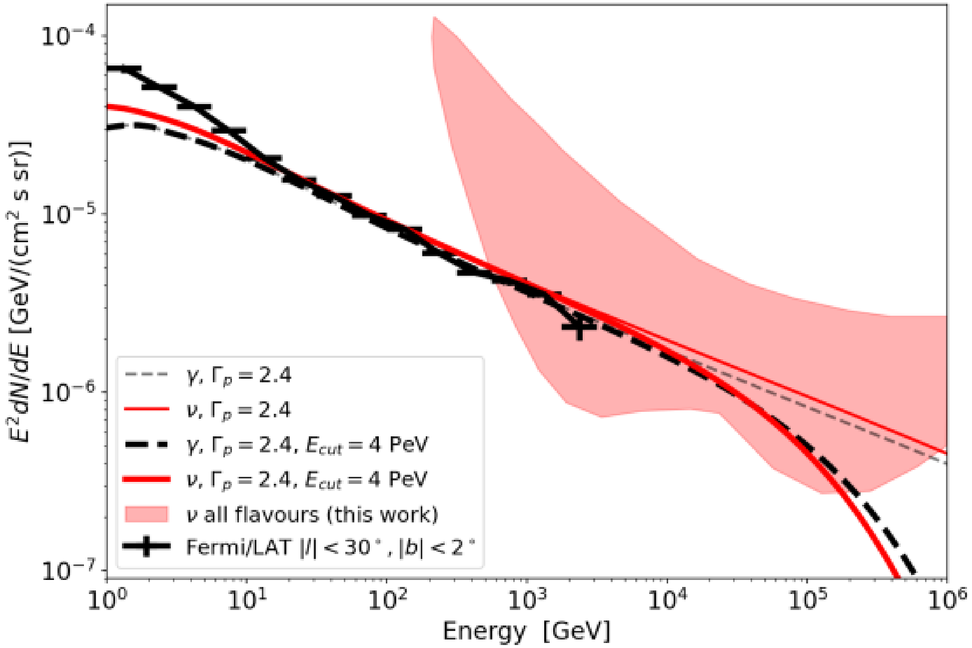


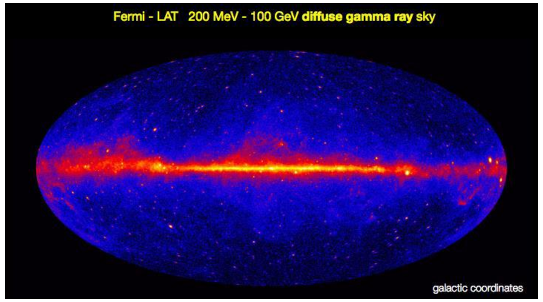


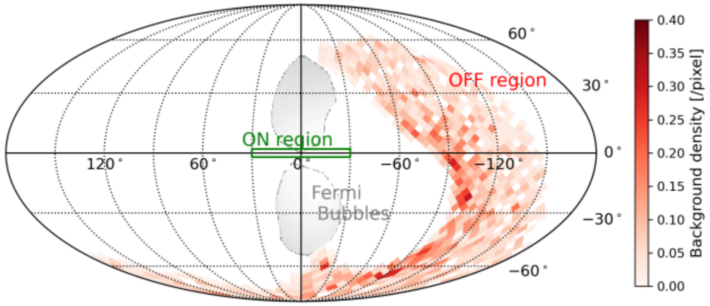
- Comparison of the neutrino flux coming from the ON region to the expected background neutrino flux
- **Background**: *scrambled* data from OFF regions [excluding Fermi bubbles]

hints of an excess of a neutrino flux from the Galactic Plane

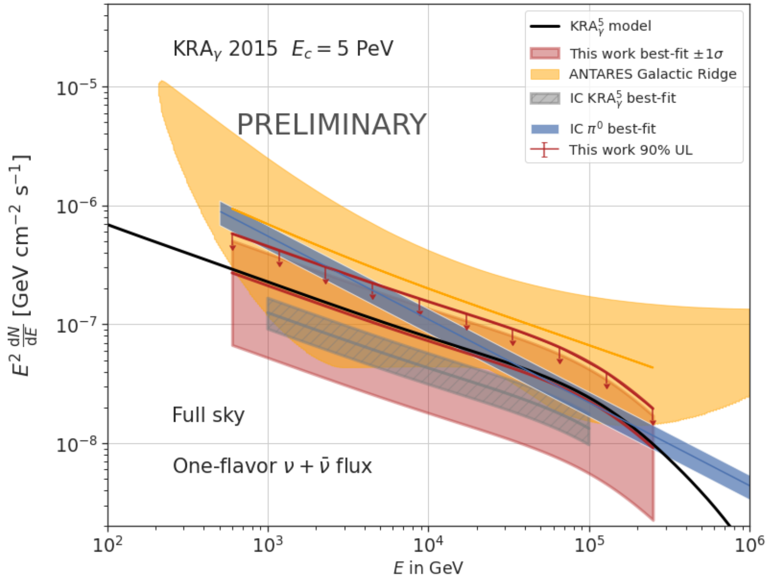
A. Albert et al., PLB 841 (2023) 137951

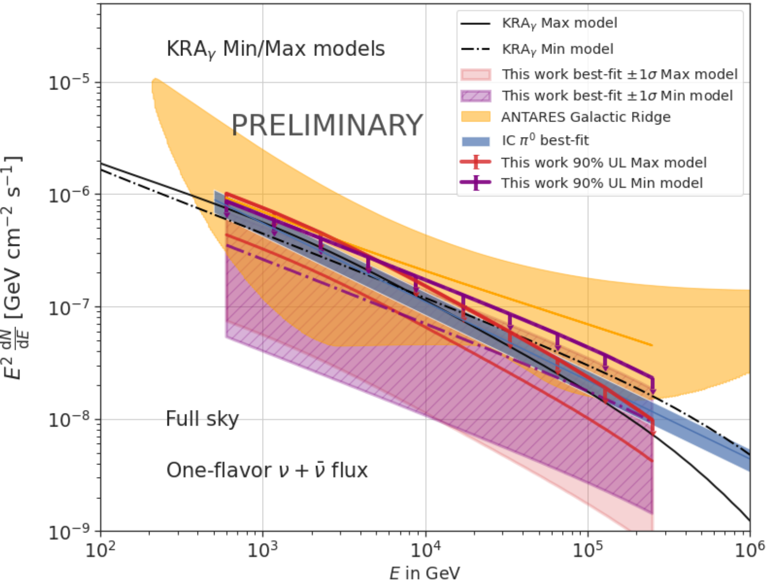






Flux from the Milky way: template model analyses





Different models tested using ANTARES data collected in 2007-2020 - 4541 days

7501 tracks (median angular resolution ~0.4°) - 3% atm. μ contamination

1145 showers (median angular resolution ~3°) - 10% atm. μ contamination

KRAγ models enhance overall γ-ray and ν fluxes in particular in the central region of the Galactic plane

hardening of the CR spectrum

- radially dependent diffusion coefficient of CRs
- cutoff of the CRs spectrum
  - KRA$^5_\gamma$ → at 5 PeV/nucleon
  - KRA$^{50}_\gamma$ → at 50 PeV/nucleon
- KRA$^{min}_\gamma$ and KRA$^{max}_\gamma$ → optimization according to new experimental measurements of CRs spectrum and γ–rays

radially dependent model for the CR diffusion coefficient

Likelihood method for different models, full-sky analysis

No significant excess measured.

Higher significance: KRA$^5_\gamma$; post-trial p-value = 1.7σ.

Compatible with Galactic Ridge analysis

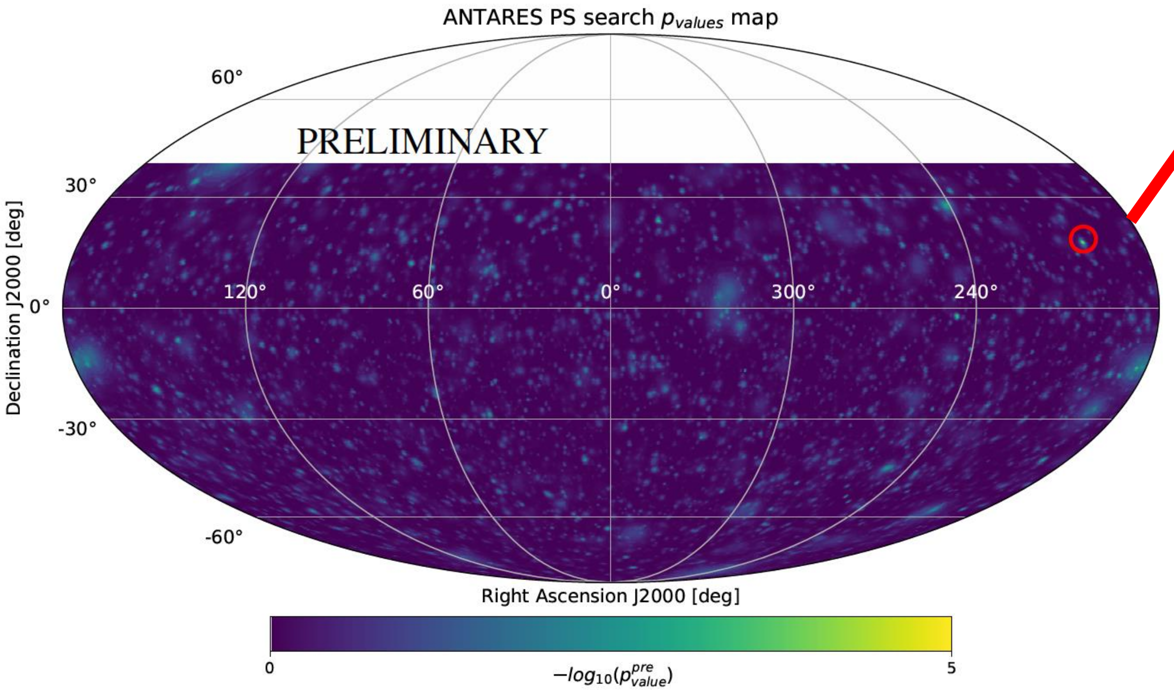
Search for cosmic sources: tracks+cascades

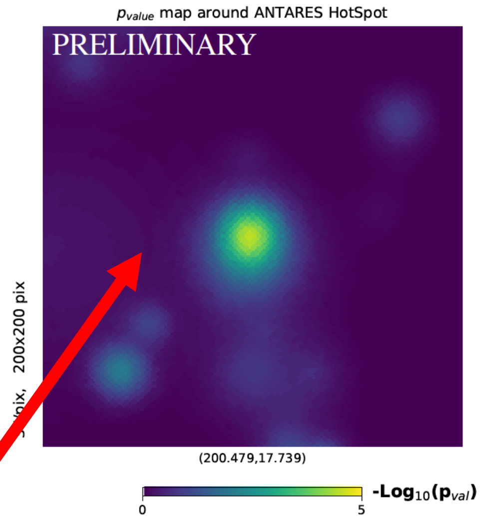
📖 PRD 96, 082001 (2017)
📖 PoS(ICRC2021)1161
📖 PoS(ICRC2023)

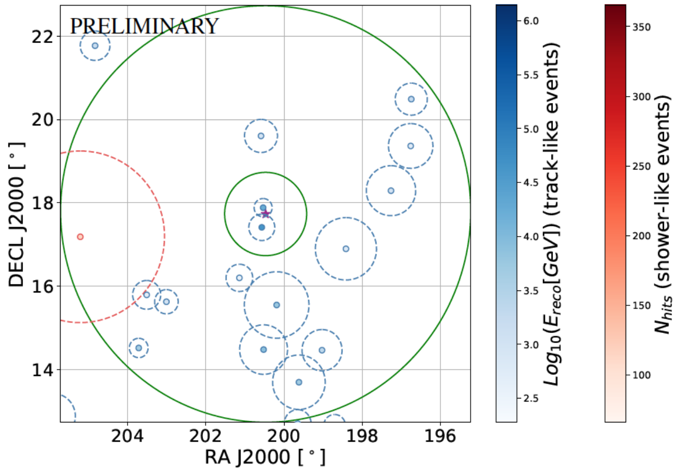
Data set 15 year (from Jan 2007 to Feb 2022); Livetime: 4541 days; 11029 tracks + 239 showers

Search for an excess of events (cluster) from any direction

full-sky







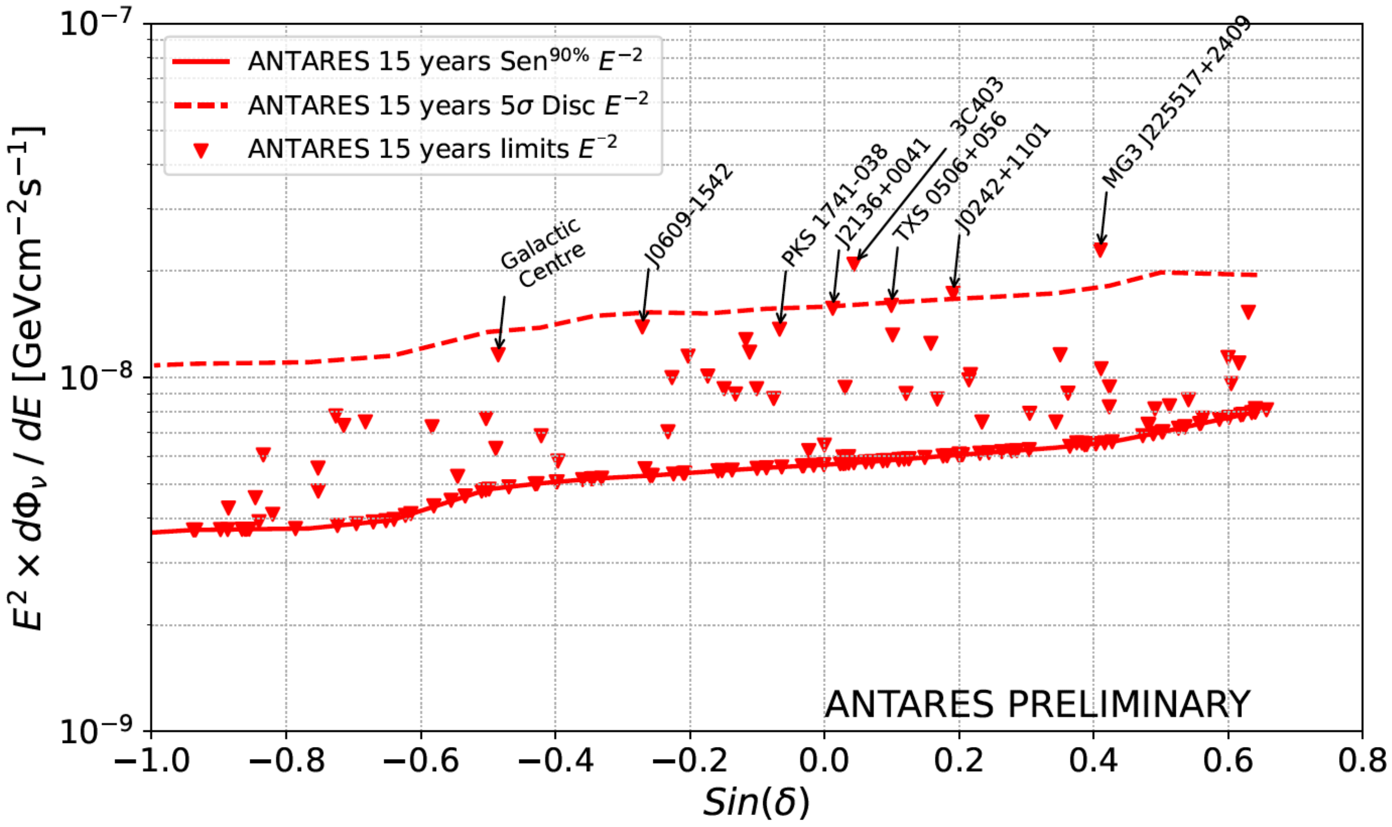
Highest significance hot spot (α, δ) = (200.5°, 17.7°)
pre-trial p-value=3x 10^{-5} → 4σ
post-trial p-value=1.1%→1.2σ

Search for cosmic sources: tracks+cascades

📖 PRD 96, 082001 (2017)
📖 PoS(ICRC2021)1161
📖 PoS(ICRC2023)

Data set 15 year (from Jan 2007 to Feb 2022); Livetime: 4541 days; 11029 tracks + 239 showers
Search for an excess of events (cluster) from any direction

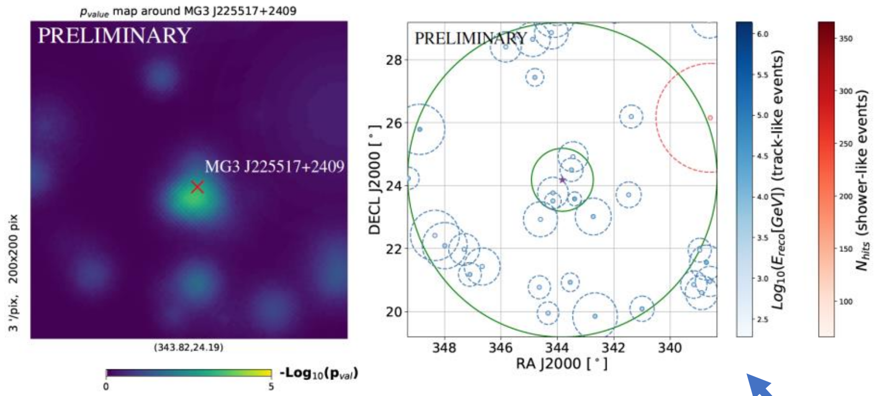
search over a predefined list of 163 candidates



No significant evidence of cosmic neutrino sources has been found

Blazar MG3 J225517+2409 is the most significant source (post-trial p-value: 1.7 σ)

pre-trial p-value map



location of events

Search for neutrinos from radio-blazars

Search for neutrino - blazar association in the data sample collected between 2007-2020

3845 days, 10504 track-like events + 227 shower-like events

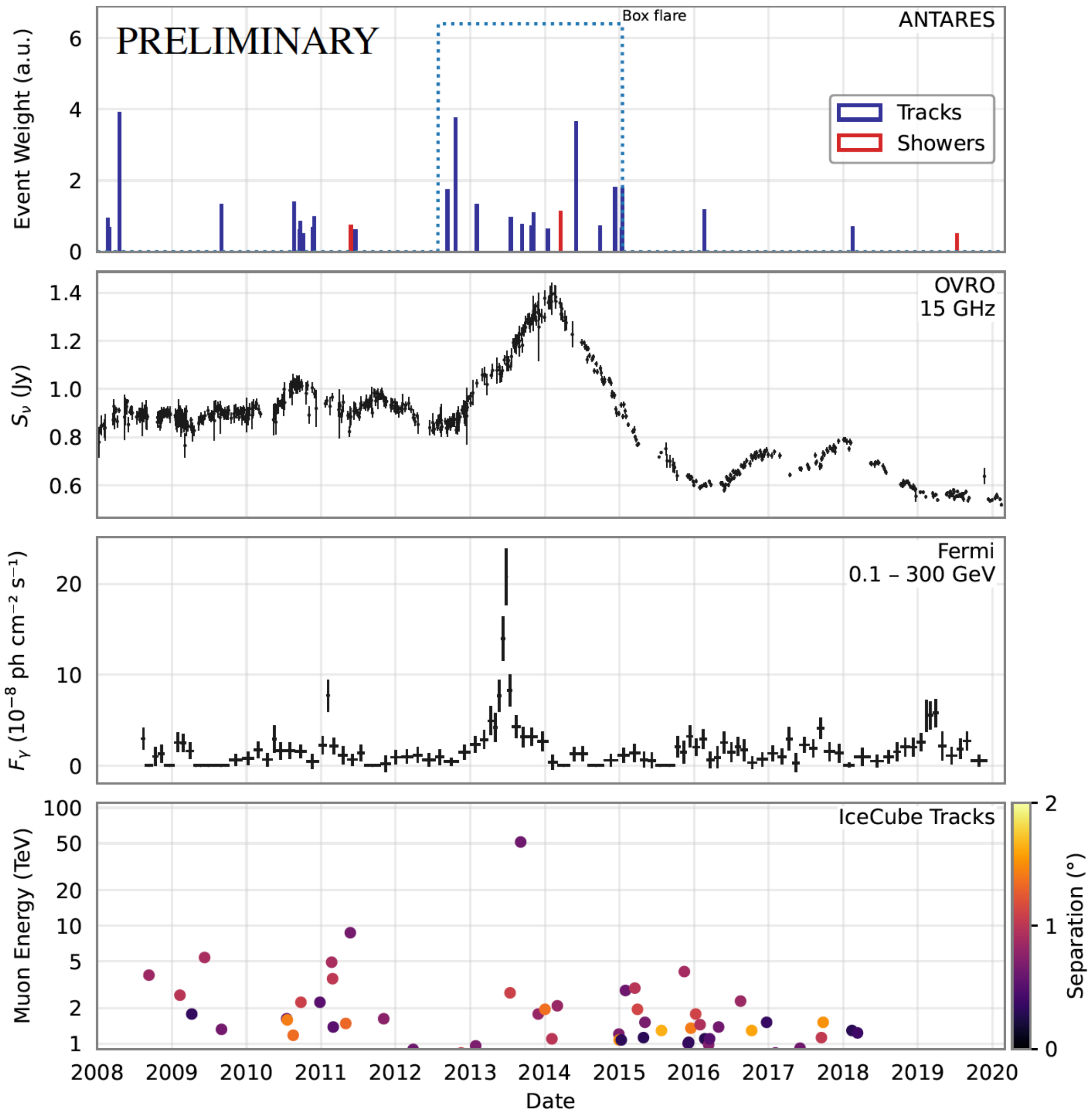
Different strategies:

- neutrino-blazar pair counting method
- time integrated likelihood analysis
- time dependent likelihood scan
- multi-messenger flares comparison

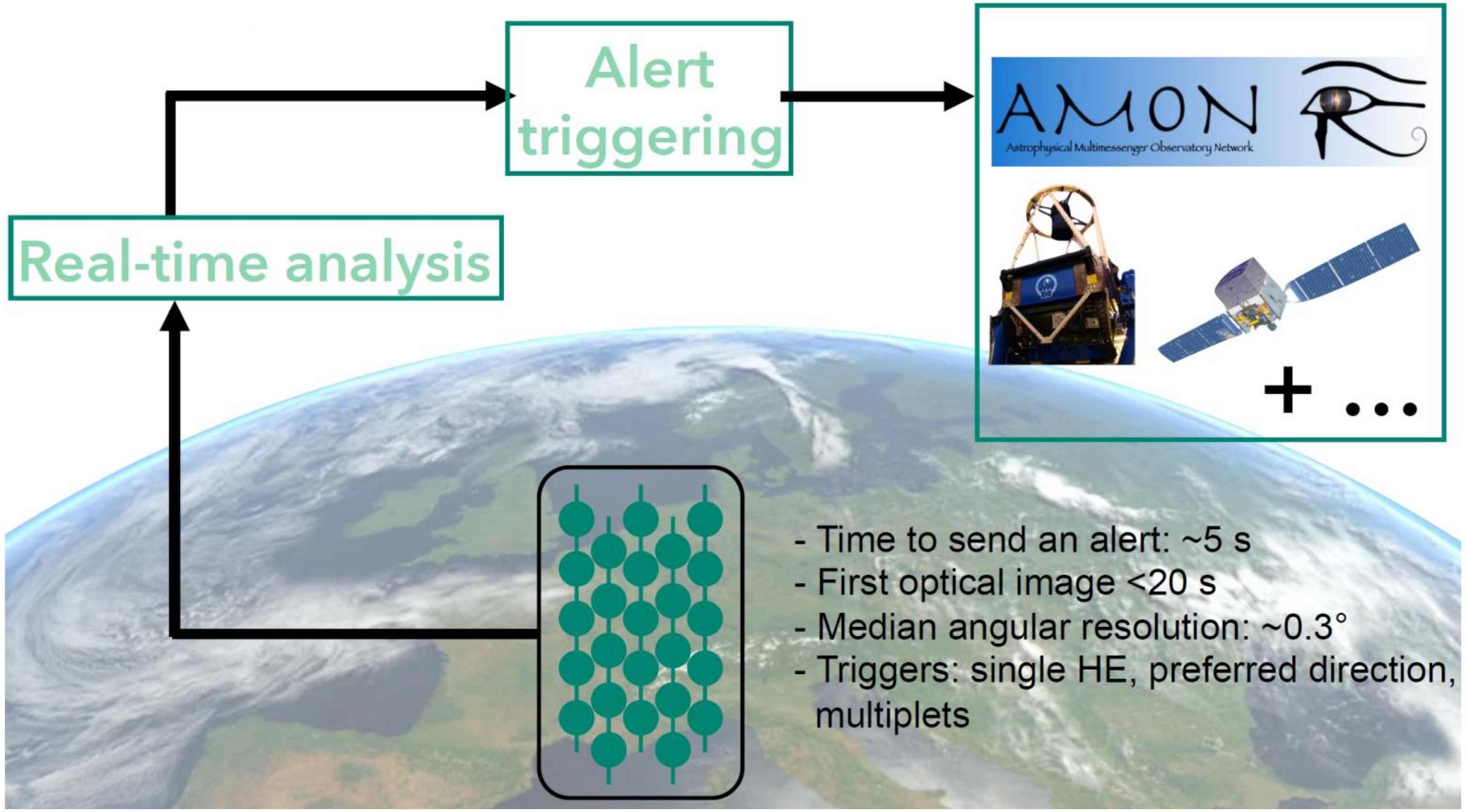
No significant excess - only hints of possible correlation

Paper in preparation

The notable case of the J0242+1101 blazar



Multi-messenger approaches - **sending alerts**

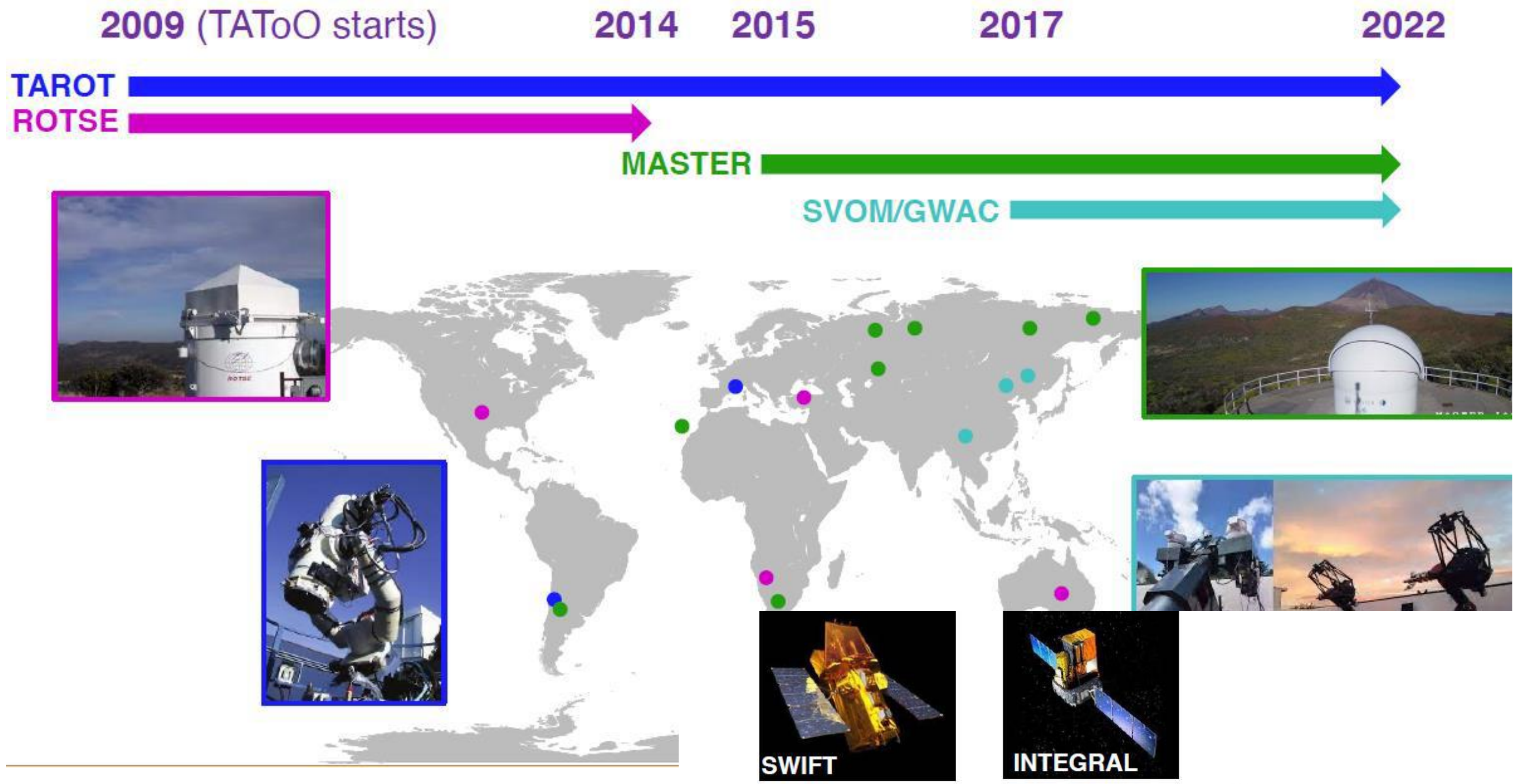


Alert system (**TAToO**: Telescopes and Antares Target of Opportunity) active since 2009
📖APP 35 (2012) 530

What triggers an alert:

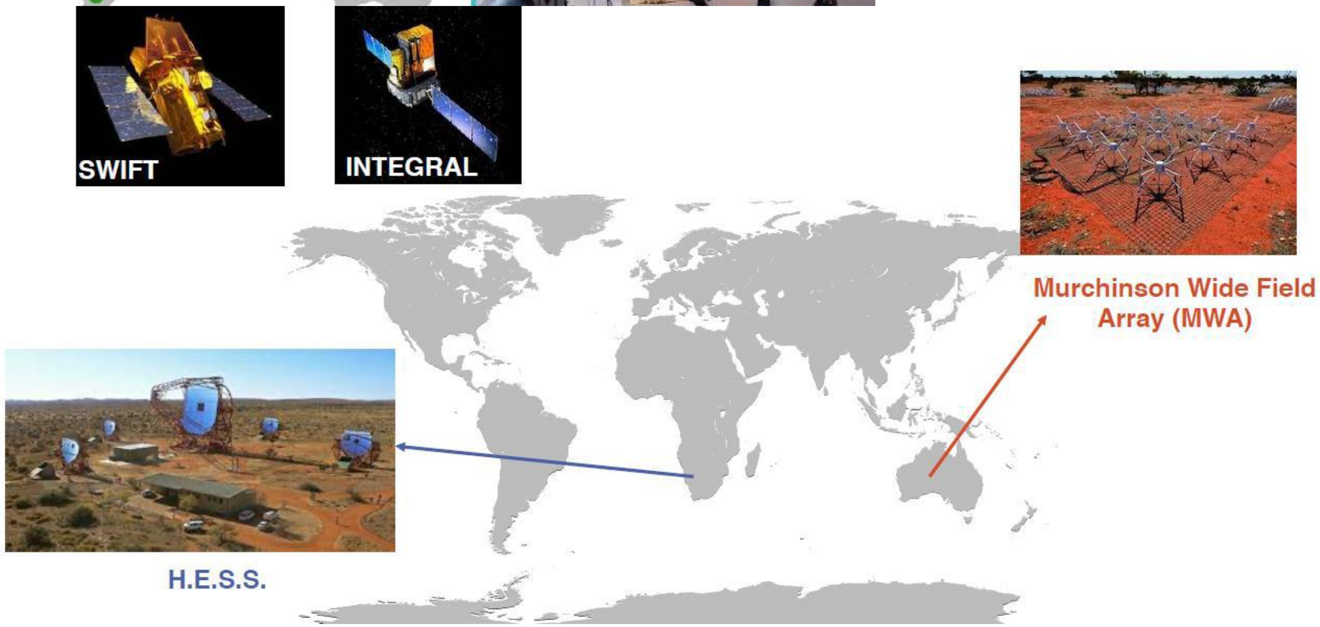
- **High energy (HE):** single neutrino with energy ≥ 5 TeV. Rate: ~1/month
- **Very high energy (VHE):** single neutrino with energy ≥ 30 TeV. Rate: ~3-5/year
- **Directional trigger:** single neutrino from the direction (≤ 0.4°) of a local galaxy (≤ 20 Mpc). Introduced to increase the chance to detect 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**



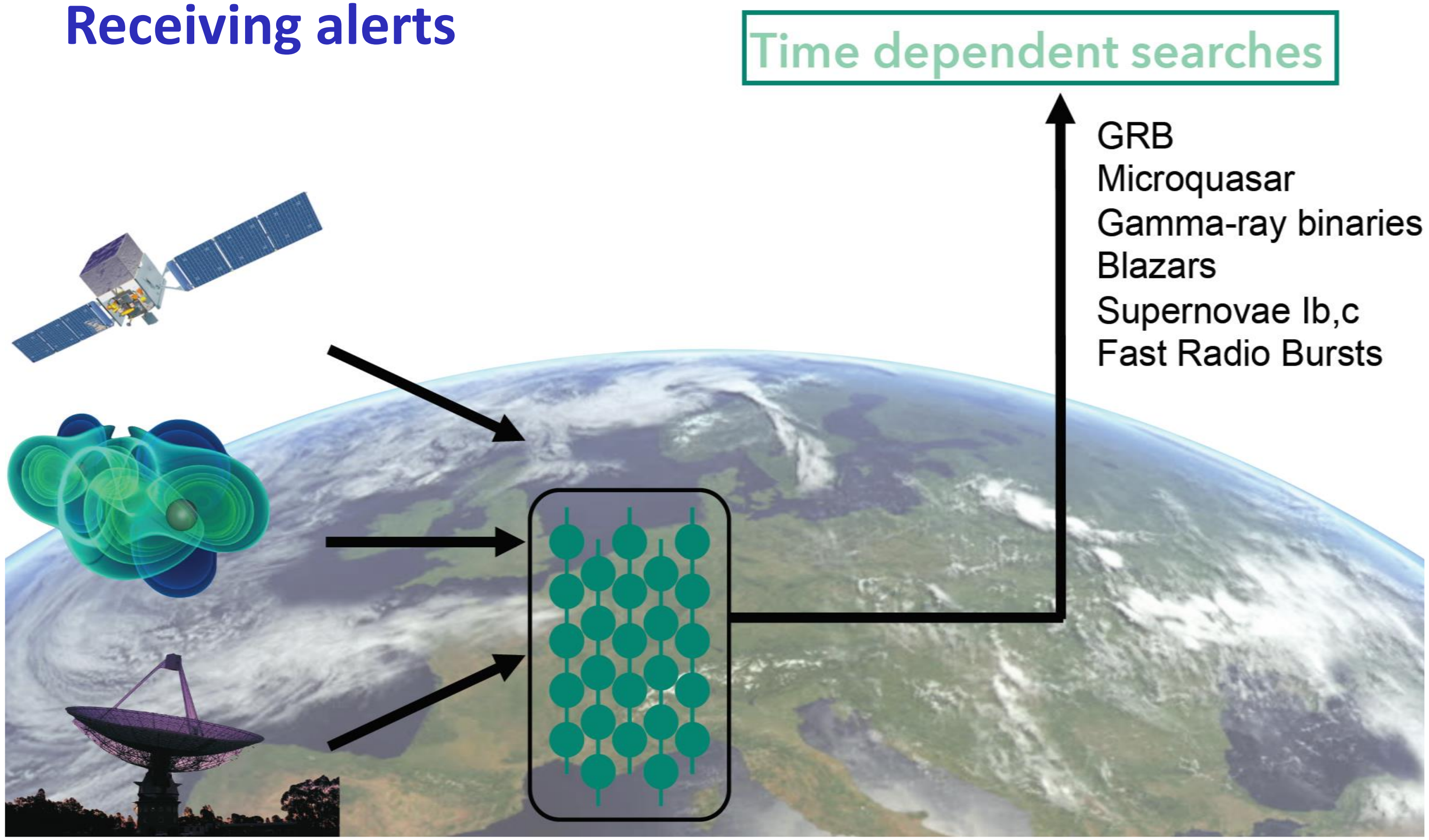
Optical telescopes

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

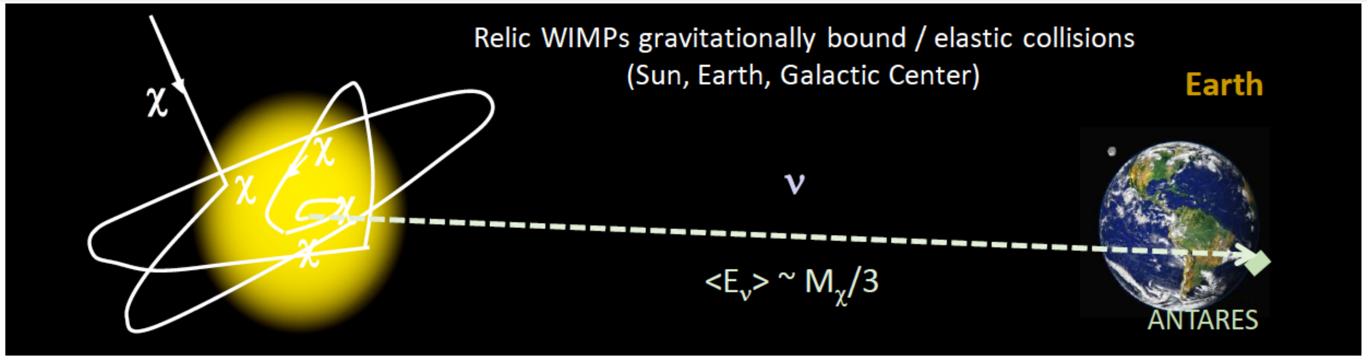
No candidates associated with GWs
📖 **JCAP04 (2023) 004** (neutrinos associated to O3 Run events of Virgo/Ligo)

Follow-up of Fermi-GBM and Swift GRBs

Follow-up of HAWC alerts

📖 **ApJ 944 (2023) 166**

Indirect search for Dark Matter



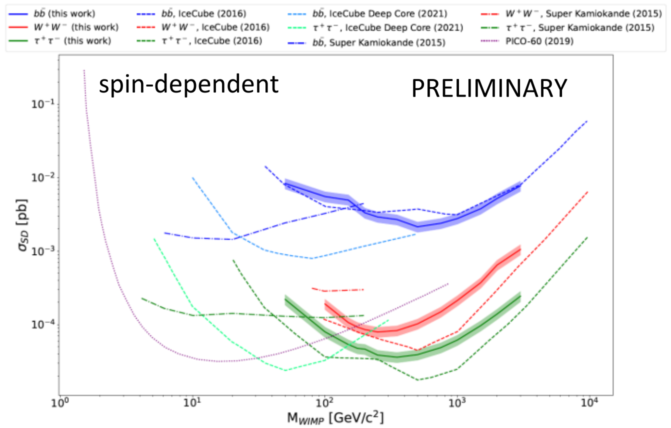
Earth
Physics of the Dark Universe, 16 (2017) 41
Sun
Phys.Lett. B759 (2016) 69
JCAP 05 (2016) 016
JCAP11 (2013) 032
Galactic Center
JCAP 10 (2015) 068
Phys. Lett. B 769 (2017) 249
Phys. Rev. D 102 (2020) 082002 (with IceCube)
JCAP06 (2022) 028 (secludedDM)
Phys. Lett. B 805 (2020) 135439

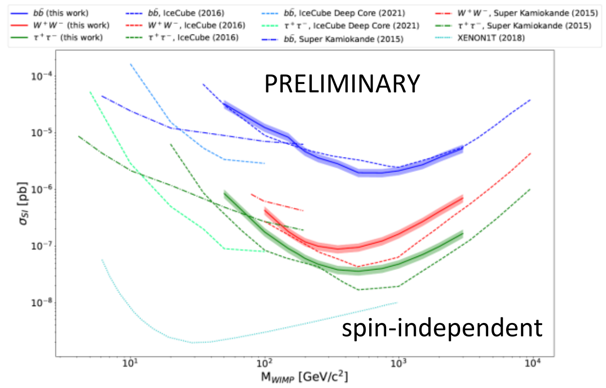
Neutrino telescopes are very versatile and good for different search channels

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

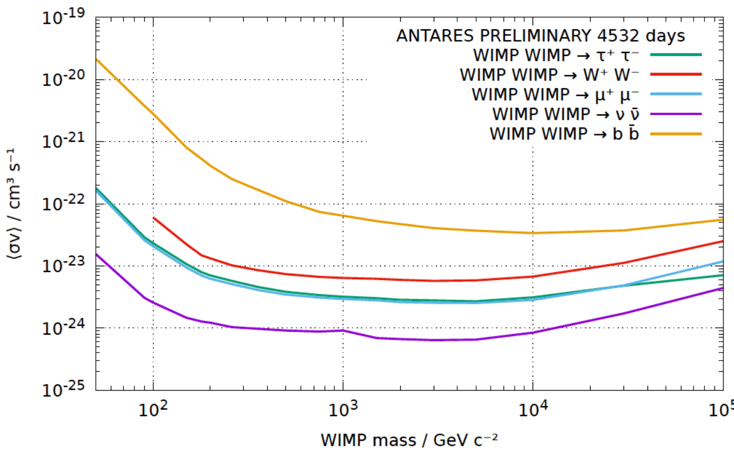
The Sun

- 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

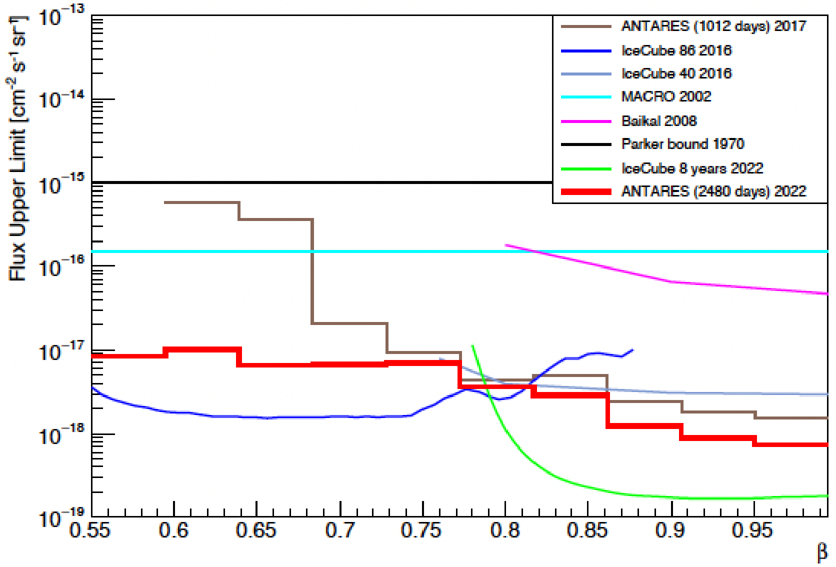


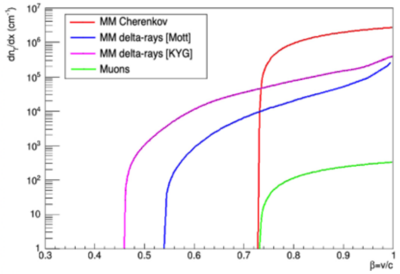
data 2007 - 2022 compatible with background

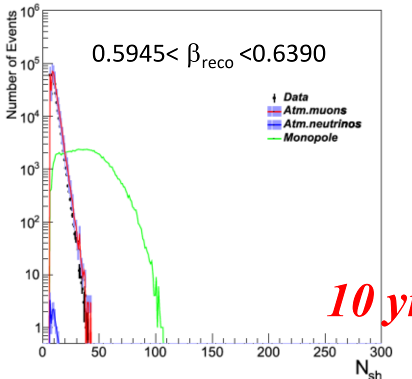
Exotic particles: Magnetic Monopoles and Nuclearites

Magnetic Monopoles JHEAp 34 (2022) 1

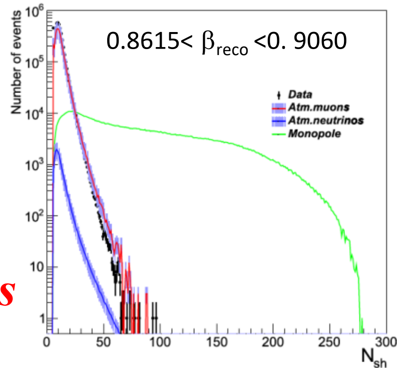
- Search for fast MM with Dirac magnetic charge
- Kasama, Yang and Goldhaber model - improved description of MM cross section ➔ increased light production
- better atmospheric muon rejection







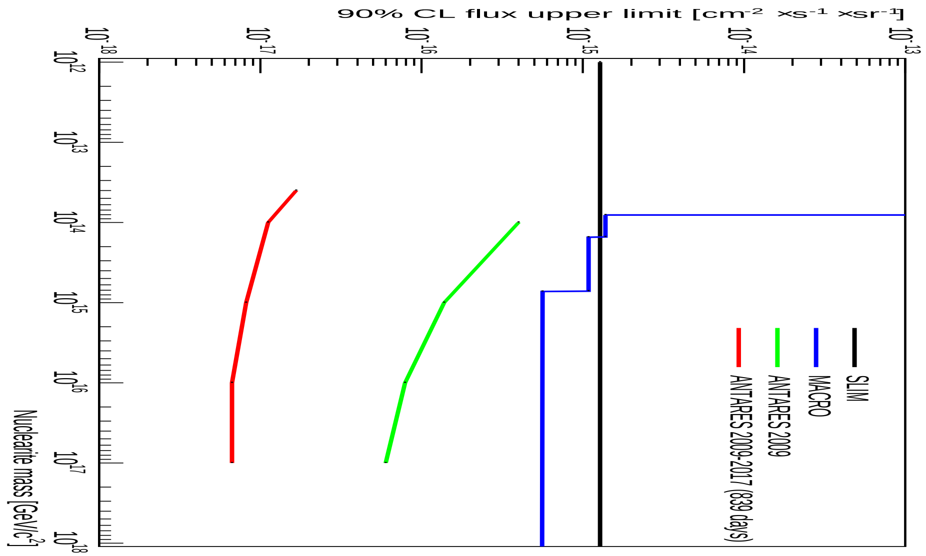
10 yrs



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 x 10^{13}GeV/c^2<M_N <10^{17} GeV/c^2
- No Cherenkov emission - Visible photons from black body radiation

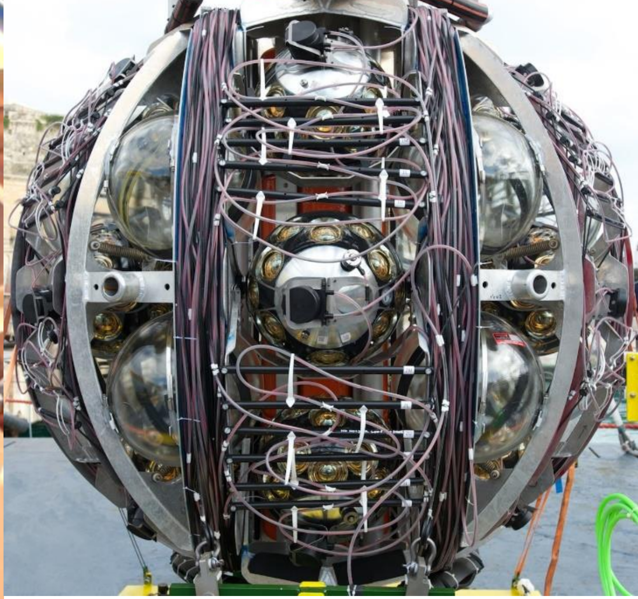
JCAP01 (2023) 012

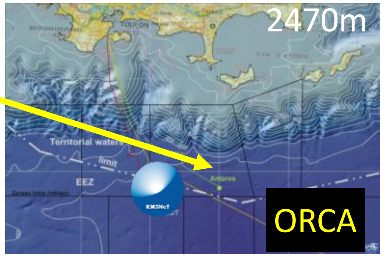


ANTARES → KM3NeT

- 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).
- more than 100 papers published & 100 PhD.

- AN EXCITING ADVENTURE ! To be continued with **KM3NeT** (Talk by A. Romanov, this conference July 12th)





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

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

Paris - June 2008