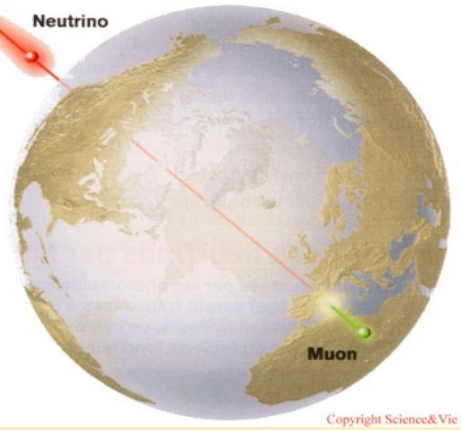
22nd edition

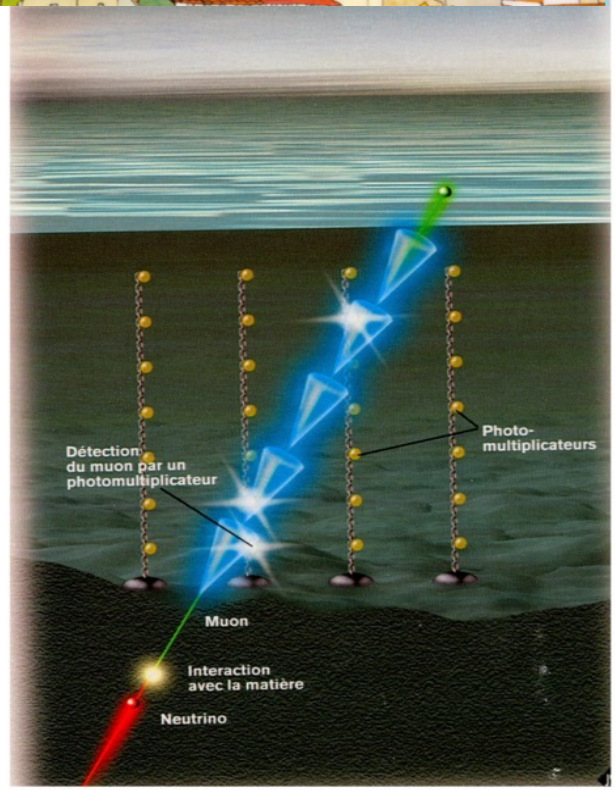
PANIC Lisbon Portugal

Particles and Nuclei International Conference

ANTARES & KM3NeT:

High Energy Astrophysical Neutrino Telescopes in the Mediterranean Sea





Antonio Capone
University La Sapienza – Roma

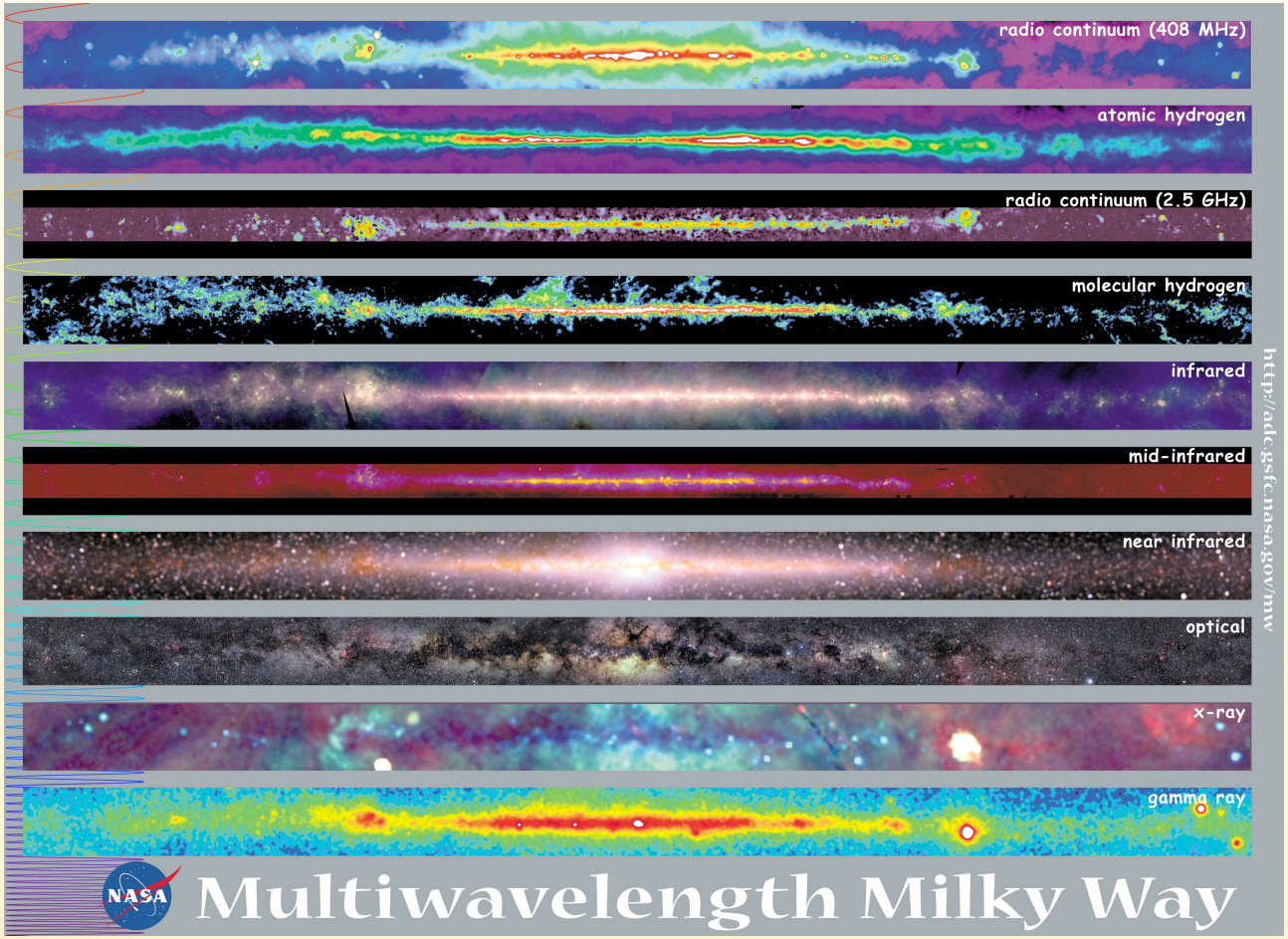
The evolution of astronomy

- From Traditional Astronomy (Optics) to Multi-Wavelength Astronomy:

  observations of light in the visible band are complemented by radio,

  X-ray and γ astronomy

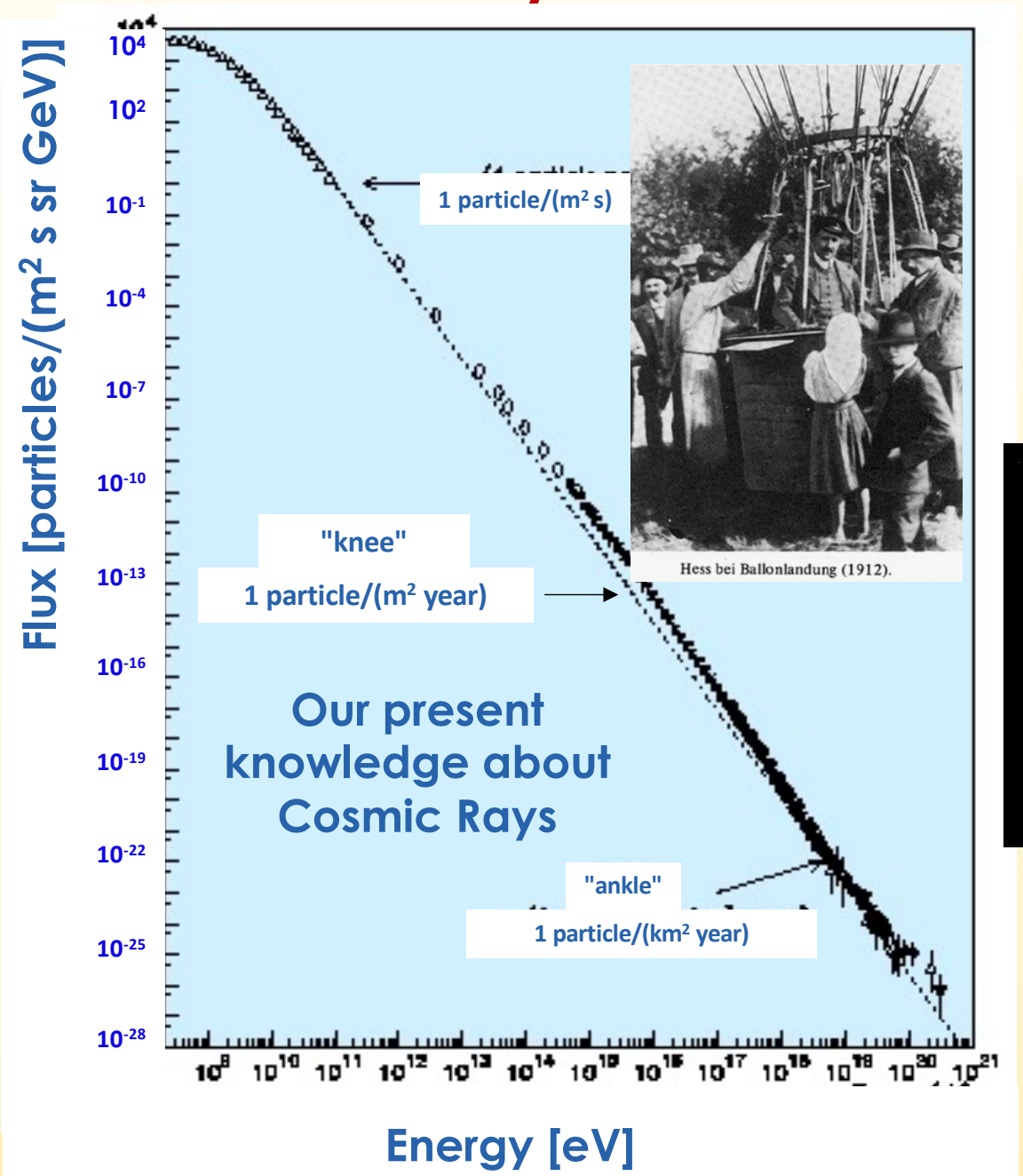
***Galileo Galilei showing the Doge of Venice how to use the telescope* (1858), fresco by Giuseppe Bertini (1825–1898)**



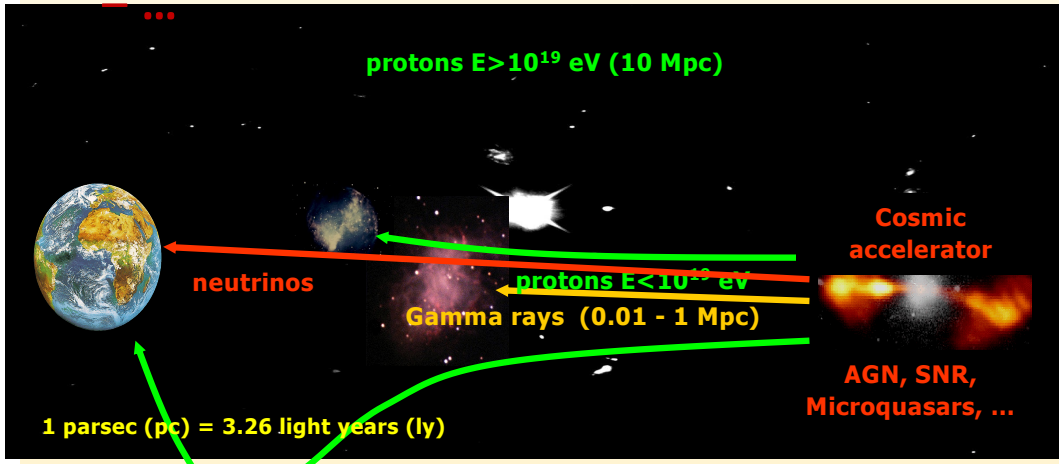
http://mwmw.gsfc.nasa.gov/

… and to Multi-Messengers Astronomy:
HE-CR, photons, neutrinos, GW …

One century of cosmic rays measurements …



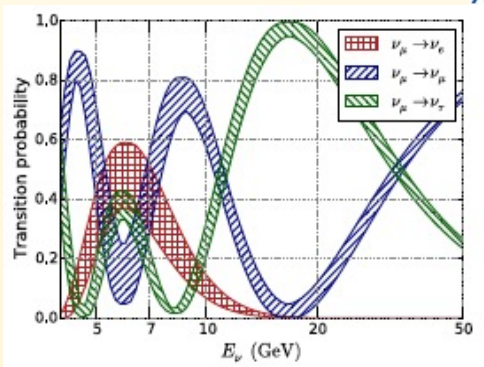
- Observed elementary particles or nuclei carrying a kinetic energy up to 10^{21}eV (like a tennis ball moving at ~150km/h)
- Many open questions:
  - Where they come from ?
  - Which acceleration mechanism ?

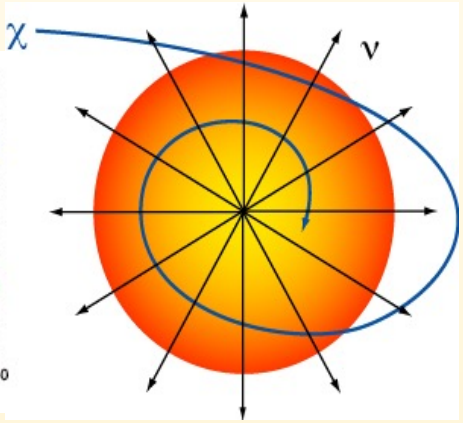


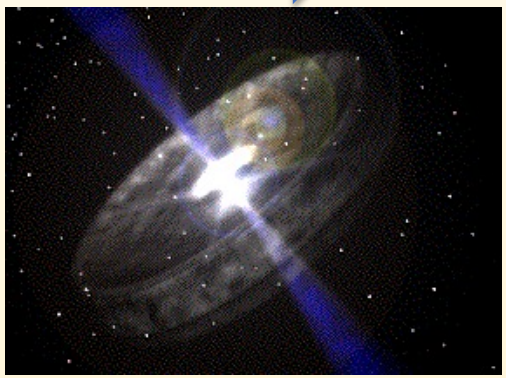
- UHE astrophysical neutrinos will extend the limits of the "visible" Universe.
- Detection of ν from point-like sources will clarify their "nature": hadronic/leptonic ??
- Multi-messenger observations

Neutrino Telescopes scientific objectives …

MeV to PeV energies







Supernova
Solar flares

atmospheric ν
ν oscillations
ν mass ordering
sterile ν

Dark matter
Monopoles,
Nuclearites,…

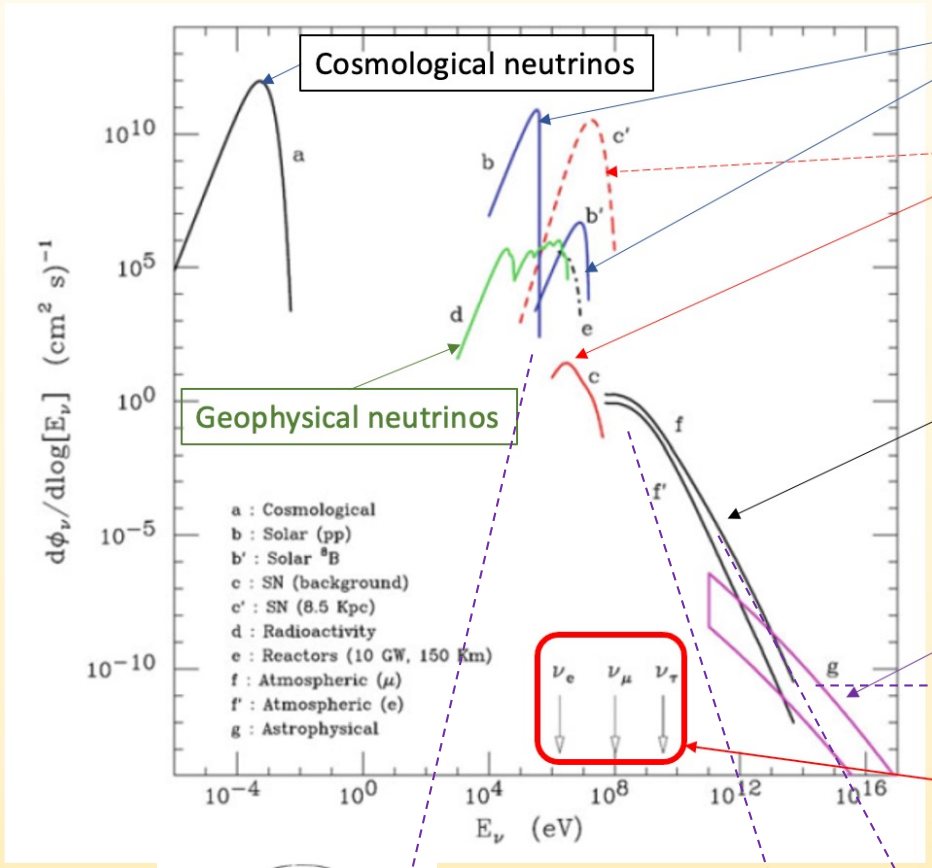
ν from extra-terrestrial sources

Cosmic rays

Origin and production mechanism of HE CR

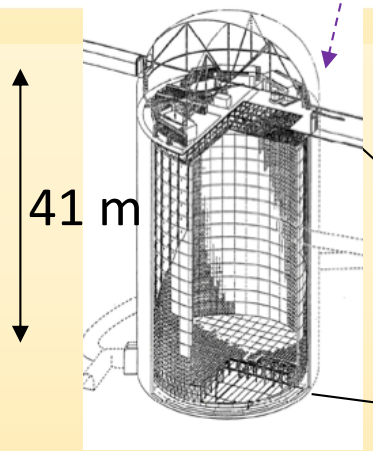
+ oceanography, biology, bioacoustics, seismology,…

Detecting neutrinos in H_2O



Proposed by Markov, Greisen, Reines in 1960

The three arrows indicate the energy thresholds for CC production of the charged lepton



41 m

SuperK
50 kton

KM3NeT-ORCA
8 Mton

200m

ANTARES
20
Mton

400 m

ICECUBE
GVD
KM3NET-ARCA
1 Gton

1000m

Light propagation in water

In a transparent medium the light propagation is limited by absorption (the photon disappears)

$$I(x) = I_o\, e^{-ax}$$
$$L_a = 1/a$$

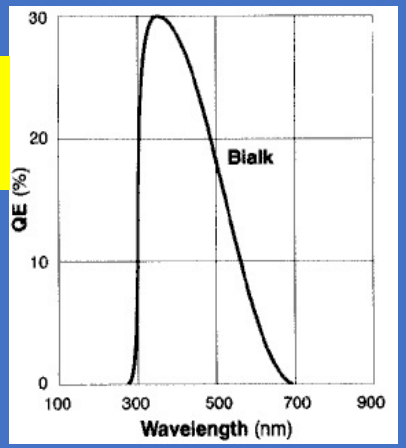
by diffusion (the photon changes direction),

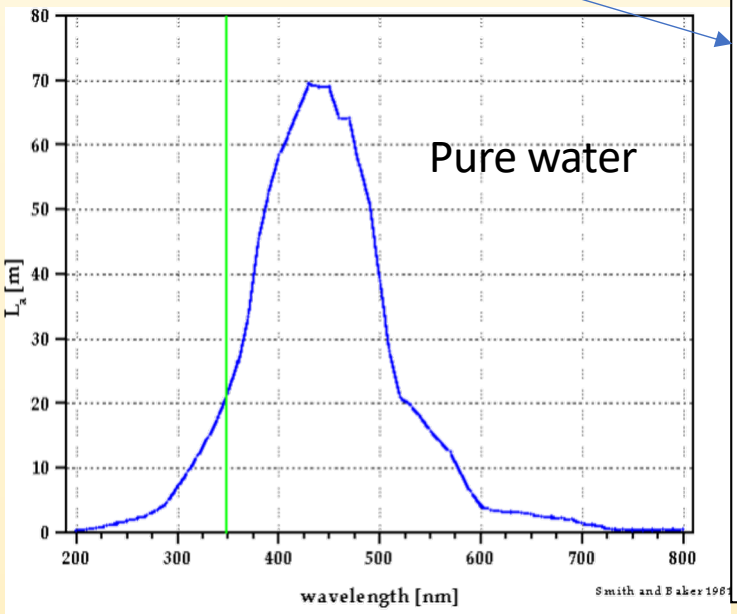
$$I(x) = I_o\, e^{-bx}$$
$$L_b = 1/b$$

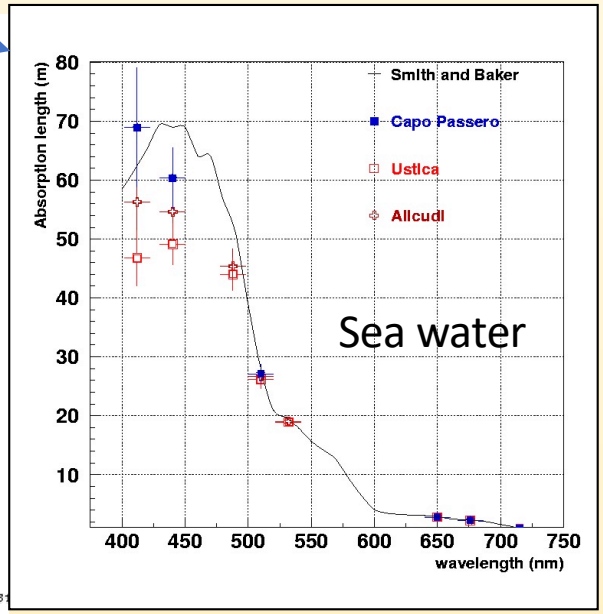
by attenuation

$$c = a+b$$
$$I(x) = I_o\, e^{-cx}$$
$$L_c = 1/c$$

PMT quantum efficiency

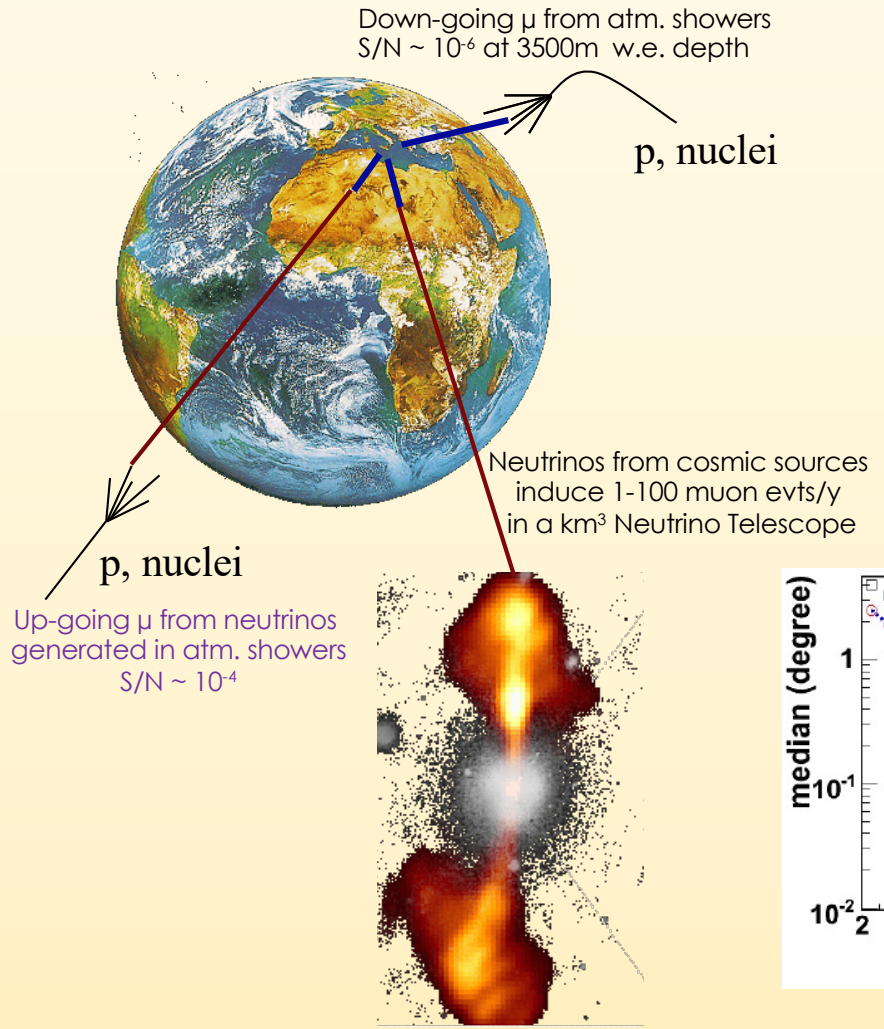






Schematics of a Cherenkov Neutrino Telescope

Search for neutrino induced events, mainly $\nu_\mu N \to \mu X$, deep underwater

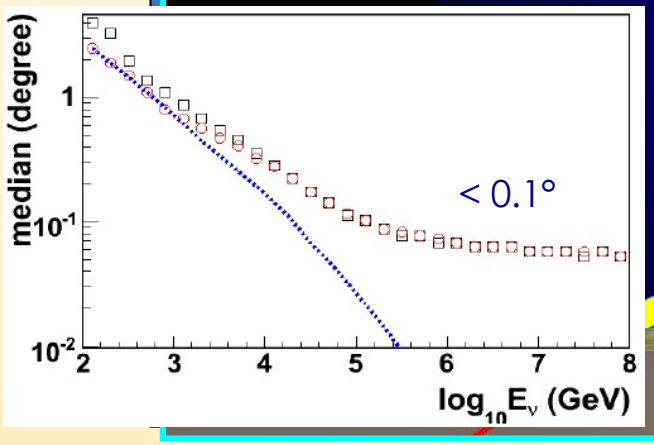


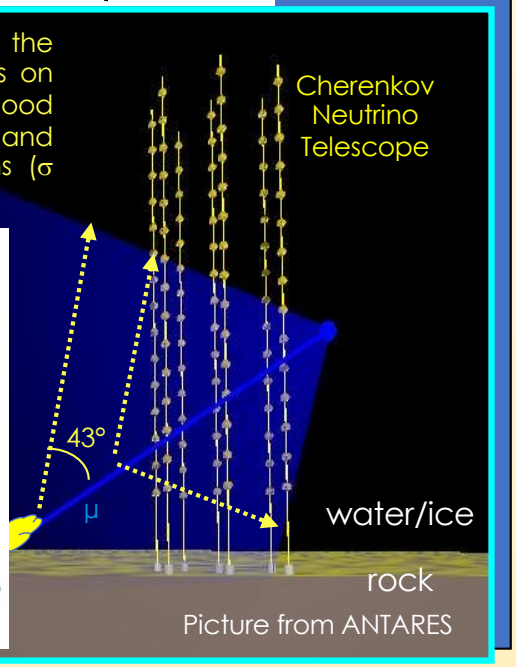
- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

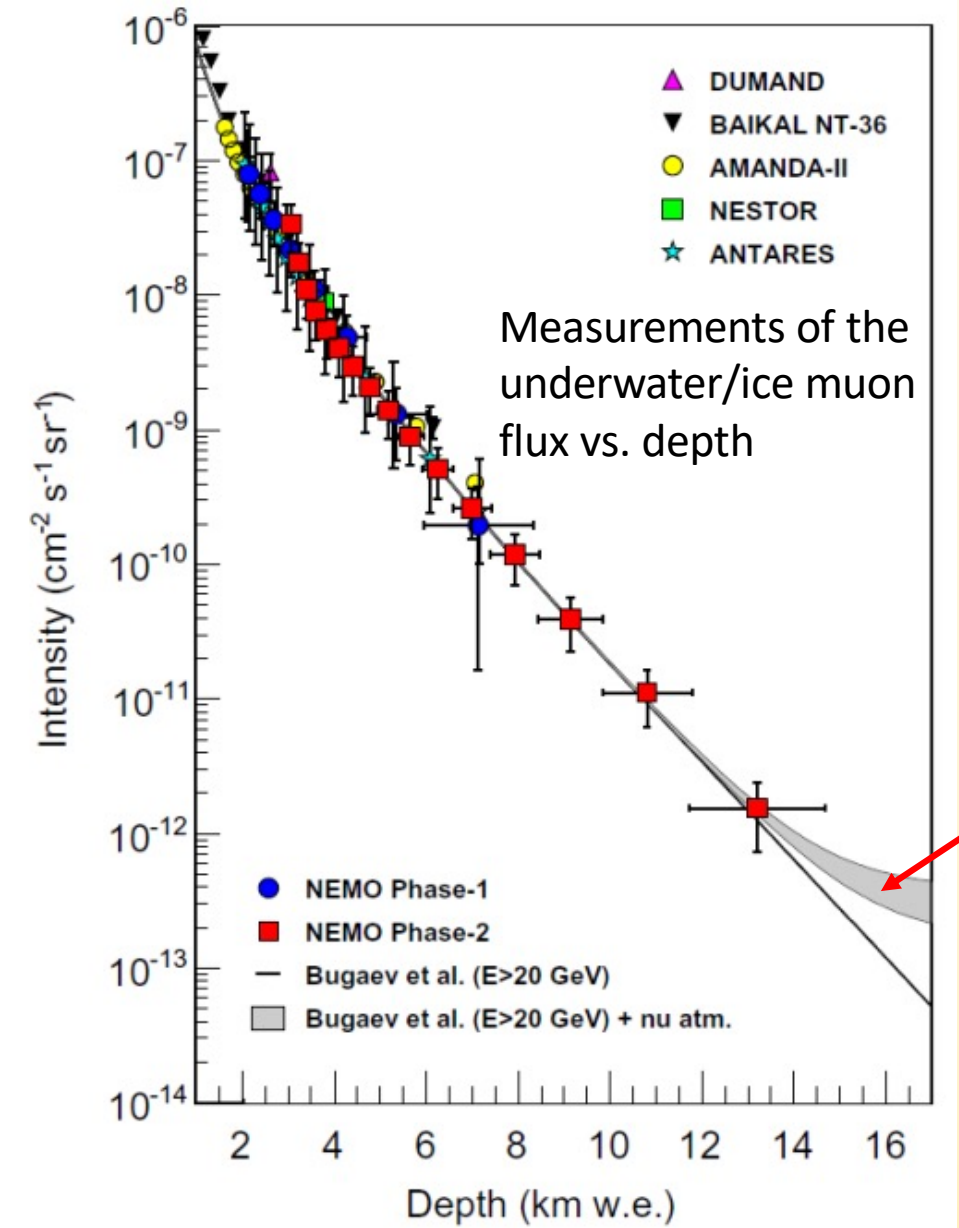
$$For\ E_\nu \geq 1TeV \quad \theta_{\mu\nu} \sim \frac{0.7°}{\sqrt{E_\nu[TeV]}}$$

μ direction reconstructed from the arrival time of Cherenkov photons on the Optical Modules: needed good measurement of PMT hits, σ(t)~1ns, and good knowledge of PMT positions (σ ~10cm)





Atmospheric muons (down-going): main background



Events with a muon measured in a detector "protected" by > 15km of "water equivalent" are, probably, events where atmospheric neutrinos interact via CC giving a muon

The ANTARES experiment

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking PMTs, axis at 45º to vertical;
- 2475 m deep.

14.5m

25 storeys, 348 m

100 m

~70 m

•40 km
•cable to
•shore

Junction Box

- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Completed 2008
Decommissioning 2022

© François Montanet

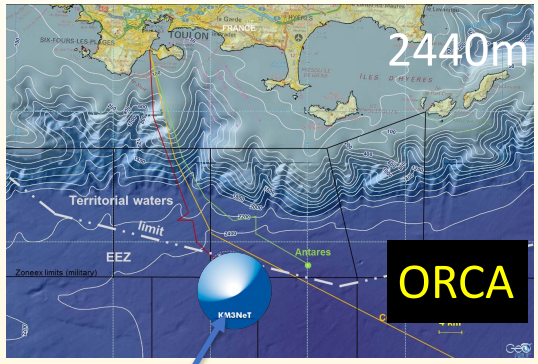
KM3NeT

Multi-site, deep-sea infrastructure

Part of ESFRI roadmap

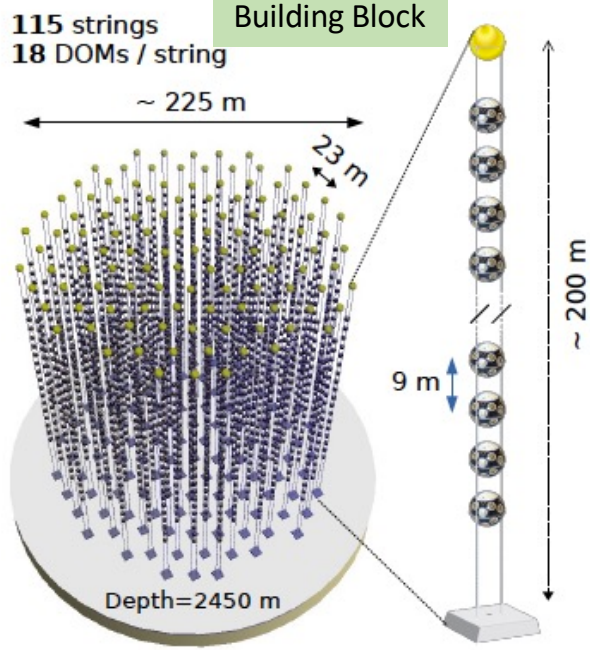
Single collaboration, Single technology

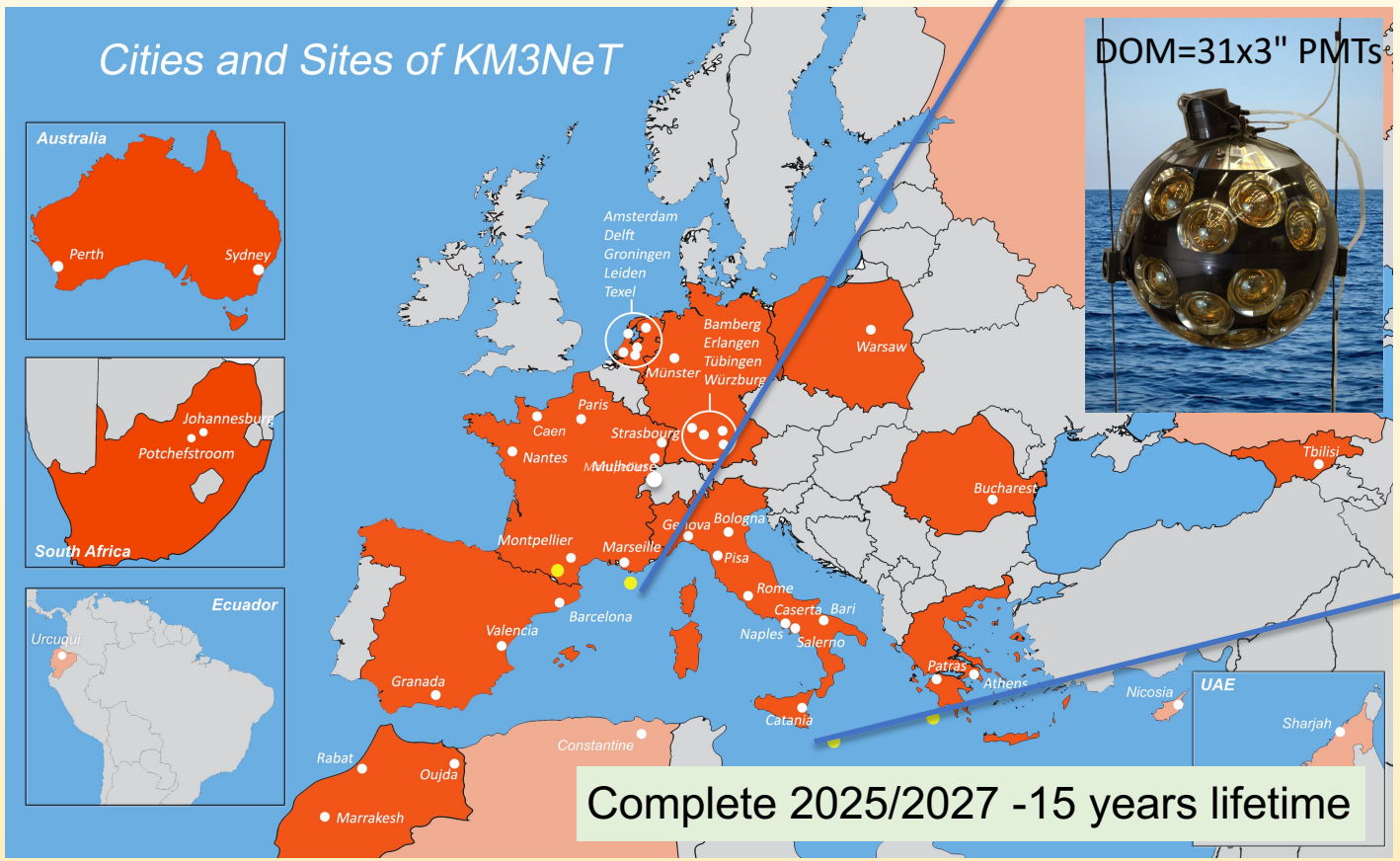
ARCA / ORCA = 2 / 1 Building Blocks



Oscillation Research with Cosmics In the Abyss

Building Block

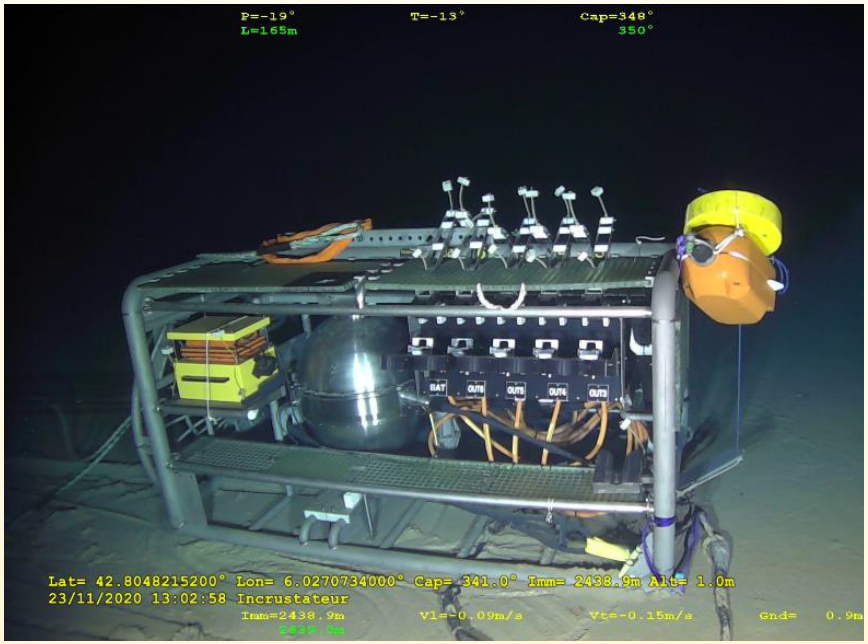


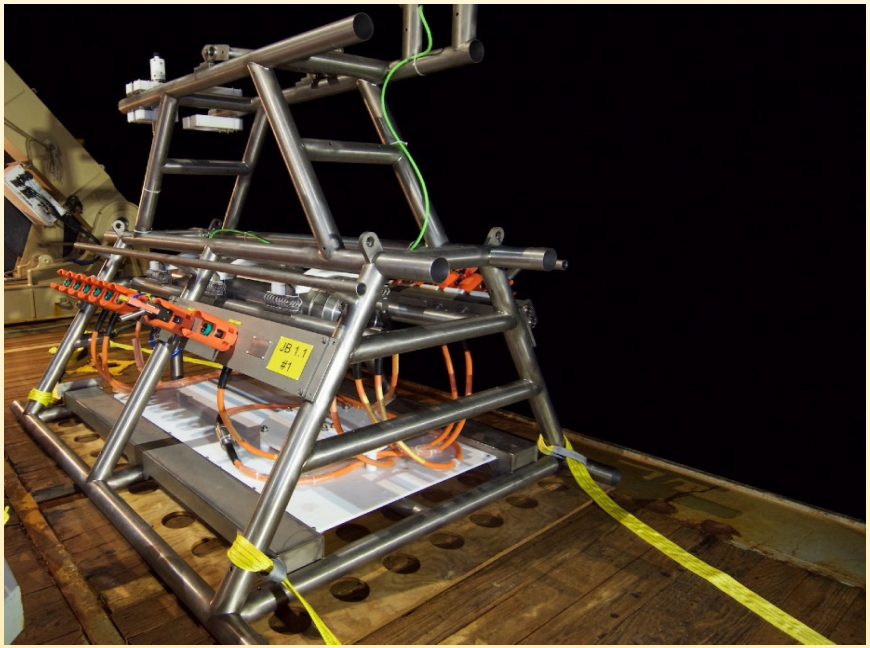


Astroparticle Research with Cosmics In the Abyss

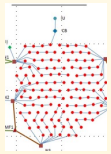
Connection nodes of european multidisciplinary seafloor & water column observatory emso

KM3NeT Seafloor infrastructure





ORCA
(France)

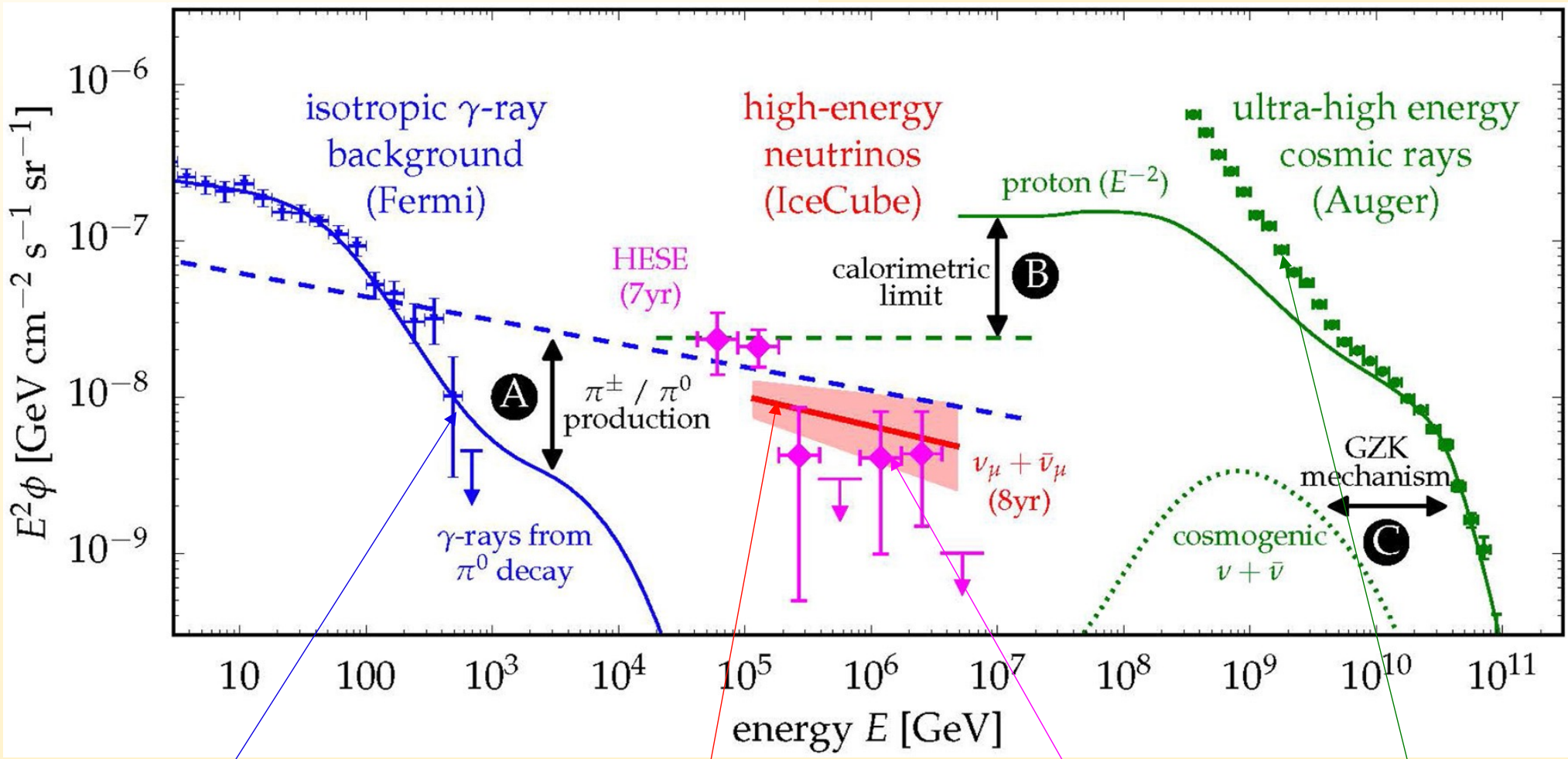


200 m

ARCA
(Italy)

The p - γ - ν connection

Halzen and Kheirandish, 2019 doi: 10.3389/fspas.2019.00032



isotropic diffuse gamma ray spectrum

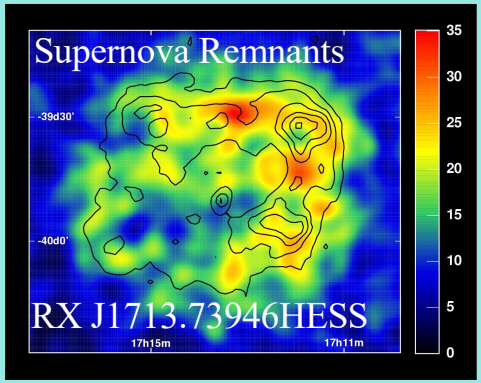
spectral flux (ϕ) of ν_μ from the 8-years upgoing track analysis

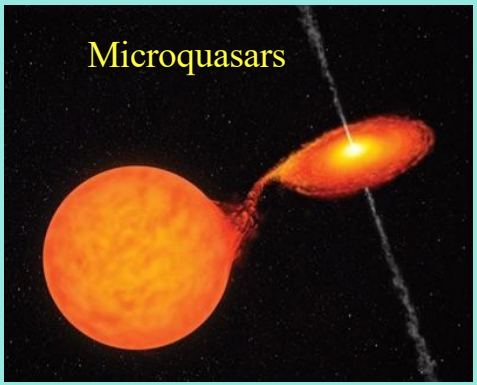
spectral ν flux from the 7-years HESE analysis

ultra-high-energy cosmic rays

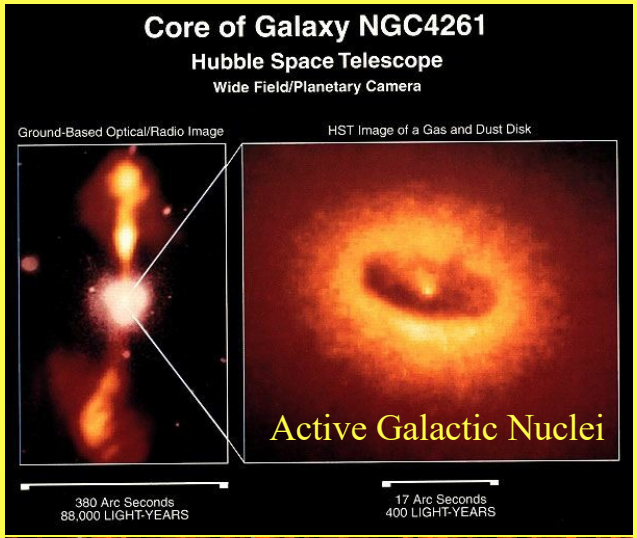
Search for "Point like" cosmic Neutrino Sources

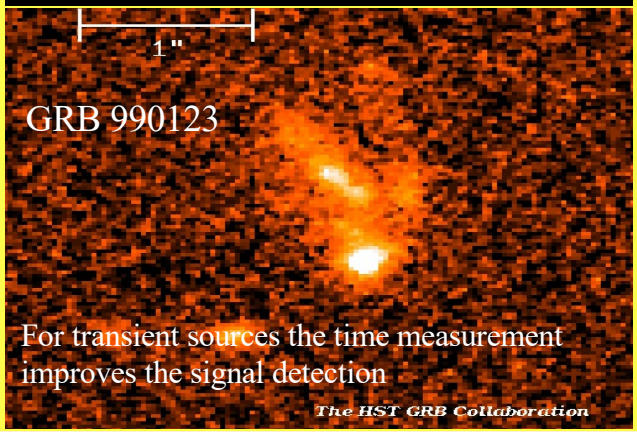
Galactic





Extragalactic





- Their identification requires a detector with accurate angular reconstruction

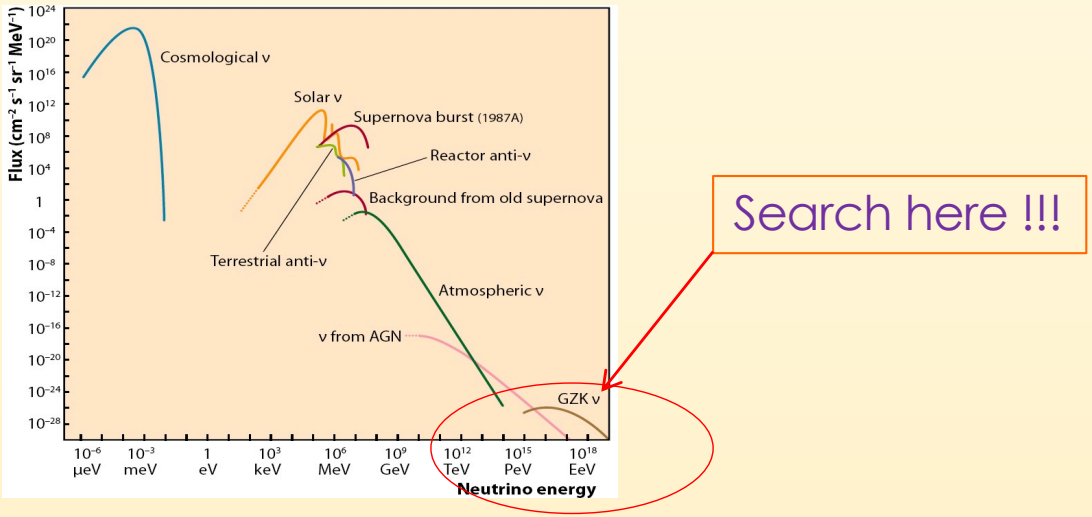
$$\sigma(\vartheta) \leq 0.5^{\circ} \text{ for } E_{\nu} \geq 1 TeV$$

Experimental signal : statistical evidence of an excess of events coming from the same direction

Search for ν from "Diffuse Cosmic Neutrino Sources"

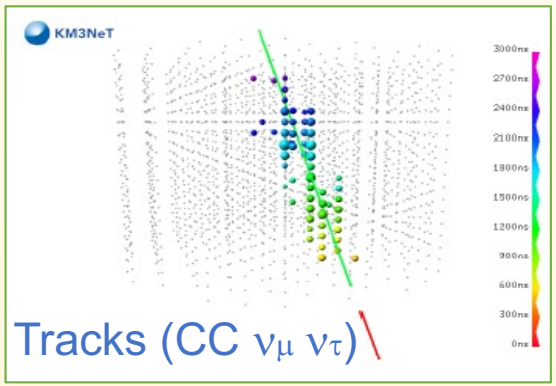
- **Unresolved AGN**
- **Neutrinos from "Z-bursts"**
- **Neutrinos from "GZK like" p-CMB interactions**
- **Neutrinos foreseen by Top-Down models**
- **….**

Their identification out of the more intense background of atmospheric neutrinos (and muons) is possible at high energies (E > TeV) and implies accurate energy reconstruction.

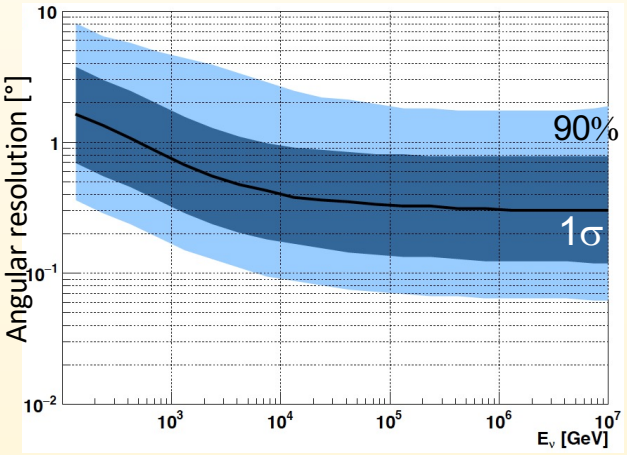


- **2013, first evidence for a diffuse flux of cosmic neutrinos: 28 contained VHE astrophysical ν events reported by IceCube**

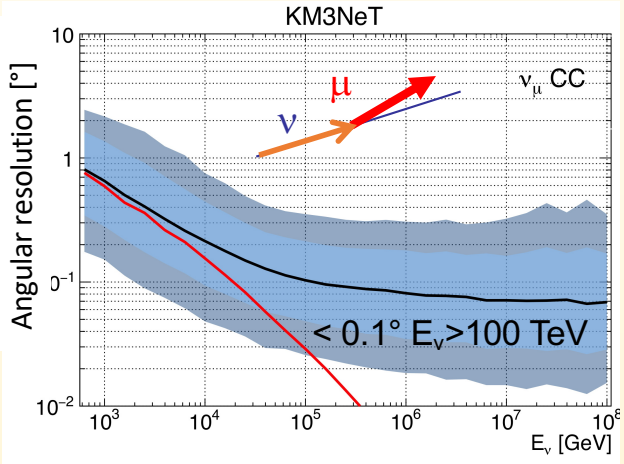
Event types & angular resolution

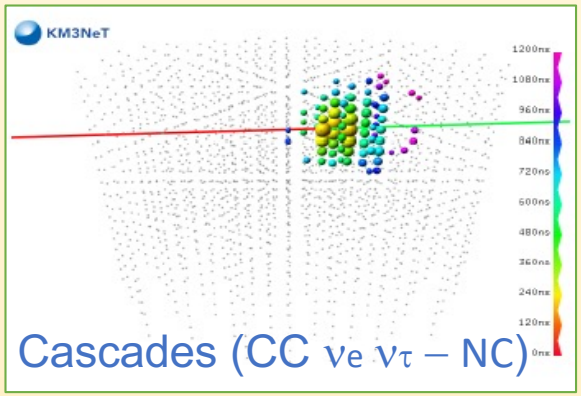


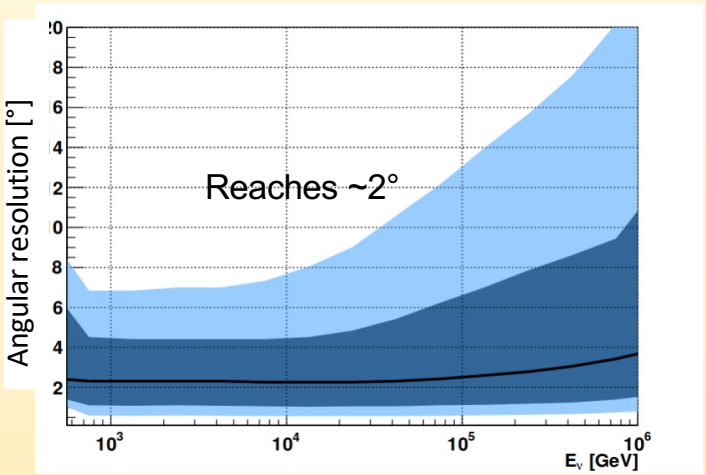
ANTARES

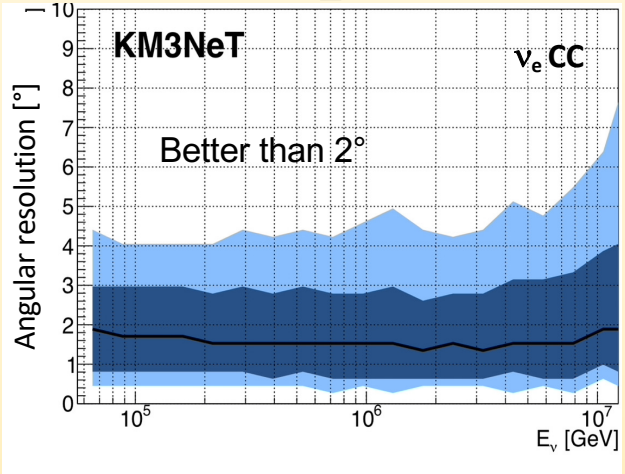


KM3NeT





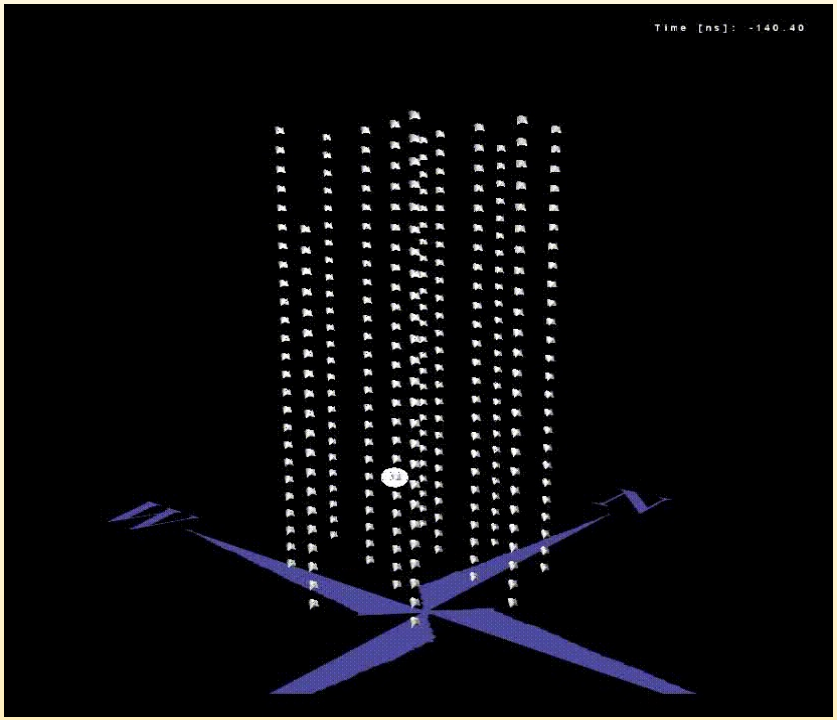




ANTARES on-line event display

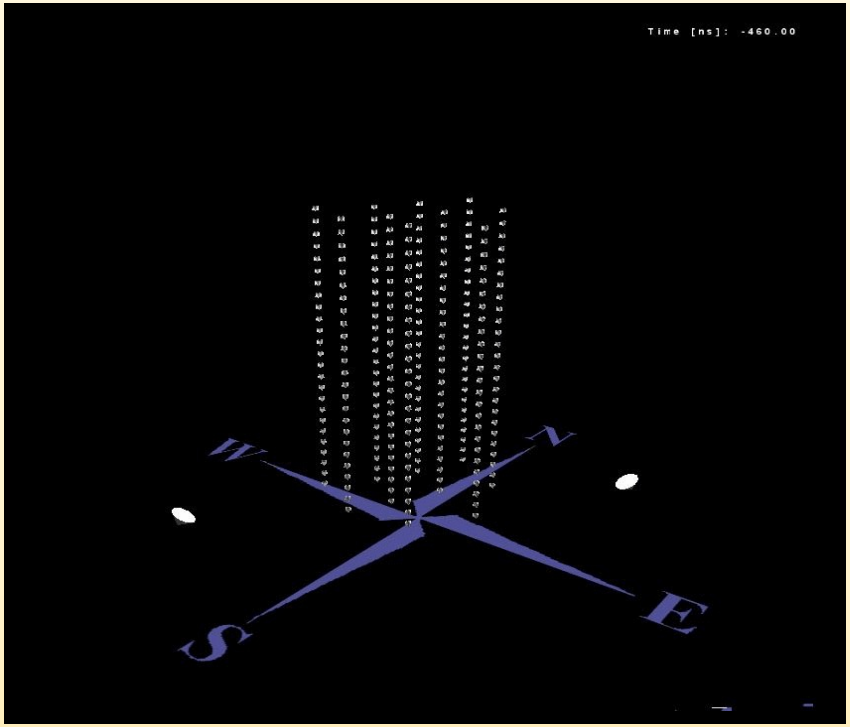
Down-going multi-μ event

Example of a reconstructed down-going muon, detected in all 12 detector lines:



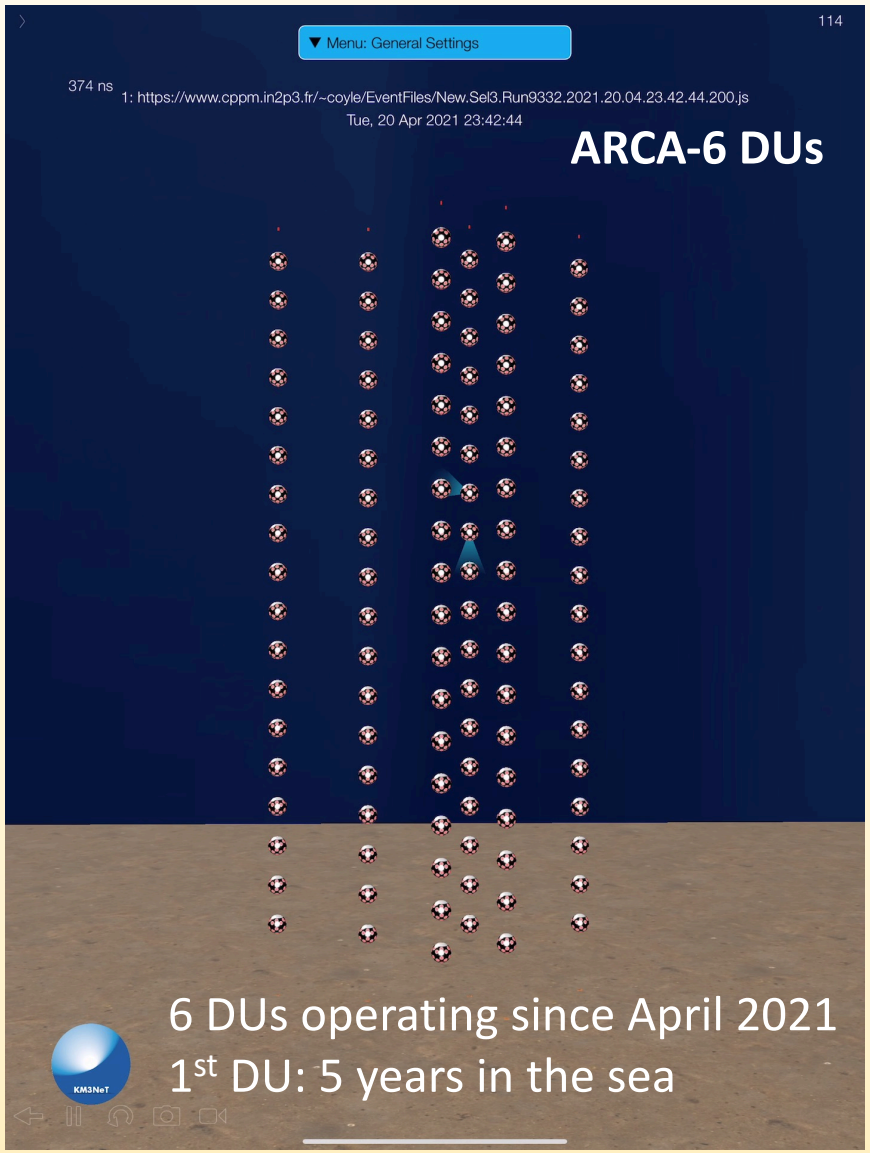
Up-going track: a neutrino candidate

Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:

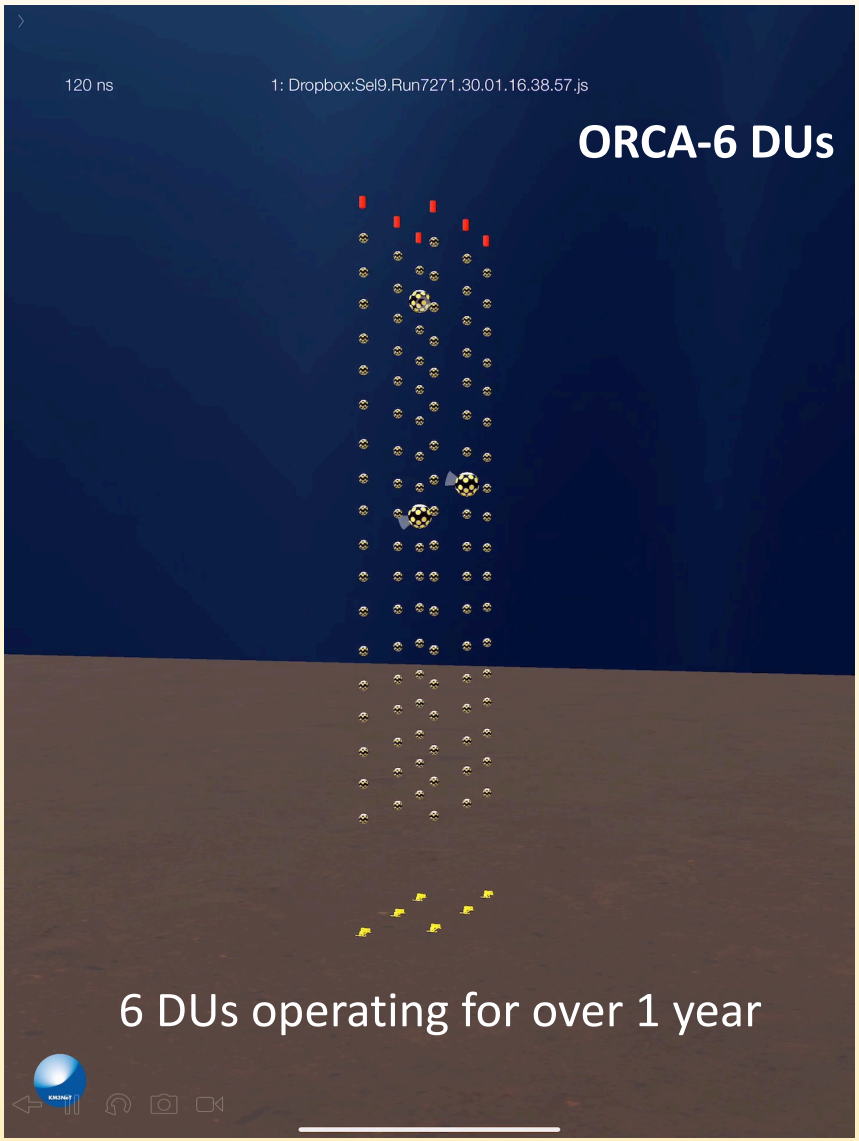


KM3NeT ARCA & ORCA in operation with 6 DUs

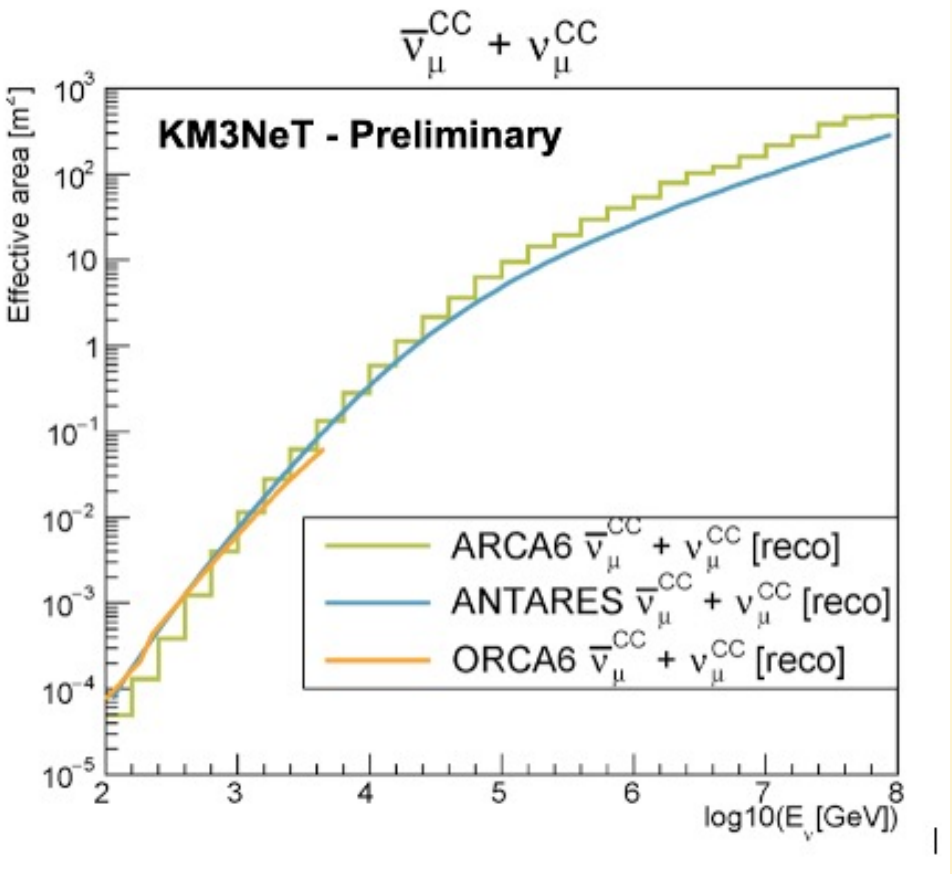
Downgoing muons from cosmic ray showers

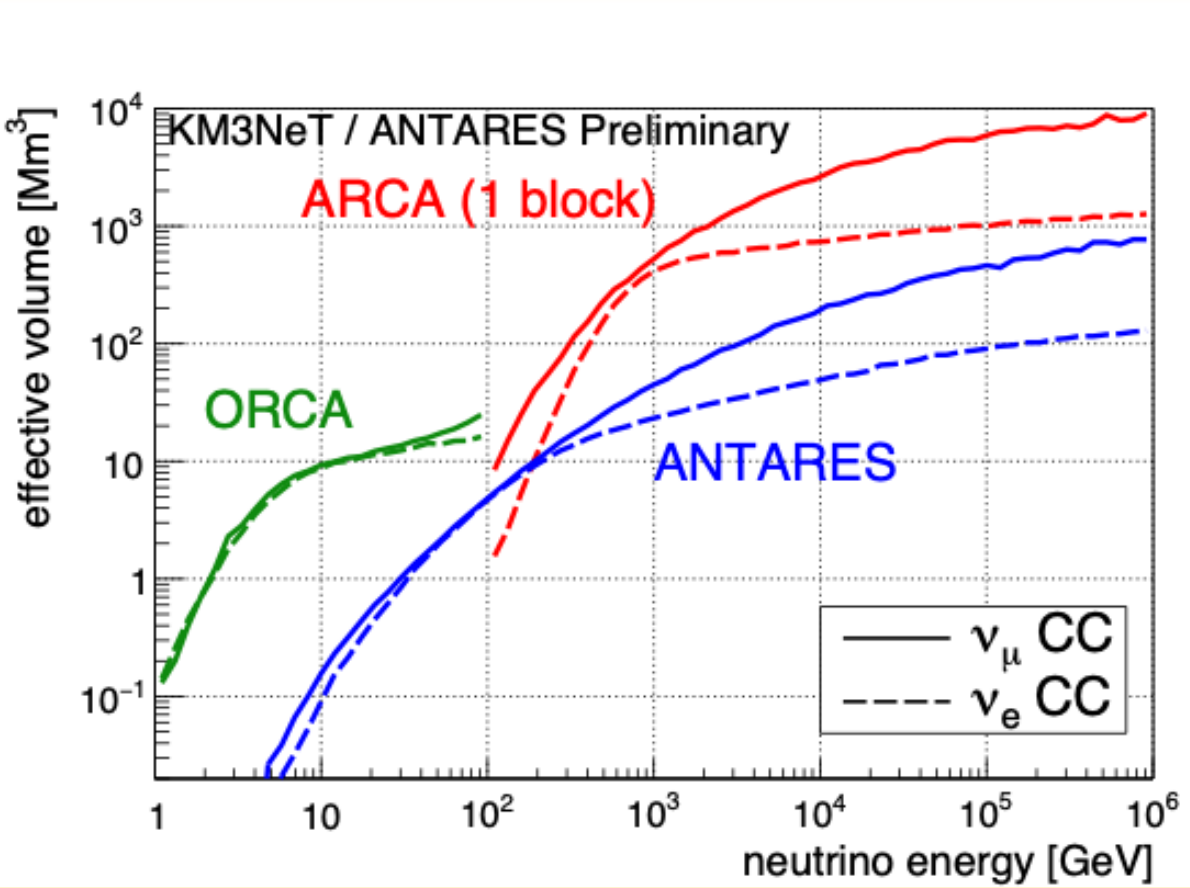


Upgoing muons from atmospheric neutrinos



KM3NeT and ANTARES effective areas





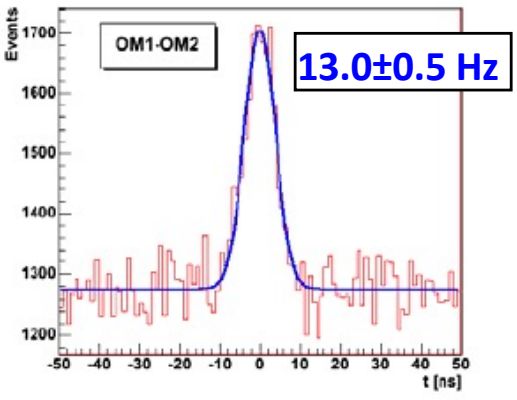
ARCA6+ORCA6 already better than ANTARES

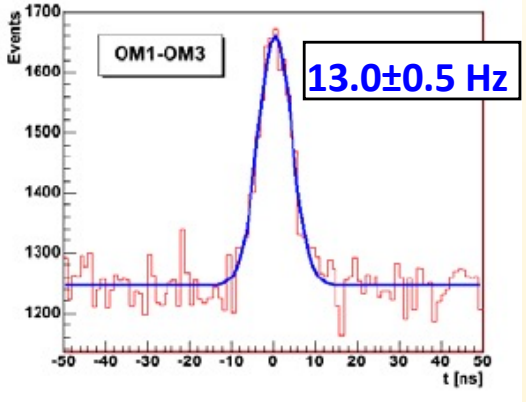
Doubling of detector in Sept 2021
(ARCA11 + ORCA13)

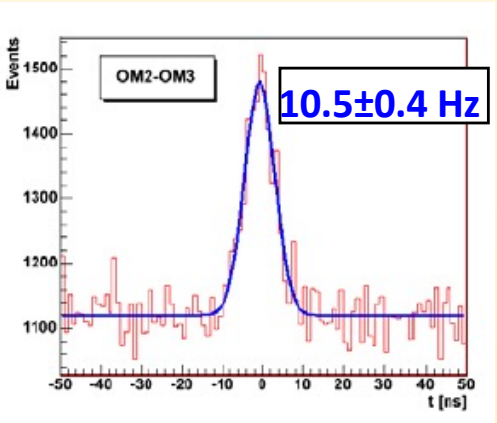
Completion of ORCA115 array in 2025
and ARCA230 in 2027

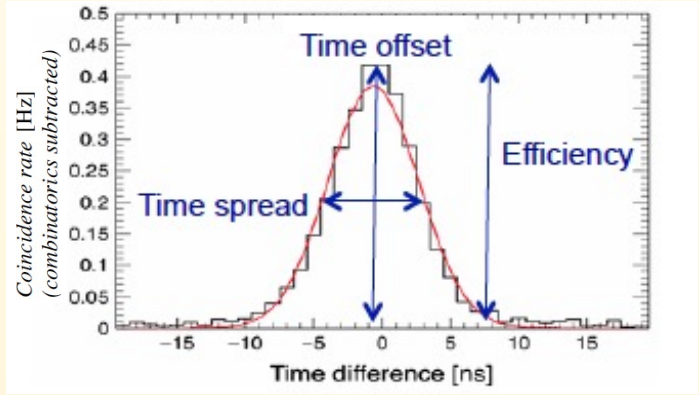
ANTARES & KM3NeT: PMTs efficiencies from ^{40}K decays

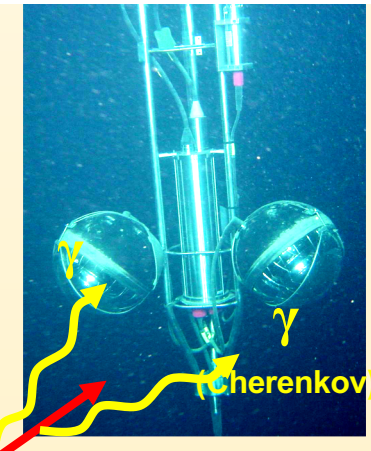
Simulation: 12 Hz ± 4 Hz (sys)

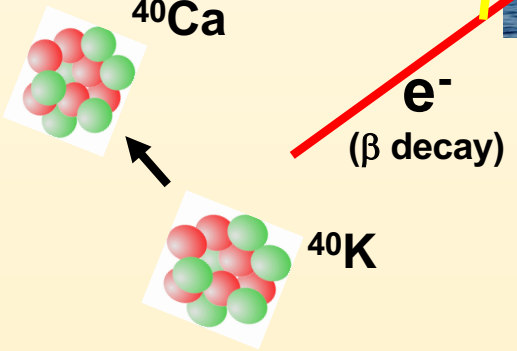


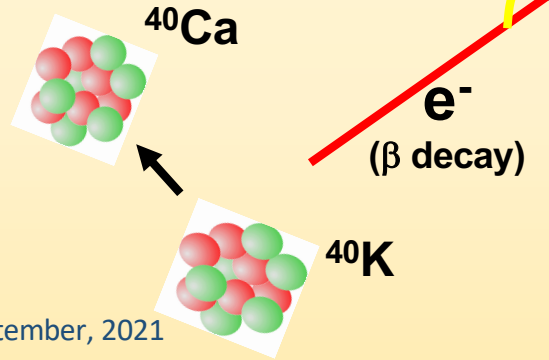


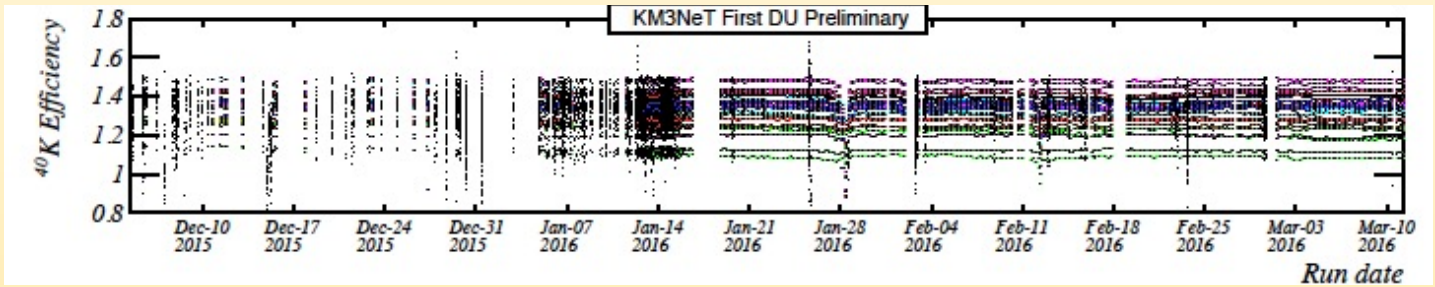








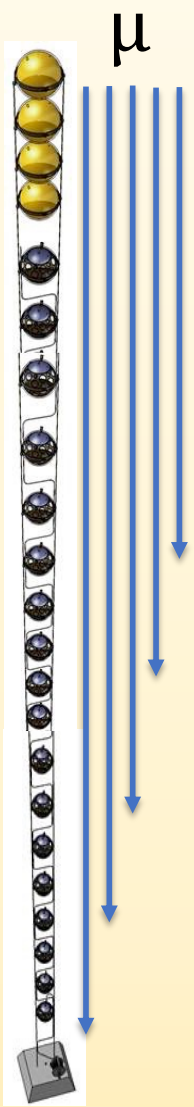


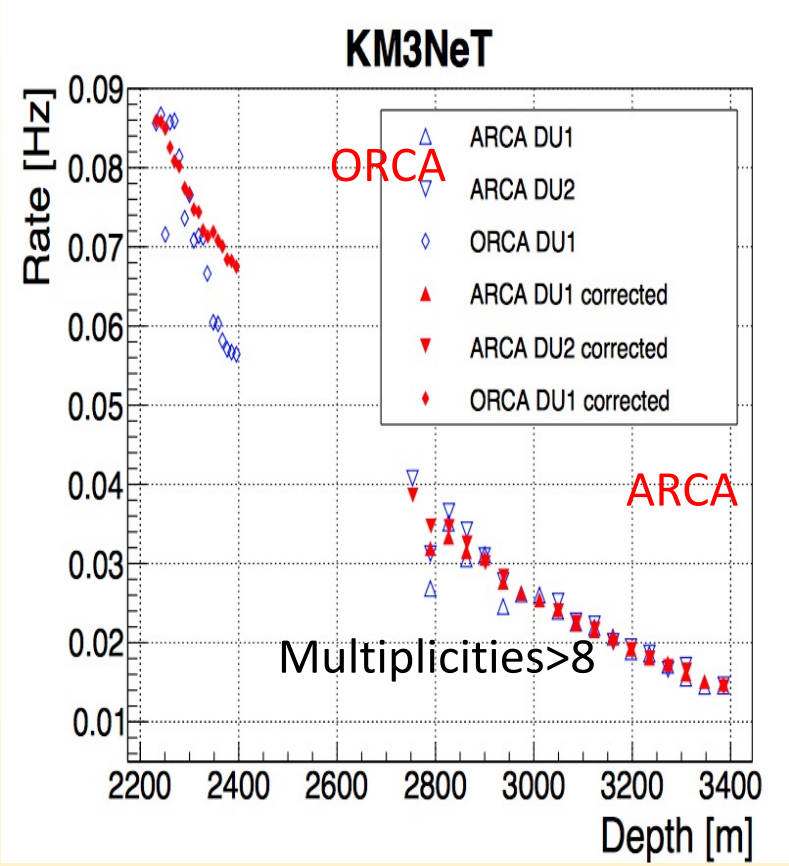


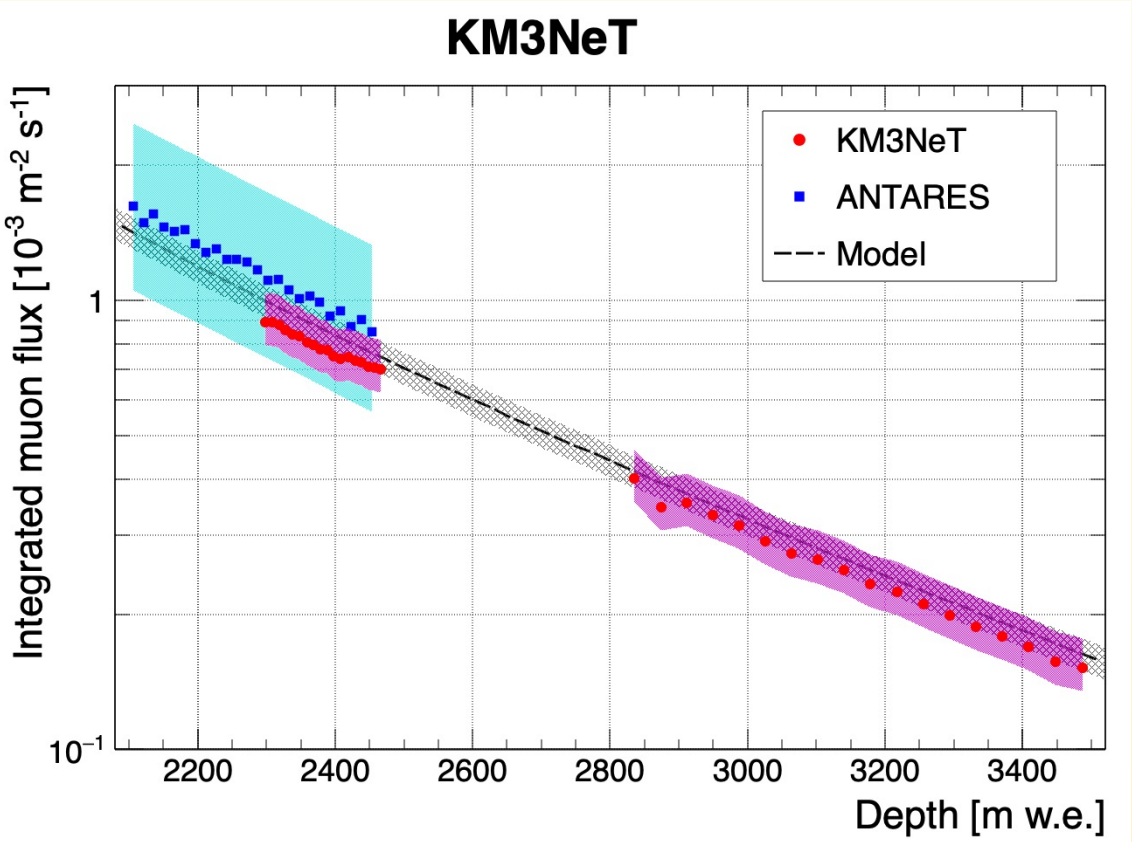
Muon depth dependence from ARCA & ORCA

2 DUs of ARCA (23/12/2016-2/3/2017) &
1 DU of ORCA (9/11/2017-13/12/2017)

Muon flux as function of depth compared to Bugaev model (Bugaev et al, Phys. Rev. D 58 1998 054001)



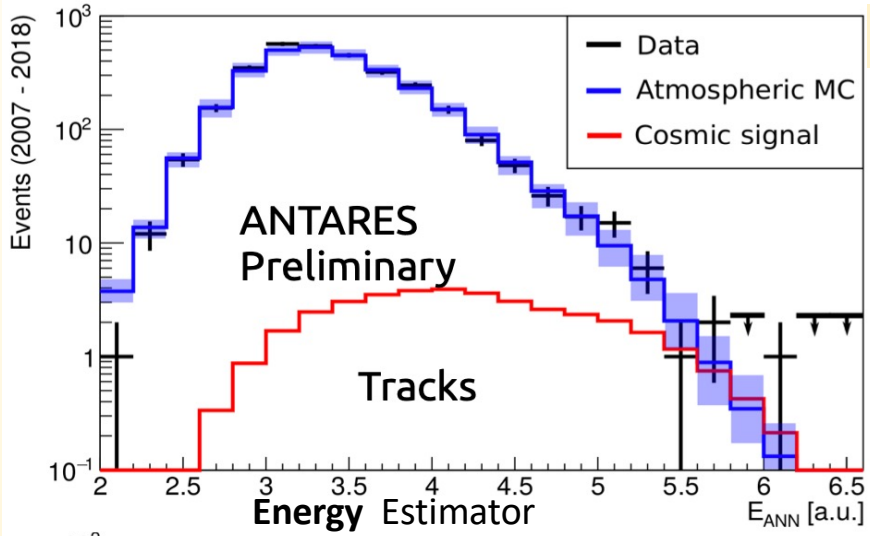


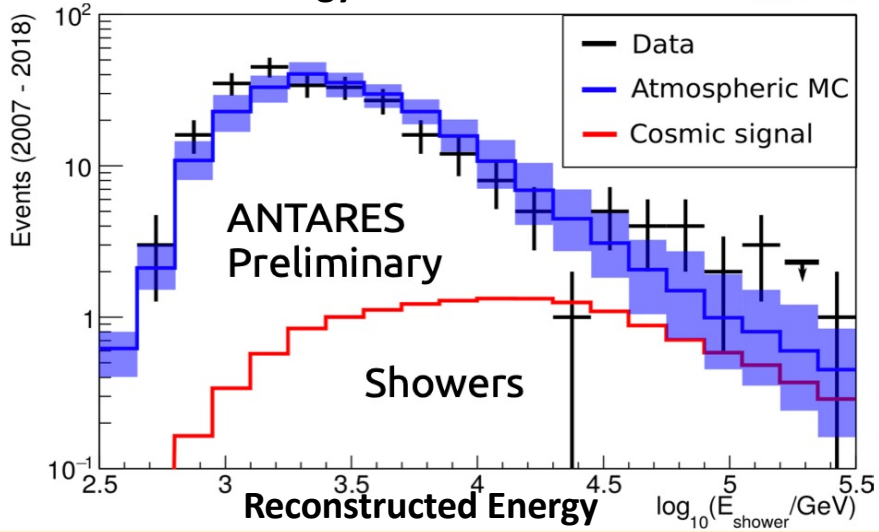


https://arxiv.org/pdf/1906.02704.pdf

PMT detection efficiency verified

ANTARES recent results on the search for diffuse ν flux

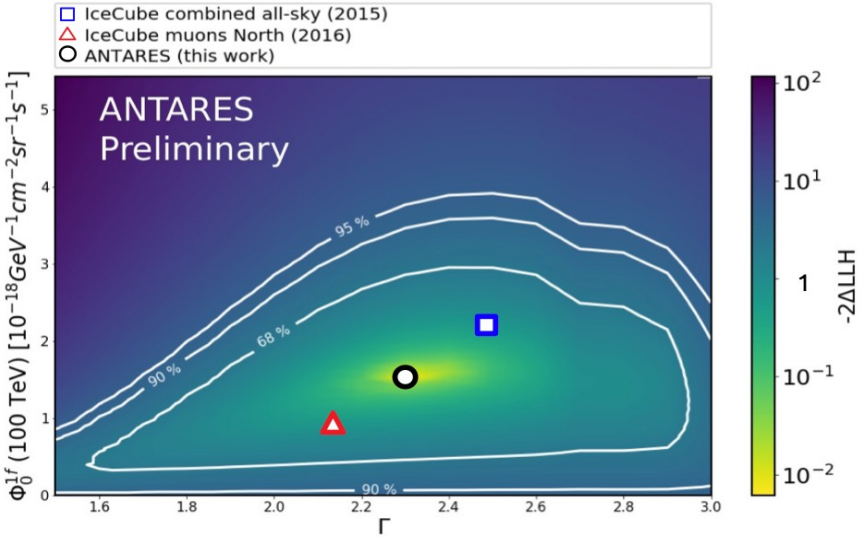




ANTARES 2007-2018 (3330 days) PoS (ICRC2019) 891

Overall → data: 50 events
(**27** tracks + **23** showers)
Overall → bkg MC: 36.1 ± 8.7 (stat.+syst.)
(**19.9** tracks and **16.2** showers)

1.8σ excess
0-cosmic excluded c.l. >90%



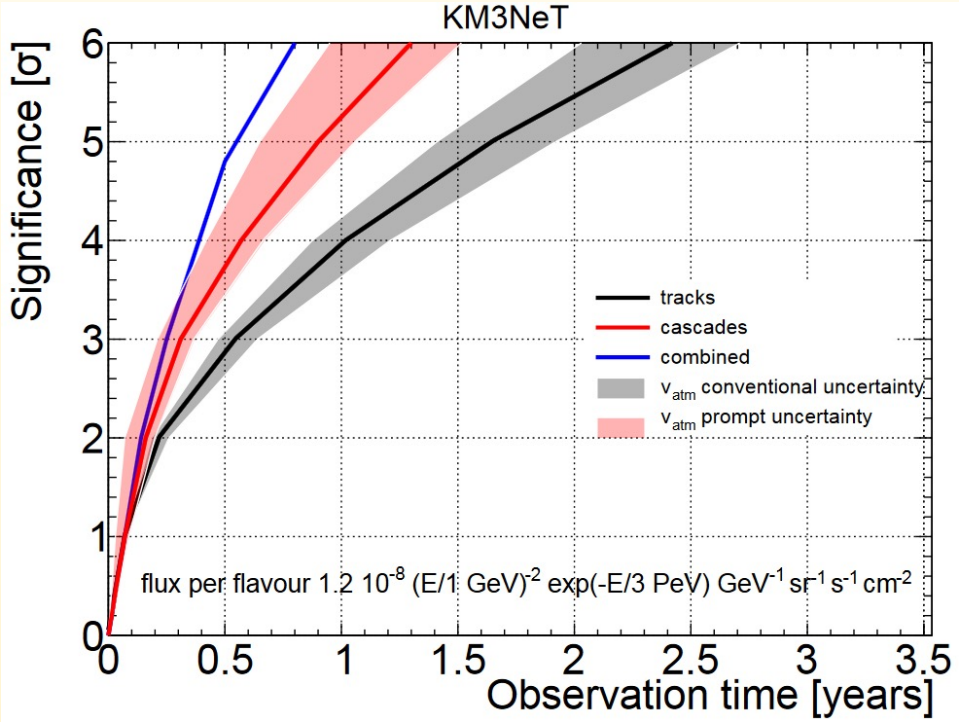
Combined tracks & showers likelihood fitting:

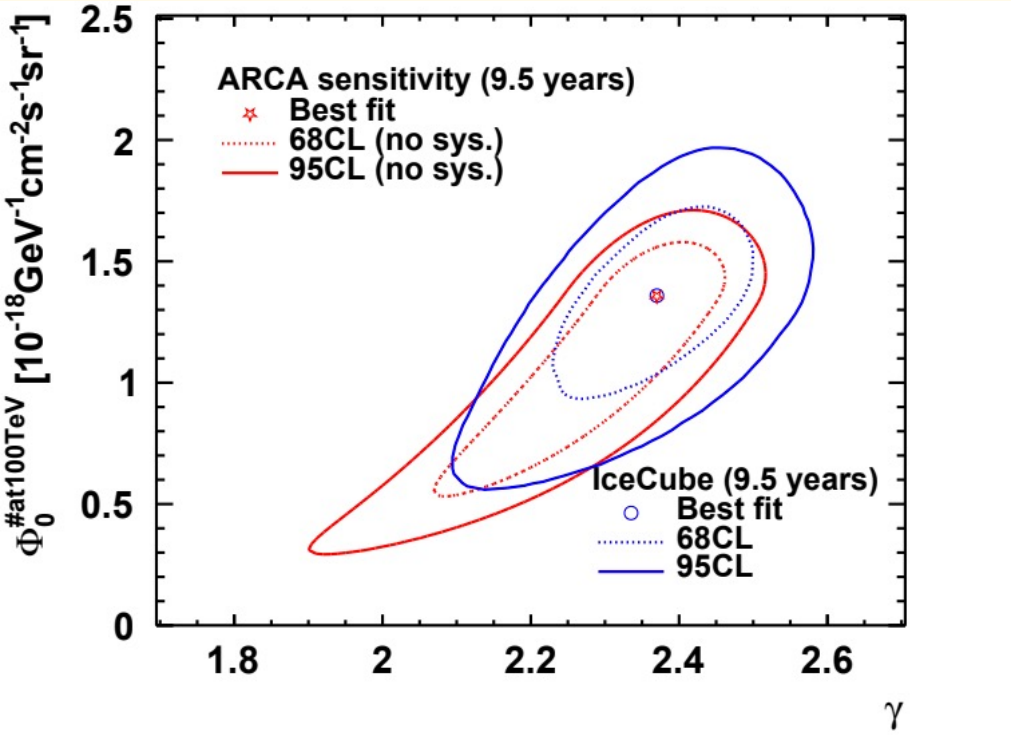
Atmospheric: $\Phi_{atm} = 1.25 \cdot (\text{Honda} + \text{Enberg})$

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

$\Gamma = 2.3 \pm 0.4$

KM3NeT and diffuse cosmic ν flux measurement



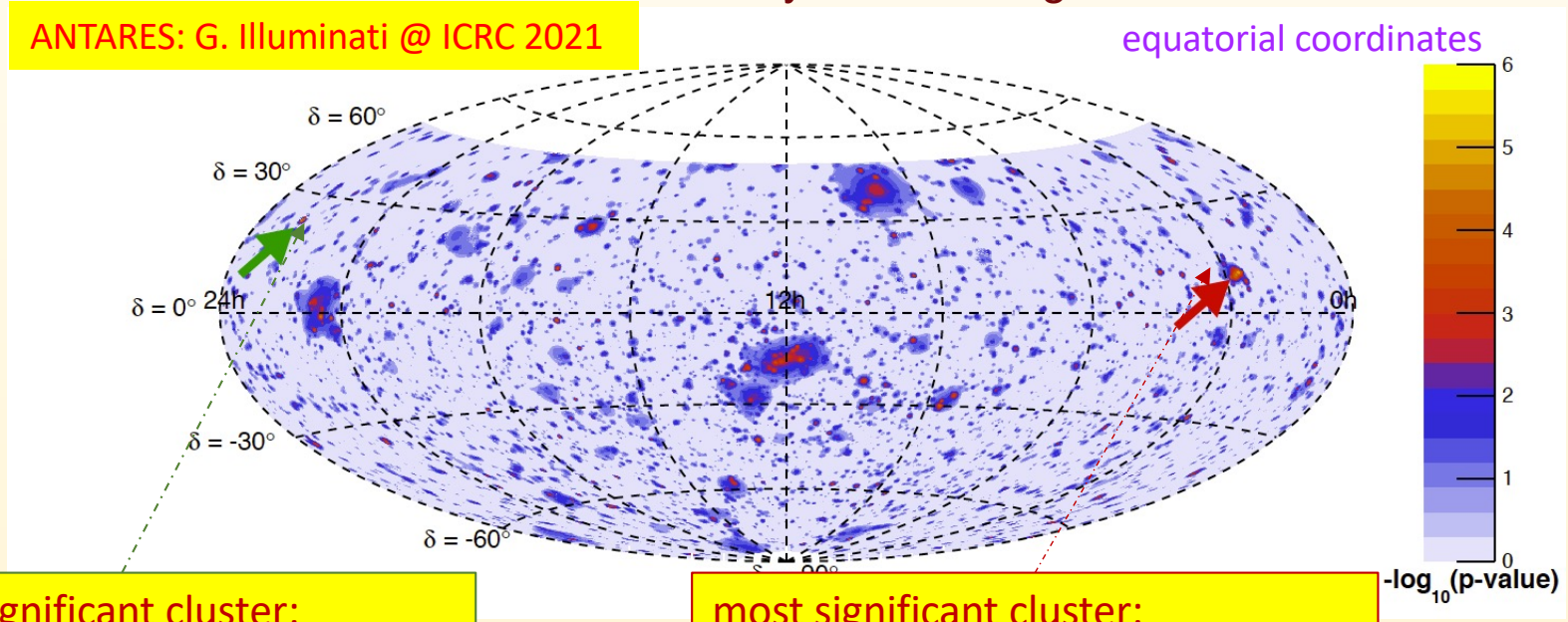


5σ in ~ 0.5 year for the full detector (230 DUs)
5σ ~ 1 year for one block detector (115 DUs)

ANTARES results: "full sky search" of ν sources

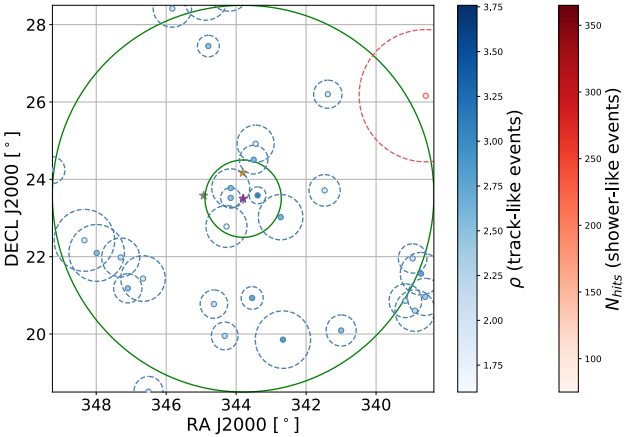
The visible sky of ANTARES divided on a $1^0 \times 1^0$ (r.a x decl.) boxes.
Maximum Likelihood analysis searching for clusters

ANTARES: G. Illuminati @ ICRC 2021



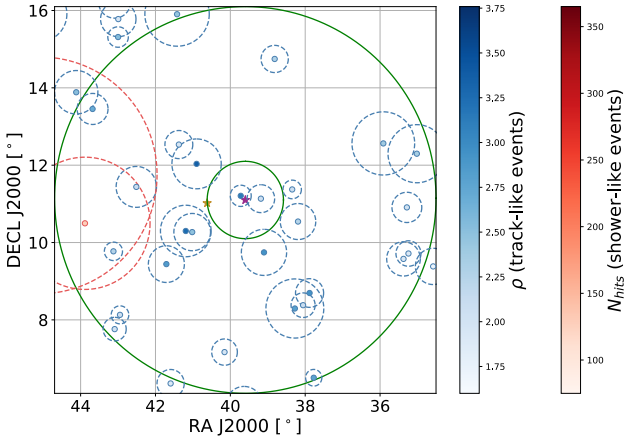
2nd most significant cluster:
RA=343.8° δ=+23.5°, pre trial: 3.8 σ
Close to blazar MG3 J225517+2409

most significant cluster:
δ = 11.1^0, r.a. = 39.6^0, pre-trial 4.3σ
Within 1 degree of J0242+1101

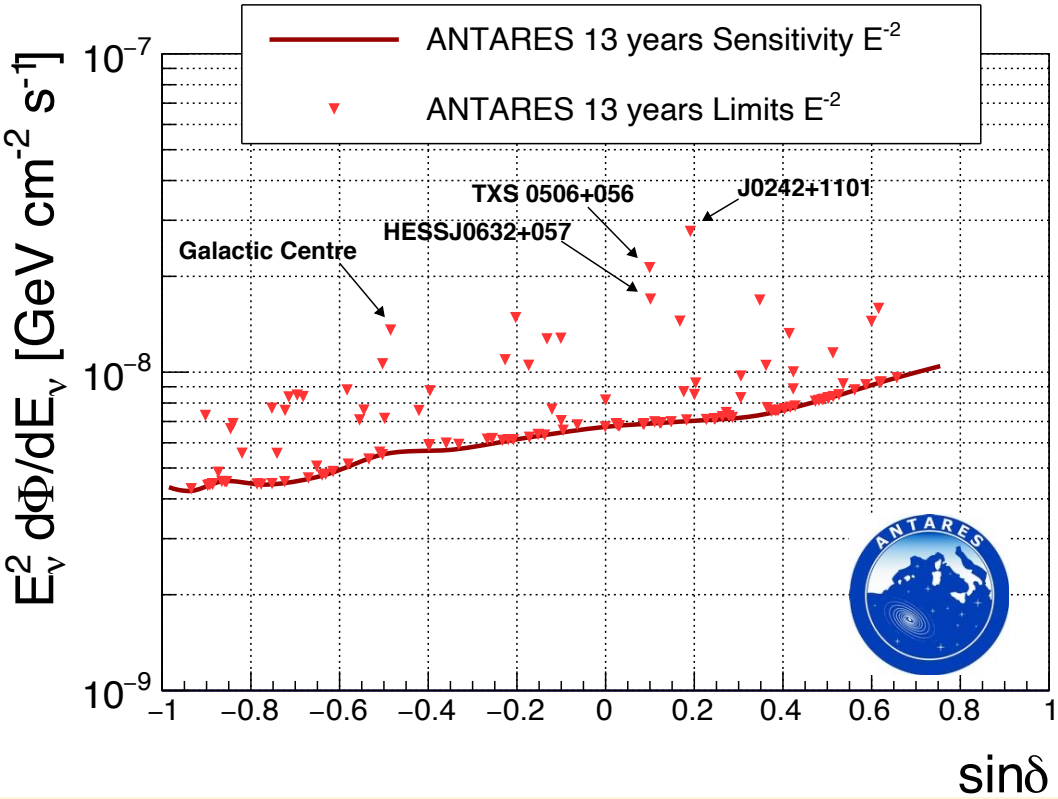


ANTARES 13 years (3845 days livetime):
- 10162 track
- 225 showers

ANTARES: J. Aublin @ ICRC 2021

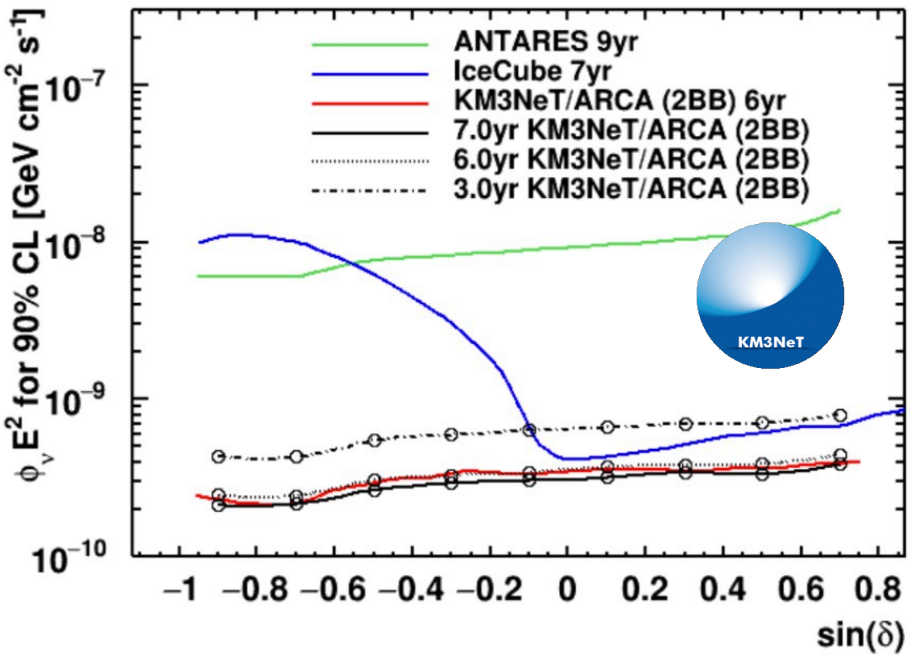


ANTARES results: searching for ν events from candidate sources



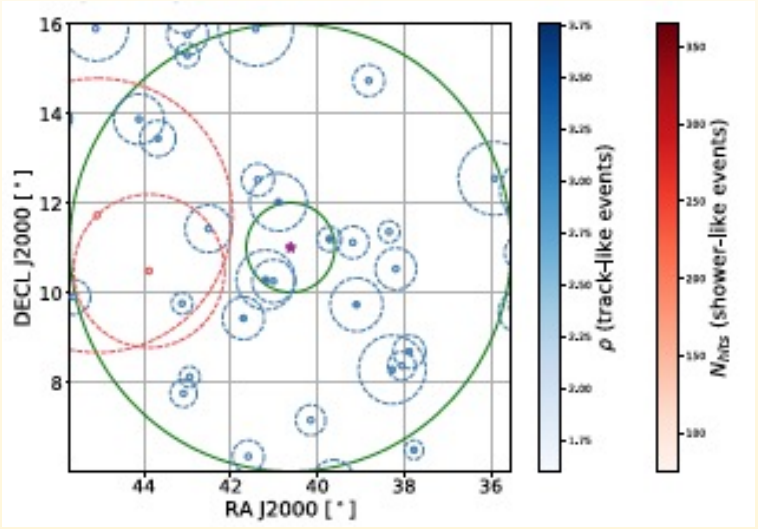
ANTARES: G. Illuminati @ ICRC 2021

… and KM3NeT sensitivity



ANTARES results: searching for ν events from candidate sources

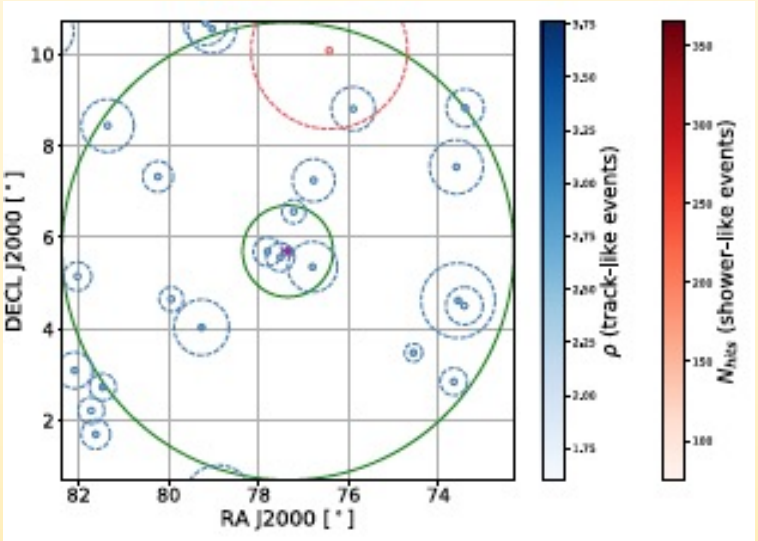
1st: J0242+1101



ANTARES: G. Illuminati @ ICRC 2021

Pre-trial: 3.8σ (1-sided), 4.0σ (2-sided)
Post-trial: 2.4σ (1-sided), 2.6σ (2-sided)

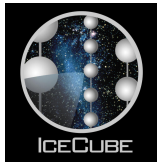
2nd: TXS 0506+056

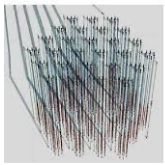
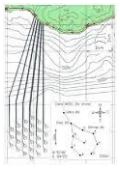


4 events within 1°
Pre-trial: 2.9σ (1-sided), 3.1σ (2-sided)

Neutrino Telescopes in a Multi-Messenger Search Programme

Neutrinos



IceCube – BAIKAL/GVD

The case for ANTARES/KM3NeT

Flaring Sources

(ν emission from γ-flaring blazars/μQuasars)

GeV-TeV g Rays
Fermi, HESS, HAWC

blazars: APP 36 (2012) 304;
μQuasars: JHEAp, 3-4 (2014) 9-7

VIRGO - LIGO

common working group (GWHEN)
S. Adrián-Martínez et al.,
JCAP 06 (2013) 008

TAToO

(Telescopes – ANTARES Target of Opportunity)

Optical follow-up of neutrino alerts for transient source search (GRBs, SNae).
Analysis in progress!

Radio, Optical, X-ray Telescopes

TAROT, ROSTE, VLBI, MWA,
MASTER, Swift,Integral, ..

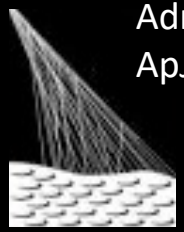
Ageron *et al.*, *Astrop.Phys* 35 (2012) 530-536

GCN (Gamma-ray Coordination Network)

GCN

A&A 559, A9 (2013),
JCAP 1303 (2013) 006

AUGER, T.A.



Adrian-Martinez et al.,
ApJ 774 (2013) 008

Multi-Messenger analysis: searching for ν stacking sources

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

1.6 σ

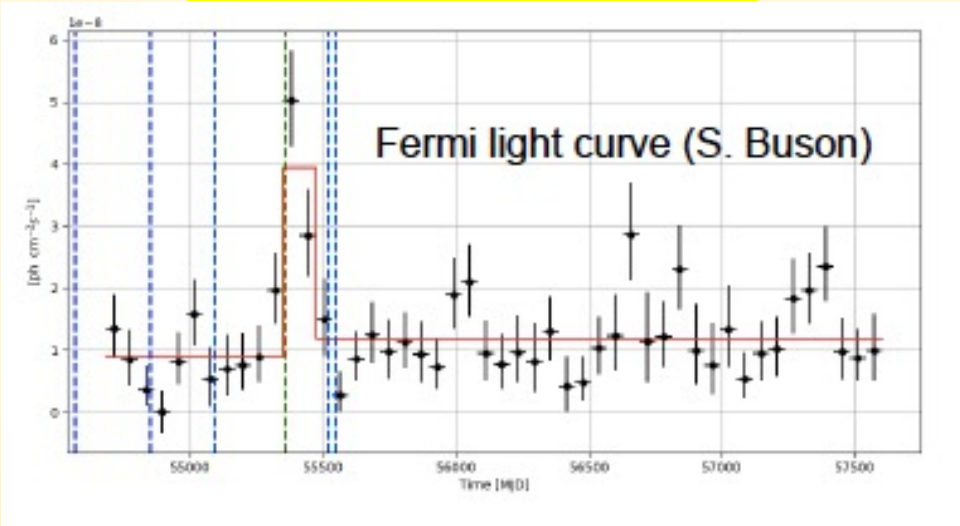
ANTARES: J. Aublin @ ICRC 2021

Dominant source within Fermi 3LAC BLLacs:
Blazar MG3 J225517+2409

RA = 343.81°, δ = +24.17°:
almost coincident with all-sky hotspot!
Pre-trial p-value: 1.4 x 10^{-4} (3.8σ)

Source flare (~ 4 months) in Fermi 3FGL γ-ray light curve

One IC high-energy through-going track (ID#3)
during the flare (July 2010)



Time-dependent combined likelihood analysis (ANTARES+IC):

Continuous emission: p = 2 10^{-7} (5.2σ pre trial)

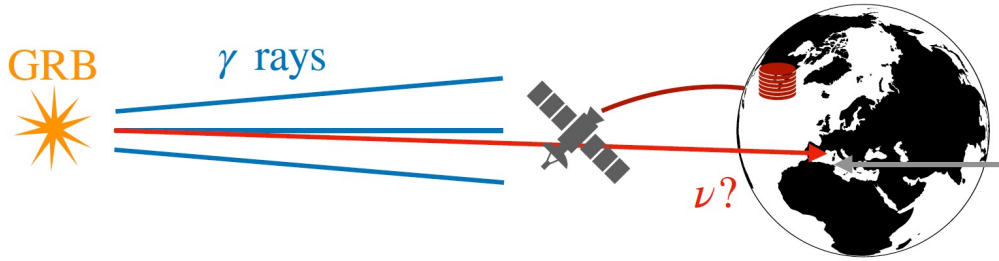
Transient emission: p = 5 10^{-4} (3.5σ pre trial)

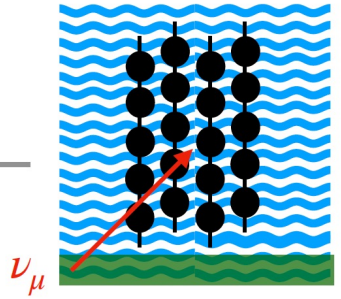
ANTARES Multi-messenger program

search for ν_μ by stacking long GRB sources (1)

GRB searches with ANTARES

ANTARES: A. Zegarelli @ ICRC 2021

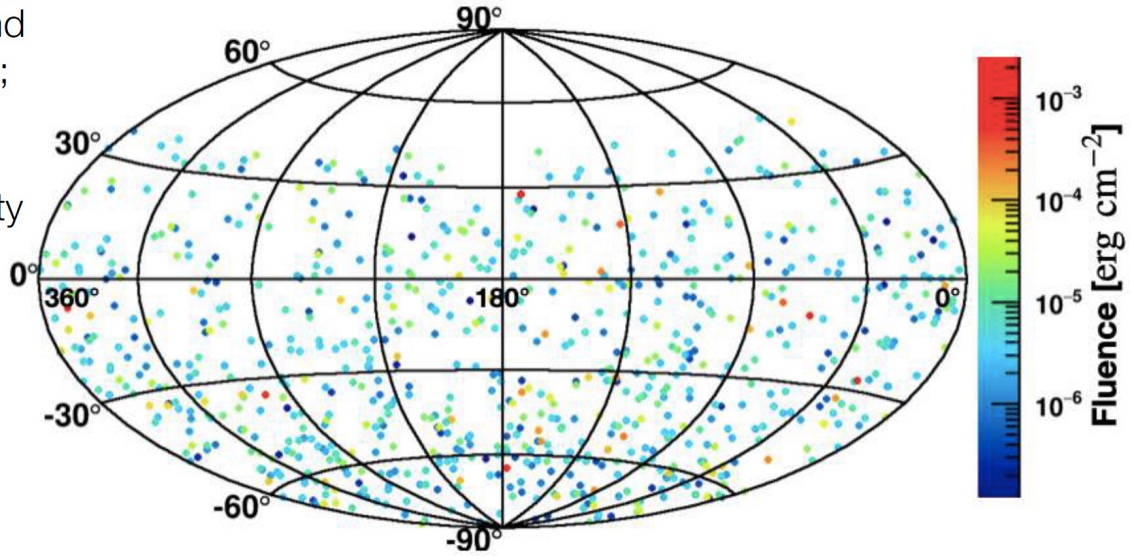




10 years of ANTARES data

- ★ **Long bursts** in **2007-2017** from Fermi (GBM + LAT), Swift (BAT + XRT + UVOT) catalogs and Konus-Wind GCN (https://gcn.gsfc.nasa.gov/gcn3_archive.html);
- ★ Spectrum is measured;
- ★ T90 (~ duration) is measured;
- ★ Position is measured and satellite angular uncertainty is less than 10 degrees;
- ★ One among fluence and redshift is measured;
- ★ **Below ANTARES horizon at trigger time**;
- ★ ANTARES in Physics run;
- ★ GRBs fully contained is a single ANTARES run.

784 GRBs



ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

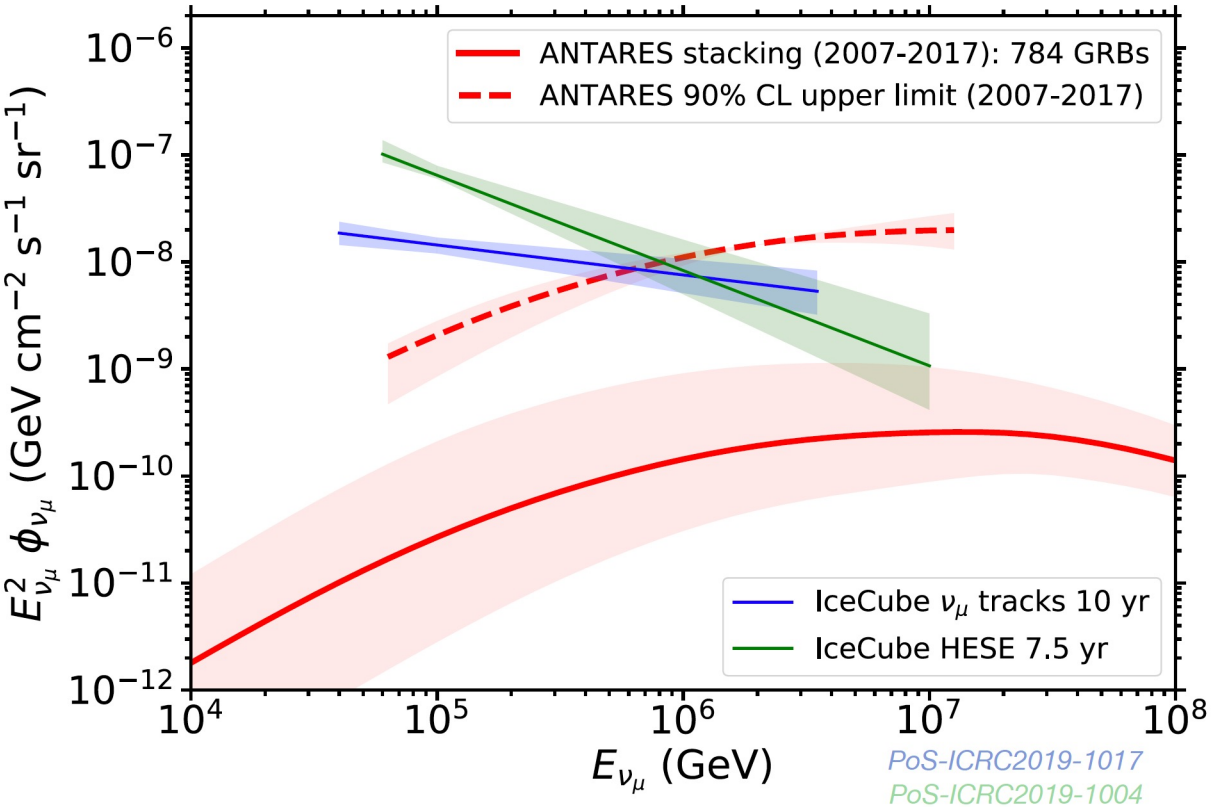
ANTARES Multi-messenger program

search for ν_μ by stacking long GRB sources (2)

Results: constrain to HE diffuse neutrino flux

ANTARES: A. Zegarelli @ ICRC 2021

- For a sample size of 784 GRBs the level of systematic error around the 90% C.L. upper limits is of the order of $^{+30}_{-70}$ %
- **GRBs are not the main contributors to the observed flux below ~ 1PeV,** within the NeuCosmA model framework with benchmark baryonic loading, $f_p = 10$
- **In the energy region where ANTARES is most sensitive (below 100 TeV), GRBs do not contribute by more than 10%**



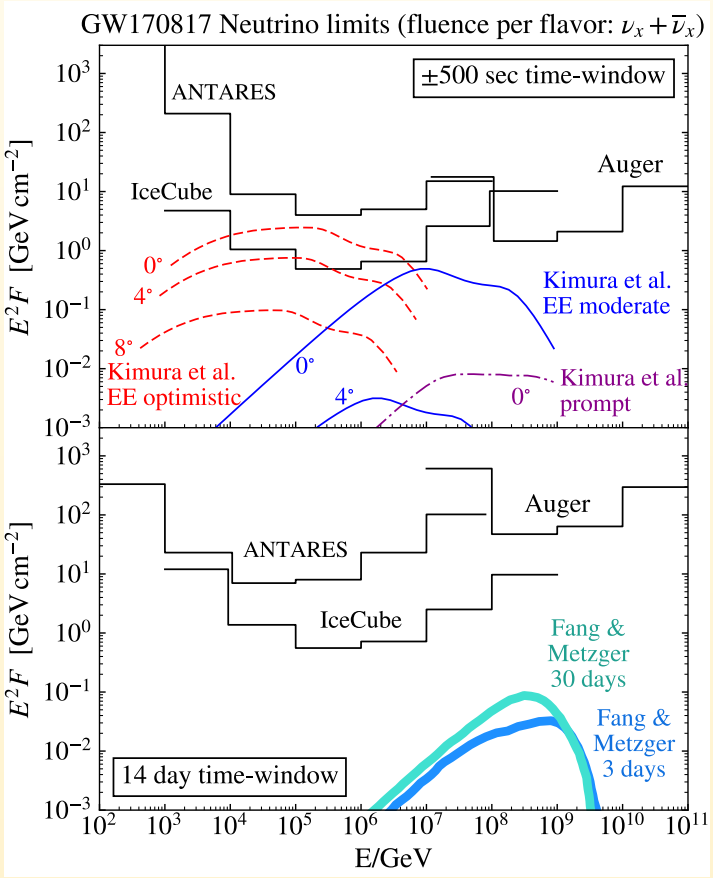
PoS-ICRC2019-1017
PoS-ICRC2019-1004

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

A joint ANTARES/IceCube/LigoSC/Virgo/Auger analysis

performed as "Neutrino follow-up" of GW170817

- **No neutrinos** directionally coincident with the source were **detected within ±500 s** around the merger time**.**
- Additionally, **no MeV neutrino burst signal was detected (in IceCube)** ***coincident with the merger*****.**
- In **Pierre Auger Observatory no** inclined showers passing the Earth-skimming selection (**neutrino candidates**) **were found in the time window ±500 s** around the trigger time of GW170817**.**
- **No neutrino found in an extended search in the direction within the 14-day period following the merger.**
- **GRB170817A's** observed **prompt gamma-ray emission**, as well as Fermi-GBM's luminosity constraints for extended gamma-ray emission, are **significantly below typical values for observed short GRBs**. One possible explanation for this is the **off-axis observation of the GRB**.

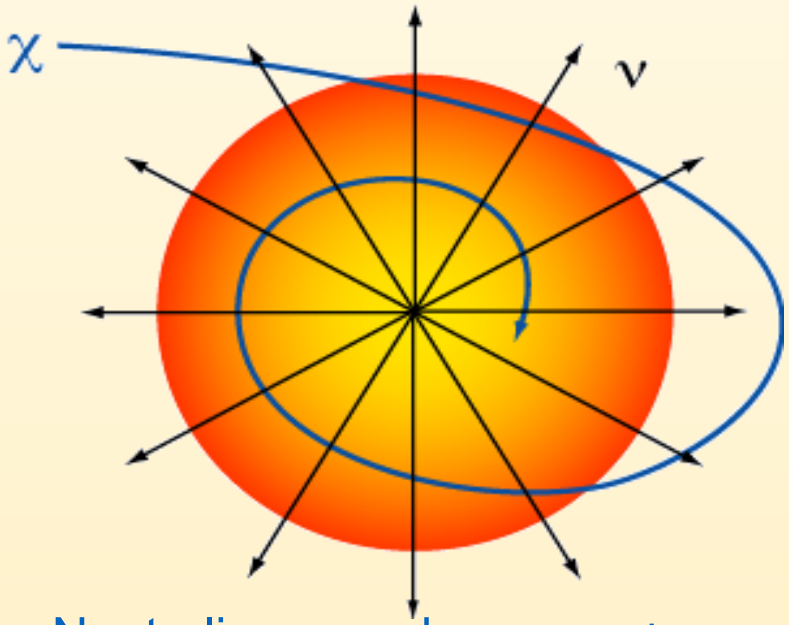


- The non observation of neutrinos allow to put limits both extended emission (EE) and prompt emission (scaled to a distance of 40 Mpc): limits are shown for the case of on-axis viewing angle (0) and selected off-axis angles to indicate the dependence on this parameter.

… not only searching for cosmic neutrinos …

… also open problems in particle physics …

- Dark Matter searches:
  - Neutralino annihilation in Sun, Earth, Galactic Center
- Magnetic Monopoles
- Particle acceleration mechanisms
- Search for Sterile Neutrinos
- …

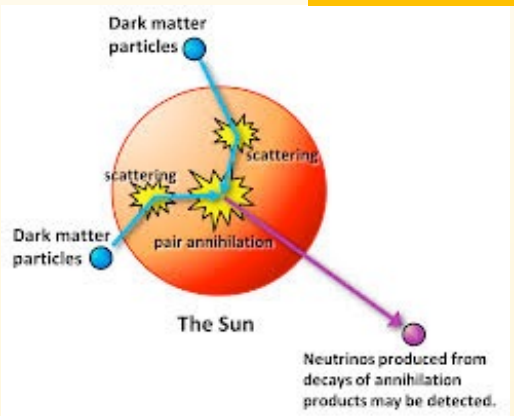


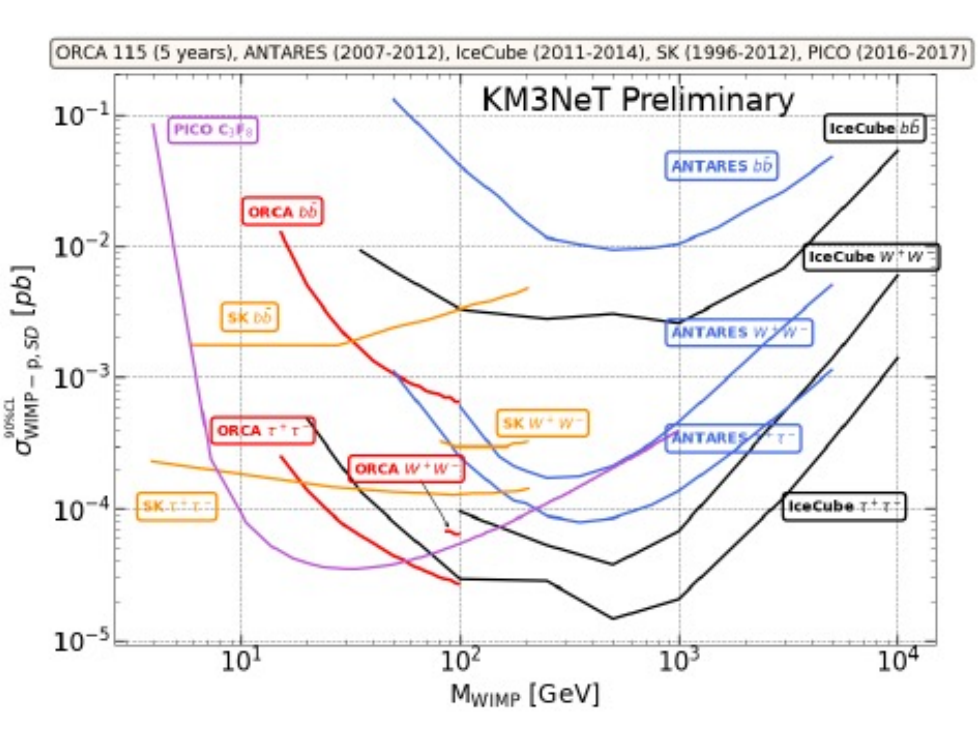
Neutralino search: $\chi\chi \rightarrow \nu$+…

Indirect search for Dark Matter searching for ν from…

Sun

C. Poire @ ICRC 2021

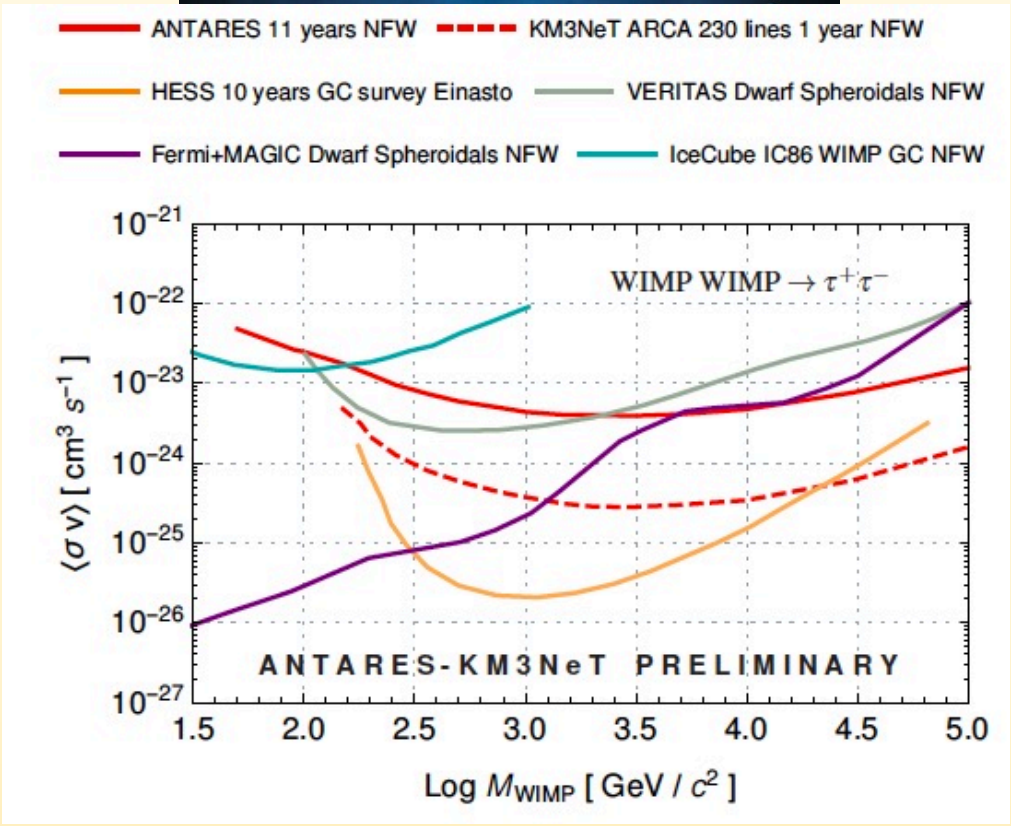




Phys.Lett. B759 2016

Galactic Centre

R. Gozzini @ ICRC2201



Phys. Lett. B 805 135439 (2020)

Conclusions

ANTARES, in operation since 2008, is validly contributing to the search for cosmic neutrinos:

- intriguing hints of cosmic neutrinos from known sources

KM3NeT Neutrino telescopes (ARCA & ORCA), in construction and operation) will allow:

- neutrino physics and neutrino astronomy from the MeV scale to the PeV scale

Exciting role for Neutrino Telescopes in multi-messenger astronomy