

ANTARES and KM3NeT: status, results and perspectives

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**UNIVERSIDAD
DE GRANADA**

On behalf of the ANTARES and KM3NeT Collaborations

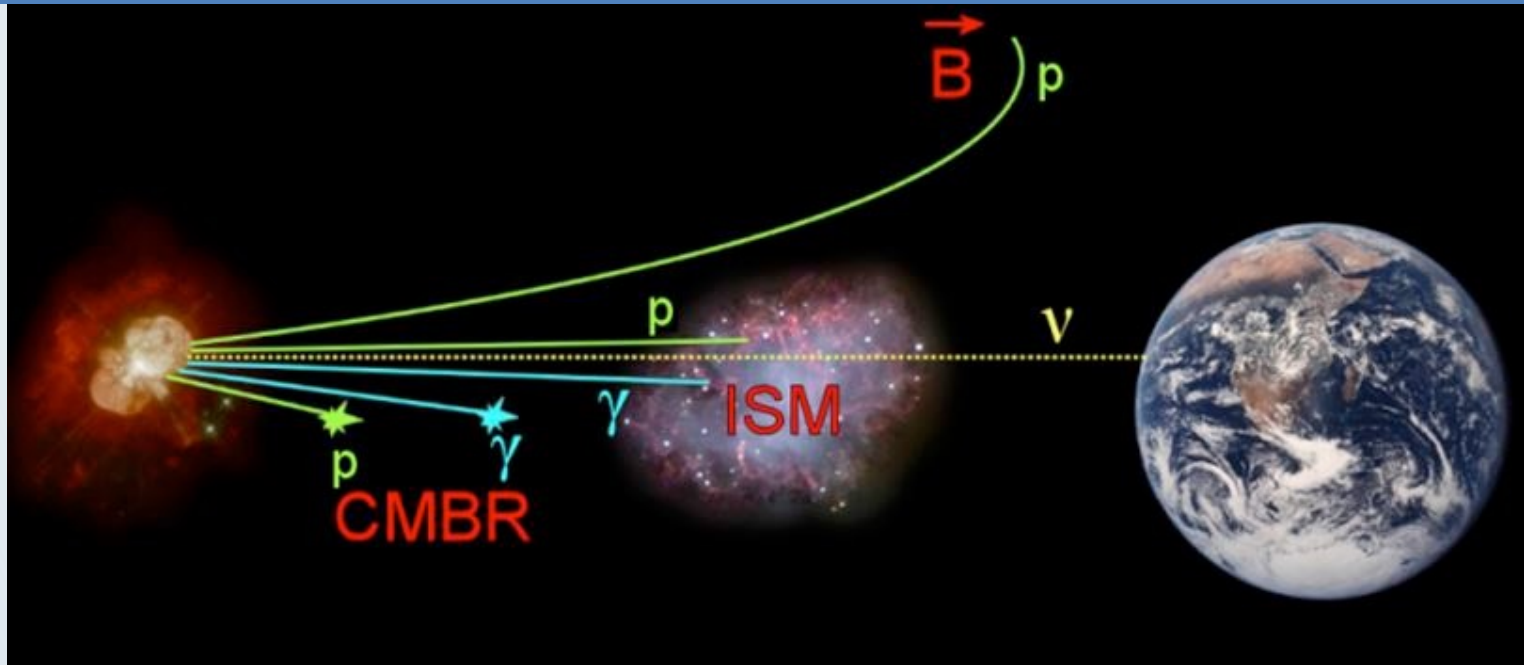
28th International Workshop on Weak Interactions and Neutrinos

WIN2021

University of Minnesota (*online*), June 7–12, 2021



Neutrino Astrophysics



- ❑ **Origin and acceleration of Cosmic Rays ?**
- ❑ **Neutral messengers point back to their sources**
 - ✓ neutrons are short-lived, photons are likely to interact → **neutrinos**
- ❑ **CR interactions produce neutrinos in meson decays**
 - ✓ **Search for a diffuse flux from unresolved sources**
 - ✓ **Search for individual sources**
 - ✓ **Multi-messenger approach for neutrino astronomy**

Mediterranean Neutrino Telescopes

Physics Motivation and Detection Principle

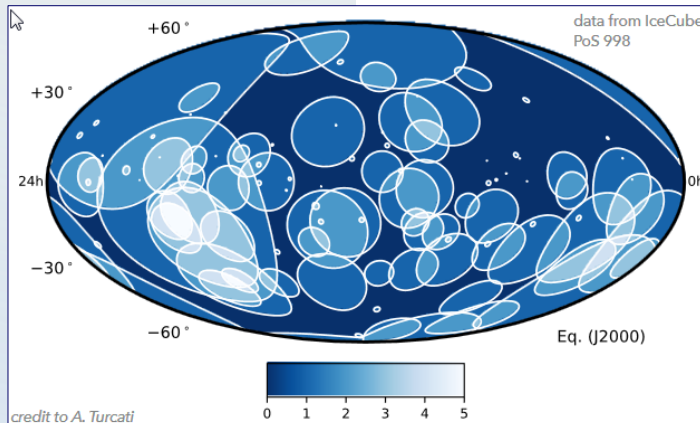
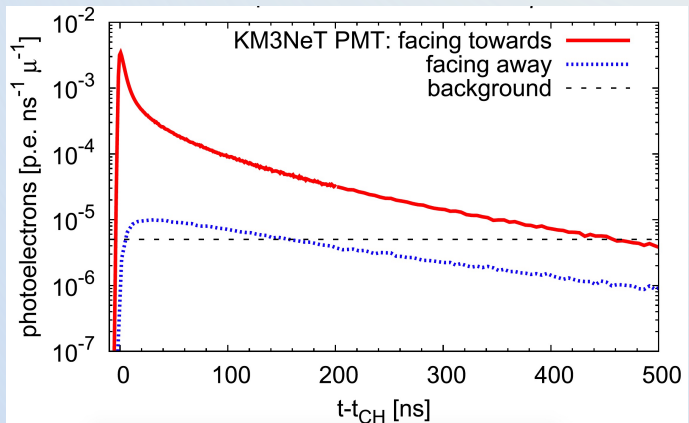
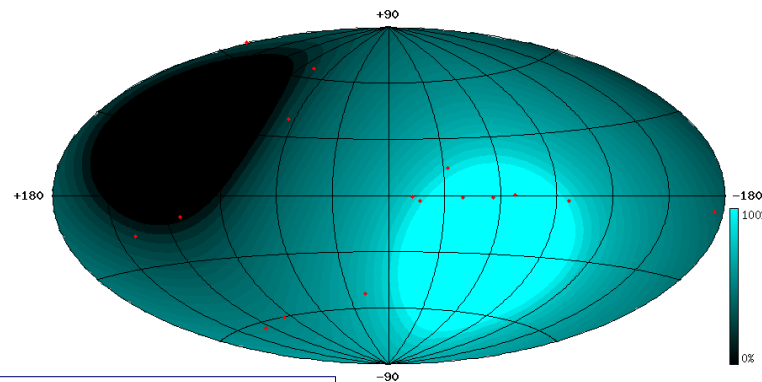
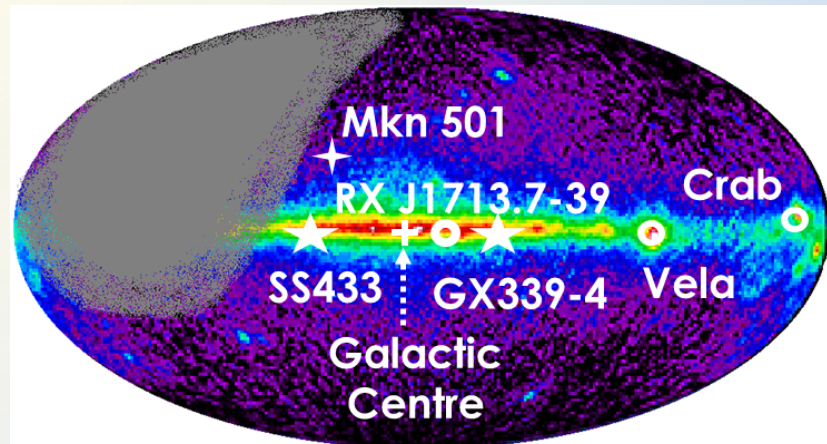
- High energy ν astronomy and ν properties
- Detection: large volume of transparent medium surveyed by photodetectors

Location: Northern Hemisphere

- Complementary to IceCube
- Golden channel for Southern sky sources. (“Milky-Way optimized”)

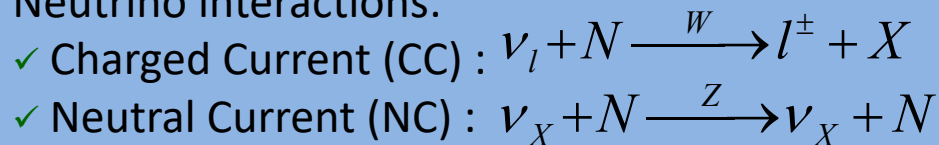
Medium: Deep Sea Water

- Very small light scattering (good angular resolution)
- Natural backgrounds (^{40}K and bioluminescence) can be handled.



Neutrino detection principle

Neutrino interactions:



Neutrino topologies:

✓ **Tracks & Showers**

Atmospheric μ^\pm
(background)

Cherenkov light
 $\theta_{Ch} \sim 43^\circ$

ν or l^\pm
+ hadrons

ν_X

ν_μ muon neutrino, CC only
(track reconstruction)

all neutrino flavors, CC & NC
(shower reconstruction)

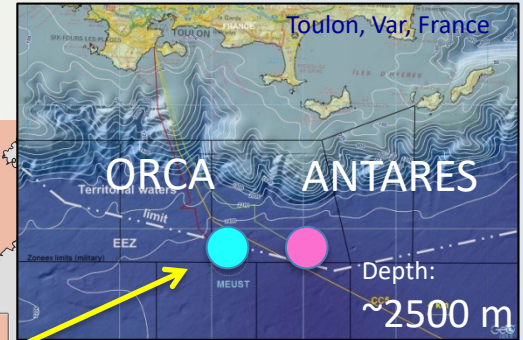
Mediterranean ν telescopes

ANTARES: ~ 10 Mt instrumented mass. Completed in 2008

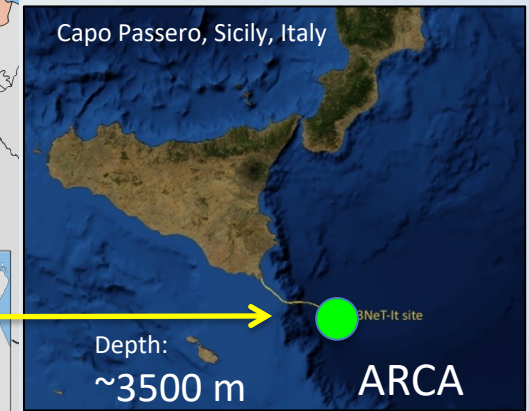
KM3NeT: A distributed research infrastructure with
2 main physics topics: ORCA & ARCA

Cities and Sites of KM3NeT

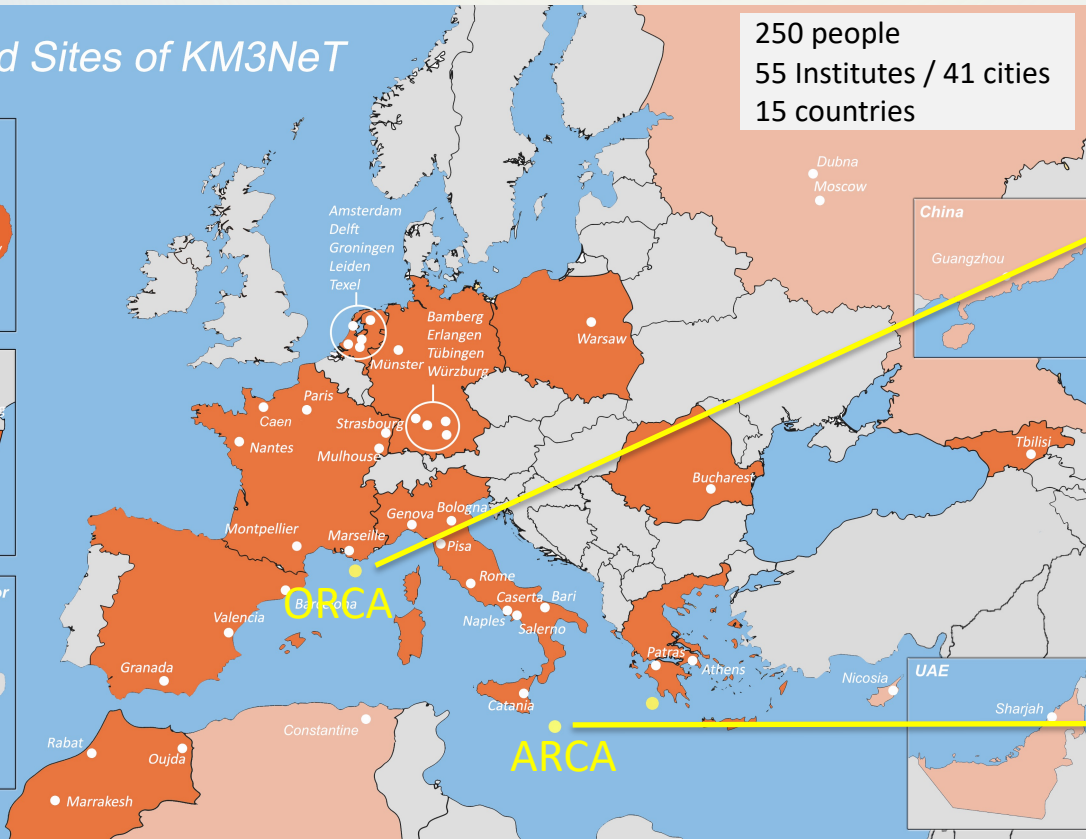
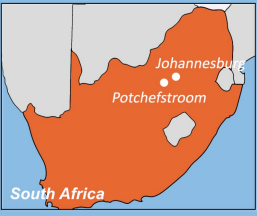
250 people
55 Institutes / 41 cities
15 countries



Low-energy (\sim GeV) studies
of atmospheric neutrinos



High-energy (TeV-PeV)
neutrino astrophysics





12 lines (885 PMTs)

25 storeys / line

3 PMTs / storey

5-line setup in 2007

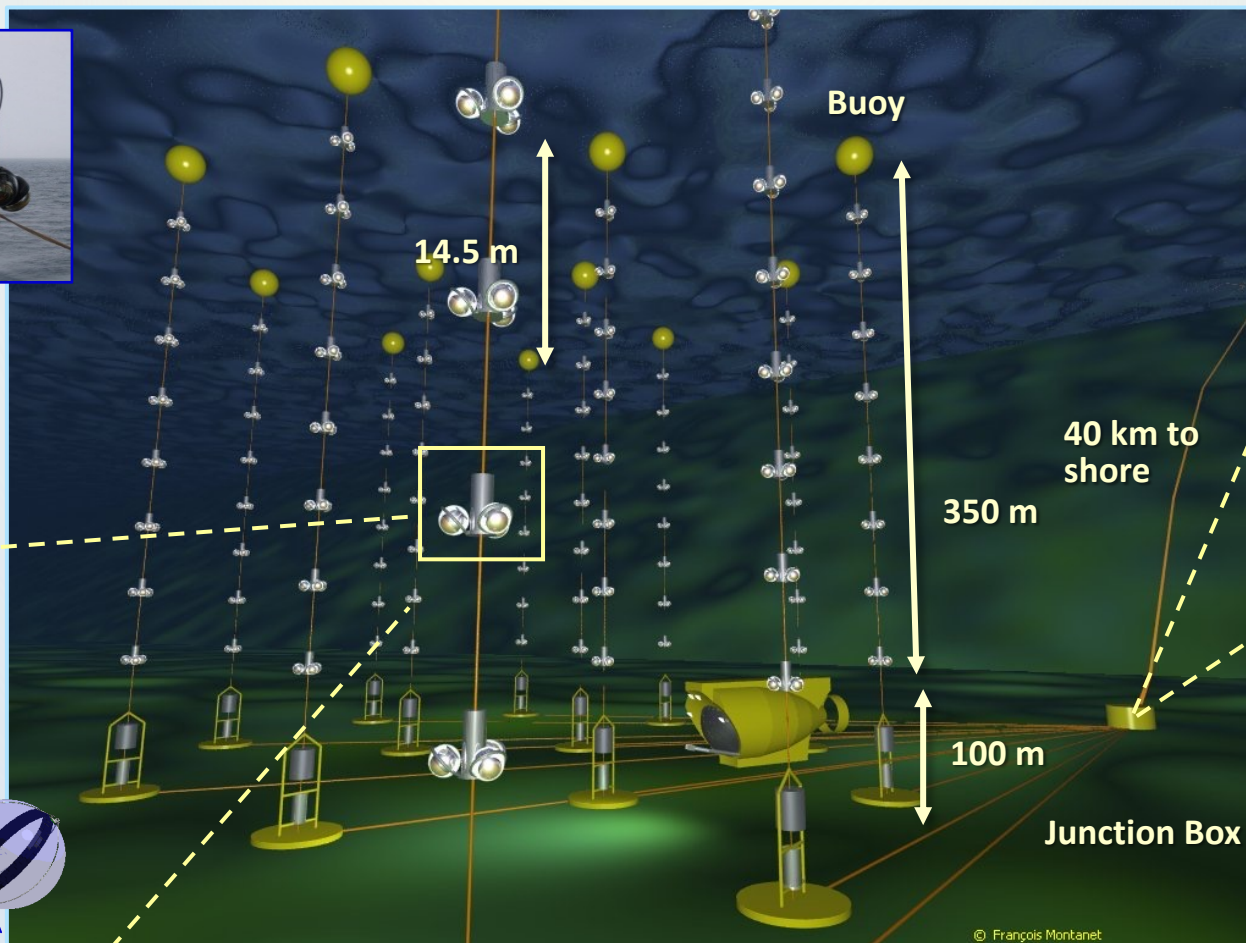
Completed in 2008



Junction Box



Shore station

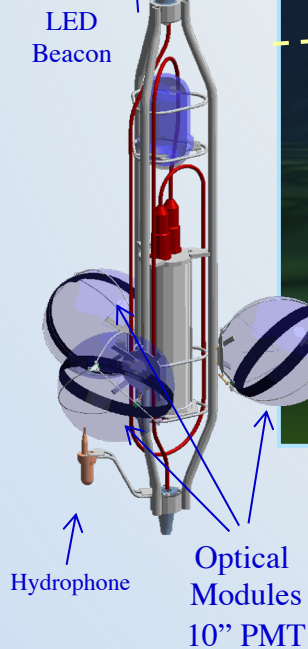


© François Montanet



Mediterranean Sea
(near Toulon)
at **2500 m** depth

- NIM A484 (2002) 369, AP 19 (2003) 253
- AP 23 (2005) 131, NIM A555 (2005) 132
- AP 26 (2006) 314, NIM A570 (2007) 107
- NIM A578 (2007) 498, NIM A581 (2007) 695 AP
- 31 (2009) 277, NIM A622 (2010) 59-73 AP 34
- (2011) 539, NIM A656 (2011) 11

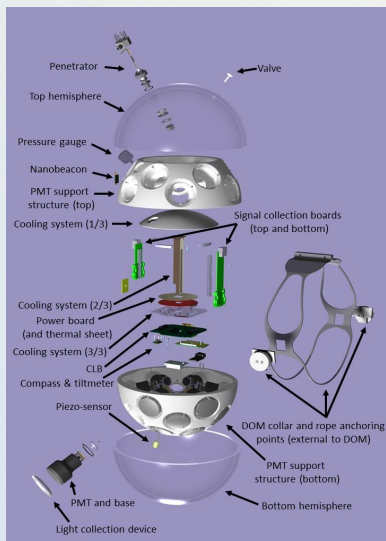


Optical Sensors (DOMs)



- All data to shore
- Gbit/s on optical fiber
- Hybrid White Rabbit
- LED flasher & hydrophone
- Tiltmeter/compass
- 18 DOMs / String

- DOM: 31 × 3" PMTs
- Digital photon counting
- Directional information
- Wide acceptance angle
- Cost reduction



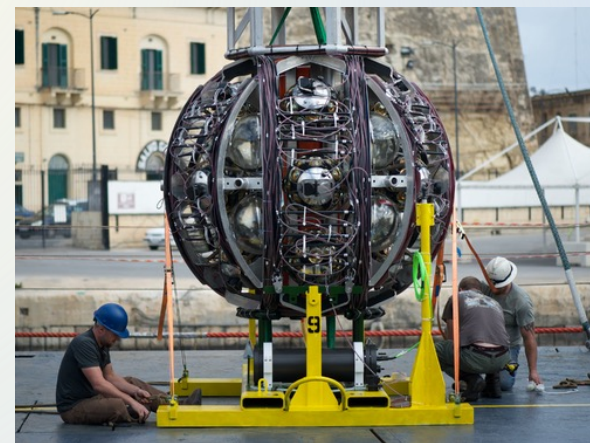
String (Detector Unit)



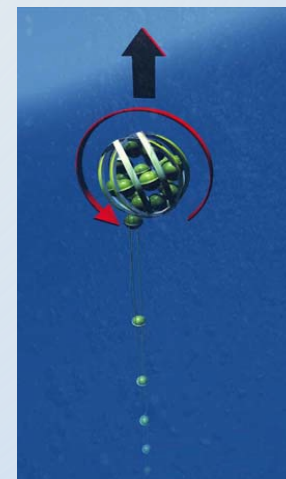
- Polyethylene ropes
- Oil filled PVC tube
- Low drag, Low cost

~ 700 / 200 m

LOM Deployment



- Unfurling by autonomous ROV
- Rapid deployment
- Multiple strings in one sea campaign



Junction Boxes

Seafloor network  Electro-optical cables and JBs

KM3NeT : ARCA and ORCA



115 strings
 18 DOMs / string
 31 PMTs / DOM
 Total: 64k × 3" PMTs

Building Block

□ **ARCA (Gigaton scale)**

2 building blocks

□ **ORCA (Megaton scale)**

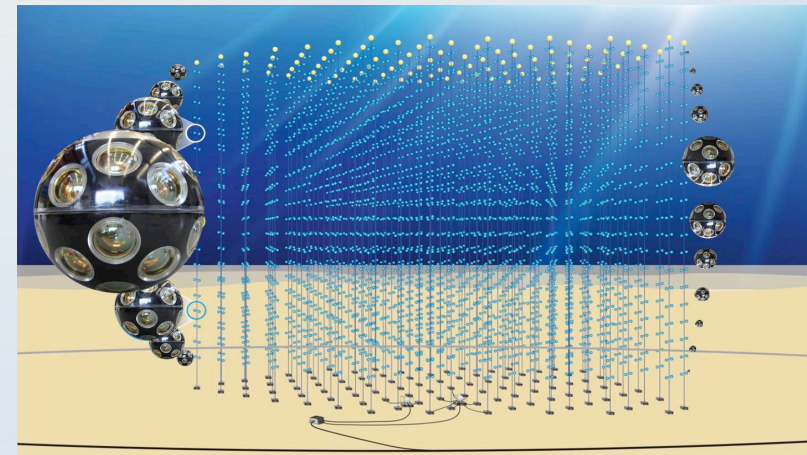
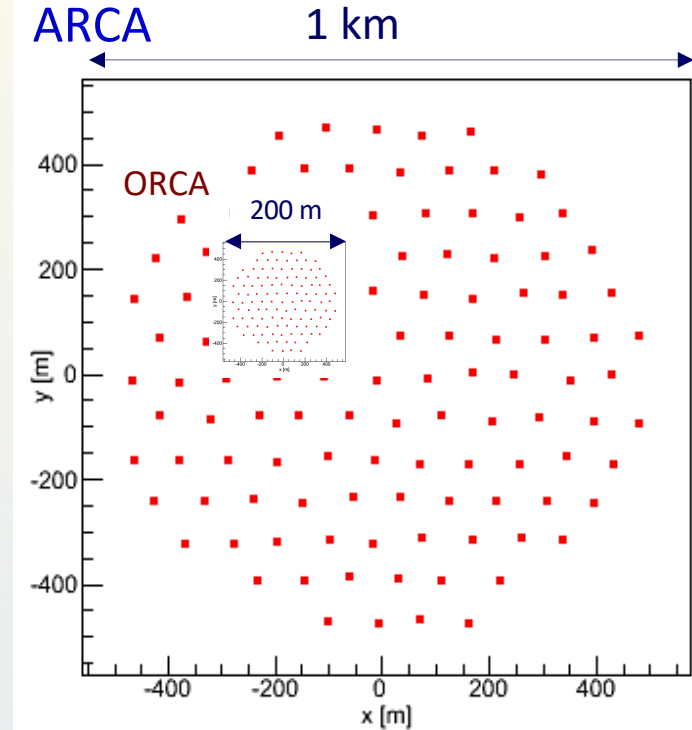
1 building block

See:

talk by: **V. VAN-ELEWYCK** on ORCA

poster by: **J. Coelho** on Sterile ν & NSI

Same technology, denser layout



	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mton	~ 2 × 0,5 Gton

Physics Studies with Mediterranean ν telescopes

Supernovae
Explosion

ν Oscillations
 ν Mass Hierarchy

Dark Matter searches
+ Exotic searches

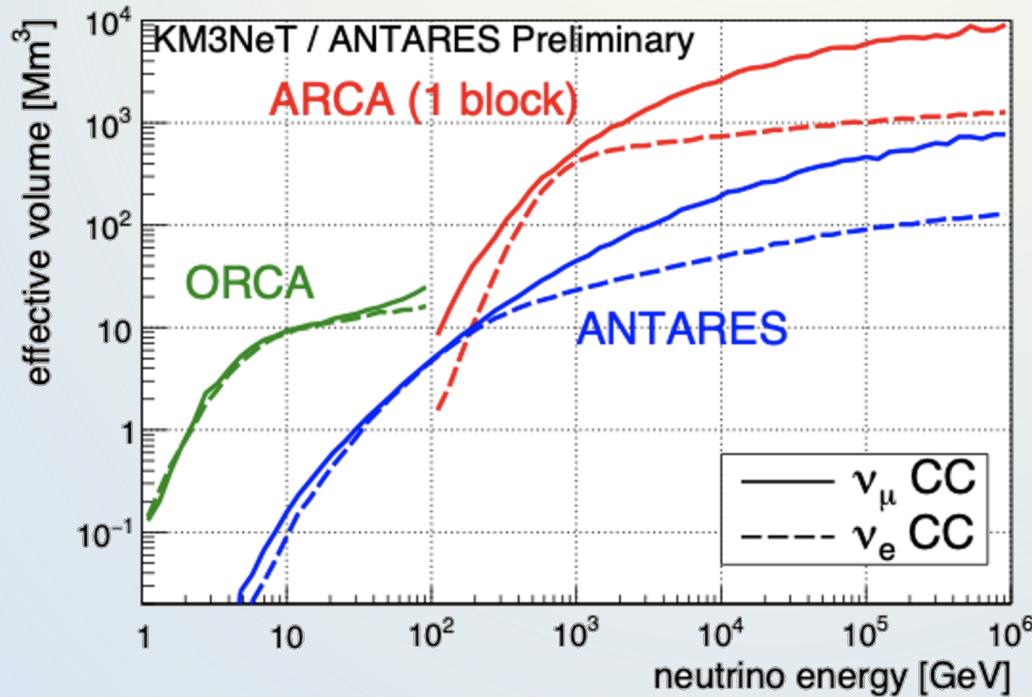
Cosmic neutrinos
Multi-messenger program

MeV

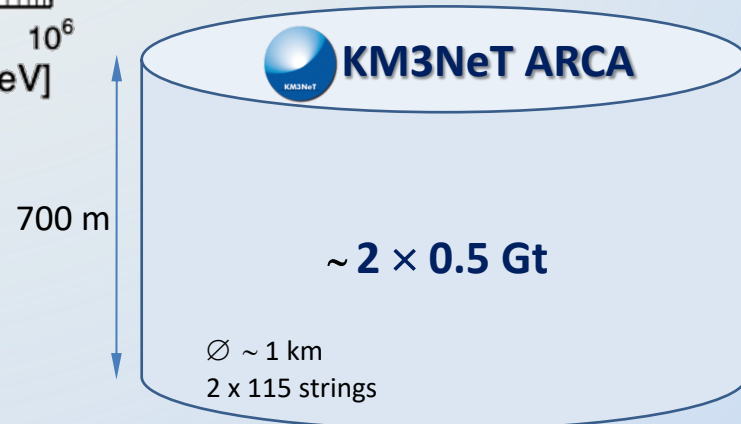
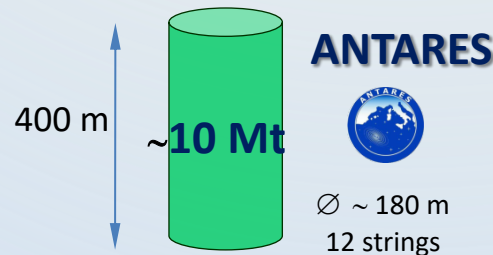
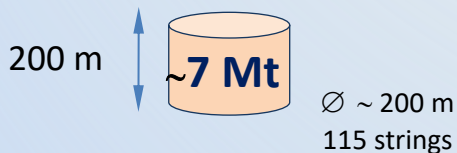
GeV

TeV

PeV



KM3NeT
ORCA



✓ BIOLUMINESCENCE

📖 PLoS ONE 8 (7) 2013

Deep-sea bioluminescence blooms after dense water formation at the ocean surface

📖 In preparation

Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope



✓ SEDIMENTS

📖 J. Geophysical Research: Oceans, Vol 122, 3, 2017

Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

✓ ACOUSTICS

📖 Deep-Sea Research I 58 (2011) 875–884

Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

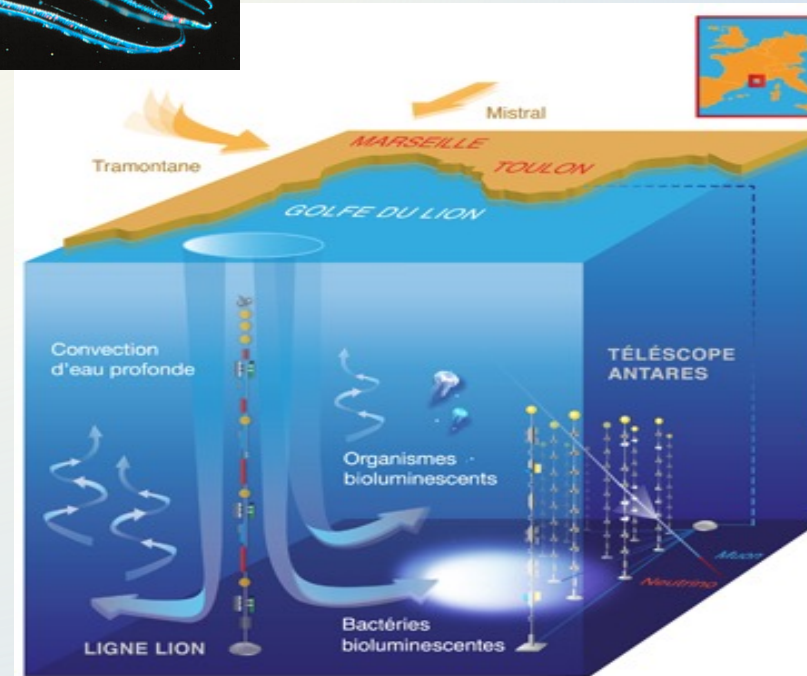
✓ SEA MAMMALS BEHAVIOUR

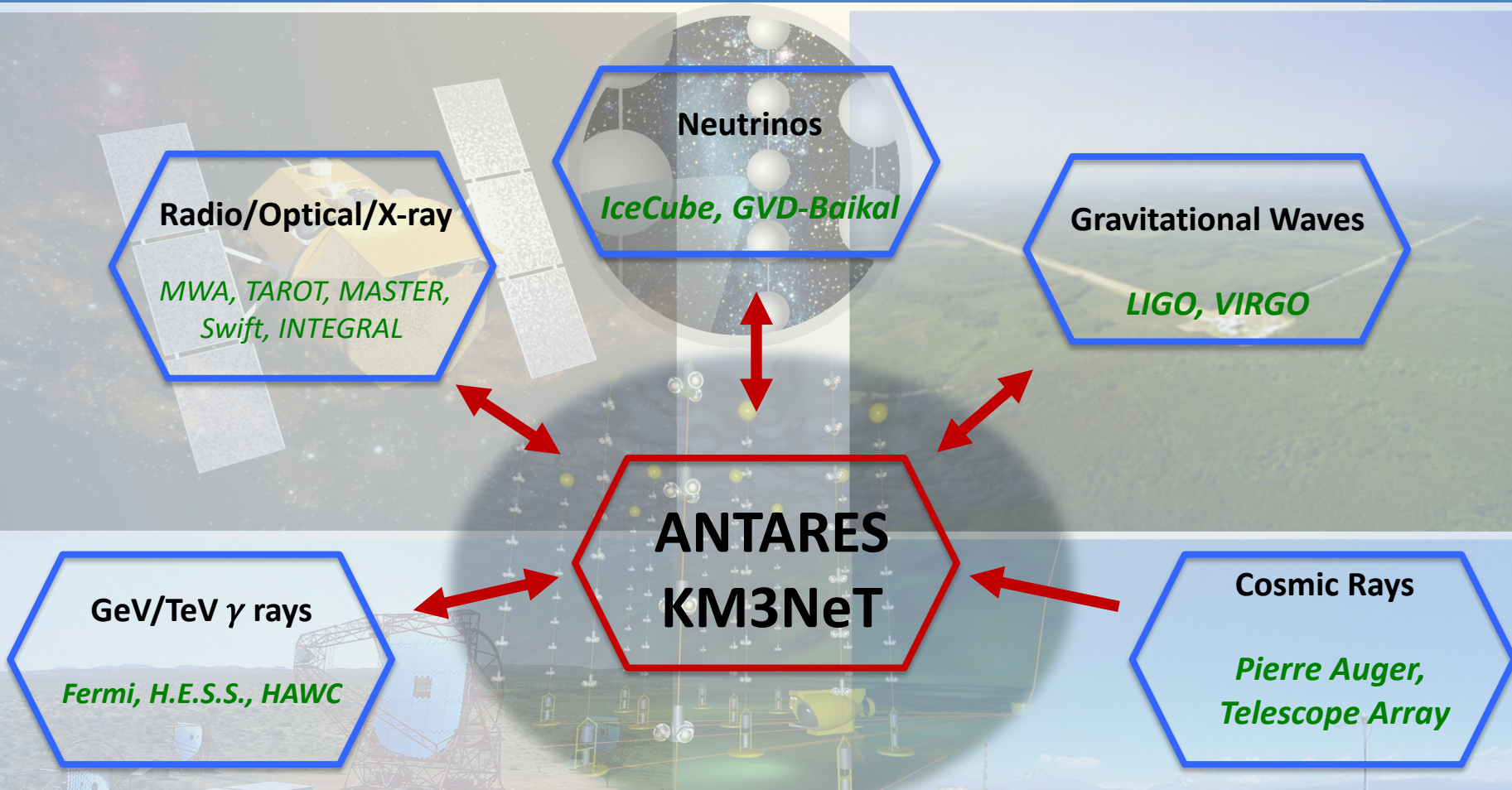
📖 Sci. Rep. 7 (2017) 45517

Sperm whale long-range echolocation revealed by ANTARES, a deep-sea neutrino telescope

📖 Ocean Dynamics, April 2014, 64, 4, 507-517

High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean





ANTARES receives alerts (GCN)

- “Time-dependent” searches
- γ -ray Coord. Network, IceCube, MAGIC, HESS, VERITAS, FERMI, optical or radio instruments, and GW alerts from VIRGO, LIGO.

ANTARES sends alerts (TAToO)

- “Real-Time” analysis
- Time to send alert 5s, median resolution $<0.5^\circ$. Triggers: single HE, multiplets, direction
- A few 10 alerts per year sent

Reconstruction Performances (1/2): “tracks”

CC ν_μ

Tracks (ν_μ CC) ideal tool for astronomy

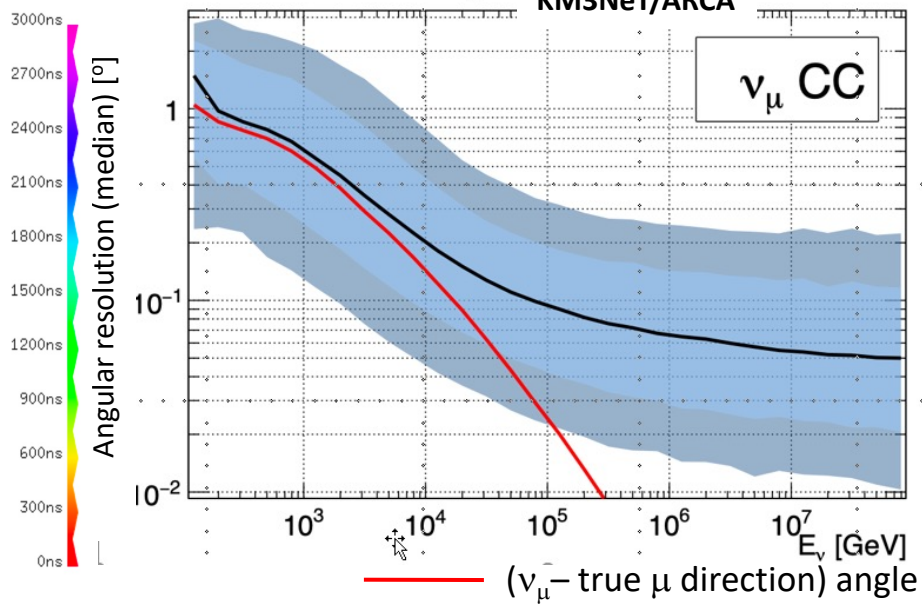
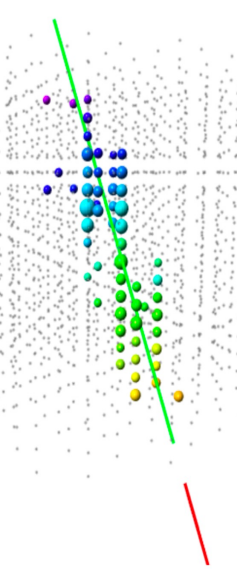
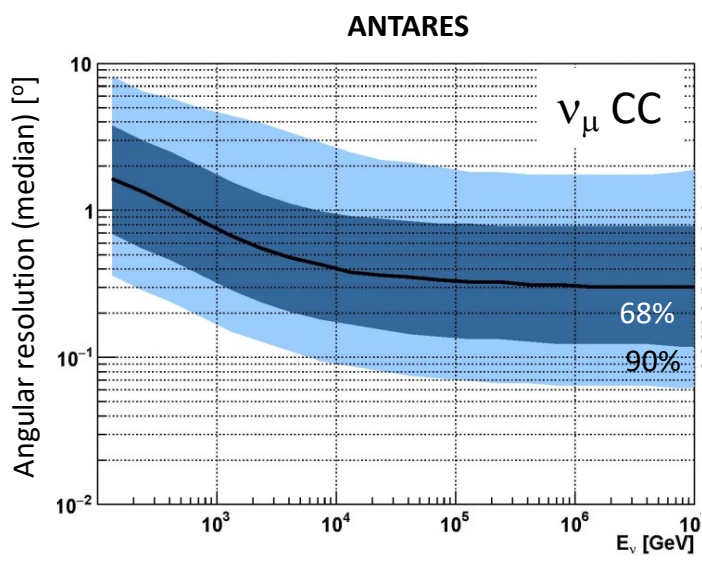
- ❖ Excellent angular resolution + Large effective volume
- ❖ Larger atmospheric background



Angular Resol. $< 0.4^\circ$ above 10 TeV
 Energy Resol. ~ 0.35 in $\log_{10}(E_{\text{reco}}/E_\mu)$



Ang. Resol. $< 0.2^\circ$ above 10 TeV
 Energy Resol. ~ 0.27 in $\log_{10}(E_{\text{reco}}/E_\mu)$
 (10 TeV $< E_\mu < 10$ PeV)



Reconstruction Performances (2/2): “Showers”

NC ν_{all}
CC ν_e

Shower events also used for astronomy

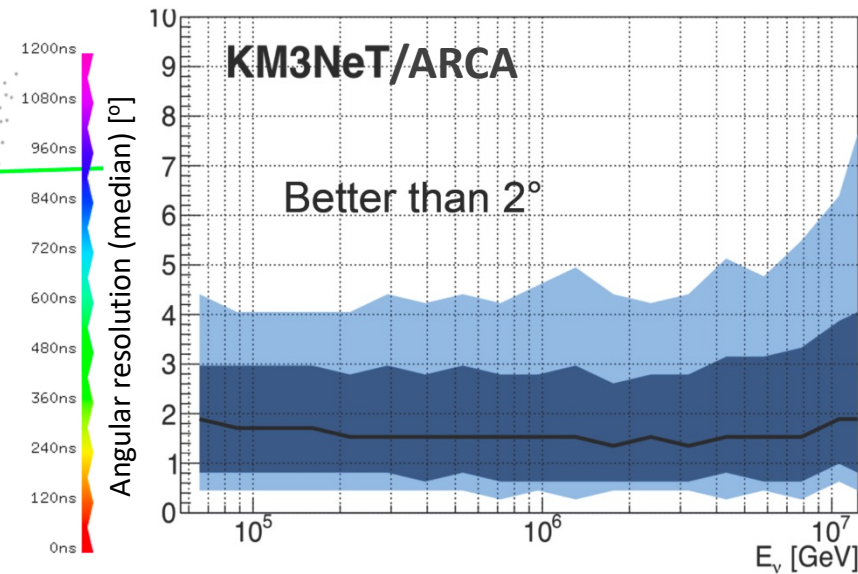
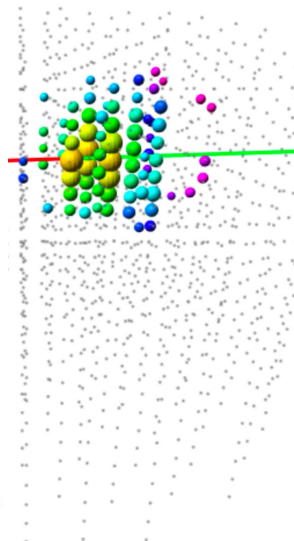
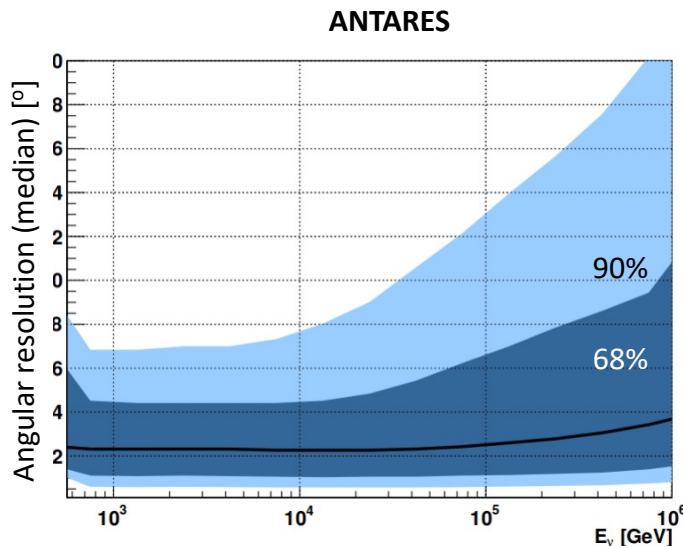
- ❖ Contained events → Better energy resolution
- ❖ Almost no atmospheric background

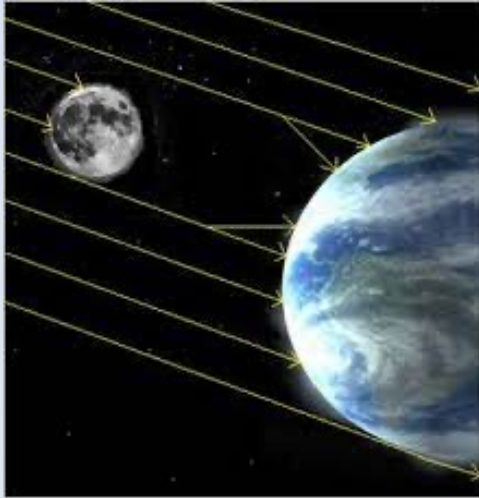


Angular Res. $< 3^\circ$ ($1 \text{ TeV} < E < 0.5 \text{ PeV}$)
Energy Res. for ν_e CC better than **10%**
Shower confined within $\sim 10 \text{ m}$ (long)



Angular Res. $< 2^\circ$ above 50 TeV
Energy Res. $< 5\%$



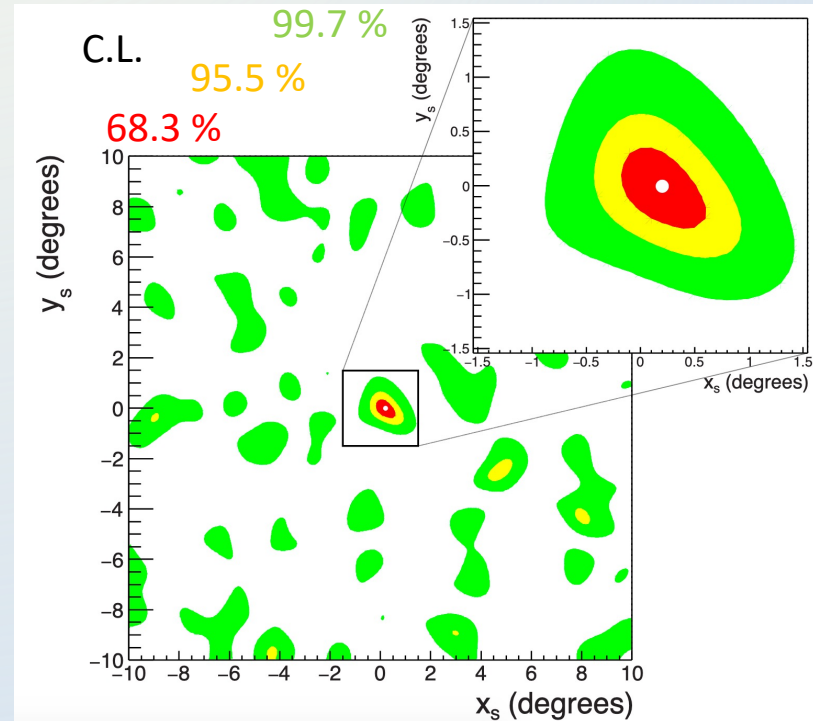
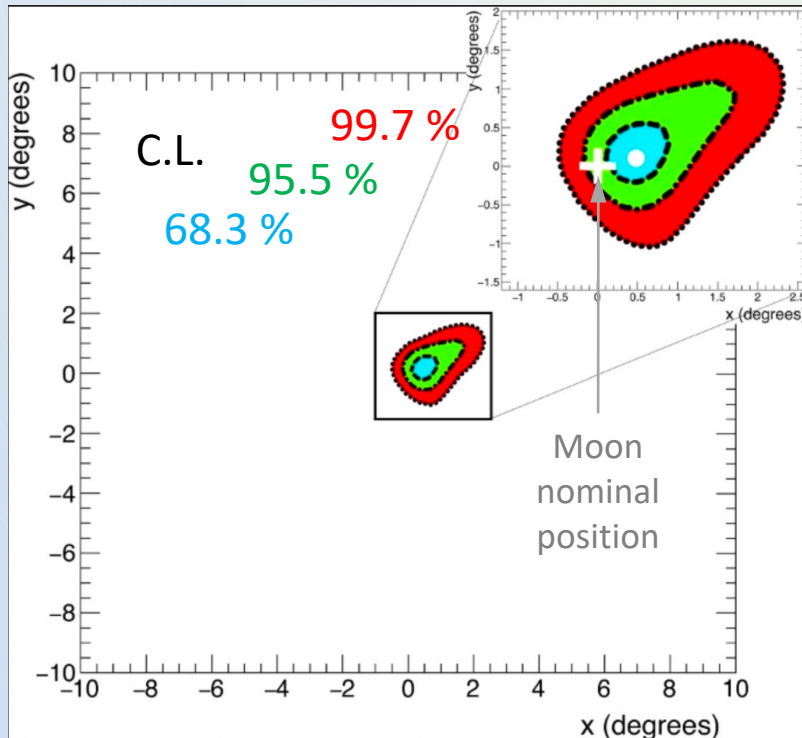


Deficit of the atmospheric muon flux from the direction of the Moon & Sun induced by the absorption of cosmic rays

Shadow Observed with downward going muons
Data :
Statistical significance :
Angular resolution :

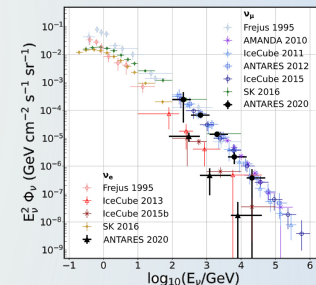
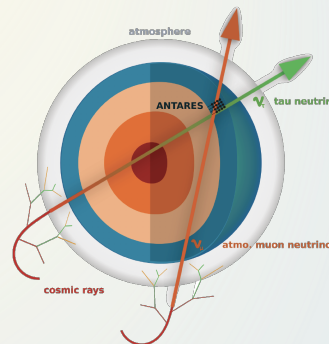
Moon
2008 – 2016
2.5 σ
0.73° ± 0.14°

Sun
2008 – 2018
3.7 σ
0.59° ± 0.10°



Atmospheric neutrinos

- Energy Spectrum
- Neutrino oscillation
- (3+1) Sterile Neutrino Models
- Non Standard Interactions

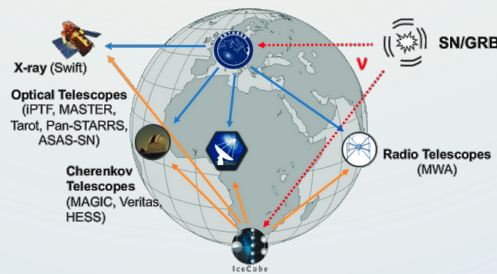
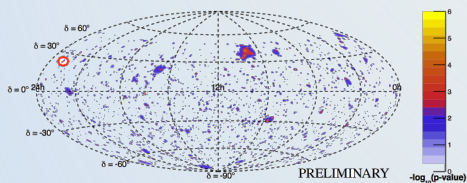


Cosmic neutrinos

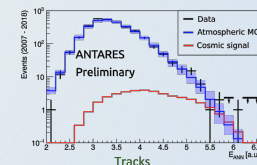
- Multi-messenger Search / Alerts (Time & Space coincidences)

- Diffuse Search

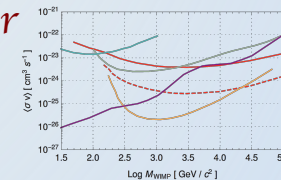
- "All Sky" Point-source



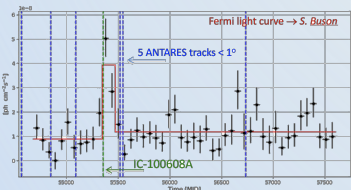
- Galactic Ridge



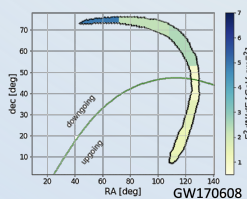
- Dark Matter (GC, Sun...)



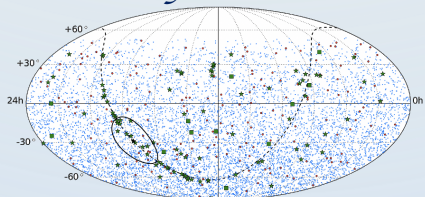
- "Stacking" Catalogue & GRBs



- "GW"

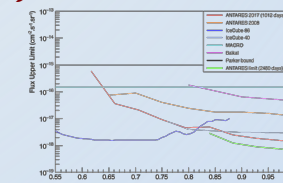


- IceCube tracks ("Steady" & "Transient")



- "Catalogue" (Space coincidences)

- Exotics (Nuclearities, Monopoles)



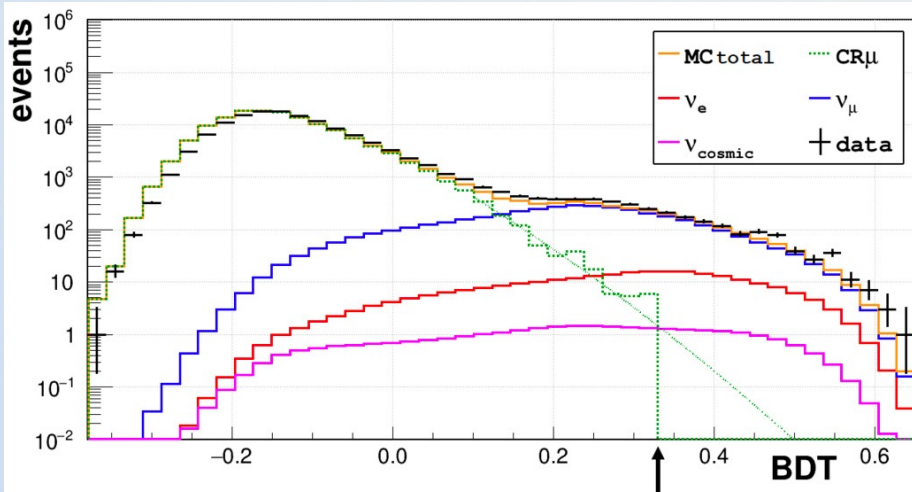
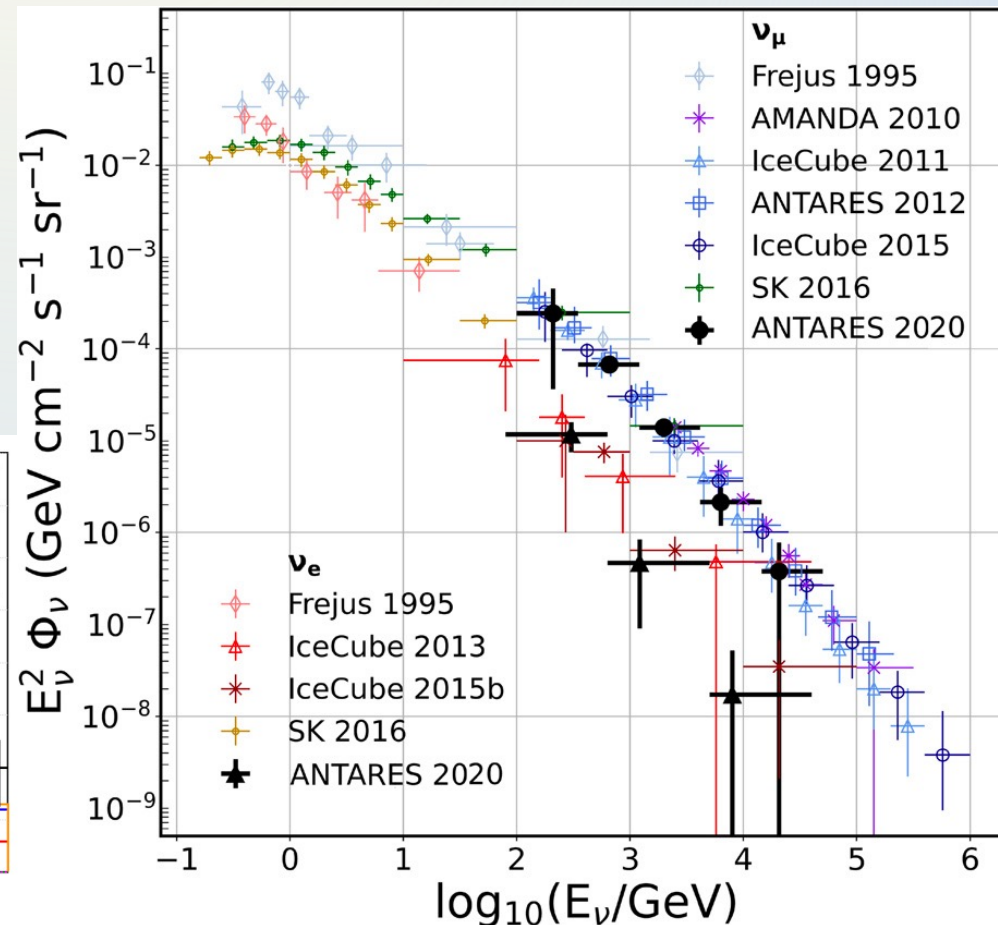


ANTARES Data: 2007 – 2017 (3012 days livetime)

- Pre-selection + Reco. cuts ($\Lambda > -5.7$) + BDT selection > 0.33 (15 parameters)
- Events after cuts:

MC CR_μ	~ 3
MC Atmospheric ν_e CC	96
MC Atmospheric ν_e NC	9
MC Atmospheric ν_μ CC	620
MC Atmospheric ν_μ NC	180
MC Cosmic ν	9.2
MC total	917
Data (3012 days)	1016

Unfolded energy spectrum
World wide consistent results



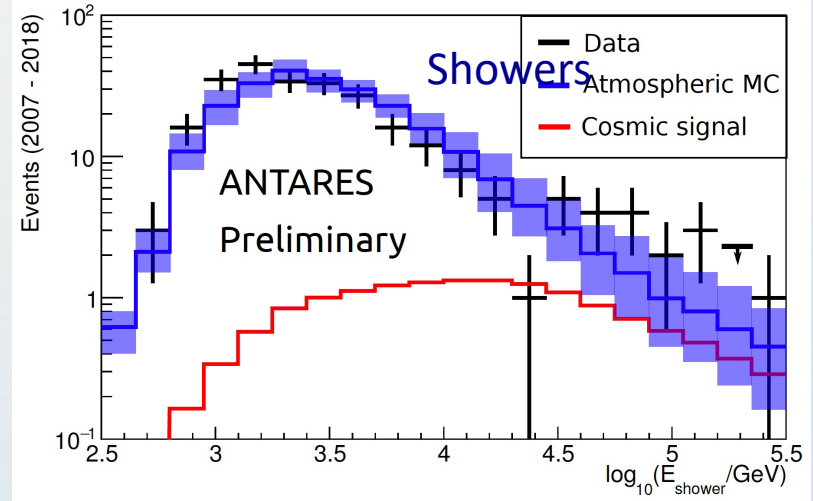
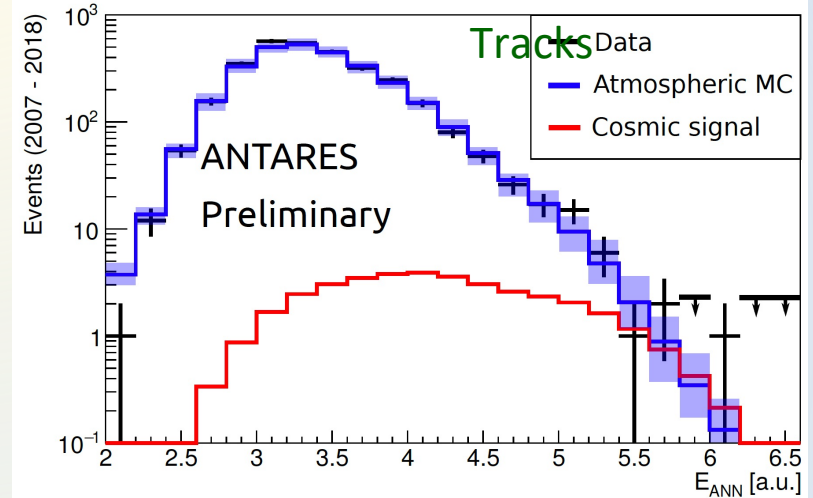


- Data Sample 2007 – 2018 (3330 days)
- All sky / All-flavour ν search
- Unblinding: 1.8σ excess

	Events	tracks	showers
Observed:	50	= 27	+ 23
Expected:	36.1 ± 8.7	= 19.9	+ 16.2

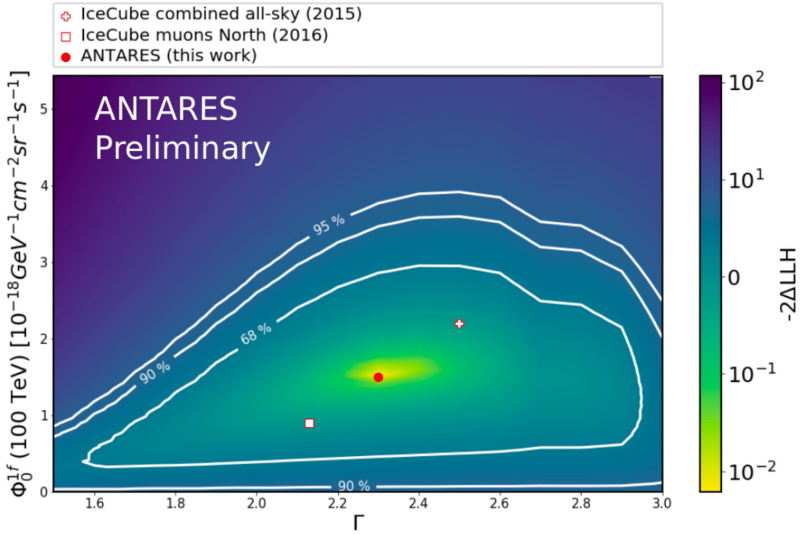
Selection cuts optimized with MRF
Assumed spectral index $\Gamma=2.5$
Look for excess above a given $E_{\text{Threshold}}$

- Results compatible with IceCube diffuse flux



Best fit (1 flavour flux normalization at 100 TeV)

- Flux: $\Phi_0(100 \text{ TeV}) = (1.5 \pm 1.0) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Spectral index: $\Gamma = 2.3 \pm 0.4$





KM3NeT Diffuse Flux : Full sky

Track channel

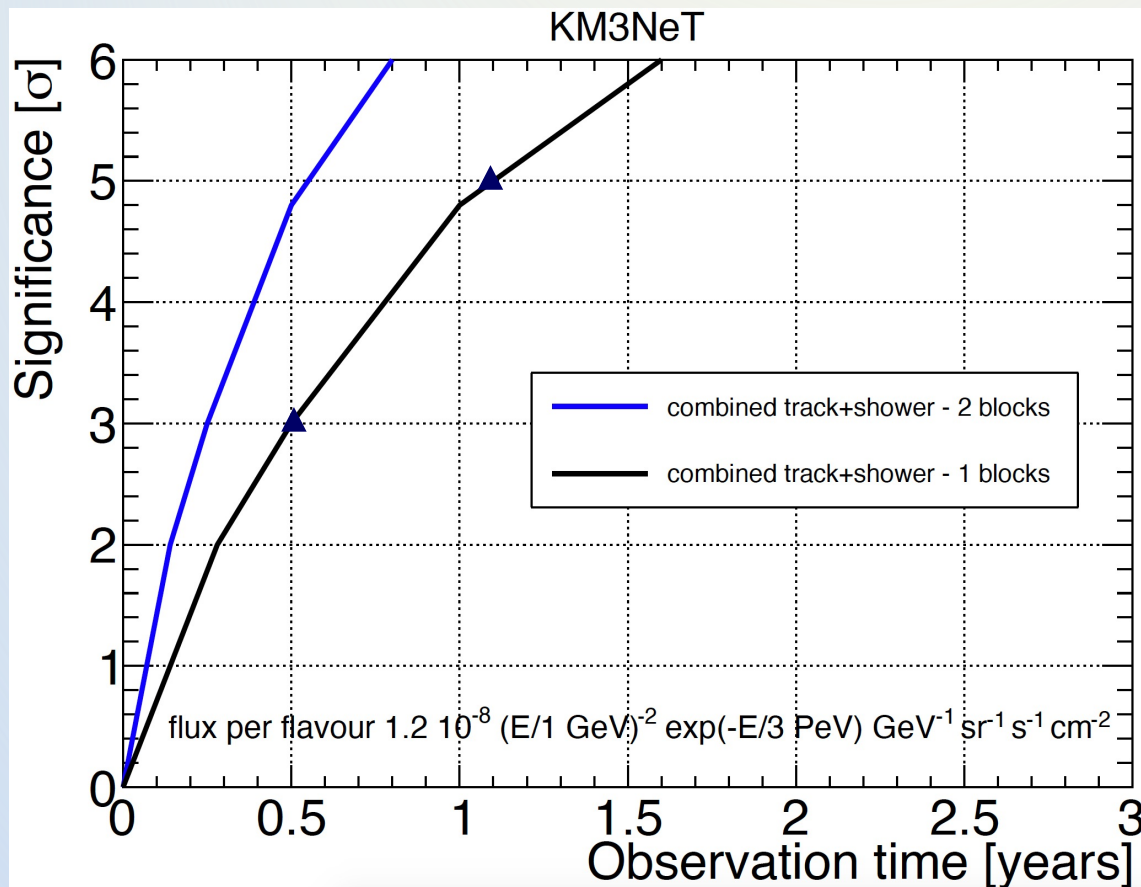
Analysis for upward-going events based on a maximum likelihood

Pre cuts on θ_{zenith} , Λ reconstruction quality parameter and N_{hit} (proxy for muon energy)

Shower channel

Containment cut on reconstructed vertex to remove atm. muons (excludes 100 m layer)

All sky analysis based on BDT and maximum likelihood



KM3NeT 2.0 can observe

(3 σ) IceCube signal in
3 months

and confirm it
(5 σ) in **six months**

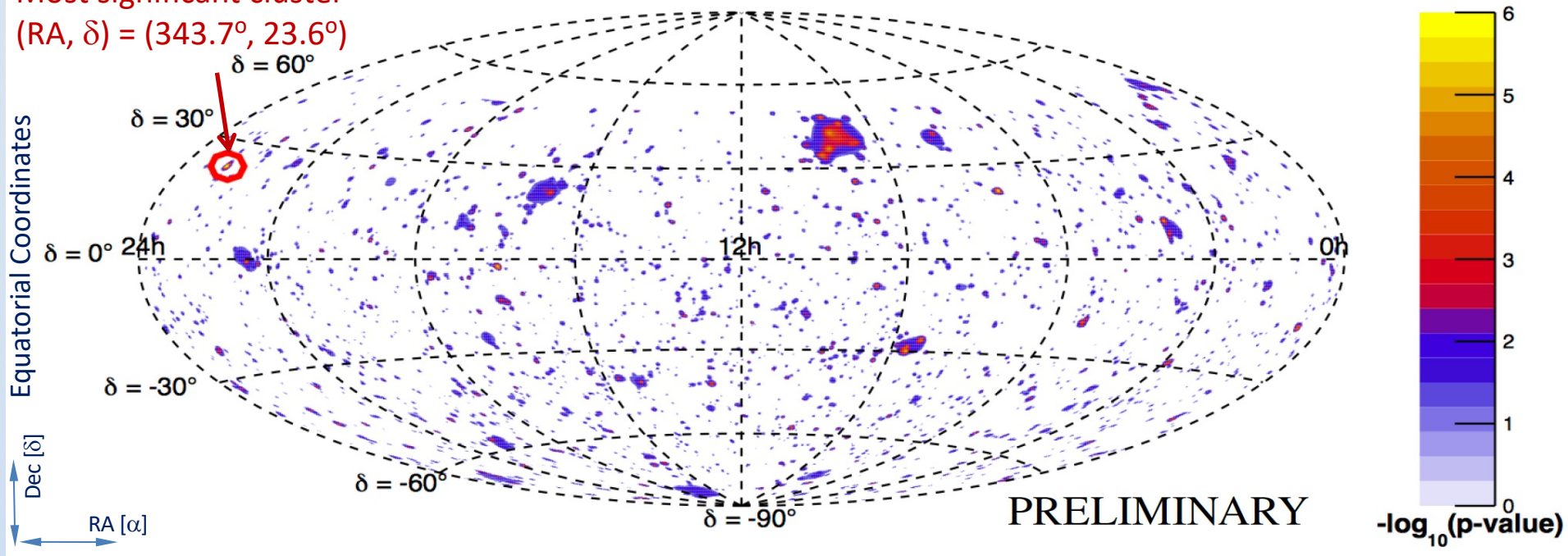


ANTARES Data: 2007 – 2017 (3136 days livetime) → 8754 tracks + 195 showers

- Full sky (steps of $1^\circ \times 1^\circ$, no source assumption) (Phys. Rev. D 96 082001 (2017))
- Catalogue: 112 sources (galactic + extra-galactic) (PoS (ICRC2019) 920)
- IC tracks : 75 (HESE+ESE) tracks “steady”
- IC tracks : 54 time-correlated tracks “transient” (ApJ 879 (2019) 108)
- TXS0506+056 follow up (ApJ Lett. 863 (2018) L30)

No significant evidence of cosmic neutrino sources found

Most significant cluster
(RA, δ) = (343.7°, 23.6°)



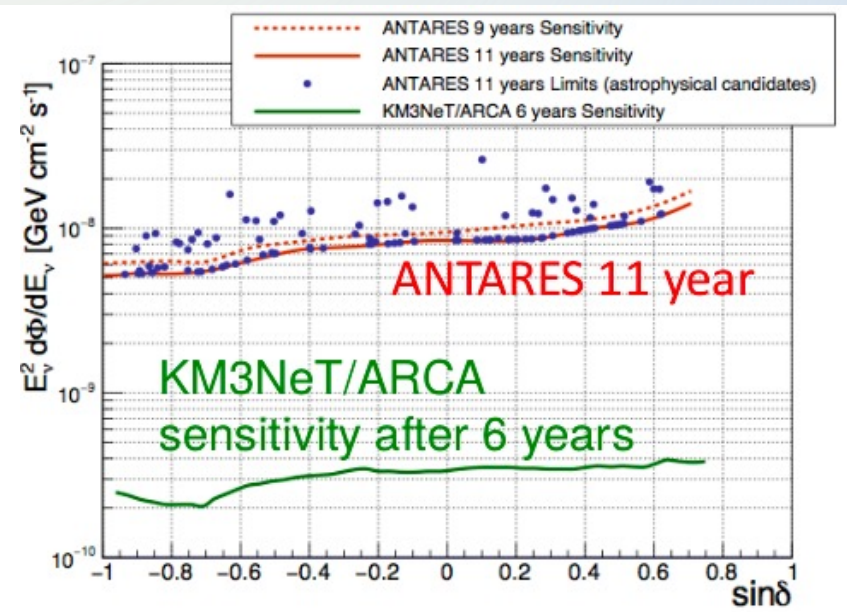
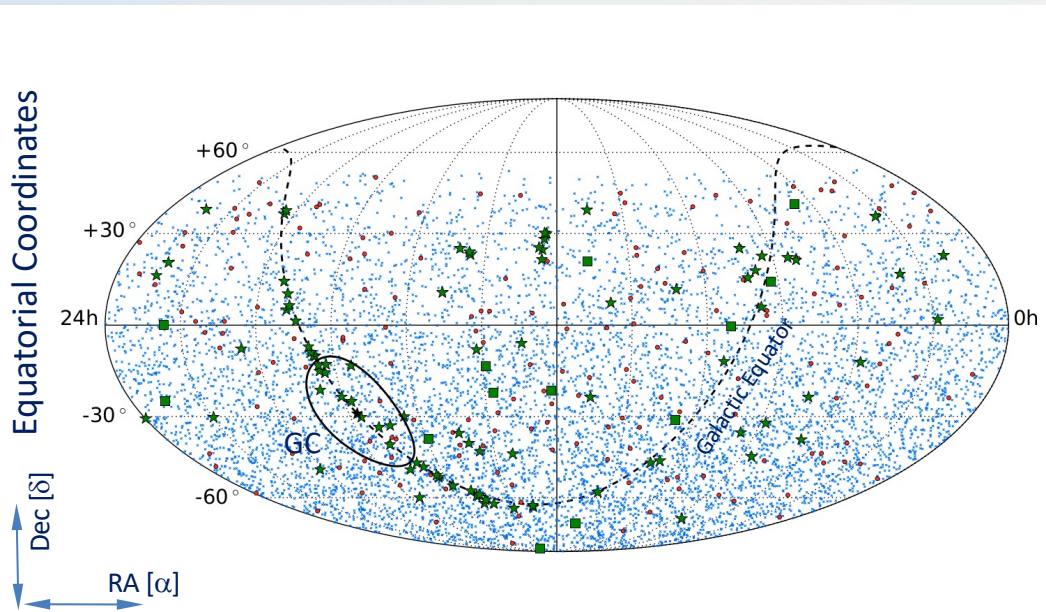
Full sky search: pre-trial p -values for a point-like source of the ANTARES visible sky.



ANTARES Data: 2007 – 2017 (3136 days livetime) → 8754 tracks + 195 showers

- Full sky (steps of $1^\circ \times 1^\circ$, no source assumption)
- Catalogue: 112 sources (galactic + extra-galactic)
- IC tracks : 75 (HESE+ESE) tracks “steady”
- IC tracks : 54 time-correlated tracks “transient”
- TXS0506+056 follow up

No correlation found with list of preselected sources



Dots: ANTARES tracks & Showers. **Stars:** 112 astrophysically interesting source candidates.
Squares: 54 IceCube HESE tracks.

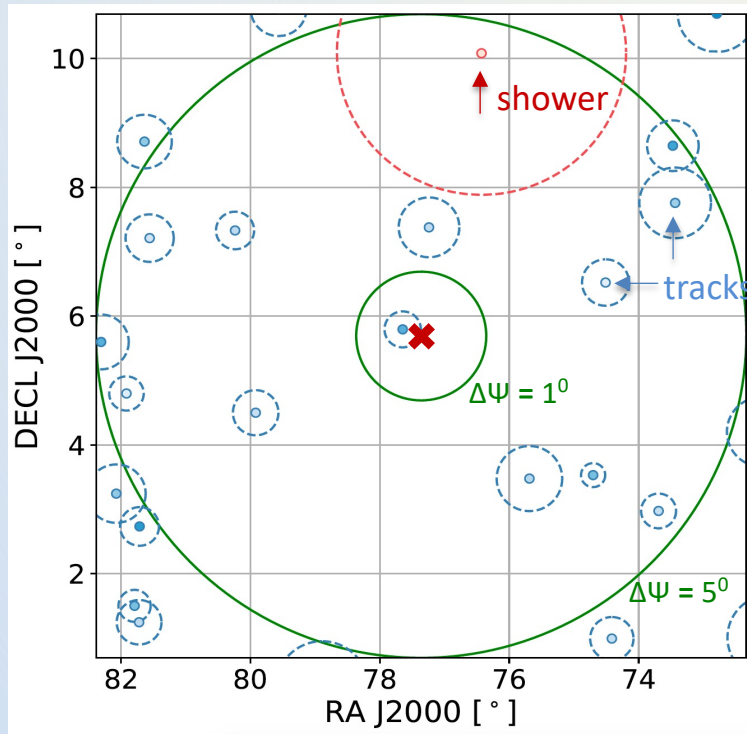


Three searches performed:

- I. **Online prompt** search for neutrinos associated with **IC170922A**
 - No counterpart events seen in ANTARES data

- II. **Time-dependent** search for neutrinos in **TXS 0506+056** historical bursting periods
(Gaussian & Box-shaped flare time profiles)

No significant evidence of cosmic ν 's \rightarrow upper limits



TXS 0506+056 Equatorial Coord.

$$(\alpha, \delta) = (77.36^\circ, 5.69^\circ)$$

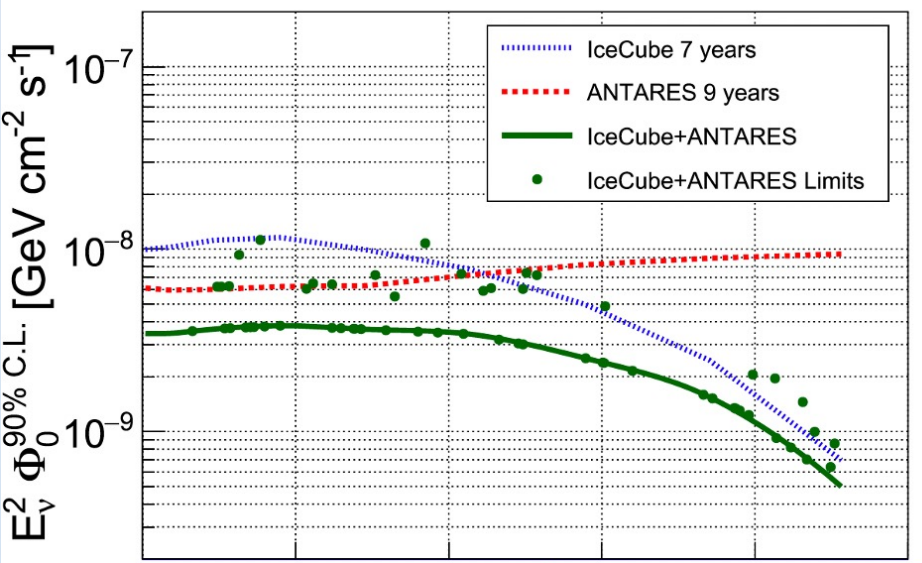
- III. **Time-integrated** search from **TXS 0506+056**

- Point Source analysis approach
- 2007 – 2017 data (3136 livetime days)
107 sources. **3rd most significant source**
- Likelihood fit result: $\mu_{\text{sig}} = 1.03$ events.
Post-trial *p-value* = 87%
- **13 tracks + 1 shower** ($\Delta\Psi = 5^\circ$).
 17 ± 4 atm. ν expected
- $\Phi^{90\%}_{100 \text{ TeV}} = 1.6 \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ($\Gamma=2$)
[2TeV - 4PeV]

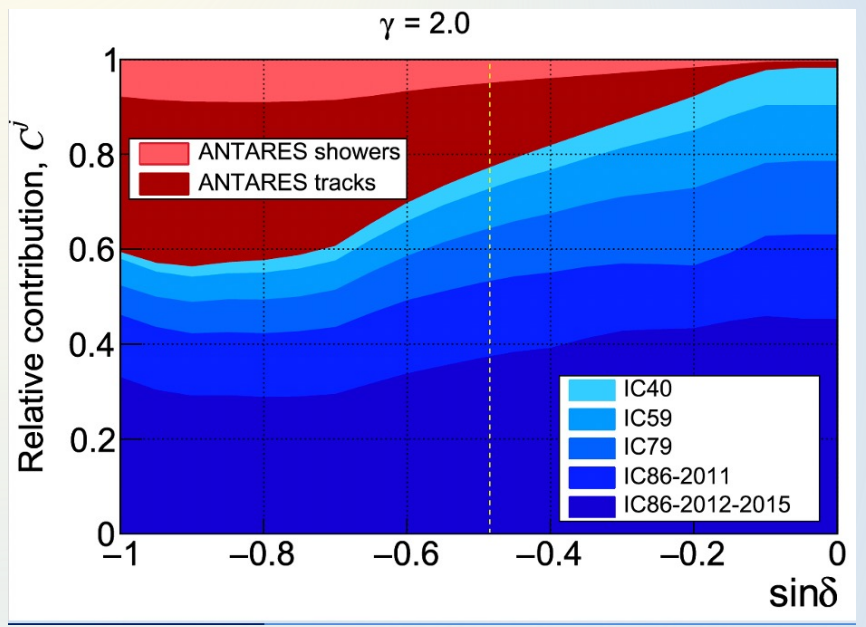
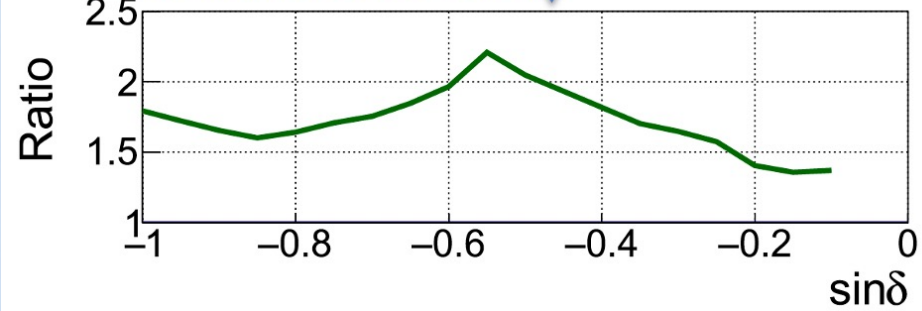


- ANTARES 2007–2015 : tracks & showers
- IceCube 2008–2015 : tracks
- Samples for the Southern Hemisphere

90% C.L. Sensitivity and Limits for $\gamma = 2.0$



Declination of Galactic Center \updownarrow



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>

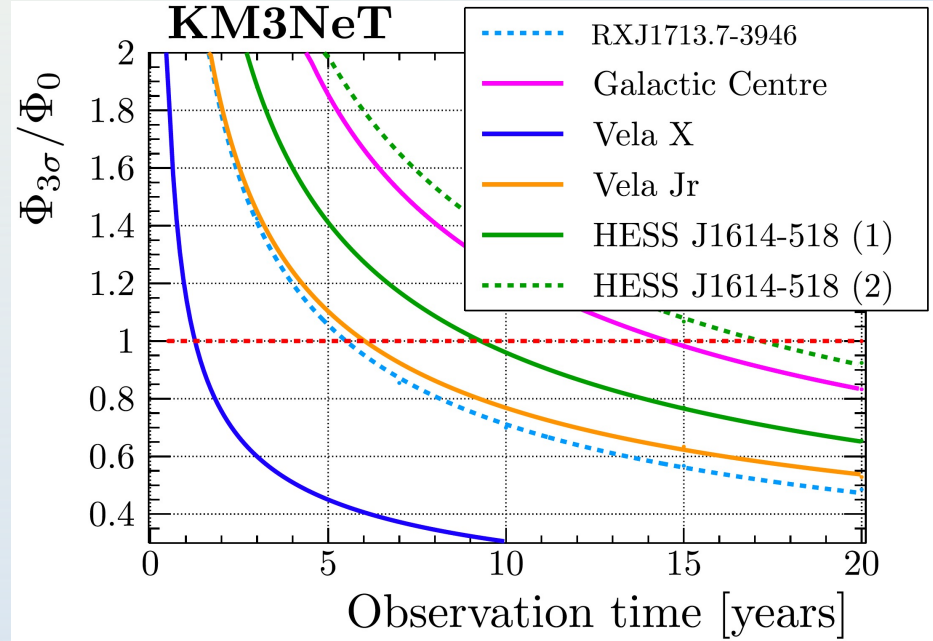
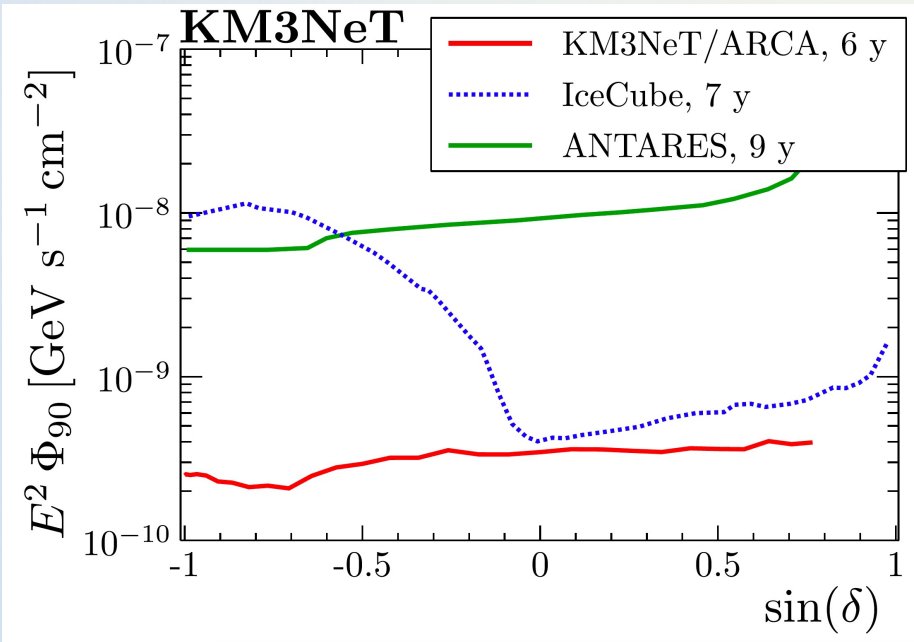
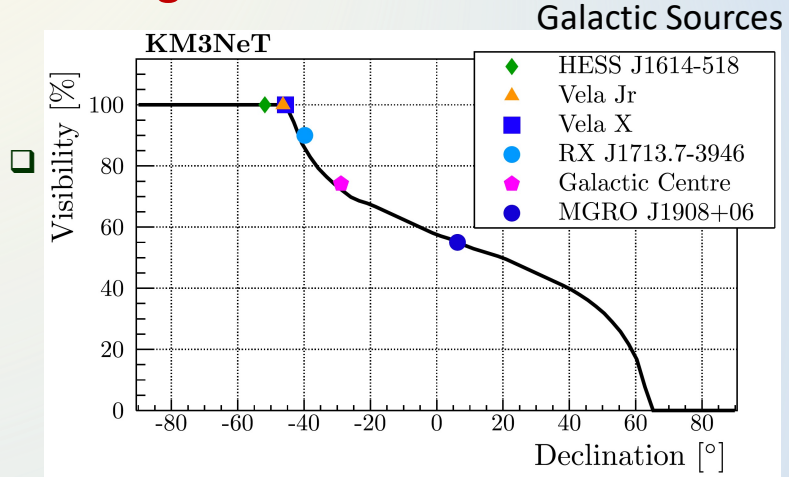


- ❑ Science case for KM3NeT-ARCA is centered on astronomy.
- ❑ 3σ median sensitivity reached in < 6 years for the strongest sources

❑ E^{-2} spectrum & fully hadronic scenario assumed

❑ Broad coverage.

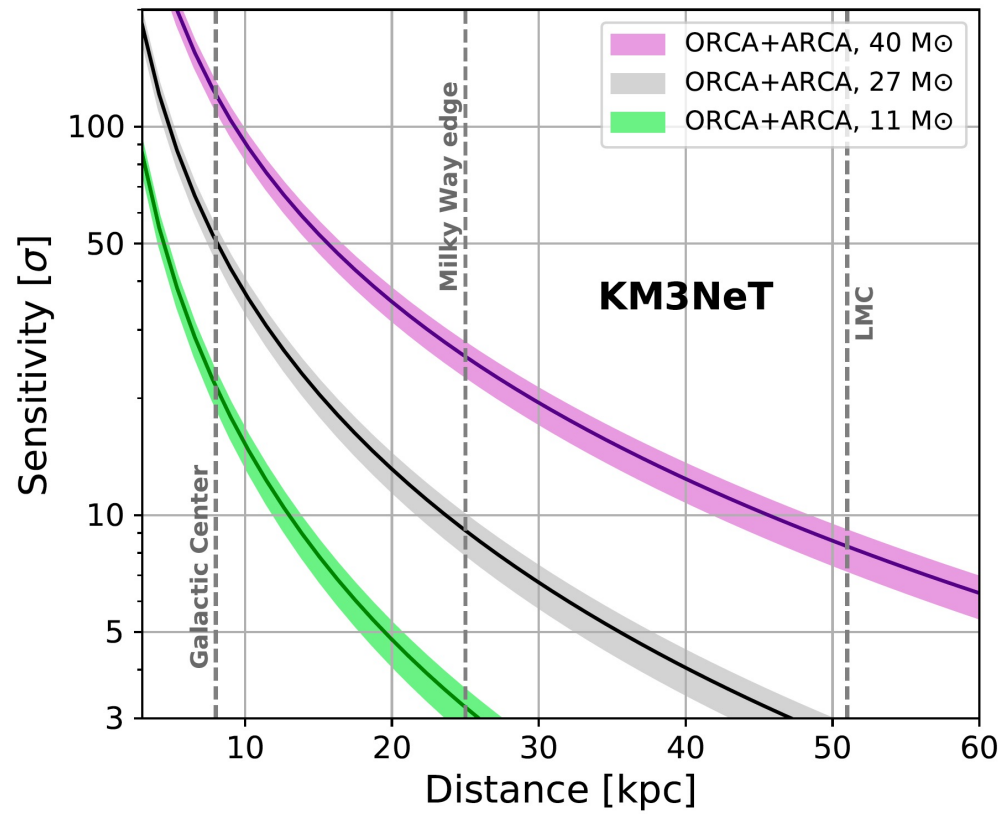
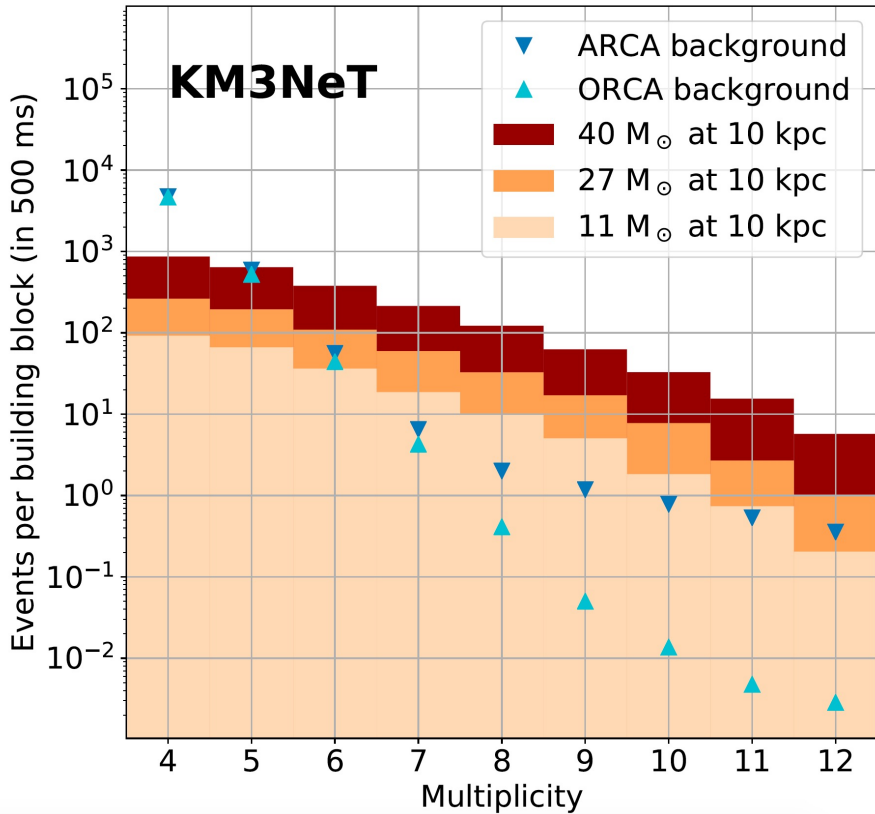
❑ Best sensitivity on Northern and Southern Sky





A trigger for CCSN already implemented Integrated in SNEWS

Supernova MeV neutrinos → collective excess of multi-fold coincidences on all DOMs
Real Time monitoring activity



ANTARES: Stacking catalog-based search



Catalog	ANTARES 2007–2017 : tracks p <i>pre-trial</i>	P <i>post-trial</i>	$\Phi_{90\%}^{UL}$
Fermi 3LAC All Blazars	0.19	0.83	4.3
Fermi 3LAC FSRQs	0.57	0.97	2.2
Fermi 3LAC BL Lacs	0.088	0.64	4.8
Radio Galaxies	4.8×10^{-3}	0.10	4.2
Star-forming Galaxies	0.37	0.93	2.0
Dust-obscured AGNs	0.73	0.98	1.5
IceCube High-energy Tracks	0.05	0.49	5.2

← in terms of the total E^{-2} flux normalization at 1 GeV (in units of $10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$).

Most significant:

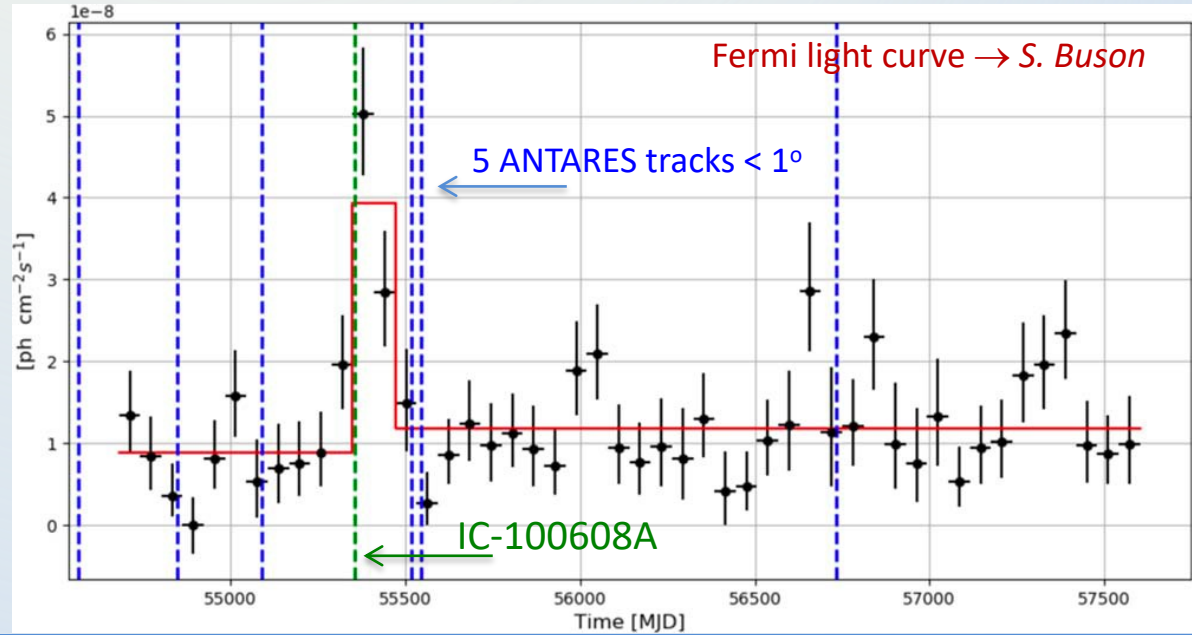
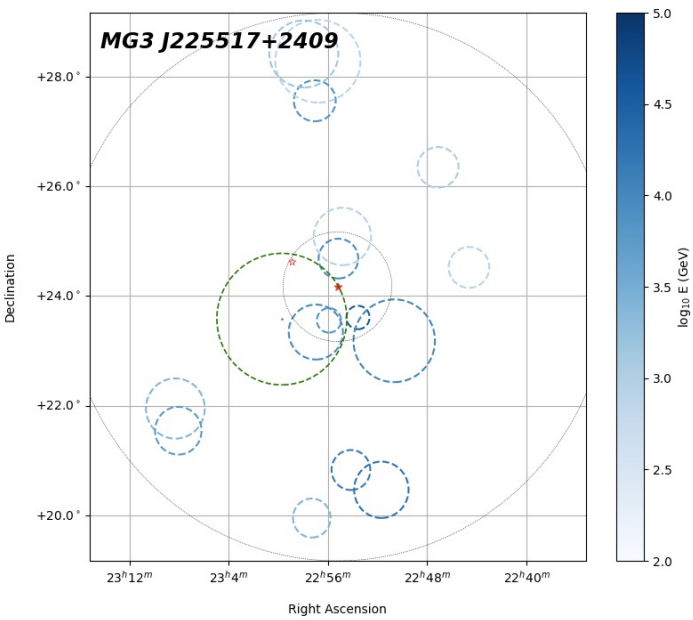
← MG3 J225517+2409

← 3C403

1.6 σ

Blazar MG3 J225517+2409 with ANTARES tracks & IceCube track

Mild excess seen for radio galaxies. Space & Time association:
ANTARES -> 2.3 σ & IceCube track -> 2.6 σ



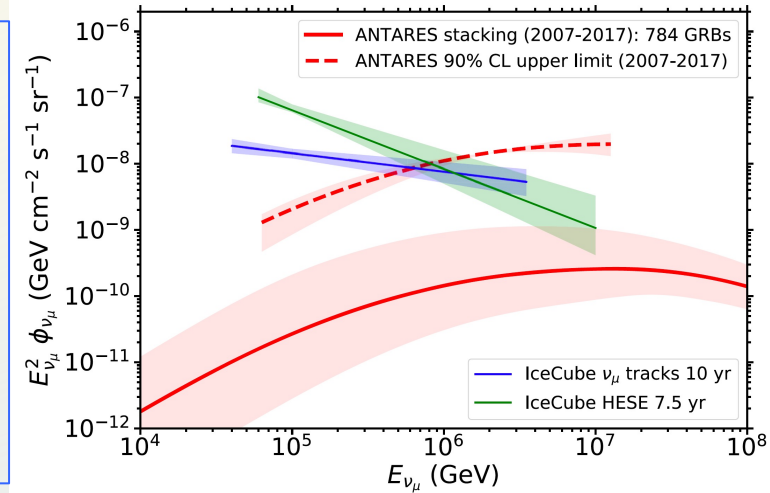


Search for ν counterparts to GRBs

Extremely energetic γ -ray bursts \rightarrow Associated ν production detectable?

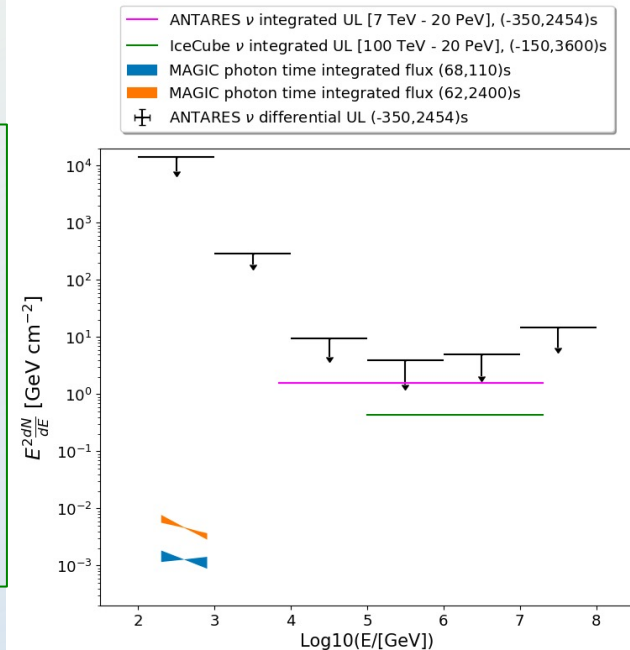
Stacking analysis of 784 GRBs (observed by “satellite-based” γ -ray instruments): ANTARES tracks 2007-2017

- ✓ No ν in **time & space coincidence** with prompt temporal phase of GRBs found
 \rightarrow 90% CL upper limits limits on ν Flux
- ✓ **GRBs contribute <10% of astrophysical flux < 100 TeV**



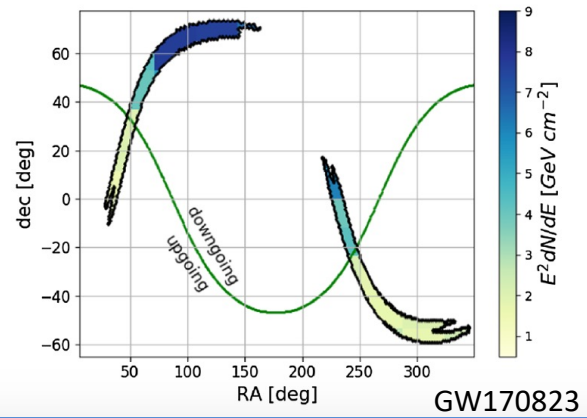
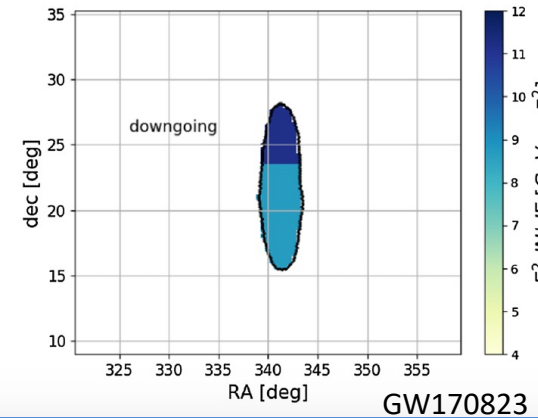
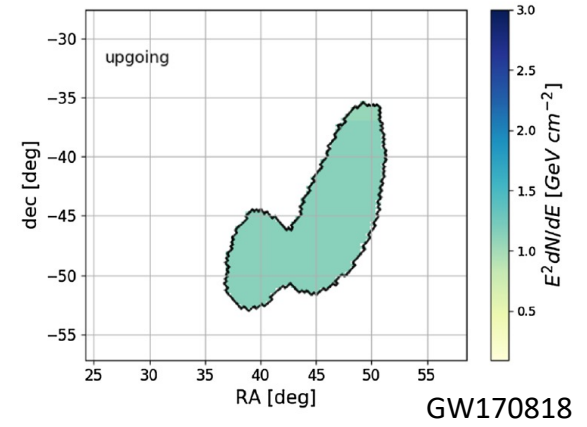
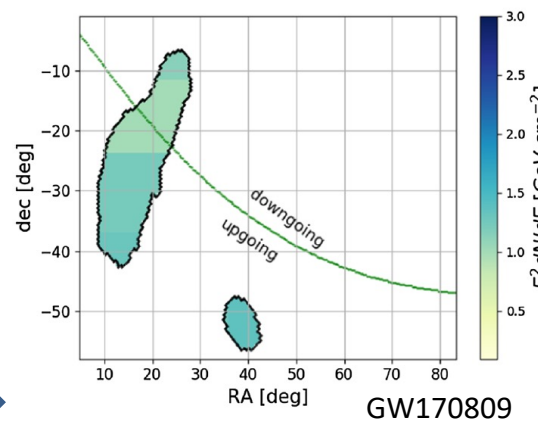
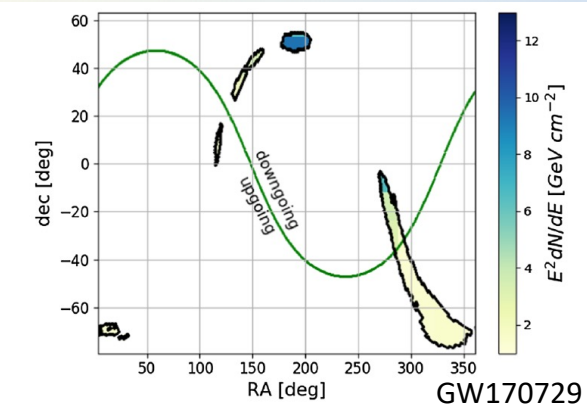
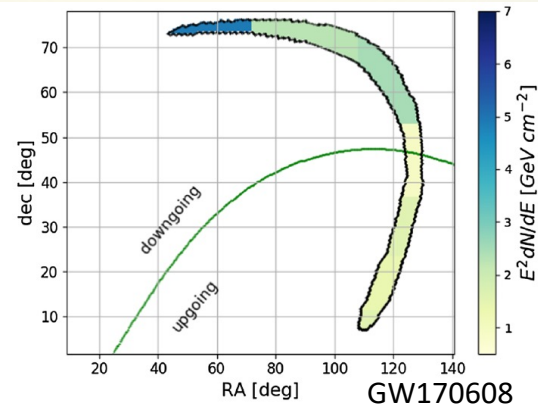
First 3 High energy γ -ray emissions observed by “ground-based” Imaging Atmospheric Cherenkov Telescopes:
H.E.S.S. : GRB180720A, GRB190829B ; MAGIC GRB190114C

- ✓ Follow-up search using ANTARES tracks & cascades during time of γ -ray emission
- ✓ No ν events found in time & space coincidence



Search for ν counterparts to Gravitational Waves

- Online alerts followed
- Results from counterpart searches after 24hr through GCN
- Refined offline searches (fully calibrated sample)
- Spatial + Time coincidence of GW
 - ➔ All-neutrino Flavour
 - ➔ All-sky time dependent analysis
- ➔ No events found ➔ Set limits
- Latest O2 BBH: Constraints on fluence and $E_{\nu,iso}$ for BBH
- Run O3 analysis ongoing ...

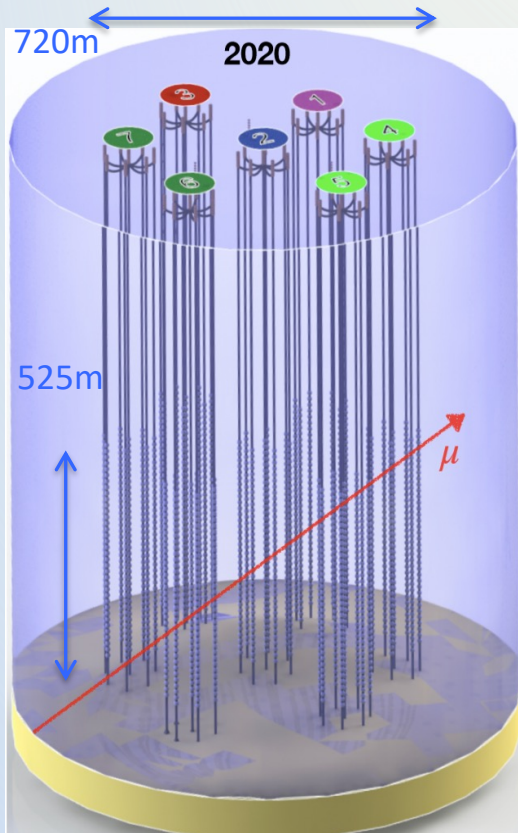


Eur. Phys. J. C 80, 487 (2020) | ApJ 870 (2019) 2 | Phys. Rev. D 96 (2017) 022005 | ApJL 848 L12 (2017) | Phys. Rev. D 93 (2016) 122010 | ApJL 850 L35 (2017) | JCAP 06 (2013) 008

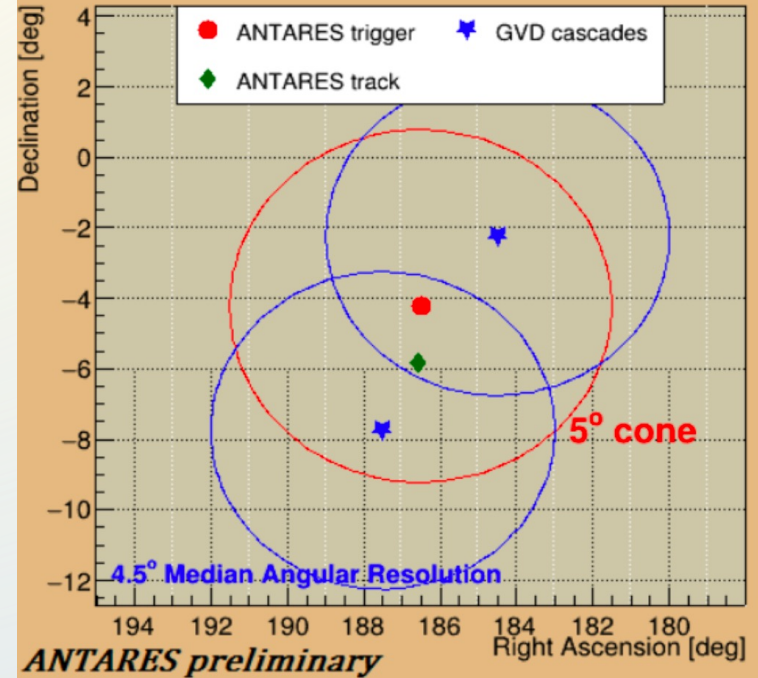
ANTARES alerts: GVD Baikal follow-up

31 ANTARES alerts sent to GVD Baikal, 25 followed up:

- Search within ± 500 s, ± 1 hour, ± 1 day within 5°
- GVD median resolution: “cascade” 4.5° | “track” 1.5°
- Search for time-space correlations in “single clusters”
- 2020: 7 clusters \rightarrow 2024: 14 clusters



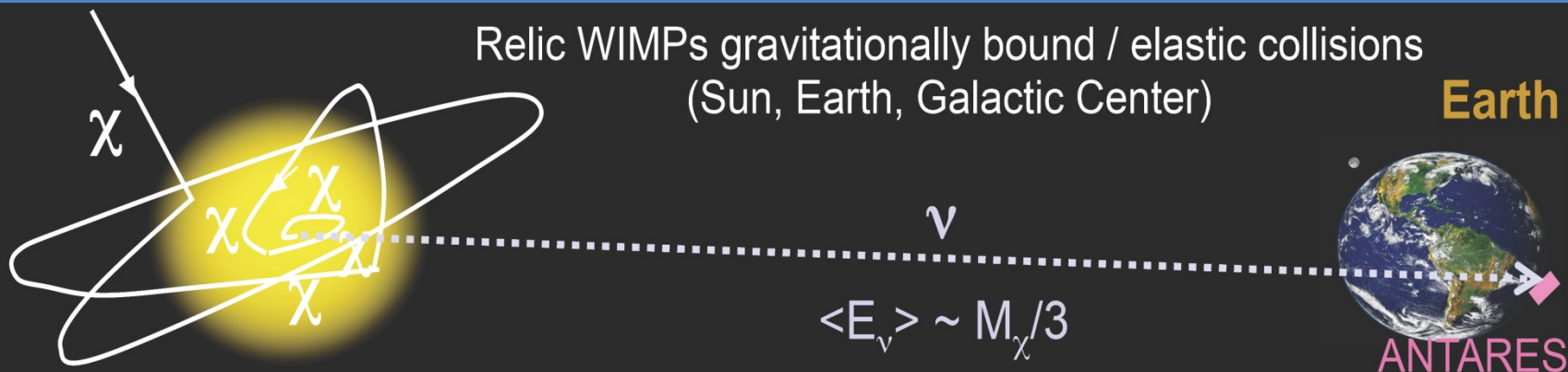
Alert A16: $RA = 186.5^\circ$, $\delta = -4.2^\circ$. HE trigger.



For 3 alerts, multiplets of GVD cascades reconstructed within ± 1 day

For 1 alert, additional ANTARES track found 9h after the alert at 2°

- 5 GVD clusters running during that period
- Background events/cluster/days within 5° : ranging from 0.02–0.05
- **No obvious source candidate close by**
- Follow-up ongoing with cascades (ANTARES) and tracks (GVD) in same time window



- ❑ Gravitational trapping & accumulation of DM particles in the center of massive astrophysical objects like the **Galactic Center**, the **Sun core** or the **Earth nucleus**.
- ❑ Searches for a possible ν_μ **excess from these objects** due to DM annihilation \Rightarrow very clean signature with **no significant astrophysical background expected**.
- ❑ Explored Signal channels: $WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu_\mu \bar{\nu}_\mu$
- ❑ WIMP annihilations/decays can yield significant flux as secondary products, sensitive to halo models, at medium-high energies [10 GeV–100 TeV].
- ❑ Background estimated from *time-scrambled* data

Galactic Center/Milky Way:

- PRD 102 (2020) 082002 ANTARES + IC
- PLB 805 (2020) 135439
- PLB 769 (2017) 249
- JCAP 10 (2015) 068

Sun:

- PLB 759 (2016) 69
- JCAP 05 (2016) 016
- PoS 536 (ICRC2019)

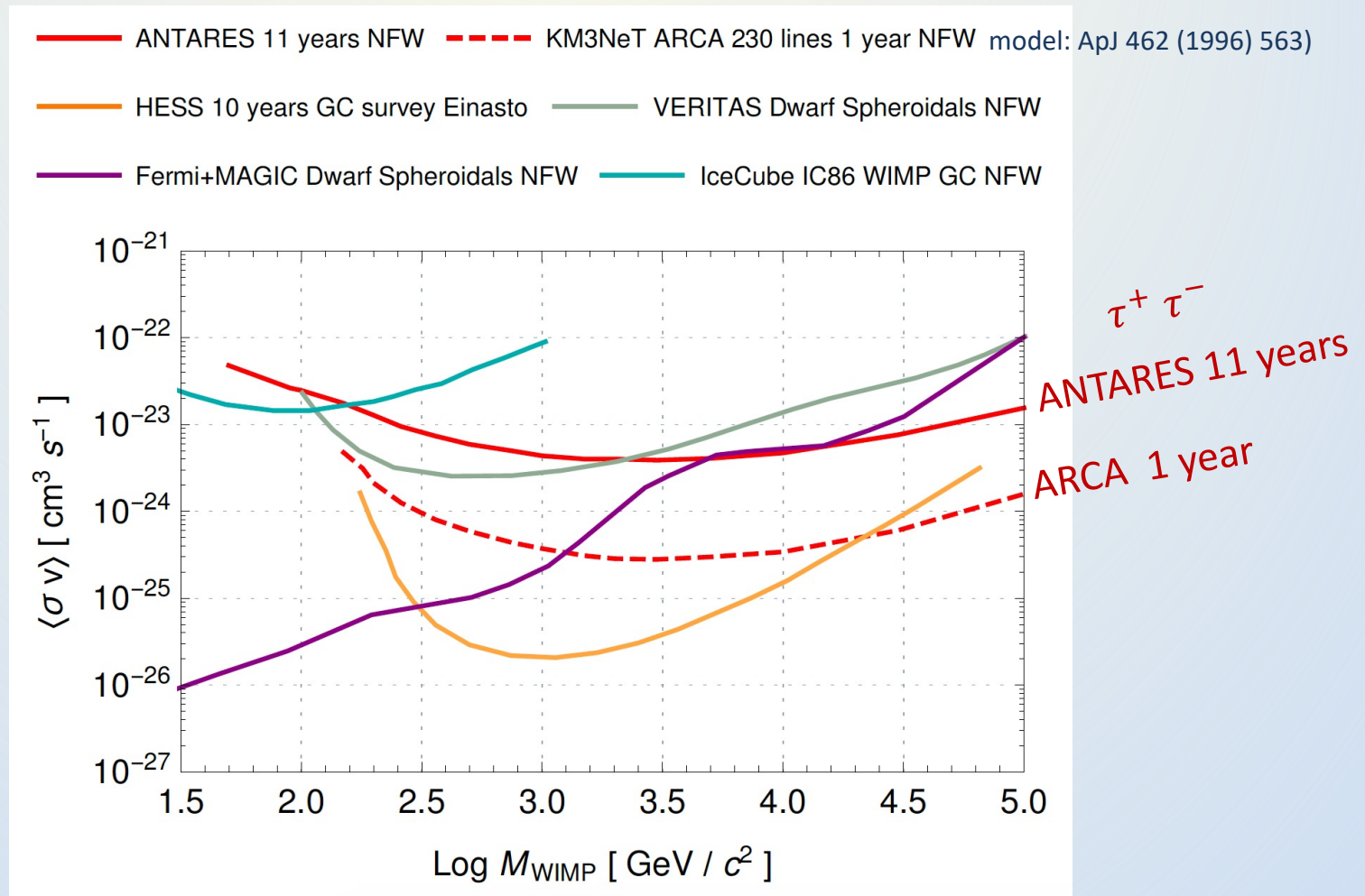
Earth:

- Phys. Dark Univ. 16 (2017) 41



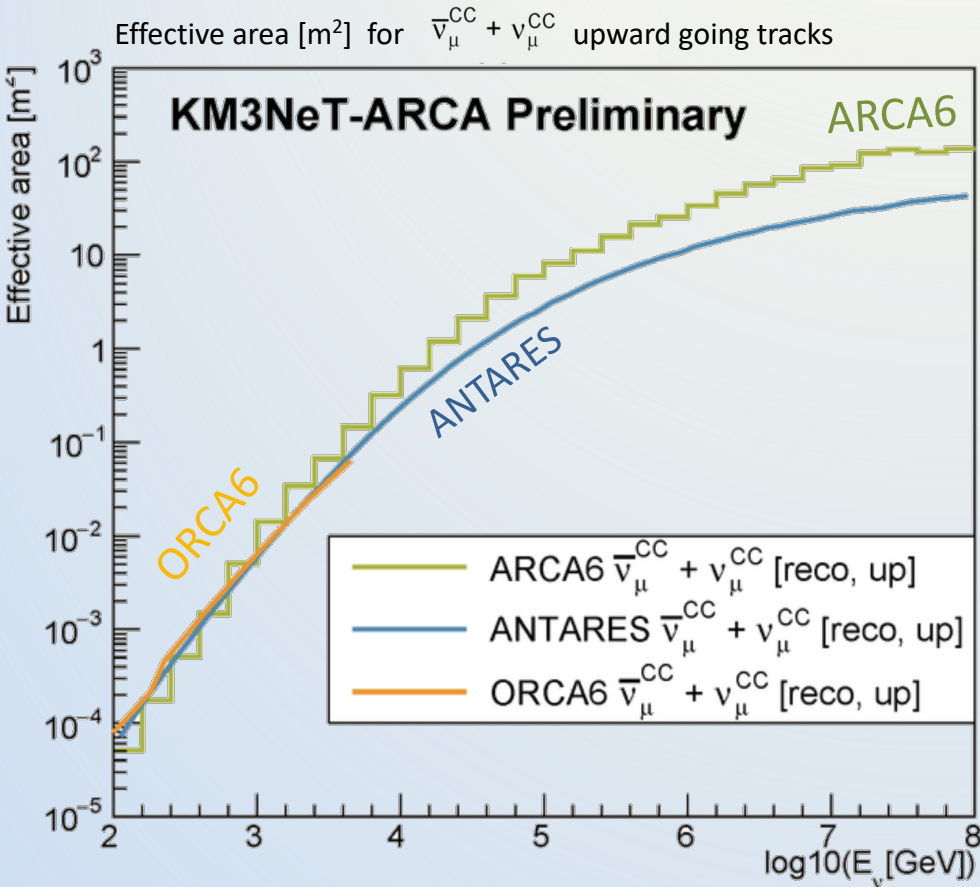
ν_μ tracks only

- Data: 2007 – 2017 (3170 livedays)
- Galactic Center: Good visibility by ANTARES (~66%)
- Five annihilation channels. Three halo profiles tested (NFW...). $m_\chi \in [50 \text{ GeV} - 100 \text{ TeV}]$
- Limits on the thermally averaged annihilation cross section $\langle \sigma \cdot v \rangle$ inferred in the absence of signal excess

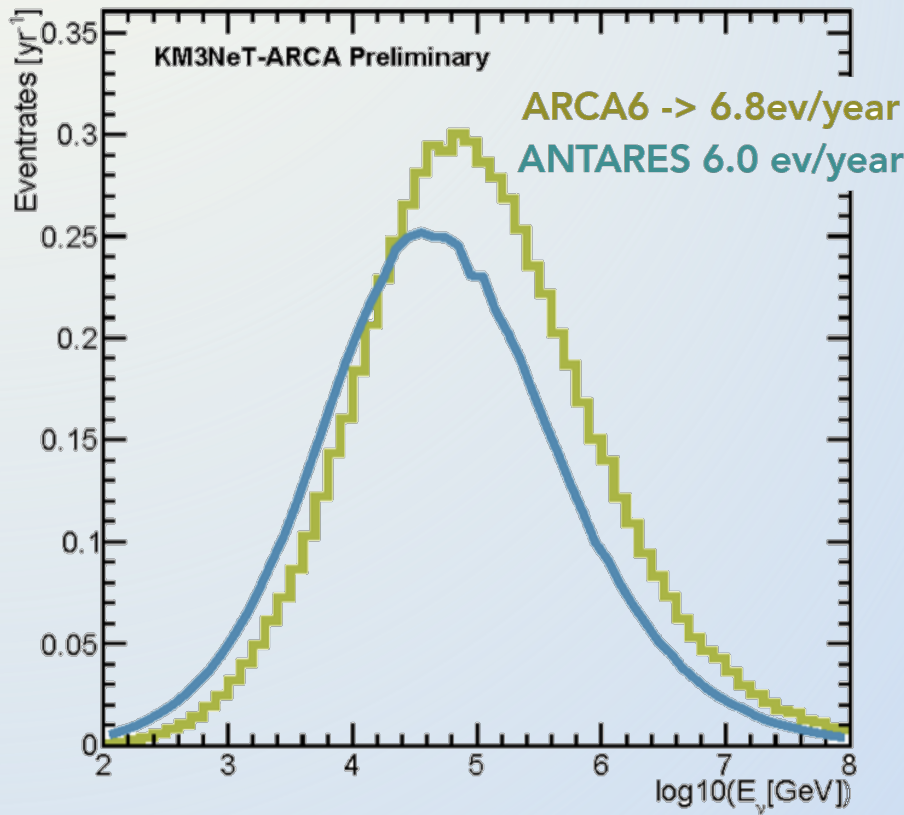


ORCA : 6 DUs deployed & taking data
ARCA : 6 DUs deployed & taking data

Number of events per year for a cosmic diffuse flux
 $\phi_\nu = 10^{-8} E^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

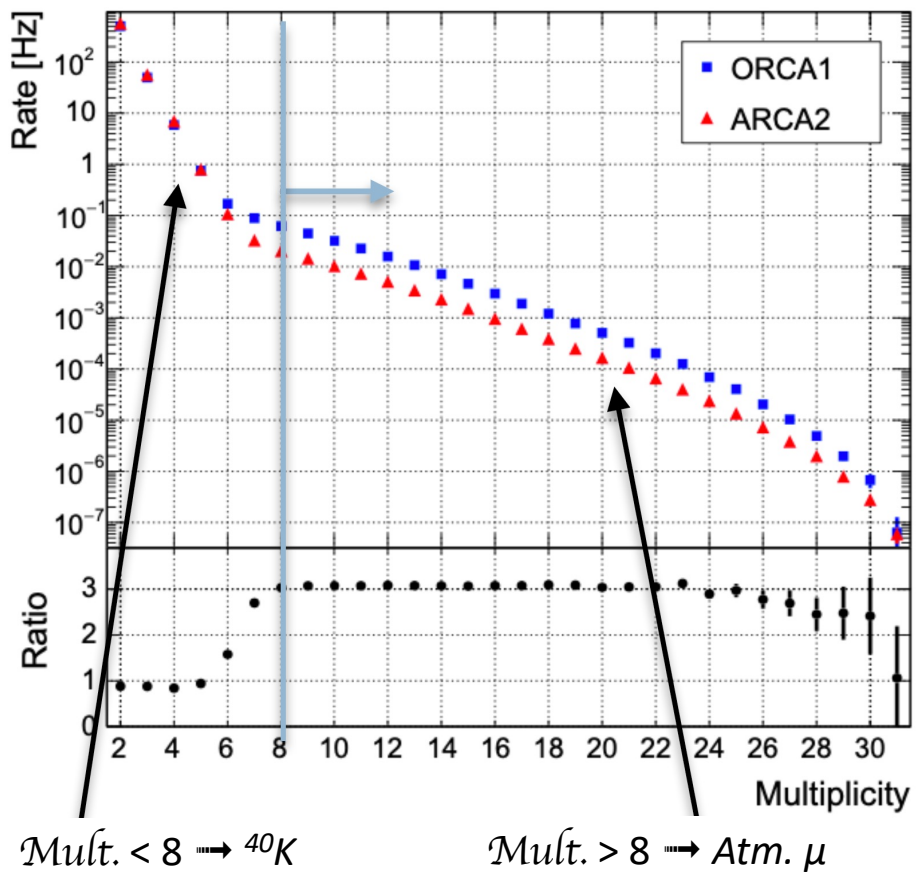


Event rate [yr⁻¹] for $\bar{\nu}_\mu^{\text{CC}} + \nu_\mu^{\text{CC}}$ upward going tracks

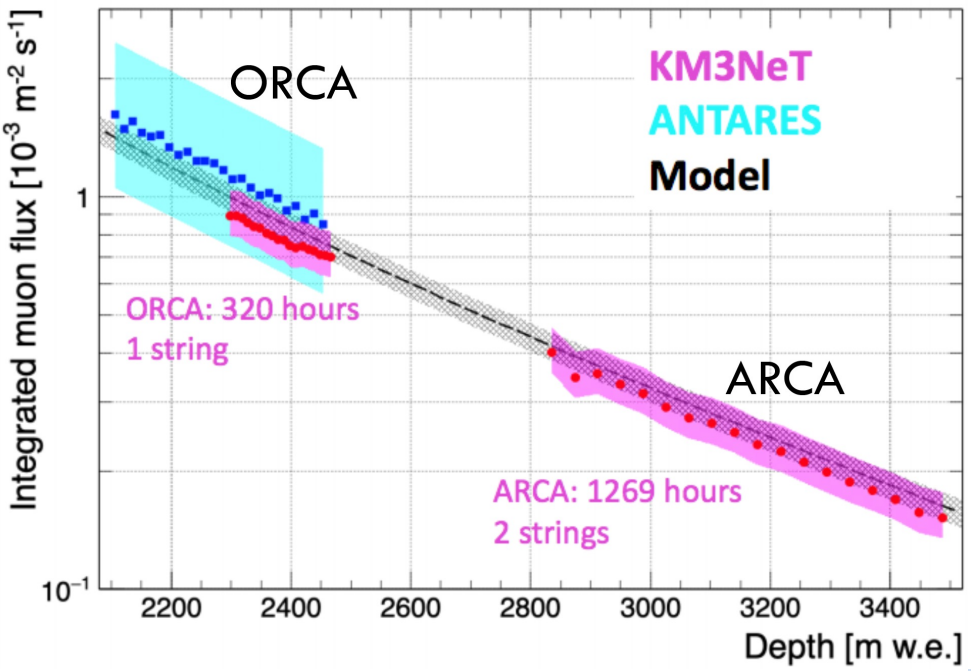


Measurement of the atmospheric muon flux as a function of the depth

KM3NeT Multiplicity plot for PMTs in DOM



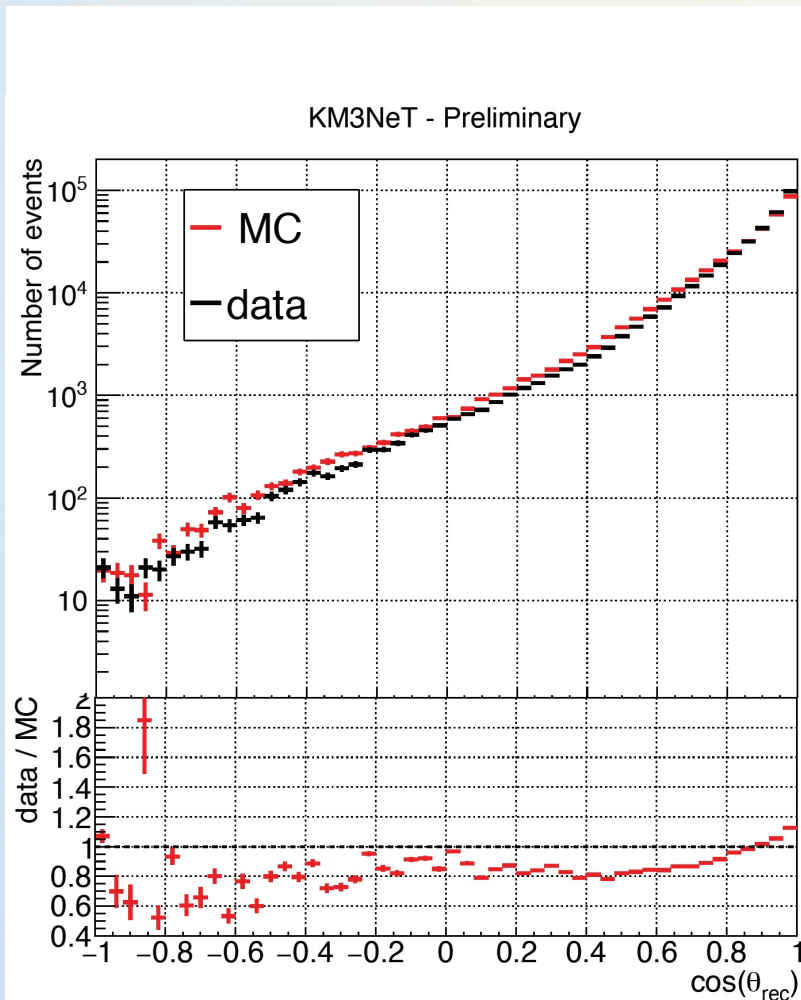
Atmospheric μ flux depth dependent: Mult. ≥ 8



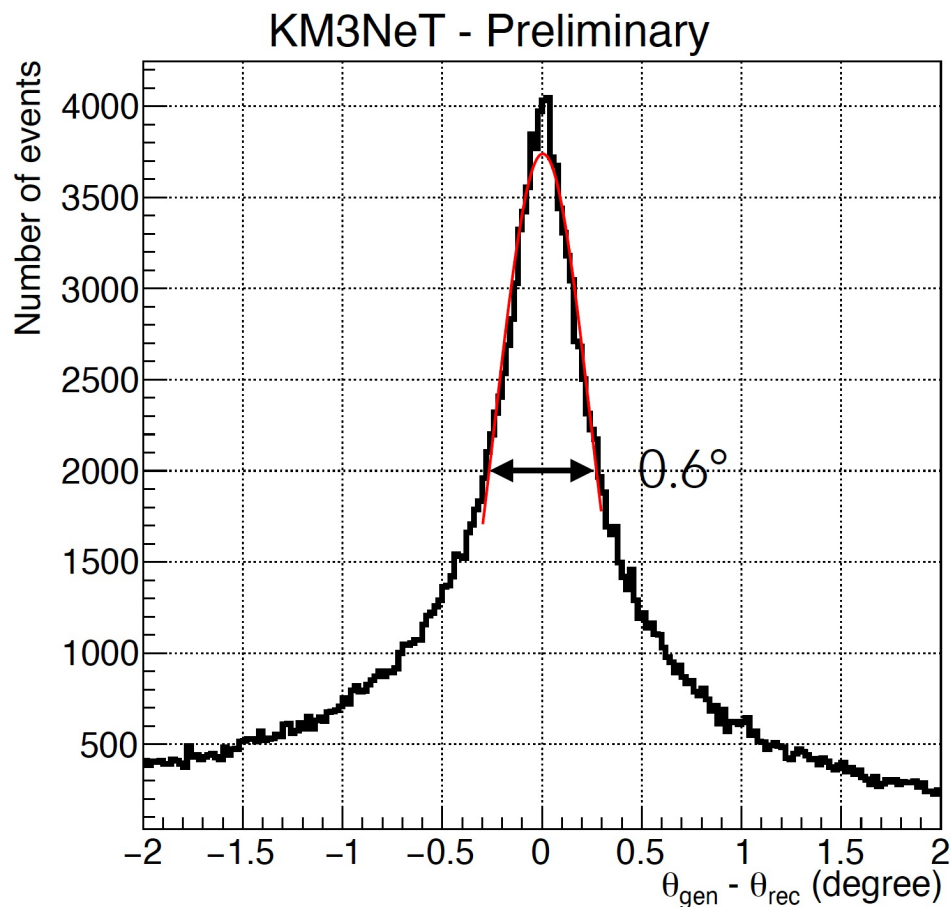
About 1 month after deployment:

- ✓ First results from **time/position calibration** setup
- ✓ First results from **“run-by-run” Monte Carlo**

More results on ORCA6 in talk by:
V. VAN-ELEWYCK



Zenith angular resolution 0.6° (FWHM)



June 2021 🖱️

4 DUs at ORCA site

September - October 2021 🖱️

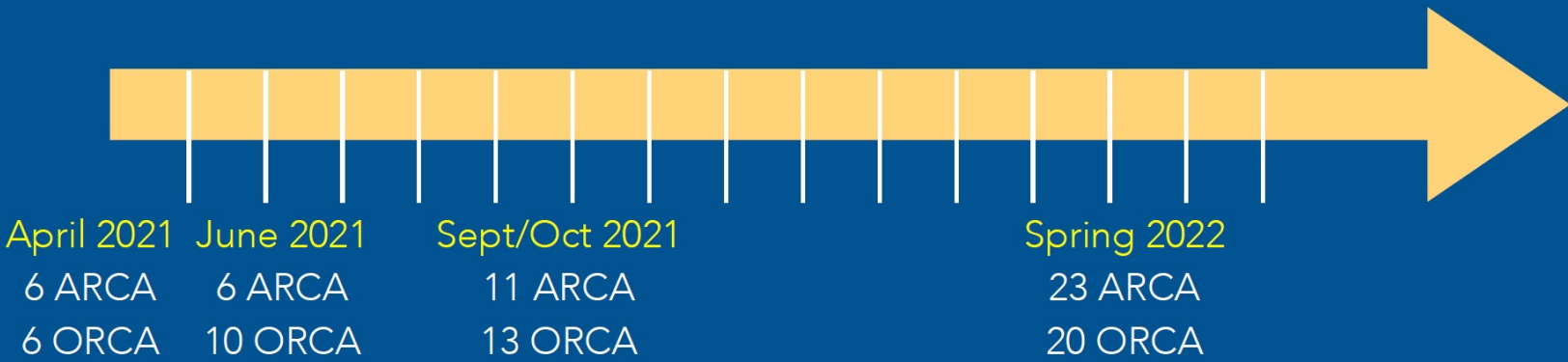
5 DUs at ARCA site

3 DUs + CU (Calibration Unit) at ORCA site

Spring 2022

12 DUs + 1JB +1 CB (Calibration Base) + 1 IU (Instrumentation Unit) at ARCA site

7 DUs at ORCA site



ANTARES

- ✓ **Good/stable** data taking since 2008 – a multi-disciplinary observatory
- ✓ **Broad Science Program** : competitive results thanks to excellent performance
- ✓ A lively and vibrant **multi-messenger program** search
- ✓ **Joint studies** with several partners

KM3NET

- ✓ **First results** from 6 ARCA + 6 ORCA DUs
- ✓ **Good Data/MC agreement**
 - ➔ good understanding of detector
- ✓ Expect to **Double number of DUs** by the end of **2021**
- ✓ **Spanning 8 decades** in energy: oscillations (ORCA) & astronomy (ARCA)

