ANTARES and KM3NeT:

status, results and perspectives

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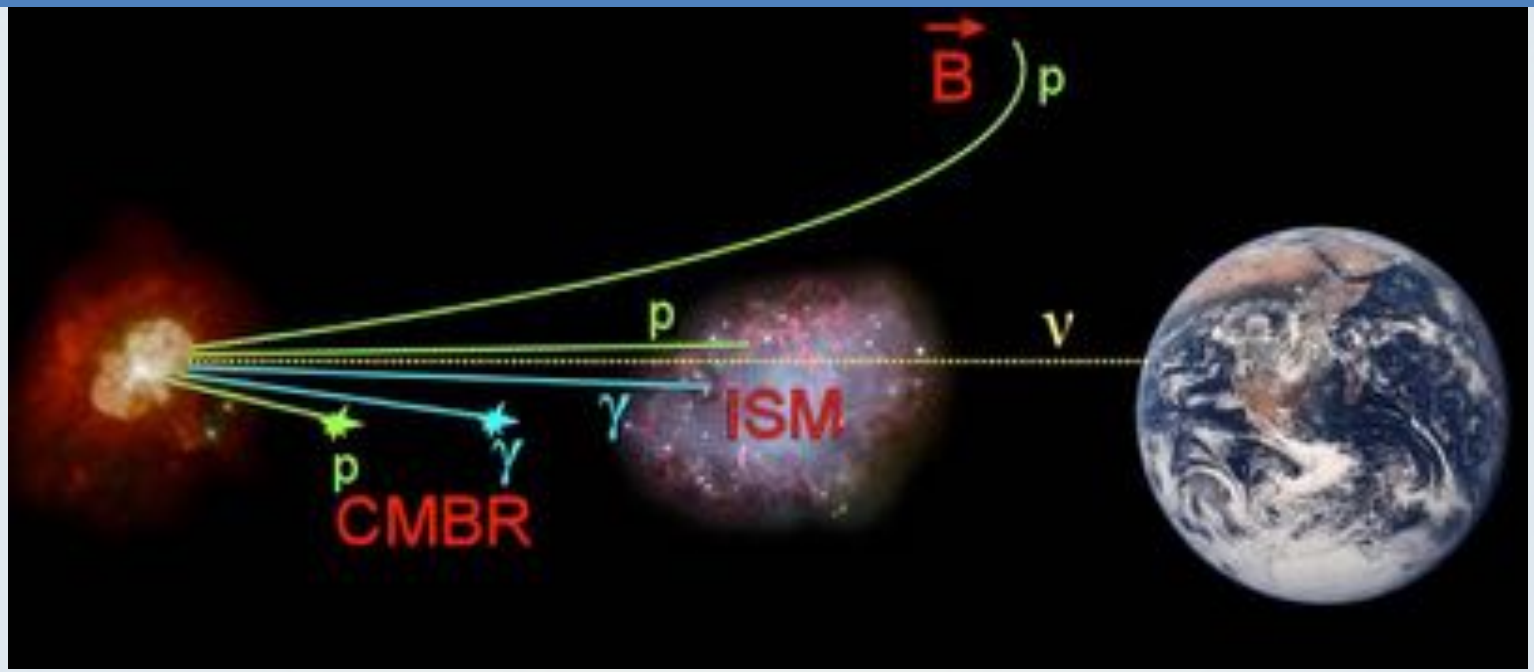
On behalf of the ANTARES and KM3NeT Collaborations

28th International Workshop on Weak Interactions and Neutrinos
WIN2021
University of Minnesota (*online*), June 7–12, 2021

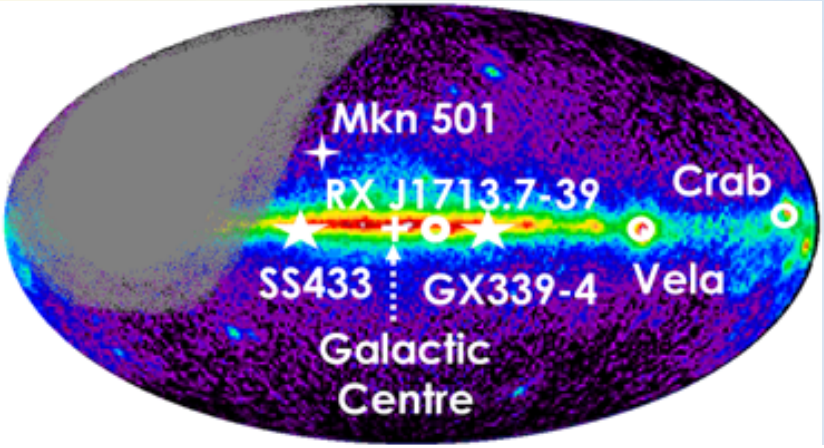
Neutrino Astrophysics

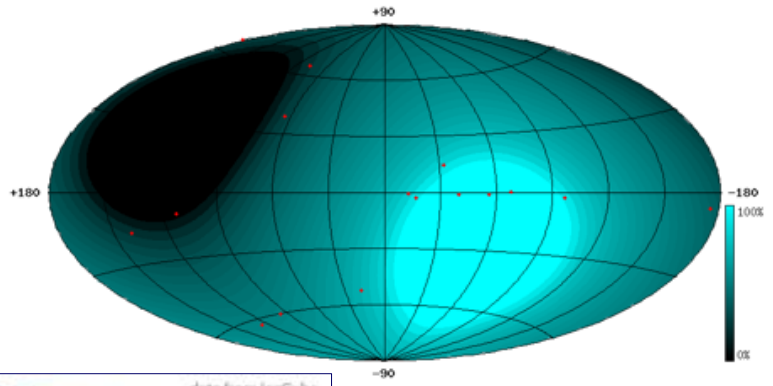


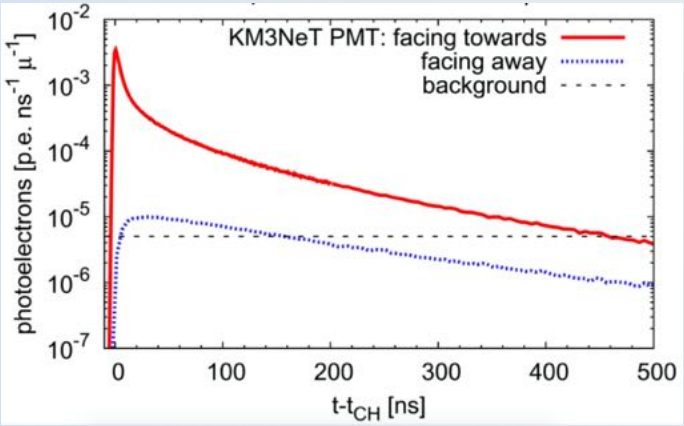
- **Origin and acceleration of Cosmic Rays ?**
- **Neutral messengers point back to their sources**
  - ✓ neutrons are short-lived, photons are likely to interact ➔ neutrinos
- **CR interactions produce neutrinos in meson decays**
  - ✓ Search for a diffuse flux from unresolved sources
  - ✓ Search for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

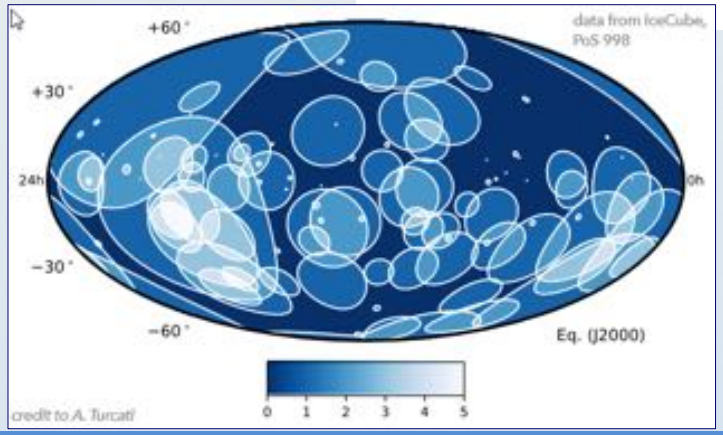
Mediterranean Neutrino Telescopes

- **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.









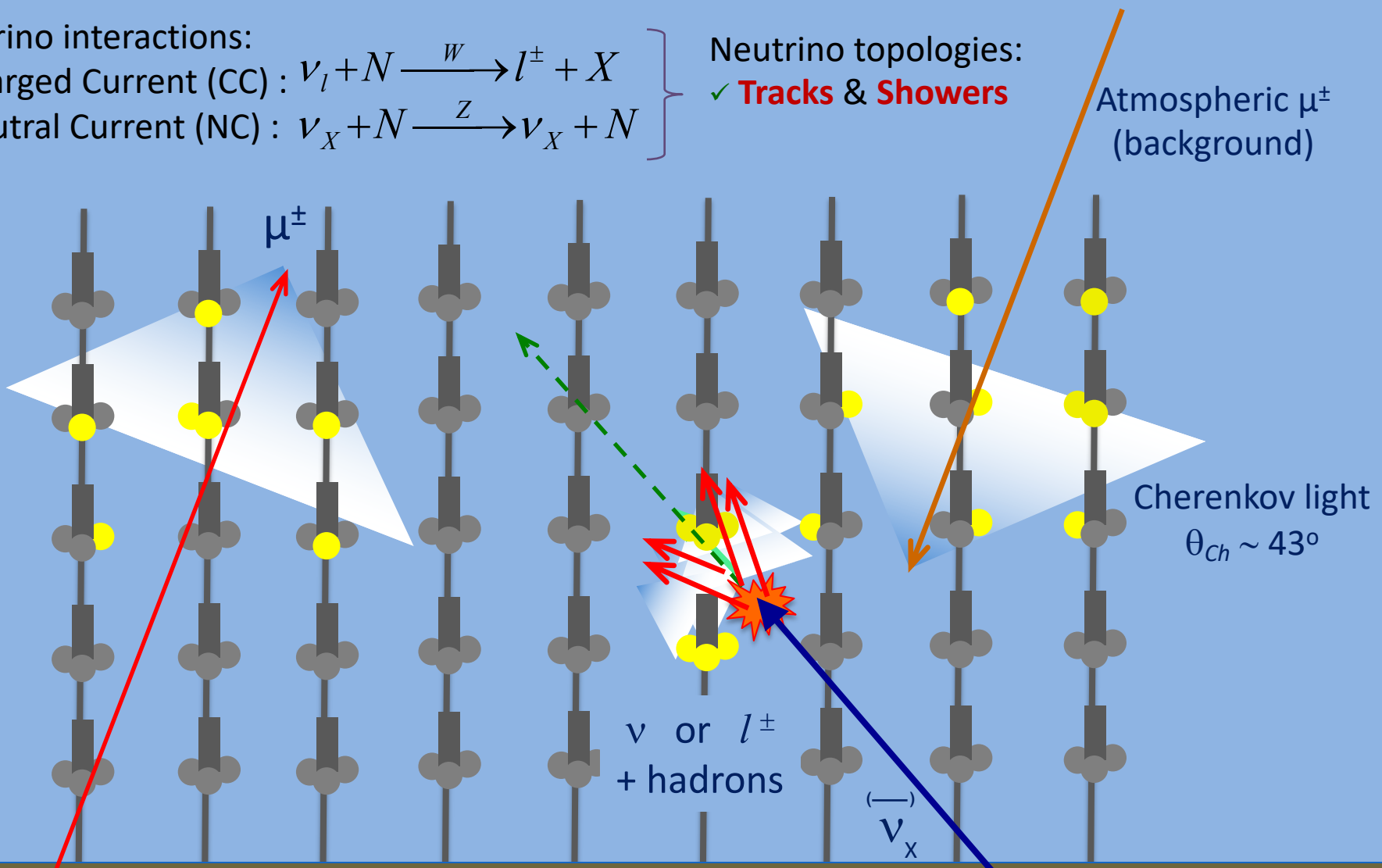
Neutrino detection principle

Neutrino interactions:

- ✓ Charged Current (CC) : $\nu_l + N \xrightarrow{W} l^{\pm} + X$
- ✓ Neutral Current (NC) : $\nu_X + N \xrightarrow{Z} \nu_X + N$

Neutrino topologies:

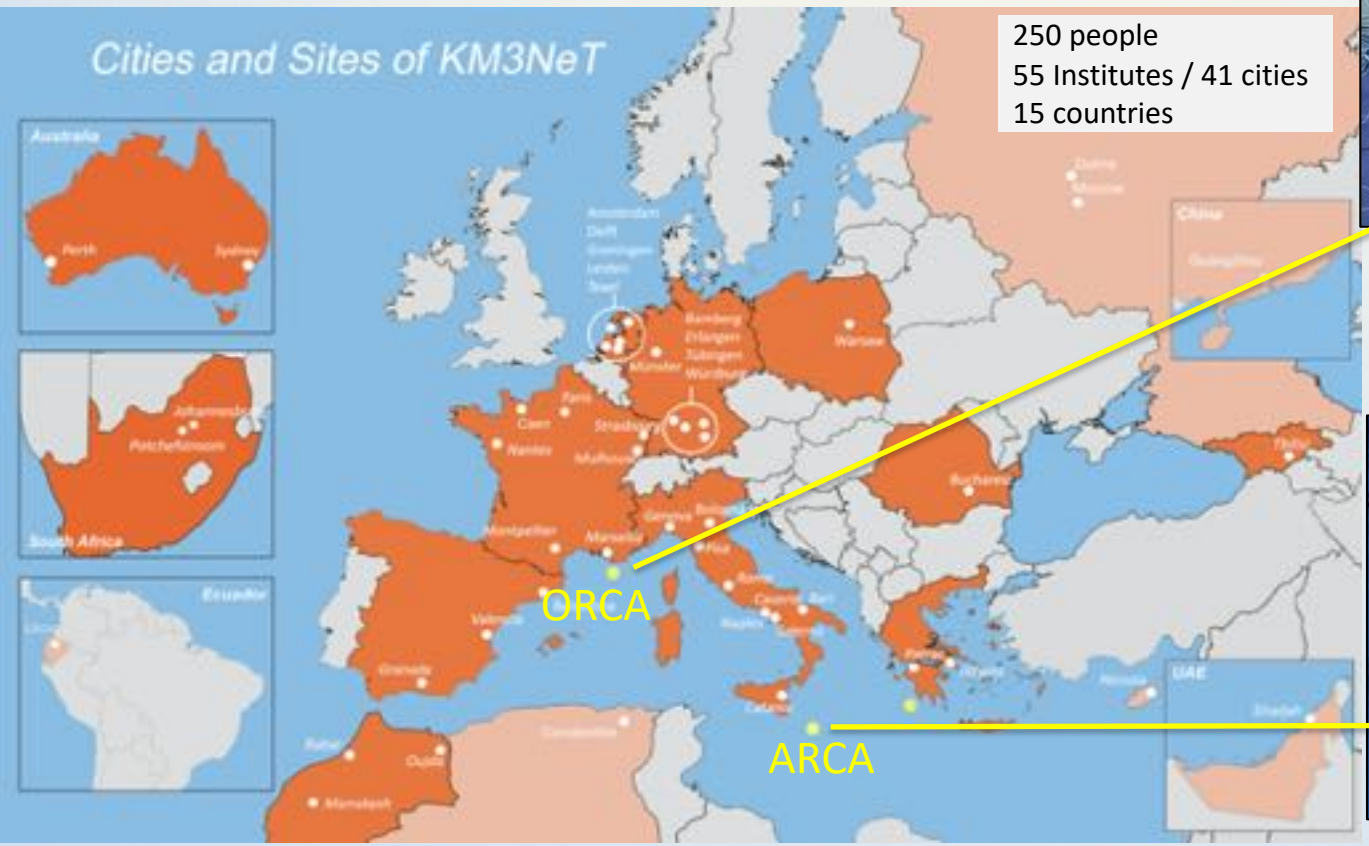
- ✓ **Tracks** & **Showers**

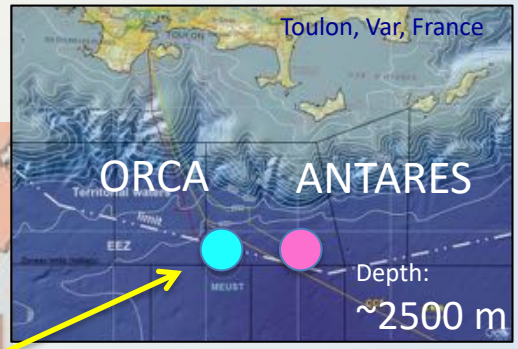


Mediterranean ν telescopes

ANTARES: ~10 Mt instrumented mass. Completed in 2008

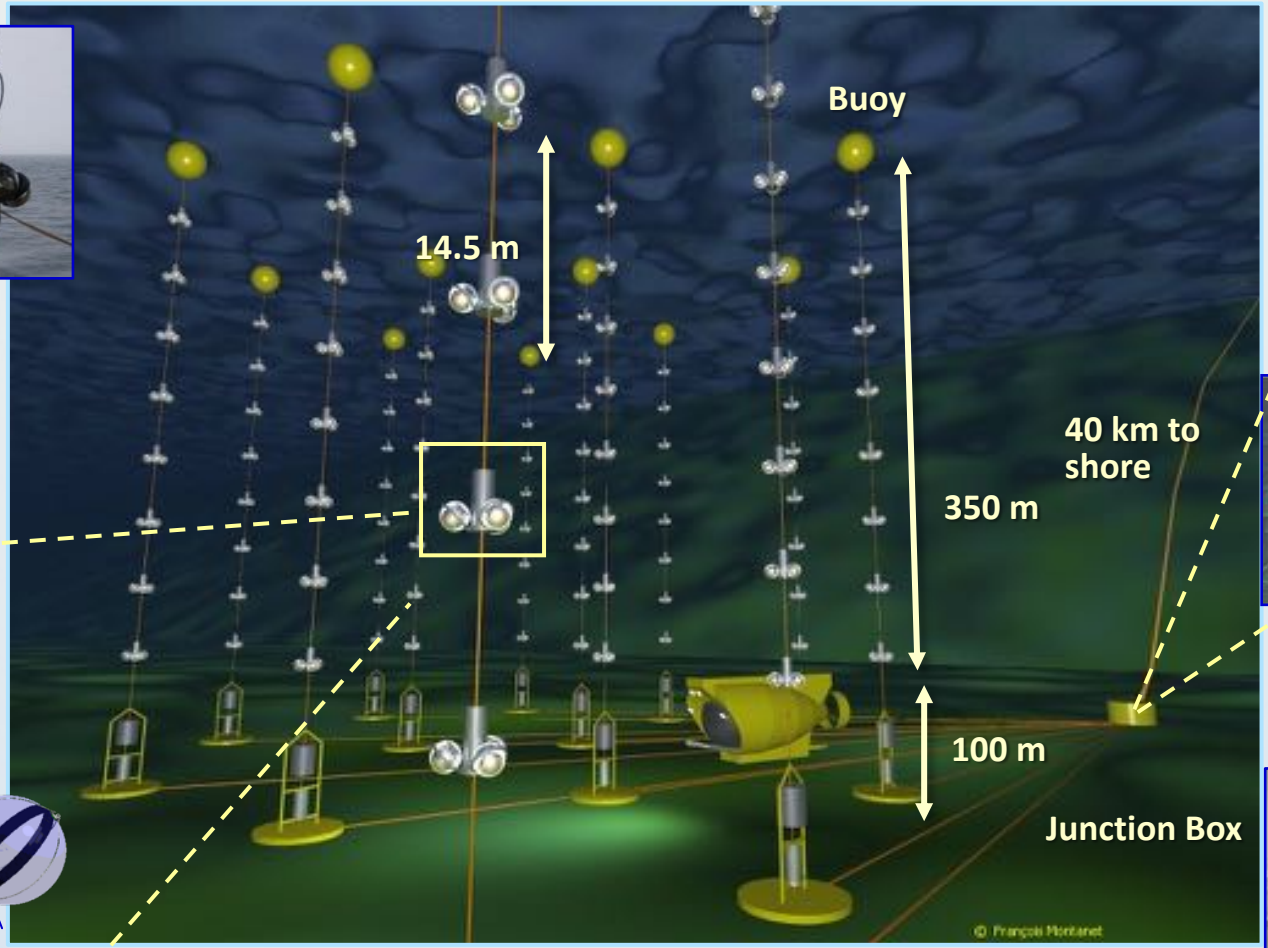
KM3NeT: A distributed research infrastructure with
2 main physics topics: ORCA & ARCA





Low-energy (~GeV) studies of atmospheric neutrinos

High-energy (TeV-PeV) neutrino astrophysics



12 lines (885 PMTs)

25 storeys / line

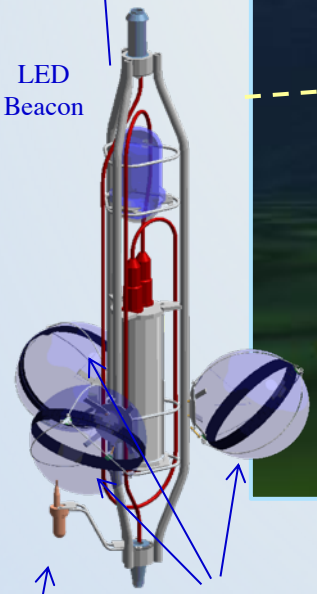
3 PMTs / storey

5-line setup in 2007

Completed in 2008

Junction Box

Shore station



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

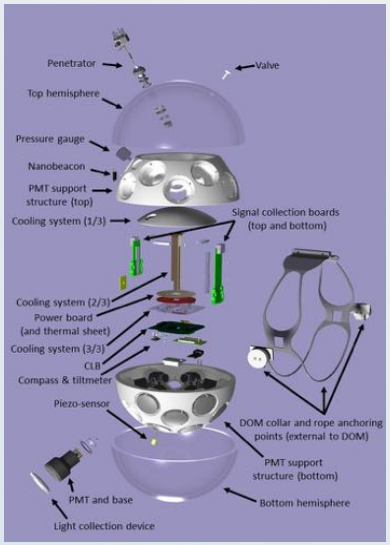
KM3NeT Technology

Letter of intent for KM3NeT 2.0
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

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

LOM Deployment

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

Junction Boxes

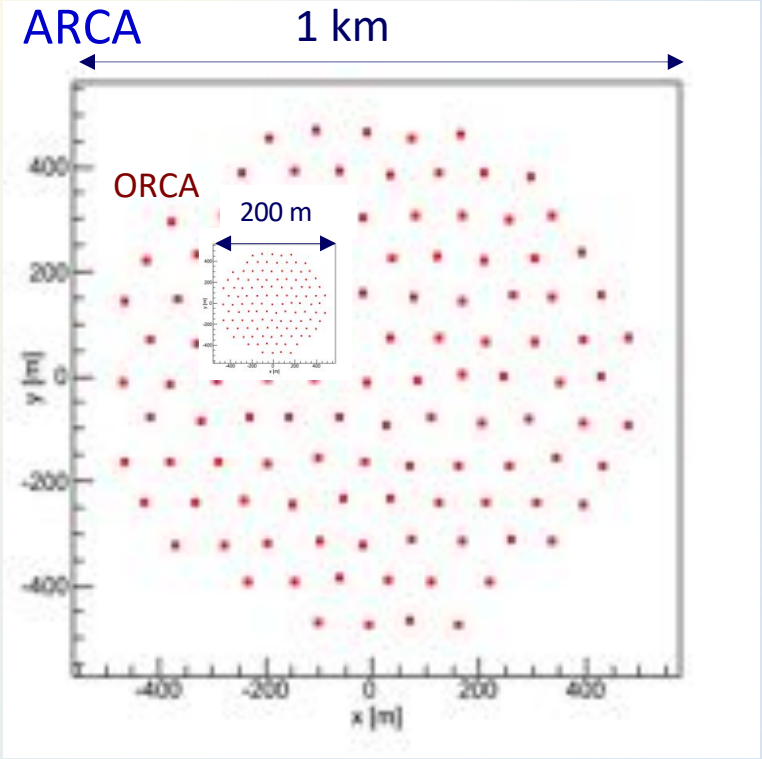
Seafloor network 👉 Electro-optical cables and JBs

KM3NeT : ARCA and ORCA

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

Building Block

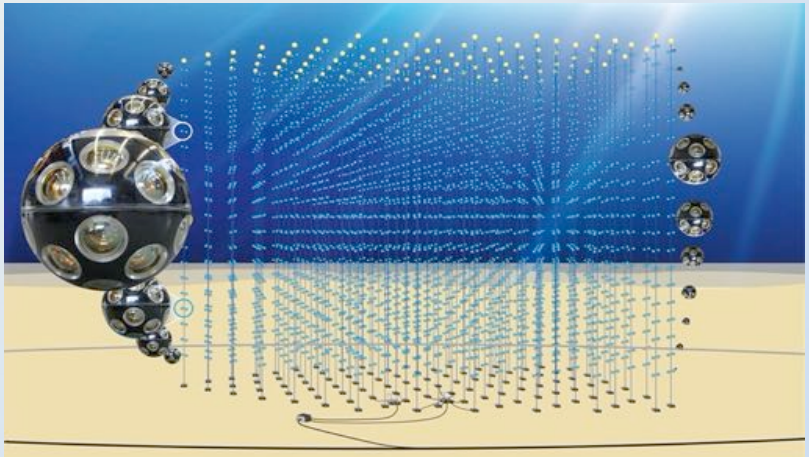
- **ARCA (Gigaton scale)** — 2 building blocks
- ORCA (Megaton scale) — 1 building block



See:
talk by: V. VAN-ELEWYCK on ORCA
poster by: J. Coelho on Sterile ν & NSI

Same technology, denser layout

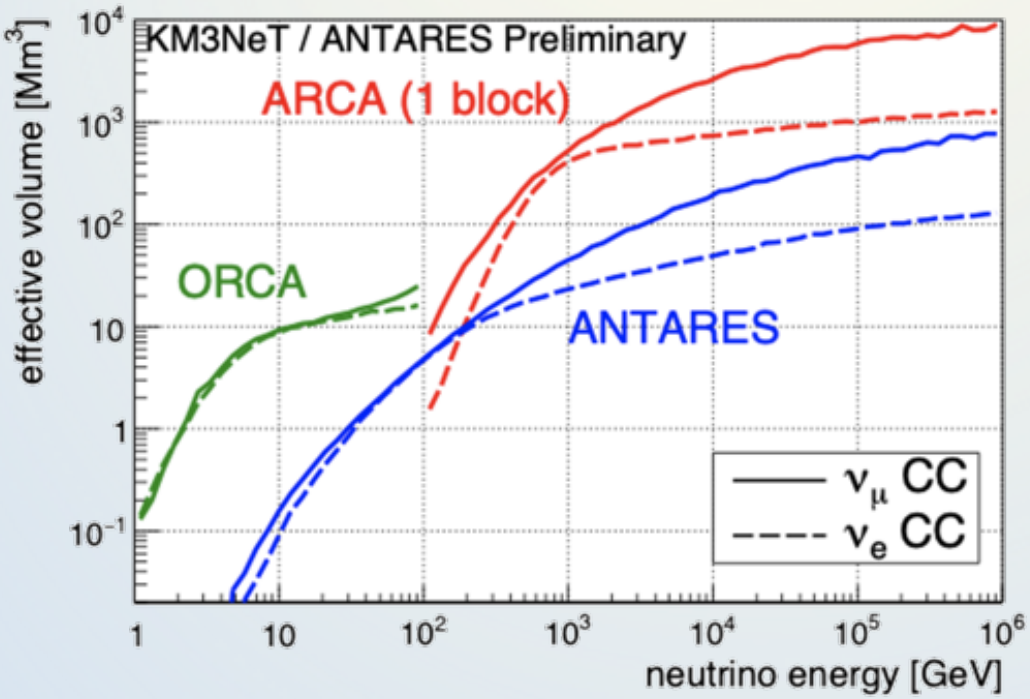
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mton	~ 2 × 0,5 Gton



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

200 m

~7 Mt

∅ ~ 200 m
115 strings

400 m

~10 Mt

ANTARES

∅ ~ 180 m
12 strings

700 m

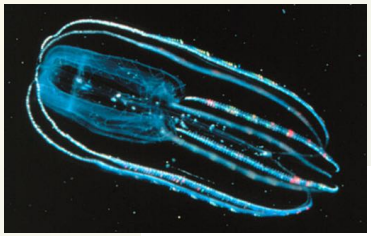
KM3NeT ARCA

~ 2 × 0.5 Gt

∅ ~ 1 km
2 x 115 strings

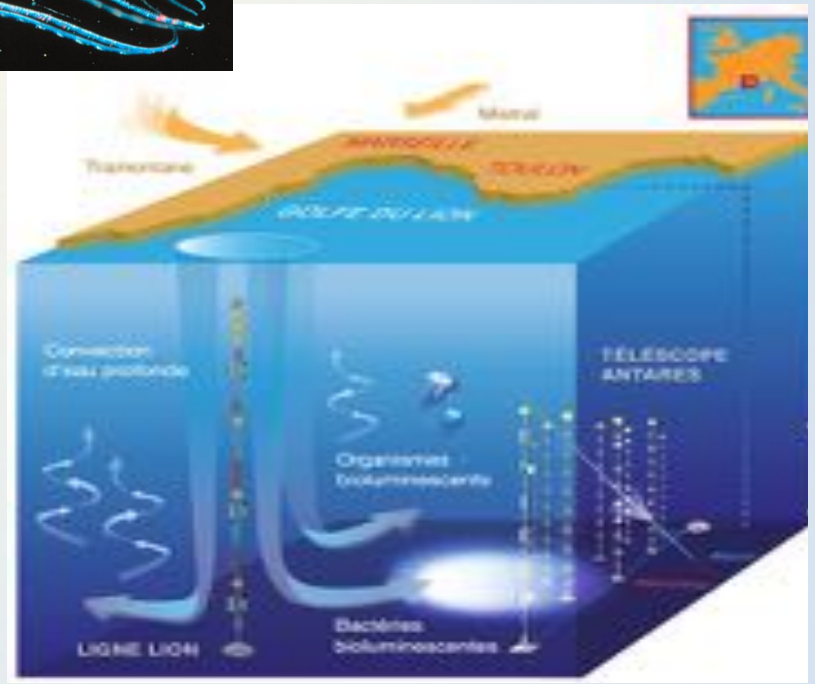
Connections to Earth and Sea sciences

✓ 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

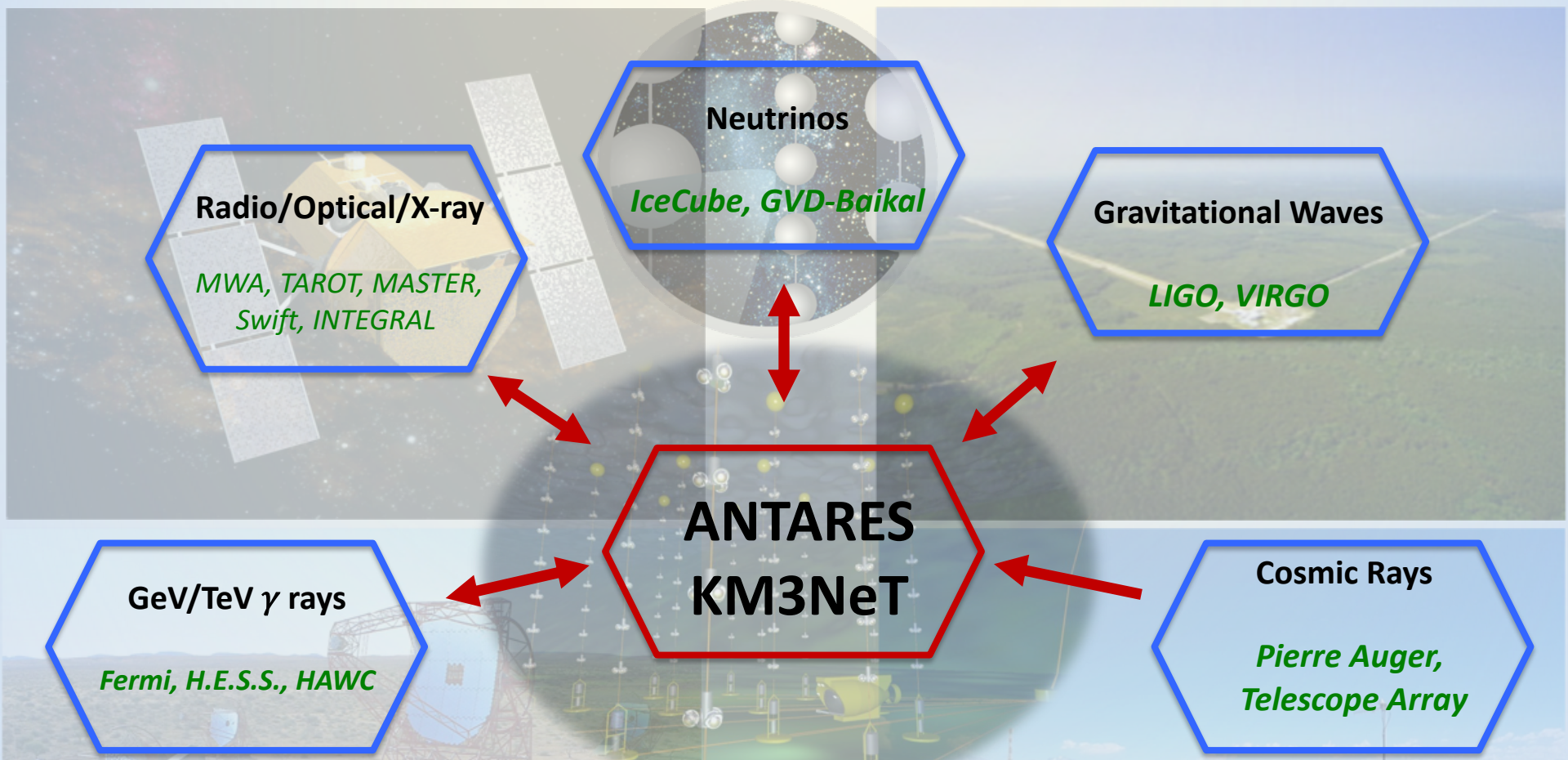
📖 Deep-Sea Research I 58 (2011) 875–884
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

✓ 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

Multi-messenger Network



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 <0.5º. 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° above 10 TeV

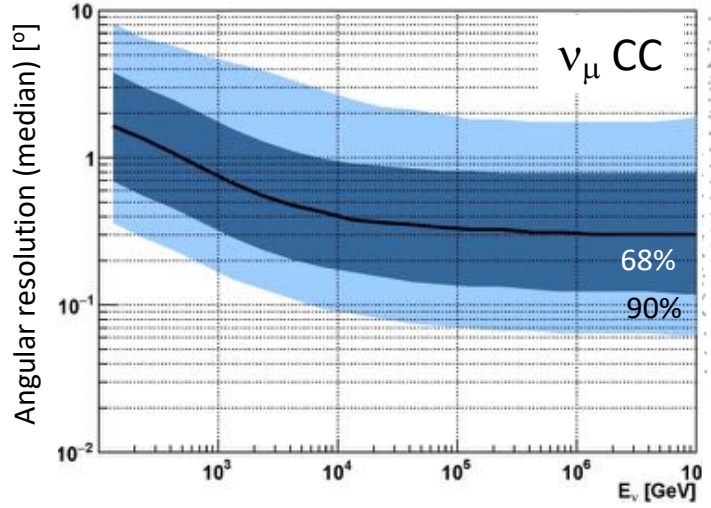
Energy Resol. ~ 0.35 in $\log_{10}(E_{reco}/E_\mu)$

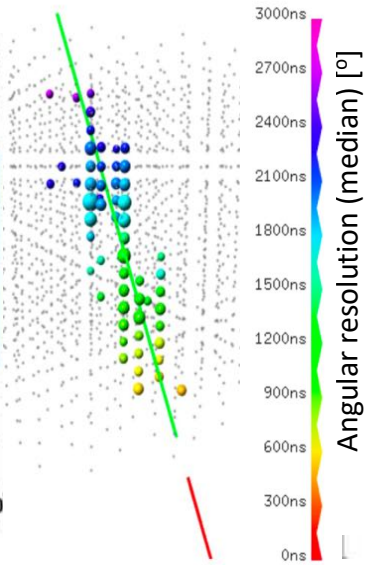
Ang. Resol. < 0.2° above 10 TeV

Energy Resol. ~ 0.27 in $\log_{10}(E_{reco}/E_\mu)$

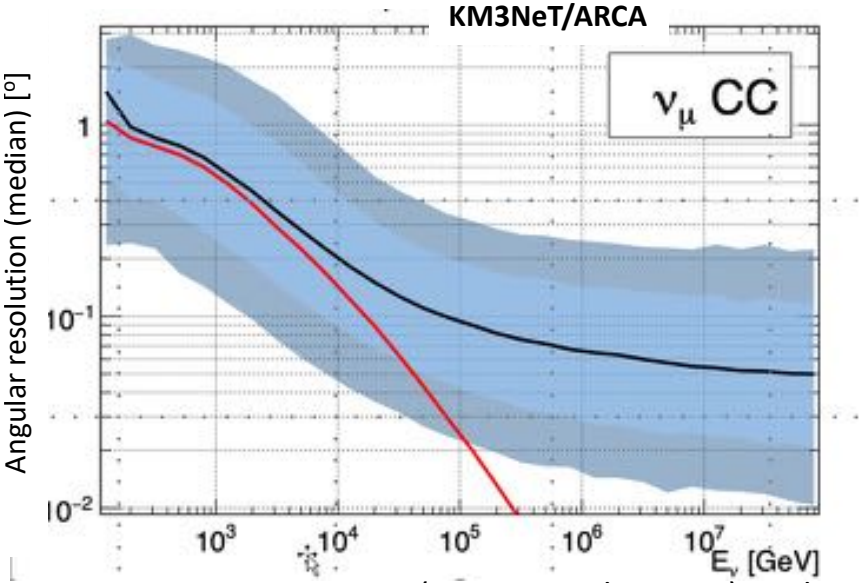
(10 TeV < E_μ < 10 PeV)

ANTARES





KM3NeT/ARCA



(ν_μ – true μ direction) angle

Reconstruction Performances (2/2): "Showers"

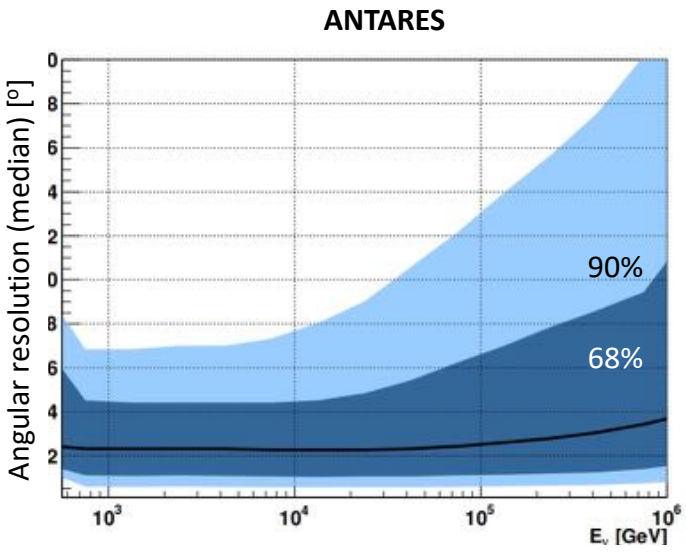
NC ν_{all}
CC ν_e

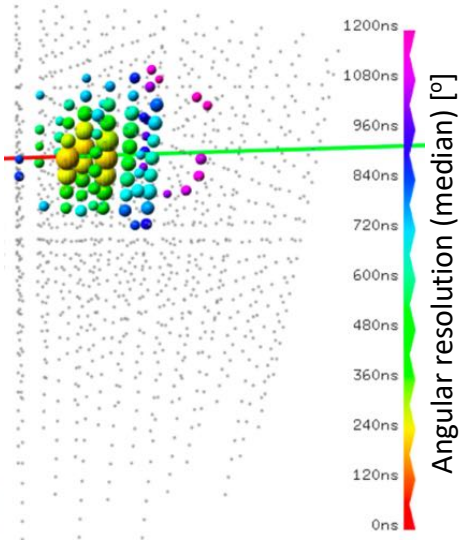
Shower events also used for astronomy

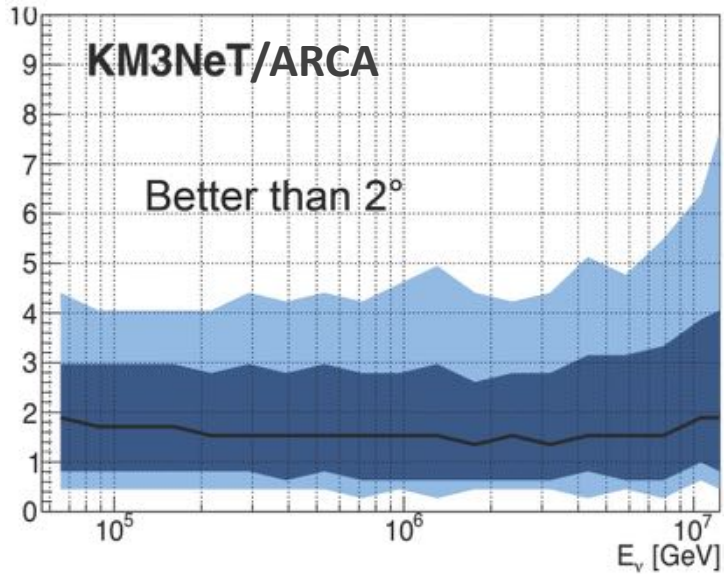
- Contained events → Better energy resolution
- Almost no atmospheric background

Angular Res. < 3° (1 TeV < E < 0.5 PeV)
Energy Res. for ν_e CC better than **10%**
Shower confined within ~10 m (long)

Angular Res. < 2° above 50 TeV
Energy Res. < 5 %

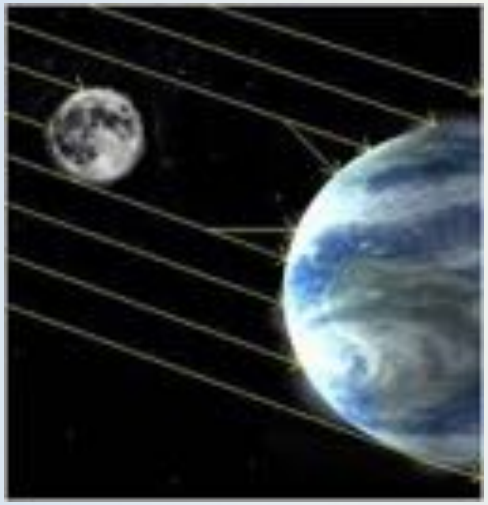






Cosmic Ray Shadow

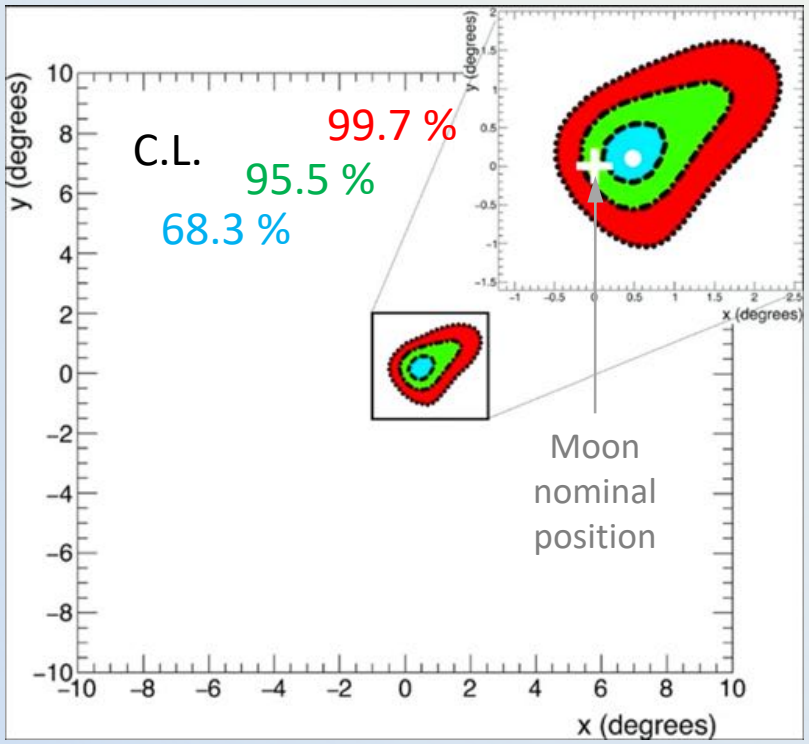
Moon shadow: Eur. Phys. J. C78 (2018) no.12, 1
Sun shadow : Phys. Rev. D 102, 122007 (2020) 006

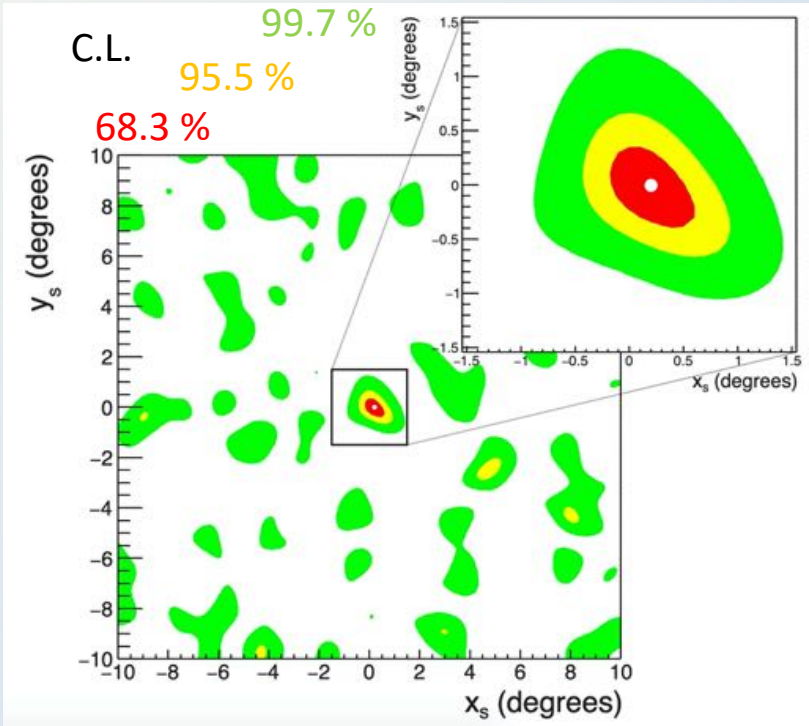


Deficit of the atmospheric muon flux from the direction of the Moon & Sun induced by the absorption of cosmic rays

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

Moon	Sun
2008 – 2016	2008 – 2018
2.5σ	3.7σ
0.73° ± 0.14°	0.59° ± 0.10°

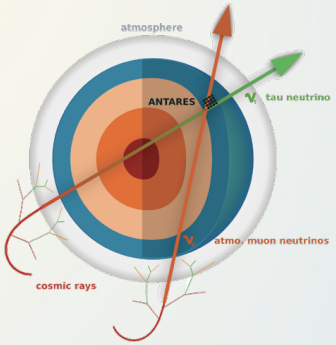


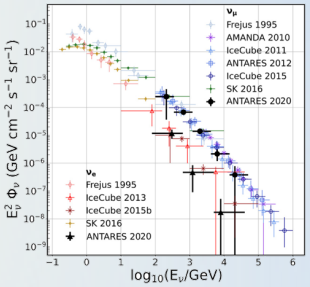


Broad Physics Science Program

Atmospheric neutrinos

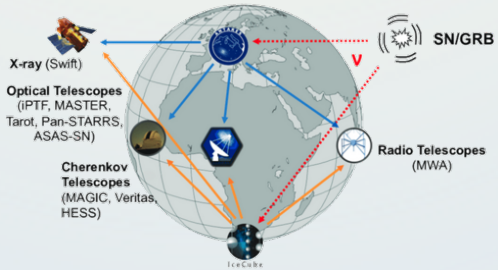
- *Energy Spectrum*
- *Neutrino oscillation*
- *(3+1) Sterile Neutrino Models*
- *Non Standard Interactions*



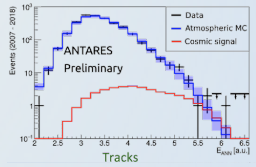


Cosmic neutrinos

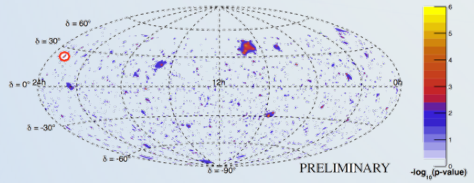
- *Multi-messenger Search / Alerts (Time & Space coincidences)*



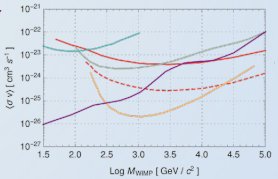
- *Diffuse Search*



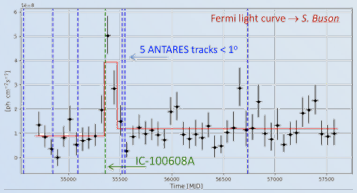
- *Galactic Ridge*
- *"All Sky" Point-source*



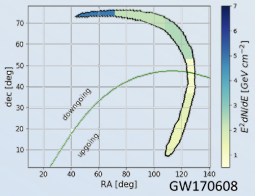
- *Dark Matter (GC, Sun…)*



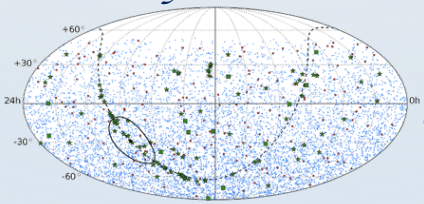
- *"Stacking" Catalogue & GRBs*



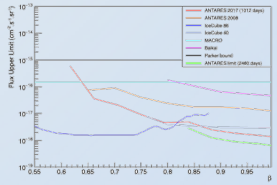
- *"GW"*



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



- *Exotics (Nuclearities, Monopoles)*



- *"Catalogue" (Space coincidences)*

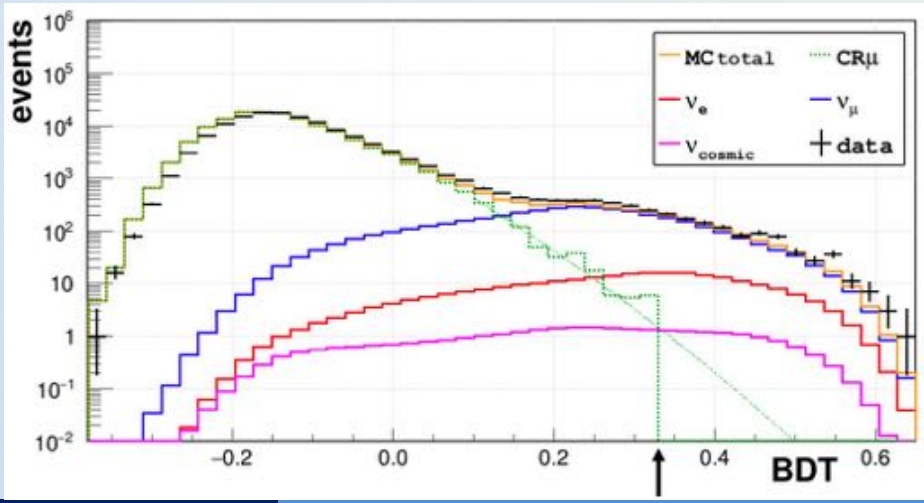
ANTARES : atmospheric neutrino Flux

PLB 816 (2021) 136228

ANTARES Data: 2007 – 2017 (3012 days livetime)

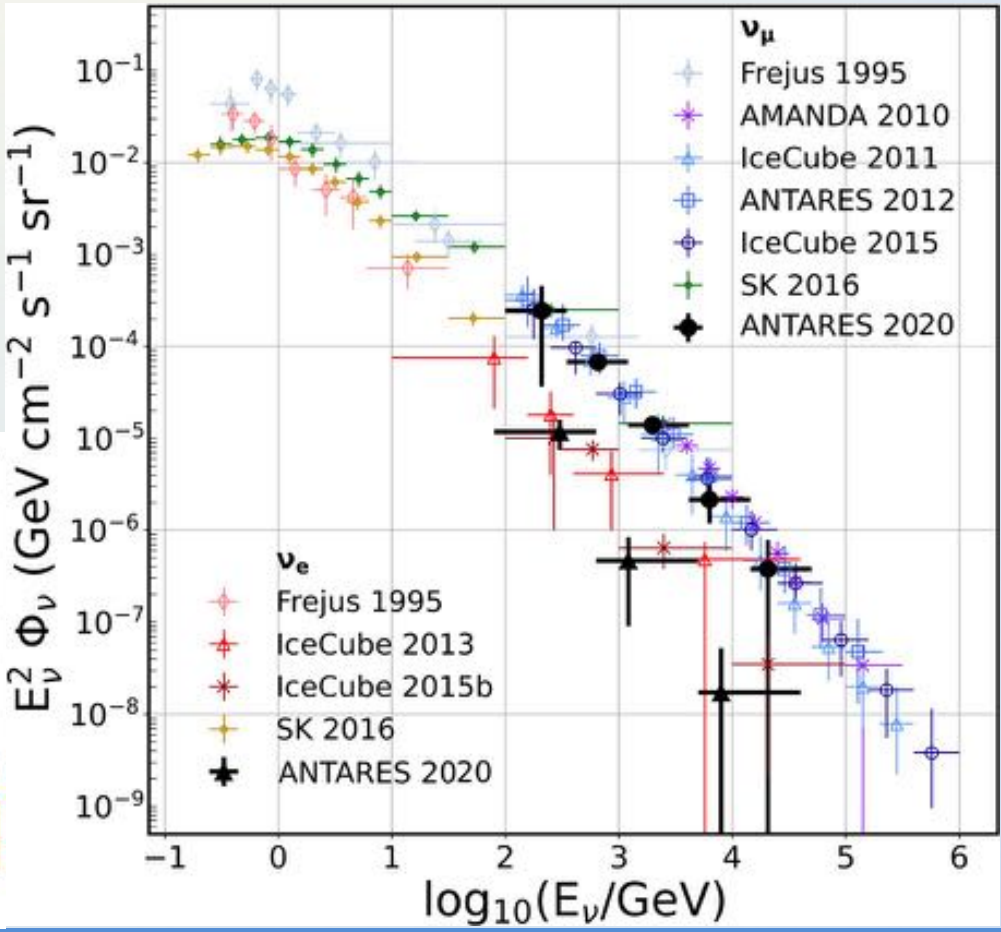
- Pre-selection + Reco. cuts ($\Lambda > -5.7$) + BDT selection > 0.33 (15 parameters)
- Events after cuts:

MC CRμ	$\sim$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



Diffuse Flux : Full sky + all flavor search

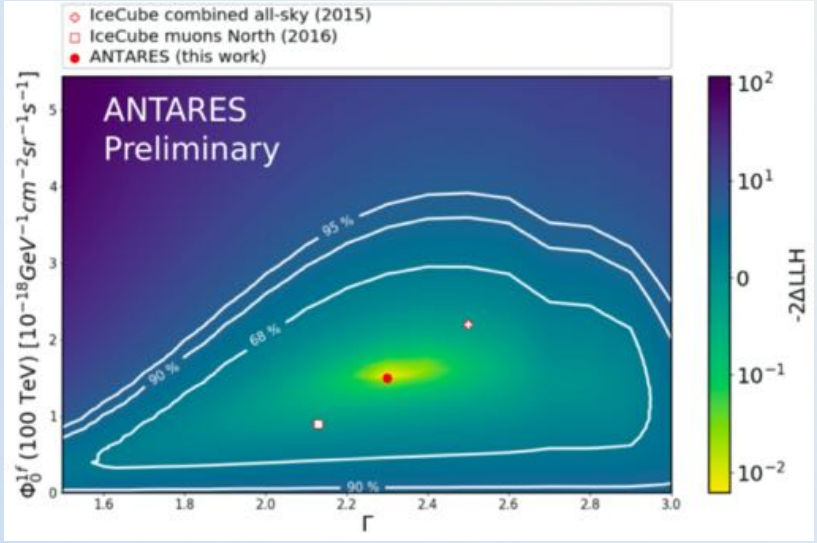
ApJ Lett. 853, L7 (2018)
PoS (ICRC2019) 891

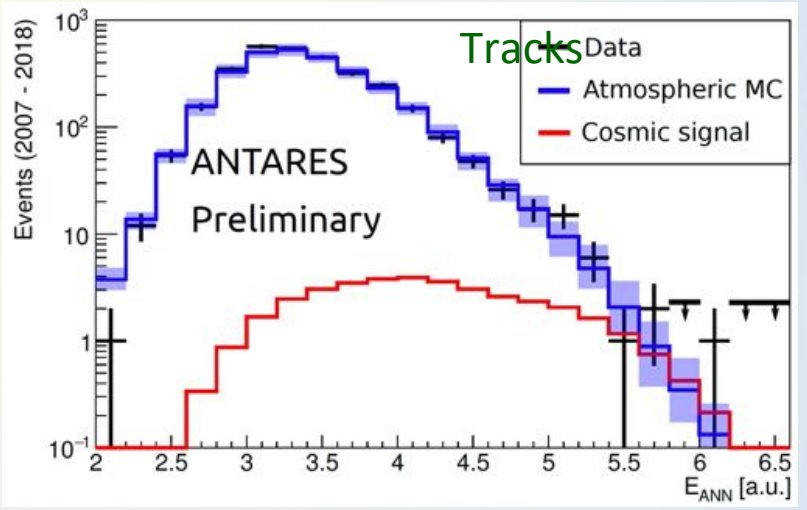
- Data Sample 2007 – 2018 (3330 days)
- All sky / All-flavour ν search
- Unblinding: 1.8σ excess

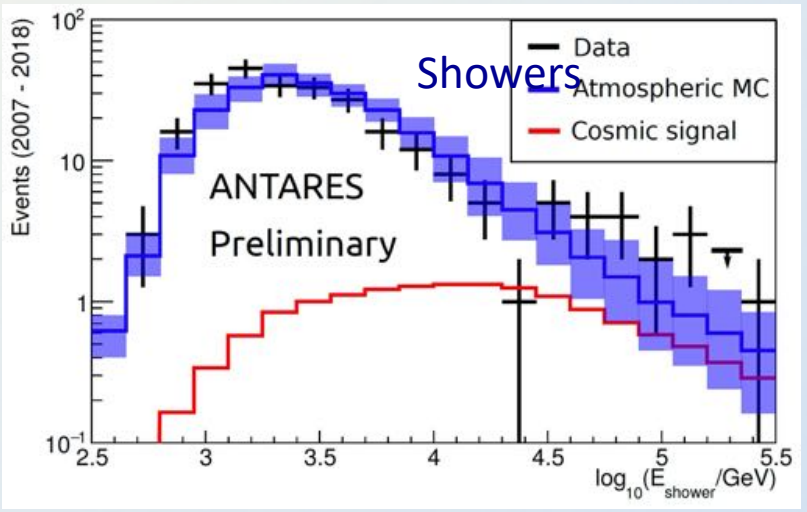
	Events		tracks		showers
Observed:	50	=	27	+	23
Expected:	36.1 ± 8.7	=	19.9	+	16.2

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

- Results compatible with IceCube diffuse flux







Best fit (1 flavour flux normalization at 100 TeV)

- Flux: $\Phi_0(100\ TeV) = (1.5 \pm 1.0)\times10^{-18}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$
- Spectral index: $\Gamma = 2.3 \pm 0.4$

KM3NeT Diffuse Flux : Full sky

J. Phys. G43 (2016) no.8, 084001

Track channel

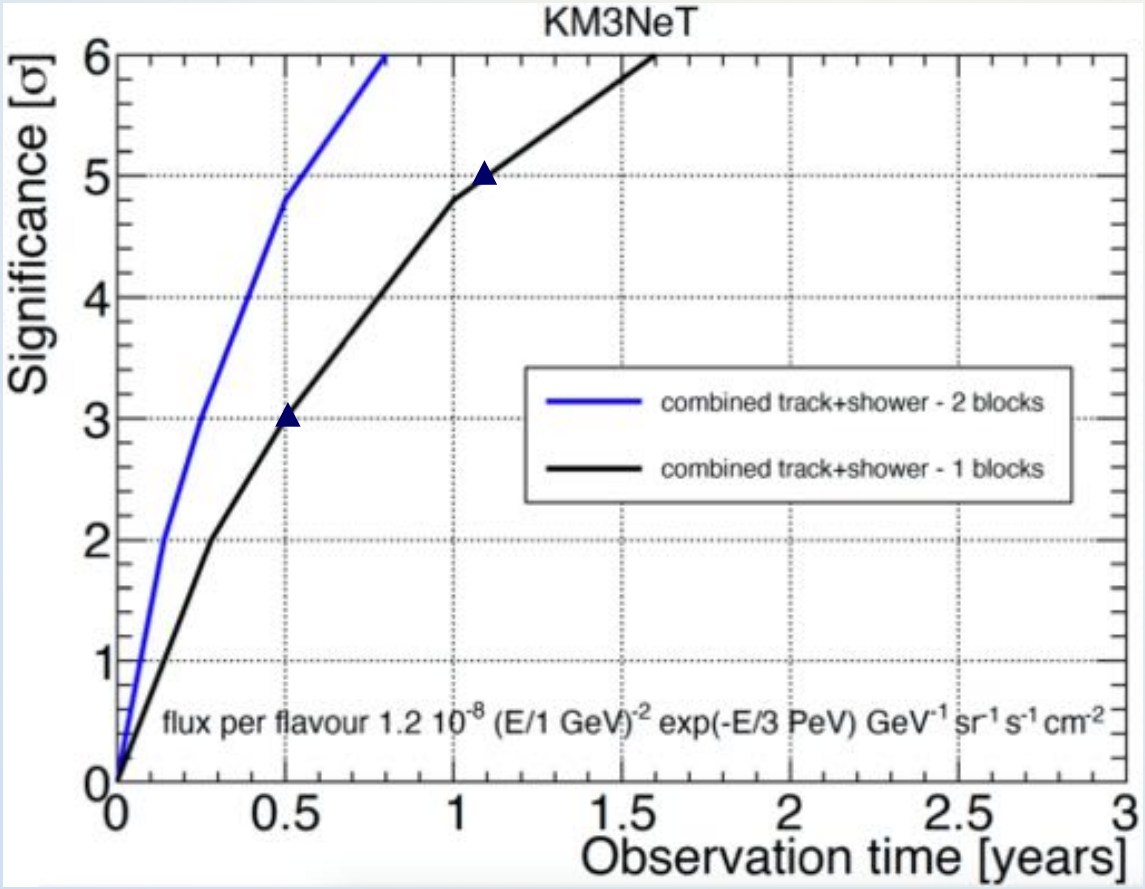
Analysis for upward-going events based on a maximum likelihood

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

(3σ) IceCube signal in 3 months

and confirm it (5σ) in six months

ANTARES : Point Sources

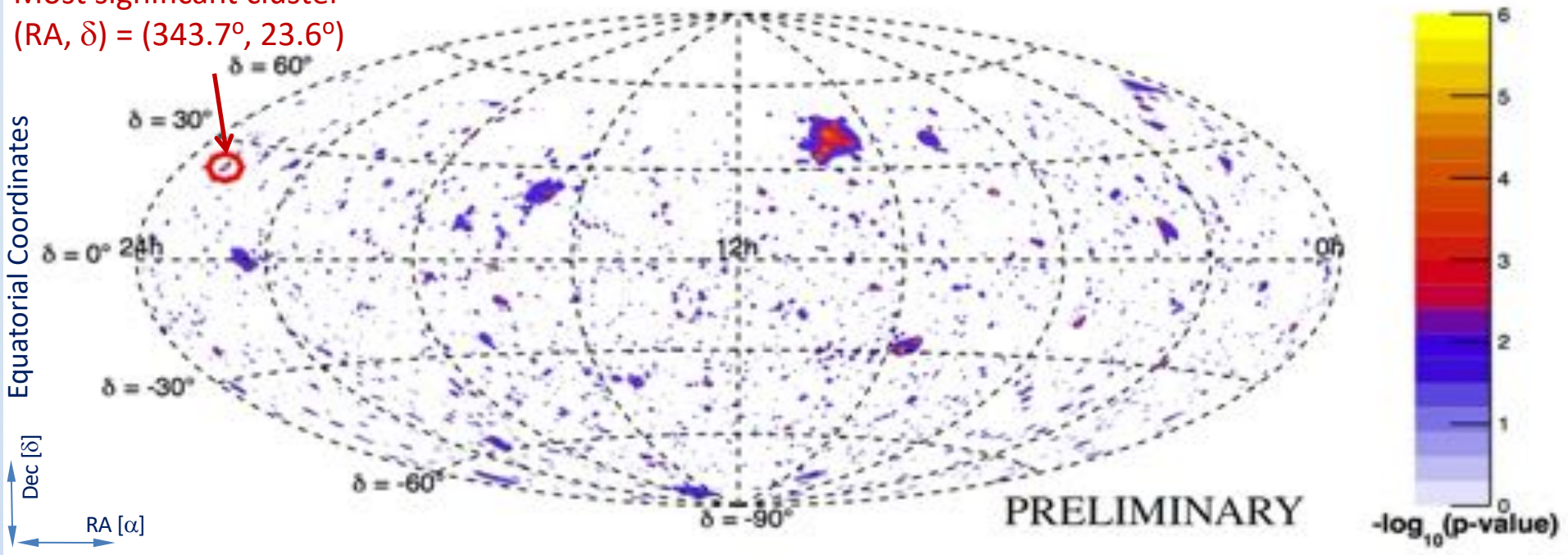
PRD 96 (2017) 082001 PoS (ICRC2019) 920 ApJ 879 (2019) 108 ApJ Lett. 863 (2018) L30

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

- Full sky (steps of 1°×1° , 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.

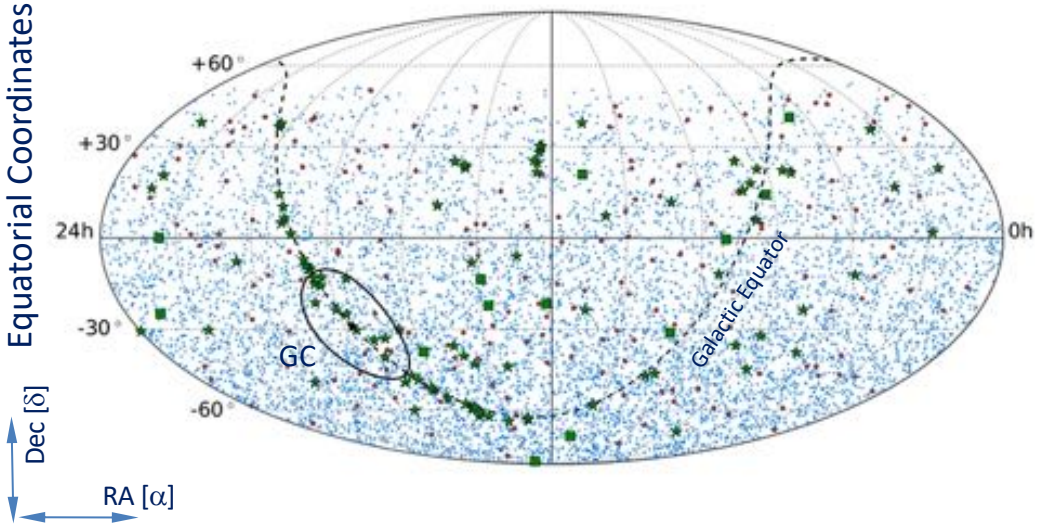
ANTARES : searches from selected sources

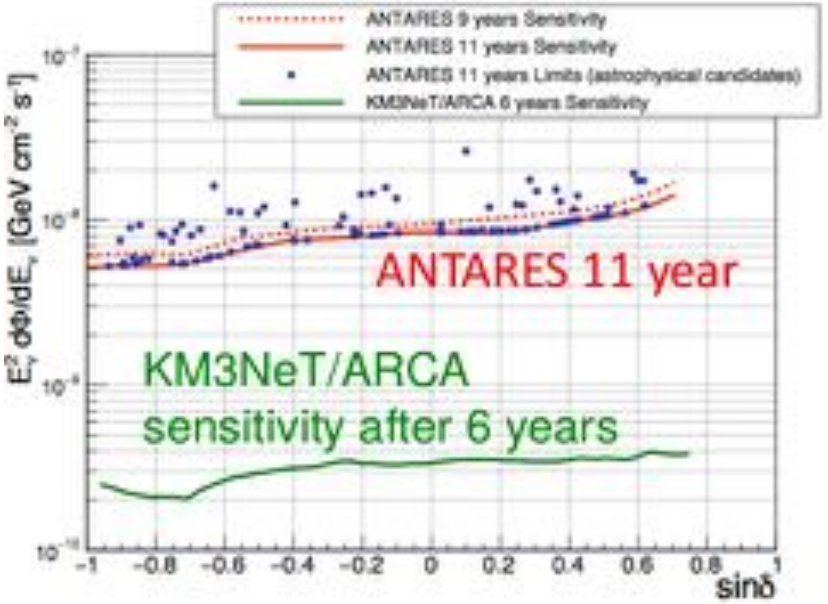
ApJ 879 (2019) 108
PoS (ICRC2019) 920

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

- Full sky (steps of 1°×1° , 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.

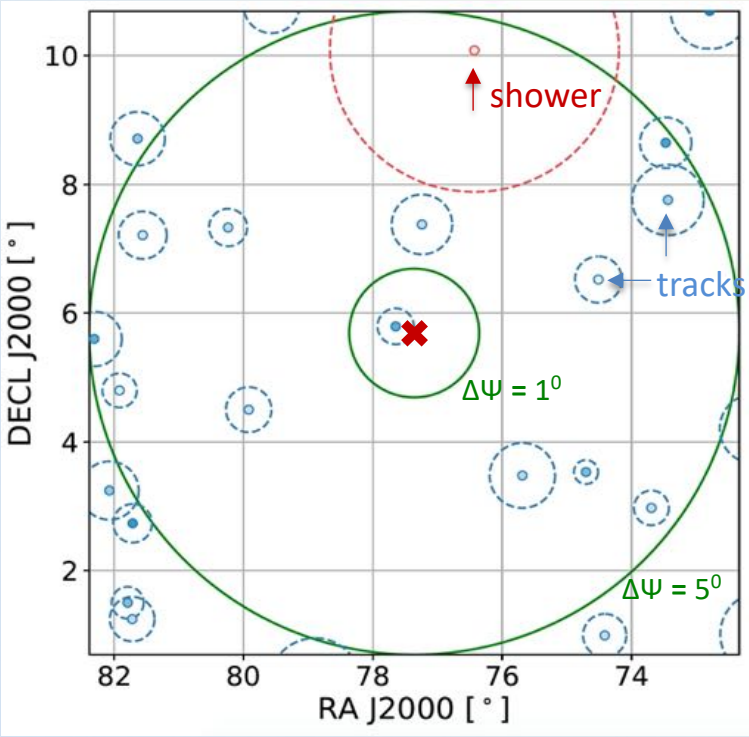
ANTARES : TXS 0506+056 follow up

ApJ Lett. 863 (2018) L30
PoS (ICRC2019) 920

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 →upper limits



TXS 0506+056 Equatorial Coord.
(α, δ) = (77.36° , 5.69°)

III. Time-integrated search from TXS 0506+056

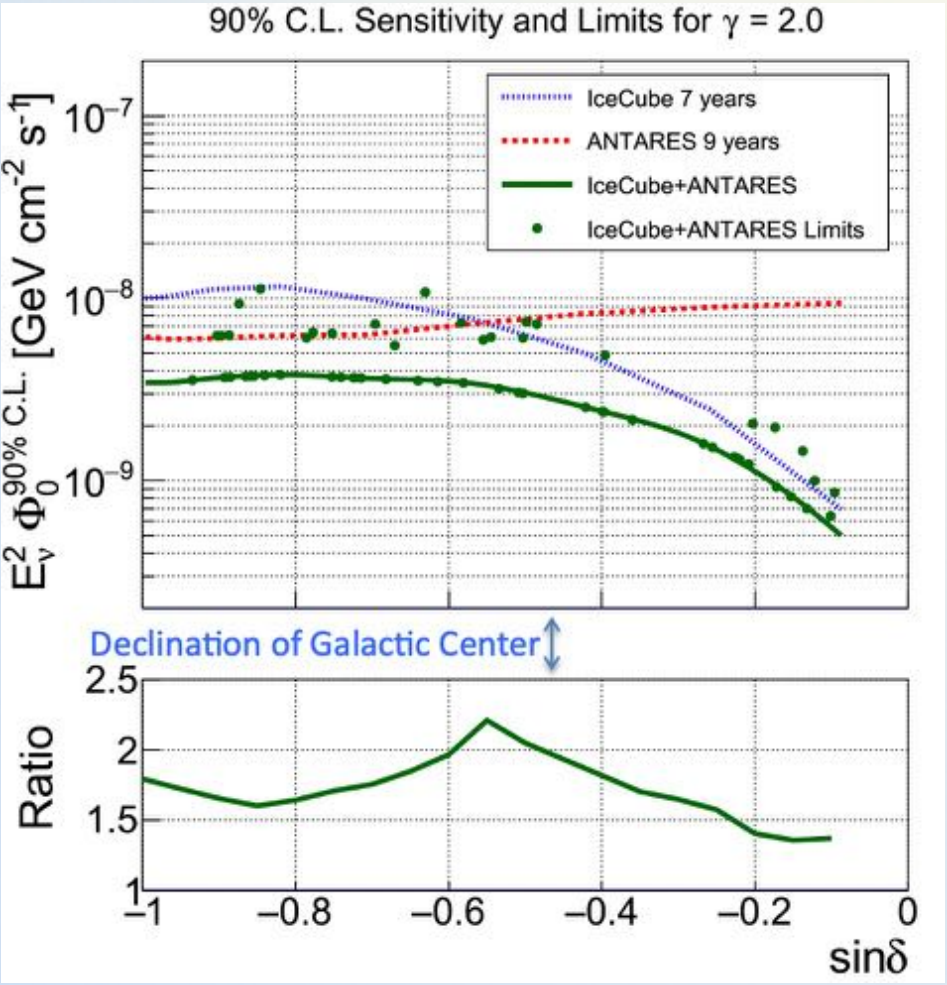
- Point Source analysis approach
- 2007 – 2017 data (3136 livetime days)
  107 sources. 3rd most significant source
- Likelihood fit result: μ_{sig} = 1.03 events.
  Post-trial *p-value* = 87%
- 13 tracks + 1 shower ($\Delta\Psi = 5^0$).
  17 ± 4 atm. ν expected
- $\Phi^{90\%}_{100\ TeV} = 1.6 \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} (Γ=2)
  [2TeV - 4PeV]

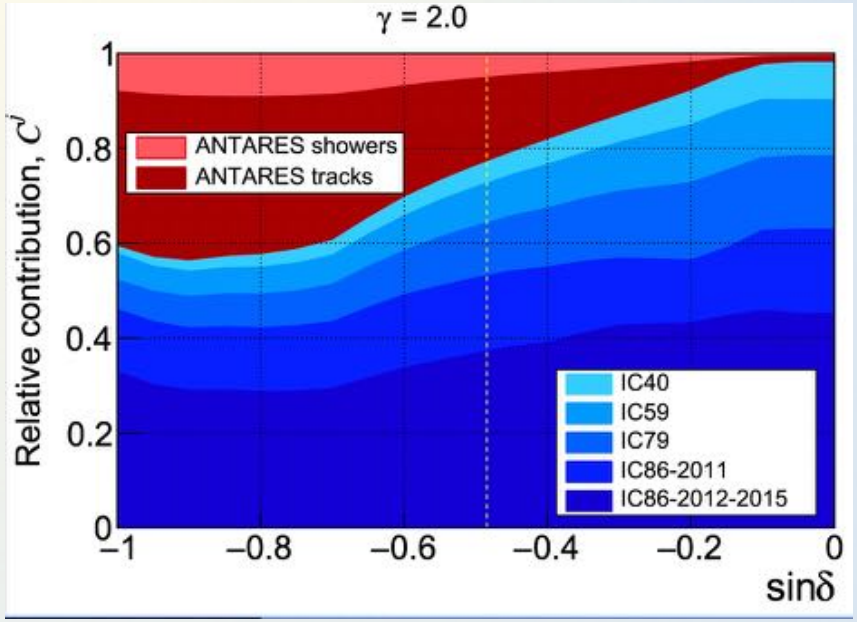
ANTARES + IC: combined PS search

ApJ 892 (2020) 92

- ANTARES 2007–2015 : tracks & showers
- IceCube 2008–2015 : tracks

- Samples for the Southern Hemisphere





Significant improvement of limits especially for hard energy spectra

Best limits on neutrino point source emission in Southern Hemisphere

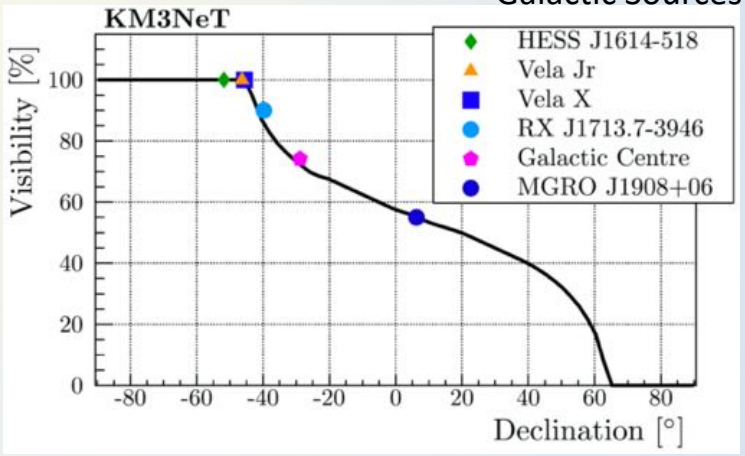
ANTARES data set is public : see https://antares.in2p3.fr

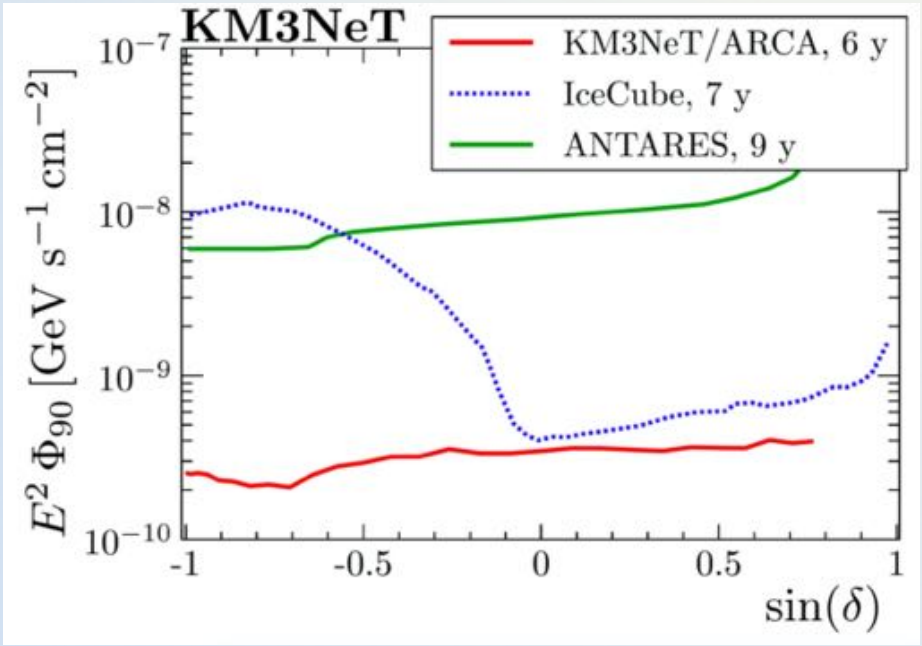
KM3NeT: Expectations for point-sources

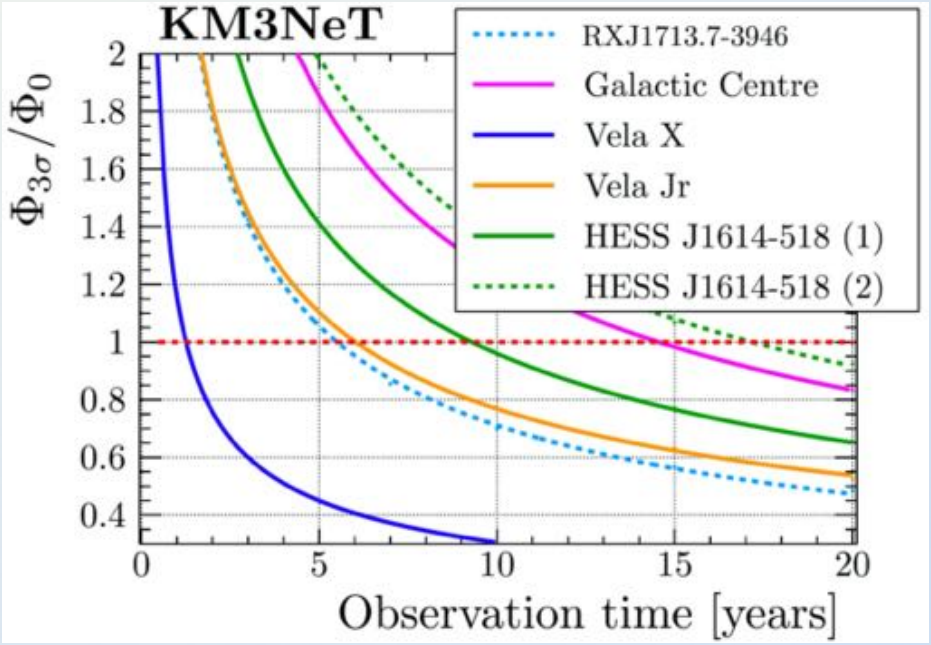
Astropar. Phys. 111 (2019) 100

- 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

Galactic Sources





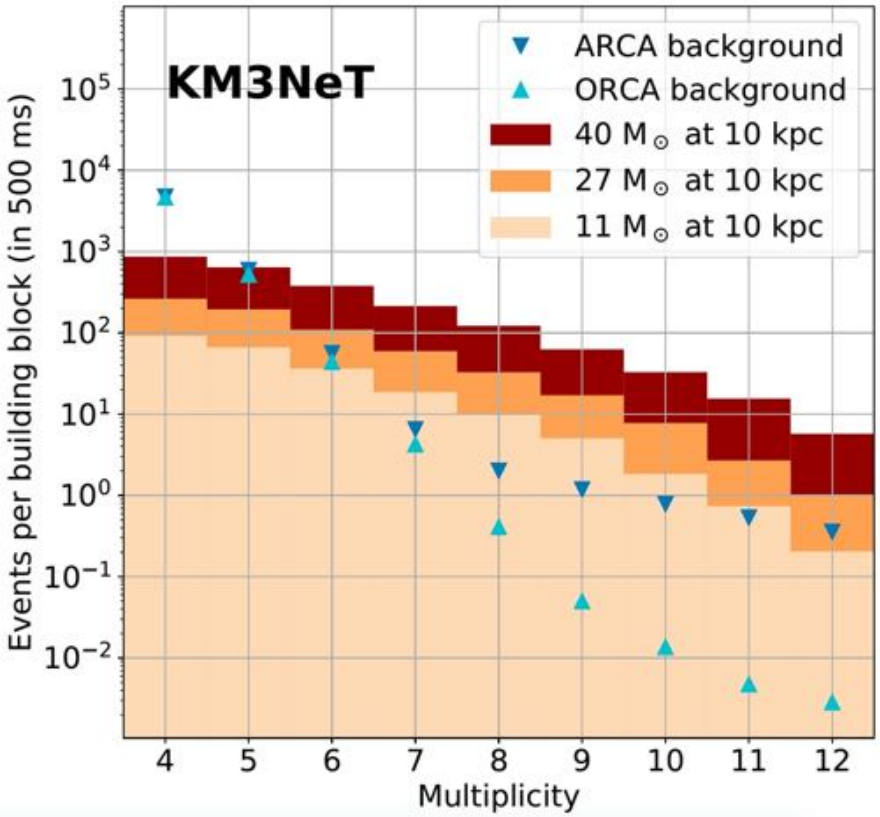


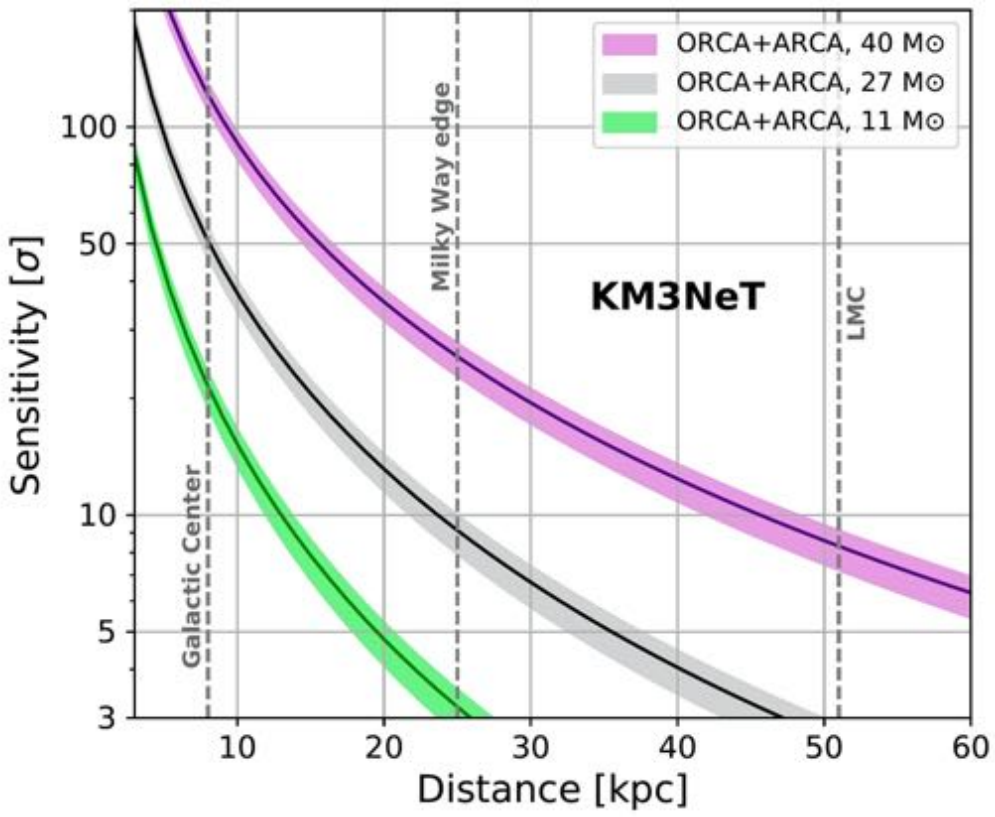
KM3NeT : Core Collapse Supernovae

Accepted on APJ C
arXiv 2102.05977

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

ApJ 911 (2021) 48

Catalog (ANTARES 2007–2017 : tracks)	p pre-trial	P post-trial	$\Phi^{UL}_{90\%}$
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

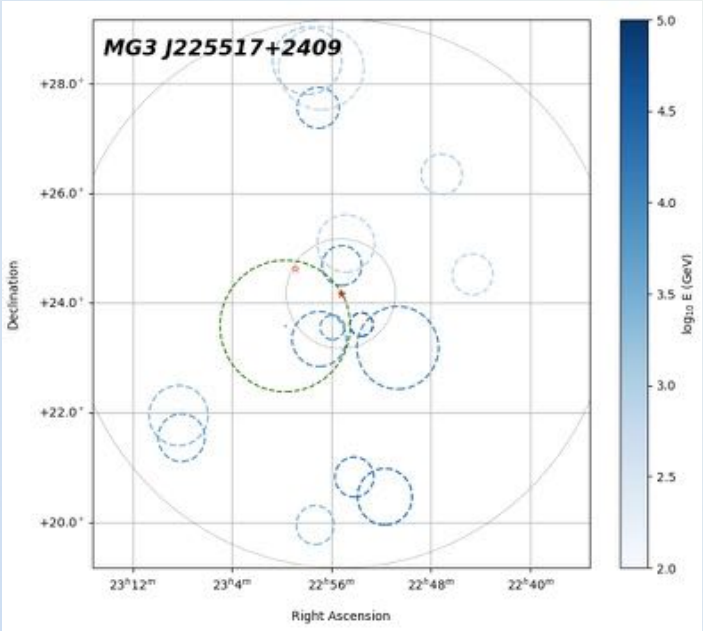
1.6σ

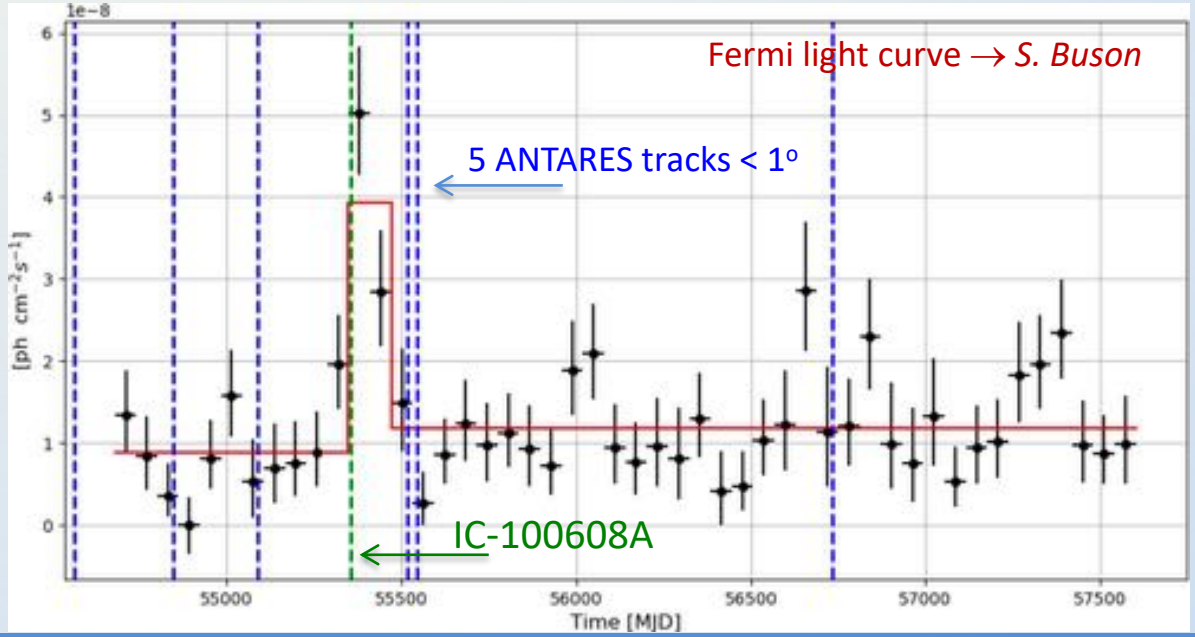
← in terms of the total E^{-2} flux normalization at 1 GeV (in units of 10^{-8} GeV^{-1} cm^{-2} s^{-1}).

Most significant:
← MG3 J225517+2409
← 3C403

Blazar MG3 J225517+2409
with ANTARES tracks & IceCube track

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





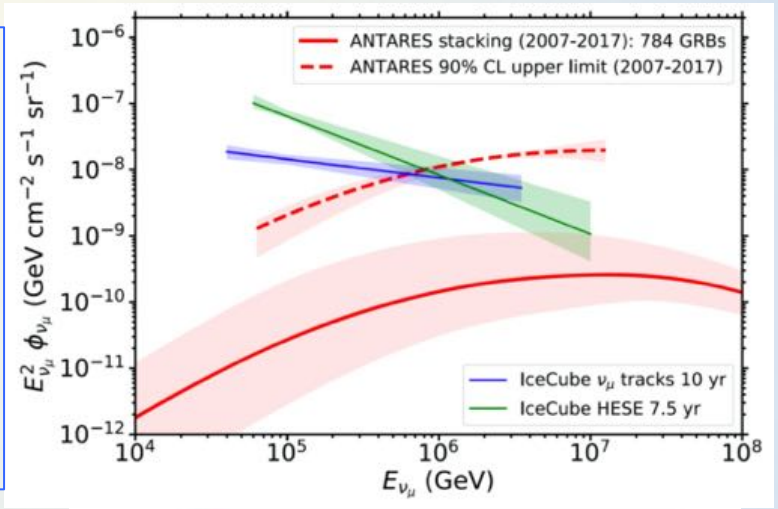
Search for ν counterparts to GRBs

MNRAS 500 (2021) 5614
JCAP 03 (2021) 092

Extremely energetic γ-ray bursts → Associated ν production detectable?

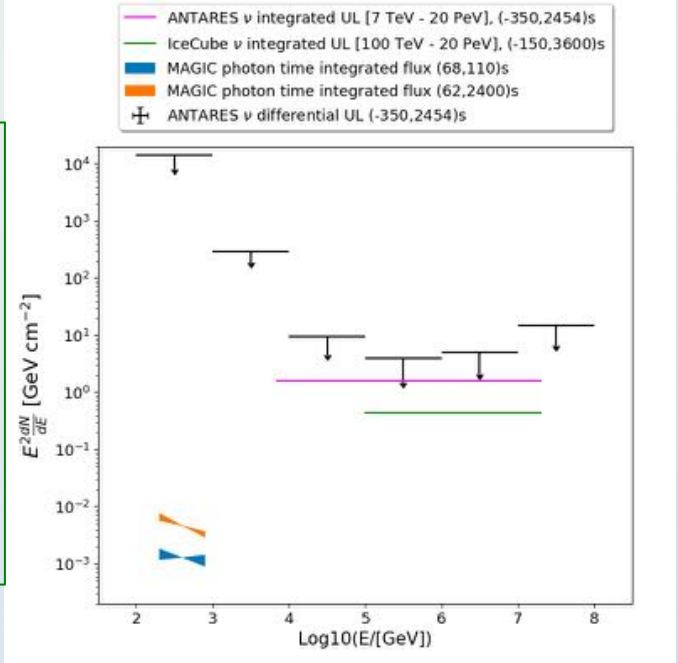
Stacking analysis of 784 GRBs (observed by "satellite-based" γ-ray instruments): ANTARES tracks 2007-2017

- ✓ No ν in time & space coincidence with prompt temporal phase of GRBs found
  → 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

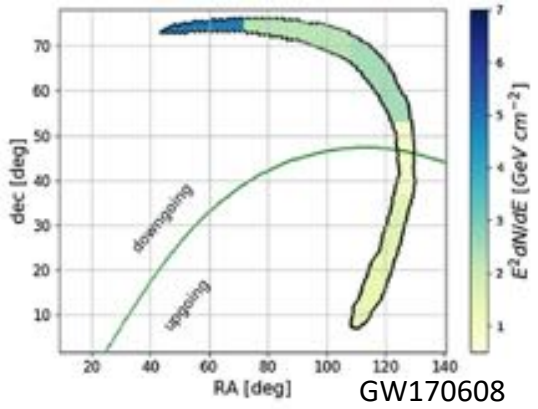
- ✓ Follow-up search using ANTARES tracks & cascades during time of γ-ray emission
- ✓ No ν events found in time & space coincidence



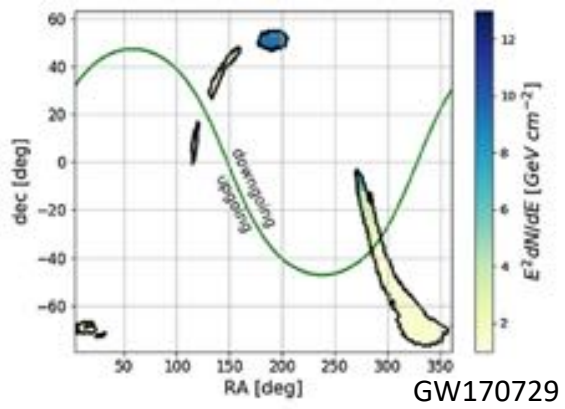
Search for ν counterparts to Gravitational Waves

- 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

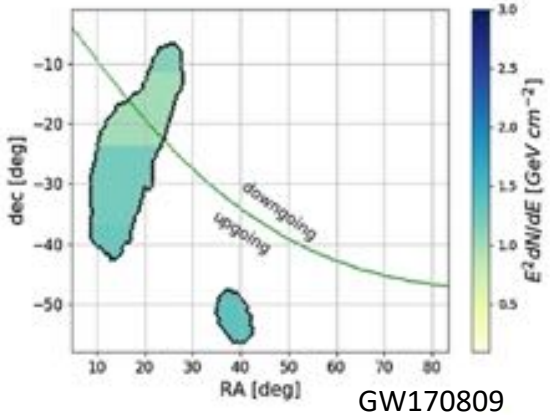
  ➞ No events found ➞ Set limits
- Latest O2 BBH: Constraints on fluence and $E_{\nu,iso}$ for BBH
- Run 03 analysis ongoing …



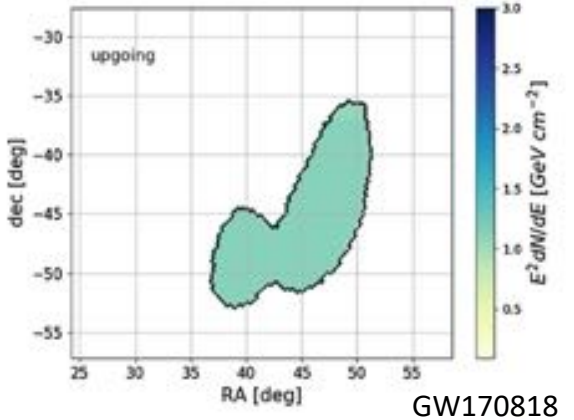
GW170608



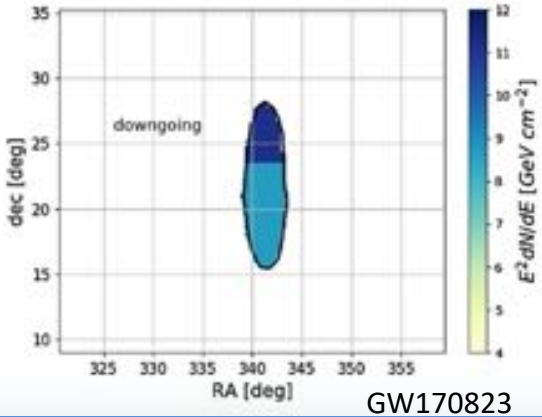
GW170729



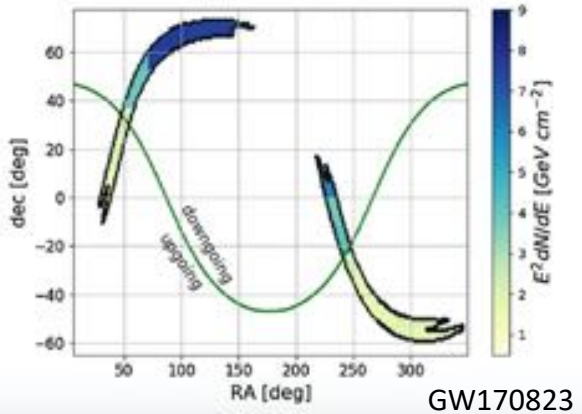
GW170809



GW170818



GW170823



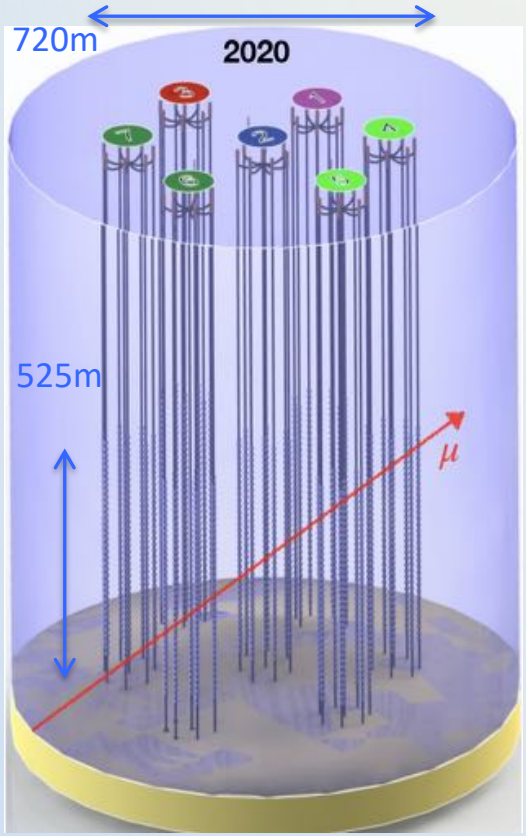
GW170823

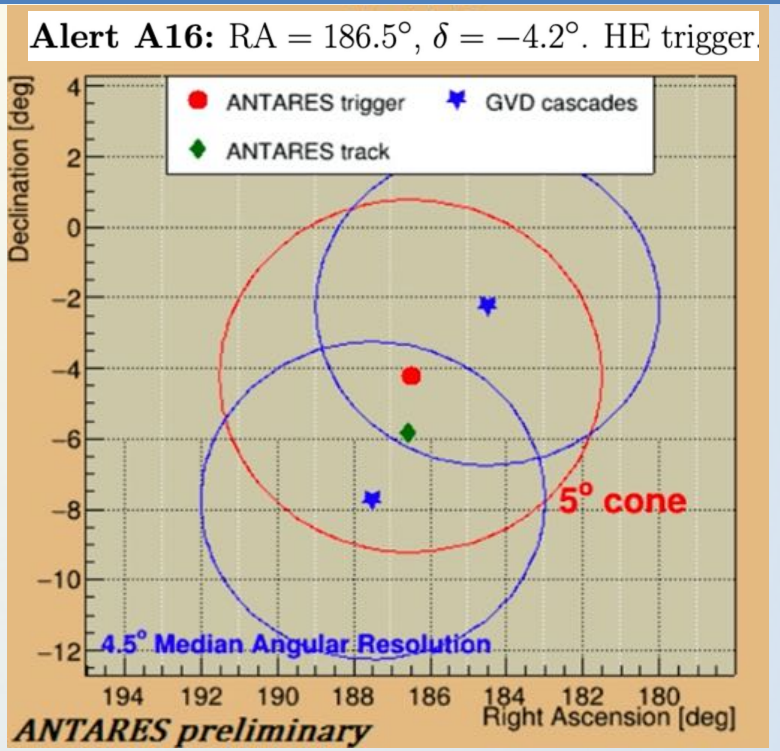
Eur. Phys. J. C 80, 487 (2020) | ApJ 870 (2019) 2 | Phys. Rev. D 96 (2017) 022005 | ApJL 848 L12 (2017) | Phys. Rev. D 93 (2016) 122010 | ApJL 850 L35 (2017) | JCAP 06 (2013) 008

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 ↣ 2024: 14 clusters



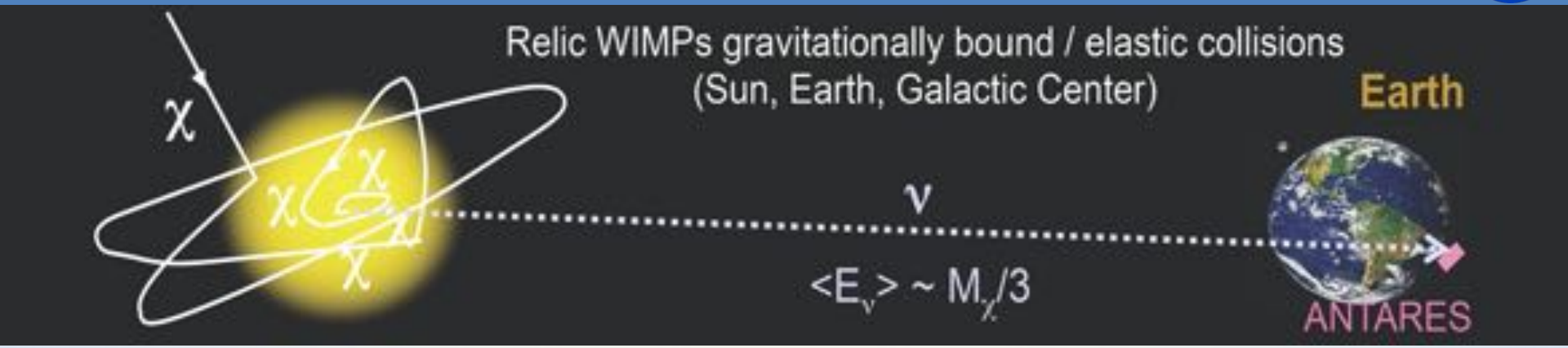


For 3 alerts, multiplets of GVD cascades reconstructed within **±1 day**

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

Dark Matter Searches



- 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

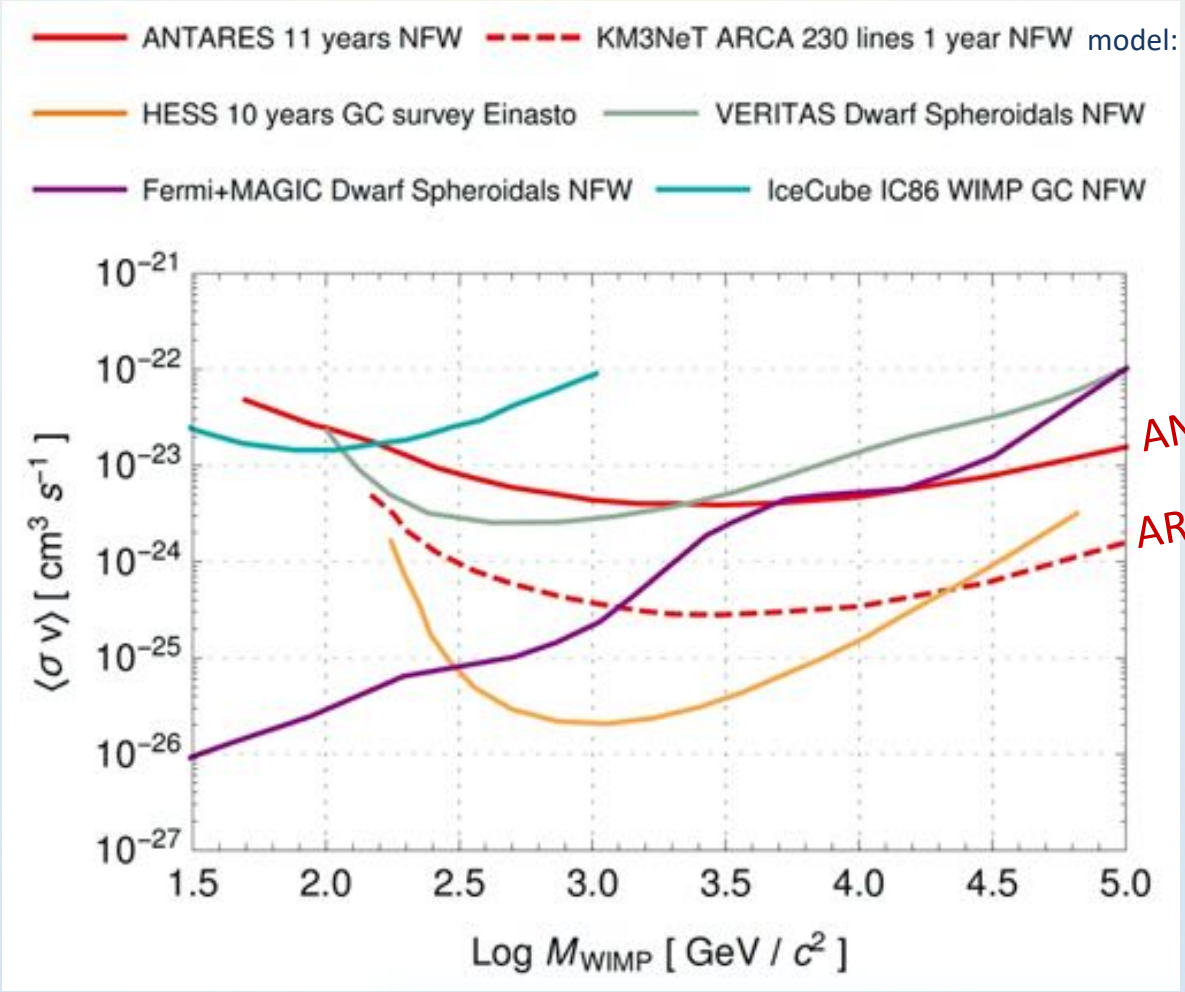
Dark Matter from the Galactic Center

PLB 805 (2020) 135439

ANTARES + IC : PRD 102 (2020) 082002

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

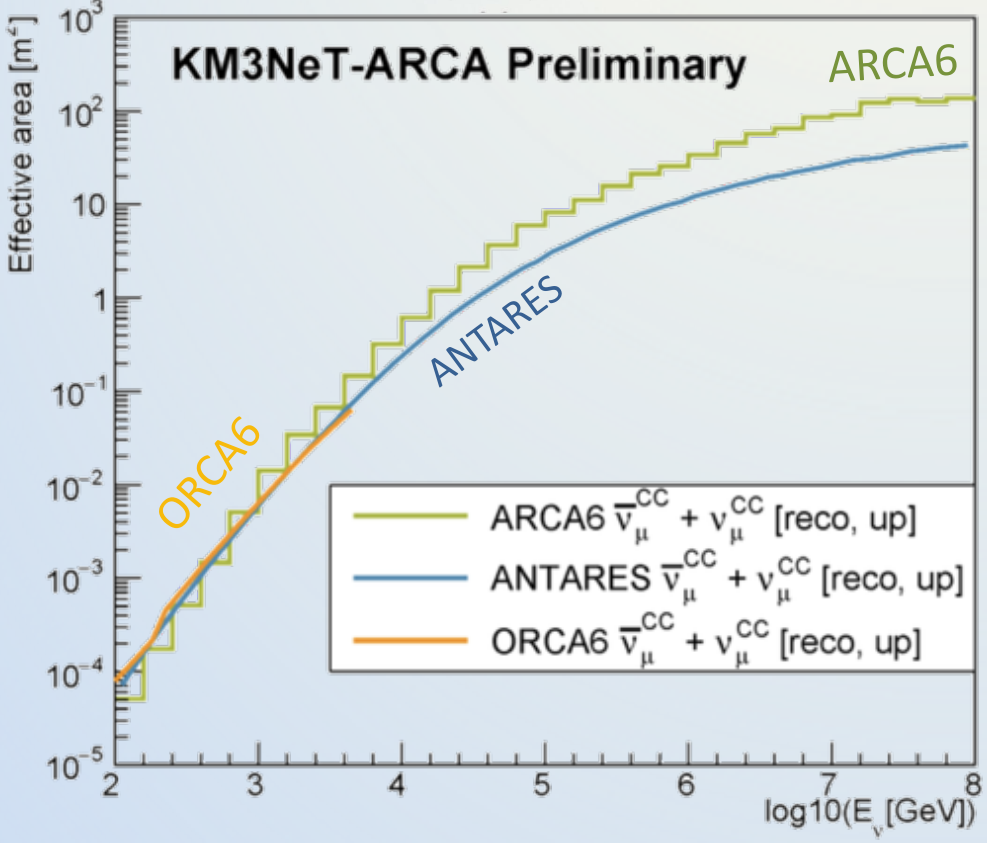


KM3NeT : Current Detector Status

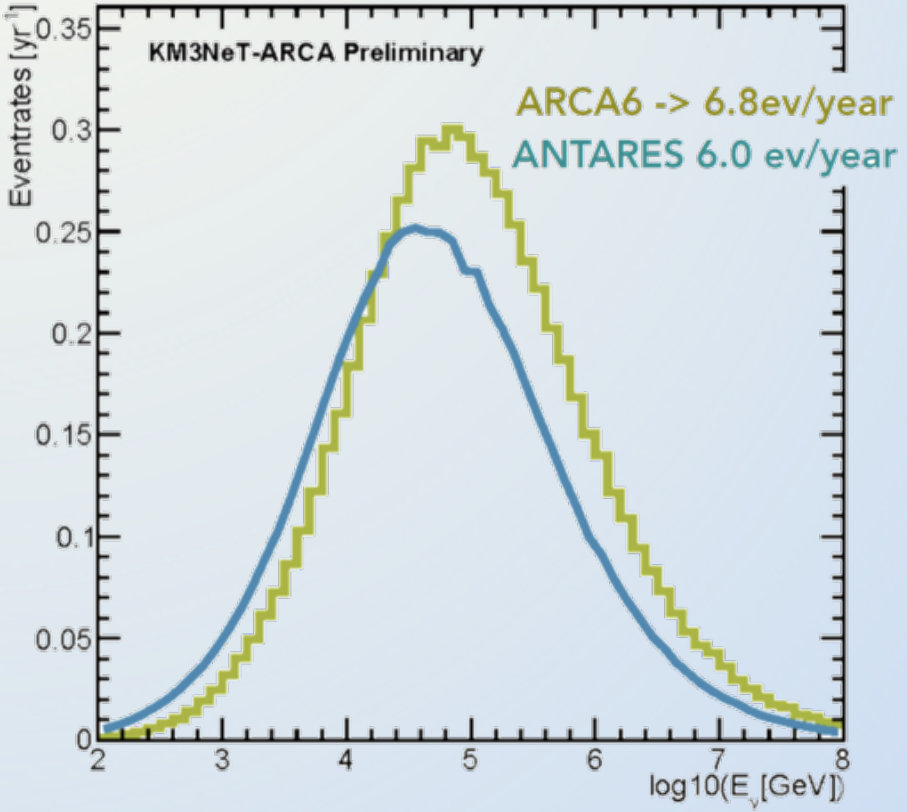
ORCA : 6 DUs deployed & taking data
ARCA : 6 DUs deployed & taking data

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

Effective area [m^2] for $\overline{\nu}_\mu^{CC} + \nu_\mu^{CC}$ upward going tracks



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

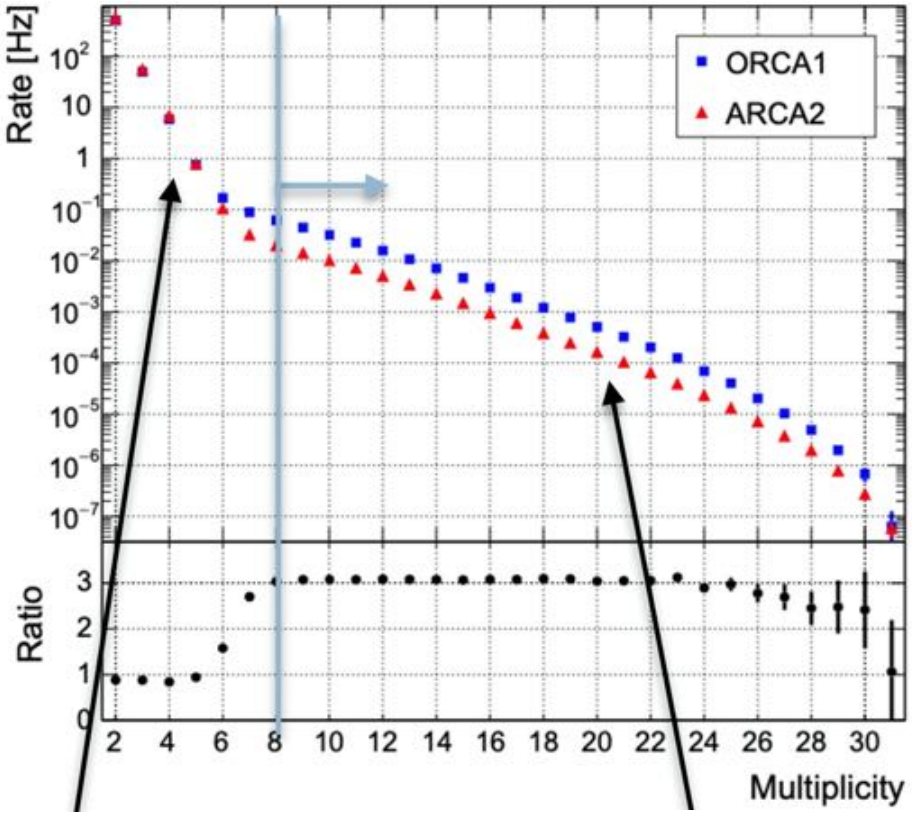


KM3NeT First results: Atmospheric μ Flux

Eur. Phys. J. C 80:99 (2020)

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

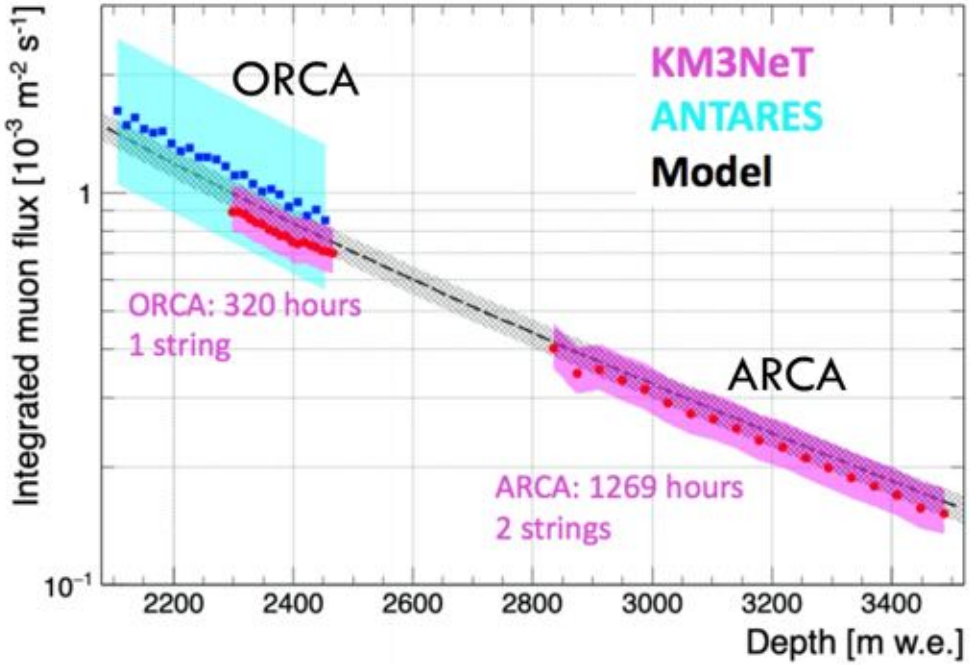
KM3NeT *Multiplicity* plot for PMTs in DOM



Mult. < 8 ⟶ ^{40}K

Mult. > 8 ⟶ *Atm.* μ

Atmospheric μ flux depth dependent: *Mult.* ≥ 8

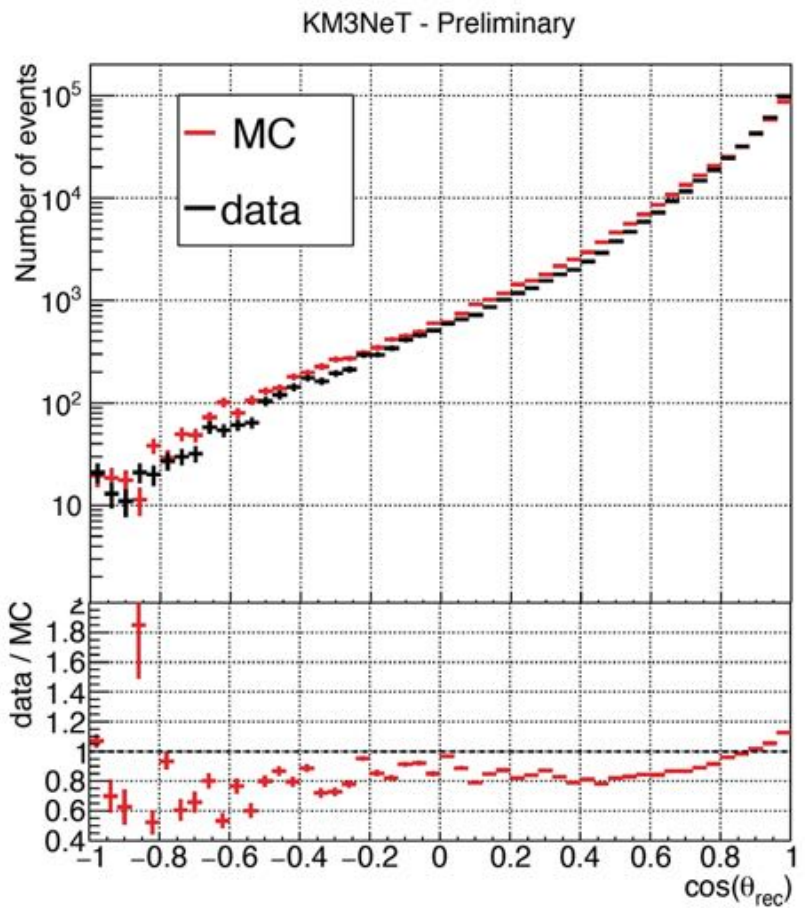


KM3NeT First results: ARCA 6 lines

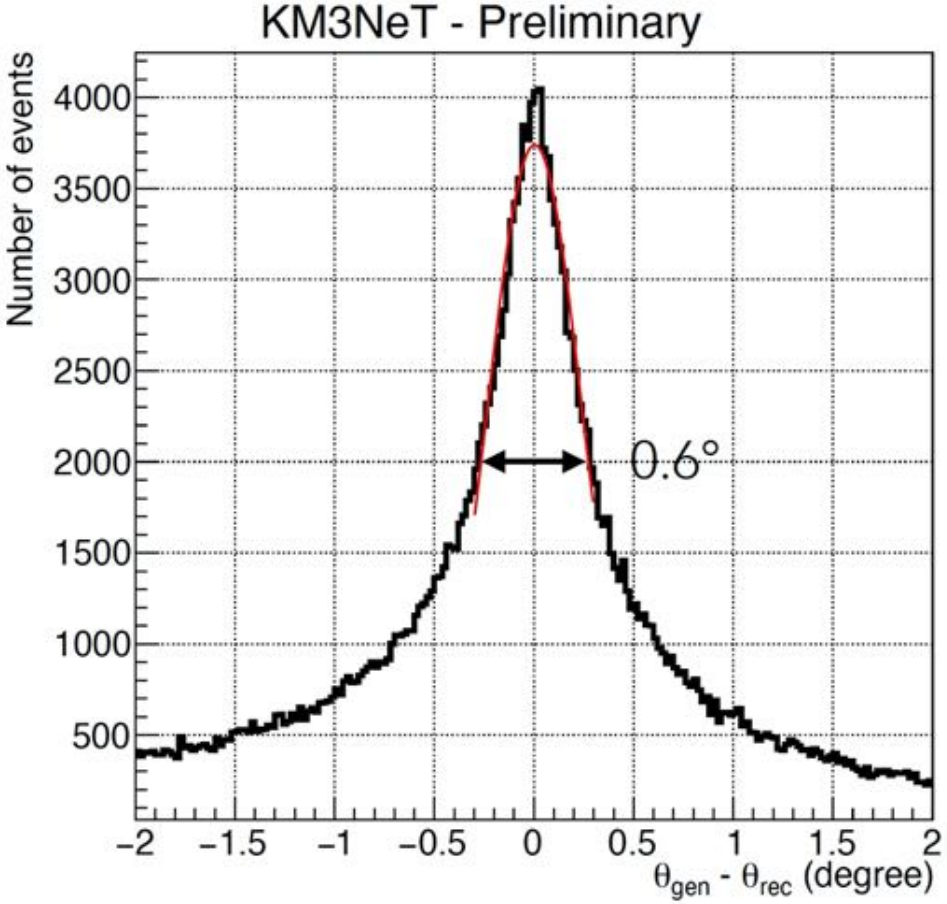
About 1 month after deployment:

- ✓ 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)



KM3NeT : Next Sea Campaigns

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

April 2021	June 2021	Sept/Oct 2021	Spring 2022
6 ARCA	6 ARCA	11 ARCA	23 ARCA
6 ORCA	10 ORCA	13 ORCA	20 ORCA

SUMMARY & Outlook

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)