The ANTARES neutrino telescope: main results and perspectives for KM3NeT

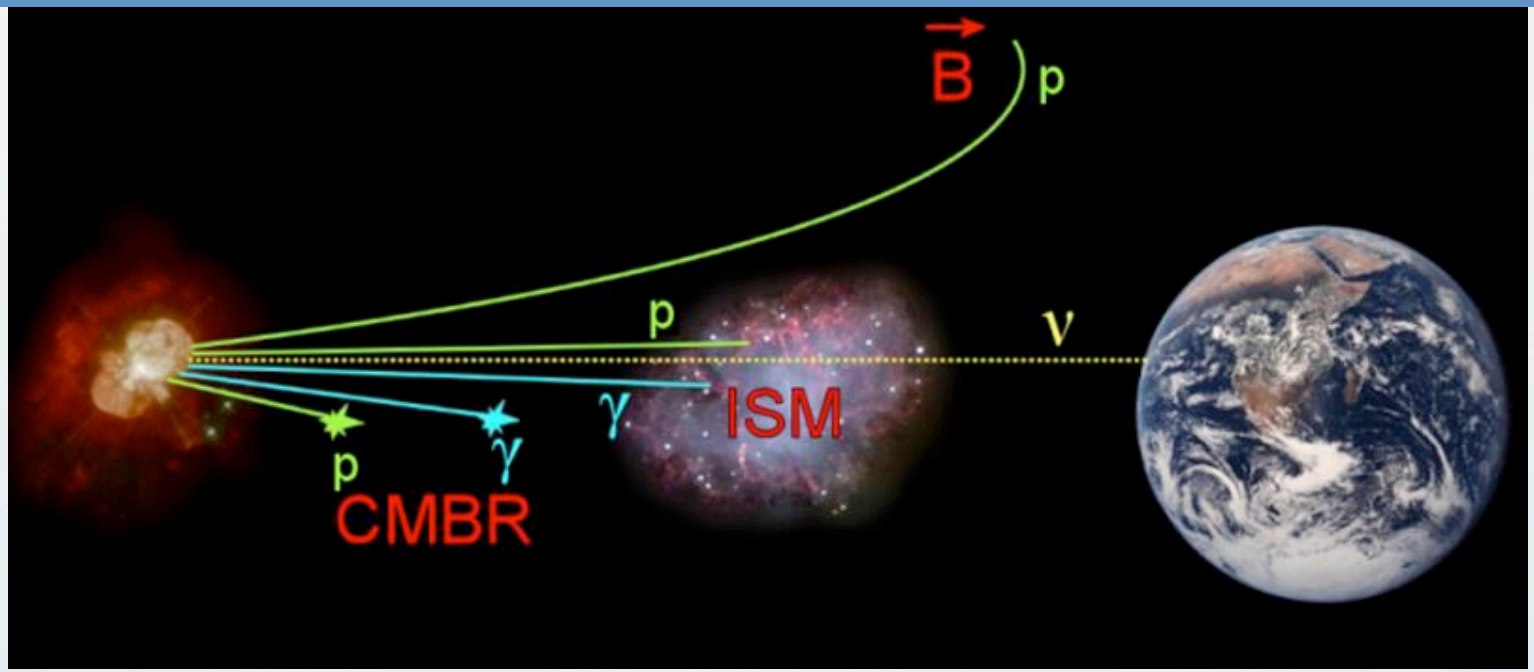
Sergio Navas
University of Granada, Spain

UNIVERSIDAD DE GRANADA

On behalf of the ANTARES and KM3NeT Collaborations

14th Rencontres du Vietnam: Very High Energy Phenomena in the Universe
Quy Nhon, Vietnam, August 12−18, 2018

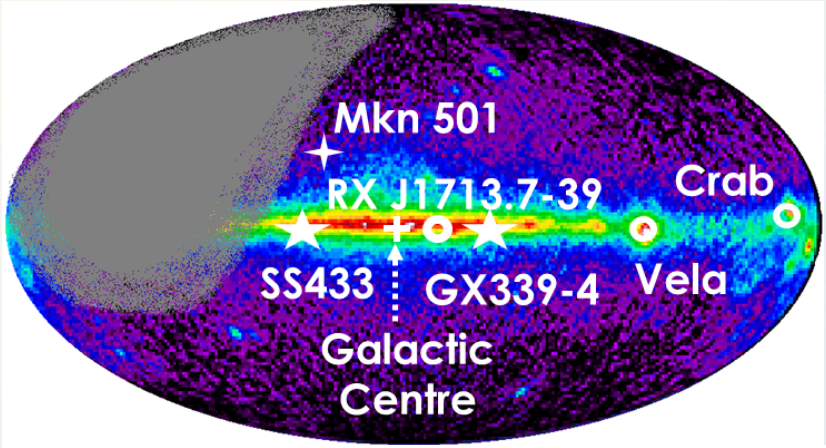
Neutrino Astrophysics

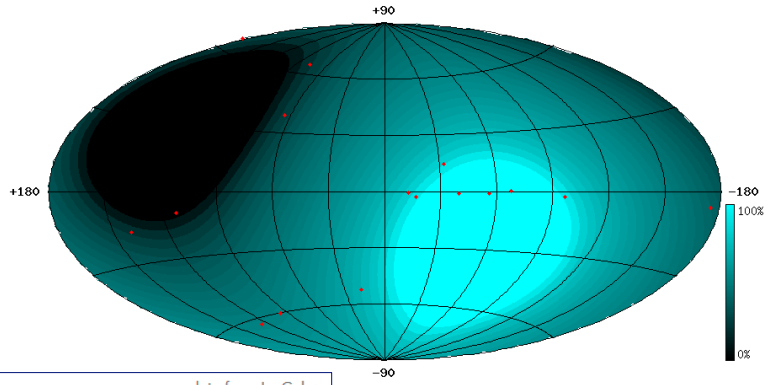


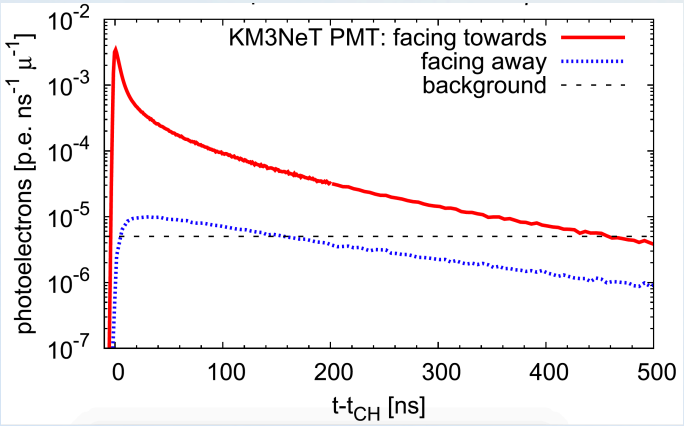
- **Origin and acceleration of Cosmic Rays ?**
- **Neutral messengers point back to their sources**
  - ✓ neutrons are short-lived, photons are likely to interact ➔ neutrinos
- **CR interactions produce neutrinos in meson decays**
  - ✓ Search for a diffuse flux from unresolved sources
  - ✓ Search for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

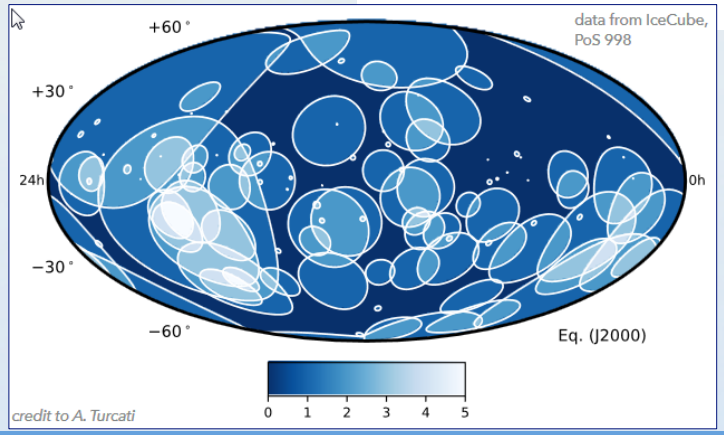
Mediterranean Neutrino Telescopes

- **Physics Motivation and Detection Principle**
  - High energy ν astronomy and neutrino 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.









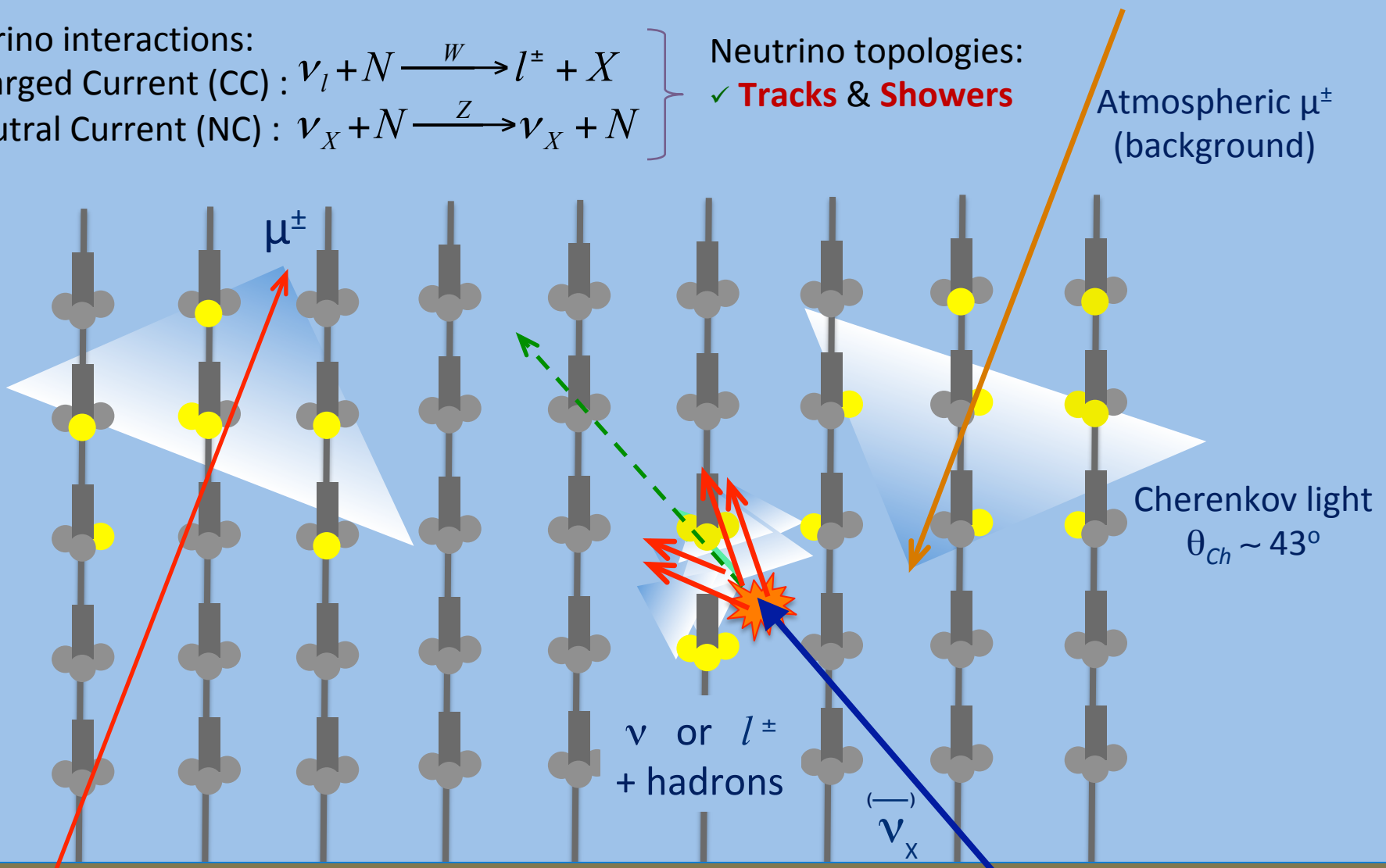
Neutrino detection principle

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:

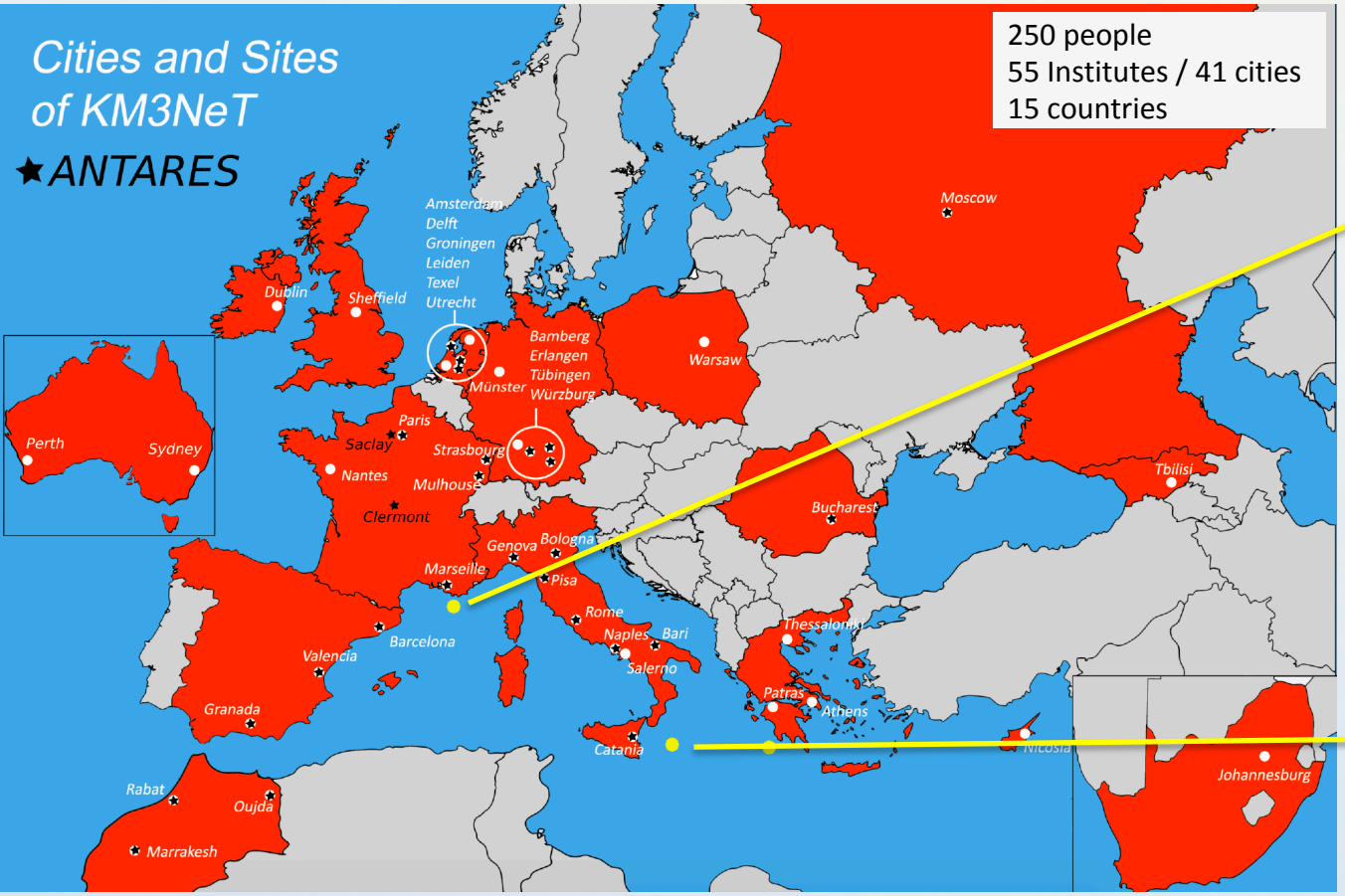
- ✓ **Tracks** & **Showers**

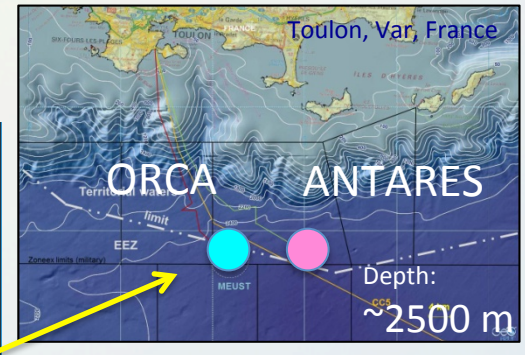


Mediterranean ν telescopes

ANTARES: ~10 Mt instrumented mass. Completed in 2008

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

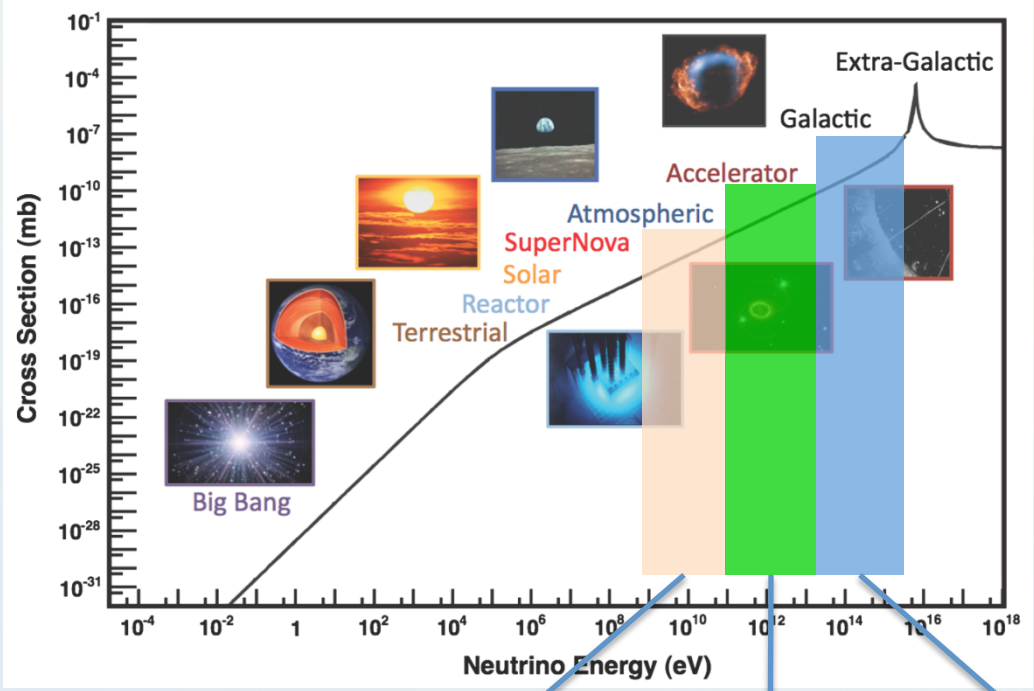


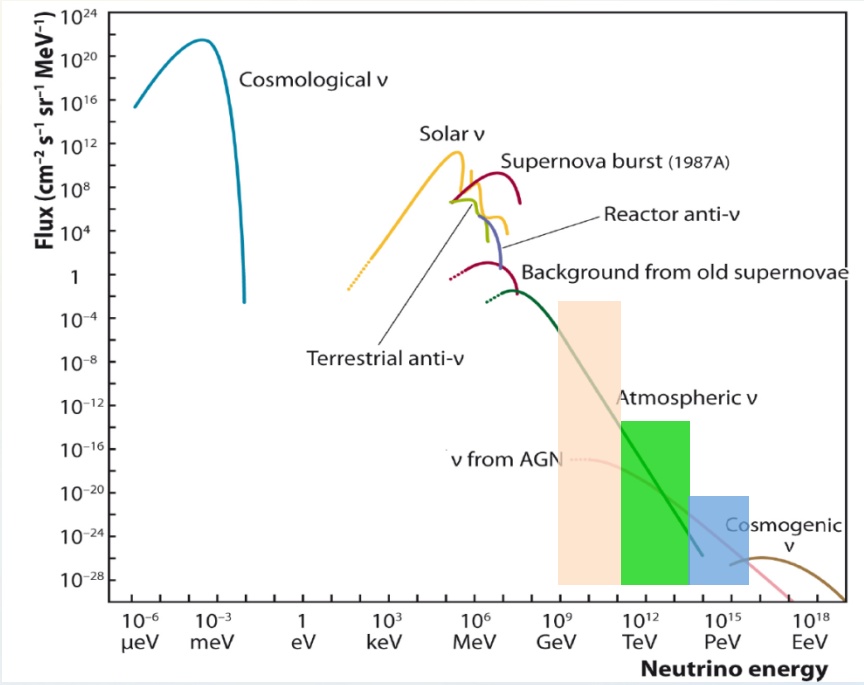


Low-energy (~GeV) studies of atmospheric neutrinos

High-energy (TeV-PeV) neutrino astrophysics

Physics Studies with Mediterranean ν telescopes





GeV

TeV

PeV

KM3NeT ORCA

200 m

6 Mt

∅ ~ 250 m
115 strings

ANTARES

400 m

10 Mt

∅ ~ 180 m
12 strings

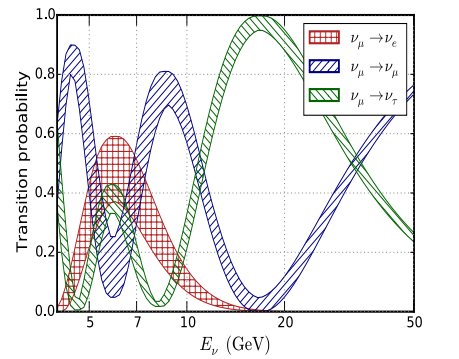
KM3NeT ARCA

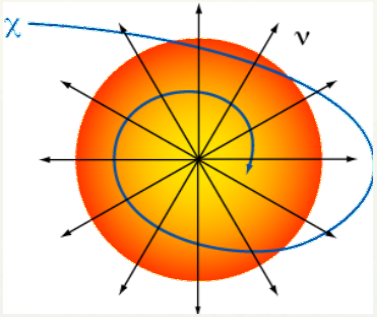
700 m

2×0.5 Gt

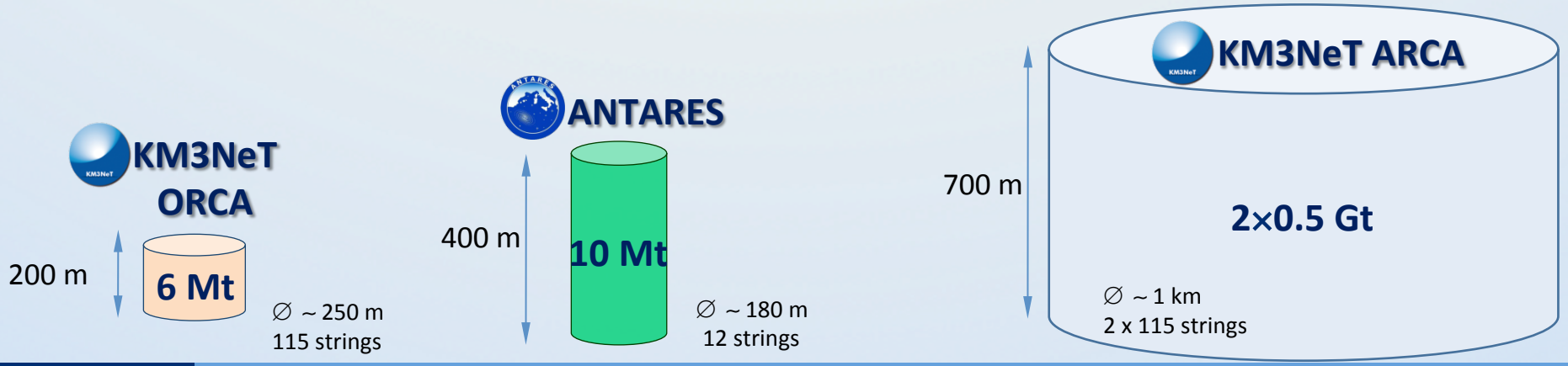
∅ ~ 1 km
2 x 115 strings

Physics Studies with Mediterranean ν telescopes





Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 50 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations **ν Mass Hierarchy**	**Dark Matter searches** **+ Exotic searches**	**Cosmic neutrinos** Origin & production mechanism of HE CR
talks by: A. Domi (ORCA)	*D. Dornic (multimessengers)*	*K. Melis (KM3NeT results)*



Connections to Earth and Sea sciences

✓ BIOLUMINESCENCE

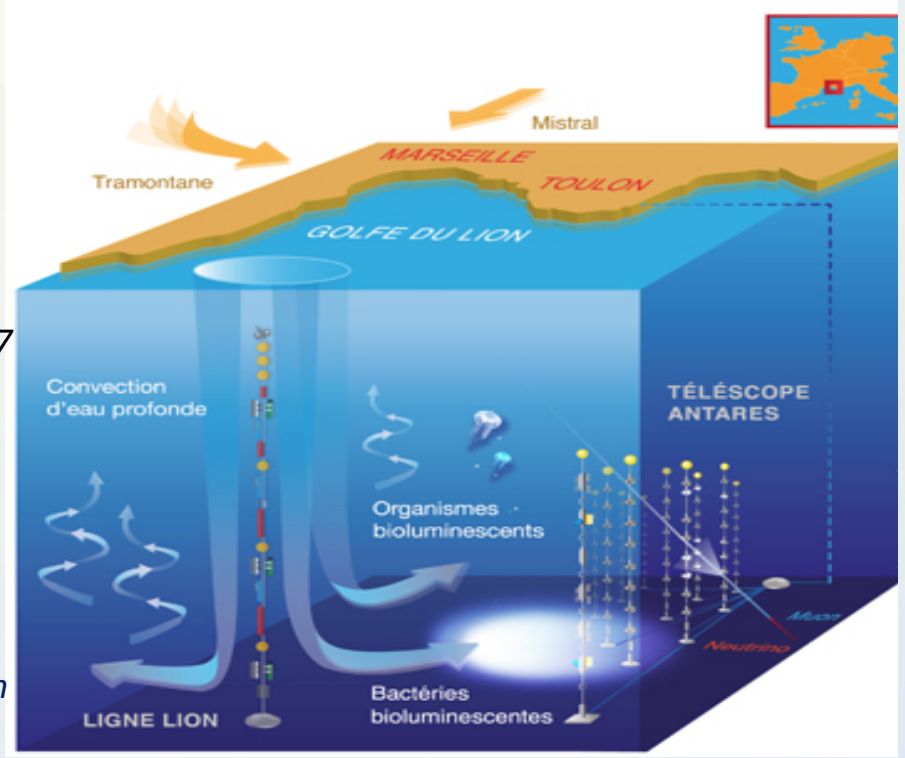
📖 PLoS ONE 8 (7) 2013
Deep-sea bioluminescence blooms after dense water formation at the ocean surface

✓ SEDIMENTS

📖 *Journal Geophysical Research: Oceans, Vol 122, 3, 2017*
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

✓ ACOUTICS

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

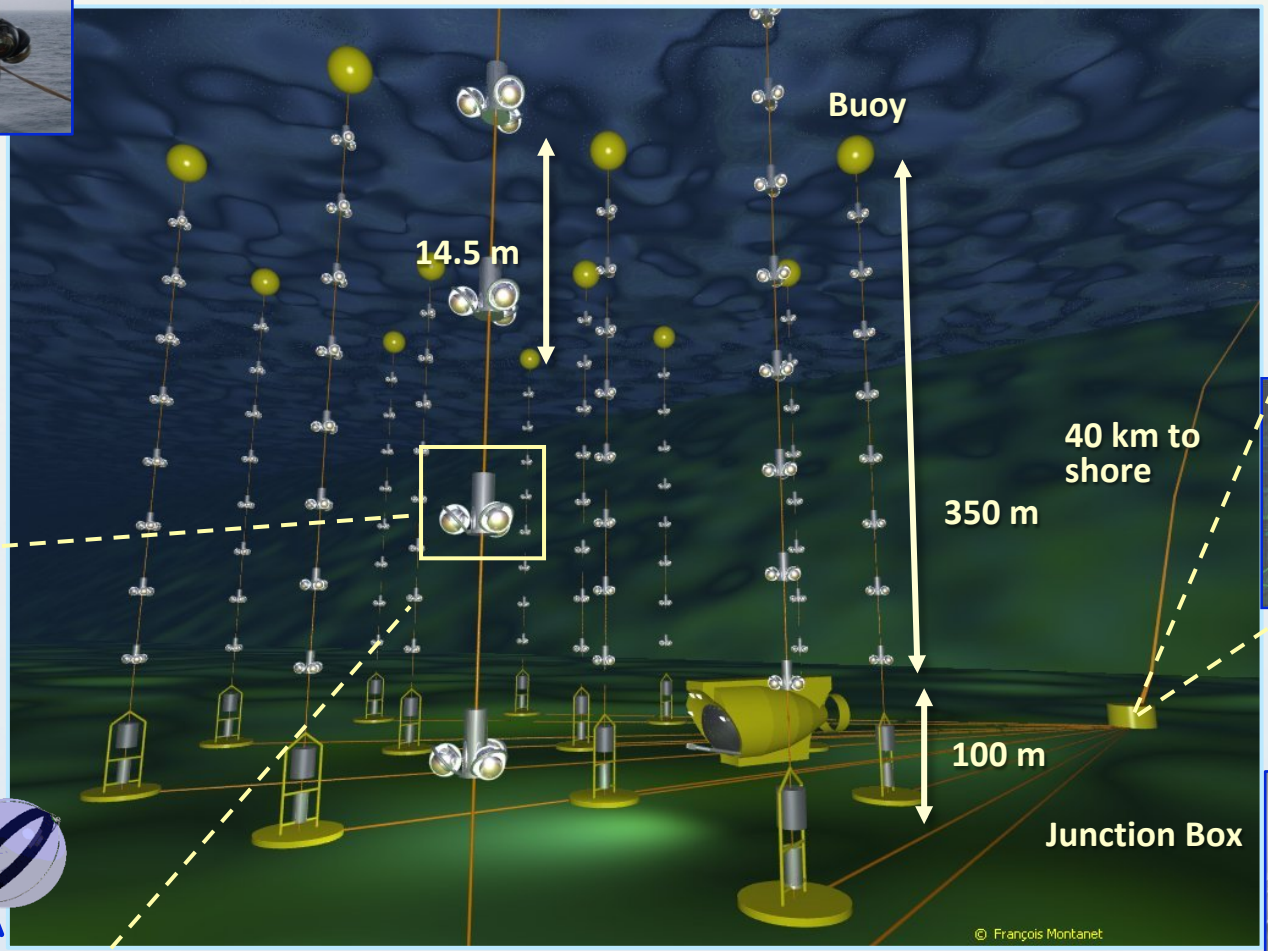


✓ SEA MAMALS BEHAVIOUR

📖 *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



12 lines (885 PMTs)

25 storeys / line

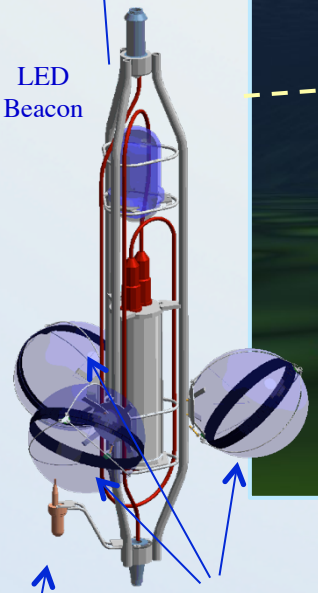
3 PMTs / storey

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

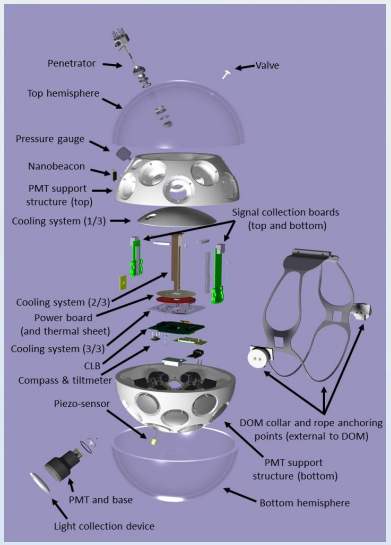
KM3NeT Technology

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Digital Optical Module

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

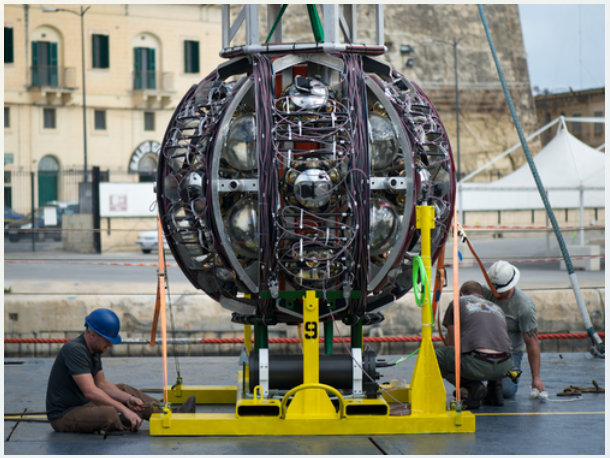
- All data to shore
- Gbit/s on optical fiber
- Hybrid White Rabbit
- LED flasher & hydrophone
- Tiltmeter/compass

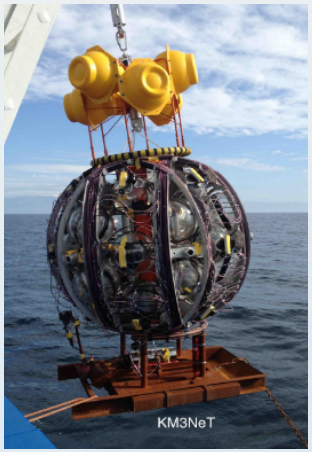


String (Detector Unit)

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

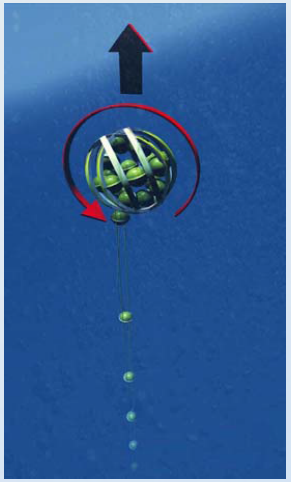
Deployment Vehicle





- Unfurling by autonomous ROV
- Reusable

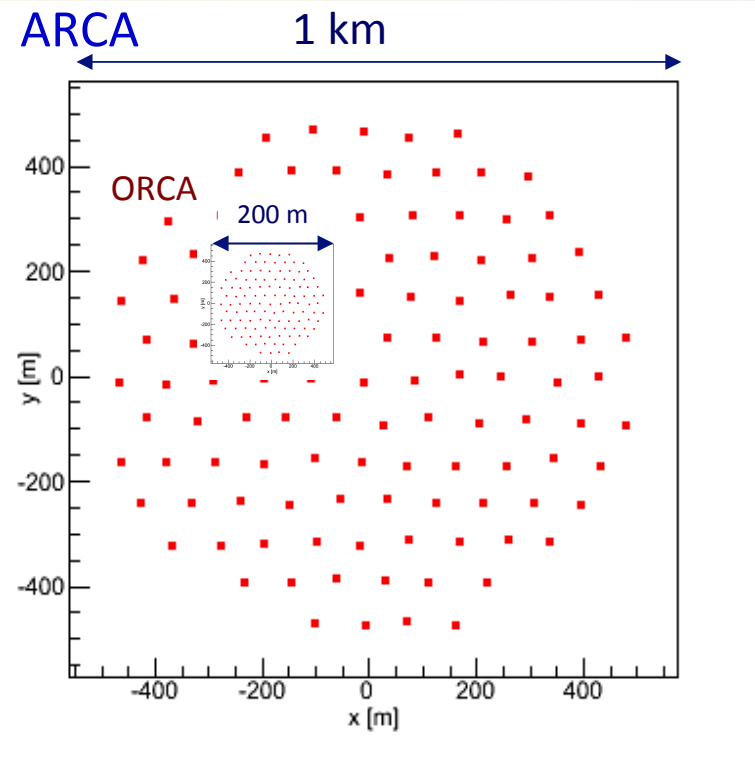
- Rapid deployment
- Multiple strings in one sea campaign



ARCA (Astronomy, Gton scale)

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

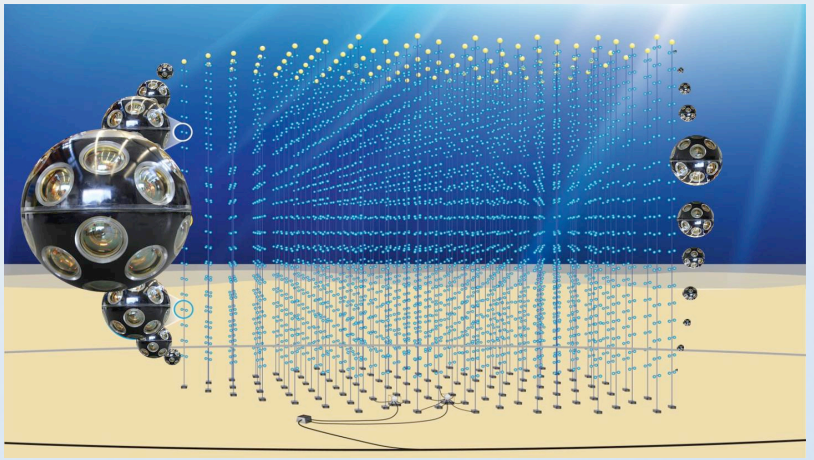
Building Block



ORCA (NMH+ ν properties, Mton scale)

Same technology, denser layout

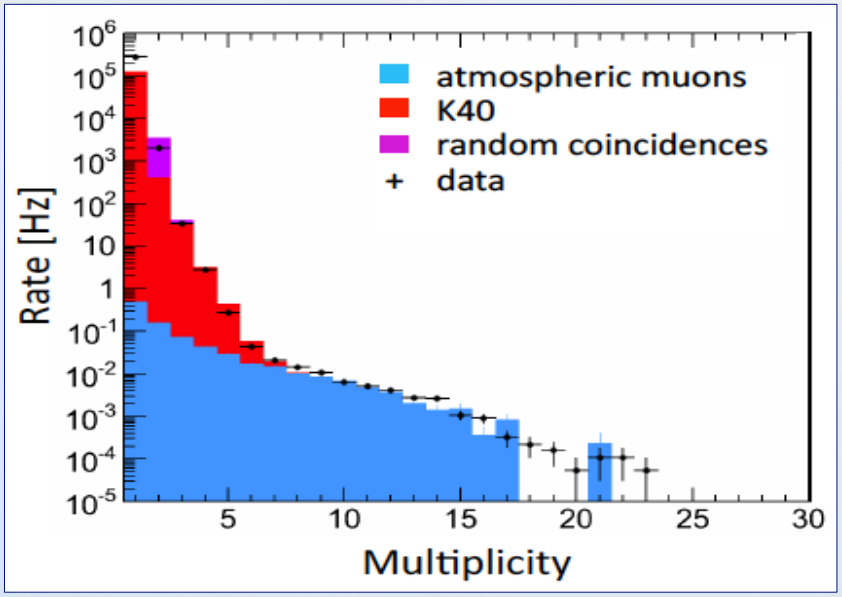
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 8 Mton	0.6 × 2 Gton



KM3NeT first Detection Units

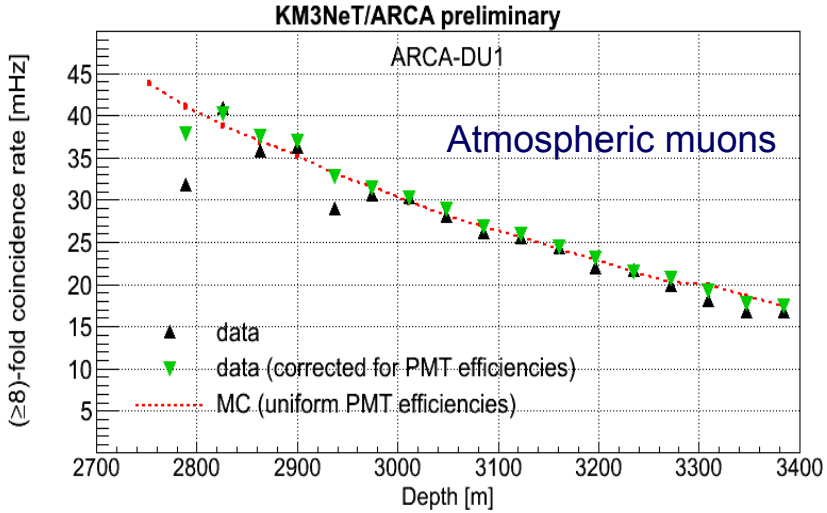
Eur. Phys. J. C 76 (2016) no.2, 54
Eur. Phys. J. C 74 (2014) no.9, 3056

- DOM in ANTARES site
  - April 2013, 2.500 m
  - Muons from a single DOM
- Mini-string in ARCA site
  - May 2014, 3.500 m, 3 DOMs
  - Muon reconstruction, angular distribution

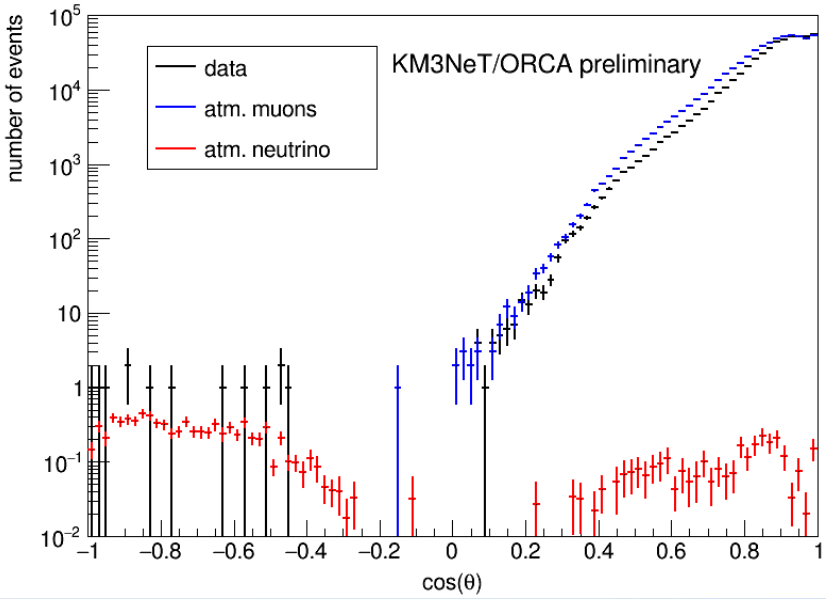


Watch https://www.youtube.com/watch?v=tR8jwgG6uzk
https://youtu.be/7HKHW0hLxt4?t=44s

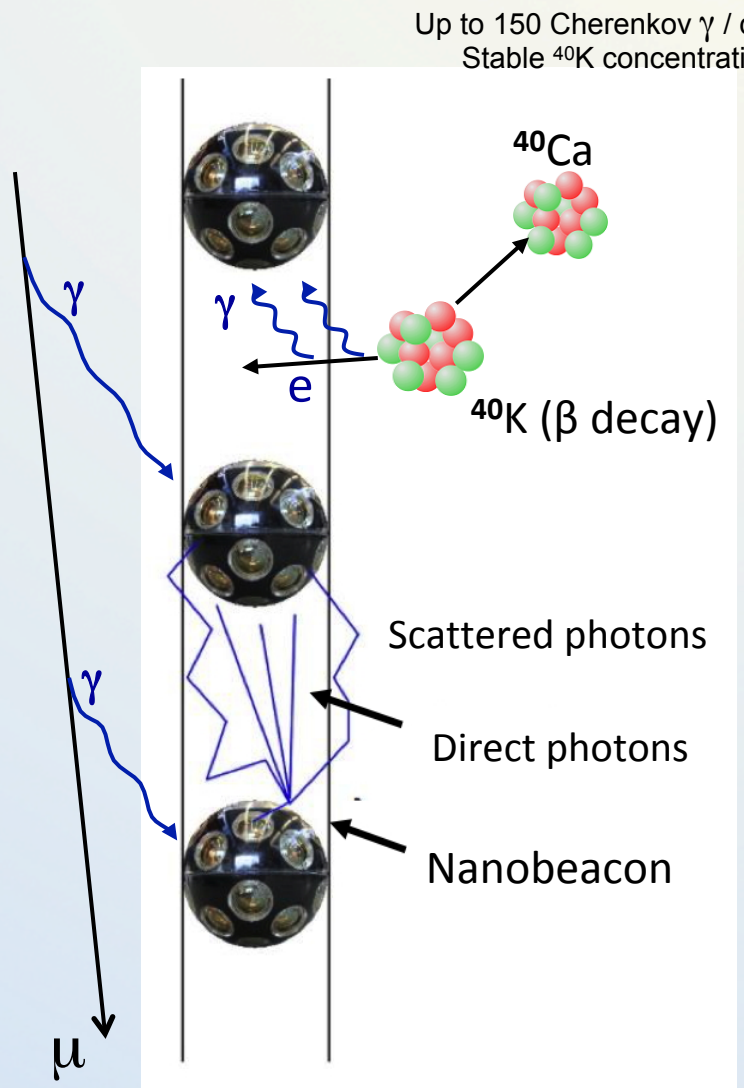
- Two full strings in ARCA site



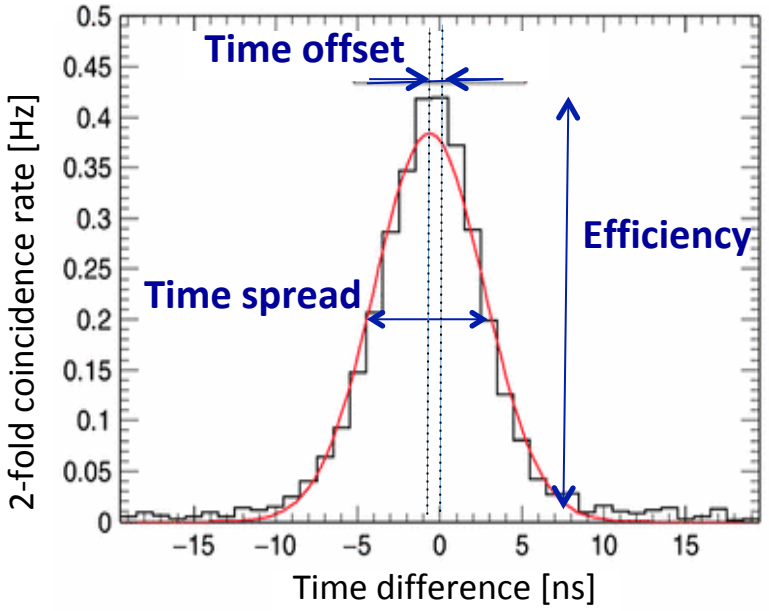
- First string in ORCA site

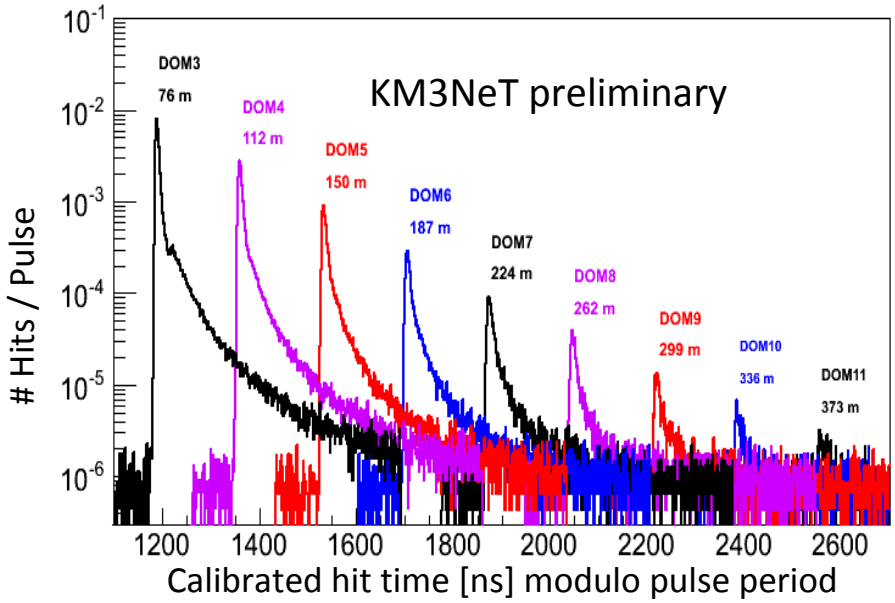


Calibration Procedures



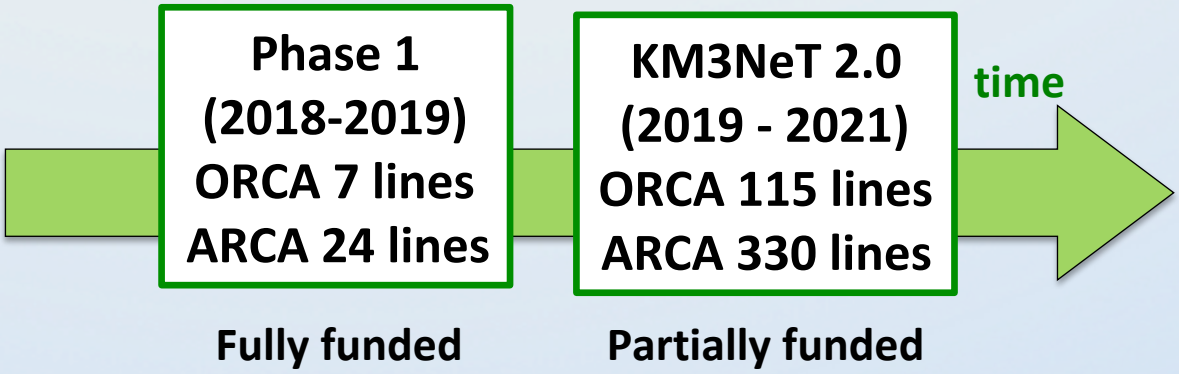
Cross-calibration with muons





KM3NeT status

- ARCA
  - Dec 2015 – May 2016, 3 strings deployed
  - string #3 with short in power system ← recovered
  - Improvements in seabed networking on-going
  - String deployment will resume by mid-2019
- ORCA
  - First string deployed in September 2017
  - Cable problem, replacement in summer 2018



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

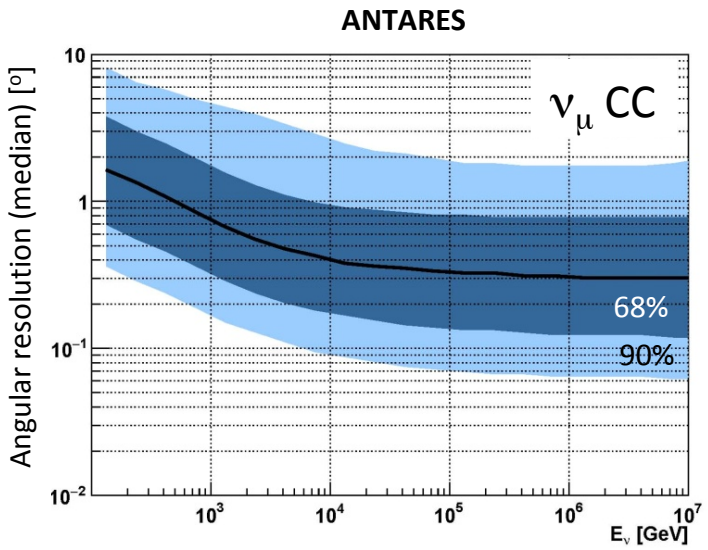
Angular Resol. < 0.4° above 10 TeV

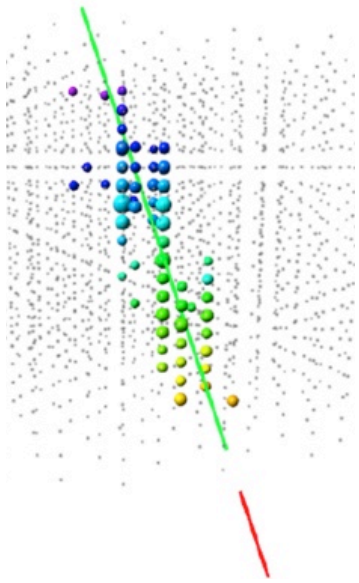
Energy Resol. ~ 0.35 in $\log_{10}(E_{reco}/E_\mu)$

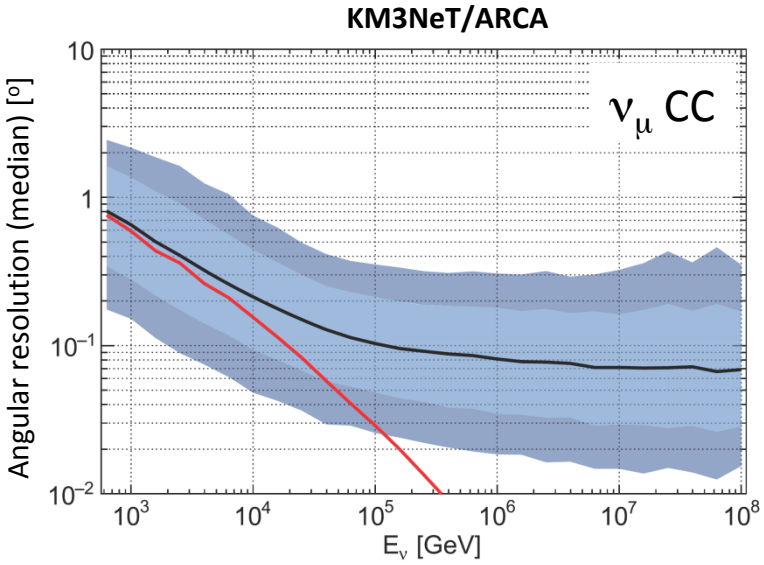
Ang. Resol. < 0.2° above 10 TeV

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

($10\ TeV < E_\mu < 10\ PeV$)







(ν_μ – true μ direction) angle

Reconstruction Performances (2/2): "Showers"

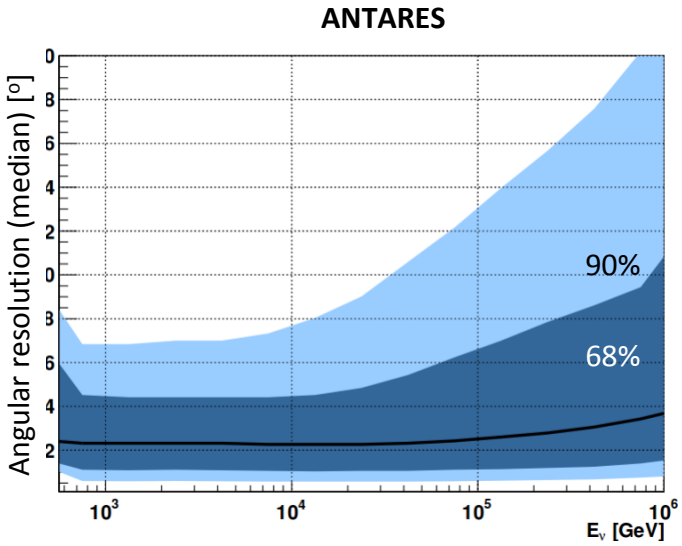
NC ν_{all}
CC ν_e

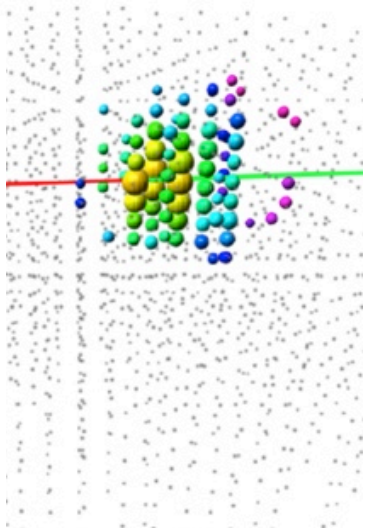
Shower events also used for astronomy

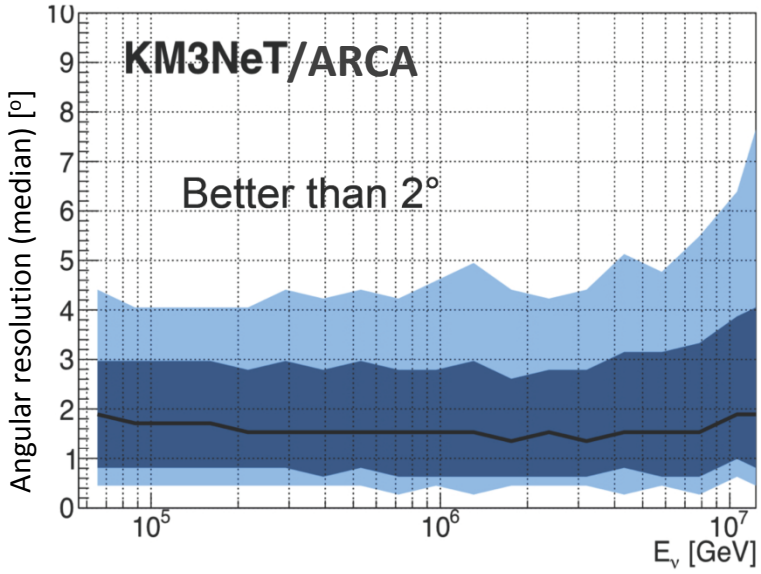
- Contained events → Better energy resolution
- Almost no atmospheric background

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 %







Diffuse Flux : Full sky + all flavor search

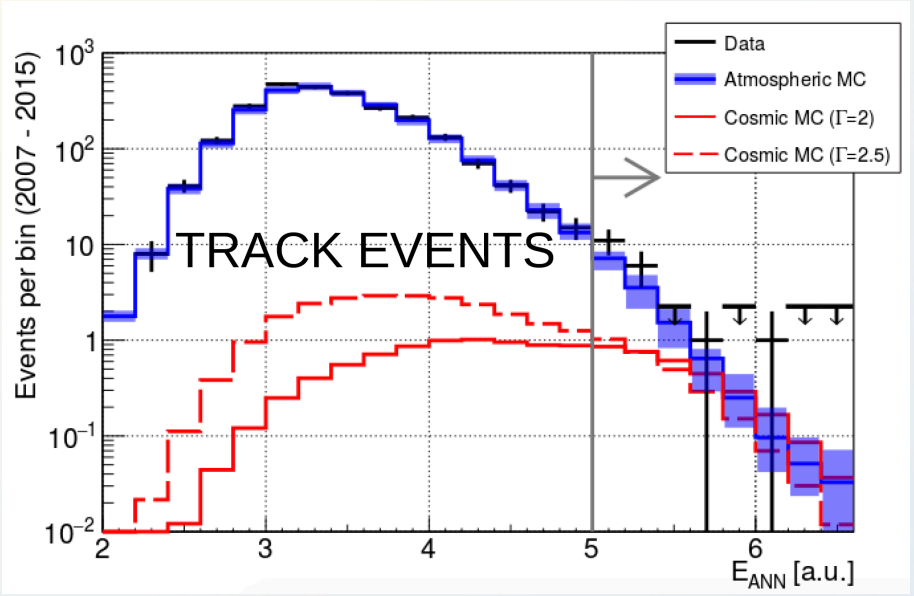
ApJL 853, L7 (2018)

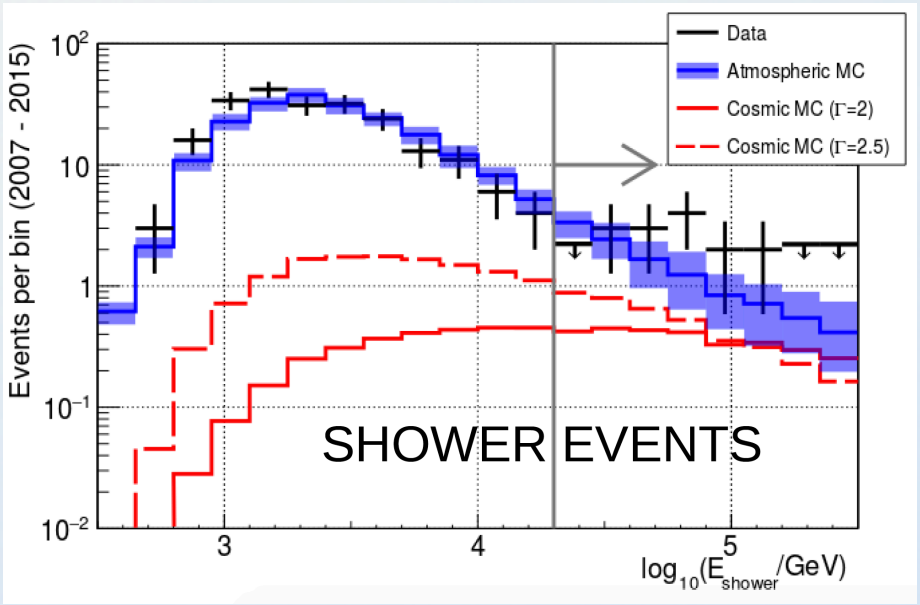
- Data Sample 2007 – 2015 (2450 days)
- All sky / All-flavour ν search
- Unblinding:

	Events		tracks		showers
Observed:	33	=	19	+	14
Expected:	24	=	13.5	+	10.5

- Results compatible with IceCube diffuse flux:

- 1.6 σ excess
- No-signal hypothesis excluded at 85% CL





Diffuse Flux : Full sky + all flavor search

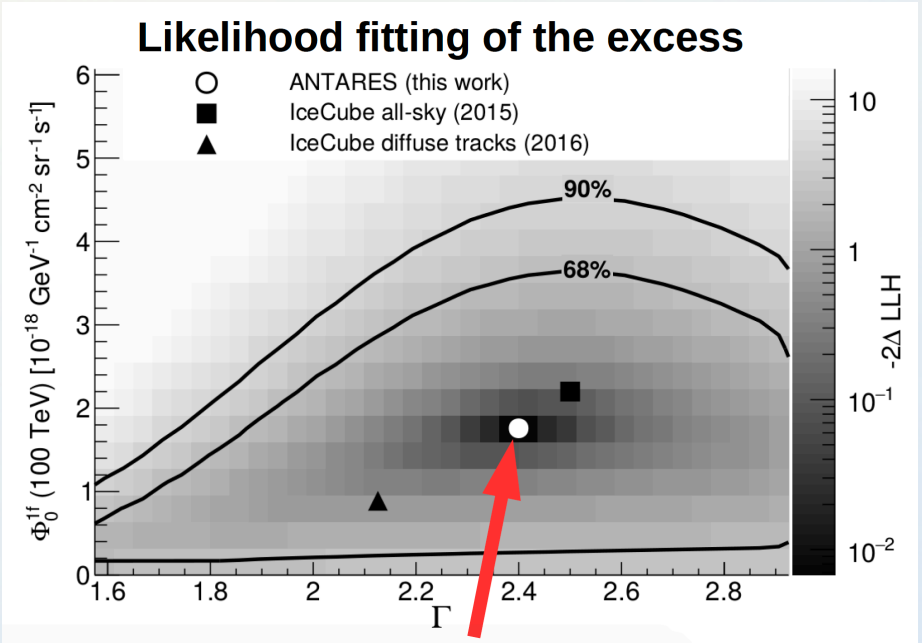
ApJL 853, L7 (2018)

- Data Sample 2007 – 2015 (2450 days)
- All sky / All-flavour ν search
- Unblinding:

	Events		tracks		showers
Observed:	33	=	19	+	14
Expected:	24	=	13.5	+	10.5

- Results compatible with IceCube diffuse flux:

- 1.6 σ excess
- No-signal hypothesis excluded at 85% CL



Best fit (1 flavour flux normalization at 100 TeV)

- Flux: $\Phi_0(100\ \text{TeV}) = (1.7 \pm 1.0)\times10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$
- Spectral index: $\Gamma = 2.4\ ^{+0.5}_{-0.4}$

KM3NeT Diffuse Flux : Full sky

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

Track channel

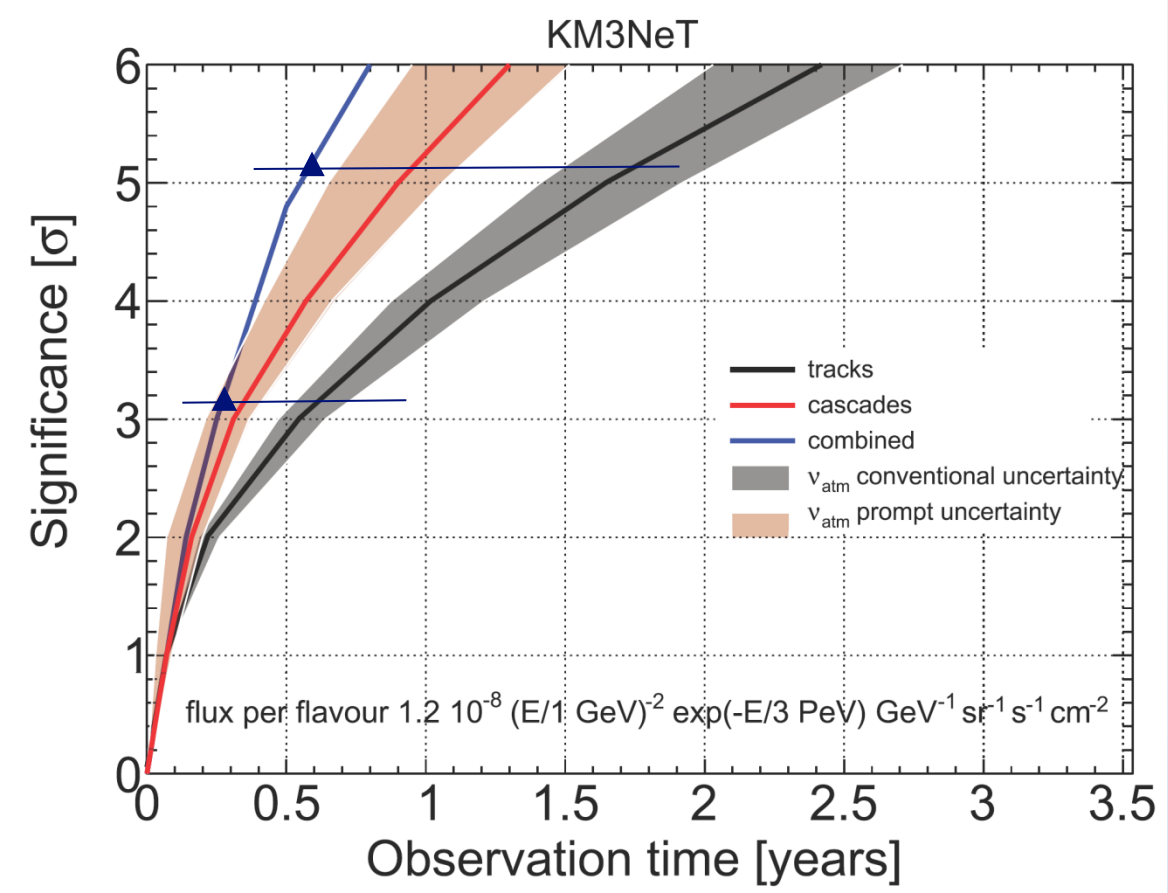
Analysis for upward-going events based on a maximum likelihood

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

Expected events per year
Tracks: 6 signal / 4 bkg.
Showers: 18 signal / 9 bkg.

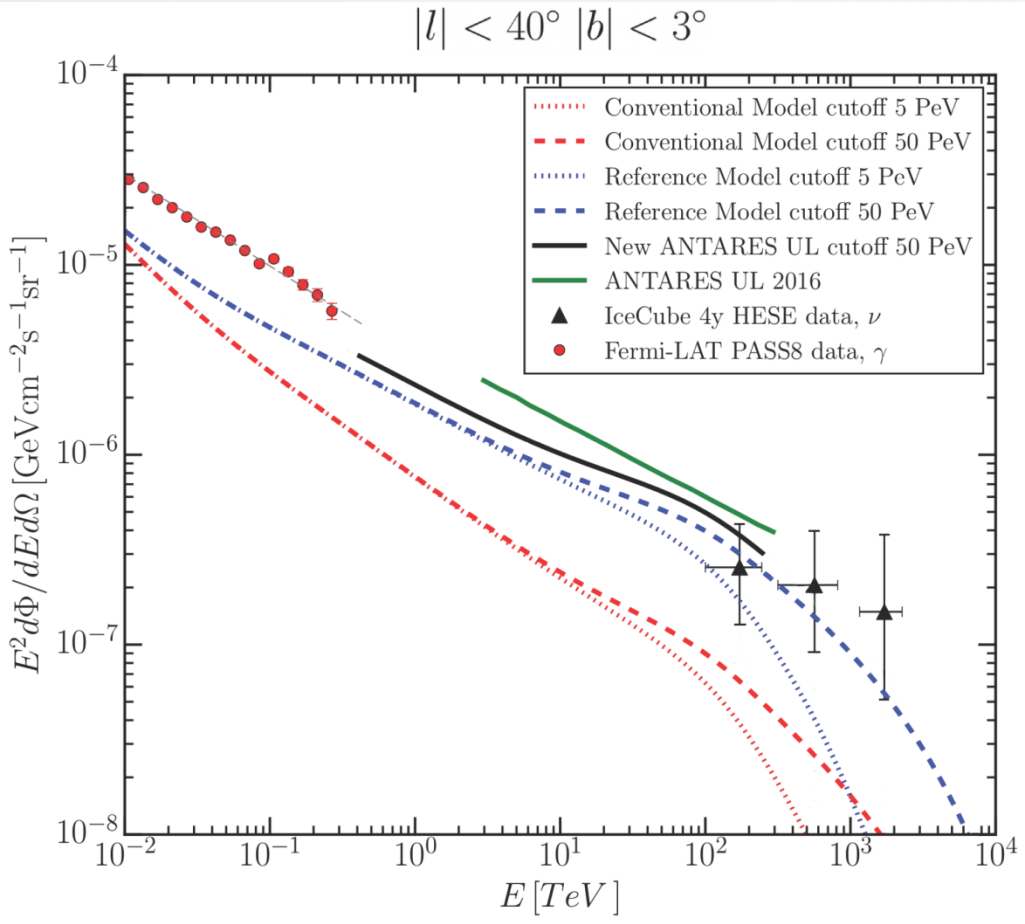
Diffuse Flux : Galactic Ridge

Phys. Rev. D 96 062001 (2017)

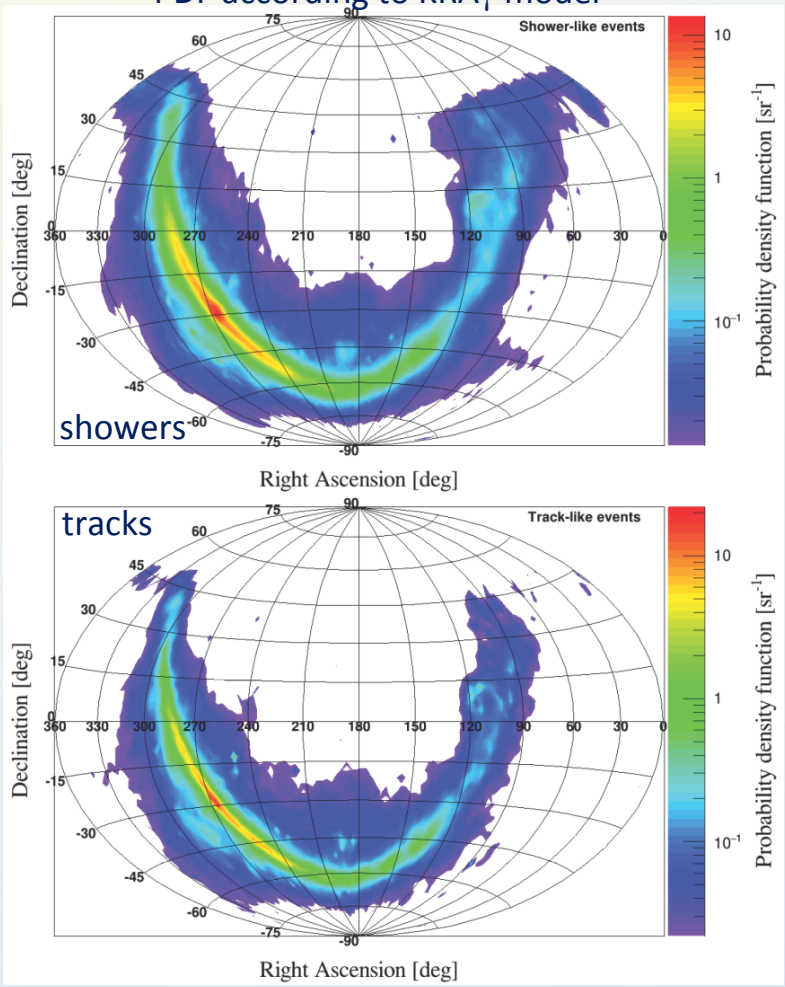
7300 tracks + 208 showers

- Data: 2007 – 2015 (2424 livedays)
- KRAγ " *gamma model* " assumed as reference
- Likelihood (signal + bkg.)
- No excess observed in data → $UL^{90\%\ CL} = 1.2 \times \Phi_{ref}$

($E^{p}_{cut\text{-}off}$ = 50 PeV)



PDF according to KRAγ model



Combined ANTARES + IceCube analysis ⇒
The ν flux produced by Galactic CR interactions with gas cannot explain by itself the IceCube "spectral anomaly"

ANTARES : Point Sources

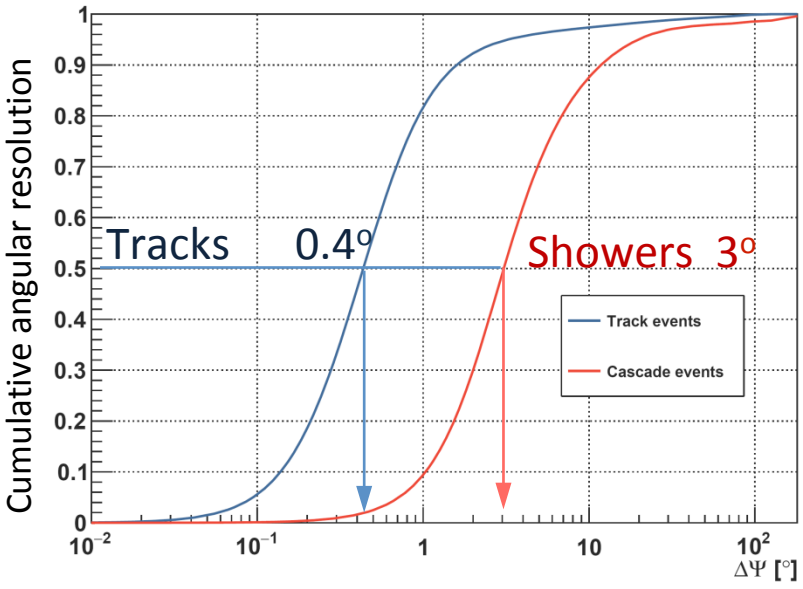
Phys. Rev. D 96 082001 (2017)

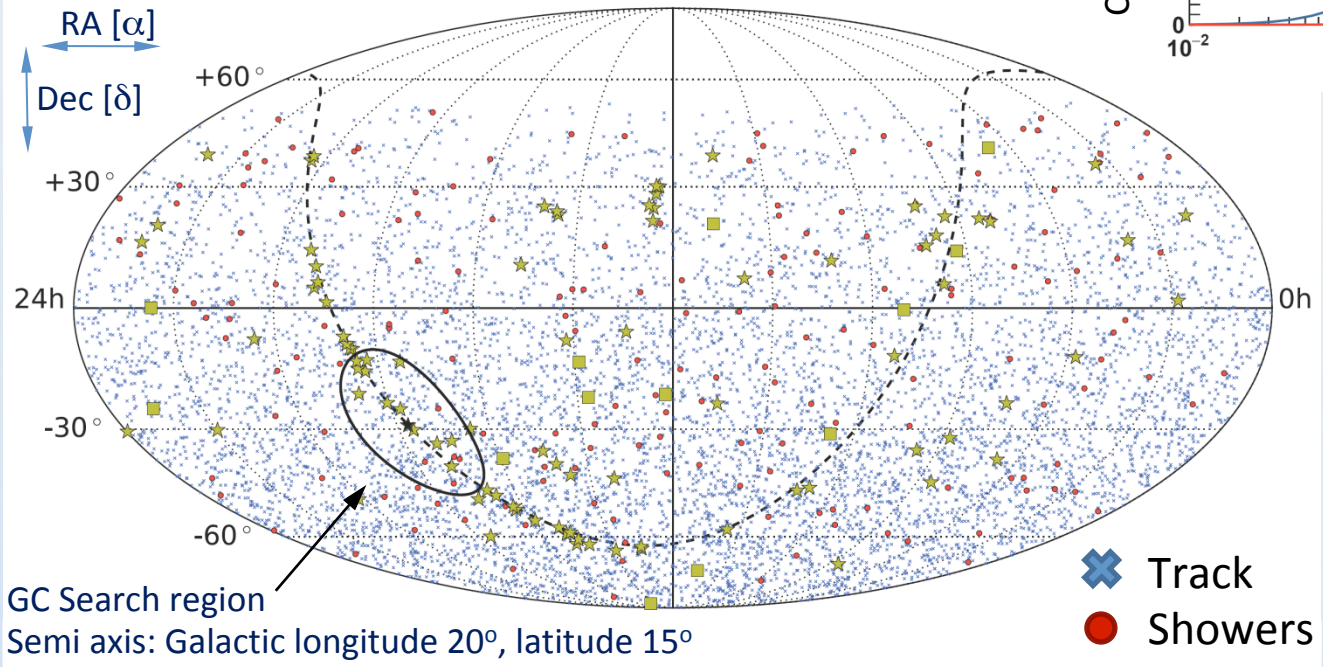
"First all-flavor (ν_μ tracks + showers) and all-sky neutrino point-like source search"

- ANTARES Data: 2007 – 2015 (2424 days livetime)

  → 7629 tracks + 180 showers

- Full sky (steps of 1°×1° , no source assumption)
- 106 sources (galactic + extra-galactic)
- 13 IceCube HESE events (μ track candidates)
- Galactic Center Region (Ellipse 15°×20°)
- Sagittarius A* (extended source, Gaussian profile 0° – 2°)





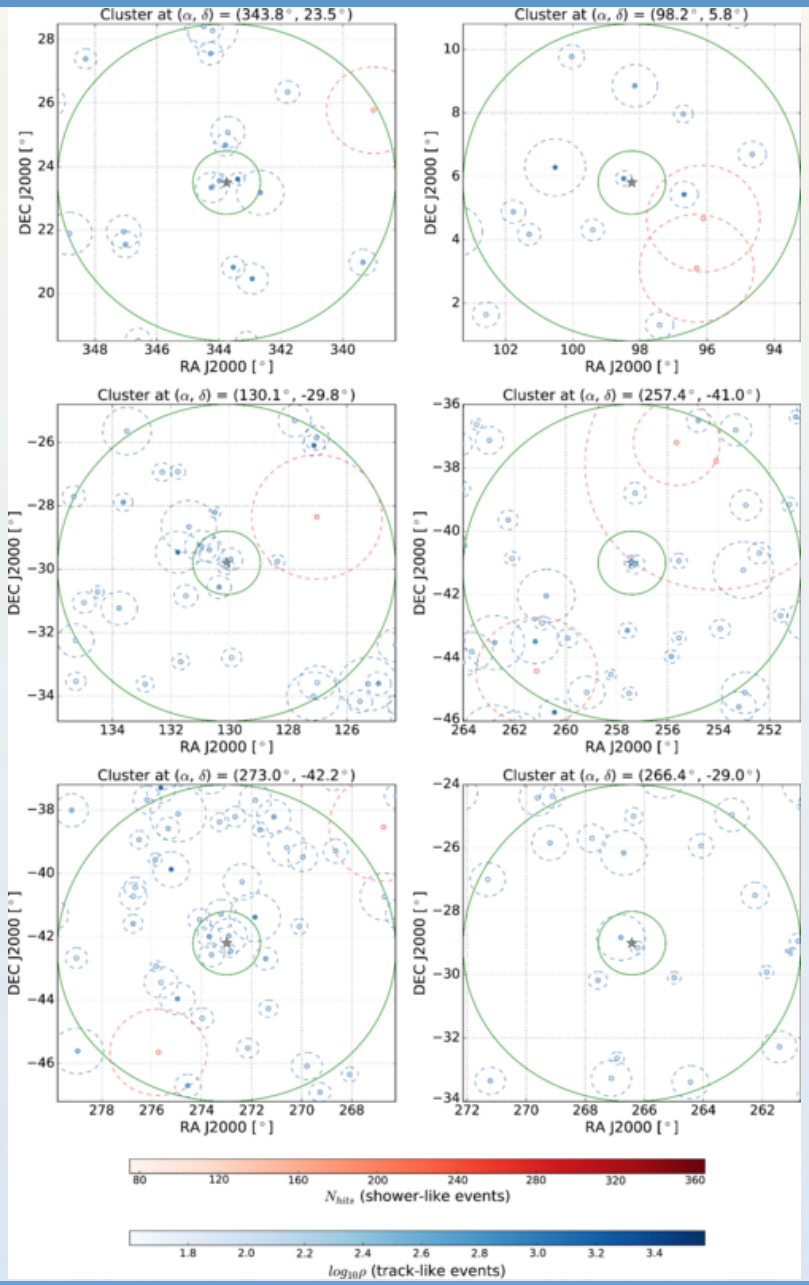
ANTARES : Point Sources

Phys. Rev. D 96 082001 (2017)

Full sky
Most significant cluster
(α,δ) = (343.8°, 23.5°)
Post-trial significance:
5.9% or 1.9σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

13 HESE tracks
Most significant cluster:
(α,δ) = (130.1°, -29.8°)
at a distance of 1.5° from the HESE track with ID 3
Post-trial significance:
20% or 1.3σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 2.1 \times 10^{-8}$ GeV cm^{-2} s^{-1}

Galactic Centre
(γ = 2.1, 2.3, 2.5)
(σ = 0.5°, 1.0°, 2.0°)
(α,δ) = (273.0°, -42.2°)
$E^{-2.5}$ spectrum
point-like source
Post-trial significance:
30% or 1.0σ



Candidate List:
Most significant cluster:
HESSJ0632+057
(α,δ) = (98.24°, 5.81°)
Post-trial significance:
13% or 1.5σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 2.4 \times 10^{-8}$ GeV cm^{-2} s^{-1}

Galactic Centre
Spec indices γ = 2.1, 2.3, 2.5
Extension σ = 0.5°, 1.0°, 2.0°
Most significant cluster:
(α,δ) = (257.4°, -41.0°)
for a E^{-2} spectrum + point-like source
Post-trial significance:
60% or 0.5σ

Sagittarius A*:
(α,δ) = (266.42°, -29.01°)
Point-like source (σ = 0°) and
Extended source (σ = 0.5°,1.0°, 2.0°)
Largest excess as point-like
Pre-trial significance:
22% or 1.2σ

ANTARES : Point Sources

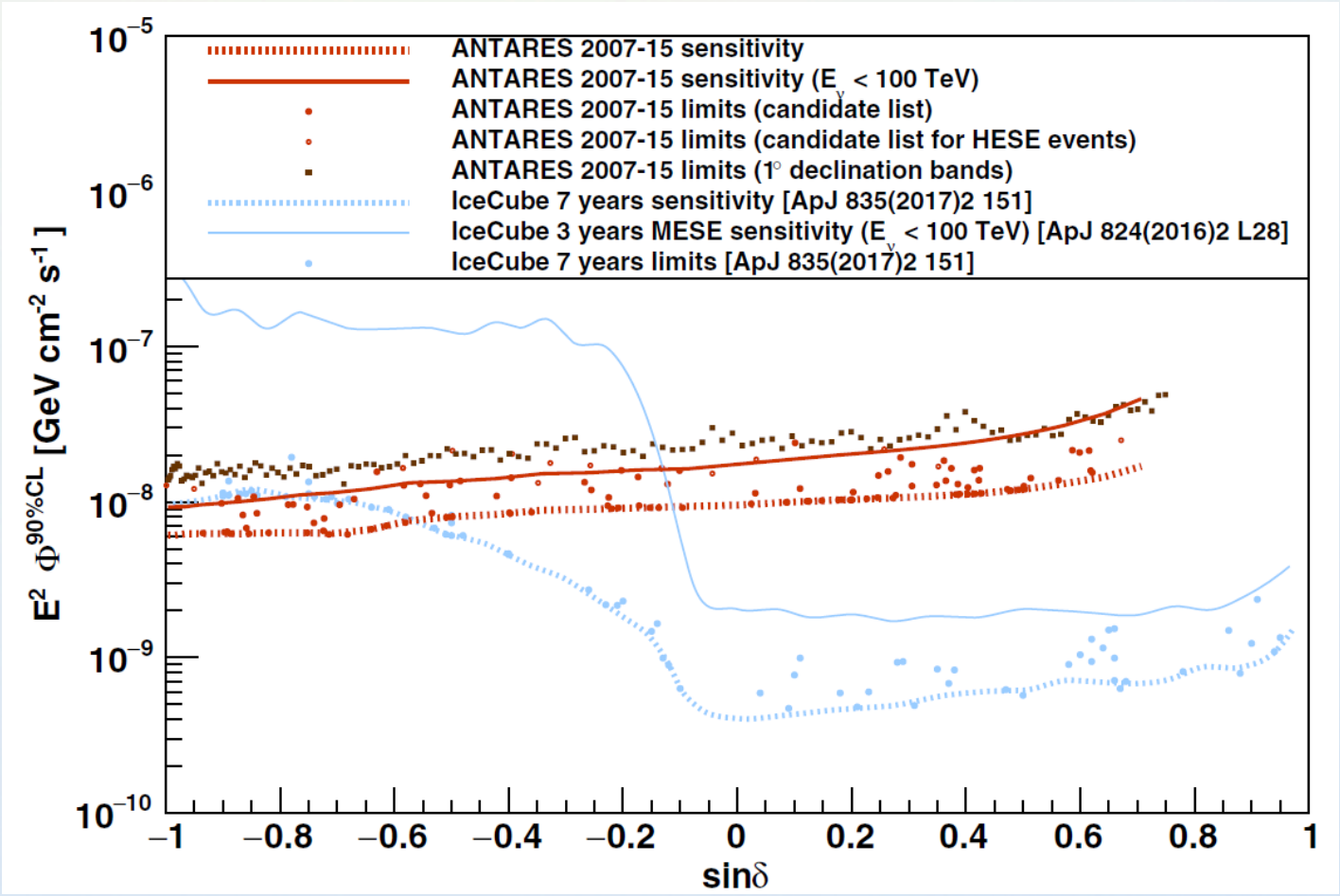
Phys. Rev. D 96 082001 (2017)

No significant cluster found

Sensitivities and upper limits at a 90% CL on the signal flux from the full-sky and the Candidate List searches

ANTARES

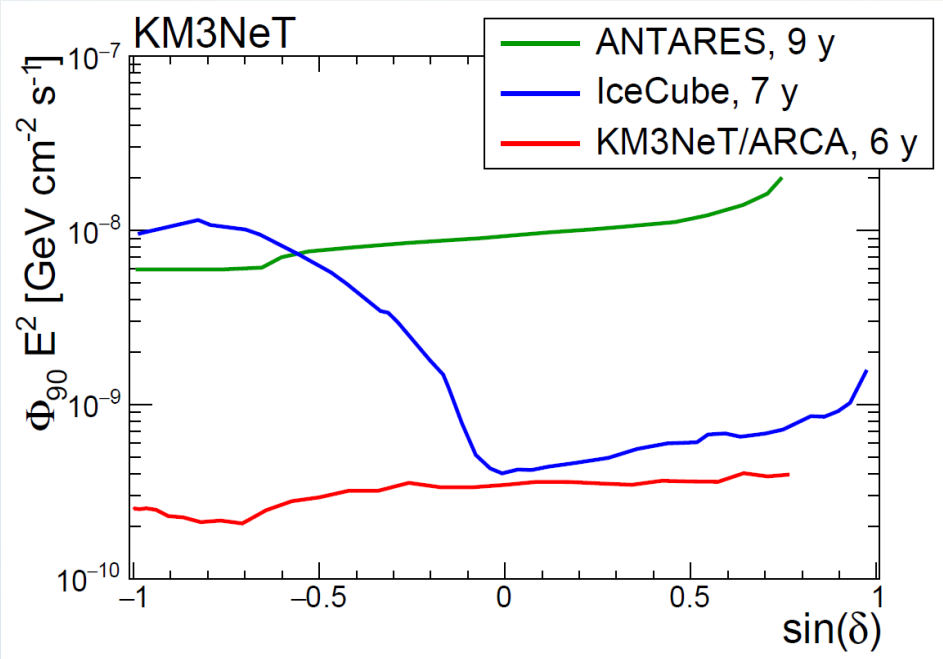
- Best limits for part of Southern Hemisphere
- Excellent sensitivity for $E_\nu < 100$ TeV

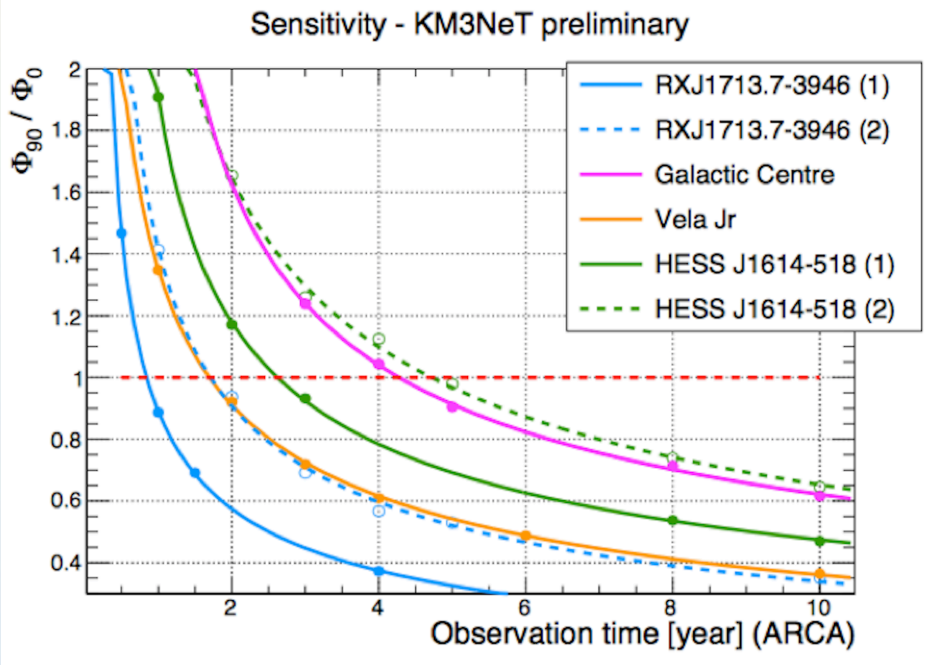


KM3NeT: Expectations for point-sources

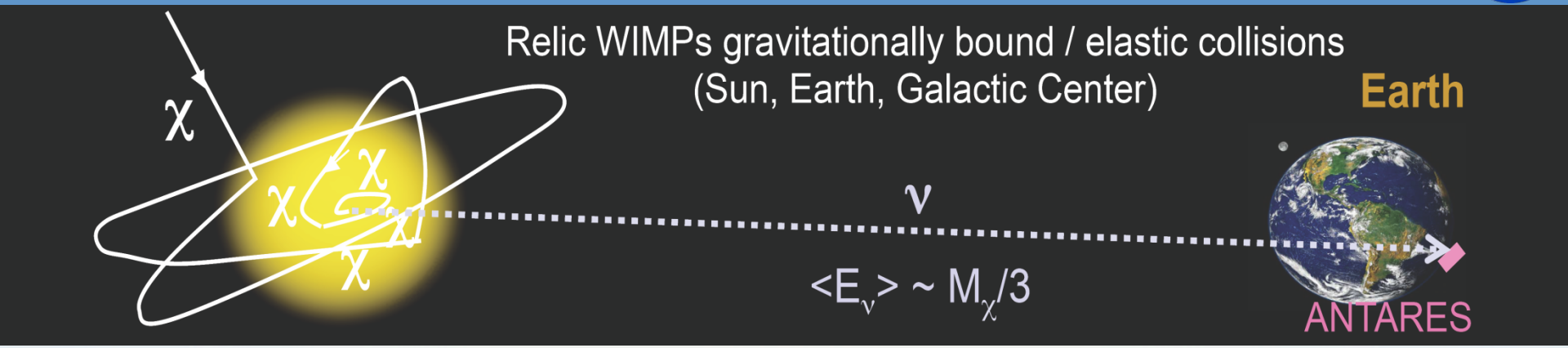
PoS (ICRC2017) 999

- Sensitivity for 6 yrs of observation with ARCA (2 building blocks)
- Broad coverage. E^{-2} spectrum assumed.
- Sensitivity for Galactic sources





Dark Matter Searches



- Gravitational trapping and 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 ⇒ very clean signature with no significant astrophysical background expected
- Explored Signal channels:

$$WIMP + WIMP \rightarrow b\bar{b},\ W^+W^-,\ \tau^+\tau^-,\ \mu^+\mu^-,\ \nu_\mu\ \bar{\nu}_\mu$$

- Background estimated from time scrambled data

Galactic Center/Milky Way:
- PLB 769 (2017) 249
- JCAP 10 (2015) 068

Sun:
- Phys. Lett. B 759 (2016) 69
- JCAP 05 (2016) 016

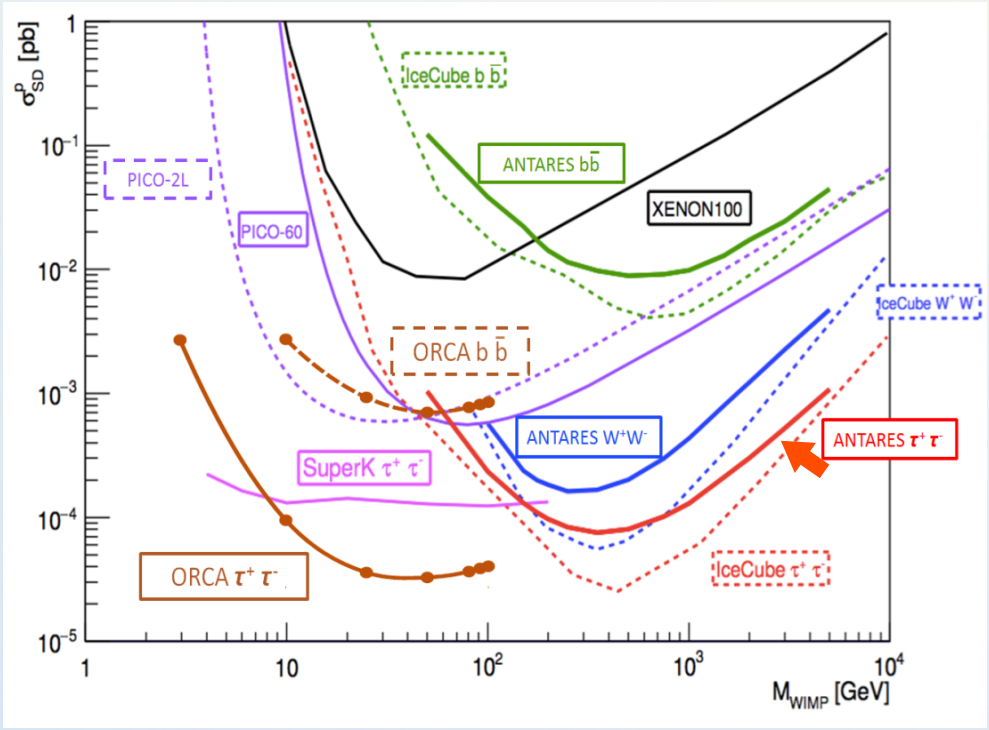
Earth:
- Phys. Dark Univ. 16 (2017) 41

Dark Matter annihilation as a source of neutrinos

ν_μ tracks only

- Data: 2007 – 2012 (1321 livedays)
- Competitive limits for SD WIMP-nucleus spin-dependent cross-sections

SUN Spin dependent cross section

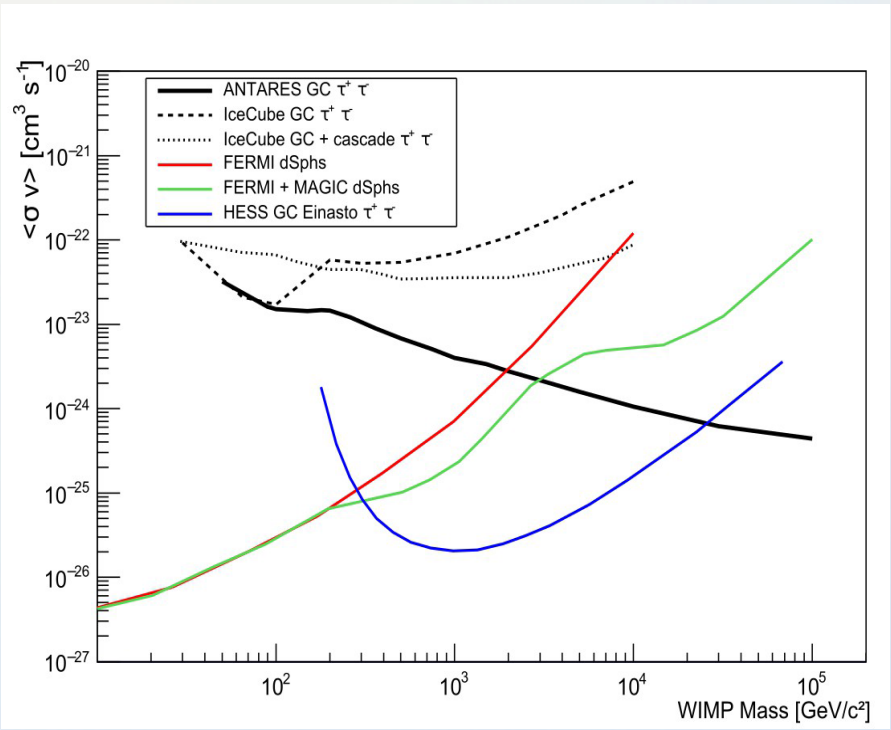


Phys. Lett. B 759 (2016) 69

ν_μ tracks only

- Data: 2007 – 2015 (2102 livedays)
- Galactic Center: Good visibility by ANTARES (~66%) $m\chi \in [\ 50\ GeV – 100\ TeV\ ]$

Galactic Center



Phys. Lett. B 769 (2017) 249

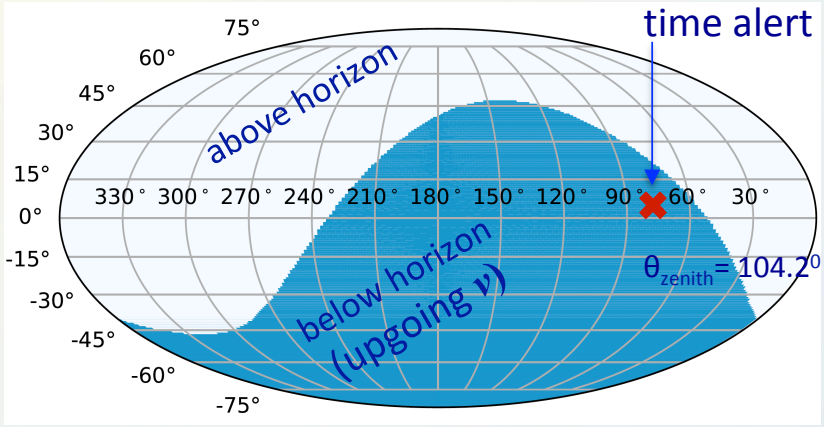
Search for neutrinos from TXS 0506+056

arXiv: 1807.04309

- **IceCube event IC170922A**
  (GCN circular IC #21916)
  - T_0 = 17/09/22, 20:54:30 UT
  - Extremely HE track: $E_\nu \approx$ 0.3 PeV
  - (α, δ) = [77.43°, 5.72°]

- Connected with observations in γ-rays (100 GeV, MAGIC) and other wavelengths of the e.m. spectrum (Fermi-LAT) from **Blazar TXS 0506+056**

ANTARES Visibility map at IC170922A time alert



ANTARES searches *(see D. Dornic talk)*

1st "ONLINE DATA STREAM" SEARCH: fast reconstruction

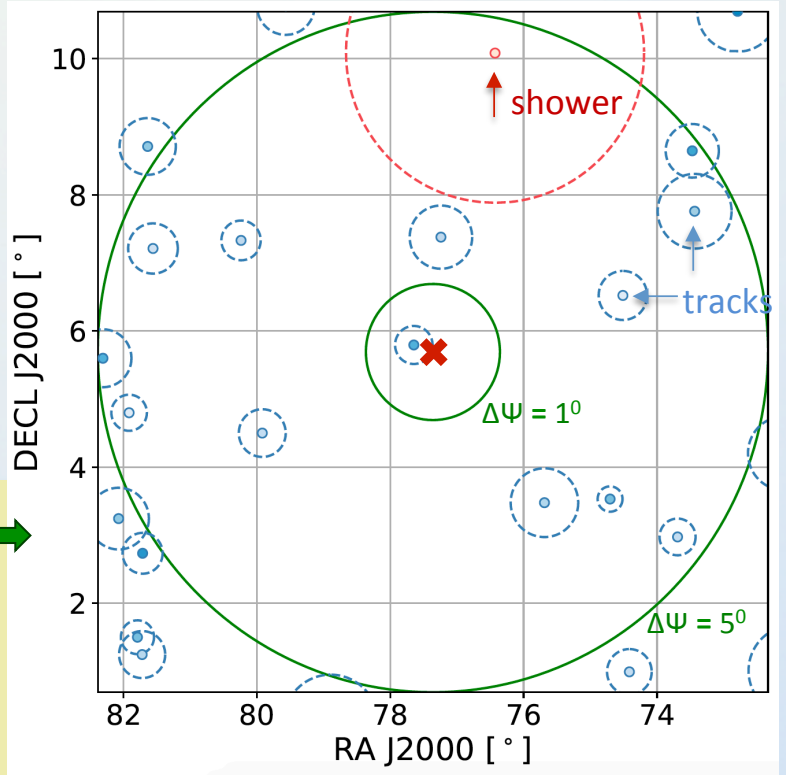
- **0 upgoing track muon ν** *candidate events*

3rd "2015 BURSTING PERIOD" SEARCH: time-dependent

- **0 events** in flaring periods

2nd "TIME-INTEGRATED" SEARCH: point-source approach

- 2007 – 2017 data (3136 livetime days): 107 sources
- Likelihood: μ_{sig}=1.03 evts. 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]



SUMMARY

ANTARES

- ✓ 10 years of good data taking experience.
- ✓ Tracks & Showers reconstructed with excellent angular resolution
- ✓ Diffuse flux: small excess at high energy compatible with cosmic signal
- ✓ Point sources: best limits for Southern Sky Galactic Sources (E_ν<100 TeV)
- ✓ A lively and vibrant multi-messenger program search

KM3NET

- ✓ 2 ARCA + 1 ORCA strings in water
- ✓ ARCA : high-resolution follow up of Ice Cube flux
- ✓ ORCA : Measure neutrino mass hierarchy
- ✓ ESFRI Roadmap 2016, APPEC European Strategy 2017