# ANTARES highlights and KM3NeT/ARCA prospects

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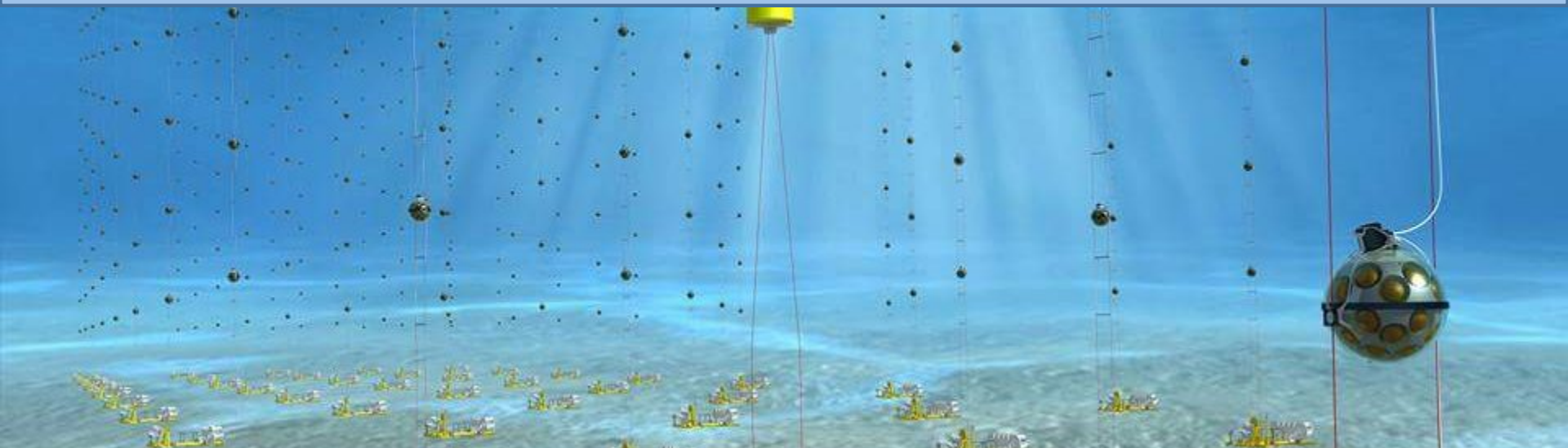
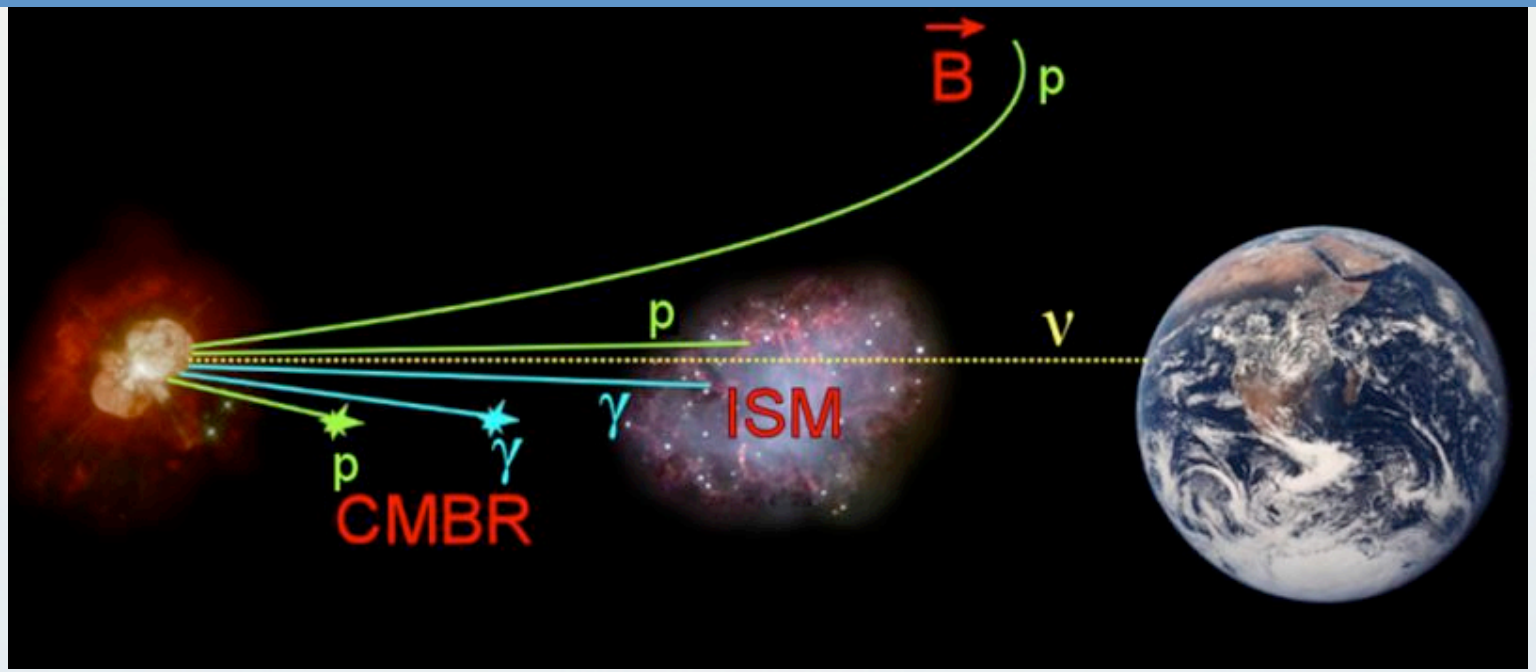
On behalf of the ANTARES and KM3NeT Collaborations

26th International Conference on Supersymmetry and Unification of Fundamental Interactions
Barcelona, July 23–27, 2018



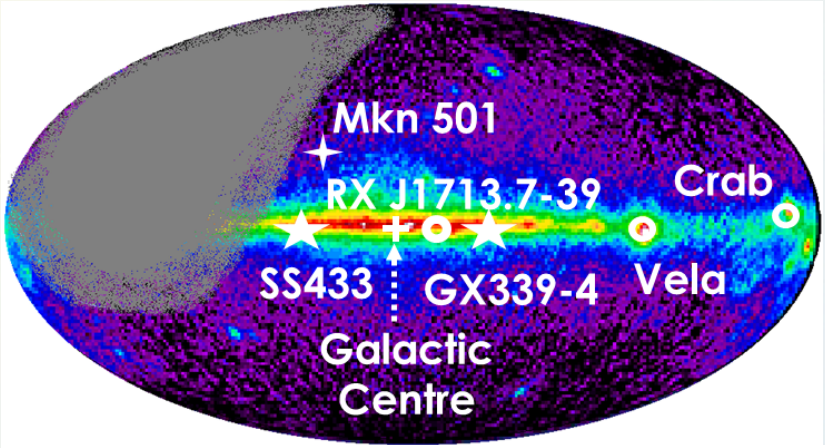
# Neutrino Astrophysics

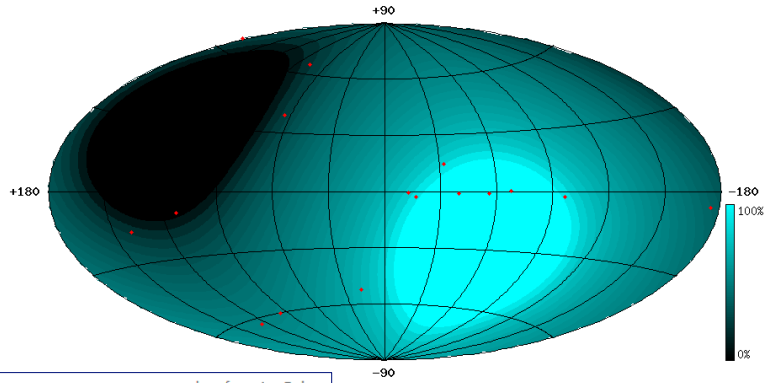


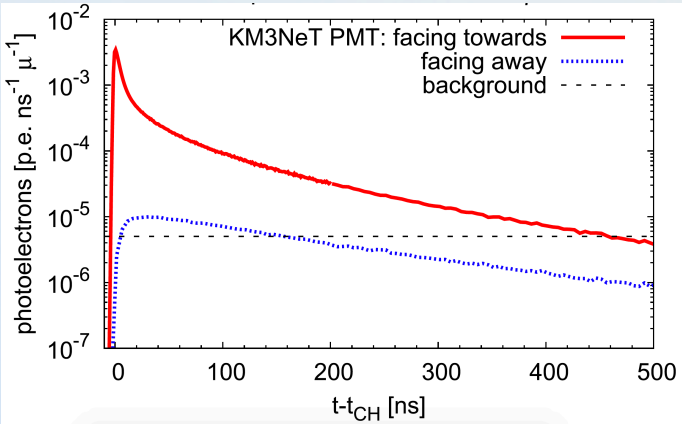

- **Origin and acceleration of Cosmic Rays ?**
- **Neutral messengers point back to their sources**
  - ✓ neutrons are short-lived, photons are likely to interact ➔ neutrinos
- **CR interactions produce neutrinos in meson decays**
  - ✓ Search for a diffuse flux from unresolved sources
  - ✓ Search for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

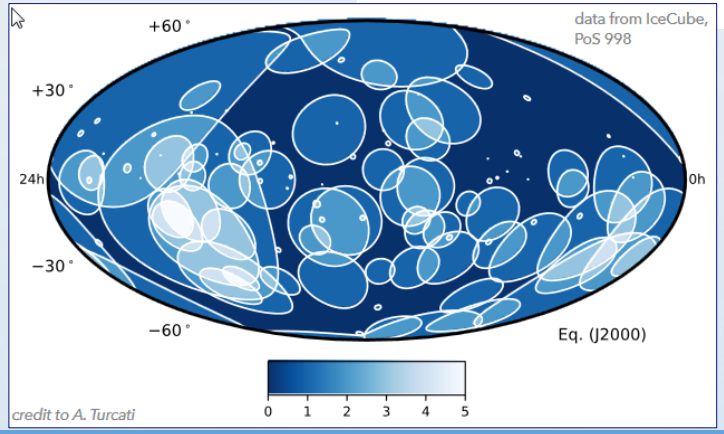
# Mediterranean Neutrino Telescopes

- **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.



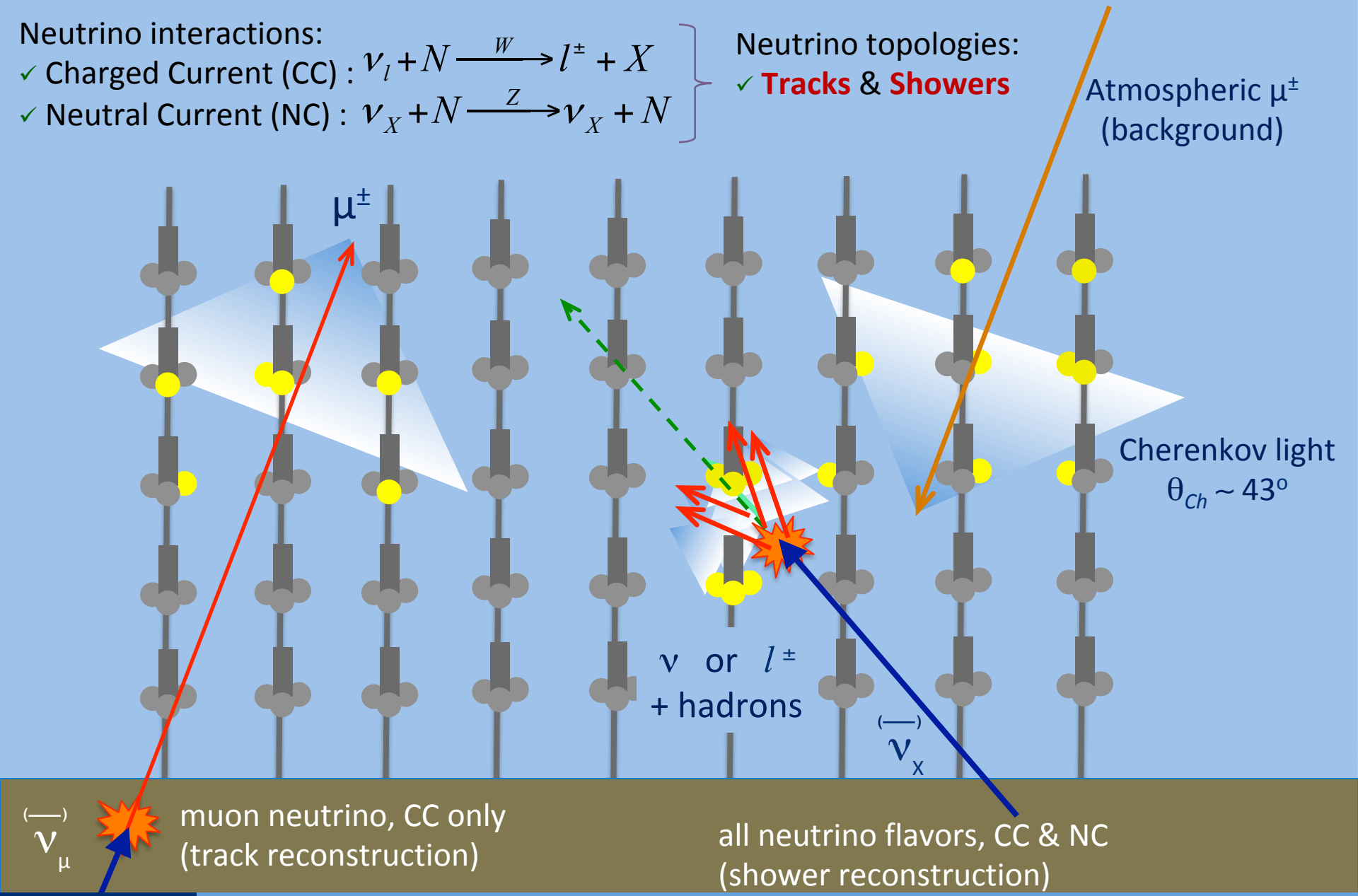
# Neutrino detection principle

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:

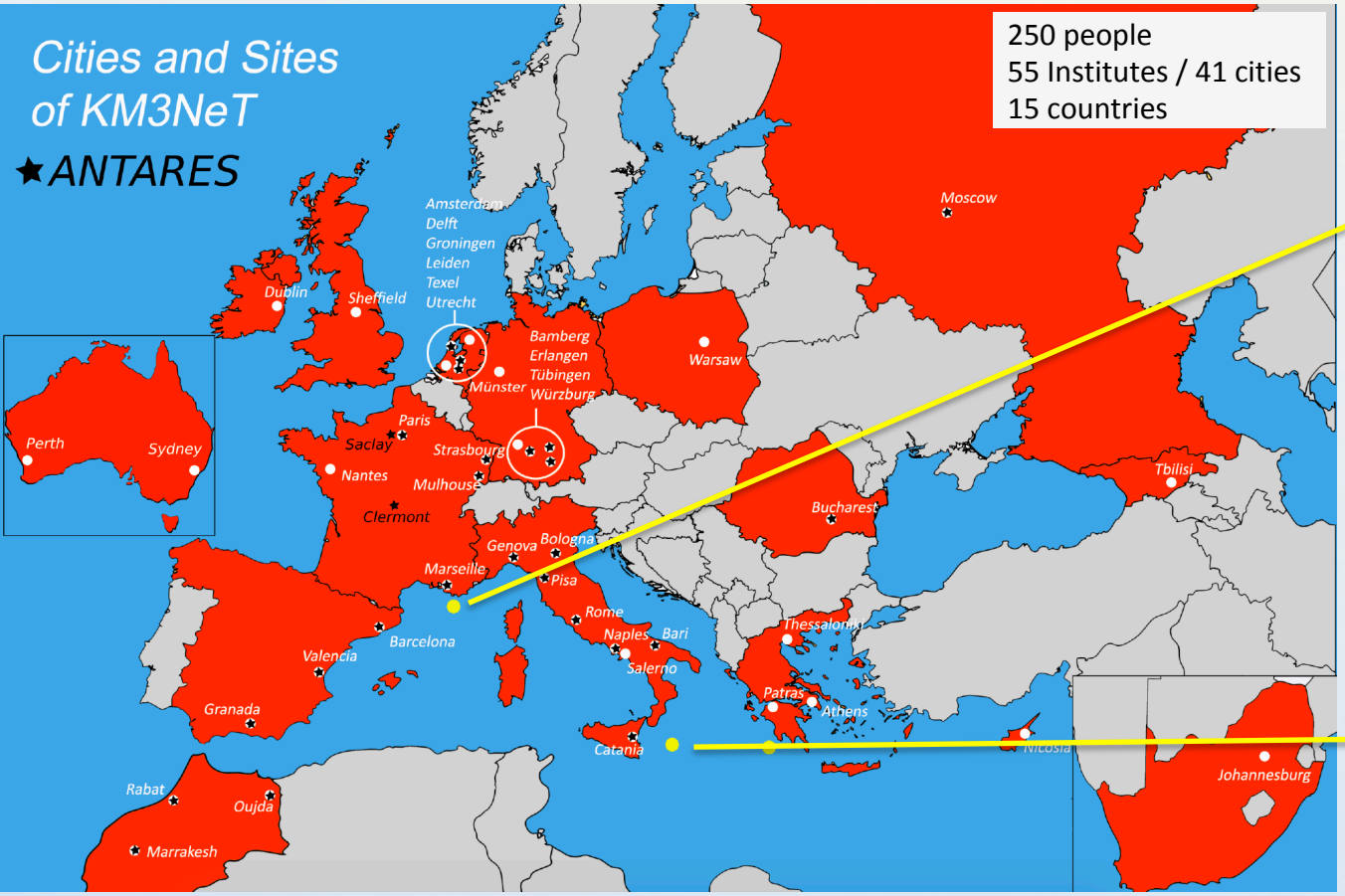
- ✓ **Tracks** & **Showers**

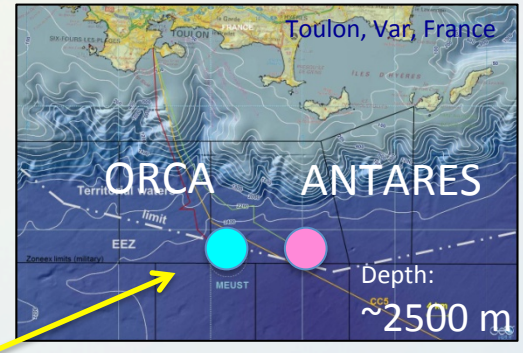


# Mediterranean ν telescopes

**ANTARES:** ~10 Mt instrumented mass. Completed in 2008

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

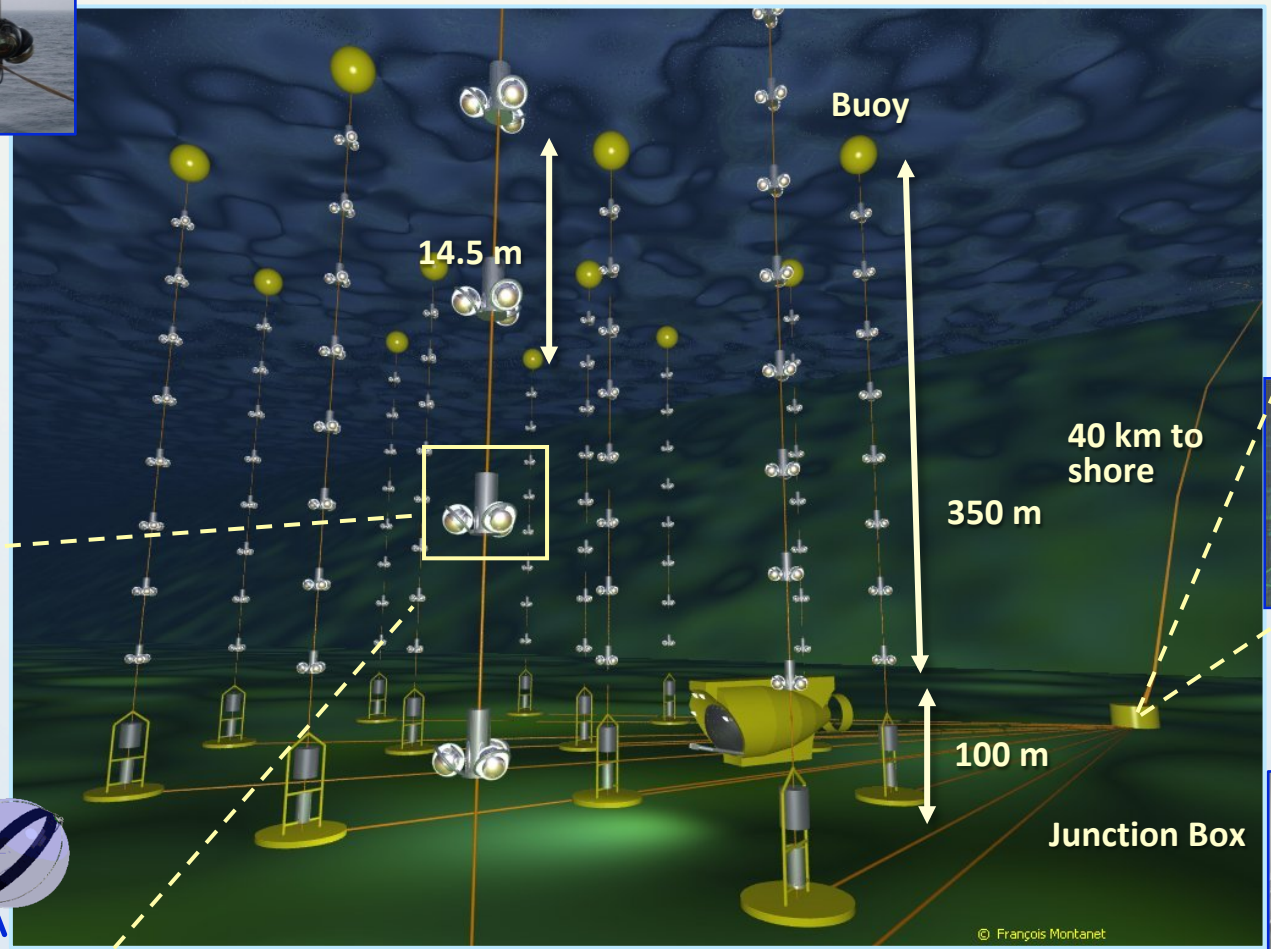



Low-energy (~GeV) studies of atmospheric neutrinos

High-energy (TeV-PeV) neutrino astrophysics

# ANTARES



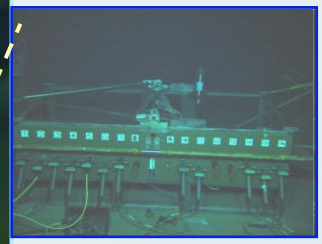

**12 lines (885 PMTs)**

**25 storeys / line**

**3 PMTs / storey**

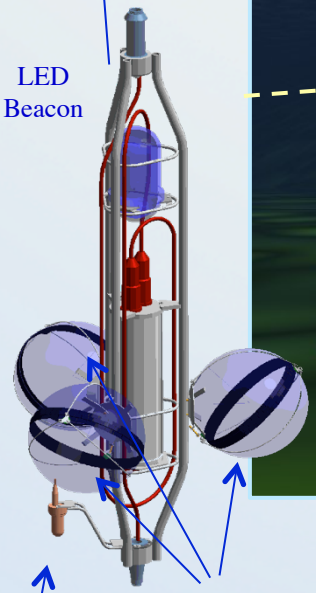
**5-line setup in 2007**

**Completed in 2008**



Junction Box

Shore station



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

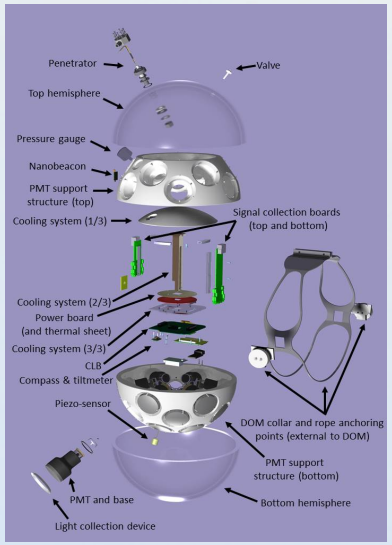
NIM **A484** (2002) 369, AP **19** (2003) 253
AP **23** (2005) 131, NIM **A555** (2005) 132
AP **26** (2006) 314, NIM **A570** (2007) 107
NIM **A578** (2007) 498,NIM **A581** (2007) 695 AP **31** (2009) 277, NIM **A622** (2010) 59-73 AP **34** (2011) 539, NIM **A656** (2011) 11

# 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

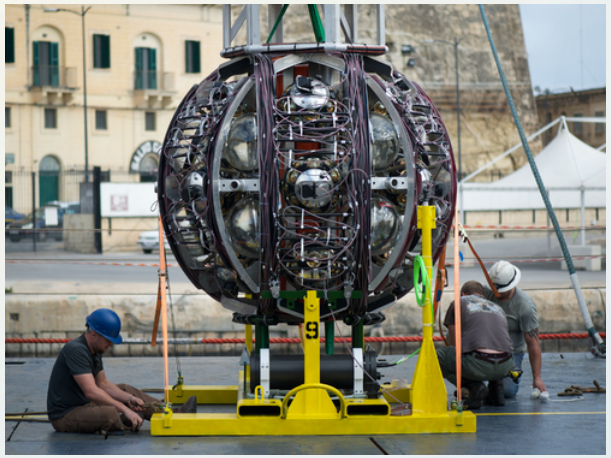


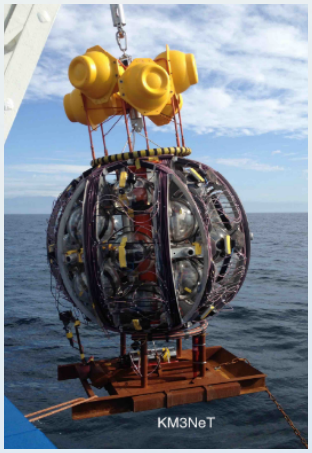

- All data to shore
- Gbit/s on optical fiber
- Hybrid White Rabbit
- LED flasher & hydrophone
- Tiltmeter/compass

## String (Detector Unit)

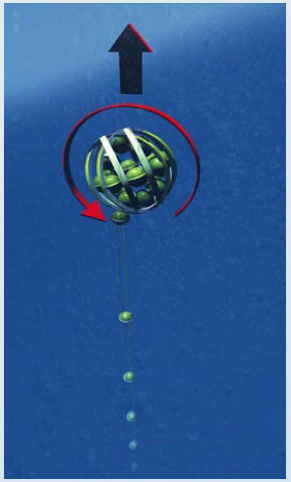
- Polyethylene ropes
- Oil filled PVC tube
- Low drag
- Low cost

## Deployment Vehicle






- Rapid deployment
- Multiple strings in one sea campaign

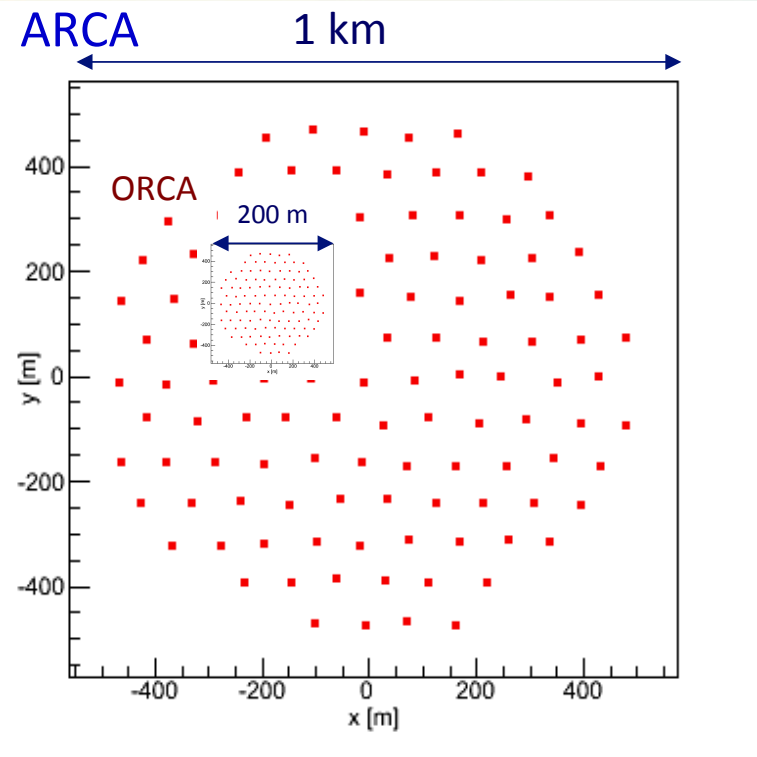


- Unfurling by autonomous ROV
- Reusable

## ARCA (Astronomy, Gton scale)

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

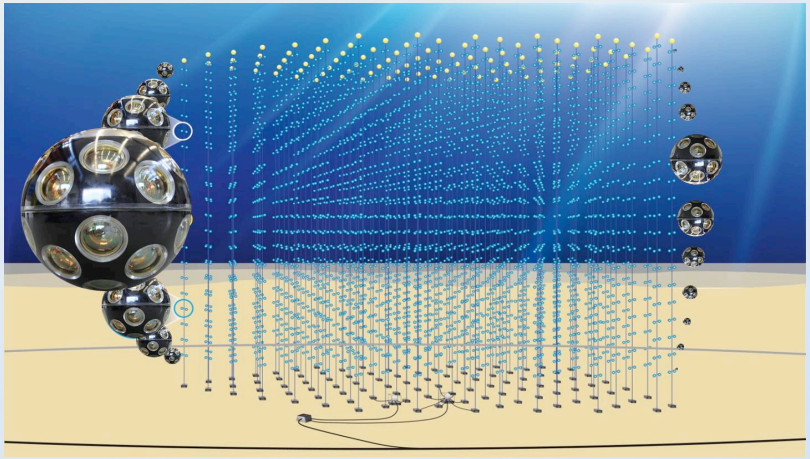
Building Block




## ORCA (NMH+ ν properties, Mton scale)

Same technology, denser layout

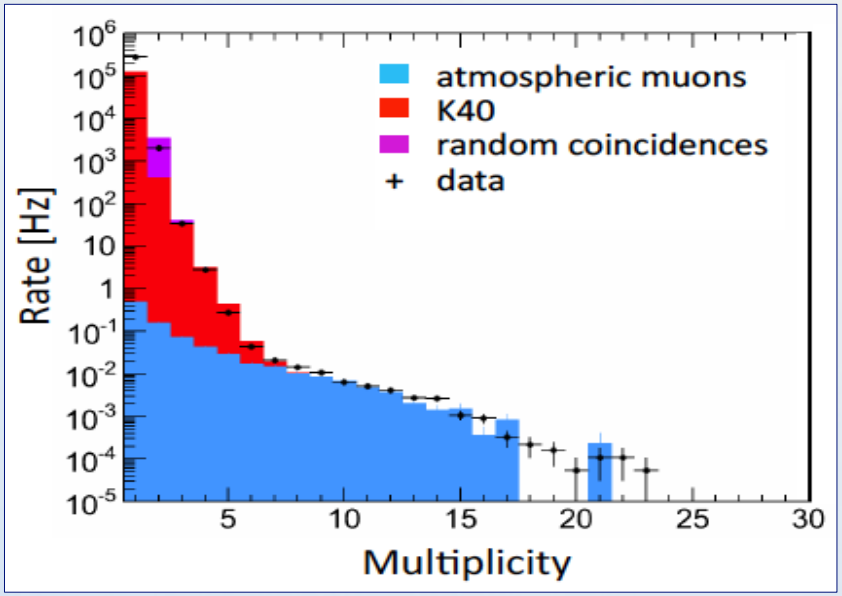
| | ORCA | ARCA |
|---|---|---|
| String spacing | 20 m | 90 m |
| OM spacing | 9 m | 36 m |
| Depth | 2470 m | 3500 m |
| Instrumented mass | ~ 8 Mton | 0.6 × 2 Gton |



# KM3NeT first Detection Units

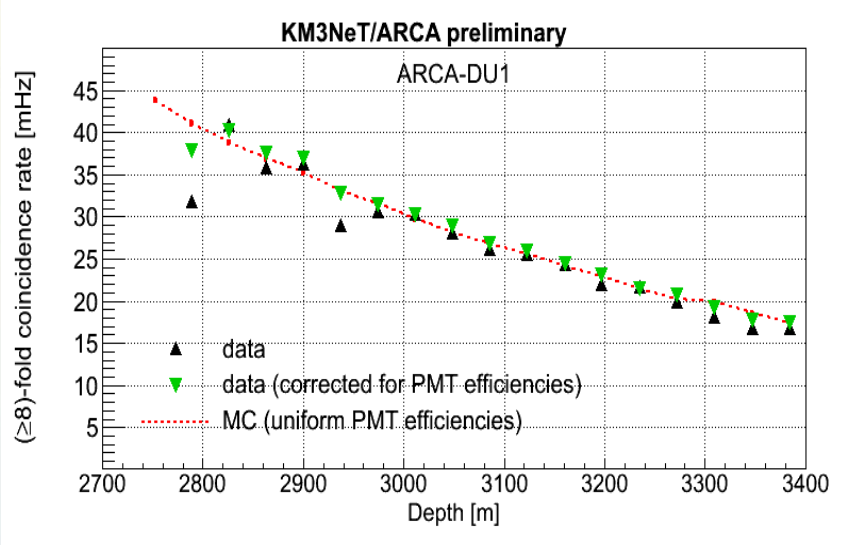
Eur. Phys. J. C 76 (2016) no.2, 54
Eur. Phys. J. C 74 (2014) no.9, 3056

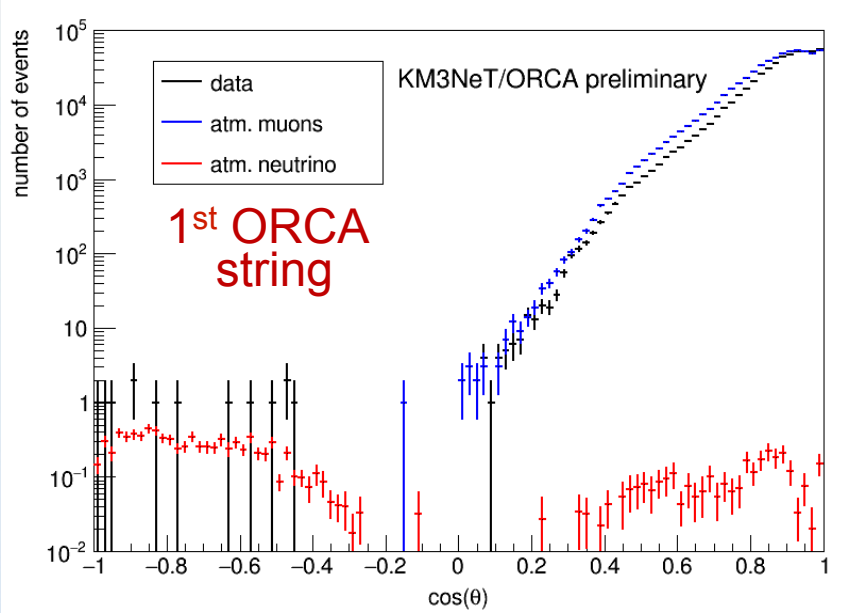
- DOM in ANTARES site
  - April 2013, 2.500 m
  - Muons from a single DOM
- Mini-string in ARCA site
  - May 2014, 3.500 m, 3 DOMs
  - Muon reconstruction, angular distribution



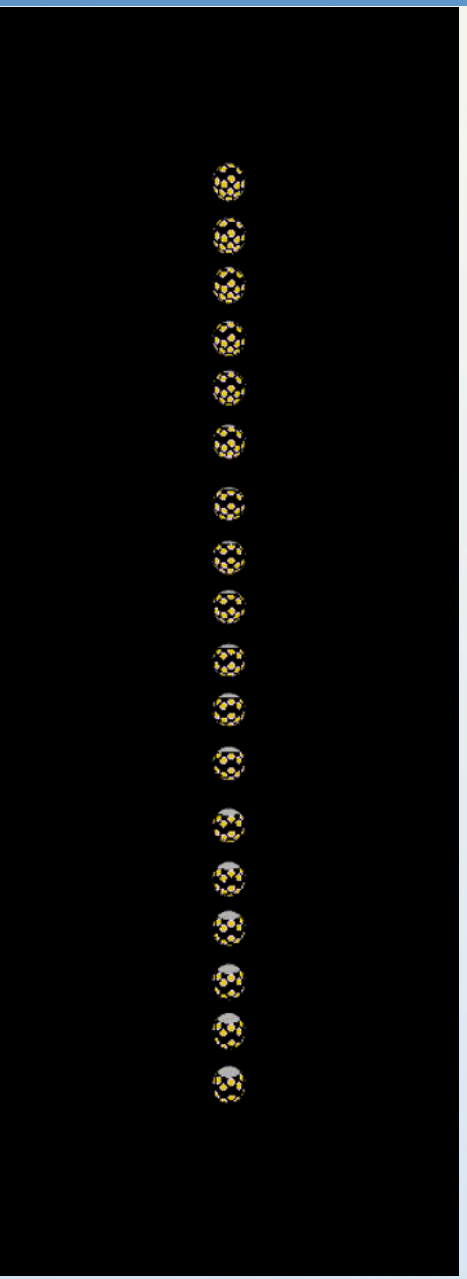

Watch https://www.youtube.com/watch?v=tR8jwgG6uzk
https://youtu.be/7HKHW0hLxt4?t=44s

- Two full strings in ARCA site

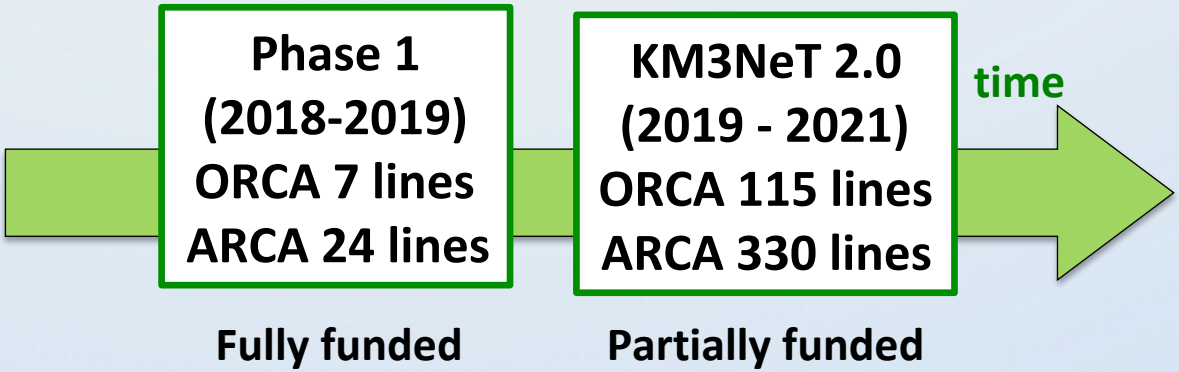


# KM3NeT status



- **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 $\nu_\mu$**

**Tracks ($\nu_\mu$ CC) ideal tool for astronomy**

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

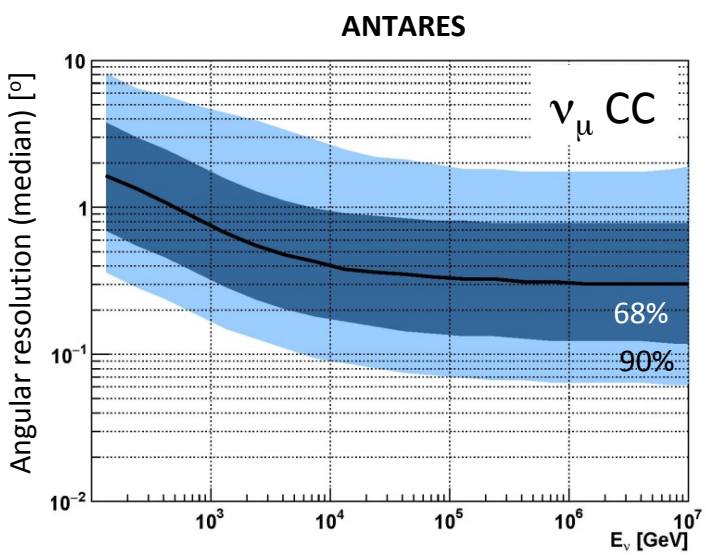
**Angular Resol. < 0.4°** above 10 TeV

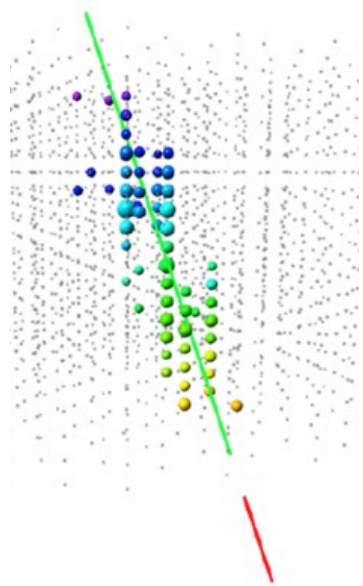
**Energy Resol. ~ 0.35** in $\log_{10}(E_{reco}/E_\mu)$

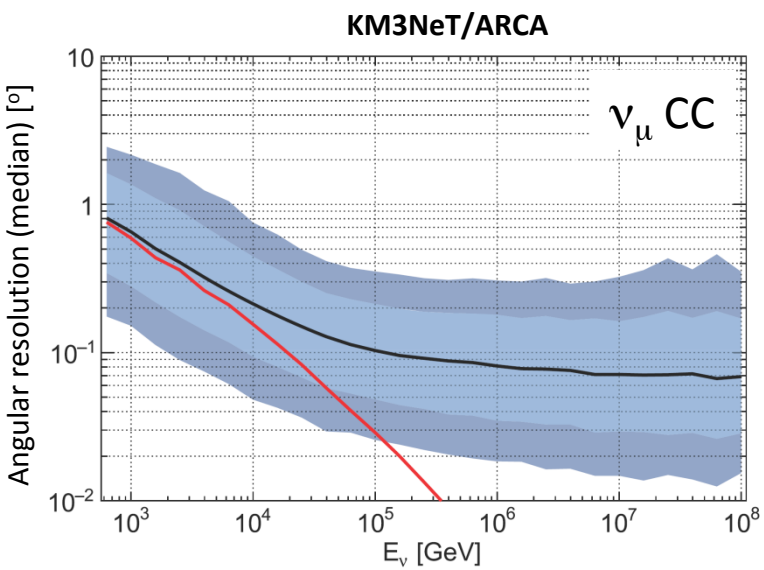
**Ang. Resol. < 0.2°** above 10 TeV

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

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






($\nu_\mu$– true $\mu$ direction) angle

# Reconstruction Performances (2/2): "Showers"

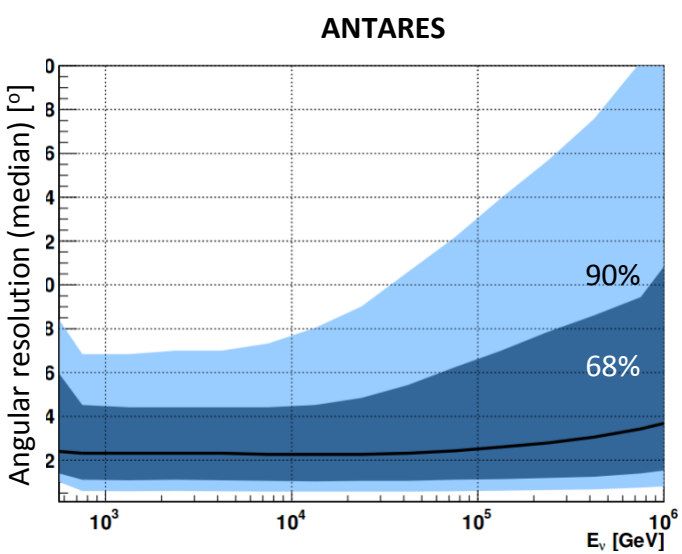
**NC** $\nu_{all}$
**CC** $\nu_e$

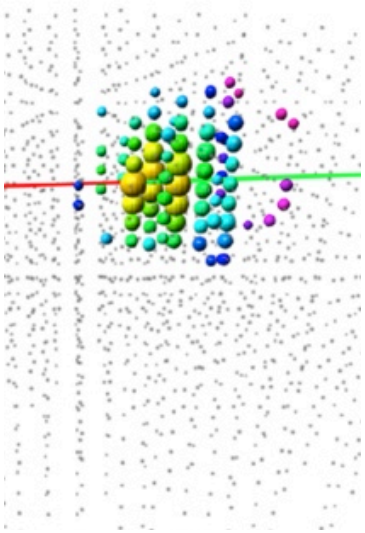
**Shower events also used for astronomy**

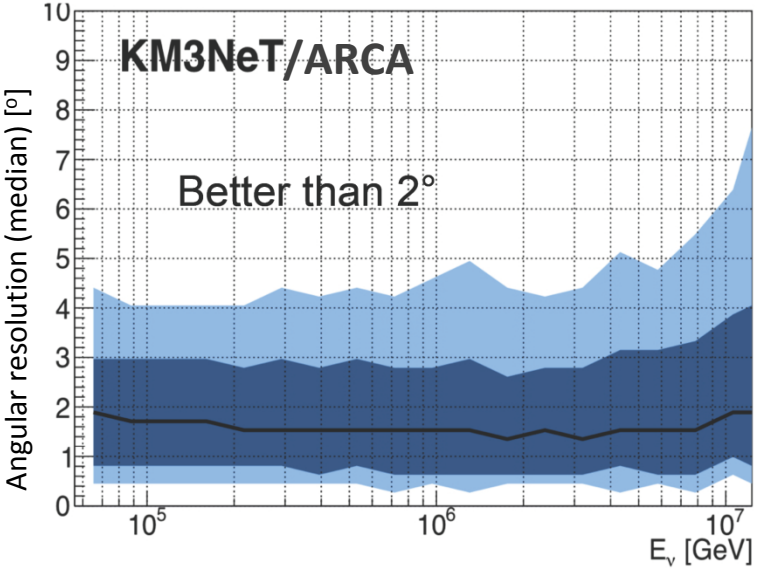
- Contained events → Better energy resolution
- Almost no atmospheric background

**Angular Res. < 3°** (1 TeV < E < 0.5 PeV)
**Energy Res.** for $\nu_e$ 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

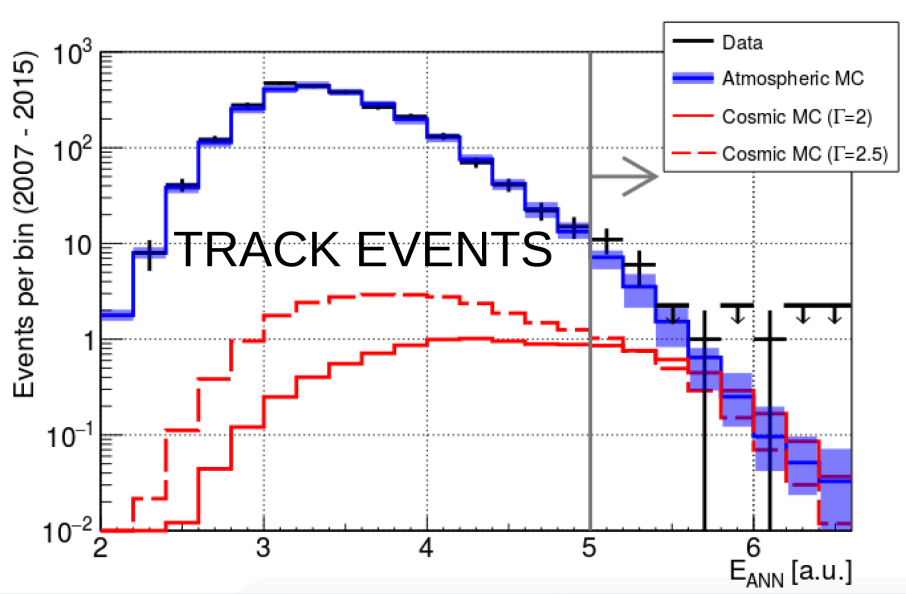
ApJL 853, L7 (2018)

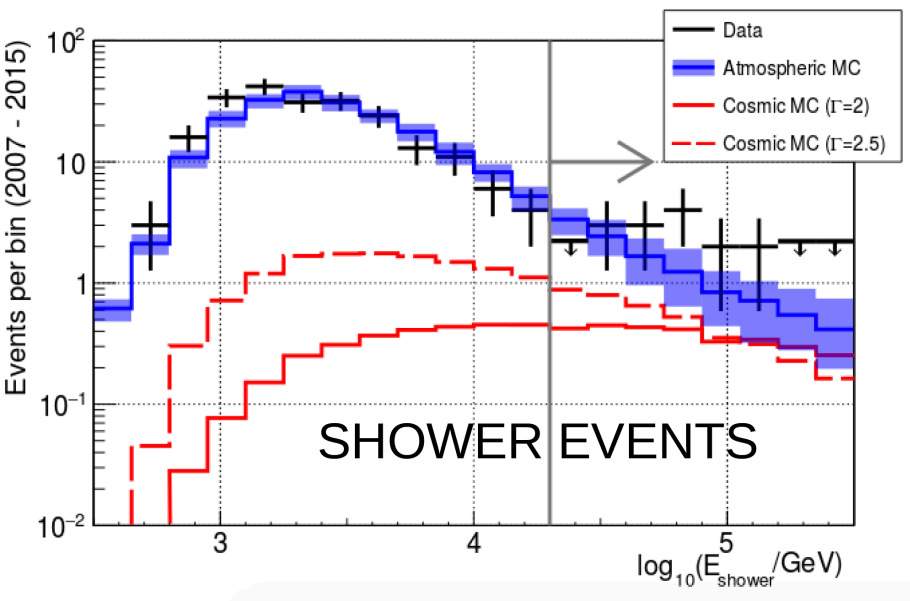
- Data Sample 2007 – 2015 (2450 days)
- All sky / All-flavour ν search
- Unblinding:

| | 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



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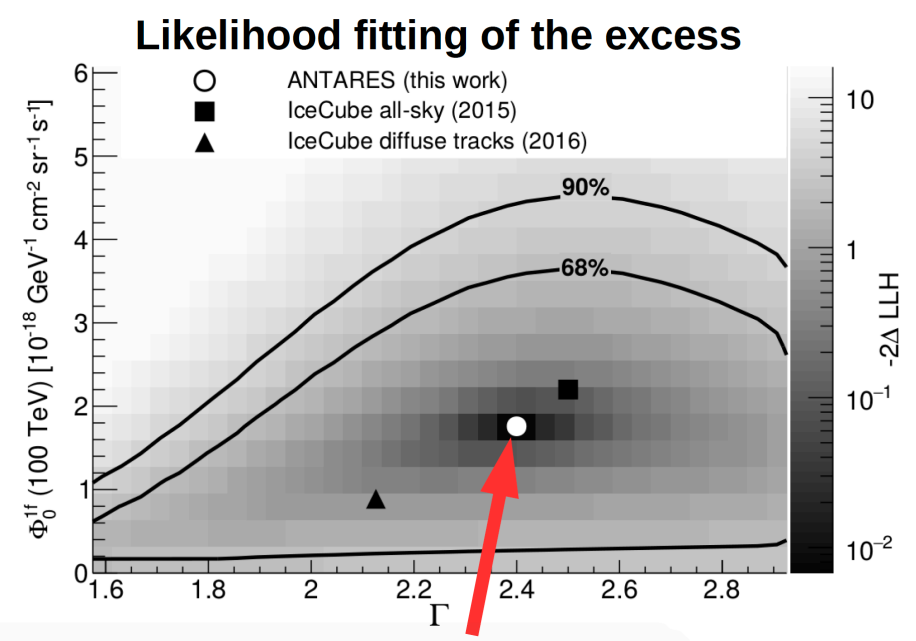



Best fit (1 flavour flux normalization at 100 TeV)

- 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**

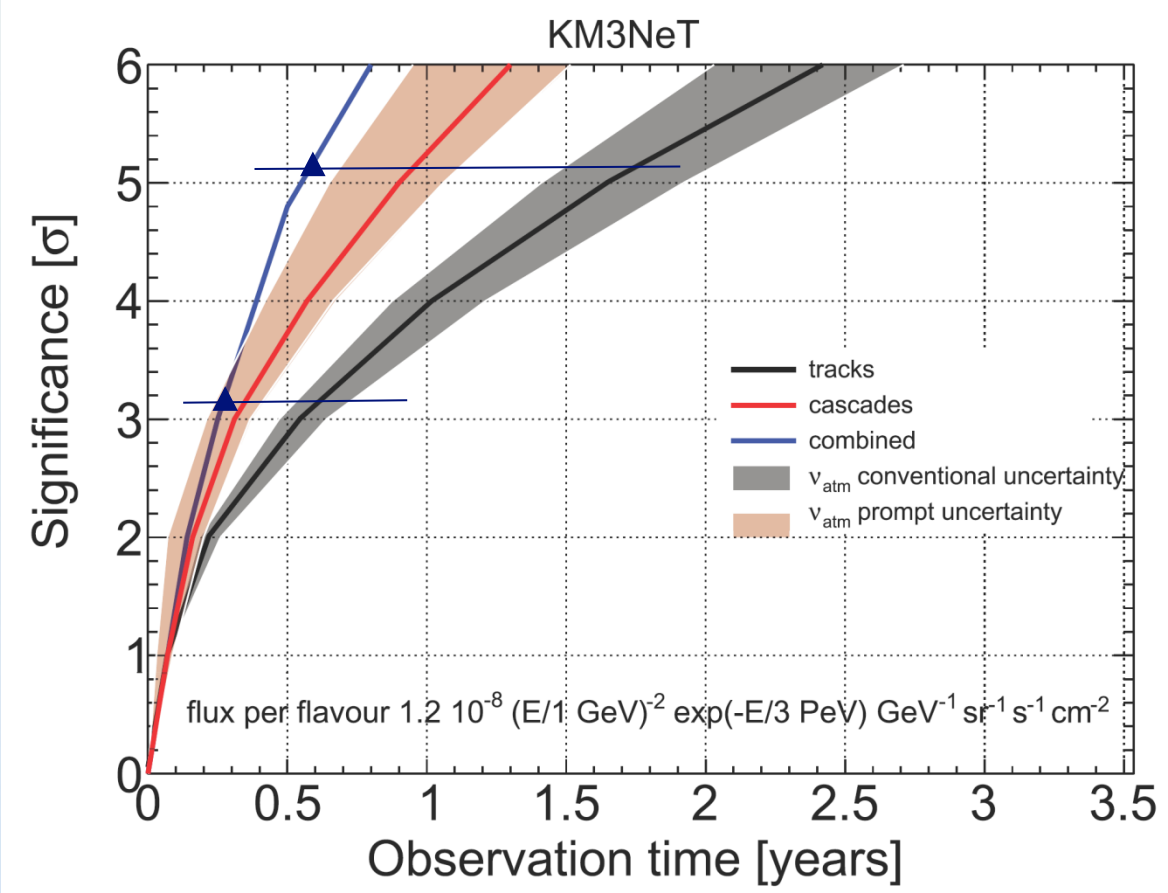
Analysis for upward-going events based on a maximum likelihood

Pre cuts on $\theta_{zenith}$ , $\Lambda$ reconstruction quality parameter and $N_{hit}$ (proxy for muon energy)

**Shower channel**

Containment cut on reconstructed vertex to remove atmospheric muons

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

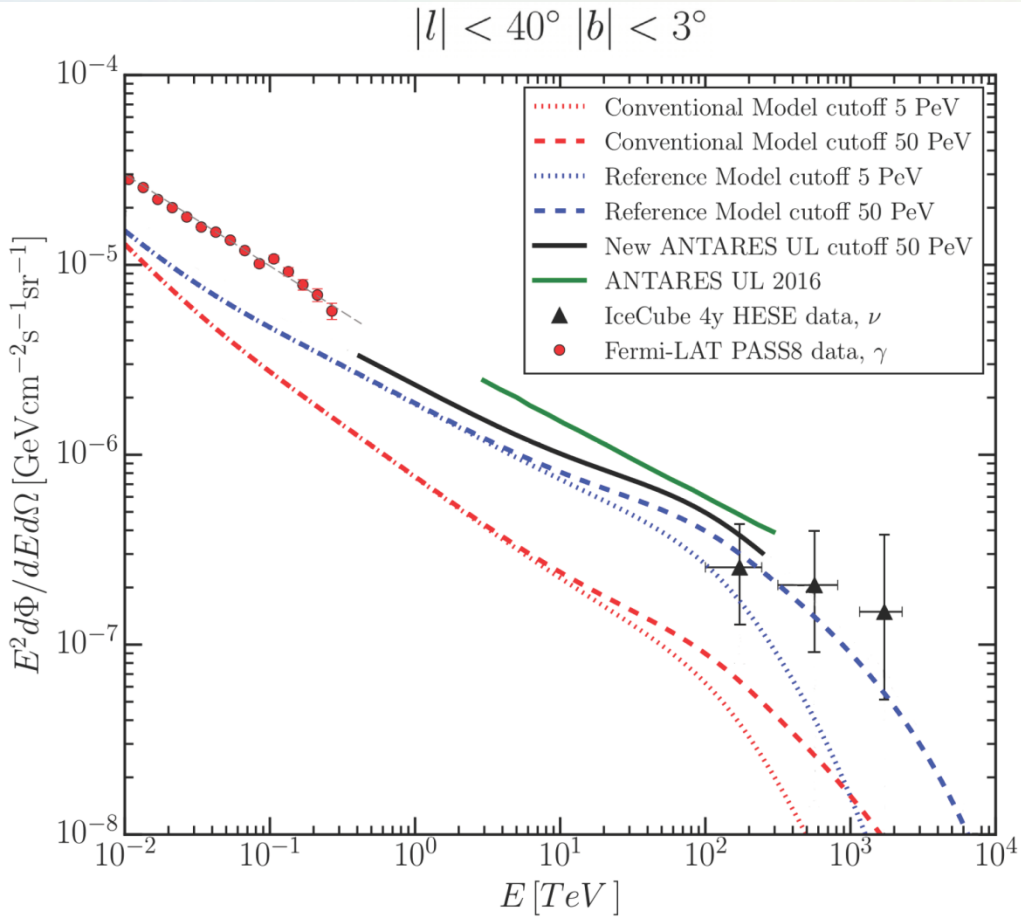
# Diffuse Flux : Galactic Ridge

Phys. Rev. D 96 062001 (2017)

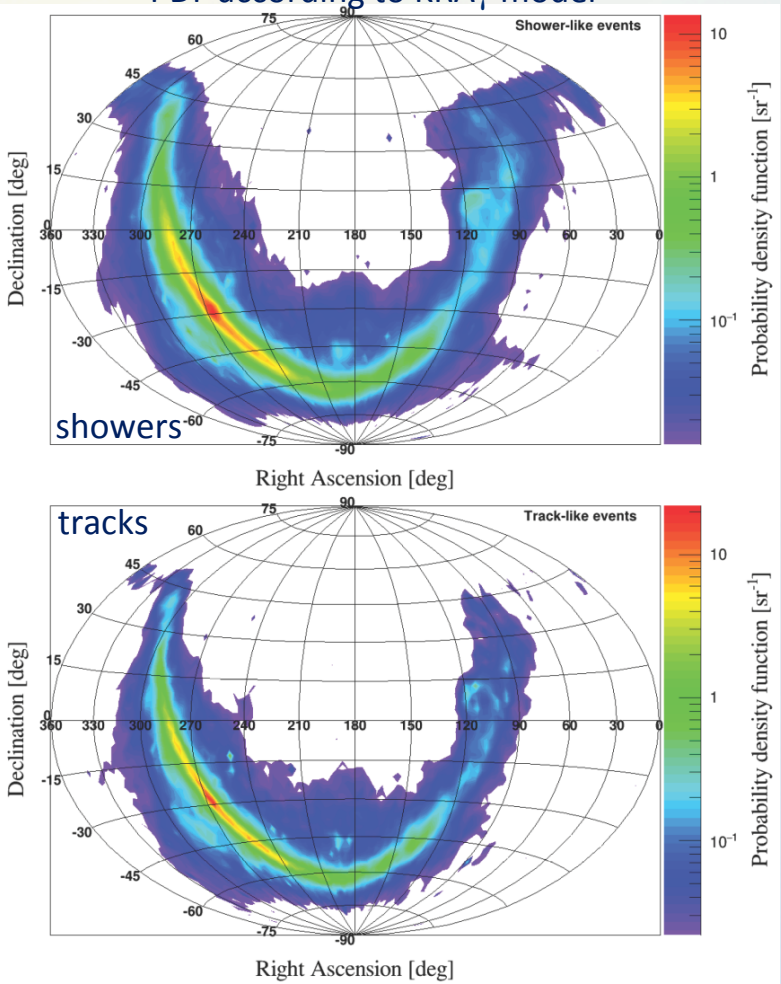
**7300 tracks + 208 showers**

- 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




⇒ The ν flux produced by Galactic CR interactions with gas cannot explain by itself the IC "spectral anomaly"

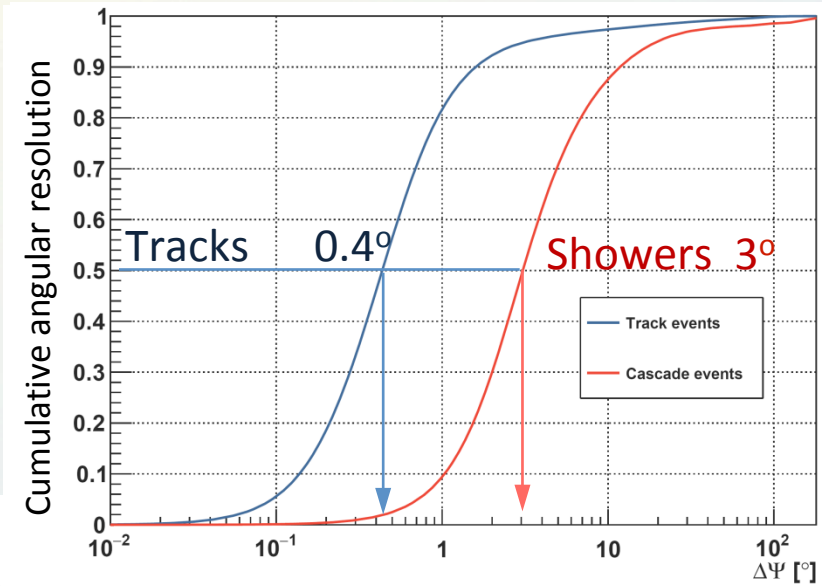
# ANTARES : Point Sources

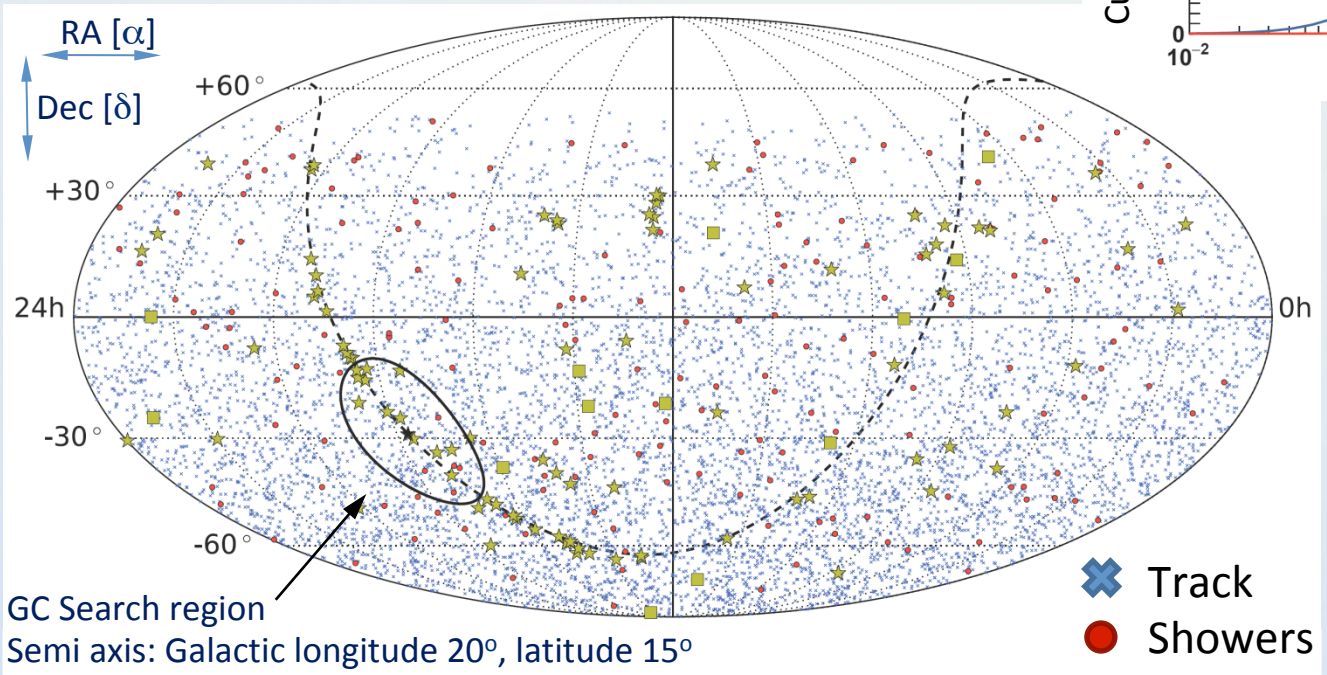
Phys. Rev. D 96 082001 (2017)

**"First all-flavor ($\nu_\mu$ 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°)



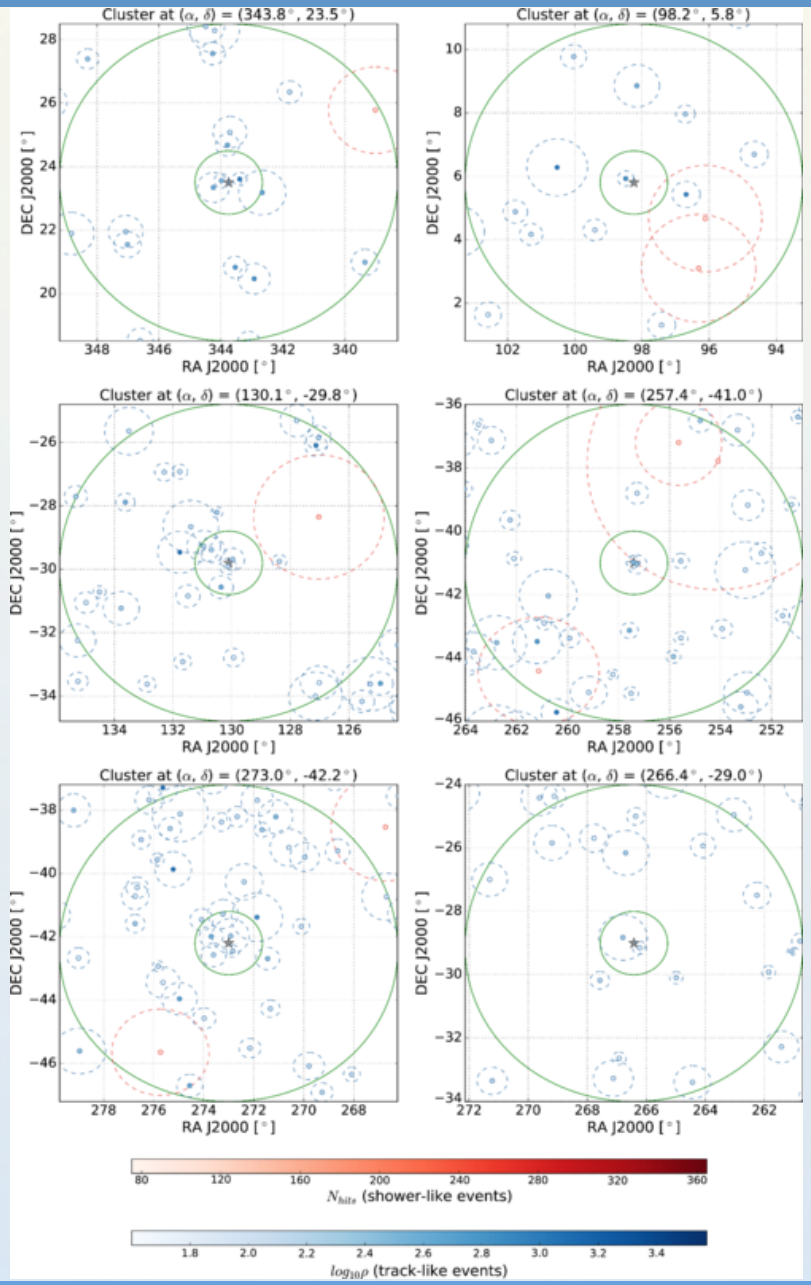
# ANTARES : Point Sources

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

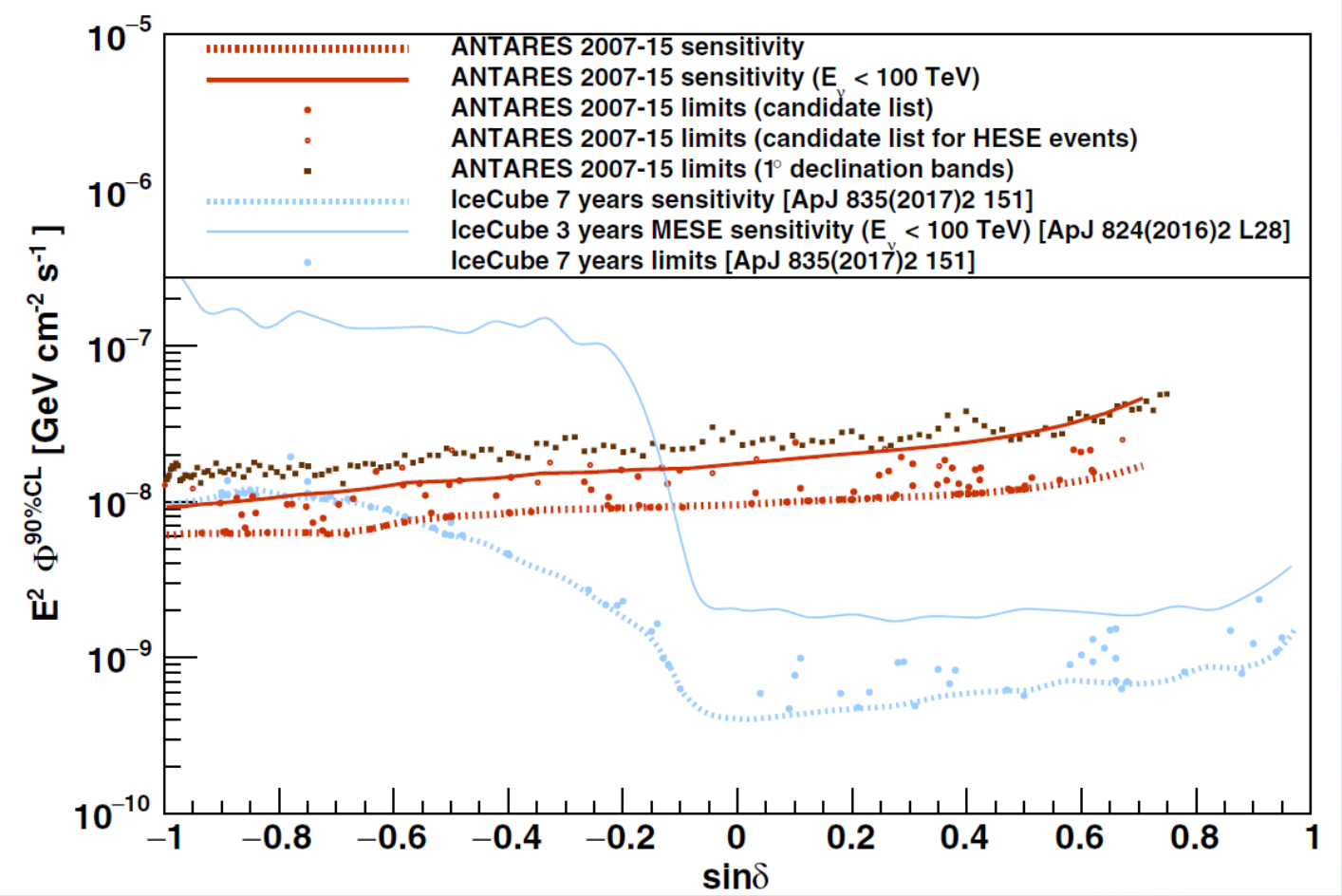
Phys. Rev. D 96 082001 (2017)

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

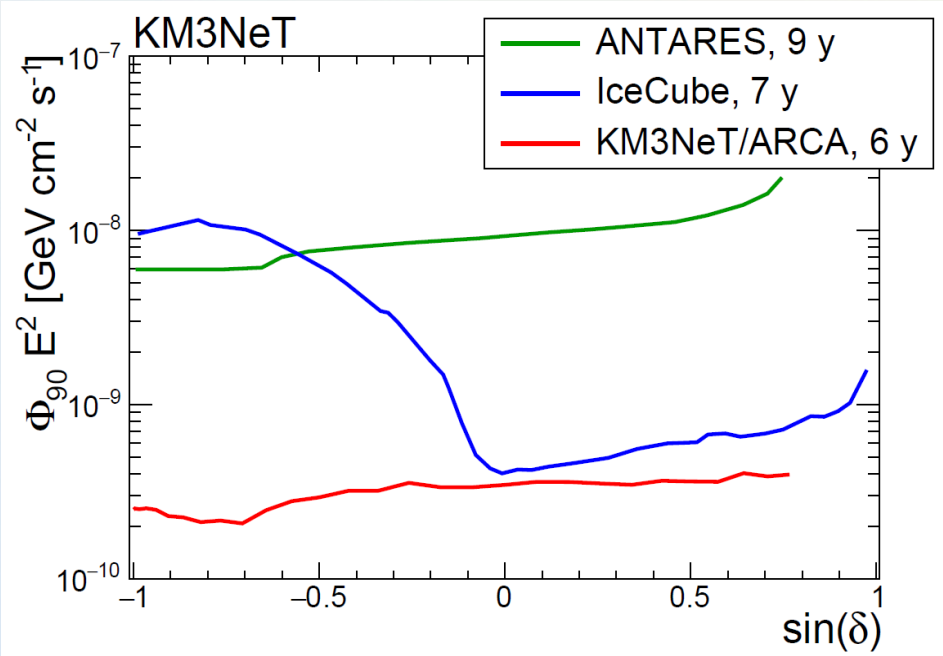
ANTARES

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

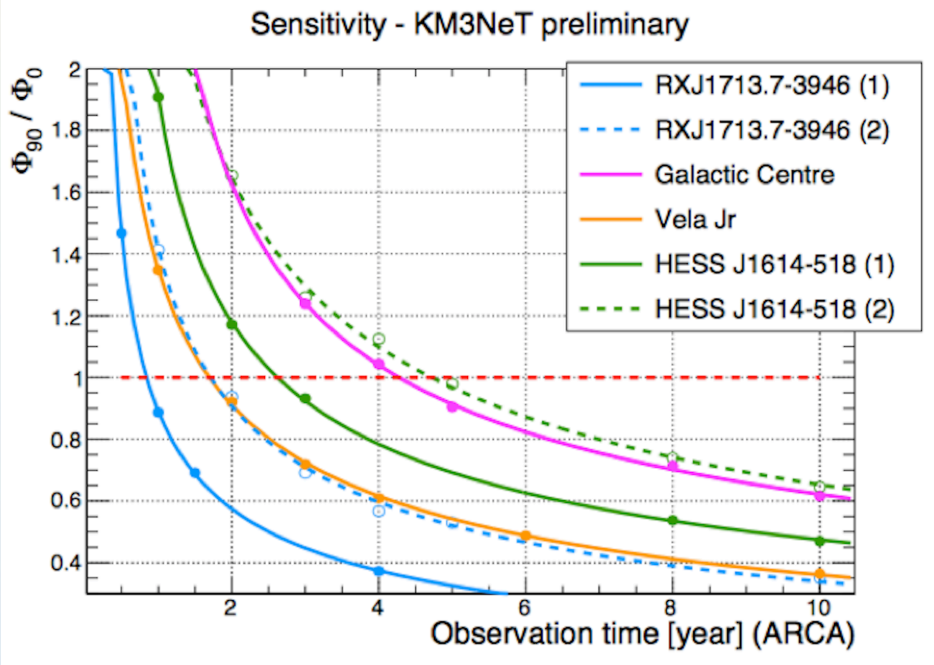


# KM3NeT: Expectations

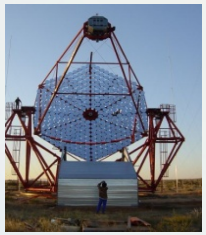
- Sensitivity for 6 yrs of observation with ARCA (2 building blocks)
- Broad coverage. $E^{-2}$ spectrum assumed.

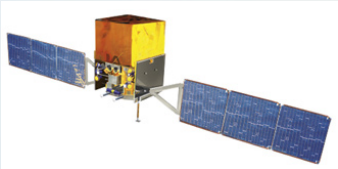


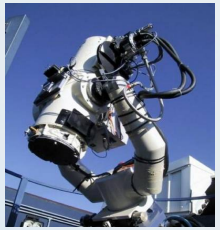

- Sensitivity for Galactic sources

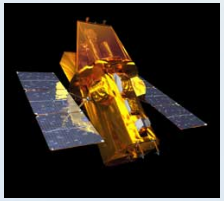


# The multi-messenger program









**GeV – TeV $\gamma$-rays**

*Fermi, HESS, HAWC*

JCAP 03 (2013) 006
A&A 559 (2013) A9
JCAP 05 (2014) 001
JCAP 12 (2015) 014
EPJ C77 (2017) 1, 20

**Radio-Visible-X**

*MWA, SUPERB*
*TAROT, ZADKO, MASTER,*
*Swift*

APP 36 (2012) 204
A&A 559 (2013) A9
JCAP 02 (2016) 062
AJ 820 (2016) 2, L24
JCAP 04 (2017) 019

**HE neutrinos**

*ANTARES*
*Ice Cube*

**UHECR**

*Auger, TA*

APJ 774 (2013) 19

**Gravitational Waves**

*LIGO-VIRGO-EGO*

JCAP 06 (2013) 008
PRD 93 (2016) 122010
APJ Lett 850 L35 (2017)

- Neutrino telescopes suited for transient sources: continuous monitoring >2$\pi$ sr
- A way to better understand the related physics mechanisms
- A way to increase the detector sensitivities (suppression of the uncorrel. background)

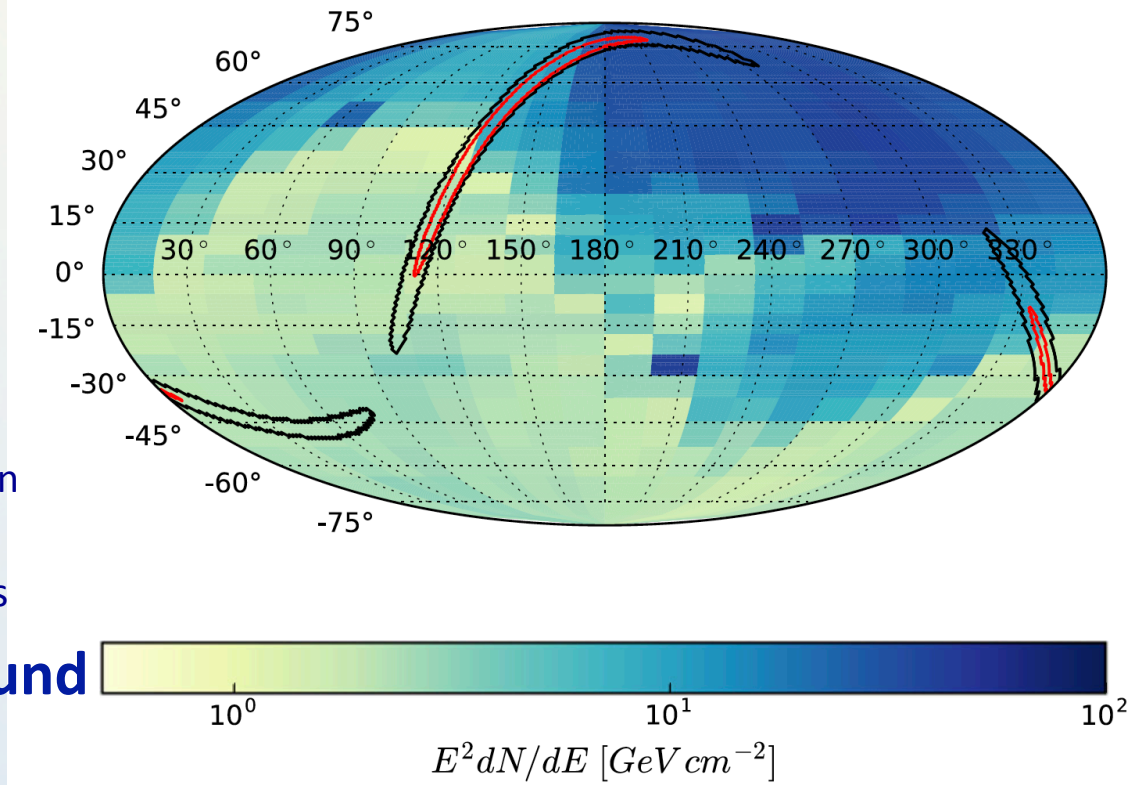
# Gravitational Waves follow up

Phys.Rev. D93 (2016) no.12, 122010
Eur. Phys. J C (2017) 77:911
ApJ Letters 850 L35 (2017)

- **Search $\nu$ in coincidence with:**
  - BBH's: GW150914, LVT151012, GW151226, GW170104
  - BNS: GW170817
- **Search features:**
  - Most recent reconstruction (offline search advantage)
  - ± 500 s around GW time
  - Extended time-window searches
  - Individual optimization (3σ detection if event within 90% GW contour)
  - Combined IceCube-Antares analyses
- **No coincident events found**
  - GW151226 (1 event)
  - GW170817 (5 events/downgoing)
  - Upper limit on Fluences:

    $E_{iso} < 10^{51} - 10^{54}$ erg

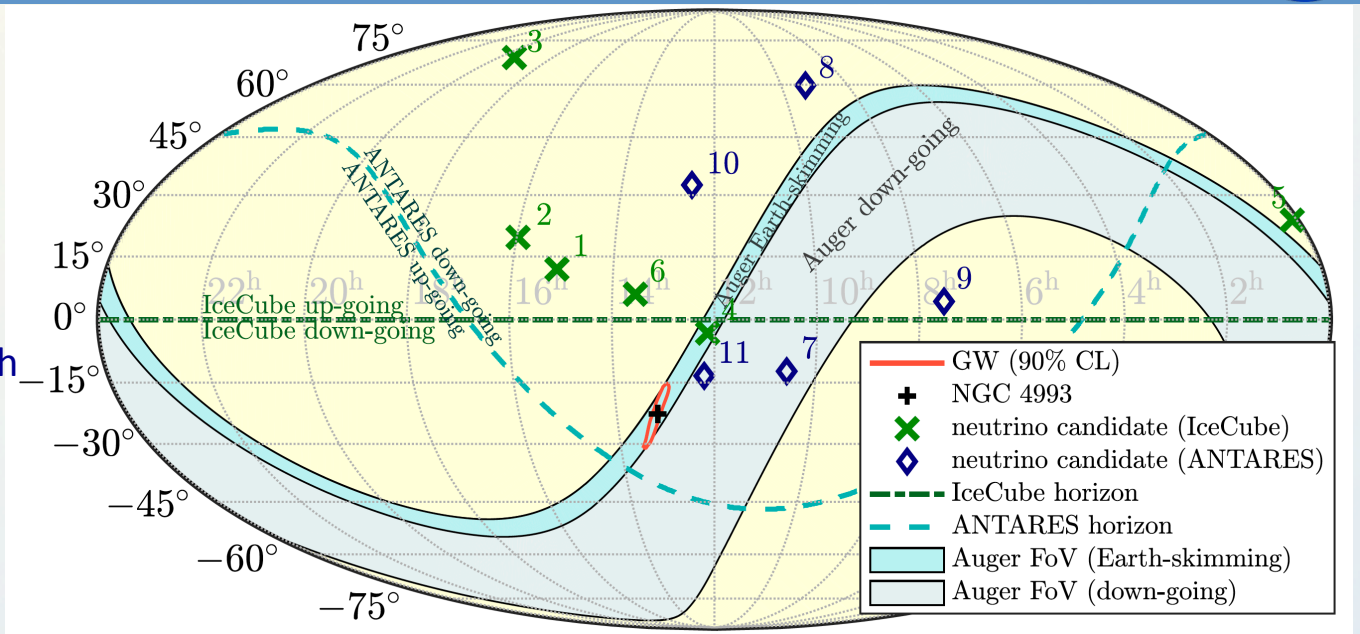
Limits on neutrino spectral Fluence from GW170104
0 neutrino events

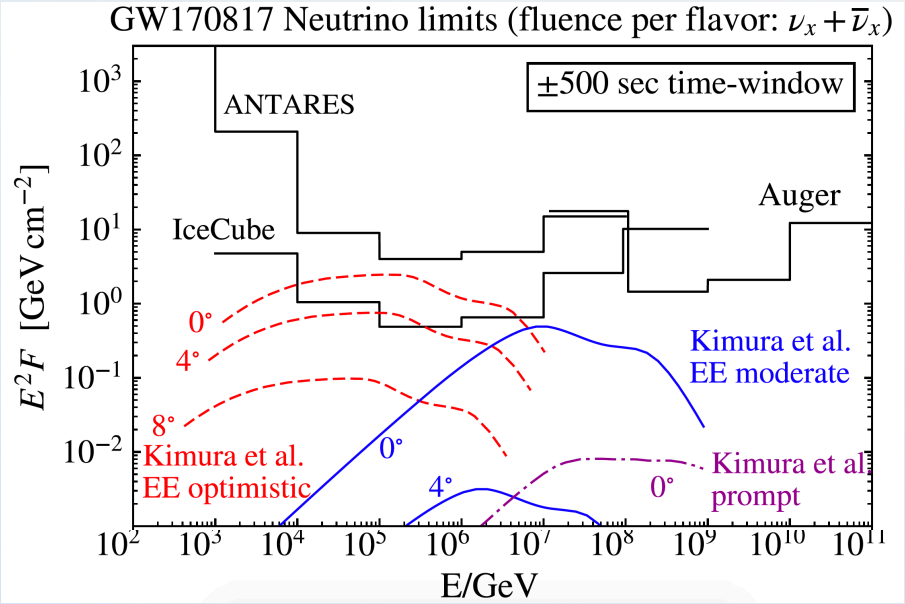


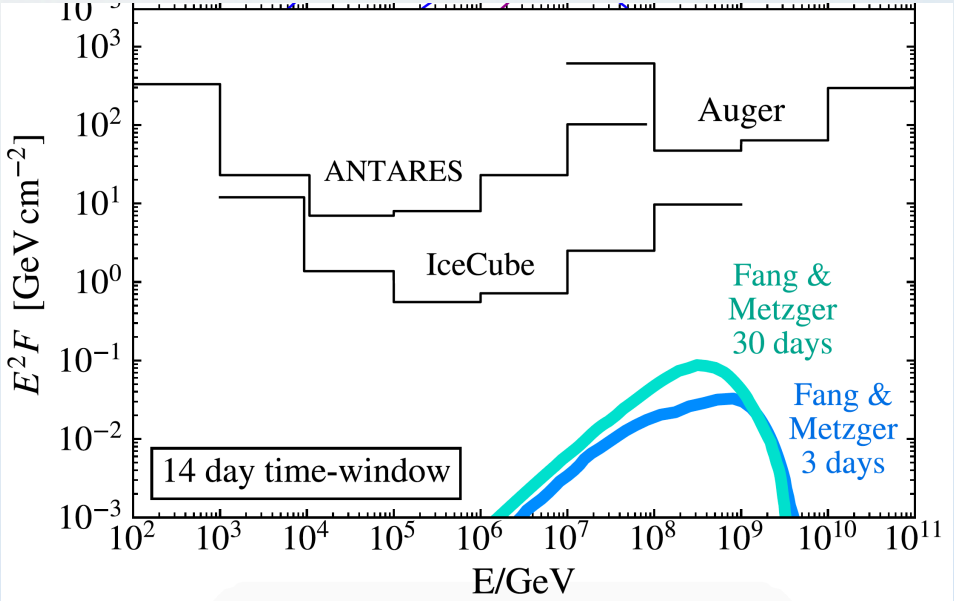
# GW170817

Phys.Rev. D93 (2016) no.12, 122010
Eur. Phys. J C (2017) 77:911
ApJ Letters 850 L35 (2017)

- **Search features:**
  - **± 500 s** around GW time (down-going optimized). 5 events no spatially coincident found
  - Extended **+14 days** search (up-going optimized). 0 events found
- **Limits on $\nu$ spectral Fluence**



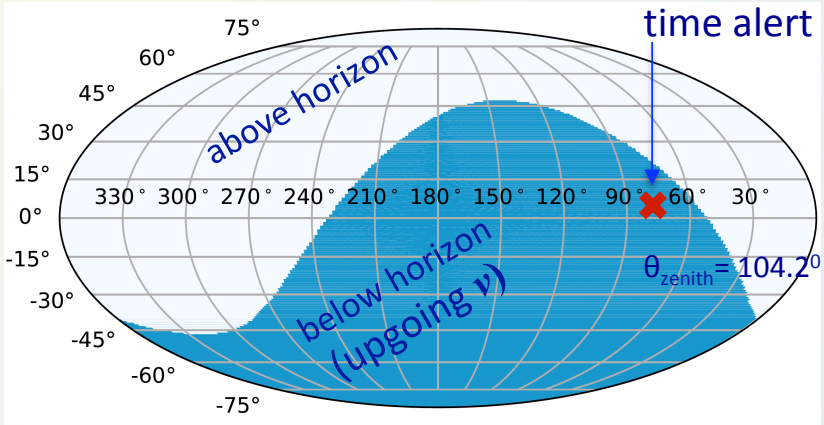
# Search for neutrinos from TXS 0506+056

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
  - $(\alpha, \delta)$ = [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



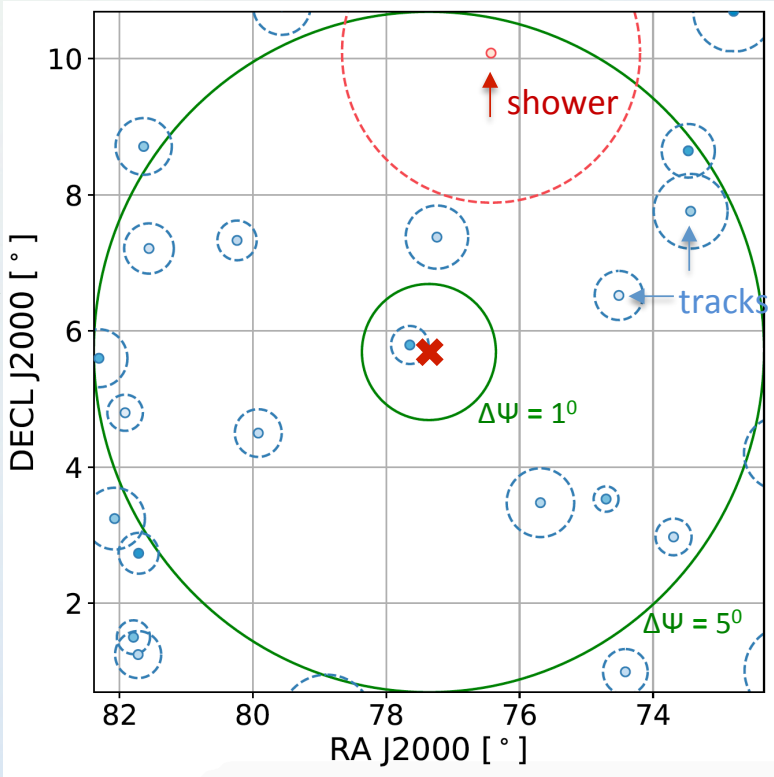

**ANTARES searches**

**1st "ONLINE DATA STREAM" SEARCH: fast reconstruction**

- **3° cone/ ±1h & ±1 day** time-window around source
- **0 upgoing track muon ν** *candidate events*

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

- 2007 – 2017 data (3136 livetime days): 107 sources
- Likelihood: $\mu_{sig}$=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$^{-1}$ ($\Gamma$=2) [2TeV - 4PeV]




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

- Gaussian- (550 days) and Box- (158 days) time-window shapes ( ***Flares*** ) centered in MJD 57004
- Relaxed selection criteria: **0 events in flaring periods**

# 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 ($E_\nu$<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