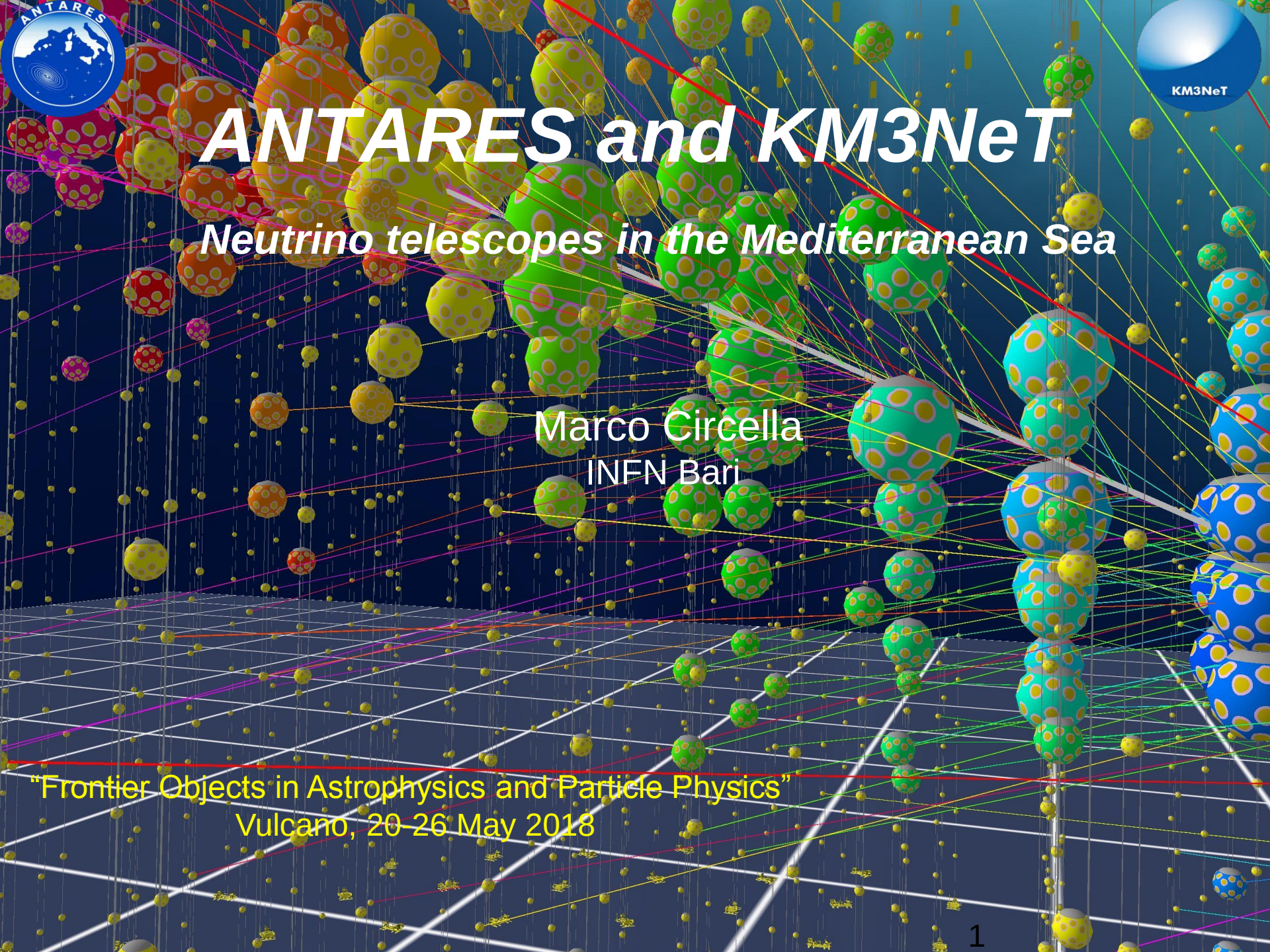


ANTARES and KM3NeT

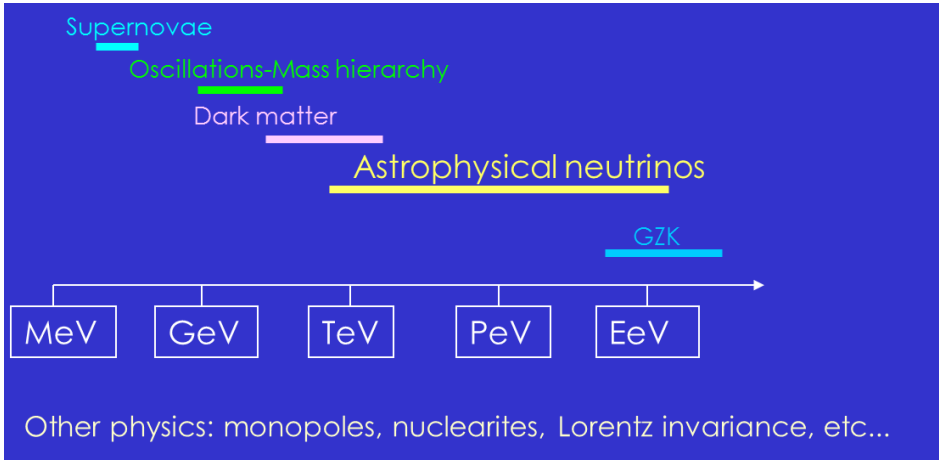
Neutrino telescopes in the Mediterranean Sea

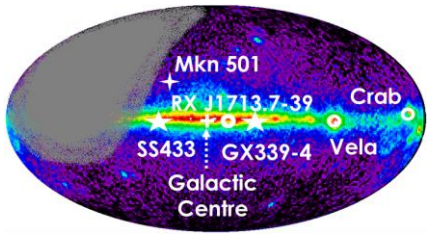
Marco Circella
INFN Bari

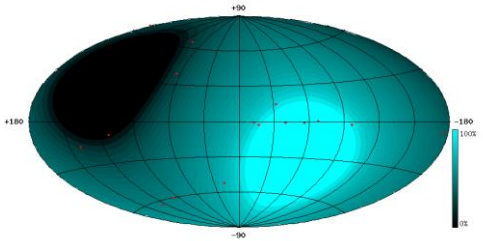
"Frontier Objects in Astrophysics and Particle Physics"
Vulcano, 20-26 May 2018

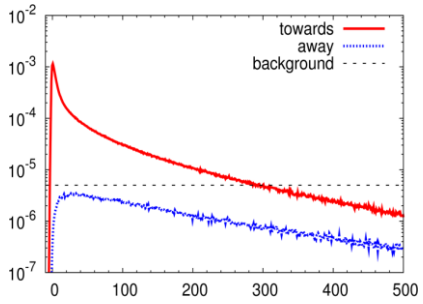
Mediterranean Neutrino Telescopes

- Physics motivation and Detection principle
  - High energy ν astronomy and neutrino properties
  - Detection: large volume of transparent medium surveyed by photodetectors
- Location:
  - Northern terrestrial 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 biolum) can be handled.





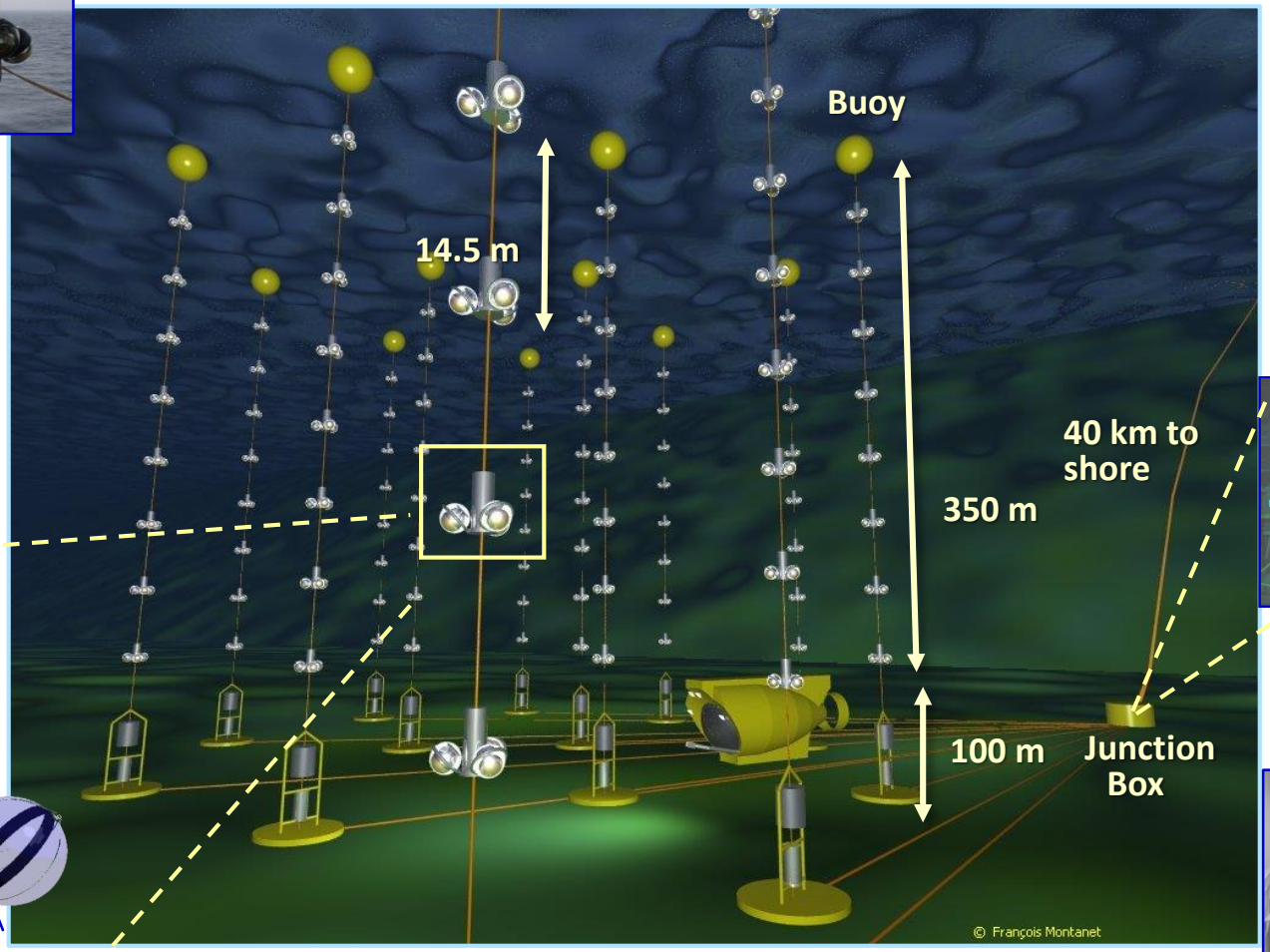




Antares and KM3NeT Collaborations

+ Western Sydney University, Australia

ANTARES



12 lines (885 PMTs)

25 storeys / line

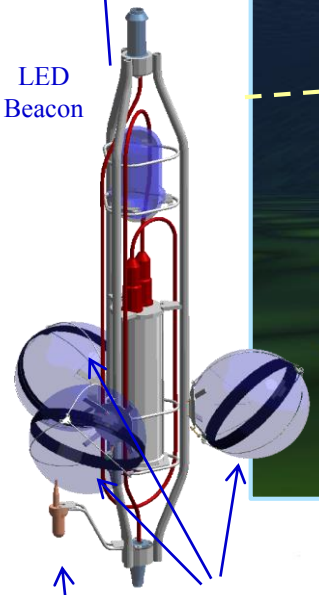
3 PMTs / storey

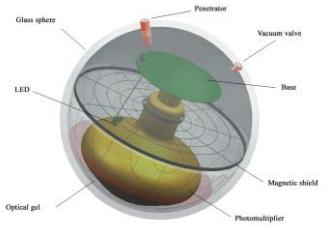
5-line setup in 2007

Completed in 2008

Junction Box

Shore station





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

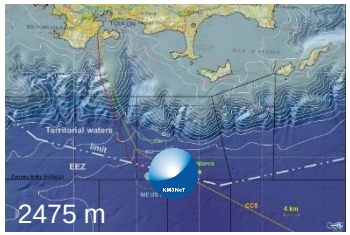
NIM **A484** (2002) 369, AP **19** (2003) 253
AP **23** (2005) 131, NIM **A555** (2005) 132
AP **26** (2006) 314, NIM **A570** (2007) 107
NIM **A578** (2007) 498,NIM **A581** (2007) 695
AP **31** (2009) 277, NIM **A622** (2010) 59-73
AP **34** (2011) 539, NIM **A656** (2011) 11

KM3NeT

ARCA
Astroparticle **R**esearch with **C**osmics In the **A**byss

Capo Passero, Sicily, Italy

ORCA
Oscillation **R**esearch with **C**osmics in the **A**byss

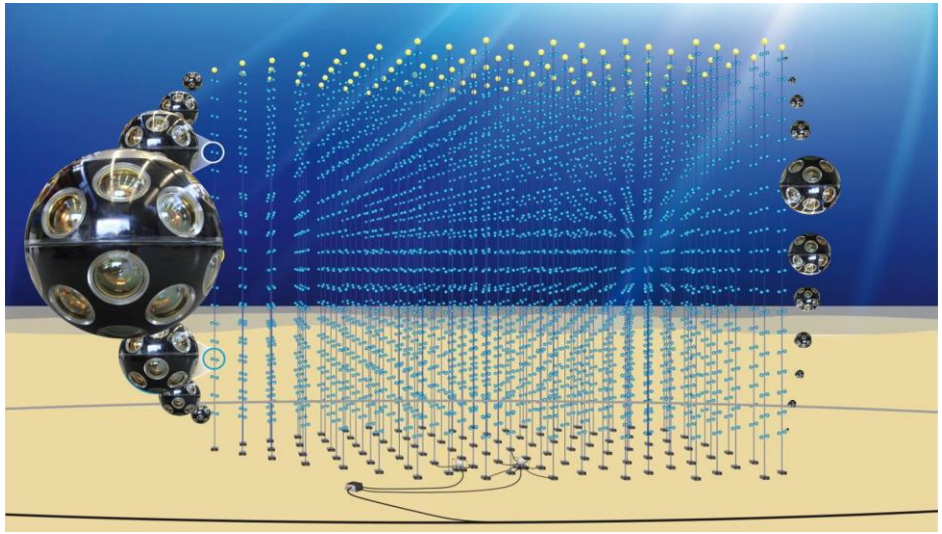


Toulon, Var, France

- ARCA (Astronomy)
  - Building Block:
    - 115 strings
    - 18 DOMs / string
    - 31 PMTs / DOM
    - Total: 64k*3¨ PMTs

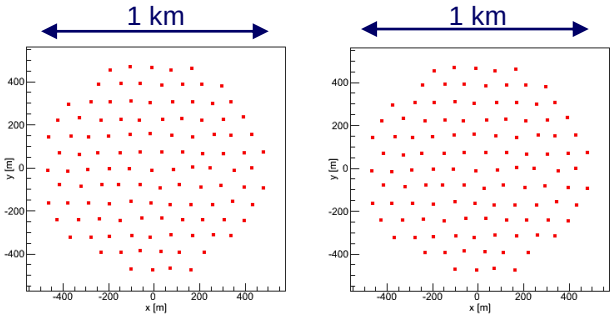
- ORCA (NMH+ ν properties)
  - Same technology, denser layout

	ORCA	ARCA
String spacing	23 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	5.7 Mton	0.6*2 Gton

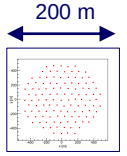


- Stages:
  - Phase 1: 24 ARCA + 7 ORCA strings (already funded, being deployed)
  - KM3NeT 2.0: 2 ARCA +1 ORCA blocks (~50% funded)
  - Phase 3: 6 ARCA + 1 ORCA blocks

ARCA



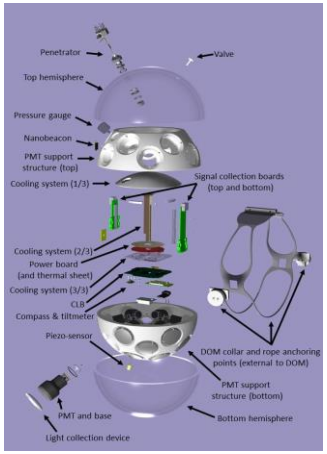
ORCA



KM3NeT Technology

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 fibre
- Hybrid White Rabbit
- LED flasher & hydrophone
- Tiltmeter/compass

String (Detector Unit)

- High modulus polyethylene ropes
- Oil-filled backbone
- Low drag
- Low cost

Deployment Vehicle

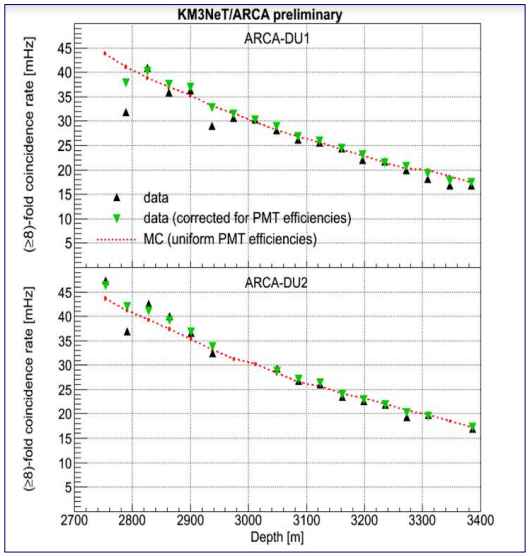
- Rapid deployment
- Multiple strings in one sea campaign

- Unfurling started by ROV
- Reuseable

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

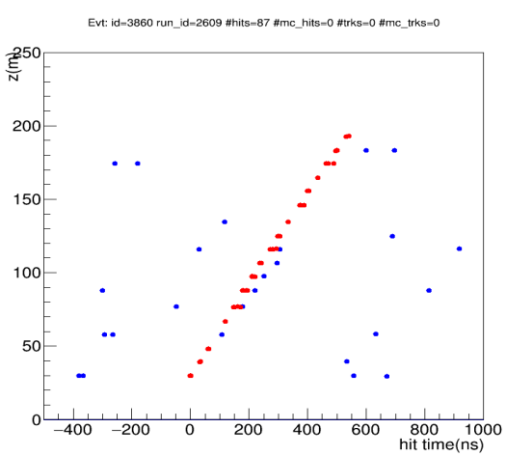
First KM3NeT Detection Units

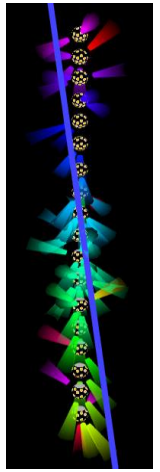
- Two full strings in ARCA site
  - Dec 2015 and May 2016
  - Muon reconstruction
  - Muons vs depth



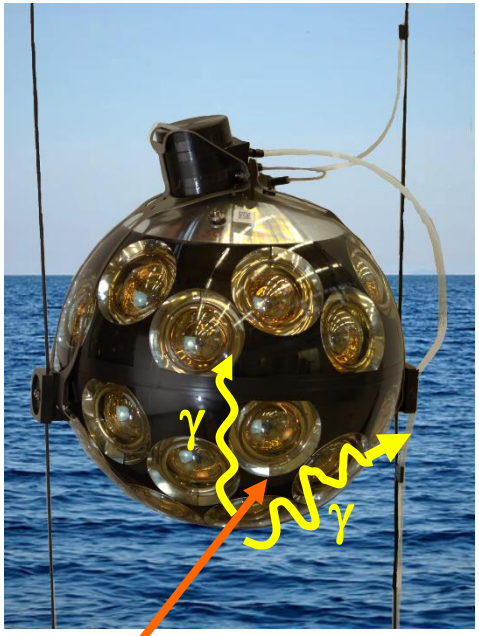
- One full string in ORCA site
  - Sept 2017
  - Atmospheric neutrinos

- Some seafloor infrastructure teething problems, soon to be fixed





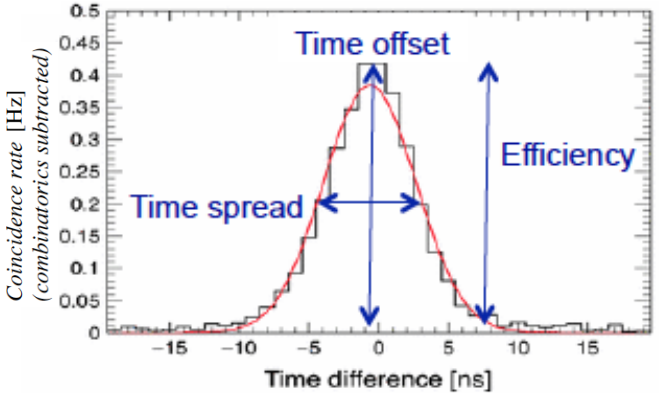
K40 Calibration

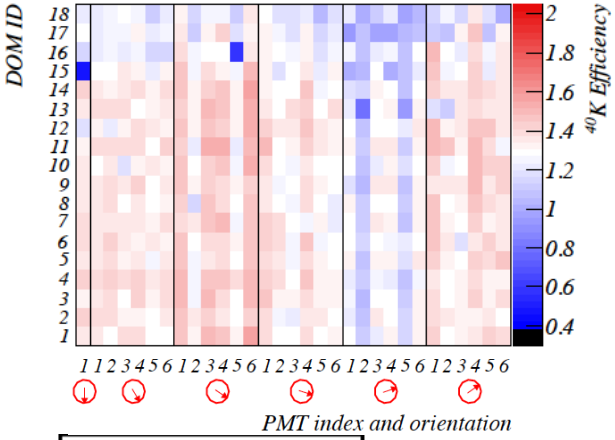


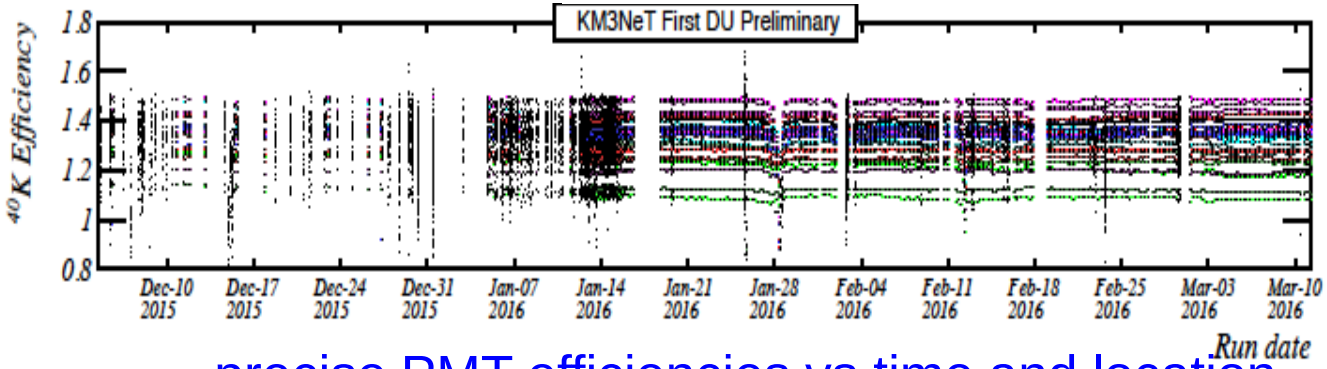
^{40}K e^- (β decay)

^{40}Ca

Up to 150 Cherenkov photons per decay; stable ^{40}K concentration







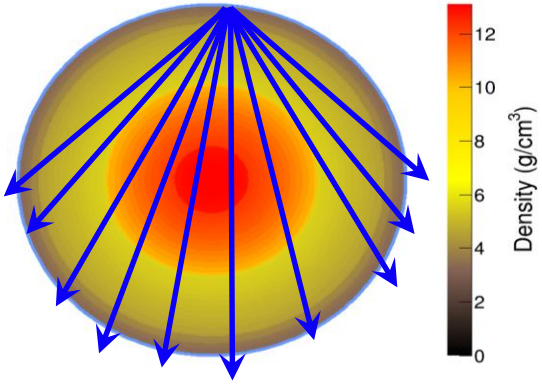
precise PMT efficiencies vs time and location

Neutrino mass hierarchy with ORCA

- A “free beam” of known composition (ν_e, ν_μ)
- Wide range of baselines (50 → 12800 km) and energies (GeV → PeV)

- Oscillation affected by matter (ordering-dependent):

  maximum difference IO vs. NO at $\theta = 130°$ (7645 km) and $E_\nu = 7$ GeV



- Opposite effects on neutrinos and anti-neutrinos: IO(ν) ≈ NO(anti-ν)

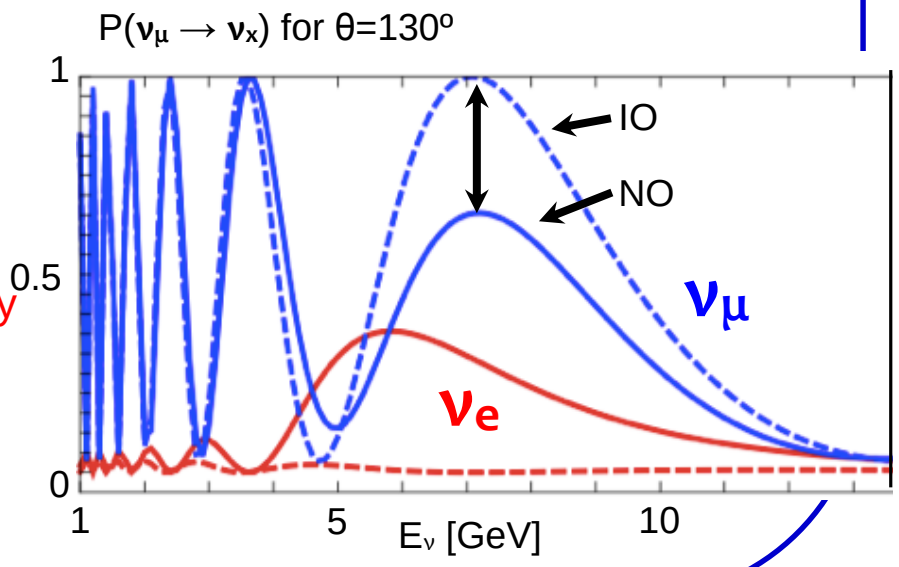
But differences in flux and cross-section:

$\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$

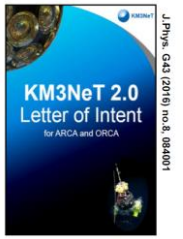
$\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies

- Approach: measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count track and shower channel events

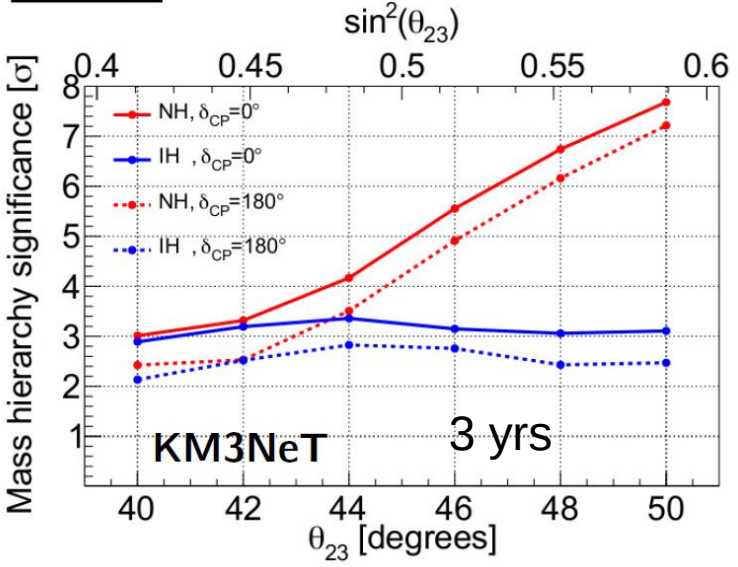
- Careful treatment of systematics mandatory!

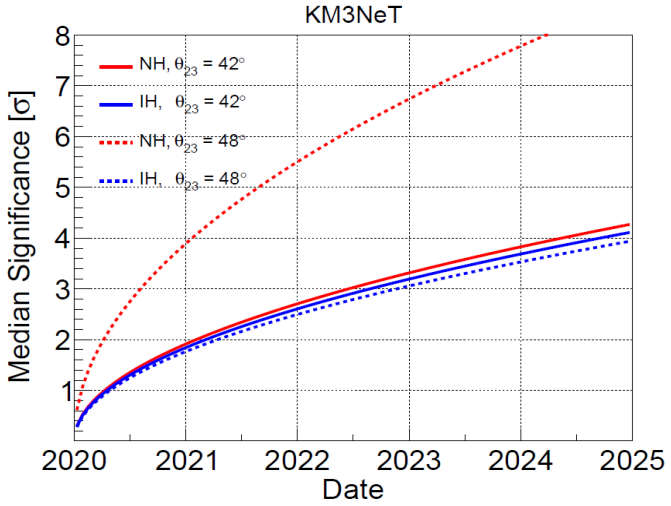


ORCA- neutrino properties

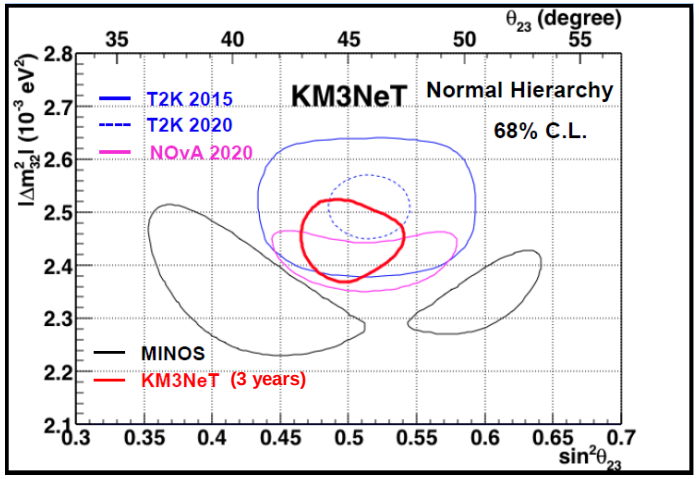


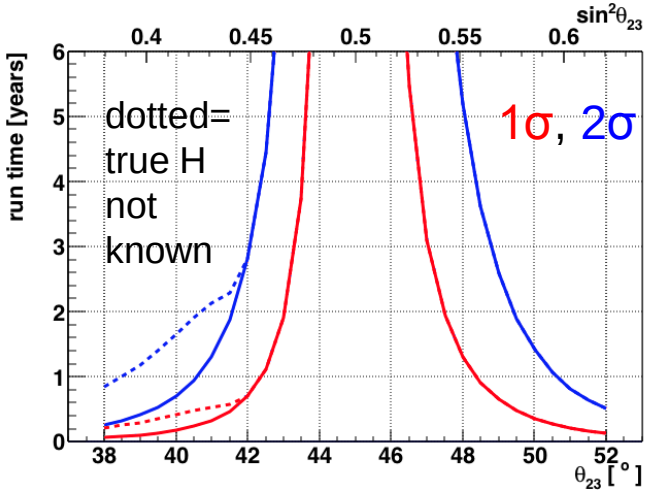
KM3NeT 2.0: Letter of Intent
http://dx.doi.org/10.1088/0954-3899/43/8/084001
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001





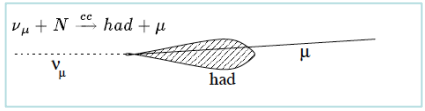
Time to measure octant





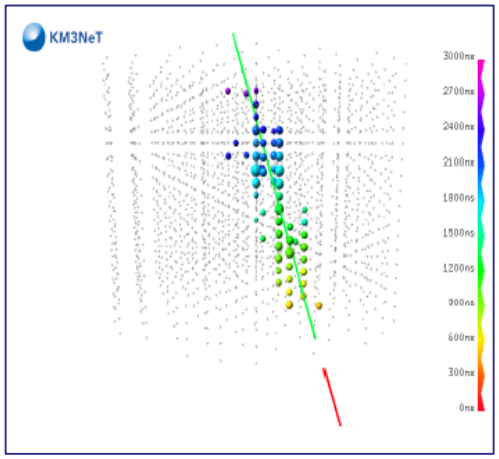
Performance – Track events

CC ν_μ

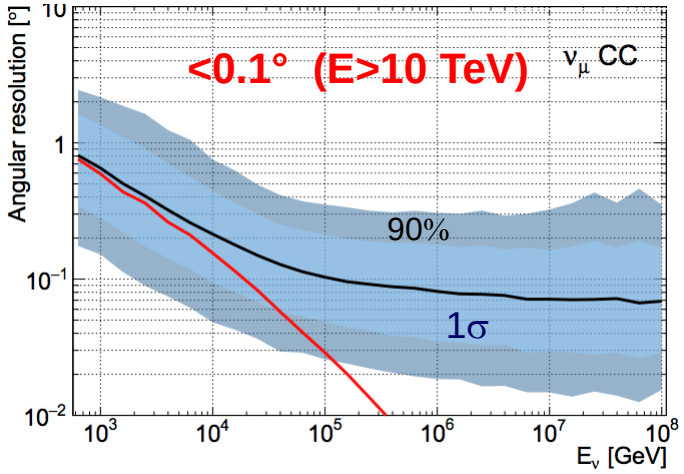


- Golden channel
- High angular accuracy
- Enhanced volume
  (100's m to a few km muon range)

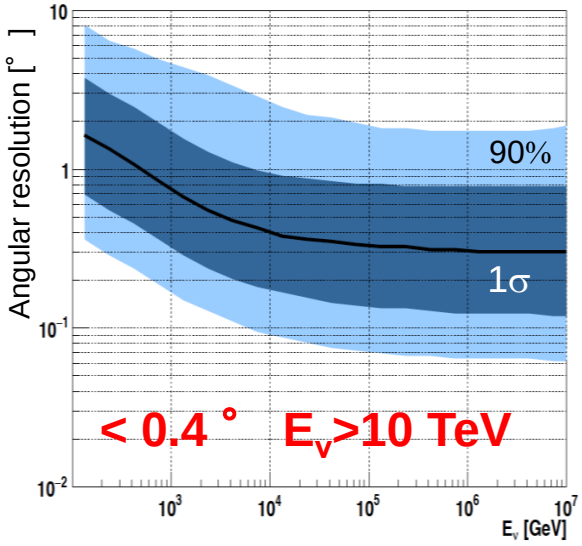
KM3NeT event



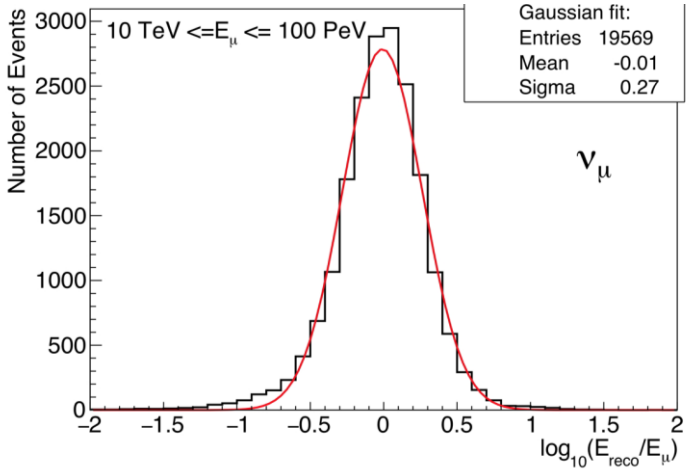
Direction (KM3NeT)



Direction (ANTARES)



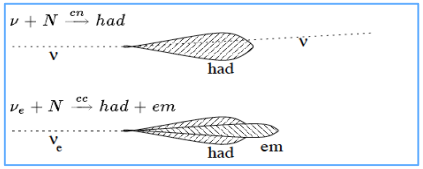
Energy (KM3NeT)



0.3 Log E (E>10 TeV)

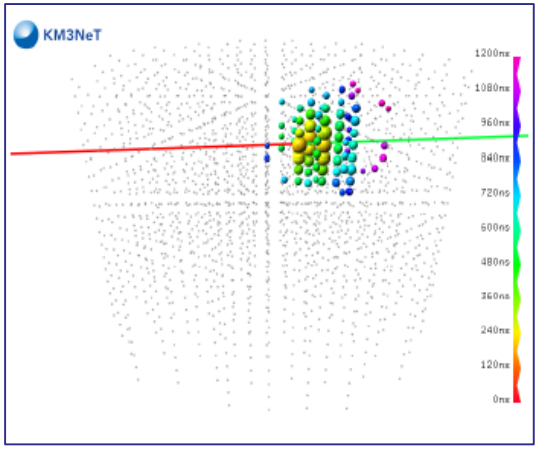
Performance – Shower events

NC ν_{all}
CC ν_e

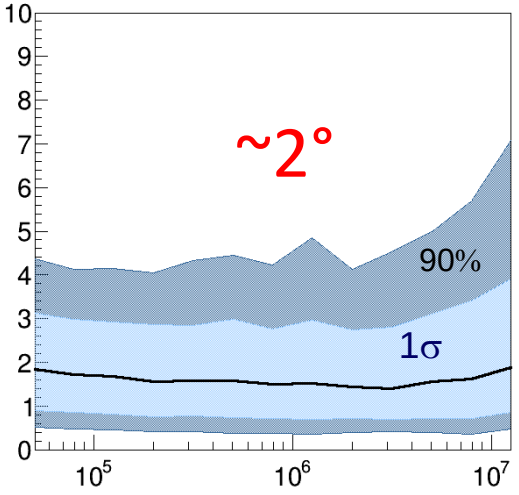


- Good energy reconstruction
- Fair angular resolution (low light scattering in water)

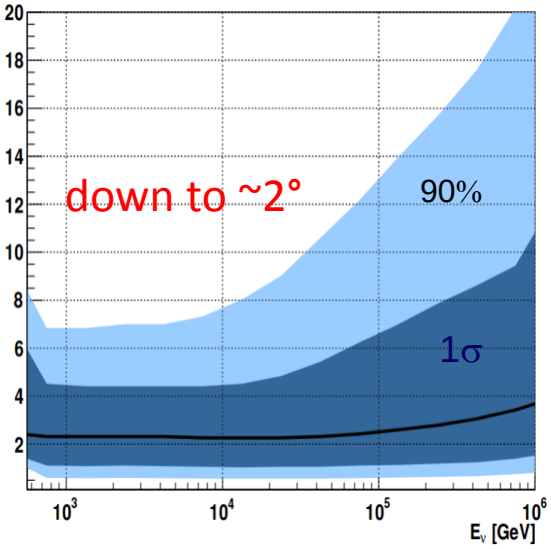
KM3NeT event



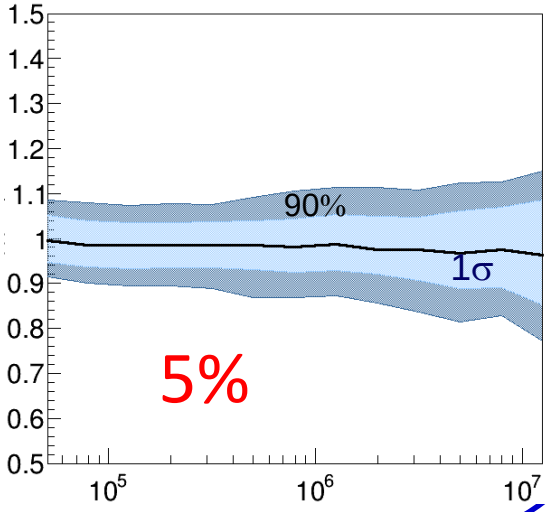
Direction (KM3NeT)



Direction (ANTARES)



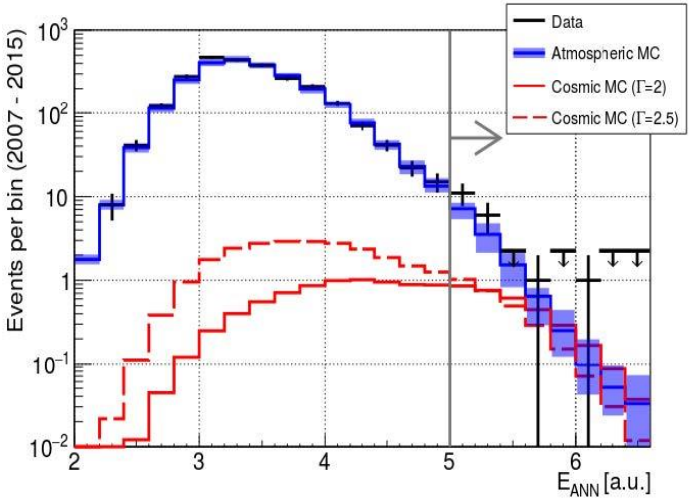
Energy (KM3NeT)



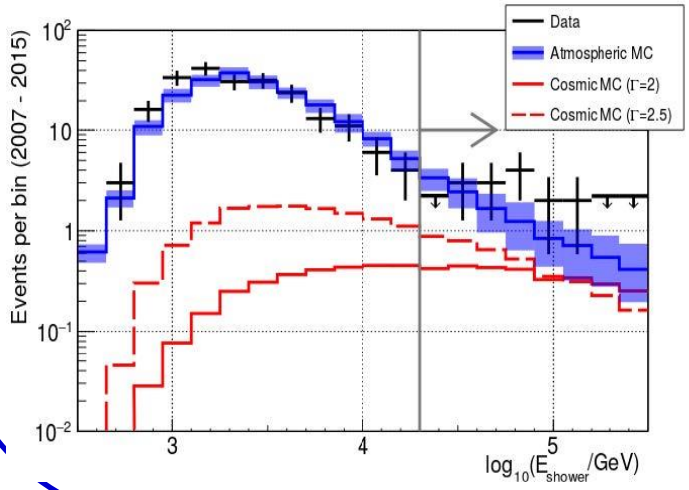
ANTARES – Diffuse Flux Search

ApJL 853, L7 (2018)

Tracks



Showers

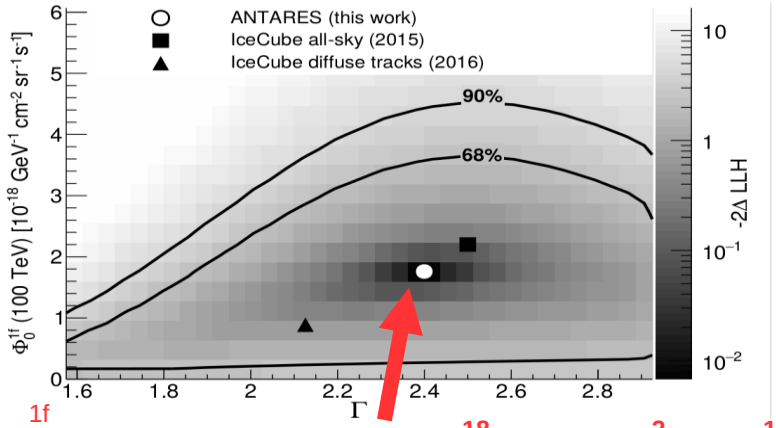


All-sky / All-flavor neutrino search

- Look for excess above a given E_{th}
- 9 (7) yrs of data for tracks (cascades)

	Bkg expectation	Signal exceptation	Nb events measured
Track	**13.5+/-4**	**3-3.5**	**19**
Shower	**10.5+/-4**	**3-3.5**	**14**

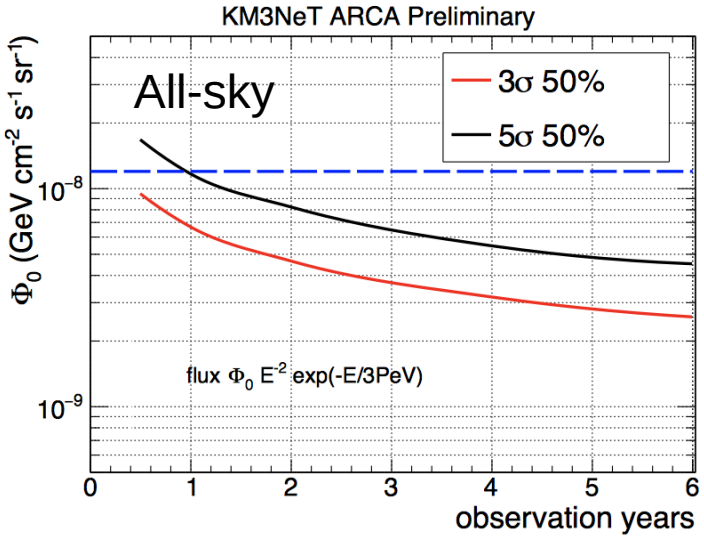
=> **1.6σ excess, null cosmic rejected at 85% CL**

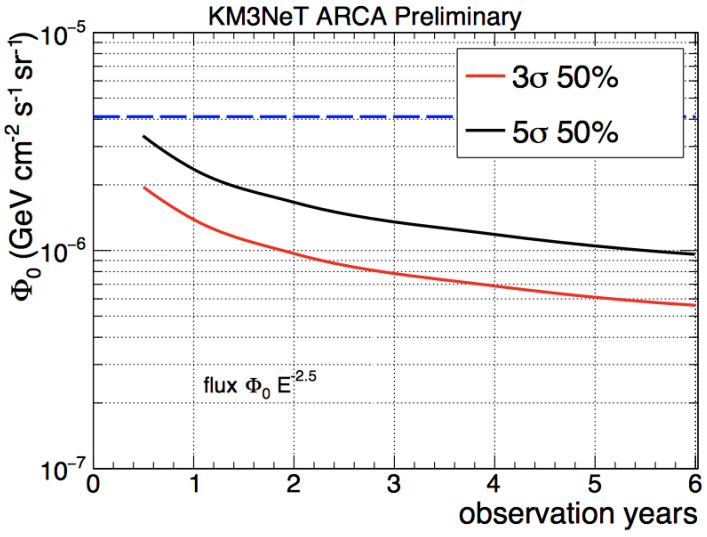


Φ_0^{1f} (100 TeV) = (1.7±1.0) 10^{-18} (GeV cm^2 s sr)$^{-1}$

Γ = 2.4+-0.5

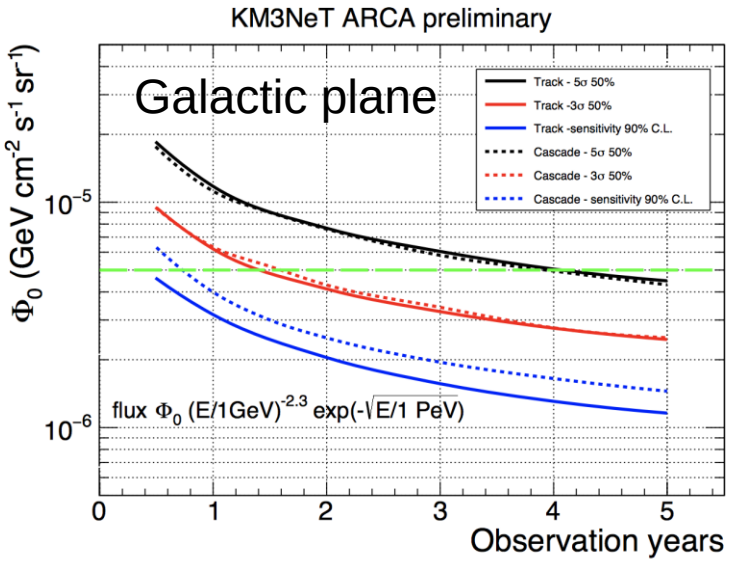
KM3NeT- Diffuse Flux





KM3NeT/ARCA is expected to observe the IC signal in less than 1 yr.

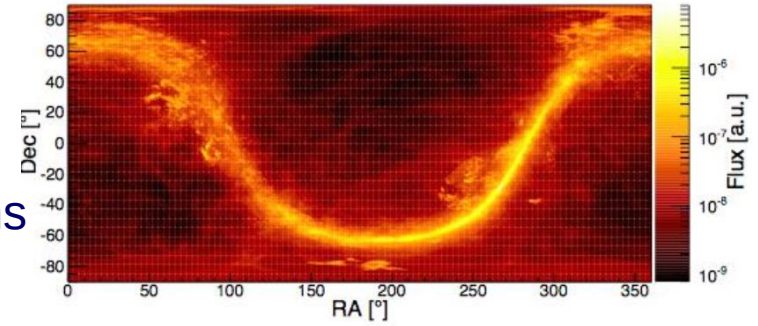
- ➞ Precise characterization (spectral shape, flavor composition, anisotropy)
- ➞ Excellent sensitivity in the galactic plane: identify gal/extra-gal components ?



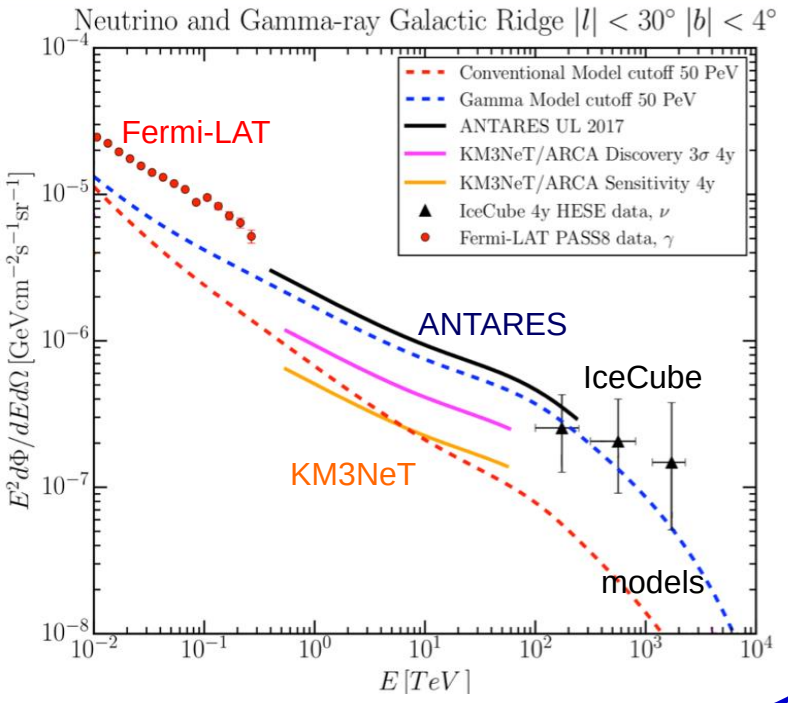
Galactic Plane

- ν's from CR-gas interactions
- KRA_γ model of diffuse gammas
  - CR local features and gamma observations reproduced
- Search strategy:
  - Signal map according to KRA_γ modelling
  - Two ref models: 5 PeV and 50 PeV cutoffs
- Data 2007-2015
  - 7300 Tracks and 208 showers
- Results:
  - No excess of events
  - 90% flux limits for ref models:

    < 1.1 Φ(5 PeV) < 1.2 Φ(50 PeV)
  - Not the source of "spectral anomaly" (IC spectrum in hemispheres)



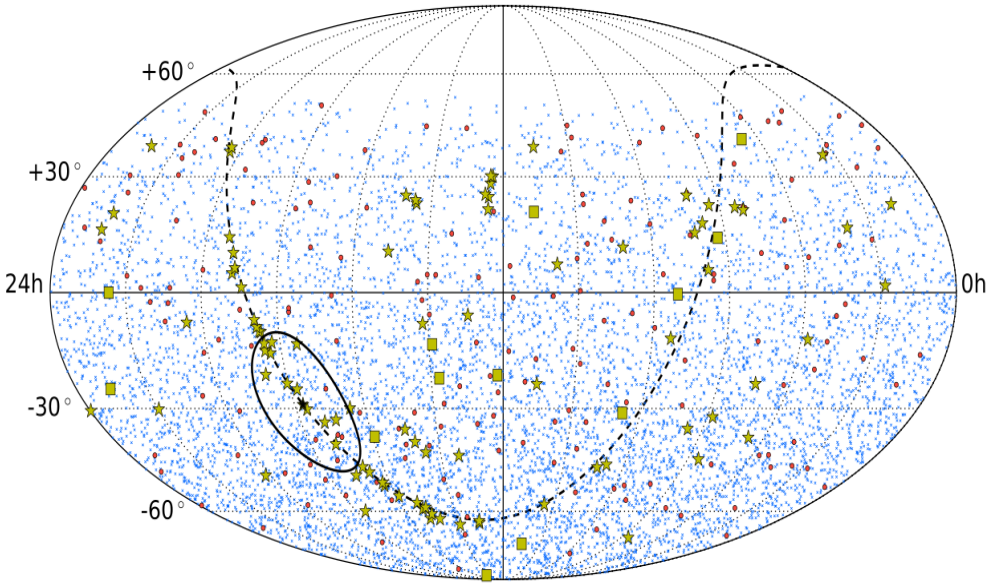
(a) KRA-γ (50 PeV cutoff) template



Phys. Rev. D **96** 062001 (2017)

Antares - Point Sources

- Sample:
  - 2007-2015
  - 2424 days of live time
  - 7629 Tracks, 180 Showers (all flavour analysis)



Track
Showers
Source candidate
HESE track

Phys. Rev. D 96, 082001 (2017)

- *Full-sky Search*
- *Candidate list Search*
  - 106 objects (pulsars, SNRs, etc.)
  - 13 IceCube HESE tracks
- *Galactic Centre Region*
  - Ellipse 15°x 20°
  - Test:

  Spectral indices γ = 2.1, 2.3, 2.5

  Extension σ = 0.5°, 1.0°, 2.0°
- *Sagittarius A* location*
  - Extended source. Gaussian profile of various widths:

  σ = 0°, 0.5°,1.0°, 2.0°

PRELIMINARY

Full sky

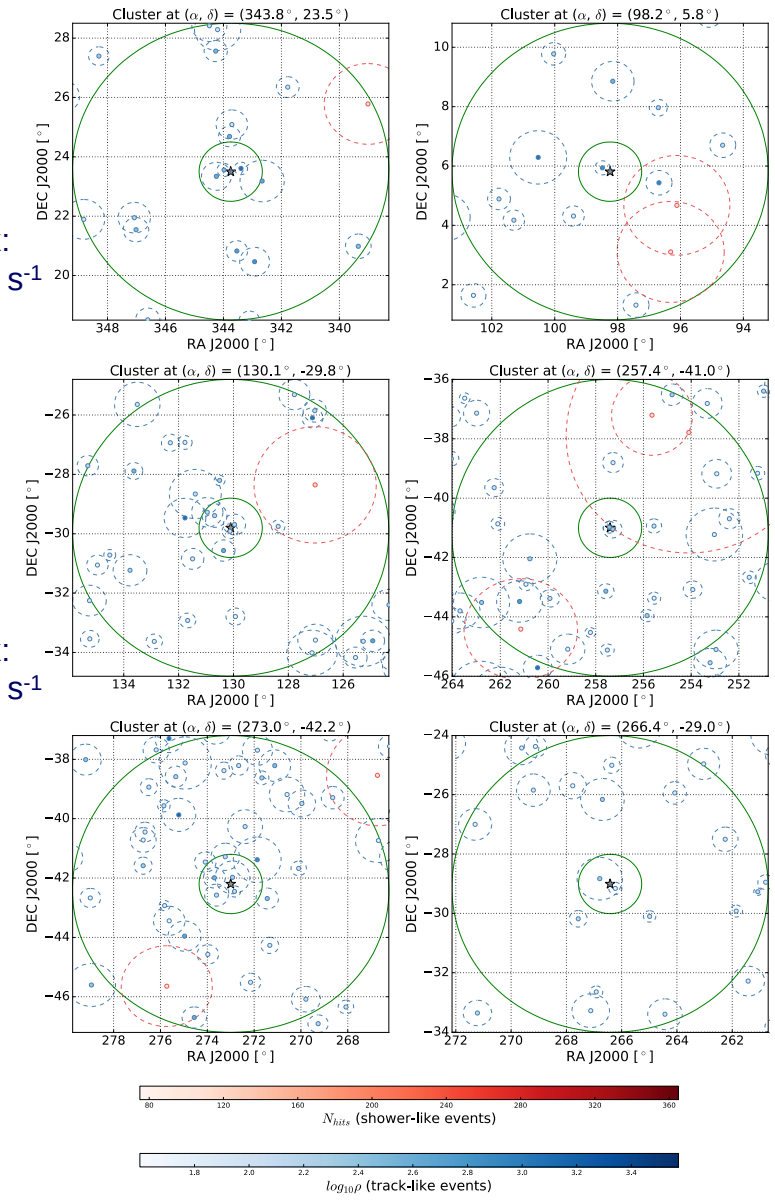
Most significant cluster
(α,δ) = (343.8°, 23.5°)
Post-trial significance:
5.9% or 1.9σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

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

Most significant cluster:
(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

Most significant cluster:
(α,δ) = (257.4°, -41.0°)
for a E^{-2} spectrum + point-like source
Post-trial significance:
60% or 0.5σ

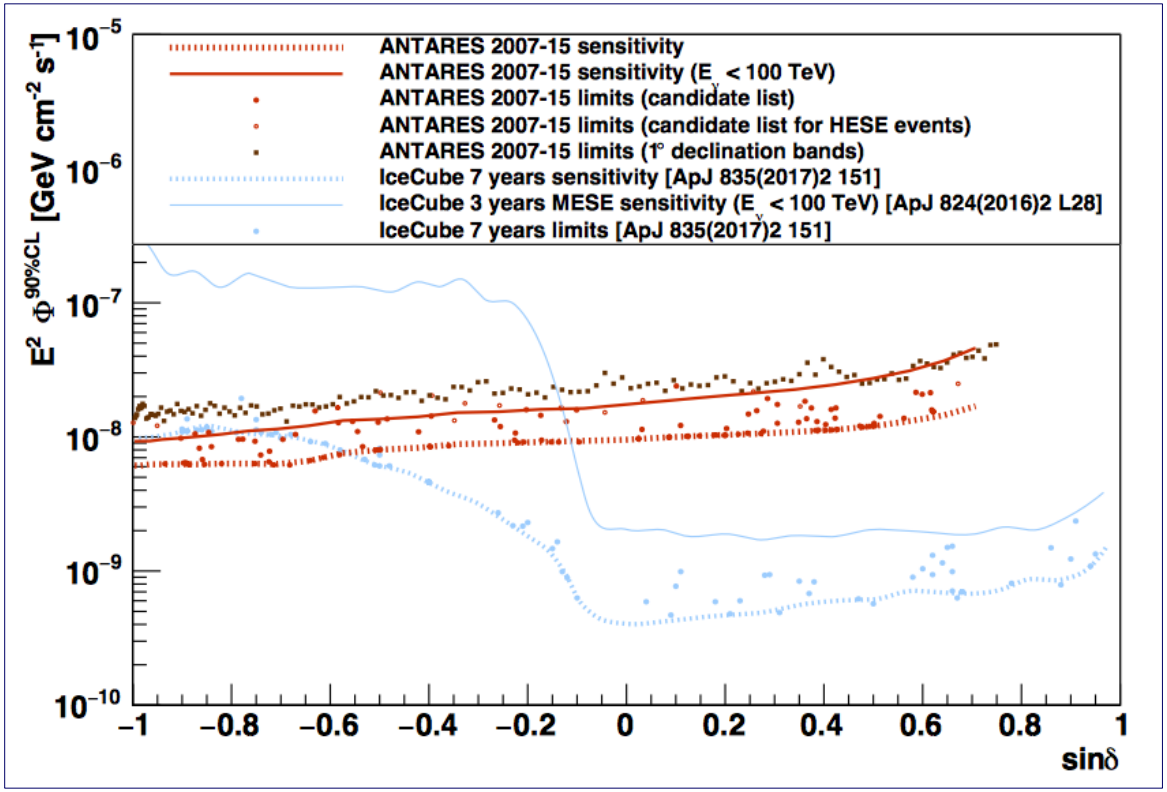
Sagittarius A*:

(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

Phys. Rev. D **96** 062001 (2017)

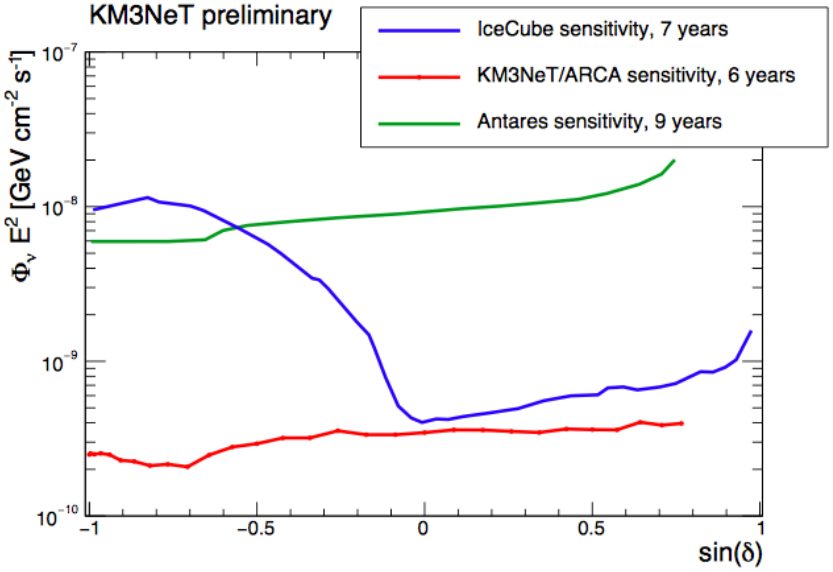
ANTARES- Full sky and candidate list searches

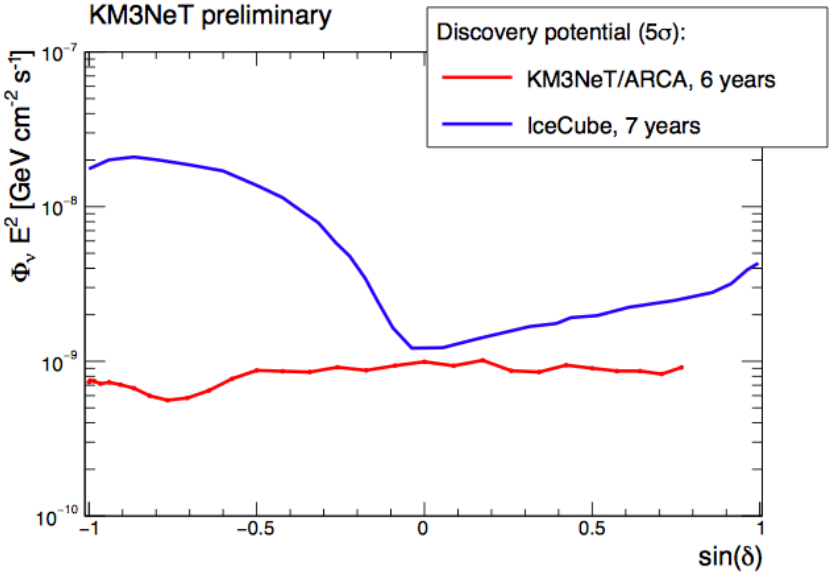
Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches



ANTARES provides the best results for low declination or soft spectra or 100 TeV-ish cutoff

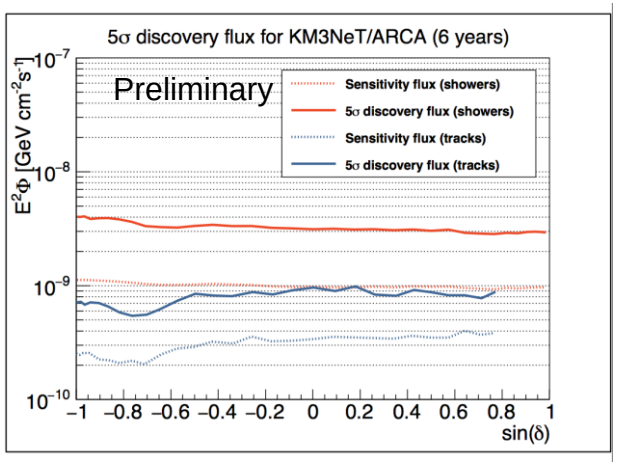
KM3NeT/ARCA Expectations (E^{-2} Spectrum)





KM3NeT/ARCA is expected to have more than one order of magnitude better sensitivity than IC in the Southern sky.

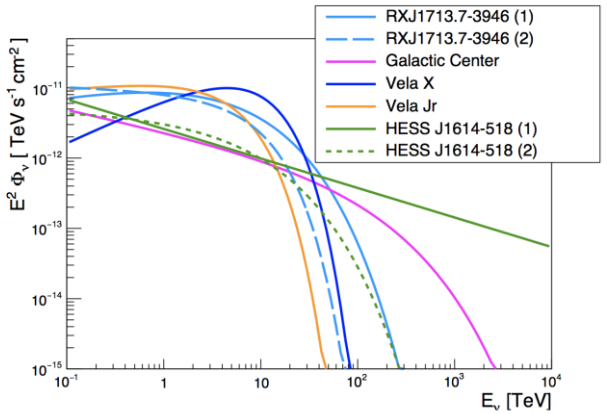
- ➞ Due to the good angular resolution for shower events, the shower point-source search is also very efficient.
- ➞ Expect better performances for the transient neutrino sources (GRB, AGN…)



KM3NeT/ARCA - point sources

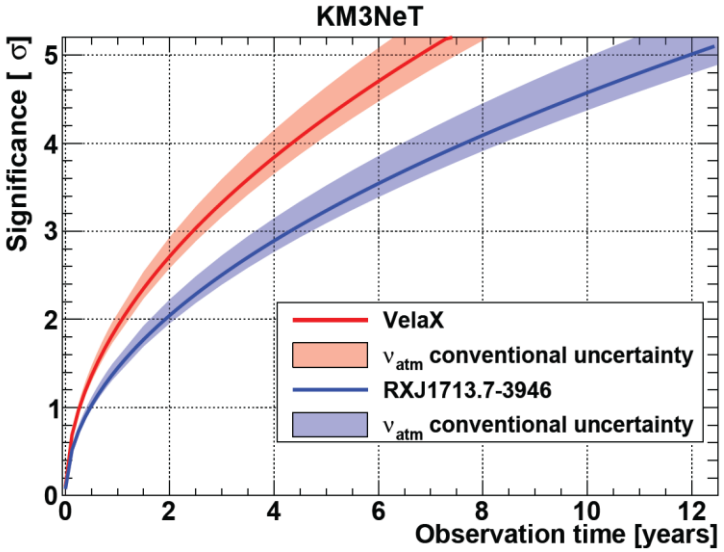
Specific galactic sources

Source	δ	extension	Φ_0	Γ	E_{cut}	β	γ-ray data
RX J1713.7-3946 (1)	-39.77°	0.6°	1.68	1.72	2.1	0.5	[13]
RX J1713.7-3946 (2)	-39.77°	0.6°	0.89	2.06	8.04	1	[14]
Vela X	-45.6°	0.8°	0.72	1.36	7	1	[15]
Vela Jr	-46.36°	1°	1.30	1.87	4.5	1	[16]
HESSJ1614-518 (1)	-51.82°	0.42°	0.26	2.42	-	-	[17]
HESSJ1614-518 (2)	-51.82°	0.42°	0.51	2	3.71	0.5	[17]
Galactic Centre	-28.87°	0.45°	0.25	2.3	85.53	0.5	[18]
MGRO J1908+06 (1)	6.27°	0.34°	0.18	2	17.7	0.5	see text
MGRO J1908+06 (2)	6.27°	0.34°	0.16	2	177	0.5	see text
MGRO J1908+06 (3)	6.27°	0.34°	0.16	2	472	0.5	see text



γ→ν flux conversion:

F. Vissani, *Astropart. Phys. 26* (2006), 310.
F. L. Villante and F. Vissani, *Phys. Rev. D 78* (2008), 103007.
F. Vissani and F. Villante, *Nucl. Instrum. Methods A 588* (2008), 123.



Galactic sources in reach

Constrain hadronic component

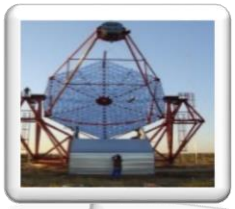
Starting-event study in pipeline and also very promising

Multi-messenger Programme

- Advantages:
  - A-priori interesting sources or events
  - Reduced background:
    - Uncorrelated between techniques
    - Transient/short time events
    - Spatial location
  - Fully exploit the ν telescopes features:
    - Continuous monitoring
    - Wide angle survey
    - High efficiency, low latency (all-data-to-shore, fast reconstruction)

GeV-TeV γ-rays

Fermi, HESS, HAWC



Radio-Visible-X

MWA, SUPERB
TAROT, ZADKO, MASTER
Swift

- Send and receive alerts:
  - Alerts from:
    - Flaring AGNs, X-ray binaries
    - GRBs, FRBs
    - Gravitational waves
    - SN Ib,c
  - Alerts sent out if:
    - High energy neutrino
    - Multiplets
    - Preferred direction

UHE Cosmic rays

Auger, TA

Gravitational waves

LIGO-VIRGO-EGO

Summary

ANTARES:

- 10 year experience. Thousand of neutrinos reconstructed (tracks and showers)
- Excellent resolution (down to 2° for showers!)
- Diffuse flux: a small excess at high energy compatible with a cosmic signal
- Point sources: best limits for southern sky Galactic sources (E<100 TeV)
- A lively and vibrant multi-messenger programme. We need a larger detector!

KM3NeT:

- KM3NeT 2.0:
  ESFRI Roadmap 2016, APPEC European Strategy 2017
  ARCA: high-resolution follow up of IceCube flux (5 sigma within 1 yr)
  ORCA: Measure neutrino mass hierarchy (3 sigma in 4 years)
- On the move!
  2 ARCA and 1 ORCA strings in water
- Mass production of DUs starting (about 400 DOMs mounted, and counting...)