Neutrino telescopes in the Mediterranean Sea: status and perspectives

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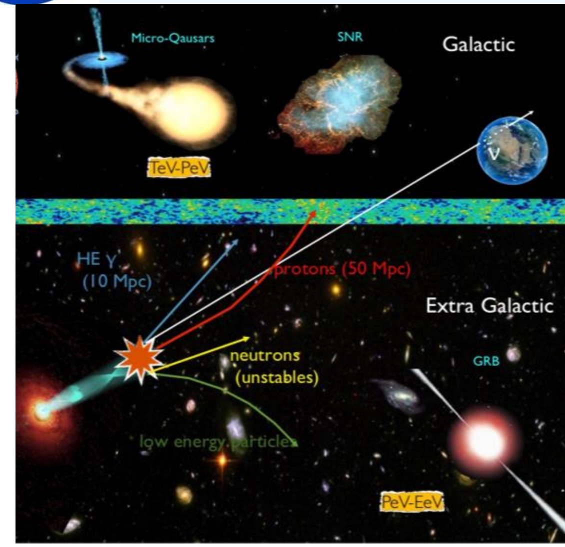
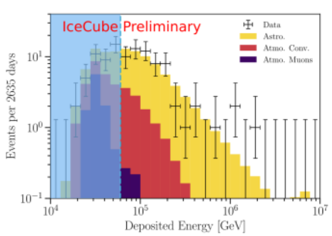
Motivations & Objectives



Perfect prob
unabsorbed
Multimessenger approach



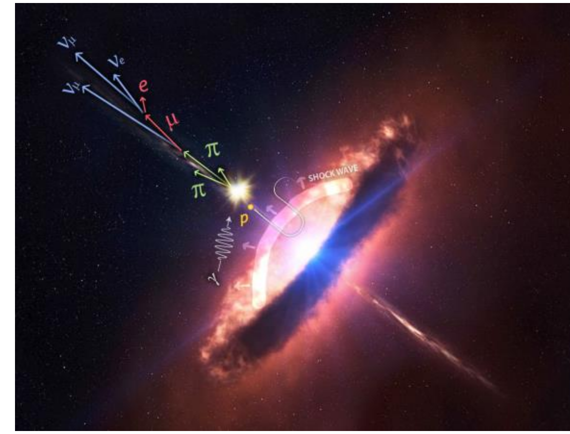
IceCube diffuse flux

D. Williams – ICRC 2019

COSMIC NEUTRINOS

- Sources of cosmic ν
- Production and acceleration of ultra high-energy cosmic rays

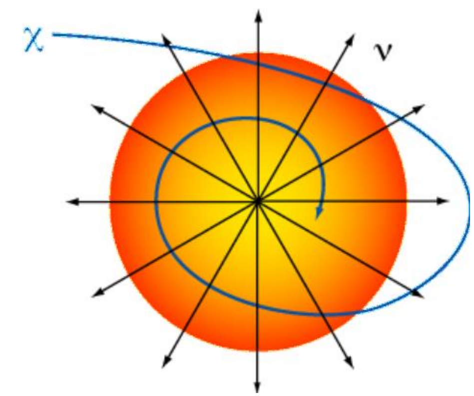
High Energy
E_ν > 1 TeV



ASTROPHYSICS

- Dark matter
- Monopoles, Nuclearites

Medium Energy
10 GeV < E_ν < 1 TeV



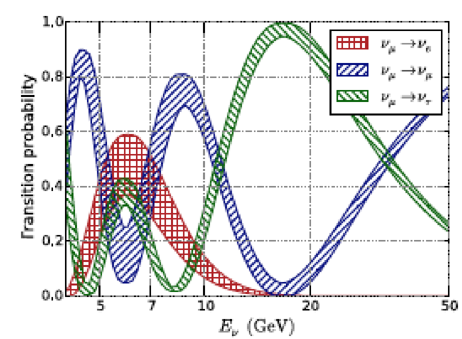
ATMOSPHERIC NEUTRINOS

- ν oscillations
- sterile neutrinos
- mass hierarchy
- tau appearance
- mass hierarchy
- Non-standard interactions

- Supernovae

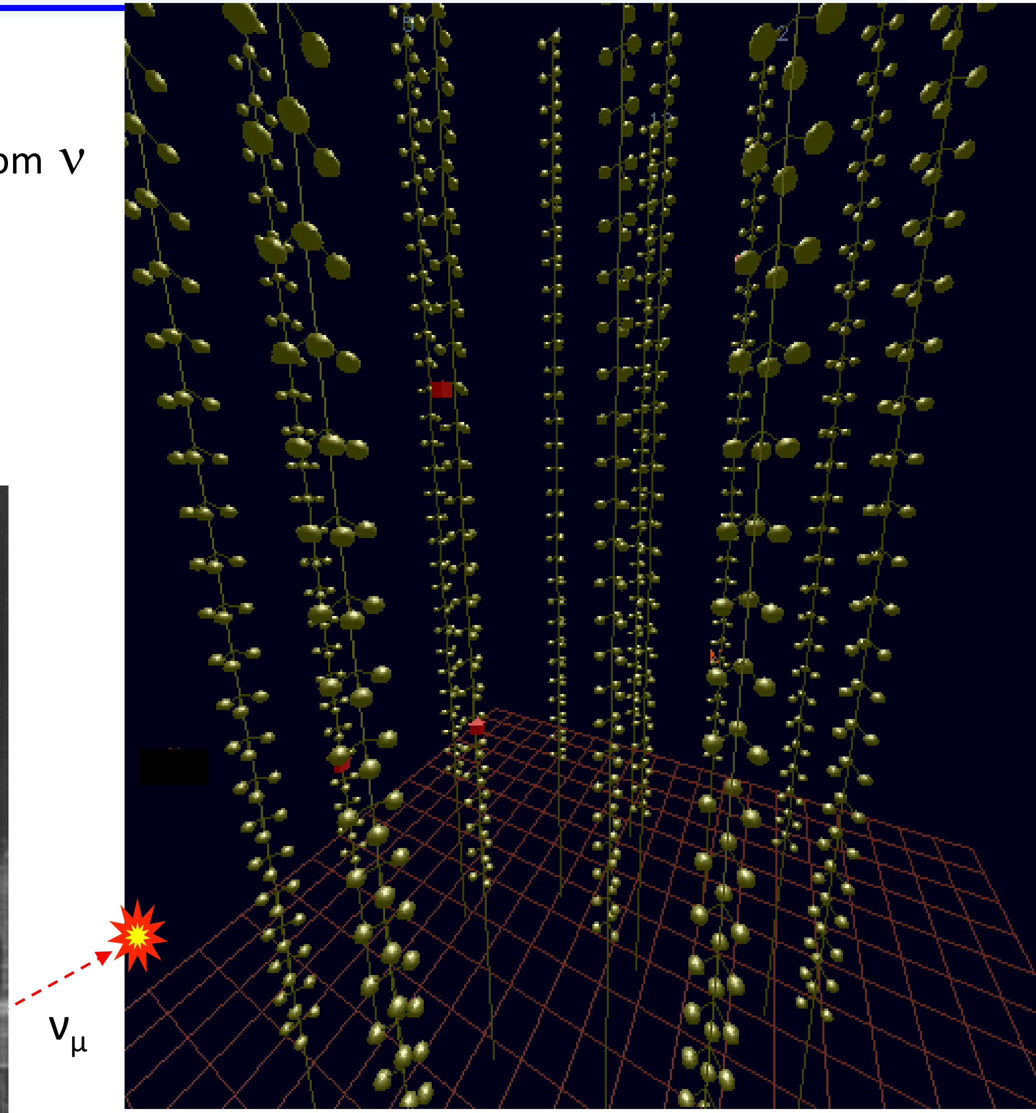
Low Energy
MeV < E_ν < 100 GeV

PARTICLE PHYSICS

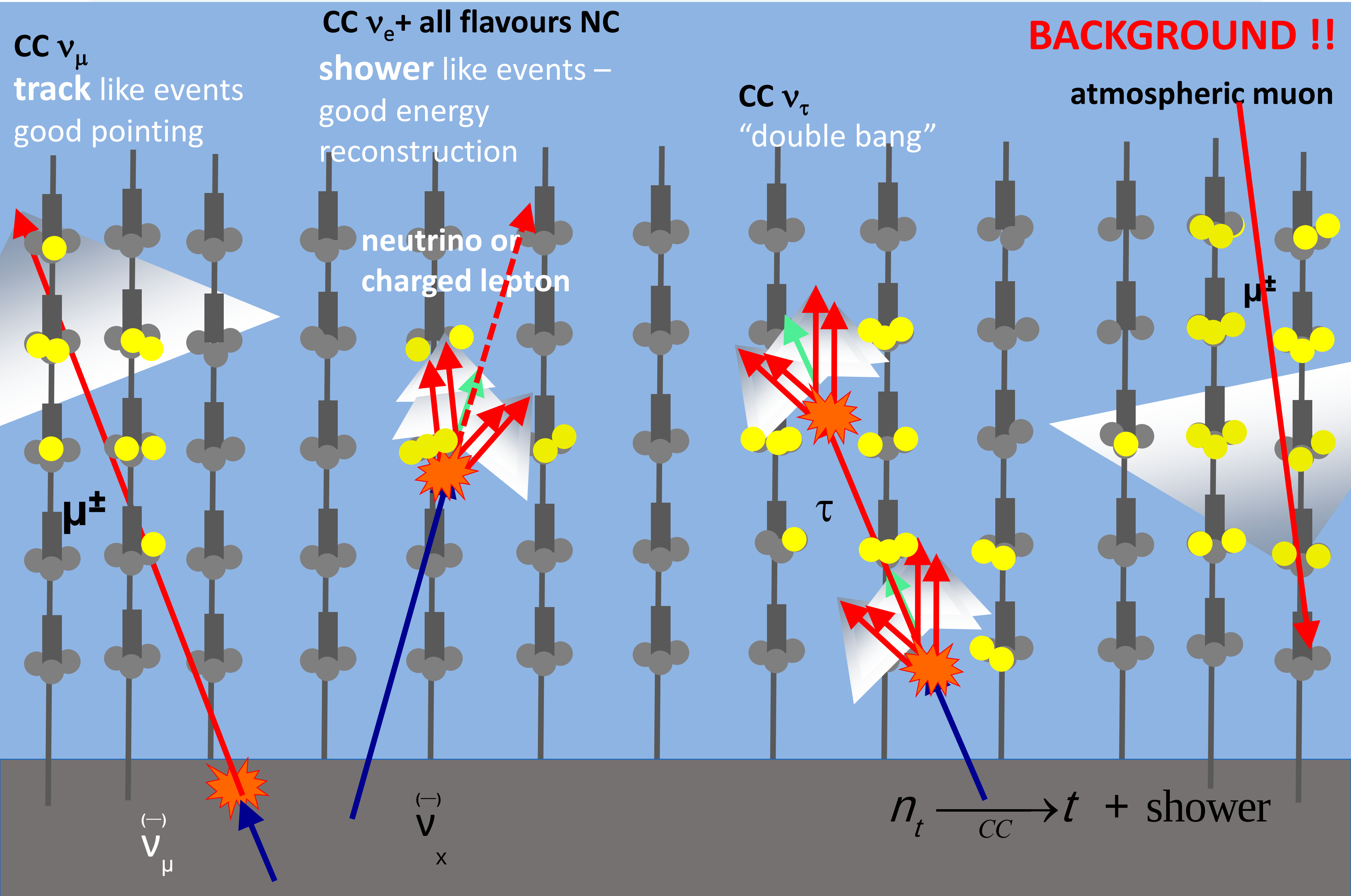


The concept of Cherenkov neutrino telescopes

- Photomultipliers (PMTs) collecting Cherenkov photons due to relativistic charged particles from ν interactions
- Parent ν direction reconstructed using time & position



Events in a neutrino telescope



Background

Atmospheric muons

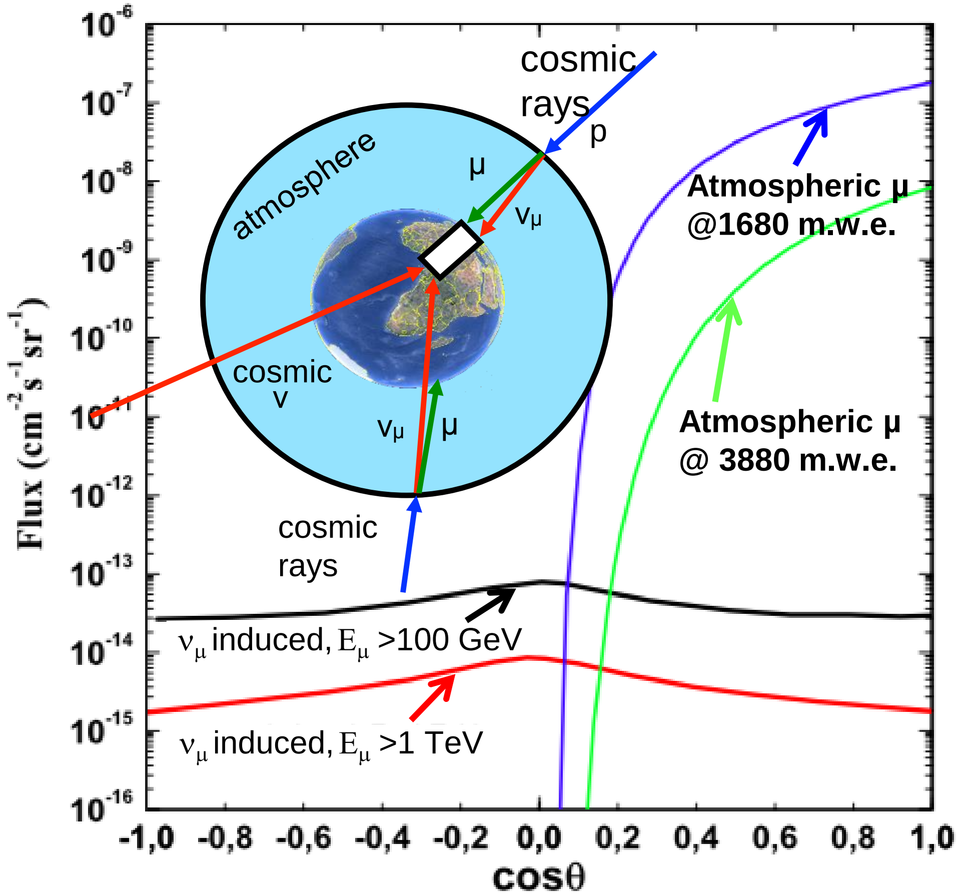
direction cut → upward going events

useful for detector calibration

Atmospheric neutrinos

irreducible background

neutrino oscillations → mass hierarchy

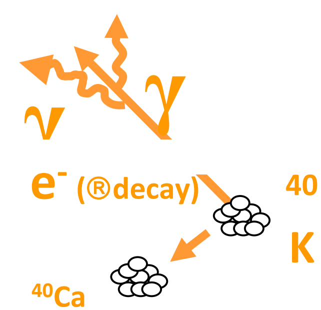


Environmental background

- ^{40}K decay
- bioluminescence
-

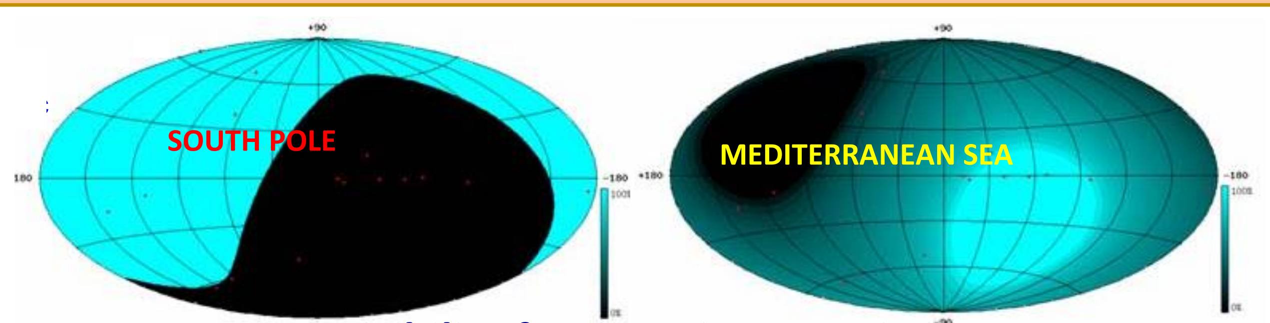
rejection : causal correlation of the signals

$$^{40}K \to {}^{40}Ca + e^- + \overline{\nu}_e \quad (89.3\%)$$
$$^{40}K + e^- \to {}^{40}Ar^* + \nu_e \quad (10.7\%)$$
$$\hookrightarrow {}^{40}Ar + \gamma$$



Why the Mediterranean Sea

- Optical properties of water ➔ Mapping the **Southern sky** with unprecedented angular resolution
  - tracks: < 0.1 ° (KM3NeT) - 0.4° (ANTARES) @ 10TeV
  (IceCube : 0.3° @ >100 TeV)
  - showers: few degrees 2° (KM3NeT)- 4° (ANTARES) @10 TeV
  (IceCube: 10° @ > 100 TeV)
- Visibility of the Galactic region ➔ ~ 70 % for the Galactic Centre
- Investigation of the IceCube diffuse flux from another point of view



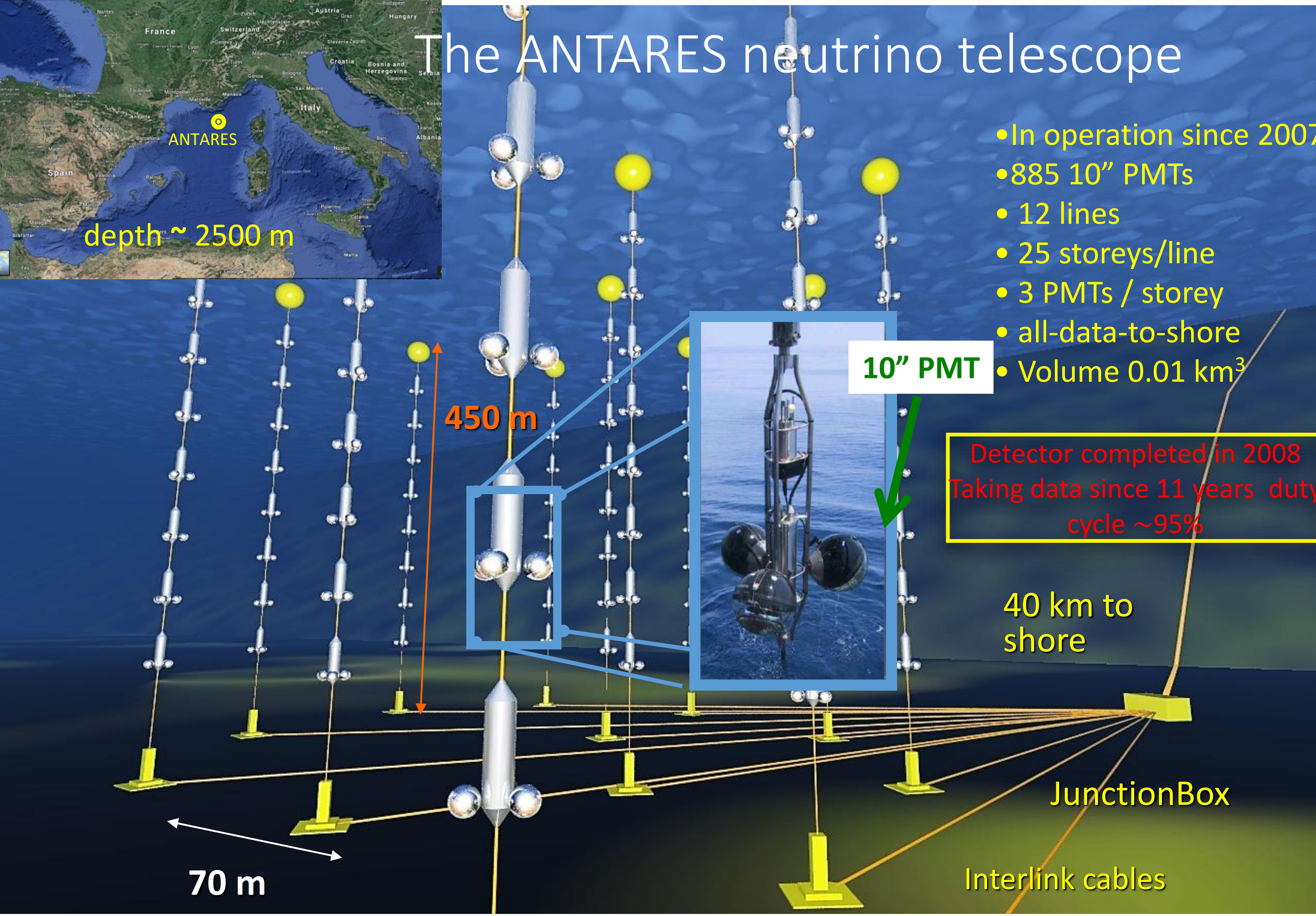
Visibility for up-going neutrinos

The detectors

The ANTARES neutrino telescope

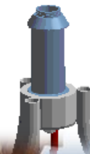
- In operation since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- all-data-to-shore
- Volume 0.01 km^3

Detector completed in 2008
Taking data since 11 years duty cycle ~95%

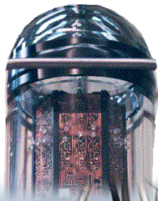


The storey

titanium frame: support structure (2m)



Optical Beacon with blue LEDs: timing calibration



Optical Module:
" Hamamatsu PMT
17" glass sphere
(σ_{TTS} ≈1.3 ns)
hoton detection

Lo

Fron

Clock

coustic positioning

The KM3NeT detectors

KM3NeT/ARCA (**A**stroparticle **R**esearch with **C**osmics in the **A**byss)

- discovery and observation of high energy neutrino sources of cosmic origin (E_ν ~ GeV-PeV)

Depth – 3500 m

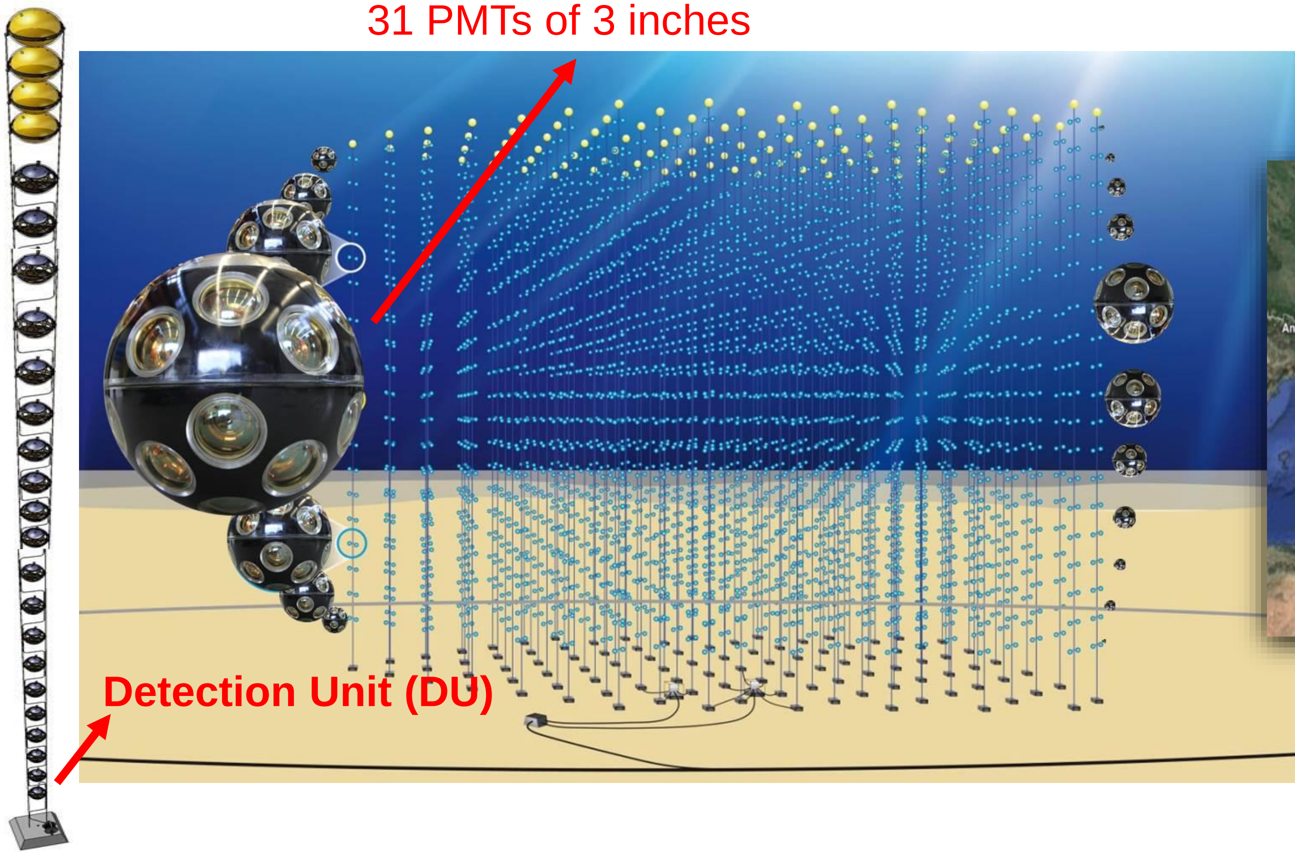
KM3NeT/ORCA (**O**scillation **R**esearch with **C**osmics in the **A**byss)

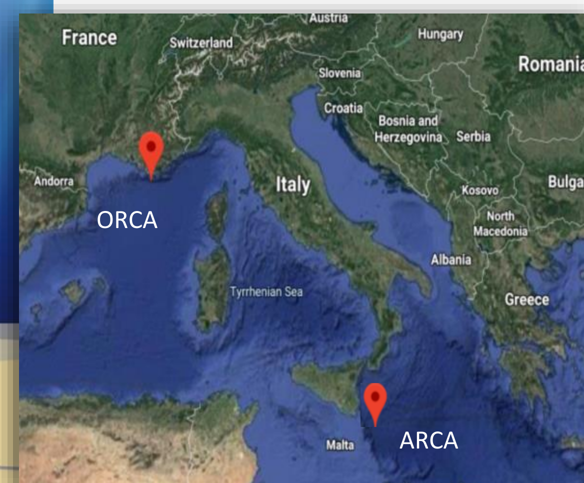
- determination of the neutrino mass hierarchy (E_ν ~ MeV - GeV)

Depth – 2500 m

KM3NeT 2.0 Letter of Intent:
J.Phys. G43 (2016) 084001

Optical sensor (DOM)
31 PMTs of 3 inches

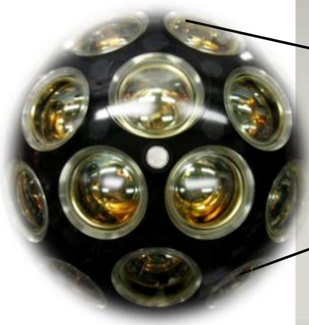




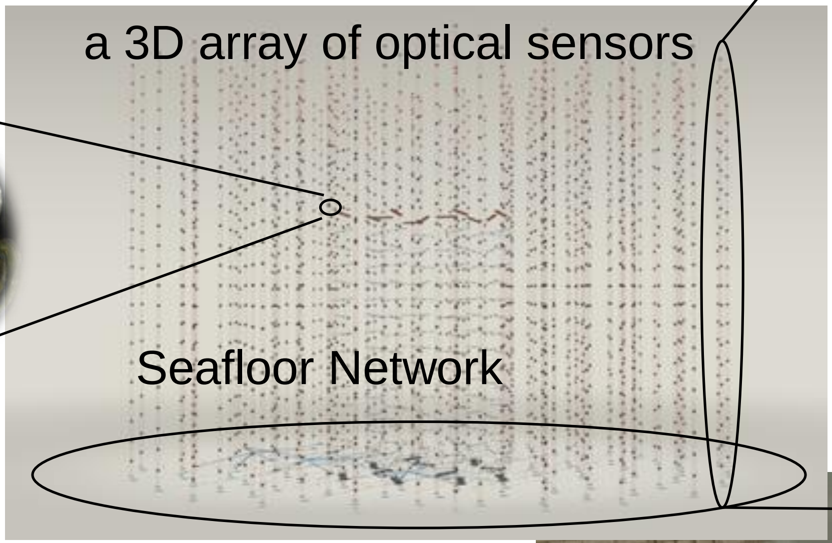
The KM3NeT detectors - Design

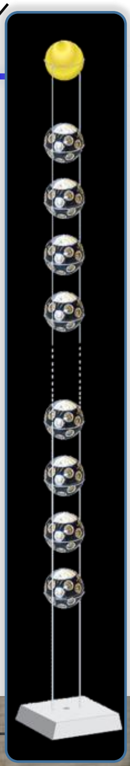
The optical sensor:
the Digital Optical Module (DOM)

31 PMTs x 3” PMTs



~ 40 cm





The Detection Unit (DU)

String:

- 1 Buoy
- 2 Dyneema ropes
- 18 DOMs
- 1 Anchor
- Electro-optical backbone:
  - Flexible hose 7mm
  - Oil-filled
  - 18 fibres
  - 2 copper wires

Improved background rejection
Compact and cost effective design:
photocathode area ≃ 3 x 10” PMTs

1 Building Block (BB) = 115 DUs
ARCA= 2 BB = 230 DUs
ORCA= 1 BB

The KM3NeT detectors - Design

- The same technology and design – different density of active sensors
- Modular design
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Sea network of submarine cables and Junction Boxes connected to shore via a main e/o cable
- All-data-to-shore → no trigger off-shore

	ARCA	ORCA
Location	Italy	France
DU distance	90 m	23 m
DOM spacing	36 m	9 m
Instrumented mass	2*500 Mton	8 Mton
Depth	3500 m	2500 m

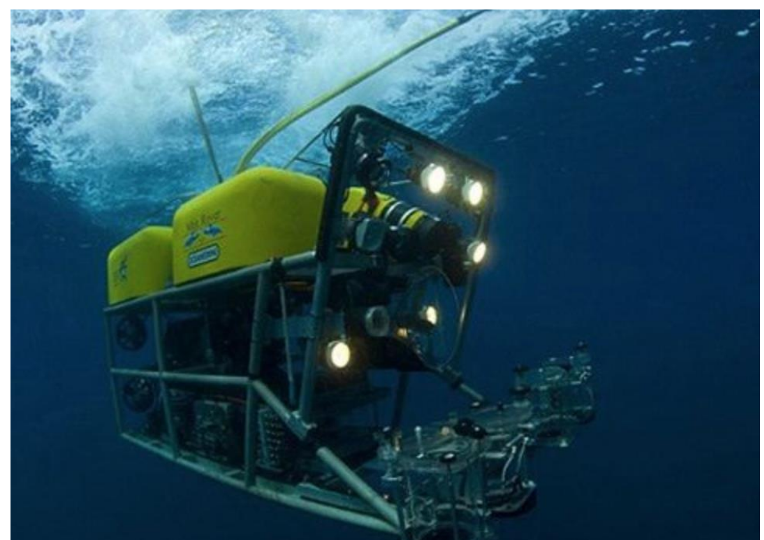
ARCA shore station @ Portopalo di Capo Passero

ORCA shore station @ La Seyne-sur-mer

The Detection Unit Deployment

The Launcher of Optical Modules (LoM)

2 m diameter



Physics

Recent results presented at the 36th International Cosmic Ray Conference, July 2019, Madison WI, USA
https://pos.sissa.it/358/

Summary here:
PoS(ICRC2019)006

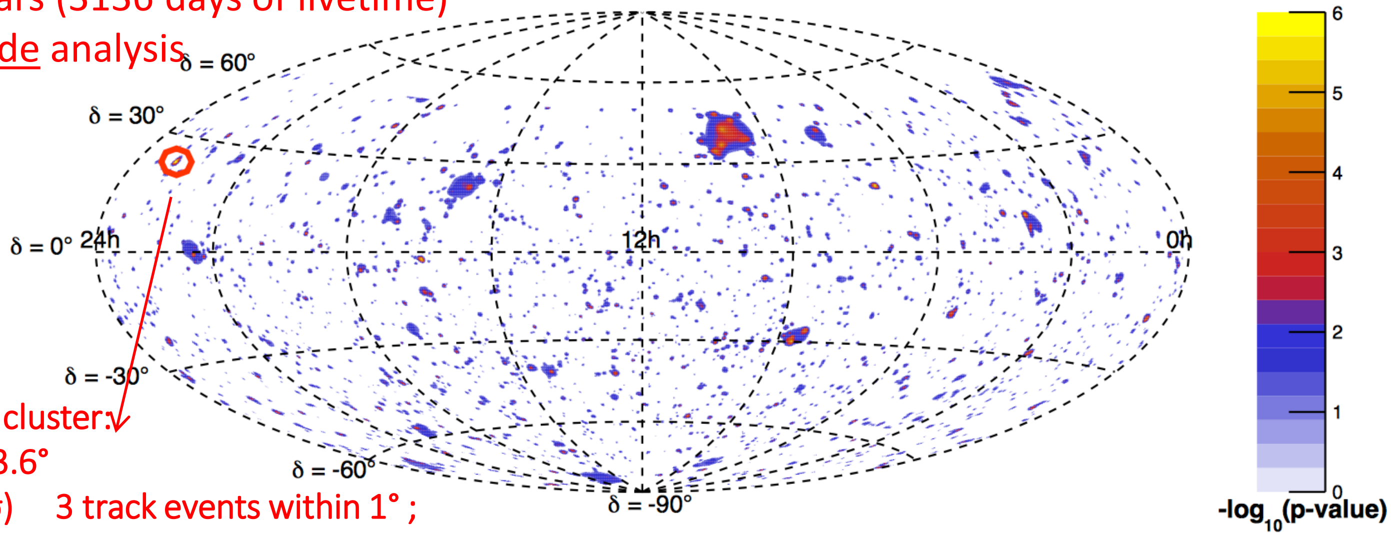
Pointlike sources: search for an excess of events over the expected background

G. Illuminati S. Navas - PoS920 ICRC2019

ANTARES 11 years (3136 days of livetime)
track and cascade analysis

1°x 1° bins

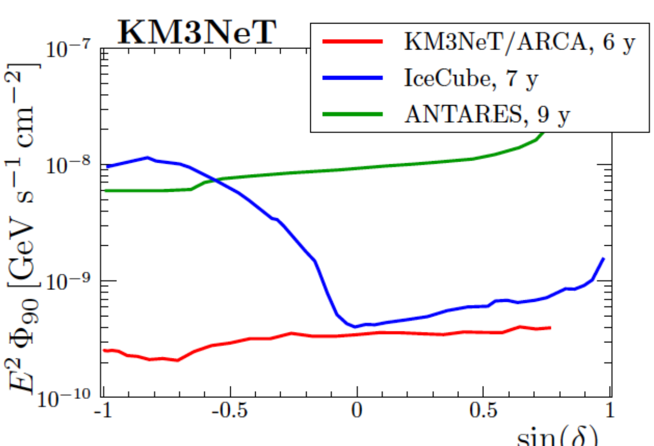
Full sky search



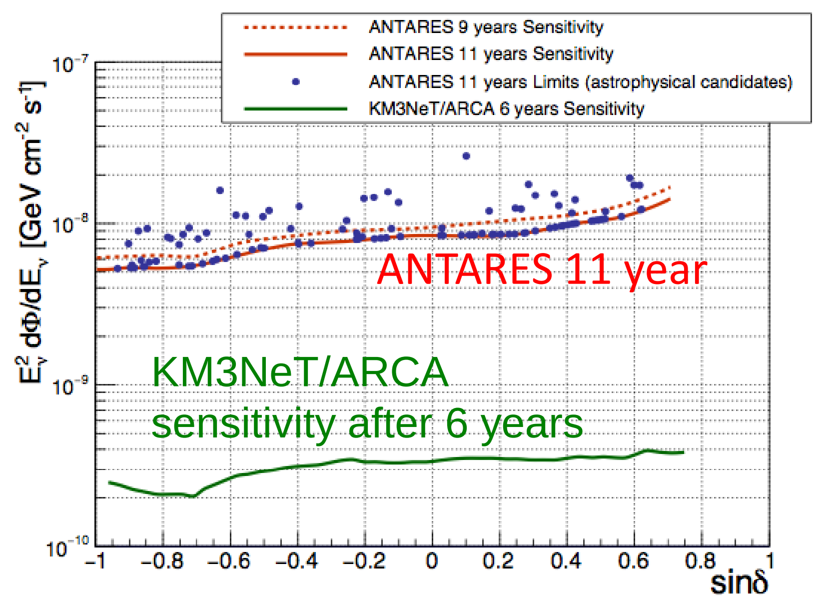
the most significant cluster:
α=343.7° δ=+23.6°
post trial 0.23 (1.2 σ)

3 track events within 1° ;
15 tracks + 1 shower within 5°

upper limits and sensitivities
E^{-2} spectrum



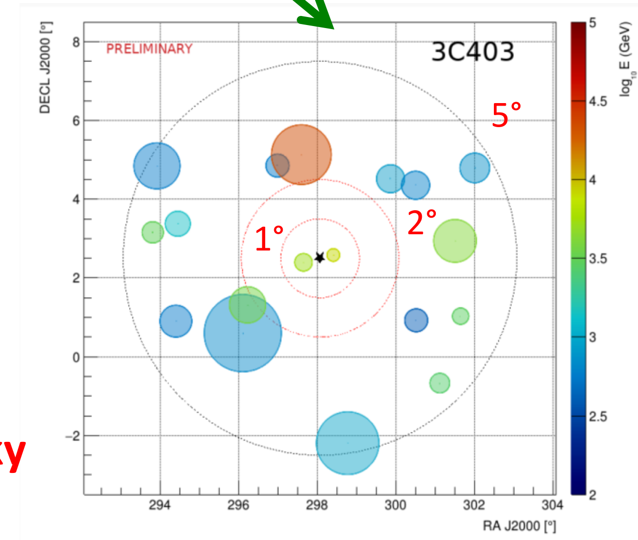
Search over a list of astrophysical objects



Point like sources – stacking analysis

CATALOG	PRE-TRIAL	POSTTRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSQR	0.57	0.97	
Fermi 3LAC BL Lacs	0.088	0.64	MG3J225517+2409
Radio-galaxies	$4.8\ 10^{-3}$	0.10 **1.6 σ**	3C403
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IceCube HE tracks	0.05	0.49	

11 years of track events



Radio Galaxies are the most significant category of sources

Two individual sources look particularly interesting:

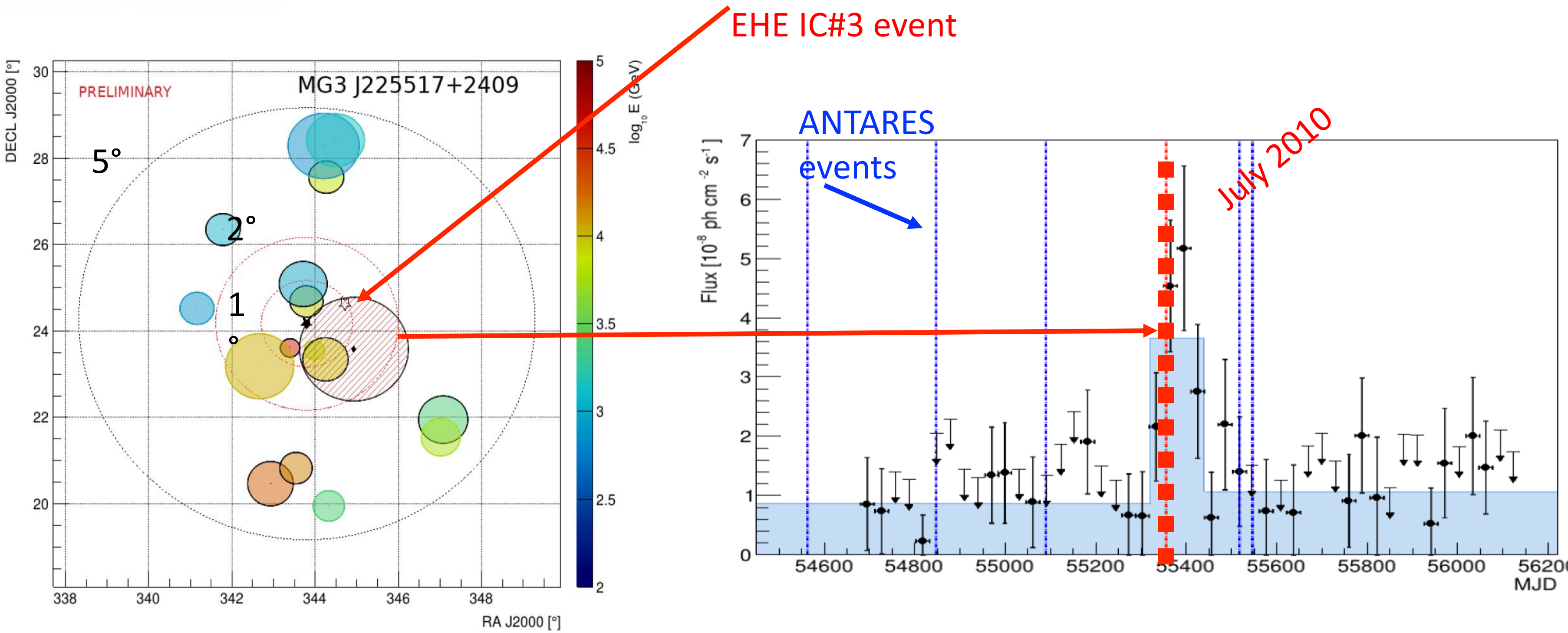
Radio Galaxy 3C403

Blazar MG3J225517+2409 → same location found in the full sky

Point like sources – stacking analysis

Blazar MG3J225517+2409
α=343.78° δ=+24.19°

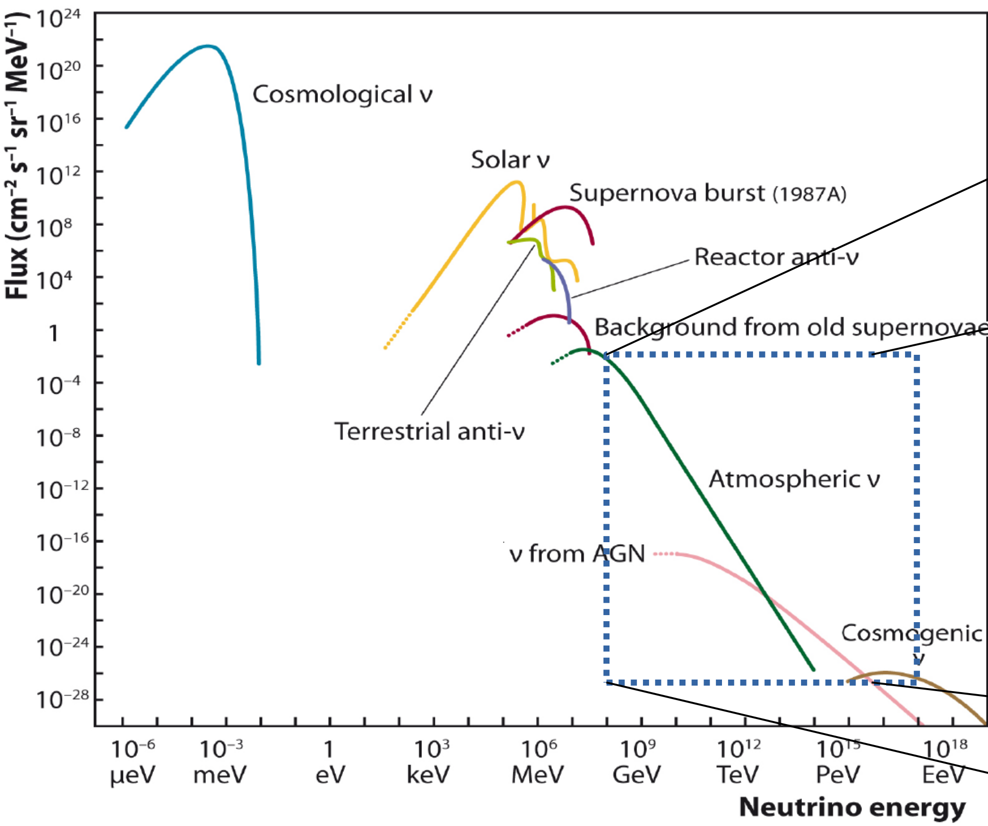
same location found in the full-sky search

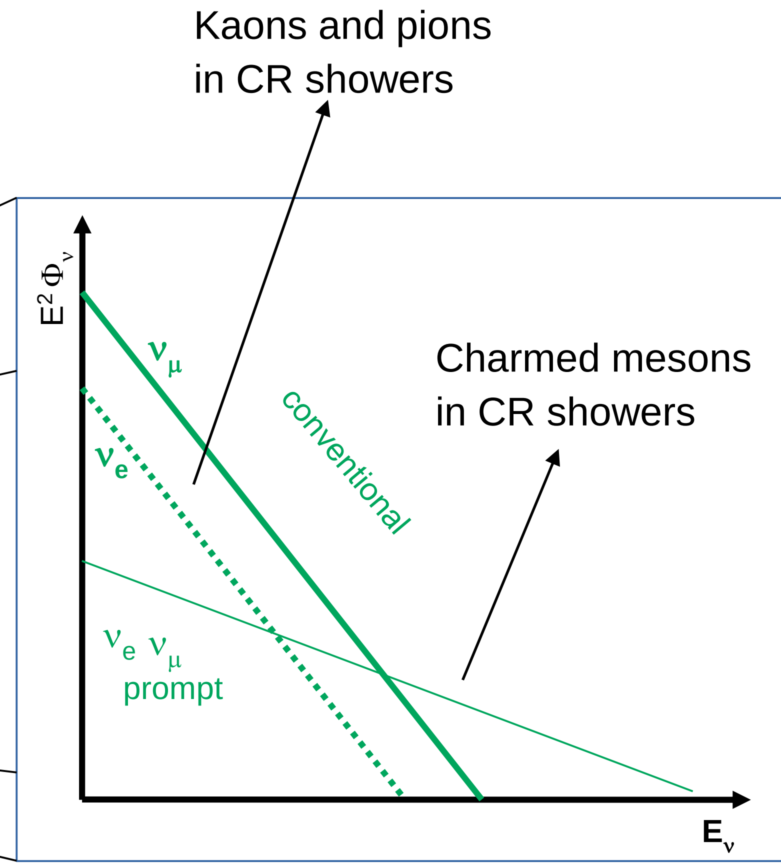


pre-trial value 3.8 σ
5 ANTARES tracks within 1°

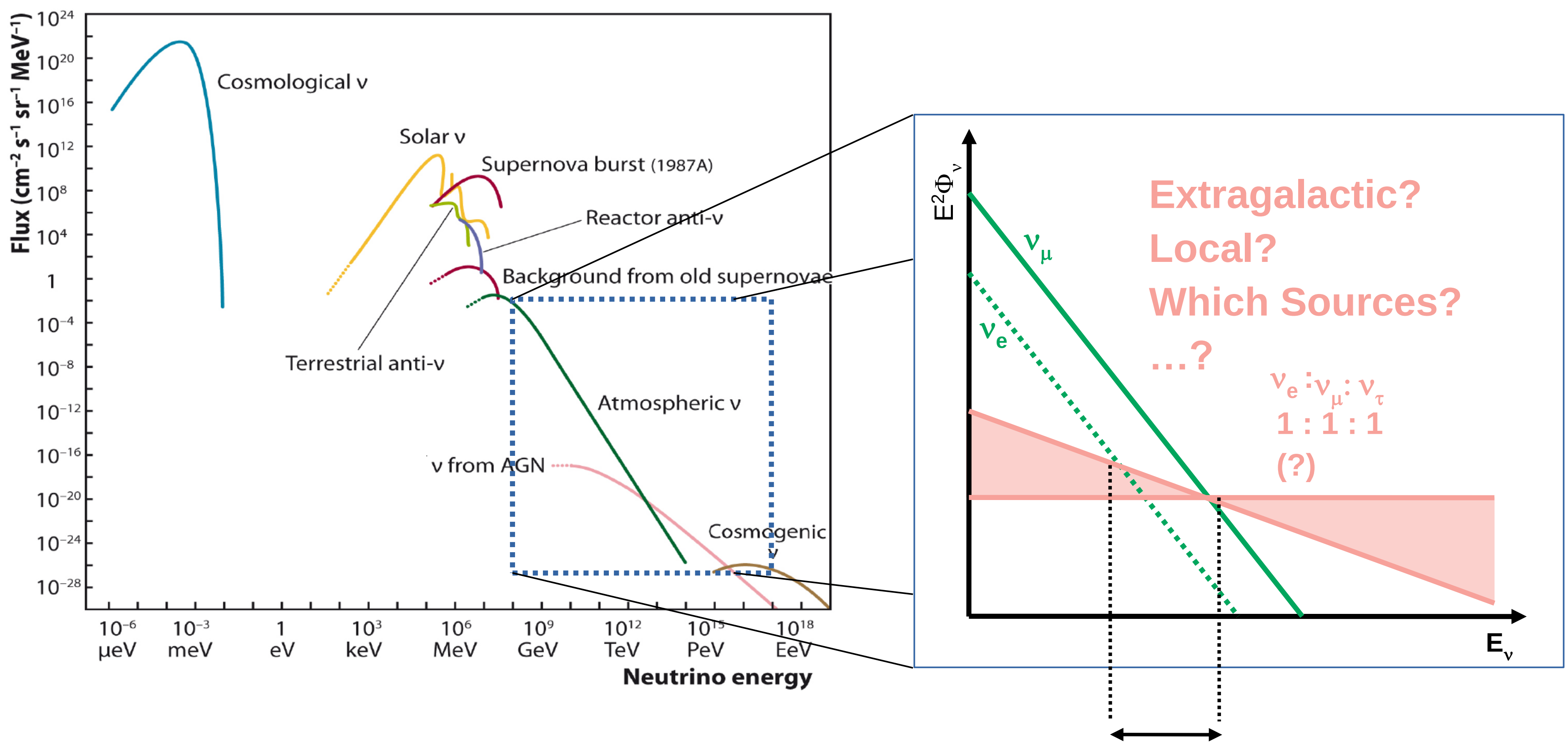
Time analysis & combining the IceCube - ANTARES events
1 EHE IC event during a source flare

Diffuse fluxes of neutrinos





Diffuse fluxes of neutrinos

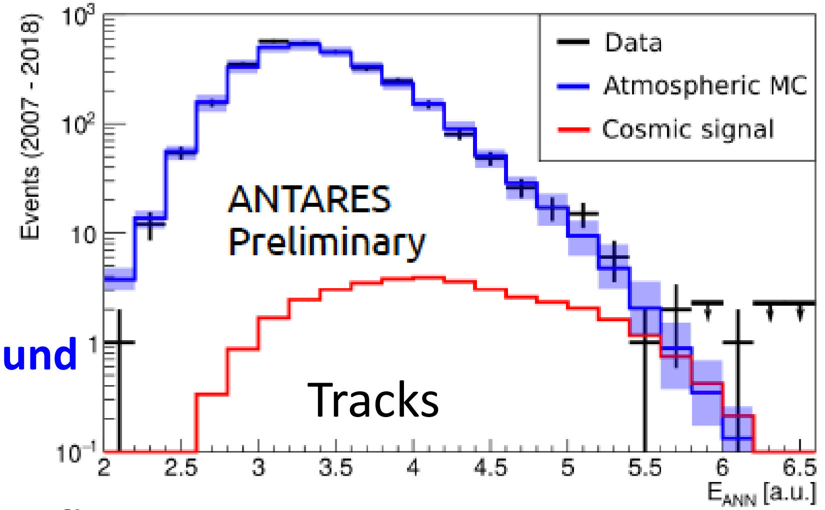


Atmos-to-Cosmic transition

30-200 TeV

Diffuse flux - ANTARES

Data sample: 2007 – 2018
Livetime: 3380 days
All-flavour events (track+showers)
Event selection chain + energy-related cut
- a high-purity neutrino sample
- maximise sensitivity

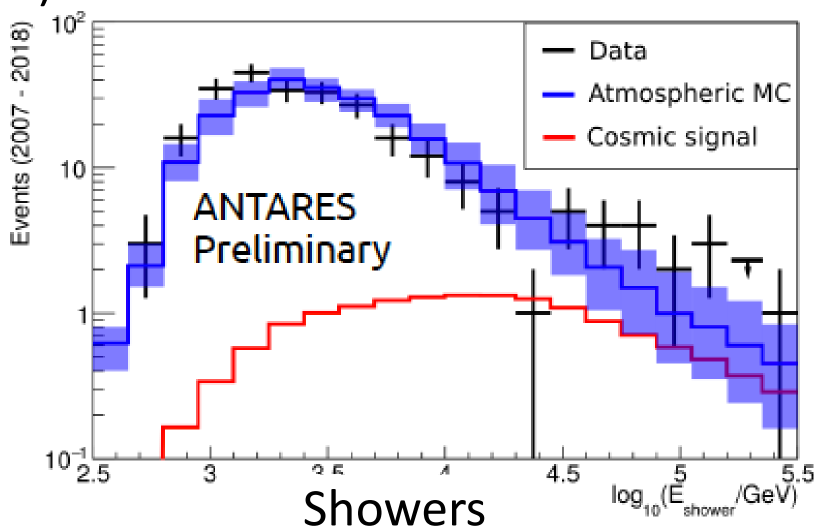


50 events found when 36.1 ±8.7 expected as background

1.8σ excess over the (Honda + Enberg) atmospheric flux increased with increased stat.(**ApJL 853 (2018) L7**)

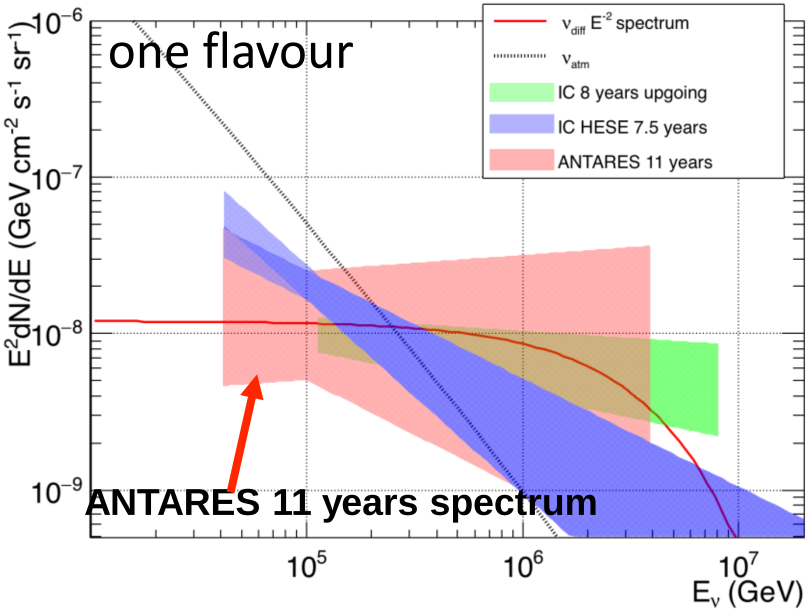
$\phi = 1.5 \pm 1\ 10^{-8}\ GeV^{-1} cm^{-2} sr^{-1} s^{-1}$
$\Gamma = 2.3 \pm 0.4$

Null-cosmic excluded at 90% c.l.

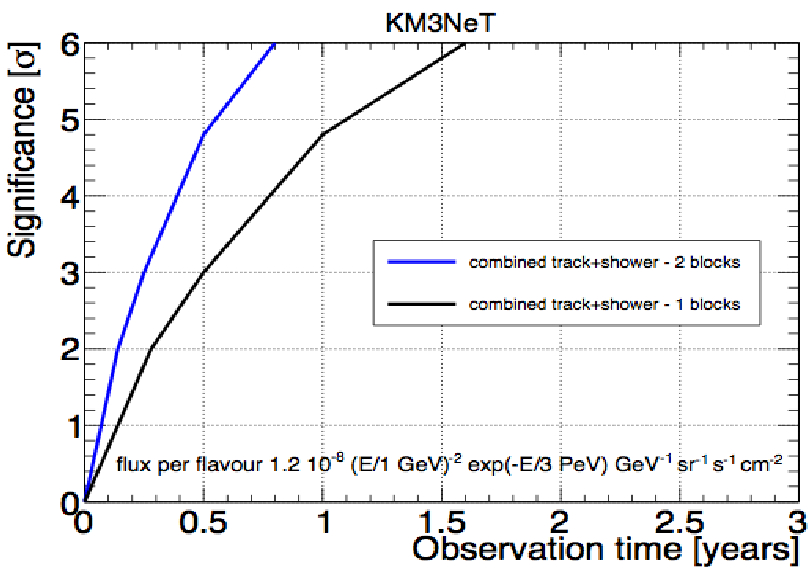


PoS(ICRC2019)891

Diffuse flux – KM3NeT



preliminary



5σ in ~ 0.5 year for the full detector (230 DUs)

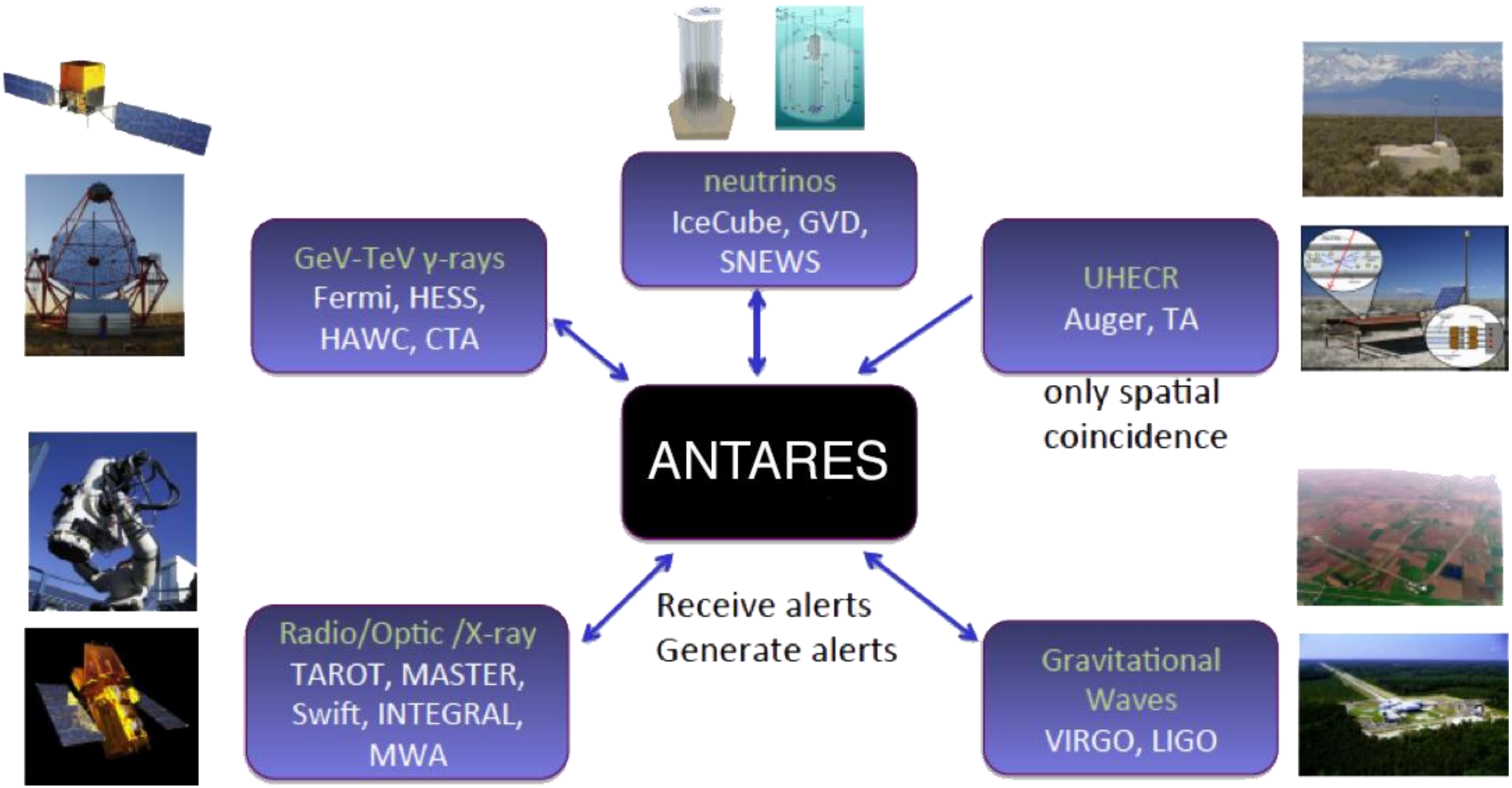
5σ ~ 1 year for one block detector (115 DUs)

Multimessenger with ANTARES

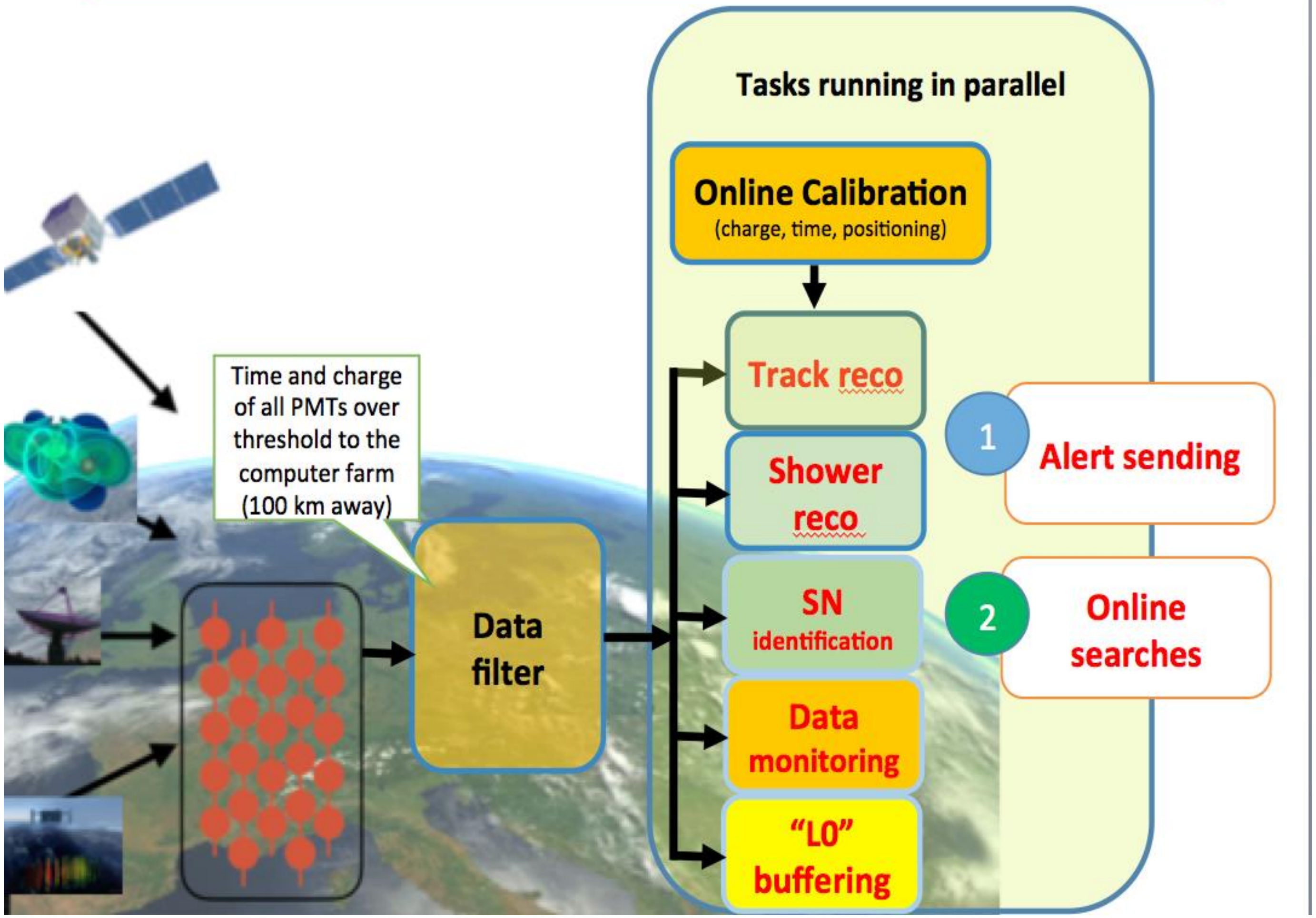
APP35 (2012)530
JCAP02(2016)062

PoS(ICRC2019)871 PoS(ICRC2019)872

Gamma-ray Coordinates Network (GCN) https://gcn.gsfc.nasa.gov/



Multimessenger with KM3NeT



on-line track reconstruction and trigger for Core Collapse Supernov already available

Open Public Alert Program is being implemented for both ORCA and ARCA detectors

Dark Matter

(Sun) Phys. Lett. B 759 (2016) 69-74
(GC) Phys. Lett. B 769 (2017) 249 (erratum PLB796(2019)253
(Earth) Physics of the Dark Universe 16 (2017) 41

WIMPs accumulate in massive celestial objects (Sun, Galactic Centre, …)

- Neutrinos could be produced in WIMP-WIMP annihilation
- Clean signal and low expected background

Ingredients used in the analysis:

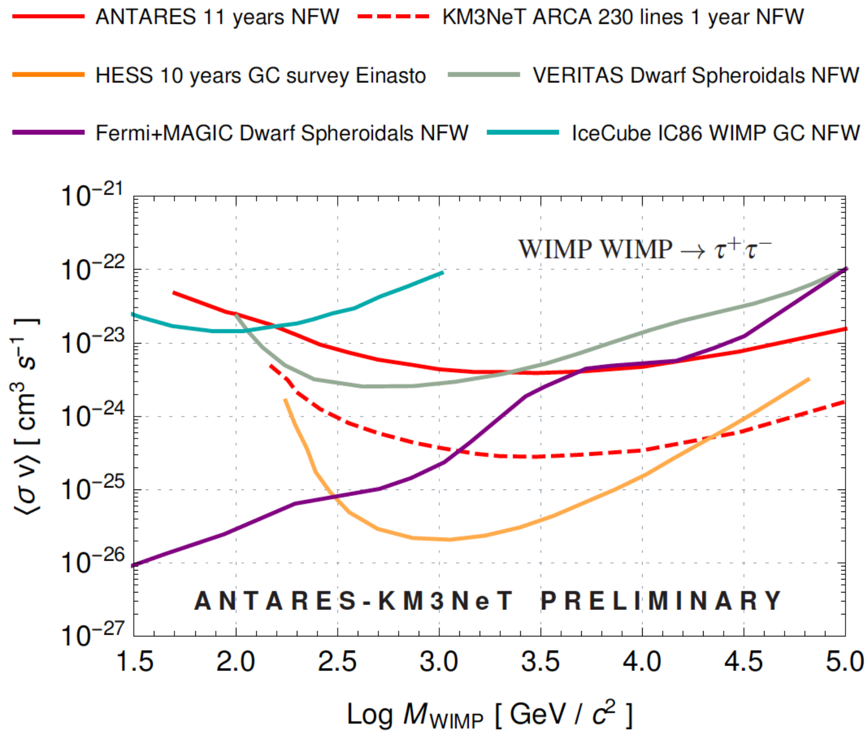
- Signal energy spectra for each considered WIMP mass and annihilation channel:

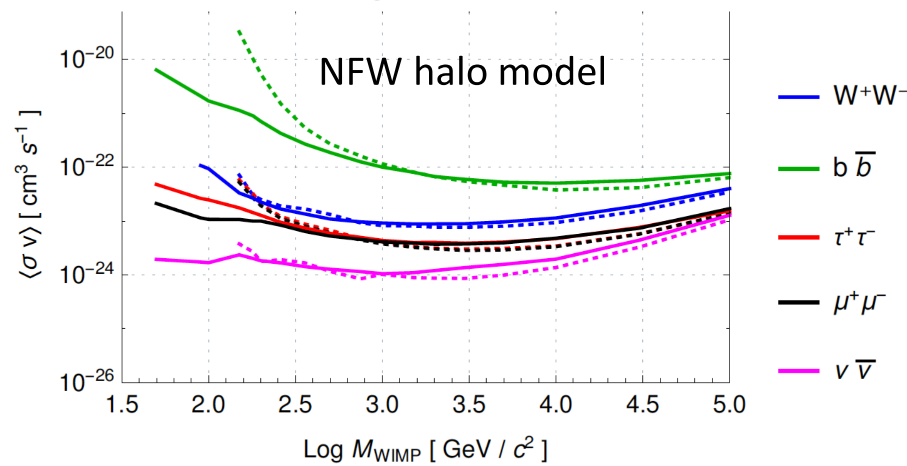
$WIMP + WIMP \rightarrow bbs, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}$

- Spatial distribution of dark matter in the source:
  - Point-like (Sun)
  - NFW, Burkert, McMillan halos (GC)

- **No excess** above background observed;
- Upper limits derived, as a function of the WIMP mass and annihilation channel on
  - spin-(in)dependent WIMP-nucleon scattering cross-section **(Sun)**
  - thermally averaged annihilation cross-section **(Galactic center)**

Dark Matter from the Galactic Center

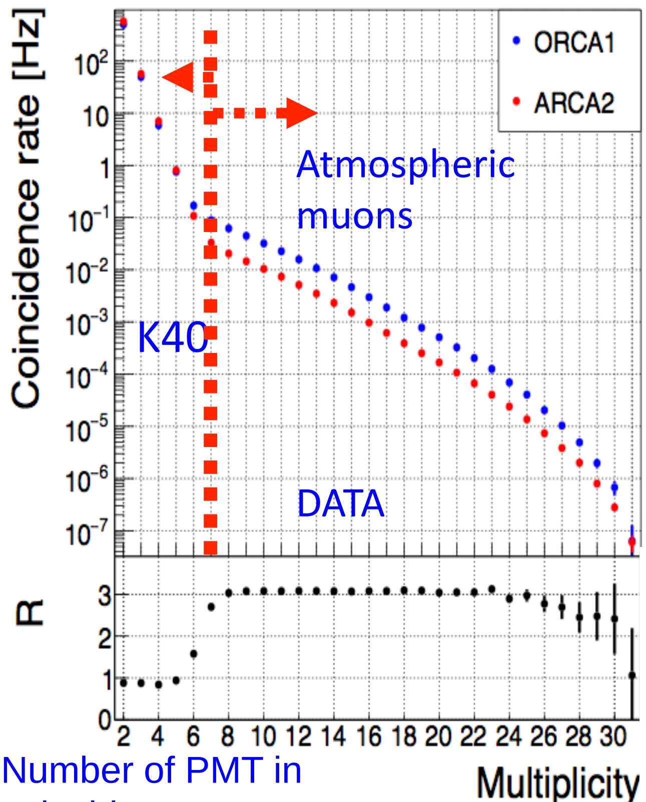




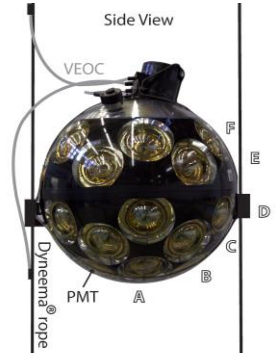
PoS(ICRC2019)536 PoS(ICRC2019)552

Core Collapse SuperNovae (CCSN)

Increase of the DOM rates due to many MeV neutrinos from the collapse



Number of PMT in coincidence



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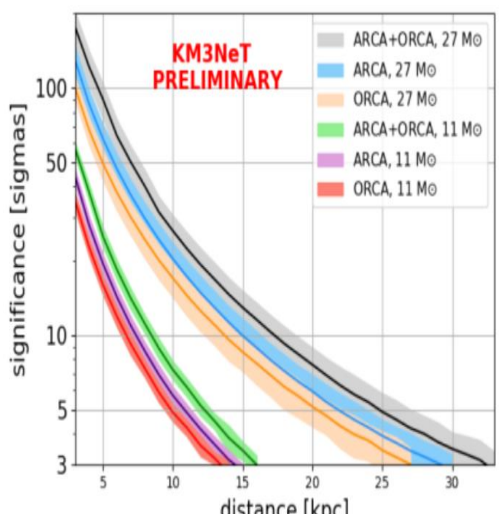
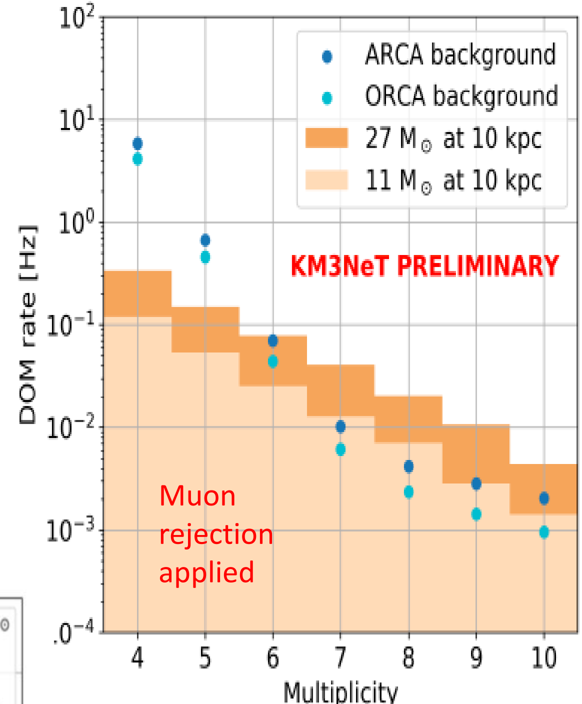
Each single DOM can act as a detector





ARCA 230 DU + ORCA 115 DU		
Threshold	11 M⊙	27 M⊙
1 / 14 days	12.5 kpc	23 kpc

>5σ for ARCA+ORCA for 27M⊙ at a distance <25kpc

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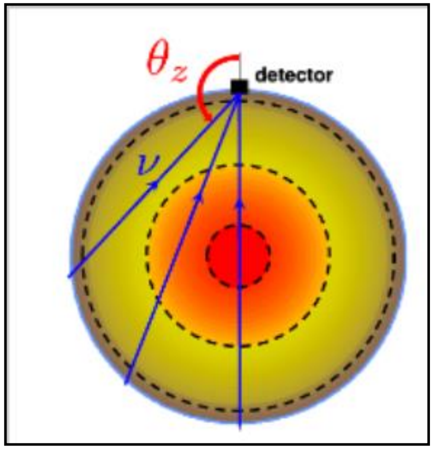
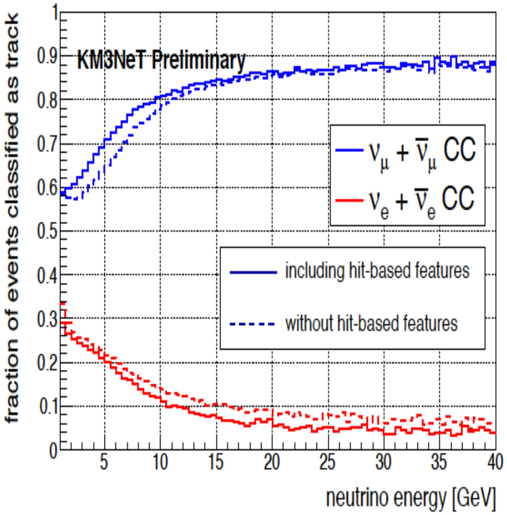
Neutrino oscillation studies with KM3NeT/ORCA

Baseline from 50 to 12800 km



track-cascade discrimination with Random Decision Forest



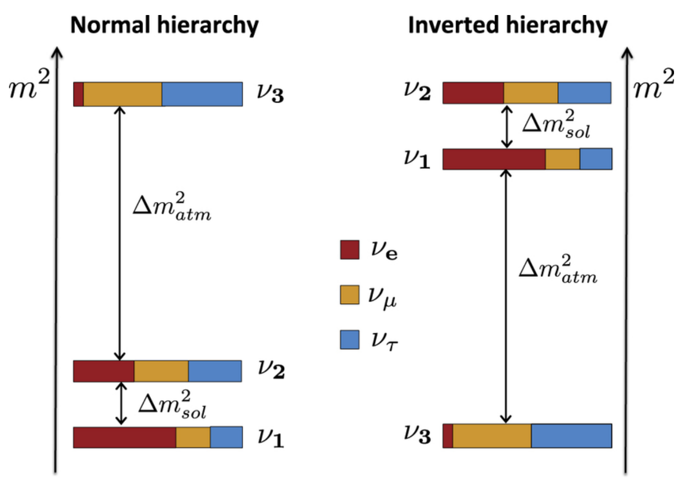
Energy resolution ~25% @ 10GeV
Zenith angular resolution ~ 5° @ 10GeV
Good track-cascade discrimination
(flavour determination)

<u>Search for deviations from the predictions for standard 3-flavour ν oscillations:</u>

- Neutrino Mass Ordering (NMO)
- Sterile Neutrinos
- Non Standard Interactions (NSI)

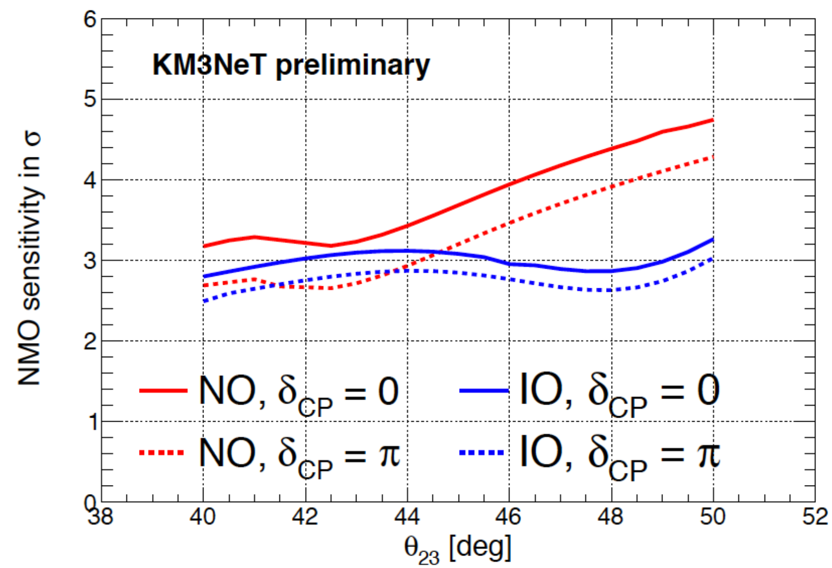
PoS(ICRC2019)931
PoS(ICRC2019)1019

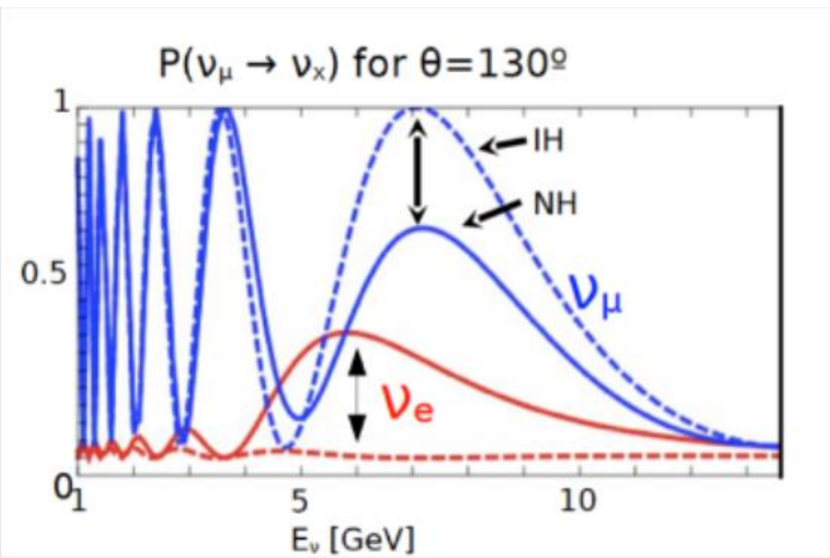
Neutrino oscillation studies with KM3NeT/ORCA



Systematics

- Neutrino oscillation parameters
- Atmospheric neutrino flux parameters



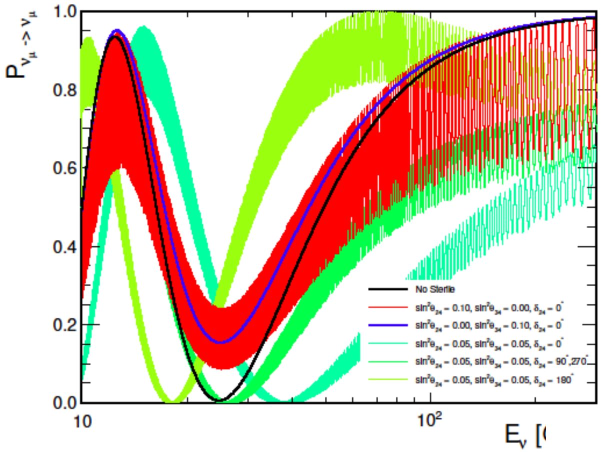


$\gtrsim 3\sigma$ in 3 years

$> 4\sigma$ in 3 years for NO and large θ_{23}

Sensitivity to sterile neutrinos

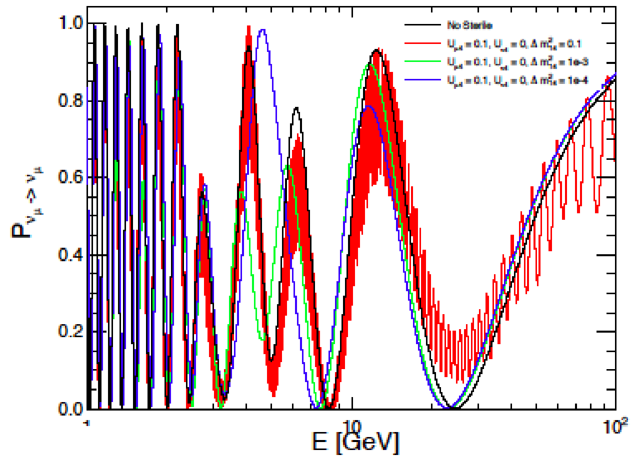
ANTARES

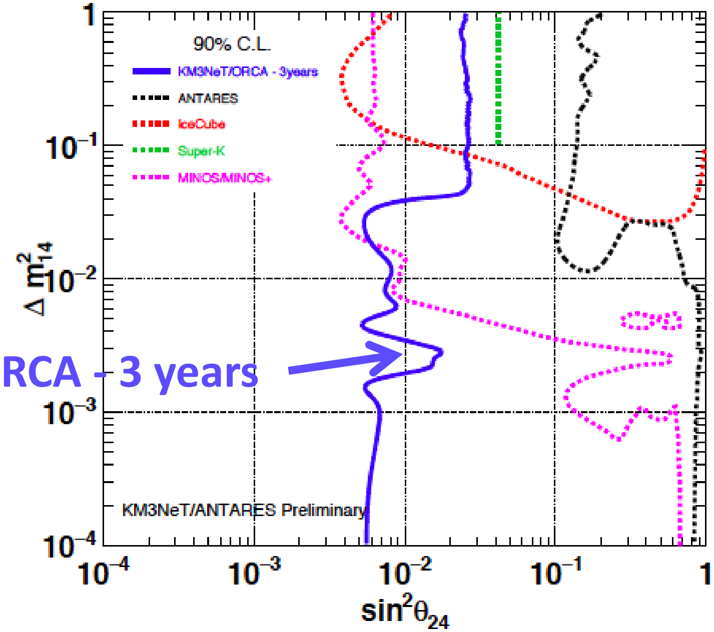


J. High Energ. Phys. 06 (2019) 113

- distortion in the ν oscillation pattern
- Honda model (2014 @ Gran Sasso site)
- PREM for the Earth interior

KM3NeT/ORCA



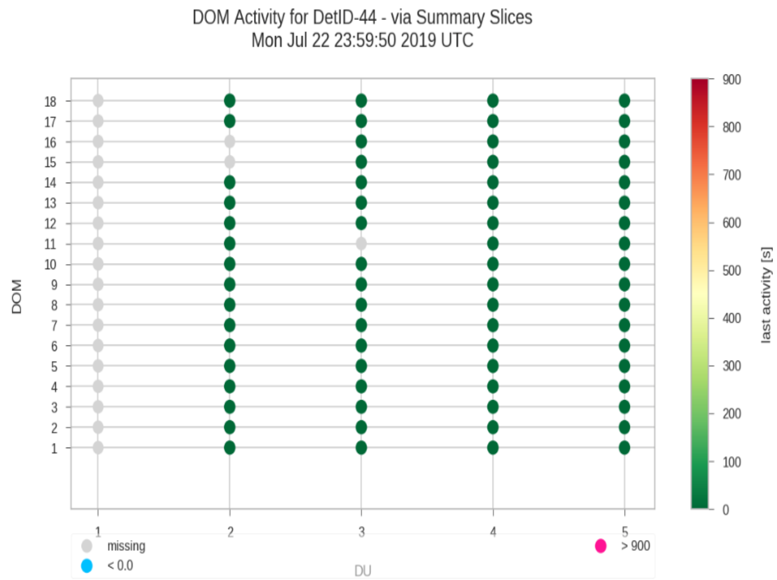


ORCA: competitive sensitivity to constrain low sterile masses

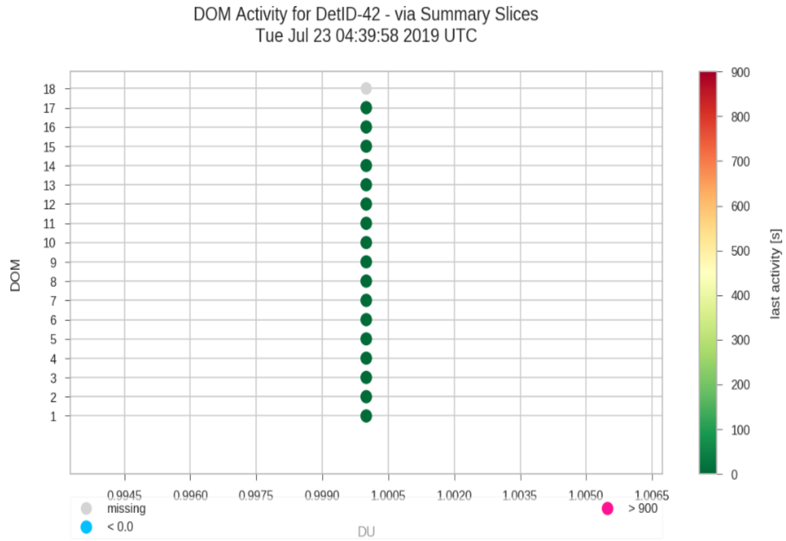
PoS(ICRC2019)870

KM3NeT status

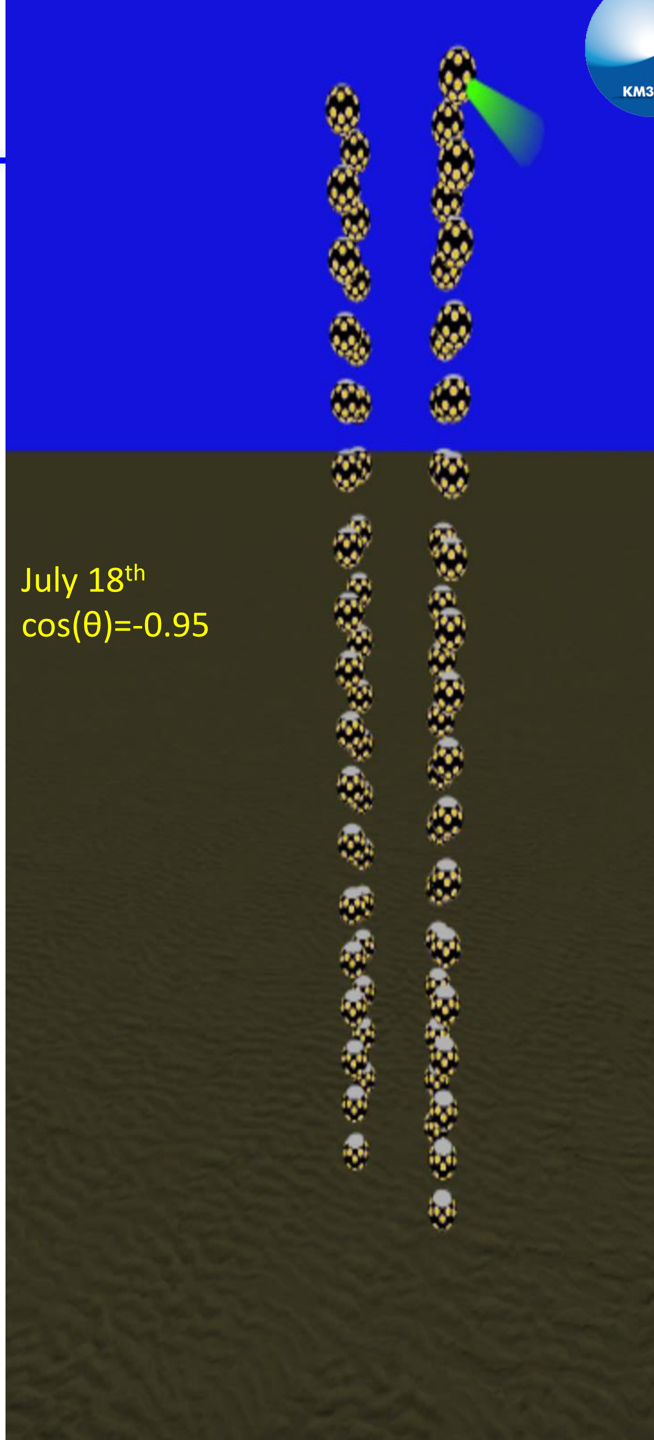
DUs in data taking
TODAY



4 DUs
@ORCA site



1 DU
@ARCA site

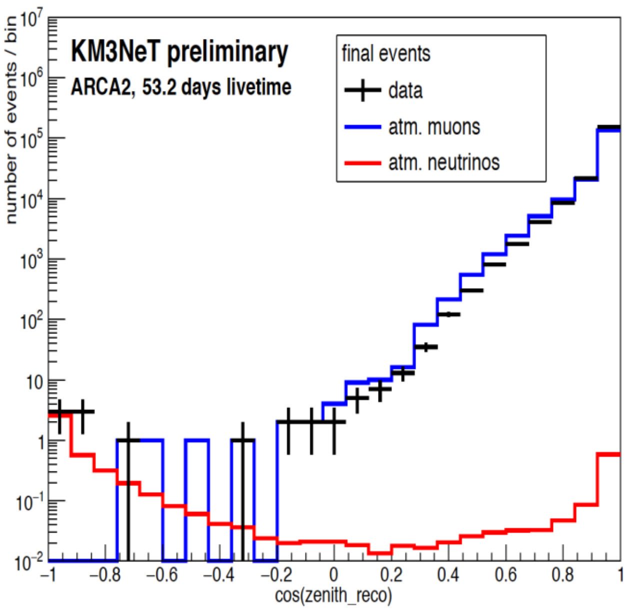


KM3NeT detectors – first results

Up-going atmospheric neutrino selection

ARCA2 = 2 DUs @ ARCA SITE
Dec 23rd 2016 - Mar 2nd 2017

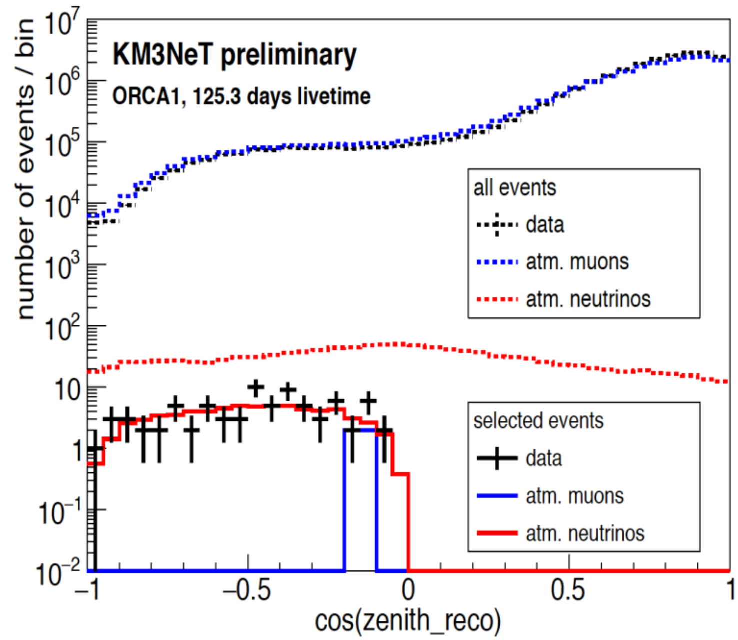
E_{th} ~100 GeV
trigger rate μ_{atm} ~0.2 Hz ; ν_{atm} ~1/day



DATA: ~6 neutrinos cos(θ_{rec})<-0.8
MC: μ_{atm} 0 + ν_{atm} 3.3

ORCA1 = 1 DU @ ORCA SITE
Sep 28th 2017 – Dec 13th 2017
Mar 13th 2019 – May 15th 2019

E_{th} ~ few GeV
trigger rate μ_{atm} ~2 Hz ; ν_{atm} ~10/day



DATA: ~77 neutrinos cos(θ_{rec})< 0
MC: μ_{atm} 4 + ν_{atm} 67.5

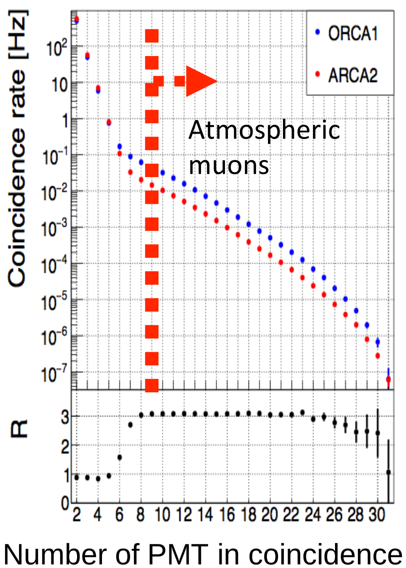
PoS(ICRC2019)910

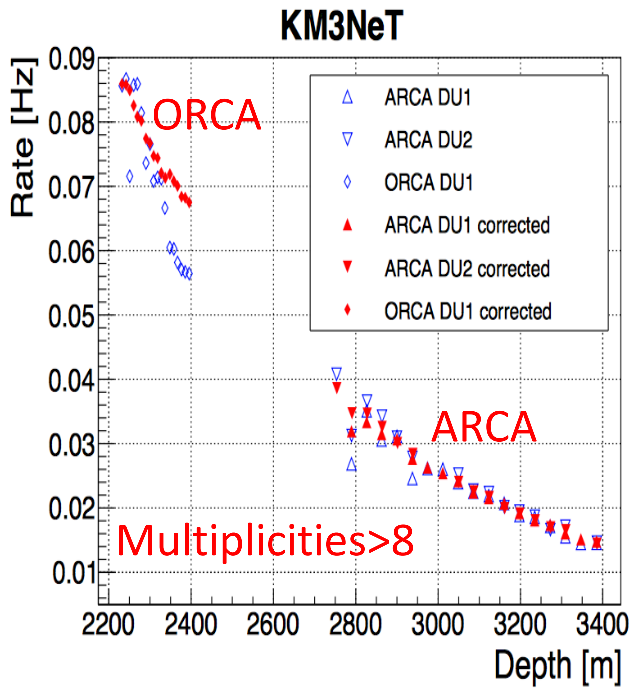
Good Data-MC agreement
Detecting neutrinos with 1-2 DUs

KM3NeT detectors – first results

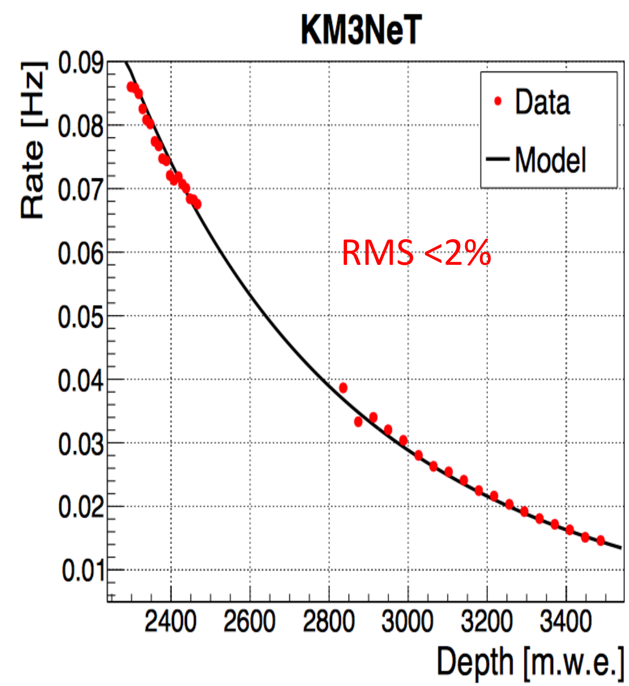
Data collected with 2 DUs of ARCA (Dec 23rd 2016 - Mar 2nd 2017) and 1 DU of ORCA (Nov 9th 2017 – Dec 13th 2017)

Paper in preparation
https://arxiv.org/pdf/1906.02704.pdf





Measured rate as proxy of the muon flux
Compared a muon depth dependence model
(Bugaev et al, Phys. Rev. D 58 1998 054001)



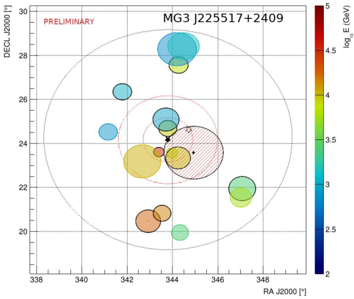
PMT detection efficiency evaluated with K^{40} (run-by-run)

PoS(ICRC2019)943

Calibration procedure and PMT detection efficiency tested

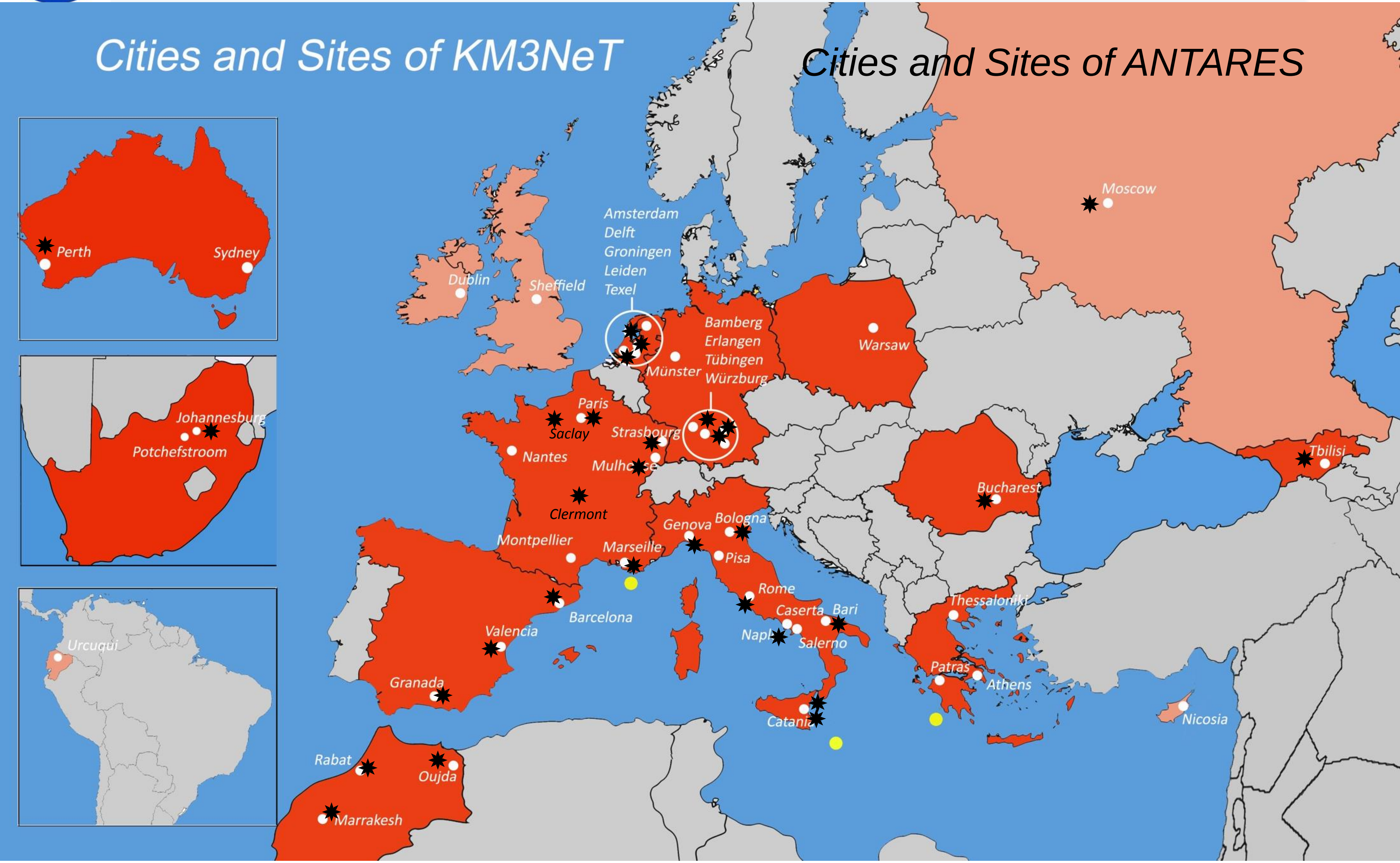
Conclusions

- Mediterranean Sea is an excellent location to look at the Southern sky
- Water properties allow for good angular resolution
- Technological challenges have been successfully overcome
- ANTARES paved the way to Mediterranean neutrino telescopes
- Promising results:
  - Mild excess of a neutrino diffuse flux (~1.8 σ)
  - Interesting region identified (α=343.78° δ=+24.19°) in coincidence with the Blazar MG3J225517+2409



- KM3NeT Collaboration constantly growing, several extra–Europe Institutes (Australia, Morocco, South Africa, Georgia…)
- 5 DUs in data taking
- Analysis of data :
  - Calibration procedure tested
  - Reliable MC simulations
  - SuperNovae alert system already active

Mediterranean collaborations: ANTARES & KM3NeT



Backup slides

How does a { telescope work?