Mediterranean Neutrino Telescopes: ANTARES & KM3NeT

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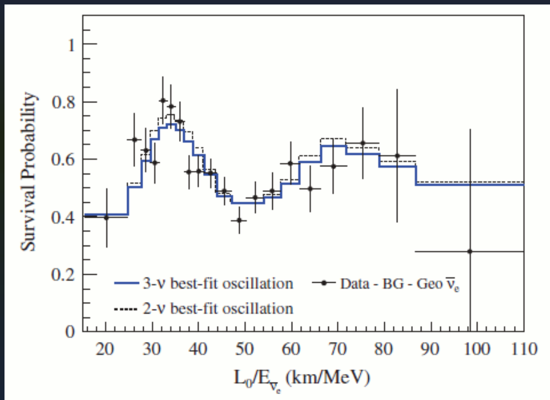
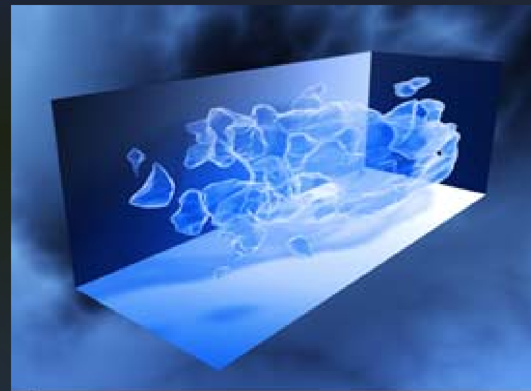
INFN –GENOVA

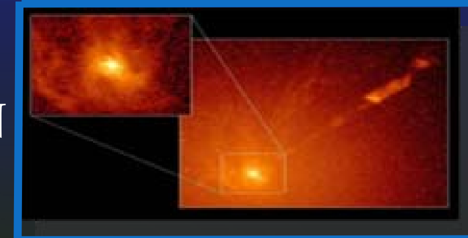
- Scientific motivations & Detection principles
- Today’s context & IceCube discovery
- Status of ANTARES
- New generation detector : KM3NeT
  - /ARCA: High Energy neutrino astrophysics
  - /ORCA The Low-Energy Physics Case

The Physics case



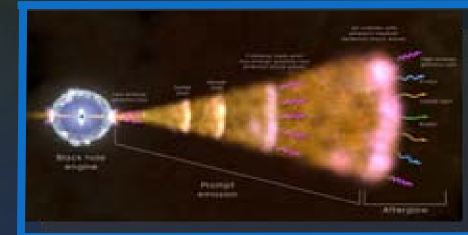


AGN



micro-
quasar

GRB



Low Energy
E_ν~ 5-100 GeV

Medium Energy
E_ν~ 10GeV-1 TeV

High Energy
$E_\nu \geq$TeV

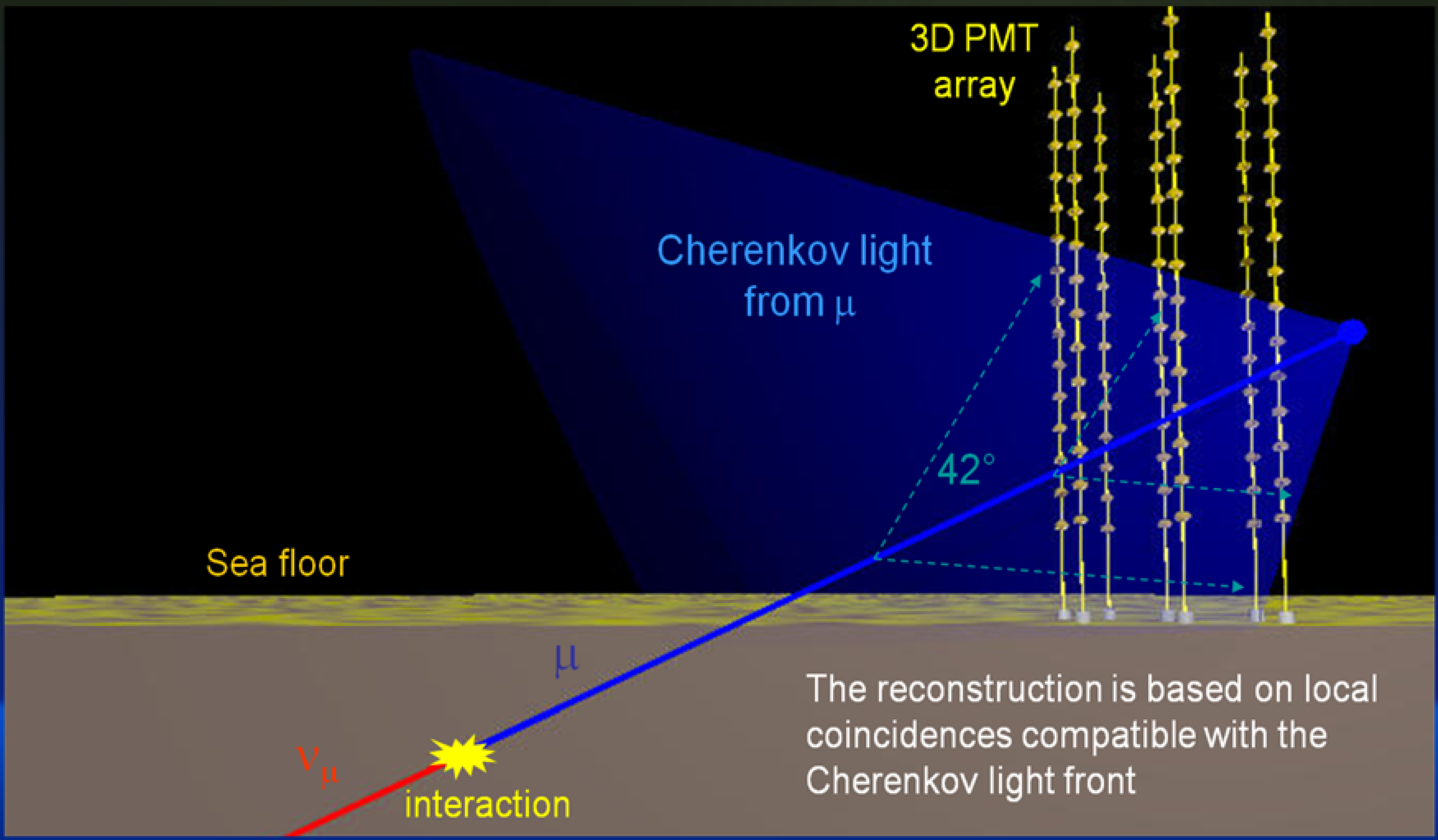
ν-oscillations
Mass hierarchy

Dark-matter search

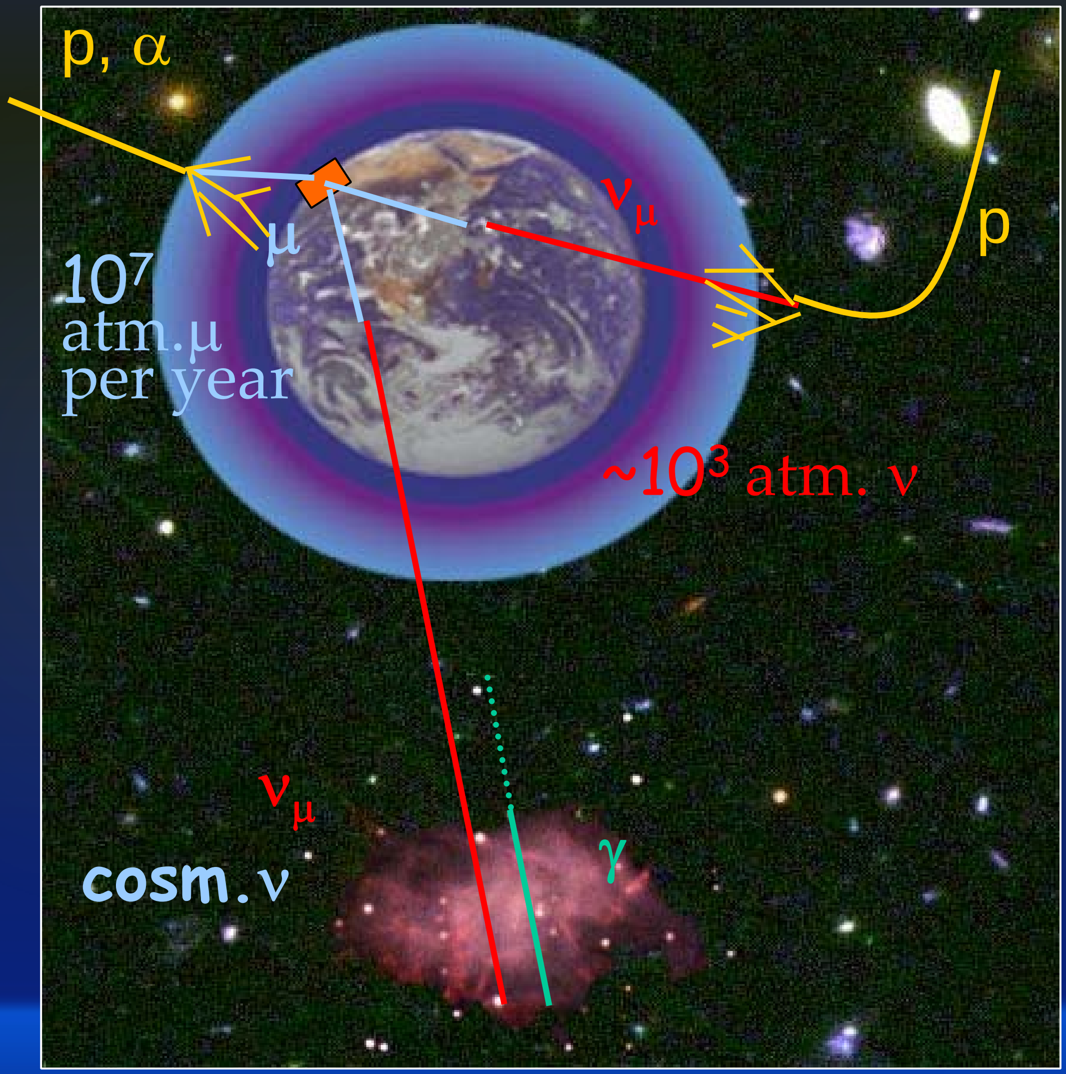
ν from extra-terrestial sources.
Origin and production of HE Cosmic Rays

Detection Principle

Neutrinos (E ≥ 10 GeV)can be detected using the visible Cherenkov radiation produced as the high-energy charged leptons (final state of CC interactions) propagate through a transparent medium with superluminal velocity.

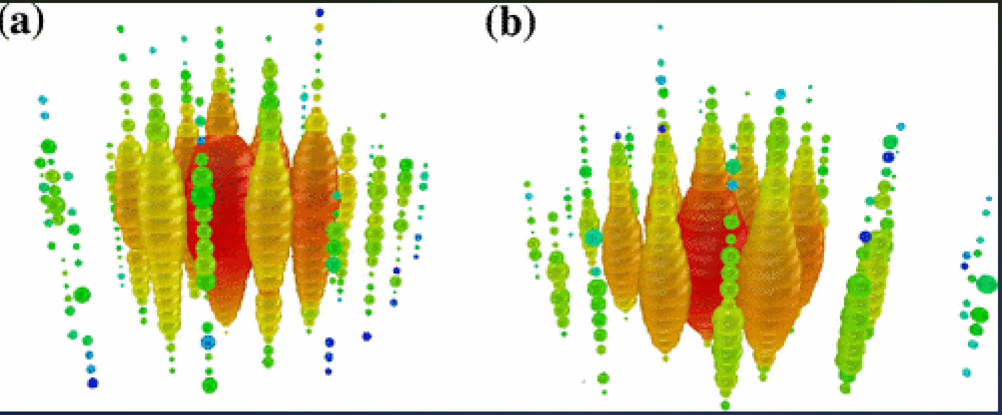


Signal to noise



Neutrino Telescopes

IceCube Discovery of HE neutrinos



2013

Two interesting cascade events found in IC79/IC86:
analysis targeting GZK neutrinos (~EeV)
significance 2.8σ (expected 0.08±0.05)
Phys. Rev. Lett. 111, 021103 (2013

2 year analysis:
28 events
4.1σ
(Science 342, 2013)

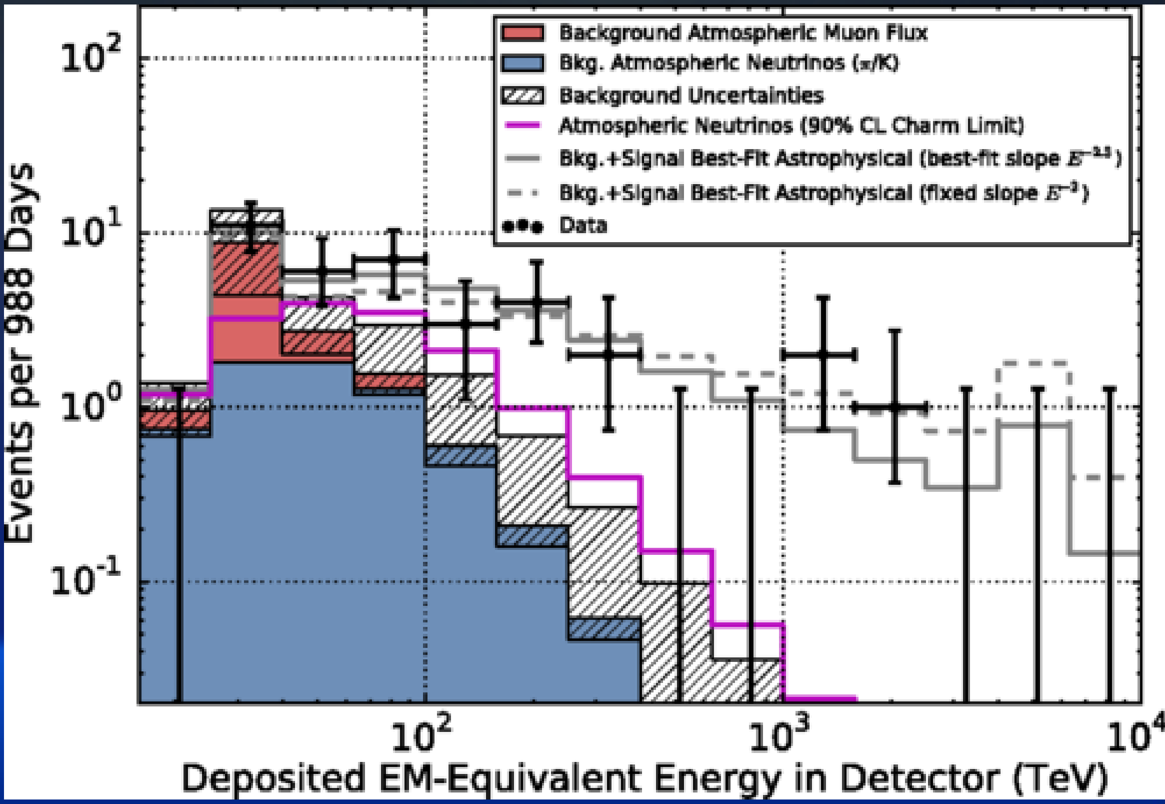
3 year analysis:
37 events
5.7σ
(PRL, 113, 101101, 2014)

the IceCube signal

3-years analysis

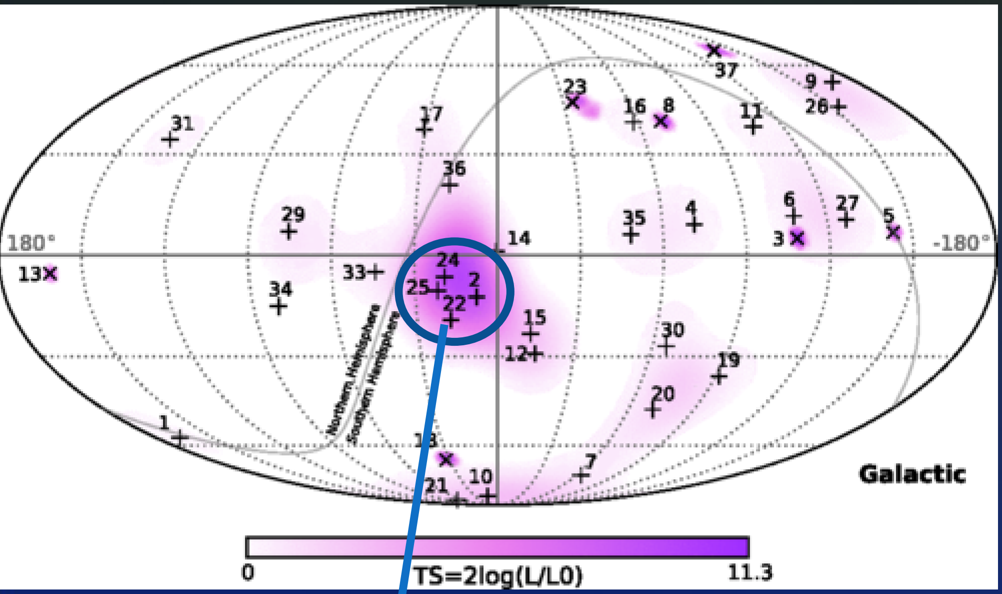
9 track-like events
•1° angular resolution
•muon takes some energy away

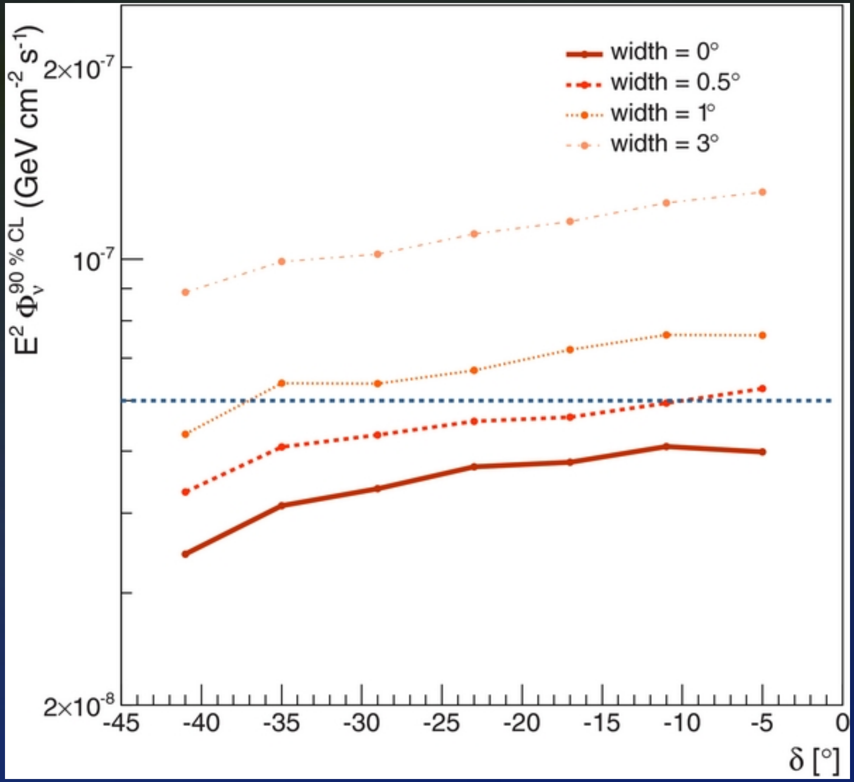
21 cascade-like events
•10° - 45° angular resolution
•highest energy event @ 2 PeV
•cutoff at ~2.3 PeV ?
•Now 4 years of data (6.5 σ)
•Best fit spectral index 2.58



A source near the Galactic Center?

Hypothesized Galactic Source ?
! *Gonzalez-Garcia et al, APP 57 (2014)*
Point Source at (α,δ)=(−79°, −23°):
Φ = 6 x 10-8 E-2 GeV cm-2 s-1

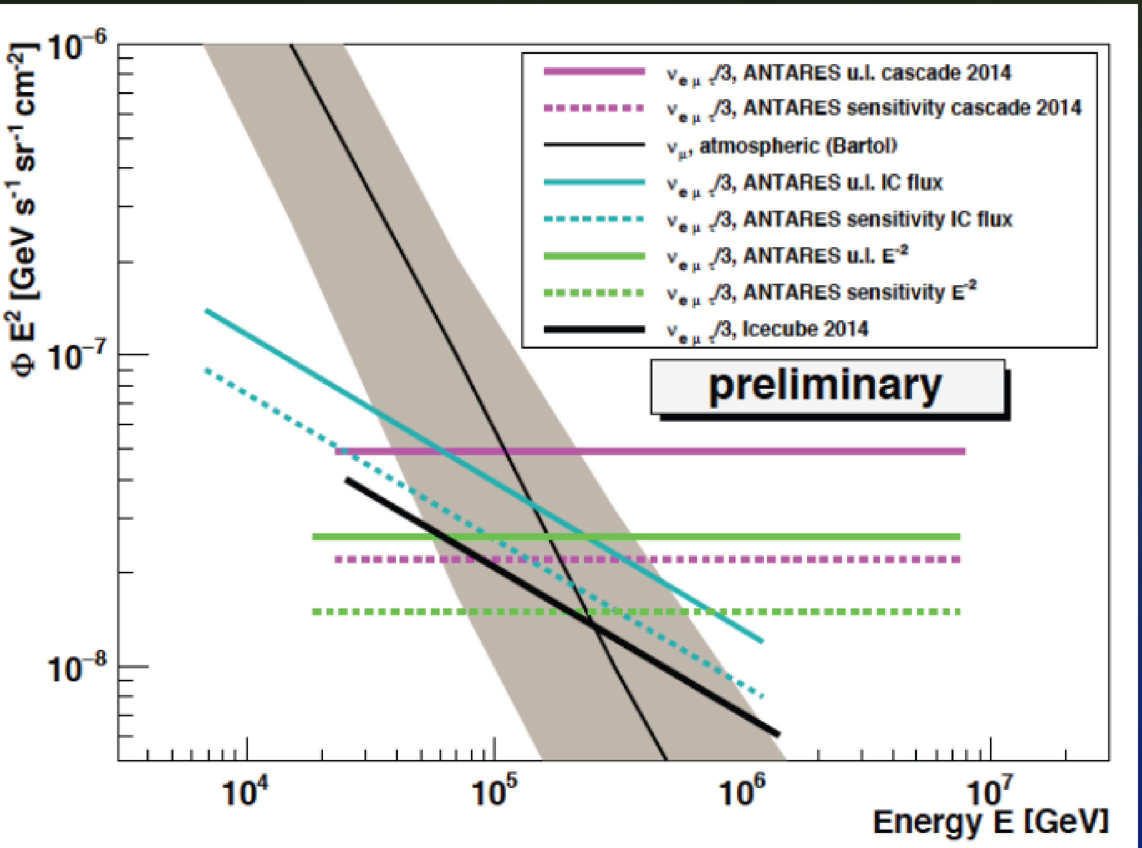




ANTARES excludes single point source (E-2 spectrum) as origin of the cluster within 20° off GC
Astrophys. J. Lett. 786:L5 (2014)

ANTARES 90% CL upper limits obtained for different source widths as a function of the declination.

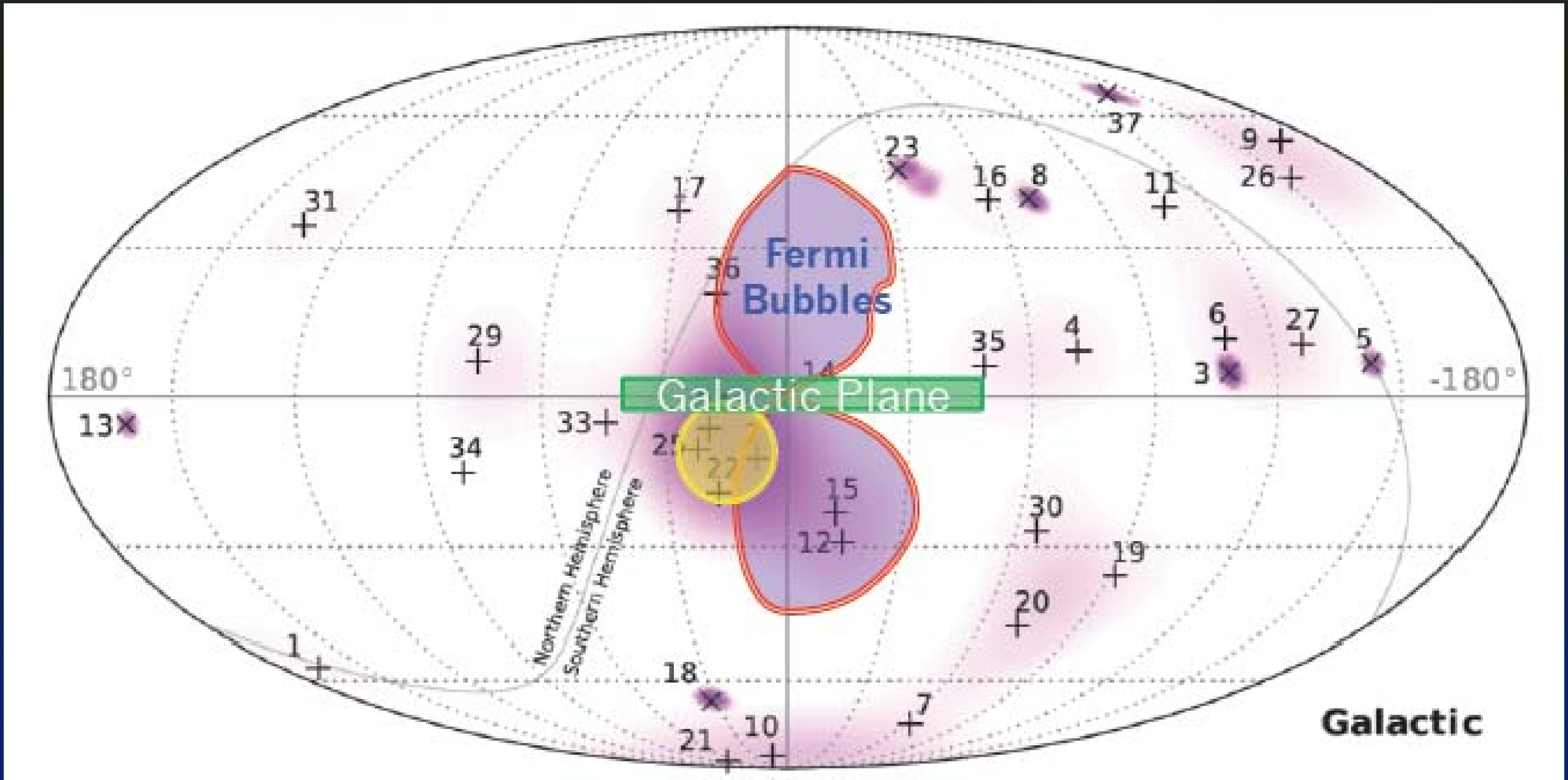
ANTARES Diffuse Neutrino Searches



Data sample 2007 – 2013, strong quality cuts (data/MC agreement): 913 days effective lifetime (= about half available sample)

- Expected:
  - 9.5 ± 2.5 bkgd
  - 5.0 ± 1.1 IC flux
- Observed:
  - 12 events
  - 1.75σ excess
- Results:
  - Consistent with bkgd
  - Consistent with IC

Reducing the search window

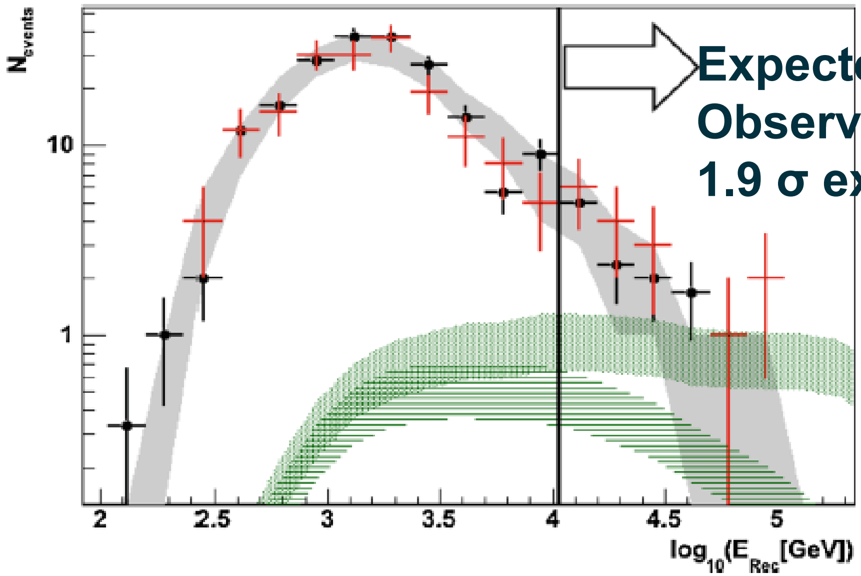


- Fermi-Bubble region.
- Galactic Center region.
- IC hot spot.

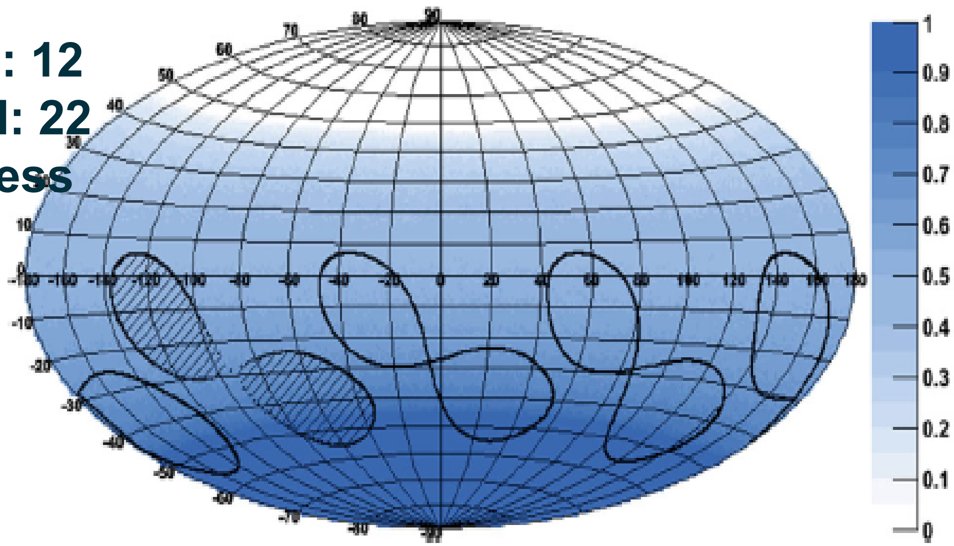
Muons only !

Fermi Bubbles

- Two gigantic structures centered around the galactic centre
- Discovered in 2013 by FERMI in the GeV gamma ray spectrum
- Analysis performed in the neutrino channel with the 2008-2012 ANTARES data
- PHD thesis by Vladimir Kulikovskiy (INFN-Genova and Moscow State Univ.)
- Eur. Phys. J. C (2014) 74:2701

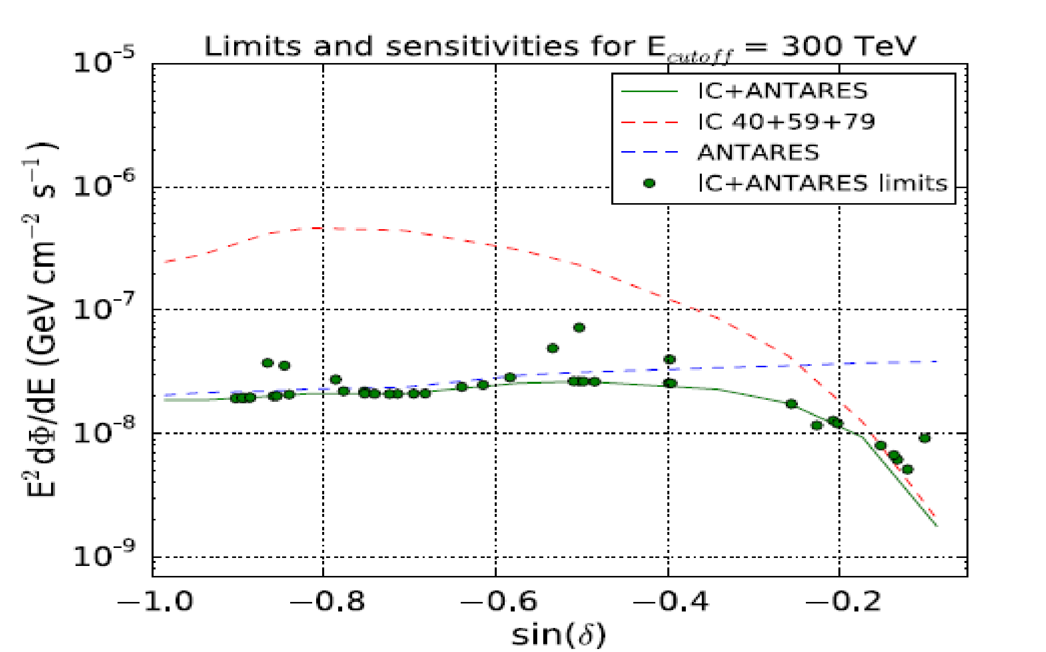


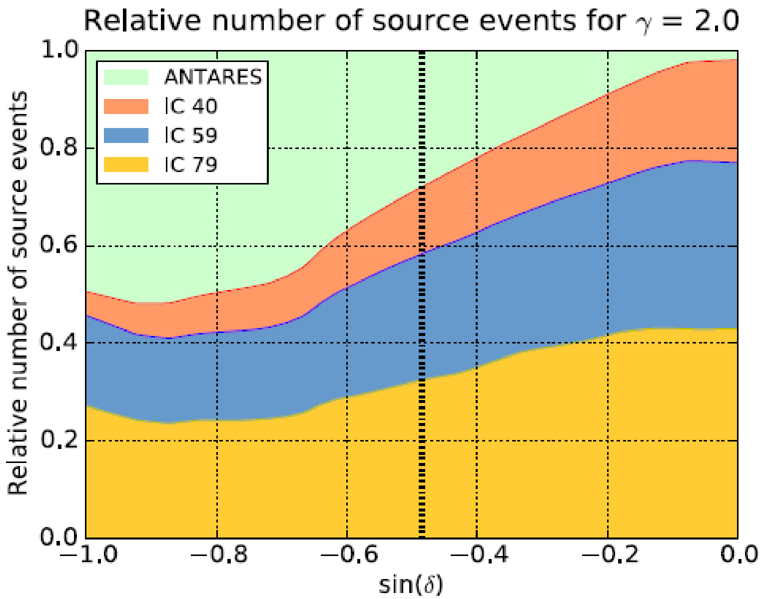
Expected: 12
Observed: 22
1.9 σ excess

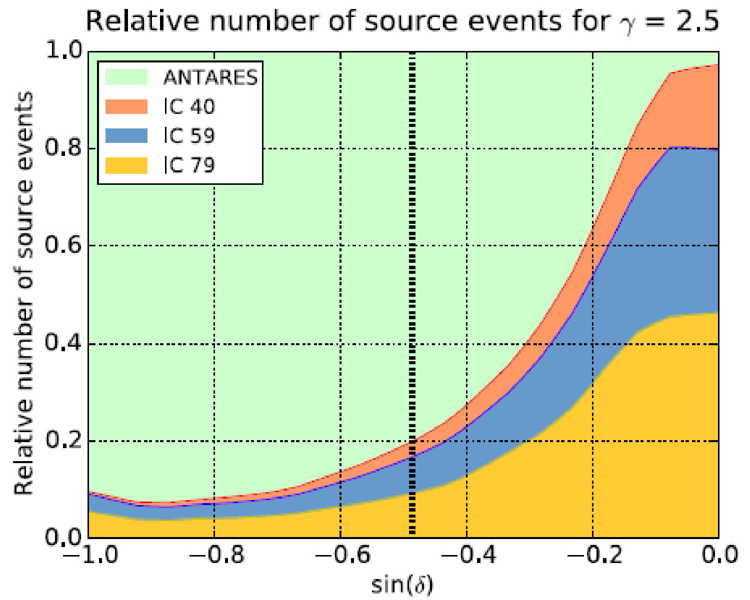


Joint ANTARES-IceCube search

First combined search for point-sources over the Southern Sky using the ANTARES and IceCube neutrino telescopes
The Astrophysical Journal, 823:65 (12pp), 2016 May 20



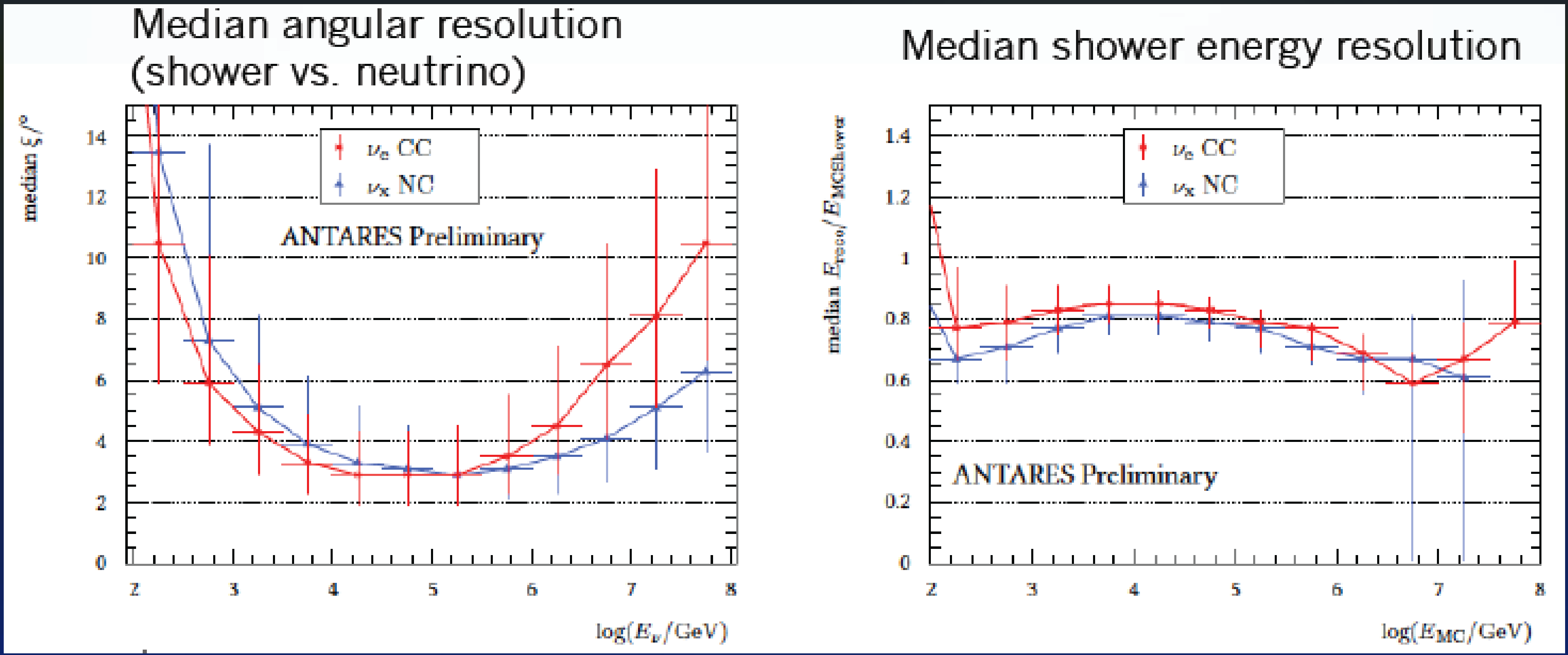




Fraction of signal events detected by each sample (E-γ)

ANTARES 2007–2012 data

ANTARES can add the cascades

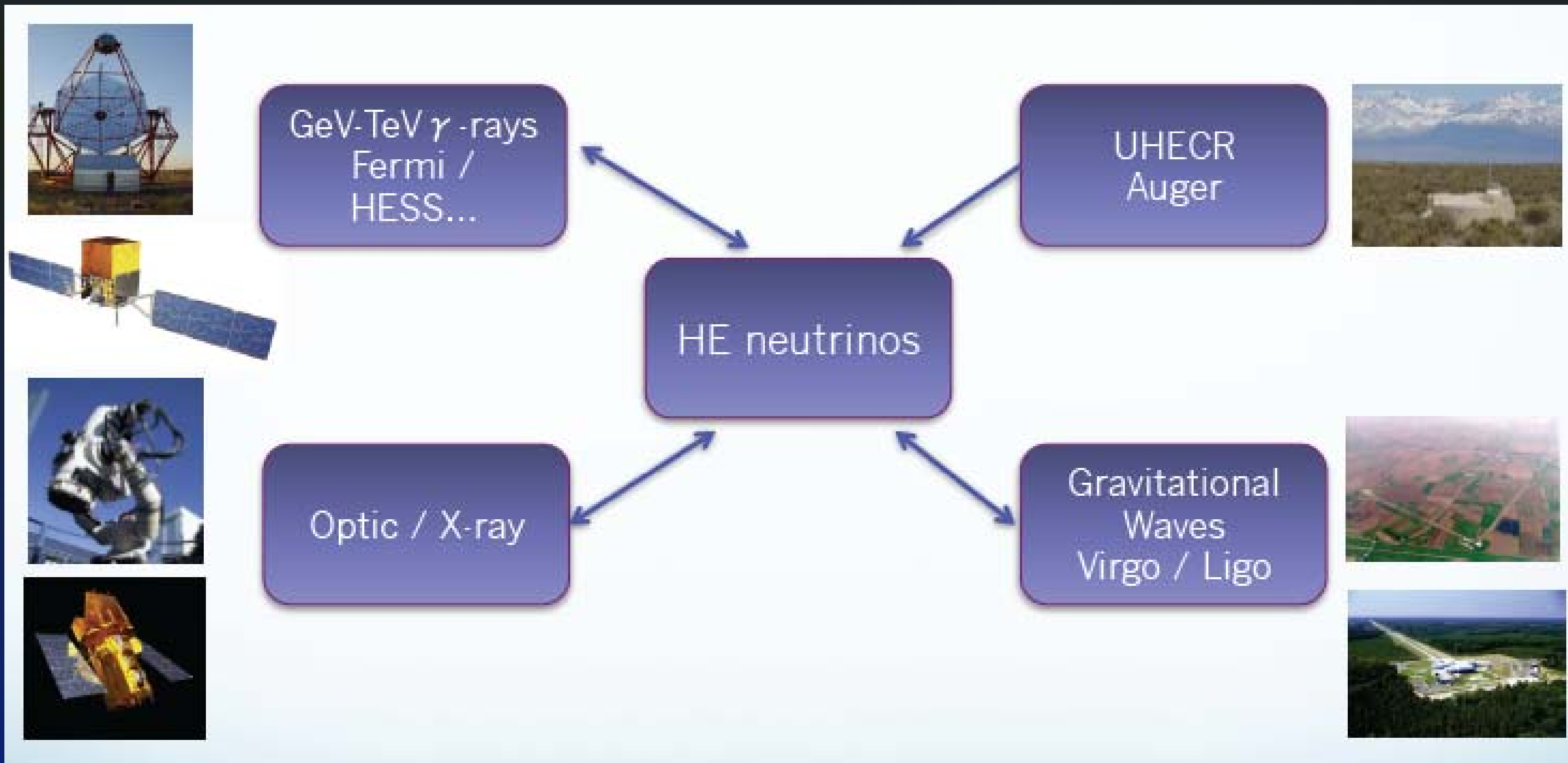


Too few photons,
too sparse detector

PMT saturation,
limited size of the
detector

~5% resolution
~20% systematic underestimation
bias corrected a posteriori

The Multi-messenger Program



- A way to better understand the sources and the related physics mechanisms
- A way to increase the detector sensitivities (uncorrelated backgrounds)

GW150914 follow-up

File Modifica Visualizza Cronologia Segnalibri Strumenti Aiuto

Detection Papers | LIGO La...

https://www.ligo.caltech.edu/page/detection-companion-papers

ligo companion papers

LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
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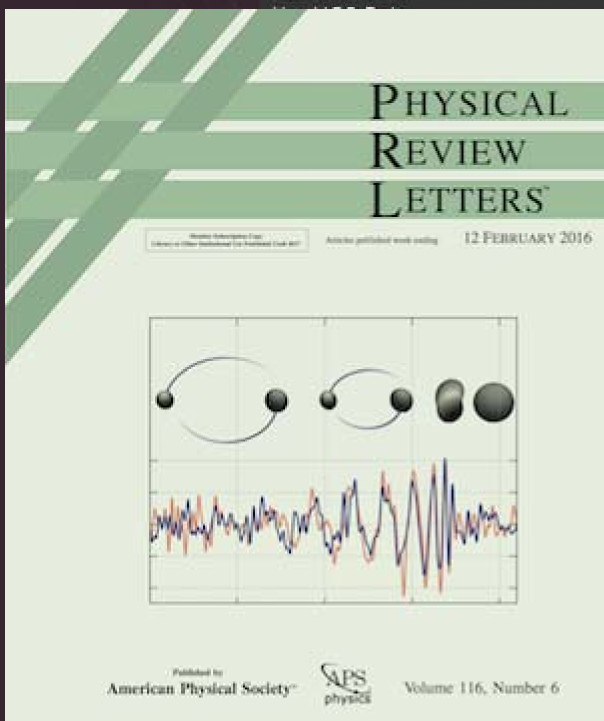


Detection Papers

First Detection 'Discovery Paper'

"Observation of Gravitational Waves from a Binary Black Hole Merger"
Published in *PRL* **116**, 061102 (2016).

Related papers

"Observing gravitational-wave transient GW150914 with minimal assumptions"

"GW150914: First results from the search for binary black hole coalescence with Advanced LIGO"

"Properties of the binary black hole merger GW150914"

"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"

"Astrophysical Implications of the Binary Black-Hole Merger GW150914" - published in *Astrophys. J. Lett.* 818, L22 (2016)

"Tests of general relativity with GW150914"

"GW150914: Implications for the stochastic gravitational-wave background from binary black holes" - published in *Phys. Rev. Lett.* 116, 131102 (2016)

"Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914"

"Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914"

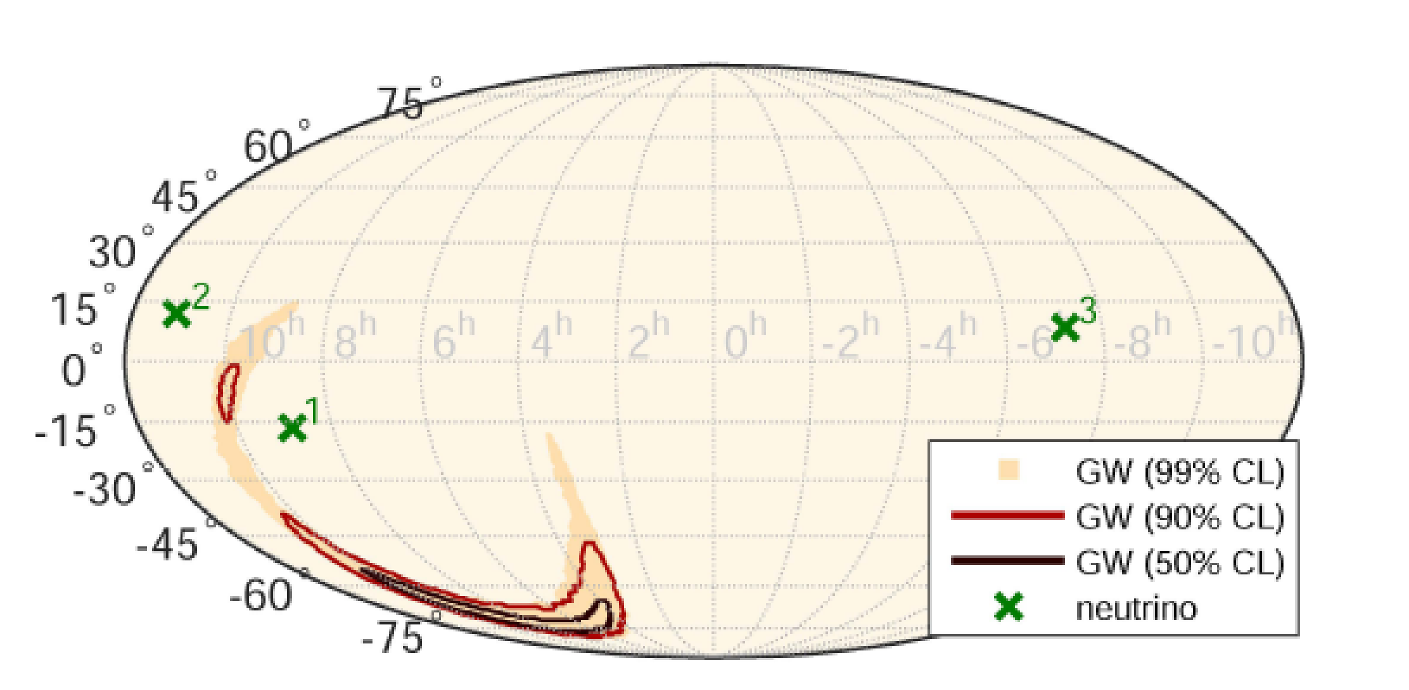
"High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES"

"GW150914: The Advanced LIGO Detectors in the Era of First Discoveries" - published in *Phys, Rev. Lett.* 116, 131103 (2016)

"Localization and broadband follow-up of the gravitational-wave transient GW150914"

https://www.ligo.caltech.edu/page/collaborate

GW150914 follow-up

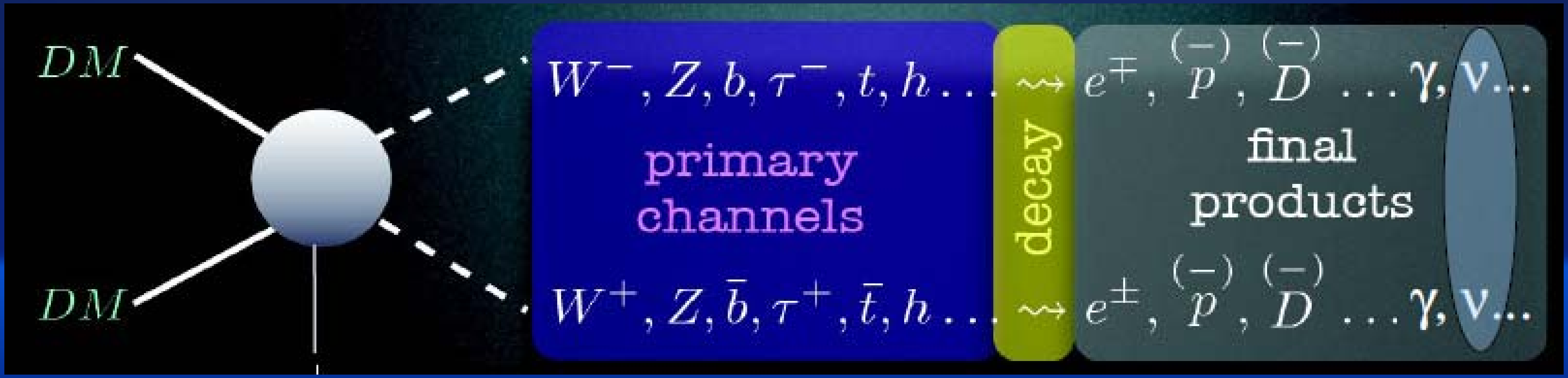


GW skymap in equatorial coordinates, showing the reconstructed probability density contours and the directions of high-energy neutrino candidates detected by Ice-Cube (crosses) during a ±500 s time window around the GW event.

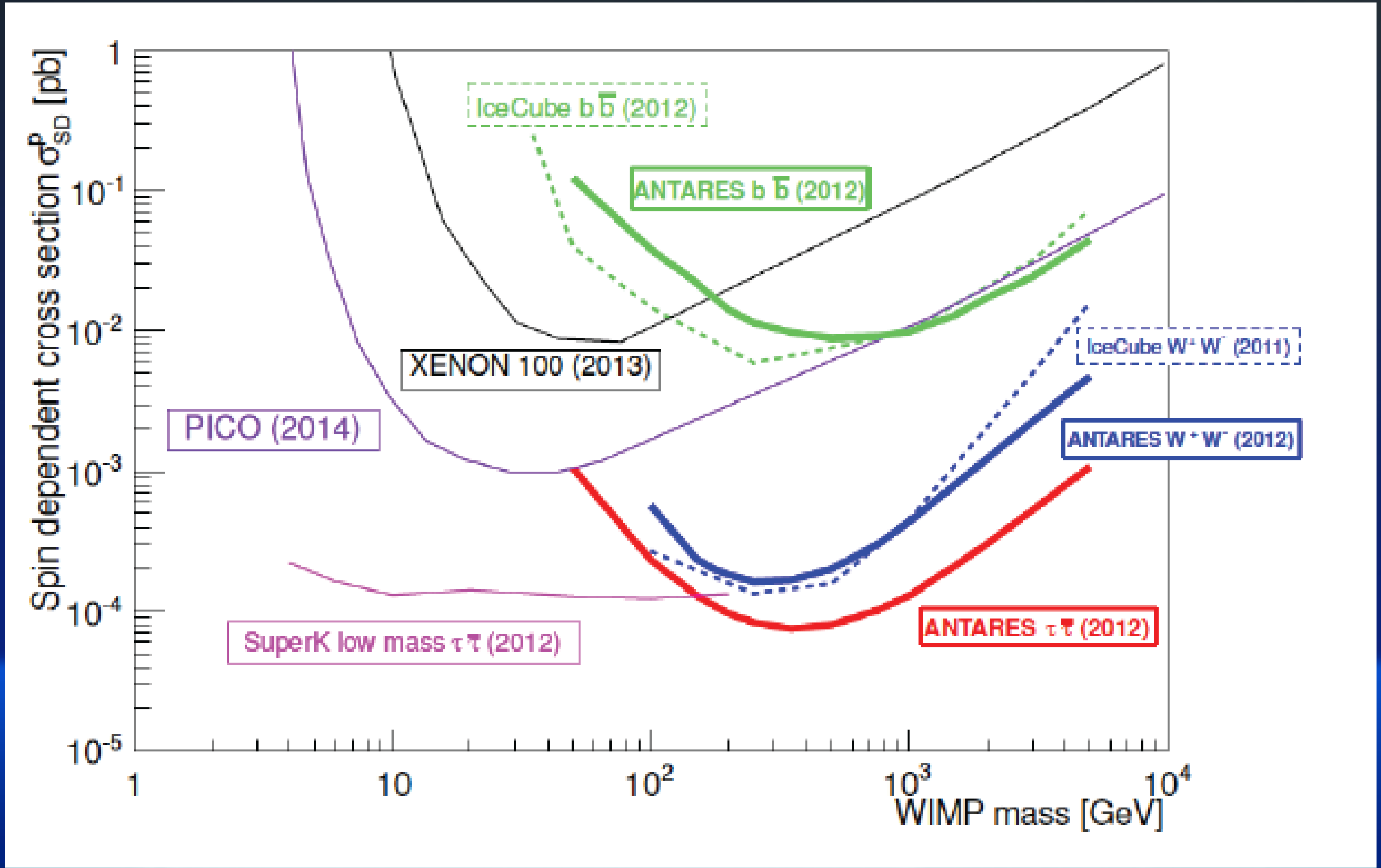
- In IceCube, none of the three neutrino candidates temporally coincident with GW150914 were compatible with the GW direction at 90% CL.
- The reconstructed energy of the neutrino candidates with respect to the expected background does not make them significant.
- The search identified no Antares neutrino candidate that were temporally coincident with GW150914.

Indirect searches for dark matter with neutrinos

Possible characteristics of a dark matter particle:
•Spin: from 0 (sneutrino), ½ (neutralino), to 3/2 (gravitino)
•Mass: from 10^{-15} GeV (axion) to 10^{18} GeV (Wimpzillas)
•Self-annihilation Xsection or interaction Xsection to SM particles:
from 10^{-10} pb to 10^{-5} pb
Lifetime: 10^{9} yr to infinity
•Can be constrained by neutrino telescopes



The Sun



Very competitive limits from the Sun (angular accuracy)

KM3NeT: Next generation detectors-1

The main objectives of the KM3NeT Collaboration are
•the discovery and subsequent observation of high-energy neutrino sources in the Universe and
•the determination of the mass hierarchy of neutrinos.

These objectives are strongly motivated:
1.the discovery of the high-energy astrophysical neutrino signal reported by IceCube is a new window to see the Universe,
2.the knowledge of the neutrino mass hierarchy is a prime discriminator for theory models

To meet these objectives the KM3NeT Collaboration plans to build a new Research Infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea.

KM3NeT: Next generation detectors-2

The infrastructure will consist of three so-called building blocks.
•A building block comprises 115 strings,
•each string comprises 18 optical modules and
•each optical module comprises 31 photo-multiplier tubes (PMTs).

TWO building blocks will be sparsely configured to fully explore the IceCube signal with comparable instrumented volume, improved resolution and complementary field of view, including the Galactic plane. Collectively, these building blocks are referred to as **ARCA**: **A**stroparticle **R**esearch with **C**osmics in the **A**byss.

ONE building block will be densely configured to precisely measure atmospheric neutrino oscillations.
This building block is referred to as **ORCA**: **O**scillation **R**esearch with **C**osmics in the **A**byss.

ARCA will be realised at the Capo Passero site and ORCA at the Toulon site.

KM3NeT: Next generation detectors-3

The whole project is organised in a single Collaboration with a central management and common data analysis and repository centres.

A Memorandum of Understanding for the first phase (Phase-1), covering the currently available budget of about 31M€, has been signed .

During Phase-1, the technical design has been validated through in situ prototypes; data analysis tools have been developed; assembly sites for the production of optical modules and strings have been setup; and deployment and connection of strings in the deep sea are being optimised for speed and reliability.

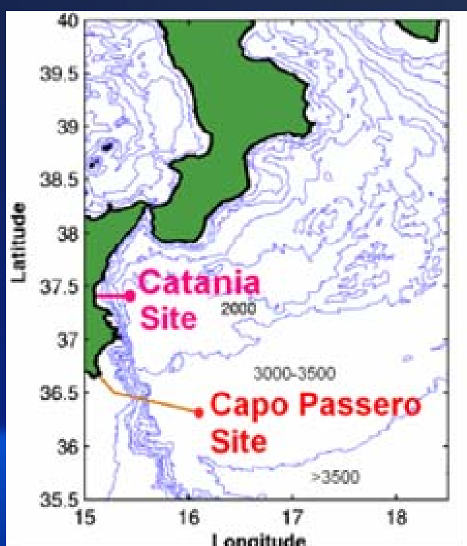
During the next phase (Phase-2.0), the Collaboration will complete the construction of ARCA and ORCA by 2020.

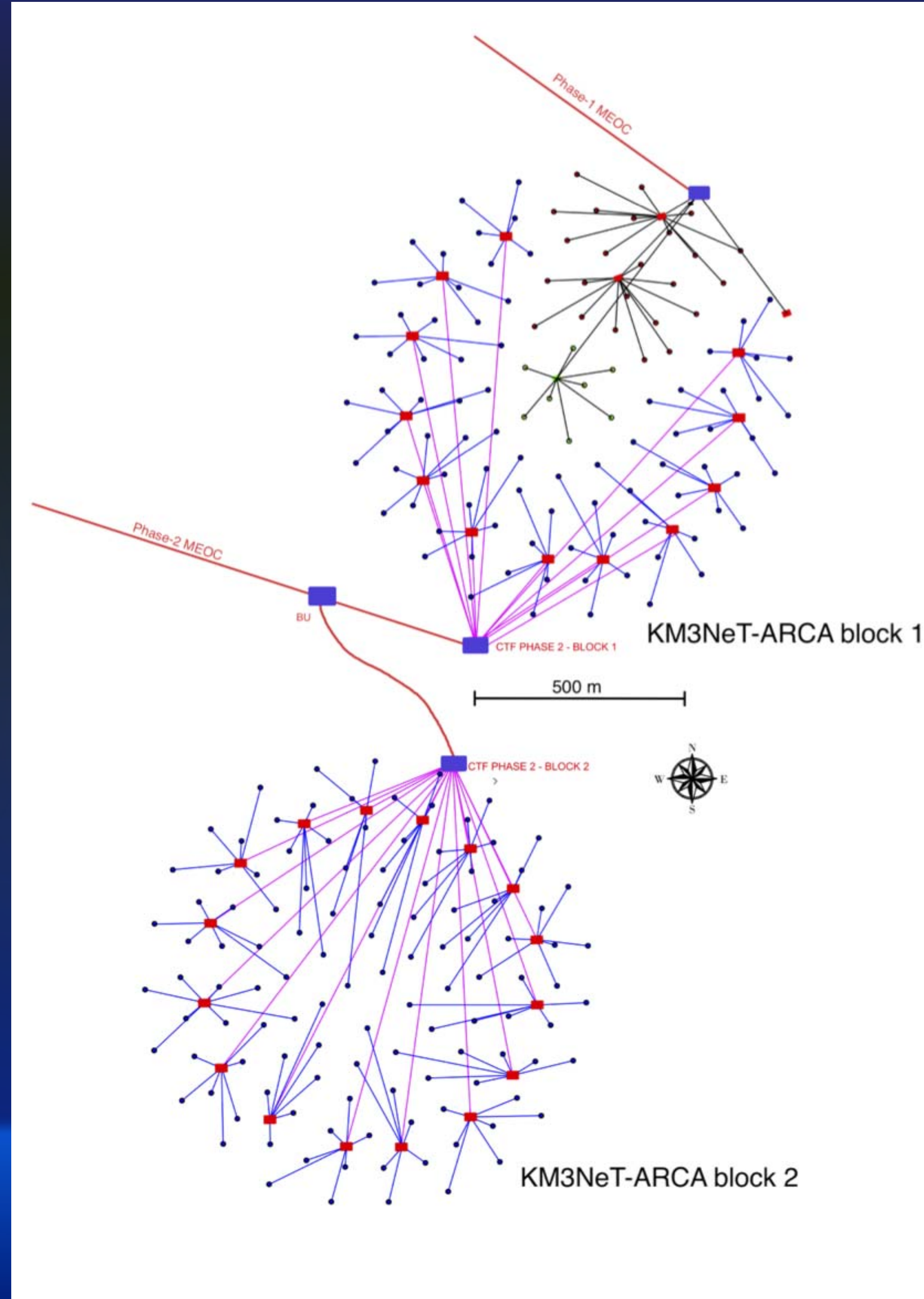
Phase	**Total costs** (cumulative) M€	**Building blocks**	**Start**	**Primary deliverables**
1	31	0.2	2013	Proof of feasibility and first science results.
2.0	125	2 1	2017	Study of the neutrino signal reported by IceCube; Determination of the neutrino mass hierarchy.
3	220–250	6	2025	Neutrino astronomy including Galactic sources.

KM3NeT: ARCA

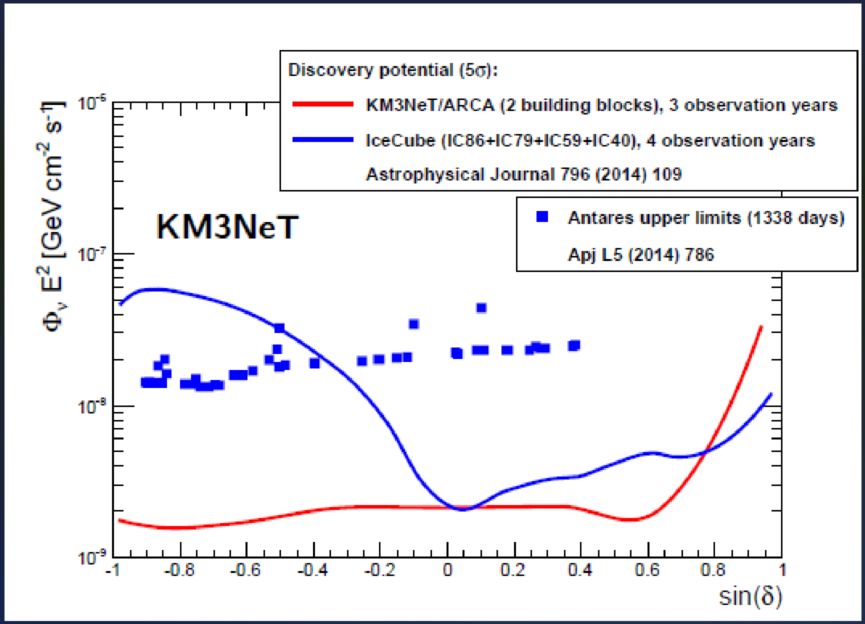
The KM3NeT-Italy infrastructure is located at 36 16’ N 16 06’ E at a depth of 3500 m, about 100 km offshore from Porto Palo di Capo Passero, Sicily, Italy (Fig. 4, left).

The site is the former NEMO site and is shared with the EMSO facility for Earth and Sea science research.

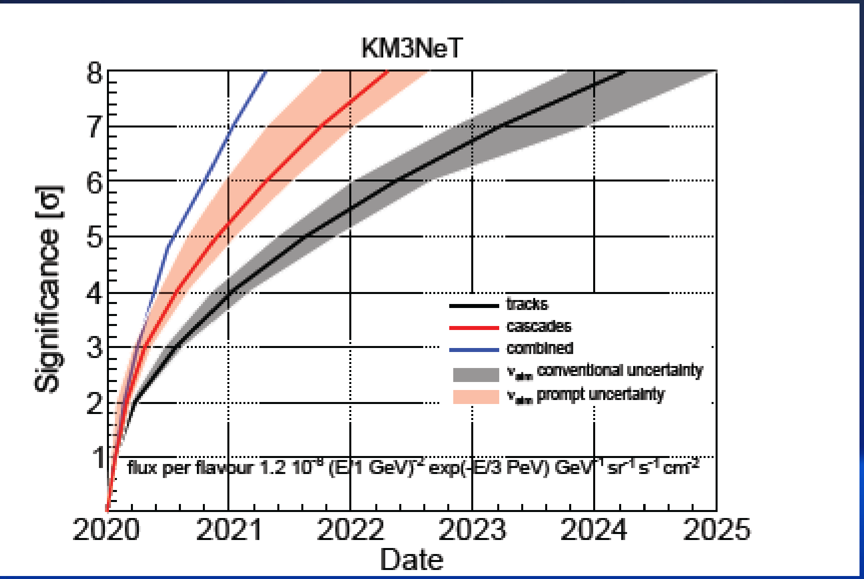




KM3NeT: ARCA

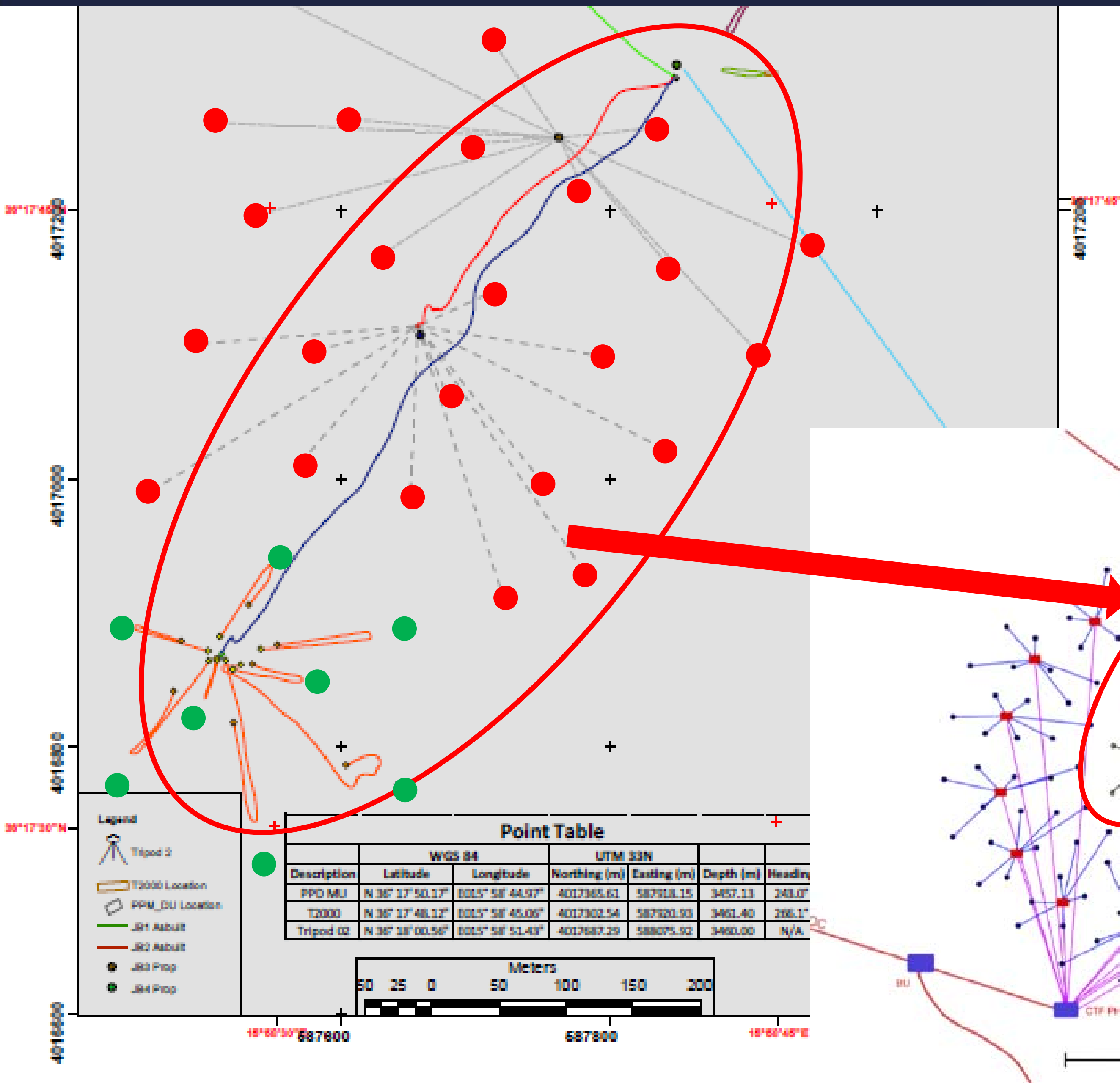


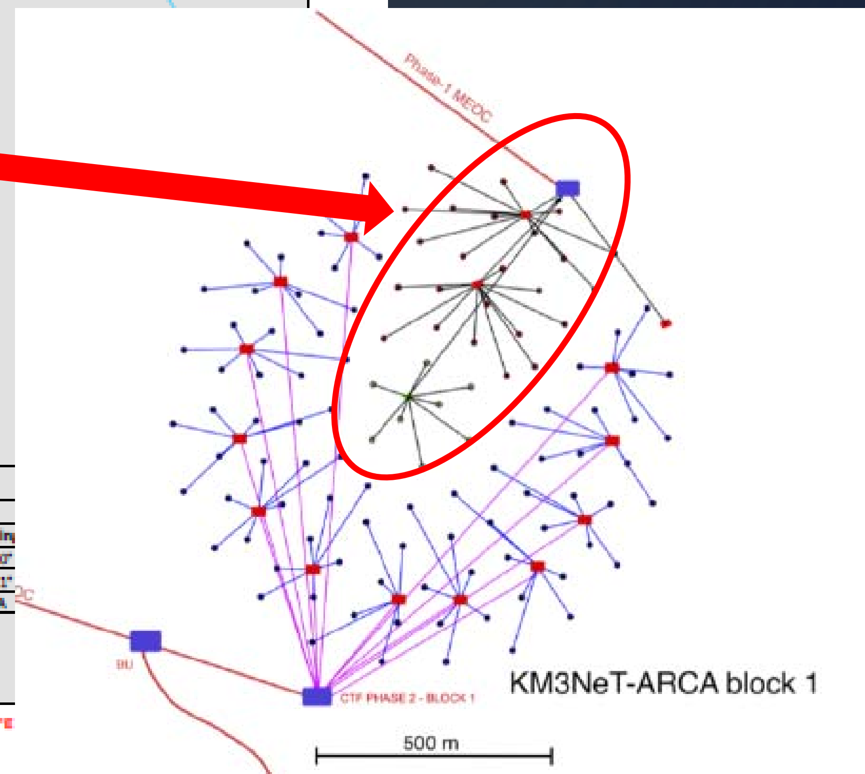
Expected performancies with respect to ANTARES and ICECUBE



Significance for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube.
Cascades (red line) and track-like events (black line) contributions are indicated.
Black and red bands represent the uncertainties due to the conventional and prompt component of the atmospheric neutrino flux.
The blue line indicates the result of the combined analysis.

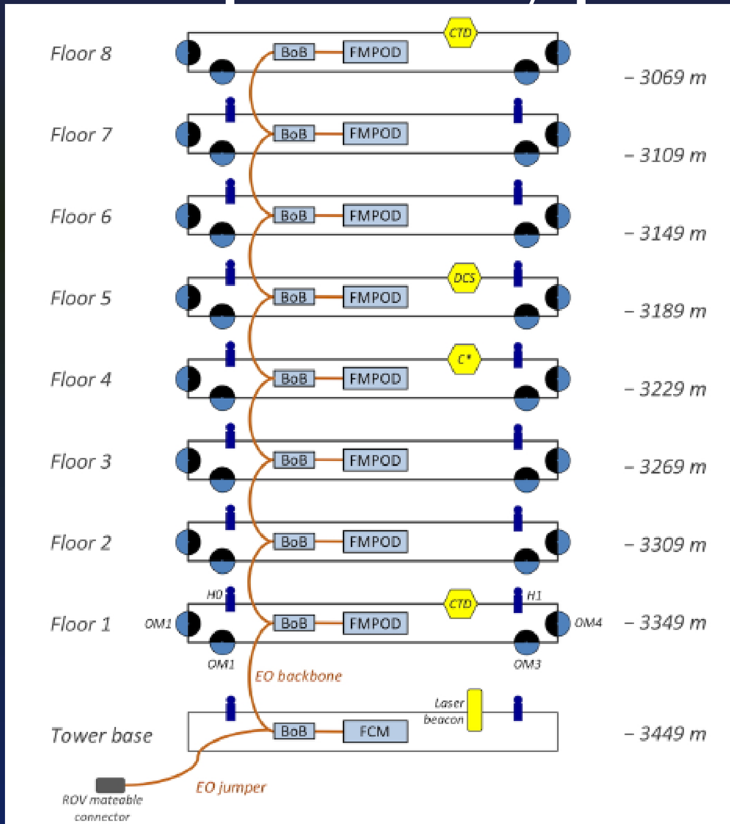
KM3NeT: ARCA Phase-1





- Detection unit: string
- Detection unit: tower

First prototype: the tower

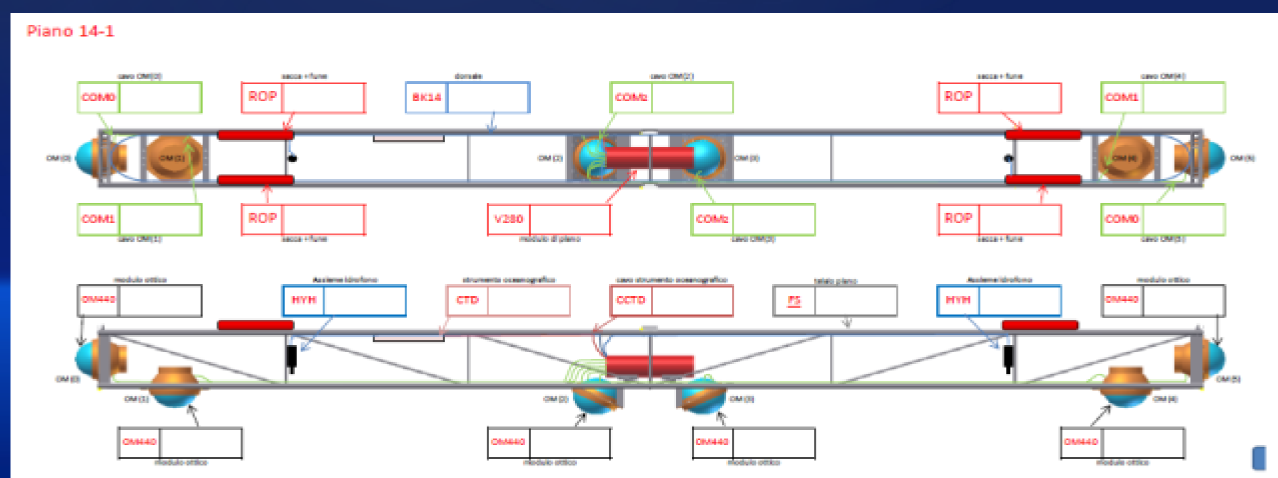


First 8-floor prototype deployed in 2013.

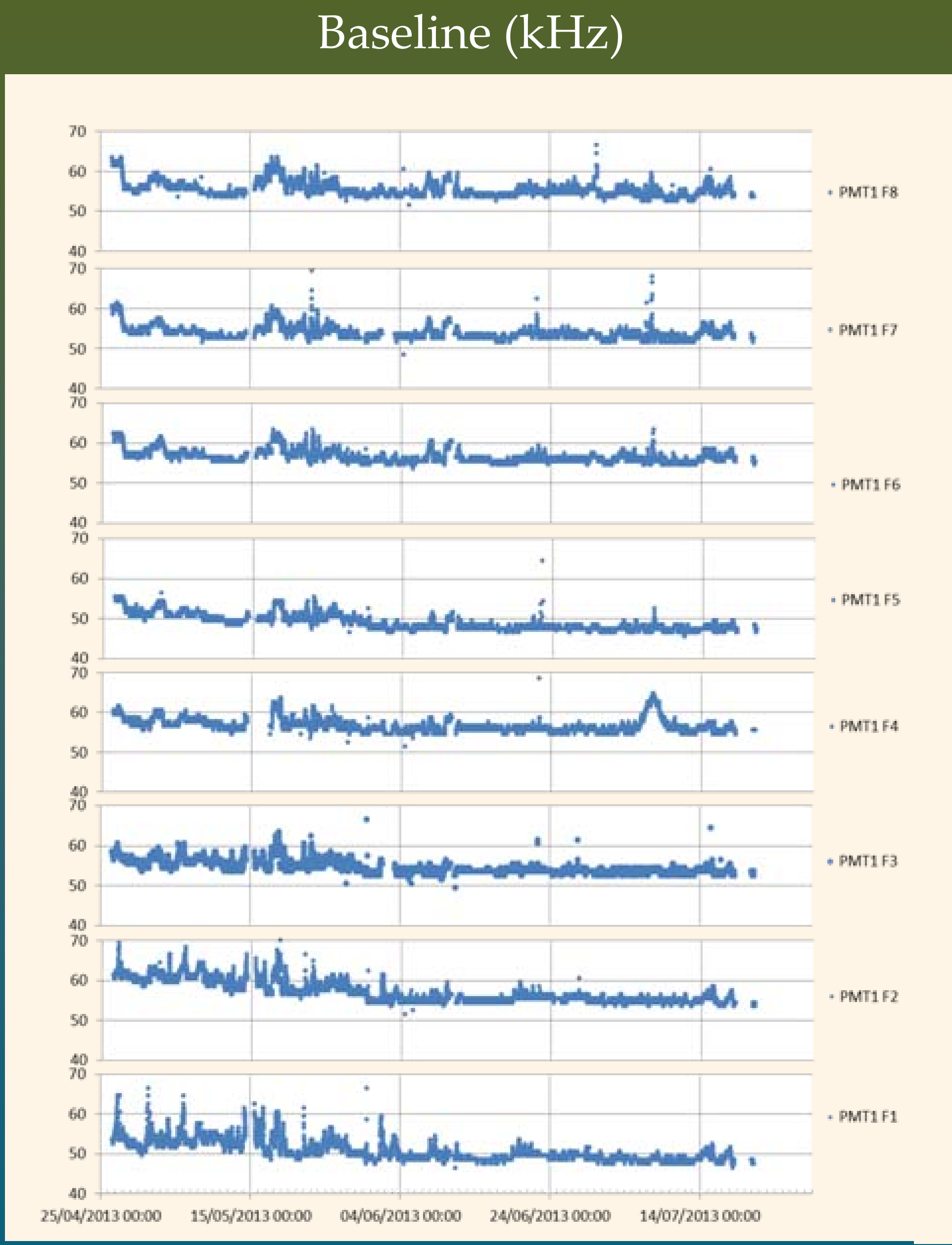
- 4PMTs/floor,
- 8 m long floor
- 8 floors
- Inter-floor distance :40m .
- One year of continuous data taking

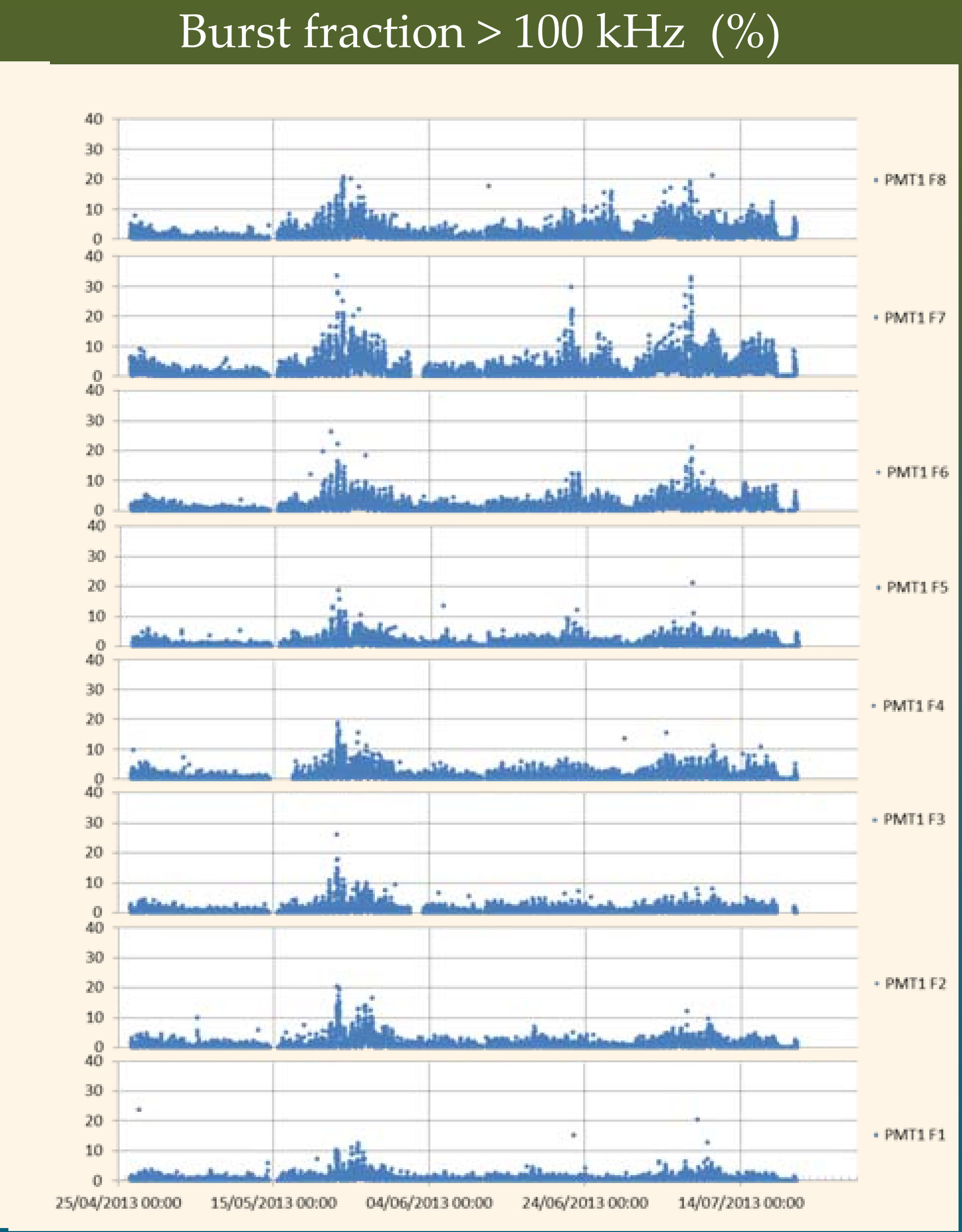
New design in 2014.

- 6PMTs/floor,
- 8 m long floor
- 14 floors
- Inter-floor distance :20m .



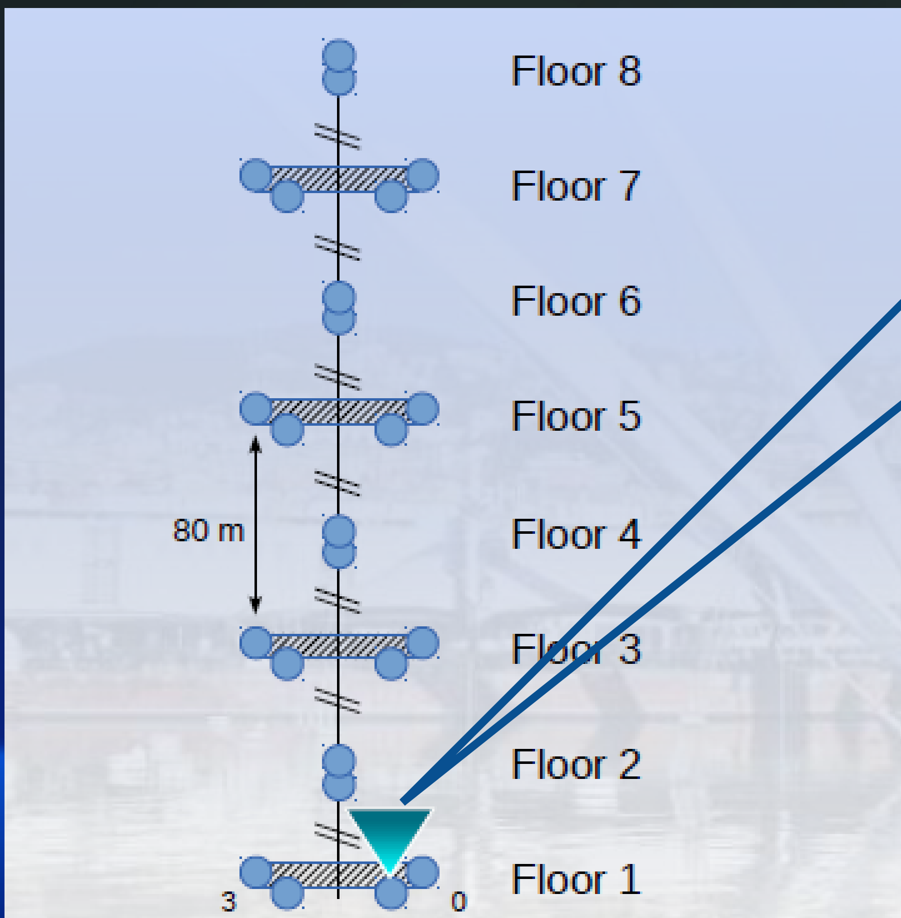
Bioluminescence rate

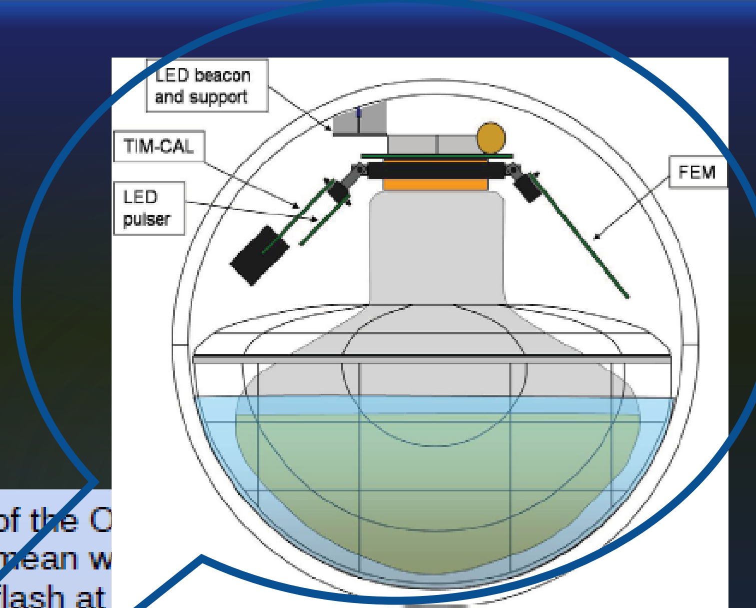




LED beacon analysis

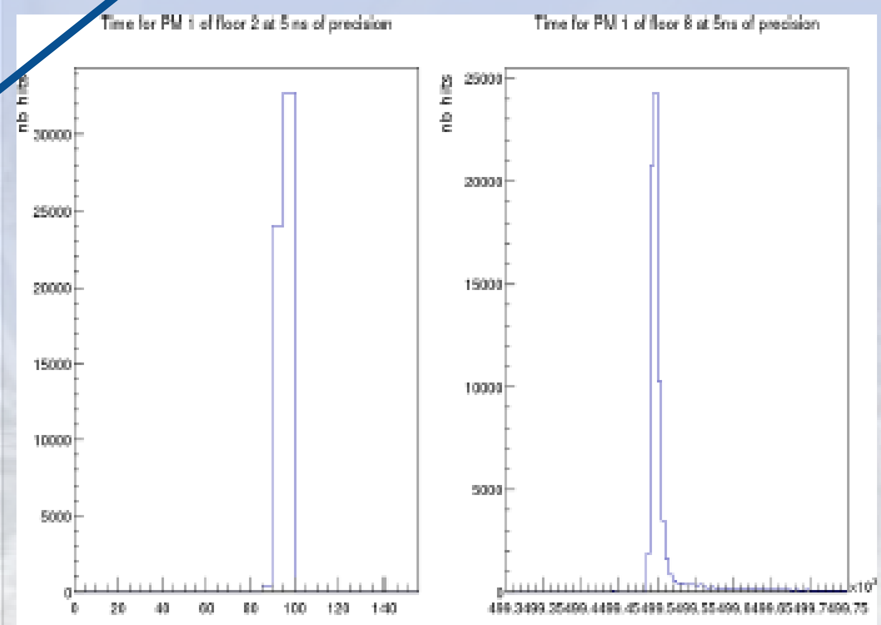
Analisys done by BRIUKHANOVA NATALIIA
•Timing calibration
•Scattering of light in the water





- LED of the O
- LED mean w
- LED flash at

=> peaks observables within a modulo 500 us timing plot

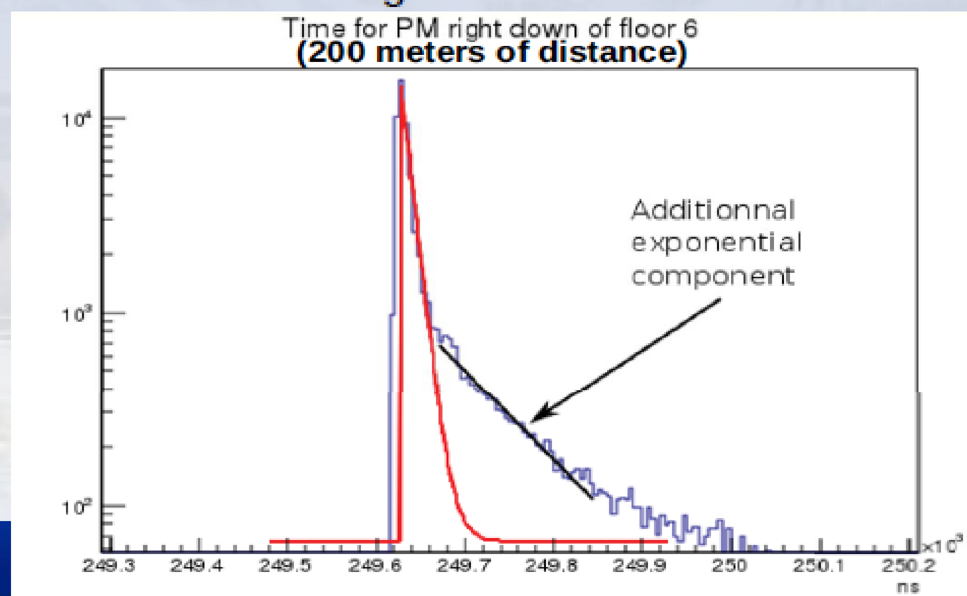


LED beacon analysis

$$b_P = 1.34\,\nu_S \left(\frac{550\,nn}{\lambda}\right)^{1.7} + 0.312\,\nu_l \left(\frac{550\,nm}{\lambda}\right)^{0.3}$$

Clancy W. James
Km3 internal note

- 2 components to the scattering :
  - On molecule (isotropic angular distribution)
  - On particles (Forward going angular distribution)
- The both processes depend on the wavelength on a different exponent.
- They imply a delay in time arriving
  - In function of distance
  - In function of wavelength



The final KM3NeT Detection Unit: the string

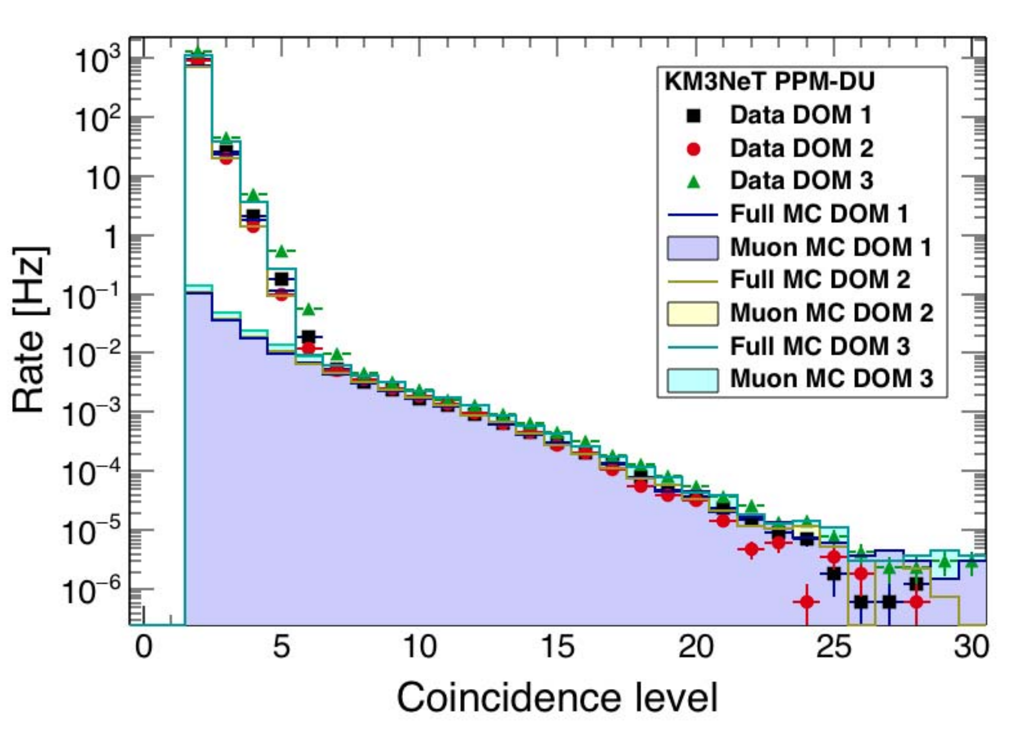
The Digital Optical Module (DOM)

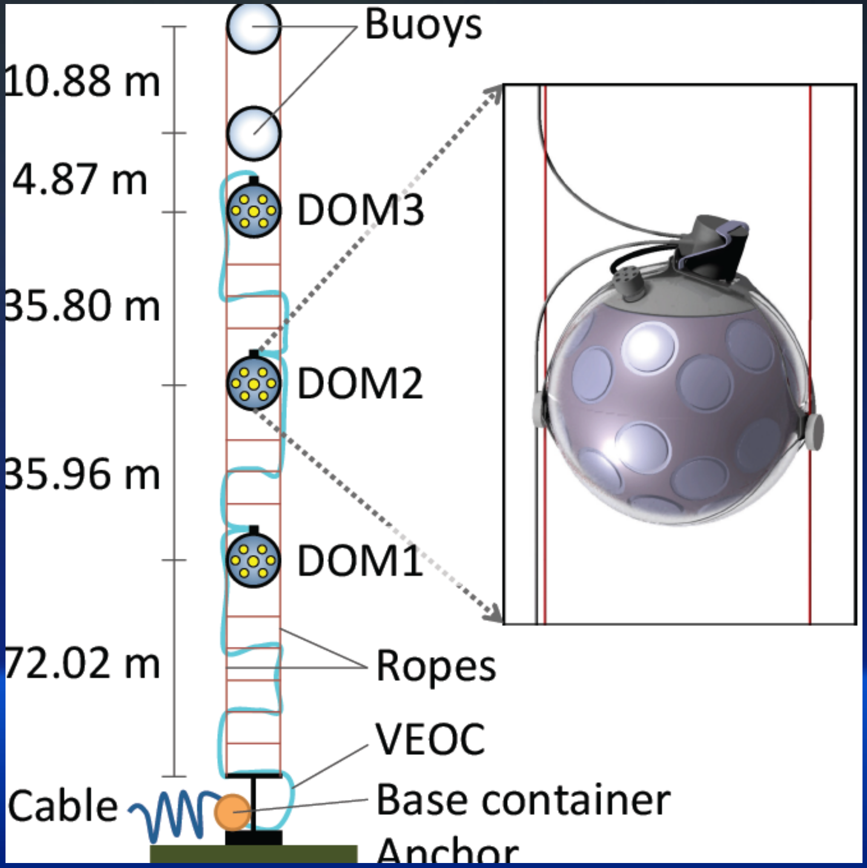
The 18 DOM string

Three DOMs string prototype

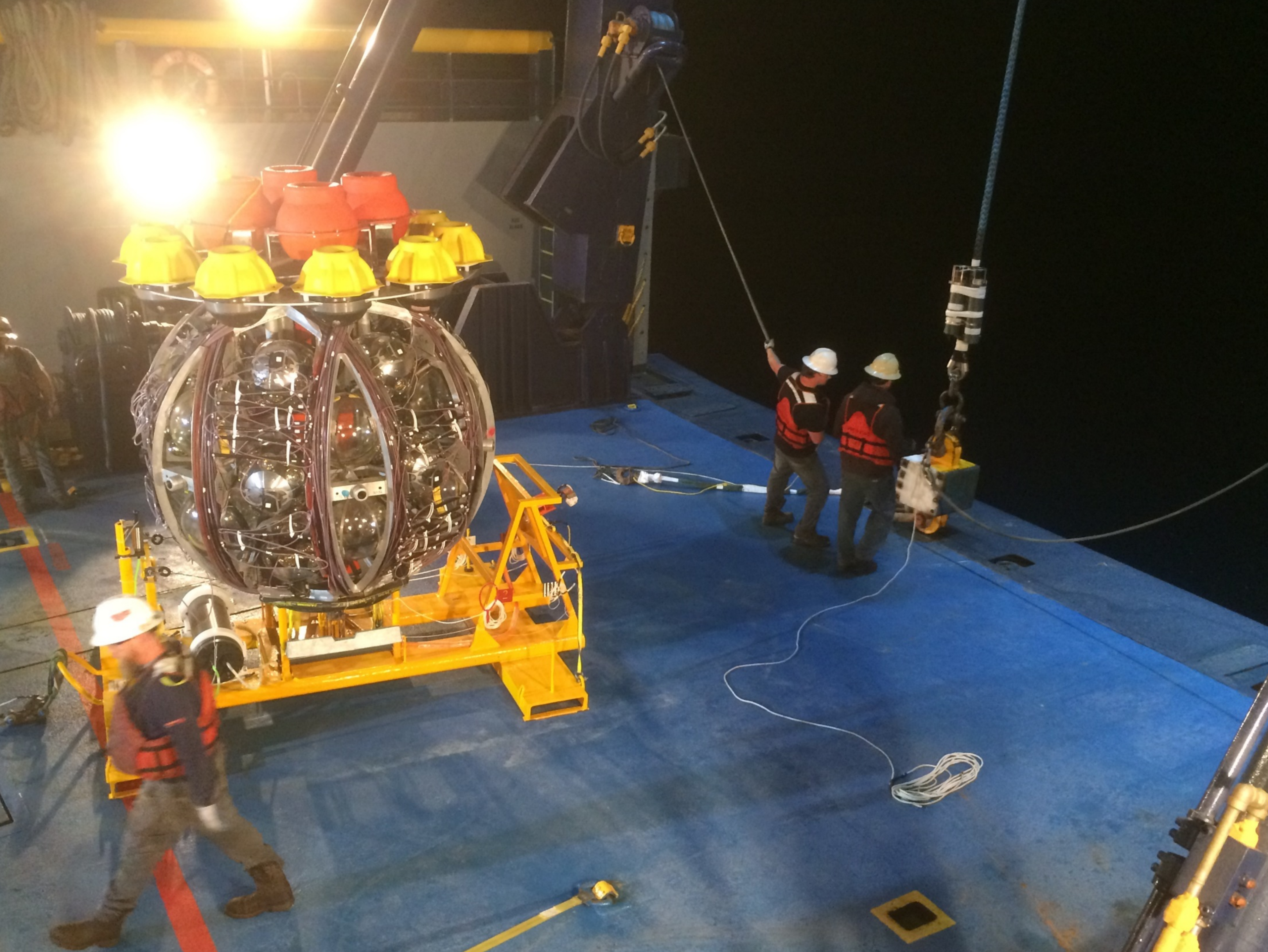
•Deployed in may 2014
•1 year of full operation in the Italian site at 3500 m depth
•Conceptual design validated

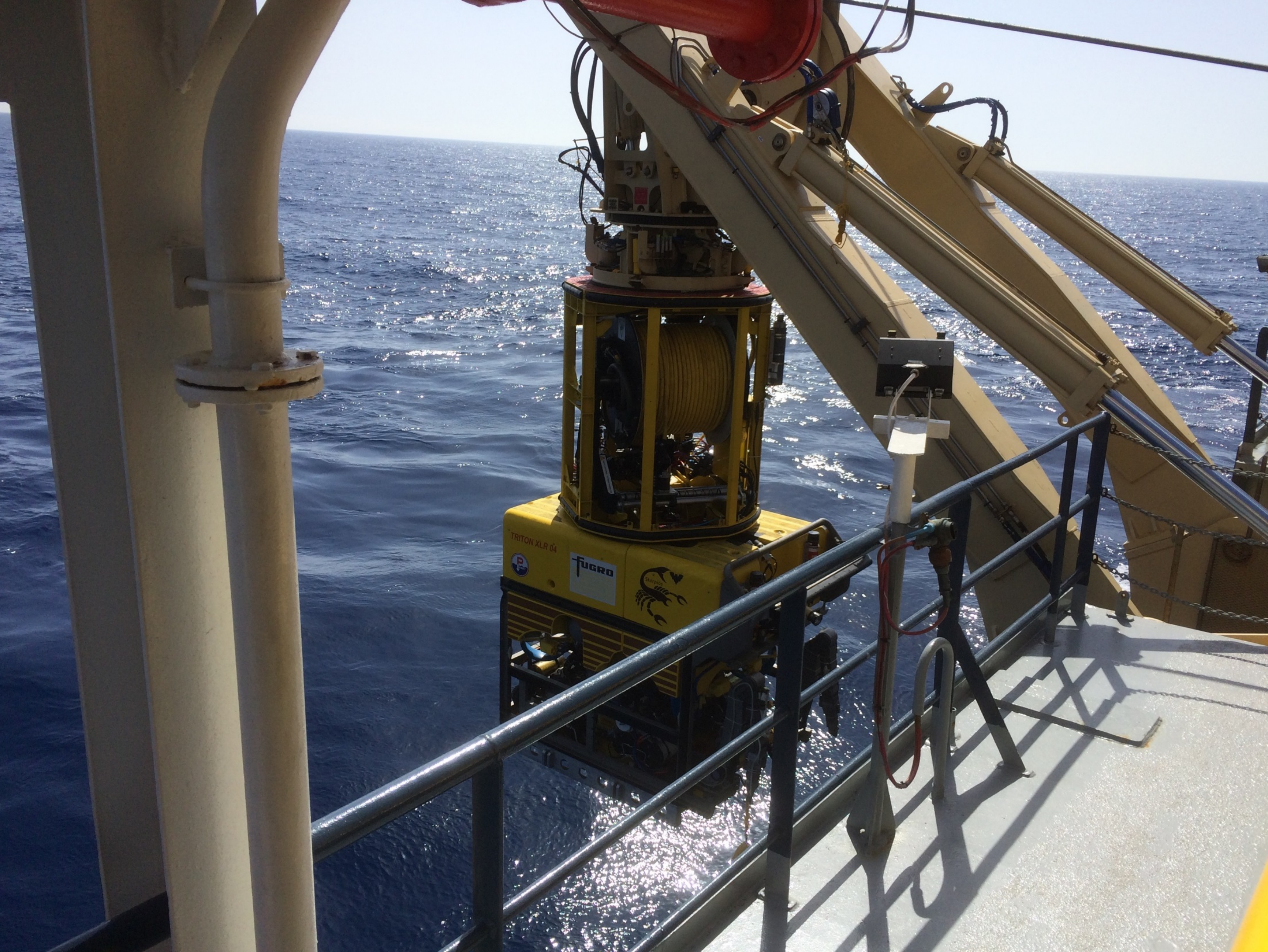
Eur. Phys. J. C (2016) 76:54



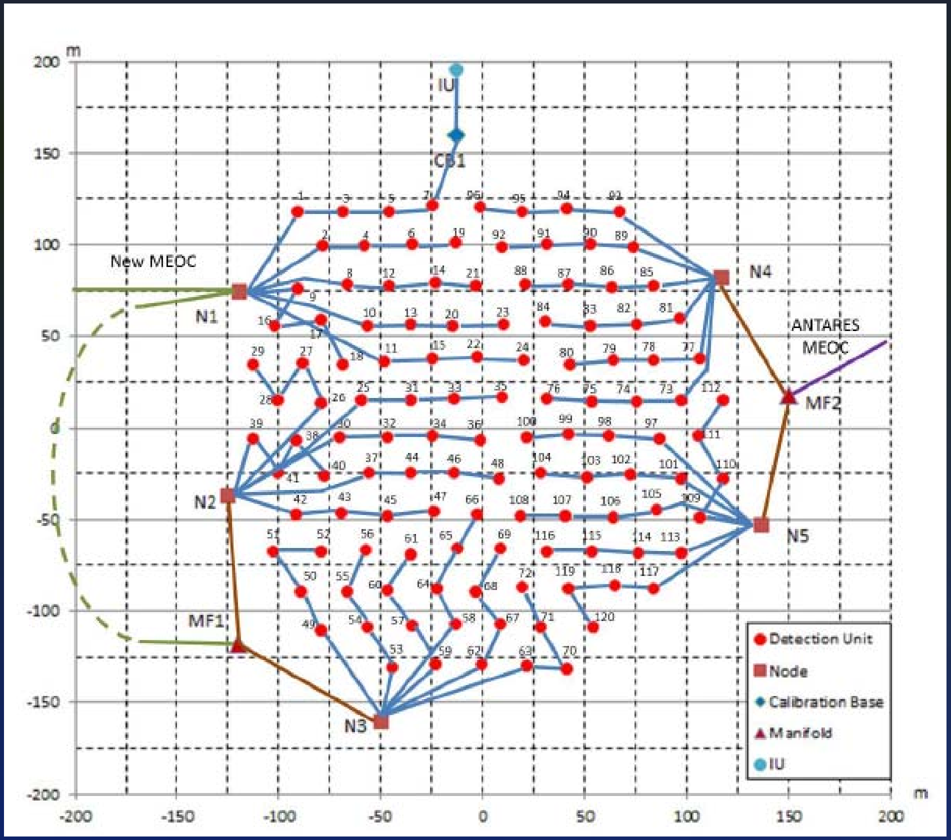



PILOT



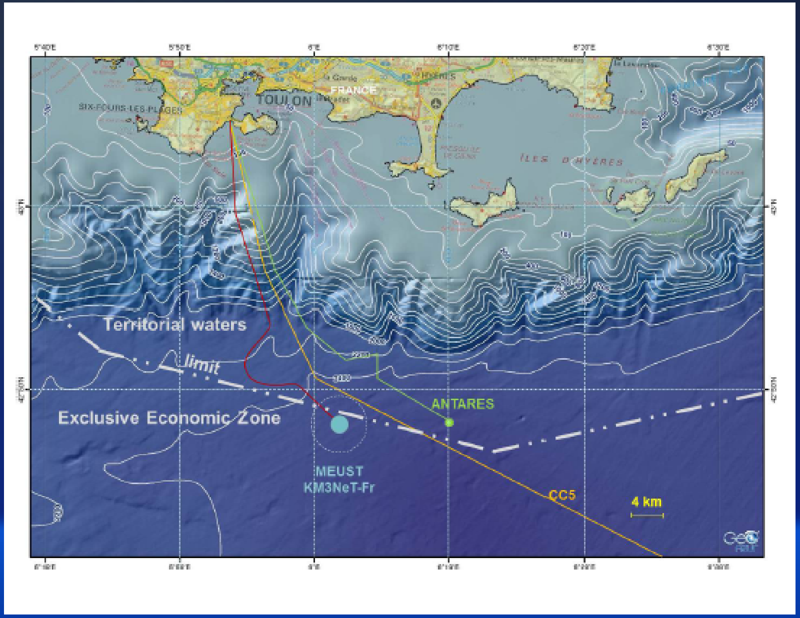

TRITON XLR 04
FUGRO
Skorpiós

KM3NeT: ORCA



- 115 lines 20m spaced,
- 18 DOMs/line 9m spaced
- Instrumented volume ~6.5 Mt,
- 2070 OMs

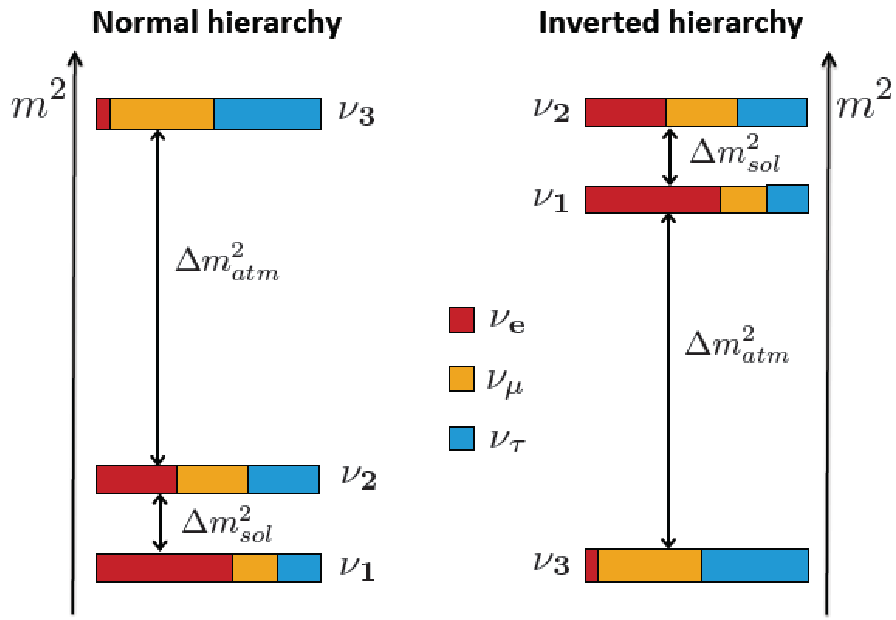
- Detector more 'compact' with respect to ARCA.
- 1 block of DUs
- Optimized for intermediate energy neutrinos (5-500GeV)
- Located close to the ANTARES site



KM3NeT: ORCA

- Main pupose: measure the neutrino mass hierarchy using atmospheric neutrinos
- Letter of Intent for KM3NeT 2.0
- Article reference: JPhysG-101230.R1

The ordering of neutrino mass eigenstates has indeed not been determined so far. After fixing $\Delta m^2_{21} = (\Delta m^2)_{sol} > 0$, two solutions remain possible depending on the sign of Δm^2_{31}: the **normal hierarchy** (NH: $m_1 < m_2 < m_3$) and the **inverted hierarchy** (IH: $m_3 < m_1 < m_2$), as can be seen from Fig. 46.



Neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric $\theta_A \sim 45°$ | Reactor $\theta_{13} \sim 9°$ | Solar $\theta_\odot \sim 30°$ | Majorana

All parameters measured to fair precision except:

- mass hierarchy
- octant of θ_{23}
- CP phase

In the standard approach the transition $\nu_\mu \rightarrow \nu_e$ is governed by Δm^2_{31} and it is insensitive to its sign

$$P_{3\nu}(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\, \sin^2 2\theta_{13}\, \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

Neutrino oscillations-2

But matter effects (MSW) come to the rescue!!!

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{31}\,L}{4E_\nu}\right)$$

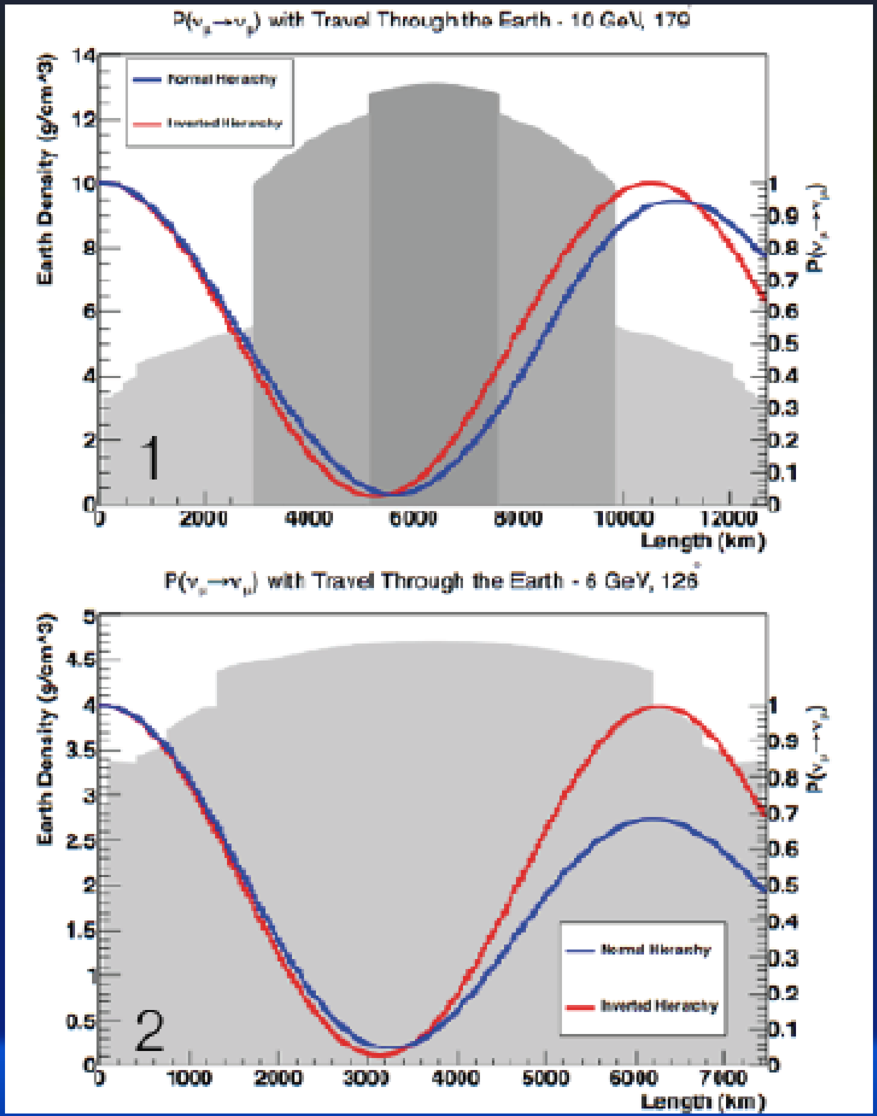
$$\Downarrow$$

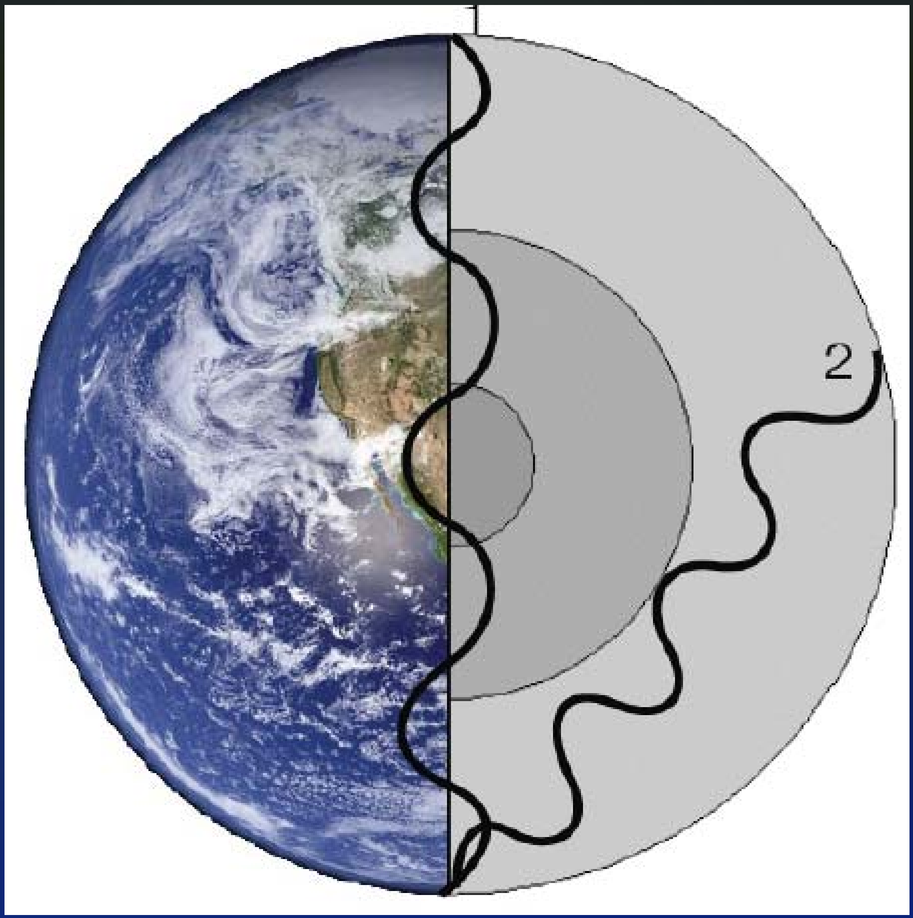
$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta^m_{13}\,\sin^2\left(\frac{\Delta^m m^2 L}{4E_\nu}\right)$$

$$\begin{aligned}
\sin^2 2\theta^m_{13} &\equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^m m^2}\right)^2 \\
\Delta^m m^2 &\equiv \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - 2\,E_\nu\,A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}\,,
\end{aligned}$$

Additional potential A in the Hamiltonian
$A=\pm\sqrt{2}G_F N_e$ (-)/+ for (anti)neutrinos
Modify the oscillation probability

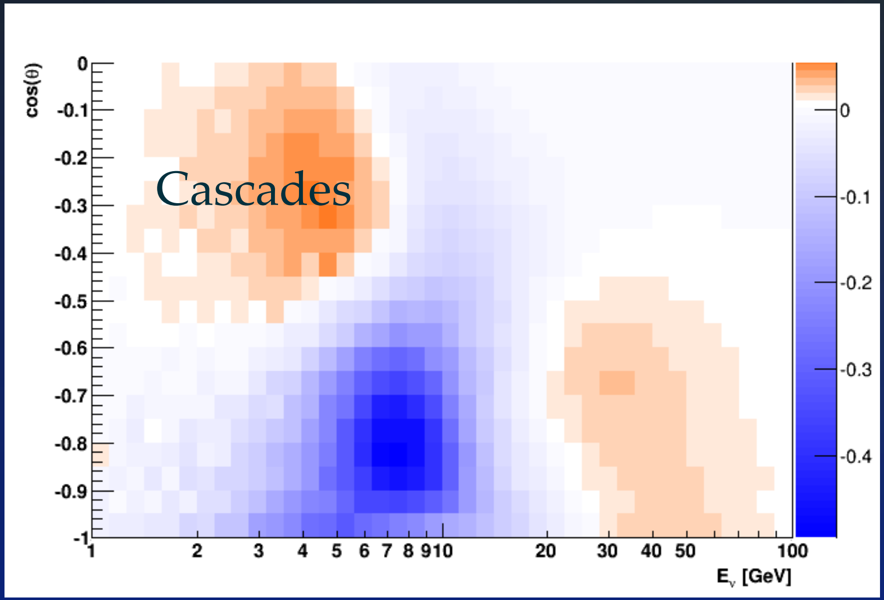
Matter effect in the Earth

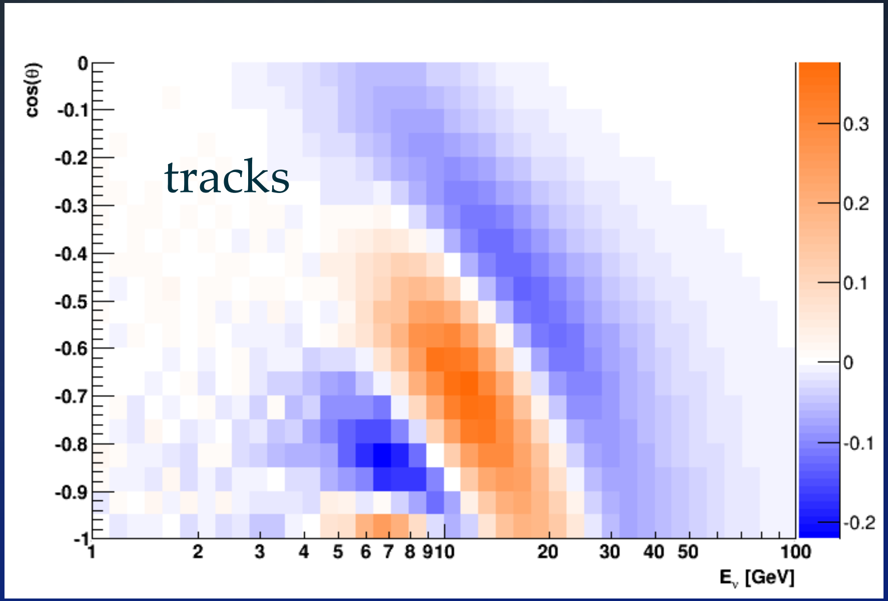




Method to Determine NMH

Determine P_{osc} from Globes in 40x40 bins in cosθ & log(Eν),
Fold in Neutrino Flux, Cross section
Fold in detector response
Evaluate (IH-NH)/$\sqrt{NH}$ including systematic effects

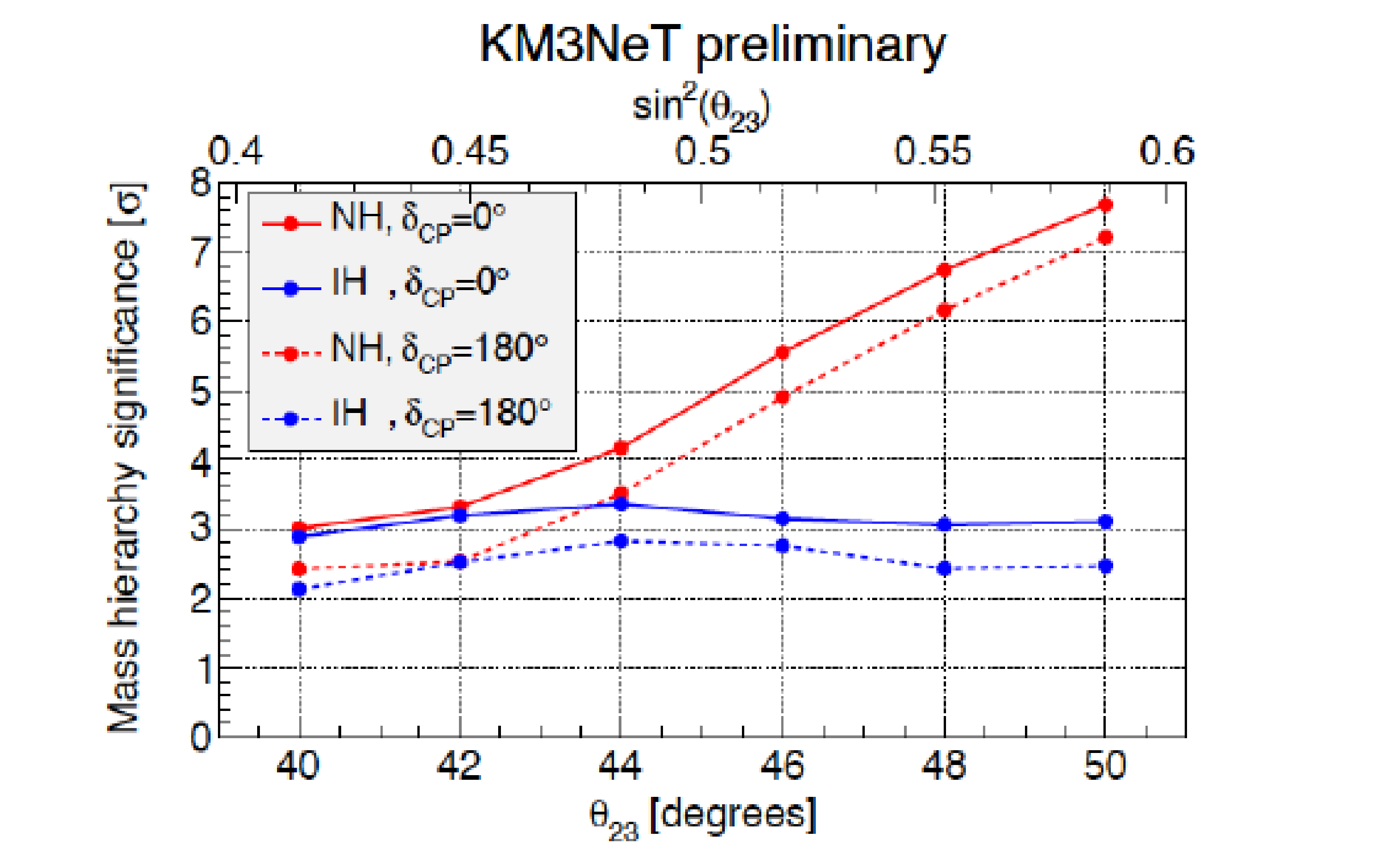




(IH-NH)/$\sqrt{NH}$ in one year

Neutrino Mass Hierarchy

Reachable sensitivity with 3 years data taking as function of θ23 and δCP



Summary and perspectives-1

IceCube
•has just opened the field of neutrino astronomy
•Sources remain to be identified.

ANTARES:
•first undersea Cherenkov detector
•Excellent angular resolution, view of Southern sky
•Competitive sensitivities (especially for Galactic neutrino component, Dark matter
•searches)
•Improvements still to come: include showers in all analyses
•Taking data until superseded by KM3NeT in 2017

KM3NeT:
Represents next-generation neutrino telescope
Letter of Intent submitted
Prototypes performing well
Deployment of the first detection units (Phase 1).
ARCA → HE neutrino astronomy (tracks & showers)
ORCA for the measurement of NMH

Thank you