KM3NeT

Status and Perspectives

January 5-11, 2020

16th Rencontres du Vietnam – Quy Nhon

Mauro Taiuti - on behalf of the **KM3NeT** collaboration

INFN

DIFI 2018-2022 DIPARTIMENTO DI ECCELLENZA MIUR

Outline

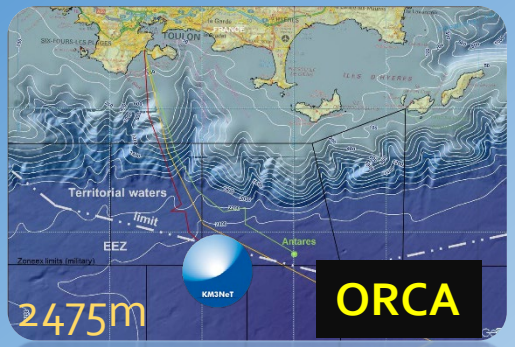
- Preamble
- The Detectors
- The Performances
- First Results
- The Physics Program
- Conclusions

Motivations & Objectives

Astroparticle Research with Cosmics In the Abyss

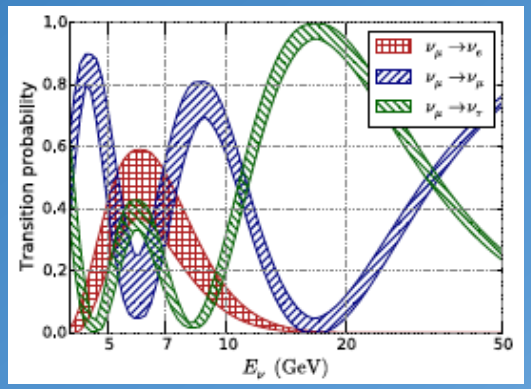
Oscillation Research with Cosmics In the Abyss

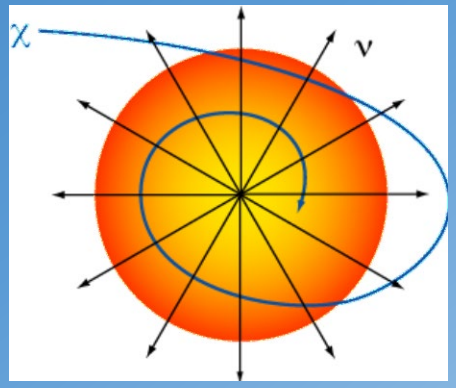
- **KM3NeT** is the neutrino research infrastructure in the deep Mediterranean Sea
  - **ARCA** (off shore Capo Passero, It @ 3500 m depth)
  - **ORCA** (off shore Toulon, Fr @2500 m depth)

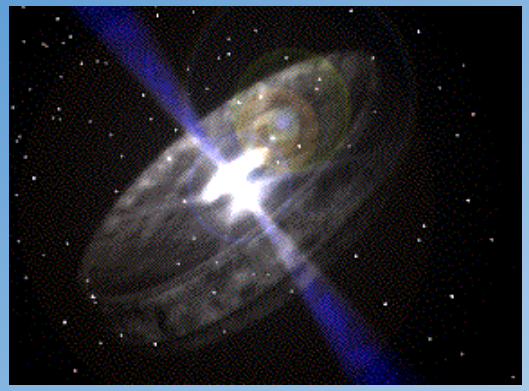


- Same collaboration, same technology, two deep sea sites

Motivations & Objectives







Low Energy	Medium Energy	High Energy
MeV < E_ν < 100 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations Mass hierarchy Supernovae	Dark matter Monopoles, Nuclearites	Cosmic ν Identification and study of HE neutrino sources Origin and production mechanism of HE CR

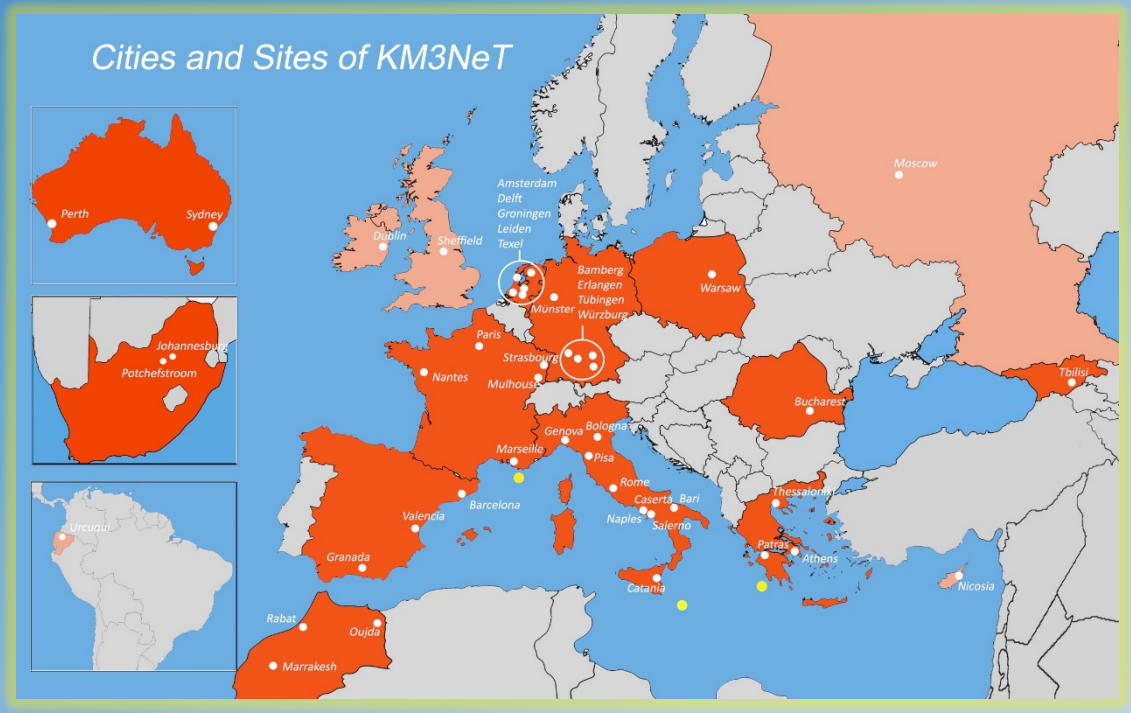
KM3NeT - ORCA ⟷ KM3NeT - ARCA

+ oceanography, biology, seismology,…

LoI: *J. Phys. G*, 43 (2016) 084001

The KM3NeT Collaboration

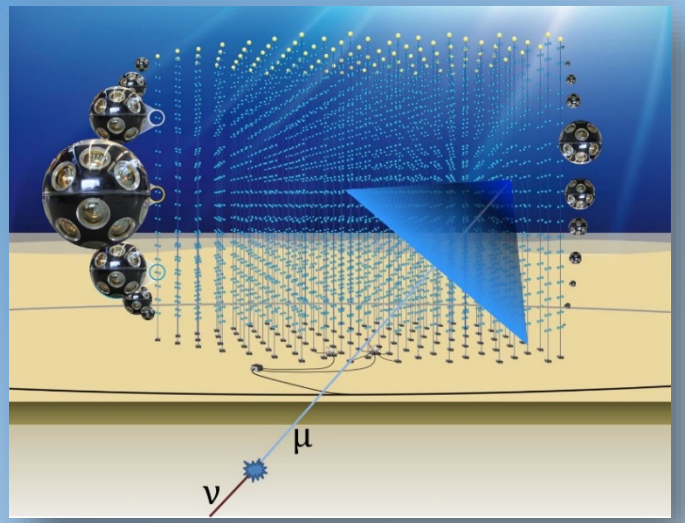
- 15 Countries
- 55 Institutes
- >240 Scientists



The Detectors

The KM3NeT Telescope Design

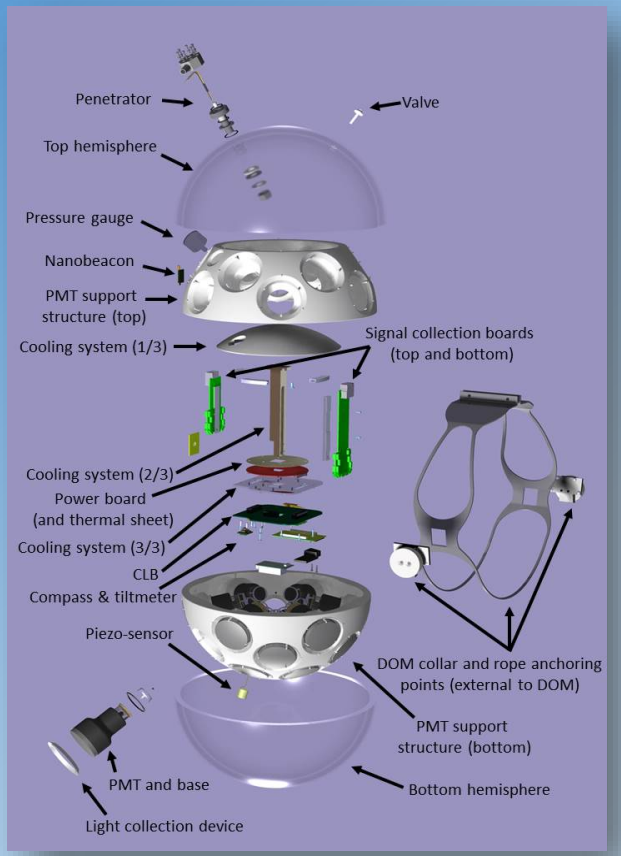
- Detection principle Cherenkov radiation induced by charged particles produced in neutrino interactions
  - 6 order of magnitude in ν energy (GeV-PeV)
  - All flavour detection
- 3D arrays built with a modular design
- Optical sensor: multi-PMT (DOM)
- Detection units (DU)
  - vertical slender strings host 18 DOMs
- 3 Building blocks of 115 DUs each
- DOM and DU spacing optimized for the studied ν energy range
- Power and data distributed by a single cable with breakouts at DOMs
- Sea network of submarine cables and Boxes connected to shore
- All data to shore



	ARCA	ORCA
Location	Italy	France
DOM spacing	36 m	9 m
DU length	612 m	153 m
DU spacing	90 m	23 m
Instrumented mass	2*500 Mton	8 Mton

The DOM - Digital Optical Module

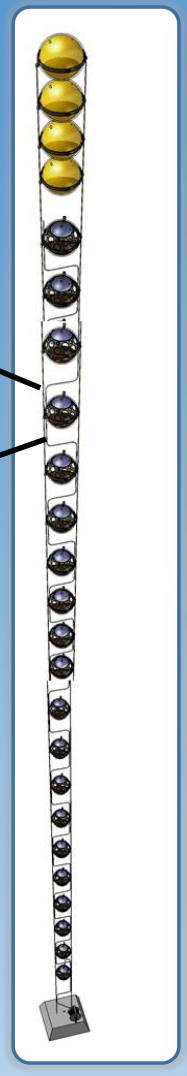
- 31 x 3" PMTs
- LED & acoustic piezo inside
- Tiltmeter/compass
- Gbit/s fibre DWDM
- Hybrid white rabbit



- Digital photon counting
- Directional information
- Wide angle of view
- Improved background rejection
- Compact and cost effective design: 1 DOM ≅ 3 ANTARES OMs (photocathode area)

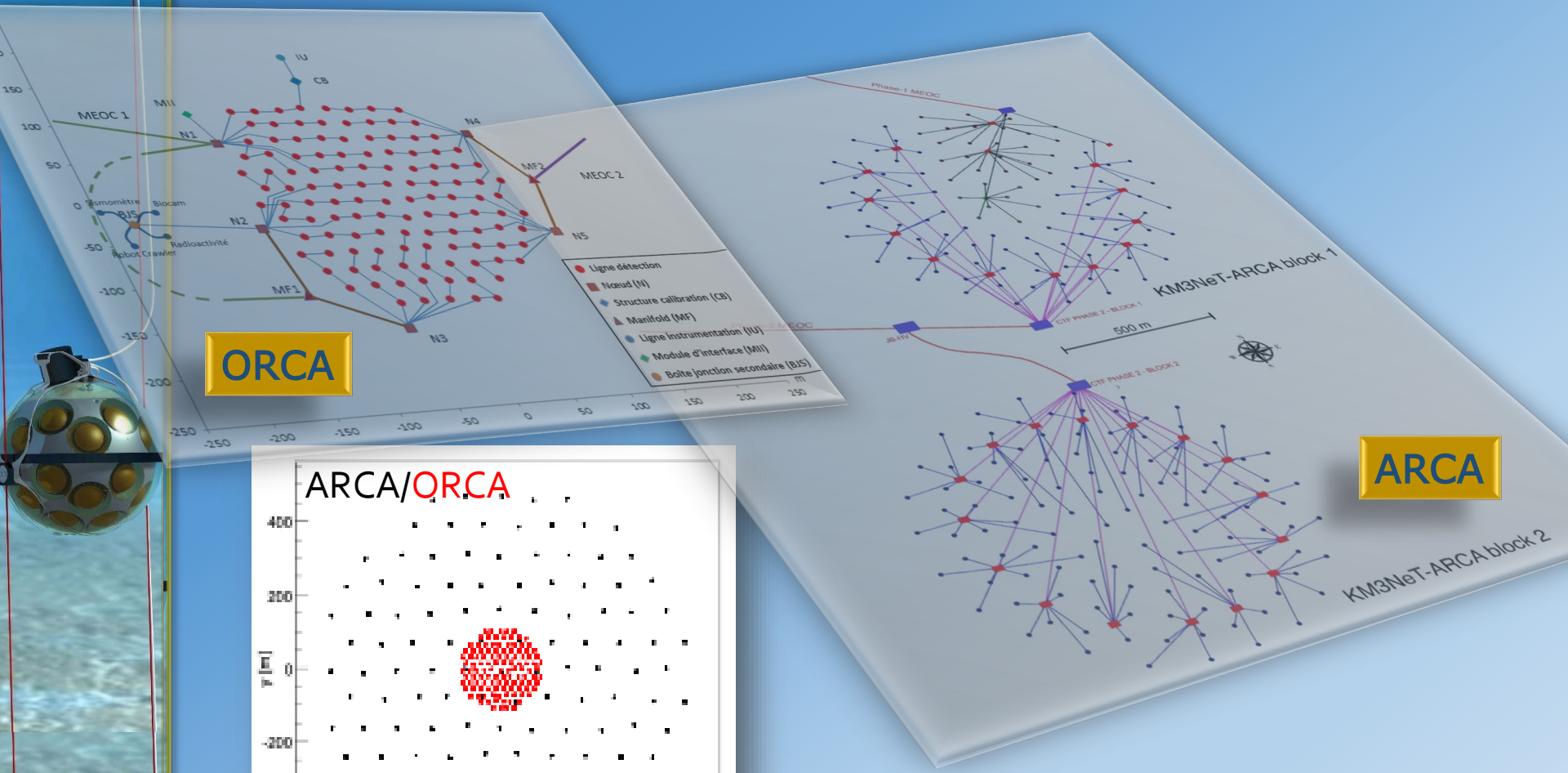
The Detection Unit

- 18 DOM integrated on a vertical slender strings supported by two parallel Dynema ropes



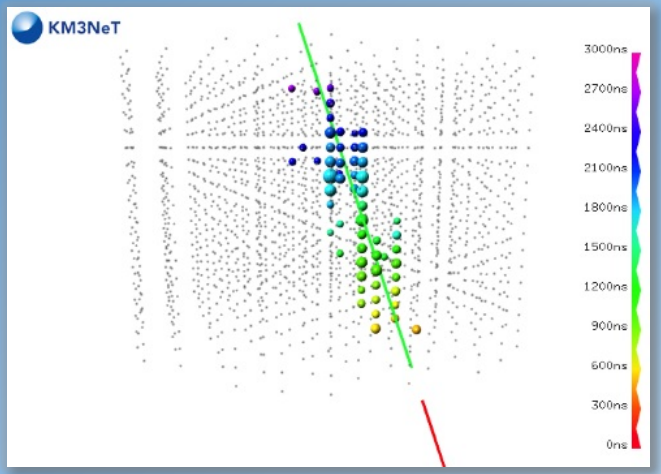
- Strings arranged on the LOM, mounted on the anchor and ready for deployment

The Seafloor Network

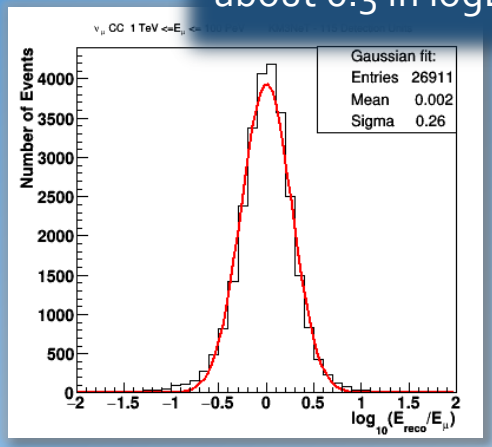


Event Topologies and Detector Response

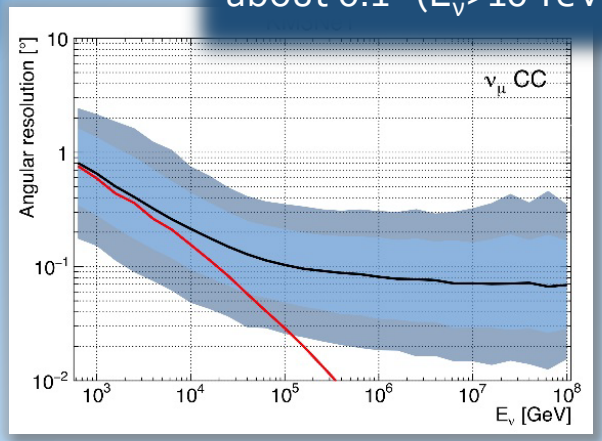
- ν_μ are the golden channel for neutrino astronomy
- Deep sea water properties, i.e. long scattering length allow to achieve very good angular resolution



Energy resolution about 0.3 in $\log E_\mu$

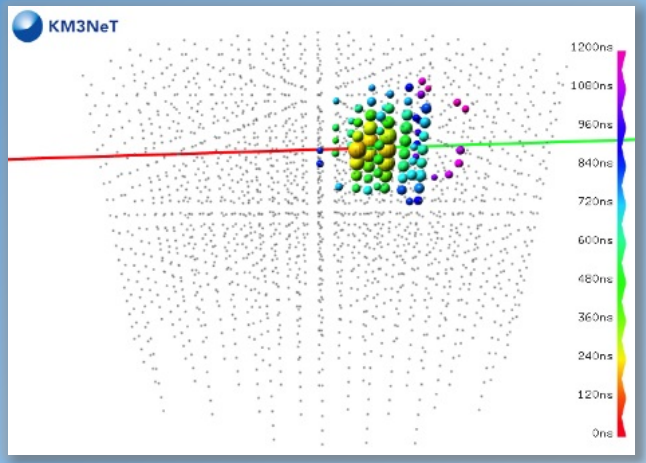


Angular resolution about 0.1° (E_ν>10 TeV)

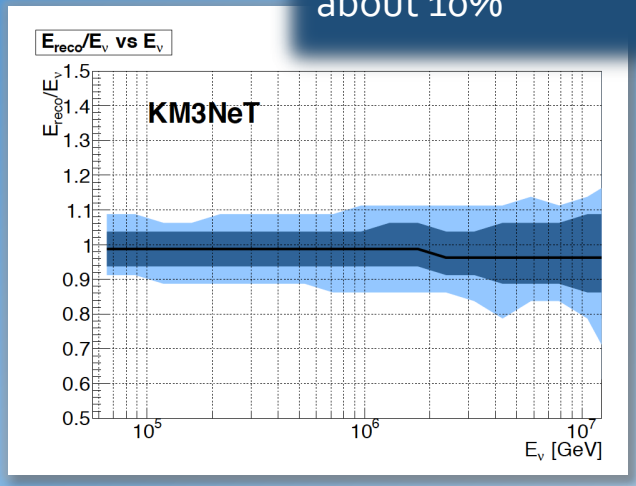


Event Topologies and Detector Response

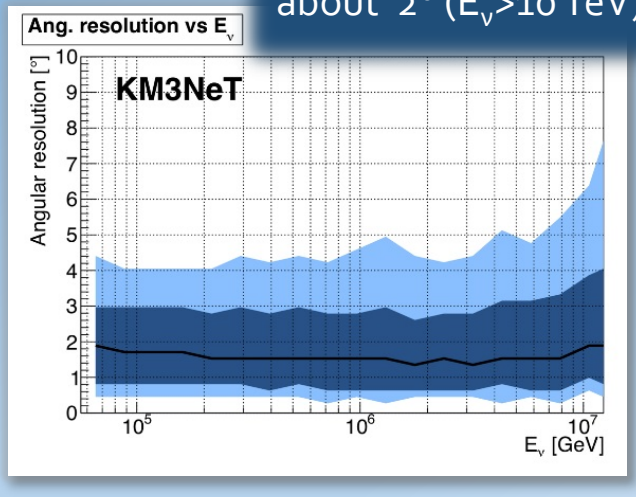
- Contained shower ν_e



Energy resolution about 10%

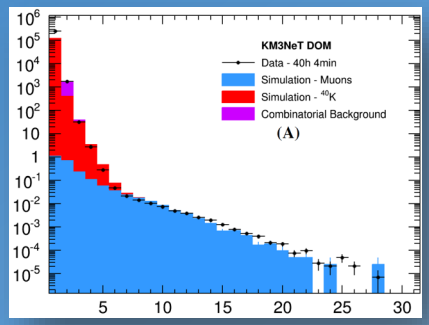


Angular resolution about 2° (E_ν>10 TeV)



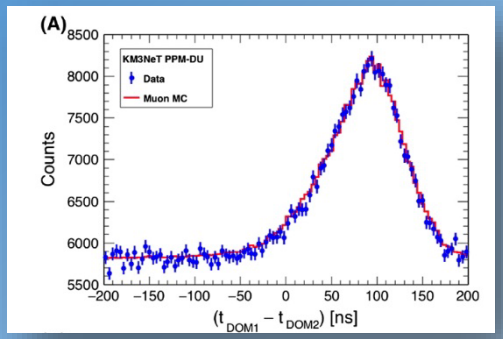
From Validation to Construction

Prototype DOM deployed at Antares site April 2013



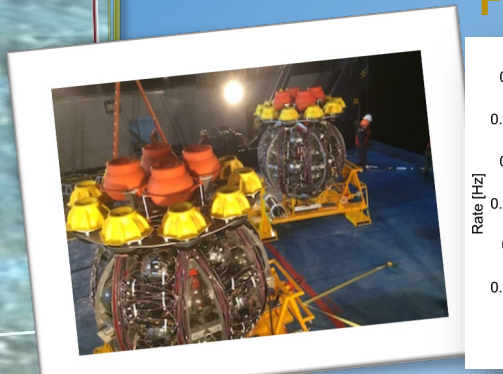
Test of photon counting capabilities and directional sensitivity of DOM
Eur. Phys. J. C (2014) 74:3056

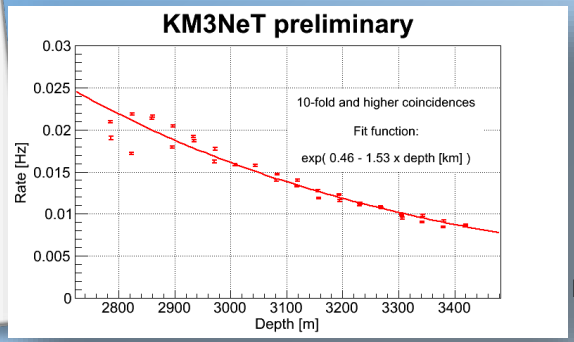
Prototype DU (three DOMs) deployed in Capo Passero May 2014



Test of DU structure functionality
Test of intra-DOM and inter-DOM calibration - *Eur. Phys. J. C (2016) 76:54*

First ARCA DU deployed in Capo Passero December 2015

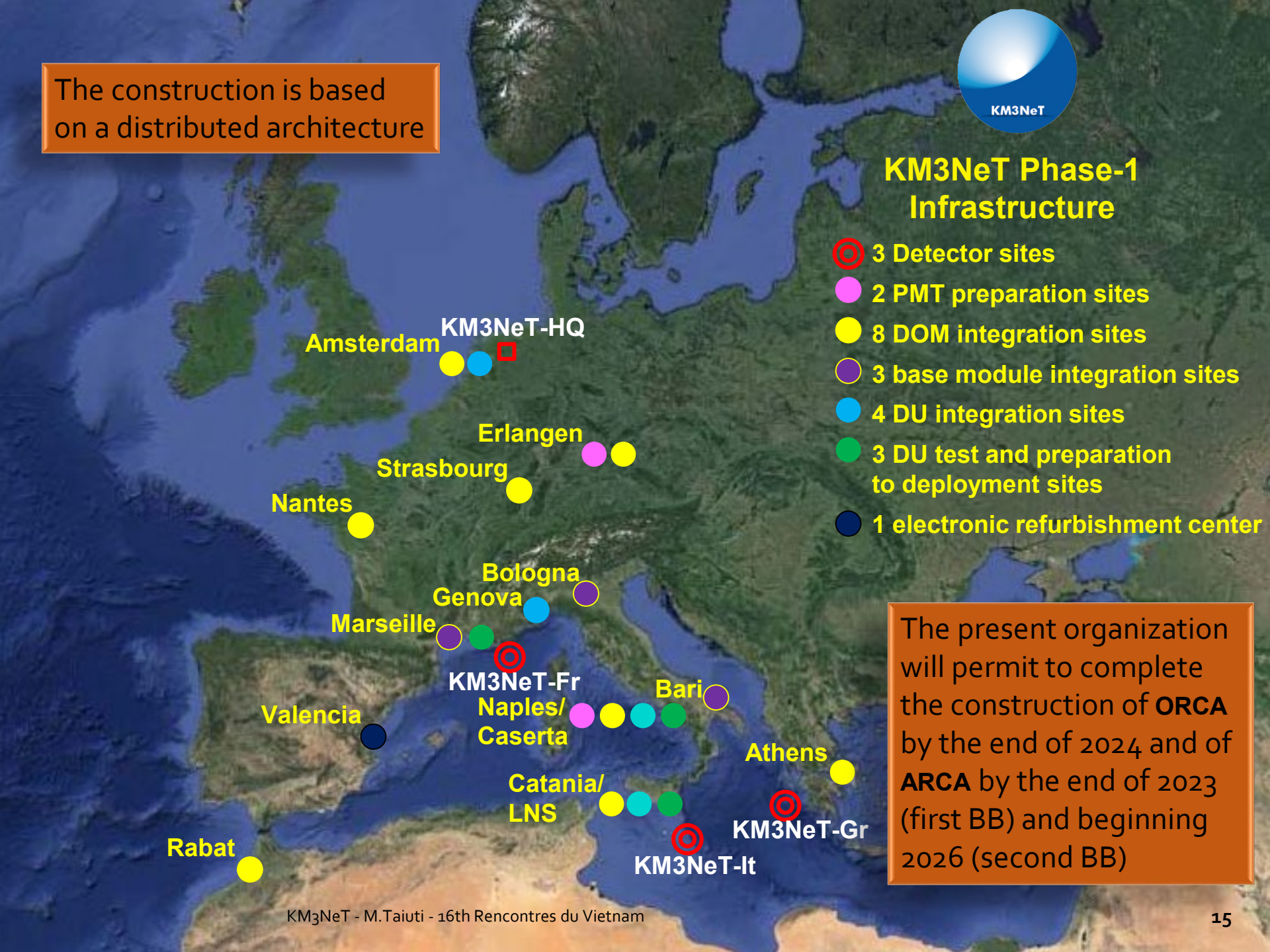




Muon flux dependence on depth
DU calibration
Trigger implementation
Track reconstruction and MC comparison (papers in preparation)

A Phased Approach

PHASE	BLOCKS	PRIMARY DELIVERABLES	FUNDS
1	0.2	Proof of feasibility and first science results 24 **ARCA** + 6 **ORCA** strings	Fully funded
2	2+1	All flavor neutrino physics and astronomy 2 x 115 **ARCA** strings 1 x 115 **ORCA** strings	Funding in progress (presently 1/3 available)
3	6	Neutrino astronomy including Galactic sources **P2O** – Long Base Line **Protvino**-**ORCA**	Next step


The construction is based on a distributed architecture
KM3NeT
KM3NeT Phase-1 Infrastructure
3 Detector sites
2 PMT preparation sites
8 DOM integration sites
3 base module integration sites
4 DU integration sites
3 DU test and preparation to deployment sites
1 electronic refurbishment center
Amsterdam
KM3NeT-HQ
Erlangen
Strasbourg
Nantes
Bologna
Genova
Marseille
KM3NeT-Fr
Bari
Valencia
Naples/ Caserta
Athens
Catania/ LNS
KM3NeT-Gr
KM3NeT-It
Rabat
The present organization will permit to complete the construction of ORCA by the end of 2024 and of ARCA by the end of 2023 (first BB) and beginning 2026 (second BB)

Phase 1 - ARCA

- ARCA-DU1 and ARCA-DU2 deployed December 2015 and May 2016 at Capo Passero, Sicily and worked till April 2017
- ARCA-DU1 operativity resumed in January 2019
- Plenty of data
- Presently the on-shore station is under renovation to host the second cable power supply
- The seafloor network is scheduled to return operative before summer 2020 with 6 DUs connected

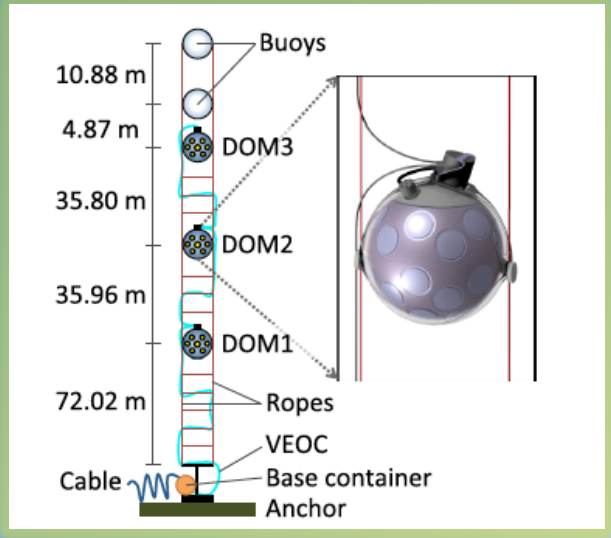
Phase 1 - ORCA

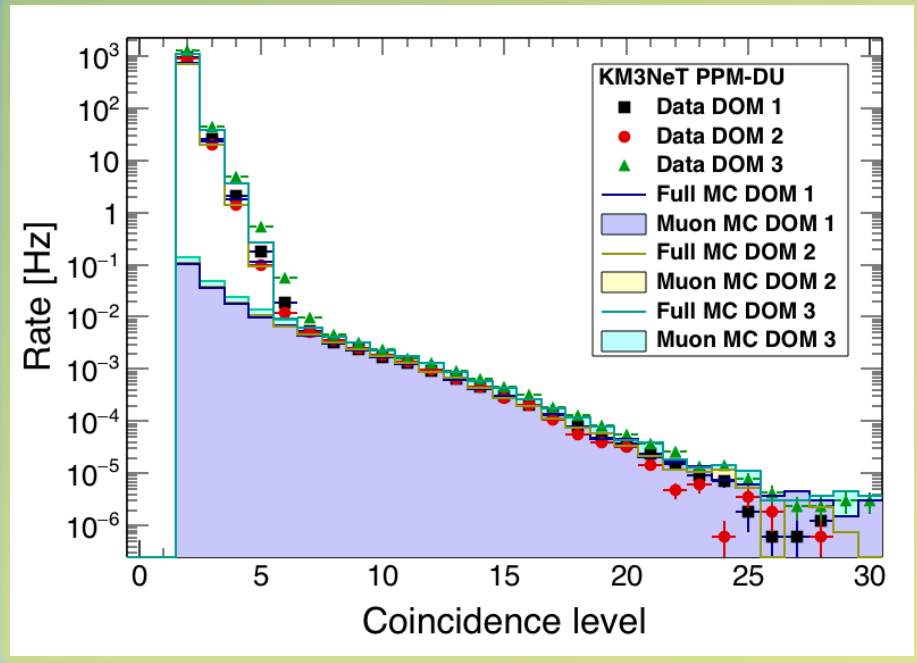
- First ORCA DU successfully deployed and connected in September 22nd, 2017
- Replacement of the cable during two different sea campaigns in October 2018 (12th-16th and 22nd-26th)
- Two DUs in operation since May 17th, 2019
- Four DUs in operation since July 1st, 2019
- The deployment of two additional DUs postponed to early 2020 due to bad weather conditions

The Performances

DOM Performances

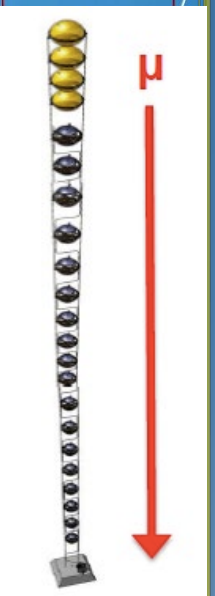
- The DOM design allows the rejection of environmental background setting a threshold on multiplicity
- The DOM provides also info on the direction of the detected light

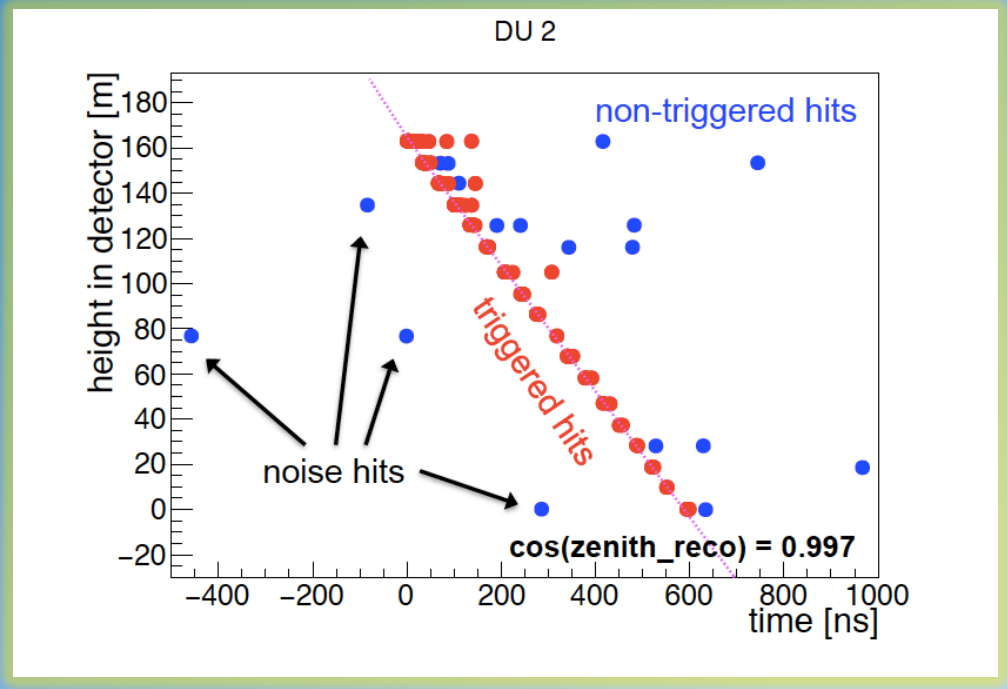


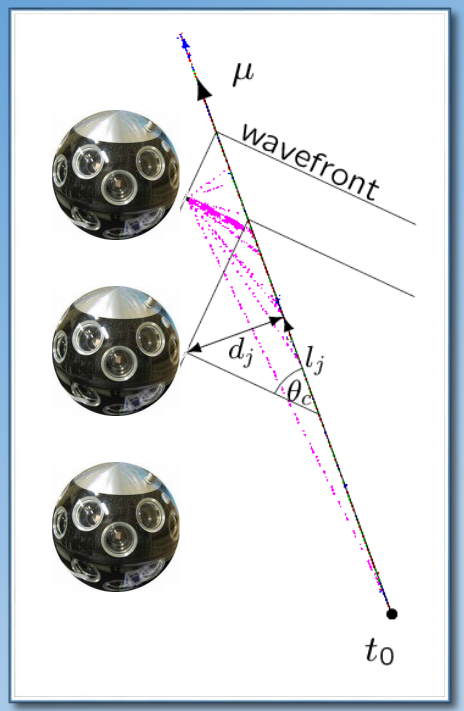


DU Performances

- Events are reconstructed with timing DOM correlation
- Very low ambiental noise

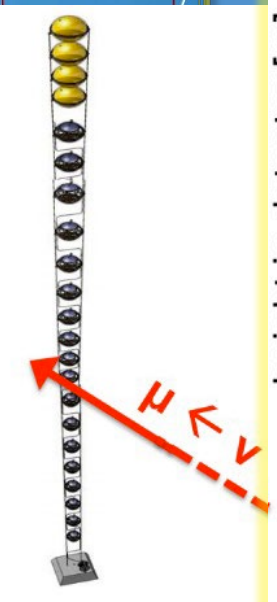


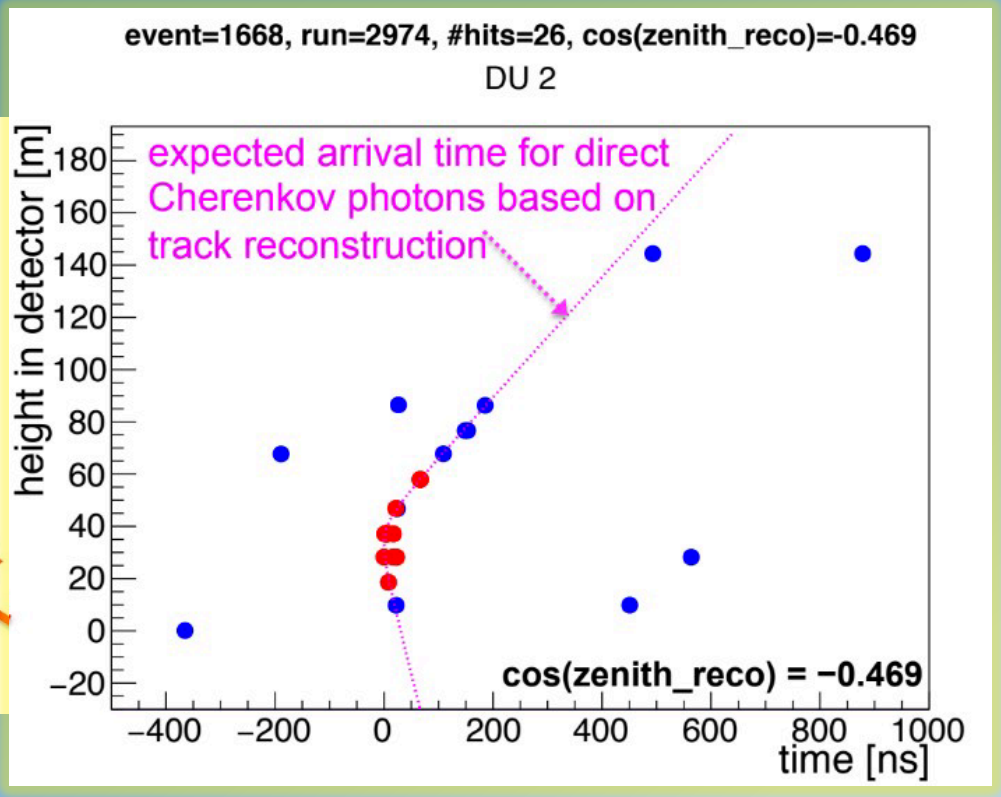


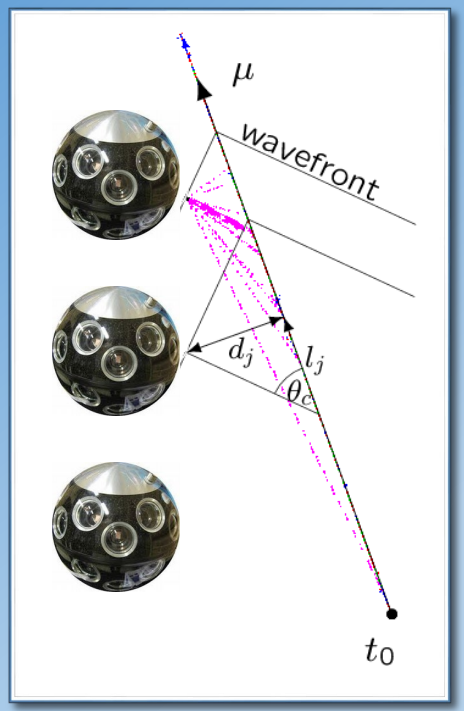


DU Performances

- Events are reconstructed with timing DOM correlation





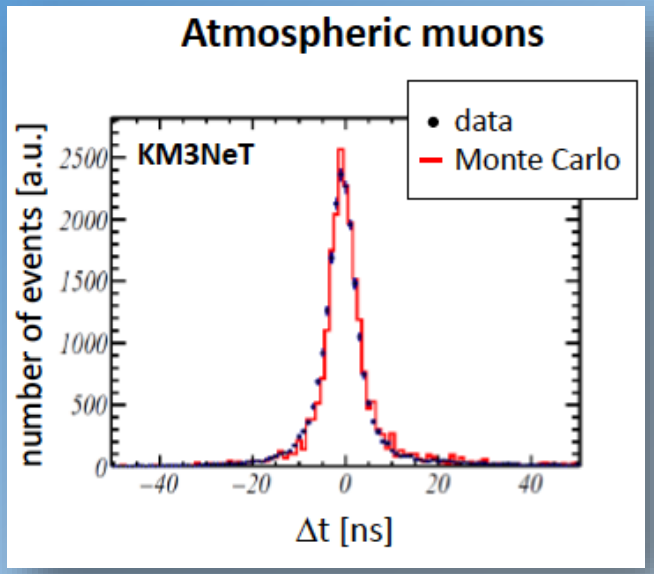


Detector Performances

- **KM3NeT-ARCA** project goals
  - For E_ν >10 TeV track events (muons) ⟶ Median angular resolution <0.2°
- Requirements
  - *Timing* - Relative hit time accuracy ~ 1 ns
  - *Orientation* - PMT orientation accuracy < 3°
  - *Positioning* - DOM position accuracy < 20 cm (corresponding to the distance traveled by Cherenkov photons in 1 ns)

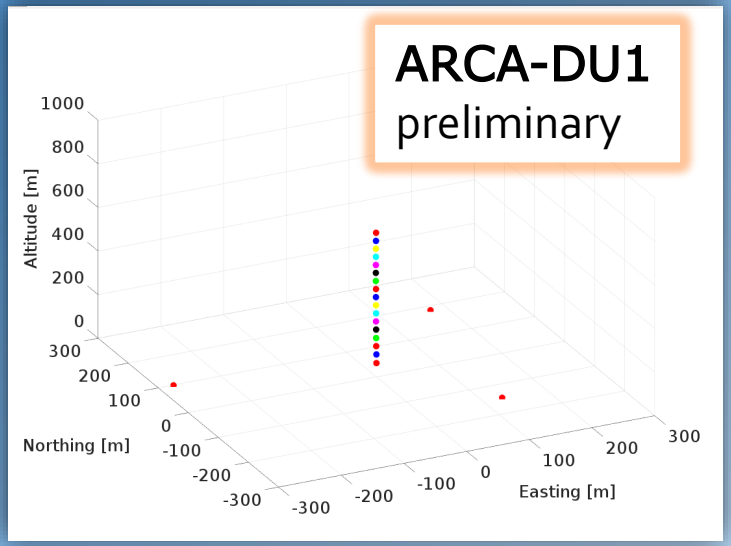
Technical Solutions

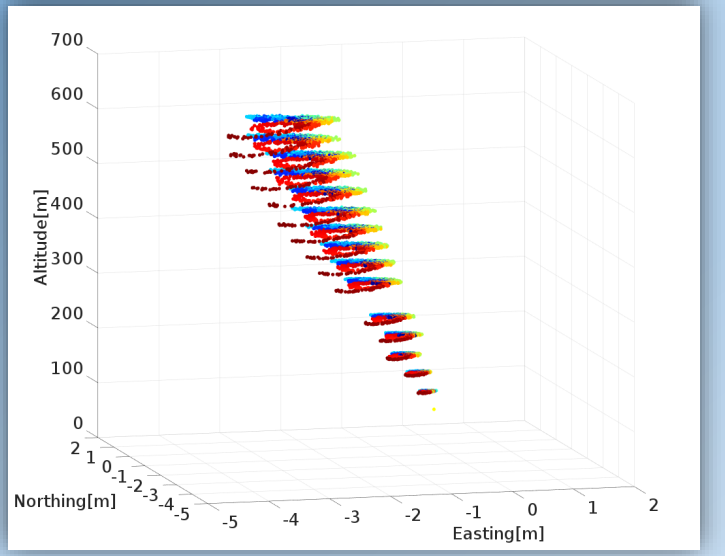
- Timing:
  - synchronization based on White Rabbit time distribution protocol
- Orientation:
  - Compass installed in each DOM
- Positioning:
  - Long Base-Line (LBL) of acoustic transmitters (beacons) and receivers, located at known positions as provided by NAAPS (Navigation and Absolute Acoustic Positioning System)
  - Piezo-electric Digital Acoustic Receivers (DAR) glued to the glass sphere of each DOM (used also to monitor the movement of the DUs)



Positioning System

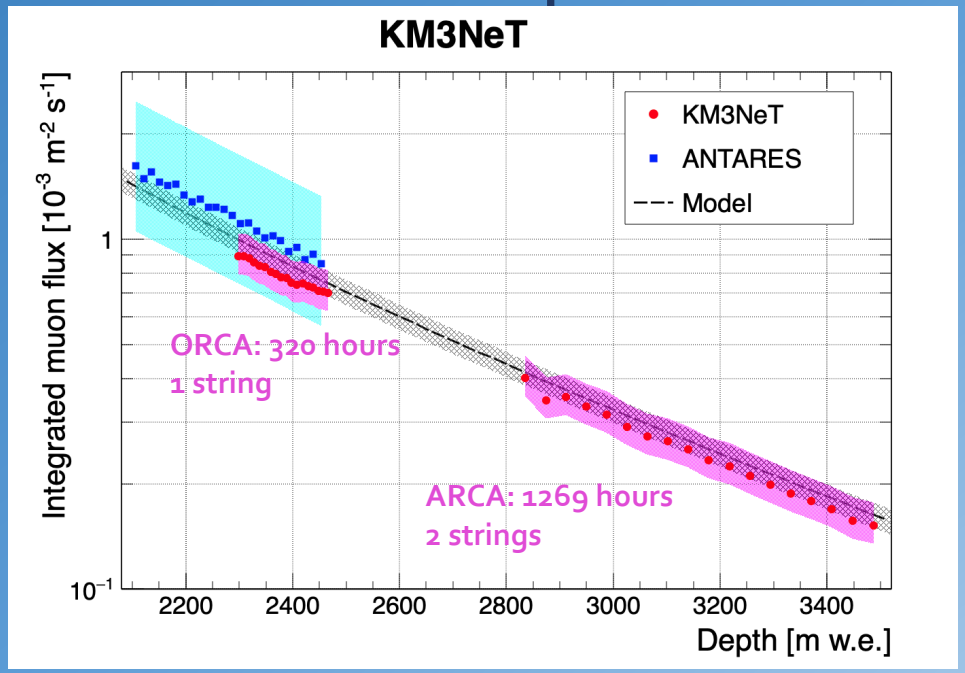
- The DU shape and the DOM position is known at the level of few cm!





First Results

ARCA + ORCA Muon Flux Depth Dependence

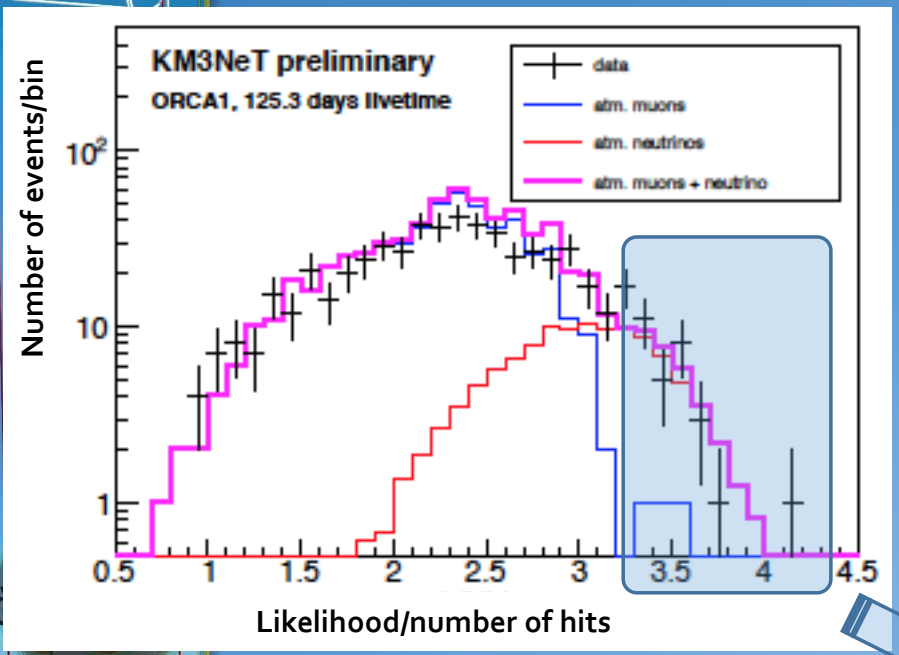


Absolute muon flux

Single DOM A_{eff}=96±4 m²

Integrated atmospheric muon flux measured as a function of depth below the sea level (red points). The systematic errors are displayed as light red shadowed areas.
The Bugaev model of the atmospheric muon flux is drawn with a dashed black line.
ANTARES data are included as blue points for comparison (systematic errors are the light blue shadowed area).
The depth is expressed in water equivalent (w.e.). Statistical uncertainties are included and smaller than markers.

Neutrinos in ORCA

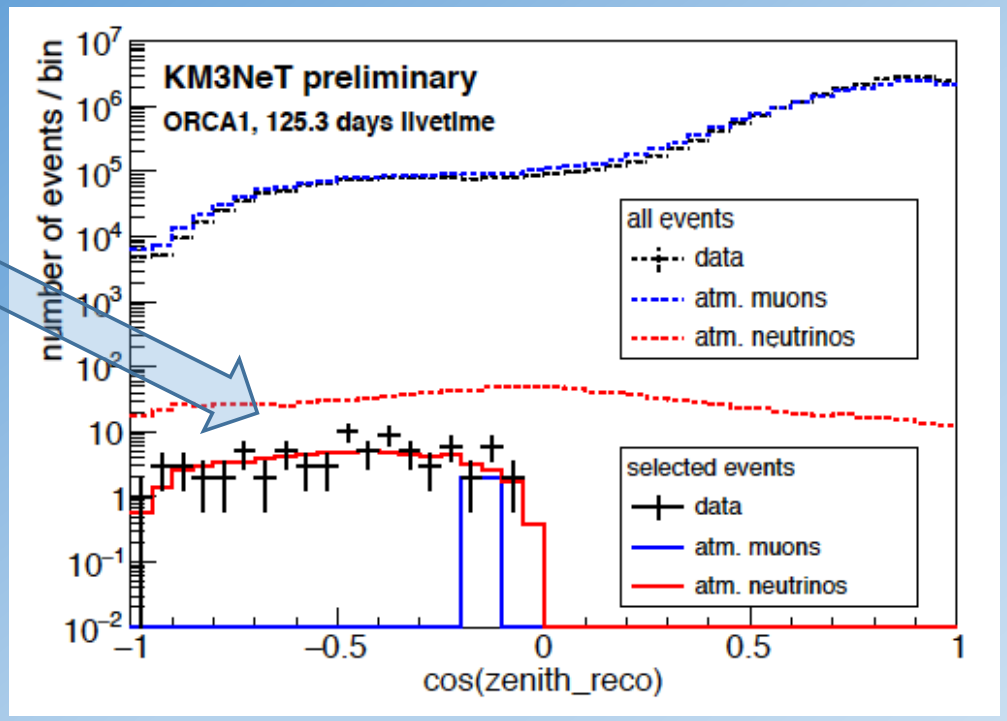


surviving events after quality track cuts:

Data: 77

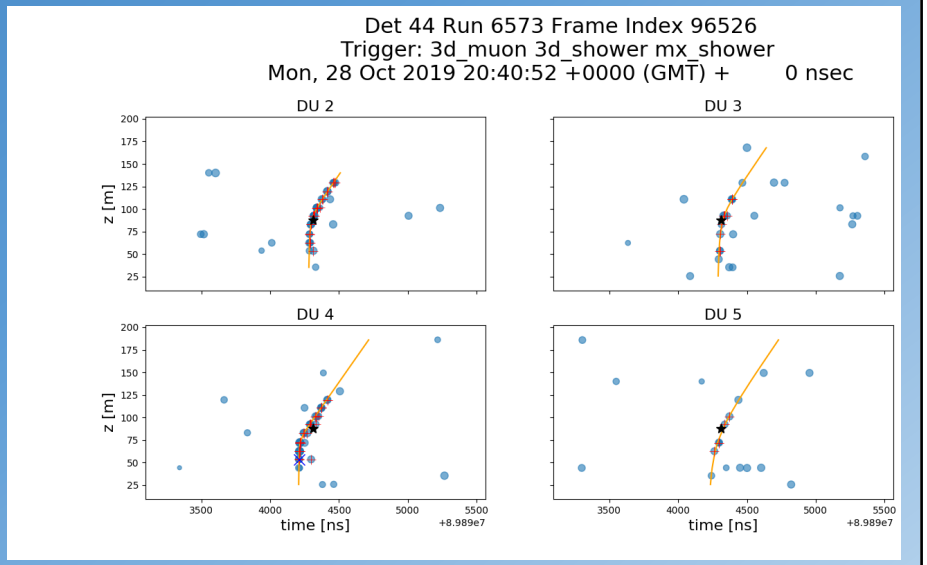
ν MC: 67.5

μ MC: 4



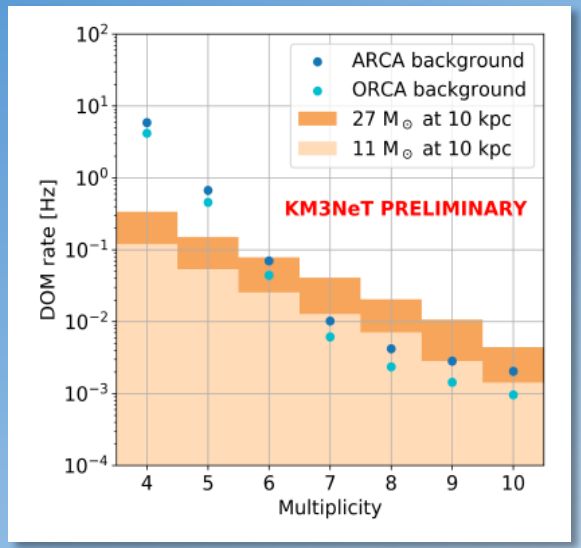
Neutrinos in ORCA

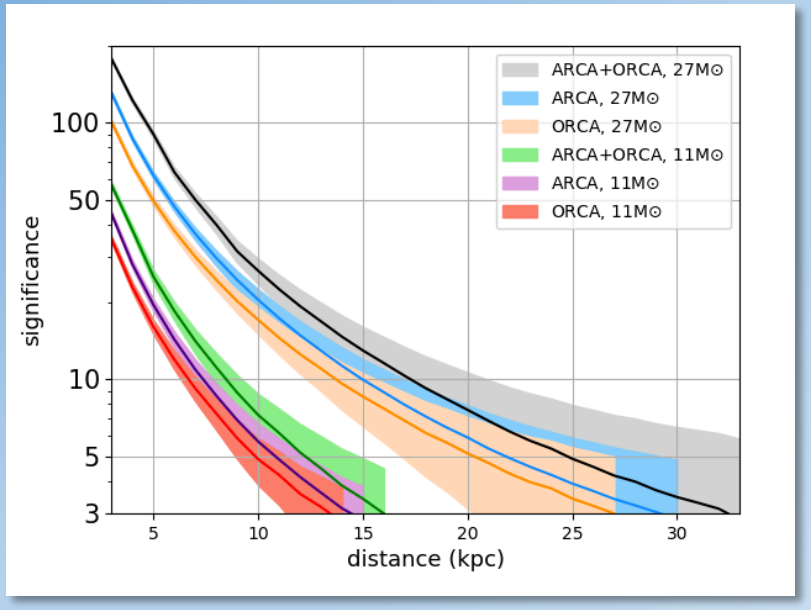
- Neutrino candidates with 4 DUs



Sensitivity to Supernovae

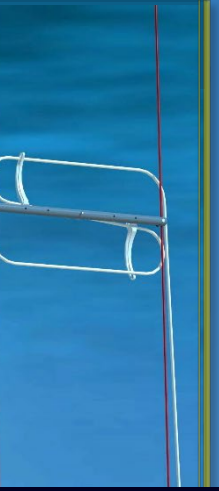
- Single DOMs can be used as Supernova neutrino detector
- Coincidences due to Supernova neutrinos show a harder distribution than ^{40}K but softer than muons
- Best sensitivity for PMT coincidence level 6-10
- Combined sensitivity : 5σ for **ARCA+ORCA** for 27M⊙ at a distance 25kpc

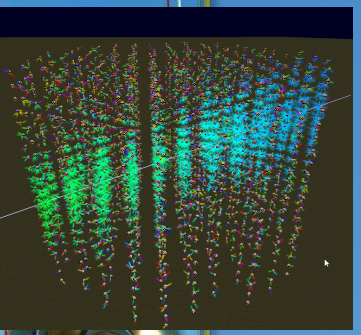


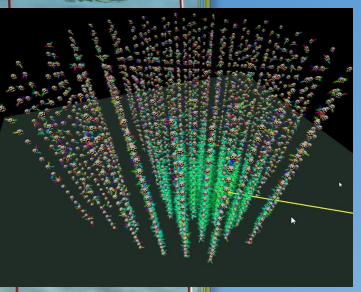


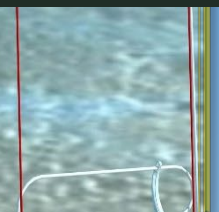
Physics Program

ARCA Sensitivity to Diffuse Neutrino Flux



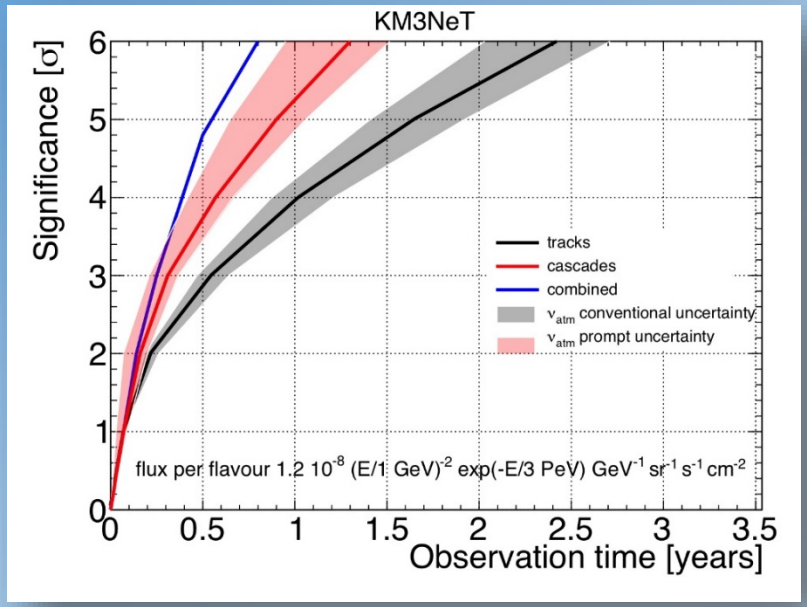




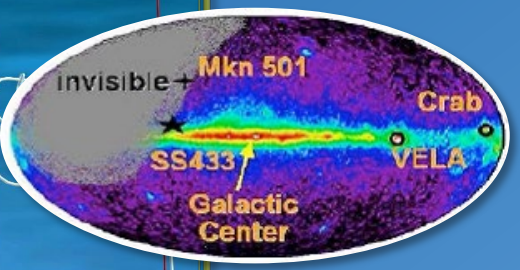


Monte Carlo studies

- ***Track channel***: analysis for up-going events based on max. likelihood
  - Pre-Cuts on θ_{zen} >80°, Λ (reconstruction quality parameter), N_{hit} (number of hits → parameter related to the muon energy)
- ***Cascade channel***: contained events
  - **Vertex cut**: cut on position of reconstructed vertex (z<200 m .AND. r<500 m)
  - **Energy cut**: cut on the total Time-over-Threshold (ToT) of the event (ToT>12 μs)

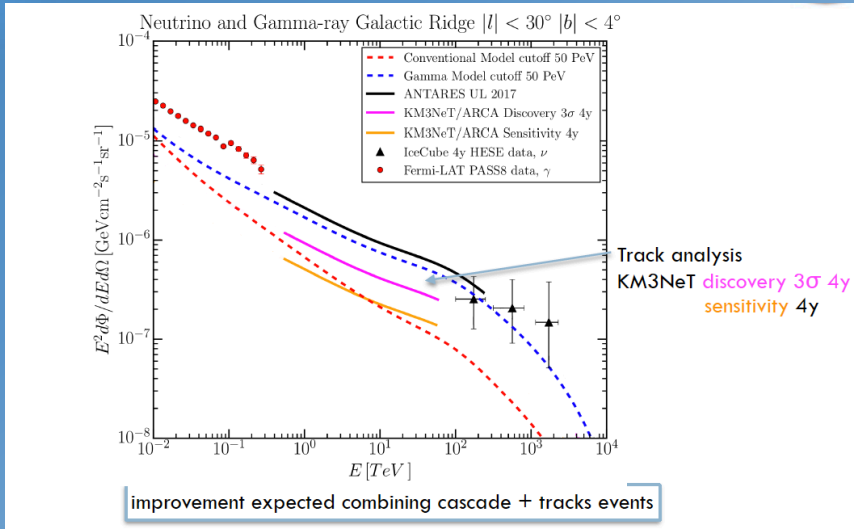


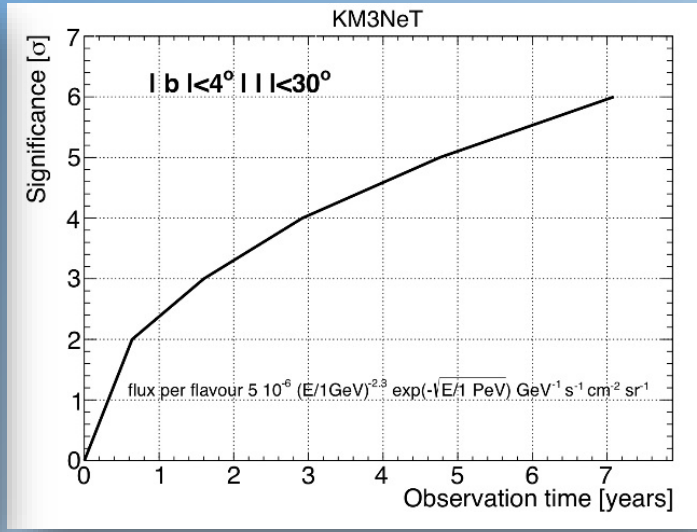
Discovery at 5σ significance in less than one year



ARCA Sensitivity to Diffuse Flux from the Galactic Plane

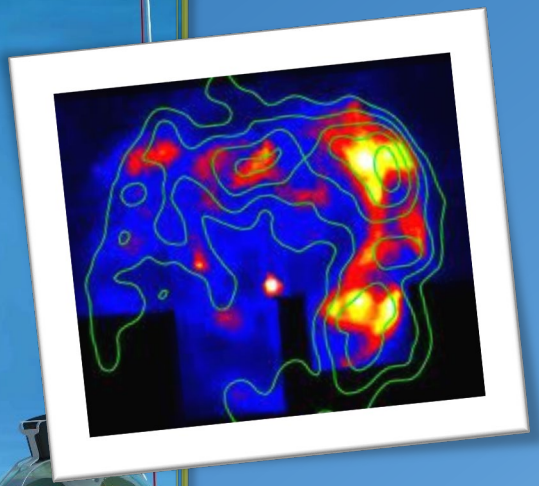
- **ARCA** sensitivity to a flux from a region of the Galactic Plane near the Galactic Center. Neutrino flux estimate based on a radially-dependent cosmic-ray transport model

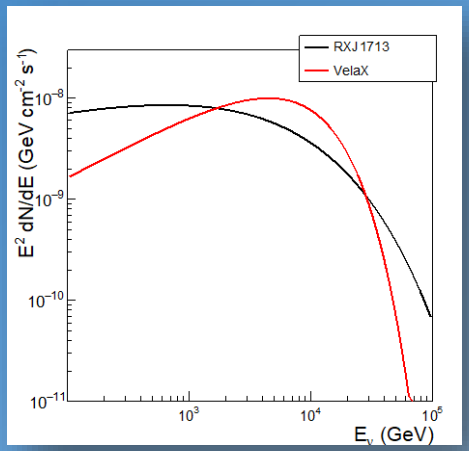


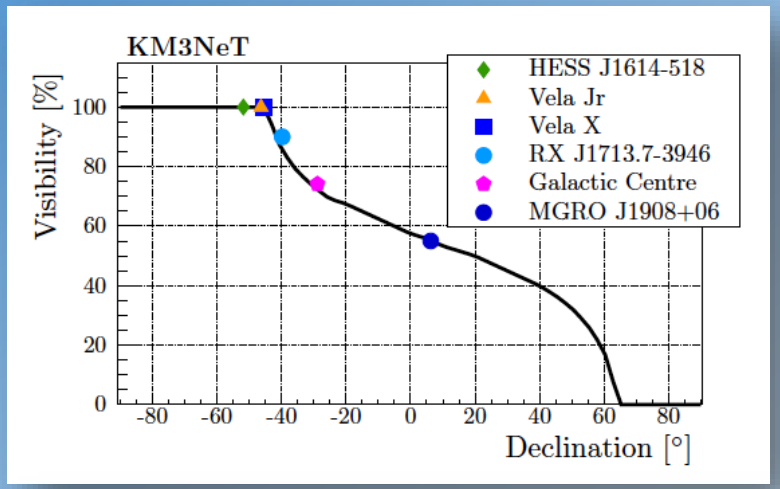


Discovery at 5σ significance in about 5 years

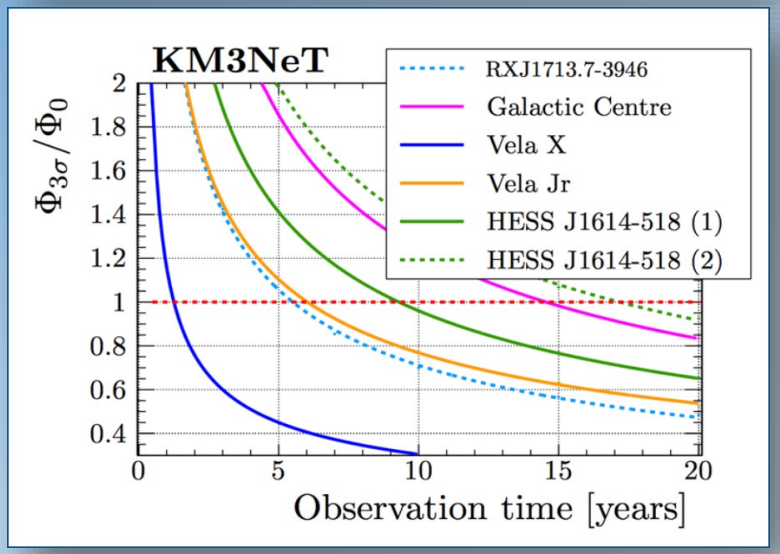
ARCA Sensitivity to Point-like Galactic Sources





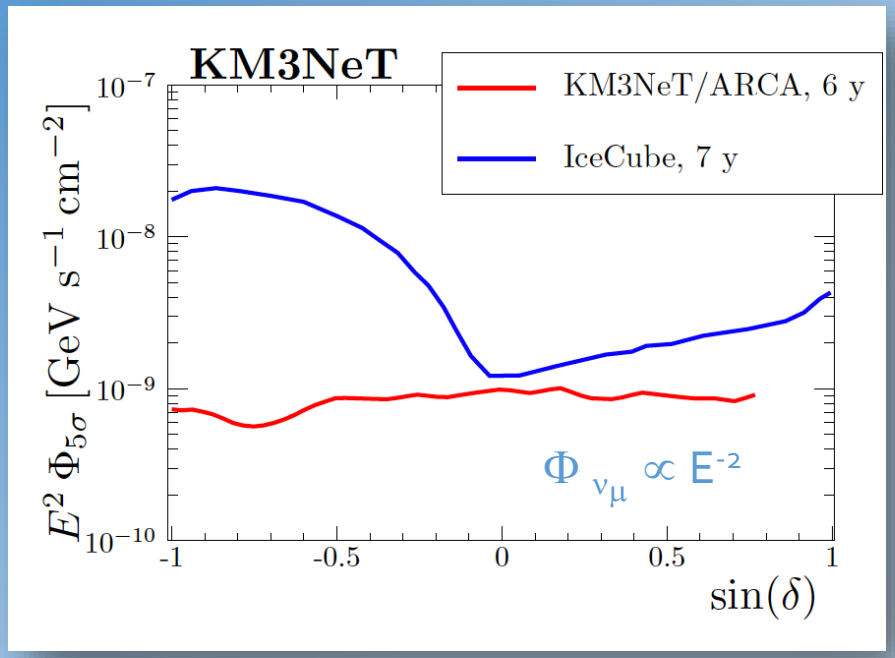


- HE gamma emission observed by HESS in SNRs
- Neutrino spectra predicted using gamma spectra
  - ¶ S.R. Kelner, *et al.*, PRD 74 (2006) 034018
  - § F.L. Villante and F. Vissani, PRD 78 (2008) 103007
- Hypotheses: 100% hadronic emission and transparent source



ARCA Sensitivity to Point-like Sources

- **ARCA** can survey almost the whole sky with a discovery potential @ 5σ about one order of magnitude better than **IceCube** for equivalent exposure

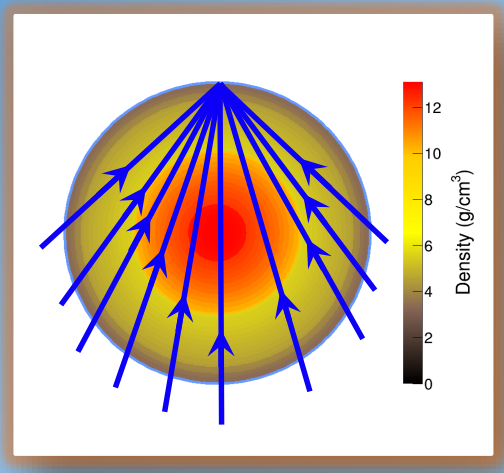


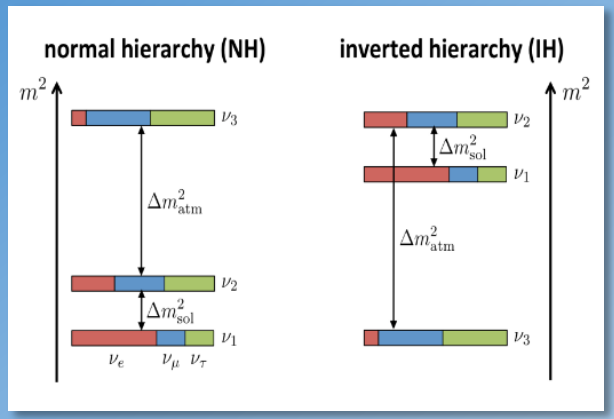
Neutrino Mass Hierarchy with ORCA

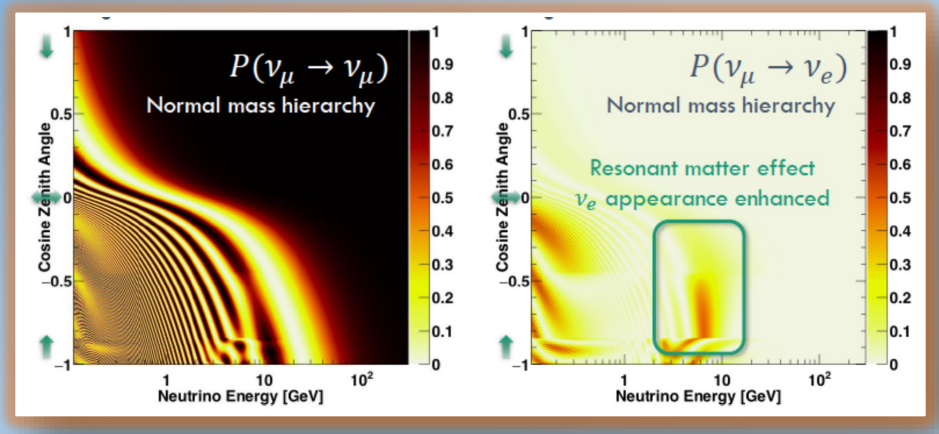
- A "*free beam*" of known composition (ν_e, ν_μ)
- Wide range of baselines and energies
- Oscillation pattern distorted by Earth matter effects

  maximum difference IH vs NH for resonance in

  Earth mantle: θ=130° (7645 km) and E_ν = 7 GeV

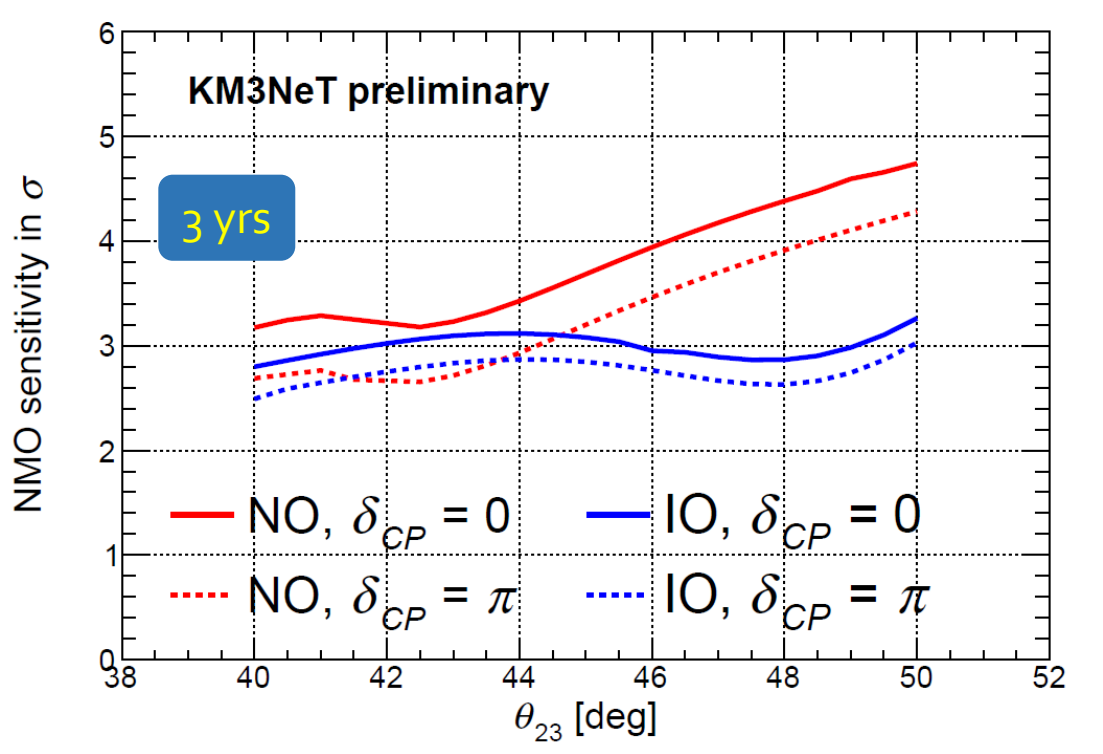






ORCA Sensitivity to Mass Hierarchy

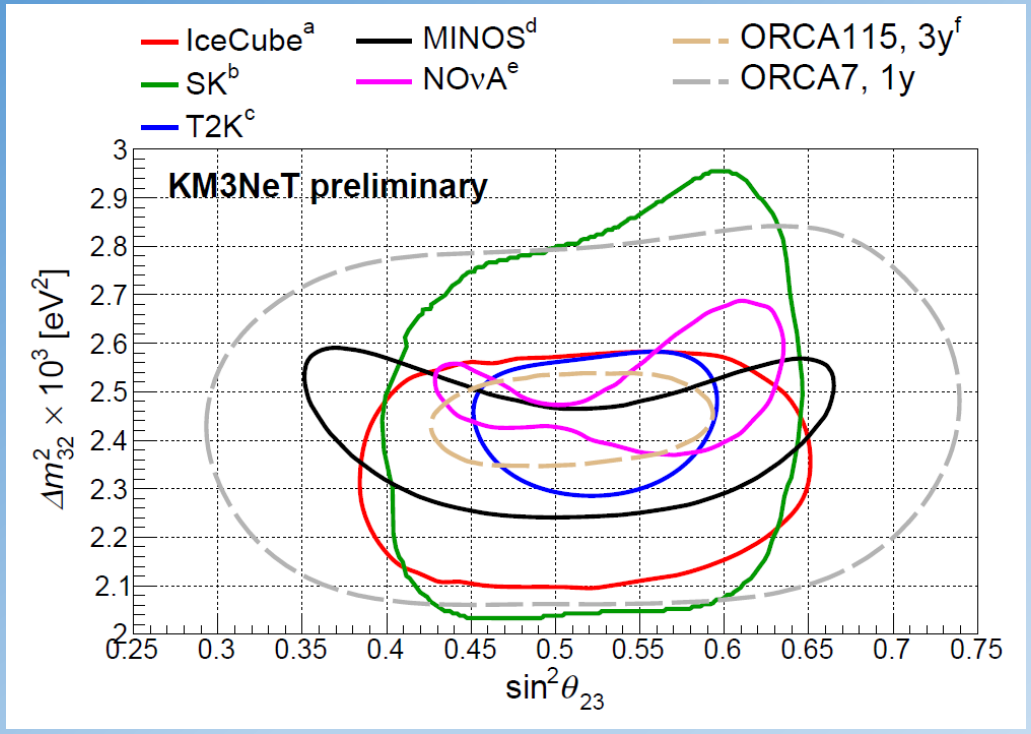
- 3σ for most of the parameter space after 3 years
- much better if NH and 2-nd Octant of θ_{23}



ORCA Measurement of Δm^2_{32} and $\sin^2\theta_{23}$

- Achieve 2-3% precision in Δm^2_{32} and 4-10% in $\sin^2\theta_{23}$
- Competitive with NOvA and T2K projected sensitivity in 2020
- T2K 7.8 10^{21} p.o.t.

Normal Hierarchy



Additional **ORCA** Physics Topics

- Unitarity of PMNS matrix
- Exotic physics
  - sterile neutrino, non-standard interactions
- Dark Matter
- Earth tomography
- Low energy neutrino astronomy
  - Transient phenomena
- Earth and Sea Science

Multi-messenger Program

- Alerts:
  - Online reconstruction
  - Dedicated triggers for events of interest
  - Distribute alerts via the GCN network
  - The optimization of the dedicated trigger for Galactic Core Collapse Super Novae has already begun
- Follow up EM / GW alerts
- Offline correlation with catalogs (GRBs, AGNs, XRBs, SNs, FRBs, …)
- Synergies and MoUs are in the process of being formed.

Summary

- Several lessons learned
- The measured detectors performances respect the design parameters
- We are confidently proceeding with the integration of the next DUs
- **KM3NeT** is going to become a key infrastructure for neutrino astronomy in the next decade


Thank you!