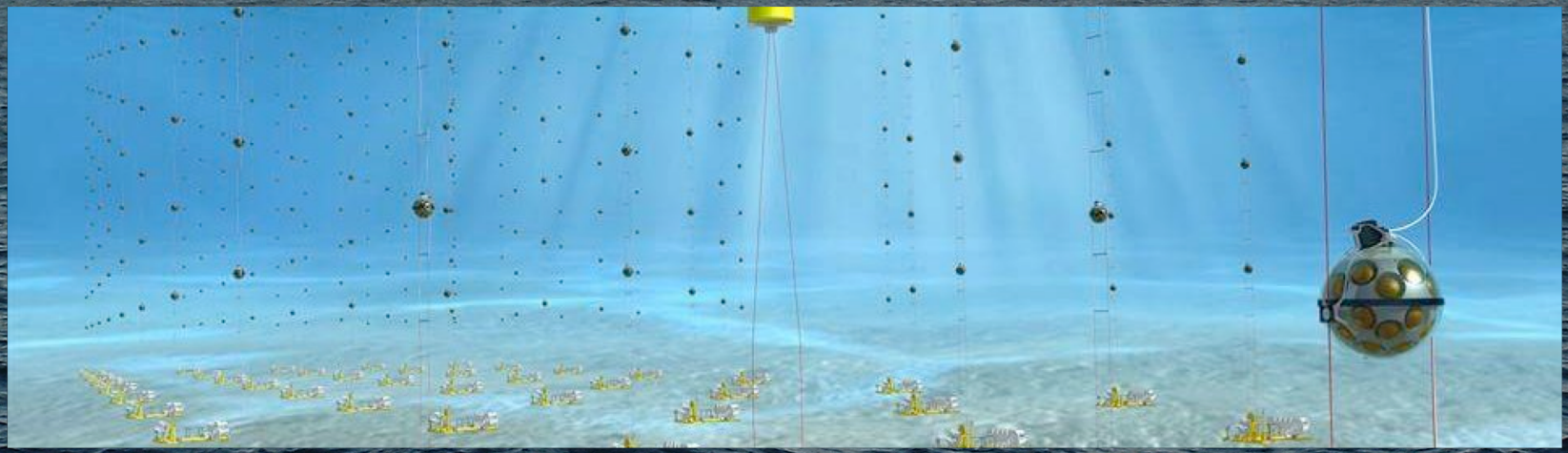
The KM3NeT project: status and future perspectives

C. Distefano

LNS-INFN

On behalf of the KM3NeT Collaboration



The KM3NeT project

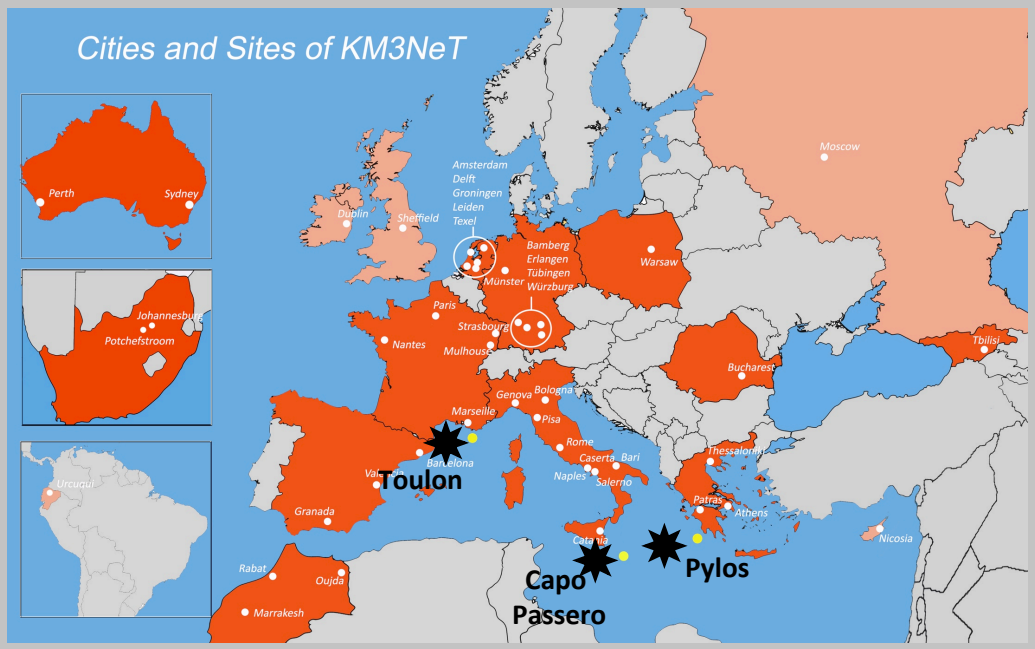
KM3NeT is a research infrastructure in the Mediterranean Sea hosting neutrino detectors

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

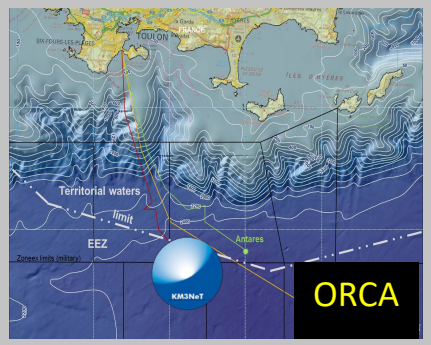
- neutrino physics and low energy neutrino astronomy (neutrinos of tens of GeV)

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

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



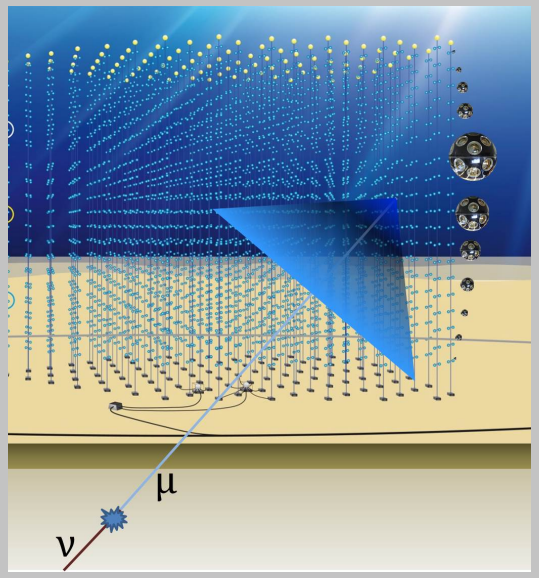
Potential 3rd site: Pylos, Greece

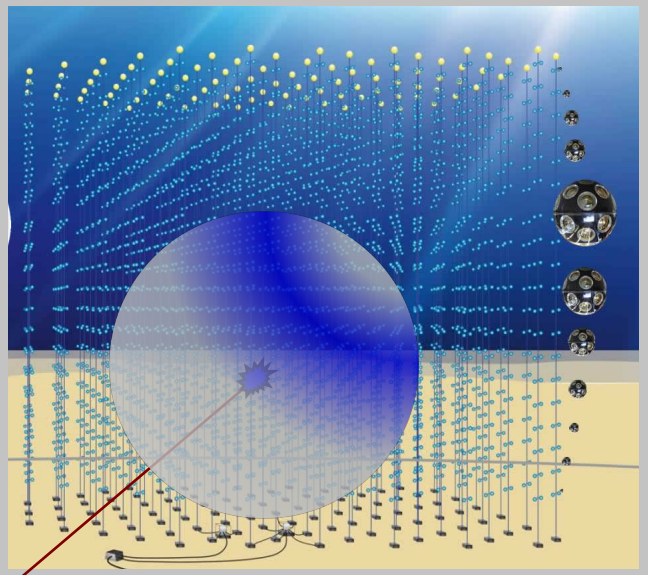


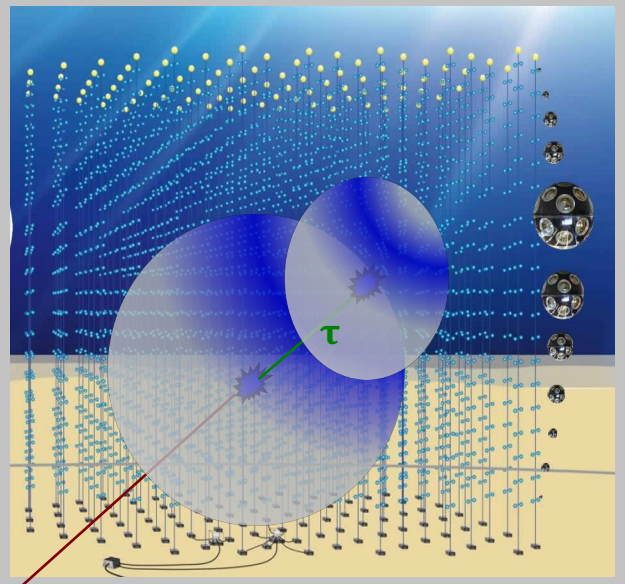
Toulon, France
Depth: 2500 m

Capo Passero, Italy
Depth: 3500 m

Neutrino detection channels







$$\nu_\mu \xrightarrow[CC]{} \mu + \text{shower}$$

$$\nu_\ell \xrightarrow[NC]{} \nu'_\ell + \text{shower}$$

$$\nu_e \xrightarrow[CC]{} \text{shower}$$

$$\nu_\tau \xrightarrow[CC]{} \tau + \text{shower}$$

$$\tau \xrightarrow[\sim 83\%]{} \nu_\tau + \text{shower}$$

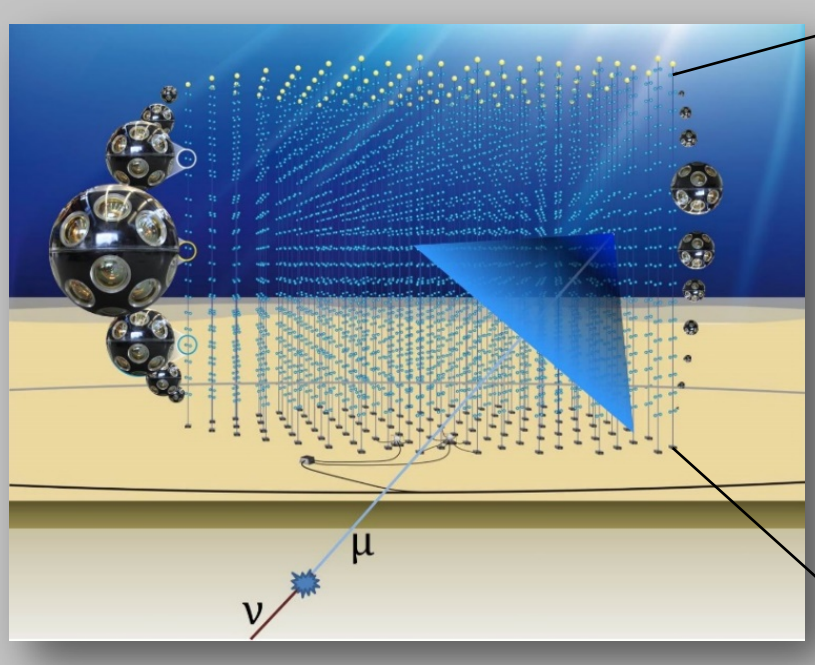
$$\tau \xrightarrow[\sim 17\%]{} \nu_\tau + \mu + \bar{\nu}_\mu$$

Muons:
highest effective area, good angular resolution (~0.1°)
High atmospheric muon background: look at events from below only

Showers:
Remove atmospheric muon background: studies over 4π.
'Good' energy resolution, worse directional resolution: diffuse flux!

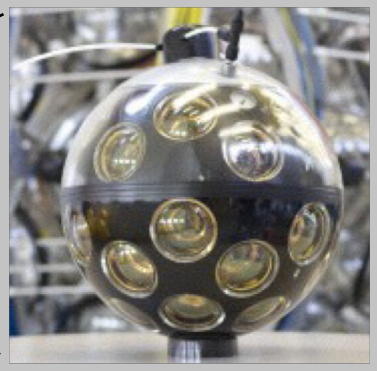
Taus:
Unambiguous topology

The KM3NeT detector design



The Detection Unit (DU)

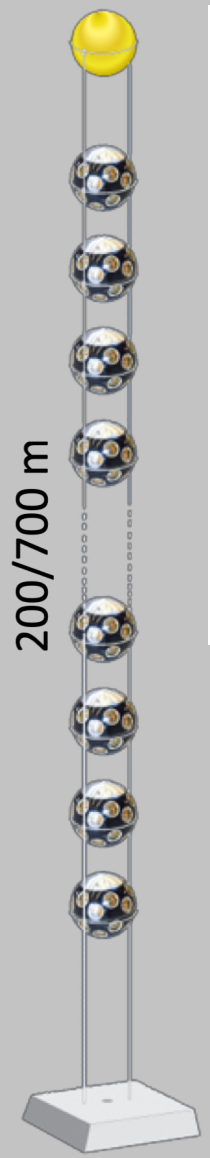
The optical sensor: the Digital Optical Module (DOM)

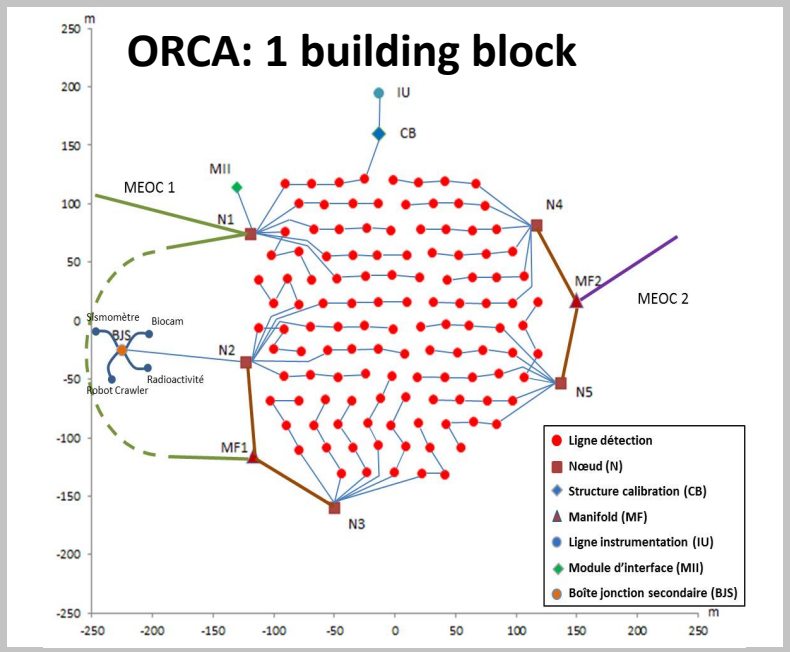


A 3D array of optical sensors built with a modular design:

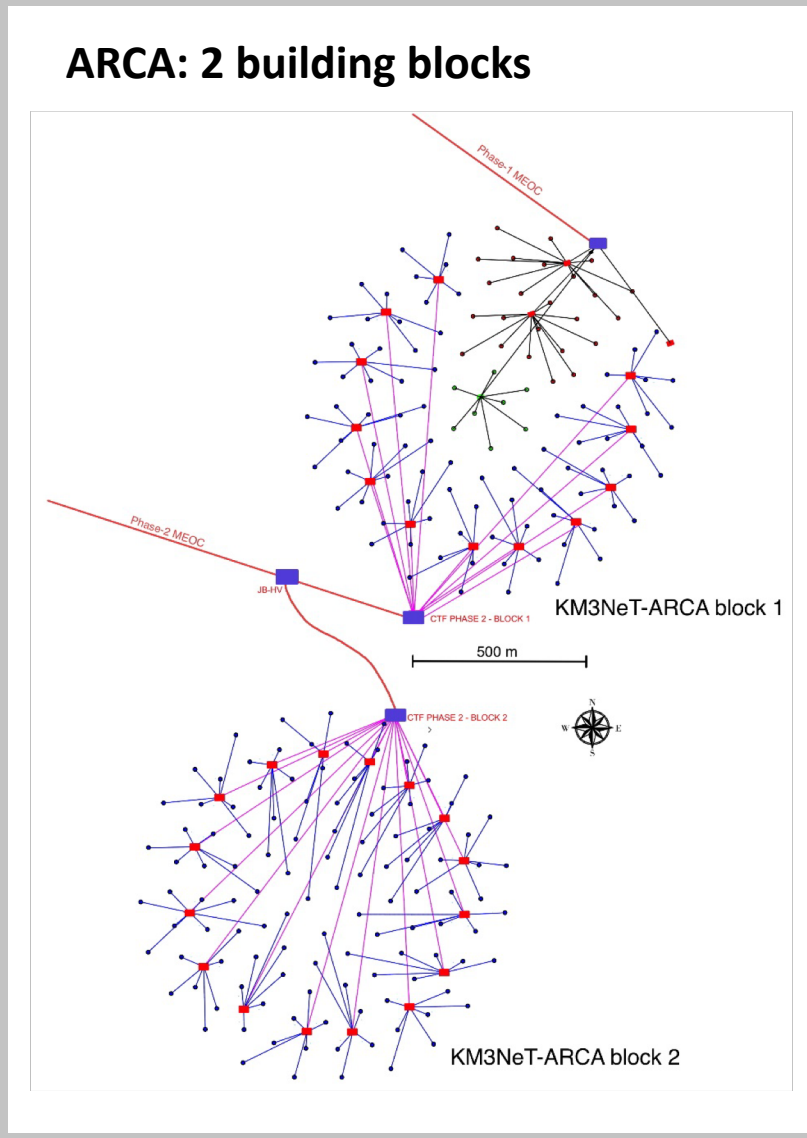
- Digital Optical Module (DOM): multi-PMT optical module consisting of 31 3'' PMTs.
- Detection unit (DU): vertical slender string host 18 DOMs
- Building blocks (BBs) of 115 DUs each (ORCA: 1 BB, ARCA: 2 BBs)
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Sea network of submarine cables and Junction Boxes connected to shore via a main e/o cable
- All data to shore

The KM3NeT detector layouts





	ORCA	ARCA
Location	France	Italy
Depth	2500 m	3500 m
DU distance	23 m	90 m
DOM spacing	9 m	36 m
DU height	200 m	700 m
Instrumented mass	8 Mton	2*500 Mton



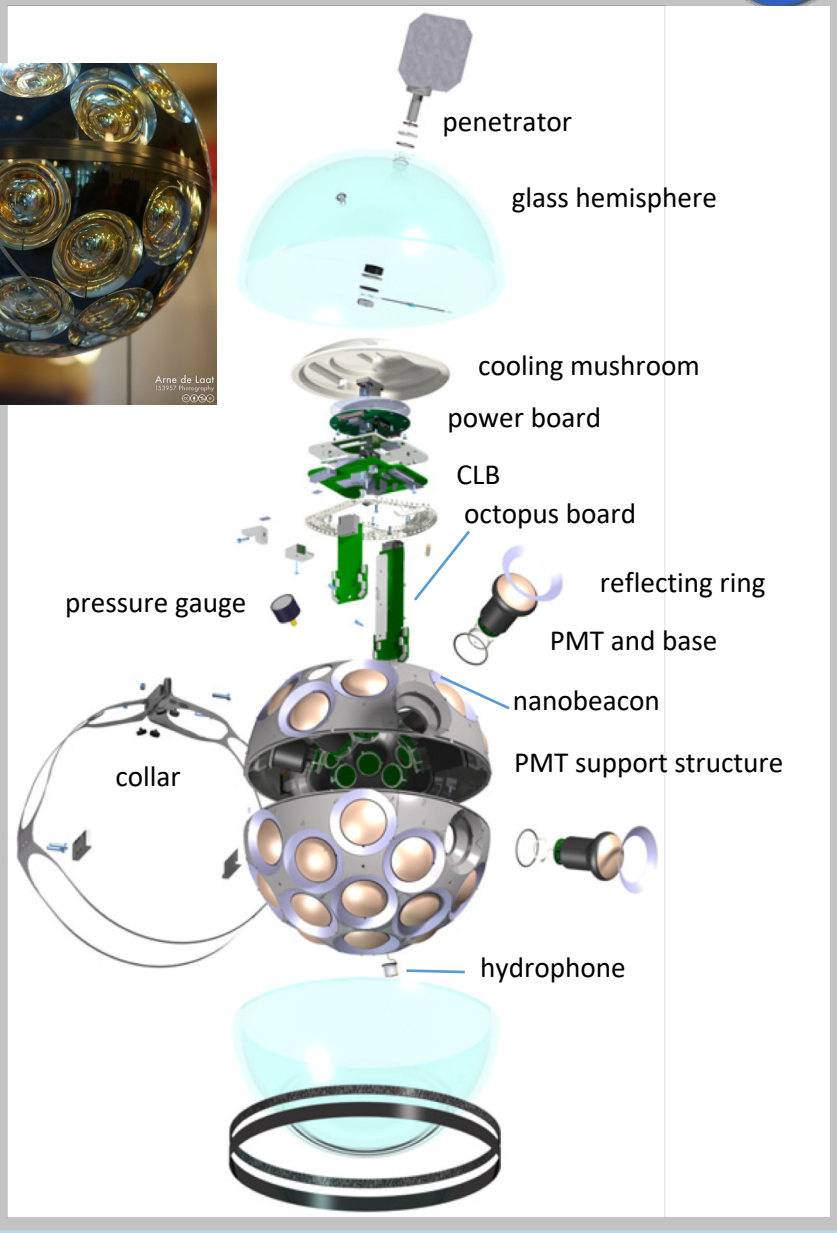
The KM3NeT Optical Module

The DOM is a new design for optical sensors developed in the collaboration.

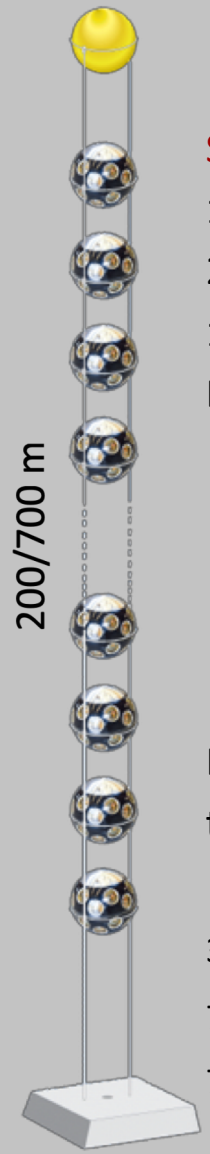
It is a 17” glass sphere with inside:

- 31 x 3” PMTs
- Light reflector rings around PMTs
- LED beacon and acoustic piezoelectric
- Tiltmeter/compass
- Gbit/s fibre DWDM for data transmission
- Hybrid White Rabbit for time synchronization

- Digital photon counting
- Directional information
- Wide angle of view
- Improved background rejection
- Compact and cost effective design:
  photocathode area ≃ 3 x 10” PMTs
  1 DOM equivalent to 3 ANTARES OMs



The KM3NeT detection unit



Detection Unit: vertical slender string with 18 DOMs

String:

1 Buoy

2 Dyneema ropes

18 DOMs

Electro-optical backbone:

- Flexible hose 7mm
- Oil-filled
- 18 fibres
- 2 copper wires (375VDC)

Different geometric arrangement for the two detectors:

36 (ARCA) /9 (ORCA) m distance between DOMs

72 (ARCA) /36 (ORCA) m anchor-first storey

700 (ARCA) /200 (ORCA) m total height from seabed

DU Base:

Anchor with electro-optical ROV mateable connector

Base Module:

- CLB (white rabbit timing)
- Power control board
- Optical amplifier

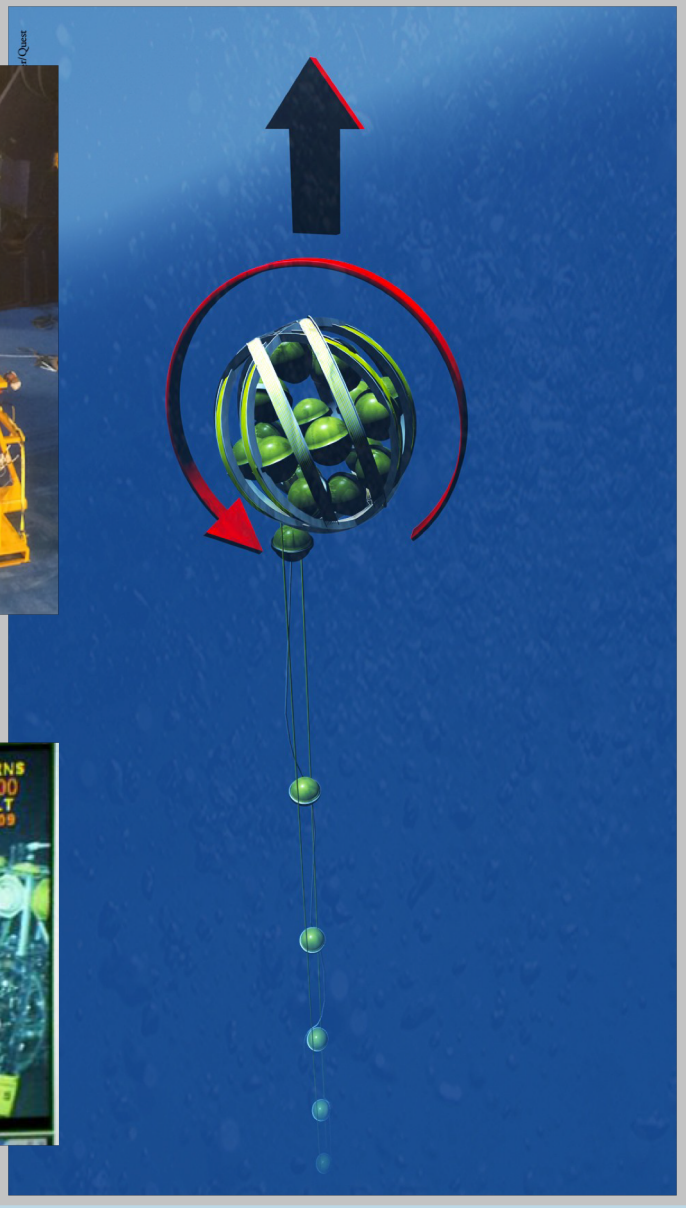
Hydrophone

LBL beacon

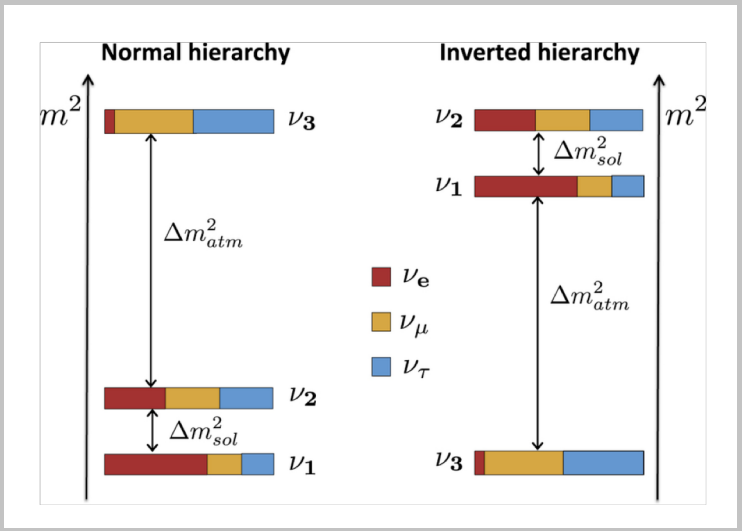
Detection unit deployment

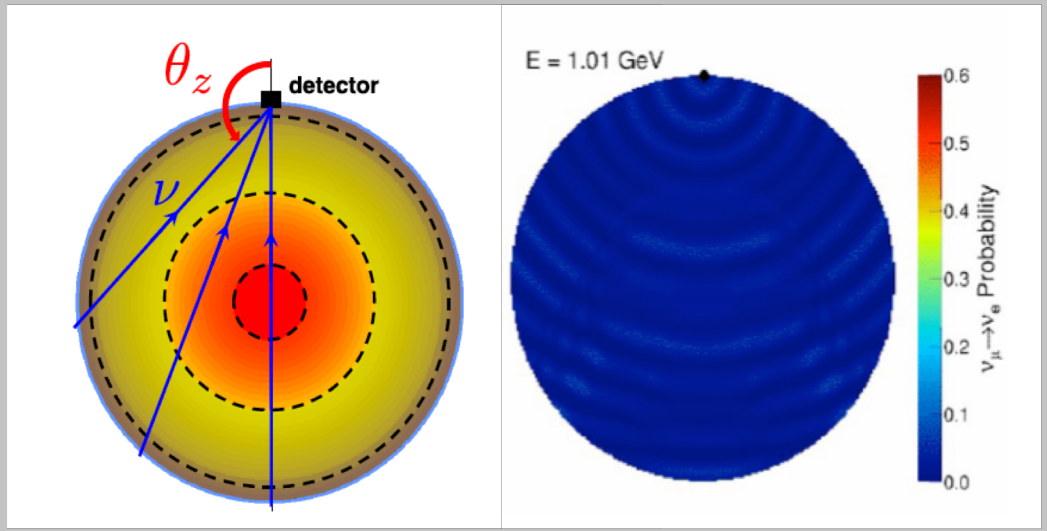
The Launcher of Modules (LoM)

- 2m diameter
- efficient deployment
- autonomous unfurling
- reusable
- deployment of several strings per sea operation

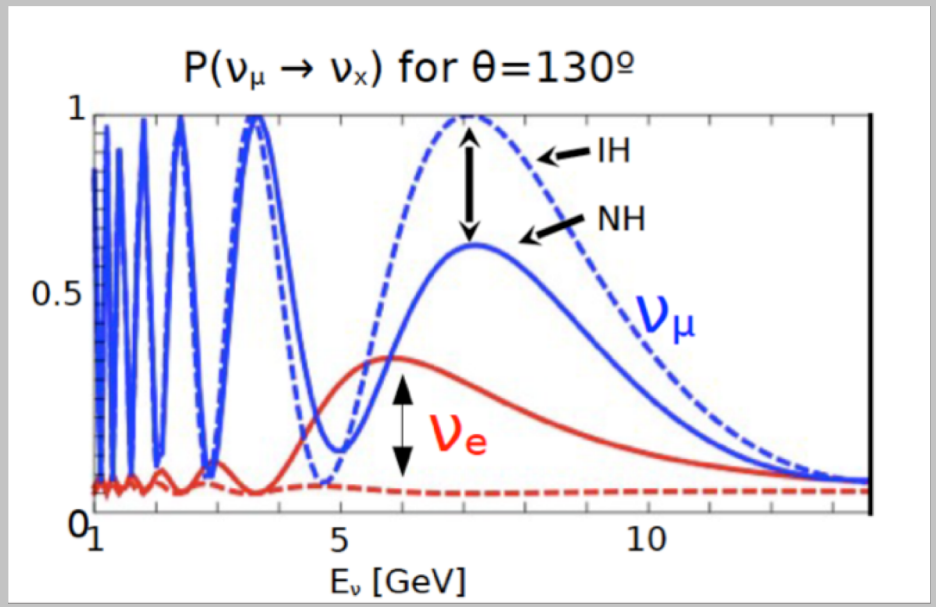


KM3NeT/ORCA: science goals



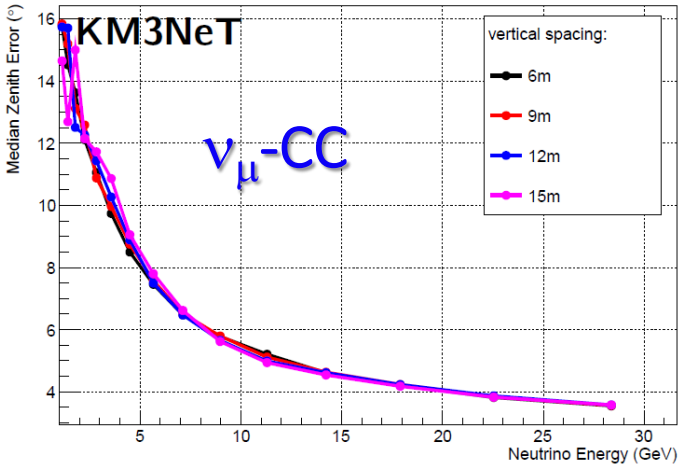


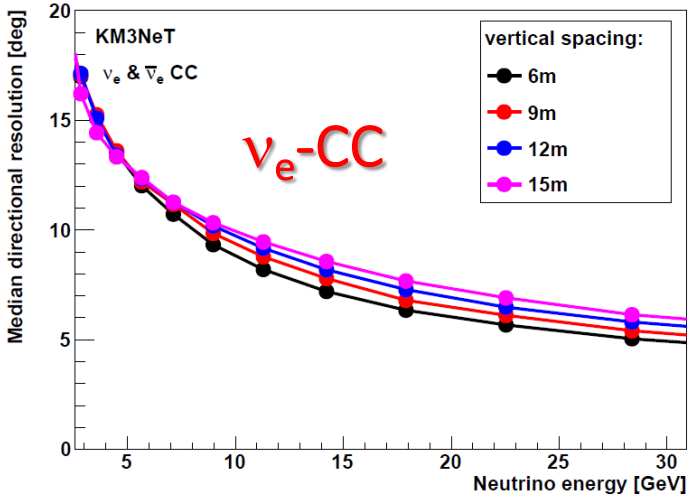
- Atmospheric flux of ν_e and ν_μ well known
- Wide range of neutrino energies (GeV - PeV)
- Wide range of zenith angles -> wide range of baselines (50 – 12800 km)
- Distortion of the neutrino oscillation pattern due to matter effects in the Earth



Angular resolution

Event reconstruction: fit hit position, time and multiplicity



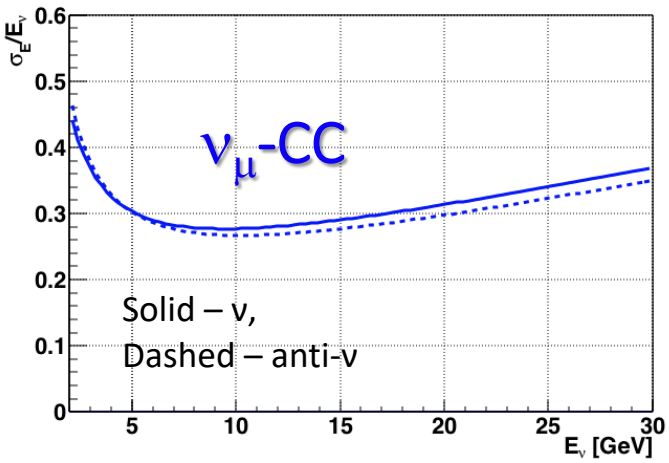


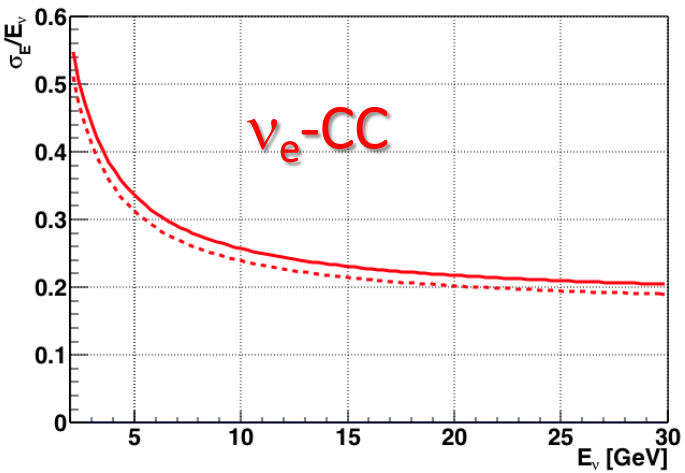
- Median zenith angle resolution of 7°(5°) for 5(10) GeV for both track and shower channels.
- Dominated by the intrinsic ν-lepton scattering angle
- Largely independent of vertical spacing

Energy resolution

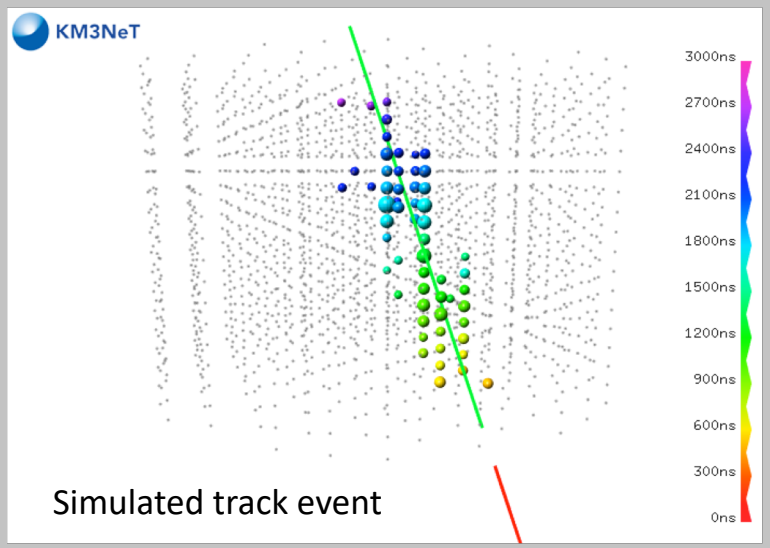
Energy reconstruction: fit number of hits and event topology (neural network)

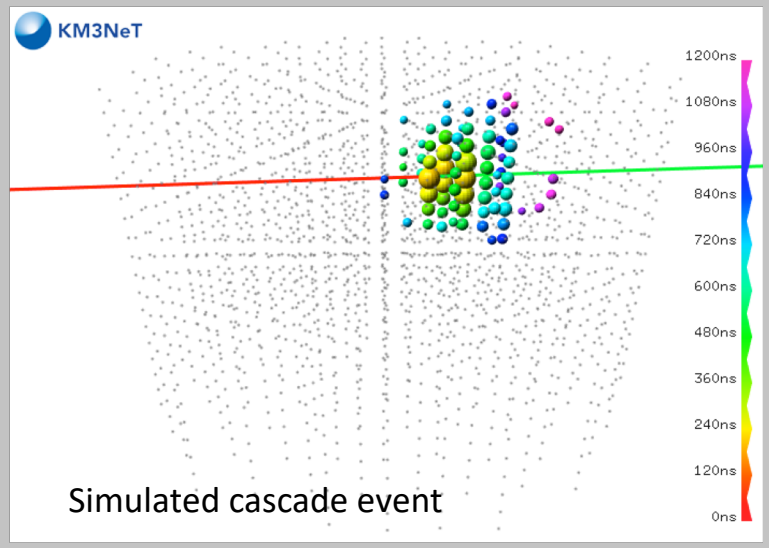
- Energy resolution better than 30% in the relevant energy range





Particle identification



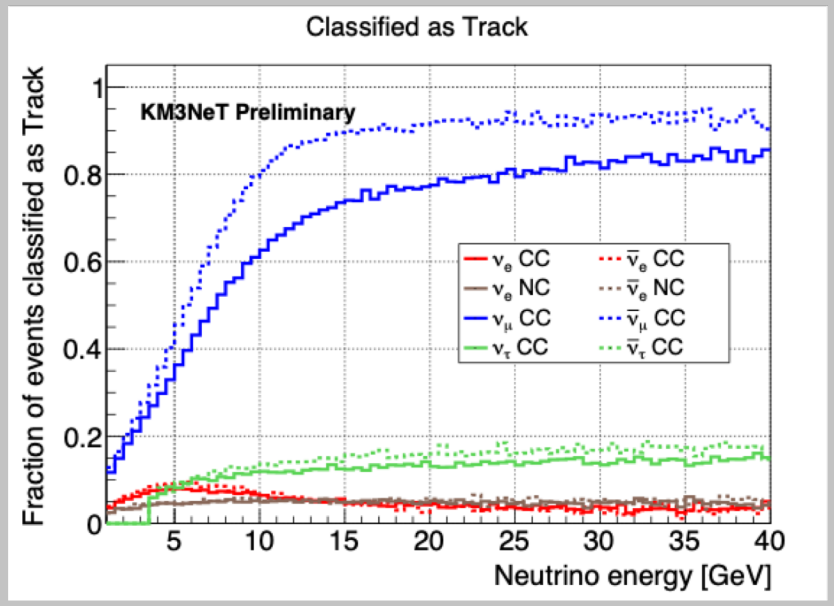


Random Decision Forest technique to both identify atmospheric muons and perform track-shower separation

- At 10 GeV:
  90% correct ID for ν_e CC
  70% correct ID for ν_μ CC

- Able to suppress atmospheric muon background and noise to the 3% level

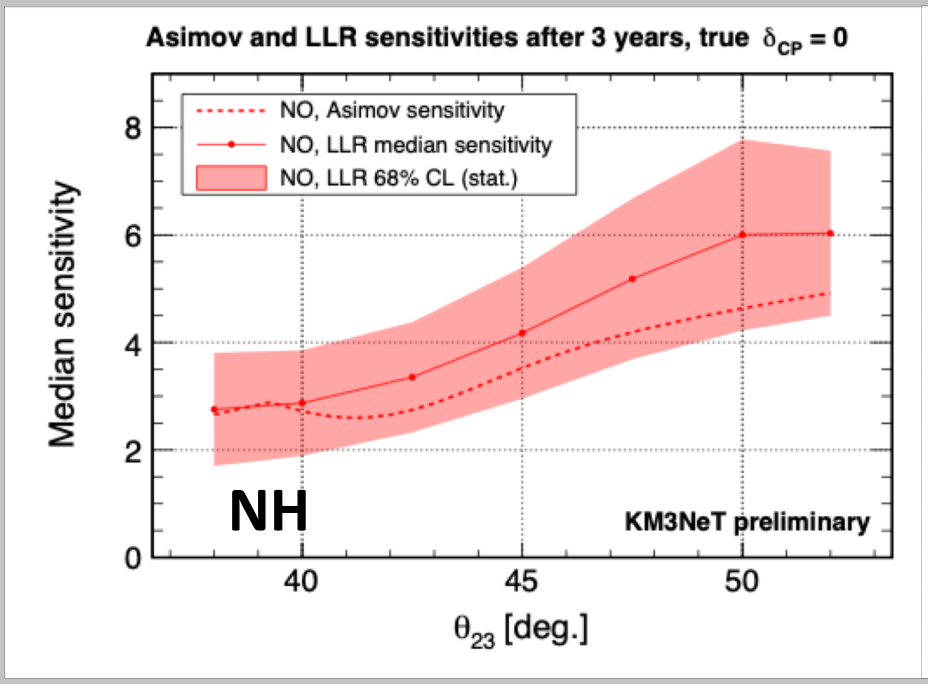
- Still preserves 95% of the neutrino signal

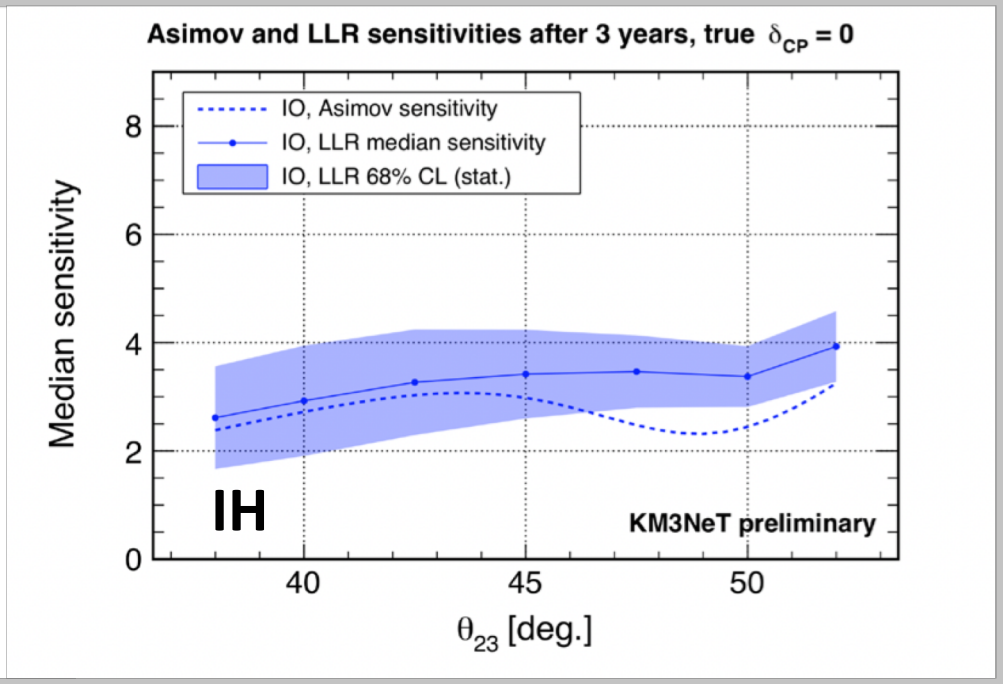


Sensitivity to NMH

Sensitivity to exclude the wrong hierarchy

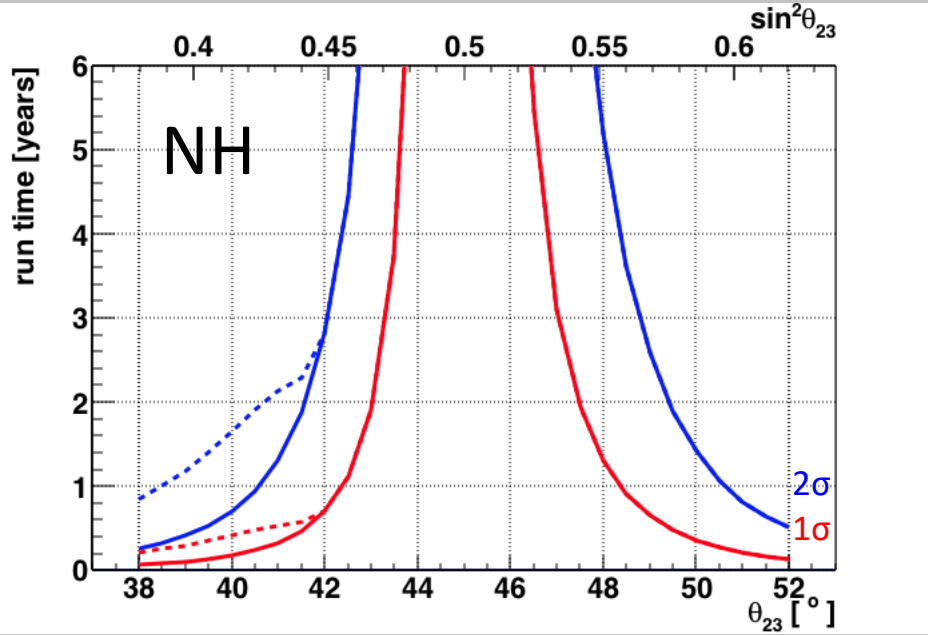
Systematics:
– Atmospheric flux parameters
– Neutrino oscillation parameters

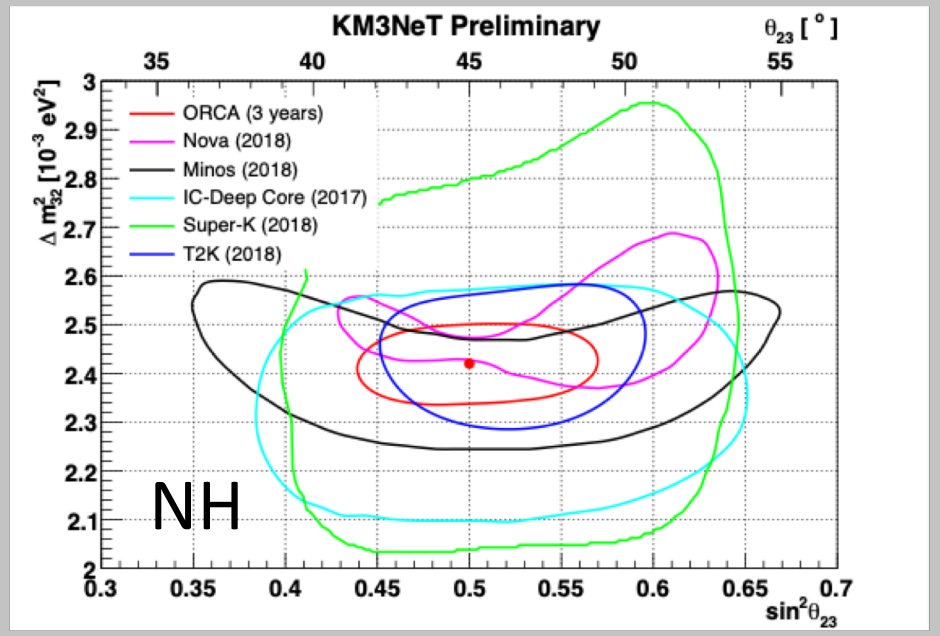




Measurement of the oscillation parameters

- $\sin^2\theta_{23}$ and Δm^2_{23} measured via the disappearance of ν_μ in the atmospheric flux
- 2-3 % precision in Δm^2_{23} and 4-10% in $\sin^2\theta_{23}$



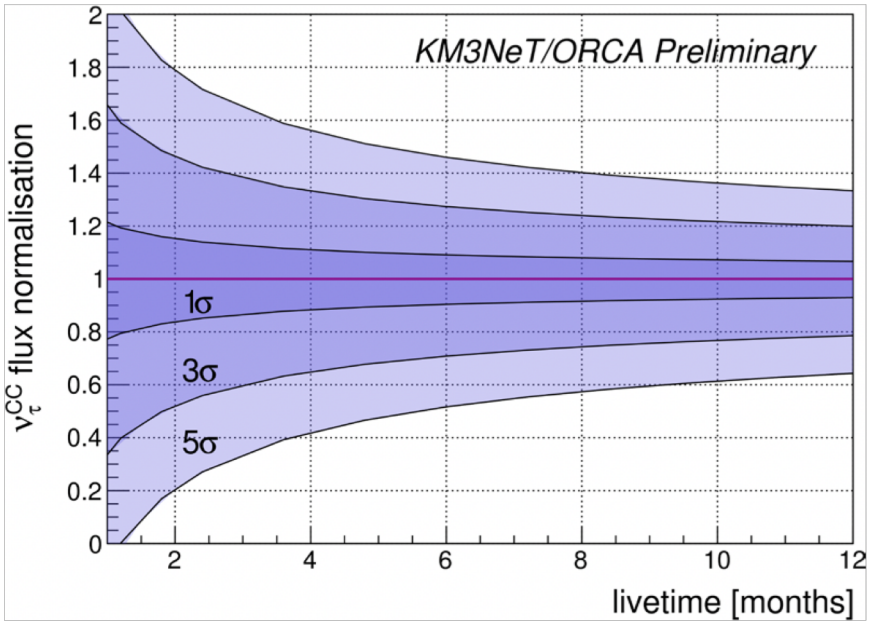


Solid : NH correct

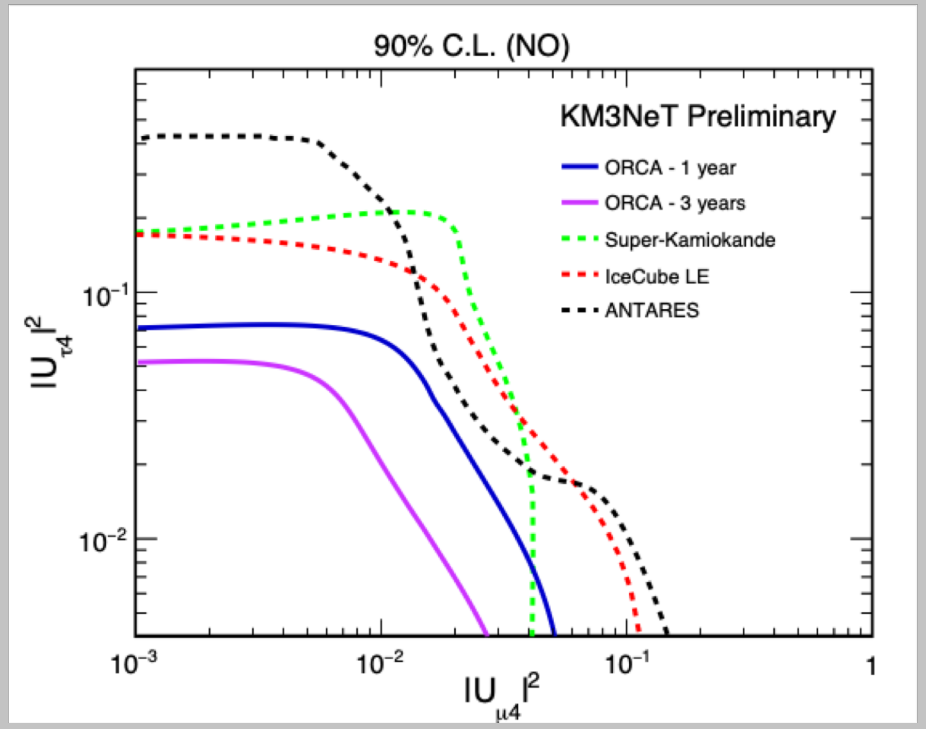
Dashed : NH wrong

Other potential physics avenues

PMNS unitarity



Sterile neutrinos



But also:

- Earth tomography and composition
- Supernova monitoring
- Indirect search for Dark Matter
- Low energy (GeV-TeV) neutrino astrophysics

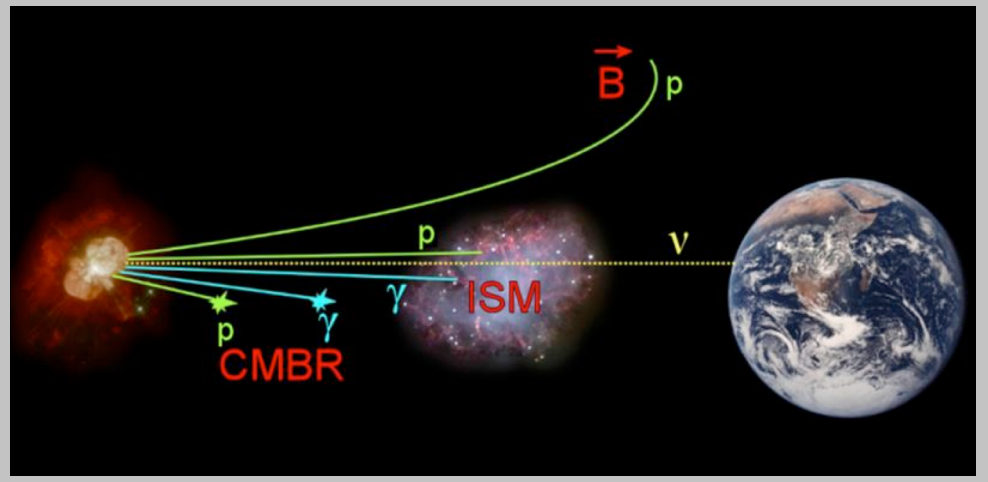
KM3NeT/Arca: science goals

Astrophysical neutrinos:

- are optimal probes to observe high energy processes also in the deep Universe.

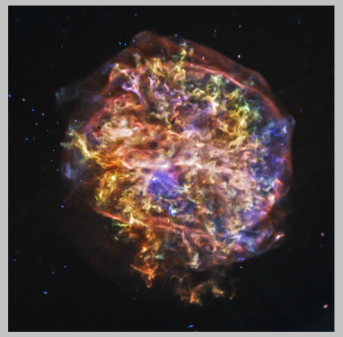
- are smoking gun of hadronic process in cosmic accelerators.

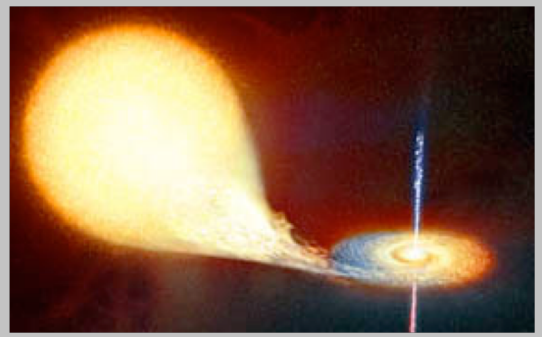
- complete the multi-messenger scenario: Electromagnetic counterparts, Cosmic Rays, Gravitational Waves…



Candidate High Energy neutrino sources in the Universe: cosmic accelerators!

Galactic: SNRs, Microquasars,…

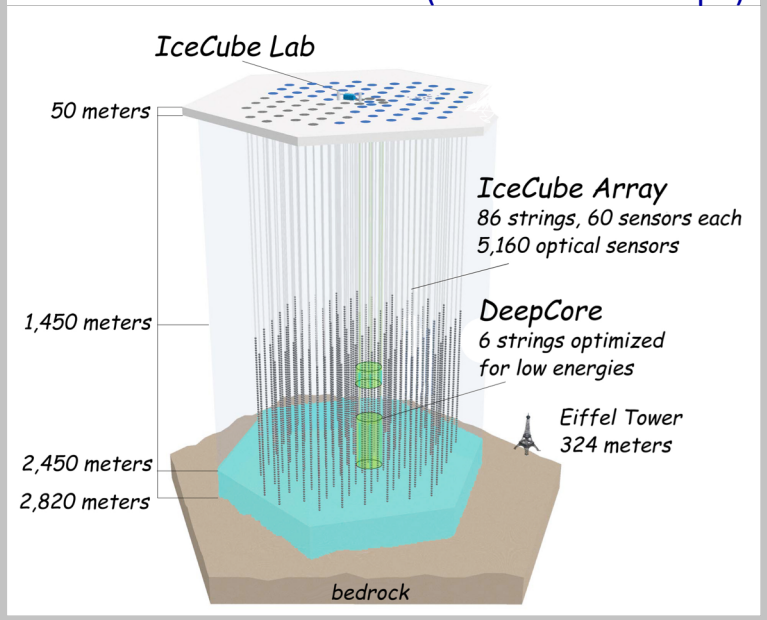


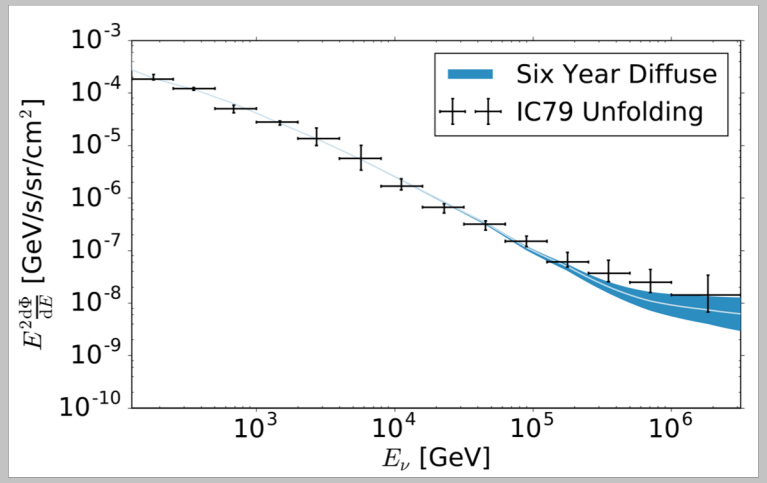


Extragalactic: AGNs, GRBs,…

IceCube: the first km³ telescope

IceCube at South Pole (under-ice telescope)





The era of neutrino astronomy has begun!

Evidence for High-Energy Extraterrestrial Neutrinos with IceCube
(*Science* 2013, 342, 1242856)

Neutrino emission from the direction of the blazar TXS 0506+056
(*Science* 2018, 361, 147)

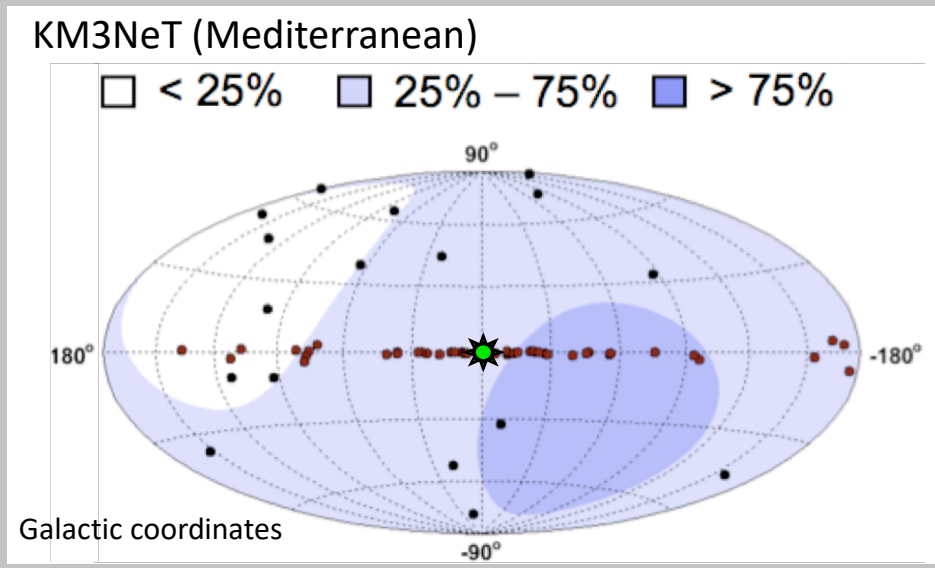
Questions:

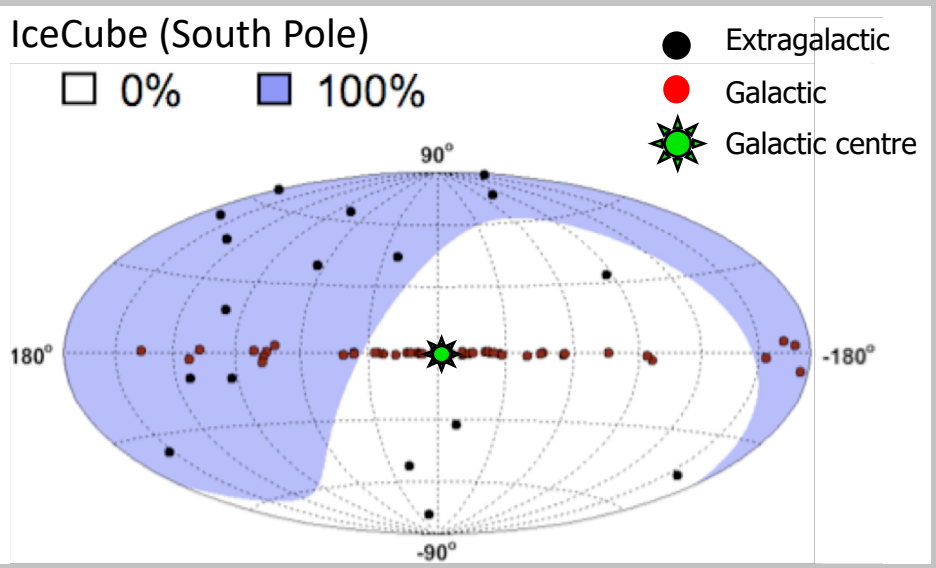
- What are the sources
- Galactic vs extragalactic
- Is there a spectral break
- Flavour composition
- All constrained, but weakly

Why a second neutrino telescope in the Mediterranean

- **A km^3 telescope in the Mediterranean (North Hemisphere) means:**
  - full sky coverage
  - visibility of Galactic Plane + Galactic Center
  - 1.5 sr common view per day

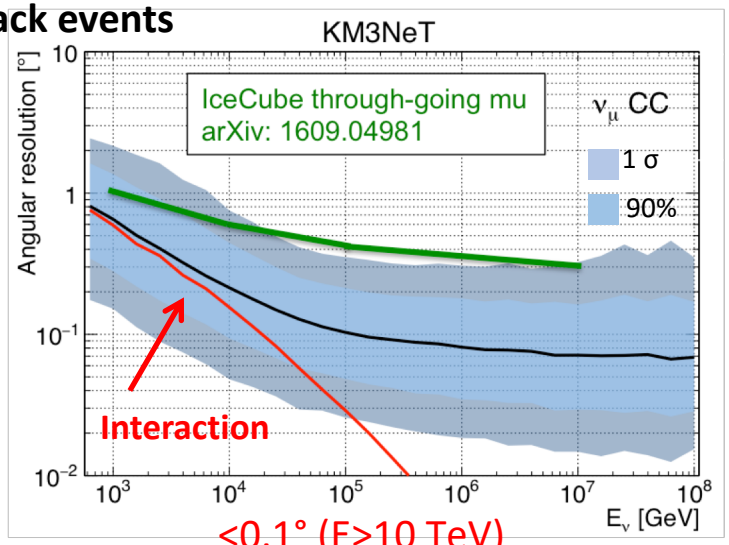
- **Water vs ice:**
  - In ice less light absorption → better energy reconstruction
  - In water less scattering → better pointing accuracy (point source identification!)
  - In seawater: K40 optical background requires causality filters but useful for calibration



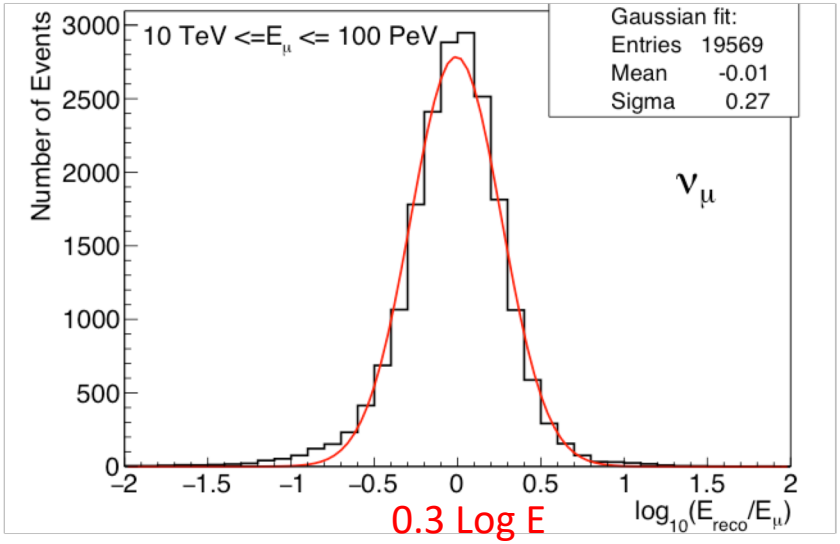


Angular and energy resolution

Track events

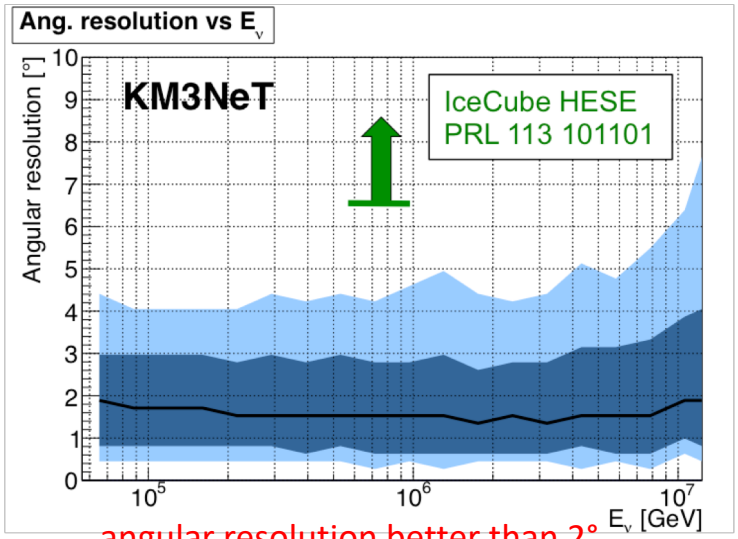


<0.1° (E>10 TeV)

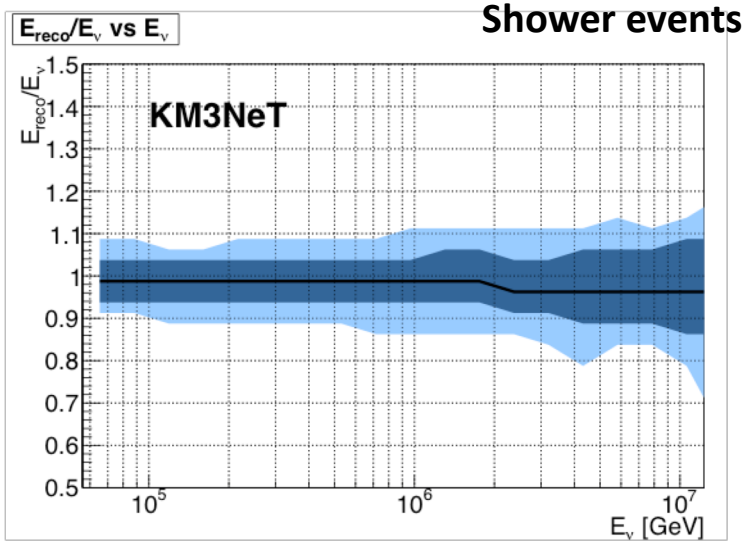


0.3 Log E

Shower events



angular resolution better than 2°



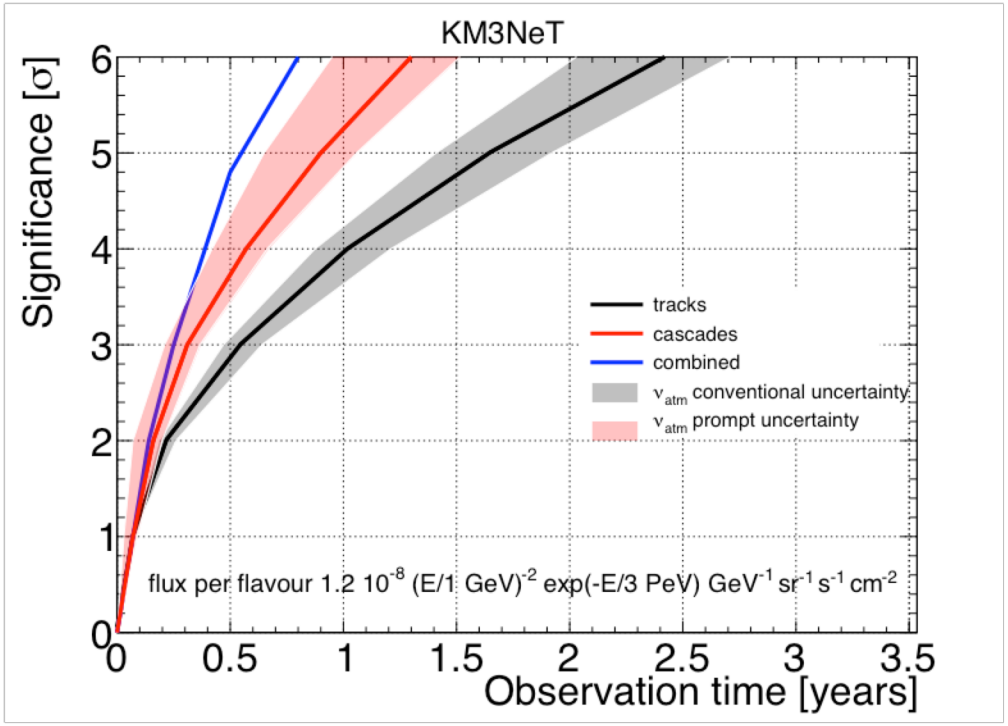
energy resolution better ≈ 5% at 1σ

Sensitivity to diffuse fluxes

Benchmark flux : IceCube flux (isotropic and flavour symmetric)

$$\Phi(E) = 1.2 \cdot 10^{-8} (E/1\ \mathrm{GeV})^{-2} \exp(-E/3\ \mathrm{PeV})\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

Goal: don't just re-discover the IceCube flux, investigate it!



Discovery at 5σ (50% probability) in 6 months of ARCA

- **Track event channel**

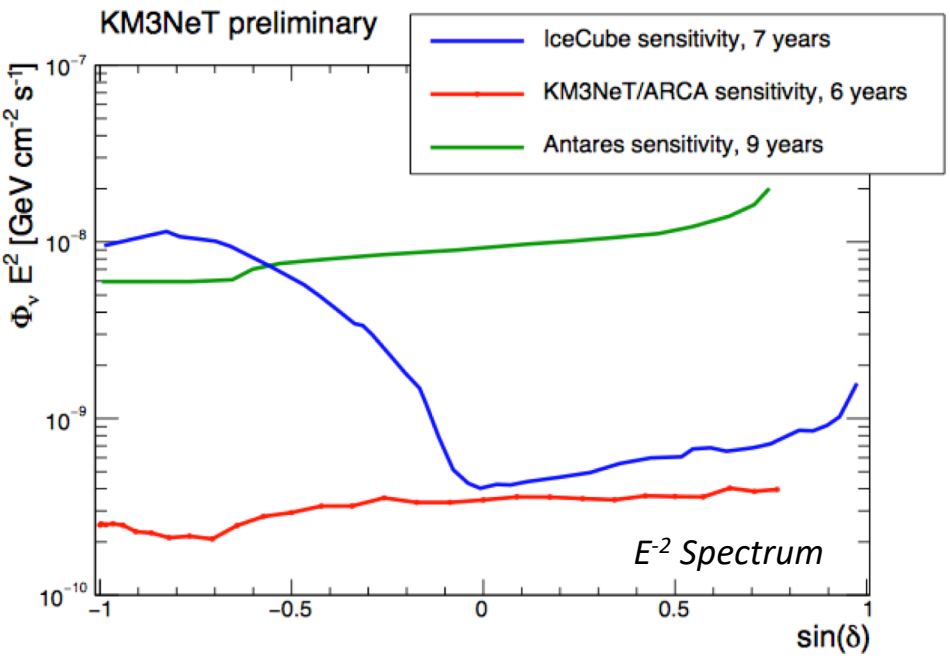
Analysis for up-going events based on maximum likelihood of preselected events. Pre-cuts on θ_{zen} >80°, reconstruction quality parameter and Nhit (proxy for muon energy)

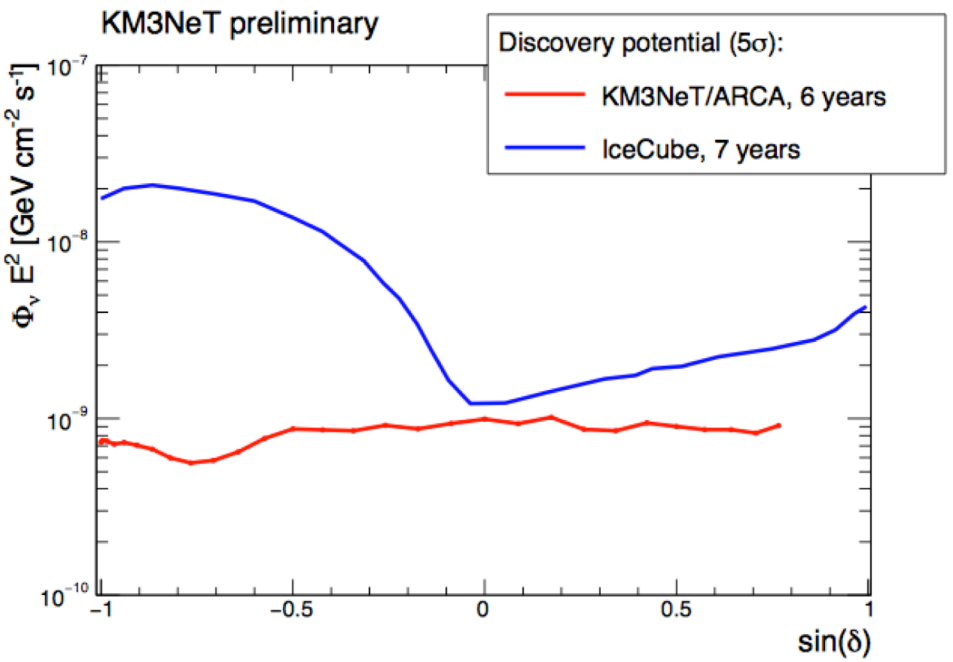
- **Shower event channel**

Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100m layer)
All sky analysis based on BDT and maximum likelihood.

Source identification: point-like sources

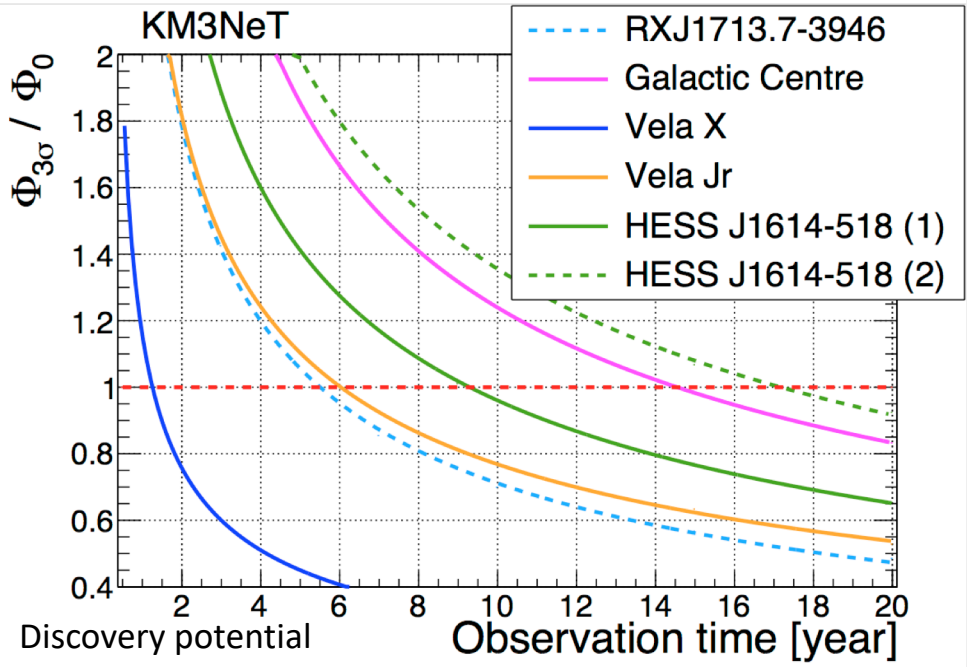
Visibility of Galactic Plane + Galactic Center
Better angular resolution in water will help the source identification

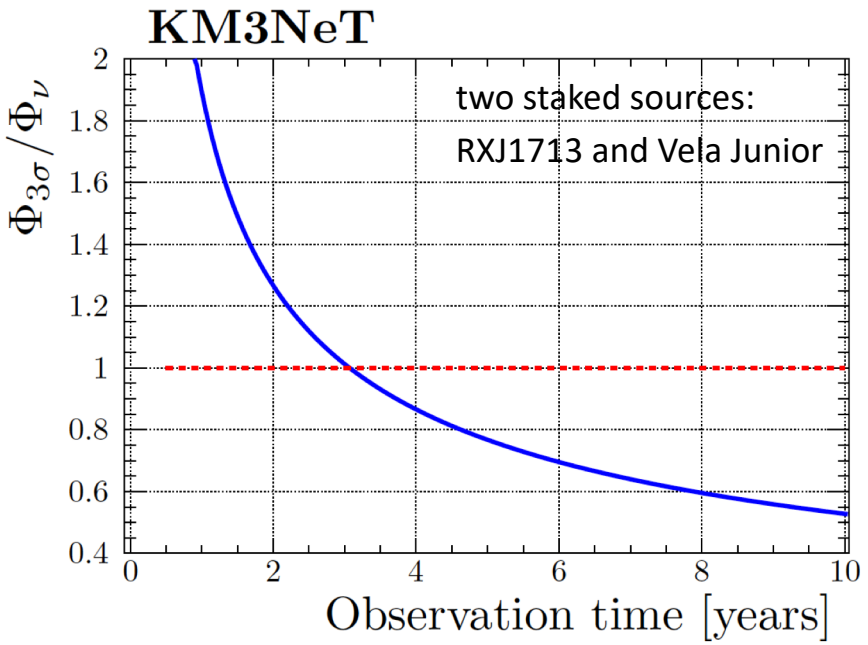




Up-going muon neutrinos analysis
Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

Source identification: Galactic sources





Expected neutrino spectra estimated from the observed gamma rays spectra:

$$\Phi_\nu(E) = \Phi_0\, E^{-\Gamma}\, exp(-(E/E_{cut})^\beta)\ \mathrm{TeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$$

Φ_0 [10^{-11} TeV^{-1}s^{-1}cm^{-2}]

Source	δ	radius	k_0	Γ	E_{cut}	β
RX J1713.7-3946	-39.77°	0.6°	0.89	2.06	8.04	1
Vela X	-45.6°	0.8°	0.72	1.36	7	1
Vela Jr	-46.36°	1°	1.30	1.87	4.5	1
HESSJ1614-518 (1)	-51.82°	0.42°	0.26	2.42	-	-
HESSJ1614-518 (2)	-51.82°	0.42°	0.51	2	3.71	0.5
Galactic Centre	-28.87°	0.45°	0.25	2.3	85.53	0.5

F. Vissani, Astr. Phys. 26 (2006) 310
F. L. Villante and F. Vissani, Phys. Rev. D78 (2008) 103007

A Phased Approach

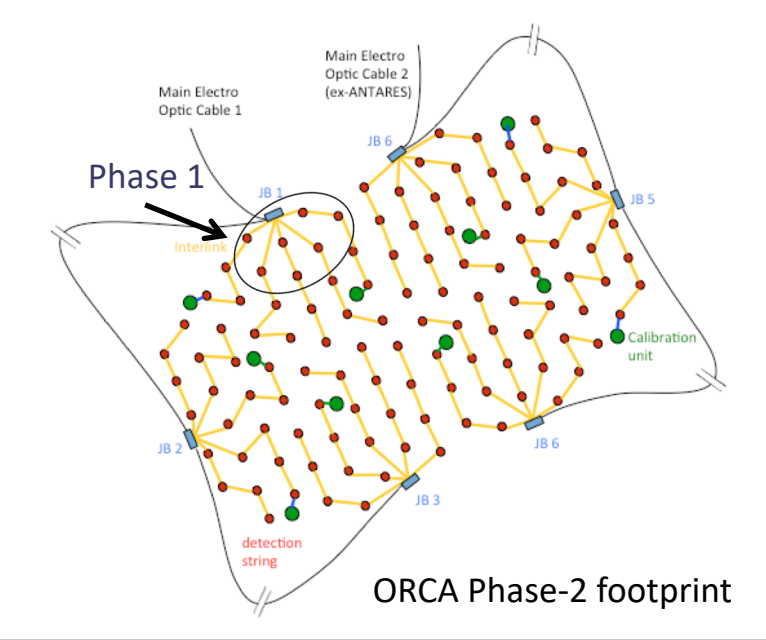
Phase	Building blocks		Number of DUs		Physics goal		Status
	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA	
1	0.2	0.06	24	6	Proof of feasibility and first science results. Joined analysis with ANTARES data		Fully funded. First 2 DUs installed and functioning at Capo Passero
2.0	2	1	230	115	All flavor astronomy. Study of the neutrino signal reported by IceCube.	Determination of the neutrino mass hierarchy	Partially funded
3	6	-	690	-	Neutrino astronomy including Galactic sources.		Not yet funded

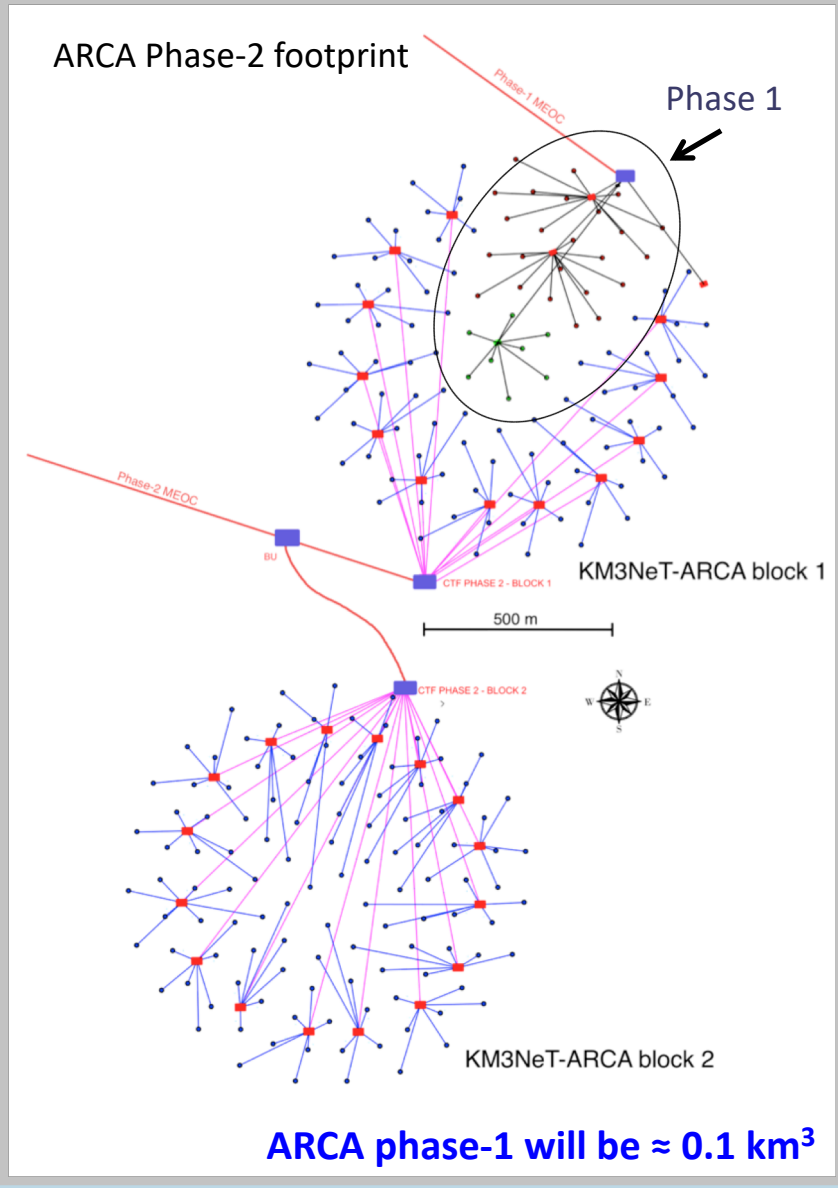
Present status

KM3NeT Phase-1 under construction

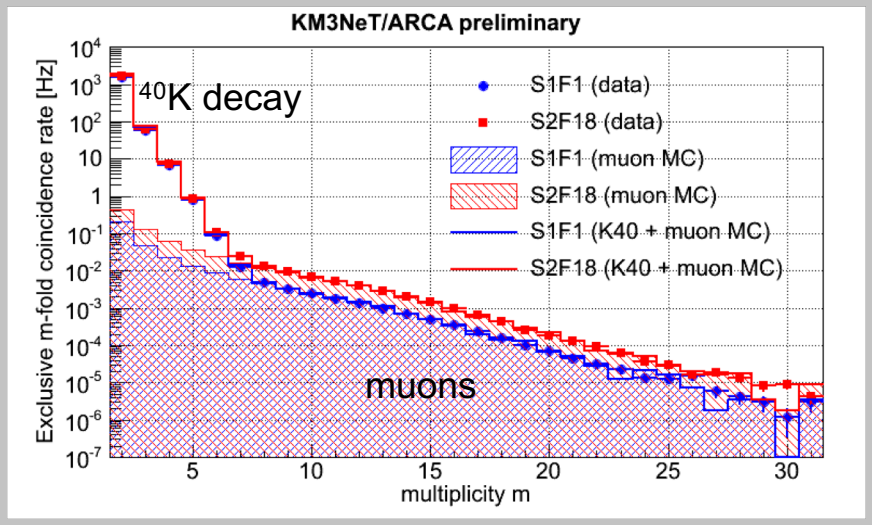
Data taking: 4 ORCA strings and 2 ARCA strings

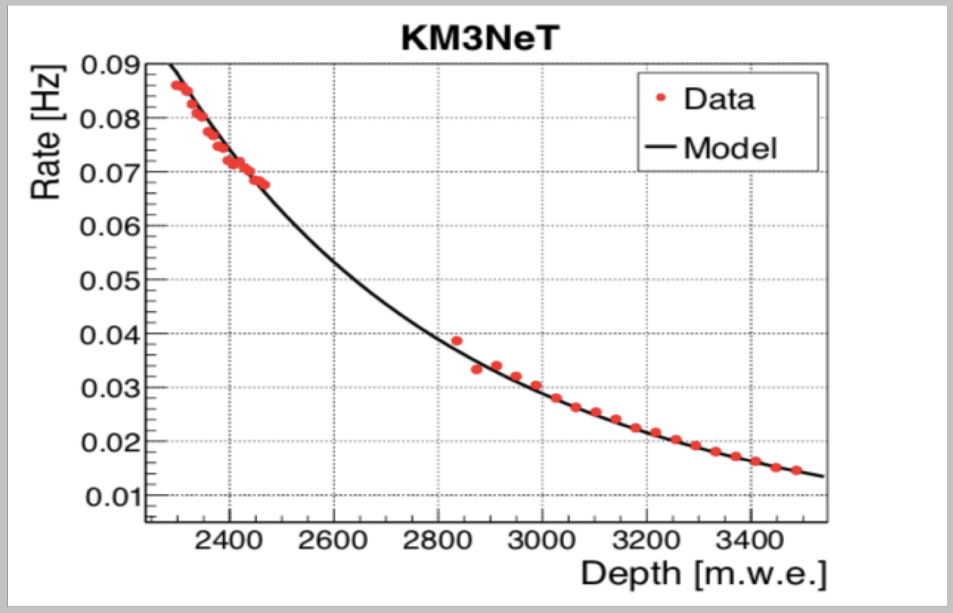
Data under analysis: time calibration, check of Monte Carlo simulations, atmospheric muons…





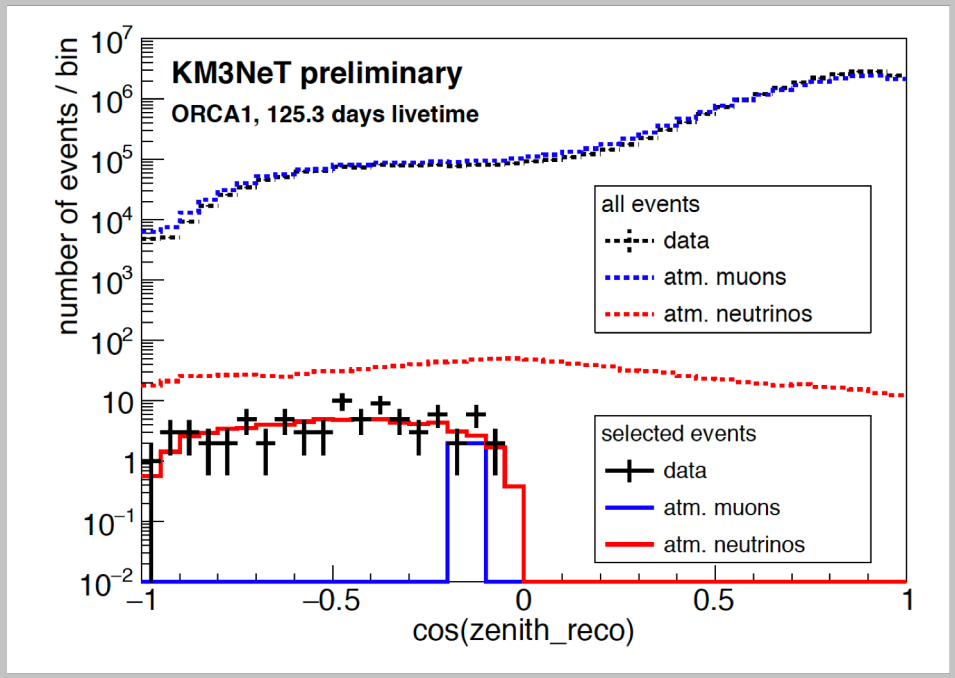
Muon Depth Dependence

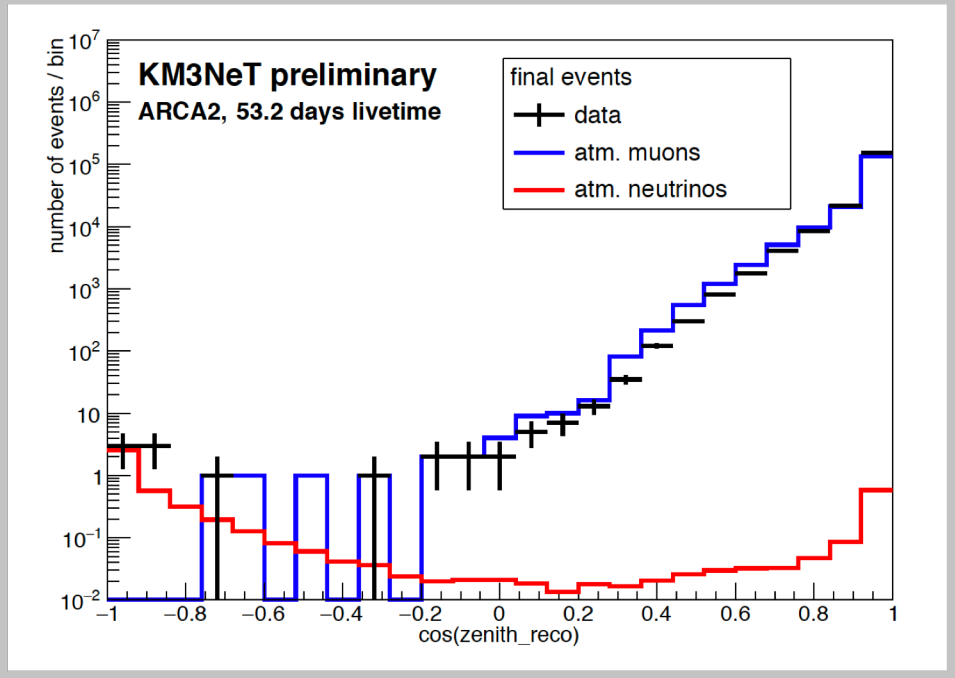




Event angular distribution

- Reconstruction algorithms under check
- Data – Monte Carlo comparison
- Optimization of selection criteria for atmospheric muon rejection





Conclusions

- KM3NeT is a research infrastructure in the Mediterranean Sea, housing the next generation neutrino telescopes: **ORCA** (Toulon, France) and **ARCA** (Capo Passero, Italy).

- KM3NeT Phase-1: Under construction
  - Data-taking: 2 ARCA and 4 ORCA DUs at the Italian and French sites respectively
  - Data under analysis: time calibration, check of Monte Carlo simulations, atmospheric muons…

- Following phase KM3NeT 2.0: Partially funded

- Exciting physics prospects:
  - Determination of the neutrino mass hierarchy in ~3 years
  - Measurement of the oscillation parameters, test of the PMNS unitarity, sterile neutrinos…
  - Study IceCube flux from a different hemisphere (5σ in 1 year)
  - Excellent angular resolution: perform neutrino astronomy; discover galactic plane emission, and galactic sources
  - Allows for all flavour neutrino astronomy and spans with ARCA and ORCA a large energy window from GeV to PeV