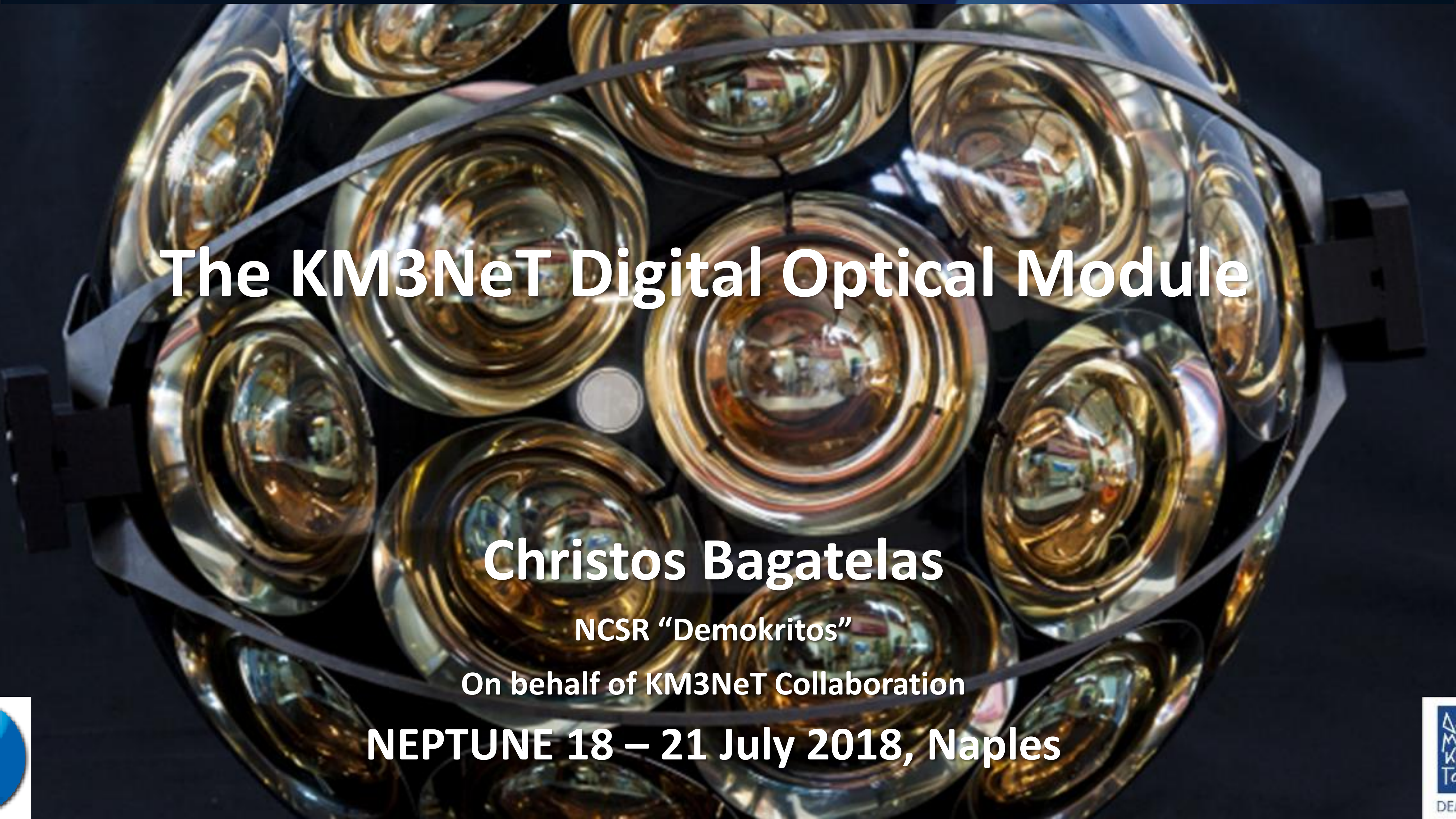
NEPTUNE
New and Enhanced Photosensor Technologies for Underground/underwater Neutrino Experiments



The KM3NeT Digital Optical Module

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NCSR "Demokritos"
On behalf of KM3NeT Collaboration

NEPTUNE 18 – 21 July 2018, Naples

Outline

- The KM3NeT telescope
- The Multi - PMT concept
- Digital Optical Module components
- Production phases
- Conclusions

The KM3NeT Collaboration

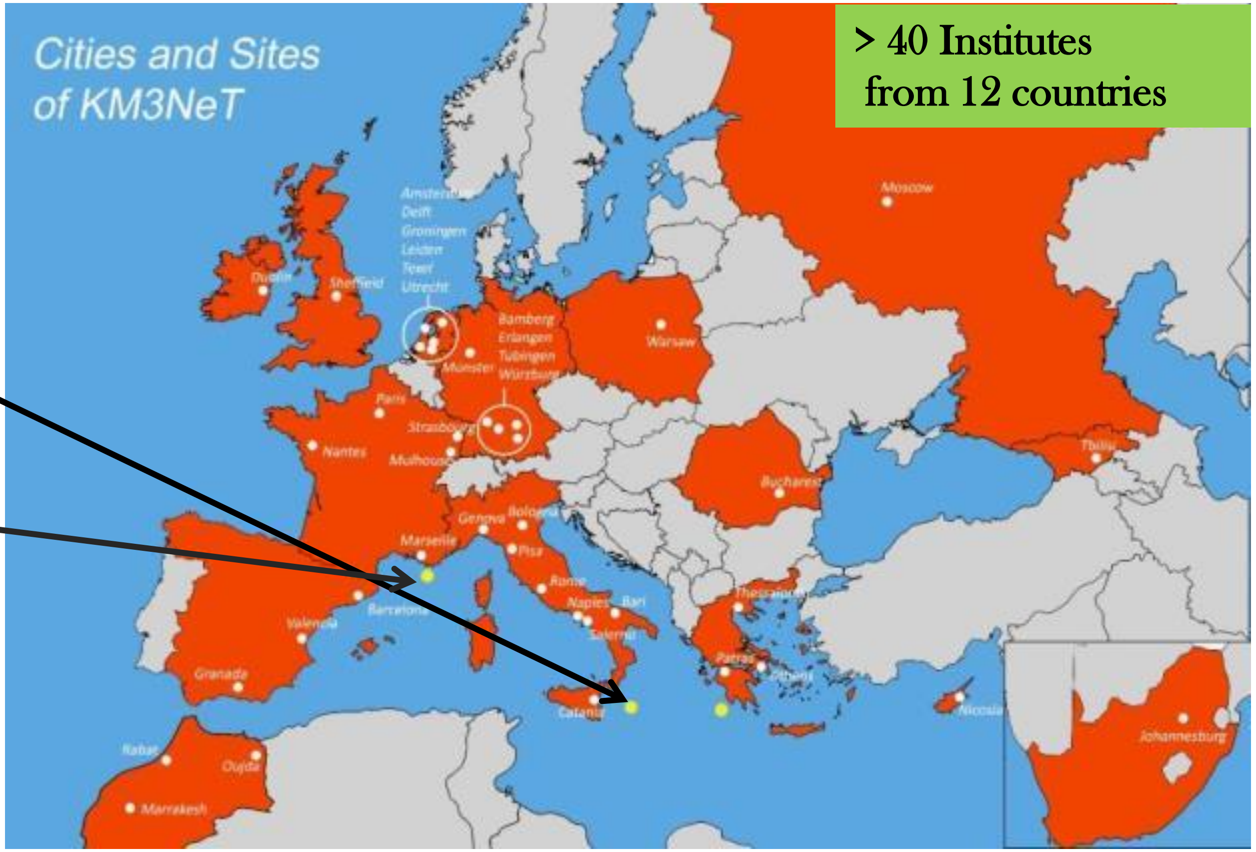
Two main scientific goals:

- **Discovery and observation of high energy neutrino sources in the Universe.**
- **Determination of the neutrino mass hierarchy.**

Two main detector sites and configurations:

- **ARCA: Astroparticle Research with Cosmics in the Abyss**
  High-energy neutrino astrophysics
  - ✓ ***KM3NeT-It site; 3400 m; Capo Passero, Italy***
- **ORCA: Oscillation Research with Cosmics in the Abyss**
  Low-energy studies of atmospheric neutrinos
  - ✓ ***KM3NeT-Fr site; 2475 m; Toulon, France***

KM3NeT Letter of Intent, J. Phys. G 43 (2016)



+ Since April 2017:
CIRA Perth Australia
as observer

+ Since May 2018:
Western Sydney University
Australia

The KM3NeT Detection Unit

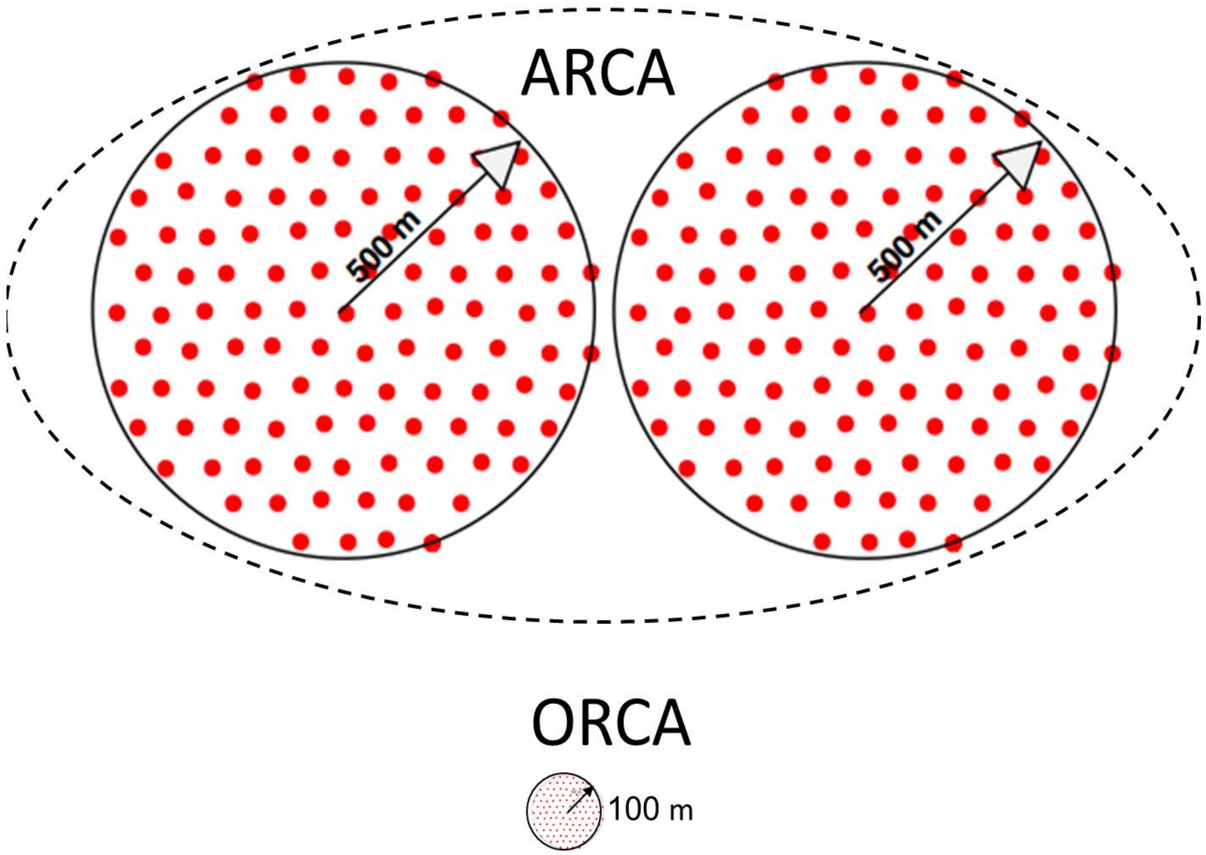
- Each Detection Unit (DU) is a vertical structure comprising 18 Digital Optical Modules (DOMs).
- The DOMs are attached to two Dyneema® ropes by an external titanium collar.
- At the top of the DU a submerged buoy keeps the structure close to vertical.
- Attached to the ropes is the vertical electro-optical cable (VEOC), that contains 2 wires for power transmission and 18 optical fibers for data transmission.
- The VEOC connects the DOMs with the base container and thus to the shore station via the main electro-optical cable.

Digital Optical Module

ARCA & ORCA Detectors

ARCA: Astroparticle Research with Cosmics in the Abyss

- ✓ Astrophysical Neutrinos (TeV-PeV Energies).
- ✓ Larger Detector: 2 blocks of 115 DUs each (~1 km^3 total).
- ✓ Each DU is about 700 m in height, with DOMs vertically spaced by 36 m. The DU horizontal spacing is about 90 m.
- ✓ Large volume, sparsely instrumented.

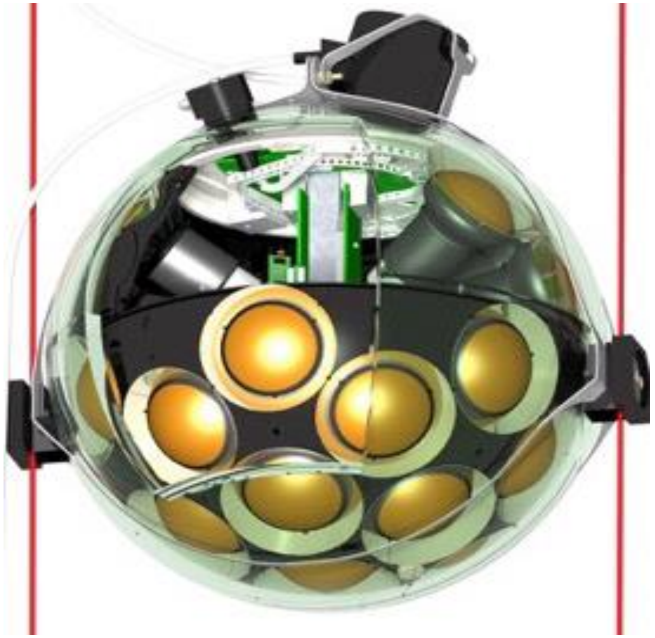


ORCA: Oscillations Research with Cosmics in the Abyss

- ✓ Atmospheric neutrinos (GeV Energies).
- ✓ Smaller detector: 1 block of 115 DUs.
- ✓ Each DU is 200 m in height, with DOMs vertically spaced by 9 m. The DU horizontal spacing is about 23 m.
- ✓ Smaller volume, more densely instrumented.

The Multi–PMT concept

Each DOM consists of a transparent 17-inch diameter pressure resistant glass sphere that hosts 31 3-inch photomultipliers and all the front-end and readout electronics.



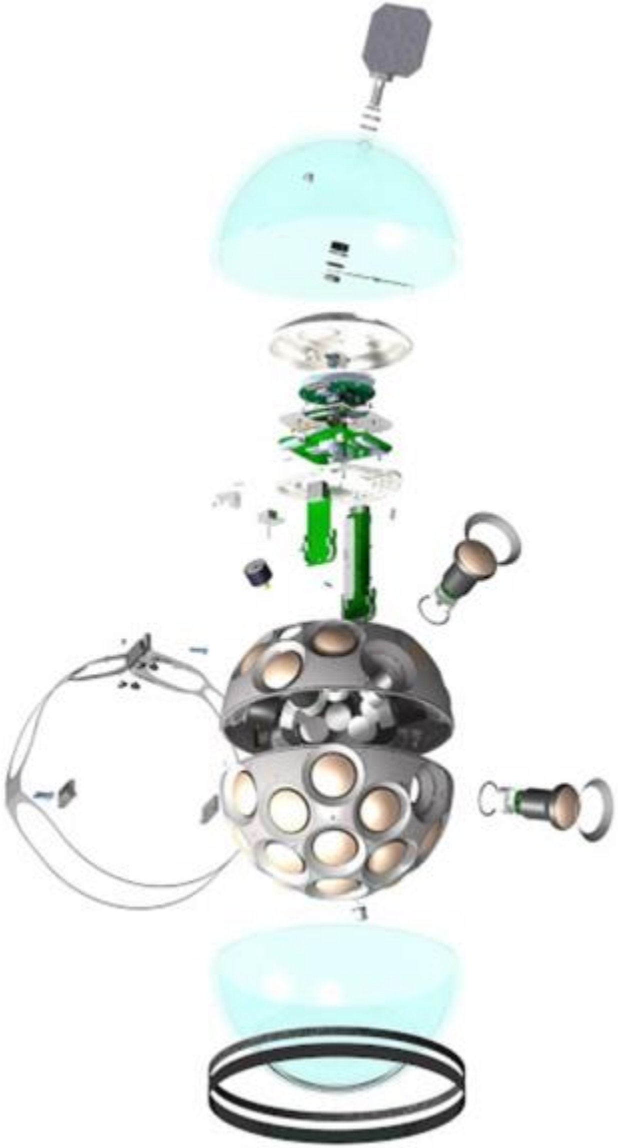
DOM multi-PMT design

Advantages of a multi-PMT design vs. single large area PMT

- ✓ a photocathode area almost three times larger than that of a single 10" PMT;
- ✓ an almost isotropic field of view;
- ✓ directional information;
- ✓ small size PMTs → better timing and amplitude measurement characteristics, magnetic shield is not required;
- ✓ segmentation allows photon-counting. High background rejection possible (based on coincidences) already at DOM level.

The KM3NeT DOM

- Mechanical parts:
  - Nautilus Vitrovex 17 ‘’ glass sphere
  - Titanium penetrator for data and power
  - Cooling mushroom
  - PMT support structure
  - 31 reflector rings
  - Optical gel
  - Titanium collar
- Electronics:
  - Central Logic Board (CLB)
  - 2 Octopus Boards
  - Power Board
- Optical parts:
  - Single-mode laser transceiver (SFP)
  - Add/drop filter
- Sensors/instruments:
  - 31 3” inch PMTs + Base Boards
  - Piezo acoustic sensor
  - Temperature/humidity sensors
  - Compass/accelerometer
  - Nanobeacon LED
  - Pressure gauge

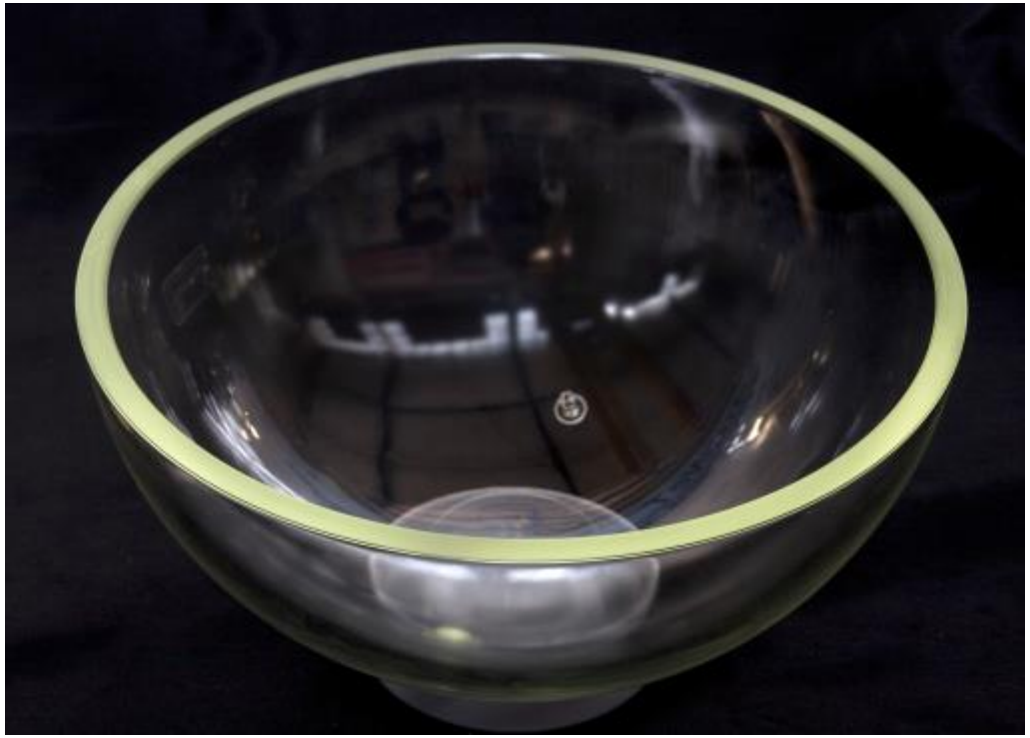


DOM components: glass sphere

NAUTILUS VITROVEX: 17-inch, 14mm thick borosilicate glass spherical housing

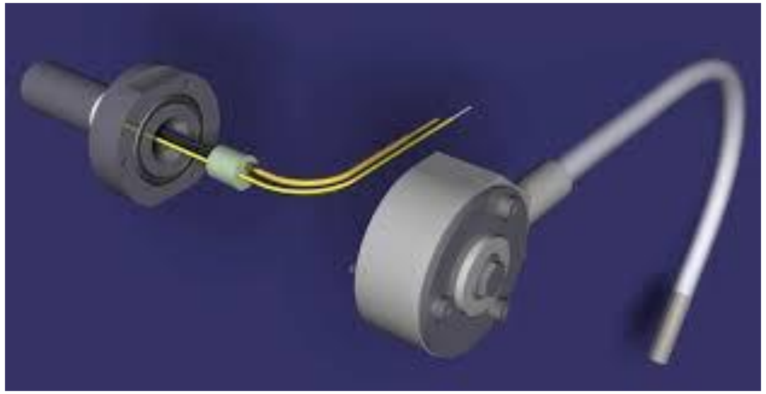
Requirements

- Mechanical resistance to the extreme compressive stresses of deep-sea environment (hydrostatic pressure up to 500 bar).
- Good transparency (400-500 nm)
  - ✓ refractive index: 1.47;
  - ✓ transmissivity: > 95% for λ>=350 nm.
- Resistance to corrosion, shocks and vibrations.



DOM components: glass sphere, cooling mushroom, penetrator

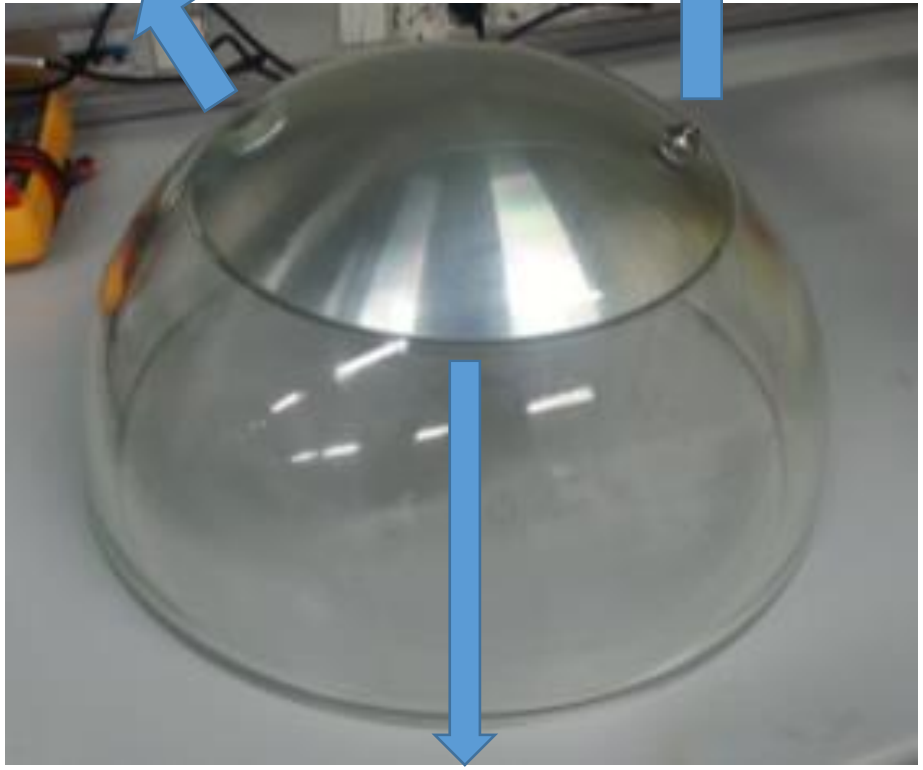
DOM Penetrator



- ✓ Custom-designed device.
- ✓ Titanium housing.
- ✓ Feedthrough for power cable and one optical fiber for communication.

Penetrator hole

Vacuum valve
0.2 bar under-pressure after closing the DOM



Cooling mushroom

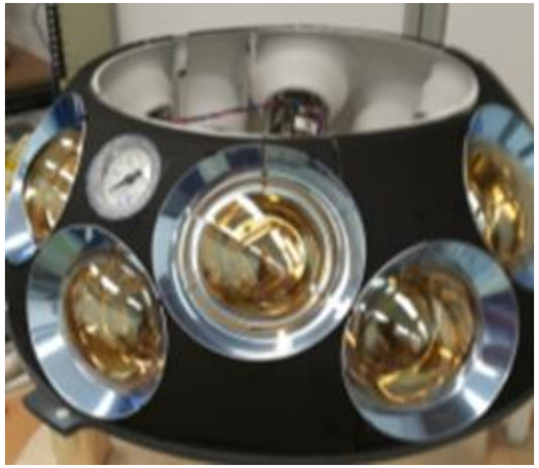
- ➢ Aluminum structure.
- ➢ Mechanical support to electronics and heat dissipation.

DOM components: PMT support structure

Nylon 3D-printed (SLS) custom design with the selective laser sintering method

Main functions:

- ➢ **Structural support for PMTs, defining positions and distances from glass.**
- ➢ **Housing for instrumentation.**



- ✓ **19 PMTs are arranged in 3 rings of 6 PMTs, at zenith angles of 107°, 123° and 148° degrees and 1 PMT points vertically down (180°).**
- ✓ **12 PMTs are arranged in 2 rings of 6 PMTs, at zenith angles of 56° and 72° degrees.**

DOM components: PMT support structure

Upper PMT support structure

Nanobeacon
- ➢ LED flasher (470nm) with adjustable frequency and intensity.
- ➢ Pointing upwards for time-calibration between DOMs.

Reflector rings
Each PMT is surrounded by a reflector ring, to increase the photon collection efficiency.
- ✓ Aluminum structure (92% reflectance for 375-500 nm);
- ✓ 45° tilted reflective surface improved by silver evaporation;
- ✓ Photon yield increase 20 – 40%.

KM3NeT Collaboration, JINST 8, T03006 (2013)

Pressure gauge
Monitoring the pressure inside the DOM before deployment.

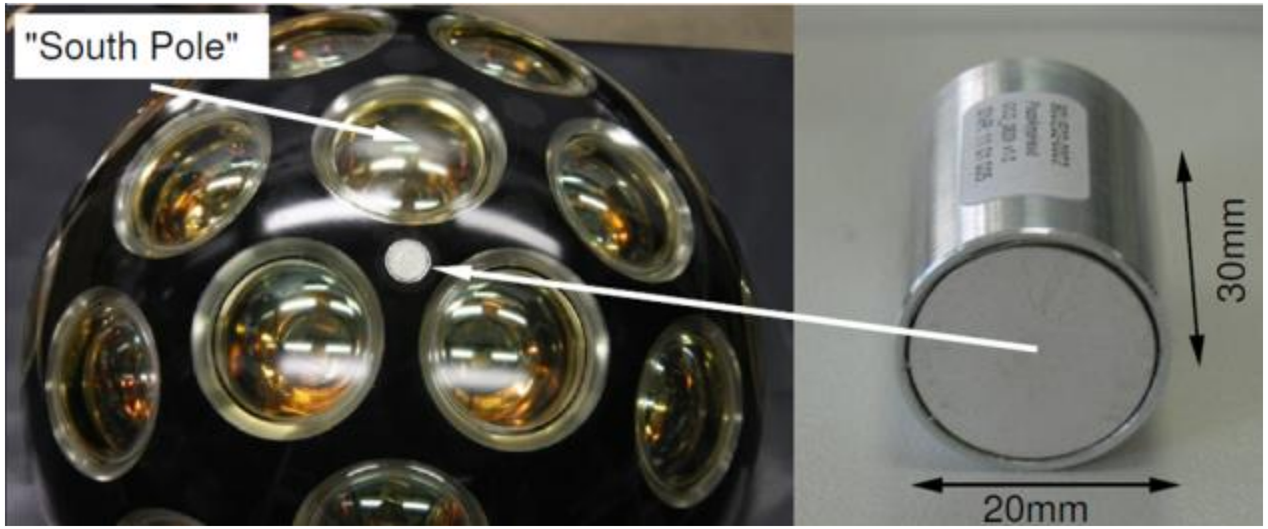
12 PMTs

DOM components: PMT support structure

Lower PMT support structure

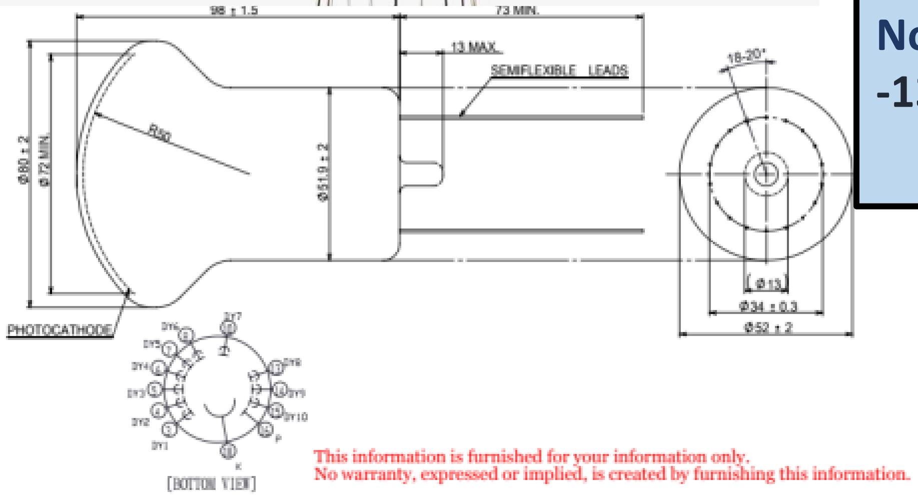
- 19 PMTs.
- 19 reflector rings.
- Feedthrough for the piezo acoustic sensor (piezo) attached to the glass sphere, for DOM acoustic positioning in water.

Piezo sensor



DOM components: Photo Multiplier Tubes

The PMT adopted for KM3NeT phase 1.0



[Photomultipliers for the KM3NeT optical modules -KM3NeT Collaboration Nucl.Instrum.Meth. A695 (2012) 313-316]

Hamamatsu R12199-02

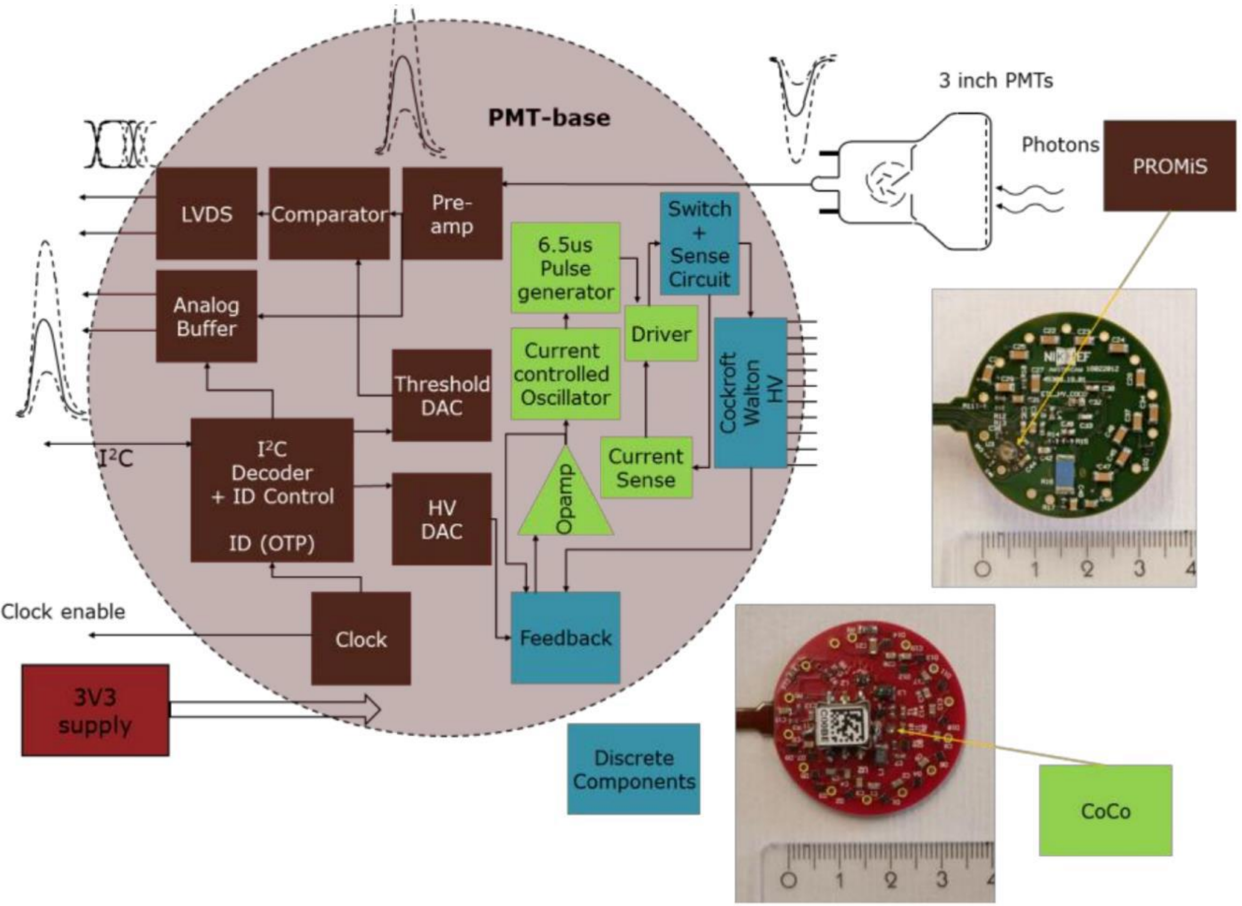
Type Number: R12199-02
Outer Diameter: 80 mm
Length: 97 mm
Window Shape: Concave-Convex
Window Material: Borosilicate Glass
Photocathode Material: Bialkali
Number of Dynode Stages: 10
Nominal operation voltage: -900 ÷ -1300 V

KM3NeT requirements

- ✓ Quantum Efficiency: ≥18% @ 470 nm, ≥23% @ 404 nm
- ✓ Gain: 3×10^6
- ✓ TTS (Transit Time Spread FWHM): < 5 ns
- ✓ Time-Over-Threshold (ToT): 26.4 ns for a single photoelectron
- ✓ Dark count rates: 200-1500 Hz @ 0.3 photoelectrons threshold
- ✓ Peak to valley ratio: >3

DOM components: PMT base

Custom-design, low-power base



Each PMT of DOM works as an individual optical sensor

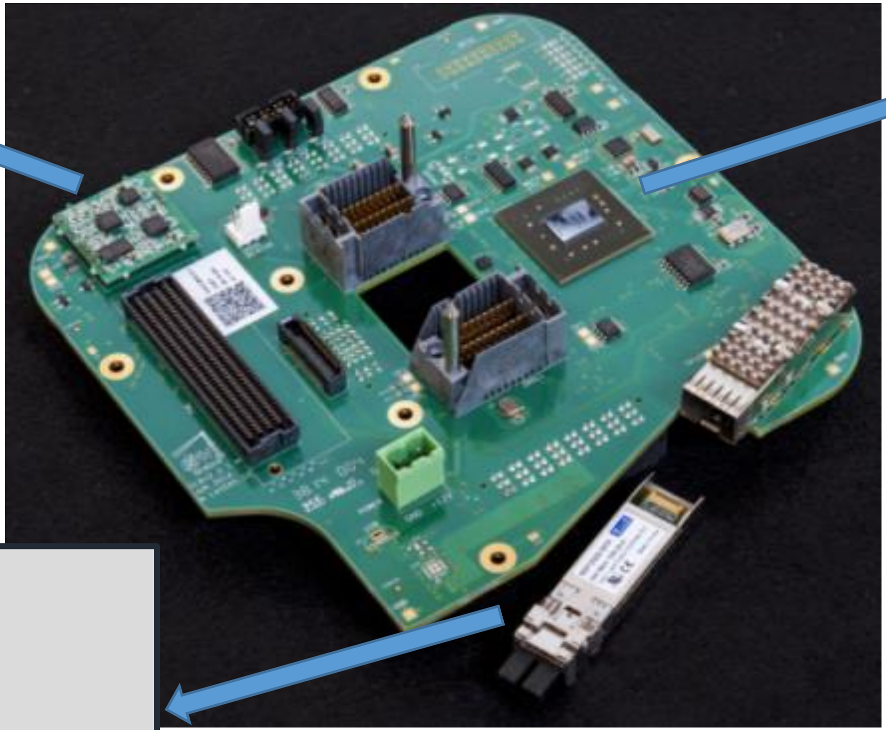
- Individual low-power active base.
- Individual integrated amplification and tunable discrimination.
- High voltage generated on the base by a Cockroft-Walton circuit controlled by an ASIC ("CoCo").
- Input 3.3 V; Output to -1400 V.
- The photon arrival time and the time-over-threshold (ToT) of each PMT, are implemented in an ASIC ("ProMiS").
- Threshold and HV adjustable.
- I2C communication for HV and threshold settings and base identification.
- Low power consumption, below 5 mW.
- Adjustable for different PMT manufacturers.

DOM components: Central Logic Board (CLB)

The CLB is the main board for signal processing, communication and control.

Compass board

Provides compass and accelerometer data used to reconstruct the orientation and position of DOMs in water, in conjunction with the acoustic positioning system.



FPGA Xilinx Kintex 7

- TDC channels for signals from PMTs and acoustic sensor.
- Pipeline to process all data to IP/UDP packets.
- White-Rabbit precision timing protocol core for time synchronization and Ethernet over optical fibers.
- LM32 processor for communication and control.

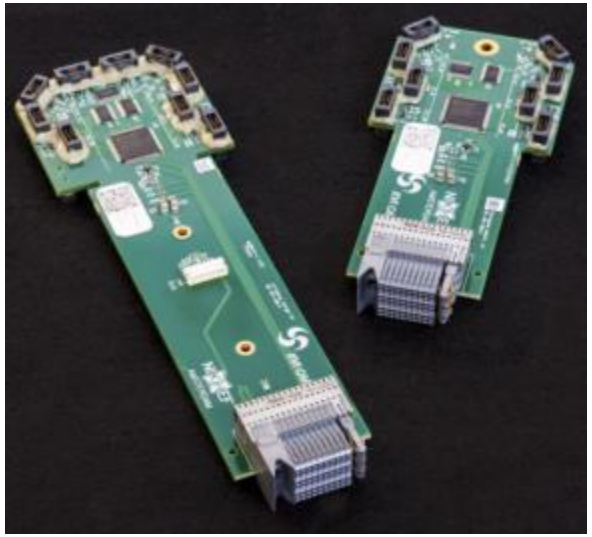
SFP cage

- Equipped with single mode laser transceiver.
- Each DOM in a DU uses a unique wavelength for transmitting data.

R. Bruijn and D. van Eijk (KM3NeT Collaboration), The KM3NeT Multi-PMT Digital Optical Module, PoS (ICRC2015) 1157.

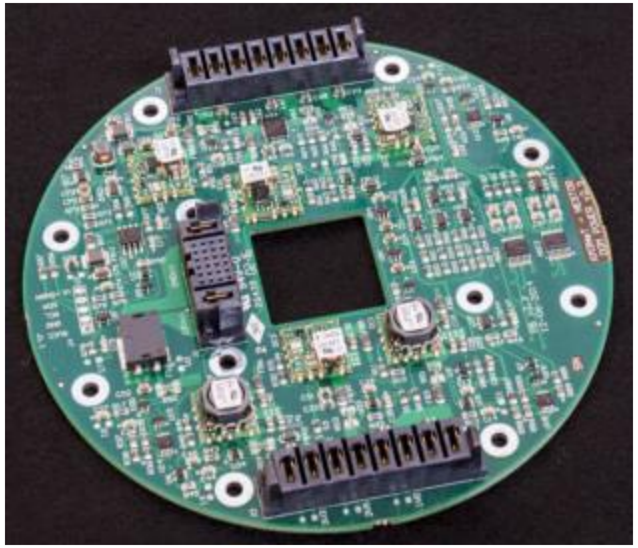
DOM components: Signal Collection Boards and Power Board

- Two signal collection boards, Octopus Boards, carry the signals from PMTs to the Central Logic Board (CLB).
- Small octopus board: connects the 12 PMTs of the top hemisphere to the CLB.
- Large octopus board: connects the 19 PMTs of the bottom hemisphere and the acoustic sensor to the CLB.



Octopus board, large and small

Pig tails from the PMT bases to small octopus board



Power Board

- A Power Board (PB) provides the DC power for all the systems inside the DOM.
- PB is fed with 12V DC supplied via the penetrator connected to a DC/DC converter outside the DOM.
- PB is monitored and controlled by the FPGA mounted on the Central Logic Board (CLB).

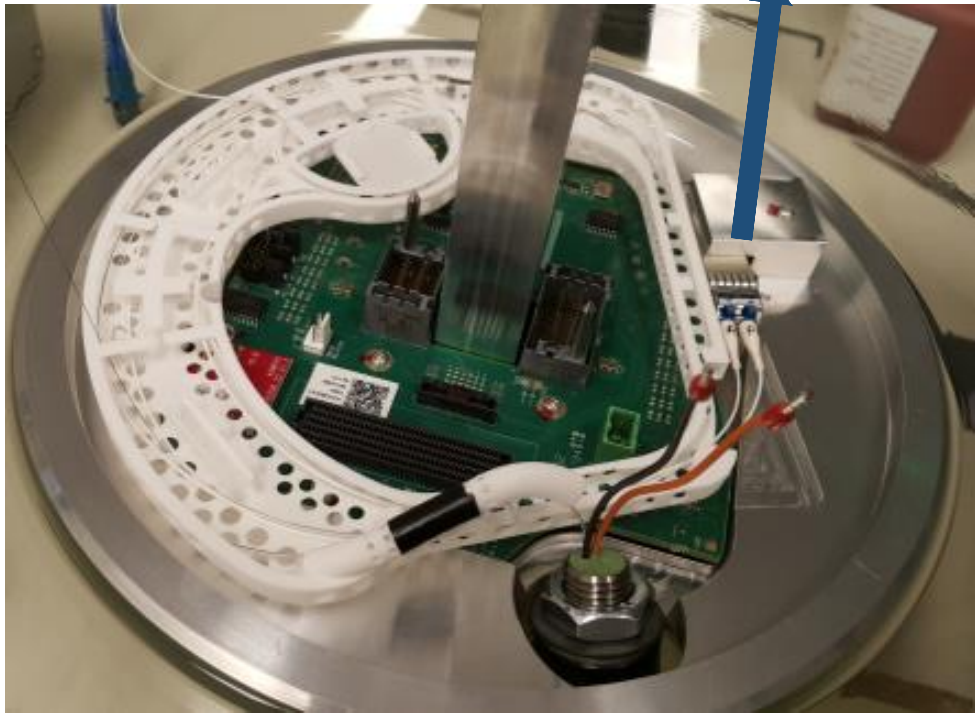
DOM components: Fiber optics system

Single-mode laser transceiver (SFP) installed on the CLB

- Each DOM in a detection unit uses a unique wavelength for transmitting data.
- Add/drop filter used to combine the transmit and receive channels onto the one fiber passing through the penetrator.

SFP transceiver

Splicing of optical fibers is required to create the connection between the SFP transceiver and the fiber leading to the outside through the penetrator.

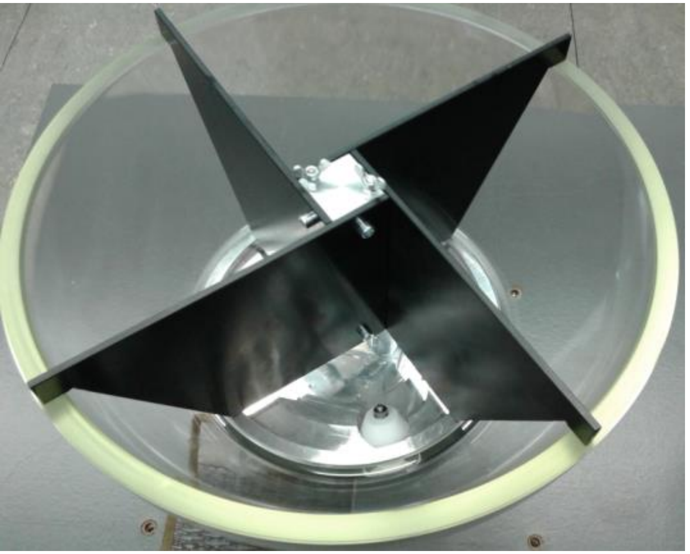


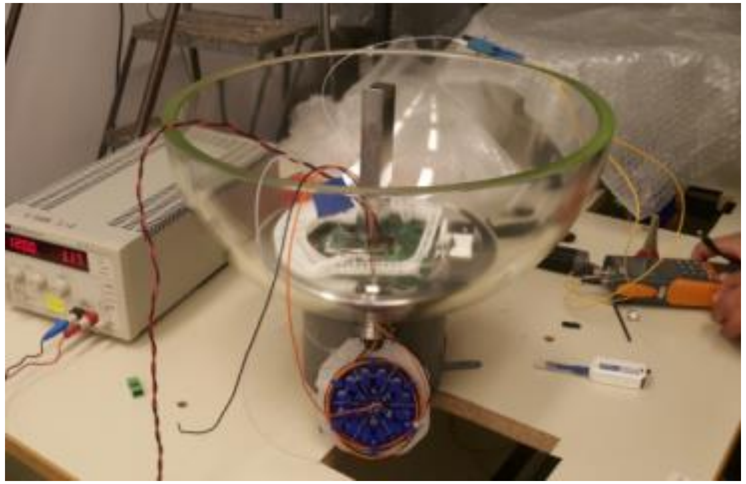
Fiber tray and Add/drop filter

DOM integration procedure

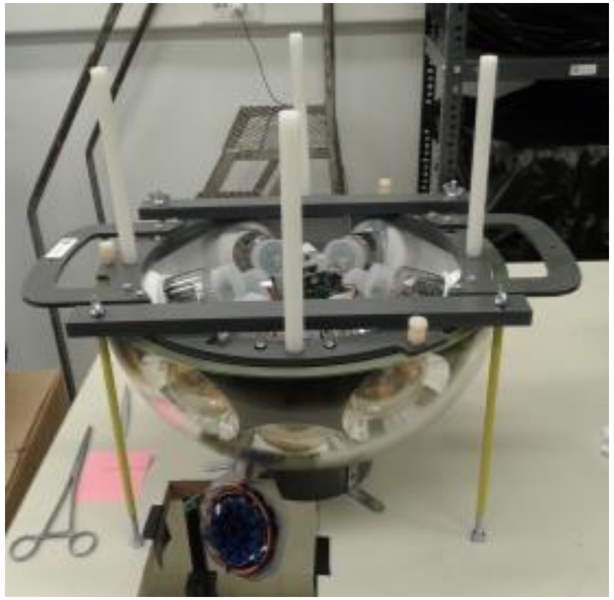
- All components have their own identification (QR code) with associated database entry.
- The two halves are constructed separately and are finally connected to form the DOM.
- Splicing of optical fibers is required to create connection between the laser transceiver and outside through the penetrator.
- Critical components (PMTs, CLBs, penetrators etc.) have been tested, calibrated (if applicable) prior to integration.
- Tests performed during DOM integration :
  - ✓ Helium leak test of the mounted penetrator.
  - ✓ Functional test of all systems before any irreversible mechanical steps are taken (gel pouring);
    - functionality of electronics and sensors (piezo, nanobeacon);
    - check for PMT cabling swaps
- The space between support structure, PMTs and glass sphere is filled with optical gel (SilGel 612 A&B from Wacker) in order to ensure the optical and mechanical coupling.
- After DOM closing an extensive final acceptance test is performed in a light-tight box, in order to determine all relevant parameters and decide whether the DOM is accepted or not.

DOM integration procedure



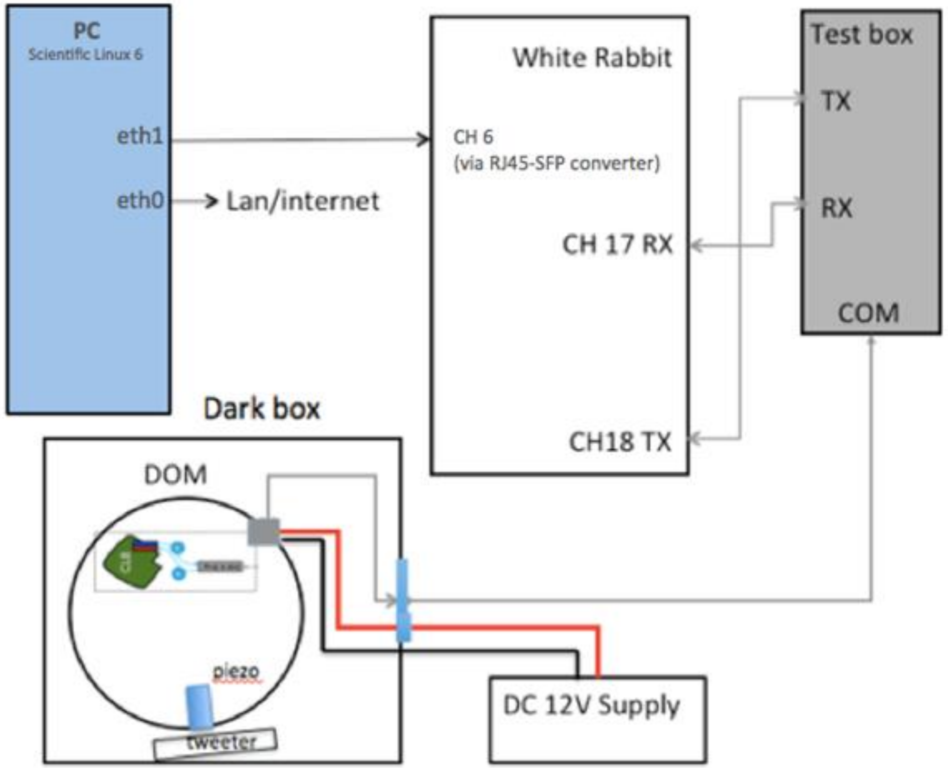




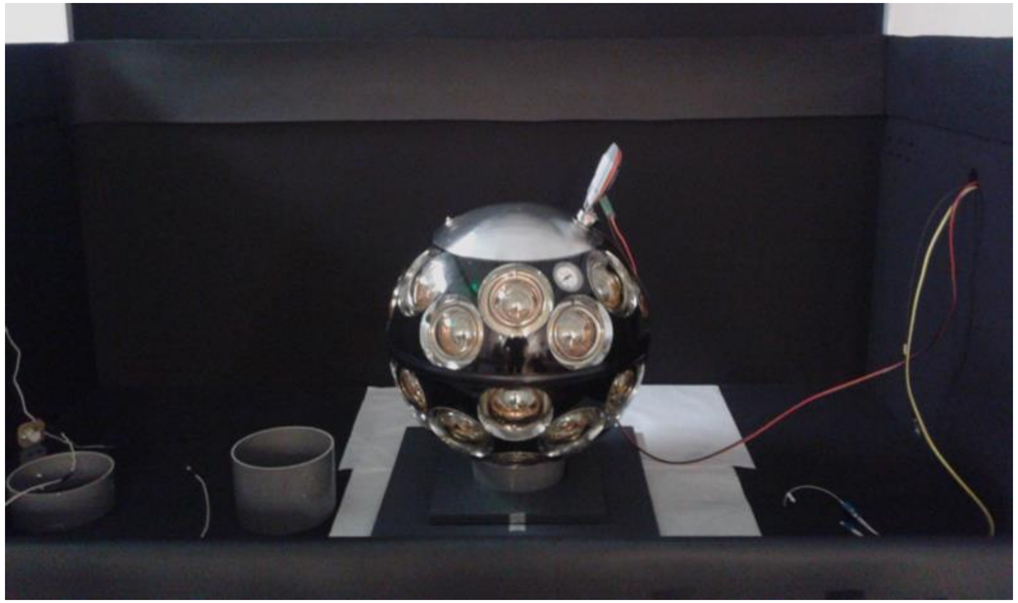


DOM testing and calibration

Each produced DOM is submitted under acceptance test and calibration



DOM test set-up



DOM inside the dark box

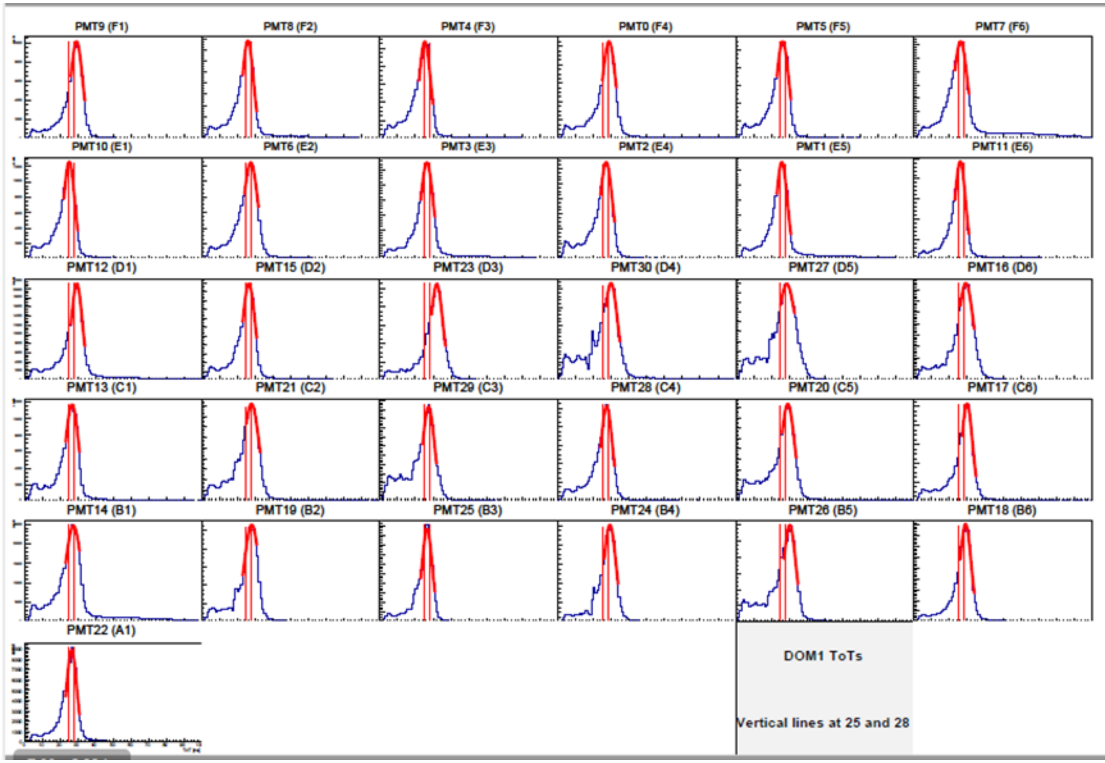
DOM testing and calibration

Each produced DOM is submitted under acceptance test and calibration

- ✓ **PMT dark count rate.**
- ✓ **PMT ToT.**

Dark Count Rate of each PMT

Time Over Threshold of each PMT



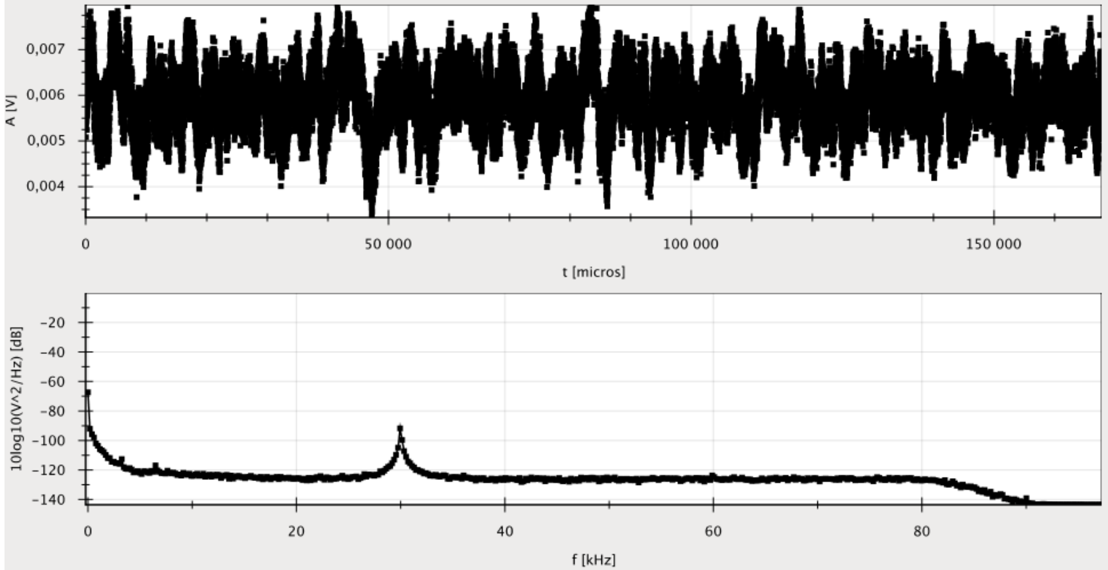
All test and calibration results are stored in KM3NeT Data Base

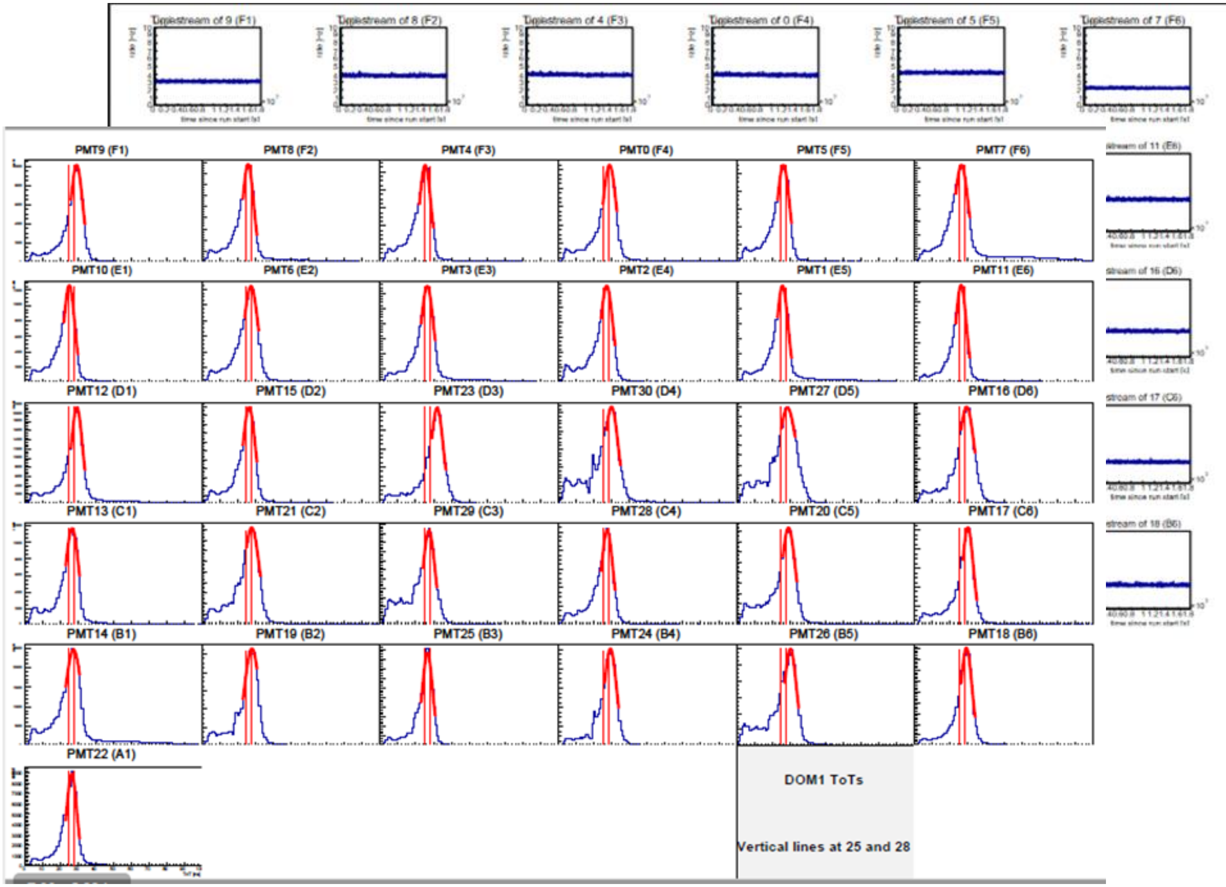
DOM testing and calibration

Each produced DOM is submitted under acceptance test and calibration

- ✓ **PMT dark count rate.**
- ✓ **PMT ToT.**
- ✓ **Signal and background noise recording and analyzing of piezo acoustic sensor.**
- ✓ **Calibration check of compass.**

Spectrum of piezo acoustic sensor





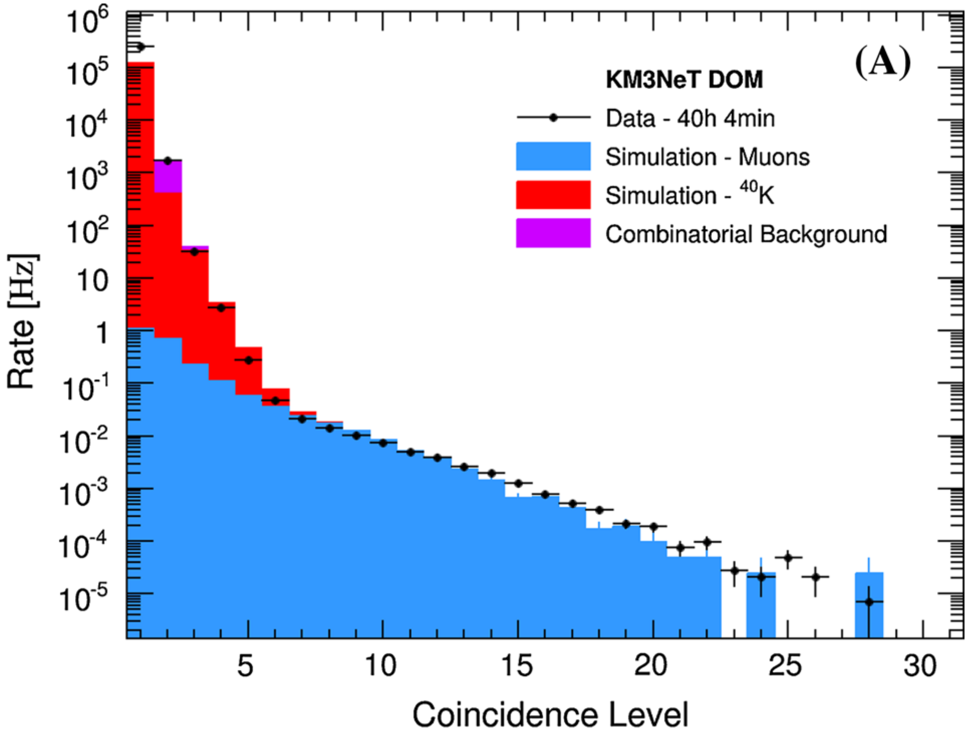
All test and calibration results are stored in KM3NeT Data Base

DOM production

- DOM integration procedure has been finalized and externally reviewed.
- A robust QA/QC guarantees uniformity of the distributed DOM production.
- The design has been validated *in-situ* by several prototypes.
- Production of the KM3NeT DOMs is currently on-going in 8 integration sites in 6 countries.
- DOM production of the Phase-1 (540 DOMs) will be accomplished by the end of the year; ~400 DOMs already integrated.
- Mass production has been estimated to 5 DOMs/week/site. Its feasibility has already been demonstrated.

DOM: photon counting and directional sensitivity

Photon counting (muons cause higher multiplicity coincidences)

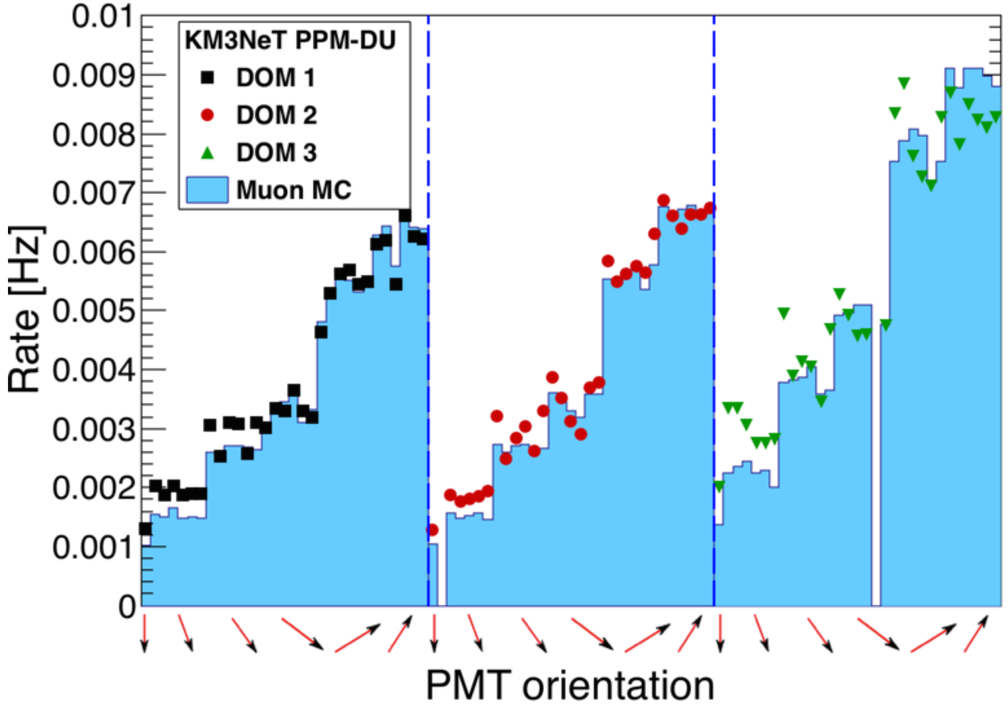


(data in this plot is from prototype PPM-DOM (Eur. Phys. J. C (2014) 74:3056)

- ✓ **Coincidence level: number of PMTs that detect a photon in a coincidence time window of 20 ns.**
- ✓ **Below a coincidence level of 6 the measured event rate is essentially due to the ^{40}K decay.**
- ✓ **Event rate in agreement with simulations.**
- ✓ **For higher coincidence levels (≥ 8) atmospheric muons are dominating.**

DOM: photon counting and directional sensitivity

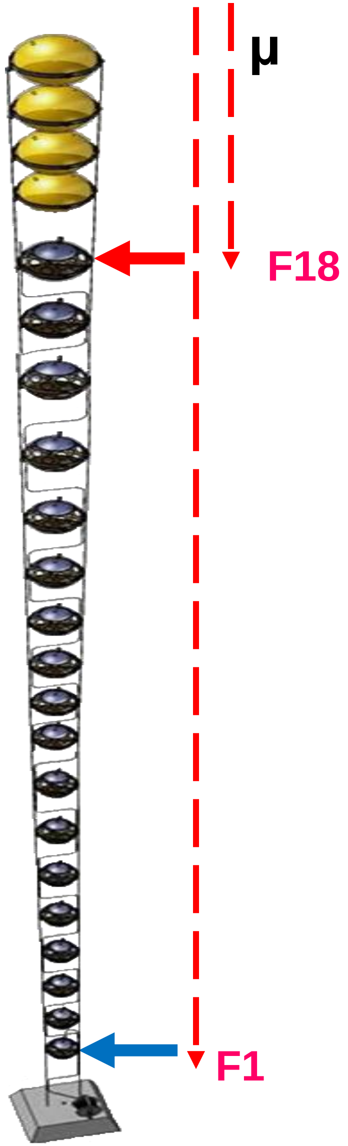
Directional sensitivity (photons from atmospheric muons come from above)

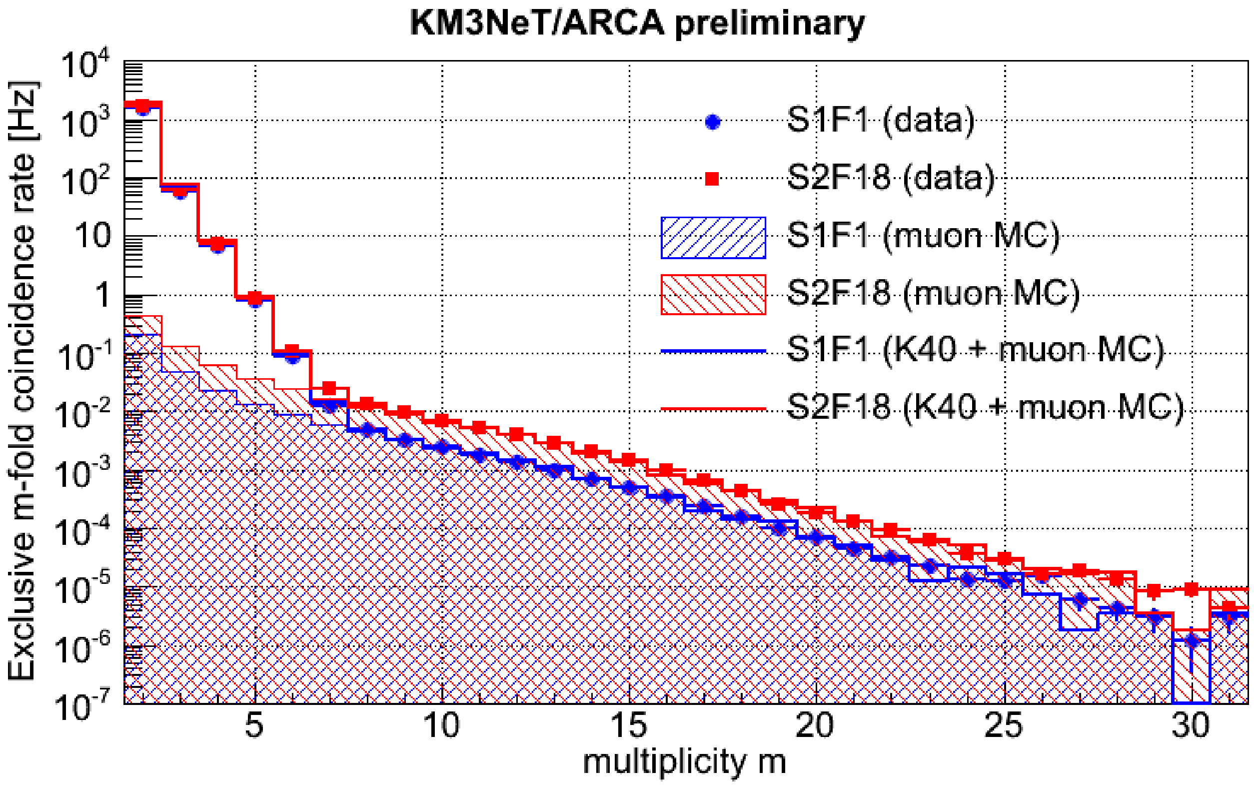


(data in this plot is from prototype PPM-DU (Eur.Phys.J. C76 (2016) no.2, 54))

- ✓ Number of hits detected by each PMT as a function of the zenith angle (coincidence level >7).
- ✓ Atmospheric muons come from above, therefore the number of events increases when the zenith angle of the PMTs decreases.
- ✓ Monte Carlo simulations are in a good agreement with data.

ARCA: Muon depth dependence





- Require ≥ 8 PMTs in coincidence
  → remove optical background at DOM level
- Measure the atmospheric muons versus depth

Conclusions

- ARCA & ORCA detectors are under construction in order to study cosmic neutrino sources and neutrino properties.
- The KM3NeT collaboration has adopted an innovative design of a multi-PMT layout for the Digital Optical Module.
- The DOM design has been validated and proved its performance in terms of
  - ✓ photon counting;
  - ✓ background rejection capabilities;
  - ✓ direction sensitivity.
- Production of the KM3NeT DOMs is currently on-going in 8 integration sites.
- Installation of Detection Units at the two KM3NeT sites in the Mediterranean Sea has already started.

Thanks for your attention