The multi-PMT optical module of KM3NeT

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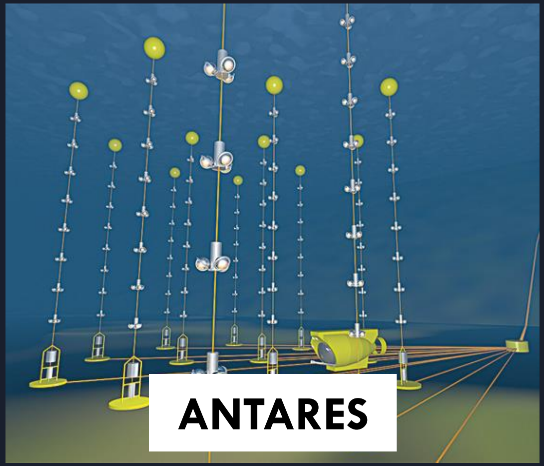
Outline

- Introduction
- KM3NeT design
- The KM3NeT Digital Optical Module
- Technical implementation
- Production model
- Performance

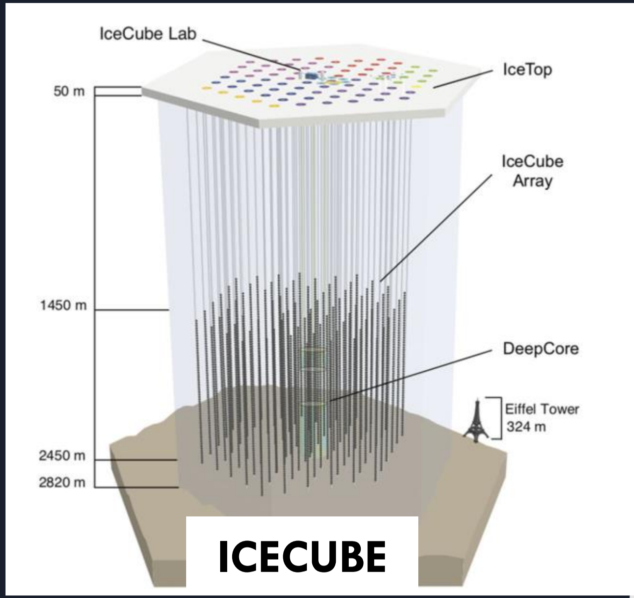
Neutrino telescopes: World map

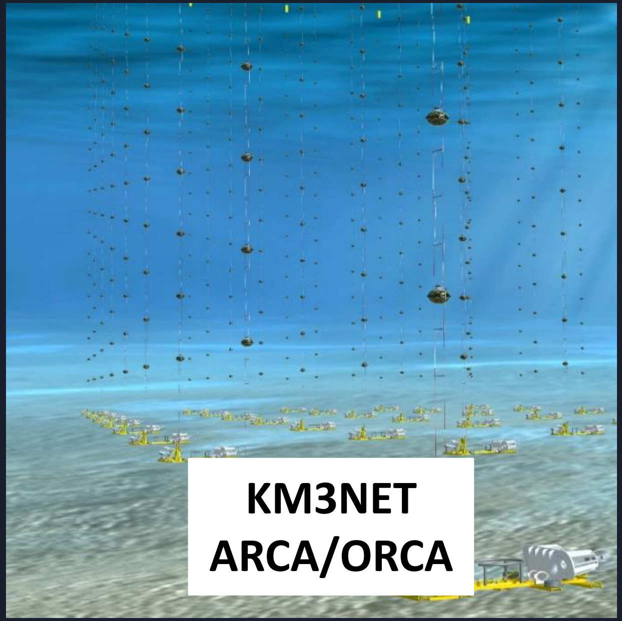
The extremely low neutrino cross-section and low high-energy neutrino fluxes motivated the scientific community to instrument different cubic kilometers of water and ice with matrix of light detectors around the World.

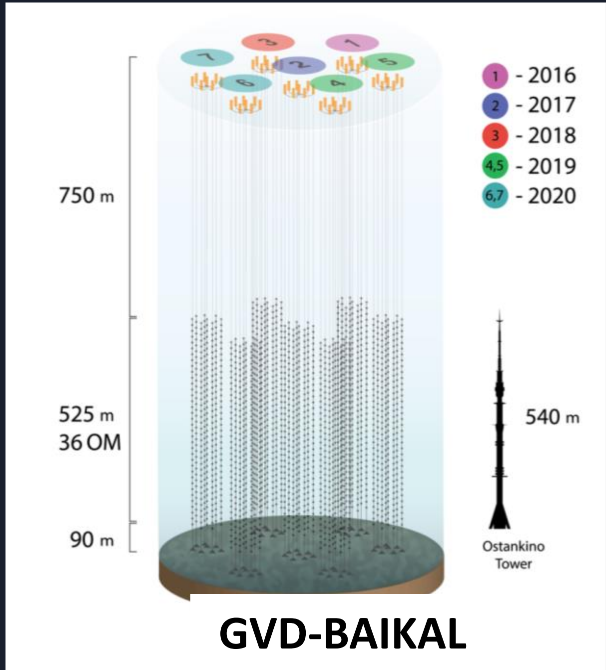
Neutrino telescopes: design



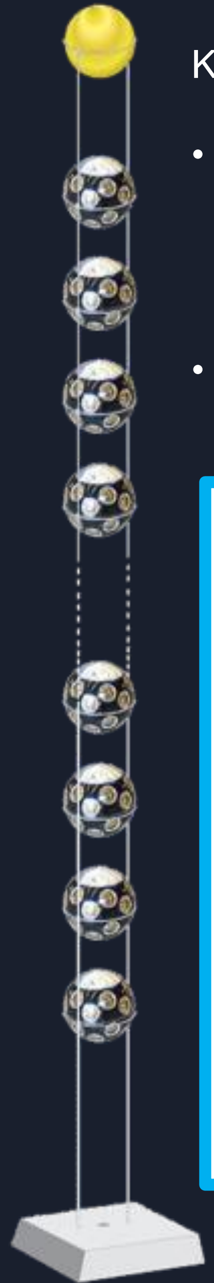
- Large volumes of water instrumented with arrays of "strings": vertical structures coupled to electro/optical cables, equipped with optical modules.
- The strings, with a typical length of several hundreds of meters, are distributed in specific geometries, optimized for the targeted energy region.
- The optical modules can host one or more Photomultiplier Tubes (PMTs), with different photocathode areas.







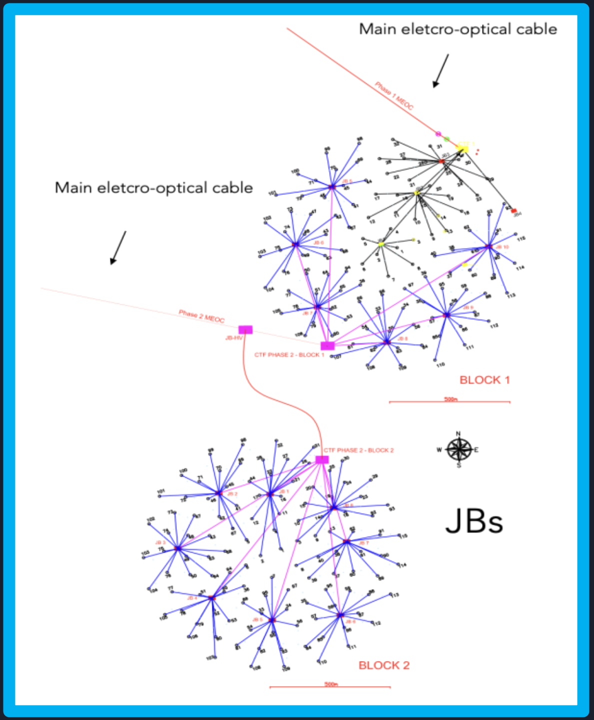
The KM3NeT detector design



KM3NeT is currently under construction at two different sites in the Mediterranean Sea:

- **KM3NeT/ARCA** (**A**stroparticle **R**esearch with **C**osmics in the **A**byss) 90 km offshore Portopalo di Capopassero, Sicily at 3500 m depth, aiming at the detection of HE cosmic neutrino sources (E_ν ~ GeV-PeV)
  → GOAL: 1 km^3 of instrumented water

- **KM3NeT/ORCA** (**O**scillation **R**esearch with **C**osmics in the **A**byss) 40 km offshore Toulon, France at 2500 m depth, aiming at the study of the neutrino oscillations (E_ν ~ MeV - GeV)
  →GOAL: 7 megatonnes of instrumented water



The two infrastructures share the same technology with different geometries, each one optimized for its scientific goal

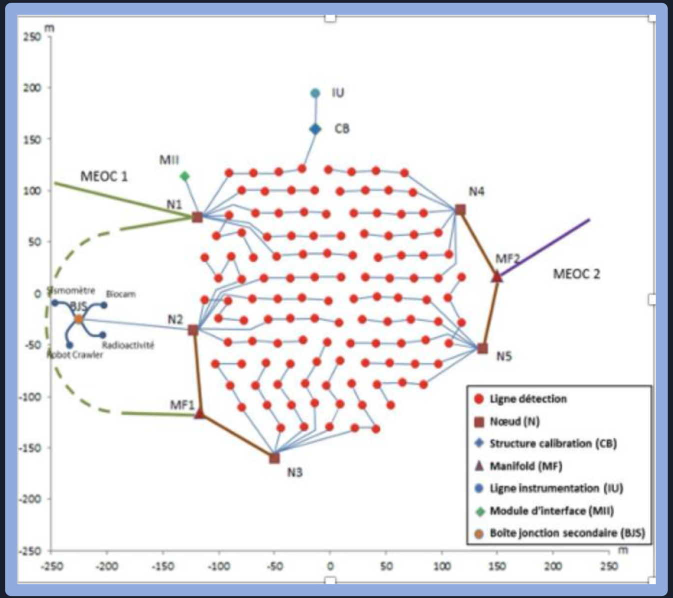
- ❑ ARCA = 2 BB = 230 Detection Units (DUs) with 4100 Digital Optical Modules (DOMs)

  (currently 19 DUs, June 22)

- ❑ ORCA = 1 BB

  (currently 11 DUs, June 22)

** 1 Building Block (BB) = 115 DUs*



The KM3NeT DU design

Starting design requirements for KM3NeT:

- instrument gigatonnes/megatonnes of water to detect adequate neutrino fluxes
- high angular resolution
- operational lifetime of at least 15 years
- 70 m absorption length and 100 m scattering length at 440 nm (ARCA) → sparse instrumentation

The Detection Unit of KM3NeT (DU) is a mooring line (~ 700 m for ARCA and 200 m for ORCA) consisting of:

- 1 Buoy
- 2 Dyneema ropes
- 18 DOMs
- 1 Anchor
- Oil-filled electro-optical backbone cables with 18 optical fibers and 2 copper wires for long-distance communication

The KM3NeT multi-PMT design

Implementation of the multi-PMT design:

- **<u>Cost efficiency (& high reliability):</u>** use of off-shelf components (as much as possible)
- **<u>Scalability:</u>** uniform module design
- **<u>High modules production rate:</u>** module assembly process distributed at different sites

The Digital Optical Module (DOM) has an innovative design:

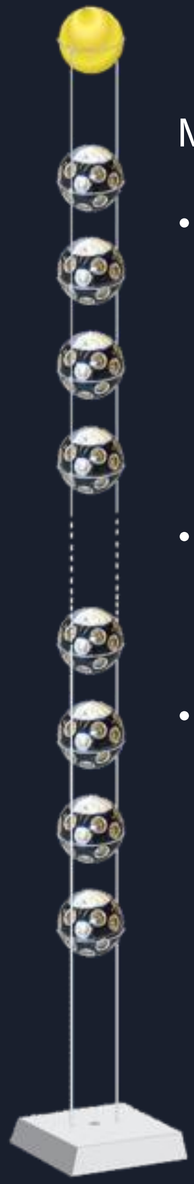
- 17 ” diameter high-pressure resistant glass sphere (44 cm diameter)
- dense packing of 31 **PMTs** with 3” photocathode diameter
- **calibration devices** (positioning and timing)
- **electronics** for power, readout, data acquisition and transmission
- low electrical power consumption: DOM ~ 7 W
- low risk of water leaks minimizing the number of feed-throughs

Multi-PMT
design description

Distribution production model
among integration sites

The KM3NeT multi-PMT optical module, S. Aiello *et al* 2022 *JINST* **17** P07038 https://iopscience.iop.org/article/10.1088/1748-0221/17/07/P07038

The KM3NeT multi-PMT design



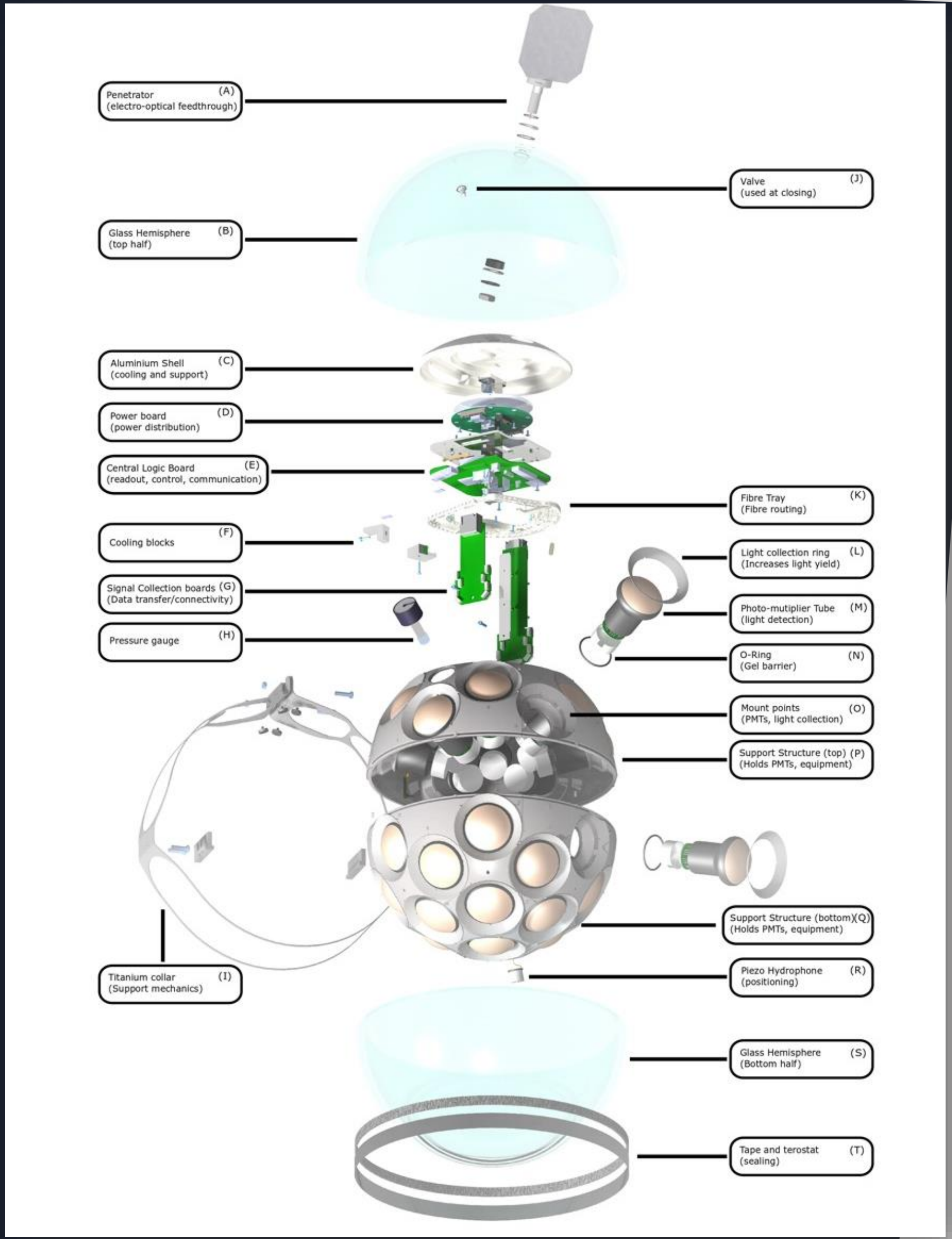
Main features:

- the segmented photocathode area of about 1200 cm^2 in each sphere increases the sensitivity of each DOM for the incoming direction of the detected photons

  → **broad angular coverage** and **good photon counting performance**

- the nanosecond accuracy of photon arrival time helps the reduction of the background coming from K-40 decay and bioluminescence

- the impact of a PMT failure on the performance of the telescope is lowered as the module can still be operated efficiently with fewer PMTs



Photodetection: the PMT

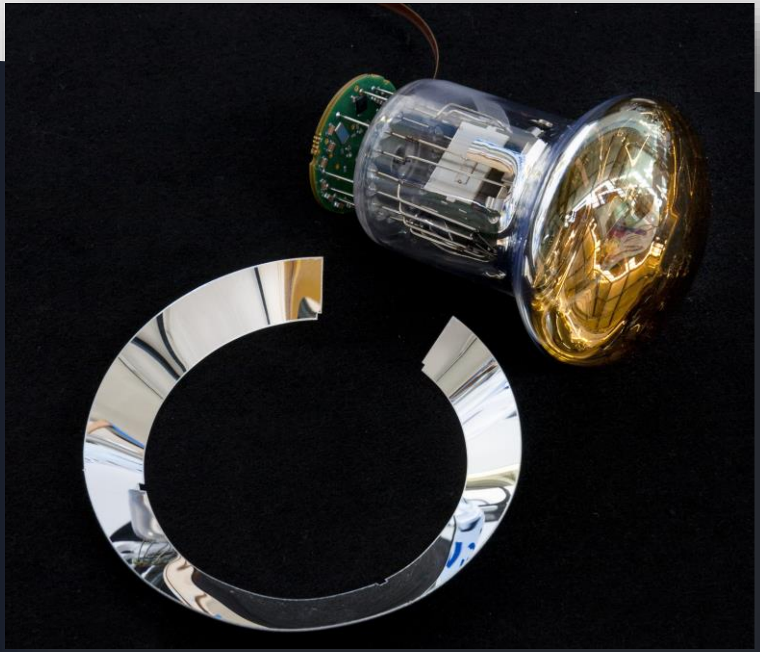
- The adopted PMT has a convex bialkali photocathode with a 3” diameter and a 10-stage dynode structure:
  Hamamatsu **R12199-02** and **R14374** → performance improvement (lower TTS)

Characterisation of the Hamamatsu photomultipliers for the KM3NeT Neutrino Telescope, *The KM3NeT Collaboration, S. Aiello, et al.* JINST13 (2018) P05035 doi:10.1088/1748-0221/13/05/P05035

- A **collection ring** made of polished metal, placed at an angle of 45° around the head of the PMTs in a convex shape, provides a 92% reflectance for photons in the wavelength range 375-500 nm.
  In this way, the acceptance is increased by 20-40%.

Expansion cone for the 3-inch PMTs of the KM3NeT optical modules, *KM3NeT Collaboration: S. Adrián-Martínez et al.* JINST 8 (2013) T03006 https://doi.org/10.1088/1748-0221/8/03/T03006

- Custom-designed **active base**:
  - HV generated by Cockroft –Walton circuit
  - analog pulse → charge amplifier → digitization by a circuit called PROMiS (PMT Read Out Mixed signal)
  - comparator discriminates the amplified PMT signal against a tunable threshold: the output level is kept «high» for the time that the PMT signal remains above the threshold → the interval of Time over Threshold, the ToT, is then measured



- ❑ Negative HV on the photocathode.
- ❑ An insulating coating on the outside and on the PMT bases to avoid electrical discharge between PMT and the surroundings.

A method to stabilise the performance of negatively fed KM3NeT photomultipliers
KM3NeT Collaboration: S. Adrián-Martínez et al. JINST 11 (2016), P12014
http://dx.doi.org/10.1088/1748-0221/11/12/P12014

Calibration devices: position

A detection unit can be bent by sea currents. Therefore, the position of the optical modules varies.

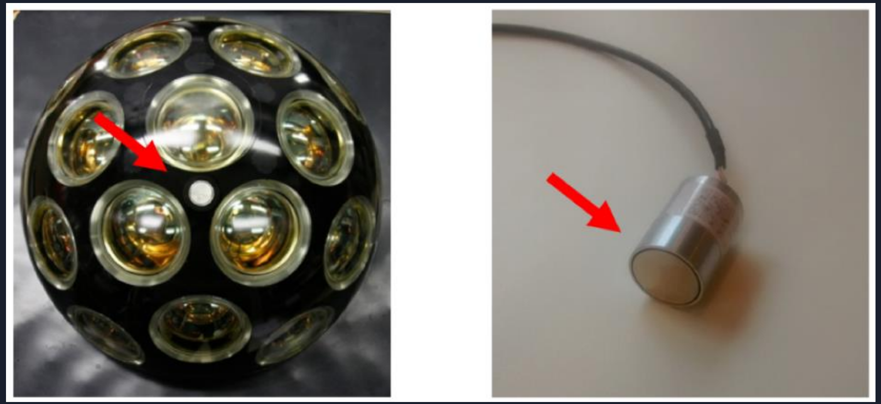
To continuously measure the *position* of the modules, *an* ***Acoustic Positioning System (APS)*** composed of three main sub-systems is used:

- Long baseline (LBL) of **acoustic emitters** anchored to the seabed at known positions
- **Acoustic piezo sensors** in each optical module (glued inside the glass of the lower hemisphere to maximize acoustic coupling)
- **Hydrophones** at the bases of the detection units

In addition, in order to monitor the *orientation* of the optical module with respect to the telescope coordinate system:

- **Compass** and **accelerometer**, whose data are sent to shore and converted into orientation coordinates Pitch, Yaw, and Roll of the optical module

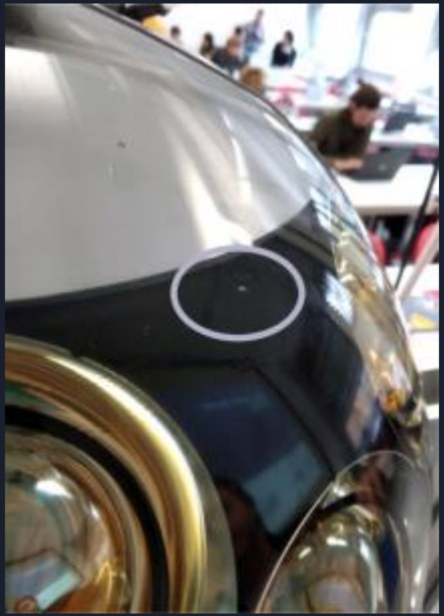
<u>This system updates the position of the detector every minute and the information is stored in the database.</u>



Calibration devices: time

Every DOM is equipped with a 470 nm LED pulser referred to as ''nanobeacon'' emitting fast light pulses for timing calibration of neighbouring DOMs.

- Intensity, timing, and pulse frequency can be controlled remotely from the onshore control station
- The nanobeacon is operated only during dedicated timing calibration runs (the operated frequency is 1 kHz and the intensity of the pulse is set to reach the single photoelectron level to the adjacent module)
- The runs aim to measure the propagation time of light from one module to the adjacent one
- Moreover, these data can be used to study the optical properties of the water



The nanobeacon is optically connected to the glass hemisphere (on the TOP), pointing upwards

The LED is soldered on a small electronics board, connected to the main PCB through a twisted-pair cable

Nanobeacon: A time calibration device for the KM3NeT neutrino telescope https://doi.org/10.1016/j.nima.2022.167132

Front-end electronics and DAQ

To minimize the required bandwidth and still deliver sufficient information, the PMT photon measurement is reduced to two values only: photon arrival time and time-over-threshold.

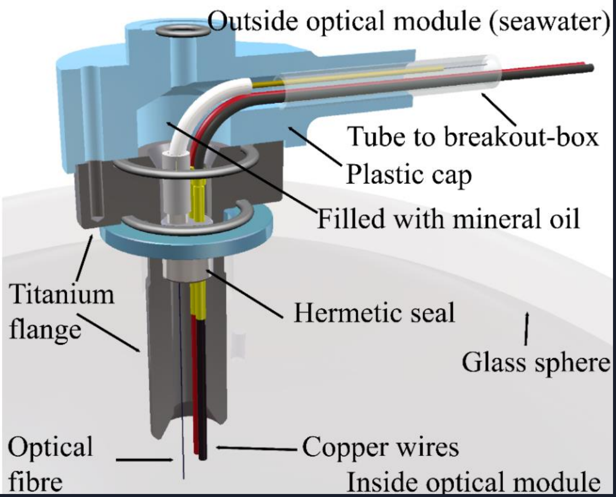
- All data collected offshore are digitized and sent without reduction to shore ("all data to shore")
- A farm of processors, with data trigger and selection algorithms, reduce the data volume and filter the signals from the background
- The observables that are needed for physics analysis are then identified

This approach requires that the clocks of the DOMs are synchronized to sub-nanosecond precision.

The electronics inside the DOM is composed by:

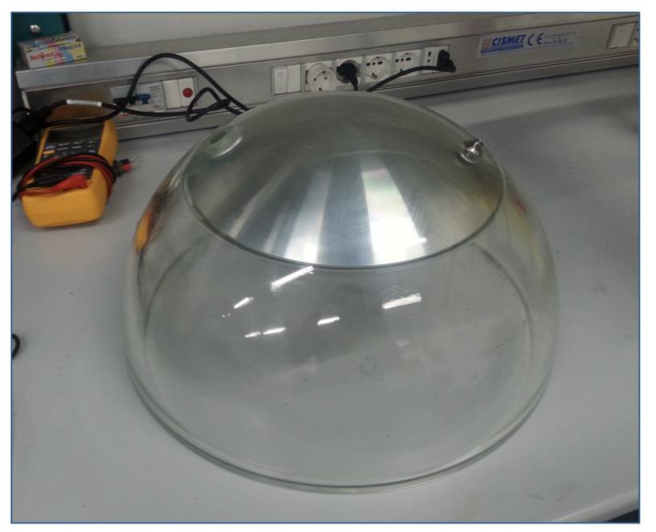
- the central logic board – CLB
- two PMTs signal collection boards (long/short Octopus)
- 31 PMT active bases
- the power distribution board – the power board

The DOM is connected to the electro/optical cable through a custom-designed penetrator, hosting two power cables and one optical fiber in a hermetic titanium housing



The mechanics

Two holes into the glass hemispheres: one for the vacuum valve, and one for the penetrator.



The **vessel** is a 0.44 m diameter Vitrovex, borosilicate glass sphere with 14 mm thickness:

- designed to withstand pressures up to $6.7 * 10^7$ pascal
- resistance to corrosion, shocks, and vibrations
- internal underpressure of $2 * 10^4$ Pa below atmospheric pressure for stability and tightness during transportation, storage, and deployment.
- around the equator, a layer of sealing tape, covered with black scotch tape, is applied
- two hemispheres, glass-to-glass contact at the equator
- light transmission > 95% above 350 nm, matching the sensitivity range of PMTs
- refractive index: 1.47
- low radioactivity

The aluminum cooling system is thermally coupled to the glass sphere: dissipating excess heat and minimizing the operative temperature of the DOM

- cooling mushroom, attached to the top glass with a thin layer of silicone gel. It houses the main electronics and is mechanically and thermally connected to the other aluminum parts
- two cooling blocks and heat conducting pads → FPGA and SFP
- cooling bar → octopus boards

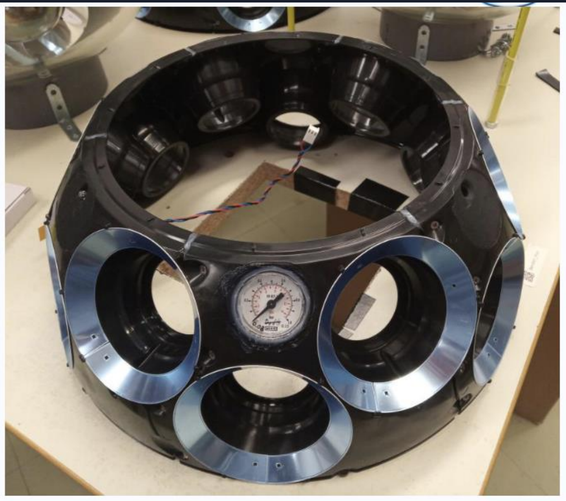
The mechanics

The **support structure**:

Two internal support structures, one for each hemisphere. Manufactured by 3-D printing technique (bottom) and by injection molding technique (top). Black material to minimize reflections.

Functions:
- structural support for PMTs, defining positions and distances from the glass;
- housing for accessory instrumentation;
- guides for integration

The **BOTTOM** PMT support structure holds:
- 19 PMTs (3 rings of 6 PMTs at angles of 106°, 122.5°, 146.75° from the zenith and one PMT pointing downwards at 180°)
- 19 light collection rings
- a feedthrough for the piezo sensor, which is glued to the glass sphere



The **TOP** PMT support structure holds:
- 12 PMTs (2 rings of 6 PMTs at angles of 57.5° and 74° from the zenith)
- 12 light collection rings
- a nanobeacon
- a pressure gauge to monitor the internal underpressure of the DOM

The mechanics

The optical contact between glass and PMTs is performed using a **two-component silicone Wacker SilGel A/B gel**, poured into the cavity between the support structure and the glass.

- refractive index = 1.40, close to both the refractive indexes of the glass vessel (1.47) and the PMT window (1.51-1.54)
  → unwanted reflections are minimized

- light transmission optimized in the wavelength range of interest

- optimal softness (determined by the mixing ratio): contributes to accommodate the shrinkage of the glass vessel under the high operational hydrostatic pressure and absorbing the shocks and the vibrations induced by transportation

- <u>all components in contact with the gel are routinely qualified for compatibility, to avoid polymerization issues</u>



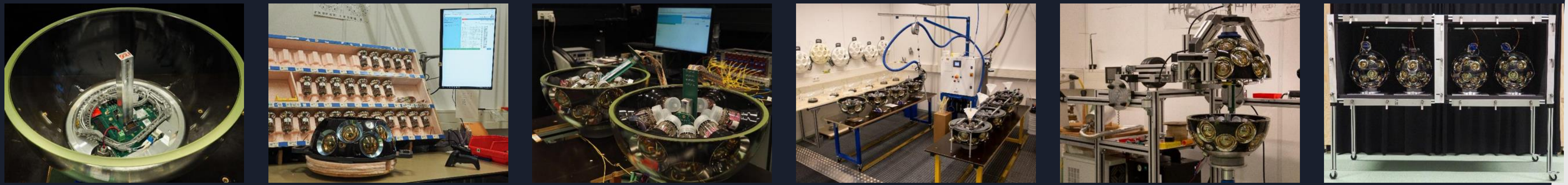
Production model: the integration

In its final configuration, KM3NeT will consist of more than 6000 DOMs: a distributed production model has been established.

- The DOM integration procedure has been optimized for protection against errors and maximization of the production rate: as of today, the 8 KM3NeT DOM integration sites are able to guarantee a baseline production rate of 100 DOMs per month.

- CONS: challenging procurement and logistics → a very high level of QAQC (quality assurance - quality control) is mandatory!

The integration process is divided into several steps, following a strict protocol. A dedicated software **(the KM3DIA)** guides the integrators through the right sequence of operations, logs all relevant information and registers all DOM details.



Each hemisphere is filled bottom-up:

1) Glueing the cooling mushroom (TOP) and acoustic piezo (BOTTOM)
2) Electronics, penetrator → helium leak test, optical fiber splicing
3) Installation of PMT and light collection rings
4) Functional test
5) Gel pouring
6) DOM closure (custom made tool)
7) Acceptance test in a dark box

Minimisation of the error

↓

Check all components

↓

Problem?

Non-conformity report (NCR)

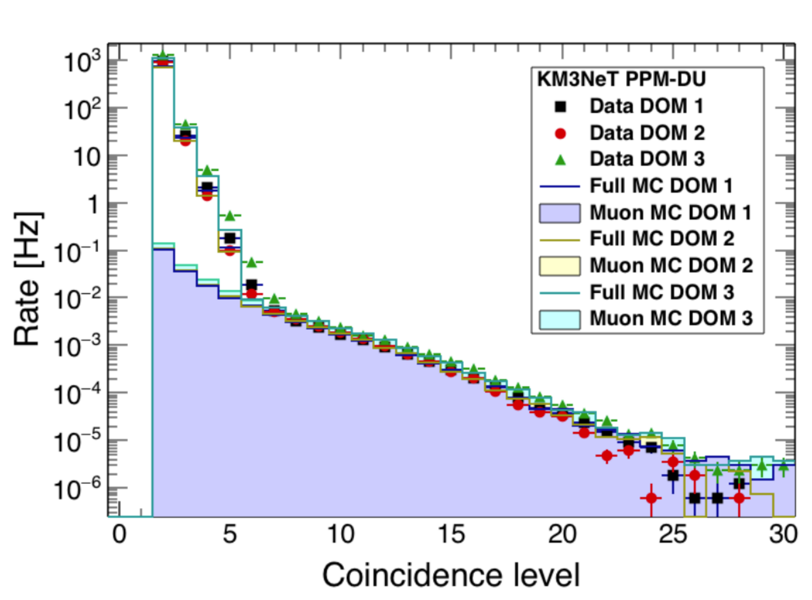
- All component are registered in a central database with a unique **product identifier code** UPI.

- The history of the components is tracked in the database and the tests values can be recovered from the database during the detector operation and data analysis.

DOM performance

- In total 30 detection units deployed in ARCA and ORCA, with 540 DOMs (16740 PMTs)

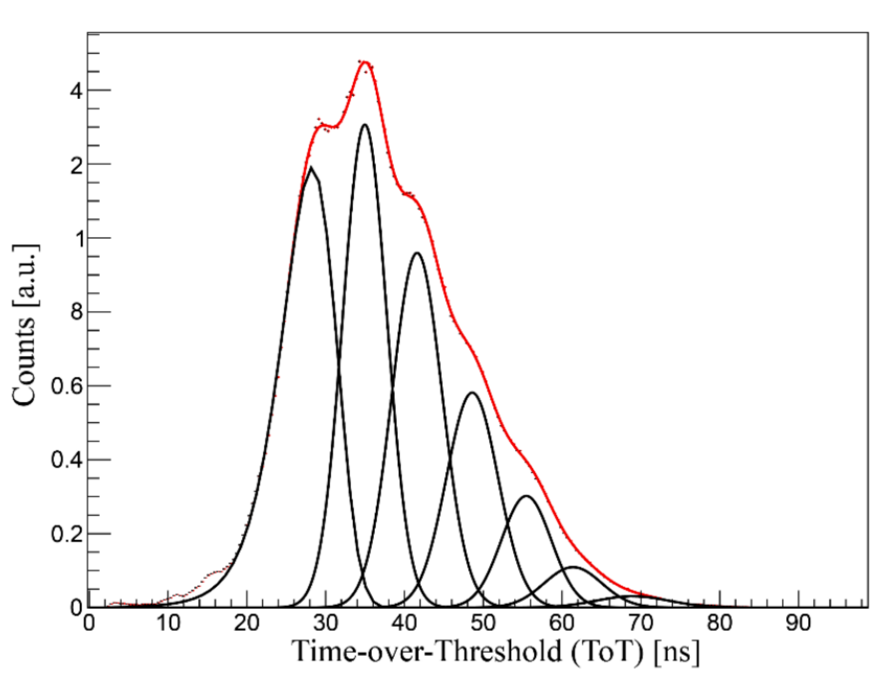
- Even with a single DOM, the signal from atmospheric muons can be distinguished from the background of K-40 and bioluminescence, exploiting multi-PMT coincidences.



The ToT response of the PMTs detecting multiple photons has been studied in lab measurements and situ.

The shape of the distribution of the ToT values due to single photoelectron signals is described with an analytic model that takes into account as free parameters the *gain* and the *gain-spread*.

With the model, the PMT gain can be monitored in situ and, if needed, adjust the High Voltage (HV) by tuning it.



Lab measurement of time-over-threshold response of the Hamamatsu R12199-02 PMT to different numbers of photo-electrons. The black lines are model fits for increasing numbers of photo-electrons, starting at 1 photo-electron, and the red line is an overall fit.

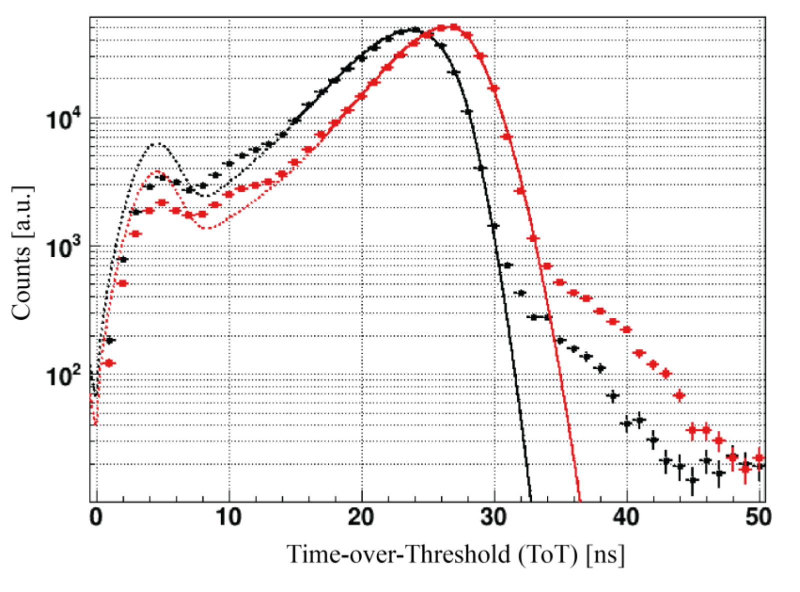
The KM3NeT multi-PMT optical module, S. Aiello *et al* 2022 *JINST* **17** P07038
https://iopscience.iop.org/article/10.1088/1748-0221/17/07/P07038

DOM performance

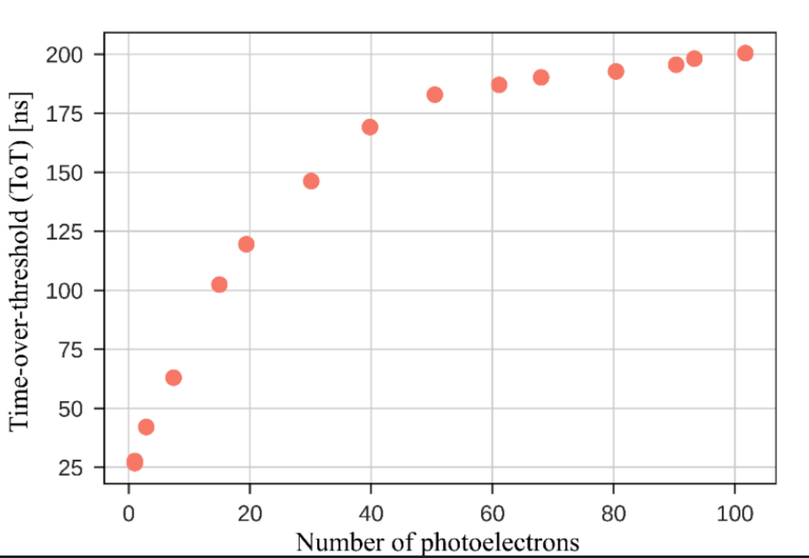
To minimize the effect of aging (and hence to maximize the lifetime of the PMTs), given the typical rate of the deep-sea environment, a low nominal gain of $3 * 10^6$ has been chosen (ToT of 26,4 ns).

The operational gain is obtained by tuning the HV of each PMT in situ during the telescope operation.

The gain tuning process is done considering the distribution of the ToT of each PMT for different HVs, fitting the gain and gain spread in each instance and interpolating the HV value that corresponds to the nominal gain.



In situ measured time-over-threshold distribution with single photo-electron model fits for a single PMT operated at different high voltages (black: −1130 V; red: −1180 V, solid lines indicate fit region)



The average time-over-threshold as a function of the number of photo-electrons (G = $3 * 10^6$)

Thanks for the attention