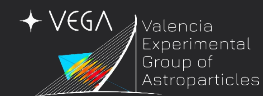


*Taller de Instrumentación y Detectores en Física de Partículas,
Astropartículas y Nuclear, Jun 15-26, 2026*

Instrumentation for Neutrino Telescopes

Credit: Agustín Sánchez-Losa



Francisco Salesa Greus
(sagreus@ific.uv.es)

IFIC (CSIC-UV) | VEGA



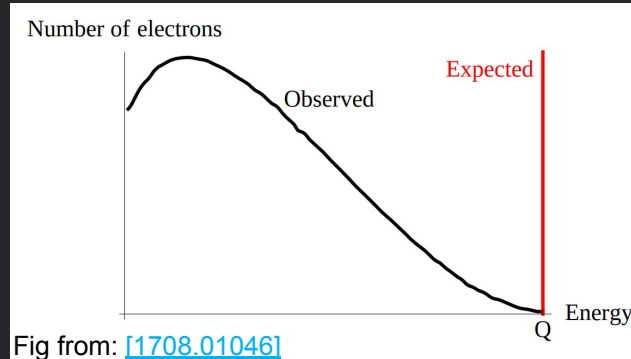
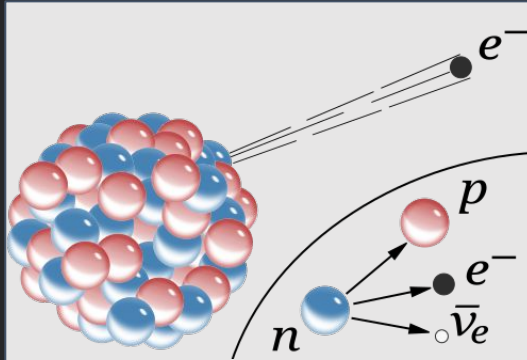
Outline

- Introduction to Neutrino Telescopes: detection technique, early projects & challenges.
- Instrumentation for Neutrino Telescopes. The cases of: ANTARES, KM3NeT, and IceCube.
- Instrumentation Plans for Future Projects.

Introduction to Neutrino Telescopes

Neutrino Discovery

- Rutherford (1903) named the three types of radiation: alpha (α), **beta (β)**, and gamma (γ) rays. Then (Kaufmann, Schuster, 1900-1902) discovery that β rays are electrons.
- In β decay the electron **spectrum is continuous** (Chadwick, 1914) instead of a fix value ($E_e = E_{\text{parent}} - E_{\text{daughter}}$).
- To explain β decay spectrum (Pauli, 1930) proposed a **new particle**, the neutrino (originally called the "neutron", Fermi **neutrino**), as a "desperate remedy" **to save energy conservation**.
- Fermi makes successful predictions for the energy spectrum. Bethe and Peierls (1934) estimate the cross section for such process, saying that "it is absolutely **impossible to observe processes of this kind**".



Beta Minus Decay (β^-)

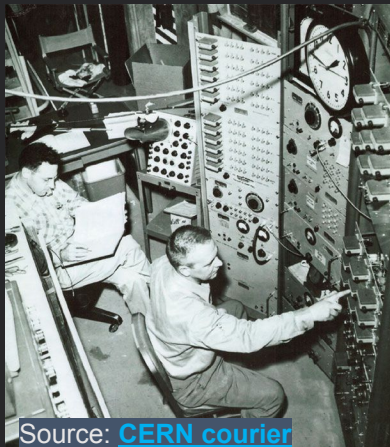


Beta Plus Decay (β^+)

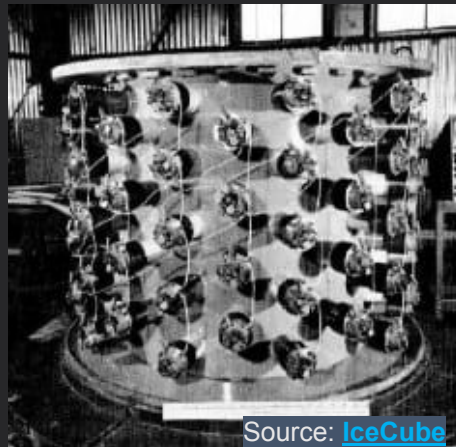


Neutrino Discovery

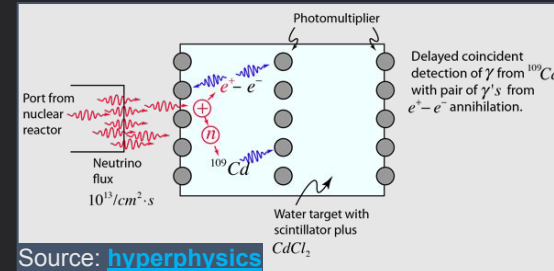
- **Neutrinos interact very weakly**, so detection is difficult. Still, Pontecorvo showed that a **ton-scale detector** near a nuclear reactor (flux $\sim 10^{11}$ v/cm²/s) could see a **few events per day**.
- **Reines and Cowan in 1956**, discovered antineutrinos via inverse β decay using a massive detector (12 m underground, 11 m from the reactor, 110 PMTs) and a delayed-coincidence signature (positron + neutron) from a inverse beta decay reaction. [Science 124 \(1956\)](#).
- Their technique **remains the standard method** in modern reactor-neutrino experiments.



Source: [CERN courier](#)

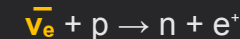


Source: [IceCube](#)



Source: [hyperphysics](#)

Distinctive signature for the neutrino reaction:
 γ pair in coincidence + γ within 5 μ s.

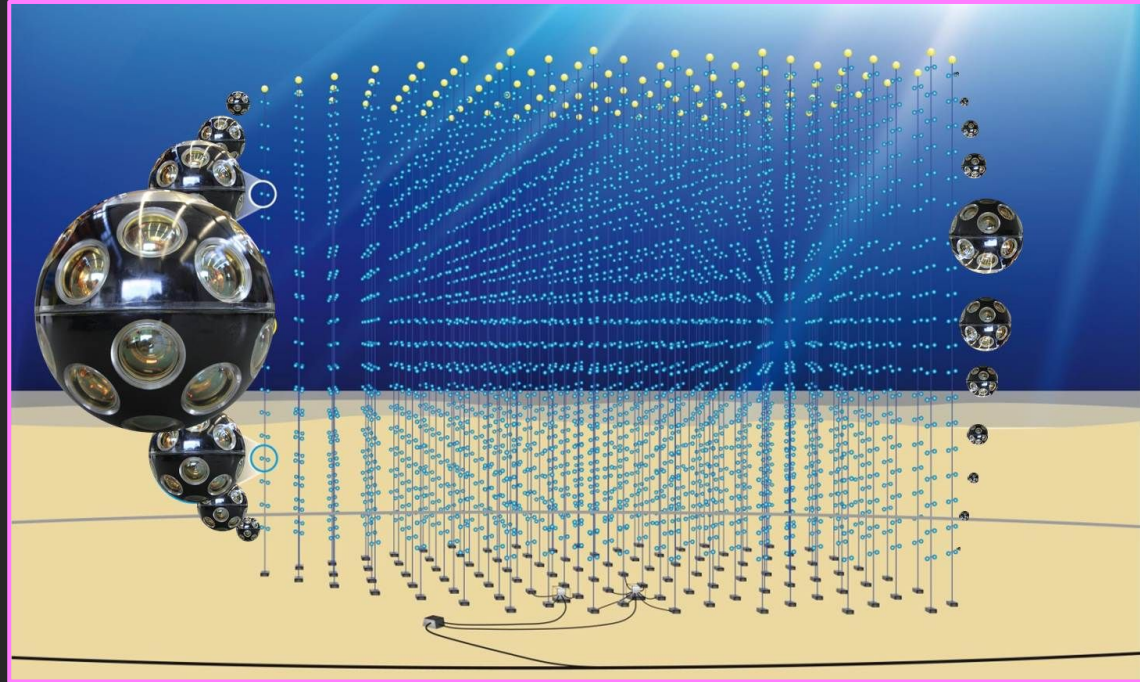


Neutrino Telescopes

“We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation”, **Markov 1960**

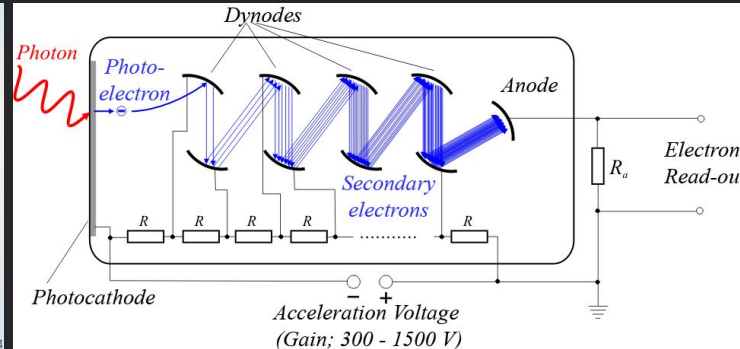
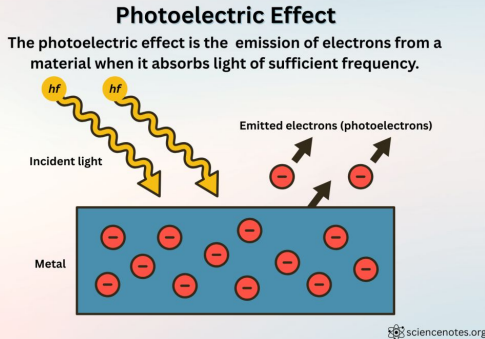


Markov (left) and Pontecorvo (right)



Photomultiplier Tubes

- Discovered by Hertz in 1887, the **photoelectric effect** is the emission of electrons from a material caused by electromagnetic radiation such as ultraviolet light.
- Photons behave like a discrete energy packets. Explained by Einstein in 1905, [Nobel Prize](#) in 1921.
- Photomultiplier tubes** (PMTs) use the photoelectric effect to **release electrons** from a photocathode, then amplify them through a chain of dynodes, producing a **strong output signal**.
- Fast response and high gain (amplification factors up to 10^6 - 10^7), making PMTs **ideal for detecting Cherenkov light, scintillation**, or other fast optical signals in particle and astroparticle experiments.



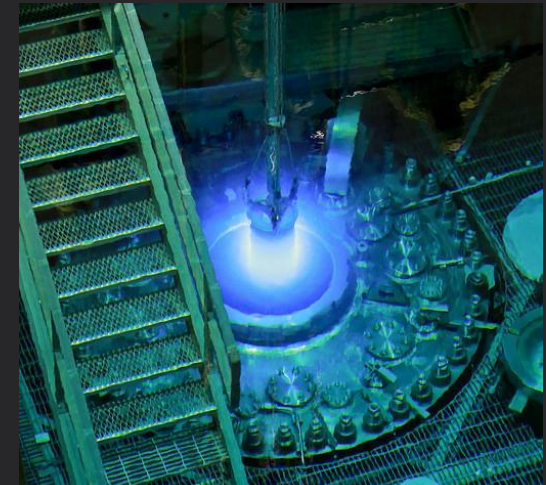
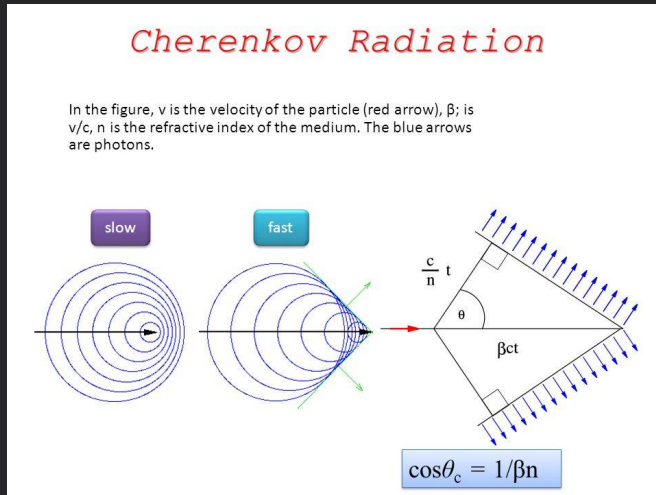
Transit Time: the total time interval between the arrival of an incident photon at the photocathode and the peak of the resulting electrical signal output at the anode.

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Cherenkov Radiation

- Discovered by Pavel Cherenkov in 1934.
[Nobel prize](#) in 1958.
- Electromagnetic radiation (peaked at blue/UV) emitted when a charged particle passes through a dielectric medium at a speed higher than the light in that medium.

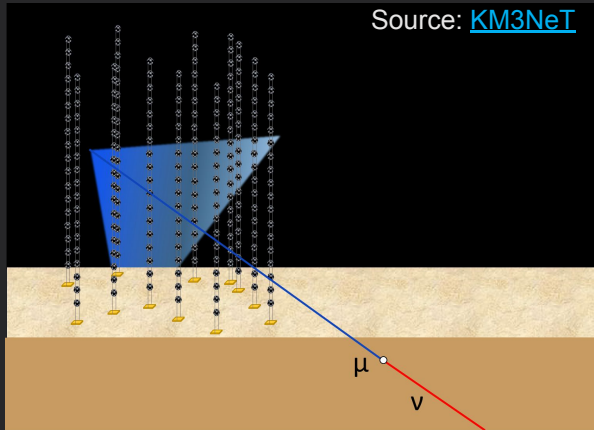


Water Cherenkov Detectors

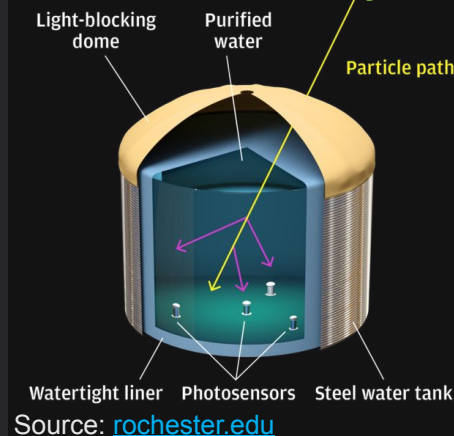
- **Energetic charged particles** crossing a transparent medium (e.g., water) **induce Cherenkov light**, producing a faint, fast optical signal that can be detected with PMTs.
- **Large volumes of natural water** can be instrumented with arrays of PMTs to capture these Cherenkov photons. This is the principle behind underwater and ice-based **neutrino telescopes**.
- Alternatively, **water tanks** equipped with PMTs can be used to detect **particle showers at the surface**, as demonstrated by observatories like HAWC and Pierre Auger.

ANTARES/KM3NeT

Source: [KM3NeT](#)

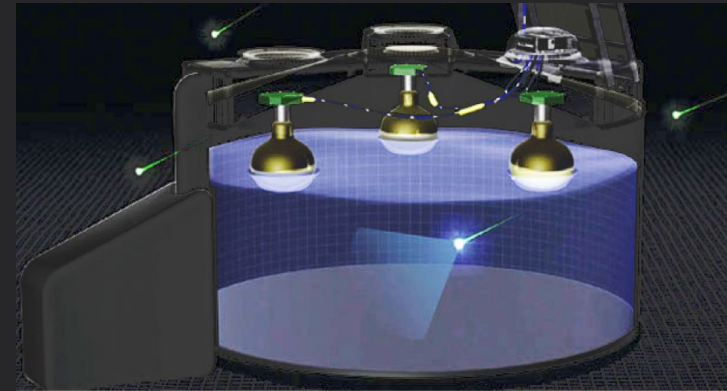


HAWC Observatory



Source: [rochester.edu](#)

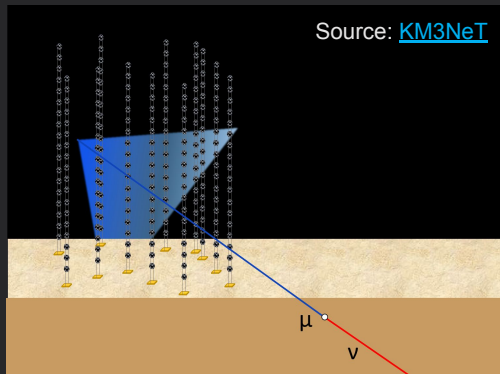
Pierre Auger Observatory



Source: [NIM A 970, 2020](#)

Event Reconstruction

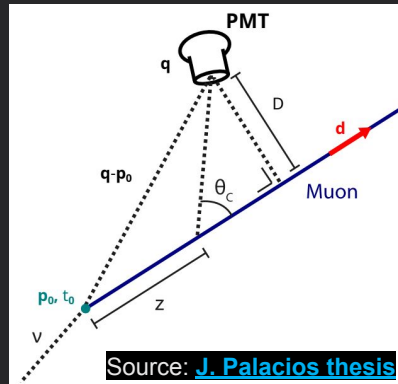
- Event reconstruction uses the **charge and timing** from **hits** to infer the event **arrival direction & energy**.
- **Direction reconstruction** fits the **timing pattern** to determine the particle's arrival direction.
- **Energy reconstruction** relies on signal amplitude, total detected light, or proxy observables (e.g., number of stations, number of hits, charge, etc) to determine the energy of the event.
- **Quality cuts** and reconstruction algorithms **refine the final event sample**, improving angular resolution, energy resolution, and background rejection.
- Usage of likelihood methods, machine learning, and MC templates to achieve optimal performance.



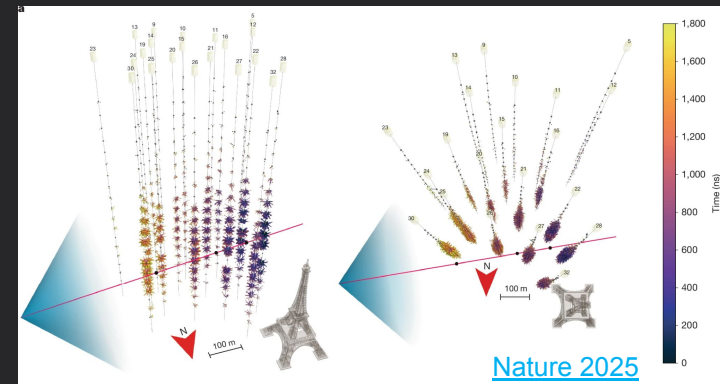
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★ VEGA

Muon travelling in a **direction d** , after a neutrino interaction at **position p_0 and time t_0** , then the arrival time t of a Cherenkov photon at a **PMT located in a position q** .



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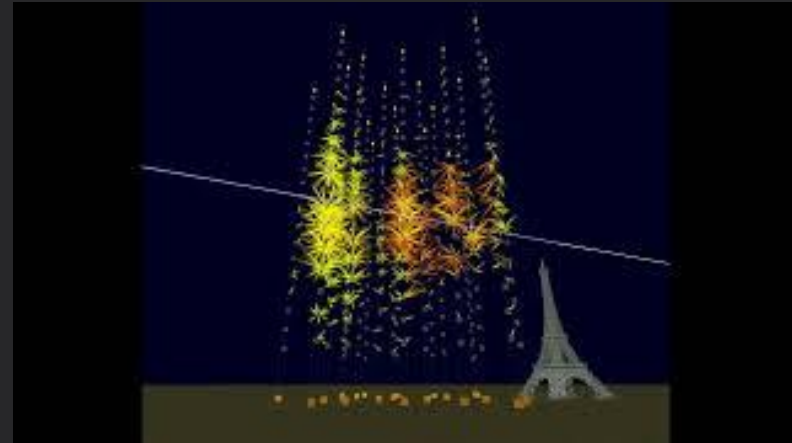


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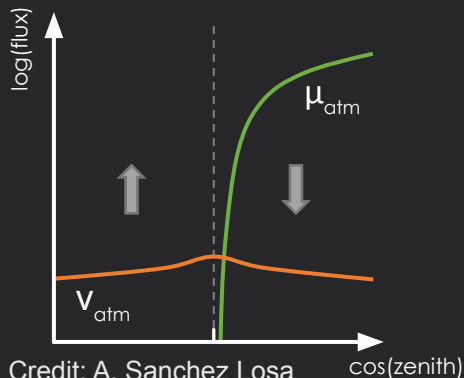
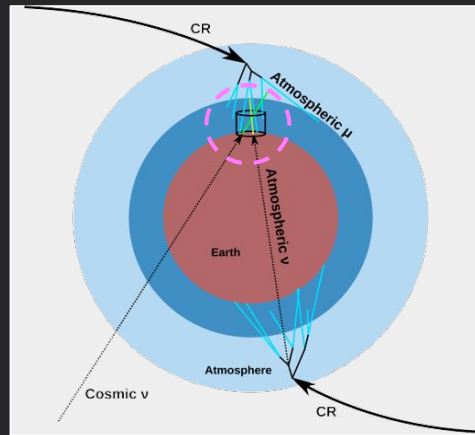
10

A Remarkable Event

- A **muon** detected with $E = 120^{+110}_{-60}$ PeV
- Event is near horizontal, travelling 140 km through Earth -> extremely unlikely to be an atmospheric muon.
- Inferred **neutrino** energy 220^{+570}_{-110} PeV (assuming E^{-2} spectrum)



Detection Principle



Credit: A. Sanchez Losa

cos(zenith)

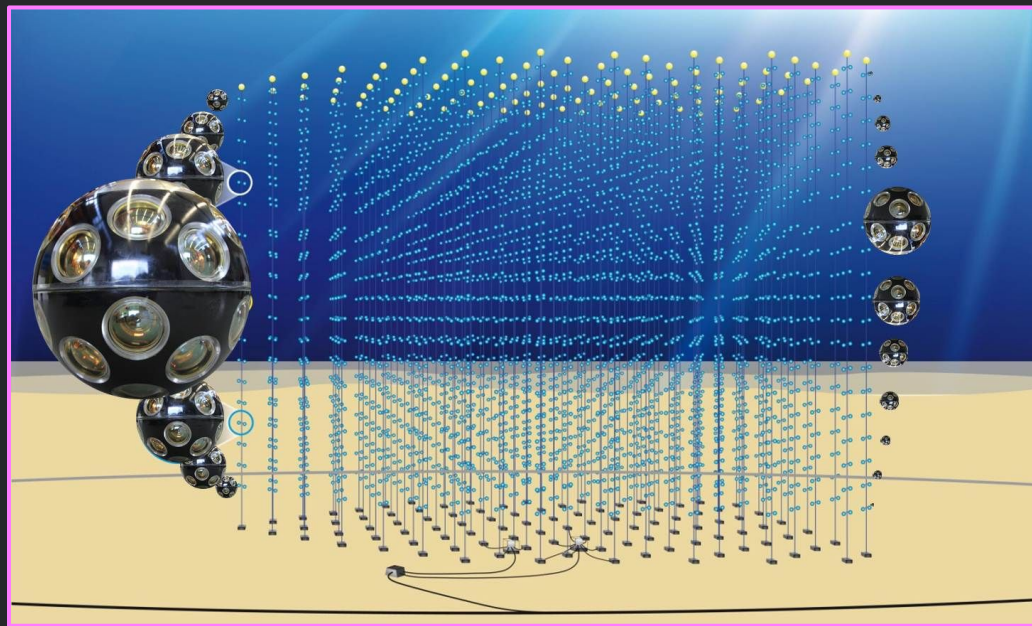
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+ VEGA

In a km³ detector:

μ_{atm}	$\sim 2000 / \text{s}^{(1)}$
ν_{atm}	$\sim 400 / \text{day}^{(2)}$
ν_{cos}	$\sim 200 / \text{year}^{(2)}$

(1): depth dependent (2): analysis dependent

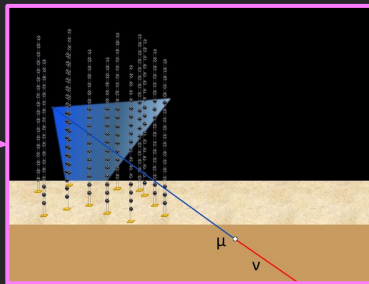
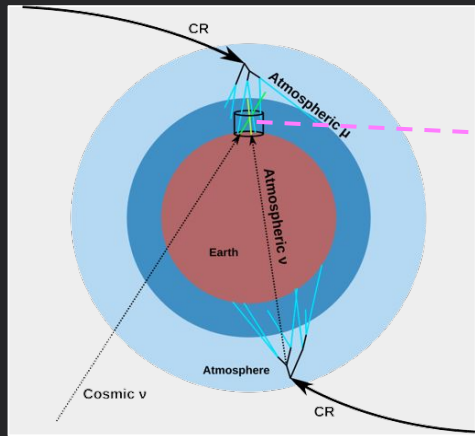


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Detection Principle



Track-like
 Good **angular** resolution:
 0.25° (0.5°) at 10 TeV in water (ice)
 0.08° (0.3°) at 1 PeV in water (ice)
Energy resolution factor ~ 2

Shower-like
Angular resolution ~2° (5°) in water (ice)
 Better **energy** resolution < 10 % for $E > 10\text{TeV}$

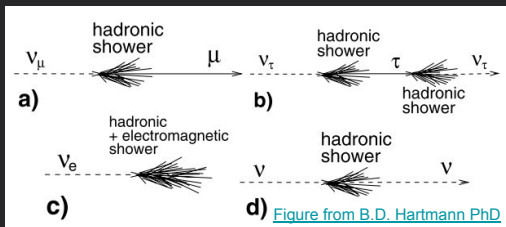
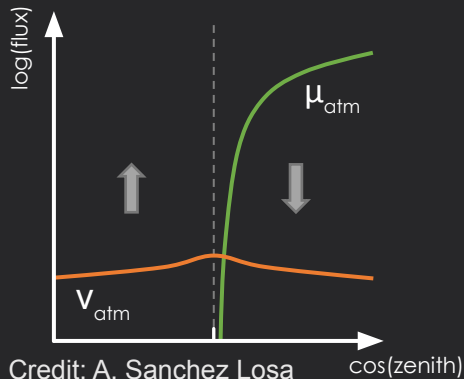


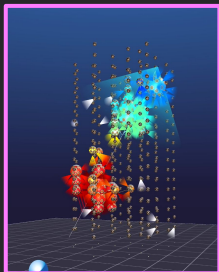
Figure from B.D. Hartmann PhD



Credit: A. Sanchez Losa

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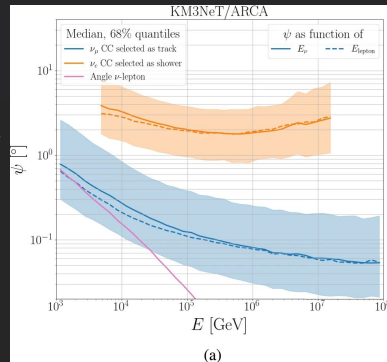
+ VEGA



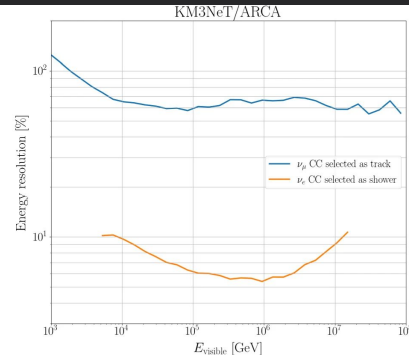
track



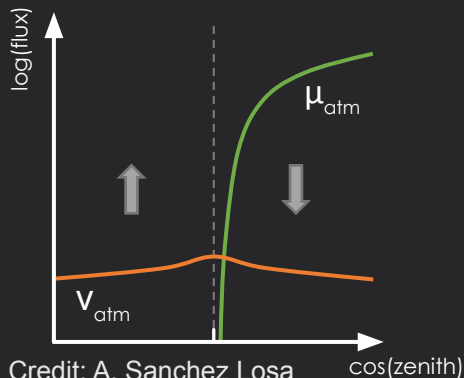
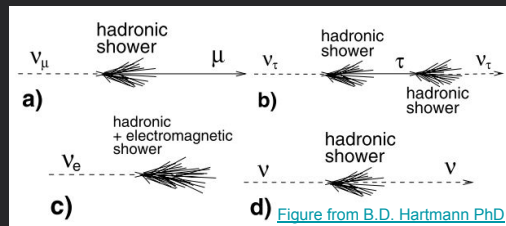
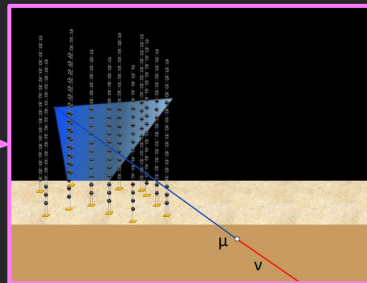
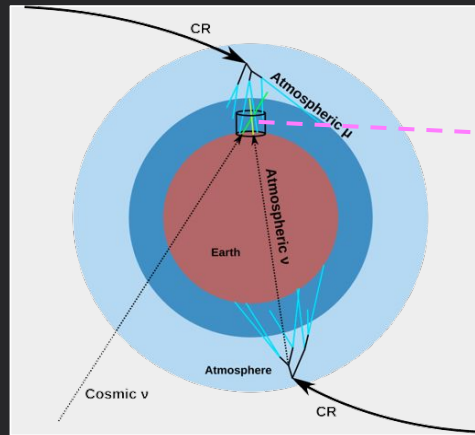
shower



(a)



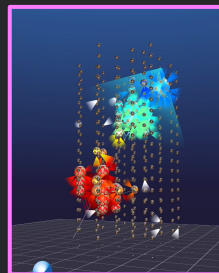
Detection Principle



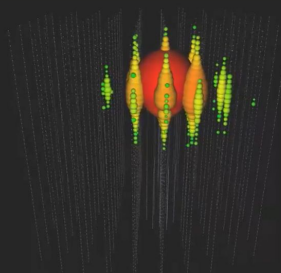
Credit: A. Sanchez Losa

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+ VEGA

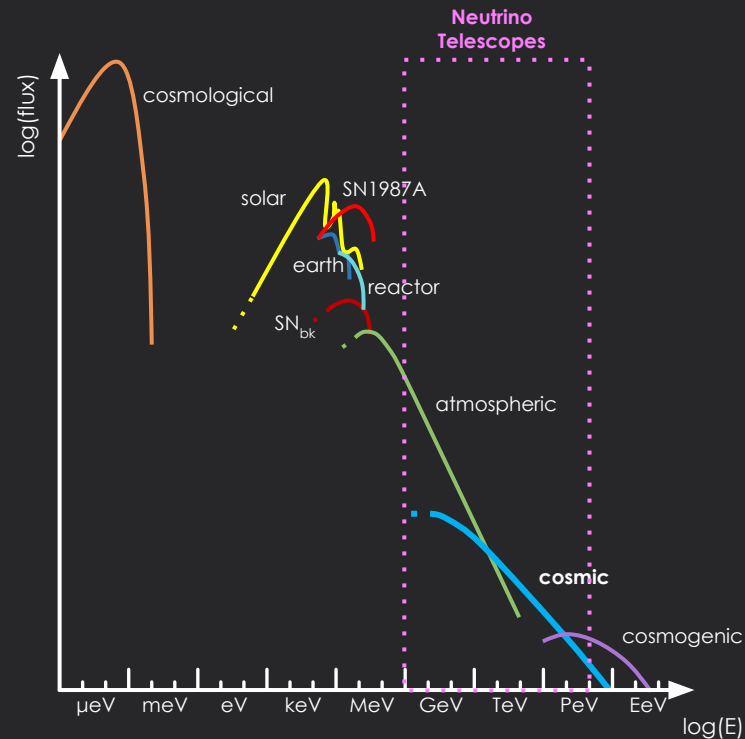


track



shower

Measured/expected neutrino fluxes



Broad Physics Scope

KM3NeT - ARCA

KM3NeT - ARCA

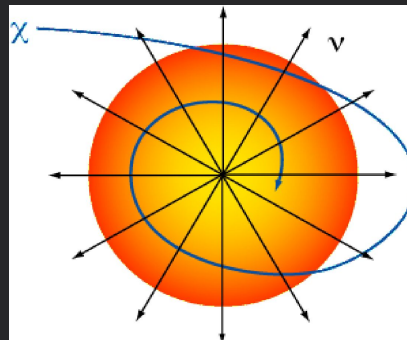
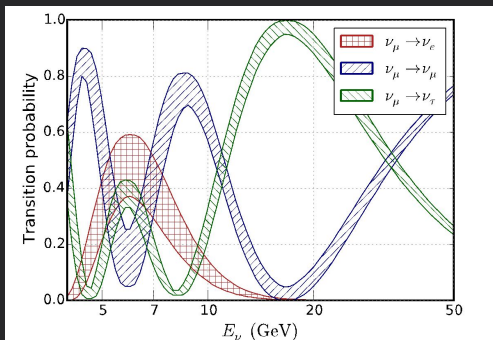
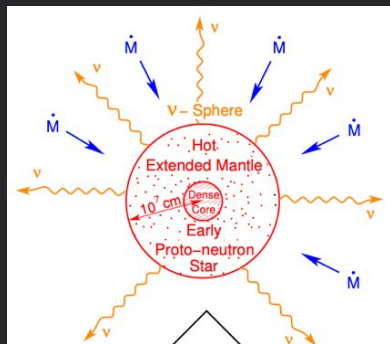
KM3NeT - ORCA

Low Energy
~ MeV

Low Energy
> 10 GeV

Medium Energy
 $10 \text{ GeV} < E_\nu < 10 \text{ TeV}$

High Energy
 $E_\nu > 1 \text{ TeV}$



CCSN detection

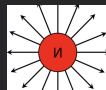
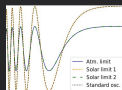
ν oscillations

dark matter search

ν from extra-terrestrial sources,
origin and production mechanism
of HE CR

...and exotic searches

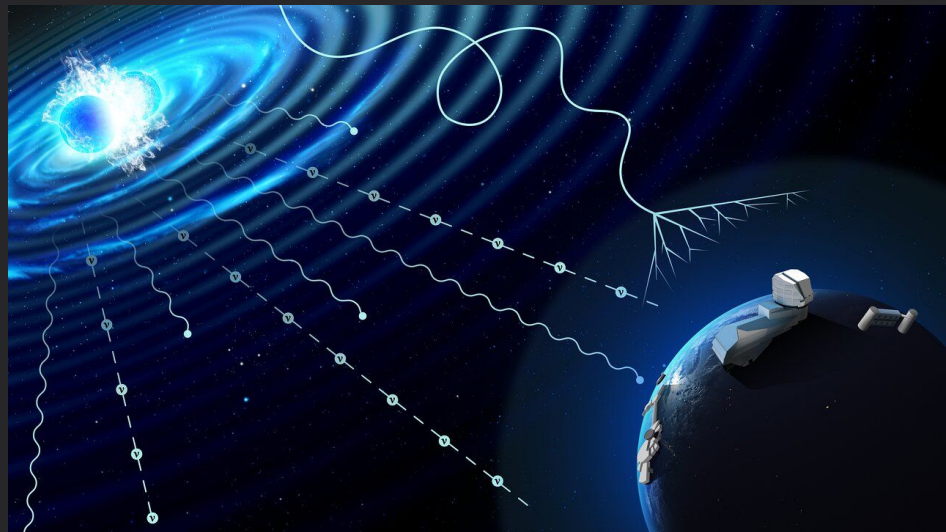
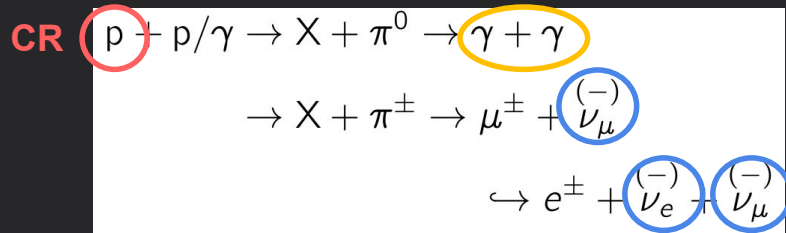
NEUTRINO ASTRONOMY



Astroparticle Physics: The Multi-Messenger Connection

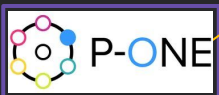
Credit: [RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/P. Marenfeld](#)

- Cosmic accelerators can produce different *messengers*: **cosmic rays**, **gamma rays**, **neutrinos**, and **gravitational waves**.
- **Common origin**: **CR** accelerators produce both **γ** and **ν** through hadronic processes: **$p\gamma$** and **pp** interactions.



Multi-messenger astronomy concept:
Combination of two or more messengers in
spatial and/or temporal coincidence enhancing
the discovery potential of a source.

Neutrino Telescopes



Pathfinders

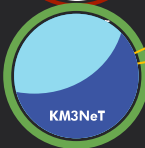
DUMAND (Hawaii)
Baikal
Amanda (Ant.)
NESTOR (Med.)
NEMO (Med.)
ANTARES (Med.)

Taking data

IceCube (Ant.)
KM3NeT (Med.)
GVD (Baikal)

Planned

IceCube Gen2
P-ONE (Pac.)
TRIDENT (China)
HUNT (China)



Operating in full configuration:

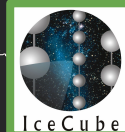
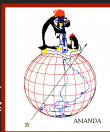
- **ANTARES** (*) 0.01 km³
(*) Shut down Feb'22
- IceCube 1 km³

Under construction, taking data:

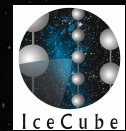
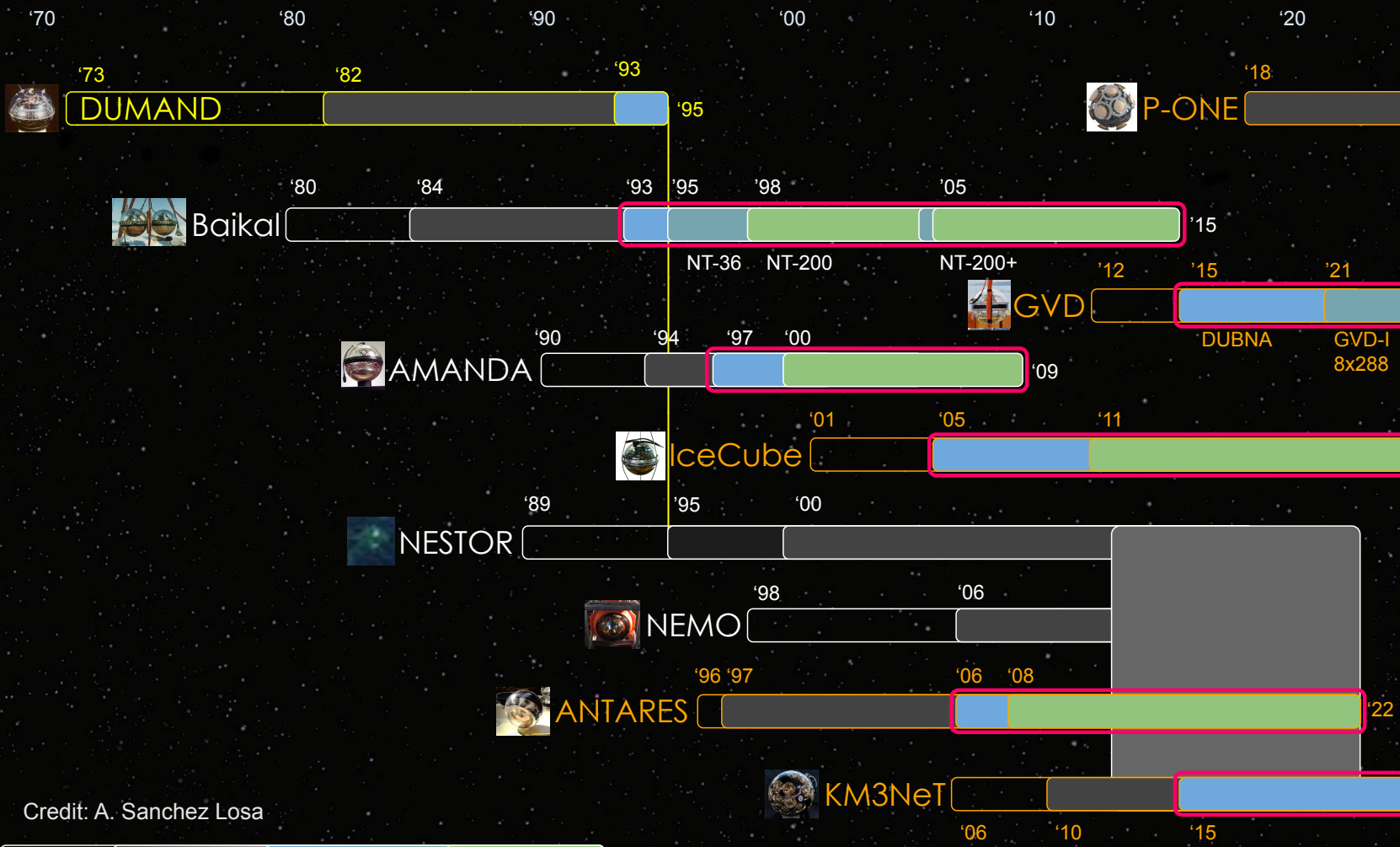
- **KM3NeT** 1 + 0.006 km³
- Baikal GVD ~1 km³

In planning phase:

- IceCube-Gen2 ~8 km³
- P-ONE >1 km³
- TRIDENT ~7.5 km³
- HUNT ~30 km³



www.globalneutrino.org
Frame for enhanced cooperation

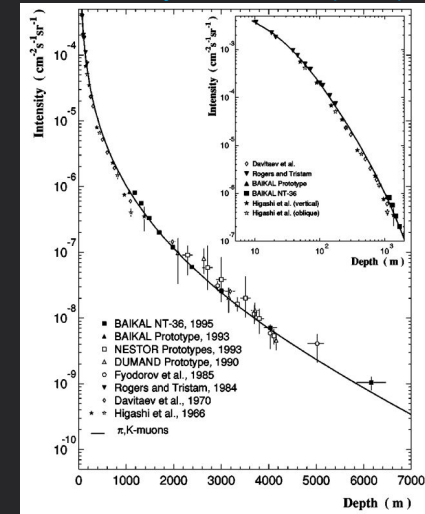


Credit: A. Sanchez Losa

Neutrino Detection Challenges

- Neutrinos have small interaction cross section. Detecting neutrinos requires a large, transparent, inexpensive detector: air, **water or ice**.
- **Air**, has **intrinsic problems**: limited observing time (~15%), large amount of muons (background) created by cosmic ray interactions in the atmosphere.
- Water allows us to go deeper and reduce the atmospheric muon background.
- **Lake or Ocean?** Freshwater lake has less background noise (^{40}K in salt) and corrosion. But not very deep, e.g. Baikal, is ~1.2 km deep.
- **Challenges in the ocean include**: instruments must withstand high-pressure, difficulty of installation and accessibility for repairs, **bioluminescence** plants and animals, power supply to the array, and transmission of data to shore.
- Highly transparent **Antarctic ice** can also be used. It provides excellent optical properties and low background. However, technological challenges: drilling deep holes, sensor deployment, and limited accessibility for maintenance.

Source: [Phys. Rev. D 58 \(1998\)](#)

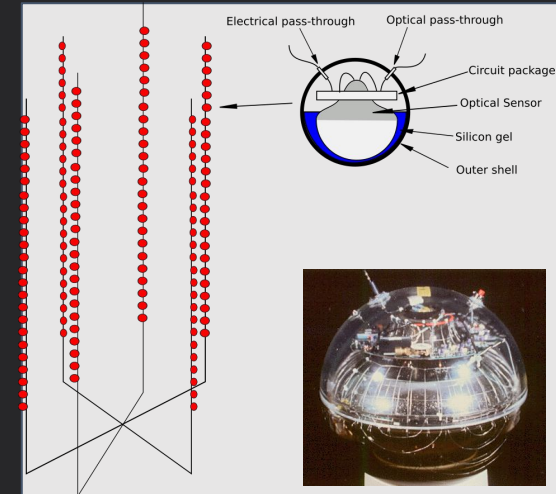


The DUMAND Project

- It was **the pioneer Neutrino Telescope** project: **planned in 1978** for 1261 lines with 18 OMs each, at 5 km depth, 30 km off the coast of Hawaii.
- Full design quickly scaled down (technology was not ready: deep-sea PMTs, connectors, robotics). By ~1980 the plan became a 6×6 array.
- DUMAND-I (1987): deployed the Short Prototype String (1 line, 7 PMTs). Performed engineering tests and water-properties measurements.
- DUMAND-II (1993): planned 9-line octagon (24 OMs per line). Only one line was deployed; it operated for ~10 hours before failing.
- Despite **cancellation in 1995**, DUMAND achieved key **milestones**: proved deep-ocean feasibility, **first deep-sea fiber-optic readout**, and **validated pressure-resistant glass spheres**.
- **Paved the way** for AMANDA, ANTARES, IceCube, KM3NeT, etc.
- Full story: [Arthur Roberts: The DUMAND Project](#)



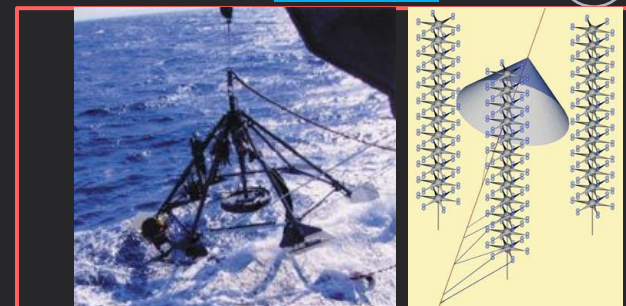
Source: [wikipedia](#)



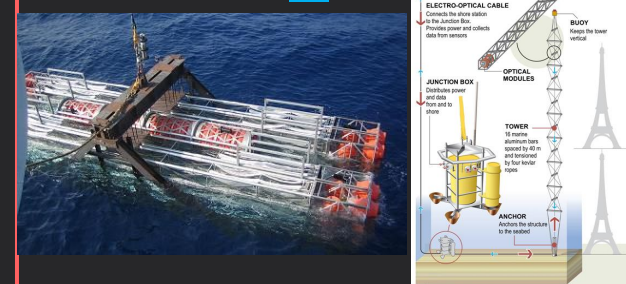
Early Neutrino Telescope Projects

- Several projects took over from DUMAND: AMANDA in the south pole, Baikal in Russia; and **NESTOR**, **NEMO**, and **ANTARES** in the Mediterranean these projects **formed the KM3NeT collaboration** later.
- **NESTOR** (Greece) project focused on rigid tower structures, demonstrating early underwater detection techniques and infrastructure. Site remains available for a potential KM3NeT upgrade.
- **NEMO** (Italy) project performed a R&D activity during 1998-2004 in the Sicily coast (site of KM3NeT/ARCA). Developed flexible detection lines, deep-sea site studies, and technologies to build a km^3 scale detector.
- **Baikal-GVD** project in **lake** Baikal (Russia) underwent several upgrades. Early phase in the 1990s. Latest construction (GVD) since 2016 aiming for the **completion of a km^3 scale detector** in the **next couple of years**.
- AMANDA was the first successful neutrino telescope **deployed in Antarctic ice** in the 1990s. Demonstrated the feasibility of using natural ice as a Cherenkov medium, detecting atmospheric neutrinos.

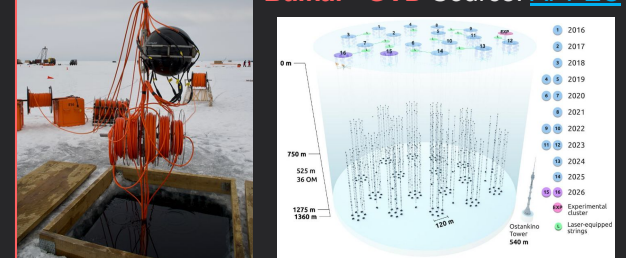
NESTOR Source: [CERN courier](#)



NEMO Source: [link](#)



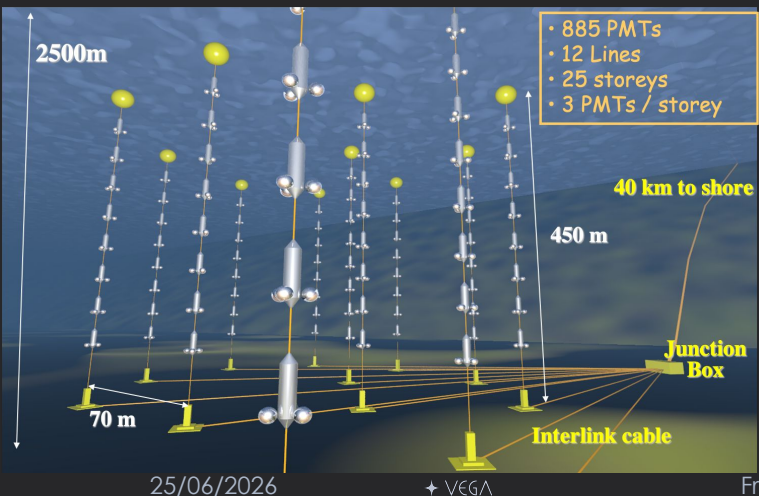
Baikal - GVD Source: [APPEC](#)



First generation: Instrumentation in ANTARES

The ANTARES Detector

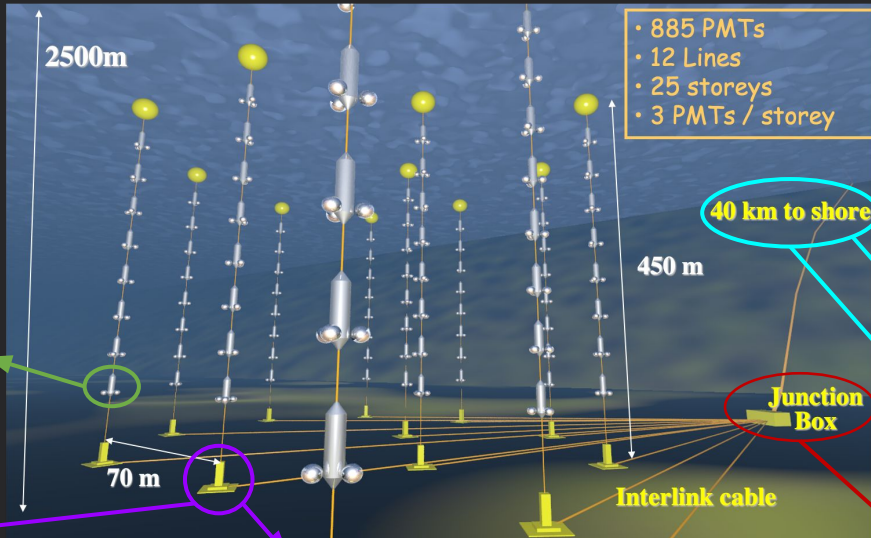
- **ANTARES** was an underwater neutrino telescope (2006 - 2022).
- Located at 2500 m depth, 40 km off Toulon coast, France (**42°48'N**)
- Temperature is stable around 13°C, and pressure is ~250 bars.
- 3D array of 885 PMTs (10-inch) distributed in 12 lines of 25 storeys with an instrumented volume of ~0.01 km³.
- Sensitive to energies from hundreds of GeV to PeV.



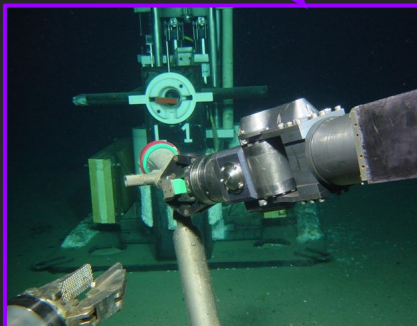
Francisco Salesa Greus | TIDPAN 2026



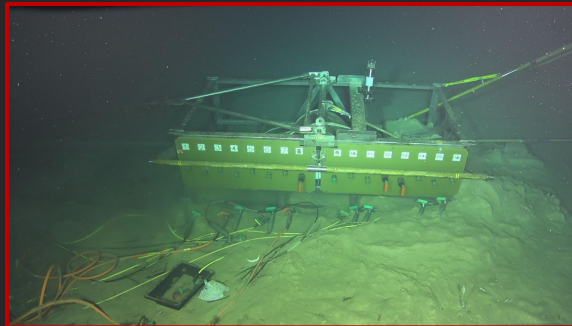
Breaking Down the Instruments in ANTARES



25/06/2026



+ VEGA

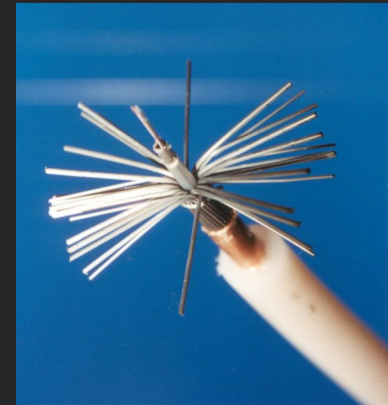
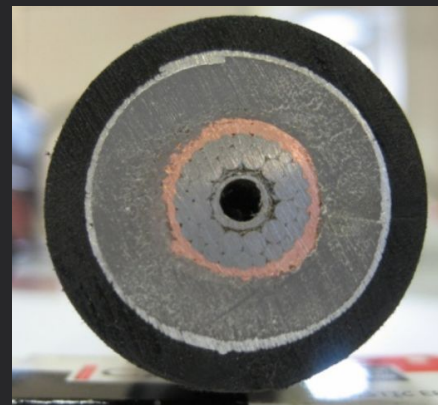
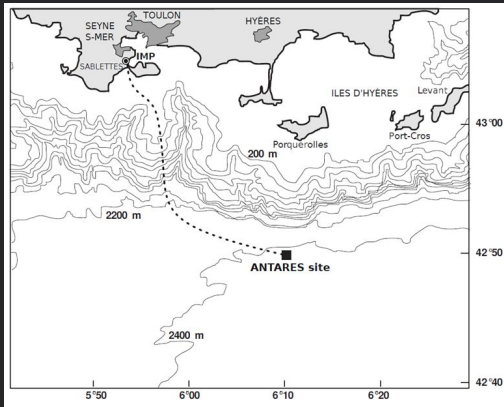


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ANTARES Main Electro-Optical Cable

- It is a 45 km ALCATEL electro-optical cable deployed in Oct 2001 that connected the shore station at La Seyne-sur-Mer to the ANTARES site.
- It has a single high-voltage conductor for power transmission (sea return).
- Moreover, 48 optical fibers used for **data transmission, clock & control distribution**.
- It linked at the Junction Box, which then distributed power, data, and timing to the detector lines.



ANTARES Junction Box

- The Junction Box is the device that acts as the **interface between the MEOC and the detector lines**.
- Constructed from titanium alloys due to their excellent pressure resistance and corrosion durability.
- It had 16 identical outputs to distribute power, data, and timing. Main functions are:
 - Power distribution: Transformer: 3000 VAC $\rightarrow$ 16 $\times$ 500 VAC.
 - Data collection: Ethernet over Dense Wavelength Division Multiplexing (DWDM), 7 $\times$ 1 Gb/s per line.
- It was deployed in Dec 2002 and **worked reliably for 20 years**. No failure, no repairs were needed!

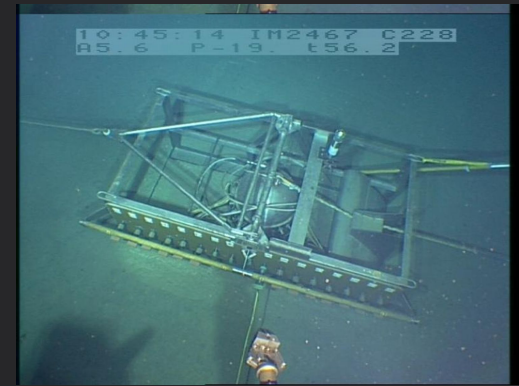


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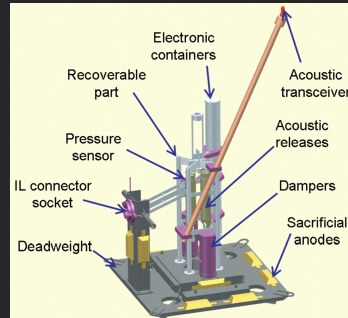
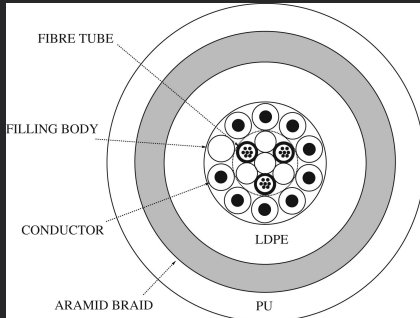
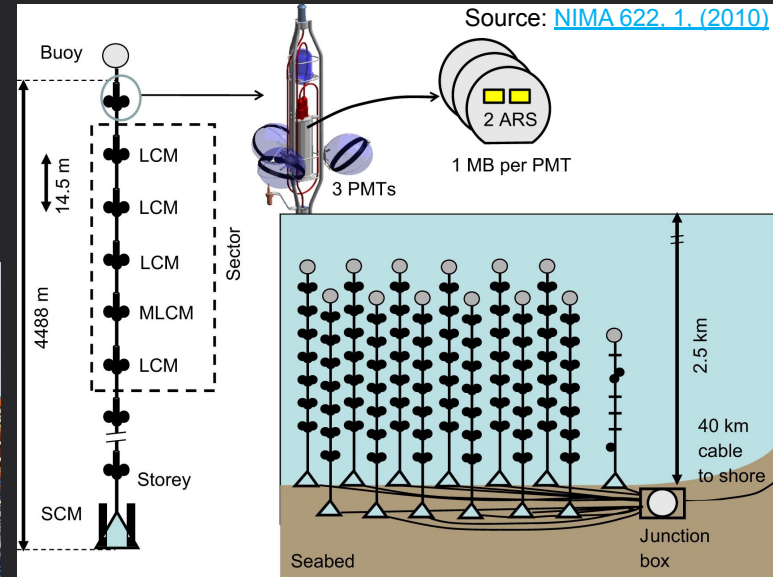


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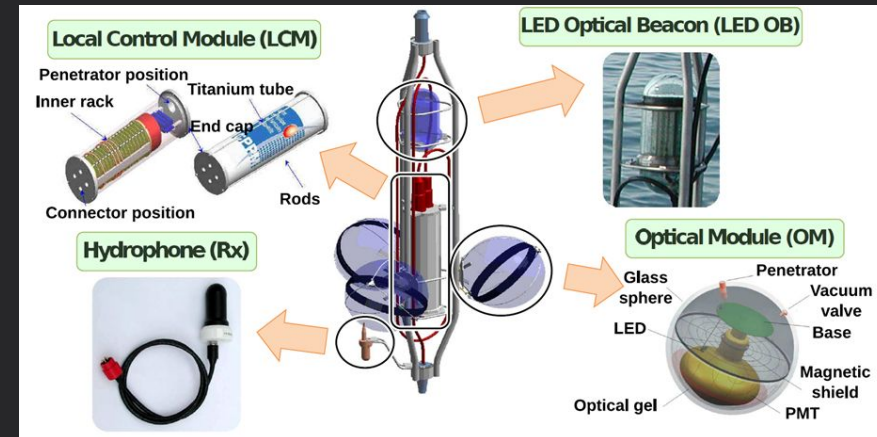
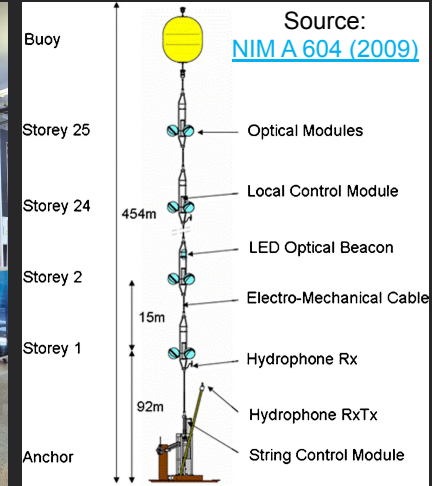
ANTARES Detector Line

- **12 vertical lines** with the following key elements: base, storeys, Electro-optical mechanical cable, and buoy.
- Bases linked to the junction box. Then ~100 m left without instrumentation to avoid sedimentation.
- EMC provides mechanical support, power, and data connections to the storeys.
- A line in ANTARES had 25 storeys, grouped in sectors of 5.
- Laser beacons at the base of lines 7 and 8.



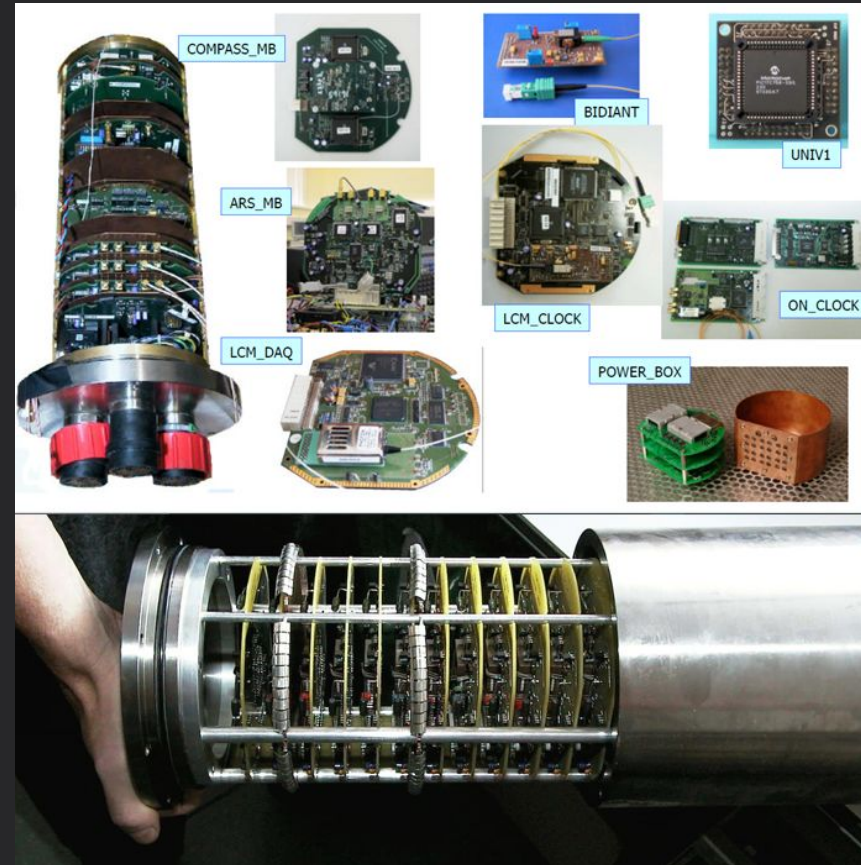
ANTARES Storey Elements

- **Titanium (T40) frame**, ~2.3 m tall, used to fix **Optical Modules (OMs)** and electronics to the line.
- Each storey had **3 OMs** with 10" PMTs, oriented 45° downwards and separated by 120° in azimuth.
- **Local Control Module (LCM)**. Non-magnetic cylinder of 60 cm x 18 cm housing: Front-end **readout** electronics, Clock and synchronization electronics, Slow control and monitoring.
- **LED beacons** for calibration on storeys, 2, 9, 15 and 21.
- Each line was equipped with an acoustic transceiver (RxTx module) on its anchor and **receiving hydrophones** (Rx modules) on storeys 1, 8, 14, 19 and 25.
- A **real ANTARES storey is exhibited at IFIC** in the Experimental Building on the first floor.



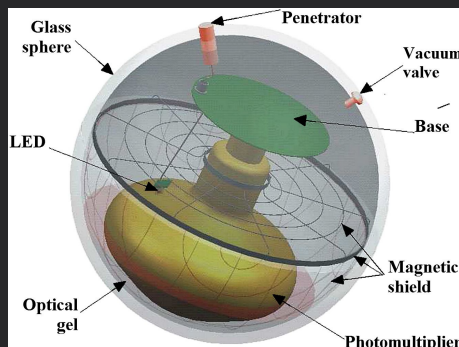
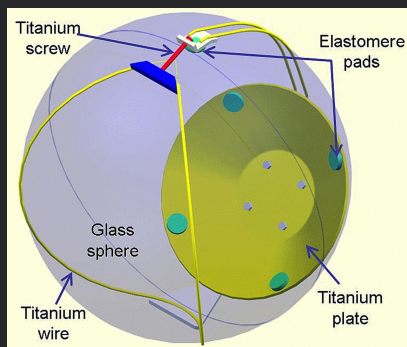
ANTARES Readout & Electronics

- **All-data-to-shore** concept: all PMT signals sent to shore without offshore triggering.
- **PMT signals digitized using ARS** (Analogue Ring Sampler) ASICs. Two ARS per OM to reduce dead time.
- Master clock distributed from shore for sub-nanosecond synchronization
- **Data transmitted via optical fibers** to the Junction Box and then to shore.
- **On-shore software triggering and filtering** selects physics events from background.
- **Power box** for voltage conversion and distribution.
- **Compass and tilt sensors** for storey orientation and geometry reconstruction.



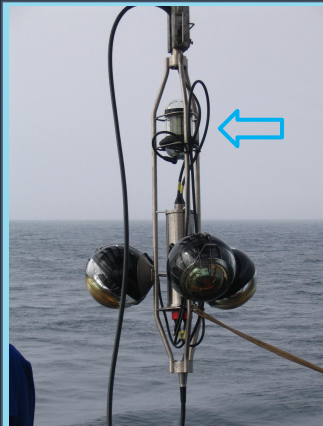
ANTARES Optical Module

- The main detection element was the Optical Module (OM), hosting a **10" PMT**.
- PMT model: [Hamamatsu R7081-20](#), optimized for single-photon detection.
- The PMT is housed in a pressure-resistant **borosilicate glass sphere**, with **optical coupling** through glass and optical gel, avoiding any water-air interface.
- OM has a μ -metal magnetic shield to reduce the effect of the Earth's magnetic field that could distort electron trajectories inside the PMT.
- Each OM includes a small internal LED that illuminates the PMT photocathode directly. Provides a self-calibration reference for each OM.

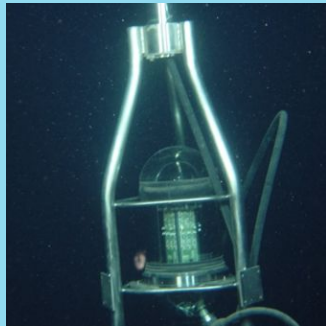


ANTARES Optical Beacons

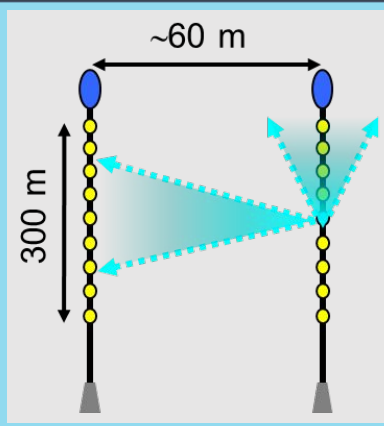
- The [ANTARES Optical Beacons](#) were pulsed light sources used for **timing calibration**.
- The time emission of the Optical Beacons was well-known, so you could use them to measure and correct relative PMTs timing offsets, achieving a complete detector synchronization.
- Mainly **developed and constructed at IFIC**. Two types:
 - **LED Optical Beacon**: Less intense, good for calibration of OMs in the same lines.
 - **Laser Optical Beacon**: More intense, good for calibration between different lines.



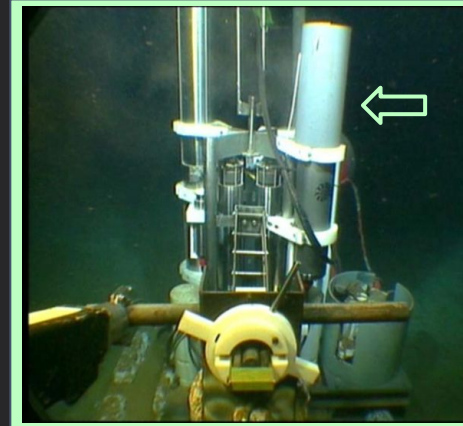
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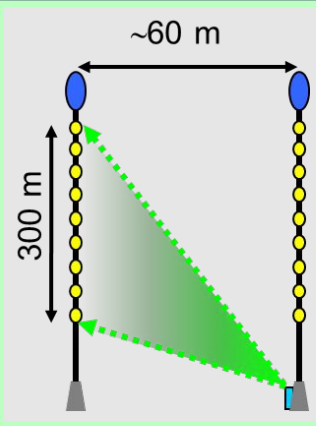
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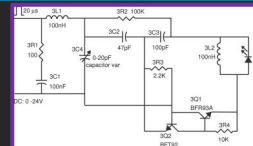
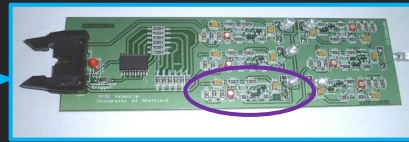
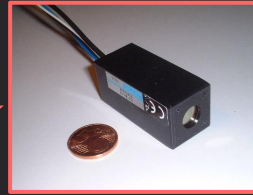
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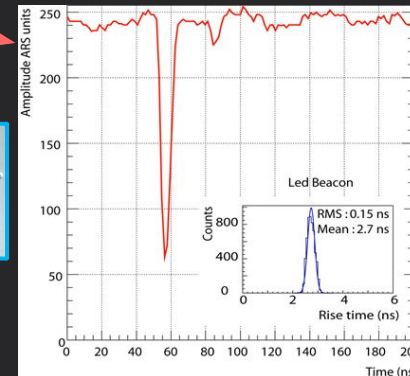
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ANTARES LED Optical Beacon

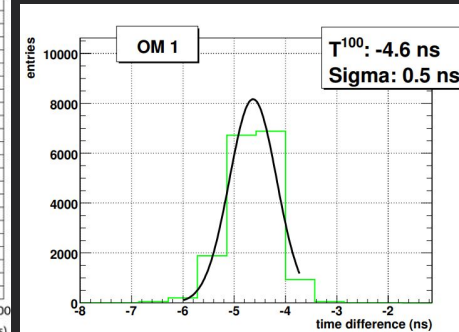
- Hexagonal prism containing **36 blue** (470 nm) **LEDs** distributed in 6 faces which could flash independently.
- Light output $\sim 4 \times 10^8$ photons per pulse, with uniform emission up to 35° and very precise (~ 2 ns rise time).
- Worked in a **triggered mode** thanks to a small pulsing circuit (trigger signal is a 1.5 V square pulse of 150 ns).
- All the components are housed in a borosilicate glass container able to **hold pressures higher than 220 atm**.
- **Internal PMT** Hamamatsu H6780-03 ($TT^*=5.4$ ns) to know the **actual emission time** of the light.



Internal PMT signal as recorded by the ANTARES DAQ

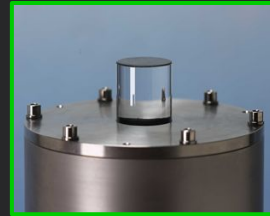
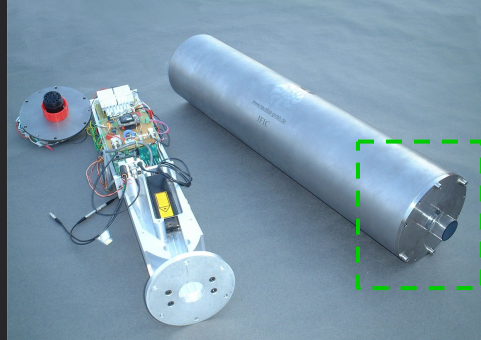


Time difference between an LED OB (on the 2nd floor) and OM just above (on the 3rd floor)

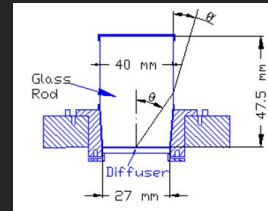


ANTARES Laser Optical Beacon

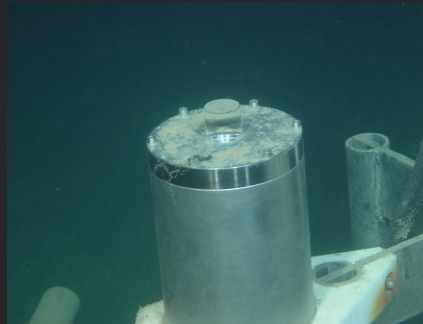
- **Solid state laser** (Diode-pumped Q-switched Nd:YAG), triggered by a TTL signal.
- **Green** (532 nm) emission, $\sim 10^{12}$ photons per shot (~ 1.5 mJ), with variable and stable intensity.
- Very fast timing, ~ 0.3 ns rise time, monitored by an internal fast photodiode (≈ 50 ps jitter)
- Lambertian ($\cos \theta$) light **emission via the sides of a quartz rod**, minimizing seabed sedimentation effects.
- Components mounted in a **titanium frame** for high-pressure deep-sea operation.



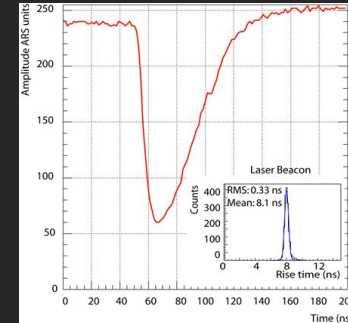
quartz rod



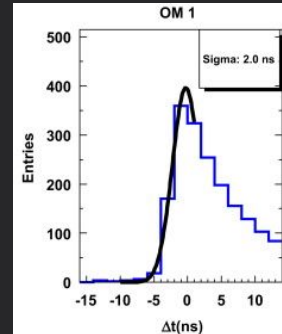
Laser on the seabed where sedimentation effects are visible



Internal photodiode signal as recorded by the ANTARES DAQ

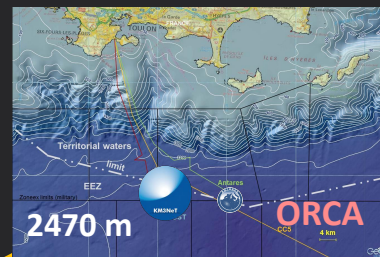
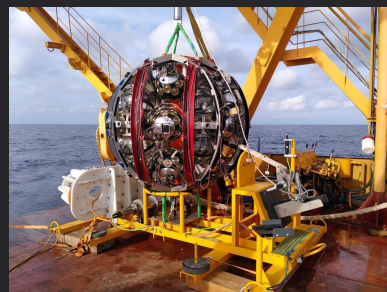
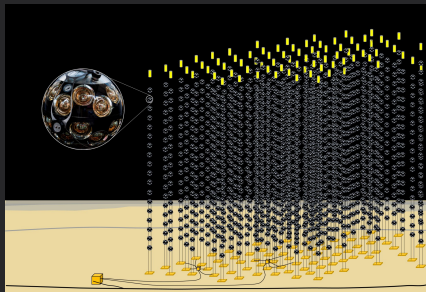


Corrected time difference between a Laser OB and an OM

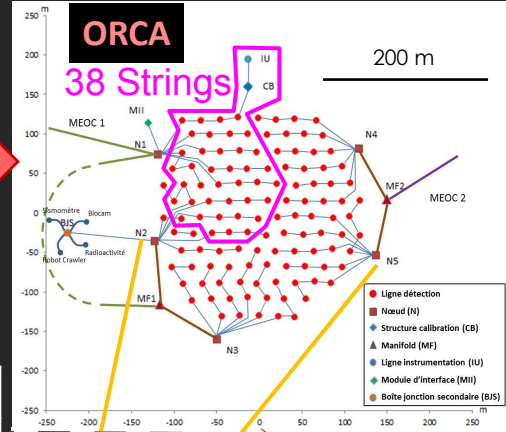


Solid state laser

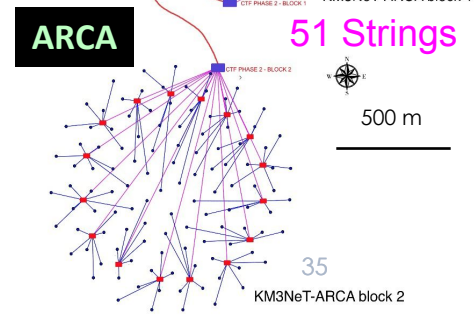
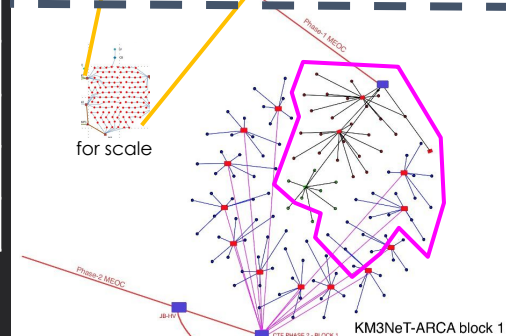
Current Generation: Instrumentation in KM3NeT



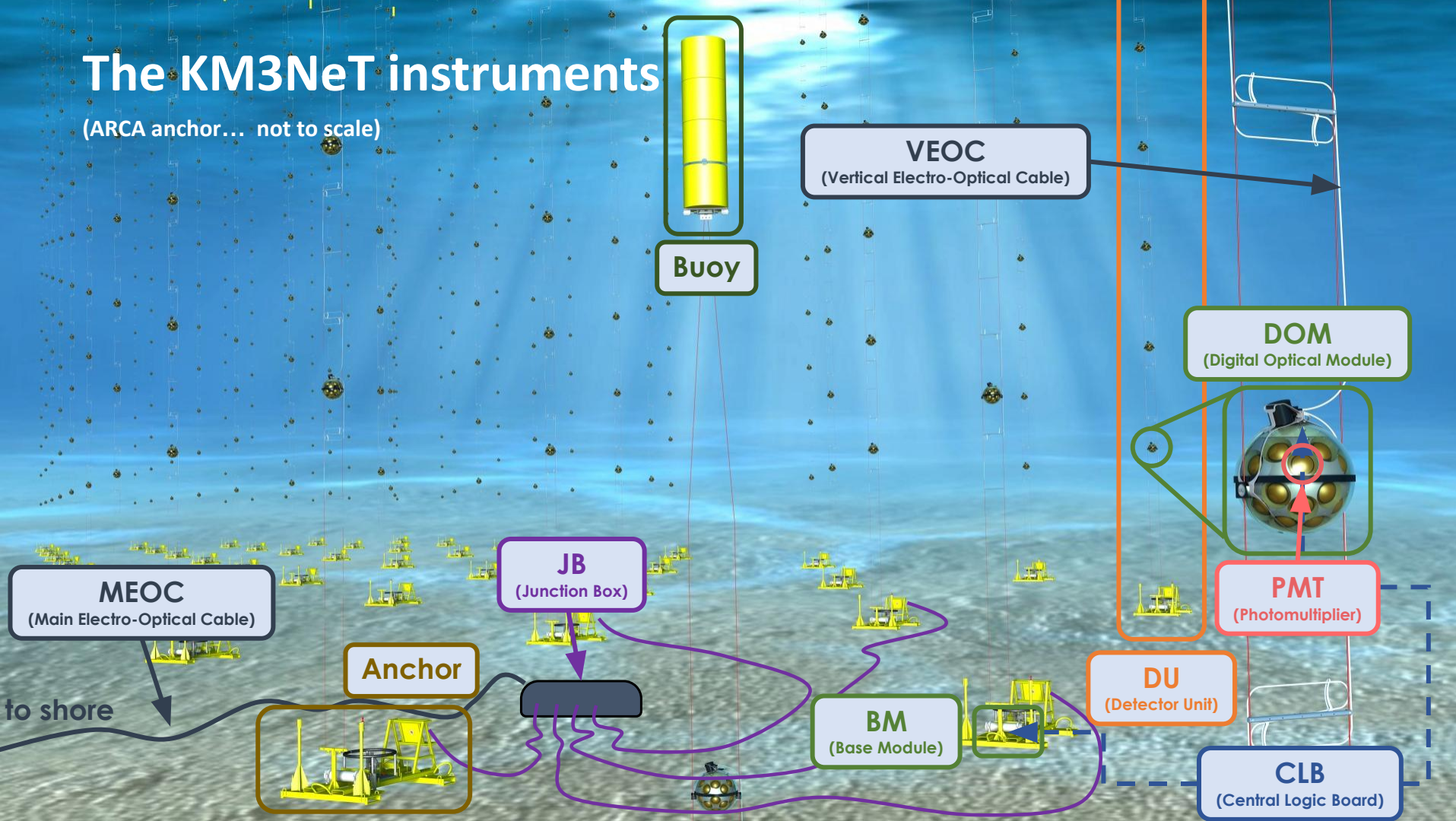
	ORCA	ARCA
Strings	115	115 × 2
String spacing	20 m	90 m
DOM spacing	9 m	36 m
Instrumented mass	7 Mton	500 × 2 Mton
Energy range	GeV	TeV – PeV



for scale

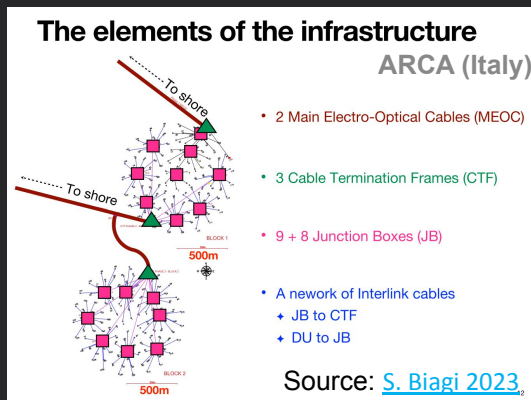
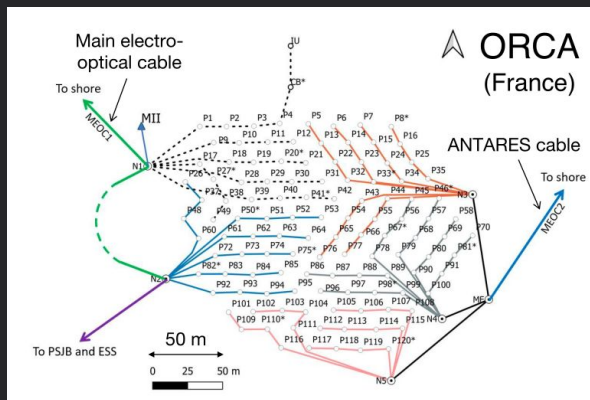


(ARCA anchor... not to scale)



KM3NeT Main Electro-Optical Cable

- KM3NeT builds on the ANTARES MEOC concept, scaling it in power, bandwidth, and **modularity**, with multiple MEOCs supplying independent detector blocks up to cubic-kilometer scale.
- **Higher power capacity** than ANTARES for multi-PMT DOMs and instrumentation: ORCA uses a series (daisy-chain) distribution, while ARCA employs a parallel, high-capacity architecture.
- Higher data bandwidth and **improved redundancy**, based on ANTARES operational experience.



KM3NeT Junction Boxes/Nodes

- **Multiple interfaces** (Junction Boxes/Nodes) between the MEOC and the Detection Units, distributing power, data, and timing.
- Technology developed together with external companies, from oil & gas sector, that meets military/space standards. **Designed for long-term operation** (>20 years) at deep-sea depths.
- Intrinsic redundancy: all critical electronics components are duplicated, **avoiding single-point failures**.

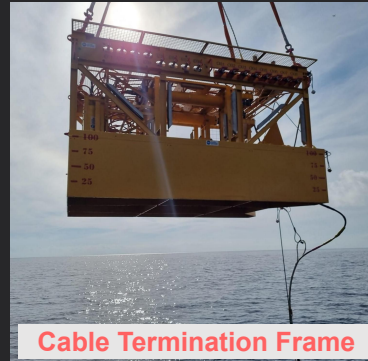
KM3NeT/ARCA



JB frame



JB electronics

Source: [KM3NeT web](#)

Cable Termination Frame



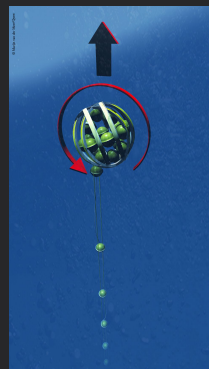
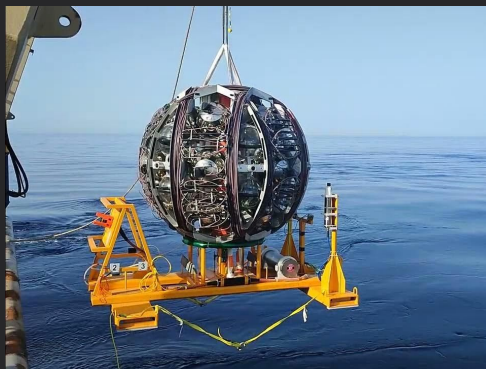
ORCA: MEOC connects directly to the JB. Power conversion and distribution happen inside.

ARCA: power is split at CTF to feed different detector regions, and then split again locally at each JB to supply the DUs.

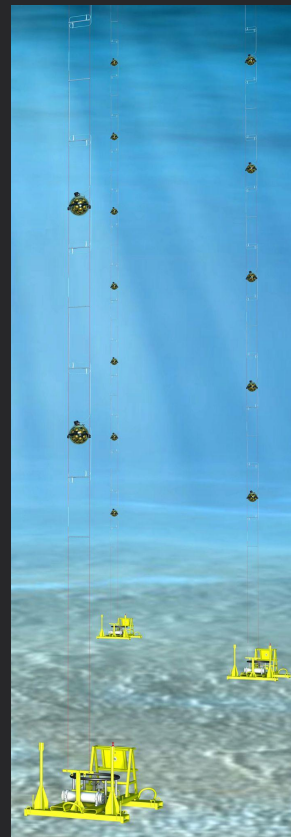
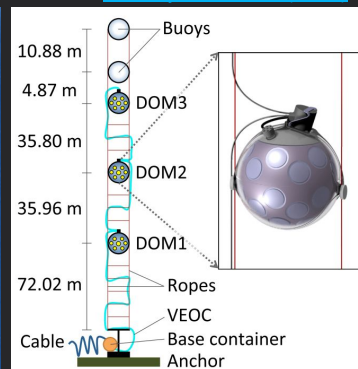
KM3NeT Detection Unit (DU)

- Vertical detection structure anchored to the seabed and held taut by a top buoy, with two high-strength **Dyneema®** ropes forming the main mechanical backbone of the line.
- The **Vertical Electro-Optical Cable** (VEOC) is like the backbone that runs along each DU distributing power, data, and timing to all DOMs.
- Composed of a string of **18 Digital Optical Modules** (DOMs). In KM3NeT, several **instruments** that were external in ANTARES are fully **integrated within each DOM**.
- The anchor **Base Module** hosts critical systems for power supply, control, communication, time synchronization, and acoustic positioning.

Base Module

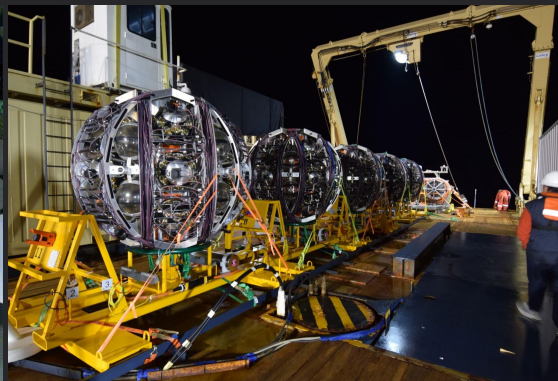


Source: [Eur.Phys.J.C76.54 \(2016\)](https://arxiv.org/abs/1605.08044)



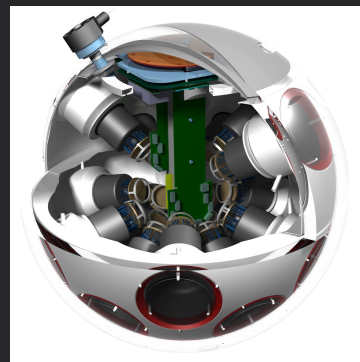
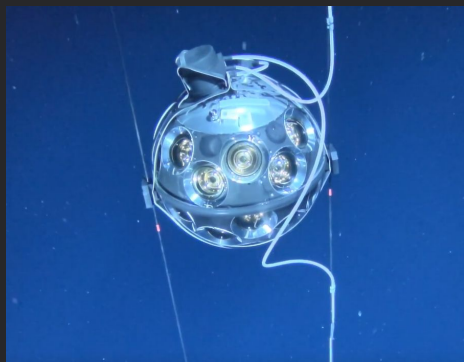
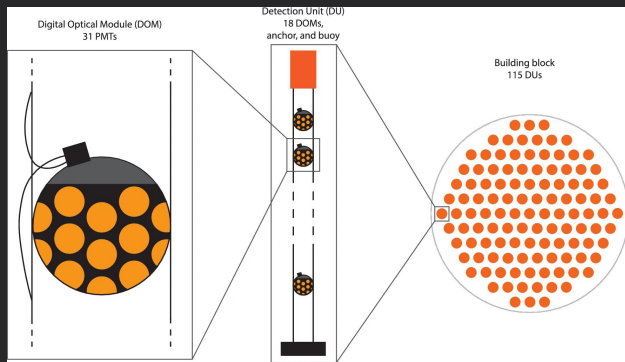
KM3NeT Launcher of Optical Modules (LOM)

- The **LOM** is a mechanical structure used to lower and deploy a KM3NeT DU to the seabed.
- The LOM keeps the DUs in a **compact structure** that allow to carry several of them on the boat.
- Designed for a more **efficient deployment**: DUs are independent and can be added progressively.
- This compact configuration is kept during descent and it is only **from the seabed** when the whole line is **released** and self-unroll driven by buoyancy.
- The LOM frame is recovered after deployment and reused for subsequent Detection Units.



KM3NeT Digital Optical Module (DOM)

- The **key detection element** in KM3NeT, the **multi-PMT optical module** is a pressure-resistant glass sphere (~17" diameter) housing light sensors, **31 × 3" PMTs**, and all front-end **electronics**.
- Includes Central Logic Board (CLB) for readout, timing, data transmission, and control.
- Integrated sensors and calibration: Nanobeacon LED (timing calibration), acoustic piezo sensor (positioning), compass and tilt sensors (orientation).
- Optical coupling via glass and optical gel, ensuring efficient light collection.
- Designed for long-term operation at deep-sea pressure (>300 bar).



Advantages of Multi-PMT DOMs

- **Larger** effective **photocathode area**: Multiple small PMTs provide a significantly larger total light-collection surface compared to a single PMT of similar size.
- Intrinsic **directional sensitivity**: The segmented PMT layout allows reconstruction of the photon arrival direction within a single module.
- Improved **background rejection**: Local coincidences between several PMTs help suppress random noise (e.g. ^{40}K or bioluminescence).
- **Better timing** performance: Detection of multiple photons within the same module improves timing precision and event reconstruction.
- **Wider dynamic range**: Multi-PMT systems can handle both low-light and high-light signals more effectively.
- **Redundancy and reliability**: Failure of individual PMTs has limited impact on overall module performance.

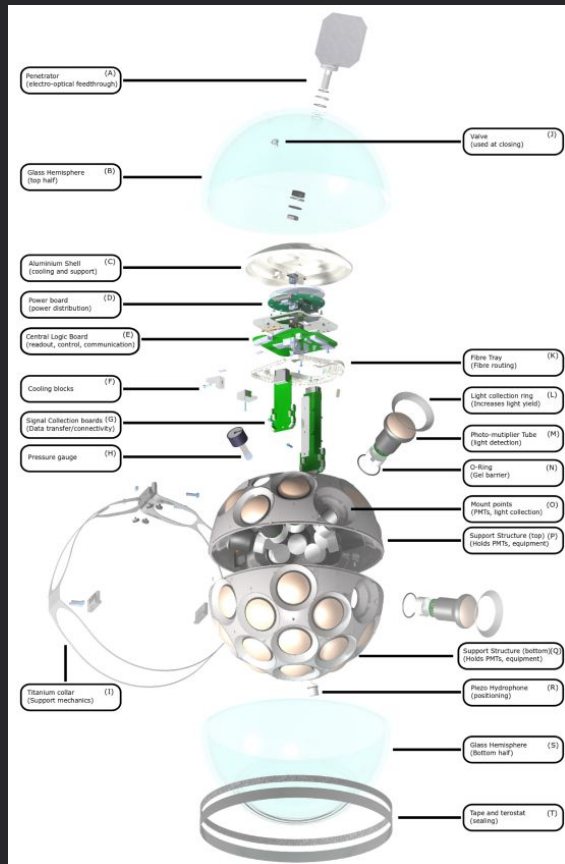
ANTARES



KM3NeT



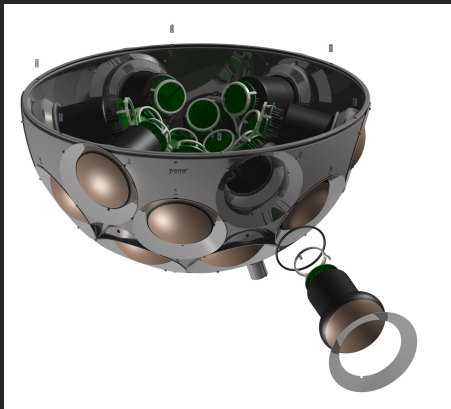
KM3NeT Digital Optical Module (DOM)



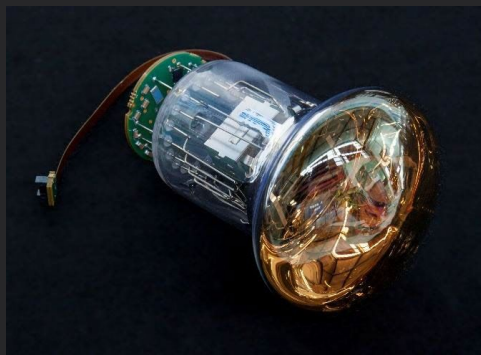
- Section of a bottom support structure
- Section of a top support structure
- Glass hemisphere (bottom)
- Bottom support structure with PMTs and light collection rings installed
- Tray for routing of optical fibres
- Cooling and support mechanics (shell with rod mounted)
- Power board
- Central Logic Board
- (Three) PMTs with base attached and light collection rings
- Pressure gauge
- Signal collection boards (2)
- Nanobeacon (led flasher) on driver board
- Penetrator flange (left) and penetrator with temporary fibre/cable routing plate (right)
- Piezo hydrophone
- Laser transceiver

KM3NeT PMTs

- Each DOM contains 31 small (3") [Hamamatsu R12199-02 3-inch PMT](#), providing **large photocathode area**, precise photon counting, and **directional detection** information.
- Wide angular acceptance: PMTs are oriented to provide nearly full 4π field of view.
- Detect Cherenkov photons from neutrino interactions with **$\sim$ ns timing resolution** (TTS < 5 ns).
- Performance: high gain ($\sim 10^6$), low noise, and $\sim 20\%$ quantum efficiency in blue light.
- **Improves rejection** of ^{40}K **background** (present in seawater) via coincidence between PMTs.

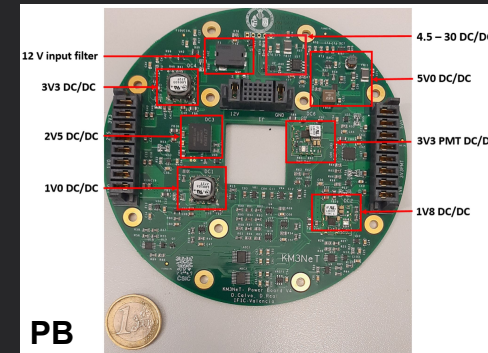
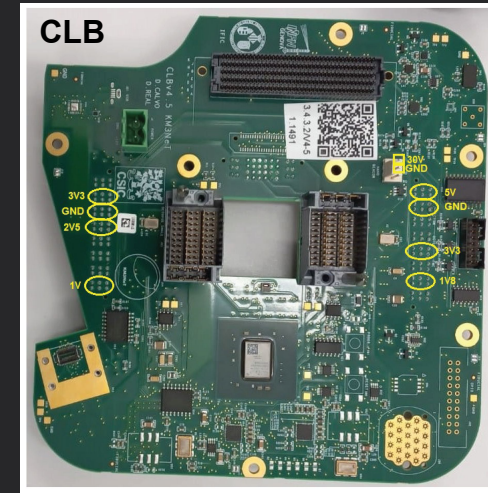


Source: [JINST 17 P07038 \(2022\)](#)



KM3NeT DOM Electronics

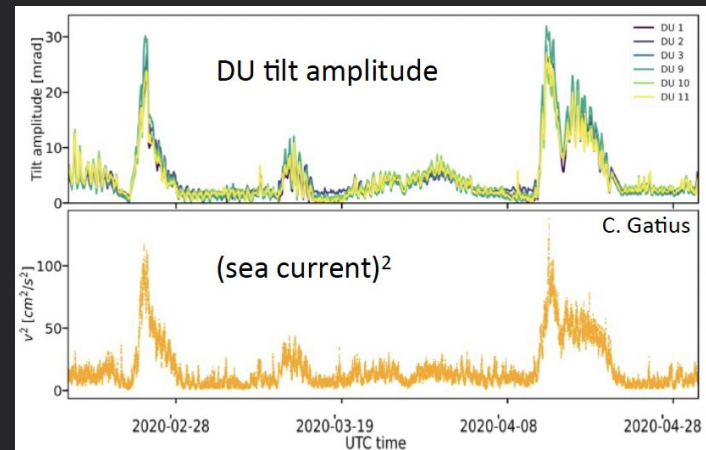
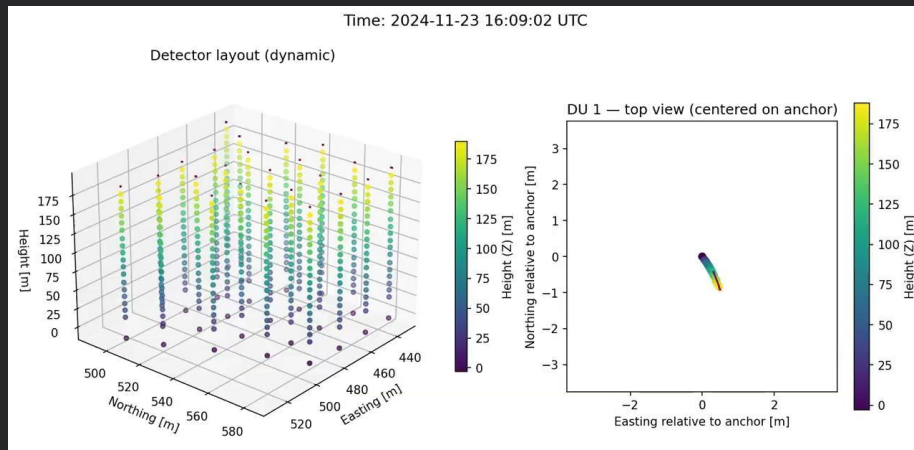
- Two key electronic components are integrated inside the DOM, optimized for low power consumption, reliability ([FIDES](#), [HALT](#)), and mass production:
- Central Logic Board:
 - FPGA-based readout system that **digitizes PMT signals** using ToT, and packages all hits into data streams continuously sent to shore.
 - Precise timing and synchronization: Implements an adapted White Rabbit protocol, providing sub-nanosecond synchronization across the detector for coherent event reconstruction.
- Power Board:
 - Distributes and regulates power feed** into voltage rails via DC/DC converters and a linear regulator for PMTs, CLB, and auxiliary devices.
 - Real-time monitoring of currents and voltages is performed using onboard 12-bit ADCs, complemented by temperature monitoring and protection mechanisms to ensure reliable long-term operation.



KM3NeT Calibration

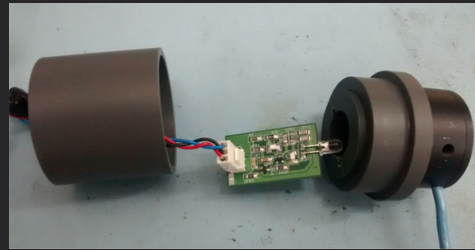
- Calibration is required to ensure that physical quantities (e.g., energy, time, charge, direction) can be properly derived from detector signals.
- **Controlled reference sources** (optical beacons, muons, acoustic emitters) to monitor the detector response.
- Corrects for detector positions, gain/charge variations, timing offsets, environmental effects, and long-term drifts in detector components (aging of PMTs, electronics, etc.).
- Essential for accurate event reconstruction, energy estimation, and inter-detector uniformity.

Credit:
Agustín
Sánchez
Losa



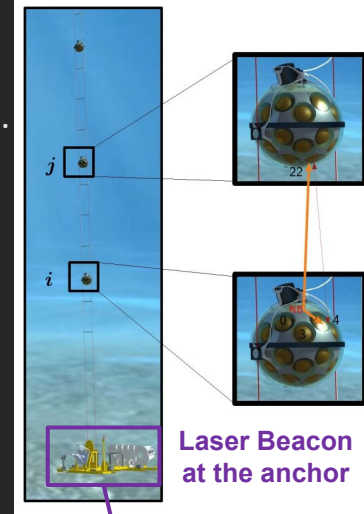
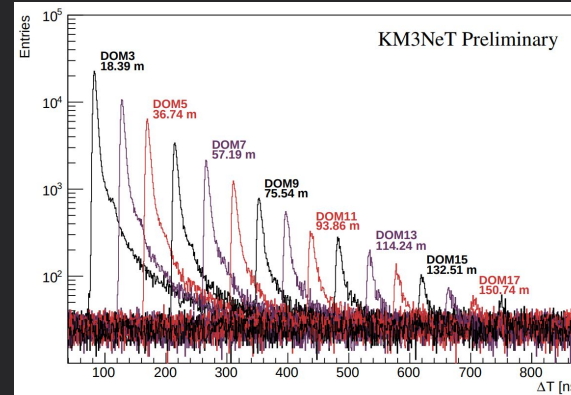
KM3NeT Time Calibration System

- The [Nanobeacon system](#) is an **evolution of the ANTARES LED Optical Beacon** concept.
- Designed for timing calibration (ns accuracy) with a **simplified design**.
- **Inexpensive** so, unlike ANTARES, every single DOM has a Nanobeacon.
- Provides **high redundancy**, and therefore more robust and reliable calibration.
- Moreover, [laser beacons](#) are also present at the **bottom of some lines**.

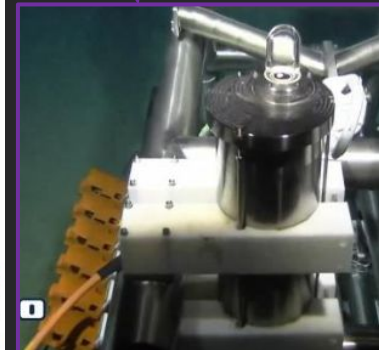


The nearby PMTs provide the LED emission time reference, from which relative timing offsets between DOMs can be extracted.

NB flash seen in all ORCA floors (> 150 m)
Source: [PoS 444 1062 \(2025\)](#)



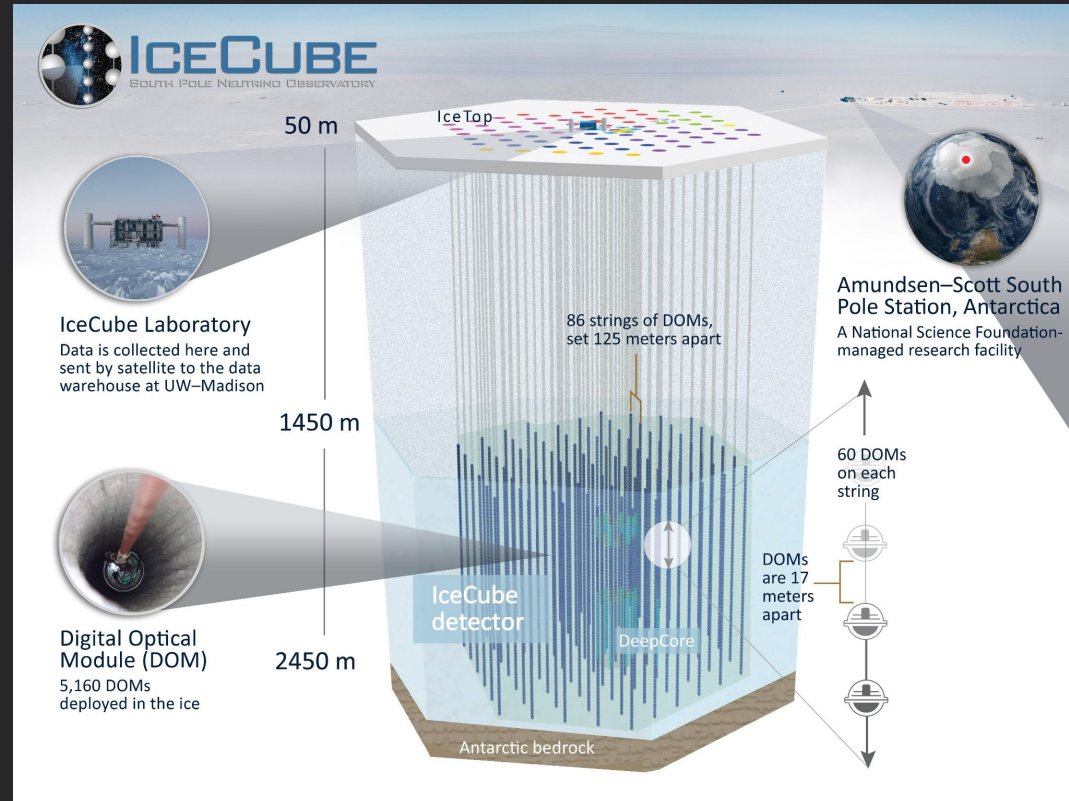
Laser Beacon at the anchor



Ice vs Water: Instrumentation in IceCube

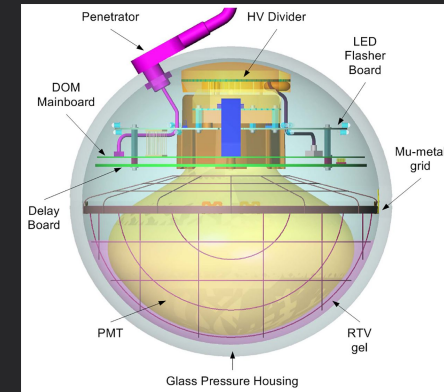
IceCube Neutrino Observatory

- Located next to the **South Pole** at 1.5-2.5 km deep.
- Cherenkov detector **in ice**.
- Fully operational since 2011, contains 86 strings (5160 DOMs).
- Deep Core array is sensitive to lower energies (~ 10 GeV): neutrino oscillations, but also astronomy.
- **Largest high-energy neutrino observatory** in the world with $\sim 1 \text{ km}^3$ instrumented volume.
- Includes a surface array (IceTop) to detect cosmic ray air showers.



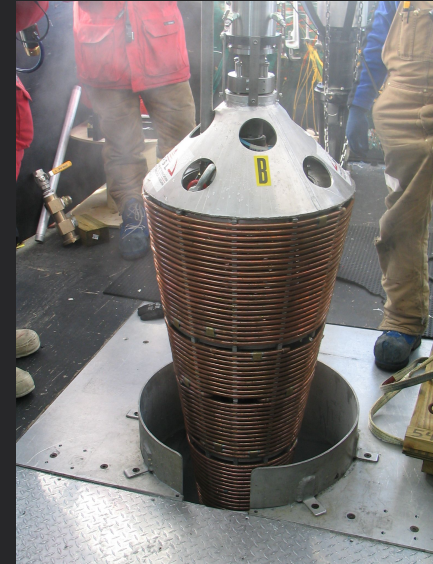
IceCube vs KM3NeT/ANTARES (I)

- Main **difference** between IceCube and KM3NeT/ANTARES: **medium** where are deployed (ice vs water).
- **Ice** is **low optical noise** environment ($\sim 300\text{--}500$ Hz per PMT), whereas noise in water is much higher due to natural backgrounds, e.g., ^{40}K decay and bioluminescence ($\sim 5\text{--}50$ kHz or higher).
- **Different readout strategies:**
 - Low noise allows signal digitization inside each DOM, so only processed data are sent to the surface, reducing bandwidth requirements.
 - KM3NeT/ANTARES adopt an all-data-to-shore approach, as high noise makes local triggering difficult.
- Light propagation differs: ice has strong scattering. KM3NeT **multi-PMT** DOMs take advantage of this providing **larger photocathode** area and intrinsic **directional sensitivity**, improving angular and timing resolution.



IceCube vs KM3NeT/ANTARES (II)

- **IceCube** has a **stable detector geometry**, since the DOMs are frozen into the ice and remain fixed. In **KM3NeT/ANTARES** the detection lines move with sea currents and require continuous acoustic **positioning** and **alignment systems**.
- The **deployment techniques** are different: IceCube is constructed by **drilling** deep **holes in the Antarctic ice** using hot-water drills and lowering the modules before the water refreezes. KM3NeT deploys Detection Units on the seabed using a self-unrolling technique.
- Operational constraints differ: **IceCube deployment** is limited to **seasonal** (summer) drilling campaigns, whereas KM3NeT/ANTARES use ships and ROVs, allowing more flexible but technically complex offshore deployment.
- IceCube uses **independent vertical cables** for each line, while KM3NeT/ANTARES use a shared subsea network with distributed power and data infrastructure.



IceCube Line Installation

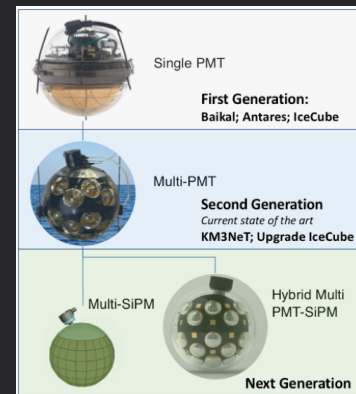


Next Generation: Instrumentation Plans for Future Projects

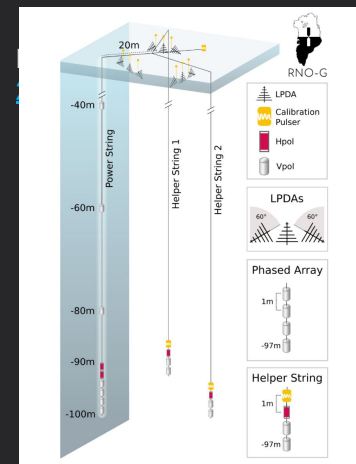
Planned Improvements for Future Projects

- Next-generation experiments aim to significantly **increase the instrumented volume** (km^3 scale and beyond) to improve statistics and therefore sensitivity.
- Large detectors require both **modular construction** for scalability and **inexpensive** designs to remain affordable.
- **Improved technology**: Multi-PMT DOMs (now standard in the field) and development of hybrid concepts (PMTs + [SiPMTs](#)) better light collection, timing, and directionality.
- **Better calibration**: Sub-nanosecond synchronization and advanced calibration systems improve reconstruction accuracy and angular resolution.
- **Higher bandwidth** and flexible data acquisition: Upgraded optical networks and software-based triggering allow more sophisticated real-time event selection.
- **New detection techniques**: Integration of complementary methods, e.g. **radio detection**, to extend sensitivity to higher energies ($> \text{PeV}$) and larger effective volumes.
- **Multi-messenger integration**: Future detectors are thought to operate in coordination with other observatories, providing alerts and allowing multi-messenger follow-ups.

Source: [Universe 2023](#)



Source: [Astrop. Phys 2025](#)

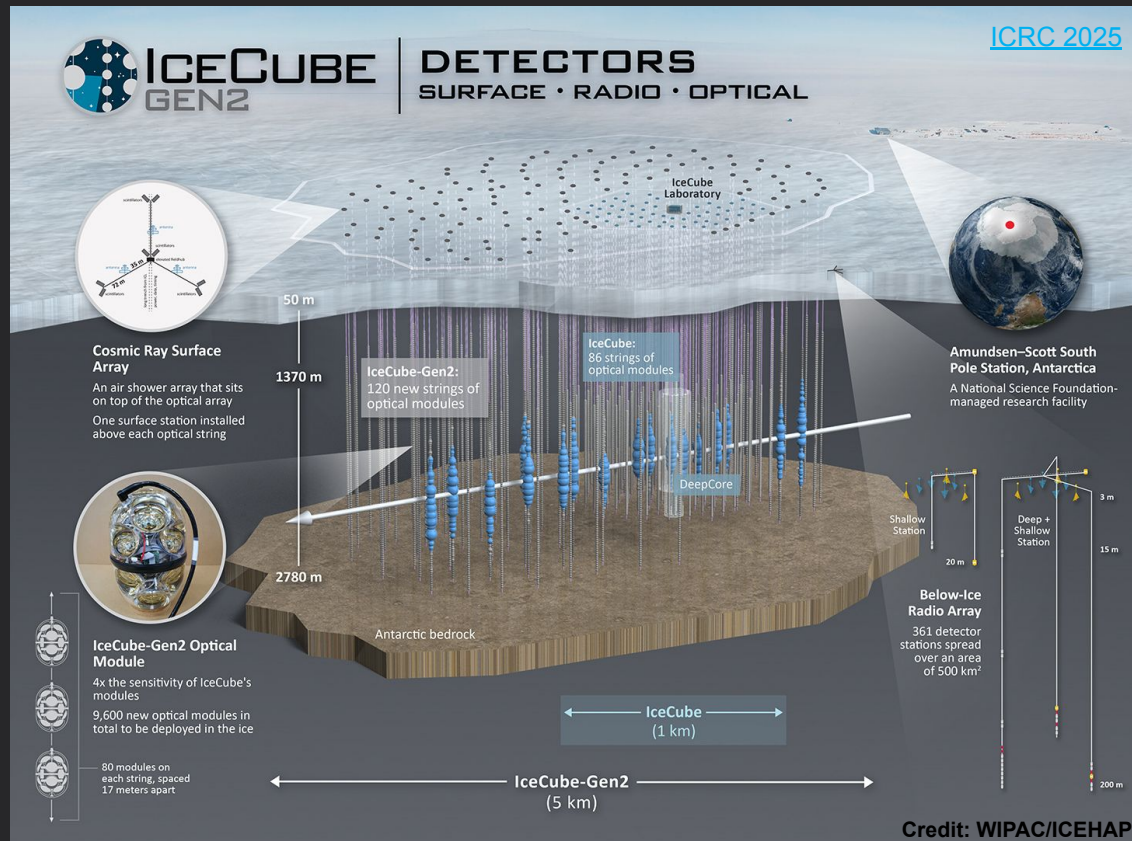
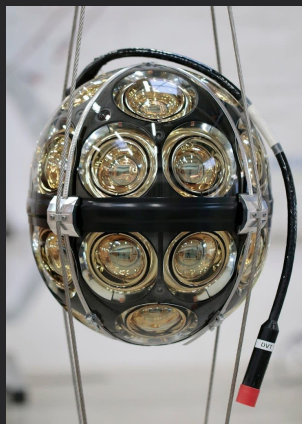


Upcoming Neutrino Telescopes: IceCube-Gen2

- Detection volume of **8 km³**.
- Improved sensitivity in all energy range from GeV to PeV.
- Improved calibrations.
- **Radio array for acoustic detection.**
- Cosmic ray surface array.

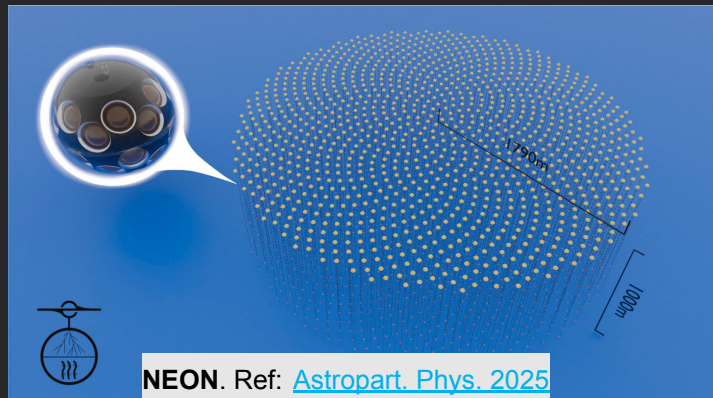
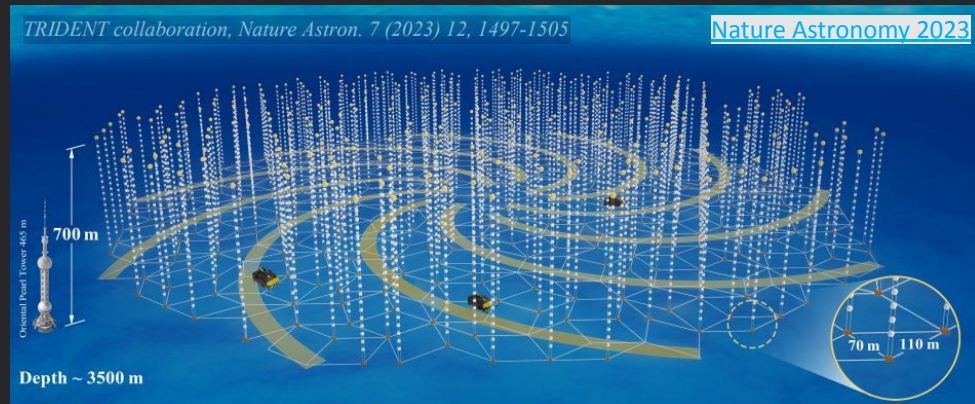
One of the selected optical sensor for IceCube-Gen2, the **mDOM** with 24 4-inch PMTs.

Source:
[IceCube webpage](https://www.icecube.wisc.edu/)



Upcoming Neutrino Telescopes: TRIDENT, NEON, HUNT

- Several Chinese projects in development:
- Tropical Deep-sea Neutrino Telescope (TRIDENT): **8 km³**, 1000 strings, 20k OMs.
- Neutrino Observatory in the Nanhai (NEON): **10 km³**, 1200 strings, 21.6k OMs.
- High-Energy Underwater Neutrino Telescope (HUNT): **30 km³**, 2300 strings, 55k OMs.



TRIDENT new DOM:

- Hybrid DOM (hDOM): 17" sphere combining 31 PMTs + 24 **SiPM**.
- Performance gain: large light collection and **ultra-fast timing**, gives ~20% more photons, and ~40% better angular resolution.

Source: [TRIDENT webpage](#)



Conclusions

- **Instrumenting neutrino telescopes** requires operating in remote places (deep Antarctic ice, bottom of ocean/lake) which makes it **challenging**.
- Early experiments such as DUMAND, in the 1970s, pioneered the development of **new technologies** for these extreme conditions.
- First completed projects, such as **ANTARES and IceCube**, demonstrated the **feasibility and long-term reliability** of large-scale neutrino detectors.
- **Next-generation** detectors like KM3NeT combine modular, **cost-efficient** design for **larger detector volumes** with the flexibility to integrate **new technologies**.

**Thanks for
your attention**

