Chasing cosmic tau neutrinos in the abyss

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THE KM3NET DETECTOR

> I know who I am. And after all these years, there's a victory in that
>
> Rust Cohle, True Detective

In this chapter a brief description of the KM3NeT detector is presented. For more details, the reader is referred to the KM3NeT letter of intent [67].

The KM3NeT detector consists of 2-dimensional arrays of detection units located in the Mediterranean Sea. Each detection unit holds the detection modules in place, which contain the photo-sensors and the electronics needed to detect the Cherenkov light from a neutrino interaction.

The main goals are to identify sources of cosmic neutrinos and to establish the neutrino mass hierarchy. To achieve these goals, the energy and direction of cosmic and atmospheric neutrinos should be measured. As these neutrinos have drastically different energies, different detector configurations are foreseen, namely: A high energy neutrino detector called ARCA and a low energy neutrino detector called ORCA. The distribution of modules in the ORCA detector will be much denser than in the ARCA detector.

A set of 115 detection units is called a building block. For KM3NeT 2.0 three building blocks are planned: two ARCA blocks and one ORCA block. Currently KM3NeT phase 1 is under construction, which will see 24 ARCA strings and 7 ORCA strings deployed. Since this work is dedicated to cosmic neutrino detection, this chapter will focus on the ARCA detector. In the following, an overview of the detection hardware and software will be given. In addition, the main background sources are discussed.

2.1 KM3NET ARCA

The KM3NeT ARCA telescope is designed to detect neutrinos with energies of TeV and beyond. Each ARCA block instruments a volume of around $0.5\,\mathrm{km}^3$ to efficiently detect the Cherenkov light produced by interactions of neutrinos with these energies. In order to instrument this volume, the horizontal distance between the detection units is set to about 90 m and the vertical distance between the modules is set to about 36 m. A top-view of detector is shown in Fig. 17. The location for the ARCA detector is at $36°16'0''$ N and $16°6'0''$ E at a depth of 3.5 km about 100 km southeast of the Sicilian coast.

The power and data transmission is provided via two electro-optical cables from a shore station at Capa Passero to the ARCA detector. The first cable was

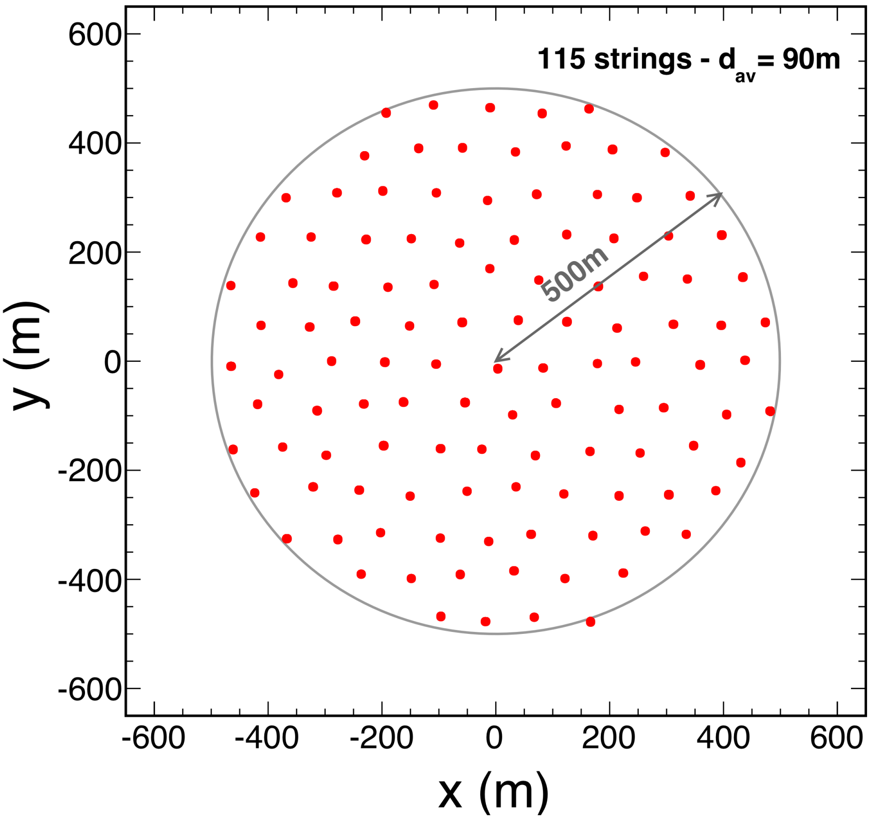

Figure 17: Top-view of an ARCA building block.

installed in December 2008, followed by a first junction box in the summer of 2015.

2.2 DETECTION UNIT

Each detection unit holds 18 modules. The lowest module is located at about 80 m above the sea floor. The modules are spaced 36 m in vertical direction, covering a total length of about 700 m. An additional buoy is mounted at the top. The mechanical backbone of the detection unit consists of two 4 mm thick ropes made out of Dyneema®. As these Dyneema ropes are flexible, the detection unit is commonly referred to as a "string" of modules. A drawing of a detection unit and a picture of a module are shown in Fig. 18.

The 18 optical fibers needed for the read-out and the two copper wires needed for the power supply are guided along the ropes in a pressure-balanced, oil-filled plastic tube. At each module, one optical fiber and two wires are branched out in a small box (black cylindrical shape on the photo in Fig. 18). They enter the glass spheres via a penetrator.

The string is anchored to the sea floor using a dead weight. The anchor contains an electronics container which interfaces each detection unit with the designated junction box.

For deployment, the strings are rolled up on a launcher vehicle as shown in Fig. 19. The launcher vehicle is a spherical metal frame which is temporarily

Figure 18: A drawing of KM3Net detection units and a photo of a KM3NeT module attached to a string.

mounted onto the anchor. A picture of a string prototype on a launcher vehicle is shown in Fig. 19. The results obtained with this prototype are presented in Chap. 4. The string, launcher vehicle and anchor are lowered to the seabed using a mooring line from a surface vessel. Once in place, the launcher vehicle is realeased from the anchor. The string then unfurls while the launcher vehicle floats to the surface. The string stays upright thanks to the buoyancy of the modules and the additional buoy. The launcher vehicle rises all the way to the surface and is then recovered.

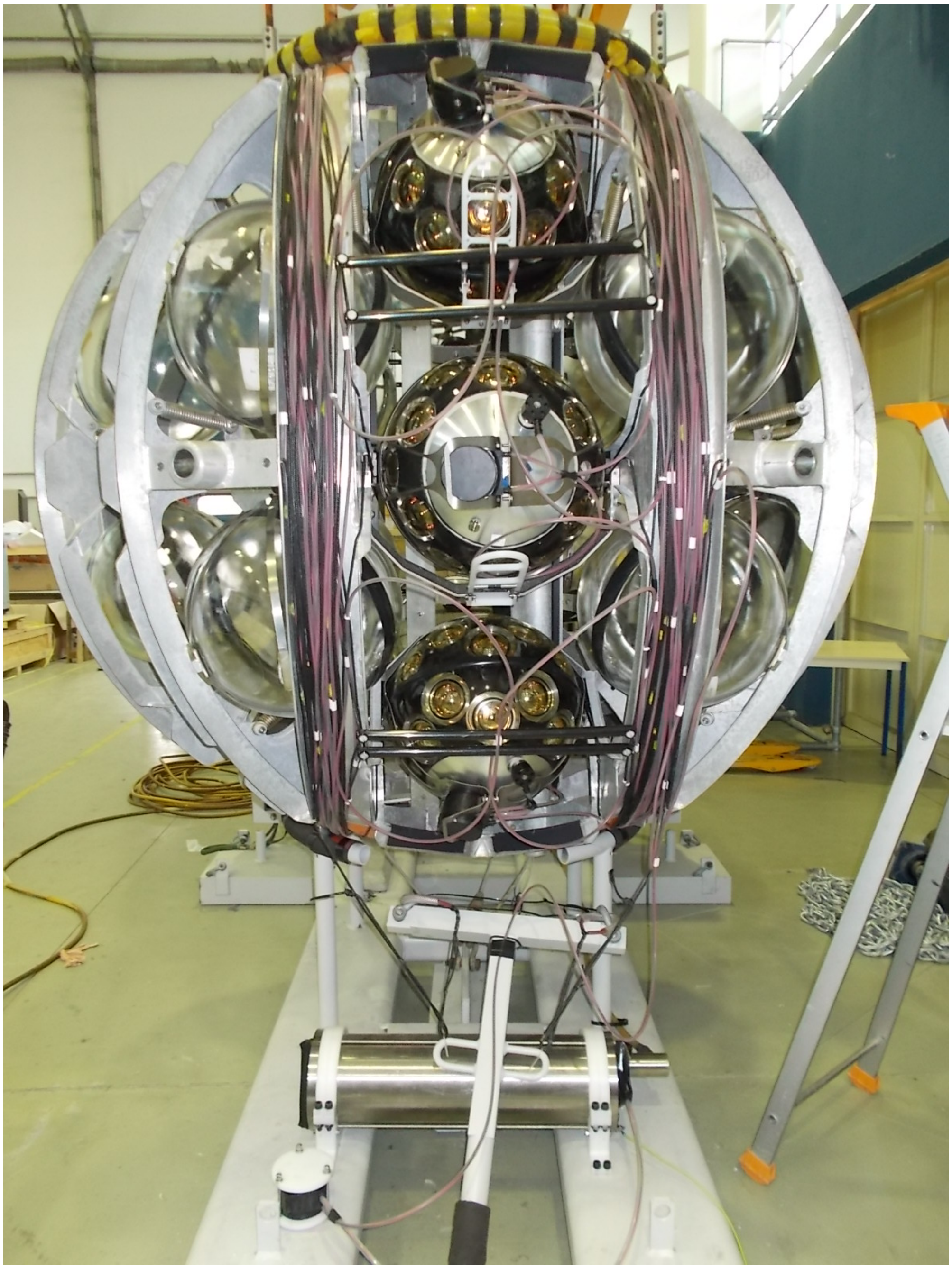

Figure 19: The string prototype (See Chap. 4) loaded on the launcher vehicle.

2.3 DETECTION MODULE

A detection module contains the photo-sensors to detect Cherenkov light. The photo-sensors are housed in a pressure-resistant 17 inch glass sphere which is attached to the string with a titanium collar. The glass sphere is punctuated at the entrance of a penetrator for power supply and data transmission. Each module has a total of 31 3-inch photo-multiplier tubes (PMTs) housed in a 3D-printed structure. The PMTs are arranged in five rings with six PMTs each and one ring with a single PMT looking downward. This design is known as "multi-PMT" and it allows for better signal discrimination compared to the traditional single 10 inch PMT designs used in IceCube and Antares. The space between the PMTs and the glass sphere is filled with an optical gel to avoid the reflection of photons. A reflector ring sourrounds each PMT, increasing its detection area by 20 % to 40 % [82].

For KM3NeT phase 1, Hamamatsu PMTs are used [83]. These PMTs have a minimum quantum efficiency of 20 % (28 %) at a wavelength of 470 nm (404 nm) and a maximal dark count of 1.5 kHz.

Each PMT is equipped with a base [84] which provides the photo-cathode and dynodes with the necessary voltages and digitizes the PMT signal. Digitization is done by processing the analog signal through a time-over-threshold (ToT) discriminator. At nominal operation, a PMT amplifies a single photo-electron to 3×10^6 electrons, which translates at a threshold of 0.3 photo-electron equivalent to a ToT of 27 ns. The leading edge and duration of each pulse are time stamped inside the modules by a so-called central logic board (CLB).

The CLB arranges the data of the 31 PMTs in data frames and sends these data frames to the shore via the optical-fiber network. The temperature of the CLB is kept low by a metal cooling structure. As the read-out of the photo-sensors is done inside the module, the system is commonly referred to as Digital Optical Module (DOM).

In addition to the PMTs, each DOM has an acoustic piezo sensor [85], an LED pointing to the DOM above [86] and a compass and tilt-meter. The piezo is used for acoustic position calibration, the compass and tilt-meter for orientation calibration and the LED for time calibration.

The reconstruction of cosmic neutrinos with sub-degree direction resolution requires a timing precision of about a nanosecond (ns). While the PMTs can supply a timing resolution of around 2 ns to 3 ns, the relative timing between PMTs requires an elaborate system, which is based on the so-called White Rabbit System [87]. It is based on the Ethernet protocol and allows to keep track of the relative timing of the CLBs in the whole detector.

2.4 BACKGROUND SOURCES

Neutrino telescopes suffer from two main sources of background, namely: Optical background and atmospheric background. Optical background encompasses all light producing effects from the detection medium, materials or biomatter. Atmospheric background are due to particles which are produced in Earth's atmosphere and reach the neutrino telescope. The two different types of background are discussed in more detail below.

Optical background

The Optical background for KM3NeT includes the PMT dark rates, bioluminescence and potassium decays from the sea salt.

PMT dark rates are property of the photo-sensor technology. The dark rates are primarily caused by the thermal noise from the photo-cathode materials and the non-perfect vacuum inside the PMTs. These dark rates are unavoidable, since PMTs are tuned to convert a single photon to a measurable electric signal. For KM3NeT, typical dark rates are around 1 kHz.

The beta-decays of the radioactive potassium isotope ^{40}K present in the salt of the sea water causes counting rates on the PMTs of KM3NeT of around 5 kHz. The light from ^{40}K decays actually is utilized for time calibration as discussed in Sec. 4.5.

Bioluminescence is caused by microscopic lifeforms such as bacteria living in the sea water. They typically emit light in localized bursts lasting a few seconds. These bursts can cause significant count rates in the PMTs. For KM3NeT they may reach several MHz.

Atmospheric background

Atmospheric backgrounds are due to particles produced in Earth's atmosphere due to cosmic rays impinging on Earth. In these interactions a variety of mesons, leptons and neutrinos are produced. Of these particles, only the neutrinos and high energy muons can reach the neutrino telescope.

The atmospheric neutrinos constitute, in first order, an irreducible background for cosmic neutrino observations. Nevertheless, the signal-to-noise ratio can be improved by taking the energy and flavor of the neutrinos into account. It is generally believed that the energy spectrum of cosmic neutrinos is harder than that of atmospheric neutrinos. Furthermore, the much larger distance traveled by cosmic neutrinos increase the relative abundance of electron and tau flavors.

The atmospheric muons make up most of the recorded events. For KM3NeT the rate of recorded atmospheric muons is about 100 000 more than that of neutrinos. An atmospheric muon traveling through the detector can mimic a neutrino interaction. As the production and propagation of atmospheric muons cause a specific zenith distribution as shown in Fig. 20, the best handle to distinguish them is limiting oneself to events which originate in the detector volume or move upwards.

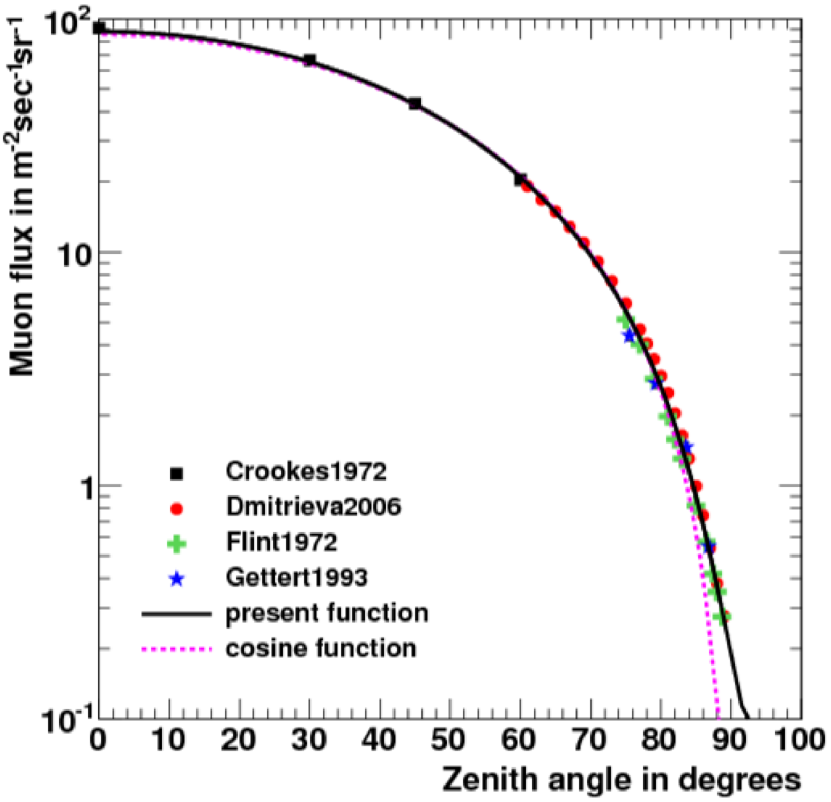

Figure 20: Atmospheric muon flux as a function of zenith angle at sea level [88].

2.5 DATA ACQUISITION SYSTEM

The data acquisition system (DAQ) of the KM3NeT detector handles the incoming data such that the interesting events can be written to disk. As all data from the detector are sent to the shore, about 25 GB of data per second needs processing. Thus, a reduction of the data rate of factor 1×10^5 is required to write the events to disk. This reduction is performed in real-time by software using a designated trigger algorithm.

The trigger selects interesting events based on certain criteria and writes them to disk. In this, all data in a certain time window around the triggered event are written to disk, so that all information is kept for further analysis.

In addition, other selections of the incoming data are written to disk for monitoring of the sea conditions and studies of the optical background.

2.5.1 *Trigger algorithm*

The trigger algorithm is the main tool to select events from the incoming data. In general, neutrino interactions are composed of a combination of shower and track signatures. Therefore, there are different triggers which search for events corresponding to these signatures. The trigger algorithm works in two stages: First a general hit selection which is then followed by a signature specific causality selection.

The hit selection is performed on all hits of all PMTs, inside the same module. By requiring at least two time coincident hits, the optical background is reduced to an acceptable level while most of the signal is maintained. The typical time window length for such a selection is 10 ns. Additionally, the angle between the PMT axes can be used to suppress the background even further.

Following the general hit selection, the trigger is used to select either of the two main event types: shower and track events. For track events, the sky is scanned using a set of directions with a relative angular distance of about 10°. For each direction, only hits inside a cylinder oriented in that direction with a typical radius of 120 m are considered. By requiring a minimum of 5 hits that are causally related, the track trigger improves the signal-to-noise ratio by at least a factor 1×10^4 compared to a standard trigger.

For the shower events, no scanning of direction is needed due to limited size of the object. By requiring a maximal distance of 250 m between PMTs and a minimum of 5 causally related hits the background is reduced to an acceptable level.

The achieved event rate due to random background is below 10 Hz and the overall event rate is about 200 Hz.

Although the trigger only targets a track or shower event signature, other signatures, such as a “Double Bang” signature is triggered equally well.