Chasing cosmic tau neutrinos in the abyss

Bormuth, R.; Bormuth R.

Author: Bormuth, R.
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Issue Date: 2017-12-07

SUMMARY

Human societies share a fascination for the night sky. This led to independent development of astronomy in various ancient civilizations such as the Babylonians or the Chinese. Today, astronomy is a major field of scientific research with the aim to probe the Universe in time and space. Throughout its long history astronomy has primarily relied on light-based observations, known as optical astronomy. During the past decades, optical astronomy has expanded from observations of light in the visual spectrum to observations extending over 12 orders of magnitude in wavelength. Despite its many successes, optical astronomy has so far not been able to answer several fundamental questions and may never be.

Among these questions is the topic of Cosmic Rays. Cosmic Rays are charged particles (mainly nuclei) traversing the Universe. Their energy spectrum extends up to the highest energies ever observed. Since their discovery more than 100 years ago, one has not been able to identify their sources nor explain how they obtain their energies. The lack of conclusive observations is caused by the interactions between Cosmic Rays and the magnetic fields present in the Universe. When a Cosmic Ray traverses a magnetic field it is forced onto a curved trajectory, which makes location of the sources fade away.

This inherent problem can be overcome by observing neutrinos. Neutrinos are almost massless elementary particles with two properties that make them suitable candidates for observing the Universe: they have a very low interaction probability with matter and they have no charge. The former allows them to travel quasi infinite distances through the Universe and the latter keeps their trajectories straight. Neutrinos are well-suited to investigate the sources of Cosmic Rays as they are produced by interactions of Cosmic Rays with matter or light surrounding their sources. The different behavior of neutrinos compared to other particles traversing the Universe is illustrated in Fig. 1.

Although the low interaction probability makes neutrinos ideal for investigating the origin of Cosmic Rays, it also makes their detection challenging. A large detection volume is necessary in order to record sufficient statistics. Once a neutrino interacts in the detection volume, the subsequently produced particles generate light along their trajectories (so-called Cherenkov light). The light is emitted at a fixed angle relative to the particle trajectory, which is related to the known refractive index of the medium. By detecting the Cherenkov light, the direction of the particles and therefore the direction of the initial neutrino can be reconstructed. In order to detect the light, the detection volume has to be instrumented with sensors and the instrumented medium has to be transparent. This makes natural ice and water good candidates. In the detector volume, the sensors are arranged in a three dimensional array. To ensure that the detected light is produced by neutrino interactions, neutrino telescopes are located at large depths to provide shielding. For these reasons, neutrino telescopes typi-

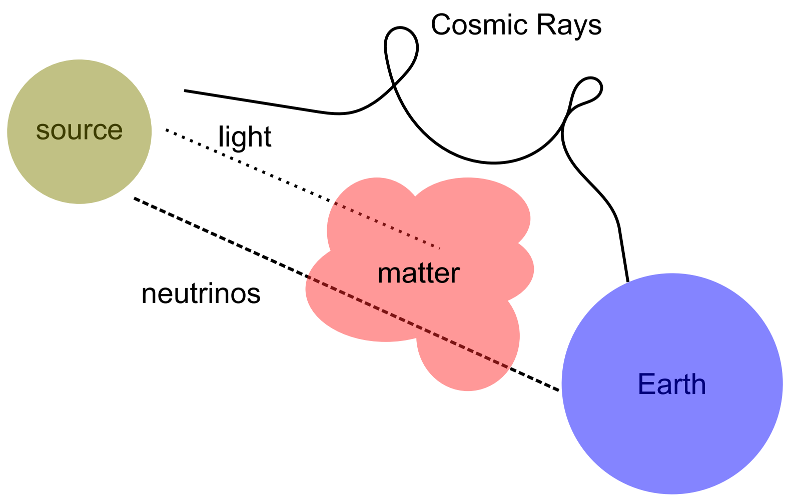


Figure 1: An illustration of the trajectories of different cosmic particles from a source to the Earth. The magnetic fields are not drawn but are omnipresent. As a consequence of the different interactions particles can undergo during their propagation through the Universe, neutrinos are ideal particles to find the origin of Cosmic Rays.

cally instrument around a cubic-kilometer of ice or water at depths between 2 to 4 kilometers.

The first and currently only neutrino telescope that observed cosmic neutrinos is the IceCube detector. The first evidence for a cosmic neutrino signal was reported in 2013. Since then, the IceCube telescope has proven the signal to be of cosmic origin. However, other properties such as the neutrino sources and the energy spectrum need further investigation due to the low number of events and the limited angular resolution.

In order to improve our understanding of this cosmic neutrino signal, more neutrino telescopes of a comparable volume with enhanced performance are needed. One such telescope will be the KM3NeT detector located in the abyss of the Mediterranean Sea, which is currently under construction. For KM3NeT, the sensors are mounted inside glass spheres as shown in Fig. 2. Of these spheres 18 are in turn attached to a string, resembling a pearl necklace. The strings are anchored to the sea floor and held upright by the intrinsic buoyancy of the glass spheres. A set of 115 strings makes up one KM3NeT block.

The KM3NeT telescope is expected to yield a more accurate measurement of the cosmic neutrino signal compared to the IceCube telescope. The improvement is mainly due to two factors: the optical properties of water compared to ice and the detection technology employed by KM3NeT. The latter can largely be attributed to the transition from a single large light sensor to 31 small light sensors. This allows to point sensors in one sphere in almost all directions and to separately count the photons of the detected light signal. A comparison between the IceCube and the KM3NeT spheres is shown in Fig. 2. The new technology of KM3NeT required thorough planning and prototyping. In this

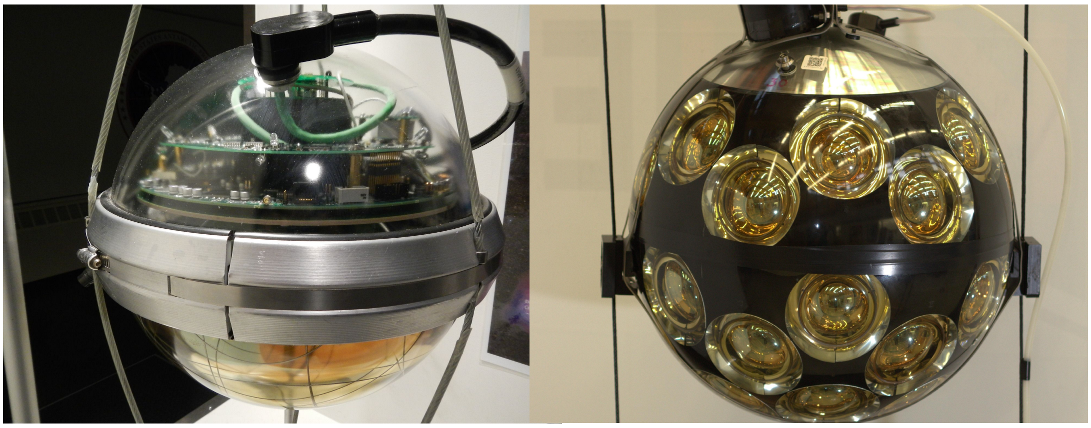


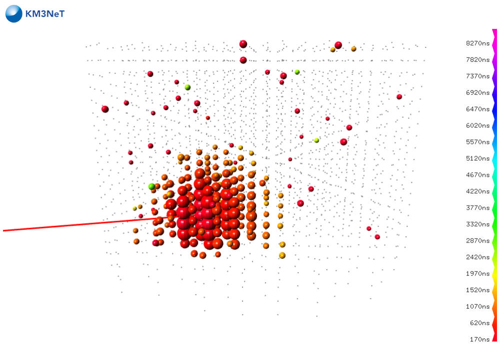
Figure 2: A picture of an IceCube module (left) and a KM3NeT module (right), showing the difference in light sensors.

work results of the string prototype are shown. The prototype, installed in 2014 at the KM3NeT Italy site, allowed to test important parts of the KM3NeT hardware and helped to establish protocols for future detector construction and operation. The results include the time calibration procedure and the identification and reconstruction of atmospheric muons.

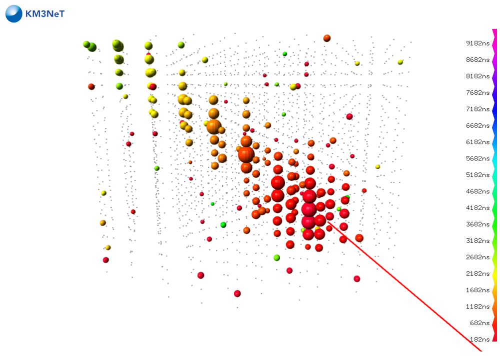
The performance improvements enable the KM3NeT telescope to identify the type of the interacting neutrino with unprecedented accuracy. There are three neutrino types (distinguished by *flavor*), one for each charged lepton: electron, muon and tau. Neutrinos can change from one type to another during propagation depending on the path length and energy. This phenomenon is referred to as *neutrino oscillations* and as a result an approximately equal share of neutrino flavors is expected to arrive on Earth from a cosmic neutrino signal. Nevertheless, the exact flavor composition of a cosmic neutrino signal can in principle be reconstructed with a neutrino telescope. This allows to scrutinize theoretical models for neutrino sources and helps to reduce backgrounds from non-cosmic neutrinos.

The three different neutrino types can be distinguished from another by the different signatures of light they leave in the detector after an interaction. The different signatures are caused by the different neutrino flavors producing different particles. The signatures are combinations of the so-called *shower* and/or *track* signatures. Shower signatures are caused by multiple particles with short trajectories resulting in light emitted from an approximately point-like source, akin to a firework explosion. Track signatures are caused by muons which can travel kilometers before they decay and emit light along the way, akin to a shooting star. Examples of a shower, track and two shower signatures are shown in Fig. 3 for the KM3NeT detector. Shower signatures can be caused by electron neutrinos, track signatures by muon neutrinos and two shower signatures by tau neutrinos ("Double Bangs"). However, depending on energies and processes involved, these associations can be hampered.

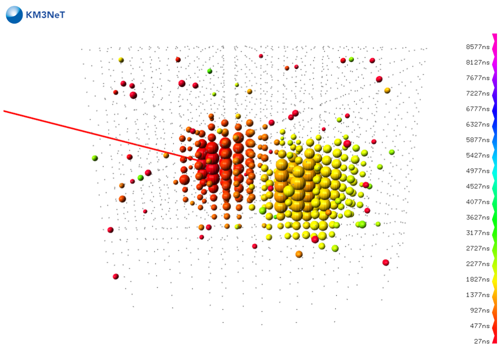
In this work, an algorithm for identifying and reconstructing "Double Bang" events using the KM3NeT detector is presented. While single shower and track



(a) A shower signature induced by an electron neutrino.



(b) A track signature induced by a muon neutrino.



(c) A two shower signature induced by a tau neutrino.

Figure 3: Simulations of the detector response for the different signatures in one KM3NeT block; shown are the positions of glass spheres housing the light detectors. The size indicates the number of detected photons and the color the time (red=early to purple=late). The red line shows the simulated neutrino trajectory.

reconstruction algorithms are well established, a reconstruction algorithm for "Double Bang" signatures was missing. With the "Double Bang" reconstruction, the tau neutrino interactions can be distinguished from the electron and the muon neutrino interactions. This is desirable for two reasons. First, it makes it possible to reconstruct the flavor composition of a cosmic neutrino signal. Second, the neutrino background for the tau flavor is expected to be much smaller compared to that of cosmic electron and muon neutrinos. Thus, the observation of a single "Double Bang" event represents a "smoking gun" for a cosmic neutrino signal.

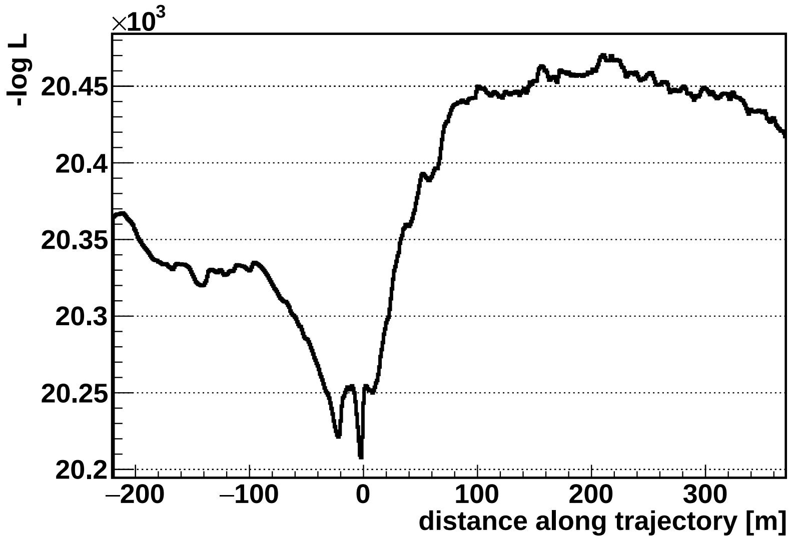
The tau "Double Bang" reconstruction algorithm is called "Belle Starr". Its implementation proceeds in four steps. The steps build upon each other, gradually becoming more intricate and tailored to identify "Double Bang" signatures.

In the first step, a robust method is provided to establish starting parameters for the following steps. For this purpose a single shower position fit combined with a single shower direction and energy fit are performed. The position fit minimizes a modified χ^2 based on the expected time of the hits given a single shower hypothesis. For two shower signatures, a fit typically yields the position of the shower that produces more light, the direction of the original neutrino and the total energy deposited in the detector.

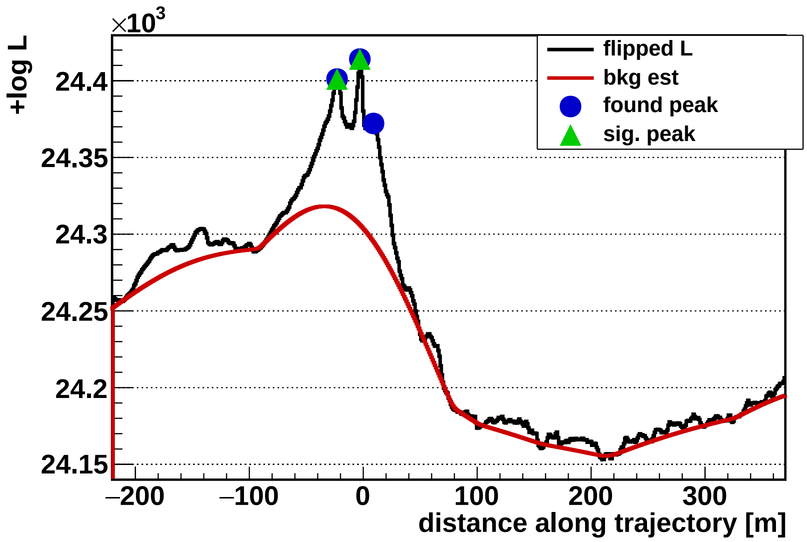
In the second step, the reconstructed position and direction from the previous step are used as starting values. The reason being, that the second shower vertex is expected to be on the trajectory found in the previous step due to the kinematics of the interaction. Therefore, a two shower likelihood is evaluated along the defined trajectory. The two shower likelihood is defined by a combination of the hit time distributions for two single shower hypotheses. The best fit of the two shower positions corresponds to minima in the negative logarithm of this likelihood. In Fig. 4a an example of the likelihood as a function of the position of the second shower along the trajectory of the first shower is shown. The two minima correspond to the simulated shower positions.

In the third step, the likelihood scans obtained in step 2 are analyzed by applying a peak finder algorithm to the inverted likelihood distribution. In the case of finding two significant peaks, the corresponding positions are used as a result. In the case of finding one or more than two significant peaks, the position of the highest peak and the position from step 1 are used. An example of evaluating the likelihood scan from step 2 is shown in Fig. 4b.

In the fourth step, the two shower likelihood is minimized for the whole detector rather than just along the trajectory defined in step 1. For this purpose the positions established in step 3 are used as starting values. This is not done immediately after step 1, since the performance of such a general minimization is strongly dependent on good starting values. Performing the general fit after step 3 allows to account for errors in the reconstruction of the position and the direction from step 1. With the general fit, a position resolution for both shower vertices of around 2 m median and a tau direction resolution of around 2° median is achieved.



(a) Scan from step 2.



(b) Analyzed scan from step 3.

Figure 4: Scans of the logarithm of the two shower likelihood along the trajectory defined in step 1; "0" on the X-axis corresponds to the position obtained in step 1.

This resolution allows to identify “Double Bang” signatures if their showers are separated by 5 m or more. By applying selection criteria based on the reconstructed parameter values and assuming an isotropic cosmic neutrino flux as observed by IceCube, a rate of 0.5 “Double Bang” events per KM3NeT block per year are expected. The background is estimated to be 0.06 events per block per year. Comparing this to IceCube, an approximately three times better performance is achieved.

The presented method will yield sufficient statistics to reconstruct the flavor composition of the cosmic neutrino signal and the detection of two or more tau neutrinos would prove the cosmic origin of the neutrino signal.