# Starlight beneath the waves : in search of TeV photon emission from Gamma-Ray Bursts with the ANTARES Neutrino Telescope

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# Summary

At the bottom of the Mediterranean Sea, at a depth of 2500 meter and approximately 40 km off Toulon in south of France, lies the ANTARES Neutrino Telescope. It is an array of light-sensitive detectors pointed towards the ground to detect neutrinos that come from the other side of Earth and have passed through it.

Neutrinos are particles that interact very weakly with matter and thus are very difficult to detect. In fact, high-energy neutrinos must pass through the Earth before they have a good chance to interact with the Earth and produce muons, which will travel in the same directions as the neutrinos. When the muons come out of the seabed, they travel with velocities exceeding the velocity of light in water. An electromagnetic shock wave will be generated along the path of the muon, which will be in the form of coherent radiation of photons emitted at a characteristic angle relative to the trajectory of the muon. This coherent photon radiation is called Čerenkov photons. The light-sensitive detectors that comprise ANTARES can detect these photons and reconstruct the tracks of the muons. Detecting upward-going tracks will confirm the neutrino origin of the muons as no other known particle can traverse the entire Earth.

One of the scientific goals to build undersea and under-ice high-energy neutrino telescopes is to search for the acceleration site of cosmic rays at the highest-energy. Cosmic rays are fully ionized atomic nuclei accelerated to relativistic velocities. They constantly shower the Earth at all times and from all directions. The energy of cosmic rays ranged from below $10^8$ eV up to $10^{20}$ eV. This extremely-high energy exceeds anything that could be performed in the currently largest manmade particle accelerators on Earth, which is of the order of $10^{12}$ eV. How these particles can be accelerated to such extreme energy and where are the sources, is still a matter of debate. Pinpointing the source of these natural accelerators could greatly help in understanding the mechanisms of the acceleration.

The search for the acceleration sites of cosmic rays is particularly difficult because they are charged particles and thus can be

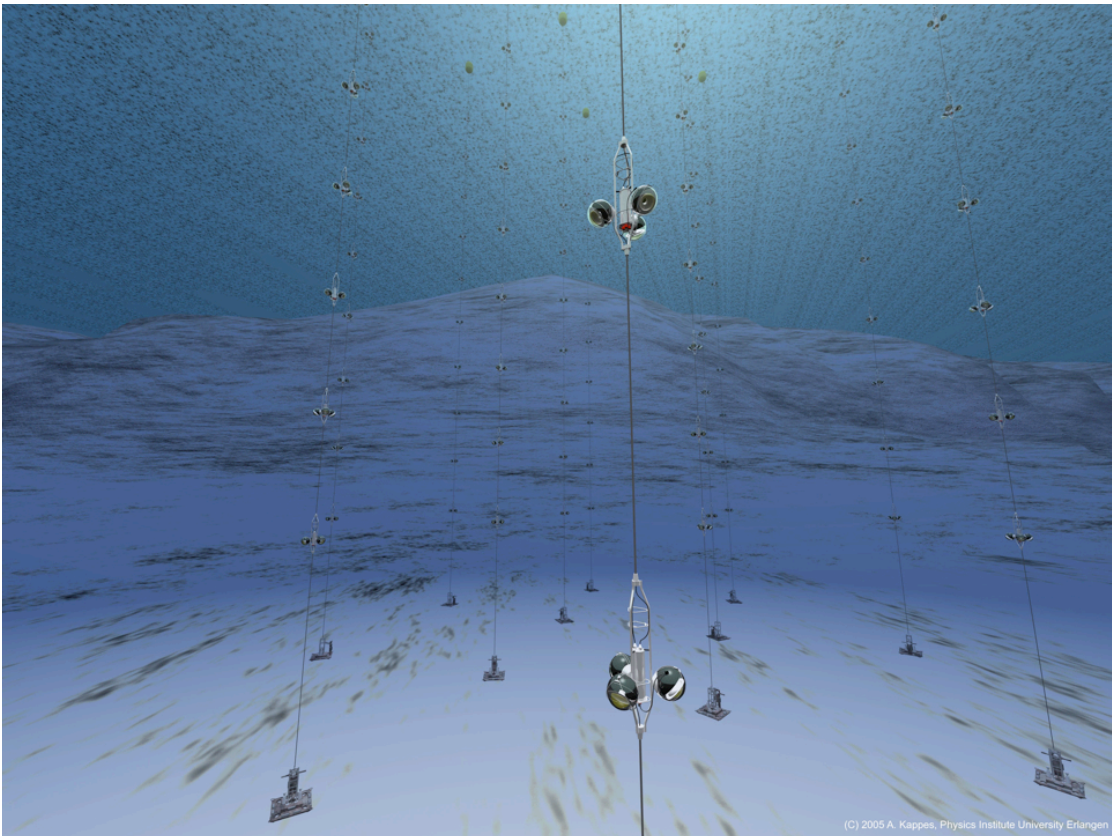

Figure 12.2: An artist impression of the ANTARES Neutrino Telescope. A discussion on the ANTARES Neutrino Telescope can be found on Chapter 6. Credit: Alexander Kappes (Physics Institute, University of Erlangen).

deflected to another random direction by ambient magnetic fields. Thus the observed directions of cosmic rays do not point back to the sources. On the other hand, cosmic rays of extremely-high energies are minimally deflected by magnetic fields. Their numbers are however are very low and their detection would require detectors of extreme size in order to detect them within reasonable time.

This is how neutrino telescopes come into the picture. Ultra-high energy neutrinos are expected as a by-product of cosmic ray interactions with the ambient matter of the acceleration site. Relativistically expanding matter will interact with its surrounding environment and create a shock wave. Shock-accelerated protons can escape to be observed on Earth as cosmic rays, but some

Figure 12.3: An artist impression of a Gamma-Ray Burst. A description of observational and theoretical aspects of GRBs can be found in Chapter 1.2, while the mechanisms of VHE photon productions in GRBs is discussed in Chapter 2.1. Credit: ESO/A. Roquette.

will interact with the ambient matter to produce ultra-high energy neutrinos.

Since neutrinos are electrically neutral they are not deflected by magnetic fields. They are also not absorbed by matter because they interact only weakly with it. Thus they point back straight to their production site.

GAMMA-RAY Bursts (GRBs) are attractive candidates for cosmic-ray acceleration sites. They are brief flashes of $\gamma$-rays occuring approximately once per day at random time and direction in space and is found to be nonrepeating. During this brief moment the $\gamma$-radiation lits up the otherwise dark $\gamma$-ray sky, outshining other $\gamma$-ray sources. GRBs have been understood to be the death throes of massive stars or the outcome of merger events between compact objects such as black holes or neutron stars. Whatever the progenitor was, the end result is an ultrarelativistic fireball expanding into the interstellar matter. In this environment, protons can be accelerated to reach extremely high energies and escape the fireball as cosmic rays, and can also produce ulta-high energy neutrinos which can be detected by large-scale neutrino telescopes. Finding these ultra-high energy neutrino sources is the main goal of neutrino astrophysics.

Cosmic rays can also interact with the fireball to produce very-high energy (VHE) photons. These photons, of energies in the order of $10^{12}$ eV and above, can also be detected by neutrino telescopes by the same principle of detection. As the photons reach Earth, they will interact with the atmosphere to produce muons, which can travel downward through the depth of the sea. They will lose their energy during their passage through the sea, but if they are energetic enough they can still invoke electromagnetic shockwaves which will generate Čerenkov photons. From these photons the telescope can then reconstruct the downward-going track of the muons. Thus by looking up like a photon astronomer would traditionally do, instead of looking down like a neutrino astronomer, a neutrino telescope could have a secondary function as a $\gamma$-ray telescope.

Neutrino telescopes have a very wide field-of-view and a very high duty cycle. Their coverage above the horizon is approximately $\pi$ sr and they constantly take data 24 hours per day, 7 days per week, barring maintenance. Taking these two capabilities into account, GRBs are then suitable targets to be observed because of their transient and nonrepeating nature.

This idea of operating a neutrino telescope as a $\gamma$-ray telescope is an old one, but can only become a reality with the recent advent of very large volume neutrino telescopes such as ANTARES in the Mediterranean Sea, IceCube at the South Pole, and the future KM3NeT. A very large detection volume is required not only because in photon showers muons are produced only in small numbers, but also because VHE photons are absorbed by ambient infrared photons on their way from the source to the Earth.

THE FIRST step in exploring the prospect of this idea is by estimating the number of detectable muons at the detector. A number of factors must be taken into account in this calculation: The intrinsic number of VHE photons produced in the GRB itself, the number of photons absorbed by ambient infrared photons during their propagation from the source to the Earth, the number of muons produced in the Earth's atmosphere, and the muon energy loss in the sea given the depth of the detector.

Part I of this dissertation is focused on answering this first step. The intrinsic number of VHE photons can be calculated by assuming a certain distance to the GRB, indicated by its redshift $z$, and that the photons are emitted with an energy spectrum in the shape of a power-law function. The severity of photon absorptions by infrared ambient matters can be estimated by using currently-available absorption models to calculate the optical depth $\tau(\epsilon_\gamma, z)$ of the universe to VHE photons as a function of energy and distance to the source.

The calculation of photon-induced muons is performed first by identifying the two most probable channels. The first one is from the decay of pions. High-energy photons interact with the nuclei in the atmosphere to produce pions through the reaction $\gamma + N \to \pi + X$, followed by leptonic decay of pions into a positive muon and a muon neutrino, or a negative muon and a muon antineutrino: $\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$. The energy spectrum of the muons resulting from this channel has been calculated for a specific photon energy spectrum obeying the $\epsilon_\gamma^{-2}$ function by Drees, Halzen & Hikasa (1989), and has been generalised to an arbitrary spectral index by Halzen, Kappes & Ó Murchadha (2009).

The second channel is the direct muon-pair production from the interaction of high-energy photons with atmospheric nuclei, $\gamma + X \to \mu^+ + \mu^-$. For this to occur, the photon energy must be higher than ~43.9 GeV. The cross section for direct lepton-pair productions has been calculated by Bethe & Heitler (1934) for electrons, but the equation can be generalised to any type of lepton by integrating the atomic form factor over the transferred momentum with the mass of the lepton involved as the upper limit (Halzen, Kappes & Ó Murchadha, 2009).

The resulting muon spectrum from these two channels can then be calculated. At low energies, the dominant channel is the pion decay; however, the number of high-energy muons that can be produced from this channel goes down rapidly with increasing energy. At energies higher than 1 TeV, the dominant channel of muon production is pair production, because the total cross section increases with photon energy before reaching a saturation point at $\epsilon_\gamma \gtrsim 10$ TeV.

As the muons traverse the sea, they will lose their energy through ionization and radiative processes. This is a stochastic process which can be evaluated by means of Monte Carlo simulations, but the average energy loss can be calculated by taking the standard muon energy loss formula (Barrett et al., 1952). Using this formula, the relation between the muon energy at the sea surface and the energy at a certain depth can be calculated. It is now also possible to calculate the muon spectrum at the depth of the detector.

From these theoretical calculations, the three most important factors in detecting VHE photons from GRBs has been identified. The redshift $z$ of the GRB determines the number of VHE photons that survives the journey to the Earth, the hardness of the energy spectrum determines whether the electromagnetic spectrum grows or dissipate in the atmosphere, and finally the size of the detector determines the number of muons that can be detected. Assuming a GRB with an average physical parameters, it is found that an ANTARES-sized neutrino telescope can detect VHE photons provided that the GRBs are located at redshift $z \lesssim 0.05$. A larger telescope with a muon effective area of $A_\mu^{\mathrm{eff}} = 1$ km$^2$ can see up to $z \sim 0.1$.

To UNDERSTAND the response of ANTARES to downgoing muon signals, Monte Carlo simulations are required. This is the main subject of Part II. The simulations are performed in the environment around the detector. The volume is defined to be a cylinder, called the *can*, with the detector placed at the centre. The size of the can covers the detector with a margin equal to a few times the attenuation of light. With this definition, the Čerenkov photons produced outside the can do not reach the detector and thus do not need to be simulated. This can significantly increase the speed of the simulation.

In the atmosphere, several muons can be produced at once in a bundle. These muon bundles travel next to each other and can be inaccurately reconstructed. Monte Carlo simulations of muon production in the atmosphere, performed with the `CORSIKA` package, indicate that very high energy muon bundles that can penetrate the depth of the detector are very rare. Most of the muons that reach the detector are single muons. It is thus appropriate to generate only single muon tracks to study the detector response.

The results of the simulations indicate that the detector can accurately reconstruct downgoing muon tracks, albeit with reduced efficiency compared to upgoing tracks. This is because the light-detectors are pointed downwards to maximize light collecting from upgoing tracks. The photon effective area of ANTARES is found to be approximately 1 $m^2$ at 5 TeV. Taking into account these detector effects, the sensitivity of ANTARES to an average GRB is only up to redshift $z \sim 0.01$.

From the simulation we can also use the angular distribution of reconstructed events to model a point spread function (PSF). The PSF for the signal events can be approximated as a bivariate normal distribution. The background events, which are muons produced from the interaction of cosmic rays with atmospheric nuclei, can be studied using actual data taken by ANTARES. Using a data set taken in 2008, in which ANTARES is running with full capabilities, it is found that the angular distribution of the background events can be approximated by a constant function, assuming that only small opening angles are considered. Using these two ingredients, toy Monte Carlo simulations can be performed to generate background and signal events. These simulations can be used for hypothesis testing to evaluate the compatibility of the data with the background-only hypothesis or the signal plus background hypothesis. From this analysis it is found that detecting only 5 signal events already gives a 90% probability of making a discovery with $3\sigma$ significance.

THE FIRST attempt to find VHE photons from GRBs using a neutrino telescope is performed in this dissertation. This is described in Part III. We first compile a list of detected GRB from various sources; then the number of detectable muons from these GRBs is calculated. The most prospective GRBs are then the ones that have the highest emitted signal events.

To obtain an optimum quality cut that can maximize the discovery potential, we need to estimate the number of expected signal and background events. The former is estimated by performing a full Monte Carlo simulation from the top of the atmosphere to the detector volume, while the latter is estimated by analysing the data taken by ANTARES during the period when the GRB took place. After an optimum quality cut has been obtained, the data coinciding with the GRB is then observed.

From the two GRBs to be observed, no event was observed during the time period when the GRB took place. Limits however have been set at 90% confidence level, which is found to be $\nu f_{\nu,90\%}(10 \text{ TeV}) = 4 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. This result shows that ANTARES is much less sensitive than other ground-based $\gamma$-ray observatories such as HESS, *Milagro*, or MAGIC.

Two very nearby GRBs took place within the field-of-view of IceCube. As the largest neutrino telescope in the world, IceCube should observe these two GRBs. They should obtain interesting limits given their capabilities.

Future neutrino telescopes such as the Gigaton Volume Detector (GVD) in Lake Baikal and KM3NeT in the Mediterranean sea will have a more serious chance to impose a stricter limit or even making a discovery. KM3NeT is expected to be completed in 2020 and is expected to cover a volume of 5–8 km$^3$. Another instrument that has possibly the best chance to observe VHE photons from GRBs is HAWC, which has a photon effective area of $A_\gamma^{\text{eff}} \sim 10^5$ m$^2$ at $\epsilon_\gamma = 10$ TeV (Abeysekara et al., 2012), and an expected sensitivity of $\nu f_\nu \sim 10^{-7}$ erg cm$^{-2}$ s$^{-1}$. This is still ~10 times less sensitive than MAGIC and ~100 times less sensitive than HESS, but HAWC has a very wide field-of-view and high duty cycle. It is possible that HAWC will make the first confirmed discovery of VHE photons from GRBs after it is completed in 2014.