Ultra-high energy neutrino simulations

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Introduction

Astronomy, with several thousand years of history, is one of the oldest of the natural sciences, its roots dating back to antiquity. For all time, mankind has been gazing at the sky, seeking answers to nature's mysteries. While early astronomers watched the regular movements of visible celestial objects with just the naked eye, Galileo could observe the craters on the Moon and even the explosion of a supernova using one of the first built telescopes at the beginning of the 16^{th} century. Since this period, astronomy has continued its evolution over time and remarkable progress has been made thanks to a continuous dialogue between theory and observations. Nowadays, most of our knowledge of the Universe comes from the observation of photons. Beside their stability and electrical neutrality, photons are easy to detect and their spectrum contains detailed information about the chemical and physical properties of their source. Moreover, they are abundantly produced in the Universe as electromagnetic radiation is released in a variety of physical processes and thus constitute a crucial cosmic information carrier. The recent advent of multi-wavelengths telescopes allows the observation of the entire electromagnetic spectrum, with wavelengths well beyond the limited range of visible light used in the past. However, the ultra high energy domain, with energies far beyond the limits set by present day particle accelerators remains largely unexplored by conventional astronomical methods.

Even though gamma ray astronomy has been successful, observations are limited by attenuation of high energy photons from distant sources due to electron-positron pair production in interactions with the omnipresent 2.7 K cosmic microwave radiation [1]

$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-} \ .$$

As a result, the Universe is opaque to gamma rays from extragalactic sources and photons with energies in excess of 10^6 GeV cannot even survive the journey from the Galactic Center to the Earth [2]. In addition, gamma rays cannot penetrate nor escape the hot and dense regions which form the core of stars and other high energy astrophysical sources. It is therefore impossible to investigate the properties of these objects or regions of the Universe by direct observations. In the last decades, a new field of research has emerged to overcome these limitations.

At a crossroad between astronomy, particle physics and cosmology, astroparticle physics studies elementary particles of cosmic origin. Through the design and construction of new types of infrastructure such as underground laboratories or especially designed telescopes, antennas and satellites, astroparticle physics opens a new window on the Universe, searching not only for photons from astrophysical objects, but also for high energy cosmic rays, neutrinos and gravitational waves.

Neutrinos are of particular interest as they are stable particles which interact very weakly with matter. They can cross long distances and penetrate regions which are opaque to photons. Neutrinos are electrically neutral and their trajectory cannot be deflected by the ambiant magnetic fields in the Universe. Consequently, the direction of the observed neutrinos at Earth points back directly to their source. Thanks to their particular characteristics, neutrinos constitute an ideal high energy probe to observe distant astrophysical objects and provide information on the dynamics of the most energetic phenomena of the Universe. The study of the detectability of very high energy cosmic neutrinos is the central topic of this thesis. Such neutrinos are expected to be produced in the interactions of high energy cosmic rays with ambient matter and/or photons [2]. Models of cosmic ray production are therefore presented in Section 0.1. The shape of the observed cosmic ray energy spectrum is also discussed. The problem of the Greisen-Zatsepin-Kuz'min limit and its consequences on the possible observation of ultra high energy cosmic rays is described in Section 0.2. The most likely sources of very high energy neutrinos, active galactic nuclei (AGN) are discussed in Section 0.3. Finally, the main questions addressed by this thesis are outlined in Section 0.4.

0.1 Very high energy Cosmic Rays

Cosmic rays are atomic nuclei, predominantly protons and electrons which bombard the Earth from beyond the atmosphere with very high energies. The lowest energy cosmic rays are detected directly by experiments on board of satellites or high altitude balloons before they are absorbed in the atmosphere. High energy cosmic rays however are detected indirectly through the extensive air showers they produce which can be observed by an array of particle detectors at ground level. The measured cosmic ray spectrum is shown in Figure 1. As can be seen in the figure, the spectrum steepens at an energy of about 3×10^{15} eV which is referred to as the "knee", and flattens near 3×10^{18} eV at the "ankle". The flux of cosmic rays is well described by a broken power law of the form $\phi(E) \propto E^{-\gamma}$,

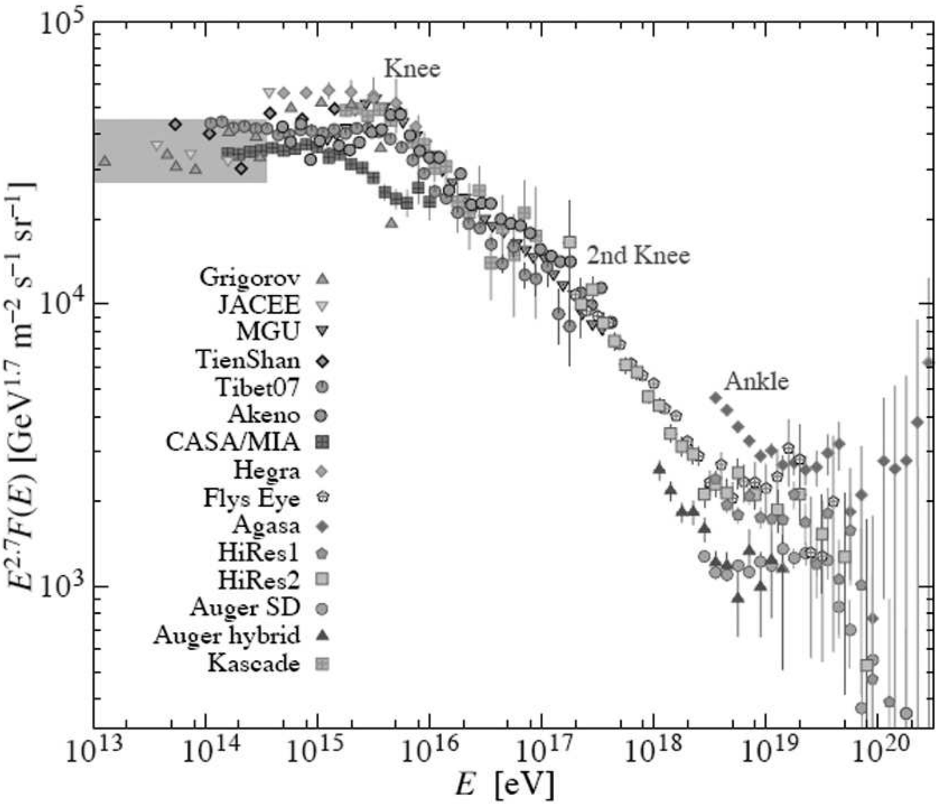

Figure 1: *The measured cosmic ray spectrum between* 10^{13} *and* 10^{21} *eV. The shaded area shows the range of direct cosmic ray spectrum measurements [3].*

with an energy dependent spectral index γ such that

$$\gamma \simeq \begin{cases} 2.7 & \text{if } E \leq 3 \times 10^{15} \text{ eV} \\ 3.0 & \text{if } 10^{15} \text{ eV} \leq E \leq 10^{19} \text{ eV} \\ 2.7 & \text{if } E \geq 10^{19} \text{ eV}. \end{cases}$$

The shape of the measured spectrum constraints possible models of cosmic ray production. It is usually assumed that cosmic rays are produced and accelerated by sources both within and outside the Galaxy. The acceleration mechanism is based on initial suggestions by Enrico Fermi [4]. First order Fermi acceleration, or diffusive shock acceleration occurs when cosmic ray particles are repeatedly reflected by fast-moving magnetic fields in the interstellar medium. By bouncing back and forth in the magnetic field randomly lets some of the cosmic ray particles gain energy. The maximum energy they can possibly obtain depends on the charge of the particle, the shock velocity, the magnetic field at the site and the size of the accelerating source. This is known as the Hillas criterion [5] which is illustrated in figure 2 where acceleration limits for possible high energy cosmic ray sources are shown. Astrophysical objects which can accelerate protons above

10^{20} eV are displayed on the top right corner, above the dotted line. The two solid lines represent the proton energies above 10^{21} eV (above) and iron nuclei [1] with energies above 10^{20} eV (below). As can be seen in the figure, only a few objects

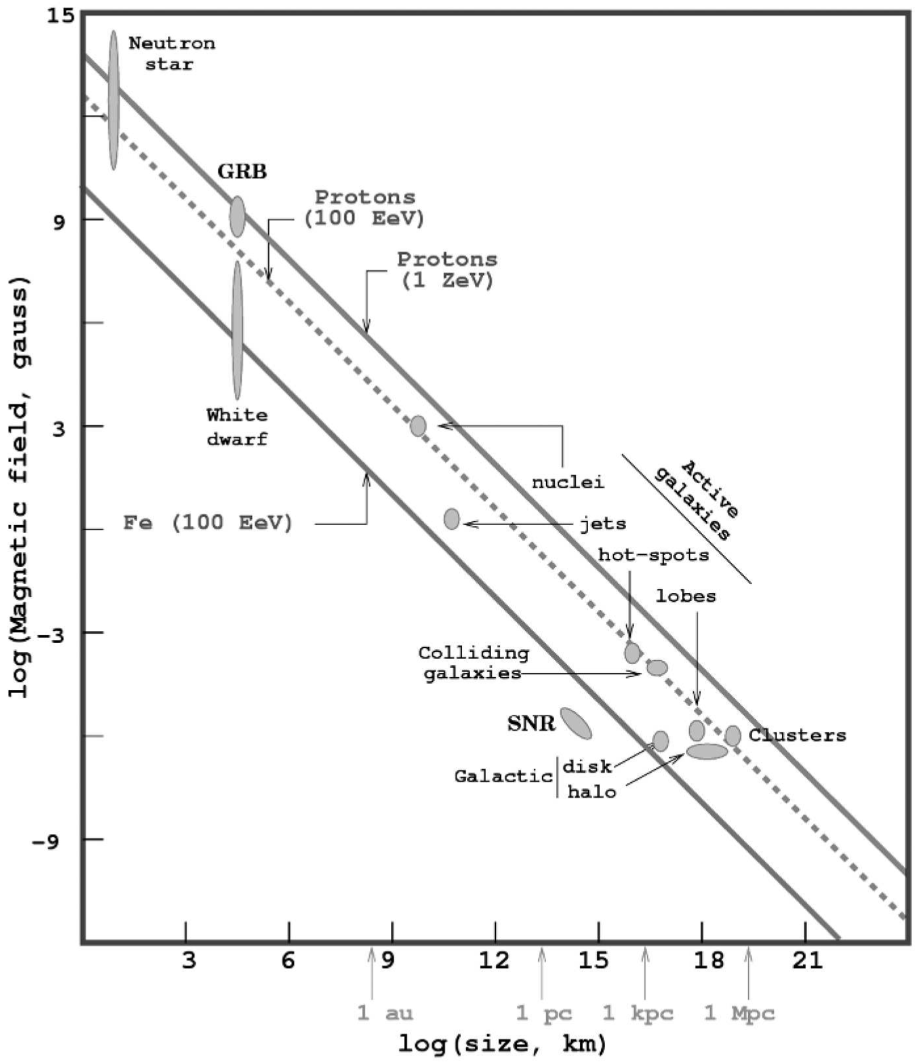

Figure 2: *A Hillas plot [5]. The strength of the electromagnetic field is shown as a function of the size of the object in which protons and nuclei are accelerated to become high energy cosmic rays. Objects above the dotted line are able to accelerate protons above* 10^{20} *eV, assuming an efficient diffuse shock acceleration mechanism.*

are able to accelerate cosmic rays up to the highest energies. This is discussed below.

Cosmic rays with energies below the knee are thought to originate inside the Galaxy, most probably from acceleration in the shock waves of supernovae rem-

[1] Iron nuclei are the heaviest abundant nuclei observed in cosmic rays

nants [3]. The knee could thus feature the highest energy that galactic accelerators can reach. Cosmic rays with energies above the knee cannot be confined by the magnetic fields within the Galaxy. They are thus believed to propagate through intergalactic space [6] what induces a steepening in the cosmic ray energy spectrum. In the region around the ankle, the galactic population of cosmic rays is overcome by the extragalactic population of cosmic rays [3]. The ankle is consequently considered to reflect the transition from galactic to extragalactic cosmic rays. Above the ankle, cosmic rays are difficult to detect since they hit the Earth at a rate of less than one per square kilometer per century. Experimental evidence suggests that such high energy cosmic rays are mostly protons accelerated in extragalactic sources [7]. Among the very few likely candidates [8] for these ultra high energy cosmic ray sources are active galactic nuclei (AGN) and gamma ray bursts (GRBs) in which also neutrino production may occur. Moreover, the associated sources should be confined within a few 10 Mpc of the Earth to contribute to the observed cosmic ray spectrum due to the Greisen-Zatsepin-Kuz'min or GZK limit [9] [10].

0.2 The Greisen-Zatsepin-Kuz'min limit

In 1965, Kenneth Greisen [9], Vadim Kuzmin and Georgiy Zatsepin [10] independently predicted that high energy cosmic rays traveling through outer space can scatter with the omnipresent photons of the cosmic microwave background [1] to create charged and neutral pions via the Δ^+ resonance

$$p + \gamma \to \Delta^+ \to n + \pi^\pm \tag{1a}$$

$$p + \gamma \to \Delta^+ \to p + \pi^0 \tag{1b}$$

when the cosmic rays energy crosses the threshold of 5×10^{19} eV. The mean free path associated with the interaction drops considerably above this energy threshold which is referred to as the GZK limit. This results in the prediction that the observed cosmic ray flux at Earth will be strongly suppressed above 5×10^{19} eV. At these extreme energies, only cosmic rays coming from within the local supercluster of galaxies, that is from astrophysical sources within 100 Mpc from Earth can be detected.

With the emergence of large high-sensitivity cosmic ray telescopes, the GZK limit can now be measured. The High Resolution Fly's Eye (HiRes) detector [11], the AGASA surface array detector [12] and the Pierre Auger Observatory (PAO) experiment [13] have studied the cosmic ray flux in this energy domain. Figure 3 presents an expanded view of the cosmic ray spectrum shown in Figure 1. Only the more recent measurements are shown for energies between 10^{18} eV and 10^{21} eV. As can be seen in the figure, both the HiRes and the PAO results show a steepening in the cosmic ray flux beyond $3 - 5 \times 10^{19}$ eV which is consistent with

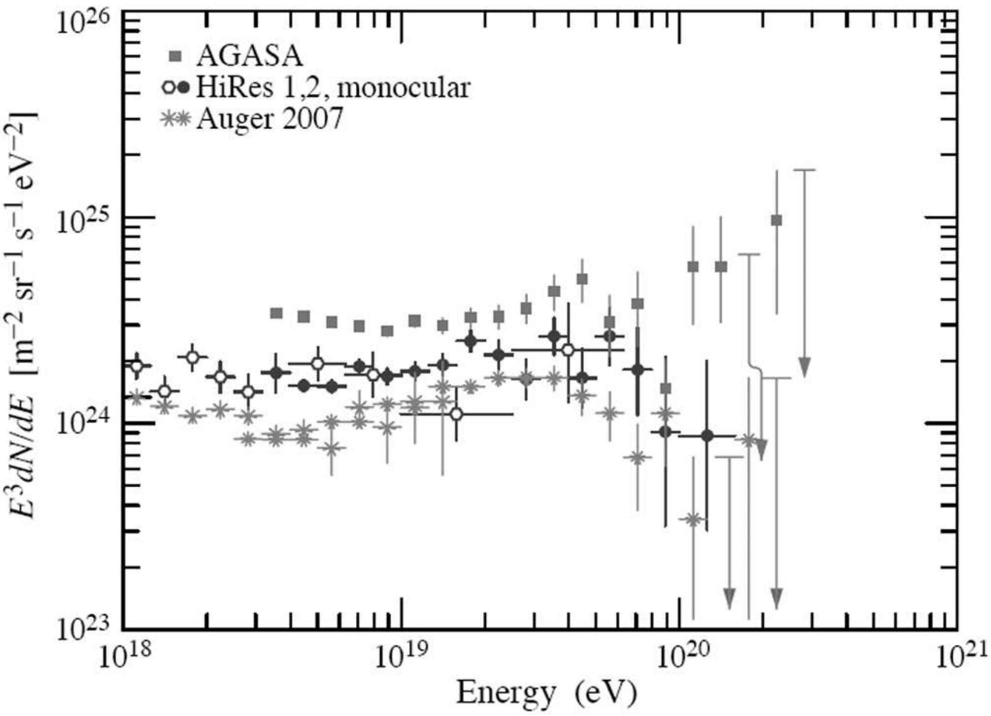

Figure 3: *The measured cosmic ray energy spectrum for energies between* 10^{18} *eV and* 10^{21} *eV. Recent measurements from AGASA [12], HiRes [11] and Auger [13] are shown. The plot was taken from reference [3].*

the existence of the GZK limit. However, the flux measurements by AGASA [12] seem in contradiction with the data of the other two observatories. They are in favor of a non-acceleration scenario for explaining the origins of ultra high energy cosmic rays. This alternative model predicts that the excess of cosmic rays measured above the GZK limit results from the decay of very massive, long-lived particles such as topological defects [14].

The discrepancy between the observed spectra is often attributed to a failing energy calibration of the AGASA detector [15], but this issue remains controversial. Further information on the origin of ultra high energy cosmic rays could be obtained by searching for high energy neutrinos. High fluxes of neutrinos are expected regardless of the cosmic ray production scenario. They are believed to be produced in the acceleration of cosmic rays or by the decay of topological defects. The detection of ultra high energy neutrinos could conclusively close the debate on the existence of the GZK limit and the origin of the very high energy cosmic rays. It would also help understand the physics of extreme astrophysical objects such as active galactic nuclei. In the framework of this thesis, only neutrinos from accelerated cosmic rays will be considered. The predicted mechanism of production for such neutrinos is described below.

While confined by the high magnetic fields at the acceleration site, some fraction of the cosmic rays suffer resonant pion photoproduction with the ambient photons as in equation 1a and 1b. This leads to electron and muon neutrinos through the decay of the produced charged pions

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu_\mu} \tag{2a}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu_\mu} \rightarrow e^- + \bar{\nu_e} + \nu_\mu + \bar{\nu_\mu} \tag{2b}$$

and the free neutron

$$n \rightarrow p + e^- + \bar{\nu_e}\ . \tag{2c}$$

According to the equations 2a, 2b and 2c, the flavour ratio of the high energy cosmic neutrino flux is typically $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 2 : 0$ at the source, where ϕ_{ν_l} is the combined flux of neutrinos and anti-neutrinos for the flavour l. After propagation over cosmological distances, a flavour ratio of $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$ is observed at Earth due to the phenomenon of neutrino oscillations [16]. All three flavors of neutrinos are therefore initially of the same importance for detection. However, the probability of detection of muon neutrinos is higher due to the long path length of the muons they produce in interaction with matter.

0.3 Active galactic nuclei

The Pierre Auger Observatory has recently reported a direct correlation between the highest energy cosmic rays observed and the presence of nearby active galactic nuclei, lying within 75 Mpc from Earth [13]. Active galaxies are therefore also likely sources of high energy cosmic neutrinos.

The term active galactic nuclei or AGN refers to the existence of very energetic phenomena occuring in the core of some galaxies. The amount of radiation emitted by the central source is at least comparable to the energy radiated by all the stars in the galaxy. Such galaxies are thought to possess a massive black hole at their center as high as 10^{6-9} solar masses that powers their enormous energy output. Several types of AGN can be recognized, based on the mass of their central engine.

The two main subclasses of AGN are Seyfert galaxies and quasars. Both possess very luminous nuclei which appear almost starlike but with strong and broad emission lines from highly ionized gas. These emission lines show evidence for the presence of large amounts of very hot and fast-moving gas, accreting around the galactic center. Seyfert galaxies were the first active galactic nuclei to be identified. They are named after Carl Keenan Seyfert who discovered them in 1943. Seyfert galaxies are thought to be powered by a moderate-mass black hole. Quasi-stellar radio sources or quasars show emission lines in their spectra which are even more prominent than for Seyfert galaxies. They also present very large redshifts, indicating by the Hubble law that they are at great distances.

Some of the quasars which have been observed so far are about 10 billion of light-years away. The fact that they are visible at such distances implies that they emit enormous amounts of energy and can not be stars in our Galaxy. Because of these observations, quasars are believed to be active galactic nuclei with a high-mass black hole.

The radiation cannot be produced by the supermassive black hole itself as it is invisible but by the surrounding interstellar gas accreting onto it. Observations show that narrow beams of energetic particles are ejected in opposite directions from this accretion disk. Even though uncertainties remain, the mechanisms involved in the production and acceleration of the jets are most likely due to acceleration in the ambient magnetic fields. The gas is attracted by the black hole and as it slowly spirals towards the center of the galaxy, its gravitational potential energy is converted into thermal energy. The thermal energy can accelerate jets of material from the accretion disk to relativistic speed. Among the radiation products of the jets are protons which can interact with the ambient radiation in the AGN to give neutrinos according to the equations 2a and 2b. With exceptional gravitational forces in the vicinity of their central massive black hole, active galaxies are believed to possess the tremendous amounts of energy needed to accelerate cosmic rays and produce neutrinos up to the highest energies.

0.4 Discussion

The main topic of this thesis is to study whether neutrino telescopes can be used to search for ultra high energy neutrinos. These neutrinos are speculated to be produced in the Fermi acceleration of cosmic ray protons in extragalactic sources. The recently reported results on ultra high energy cosmic ray production [7] [13] indicate that active galactic nuclei are likely sources of high energy cosmic neutrinos. Since cosmic rays with energies close to 10^{20} eV have been observed, neutrino beams of similar energy are expected as well [2].

The small interaction probability of neutrinos make them difficult to detect. However, the products of their interactions are observable through the Cherenkov effect in a transparent medium such as water or ice. The predicted fluxes of ultra high energy neutrinos are most likely within reach of the first generation of neutrino telescopes and certainly detectable by future kilometer-scale neutrino observatories. The neutrino telescope ANTARES is constructed to search for high energy neutrinos. Its sensitivity to neutrino events above 10^{16} eV and up to the GZK cut-off has been evaluated in the framework of this thesis. At these ultra high energies, the Earth is opaque to neutrinos and only downward-going and horizontal neutrinos can arrive at the detector. Since neutrino telescopes such as ANTARES are optimized for the detection of upward-going neutrinos in the energy range from 10^{11} eV to 10^{16} eV, it needs to be investigated whether downward-going neutrinos of energy beyond 10^{16} eV can be observed. This is of relevance not only for the ANTARES telescope but also for the future cubic kilometer-scale detector KM3NeT. It will provide information for the optimisation of the geometry of the telescope and the technologies required.

Rather than searching for neutrinos from a specific source, a non-localised flux of high energy neutrinos has been considered. Such an approach gives an higher probability of detection, in the case the neutrino flux from individual sources would be too small to be detected by a neutrino telescope of the size of ANTARES. As muon neutrinos have an higher detectability, the diffuse flux of muon neutrinos from AGN has been considered. This neutrino flux can be modelled by a generic E^{-2} spectrum with units of 10^{-6}GeV cm^{-2}s^{-1}sr^{-1} [2].

A description of the ANTARES neutrino telescope and the detection principle involved are given in Chapter 1. A chronological analysis of the development and construction of the telescope is presented in this chapter.

The expected performance of ANTARES in the high energy range relies on a good timing resolution between the signals recorded in the photo-sensors of the telescope and a good functioning of the various mechanical and electronic components of the telescope. A time calibration method and a diagnostic tool to determine whether components are functioning as expected during the operations have been developed in the framework of this thesis. They are presented in Chapter 2. The readout system of the telescope is also described in this chapter.

The sensitivity of ANTARES to ultra high energy cosmic neutrinos has been estimated using Monte Carlo simulations. Three distinct stages of simulation can be distinguished. The first one consists in the generation of neutrino interactions in the water and seabed around the telescope. The propagation of the resulting secondary leptons towards the telescope needs then to be modeled. Finally the simulation of the detector response to the Cherenkov light induced in the photo-sensors of the telescope by the relativistic moving secondary leptons is computed by a specific detector simulation. Since the available simulations accept neutrino events within a limited range of energies only, improvement of existing packages and the development of new programs were required. The implementation of the neutrino generator ANIS and the lepton propagator MMC in the ANTARES Monte Carlo event simulation chain is described in Chapter 3. Both programs were initially designed for use with the AMANDA neutrino telescope but they have been adapted to ANTARES in order to generate ultra high energy neutrino events. A comparison between ANIS and the program GENHEN which is generally used with ANTARES is also presented. A new simulation program, named SIRENE which is capable of modeling the detector response for neutrino events up to the highest energies is presented in Chapter 4. The program allows the implementation of any neutrino telescope geometry. SIRENE has been developed for the KM3NeT detector but it has been tested with the ANTARES telescope for the analysis presented in this thesis. Results of the Monte Carlo simulation study are given in Chapter 5. A dedicated method has been developed to separate the ultra high energy neutrino signal from the large background of atmospheric muons, using the characteristics of the simulated ultra high energy events in the ANTARES telescope. Optimized event selection criteria based on the arrival direction of the Cherenkov photons and the total charge deposited in the telescope have been applied. Predictions on the diffuse AGN-like muon neutrino flux limit and the associated neutrino effective area are presented.