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1 INTRODUCTION

The Milky Way Galaxy is one of billions of galaxies in the universe we call home. It appears like a dim "milky" band arching across the night sky, see figure 1.1. This band is actually only a part of our Galaxy; all stars in the night sky that are visible to the naked eye are part of the Milky Way Galaxy. Our Galaxy is disk shaped, and since we ourselves are inside it, we see a lot of matter when we look in the plane of our Galaxy and less matter when we look perpendicular to it. The milky band corresponds to the Galactic plane and is commonly referred to as the Milky Way, although also the whole Galaxy is called the Milky Way, which can be confusing. In this work, the meaning will be clear from the context. To emphasize that the Milky Way is our home Galaxy, it is referred to with a capital 'G' to distinguish it from the billions of other galaxies.

Figure 1.1: The Milky Way over the 3.6 metre telescope of the European Southern Observatory (ESO) at La Silla. Image credit ESO/S. Brunier.

In Greek mythology, the Milky Way is formed when Hermes, the messenger of the gods, brought Hercules to suckle at the breast of Zeus's sleeping wife Hera in order to gain immortality. When Hera woke up and found she was feeding the child of

Zeus and a mortal woman, she pushed the baby away. This made her breast milk spray into the heavens, thus creating the Milky Way [Walter and Hodge, 2003]. It is thought that this legend is also the origin of the name *Milky Way*. The Latin *Via Lactea* is adapted from the Greek *Galaxias Kuklos*, meaning milky circle. It is interesting to note that the root of the word "galaxy" means simply "milk".

It was also the Greeks that made the first written scientific explanations about the Milky Way. In his book *Meteorologica*, the Greek philosopher and scientist Aristole wrote that fellow Greek philosopher Democritus proposed that the Milky Way consists of distant stars, although Aristotle himself did not share that view. He instead thought that the Milky Way was caused by the ignition of the fiery exhalation of some stars that were large, numerous and close together. It wasn't until 1610 that Galileo Galilei resolved the issue when he used his telescope to observe that the Milky Way consists of a huge number of faint stars.

*Democritus: *c. 460 BC; † c. 370 BC*

*Galileo Galilei: *1564; † 1642*

In the 1780s, Sir William Herschel and his sister used a larger reflecting telescope, which allowed them to carefully count the stars as a function of location in the sky. Sir William used these measurements to create a map of our Galaxy, in which he placed our solar system near the centre. In the 1920s American astronomer Harlow Shapley realised that the Sun is not at the centre of the Galaxy. He studied globular clusters, which we now know are spherical collections of stars orbitting the core of a galaxy. He noticed that they formed a spherical halo around a point several thousands of lightyears away and realised that this point must coincide with the centre of our Galaxy [Pasachoff, 1979].

*Sir William Herschel: *1738; † 1822*

*Harlow Shapley: *1885; † 1972*

In 1931, Karl Jansky, an engineer of Bell Labs, performed experiments with a radio antenna to determine the possible sources of noise that could pose a problem for short-wave radiotelephones [Pasachoff, 1979]. He recorded a signal of unknown origin that peaked about every 24 hours. At first he thought the signal originated from the Sun, but upon more careful analysis, it turned out that the signal appeared 4 minutes earlier each day. He realised that after exactly one sidereal day the signal repeated itself and that it thus originated from outside the solar system. Later it turned out that he had observed radiation from the centre of our Galaxy. After publishing his results [Jansky, 1933], he wanted to study the Milky Way in more detail. However Bell Labs reassigned him, and he didn't do any further work on radio astronomy. The measurements of Jansky mark the birth of a new field of research: radio astronomy.

*Karl Guthe Jansky: *1905; † 1950*

A sidereal day is the time it takes for a distant star to be at the same position on the sky again after one rotation of the Earth. It is 23 hours, 56 minutes and 4 seconds and is slightly shorter than a solar day due to the rotation of the Earth around the Sun.

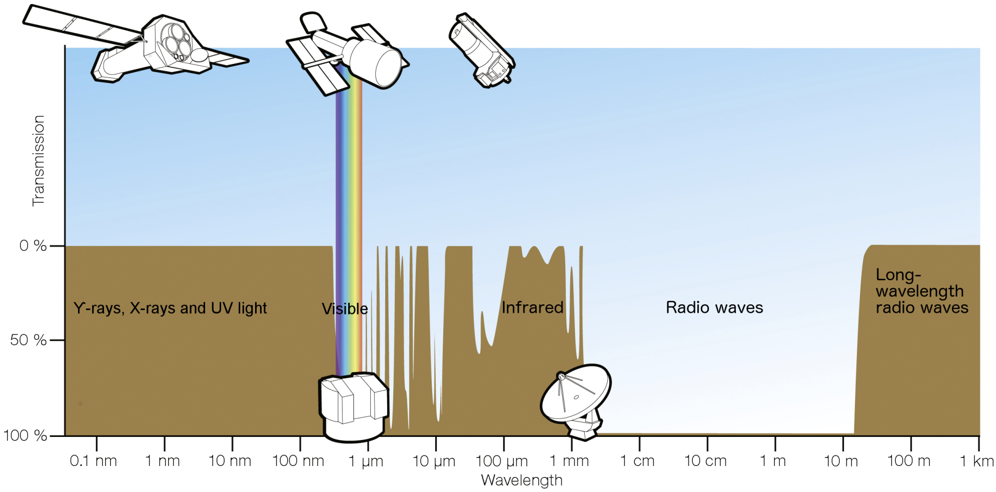

Figure 1.2: The atmospheric transmission versus wavelength and the methods used to observe the different parts of the electromagnetic spectrum. Image credit ESA/Hubble (F. Granato).

Professor Jan Oort was particularly interested in the measurements of Jansky. He was interested in determining the structure of the Milky Way and radio astronomy could help him with this, since absorption is negligible at radio wavelengths. However, the featureless spectrum measured by Jansky was of little use. A spectral line would be much more helpful, since it reflects the dynamics of its source. Since Oort knew hydrogen is a very abundant element, he asked his student Hendrik van de Hulst to find out if hydrogen could have any radio spectral lines. Van de Hulst predicted that neutral hydrogen should have a prominent line at 21 cm, caused by the hyperfine splitting of its ground state [van de Hulst, 1945]. In 1951, the now famous 21 cm line was indeed detected and the spiral structure of our Galaxy became visible [Ewen and Purcell, 1951; Muller and Oort, 1951].

*Jan Hendrik Oort: *1900; †1992*

*Hendrik Christoffel van de Hulst: *1918; †2000*

Radio astronomy opened a new window on the universe, since it allowed for the observation of objects that were not detectable with "normal" optical astronomy, like quasars and radio galaxies [Burke and Graham-Smith, 2010]. In the same manner, by observing other parts of the electromagnetic spectrum, a lot of new things can be learned [Kambič, 2010]. However, to perform observations at other wavelengths, the telescopes have to be placed outside of the Earth's atmosphere, since it absorbs or reflects these wavelengths. This can be seen in figure 1.2, in which the atmospheric transmission of the electromagnetic spectrum is shown.

Quasars, or quasi-stellar radio sources, are extremely luminous sources at the centres of galaxies.

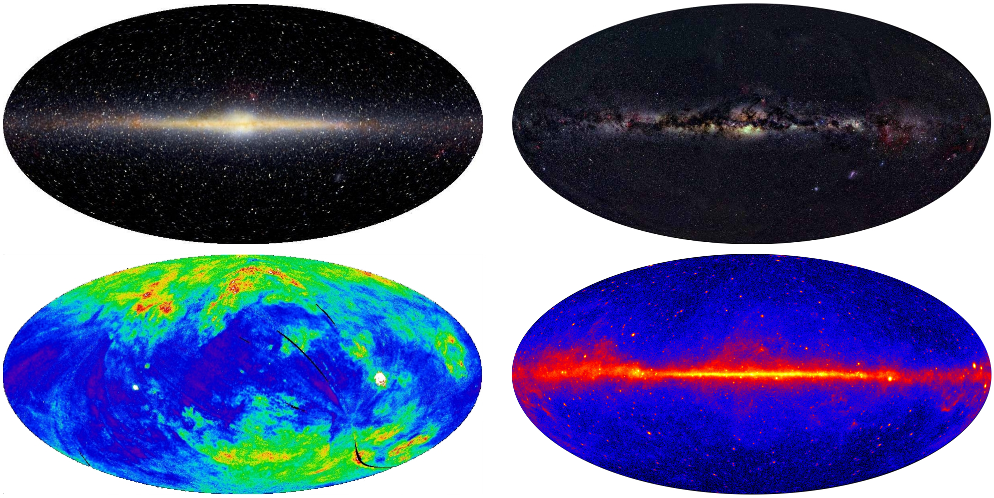

Figure 1.3: The Milky Way observed with photons at different wavelengths. TOP LEFT: in near-infrared. Image credit E.L. Wright (UCLA), The COBE project, DIRBE, NASA. TOP RIGHT: in visible light. Image credit Alex Mellinger. BOTTOM LEFT: in X-rays (between 0.1 keV and 0.3 keV). Image credit Snowden et al. [1995]. BOTTOM RIGHT: in γ-rays (above 1 GeV). Image credit NASA/DOE/International LAT Team.

At infrared wavelengths the sky looks quite different than at visible wavelengths. The dust that blocks the view of the centre of our Galaxy at visible wavelengths, becomes transparent in the near-infrared. This can be seen by comparing the top left and top right sky-maps in figure 1.3. These sky-maps show the flux of photons observed for each direction, and they are made using Galactic coordinates, with the Galactic Centre (GC) in the middle of the plot (see also figure 2.9).

Also, at infrared wavelengths, cooler, redish stars which do not radiate in visible light show up. At longer infrared wavelengths, the dust is no longer transparent and cold clouds of gas and dust become visible [Glass, 1999]. Examples of infrared telescopes include ESA's Herschel Space Observatory and the DIRBE experiment aboard NASA's COBE satellite, which was used to produce the top left sky-map in figure 1.3.

DIRBE: Diffuse InfraRed Background Experiment

COBE: COsmic Background Explorer

The bottom left sky-map in figure 1.3 shows a sky-map in X-rays (with energies from 0.1 keV to 0.3 keV) produced by the ROSAT satellite [Snowden et al., 1995]. The sky-map looks completely different than the infrared and visible sky-maps. Most of the emission actually comes from outside the Galactic plane. The low flux of X-rays from the Galactic plane is caused by the efficient photoelectric absorption of X-rays at these energies by

*ROSAT: short for Röntgensatellit, named after Wilhelm Röntgen (*1845; †1923).*

neutral hydrogen [McCammon and Sanders, 1990]. This form of hydrogen is located mainly in the disk of our Galaxy. The strongest emission comes from the Vela pulsar (the big white dot on the right side in the X-ray sky-map). X-ray satellites currently in orbit are, among others, NASA's Chandra X-ray Observatory and ESA's XMM-Newton.

XMM-NEWTON: X-ray Multi-mirror Mission - Newton

Photons that are even more energetic than X-rays are called γ-rays and are produced by objects such as supernova explosions, pulsars like the one in the Vela constellation and blazars. The γ-ray sky-map (shown in the bottom right in figure 1.3), created by the LAT instrument of the Fermi Gamma-ray Space Telescope using 5 years of data, looks again similar to the infrared and optical sky-maps. The Galactic plane is clearly visible, which is caused by the interaction of high energy charged particles (cosmic rays (CRs), see next section) with the interstellar matter in the Galaxy. Another bright source of γ-rays is the Cygnus region (located on the left of the Galactic centre). This signal is a combination of several pulsars and cosmic rays interacting with the matter present in the Cygnus region [Abdo et al., 2007; Ackermann et al., 2012a]. Besides the earlier mentioned Vela pulsar (which is also a strong source in γ-rays), the famous Crab pulsar is visible (located on the right end of the picture, slightly below the Galactic plane).

Blazars are galaxies which, like quasars, have an extremely bright central nucleus containing a supermassive black hole.

LAT: the Large Area Telescope, the main instrument aboard the Fermi satellite.

The supernova explosion that created the Crab pulsar was widely observed on Earth in 1054.

It should be noted that although the γ-ray sky-map looks similar to the optical sky-map, there is an important difference. In the optical sky-map, the sources outside of the Galactic plane are mostly stars in our own Galaxy, while in the γ-ray sky-map they are mainly extragalactic sources, such as blazars. Blazars are an important field of research in astronomy, since they can for instance be used to study the environment in which high-energy γ-rays travel [Aleksić et al., 2015].

Recently, some interesting new features were discovered in the Fermi data: two giant γ-ray bubbles extending 50° above and below the Galactic centre and with a width of about 40° [Su et al., 2010]. They are now called the Fermi bubbles, and are almost not visible in the γ-ray sky-map, but show up at higher photon energies, see also section 2.3. The mechanism creating these bubbles is not known yet.

1.1 THE ADVENT OF ASTROPARTICLE PHYSICS

Before 1912 the general consensus was that the ionisation of the air was a consequence of radiation of radioactive elements in the Earth's crust. This would imply lower ionisation rates for higher altitudes, since the emitted photons would be absorbed by the air. To test this hypothesis, Victor Hess embarked on seven balloon flights carrying three enhanced-accuracy Wulf electrometers. Instead of finding a uniform decrease, he found that the intensity of the radiation at his highest obtained altitude (about 5 km) was a factor of about 2 higher than at ground level [Hess, 1912]. From this he concluded that there was a "radiation of great penetrating power" entering our atmosphere from outside. He ruled out the Sun as a source by also performing measurements at night-time and during an eclipse. For his discovery, Victor Hess obtained the Nobel Prize in physics in 1936.

*Victor Francis Hess: *1883; † 1964*

Hess's discovery marked the birth of the field of astroparticle physics and the so-called cosmic rays were studied extensively. In the late 1930s Pierre Auger measured coincidences between Geiger counters over 300 metre apart and concluded that they were caused by extensive air showers from cosmic ray interactions with the atmosphere of the Earth. From the size of the air showers he estimated that the energy spectrum of the interacting cosmic rays extends above 10^{15} eV [Auger et al., 1939].

*Pierre Victor Auger: *1899; † 1993*

The extensive air showers are still used to study the highest energy cosmic rays, since big instrumented areas are needed to measure the low fluxes. At energies around 10^{20} eV for instance, the flux of particles is only about 1 event per km^2 per century. Examples of experiments are the Telescope Array Project in Utah, USA and the Pierre Auger Observatory in Argentina. The latter has a detection area of about $3000\,\mathrm{km}^2$ [Abraham et al., 2004]. These experiments are hybrid detectors consisting of a large number of surface detectors and some fluorescence telescopes. The surface detectors measure the interaction products of the cosmic rays that reach the ground. The fluorescence detectors measure the air fluorescence light emitted by the shower in the air.

The cosmic rays are mainly composed of nuclei (99%), consisting of protons (about 85%) and α-particles (the nucleus of the helium atom, about 12%), with elements of $Z \geqslant 3$ making up only about 3% [Grupen, 2005]. The remaining fraction of the cosmic rays consists mostly of electrons, and a very small part is made up of positrons and antiprotons [Beringer et al., 2012].

The origin of cosmic rays is still unknown. It is thought that cosmic rays with energies lower than 10^{10} eV are mostly produced by the Sun, since the solar wind acts as a shield for protons from outside of the solar system at those energies [Anchordoqui et al., 2003]. Cosmic rays with energies up to 10^{18} eV are thought to be of Galactic origin, with supernova remnants being the

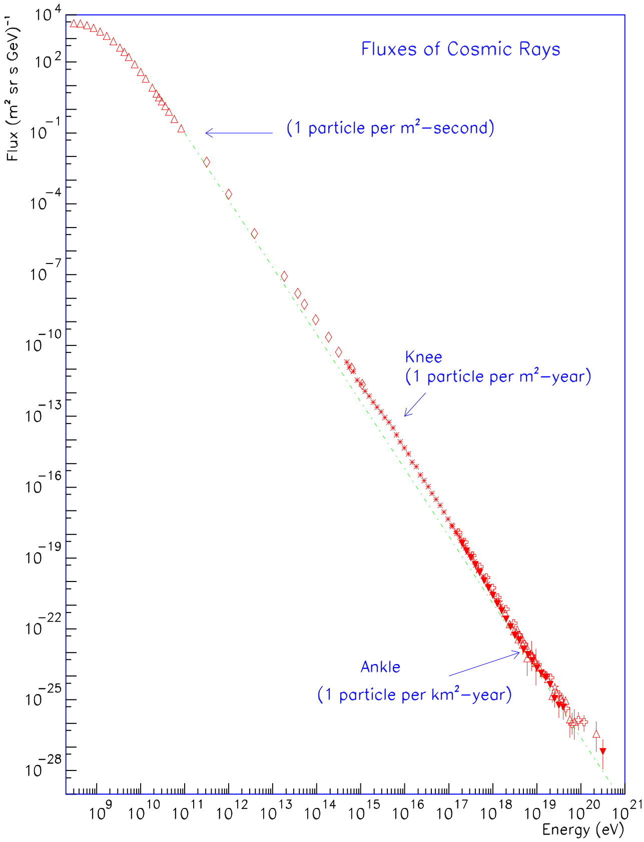

Figure 1.4: The cosmic ray energy spectrum, showing the knee and the ankle. Figure reproduced from Anchordoqui et al. [2003].

main producers. The so-called *knee* in the cosmic ray spectrum (see figure 1.4) is thought to be a combination of two factors, namely [Beringer et al., 2012]:

A. Most cosmic accelerators have reached their maximum energy.

B. Leakage of cosmic rays from the Milky Way.

Cosmic rays with energies above 10^{18} eV are thought to be of extragalactic origin.

So far, no sources of cosmic rays could be uniquely identified, which is partly due to the fact that cosmic rays are charged particles. This causes the cosmic rays to be deflected by the (extra)galactic magnetic fields, so that they do not point back to their source. Only at the highest energies (above 10^{19} eV) are cosmic rays not significantly deflected, although this depends on the charge of the particle. An iron nucleus at this energy will still be substantially deflected [Grupen, 2005]. If sources, either Galactic or extragalactic, are identified, it would give information concerning the physical processes taking place. More information about cosmic rays and their candidate sources can be found in section 2.1.4.

Neutrinos

Cosmic rays are not the only particles studied in astroparticle physics. Another particle, which recently opened a new window on the universe, is the neutrino. Neutrinos are not charged and interact only very weakly with matter, making them the perfect cosmic messenger since they can be used to probe the interior of their source, travel in a straight line and are not absorbed on their way to the Earth.

IMB: Irvine-Michigan-Brookhaven detector

The first cosmic neutrinos were measured by the Kamiokande and IMB experiments in 1987 [Hirata et al., 1987; Bienta et al., 1987]. The neutrinos were created by the supernova explosion of the blue supergiant Sanduleak, which created an estimated total of 10^{58} neutrinos [Hirata et al., 1987]. Even though only 20 neutrinos have been observed (12 by Kamiokande and 8 by IMB), some interesting astrophysical conclusions can be drawn. It allowed the estimation of the energy of the supernova explosion and also has been used to set a limit on the neutrino mass [Arnett and Rosner, 1987].

One of the advantages of using neutrinos as cosmic messengers is the fact that they only interact very weakly with matter. This is, however, also their main disadvantage. Since the neutrinos interact very weakly, they are very hard to detect, as the numbers above also illustrate. For this reason, huge instrumented volumes are needed. Neutrino telescopes, which use neutrinos in the same way as traditional telescopes use light, make use of one of two detection media: water or ice. The medium is used to measure the interaction products of the neutrino interactions, which generally emit Čerenkov light. Neutrino telescopes are different from normal telescopes, in that they look down through the Earth instead of up at the sky. This is done to reduce the main background, which consists of muons created in the air showers discussed before. These muons cannot traverse the Earth; the only particle that is able to this is the neutrino.

The first initiative to build a neutrino telescope was the DUMAND project [Hanada et al., 1998], which was planned to be located in the water off the coast of Hawaii. In December 1993 the first string with PhotoMultiplier Tubes (PMTs, used to measure the Čerenkov light) was deployed, but after just 10 hours of operation a leak occured, resulting in short circuits. In 1996 the funding was stopped, which lead to the cancellation of the project.

DUMAND: Deep Underwater Muon And Neutrino Detection

The first working neutrino telescope was the Baikal neutrino telescope [Aynutdinov et al., 2006]. It is located in the southern part of the Siberian lake Baikal, which is the deepest fresh water lake in the world. The first stage, called NT200, was completed in 1998 and consists of 8 strings with in total 192 PMTs. The strings are arranged in an umbrella-like frame and are located at a depth of about 1100 m. In 2005 the setup was extended by the deployment of 3 additional string placed 100 m from the centre of NT200. This upgraded setup is called NT200+ and increased the sensitivity of Baikal by a factor of about 4. Currently the Baikal neutrino telescope is still operating, and the collaboration is working on a successor called GVD, which will consist of several NT200 building blocks [Avrorin et al., 2011].

GVD: Gigaton Volume Detector

The AMANDA experiment [Andres et al., 2000] is the first neutrino telescope built in ice. It has been build near the Amundsen-Scott South Pole Station and construction of the final phase, called AMANDA-II [Wischnewski, 2002], was completed in 2000. The detector consisted of 677 PMTs distributed over 19 strings, located 1500 − 2000 m below the Antarctic ice. In 2005 it stopped operation and was succeeded by the IceCube neutrino telescope [Halzen and Klein, 2010], which is constructed at the same location. IceCube consists of 5160 PMTs deployed on 86 strings located at a depth from 1450 to 2450 metre. IceCube is currently the largest neutrino telescope in the world, encompassing a cubic kilometre of ice. Being located at the South Pole, the complete Northern sky is visible for 100% of the time.

AMANDA: Antarctic Muon And Neutrino Detection Array

The first operational undersea neutrino telescope is the ANTARES detector, located in the Mediterranean Sea off the coast of France at a depth of 2475 metre [Ageron et al., 2011]. It consists of 12 strings, the last of which was connected in 2008, and a total of 885 PMTs. Since the ANTARES detector is located in the Northern Hemisphere, it has a high visiblity of the Milky Way and the Galactic centre. The ANTARES experiment will be discussed in greater detail in chapter 3.

ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch

The successor of ANTARES, called KM3NeT , has recently completed its qualification phase with the deployment of a prototype

KM3NeT: KiloMetre cubed Neutrino Telescope

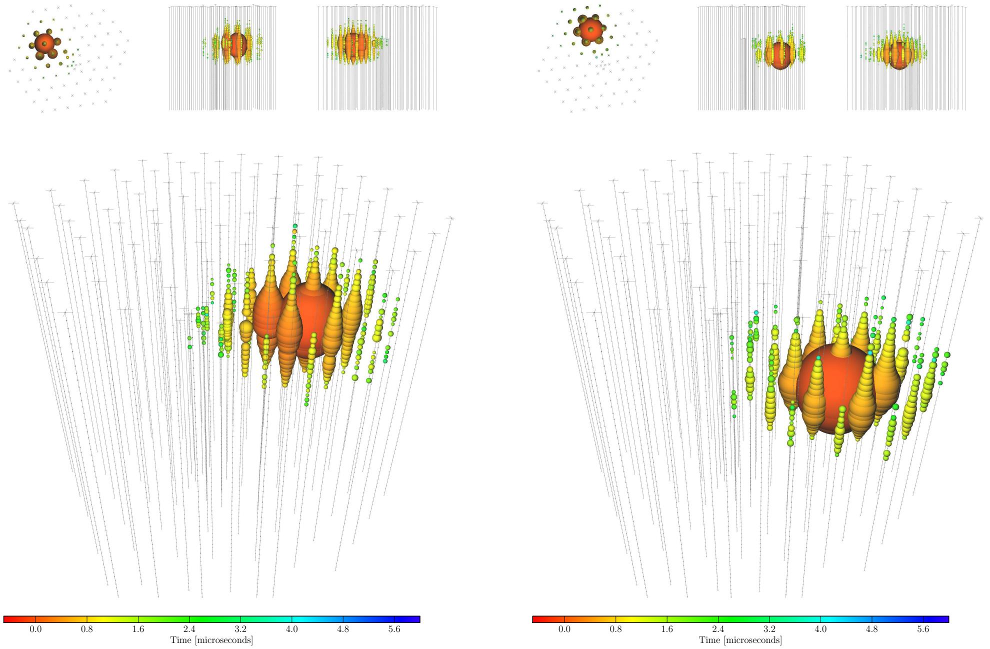

Figure 1.5: The first two PeV-energy neutrinos measured by IceCube. Figures reproduced from Aartsen et al. [2013b]. LEFT: "Bert", with an energy of (1.04 ± 0.16) PeV. RIGHT: "Ernie", with an energy of (1.14 ± 0.17) PeV.

detection unit in the night from the 6th to the 7th of May 2014. The plan of the KM3NeT collaboration is to build a neutrino telescope with an instrumented volume of about $5\,\mathrm{km}^3$ distributed over three sites in France, Greece and Italy. More information about KM3NeT can be found in chapter 6.

One of the scientific goals of neutrino telescopes is to find point sources of neutrinos. The observation of neutrinos from a source would also tell where cosmic rays are accelerated [Grupen, 2005]. There are several source candidates, such as SNRs and AGNs, but no sources have been found yet. For a recent overview see Bogazzi [2014]. Other analyses include searches for a diffuse flux [Aguilar et al., 2011b] and searches for neutrinos from dark matter annihilation in, for instance, the Sun [Lim, 2011].

SNR: SuperNova Remnant, the structure resulting from a supernova explosion.

AGN: Active Galactic Nucleus, the centre of a galaxy hosting a supermassive black hole. Blazars and quasars are types of AGN.

Recently two extremely high energy neutrinos have been observed by the IceCube detector [Aartsen et al., 2013a], corresponding to a 2.8σ excess. The events were named after muppet characters from the children's television show *Sesame Street*, see figure 1.5. These events, which have an energy around one PeV, were the highest energy neutrinos ever measured at the time. Using a more sensitive analysis, 26 more events have been found [Aartsen et al., 2013b], increasing the significance to about 4σ. Recently, the analysis has been updated with one more year of data, finding in total 37 events (including a third PeV neutrino) where 15 ± 7.2 background events are expected, giving a significance of 5.7σ [Aartsen et al., 2014]. This marks the discovery of the first high-energy cosmic neutrinos and the birth of neutrino astronomy.

Most of the events are so-called shower events, in which the neutrino interaction creates a hadronic and/or electromagnetic shower (see chapter 3 for more details). These events have a poor angular resolution, making it difficult to pinpoint their origin. Because of this, the source of these cosmic neutrinos is unknown at the time of writing, and a wide range of explanations have been brought forward. These range from Galactic sources, such as the Fermi bubbles [Lunardini et al., 2013] to extragalactic sources such as AGNs [Waxman, 2014]. See Anchordoqui et al. [2014] for a nice overview.

1.2 THESIS GOALS AND STRUCTURE

This thesis will focus on neutrinos created by cosmic ray interactions with the interstellar matter in the Milky Way. This signal of neutrinos is guaranteed, since both cosmic rays and the interstellar matter are known to exist and the corresponding diffuse γ signal has been observed [Ackermann et al., 2012b]. Measuring this diffuse Galactic neutrino flux will open a new view on our Galaxy and can give better insight into the cosmic ray and matter distribution in our Galaxy.

So far, only an upper limit on the diffuse Galactic neutrino flux is published, which has been set using the AMANDA-II detector. This experiment has measured the number of neutrinos coming from a region extending 4.4° above and below the Galactic plane and extending from 33° to 213° in Galactic longitude [Kelley et al., 2005]. This longitude range has been used, since it is the part of the Galactic plane which is visible from the South Pole. The advantage of a neutrino telescope in the Mediterranean Sea is that the inner Galactic plane is visible, from which the highest signal is expected (see also the γ-ray sky-map in figure 1.3).

The flux upper limit obtained by AMANDA-II is:

$$\Phi_{\nu_\mu+\bar{\nu}_\mu} < 4.8\, E_\nu^{-2.7}\, \mathrm{GeV}^{-1}\, \mathrm{m}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{s}^{-1}, \tag{1.1}$$

in the energy range from 0.2 TeV to 40 TeV, with E_ν the neutrino energy in GeV. IceCube has not published any updates of the

AMANDA-II analysis so far and according to Tchernin et al. [2013] it will take IceCube around 20 years to detect the neutrino flux of cosmic ray interactions in the Cygnus region. Other parts of the Galactic plane will require even longer exposures.

It is interesting to note that the most recent parameterisation of the flux measured by IceCube [Aartsen et al., 2015] gives a best-fit spectral index that is close to that expected from the diffuse Galactic neutrino flux and is softer than that typically expected from neutrino point sources [Waxman and Bahcall, 1998]. The neutrino flux measured by IceCube could thus be caused by the interaction of cosmic rays in our Galaxy. For instance, Neronov et al. [2014] propose that they are created by a multi-PeV cosmic ray source at the edge of the Norma arm/tip of the Galactic Bar, which could also explain the arrival directions of the neutrinos observed by IceCube. However, other theoreticians discard this hypothesis and point out that the matter density in our Galaxy is about a factor of 100 too low to explain the IceCube flux [Joshi et al., 2014; Kachelrieß and Ostapchenko, 2014]. The possible origin of the IceCube signal will be discussed in more detail in section 5.4.1.

This thesis will be organised as follows. In chapter 2 different models are described to estimate the diffuse Galactic neutrino flux. Two ways to determine this neutrino flux are presented: using theoretical models and using the γ-ray measurement performed by the Fermi satellite. The signal is also compared to the background, which for neutrino telescopes consists mainly of atmospheric neutrinos (which are produced by cosmic rays interacting with our atmosphere).

The ANTARES neutrino telescope, used to perform a measurement of the diffuse Galactic neutrino flux, is introduced in chapter 3. ANTARES is well suited to perform this measurement, since it has a high visibility of the Galactic plane. Several algorithms used to select interesting physics events, as well as the reconstruction strategies currently available within ANTARES, will be described in more detail in chapter 4.

The analysis follows the flow of defining an *on-source* region (a rectangular area centred around the Galactic centre) and a number of comparable *off-source* regions (which are used to obtain an estimate of the background from the data). The number of events from the *on-source* and *off-source* regions are then compared to detect a possible signal.

The Galactic plane region is in any case an interesting region to consider, since besides the diffuse neutrino emission considered here, also sources reside there that are expected to emit neutrinos.

For example, the flux measured by IceCube could also be caused by these sources. The measurement can thus give an idea of the total number of neutrinos (diffuse and otherwise) that originate from the Galactic plane. In chapter 5 the analysis and the optimisations performed to remove the background are described in detail and the results are presented. Furthermore, the results are discussed, also in light of the flux measured by IceCube.

Chapter 6 gives a description of the next generation neutrino telescope, KM3NeT. In this chapter the sensitivity and discovery potential of KM3NeT for the diffuse Galactic neutrino flux are presented.

Finally, the conclusions and outlook are presented in chapter 7.