Universiteit van Amsterdam

Enlightening the Dark. Exploring the Dark Sector with Gamma-Rays and Neutrinos
L.B. Klop

Popular Summary

Everything that you see around you, including yourself, is build up from molecules, which, in their turn, are build up from atoms. Atoms again can be divided into protons and neutrons, that make up the nucleus of an atom. Protons and neutrons consist of quarks, which are elementary particles. Elementary particles are the smallest particles possible, of which all matter is made up. The protons and neutrons in the nucleus are surrounded by electrons, which we also know from, for example, the electricity in our houses. Another particle that everybody knows of, is the photon, the light particle. But there are also particles that are less famous, but still present in immense amounts: for example, about 45 trillion neutrinos coming from the sun are crossing your body every second! Neutrinos are light-weighted neutral particles, that travel almost with the speed of light. They are produced in astrophysical sources, such as the Sun and other stars, but also in nuclear reactions at Earth. Neutrinos exist in three distinct flavors: electron neutrinos, muon neutrinos and tau neutrinos. The special thing about neutrinos is that they usually are a combination of these three flavors, which continuously changes during their journey. So, a neutrino starting as an electron neutrino, could be a tau neutrino at some later point. We call this *neutrino oscillation*. Some particles are not stable enough to appear on Earth under ordinary circumstances. To investigate these particles, scientists use enormous particle accelerators to try to create similar circumstances as those during the early Universe. This way, the Higgs particle was discovered a few years ago, which gives the other particles their masses. All these particles, and some others that I did not mention, are described in the Standard Model of elementary particles.

However, the matter described by the Standard Model, which is so ordinary to all of us, is actually quite special. It turns out that this ordinary matter makes up only 20% of the total matter in the Universe. We do not know what the other 80% is made of! We call this unknown matter *Dark Matter*. One of the indications for the existence of dark matter, are the rotation curves of galaxies. The stars in a galaxy orbit its center, where often a black hole is located, like for example in our own Milky Way. According to Newton's laws of gravity, the stars located more in the outer regions of the galaxy should orbit on a slower speed around the center than stars located more in the inner regions. However, from observations it turned out that this orbital velocity stays constant. The stars in the outer regions orbit that fast, that according to the laws of gravity they should actually swing out of orbit. Since that does not happen, scientists think that we do not observe all the matter that is in there, but that there is some invisible matter present as well, keeping all the stars together.

Scientists try to find out what this dark matter is actually made of. One of the most popular ideas is that this dark matter consists of WIMPS, *weakly interacting massive particles*. These are particles that only undergo interactions with other particles in the SM very weakly, and therefore they are difficult to observe. If these particles are their own antiparticles, they could annihilate with themselves. This means that they cancel each other out, in which energy and other particles are released which we are able to observe. One method to observe dark matter is through *indirect detection*, in which we look for this released particles. The particles that we look for are gamma-rays, photons in a specific energy range, and neutrinos. We look for these particles by aiming detectors and telescopes at the sky in the direction that we suspect to comprise a lot of dark matter. This is for example the case in the center of the Milky Way, but also in the so-called *dwarf spheroidal galaxies*. Dwarf spheroidal galaxies are satellite galaxies of the Milky Way: small galaxies that orbit our own galaxy. There is only little star-activity in these galaxies, while they are quite heavy in mass. Therefore we think they contain a lot of dark matter, which make them very suitable to search for dark matter using indirect detection. We use the detectors to look for gamma-rays and neutrinos coming from the direction of such a dwarf system. If we detect more of such particles than we expect based on other astrophysical processes, this could mean that we detected the particles that were released in annihilations of dark matter. Unfortunately this did not yet clearly happen. When no dark matter is observed, we can modify our image of the precise properties of the dark matter particle, such as its mass and the *cross section* of dark matter annihilation. The cross section tells us how likely it is that two dark matter particles that come across actually annihilate. Scientists have an idea of this likeliness and calculate the amount of gamma-rays or neutrinos that we would expect to see. If we do not see this calculated amount, we need to adjust this likeliness to some lower value. This way we put upper limits on the possible value of the cross section.

In the research that I performed for this thesis we also contributed to the indirect detection in dwarf galaxies. In chapter 2 I describe our research on dark matter in seven dwarf galaxies. To be able to search for dark matter, it is important to know how it is distributed. In most analyses of dwarf galaxies the so-called *NFW model* is being used to describe the dark matter density distribution. In this model the distribution of dark matter is spherical of shape. Its density is very large in the center of the sphere and decreases very steeply towards the outer parts. This model is a universal model, determined by putting all galaxies on one big pile. This turns out to be a very good approximation, but of course it is more precise to determine the dark matter distribution for every individual galaxy separately. When you do this it turns out that the dark matter distribution in most galaxies looks more like a rugby ball than like a perfect sphere. Furthermore, the density is much shallower in the center. We studied gamma-rays coming from the direction of seven dwarf galaxies and looked for signs of dark matter. We did this for both the NFW profile and the customised profile. We did not find any signs of dark matter and put limits on the dark matter annihilation cross section. We find that the limits on the cross section determined with the customised profile are weaker than the limits determined using a NFW profile. This means that up til now, scientists adjusted the possible value of the likeliness that two dark matter particles annihilate to a lower value than one is actually allowed to.

While we looked for gamma-rays possibly coming from dark matter in chapter 2, in chapter 3 we looked for neutrinos coming from dark matter. Recent results of an experiment studying the gas during the early Universe imply that this gas was much cooler than expected. Scientists think that this is due to interactions between the gas and dark matter particles, resulting in the cooling of the gas. Other particles were too energetic in this period: interactions between these particles and the gas would result in the heating of the gas instead. More research on this explanation taught us what conditions these dark matter particles need to fulfil. To be able to explain the cooling of the gas, the dark matter particles need to be relatively light (about thousand times lighter than the mass that we usually expect), and they could only make up 2% of the total dark matter in the Universe. Furthermore, their cross section needs to be of a certain value. We investigated a dark matter model that fulfils these conditions, in which dark matter can only annihilate into muon- and tau neutrinos. We calculated how many neutrinos we would expect to detect on Earth, coming from the annihilation of this type of dark matter in both the Milky Way and outside. Thereafter we analysed about ten years of data from the neutrino detector Super-Kamiokande and put limits on the annihilation cross section. The limit is not strong enough to exclude the dark matter model. Therefore we also predicted the limits that we could obtain using several future experiments, which are larger and more sensitive than Super-Kamiokande. It turned out that these future experiments are also not able to exclude the dark matter model using ten years of data, but they might be able to do this when they run for a long enough time. We also found that a hypothetical experiment with the size of Hyper-Kamiokande (the successor of Super-Kamiokande) and the specifications of JUNO (another future experiment) would probably be able to exclude the model. We also determined the limits on the cross section in the case of a more general light dark matter model, in which it makes up the entire 100% of the dark matter in the Universe and annihilates into all three neutrino flavors.

In chapter 4 we did not study dark matter. Instead we studied another subject in the dark sector: *dark energy*. This is the name for the energy driving the expansion of the Universe. This could be a constant, the cosmological constant, but it could also be a scalar-field that varies over space and time. In the latter case this could have an effect on neutrino oscillation. Like explained earlier, during their journey the neutrinos can change flavor. Every flavor neutrino has some probability to, after some distance, turn into a neutrino of another flavor. When a neutrino travels through matter this probability differs from the probability when a neutrino travels through vacuum, due to possible interactions between neutrinos and the particles in the matter. A similar effect could arise between neutrinos and dark energy. Neutrinos are produced in astrophysical sources with the ratio of one electron neutrino to two muon neutrinos to no tau neutrinos. Under normal circumstances we would measure, after neutrino oscillation, the ratio of one electron neutrino to one muon neutrino to one tau neutrino at Earth. When the neutrino oscillations get affected by physics that we not yet know of, the measured flavor ratio at Earth could deviate from the expectation. We determined the effect on this flavor ratio of a coupling between dark energy and neutrinos. In case we measure a flavor ratio at Earth that is not compatible to the expected ratio, this could be due to this coupling. Furthermore, the expansion of the Universe has a preferred direction: it goes outwards in all directions. This means that the effects on neutrino oscillation also have a directional dependence. We also studied this directional dependence. The effects we found are so small that it is not possible to observe them with the current neutrino telescopes. However, the observation of this directional dependence would be the smoking gun for the existence of a dark energy-neutrino coupling.