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1 | Introduction

1.1 The Case for Dark Matter

The first time the existence of Dark Matter was formulated as such was by Zwicky (1933), in order to explain the large discrepancy observed between the velocities of members of the Coma galaxy cluster and the amount of luminous matter present that could induce those velocities. One of the most important bodies of work that led to the common acceptance of Dark Matter as a phenomenon was that regarding the rotation curves of spiral galaxies. As early as the 1940's (Oort, 1940) it was observed that galaxy rotation curves tended to flatten out towards the outskirts and the mass-to-light ratio increased dramatically, and by the 1980's the influential work of e.g. Rubin et al. (1980) had firmly established this line of reasoning.

Currently, the existence of Dark Matter is a well established astrophysical phenomenon and is one of the components of the ΛCDM standard model of cosmology. In that framework, only 6 parameters are required to accurately describe the expansion history of the universe, the cosmic microwave background, the primordial elemental abundances and the formation of the large scale structures of the universe. It tells us that the total energy density of the Universe at current times consists of only about 5% known matter, 70% Dark Energy (denoted by Λ and responsible for the accelerated expansion of the universe although its nature is completely unknown) and 25% of Dark Matter.

Not only in the spiral galaxies that were mentioned above, but in all types of galaxies the presence of Dark Matter is required to explain the dynamics of stars and gas, from the dwarf satellites of the Milky Way, to the largest of elliptical galaxies (Corbelli et al., 2010; Dekel et al., 2005; Bertone et al., 2005; Walker, 2013).

In clusters of galaxies, the dynamics of the member galaxies (measured by their velocity dispersion) imply very large mass-to-light ratios in a similar fashion to the stellar dynamics in elliptical galaxies. This argument is strongly corroborated by X-ray observations. The gas trapped by the gravitational well of the galaxy cluster becomes a very hot plasma, balancing internal thermal pressure and the forces of gravity. The X-rays this plasma emits depend on its temperature and its density, which in turn also depend on the total gravitational mass. It has been shown that the density of the emitting plasma can only account for about 15% of the total gravitational mass required to induce the high temperature and high emissivity observed (e.g. Vikhlinin et al., 2006).

Studies of the large scale structure of the universe all show that Dark Matter is required for the structures that we observe to have been able to form. This is usually expressed through the matter power spectrum, which describes the amount of clustering on a particular length scale. It is possible to measure the matter power spectrum through various techniques, such as galaxy redshift surveys (e.g. Colless et al., 2001), with the Lyman-alpha forest (Viel et al., 2004), and gravitational lensing cosmic shear surveys (e.g. Kaiser, 1992; Hoekstra & Jain, 2008). These measurements can be compared both to analytical descriptions of the power spectrum at different redshifts based on the theory of gravitational collapse (Press & Schechter, 1974), and to large cosmological simulations (e.g. Springel et al., 2005). In all cases, the observations and the theory (analytical or from simulations) require Dark Matter in order to be consistent (Frenk & White, 2012).

Measurements of the Cosmic Microwave Background (CMB) radiation have been instrumental for our understanding of cosmology in general, but regarding the Dark Matter it is also one of the strongest single pieces of evidence. The fluctuations in the otherwise homogeneous CMB sky are caused by acoustic oscillations of the primordial hot plasma frozen at the moment the plasma recombined. The oscillations were originally seeded by quantum fluctuation that generated small under- and over-densities, which started growing. The potential wells attracted plasma and radiation, which produced its own internal pressure to counteract gravity (Hu & White, 1996; Bennett et al., 2013). This back-and-forth depends on the amount of gravitating matter and the amount of pressure-generating particles. The fluctuations in the CMB at different scales encode information about the scales of the under- and over-densities, and in which phase of the oscillation they existed at recombination (the moment the universe became transparent, and the CMB was emitted). This information is extracted from the statistics of these fluctuations and it indicates that most of the gravitating mass was not producing any internal pressure, and can therefore not be any known form of matter.

In addition to the above, there are also experiments that confirm not necessarily the existence of Dark Matter directly, but rather some of the other ΛCDM-parameters and thereby indirectly the Dark Matter by requiring consistency across observations.

One of these is Big Bang Nucleosynthesis (BBNS), the process by which the first atomic nuclei form out of the primordial plasma, between roughly 1 and 3 minutes after the Big Bang. Although Dark Matter itself does not influence the processes, the abundances of the various elements at the end of BBNS is determined among other things by the density of the baryons participating in the process. By comparing the BBNS calculations with observations of the primordial abundance of the light elements, it was determined that the baryons can only contribute about 5% of the total mass-energy budget of the universe (Dar, 1995; Olive et al., 2014, chap. 23).

The expansion of the universe depends on the content of the universe through the laws of General Relativity, namely the energy density of all gravitating mass and that of Dark Energy (also that of radiation in the early Universe). The expansion of the universe has been measured with Type 1a Supernovae up to high redshift (Kowalski et al., 2008), and together with the CMB is able to constrain both the total mass and the Dark Energy density (about 30% and 70% respectively). Coupling this result to, for example, the results of the

BBNS, the conclusion is that 25% of the universe has to consist of Dark Matter.

Strikingly, the varied and independent evidence described above doesn't just indicate the existence of Dark Matter, they all indicate the *same abundance* of Dark Matter.

1.2 The Nature of the Dark Matter

1.2.1 Known Properties

Although most of the properties of the Dark Matter remain unknown, there are a number of characteristics that it must have that are currently known.

First of all, the Dark Matter can not be made up of any known, baryonic, matter. Although this argument has been touched upon in the previous section, it is important to acknowledge it explicitly. The study of the Bullet Cluster (Markevitch et al., 2004; Clowe et al., 2006) is famous for showing that the baryonic matter and the bulk of the gravitating mass do not spatially coincide. Most of the baryonic matter in galaxy clusters is in the form of hot X-ray emitting plasma and can be mapped using X-ray observations. The Bullet cluster is an ongoing merger of two galaxy clusters, where the cluster cores haves crossed once already. The hot plasmas of both clusters collided with each other, causing observable shock-fronts. The total gravitational mass can be mapped using gravitational lensing techniques, which do not distinguish between any dynamical or internal states of the gravitating mass, as long as it gravitates. This comparison showed that the bulk of the clusters' mass had passed right through each other without interacting (colliding). This is not only evidence for the existence of Dark Matter, but also that it does not interact with itself nor with normal baryonic matter.

The caveat that must be made with the Bullet cluster study is that on its own, it leaves open the possibility that the Dark Matter consists of very compact objects of baryonic matter. If they are compact enough, their number density can be small enough that they hardly interact with each other, and are practically unobservable in any direct manner. This kind of Dark Matter is commonly referred to as MACHOs, Massive Compact Halo Objects. However, this possibility is precluded by micro-lensing studies that have specifically studied the existence of these MACHOs by counting the number of events in which a heavy, compact, dark object passes in front of a star and thereby changes its flux and light curve due to gravitational lensing effects (Alcock et al., 2000; Tisserand et al., 2007; Moniez, 2010). The CMB also rules out any baryonic interpretation of the Dark Matter, as described in the last Section.

Secondly, then, if the Dark Matter is some non-baryonic particle, it must be dark, pressure-less, and non-selfinteracting up to a large extent. As was described, the Dark Matter must not participate in the acoustic oscillations that are inscribed onto the CMB, and it must not influence the BBNS. Interaction with the electromagnetic forces would violate both these conditions, hence it is *dark*. Any considerable self-interaction would contradict the results from the Bullet Cluster.

Thirdly, some restrictions on the Dark Matter particle mass exist. If the particles are fermionic, they have to comply by the Pauli-exclusion principle – essentially setting a maximum phase-space density. It has been found that in dwarf galaxies, this principle would be violated if 100% of the Dark Matter is in the form of particles that are lighter than a few hundred eV, known as the Tremaine-Gunn bound (Tremaine & Gunn, 1979).

Another lower bound on the Dark Matter particle mass, whether it is fermionic or not, comes from structure formation. The velocity distribution of the Dark Matter particles suppresses the gravitational collapse of overdensities below a certain scale, known as the free-streaming length. Since Dark Matter can not cool by radiating energy, an overdensity cannot collapse further than the thermal velocities allow. Structures of a small enough scale are washed out in this manner. The scale below which this happens is set by the particles' (distribution of) velocities, which, if they are produced from the primordial plasma, tend to follow thermal or near-thermal spectra according to their mass; lighter particles have higher velocities. This property can be used to classify particles as being either *hot* or *cold* Dark Matter, where cold Dark Matter becomes non-relativistic (due to the expansion of the universe) before matter-radiation equality, and hot Dark Matter only becomes non-relativistic very late into the matter-dominated epoch. It has been found from cosmological structure formation simulations that hot Dark Matter produces top-down formation of structures, ie., large scales collapse first and then fragment into smaller objects during the expansion of the universe. This is opposite to the behaviour that is observed, where small scales form first to later merge into larger objects, the so-called hierarchical scenario. This rules out hot, and therefore light, Dark Matter (Bertone et al., 2005). A grey area exists in between hot and cold Dark Matter, called *warm*, where current state-of-the-art cosmological measurements and simulations still allow for a particle as light as a few keV (Lovell et al., 2013; Garzilli et al., 2015).

Note that the conditions described above also rule out standard model neutrinos. Although neutrinos are indeed non-baryonic and electrically neutral, their masses are constrained to be at the eV scale or below from both detector and cosmological experiments (Komatsu et al., 2011; Olive et al., 2014). In addition, the relic number density of neutrinos (those having been produced during the early universe) is known, which would require neutrino masses of order 10 eV in order to explain 100% of the Dark Matter (Lesgourgues & Pastor, 2006).

Lastly, the Dark Matter must be stable or at least cosmologically long-lived, and it must have been produced in the early universe in the right quantities.

1.2.2 Dark Matter Candidates

Many explanations for the Dark Matter have been put forward over the years. A limited selection will be discussed in this section.

There are a few theories that attempt to explain the phenomena associated with Dark Matter by modifying the laws of gravity. These include MOND (Milgrom, 1983), TeVeS (Bekenstein, 2004), and various modifications of General Relativity. These modified gravity theories can typically explain observations without the need for Dark Matter in some cases but not in others. For example, both MOND and TeVeS can explain galaxy rotation curves quite well by invoking a pivot scale in the acceleration. However, they fail to explain the physics of galaxy clusters without resorting to extra hidden mass after all. For discussion see f.e. Dodelson (2011); Moffat & Toth (2011) and for a review Sanders (2014) . Regarding the other pillars of the ΛCDM cosmology, the expansion history of the Universe is compatible with many modified gravity theories (due to a certain amount of freedom in those theories, the expansion is not a strict prediction), although the CMB and structure formation are a matter of intense debate hampered by the limited resources that are available for large scale simulations of modified gravity theories (Famaey & McGaugh, 2012).

There is no experimental nor theoretical reason that dictates that Dark Matter *can not* be a particle, nor that it *should* be a particle. However, the predominant class of explanation is the particle explanation, where Dark Matter is some kind of as-yet undiscovered particle, since this is extremely plausible. The Standard Model (SM) of particle physics is a very successful theory and can describe a huge wealth of physics, but despite that, there are a few so-called 'beyond the standard model' phenomena that it cannot explain and probably require new physics or new particles (Ellis, 2012; Gripaios, 2015). Fortunately, there is plenty of room in the SM for extensions and new particles where the new parameters are such that constraints from current experiments are avoided.

One of the most popular Dark Matter particle candidates is the Weakly-Interacting Massive Particle, or WIMP for short. This is a particle that interacts with the SM with a cross-section at the scale of other Weak interactions. The popularity of this kind of Dark Matter stems from the fact that at this interaction strength, the Dark Matter can be produced at the correct cosmological abundance for a large range of masses (GeV – TeV; Lee & Weinberg, 1977). Many SM particles are lighter than this mass however, meaning that the WIMP would decay to SM particles quite rapidly unless it is prevented from doing so by having a new symmetry charge. Additionally, many extensions of the SM that had been invented to explain other phenomena (e.g. Supersymmetry), naturally include a WIMP-like particle that can play the role of the cosmological Dark Matter. Many experiments, both direct and indirect, have been performed or are being set up to search for these particles. As of yet, no convincing detections have been reported (Baudis, 2013; Conrad, 2014).

Another possible Dark Matter candidate is the Axion. Some experiments for directly detecting Axions are underway, and like some of the WIMP-like particles, the Axion was not originally 'invented' to explain the Dark Matter. It is required to solve a 'beyond the standard model' problem, and it is often considered that the existence of the Axion is almost guaranteed, albeit not necessarily in a form that can be the the cosmological Dark Matter. The problem the Axion would solve, is that of the suspiciously small neutron electric dipole moment, or more generally the lack of observed CP-violating processes in quantumchromodynamics (Peter, 2012). The kind of Axion that could play the role of cosmological Dark Matter is of the order of 10 μeV. Despite its very low mass, it would not be hot Dark Matter (with all the impossibilities that entails) since they would be created with zero momentum.

The so-called hidden sector may theoretically harbour many particles that have no interaction with the SM electroweak or strong interactions. The existence of a hidden sector is an open question, but the possibility is invoked often in the context of constructing a Grand Unified Theory, or to solve another problem in the SM (like the gauge hierarchy problem). In principle, hidden sector particles are uncharged with respect to the SM, but despite that the hidden sector can have many non-trivial effects on SM phenomenology in complicated ways. With plenty of room for new physics, the hidden (sometimes also called dark) sector contains candidates such as the dark photon or asymmetric Dark Matter (Feng & Kumar, 2008; Ackerman et al., 2009; Kaplan et al., 2009).

Many more Dark Matter hypotheses exist than it is possible to cover in this work. In the next Section, we will examine the class of Dark Matter particle that is most relevant to the work in this Thesis.

1.3 Decaying Dark Matter

The general class of candidate Dark Matter particles that has not been covered above is the kind of Dark Matter that is allowed to decay. The work in this thesis relates specifically to this class of Dark Matter, but is otherwise largely model-independent. The Section starts with a description of the expected astrophysical signals from this kind of particle, followed by examples of decaying Dark Matter particle from theory, finally one of which - the sterile neutrino - is discussed in a little more detail.

1.3.1 Signal Properties of Decaying Dark Matter

In general, any decaying Dark Matter particle of fermionic nature with a mass below that of two electrons will have a (sub-dominant) decay channel into an active neutrino and a photon. For bosonic particles, the relevant decay channel will be to two photons. Since both products' masses are negligible compared to the Dark Matter particle, both will carry half the centre-of-mass energy, which is half the Dark Matter particle's mass. This creates a monochromatic spectral line. From considerations regarding the minimum mass of the Dark Matter particle from phase-space density arguments and structure formation (Section 1.2.1) and from previous experiments (Section 1.5.3), this line should be emitted at an energy somewhere in the X-ray regime. The signal will have the following characteristics:

- The energy of the monochromatic line is somewhere in the X-ray regime, at half the Dark Matter particle's mass, redshifted according to the cosmological distance to the source of the decay.
- The width of the spectral line is then only due to velocity broadening of the Dark Matter in a particular object ($\Delta E/E$ roughly between 10^{-2} and 10^{-4} depending on the object).
- The strength of the line is a function of lifetime of the particle, the number of particles in the telescope's field-of-view, and the cosmological distance to the object as follows:
$$F_{DM} = \Gamma_{DM} \frac{M_{FoV}}{m_{DM}} \frac{1}{4\pi D_{lum}^2}$$
with F the detected flux, Γ the decay rate, M_{FoV} the total Dark Matter mass in the field-of-view, m_{DM} the Dark Matter particle mass and D_{lum} the luminosity distance to the object.

1.3.2 Cosmological Effects of Decaying Dark Matter

The properties of Dark Matter have an influence on various areas of astrophysics and cosmology, which is why the existence of the Dark Matter could be deduced, and also provides an avenue for testing indirectly the nature of the Dark Matter, as has been discussed before. To date however, no 'exotic' properties have been established. The measurements are consistent with Dark Matter being cold, having no self-interaction nor interaction with other particles, not annihilating and not decaying (Section 1.2). Limits on these properties have been set though, and there is still a large range of allowed Dark Matter particle candidates with room for currently undetectable exotic properties.

For the specific case of decaying Dark Matter, there are a number of ways that its existence may be tested for indirectly, other that observing its decay products. Conversely, if we know that Dark Matter is of the decaying sort, these are fields that will benefit from this knowledge. Having determined that the decaying Dark Matter mass is likely in keV-regime, this makes the Dark Matter *warm*. The effect of this (see also Section 1.2) is to suppress the formation of small-scale structures. Depending on the exact particle mass and velocity spectrum (linked to its production mechanism), this happens at scales roughly corresponding to dwarf satellite galaxies. This effect can be measured in principle through the power spectrum from Lyman-alpha forest surveys (Garzilli et al., 2015), gravitational lensing, clustering surveys, or a census of the dwarf galaxies of the Milky Way and Andromeda galaxies (Schneider, 2016). In addition, warm Dark Matter is shown to change the mass profiles of dwarf galaxies, making the central densities more cored (Lovell et al., 2012), and modifying the mass-concentration relation (Schneider, 2015). It is currently debated if these effects may be degenerate with baryonic physics and the details of galaxy formation (Weinberg et al., 2013).

1.3.3 Decaying Dark Matter Candidates

The work in this thesis is applicable to any Dark Matter candidate particle that exhibits a signal as described in the section above. Since any potential Dark Matter signal discovered is likely to be discovered at relatively low significance and therefore with large uncertainties, the methods described in this Thesis may also be sensitive (up to a point) to particles that produce X-ray signals with similar but somewhat different behaviour.

The bahaviour described in Section 1.3.1 will be exhibited by any radiative decay process, where the rate is sufficiently independent of prior particle interactions or processes, like slowly decaying or milicharged Dark Matter (El Aisati et al., 2014; Frandsen et al., 2014). Low mass annihilating Dark Matter would show different morphology and scaling between objects since the signal should follow the Dark Matter density squared (Frandsen et al., 2014). Axion or Axion-like particles (ALPs) may decay or convert in magnetic fields, causing an additional scaling with the magnetic field strength (Cicoli et al., 2014; Alvarez et al., 2015; Higaki et al., 2014). Dark Matter that can exist in excited states and therefore emit upon de-excitation, could depend on parameters like the Dark Matter density squared or Dark Matter velocity distribution (Finkbeiner & Weiner, 2014). Additional emission features could also be produced by multi-component or composite Dark Matter, like dark atoms (Cline et al., 2014).

See references in Iakubovskyi (2014) for a more extensive sample of particle models like this.

1.3.4 Sterile Neutrinos

It is informative to describe in a little more detail one specific candidate decaying Dark Matter particle, and it shall be used throughout as our benchmark particle.

The Standard Model (SM) of particle physics can be extended by a number of so-called sterile neutrinos. These particles are similar to the neutrinos found in the SM (referred to as active neutrinos in that case), but carry no charge of any sort and are more massive than the active neutrino. Having no charge, they do not formally participate in any fundamental interactions except through gravity, hence the name. They do however mix with the active neutrinos through the neutrino oscillations, effectively participating in the weak interaction at a suppressed level. A description of this interaction can be expressed in terms of the effective characteristic interaction strength θG_F. Typical interactions of the Weak force have a characteristic strength of G_F, the Fermi constant. The effective interaction of the sterile neutrino with the active neutrinos is *superweak* with the mixing angle $\theta \ll 1$.

The Neutrino Minimal Standard Model (or νMSM for short) is a minimal extension of the SM that introduces three sterile neutrinos and is able to solve three major 'beyond the standard model' problems; the existence of Dark Matter, the generation of the matter-antimatter asymmetry, and the neutrino masses (see Adhikari et al. (2016) for an extensive review).

Active neutrinos are observed to have a non-zero mass through their oscillations. The three flavours of neutrino oscillate between each other, which is only possible if their mass eigenstates are different from their flavour eigenstates. It is not possible to measure the neutrino masses directly, but the squares of the mass differences are available experimentally. In the SM, neutrinos are formally massless however, and to generate their mass new physics is needed beyond the SM. The reason neutrino mass is not included in the SM, is that massive fermions have to come in left- and right-handed chiral states, but only left-handed neutrinos (and right-handed anti-neutrinos) have ever been observed. The sterile neutrinos are the right-chiral counterparts to the left-handed active neutrinos, providing the mechanism for generating active neutrino masses by allowing them to interact with the Higgs field, which is the usual way to generate masses in the SM. The masses of the sterile neutrinos however, are Majorana masses and are not caused by the Higgs mechanism (which is only possible because it is a singlet under all fundamental interactions, in other words it has no charges). This means that it constitutes an entirely new, unrelated mass scale and as such would classify as 'beyond the standard model' physics. In order to generate the masses required for the flavour oscillations for three flavour states, at least two sterile neutrinos are needed (leaving the third active neutrino massless still, which is currently allowed by experiment).

By adding a third sterile state (making all three active neutrinos massive), it becomes possible to simultaneously explain neutrino oscillations and the Dark Matter. Sterile neutrino Dark Matter was first described by Dodelson & Widrow (1994) and the idea was further refined by Shi & Fuller (1999); Abazajian et al. (2001); Dolgov & Hansen (2002); Asaka et al. (2005) and Boyarsky et al. (2009c) among others. In this case the lightest sterile state plays the role of the Dark Matter and is cosmologically long lived. This is possible if the mixing with the active sector is very small ($\theta \ll 1$). Consequently this lightest sterile neutrino cannot generate the active neutrino masses (which is contributed to as $\delta m_\nu \sim \theta^2 m_{DM}$), but the other two sterile neutrinos are massive enough and have enough mixing to explain the observed mass differences in the active neutrino oscillations.

By requiring that the two more massive sterile neutrinos are at least as massive as $\mathcal{O}(100 \text{ MeV})$ and nearly degenerate with each other ($\Delta M_{12} \ll M_{1,2}$), it is possible to generate the matter-antimatter asymmetry in the early universe. Schematically, at these temperatures, active-sterile mixing is large, changing active neutrinos into the heavier sterile neutrinos which in turn decay into the lightest sterile neutrino. Because the mixing of the lightest sterile state is very weak, these particles are produced out of equilibrium, meaning that the reverse process at this point has a cross-section so small that the reaction rate has become negligibly small. In the presence of CP-violating processes (ie., processes that can violate baryon- or lepton-number), this decay effectively hides away the matter-antimatter (lepton-antilepton) asymmetry in a dark and light sector. This process allows the Dark Matter relic abundance to be set to the required level according to the size of the lepton-asymmetry and the active-sterile mixing.

The choice for the sterile neutrino Dark Matter as a benchmark model and main inspiration for the search for decaying Dark Matter is due to the attractively elegant solution of three of particle physics' and cosmology's largest open questions with a single extension of the SM model. We reiterate nevertheless that the work in this thesis can be applied to any decaying Dark Matter, as described in the previous Sections.

1.4 X-Ray Astronomy

Since the decay of Dark Matter would produce X-ray spectral features, this section will describe aspects of X-ray astronomy relevant to observing it in general terms. Details regarding individual instruments can be found in the relevant Chapters and references therein.

1.4.1 X-ray Instruments and Data Processing

The current generation of X-ray telescopes use hyperbolic mirrors with specialized coatings to direct the incoming high-energy photons to CCD-like detectors for both imaging and spectroscopic analyses. The three major observatories like this in the regime covering roughly 0.1 keV to 10 keV are *XMM-Newton*, *Chandra* and *Suzaku*. They each have their own strengths and weaknesses, but often similar science can be performed with each. With regards to imaging spectroscopy the main differences are that *XMM-Newton* has the largest field-of-view and 'grasp' (the product of the FoV and effective area, see below), while *Chandra* offers the best spatial resolution and *Suzaku* exhibits relatively low background levels.

The X-ray observatories are space telescopes in highly elliptic orbits. In this way, in the phase where they are far away from Earth, they can avoid the radiation belts that would pollute any data taken to a point beyond usability. Even with this precaution however, high-background periods of non-X-ray events still occur, and are often associated with soft proton flares (SPF). These are clouds of highly energetic charged particle emitted by the sun for example, and they create artificial events in the detectors. One of the first steps in the data reduction is therefore to completely remove high-background periods. This is usually referred to as lightcurve cleaning or flare removal.

X-ray imaging CCD's are capable of registering the photons' energy as well, providing imaging spectroscopy capabilities. This is the primary data that is used throughout the work presented in this thesis. The energy registration is not perfect, and the probability that an incident photon with a particular energy is detected with some other energy depends itself on the photon energy (the typical spectral resolution for such instruments is of the order 100 eV). This can be described by a probability matrix that encodes the chance that a photon of energy E is detected with energy E', and is called the redistribution matrix. Typically, this matrix is recalculated for every observation based on ray-tracing simulations of the telescope assembly, calibration measurements, telescope attitude information, and the actual data. The produced file is usually referred to as the RMF.

Whether or not an incident X-ray photon is detected by the instrument is a complicated function of energy and incident angle. This is mainly caused by the mirror materials and assembly, but other parts of the telescope influence this as well. The resulting detection efficiency is expressed as an effective area in units of cm^2. This represents the total collecting area of the telescope corresponding to the hypothetical situation where the telescope's efficiency would be 100%. The effective area is calibrated by measurements on the ground and in-flight, with varying techniques, but as a function of incident energy it has to be recalculated as well for each observation. This is also because of an effect called vignetting, where the effective area of the telescope assembly is reduced towards the edges of the field-of-view. The resulting description of the effective area for a given observation is referred to as the ancillary response file or ARF for short.

X-ray detectors are prone to exhibiting strong levels of in-flight instrumental backgrounds. These are mostly caused by high-energy particle hitting the telescope and chip assemblies, which induce a cascade of secondary particles that can be in turn detected by the sensor arrays. This instrumental background has a characteristic spatial and spectral distribution related to the construction and materials of the camera. There are various strategies to account or correct for the instrumental backgrounds. One is to determine all the backgrounds (instrumental plus sky) from a nearby detector region outside the region of interest. Another is to obtain observations made while the telescope is in a calibration mode. For example, in the case of *XMM-Newton* this means using a blocking filter to exclude anything but the instrumental backgrounds from being detected. This observation can then be subtracted from the original spectrum. Lastly, one may model the instrumental background simultaneously with the rest of the spectrum. This requires some prior knowledge on the components expected to be present in the instrumental background, for example obtained from the calibration observations mentioned previously. The instrumental background is prone to some variability in time, inducing some systematic uncertainty and necessitating the renormalization of the presumed description of the instrumental background for each (set of) observations.

As mentioned, for every observation the telescope calibration (redistribution matrix and effective area and background if needed) has to be recalculated. In fact, since these are functions of the relative position in the field-of-view (position on the CCD), this will have to be done for every separate extraction region. All necessary data products are generated using analysis software packages particular to the instrument being used (these will be mentioned in the relevant Chapters). Once they have been obtained one can start analyzing the spectra. This is done through a process called forward-modeling. In particular because the redistribution matrix is a very non-trivial matrix, it is mathematically impossible to convert a detected spectrum back to a true emitted spectrum analytically. Therefore the only possibility is to assume a model for the true emission, propagate it through the description of the telescope's response (using the RMF and ARF files), evaluate the goodness-of-fit, and repeat until an acceptable fit to the data is found. The software used in this Thesis for that purpose is XSPEC (Arnaud, 1996), but other packages are also available (f.e. SPEX, Kaastra et al., 1996).

1.4.2 Sources in the X-Ray Sky

In order to search for X-ray signals from decaying Dark Matter, one must be able to identify the X-rays emitted by any other astrophysical sources or backgrounds first. This section offers an overview of the most important and common sources and their X-ray features.

An extended halo of hot, low-density gas surrounds the Milky Way, and emits a thermal brehmstrahlung component peaking in the soft X-rays ($T \approx 0.2$ keV). Even when observing away from the galactic center or the galactic plane, this component is present and may need to be accounted for at lower energies (Lumb et al., 2002).

The point sources that can be found in the X-ray sky mostly include AGN in the extragalactic regions, and stellar binaries or pulsars in the Galaxy (Brandt & Hasinger, 2005). Deep observations will also start to pick up faint starburst galaxies (Worsley et al., 2006). These objects have characteristic X-ray spectra, but can be easily selected and removed due to their point-source nature.

Unresolved point sources lead to (a contribution to) the extragalactic X-ray background. This background has been an object of study for many decades now. It is currently agreed that the major contribution to the XRB is from unresolved AGN, although some uncertainty remains as to the precise make-up of the XRB. Measurements by various X-ray observatories indicate that the spectral shape of the XRB is a relatively simple, clean powerlaw with a slope of ~ -1.4 (De Luca & Molendi, 2004).

Galaxy clusters are the most massive bound structures in the Universe. As a result, their potential wells accrete large amounts of gas and heat this gas to very high temperatures. A relaxed cluster, which is to say a cluster whose gas has reached hydrostatic equilibrium, has a smooth temperature gradient and the main emission component is a brehmstahlung continuum based on the temperature and density of the gas (Arnaud, 2005), typically peaking between 2–10 keV. The other important component of cluster X-ray emission is from the various ions of various elements present in the gas. The atoms in the hot plasma are highly ionized and are continually collisionally and radiatively excited, and subsequently also de-excite and in doing so will emit photons at wavelengths characteristic to the transition. So, each population of ions in the plasma produces its own characteristic set of emission lines. The strength of those emission lines depends on the abundance of the element and the temperature of the plasma. The relationship between the emmissivity of the various lines emitted by a plasma is very non-trivial and non-monotonic due to the complex interplay between the various ionizing, radiative and collisional processes. A particular emission line will typically peak at a single temperature, and have reduced intensity at higher or lower temperatures. Therefore, the relative intensities of lines produced by the same ion are a good tracer of the plasma temperature (Boehringer & Werner, 2009).

Galaxies are less massive and contain less gas than clusters of galaxies, meaning that their X-ray emission is dimmer, and peaks at lower energies. The brighter elliptical galaxies typically show temperatures of ~1 keV, dropping to ~0.1 keV for fainter galaxies (Sarazin, 1997; Lehmer et al., 2007). Some atomic lines can still be excited, although at much lower luminosities than in clusters, since the densities are lower.

1.5 Search Strategy for Decaying Dark Matter X-Ray Signals

Taking into account the considerations regarding the properties of the Dark Matter decay signal (Section 1.3.1) and regarding the practicalities of X-ray astronomy (Section 1.4), in this Section the strategy for searching for decaying Dark Matter is detailed.

Two main modes of reasoning can be applied to the search. In a nutshell, the first one is to rule out, on an object-by-object basis, with high confidence all other interpretations until only one (Dark Matter decay) would be left. The second is to take a more holistic approach and judge measurements from a large range of objects and environments simultaneously against the Dark Matter decay interpretation directly. The latter, the holistic line of argumentation, is expected to yield more useful results in the face of measurements with large uncertainties. This approach receives preference in the work throughout this Thesis. Although the technical aspects of both are essentially the same, it is the 'philosophy' regarding how to answer the fundamental question and judge the measurements that is different for each. Below those differences and similarities, and their strengths and weaknesses are discussed.

1.5.1 Single Objects

To be able to detect a Dark Matter decay spectral line (described in Section 1.3.1), the X-ray spectrum of the object under consideration must be well fit with an appropriate model describing all of the components that may be expected for that object. Since the signal of decaying Dark Matter will be a weak line (seeing as no strong Dark Matter decay lines have been observed yet), it is imperative that the fit is of high quality, with a reduced-χ^2 close to one. If the residuals from the fitting of this spectrum exhibit a significant positive line-like deviation from zero that can not be identified with astrophysical emission or instrumental lines, this may be an indication of a candidate decaying Dark Matter signal.

If one wants to be able to claim a Dark Matter detection based on a single object (a single spectrum), it is necessary to exclude all possibilities of the spectral line being an artifact or an emission feature from regular astrophysical processes. This requires very careful fitting of the spectrum and thorough testing of these fits. As described in Section 1.4.2, the emission lines from the hot plasma depend non-trivially on the temperature, density and abundances, and is therefore also different for different objects. The positions and possible emissivities of a huge number of lines are known and available in databases. However, the spectral resolution of the current generation of X-ray imaging spectrometers is of the order 100 eV, which means that many lines tend to blend together, and can also obscure the continuum level in spectral regions with many excited lines. In addition, the cumulative spectrum of a relatively large extent of an object will often contain a superposition of multiple different components with different temperatures or elemental abundances, which in some cases may introduce degeneracies in the fitting process. There are various strategies for determining the various continuum and line contributions, and they will be described in the relevant Chapters in this Thesis. In brief, as also described in Section 1.4.2, it is possible to use certain (combinations) of stronger emission lines to constrain reasonably well temperatures and abundances.

Source selection for this approach is mostly a balancing of the expected signal strength with the expected astrophysical emission ‘background’ and the associated complications in the spectral modeling (high signal and high background in clusters and the Galactic center, lower signal and lower background in galaxies and dwarf galaxies).

As will be evident throughout the Thesis, this approach delivers results on some single objects where it can be shown that atomic line emission is very unlikely to be the origin a certain candidate signal, although it is very difficult to completely rule out such scenarios. In other objects, however, this is not always the case and multiple valid interpretations of the physical properties of the plasma can be found. Especially with the quality of the current generation of instruments, this issue often can not be easily or definitively resolved for the weak signals that are (expected to be) found.

Therefore, it is prudent to adopt a holistic approach that retains the high quality fitting, but compares results between objects in order to confirm or reject hypotheses as to the origin of a candidate signal.

1.5.2 Holistic Approach

The obtaining of high-quality fits and accurate estimates of possible contaminating factors described above is still part of this approach, but the central methodology by which to differentiate between scenarios is different.

Here, we make us of the fact that the signal strength of a Dark Matter decay signal depends on the total Dark Matter mass inside the field-of-view (FoV) of the telescope and the distance to the object. This is because decay is a single-body process, so that essentially the signal scales as the column-density of objects. Conveniently, as long as a given object fits inside the FoV of the telescope, a more massive but further away object will tend to provide similar signal strength. Therefore, appropriate targets for observations for searching for a decaying Dark Matter signal include all of the following. Dwarf galaxy satellites of the Milky Way halo, the Galactic Center, low redshift galaxies, and galaxy clusters.

Since the astrophysical environments of these objects are very different, and the regular X-ray emission likewise exhibits large differences, this allows for a robust and comprehensive test as to the origin of any unidentified spectral feature. For example, line emission from hot plasma scales with the temperature, with the square of the plasma density and with the elemental abundances. Continuum emission scales with temperature and density squared. But Dark Matter decay just scales with the Dark Matter mass. This holds not just for the expected scaling between objects, but also spatially within each individual object. Comparing the strength of a candidate signal in different environments to the expected scaling in those environments could provide robust conclusions regarding the origin of a potential signal.

With the spectral resolution of the current generation of detectors, a weak spectral feature may be localized to about 50 eV. It should therefore be noted that in this way potential Dark Matter decay spectral features that are detected within 50–100 eV (restframe) of each other in different observations, are to start with implicitly assumed to be emitted

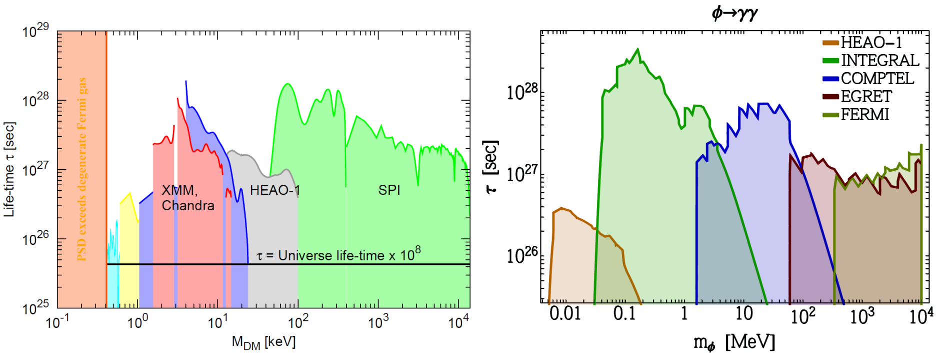

Figure 1.1: *Left:* Bounds on fermionic decaying Dark Matter lifetime from various missions (see text, figure taken from Boyarsky & Ruchayskiy, 2008). *Right:* Bounds on bosonic decaying Dark Matter lifetime from various diffuse X-ray and Gamma-ray observatories (see Essig et al. (2013), figure taken from same).

by the same physical process in each object.

The holistic approach relies on having available a large set of objects covering a wide range of environments, with individual exposures sufficiently deep that a more-or-less significant signal may be expected in each. The accumulation of archival data over the years has made it possible to cover an increasing area of parameter space (see Section 1.5.3), and allows for the effective application of this approach, as shall be seen throughout this Thesis.

1.5.3 Previous Searches

Many searches for the tell-tale X-ray emission from decaying Dark Matter have been performed in the past. All have utilized archival data from various X-ray observatories, most from *XMM-Newton*, since it provides in general the highest sensitivity per unit observing time, but also with *Chandra* (higher spatial resolution), *Suzaku*, *Swift* and INTEGRAL (higher energy range).

There have been three main categories of targets for these searches. Firstly, nearby galaxy clusters for their large Dark Matter masses (Boyarsky et al., 2006b; Riemer-Sørensen et al., 2007; Boyarsky et al., 2008c, 2010b). Secondly, the Milky Way (MW) halo since the expected signal is high due to its proximity (Riemer-Sørensen et al., 2006; Boyarsky et al., 2007b; Abazajian et al., 2007; Boyarsky et al., 2007a; Yuksel et al., 2008; Boyarsky et al., 2008b). And thirdly dwarf galaxy satellites of the MW because those exhibit the faintest astrophysical X-rays (Boyarsky et al., 2006c, 2007b; Loewenstein et al., 2009; Riemer-Sorensen & Hansen, 2009; Loewenstein & Kusenko, 2010; Boyarsky et al., 2010b; Mirabal & Nieto, 2010; Mirabal, 2010; Loewenstein & Kusenko, 2012; Kusenko et al., 2013). Observations of the M31 galaxy have also been performed (Watson et al., 2006, 2012; Boyarsky et al., 2010b, 2008a), that object holding the middle ground between clusters and dwarf galaxies in terms of (dis)advantages with regards to sensitivity to a Dark Matter decay signal. Choice of target objects was further mostly limited by the amount of available archival data. Additionally, the diffuse X-ray background

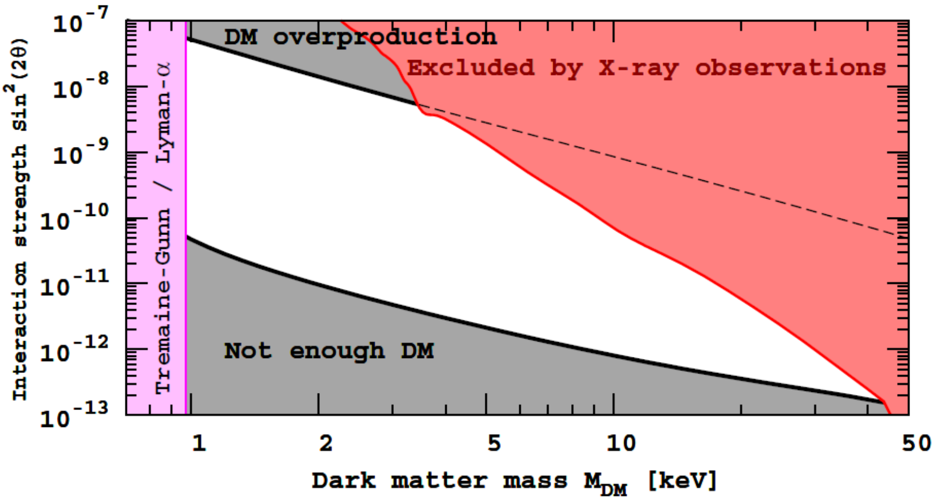

Figure 1.2: Parameters space of the sterile neutrino Dark Matter (see Section 1.3.4), in terms of the particle mass and its mixing angle (the strength of the mixing with the rest of the neutrino sector). The magenta band at low masses refers to the phase-space density constraints from dwarfs (see Section 1.2.1). The gray areas are sterile neutrino model-dependent restrictions from various production mechanisms, requiring that the correct amount of Dark Matter is produced in the early universe. The red area is excluded by non-detections from various previous studies as described in the text. Figure taken from Boyarsky et al. (2013)

as measured by HEAO-1 and *XMM-Newton* was also examined for Dark Matter decay signals (Boyarsky et al., 2006a), as were X-ray microcalorimeter measurements (better spectral resolution) of the MW halo (Boyarsky et al., 2007a). For an overview of these studies, see Table I of Neronov et al. (2014).

Up to February 2014, no convincing Dark Matter decay signals had been found, and the parameter space available was steadily being covered. The bounds on the model-independent particle lifetime obtained from these studies are shown in Figure 1.1, and specifically in terms of the sterile neutrino parameters mass and mixing angle in Figure 1.2.

1.6 Outline

The goal of the studies presented in this Thesis is to search for a signal from the decay of Dark Matter, as described in this Chapter earlier.

The majority of this thesis, namely Chapters 2 through 4, detail in roughly chronological order the discovery of such a Dark Matter decay candidate signal and the subsequent work performed to attempt to determine the origin of this signal.

Chapter 2 starts with a study that was first released in Febuary of 2014, detailing the discovery of an unidentified signal at 3.5 keV in X-ray spectra of both the Andromeda Galaxy and the Perseus Galaxy clusters (Boyarsky et al., 2014a). One week earlier, another work (Bulbul et al., 2014a) had been posted that reported an unidentified feature at the same energy, but in a stack of galaxy clusters. We note that these works were performed independently. These two papers are often referred to as Bo14 and Bu14 respectively, or together as the discovery papers.

This Chapter further includes a study on the presence of a 3.5 keV feature in the Galactic Center (Boyarsky et al., 2015), as this serves as an important initial consistency check with regards to the origin of this feature. This work was posted within days of a comment regarding both of the discovery papers (Jeltema & Profumo, 2015), which also included a brief analysis of the GC. The response to this comment (Boyarsky et al., 2014b) shall be discussed in this Chapter as well.

Chapter 3 regards an observing campaign of the Draco dwarf galaxy, a Milky Way satellite. This campaign was undertaken with the specific goal of testing the Dark Matter decay origin of the 3.5 keV signal. The Chapter will start by arguing why this approach was taken and then reports on the the analysis of the obtained data and the results.

Chapter 4 is a re-examination of the Perseus Cluster using data from the *Suzaku* telescope. The main motivation for this were the various published studies on this dataset that were starkly inconsistent with each other. In addition, with the previous studies of Perseus in hand, this work allowed for the comprehensive study of the signal's consistency between telescopes and of the signal's spatial behavior in the object.

Chapter 5 contains a proof-of-concept study and report on the development of an original and non-traditional method to search for Dark Matter decay signals. Development had originally started prior to the discovery of the 3.5 keV line, and has been continued concomitant with that work. This enabled the development of this new method to focus on ways to avoid some of biggest disadvantages of the traditional methods employed in the 3.5 keV signal studies, although the statistical power of the dataset used for training and development purposes is not high enough to detect or constrain the origins of the 3.5 keV signal.

The **Appendix** contains comments on some of the other literature concerning the 3.5 keV signals. These concern an alternative atomic interpretation and a spatial study of the signal among others.

A note on terminology; although most of the work presented here, and indeed most of the literature work, put the best-fit energy of the potential Dark Matter decay signal somewhere between 3.51 keV and 3.57 keV, we will refer to this signal simply as the 3.5 keV signal or the 3.5 keV line or similar.