



Licentiate Thesis

# Dark matter in and around stars

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**Cover illustration:** An artist's concept of the first stars forming after the Big Bang. Credit: NASA.

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## Abstract

There is by now compelling evidence that most of the matter in the universe is in the form of dark matter, a form of matter quite different from the matter we experience in every day life. The gravitational effects of this dark matter have been observed in many different ways but its true nature is still unknown. In most models dark matter particles can annihilate with each other into standard model particles. The direct or indirect observation of such annihilation products could give important clues for the dark matter puzzle. For signals from dark matter annihilations to be detectable, typically high dark matter densities are required. Massive objects, such as stars, can increase the local dark matter density both via scattering off nucleons and by pulling in dark matter gravitationally as the star forms. Dark matter annihilations outside the star would give rise to gamma rays and this is discussed in the first paper. Furthermore dark matter annihilations inside the star would deposit energy inside the star which, if abundant enough, could alter the stellar evolution. Aspects of this are investigated in the second paper. Finally, local dark matter overdensities formed in the early universe could still be around today; prospects of detecting gamma rays from such clumps are discussed in the third paper.



# Preface

This licentiate thesis consists of two separate parts. The first part is an introduction and overview over the area of dark matter and related cosmological subjects. This part overviews the signs of dark matter, dark matter candidates and ways to search for dark matter. The early universe and the first stars are also discussed, as well as the potential impact of dark matter upon them. The second part of the thesis consists of three scientific papers listed below:

## List of papers

1. Sofia Sivertsson and Joakim Edsjö  
*Accurate calculations of the WIMP halo around the Sun and prospects for gamma ray detection*  
To be submitted.
2. Sofia Sivertsson and Paolo Gondolo  
*The WIMP capture process for dark stars in the early universe*  
To be submitted.
3. Pat Scott and Sofia Sivertsson  
*Gamma-rays from ultracompact primordial dark matter minihalos*  
0908.4082 [astro-ph]

## Summary of the author's contribution to the papers

1. I performed the analytical and numerical calculations. I wrote most of the paper.
2. I largely constructed the scheme to attack the problem and did the calculations, both analytical and numerical. I wrote most of the paper.
3. I did the adiabatic contraction of the minihalos, was involved in the general discussion and wrote some of the paper.



# Acknowledgments

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## Part I

# Introduction and background material



# Chapter 1

## Dark matter

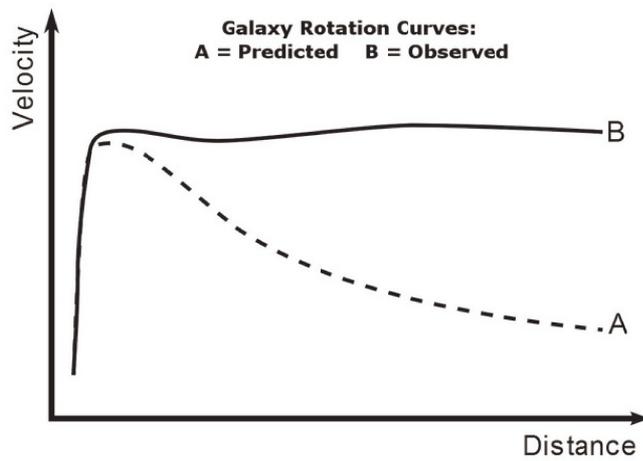
### 1.1 The need for dark matter

The first observation of missing mass, which is now ascribed to dark matter, dates all the way back to Zwicky [1] and his observations of the Coma galaxy cluster in 1933. He found, based on observations of velocity dispersions and the virial theorem, that the average mass of the galaxies in the cluster was much larger than expected from their luminosity; some extra unseen mass was needed to keep the cluster together.

In the late 1960s and early 1970s, the effect of dark matter was also seen in the rotation curves of spiral galaxies [2]. It was found that the orbital velocities of the stars in spiral galaxies are uniform out to a very large radius, as is illustrated in figure 1.1. This contradicts the assumption that most of the mass of the galaxy is in the central bulge, where most of the mass in stars and gas is. Observations instead imply that the density is much more uniform all through the galaxy. The mass responsible for this density distribution could not be observed and was subsequently referred to as “dark”.

The conclusion that the existence of some dark matter is needed is based on the assumption that our understanding of gravity is correct. The measured rotation curves could also be achieved by modifying Newtonian gravity over large distances. Theories modifying gravity instead of introducing dark matter are referred to as MOND: Modified Newtonian Dynamics [3].

In time there have been other observational signals of dark matter. One of the more spectacular ones is the merging galaxy cluster 1E 0657-56, also referred to as the “Bullet Cluster”. Observations of this cluster merger is shown in figure 1.2. In this image the non-interacting dark matter and stars of the colliding clusters have just passed through each other. The gas on the other hand collided and was heated. The heated gas emits X-rays which has been observed by the *Chandra* X-ray space telescope. The mass distribution of the merging cluster was found by



**Figure 1.1.** Illustration of the measured rotation curves and the discrepancy with the curves expected if the galactic mass profile follows the visually observed mass distribution. Credit: Wikipedia



**Figure 1.2.** Composite image showing the galaxy cluster 1E 0657-56, also known as the “Bullet Cluster”. The gas (pink) as seen in X-ray by Chandra is clearly separated from the dominant mass distribution (blue) found by weak lensing. Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

its gravitational impact on the passing light from more distant objects, through weak lensing. The finding was that the mass distribution does not follow the gas distribution as would be expected in a world without dark matter [4]. In contrast to galactic rotation curves this is very difficult to explain by modifying gravity, since one has to dislocate the gravitational impact from the source. The difficulty of reproducing the dark matter measurements by modifying gravity alone, becomes even more clear with the observations which we are about to discuss.

The imprint from dark matter has also been observed in the Cosmic Microwave Background (CMB). In the early, hot universe the atoms were completely ionized. As the universe expanded it eventually cooled enough for the electrons and ions to recombine, making the universe transparent to light. This happened when the universe was 300 000 years old and the light released then can still be observed today. The density fluctuations present then left imprints in the CMB, giving us a snapshot of the universe at that time, which has been accurately measured by *e.g.* the *WMAP* satellite.

The properties of these density fluctuations depend on the nature of the dark matter. Overdensities gravitationally attract matter, making them grow. On the other hand, the increased temperature and density increases the radiation pressure, forcing the baryons apart and diluting the overdensity. These competing processes give oscillations in the baryon-photon fluid. Since the dark matter is not expected to interact with photons, it can form structures also before the electrons and protons recombined. Because of this the CMB observations of the density fluctuations give information about the baryon fraction, *i.e.* the fraction feeling radiation pressure. The smaller scale density fluctuations also give information on the nature of the dark matter. If the dark matter is hot, meaning that it moves with relativistic speed at this time, it tends to “free-stream” out of small density enhancements and hence suppresses small scale density fluctuations. This suppression is not found in the CMB data implying that the dark matter need to be cold, *i.e.* non-relativistic at recombination [5].

The overdensities seen in the CMB are the seeds for the large scale structure of galaxies and galaxy clusters around us today. In structure formation, dark matter and baryons act quite different. Particle species interacting with light can emit energy via radiation, allowing it to contract much more than dark matter. The growth of dark matter structures have been simulated in N-body simulations and the results are overall in good agreement with observations of the universe we live in. For this success, the majority of dark matter needs to be cold and have very weak particle physics interactions [6].

The concordance model of cosmology, the  $\Lambda$ CDM model, fits large sets of data remarkably well given its rather few parameters. The  $\Lambda$ CDM model tells us that the energy of the universe is in the form of dark energy, cold dark matter, baryons and small amounts in photons and neutrinos. Combining measurements of the acceleration of the universe from observing type Ia supernova, observation of the baryon acoustic oscillations from the distribution of galaxies, and the five year data of the CMB from *WMAP* the energy content is by now well constrained. The

current best fit to the data is: dark energy content of  $\Omega_\Lambda = 0.726$ , baryonic content of  $\Omega_b = 0.0456$  and cold dark matter content  $\Omega_{DM} = 0.228$  [7]. All observations support the notion that the universe is very flat, meaning that  $\Omega_\Lambda + \Omega_{DM} + \Omega_b = 1$ .

## 1.2 What is this dark matter?

As many gravitational observations of the abundant existence of some unknown type of matter have been made, the outstanding task is to find out what this dark matter really is.

One early suggestion was that it could consist of “normal” baryonic matter in the form of MACHOs, MAssive Compact Halo Objects. Examples of MACHOs are dark planet-like objects and black holes from dead stars. Even though this could seem to be able to account for the dark matter observed today, baryonic dark matter would have interacted with light in the early universe. As discussed earlier, this gives pressure affecting the density perturbations seen in the CMB and later the formation of large scale structures. Big bang nucleosynthesis together with CMB data constrains the baryonic fraction of the matter content, contradicting the bulk of dark matter being baryonic. Baryonic dark matter also does not match our understanding of how structures form in the universe. Finally, MACHOs in our galaxy have been searched for in weak lensing surveys, constraining their mass [8].

Another discussed possibility is for the dark matter to be in the form of primordial black holes. These would be created by density fluctuations in the very early universe and would, even though their original content might be baryonic, look like non-baryonic dark matter to the CMB. However, due to better observations, primordial black holes is no longer a very good candidate to account for dark matter. Heavy black holes interact gravitationally, *e.g.* probed by lensing surveys looking for MACHOs. Light black holes emit Hawking radiation and eventually evaporate in a particle burst; this Hawking radiation has not been observed and could disrupt early well-understood processes like nucleosynthesis [9, 10].

There exists a particle in the standard model that for a while looked like a suitable dark matter candidate: the neutrino. Neutrinos are found to be massive from their observed flavor oscillations [11]; they also do not interact with light and are in that sense dark. It was, however, found that they can only account for a vanishing fraction of the dark matter. The cosmological neutrinos are created in the hot early universe and their relic abundance depends strongly on their mass. The masses of the neutrino mass eigenstates are unknown but experimental results show that they need to be very small, giving a very low relic abundance of neutrinos [12]. Also, neutrinos being so light make them relativistic at recombination, *i.e.* hot dark matter. If abundant, they would free stream out of, and obstruct the formation of small scale structures. The imprint of high abundance of hot dark matter is also not seen in the CMB.

The conclusion of all of this is that the dark matter most likely consists of some unknown type(s) of subatomic particles. Since the standard model does not have

any suitable candidate, our understanding of its particle physics nature is somewhat limited. There are, however, many theories giving suggestions for the true nature of dark matter. The most popular and studied framework for this is supersymmetry.

### 1.2.1 Supersymmetry

Supersymmetry (SUSY) is a hypothetical symmetry between fermions and bosons, and is a potential source of dark matter candidates. In unbroken supersymmetry each boson has a fermionic superpartner and vice versa, with all properties (including mass) the same except spin. However, no superpartners have been observed, so if supersymmetry is a true symmetry of nature it must be broken at the energy scales probed by our experiments. Supersymmetry cannot be broken in such a straightforward way as the familiar Higgs mechanism for electroweak symmetry breaking. In constructing an effective low energy theory of broken supersymmetry our ignorance of SUSY breaking leaves us with a high number of free parameters encoding this uncertainty.

One motivation for supersymmetry is that mass loop corrections are cancelled by the superpartners, at the energies where SUSY is restored. There is no symmetry protecting the Higgs boson from loop corrections to its mass in the standard model, giving corrections proportional to the masses of the other particles. Since more massive particle states are expected to be found, these corrections are expected to be quite large, much larger than the Higgs mass range expected on the basis of existing data. In this light, the relative smallness of the Higgs mass seems very unnatural. It requires the loop corrections to cancel to very high precision which, without being governed by some symmetry, is very unlikely, or finetuned. This is called the hierarchy problem and is really the question of why the electroweak scale is so much lower than the Planck scale. In a supersymmetric world, these loop corrections cancel, protecting the low Higgs mass. To gain this naturalness, supersymmetry needs to be broken at a reasonably low scale, which could be seen as a hint for supersymmetry to be reachable by laboratory accelerators in the not-too-distant future.

In the same way, loop corrections also give energy to the vacuum. This vacuum energy cannot be probed in particle physics experiments but is noticed by gravity. Something that looks like vacuum energy has been observed in cosmology, driving an accelerated expansion of the universe, this is known as “Dark Energy”. The problem is that the vacuum energy corresponding to the observed dark energy is immensely small compared to the value predicted by particle physics theories. Supersymmetry would reduce the expected vacuum energy density but is not enough to solve the discrepancy. However, one might hope that SUSY could play a role in relieving this tension in the future.

Another attractive feature is that supersymmetry, if broken at low enough energies, unifies the strengths of the standard model interactions at high energies. This is attractive in the search for a unified theory but one should maybe note that unified theories imply new physics below the unification scale, which in turn affects the

unification of the coupling strengths. Supersymmetry is also generally present in string theory, but in this case need not be restored anywhere near energies reachable by experiments.

### Supersymmetric dark matter

The superpartners in supersymmetry provide several candidates for dark matter. The most popular one is the lightest neutralino, which is the lightest mass eigenstate of the linear combination of the neutral Higgs bosons and the neutral bosons of unified electroweak theory. The neutralino being a dark matter candidate is provided that its decay is prohibited by R-parity. R-parity prohibits the decay of an odd number of superparticles to only standard model particles, which renders the lightest supersymmetric particle (LSP) stable.

Our ignorance of SUSY breaking encodes some uncertainty, implying that we do not know which particle is the LSP. Even though neutralino LSP is a good dark matter candidate, the neutralino need not actually be the LSP. However, having a charged LSP (both electrically and chromatically) rules it out as a dark matter candidate. Another suggestion has been to have the superpartner of the neutrino, the sneutrino, as the LSP and dark matter. Sneutrino dark matter is almost ruled out by direct detection searches, due to its high nuclear scattering cross section [13].

A maybe slightly less appealing dark matter candidate in local supersymmetry is the gravitino. The properties of the gravitino depend on how supersymmetry is broken. The mass of the gravitino could be comparable to the mass of the other supersymmetric particles, *i.e.* of the order of 100 GeV or more. If the gravitino is the LSP, it is a possible dark matter candidate. Unfortunately the interactions of these gravitinos are of gravitational strength, making them more or less impossible to detect directly if R-parity is fully conserved.

The gravitino can also be far lighter than this. In this case the gravitino is most likely the LSP and higher mass sparticles will decay to it. Naively, one would expect this decay to be very slow, but this need not be the case. The gravitino inherits the interactions of the goldstino, whose degrees of freedom it “ate” during the symmetry breakdown to become massive. This allows the gravitino to have non-negligible couplings besides gravity [14]. However, since the dark matter needs to be cold, the gravitino needs to be heavy to match cosmology data, if it accounts for the bulk of the dark matter [15]. Gravitinos are typically overproduced in the early universe. This can be avoided if the reheating temperature after inflation is low, which is a problem if one fancies the model of leptogenesis to be the source of the baryon asymmetry in the universe [16].

### 1.2.2 Other possible sources of particle dark matter

Another popular source of dark matter comes from the possibility of having extra dimensions. For example string theory postulates extra dimensions. Since these

extra dimensions have not been observed, they either have to be curled up to be small or are constrained, *e.g.* only gravity can propagate in the extra dimension. The idea of having a small, universal extra dimension was originally discussed by Kaluza and Klein as an attempt to unify electromagnetism and gravity [17, 18]. This idea has since then been studied for other purposes. For small universal extra dimensions, the particles' momenta along the extra dimension are conserved at tree level, depending on model. The momentum along the curled up small extra dimension is quantized, leading to a tower of distinct mass Kaluza–Klein modes corresponding to different momenta in the extra direction. These momenta are conserved in the four-dimensional effective theory, making them appear as distinct particles. Even though momentum conservation is broken at loop level in the high-dimensional theory, the lightest Kaluza–Klein excited state is stable. If the lightest excited state is neutral, like the excitation of a photon, this gives a viable dark matter candidate [19]. Kaluza–Klein dark matter is a weakly interacting massive particle, much like the neutralino, but with different particle physics properties.

Another dark matter candidate is the axion, which is a consequence of a suggested solution to the strong CP problem. CP violation has not been observed in the strong sector, but to conserve CP in this sector a very special choice of parameters is required. It was shown [20] that the lack of CP violation becomes natural if an extra scalar field is introduced. It was then realized that this extra scalar provided a dark matter candidate. However, the original axion construction was soon ruled out by experiments and the “invisible axion” was invented. Even though experimental and observational constraints render the axion to be very light,  $m_a < 0.01$  eV, it couples so weakly to other matter that it was never in thermal equilibrium in the early universe, making it behave as cold dark matter [21].

The list of dark matter candidates can be made much longer but those discussed here are some of the more popular scenarios. The dark matter could, of course, also turn out to be of some completely unexpected origin.

For a dark matter candidate to be a viable source for the bulk of the dark matter, the correct relic abundance must have been created in the early universe. From a philosophical point of view a candidate that is more likely to create the correct abundance can be perceived as more appealing. As will be discussed later, more massive and weakly interacting particle dark matter candidates created thermally, naturally obtains the correct relic abundance.



## Chapter 2

# The evolution of the early universe and the first stars

The early inhomogeneities, seen in the CMB, give the seeds for the future structure formation as the universe evolves. After recombination the universe is dark since stars have yet to form, often referred to as the Dark Ages. During this era the density perturbations grow, forming larger dark matter halos. In the cold dark matter paradigm structures form hierarchically; smaller dark matter halos form earlier and are more dense. Larger and larger structures form in time, partially retaining the previously formed smaller halos as substructure. The behaviour of the evolving dark matter halos is investigated by N-body simulations, tracing many “blocks” of dark matter interacting only gravitationally. Increasing computer power allows higher resolution, allowing smaller structures to be investigated, but still far from the resolution required to study small dark matter structures [22]. A universal, well used density profile has been suggested by Navarro, Frenk and White (NFW) [23]

$$\frac{\rho(r)}{\rho_c} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}. \quad (2.1)$$

Here  $r_s = r_{200}/2$  is a characteristic radius,  $r_{200}$  is an estimate of the virial radius,  $\rho_c$  is the critical density of the universe and  $\delta_c$  is a dimensionless concentration parameter, as in [23]. The NFW profile is designed to fit the density profile from 1 % of  $r_{200}$  out to  $r_{200}$ . Higher resolution simulations indicate that the region interior to this is more dense than given by the NFW profile, even though the calculated central densities vary quite a lot between different halos. Also, how baryons modify the distribution of dark matter as the halo forms is not well understood [6].

As the halo forms, parts of the baryonic component condense to the central region of the halo due to the potential well supplied by the dark matter. Since the baryonic gas can dissipate energy via radiation, which the dark matter cannot, only

the baryonic component forms dense objects. In this way, the first stars are formed at redshifts  $z \simeq 20 - 30$  in dark matter halos of mass  $10^6 M_\odot$  [24].

## 2.1 The first stars

That the particle nature of dark matter could have an important effect on the first stars was realized only recently. This possible effect is discussed in the last chapter, so it is not taken into account here.

Before any stars had been formed the abundances of elements from Big Bang nucleosynthesis were still preserved and all the gas in the universe consisted only of hydrogen, helium and trace amounts of lithium and other heavier elements [5]. Astronomers refer to all elements heavier than helium as ‘metals’ and the first stars, not containing any metals, are referred to as having zero metallicity. The first stars are called population III stars; in contrast to the higher metallicity population I stars we have around us today. The presence of metals alters the chemistry and cooling, making the properties of metal free stars different from the stars observed today.

Population III stars are typically very massive, making them shortlived because they burn their fuel fast. Since all the first stars have died long ago, they can only be found at very high redshifts, making them very hard to observe directly. This also makes the subject more theoretical as there are no direct observations. However, the lives and deaths of population III stars affect their surroundings, producing consequences to physics observable today. The light from the first stars ended the dark ages and contributed to the reionization of the universe. How these stars died could affect the abundance of heavier elements in the interstellar medium, affecting the chemistry of the stars forming afterwards. Black hole remnants of population III stars could also be the seeds for large black holes powering distant quasars.

### 2.1.1 Formation

The lack of metals makes it harder for the collapsing cloud to cool and lose its gravitational energy. For the first stars the most important cooling ingredient is molecular hydrogen,  $H_2$ . The discussion here mostly regards the very first stars, those not influenced by any other star in their neighbourhood lit before them. Molecular hydrogen is fragile and easily destroyed by radiation. Depending on ionization and radiation present, atomic hydrogen and deuterium can combine to form HD molecules, which is an important coolant. So, even though the metallicity is essentially the same for the very first and the almost first stars, the hydrogen chemistry has changed. More efficient cooling reduces the masses of the almost first stars and estimates indicate that they do not reach the masses required to form pair instability supernovae, which will be discussed later [25].

The lowest excited rotational level of  $\text{H}_2$  has an energy corresponding to 512 K. As the temperature drops below roughly 100 K, collisions cannot make this excitation, disabling  $\text{H}_2$  cooling. At this stage the cloud will only undergo gravitational collapse if it has acquired enough mass to fulfil the Jeans criterion  $M > M_J$ , where [24]

$$M_J \simeq 700M_\odot \left( \frac{T}{200\text{K}} \right)^{3/2} \left( \frac{n}{10^4\text{cm}^{-3}} \right)^{-1/2}. \quad (2.2)$$

This clump is the direct progenitor of the star forming in it, setting an upper limit of the final stellar mass. For the formation of modern stars, the presence of metals allows for more efficient cooling, which reduces the Jeans mass. This makes the star forming cloud fragment and several smaller stars are formed, making the typical mass of modern stars similar to the mass of our Sun. The formation process of population III stars has been investigated using simulations and typically the collapsing cloud does not fragment, i.e. only one star is formed per dark matter halo. Full consensus has, however, not been reached. Recent work finds that the first stars could also form binaries. If this is the case, how large fraction of the first stars this applies to is still an open question [26]. If the cloud fragments the motion of the forming stars can pick up the cloud's net angular momentum; if only a single star forms it must somehow shed its angular momentum.

The final mass of a pop III star forming in a collapsing clump depends on how large fraction of the gas the star can assimilate as it forms. The initial protostar acts as the seed which accretes mass from its surrounding halo, growing to form the final star; this makes the details of the accretion process very important for the mass of the final star. The accretion process continues until terminated by radiative feedback from the star. This happens as the star contracts towards the main sequence, greatly increasing the ionizing luminosity [25]. Numerical simulations find that the first stars were very massive, with typical masses  $M_\star \gtrsim 100M_\odot$  [24].

As will be discussed later, energy injected in the forming protostar through WIMP annihilations can delay the protostars contraction and subsequent heating. This allows more time for accretion, making the star more massive.

### 2.1.2 Life and death

The radiation produced by the star also applies an outward force on the outer layers of the star. This is especially strong for massive stars which are more luminous. If this outward pressure exceeds the inward gravitational force the outer layer is pushed away as intense stellar wind, which can make the star lose a substantial fraction of its mass. Stellar mass loss can be very important for massive modern, high metallicity, stars. However, the lack of metals in the primordial stars strongly reduces the mass loss effect, down to the point of negligibility. This allows for the first stars to sustain their high mass until the final stages of their lives, playing an important role in how the star dies [24].

Zero metallicity stars of mass less than  $\sim 35M_{\odot}$  roughly share the fate of modern stars of the same mass. Single modern stars of masses below  $\sim 8M_{\odot}$  form white dwarfs as their fuel runs out and those with higher mass explode as supernovae, forming neutron stars or black holes [27].

The ultimate fate of the ageing star depends on the mass of the helium core formed. For solar metallicities, due to mass loss, the helium core at death does normally not exceed  $\sim 12M_{\odot}$ , corresponding to an initial main-sequence mass of  $35M_{\odot}$ . Zero metallicity stars are not affected by this limit and as the helium core of the dying star increases at core collapse, eventually the infalling mass becomes too large for a successful supernova shock to be launched. The star then forms a black hole directly without supernova explosion.

A zero metallicity star with an initial mass of roughly  $100M_{\odot}$  or more encounters the electron-positron pair creation instability at the end of its life. As the central hydrogen fuel in the star runs out, the central temperature increases and the star burns heavier elements. For stars with this high mass the radiation of the core becomes energetic enough to pair create electrons and positrons. This increases the opacity and makes energy transport out of the core less efficient, increasing the central temperature, which in turn makes the pair creation more efficient. Eventually the energy released is enough to reverse the collapse into an explosion. For stars in the mass range of  $\sim 140 - 260M_{\odot}$  enough energy is released in the turnaround to completely disrupt the star. The pair instability supernova ejects all the stellar material and no black hole remnant is formed. Pair instability supernovae strongly underproduce elements of odd atomic number, leaving a peculiar imprint of metals in the interstellar medium [28]. Very energetic supernova explosions with the characteristics of a pair instability supernova have actually been observed at low redshift [29]. Pair instability supernovae at low redshift are not expected and if one has truly been observed, it is difficult to explain how they can form so late. The small number of such supernovae observed indicate that their progenitors are very rare.

If the star encountering the pair instability has an initial mass of less than  $\sim 140M_{\odot}$ , the explosion energy is not enough to completely disrupt the star. The star ejects mass and then falls back. It may encounter several subsequent pulses until enough mass has been lost for the star to collapse to directly form a black hole [27]. For stars more massive than  $\sim 140M_{\odot}$  the core heats up enough to produce gamma rays energetic enough to photo-disintegrate nuclei. This endothermic process reduces the pressure enough for the collapse not to turn around. The star then collapses directly into a black hole, probably without ejecting any metals [27]. For masses of several hundred solar masses also metal free stars become unstable to pulsations, giving possible phases of giant stars. Still the mass loss remains negligible compared to the stellar mass [30, 31].

## 2.2 Observations

The first stars are expected to all have died long ago since they were very massive. This makes direct observations quite tricky but the first stars leave imprints that can be searched for.

### 2.2.1 Reionization

When the plasma of the early universe cooled enough the free electrons and protons recombined, making the medium electrically neutral and transparent to photons. The medium stayed electrically neutral until the first stars ignited and their ultraviolet light started splitting up the atoms into ions again. When the medium becomes ionized it can no longer absorb but scatter photons, giving observational effects of the ionization history of the universe. Observations of light from distant quasars show that the optical depth increased rapidly at a redshift of  $z \sim 5.5 - 6.0$  [32]. The *WMAP* data, however, imply that the universe was mostly ionized at redshift  $z \sim 11$ , finding that if the universe was reionized suddenly this happened at redshift  $z = 11.0 \pm 1.4$ . The combination of these data suggest that reionization was an extended process rather than a sudden transition and that the reionization process started quite early [33]. Since the radiation from the first stars contribute to reionization, our increasing knowledge of the reionization process can give information about the first stars. Constraints from reionization on the dark star scenario has been discussed in [34].

### 2.2.2 Quasars and gamma ray bursts

Some of the most distant objects observed are quasars, which are active galactic nuclei powered by the accretion disk of a central supermassive black hole. For example, the mass of the central black holes have been estimated for 15 high redshift quasars, of redshift  $3.3 \leq z \leq 5.1$ , yielding a mass range of  $2 \times 10^8 M_\odot \leq M_{bh} \leq 4 \times 10^{10} M_\odot$  [35]. Hence, supermassive black holes existed also when the universe was still was quite young. Also, the observed high metallicity implies that the quasars were preceded by intense star formation. If the first stars were very massive they would, upon their death, create early quite massive black holes, which could maybe act as early seeds for the observed supermassive black holes in quasars.

Gamma ray bursts (GRB) are believed to be exploding massive stars sending out the released energy as relativistic jets. This makes them observable over very large distances if we happen to be in the direction of one of the jets. The *Swift* satellite has observed gamma ray bursts with redshifts as high as 8.2, making gamma ray bursts a potential source of vital information about the early universe [36]. Observations of distant GRBs give a tool to probe the ionization state as well as metal enrichment of the intergalactic medium. GRBs also opens a possibility to detect individual pop III stars, if the these stars were able to trigger GRBs [37].

Information about the first stars can also be retained by observing the abundances of heavier elements. Very old, extremely low metallicity stars in the halo of our galaxy are thought to trace the chemical composition of the universe after the pop III star era. By sampling the abundances of metals in these old halo stars, then gives information on the nucleosynthesis of metals in the first stars. The relative abundance of metals in these old stars match the signature of low modern core-collapse supernovae rather than the distinct signature of pair instability supernovae from the first stars [38]. This does not mean that pair instability supernovae did not happen but that their abundance must have been reasonably low. This could indicate either that the first stars are typically more massive, or less massive at death than the pair instability mass window.

## Chapter 3

# WIMP dark matter

WIMPs are weakly interacting massive particles which are stable, or at least have lifetimes comparable to cosmological time scales. Neutralinos and neutral Kaluza–Klein excited states are examples of WIMPs. The WIMPs, here denoted “ $\chi$ ”, would have been created thermally in the early universe leaving a, possibly substantial, relic abundance of these particles.

In the early, hot universe the abundance of WIMPs was given by the process  $\chi\bar{\chi} \leftrightarrow N\bar{N}$ , where  $N$  denotes all the particles  $\chi$  can annihilate into. When the temperature and densities were high both directions of this process were equally probable and this new particle species was in thermal equilibrium with the surrounding plasma. When the temperature drops below the mass of  $\chi$  the process  $N\bar{N} \rightarrow \chi\bar{\chi}$ , becomes heavily suppressed. WIMP annihilations will then reduce the abundance of WIMPs as long as the number density is high enough, given the annihilation cross section, for this process to be efficient. The plasma is diluted as the universe expands, and roughly, when the annihilation rate  $\Gamma = n_\chi \langle \sigma_A v \rangle$  drops below the Hubble rate, *i.e.*  $\Gamma \lesssim H$ , the particle species decouples from the plasma [13, 39]; this is called freeze out. If this freeze out occurs when the temperature is still comparable with the mass of the particle, *i.e.*  $M_\chi/T$  not much greater than one, the relic abundance can be substantial.

If a particle species with weak scale interactions and mass exists it naturally produces roughly the correct relic abundance to account for the observed dark matter. This is often referred to as the “WIMP miracle”. Non-WIMP dark matter candidates usually lack this naturalness.

If the dark matter candidate is assumed to give the correct relic abundance one can map WIMP mass to annihilation cross section at freeze out, at least when assuming no large non-standard effects. From this it is also possible to give a model independent upper limit on the WIMP mass. Demanding unitarity of the partial wave expansion gives, for a given WIMP mass, an upper limit on the annihilation cross section. This together with the relic abundance gives an upper mass of any stable thermal relic of approximately 300 TeV [40]. Model dependent statements

generically have substantially lower upper limit on the WIMP mass, for example in SUSY models the upper limit on the WIMP mass is roughly 3 TeV [13].

### 3.1 Detection

Although dark in the sense that WIMPs do not couple to electromagnetic radiation, the thermally produced WIMPs must still couple to ordinary matter, since they must annihilate into ordinary matter in the hot early universe. The attempts to detect dark matter use this coupling in various ways.

One way to detect dark matter is to create it in accelerator experiments, such as the Large Hadron Collider (LHC). If created, the dark matter particles will most likely escape the detector undetected and appear as missing energy when the collision is analysed. It could also be possible for accelerators to create particles which are not the dark matter but which give clues as to the particle physics framework of the dark matter particle species.

Dark matter could be detectable via scattering off nucleons in direct detection experiments, since WIMPs are expected to have a non-zero scattering cross sections with ordinary matter. As WIMPs in our galaxy pass through the detector some could scatter, deposit energy and give detectable recoils in the detector material. This could give a clear WIMP signal if background can be handled. However, while the annihilation cross section is constrained by the relic density; this is not the case for the scatter cross section, which could be many orders of magnitude below direct detection limits.

WIMPs can also scatter as they pass through the Sun. In the scatter the WIMP loses energy and could become gravitationally bound to the Sun. If this happens the WIMP will, unless disturbed by the planets, scatter again and again until it sinks to the core of the Sun, where it annihilates with another WIMP. Most of the annihilation products stay undetectable in the Sun but the high energy neutrinos produced escape and can be detectable at Earth. Since neutrinos interact weakly one need very large detectors, like Ice Cube and Antares.

In regions of very high dark matter densities, like the center of the Milky Way and in the early universe, dark matter annihilations, like those inside the Sun, could substantially heat stars living in such regions. This could affect the formation of the star or, if enough energy is injected, turn off nuclear burning inside the star. Dark matter effects on stars are discussed later.

It is also possible to look for WIMP annihilation products in space. The annihilation products to look for are gamma rays and otherwise less common particles, such as positrons and antiprotons. Gamma rays point to the source, while charged particles are deflected by the galactic magnetic fields and lose energy fast, making them useful only to probe local sources. For the standard scenario the WIMP annihilation cross section is reasonably well constrained by the relic density. The annihilation rate depends on the square of the WIMP number density making the dark matter density very important. The dark matter densities are higher in the

central regions of galaxies, such as our own. The dark matter distribution in our galaxy is also expected to have some substructure, giving higher densities locally and increase the overall annihilation rate. The importance of substructure is a highly debated question but it seems that, if non-standard effects are not included, it cannot boost annihilation rates by orders of magnitude. Both for the cases of looking for positrons/protons and diffuse gamma ray emission, the background from astrophysical sources is significant and not well understood. This makes confident detection difficult unless dark matter characteristic spectral features are observed.

One should maybe also note that detection through WIMP annihilations assumes that the WIMP is its own antiparticle. This is the case in most theoretical models of dark matter, but the true nature of dark matter is unknown so it need not be true. If WIMPs and anti-WIMPs are equally abundant everywhere this would only reduce the annihilation rate slightly and could effectively be hidden by assigning a slightly lower annihilation cross section. However, if we are extremely unlucky there could also be an asymmetry in the dark sector, similar to the baryon asymmetry. There are essentially only baryons and no antibaryons in the observed universe, which is one of the great puzzles in physics. If this would be true also for the dark matter, that WIMPs dominate completely over anti-WIMPs, looking for dark matter through WIMP annihilations is hopeless.

## 3.2 Indirect detection through $\gamma$ -rays

As discussed above one can look for dark matter signals in gamma rays either by analysing the diffuse gamma ray background or by looking at some known dark matter overdensity. The gamma ray spectrum from WIMP annihilations is very model dependent but WIMP annihilations cannot produce gamma rays with more energy than the WIMP mass. If a high fraction of the gamma rays produced have energies very close to the cutoff given by the WIMP mass, this could be observed as a sharp drop in the gamma ray spectrum. The state of the art full sky measurement of gamma rays was recently released by the Fermi collaboration [41]. This spectrum lacks the anticipated spectral feature and given our limited knowledge of the background it is currently not possible to disentangle any dark matter gamma ray signal from the data.

Gamma ray signals from dark matter can also be looked for in dark matter overdensities. The Milky Way center has very high dark matter densities which should give a high gamma ray flux. On the other hand, the galactic center has a very high astrophysical background in gamma rays which is poorly understood. Another idea is to look slightly off-center since the reduction in background leads to an increased signal-to-noise ratio despite the lower dark matter densities.

A cleaner signal could be given by the centers of nearby dwarf galaxies. These are quite rich in dark matter and the rotation curves of the stars provide information about the dark matter distribution. Dwarf galaxies without astrophysical gamma

ray sources could also provide low background. However, no signal is so far seen by the *Fermi* satellite [42].

Even though N-body simulations do not indicate abundant dark matter substructure significantly boosting the signal, this does not mean that they need not exist. For example phase transitions in the early universe (*e.g.* QCD confinement) can produce energy-density fluctuations, triggering the formation of dense objects. If these fluctuations are not large enough to produce primordial black holes they could still seed the growth of stable ultracompact minihalos [43]. As the dark matter dominates the matter content in the universe these minihalos would also be dark matter dominated. In [43] searching for these objects using gravitational lensing is discussed. For the dark matter consisting of self-annihilating WIMPs these minihalos also emit gamma rays from WIMP annihilations. The detectability in gamma rays depends on what phase transition caused the density fluctuations, as showed in the third paper included in this thesis.

Another idea is to look for gamma rays from WIMP annihilations around the Sun. Some fraction of the WIMPs going through the Sun will scatter in their passage and lose energy. If the energy the WIMP scatters to is low enough, it will become gravitationally bound to the solar system. It will then scatter again and again in the Sun, losing more and more energy until it sinks to the core of the Sun and annihilates, as previously discussed. This process is however quite lengthy. Since the WIMPs typically scatter off elements much lighter than themselves, they can only lose a small fraction of their energy in each scatter. Also, since the scatter cross section is quite low, it typically takes the WIMPs many passages through the Sun before they scatter again. All these WIMPs in the process of being captured by the Sun create an overdensity of WIMPs around the Sun, or in other words, a dark matter halo around the Sun. WIMP annihilations within this dark matter halo would produce gamma rays which could be searched for. If strong enough to be detectable, this could potentially be a quite distinct dark matter signal, since the Sun does not shine in such high-energetic gamma rays; the Sun also shields from the diffuse gamma ray background. However, interactions of cosmic rays in the solar atmosphere [44], as well cosmic rays upscattering solar photons [45] can generate gamma rays, giving a background for the dark matter signal. The first paper included in this thesis is a detailed calculation of the WIMP overdensity coming from this effect. Unfortunately, it was found that the resulting WIMP density is far too low to be detectable from Earth.

Gamma rays from WIMP annihilations can potentially be observed by the satellite telescope *Fermi* and various ground based Čerenkov telescopes, at least if the WIMP is high in mass. Most Čerenkov telescopes look at the Čerenkov light produced by the particle shower created when a high energy particle hits the atmosphere. The previous telescope Milagro and the upcoming HAWC telescope also look at Čerenkov light but in water tanks. Air Čerenkov can only operate on Moonless nights since the optical light hides the Čerenkov signal; this also implies that they cannot look for gamma ray signals coming from the Sun. The *Fermi* satellite and water Čerenkov telescopes do not suffer this limitation. For the particle shower

to be large enough to be observable by the Čerenkov telescopes it is required that the original gamma ray is high in energy which in turn demands that the WIMPs have high mass. On the other hand, Čerenkov telescopes have a larger effective area than a satellite. The Milagro detector has also searched for gamma rays from the Sun but without success [46].

### **3.3 How the particle nature of dark matter could affect the first stars**

All work about the first stars' formation have, until very recently, only looked at the behaviour of the gas. The dark matter was assumed to only provide a background gravitational potential used for the gas collapse. However, if WIMPs annihilate inside a star or protostar, they will inject energy into the plasma or gas. If the energy injected in this way is substantial, this could have large effects on the (proto)star, potentially altering mass, luminosity and lifetime of the star. The mass of a star is important for how the star dies; altering the way the first stars die could potentially have far reaching consequences. The effect of dark matter annihilations on the formation of the first stars has been investigated by the group of [47] and also by the authors of [48].

As discussed, the first stars formed in the centres of early dark matter halos. The gas component of the halo can dissipate away energy and contract towards the central potential minimum of the halo. As the gas contracts, dark matter is also dragged in gravitationally as the potential well given by the star deepens. This increases the dark matter densities inside the forming star, increasing the rate of WIMP annihilations. As WIMPs annihilate, their energy is released as high energy standard model particles. Only neutrinos are able to escape the forming star, the rest stay and locally heat the gas. For the very first stars the WIMPs might become abundant enough for WIMP annihilations to become the main energy source for the forming star; for this the name “dark stars” was coined for such objects [49]. The energy injected by dark matter slows the collapse of the star and delays the onset of nuclear burning in the star. This allows the star to accrete gas for a longer period, making the final star more massive. The increased mass makes the formed star more luminous and more short lived which affects the reionization of the universe. The increased mass affects the way the star dies; determining if it leaves a black hole remnant or not, and if it explodes as a supernova of some sort.

The dark matter gravitationally pulled in by the collapsing gas effectively annihilates away during the star formation process. This scenario leaves the formed main sequence star a “normal”, but slightly heavier population III star. So far in this discussion, the effect of WIMP-nucleon scattering has not been taken into account. It has been suggested, based on estimates using the formulas of Gould [50], that scattering could replenish the high abundance of dark matter inside the star. If true, this could potentially have far reaching consequences. If dark matter

is an important long term energy source for the formed star, this could change the physical features and color of the star. Sufficient energy injection from WIMPs could also slow down or turn off nuclear burning inside the star. If this energy injection is stable over time, this could potentially prolong the lifetime of the star significantly.

However, the formulas of Gould do not well reflect the physics of the WIMP capture process for the first stars. The second paper in this thesis looks at the energy injected in the star from WIMP annihilations, and especially the effects of scattering in detail. It was found that for a high scatter cross section the energy injected by WIMP annihilations increases but essentially only during the star formation phase. For the single star scenario investigated, the formed star does not benefit from long term dark matter heating unless turbulence effects not accounted for turns out to be extremely important.

To find the heating of the star from WIMP annihilations one needs to find how the WIMPs behave in and around the forming star. This is done by constructing a Monte Carlo simulation following the individual WIMPs from the initial NFW halo as the potential changes due to the forming star. If the evolution of the potential is slow compared to the orbital time scale of the WIMPs, the response of the orbiting WIMPs to the change of potential depend only on their orbits and not on their locations in the orbits. Such a process is adiabatic, so one can then use the adiabatic invariants to calculate the WIMPs' response to the contracting baryons.

### 3.3.1 Adiabatic contraction

In the system analysed the star forms in the center of the halo and dominates the gravitational potential in the central region of the halo. The system is spherically symmetric and the velocity of a WIMP moving in this potential is, in spherical coordinates:

$$v^2 = \dot{r}^2 + r^2\dot{\theta}^2 + r^2 \sin^2(\theta)\dot{\phi}^2. \quad (3.1)$$

A particle moving in a spherically symmetric potential will move in an orbit confined to a plane. Choosing this to be a plane of constant  $\phi$  the expression simplifies since  $\dot{\phi} = 0$ . This gives the Hamiltonian

$$H(r, \theta, p_r, p_\theta, t) = \frac{mv^2}{2} + V(r, t) = \frac{1}{2m} \left( p_r^2 + \frac{p_\theta^2}{r^2} \right) + V(r, t), \quad (3.2)$$

where  $p_i$  refers to conjugate momentum:  $p_i = \frac{\partial L}{\partial \dot{q}_i}$ . Since  $H$  does not depend explicitly on  $\theta$  neither does the Lagrangian. Using the Euler-Lagrange equations we have

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}} = \frac{\partial L}{\partial \theta} = 0 \quad (3.3)$$

and hence, the conjugate momentum,  $p_\theta$ , is a constant of motion for the orbit, usually referred to as the angular momentum,  $J$ . The action variables, defined as

$J_i = \oint p_i dq_i$ , are adiabatic invariants, i.e. unchanged during an adiabatic contraction [51]. With  $p_\theta$  being a constant we immediately have

$$J_\theta = \oint p_\theta dq_\theta = p_\theta \oint dq_\theta = 2\pi p_\theta = 2\pi J. \quad (3.4)$$

Hence, the angular momentum of the WIMP's orbit remains unchanged during the contraction.

In eq. (3.2) the Hamiltonian depends on time explicitly but the contraction process is assumed to be adiabatic and hence, the time dependence can be neglected on orbital time scales. When neglecting the explicit time dependence of the Hamiltonian, the energy becomes conserved and the Hamiltonian is constant,  $H = E$ . Using this, eq. (3.2) can be rewritten as

$$\frac{1}{2m} \left( p_r^2 + \frac{l^2}{r^2} \right) = E - V(r). \quad (3.5)$$

Solving for  $p_r$  the radial action now becomes

$$J_r = \oint p_r dr = 2 \int_{r_{\min}}^{r_{\max}} \sqrt{2m(E - V(r)) - J^2/r^2} dr. \quad (3.6)$$

For a Keplerian potential this integral can be performed analytically but for an orbit moving in a NFW potential or in an orbit passing through the forming star this is not the case and the integral has to be evaluated numerically.



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Part II

Scientific papers



**Paper 1**

Sofia Sivertsson, and Joakim Edsjö

*Accurate calculations of the WIMP halo around the Sun  
and prospects for gamma ray detection*

To be submitted.



**Paper 2**

Sofia Sivertsson, and Paolo Gondolo

*The WIMP capture process for dark stars in the early universe*

To be submitted.



**Paper 3**

Pat Scott and Sofia Sivertsson

*Gamma-rays from ultracompact primordial dark matter minihalos*

0908.4082 [astro-ph]

3

