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**Search for dark matter production in
association with top quarks in the dilepton
final state at $\sqrt{s} = 13$ TeV**

A thesis submitted in fulfillment of the requirements for the

Degree of Doctor of Philosophy

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Abstract

Resumen

Acknowledgements

Acronyms used

SM Standard Model

DM Dark Matter

LHC Large Hadron Collider

CMS Compact Muon Solenoid

ATLAS A Toroidal LHC ApparatuS

CERN European Council for Nuclear Research

CMB Cosmic Microwave Background

ML Machine Learning

MFV Minimal Flavour Violation

WIMP Weakly Interactive Massive Particles

PF Particle Flow

BSM Beyond the Standard Model

MACHO Massive Compact Halo Objects

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Chapter 1

Introduction

The Standard Model (SM) of particle physics is nowadays the most accepted mathematical model used to describe the elementary particles and three of the four fundamental forces of nature (electromagnetic, weak and strong interactions). This model is quite simple in concept, but has been able to describe most of the phenomena observed in nature so far with an incredible level of precision, and made a lot of predictions that have now been proven to be true, such as the postulate of the Higgs mechanism [1, 2] followed by the discovery of the Higgs boson itself in 2012 [3, 4] by the Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS) experiments of the European Council for Nuclear Research (CERN).

However, as accurate as it seems to be, this theory is known to have several shortcomings which require further investigation. Eventual exotic particles which do not fit in the current model could be the sign of new physics and have therefore been extensively searched for over the course of the last decades in order to enhance our understanding of the Universe and all its constituents.

In this context, the first serious Dark Matter (DM) hypothesis was introduced in the 1970s because of gravitational anomalies observed by several astrophysicists, as a way to explain the apparent non-luminous missing mass in the Universe [5]. Indeed, the visible mass in most galaxies appears to be way too low to explain several astrophysical processes, such as the rotation curves of the galaxies [6], which seems to be incompatible with the well established laws of gravitation. Some additional measurements of the gravitational lensing (in the Bullet Cluster, for example [7]) and the anisotropies observed in the CMB [8] can be quoted among other evidences for the existence of DM, as explained in details in Section 2.1.

As far as we currently know from cosmological measurements, ordinary baryonic matter only constitutes around 5% of the Universe, while DM represents around 26% of the energy density of the Universe (the rest is being considered as dark energy) [9]. Understanding the nature and properties of this new kind of exotic matter is therefore crucial to try and understand the physics in the Universe.

Nowadays, the existence of DM is well established in the physics community, even though it has never been observed directly, since our only evidences so far for its existence come from its large-scale gravitational effects. While its mass, spin, nature and basic properties are still unknown and extensively studied, one of the best DM candidate is the so-called Weakly Interactive Massive Particles (WIMP), predicted to interact both gravitationnaly and weakly with SM particles. This would allow direct and indirect direction of such candidates, used as the driving process of many of experiments over the last decades, trying to find the hint of a possible interaction between standard baryonic particles and eventual DM particles, or even between several DM particles themselves. Dark matter production through the use of

a particle accelerator colliding SM particles together, such as the Large Hadron Collider (LHC), is also a possibility, and will be considered as the main channel towards the eventual detection of this exotic matter throughout this work. The production through colliders is actually able to provide constraints on low dark matter masses as well, in a region where both the direct and indirect searches are less efficient, which makes the LHC a perfect tool to study this kind of Beyond the Standard Model (BSM) physics.

However, observing DM is still extremely difficult, mainly because it barely interacts with ordinary baryonic matter, except through gravity (we have to assume that it does interact with SM at least weakly for the sake of this work though, as we would not be able to discover it as an individual particle if it were not the case). This means that nowadays, all the experiments searching for DM have only been able to put constraints on the DM particle mass and on the interaction cross sections between the dark and standard sectors. Actually, even if the collisions between protons produced by the LHC do have a sufficient amount of energy to produce this kind of particles, we would not expect them to interact with our detector, meaning that a direct detection is out of our hands for now. The eventual presence of such matter has to be inferred from the study of the interaction between SM particles and CMS itself, since a typical DM-like event consists of at least one energetic SM particle produced in association with a large imbalance in the transverse momentum due to the presence of an eventual DM candidate that was able to escape our detection.

In the context of this work, DM is searched for in association with one or two top quarks which play the role of the SM particle allowing us to trigger the event. This is indeed a perfect channel for this kind of searches if we assume that the interaction between the dark and standard sectors respect the principle of Minimal Flavour Violation (MFV), which can be consistently defined independently of the structure of the new physics model [10]. In this case, this interaction should follow the same Higgs-like Yukawa coupling structure as the usual SM baryonic particles. This is an important consequence, since it will be shown in Section 2.2 that this coupling is actually stronger with more massive particles: the heavier the SM particle considered is, the easier it is for this particle to couple with the dark sector. This makes the top quark, the most massive of all the fundamental particles observed by far, is therefore an excellent object to study in this context.

However, this also means that its phenomenology is mostly driven by its large mass and that it decays before hadronization can occur, usually into a W boson and a bottom quark ($\sim 96\%$ branching ratio [11]). The final state of the process we are interested in is then made of some b jets, leptons and/or quarks and is categorized depending on this number of b jets and on the decay of the W itself. This work will actually be focused on the two leptons final state, also known as the dileptonic channel, mostly since this channel does not have lots of background processes raising to a similar final state, even though its branching ratio is the smallest, as will be explained in Section 2.5. Additionally, leptons are by reconstruction much cleaner than jets. This means that their identification and momentum calculation is easier to perform, and that the uncertainties associated to these measurements will be smaller.

The LHC has now been running for 10 years, and several similar searches have already been carried out and published in the past by the CMS and ATLAS collaborations, at different center of mass energies. First of all, at 8 TeV, several searches for a pair of top quarks were published by the CMS (in association with DM in the semileptonic [12] and dileptonic [13] final states) and ATLAS collaborations [14]. At 13 TeV, the ATLAS collaboration published on one hand several studies, considering different final states [15, 16, 17]. On the other hand, the CMS collaboration published a few extremely important papers

for this study [19, 20]. For the first time in 2019, the results obtained by the single top and $t\bar{t}$ analyses have also been combined and published using the 2016 data [21]. Our main objective is now to repeat and improve this analysis that was performed while considering a larger dataset, globally improving the analysis strategy and including the dileptonic final state for the first time in this combination.

After a detailed introduction about DM in general, the experimental device will be detailed in the Chapter 3. This will include a discussion about the LHC itself, along with a complete description of CMS, the detector used to collect the data that will be analyzed throughout this work. This data has been collected during the years 2016, 2017 and 2018 and corresponds to an integrated luminosity of $\sim 138 \text{ fb}^{-1}$, collected during the Run II of operation of the LHC and at a center of mass energy $\sqrt{s} = 13 \text{ TeV}$. In particular, a particular care will be given to the explanation of the Particle Flow (PF) algorithm, used to reconstruct the different objects used and that will be defined in the Chapter 4, while the estimation of the different backgrounds and the selection of interesting events will be detailed throughout the Chapters 5 and 6.

Distinguishing between the signal we are searching for and backgrounds having a much higher cross-section and kinematically really close, such as the SM $t\bar{t}$ without production of DM is not a straightforward task (sometimes a production of missing transverse energy due to the presence of physical neutrinos is even obtained). To isolate the signal and to obtain some discrimination between these kind of processes, an algebraic reconstruction of the event and top-notch Machine Learning (ML) techniques are used in this work, in order to train a network of neurons. The main objective is to make them learn how to combine the discriminating power of a set of input variables in order to create a single output variable describing the probability of a single event to be classified as signal or background. All this process will be detailed in Section 6.3.

Finally, a statistical interpretation of our data will be performed and different sources of systematic uncertainties will be considered in the Chapter 7. This will allow us to set upper limits on the cross section production value of DM particles in our particular channel and for the simplified models considered in this analysis. The conclusions of this work and some additional future prospects will then finally be presented in Chapter 8.

Chapter 2

The Dark Matter case

In this chapter the case for Dark Matter (DM) will first of all be presented in Section 2.1, along with a summary of the main evidences, mostly astrophysical, which lead to the introduction of this kind of Beyond the Standard Model (BSM) physics. Then, the main properties expected by such exotic matter will be introduced in Section 2.2 and nowadays's most accepted DM candidates, such as the Weakly Interactive Massive Particles (WIMP) briefly introduced previously will be presented in Section 2.3. The main ways we have to search for this new physics will then be shown in Section 2.4.

Finally, the searches performed in colliders such as the Large Hadron Collider (LHC) and our particular channels of interest (DM produced in association with either one or two top quarks) will be detailed in Section 2.5 and the latest similar results and exclusion plots published over the course of the previous years by the ATLAS and CMS collaborations will be shown in Section 2.6.

2.1 At the origins of dark matter

The origin of the concept of dark matter can be traced back to the 17 and 18th centuries, shortly after Newton's works on gravitation, even though this concept changed a lot over the years. Back then, DM was more considered to be ordinary matter which simply did not emit any kind of electromagnetic radiation, being therefore invisible and dark, but which does have a strong impact in the gravitational point of view because of its mass. It was for example considered in the 20th century to be found in massive astronomical objects able to absorb the light or other objects located behind them, such as black holes.

2.1.1 Zwicky and the virial theorem

Around this time, the first experimental evidences for the existence of dark matter were shown. In 1933, Fritz Zwicky managed to determine the mass of the Coma Cluster using the virial theorem [22], which states that if in a cluster in equilibrium under its own gravitation, the kinetic energy must be comparable to the gravitational binding energy.

Mathematically, the virial theorem can be written in Equation 2.1, where the brackets represents the mean value of the quantity obtained over time or position, the universal constants of gravitation $G = 6.67 \cdot 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ and where the gravitation potential energy expression can be simplified assuming a spherical

distribution of the masses and the same average density everywhere in the cluster.

$$2\langle T \rangle + \langle V \rangle = 0, \text{ where } \begin{cases} T = \frac{1}{2} \sum_i M_i v_i^2 = \frac{1}{2} M \langle v^2 \rangle \\ V = -4\pi G \int_0^R M \rho r dr \propto \frac{GM^2}{R} \end{cases} \quad (2.1)$$

Solving these simple equations gives us an approximate value of the mass of the cluster in Equation 2.2, where R is the radius of the cluster and $\langle v^2 \rangle$ is the squared velocity of all the galaxies averaged over time.

$$M \propto \frac{\langle \langle v^2 \rangle \rangle R}{G} \quad (2.2)$$

From this simple expression and astronomical observations, Zwicky then managed to compute the average mass to light ratio of its galaxies and concluded that the value obtained was around 500 times larger than the mass previously estimated by Edwin Hubble, who simply considered the number of visible galaxies within this cluster. One plausible explanation for this discrepancy is to introduce the concept dark matter, which contributes to the mass of the cluster without increasing the galactic luminosity.

Zwicky's results were actually quite controversial since they were based on statistical calculations relying on different hypotheses not always justified, such as the fact that the galaxies in the cluster must be gravitationnaly bound with each other and they were actually proven to be overestimated later on [23].

2.1.2 Spiral galaxies rotation curves

Despite being controversial and slightly off, Zwicky's results were soon followed by a series of additional astronomical observations leading to the same conclusion, the possible existence of non-luminous matter in all the galaxies, called dark matter. The most famous of these results is the study of the observed and expected rotation curves of the stars within spiral galaxies such as the Milky Way in the 1970s [6].

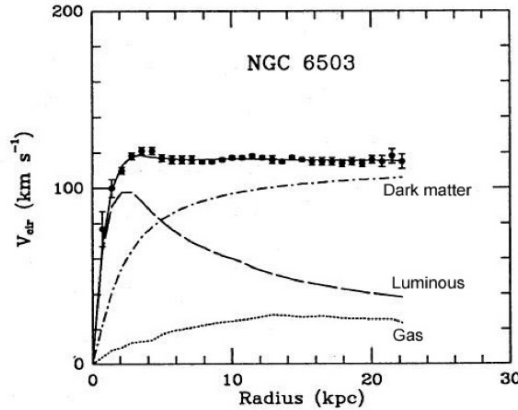
According to this study, if we assume that we can apply Newton's universal laws of gravitation at the galactic scale, then the stars within this kind of galaxies should rotate with a velocity depending on the radius to the galactic center obtained by the usual equation for centripetal acceleration in a gravitational field and represented in Equation 2.3, where $M(r)$ accounts for the total mass encountered in a radius r .

$$v_{\text{rotation}}(r) = \sqrt{\frac{GM(r)}{r}} \quad (2.3)$$

At first approximation, one can assume that most of the mass within this kind of galaxies comes from the inner core, meaning that, at large radius, the velocity of individual stars is expected to decrease proportionally to $r^{-1/2}$. Any deviation to this rule suggest that either our understanding of gravite at large scales has to be revised, or that our basic understanding of galaxies as a celestial body made of stars, dust and gas, has to be revised.

However, observations made by Vera Rubin and her team in the early 1970s with a new spectrograph

designed the velocity curves of spiral galaxies with a degree of accuracy never reached before, did not confirm these expectations [24]. Indeed, according to these results, from a given value of the radius, the velocity curve appears to be flat instead of decreasing as expected, as illustrated in Figure 2.1.



K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

Figure 2.1: Expected and observed rotation curves of the galaxy NGC 6503 [6]. The black dots correspond to the data and the *luminous* line corresponds to the expected rotation curve.

2.1.3 Cosmic Microwave Background (CMB) anisotropies

The CMB is a mostly uniform background of primary radio waves emitted when the Universe became transparent around 380.000 years after the Big Bang and was discovered accidentally in the 1940s [25]. Studying it is extremely important, as it is actually made of the oldest and cleanest electromagnetic radiation we can find in the Universe. Precise measurements of this radiation are actually critical in many different fields of physics, since any proposed model of the Universe must be able to explain this radiation, its temperature and anisotropies.

Recent measurements determined that the CMB can be considered as emitting a thermal black body spectrum at a temperature of $(2.72548 \pm 0.00057)\text{K}$ [26]. However, we now know that this temperature is actually not constant as some small anisotropies (at the 10^{-5} level) depending on the value of the angular angle of observation can be observed, as represented on Figure 2.2.

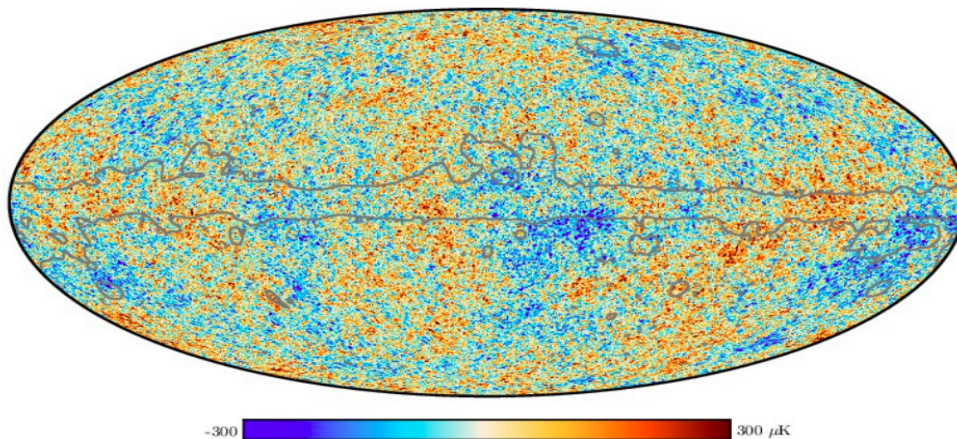


Figure 2.2: Anisotropies in the temperature of the CMB, as observed by the Planck satellite in 2018 [27].

We see these fluctuations projected over a 2D sphere, and it is therefore natural to introduce at this point Laplace's spherical harmonics, $Y_{lm}(\theta, \phi)$, a complete set of orthogonal functions defined on a sphere and defined by a few parameters such as l , the multipole, representing a given angular angle in the sky ($l=100$ corresponds to $\sim 1^\circ$) and m , the number of poles, such as $-l \leq m \leq l$ [28].

The temperature fluctuations, whose value depend on the two usual spherical angles θ and ϕ can then be expanded using these generic functions, according to Equation 2.4.

$$\frac{\Delta T}{T}(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi) \quad (2.4)$$

The information about the anisotropies can actually be extracted from the values of the a_{lm} coefficients, from which we can obtain the values needed to represent the power spectrum of the CMB, according to Equation 2.5, and from which most of the cosmological information of the CMB can actually be derived.

$$D_l = \frac{l(l-1)C_l}{2\pi} = \sum_m |a_{lm}^2| \quad (2.5)$$

Interestingly enough, this spectrum is directly affected by the value of the density of the dark matter in the Universe. Doing a multi-parameters fit on the observed data in this plot is then able to give us directly the energy density of baryonic Ω_b and dark Ω_χ matter, along with other important parameters of the Λ CDM cosmological model. Today's most precise measurements have been obtained in 2018 using the Planck satellite, and lead to the determination of these two quantities: $\Omega_b h^2 = 0.02220 \pm 0.00020$ and $\Omega_\chi h^2 = 0.1185 \pm 0.0015$ [29] and the actual power spectrum obtained represented in Figure 2.3.

By dividing these results with the value of the scaling factor for Hubble expansion rate $h = 0.674$ [30], we can obtain from these numbers a proportion of 4.9% of ordinary baryonic matter and 26.1% of dark matter in the Universe.

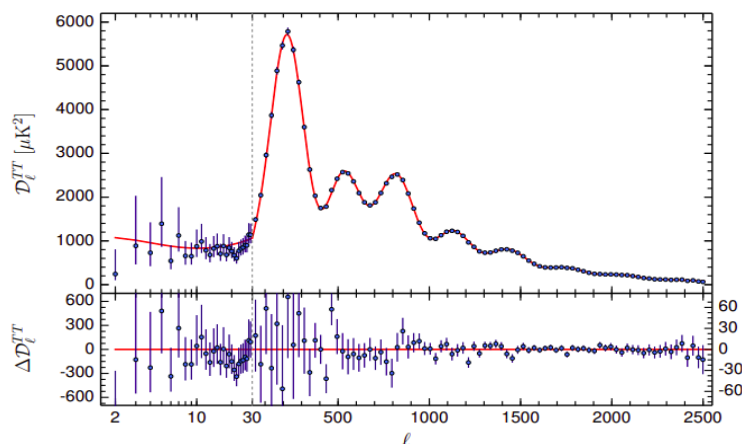


Figure 2.3: Power spectrum of the CMB obtained by Planck, representing the fluctuations of the temperature of this radiation with respect to the angular angle of observation.

2.1.4 Gravitational lensing

The last evidence supporting the existence of dark matter has been obtained by observing several clusters of galaxies in the Universe, such as the Bullet Cluster, and by studying their mass distribution through gravitational lensing. This effect is a consequence of the general relativity, a theory developed by Einstein has a way to represent gravity using the geometry or spacetime, stating that massive objects lying between distant sources and an observer should act as a lens and bend the light of the object emitted by the source. This deviation of the light is actually proportional to the mass of the object in between the source and the observer, meaning that the gravitational lensing can give us a way to measure the mass distribution within massive objects, such as galaxy clusters.

The bullet Cluster is particularly interesting in this context since it actually provides an evidence for the eventual existence of dark matter which does not rely on any mathematical assumption and cannot at principle be explained by alternate laws of gravitation. Indeed, some observations showed that the spatial deviations between the center of the total mass and the center of the baryonic mass cannot be explained with an alteration of the gravitational force law alone, with a statistical significance of around 8σ [31].

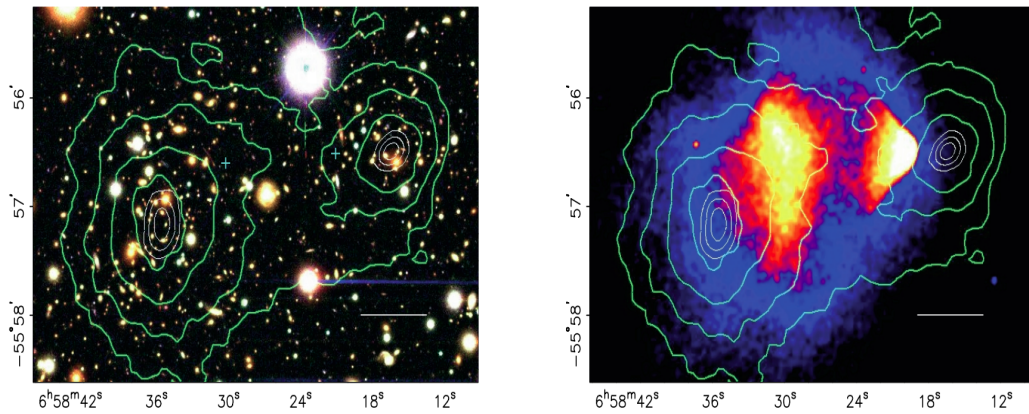


Figure 2.4: Mass distributions obtained by the Magellan in the visible (on the left) and Chandra on the X-rays spectrum (on the right) telescopes of the Bullet Cluster, yet another clear evidence for the existence of DM [31].

As seen in Figure 2.4, the image taken by Chandra clearly shows an offset between the plasma of the cluster and the actual mass distribution measured through gravitational lensing (green contours). The mass distribution appears to be slightly deviated compared to what was expected based on the X-ray emissions of this cluster.

2.2 Dark matter properties

All the previous observations allow us to list some of the most important properties that the perfect dark matter candidate should have. Even though several theories exist, each giving different properties to the DM, we will consider in this work the following mostly accepted properties for such particles:

- First of all, we will assume that DM is a **particle**. As far as we know, the Universe, is simply composed of particles so there is no objective reason to think that DM, being matter with a certain mass, might not be made of some kind of indivisible particle at some level.
- First of all, the perfect DM candidate should of course be **dark**. This means that it should not interact at all in with electromagnetic radiation such as light, and that it should therefore be **electrically neutral**. However, it has to interact gravitationnaly because of the evidences for the evidence of such a particle explained before, mostly relying on gravitational effects.
- It has to be **non-baryonic**, mainly because the energy density for the baryonic matter obtained by observing the power spectrum of the CMB is too low to account for DM as well, as explained in Section 2.1.3. Indeed, according to these results, baryonic matter account for around 5% while dark matter accounts for more than 25% of the energy density of the Universe.
- We will also only consider **cold** dark matter, since the widely accepted Λ CDM cosmological model is actually based on this assumption. By cold, we do not refer to the temperature of these particles but actually to their size, and therefore to the velocity by which they can travel in the Universe. Large scale structures of the Universe such as we can observe them today cannot actually not be explained if DM is made of hot/relativistic particles, as represented in Figure 2.5.
- It is interesting to report as well that DM particles are expected to be found near the electroweak symmetry breaking scale, between **10 GeV and 1 TeV**. This is a consequence of the expected production mechanism of such particles, the so-called thermal freeze-out.

This principle tells us that at some point in the history, DM was in thermal equilibrium with other primordial standard particles, meaning that its production and annihilation rates were equal. However, because of the expansion of the Universe, at some point DM particles were simply too far apart from each other and these reactions maintaining this equilibrium became not efficient enough to maintain this equilibrium. At this stage, the abundance of DM became fixed: this is the freeze-out, as represented in Figure 2.6.

This principle is interesting because, as a rule of thumb, we can say that if a particle interacts heavily, it will stay longer in equilibrium and its freeze-out abundance will be smaller, so there is a mathematical relation between the strength of the SM/DM interaction g , the mass of the DM particle m_χ and its actual abundance Ω_χ that can be measured, as expressed in Equation 2.6 [32].

$$\Omega_\chi \propto \frac{m_\chi^2}{g^4} \quad (2.6)$$

By using a typical value for g of the order of the Fermi coupling constant $G_0^F \simeq 4.54 \cdot 10^{-14} \text{ J}^{-2}$, we can see that, in order to observe a freeze-out abundance comparable to the current one, the DM candidate should indeed have a mass between 10 GeV and 1 TeV.

- Finally, they should be **long-lived**. Indeed, we expect that DM particles were produced 13.8 billion years ago during the Big Bang, but it seems that we still see them today. They should then be stable particles, or their lifetime should at least be larger than the age of the Universe itself.

All these properties narrow quite a lot the number of possible DM candidates, as we will see in the following section.

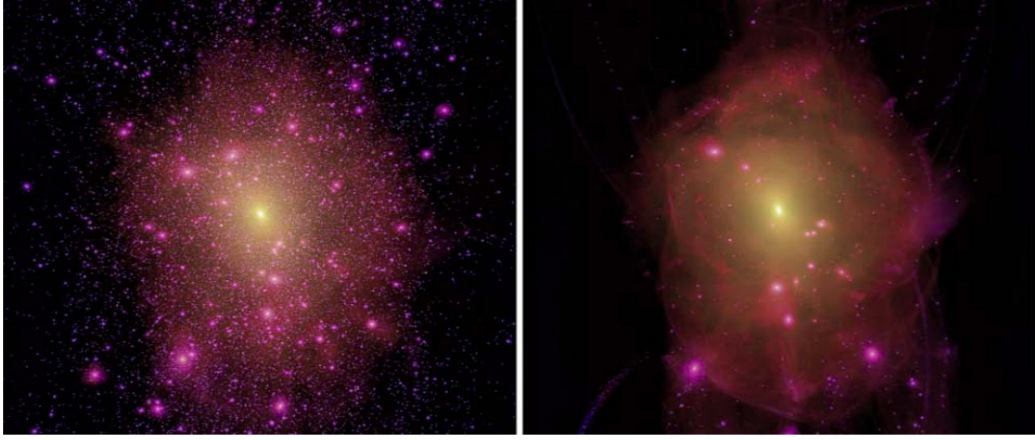


Figure 2.5: Computer simulations for cold (on the left) and warm (on the right) DM scenarios and their impact on a galactic halo at 0 redshift [33].

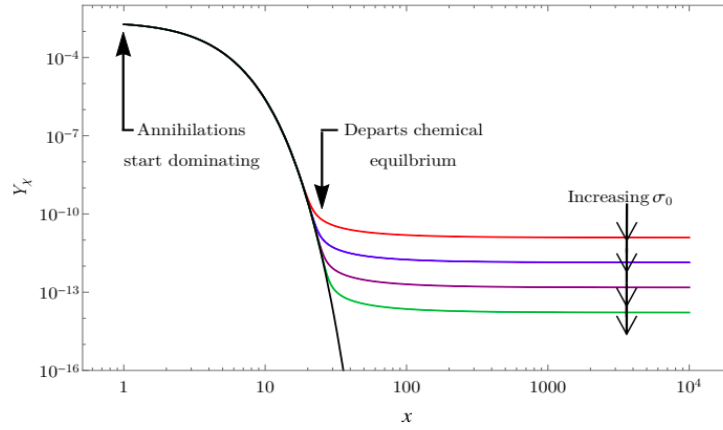


Figure 2.6: Schematic representation of the freeze-out process, representing the abundance of a 500 GeV DM as Y_χ with respect to the time and the impact of increasing cross-section values on this freeze-out abundance [34].

2.3 Dark matter candidates

Several different categories of particles could pretend to be good candidates for dark matter. However, only the most interesting ones will be quoted here, since an extensive list of all the different possible candidates is out of the scope of this work.

- The first DM candidate are the so-called **Massive Compact Halo Objects (MACHO)**. These objects are massive astronomical non-luminous bodies (such as black holes) made of baryonic matter that could be responsible of the gravitational lensing observed and that could explain the apparent missing mass in the Universe. However, as we saw in Section 2.2, DM is not expected to be made of such ordinary matter, basically because observational data of the CMB and the deduced baryonic density of energy in the Universe is able to rule out this possibility.
- Axions
- Sterile neutrinos
- Last but not least, WIMP. Hierarchy problem solved.

2.4 Dark matter searches

2.5 Production at the LHC

2.5.1 The single top production channel

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2.6 Previous results

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4.2.2 Muons

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$t\bar{t}$ reconstruction

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