Review on Dark Matter Candidates

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Abstract

Our beautiful abstract will come here.

1 Introduction

One of the most important problems in particle physics and cosmology is the nature of dark matter (DM) in the Universe. Evidence for the existence of large amounts of DM in the Universe has been increasing steadily over last decades, yet its origin and nature remain unknown at this time. A popular view on dark matter is that is consists of weakly interacting massive particles (WIMPs). This is a popular DM candidate for a number of reasons. First of all, in many theoretically well-motivated extensions of the Standard Model (SM) WIMPs arise naturally. In addition, WIMPs are attractive experimentally because their detection rates are within reach of current or future detectors [1]. The third and perhaps most enticing feature of WIMPs as a DM candidate is that the production mechanism of the DM abundance today, the *thermal freeze out* mechanism, is simple and understood entirely [2]. The freeze out mechanism will be discussed in section 2. The beauty of this mechanism is emphasised by the socalled the *WIMP miracle*. To account for the amount of DM in the Universe today, the freeze out mechanism provides constraints on the mass and the cross section of the WIMP. Using the observed DM abundance today, a particle with a mass in the range of tens-hundreds GeV and a cross section which corresponds to weak interaction is predicted [3]. These properties coincide with the expected properties of the lightest stable particle (LSP) in many supersymmetric (SUSY) models. An LSP like the lightest neutralino $\tilde{X}_1^0$ is therefore an excellent WIMP candidate [4]. The seemingly magical correlation between the DM problem and SUSY models, which were initially proposed as a solution to the hierarchy problem in the SM, is therefore named the WIMP miracle. The properties of the lightest neutralino as a DM candidate will be discussed in section 3.1.

Besides the neutralino in SUSY models, other beyond the Standard Model (BSM) theories provide other WIMP candidates. One of these theories suggests the existence of an extra spatial dimension. This extra dimension takes several forms, but this review focusses on a universal extra dimension (UED). In UED the 5-dimensional spacetime is reduced to the 4-dimensional spacetime using the Kaluza-Klein (KK) method. The DM candidate that arises in these models is known as the lightest Kaluza-Klein particle (LKP), named the pyrgon [5]. See section 3.2 for a more detailed discussed of UED.

Although WIMPs are a very popular DM candidate, conclusive evidence has not been discovered yet. Therefore alternative theories on DM remain relevant. A widely discussed non-WIMP which could explain the nature of DM is the Axion [6]. Also, models of Primordrial Black Holes (PBHs) as a DM candidate have received attention, for an excellent discussion of PBHs see [7].

This review is organised as follows. In section 2 the WIMP freeze out mechanism that explains the DM abundance as today is discussed. Section 3 provides a brief discussion of some popular WIMP candidates: the LSP in SUSY models, the neutralino, and the LKP from UED, along with physical constrains from colliders. In section 4 and 5, respectively non-WIMPs and Primordial Black Holes will be disucced.

2 The freeze out mechanism

As briefly mentioned in the introduction the freeze out mechanism is the production mechanism of the WIMP DM abundance today. In the early Universe the WIMP, X, and the SM particles were in close contact at high temperatures ($T \gg m_X$). The cosmological plasma (containing the SM particles) and the DM were in thermal equilibrium due to DM particle production from annihilations [1]. The annihilation rate is given by $\Gamma_{\text{ann}} = n_X \langle \sigma_{\text{ann}} v \rangle$ where n_X is the number density of DM particles, and $\langle \sigma_{\text{ann}} v \rangle$ thermally averaged product of the cross section and the velocity [8]. A freeze out is defined as the inability of annihilations to keep the particle in thermal equilibrium [9]. The freeze out of DM, or thermal decoupling, occurred when the annihilation rate became smaller than the expansion rate of the Universe $\Gamma_{\text{ann}} \lesssim H$. In other words, the DM particles were separated by the expansion of the Universe faster than they could annihilate to maintain equilibirium, resulting in a freeze out and a relic density of DM WIMPs. Using this mechanism we can calculate this relic density of DM.

Defining $Y \equiv n_X/T^3$, the WIMP yield, the Boltzmann equation for a DM particle can be rewritten in order to calculate the abundance of DM:

$$\frac{dY}{dt} = T^3 \langle \sigma_{\text{ann}} v \rangle \{(Y_{\text{EQ}}^2 - Y^2\}, \tag{1}$$

where $Y_{\text{EQ}} = n_X^{(0)}/T^3$ [9]. Since the freeze out roughly occurs when $H \sim H(m_X)$, It is convenient to introduce a new variable $x \equiv m_X/T$. Equation 1 then becomes:

$$\frac{dY}{dx} = -\frac{\lambda}{x^2}\{Y^2 - Y_{\text{EQ}}^2\}, \tag{2}$$

where $\lambda \equiv (m_X^3 \langle \sigma_{\text{ann}} v \rangle)/H(m_X)$ is ratio of the annihilation rate to the expansion rate [9]. Since the DM particles are relativistic in this era, $x \gg 1$, the equilibrium abundance Y_{EQ} will exponentially suppressed. Therefore equation 3 simplifies to:

$$\frac{dY}{dx} \simeq -\frac{\lambda Y^2}{x^2}. \tag{3}$$

Integrating this from the freeze out (Y_{fo}) to today (or late times) (Y_∞) and using the fact that typically $Y_{\text{fo}} \gg Y_\infty$), the DM abundance today becomes $Y_\infty \simeq x_{fo}/\lambda$. The number density at late times is $Y_\infty T^3$, so the energy density of DM today can be expressed as:

$$\rho_X = \frac{m_X Y_\infty T_0^3}{30}, \tag{4}$$

where T_0 is the temperature today [9]. The fraction of the critical density ρ_c can now be drived:

$$\begin{aligned} \Omega_X \equiv \frac{\rho_X}{\rho_c} &= \frac{m_X Y_\infty T_0^3}{30\rho_c} \\ &= \frac{x_{fo} H(m_f) T_0^3}{30 m_X^2 \langle \sigma_{\text{ann}} v \rangle \rho_c}. \end{aligned} \tag{5}$$

Putting in known quantities: $T_0 \simeq 2.35 \times 10^{-13}$ GeV, $\rho_c \simeq 8 \times 10^{-47} h^2$ GeV^4 [1], it is possible to plot the abundance of the WIMP versus x, as shown if figure 1.

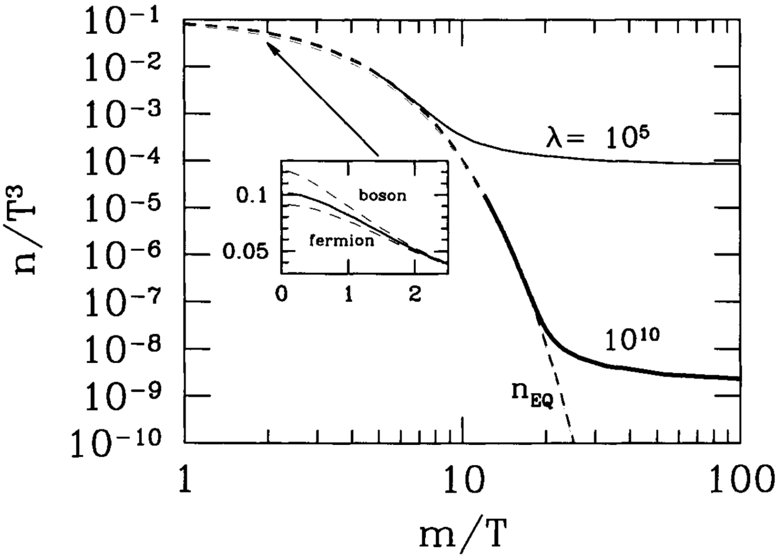

Figure 1: The abundance of heavy stable particle as the temperature drops beneath its mass. Dashed line is equilibrium abundance. Two different solid curves show heavy particle abundance for two different values of λ, the ratio of the annihilation rate to the Hubble rate. Inset shows that the difference between quantum statistics and Boltzmann statistics is important only at temperatures larger than the mass. Taken from [9].

3 WIMPs

3.1 SUSY

This needs to come before UED and I (very) briefly mention the neutralino.

3.2 Universal Extra Dimension

Although the neutralino is a strong candidate as a DM particle, while the identity of the DM particle remains unknown we will also probe alternative theories. One of these theories is the existence of an extra spatial dimension. This spatial dimension would arise at a high energy scale. The idea is motivated by string theory and M-Theory. Although these will not be discussed at length in this review; an excellent reference for this would be [10].

This has multiple benefits to the standard model, including anomaly cancellation, dynamical electroweak symmetry breaking, prevention of rapid proton decay and, for the importance of this review, a DM candidate [11]. This extra dimension takes several forms. Firstly there is a universal extra dimension (UED) [12], in which all paticles in the Standard Model will propagate on. Alternatively, our observable (3+1) dimensional space is a brane existing in a higher (3+δ+1) bulk spacetime [13]. In the Arkani-Hamed, Dimopoulos and Dvali (ADD) model, all Standard Model particles will propagate on 3 spatial dimensions whereas the graviton will propagate in the bulk. There are also intermediate theories, where only certain families will propagate in the bulk, which gives rise to the anomaly cancellations [14]. For the remainder of this review we shall be focusing on UED.

UED offers an additional feature not seen in the brane approach. There is remains translational symmetry, leading to a conservation of the momentum in all dimensions. In UED, the extra spatial dimension is flat space compactified onto S^1. The method used to reduce the 5-dimensional theory to the 4-dimensional one is known as Kaluza Klein (KK) reduction, which gives a number of interesting properites. We will give a brief, simplified description of this shortly. To account for chiral fermions, a Z_2 symmetry needs to be imposed, i.e. $x^4 \to -x^4$. Fields can be even or odd under this symmetry. The compactified space is therefore known as an S^1/Z_2 orbifold [15]. We will have orbifold fixed points at $x^4 = 0, \pi R$. These fixed points will break translational symmetry in the x^5 direction, also breaking momentum conservation. A symmetry known as the KK number, coming from momentum conservation, is therefore also broken by this Z_2 symmetry. But a residual conservation is seen; the KK-parity is given by $(-1)^m$. All modes with odd m will be charged under this parity. It is also clear there will be mixing between KK modes due to this broken momentum conservation. The DM candidate emerging from these modes is known as the lightest Kaluza-Klein particle (LKP), where $m = 1$ [16]. It was first discussed by Kolb and Slansky, who coined it the pyrgons [5]. The LKP is stable as it is protected by KK-parity, at tree-level. As stated, a DM candidate must be stable, electrically neutral and non-baryonic. The best candidates from this theory then become the first level KK modes of the neutral gauge bosons (the photon and Z boson) and the neutrino. Following the notation of [16], we will refer to the first photon mode as $B^{(1)}$.

Returning to the KK modes, first consider imposing periodic boundary conditions on our orbifold (we consider fields even under Z_2), expanding in Fourier modes gives us particles in the form (suppressing spacetime indices),

$$\psi(x^\mu, x^4) = \sum_{n \in \mathbf{Z}} e^{(inx^4/R)} \phi_n(x^\mu) \tag{6}$$

where the quantisation of the momentum in the extra dimension, x^4, keeps the wavefunction single-valued [17]. Here R is the radius of the orbifold. For completeness, $\phi_n^* = \phi_{-n}$. Using the equation of motion, it can be seen that there are mass modes of $M_n^2 \sim n^2/R^2$, and we have found the tower of KK modes. The zero modes here correspond to Standard Model states [15]. A detection of the higher modes, as seen by CERN, would appear as periodic spikes in the number of events as a function of centre of mass energy. So far no such signal has been found.

The relic density of $B^{(1)}$ has been computed in [16], where they considered coannihilations with the next lightest KK particle, $e_R^{(1)}$, the right handed first KK mode of the electron. It can been seen in Figure 2. It was assumed all other modes are too heavy to contribute. The relative mass difference between the LKP and the NLKP was inputted as

$$\Delta = \frac{m_{NLKP} - m_{LKP}}{m_{LKP}} \tag{7}$$

It is important to note that the density of the $B^{(1)}$ is increased when considering $e_R^{(1)}$ than without. This is because the cross section for self-annihilation is larger than the cross-section for coannihilation; the particles will decouple at a similar time with coannihilation as without, and the remaining $e_R^{(1)}$ will decay into $B^{(1)}$. The green region is the required relic density, which corresponds to masses between $0.6 - 1.2$ TeV depending on the model considered.

The first mode of the neutrino, $\nu^{(1)}$ has also been considered as a possible candidate. It satisfies stable, electrically neutral and non-baryonic conditions required from WIMPs. Its relic density has been discussed in further detail in [16].

There are other nuances to consider with these particles, these have been discussed in other papers at length. We have used mostly tree-level consideration, but for a paper on the radiative correction to the mass of the KK particles, see [18]. They consider the fact that the extra dimensions in our theory will violate Lorentz symmetry, giving corrections to the mass beyond tree-level. We would also stumble upon log divergences and interactions between only even or odd KK modes. Further discussion on direct detection can be found in [19]. Recent experimental bounds on R are given by $R \lesssim 40$ μm [20].

3.3 Constraints on Dark Matter from collider experiments

As WIMPs interact very weakly with normal matter, high energy particle colliders like the LHC are unsuitable for directly detecting them. These experiments however can be useful in putting constraints on WIMP properties like its mass and cross-section, which can aid in direct and indirect searches for these particles. As direct detection experiments depend on a strong coupling of a WIMP to nucleons, this means that a significant amount of WIMPs will also be produced in high-energy collisions. In particle collisions transverse momentum p_T, so momentum perpendicular to the beam line, needs to be conserved. Missing transverse momentum could then indicate unidentified particles, including WIMPs.

Next we will discuss models that can be used to determine these constraints. We would like to know how in depth these models must be treated and if these sources are fine or if more up-to-date sources would be better. https://arxiv.org/pdf/1005.1286.pdf https://arxiv.org/abs/1105.3248 https://arxiv.org/pdf/hep-ph/0404175.pdf

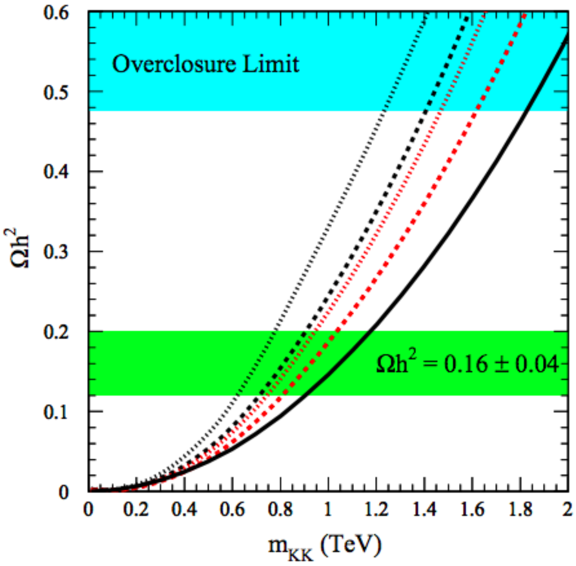

Figure 2: The relic density of $B^{(1)}$ against its mass. The solid line considers $B^{(1)}$ alone, and the dashed and dotted lines correspond to the case in which there are one or three flavors of nearly degenerate $e^{(1)}$ respectively. For each case, the black curves denote the case $\Delta = 0.01$ and the red curves $\Delta = 0.05$. Figure taken from [16].

4 Non-WIMPs

Yet to come...

5 Primordial Black Holes

Yet to come...

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