Particle Dark Matter Candidates

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Abstract. I give a short overview on some of the favorite particle Cold Dark Matter candidates today, focusing on those having detectable interactions: the axion, the KK–photon in Universal Extra Dimensions, the heavy photon in Little Higgs and the neutralino in Supersymmetry. The neutralino is still the most popular, and today is available in different flavours: SUGRA, nuSUGRA, sub–GUT, Mirage mediation, NMSSM, effective MSSM, scenarios with CP violation. Some of these scenarios are already at the level of present sensitivities for direct DM searches.

1. Introduction

About 20% of the energy density of the present Universe appears to be in the form of Cold Dark Matter (CMD) \([1]\), i.e. of particles non–relativistic at the time of their decoupling from the plasma in the Early Universe whose contribution is considered as an indispensable catalyst to the formation of galaxies. CDM clusters at the galactic level, so that it should pervade our solar system and be detectable by direct or indirect techniques. In my talk I will give a short overview on some of the most popular particle CDM candidates today, focusing on those having detectable interactions. So, while Super–Weak DM candidates such as sterile neutrinos and gravitinos represent a viable possibility to explain DM \([2]\), I will not cover them here since they cannot be measured in DM searches. Moreover, I will only discuss direct DM detection, since indirect searches have been discussed elsewhere in this Conference \([3]\).

The properties of a good DM candidate are well known: it should be stable (its decay being forbidden by the conservation of some quantum number), neutrally charged and colourless (in order to be really “dark”), possibly motivated by theory (although “ad hoc” candidates may have the advantage of minimality and simplicity \([4]\)). Moreover, its calculated relic abundance should be compatible to observation, although candidates providing a subdominant contribution to CDM represent a quite reasonable option\([1]\).

In the following \(\Omega \equiv \rho/\rho_c\) will indicate a candidate cosmological mass density \(\rho\) normalized to the critical one, \(\rho_c = 1.8791 \times 10^{-29} \text{ g cm}^{-3}\), and \(h \equiv H_0/100 \text{ km sec}^{-1} \text{ Mpc}^{-1}\) will indicate the normalized Hubble constant at present times.

2. The neutrino

The first place to look for a DM candidate is the Standard Model (SM) of interactions. In this case the only viable DM candidate is the neutrino, whose relic abundance as a function

Variety is common in Nature, and a multicomponent CDM might even have larger detection cross sections, and so be easier to detect.
of the mass is shown in Fig. 1, taken from [5]. Since LEP excludes additional neutrinos (with standard weak interactions) with masses \( m_\nu < \sim 45 \text{ GeV} \) one can see from this figure that the mass density of ordinary heavy neutrinos is bound to be very small, \( \Omega_\nu h^2 < \sim 0.001 \) for masses up to \( m_\nu \sim \mathcal{O}(100) \text{ TeV} \). At lower masses the neutrino relic abundance is given by \( \Omega_\nu h^2 = \sum m_\nu / 91.5 \text{ eV} \), that, when compared to observation, implies the constraint \( \sum m_\nu < 10 \text{ eV} \). However a more stringent limit \( \sum m_\nu < \sim 0.66 \text{ eV} \) can be derived combining CMB and Large Scale Structure (LSS) data [1], implying \( \Omega_\nu h^2 < \sim 0.007 \): in fact, neutrinos lighter than this bound, which are relativistic (hot) at decoupling, erase primordial perturbations due to their free streaming and prevent galaxy formation. So also in this case the neutrino abundance turns out to be small. The bottom line is that, unless neutrinos are mixed with some sterile component [2] they don’t work as DM candidates.

The need of a DM candidate outside the SM, when combined with the fact that the SM itself is believed to be an incomplete theory with a cut–off of \( \mathcal{O} \sim 1 \text{ TeV} \), is no doubt intriguing. Moreover, theory is in no shortage of viable DM candidates that have been proposed in the context of Particle Physics in order to solve/alleviate/explain problems that have nothing to do with Cosmology. In the following I will concentrate on some of the most popular.

3. The axion

The axion is the pseudo Goldstone boson of the Peccei–Quinn (PQ) symmetry, introduced in order to explain CP conservation in QCD [6]. Its mass can be considered as a free parameter, spanning several orders of magnitude, and is related to the (unknown) scale of the PQ symmetry breaking \( f_a \). The main production mechanism of relic axions is through misalignment, in which at \( T > \Lambda_{QCD} \) the axion field acquires a random initial phase \( \theta_i \) in its flat potential, while later on, when \( T < \Lambda_{QCD} \) and the potential gets “tilted”, it starts to oscillate coherently around the minimum, behaving like pressureless non–relativistic DM with density \( \Omega_a h^2 \simeq k_a (m_a / 10^{-5} \text{eV})^{-1.175} \theta_i^2 \) with \( 0.3 < k_a \) a few. If one assumes no inflation after the PQ phase transition, \( \theta_i \) is randomly distributed in the Universe, so that making the average, \( < \theta_i^2 > = \pi^2 / 3 \), the relic abundance falls in the observed range for \( m_a \gtrsim 10^{-5} \text{ eV} \). Axions can be observed through their conversion to photons when crossing a magnetic field. The present experimental situation is shown in Fig. 2 where axion models span the yellow (oblique) band.
Note however that the axion–photon coupling is affected by uncertainties on the light quark masses so that it might be suppressed compared to what usually expected\textsuperscript{[9]}. Axions are also produced today in the interior of the Sun and may be measured by making use of resonant Bragg reflection in the same crystal detectors used for direct DM searches\textsuperscript{[8]}. However their sensitivity scales as the exposition to the power 1/8, so that present limits have already saturated their maximal reach and cannot be significantly improved.

4. Weakly Interacting Massive Particles (WIMPs)

The appeal of WIMPs as DM candidates lies in the fact that their thermal cosmological density, given by: \( \Omega_{WIMP} \approx 10^{-38}\text{cm}^3\text{sec}^{-1}/ < \sigma v >_{\text{int}} \), falls naturally in the correct range if \( < \sigma v >_{\text{int}} \) is of the order of weak–type interactions. In the last expression \( < \sigma v >_{\text{int}} \) is the integral over \( T \) from the WIMP decoupling temperature \( T_f \) to the present one of the thermal average of the WIMP annihilation cross section \( \sigma_{\text{ann}} \) to standard particles. This simple picture is modified when the WIMP is close in mass to other particles that may either co–annihilate faster, depleting its density, or slower, enhancing the density by acting as a WIMP reservoir at their decay. Moreover, the cross section may be strongly enhanced (and the relic density suppressed) for particular values of the WIMP mass for which resonant annihilation takes place. Examples of WIMPs are the Heavy Photon in Little Higgs theories, the KK–photon in Universal Extra Dimensions and the neutralino in Supersymmetry.

In the following \( \sigma_{\text{scalar}}^{(\text{nucleon})} \) will indicate the coherent WIMP–nucleon cross section.

4.1. Little Higgs (LH)

In LH models\textsuperscript{[11]} the Higgs particle is naturally light because it is the pseudo Goldstone boson from the (collective) symmetry breaking of an effective non–linear \( \sigma \) model. New heavy particles (gauge bosons, singlet and triplet scalars, neutrinos, quarks) are present in the model, and \( T \)–parity conservation (where SM particles are even and new ones mostly odd) is introduced in order to forbid dangerous tree level couplings that would put severe constraints from precision Electro–Weak (EW) test\textsuperscript{[2]}. The Lighest \( T \)–odd Particle (LTP) is typically a Heavy Photon \( B_H \).

\textsuperscript{2} Note however that it has been pointed out that \( T \)–parity is generally broken by anomalies\textsuperscript{[12]}. 

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**Figure 2.** Constraints on the axion–photon coupling as a function of the axion mass.
which is stable and can be a dark matter candidate. Having weak–type interactions the relic abundance of $B_H$ falls naturally in the correct range. On the other hand, its direct detection cross section is expected to be smaller than the present experimental sensitivities (barring some resonant effect), $\sigma_{\text{(nucleon)}}^{(\text{scalar})} \lesssim 10^{-9}$ pbarn.

4.2. Universal Extra Dimensions (UED)
In the simplest UED model all SM fields propagate in an additional $5^{\text{th}}$ dimension which is compactified on an orbifold $S^1/Z_2$. The dispersion relation in the $5^{\text{th}}$ dimension, $E^2 = \vec{p}^2 + (p_5^2 + M^2)$ implies for each SM particle an infinite tower of massive states (KK tower) in the effective 4–dimensional theory, with $p_5 = n/R$ ($n = 1, 2, 3, ...$) while, from electroweak tests constraints, $R^{-1} \gtrsim 300$ GeV. Orbifold compactification, required in order to get rid of unwanted degrees of freedom in the ground ($n=0$) states, breaks translational invariance in the $5^{\text{th}}$ dimension, but leaves unbroken the residual invariance under discrete $\pi R$ translations (KK–parity$\equiv (-1)^n$). Typically, the Lowest KK particle is the KK photon $B^{(1)}$ which is stable and a DM candidate. Because of the peculiar evenly–spaced spectrum of KK particles, many modes in UED have similar masses (implying co–annihilations) or integer mass ratios (implying resonant annihilations). In particular, depending on whether the co–annihilating next-to-lighest KK particles are strongly interacting (KK quarks and/or gluons) or not (KK leptons) the relic abundance may be either suppressed or enhanced, so that the range of $R^{-1}$ which corresponds to a correct DM abundance is rather large: $500$ GeV $\lesssim R^{-1} \lesssim 2$ TeV. Direct detection turns out to be below present sensitivities, $\sigma_{\text{(nucleon)}}^{(\text{scalar})} \lesssim 10^{-9}$ pbarn, and depends on the degree of degeneracy between $B^{(1)}$ and the KK quarks in the propagator.

4.3. Supersymmetry (susy)
Susy is widely considered to be the most natural extension of the SM. In susy every SM particle belongs to a supermultiplet containing partners with opposite statistics (the susy partners of gauge and Higgs bosons being fermionic gauginos and Higgsinos, while those of fermions being scalar fermions or sfermions) in such a way that the total number of fermionic and bosonic degrees of freedom is the same. In general the theory has Yukawa couplings involving squarks and sleptons that violate the baryon and lepton numbers at the tree level and that imply fast proton decay. R–parity is the symmetry that the theory acquires when all these couplings are removed from the superpotential: all SM particles are parity–even, while susy partners are parity–odd, so if R–parity is conserved the Lowest Supersymmetric Particle (LSP) is stable and can be a DM candidate. Moreover, since we know from experiment that particles within supermultiplets are not degenerate in mass, susy must be broken. Unfortunately the mechanism of susy-breaking is model–dependent, so the theory has many free parameters: soft and gaugino masses, the Higgs–mixing parameter $\mu$ and the ratio of the two vacuum expectation values $\tan \beta$ (in susy at least two Higgs doublets are required, and the particle content, consisting in 5 states, contains 2 neutral scalars $h$ and $H$, one neutral pseudoscalar $A$ and 2 charged scalars $H^\pm$) along with a huge number of flavour–mixing parameters and phases that are usually neglected. In a large region of the susy parameter space the LSP is the neutralino$^3$, defined as the superposition of neutral gauginos and Higgsinos: $\chi \equiv a_1 B + a_2 W_3 + a_3 H_1 + a_4 H_2$, which clearly has all the properties of an ideal DM candidate. In the following I will discuss the neutralino DM phenomenology in three possible scenarios: SuperGRAvity inspired (SUGRA), Next-to-Minimal SuSy Model (NMSSM) and effective MSSM. Non–Universal SUGRA (nuSUGRA) [15], sub-GUT [16], Mirage mediation [17], MSSM singlet extensions [18] and CP violating models [19] are other scenarios that can be found in the literature and that I will not cover here.

$^3$ For a recent reassessment of sneutrino DM, see [14]
Figure 3. Neutralino phenomenology in the NMSSM scenario. **Left:** Contour plot of the neutralino relic abundance as a function of the superpotential parameters $\lambda$ and $k$. **Right:** Neutralino–nucleon cross section as a function of the neutralino mass. Both figures are taken from [22].

The SUGRA scenario [20] has just 5 free parameters, all defined at the Grand Unification (GUT) scale: one common soft mass $m_0$ for scalars, one common soft mass $m_{1/2}$ for gauginos, tan $\beta$, the trilinear coupling $A_0$ and the sign of $\mu$. They are evolved down to the EW scale by making use of renormalization group equations. In this scenario EW symmetry breaking is achieved radiatively, since the large top Yukawa coupling drives one Higgs mass parameter negative in the running from the GUT to the EW scale. This typically implies a large $\mu$ parameter with $\chi \approx \tilde{B}$ and a large value for $m_A$ unless $\tan \beta \approx 50$. When present experimental limits are taken into account only particular corners of the SUGRA parameter space turn out to be compatible to observation, because the neutralino relic abundance is typically too high. The cosmologically allowed regions correspond to the so-called stau co-annihilation, Higgs funnel and focus point scenarios [20]. The corresponding direct detection cross section is marginally at the level of present sensitivities, $\sigma_{\text{nucleon}}^{\text{scalar}} < \sim 10^{-7}$ pbarn [21].

The superpotential of the NMSSM [22] contains one additional Higgs singlet $S$ compared to the SUGRA or the MSSM scenarios: $W = W_{\text{MSSM}} - \epsilon_i \bar{\lambda}_i S H_1^i H_2^i + 1/3 k S^3$. Its vev generates dynamically the $\mu$ parameter at the EW scale, explaining why the natural scale of $\mu$, which is the only dimensional parameter in the superpotential, is expected on general grounds to be at the GUT or Planck scale, while it is required to be at the EW scale by phenomenology (the so-called “$\mu$ problem” of the MSSM). The main two features of the NSSMS are that one Higgs scalar can be very light because it evades experimental limits by mixing with its singlet component, and that the neutralino has an additional singlino component, $\chi \equiv a_1 \tilde{B} + a_2 \tilde{W}_3 + a_3 \tilde{H}_1 + a_4 \tilde{H}_2 + a_5 \tilde{S}$. An example of relic neutralino phenomenology in the NMSSM is shown in Fig. 3 where on the left-hand side the cosmologically allowed regions are shown in gray in the $\lambda$ and $k$ plane. In this scenario the presence of additional light Higgs bosons implies more decay channels and resonant decays for the neutralino, which tends to be relatively light and mostly singlino. Thanks to the light Higgs boson exchanged in the propagator the direct detection cross section can be strongly enhanced, as can be seen from the right-hand panel in Fig. 3.

In the effective MSSM all soft parameters are defined at the EW scale. Usually in this scenario
gaugino mass parameters are assumed to be linked by the relation $M_1 \simeq M_2/2$, which originates from embedding the model in a GUT theory and by assuming that $M_1$ and $M_2$ unify at the GUT scale. This relation implies the bound $m_\chi \gtrsim m_{\chi^\pm}/2$, where the chargino mass $m_{\chi^\pm}$ has been constrained by accelerator searches to be heavier than about 100 GeV, so that $m_\chi \gtrsim 50$ GeV. The latter limit, which is usually quoted for the neutralino mass, can however be evaded if $M_1 \ll M_2$. In fact LSP searches at accelerators through the production and decay of heavier neutralinos or the measurement of the invisible width of the $Z$ boson are not sensitive enough to put a direct lower bond on $m_\chi$. In this case, when standard assumptions are made about the history of the Early Universe, a lower bound $m_\chi \gtrsim 6$ GeV can be derived by making use of the relic abundance [23], as shown in the left panel of Fig. 4. Moreover, since $\Omega_\chi$ and $\sigma_{\text{scalar}}^{(\text{nucleon})}$ are strongly anticorrelated, an upper bound on the former implies a lower bound on the latter. This explains why the cross section $\sigma_{\text{scalar}}^{(\text{nucleon})}$ shown in the right–hand panel of Fig. 4 presents a typical low–mass funnel [24]. The theoretical points overlap nicely with the region enclosed by the solid black line, which is compatible to the annual modulation effect observed by the DAMA experiment [25]. This region is appropriately enlarged in order to take into account the astrophysical uncertainties on the WIMP velocity distribution function as well as the WIMP local density that can strongly affect rate predictions [26], especially at low WIMP masses. This is due to the fact that in direct searches lighter WIMPs need to kick a nucleus above the experimental recoil energy threshold with a higher incoming velocity, so that very light WIMPs probe the high–velocity tail of the distribution, which is more sensitive to the details of the halo modeling. Note, however, that exclusion plots calculated by experimental collaborations are usually obtained by making use of a simplified isothermal sphere model for the velocity distribution, so that some care is required in order to assess in a consistent way how they affect low–mass WIMPs [27]. Moreover, recently the modulation effect was re–analyzed by the DAMA Collaboration in light of a possible effect of channeling in the NaI crystals [28]. This effect may lead to a significant enhancement of the detector response at low recoil energies, displacing the DAMA region to lower WIMP masses, and with direct consequences for the phenomenology of the susy configurations that can explain the annual modulation [29].
5. Conclusions

WIMPs at the TeV scale can be realized in different well-motivated scenarios, like the KK-photon in UED, the heavy photon in Little Higgs and the neutralino in Supersymmetry. All these scenarios can provide CDM with the correct abundance. Neutralino is still the most popular, and today is available in different flavours, including SUGRA, nuSUGRA, sub-GUT, Mirage mediation, NMSSM, effective MSSM, scenarios with CP violation. Interestingly enough, some of these scenarios are already at the level of present sensitivities for direct DM searches.

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