WIMPs: a Brief Bestiary

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2008-02/cerdeno_david

A brief overview of the motivation, viability and direct detection properties for some of the most popular candidates for WIMP dark matter is presented.

1 Introduction

The identification of the dark matter (DM) of the Universe constitutes one of today's major goals of modern Physics. This problem, once considered solely within the realm of Astrophysics is now deeply rooted in Particle Physics, since it is in the context of theories beyond the Standard Model (SM) where the most plausible candidates for DM arise. Given the outstanding advances in dark matter detection experiments, as well as the forthcoming onset of the LHC, an exciting near future can be anticipated in which this enigma might start being unveiled.

Given a DM candidate (stable and neutral particle), the size of its interaction with ordinary matter determines the resulting amount of DM in the Universe today. A relic density of particle DM is produced in the early Universe when its annihilation rate falls below the expansion rate. It can be estimated that in order to reproduce the present relic density of DM, a thermal candidate must have interactions of order of the Electroweak-scale. Not needing to introduce a new physical scale, such *weakly interacting massive particles*, WIMPs, constitute a very well-motivated general class of DM candidates. Moreover, an extremely attractive feature of WIMPs is that, despite their feeble interactions with ordinary matter, they could be detected directly on Earth experiments through their elastic scattering with nuclei in a detector.

Many models for new physics contain well-motivated DM candidates. In these notes I briefly comment on some of the most popular constructions, their viability and future detectability.

2 The beasts

Fourth generation neutrino. A *heavy neutrino* (Dirac or Majorana), belonging to a hypothetical fourth generation, was among the first proposals for WIMP dark matter. However, LEP limits on the invisible Z width pose a stringent lower bound on its mass, $m_\nu > M_Z/2$. Such neutrinos, having a too small relic density [1], would fail to account for all the dark matter in the Universe. Moreover, direct [2], as well as indirect DM searches [3], also ruled out $m_\nu \lesssim 1$ TeV. Some of these problems can be alleviated if the neutrino coupling to the Z boson is reduced, e.g., by considering mixing with a right-handed (sterile) component [4]. However, this renders the neutrino unstable, and although a large life time can be obtained by increasing the sterile composition, this leaves an extremely weakly interacting neutrino which therefore does not enter the WIMP category. An interesting possibility which allows to preserve the WIMP character of the heavy neutrino was recently explored within the context of a model with extra dimensions and an extended electroweak gauge group [5].

Supersymmetric WIMPs Supersymmetry (SUSY) was originally proposed as a solution to to the hierarchy problem in the SM and is nowadays regarded as one of the best motivated and most promising candidates for new physics. In SUSY extensions of the SM a discrete symmetry, known as R-parity, is often imposed in order to forbid lepton and baryon violating processes. A phenomenological implication of this is that SUSY particles are only produced or destroyed in pairs, thus rendering the lightest SUSY particle (LSP) stable.

Remarkably, in large areas of the parameter space of SUSY models, the LSP is an electrically neutral particle, the lightest *neutralino*, $\tilde{\chi}_1^0$, which therefore constitutes a very well motivated WIMP candidate [6]. The neutralino is a linear superposition of the fermionic partners of the neutral electroweak gauge bosons and of the neutral Higgs bosons (Higgsinos), and the resulting detection cross section is extremely dependent on its specific composition. The scalar part of the neutralino-proton cross section receives contributions from Higgs exchange in a t-channel and squark exchange in an s-channel. The latter also contributes to the spin-dependent part of the cross section, together with a Z boson exchange in a t-channel. The expressions for the different amplitudes can be found, e.g., in [7], and the conditions under which the neutralino detection cross section is enhanced are well understood [8]. In particular, a large Higgsino component induces an enhancement of both the Higgs and Z boson exchange diagrams, thereby leading to an increase in both the spin-dependent and independent cross sections. On the other hand, the presence of very light squarks leads to an enhancement of (mainly) the spin-dependent contribution [9]. As a consequence, current direct DM experiments are already sensitive to some areas of the SUSY parameter space and future detectors will explore deep into it.

Another possibility for a SUSY WIMP is the *sneutrino*, the scalar supersymmetric partner of the neutrino, since it is electrically neutral and weakly-interacting. However, given its sizable coupling to the Z boson, the left-handed sneutrino in the MSSM either annihilates too rapidly, resulting in a very small relic abundance, or gives rise to a large detection cross section, being excluded by direct DM searches [10]. Several models have been proposed to revive sneutrino DM by reducing its coupling with Z-boson with either the introduction of a mixture of left- and right-handed sneutrino [11] or by considering a purely right-handed sneutrino [12]. The latter cannot be thermal relics, since their coupling to ordinary matter is extremely reduced by the neutrino Yukawa coupling unless a new gauge interaction is introduced and would be unobservable in direct detection experiments.

Recently, an extension of the MSSM was studied where singlet scalar superfields are included, as in Ref. [13], simultaneously addressing the μ problem as in the Next-to-MSSM and generating non-vanishing Majorana neutrino masses with a (low-scale) see-saw mechanism. The associated presence of right-handed sneutrinos with a weak scale mass provides a new viable WIMP DM candidate. These can be thermally produced in sufficient amount to account for the CDM in the Universe through a direct coupling to the Higgs sector. Moreover their spin-independent detection cross section can be large enough to allow observation in future experiments [14].

Universal Extra Dimension models. Although theoretically very well motivated, SUSY is not the only possible extension of the SM leading to a viable DM candidate. An interesting alternative arises in theories with Universal Extra Dimensions (UED), in which all fields are allowed to propagate in the bulk [15]. These models predict an infinite tower of massive particles associated to each SM state. The masses of such KK excitations are related to the compactification scale, which can be chosen of order of the TeV. In the construction of realistic models the extra dimension has to be compactified in an orbifold in order to obtain chiral fermions. This leads to the occurrence of a conserved discrete symmetry, which is called KK-parity.

In this case, the *Lightest Kaluza-Klein Particle* (LKP) becomes stable and thus another viable DM candidate. The LKP usually corresponds to the first KK excitation of the hypercharge gauge boson [16, 17], $B^{(1)}$. In absence of spectral degeneracies, $B^{(1)}$ would achieve the appropriate relic density for masses in the 850–900 GeV range [17]. However, due to the quasi-degenerate nature of the KK spectrum, this range can be significantly modified, due to coannihilations with first and second KK-level modes. The allowed mass range was also found to depend significantly on the mass of the Standard Model Higgs boson.

In UED the leading contribution to the direct detection cross section of $B^{(1)}$ comes from the exchange of the Higgs (for spin-independent contribution) and of first level KK quarks $q^{(1)}$ (for both spin-dependent and independent) [18, 17]. The first diagram increases when the mass of the Higgs decreases, whereas the second contribution is very sensitive to the mass difference between the LKP and the exchanged KK quarks. In particular, when this mass difference is small, both the spin-independent and dependent detection cross section become large [9].

Little Higgs theories. These constructions were proposed in order to stabilize the Higgs mass through a collective symmetry breaking mechanism [19], in such a way that the Higgs would correspond to a pseudo-Goldstone boson. The inclusion of new Physics at the TeV scale, in particular of additional gauge bosons, gives rise to sizable contributions to low-energy observables and the model becomes severely constrained from electroweak precision fits. A discrete symmetry, called T-parity, can be introduced in order to alleviate these bounds [20]. The new gauge bosons would be odd under T-parity, thus forbidding tree-level corrections to precision electroweak observables. A phenomenological consequence of T-parity is that the *Lightest T-odd Particle* (LTP) becomes absolutely stable. Interestingly, the LTP is usually the partner of the hypercharge gauge boson [21], B_H. This is a neutral, weakly-interacting particle which therefore constitutes yet another candidate for WIMP dark matter.

The thermal relic abundance of B_H typically exceeds the WMAP constraint. The correct DM density is only obtained through the resonant annihilation of the Higgs s-channel or via coannihilation effects with another T-odd particle. The resulting direct detection cross section was found to be quite suppressed, given the fact that the heavy photon predominantly couples to SM particles through the Higgs boson, whose interactions with nucleons are weak. Thus, although the cross section increases when the Higgs mass decreases, only future dark matter experiments with targets of order 1 Ton would be sensitive to some regions of the parameter space [22]. Indirect detection, on the other hand, might better suited to study these candidates.

Other dark matter models Instead of looking for DM candidates in existing theories beyond the SM, a bottom-up approach can be adopted in which minimal additions to the SM are considered, involving the inclusion of a WIMP field (usually a new singlet) and new symmetries that protect their decay (in some occasions, also a new "mediator" sector that couples the WIMP to the SM). Examples in this direction include WIMPs with singlet mediation [23], models with an extended electroweak sector [24], models with additional gauge groups, and the *Secluded Dark Matter* scenario [25] in which WIMPs could escape direct detection.

3 Final comments

If WIMPs constitute the DM of the Universe we might have a good chance to detect them in the near future through a combination direct and indirect searches, as well as from the results of the search for new Physics with the LHC. Also, the combination of the results from these three different sources might help identifying this elusive ingredient of our Universe.

Acknowledgements

Work supported by the Spanish MEC under program "Juan de la Cierva" and Proyecto Nacional FPA2006-01105, the EU network MRTN-CT-2006-035863, the European Network of Theoretical Astroparticle Physics ILIAS/ENTApP under contract RII3-CT-2004-506222 and the project HEPHACOS P-ESP-00346 of the Comunidad de Madrid.

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