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Understanding the Dark Universe

Theories of particle dark matter

Théories de la matière noire particulaire

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ABSTRACT

This brief review outlines some of the most attractive theoretical motivations for particle dark matter, and illustrates how they fit into the bigger context of physics beyond the Standard Model. Particular emphasis is given to the generic properties of theories of dark matter, and how the mechanism by which it interacts with the Standard Model particles influences its phenomenology. Brief descriptions of the most popular models, including supersymmetric theories and theories with universal extra dimensions are discussed.

RÉSUMÉ

Cette courte monographie esquisse certaines des motivations théoriques les plus attrayantes pour la matière noire particulaire, et les place dans le contexte plus vaste de la physique au-delà du modèle standard. On met en particulier l'accent sur les propriétés génériques des théories de la matière noire, et sur les conséquences du mécanisme par lequel elle interagit avec les particules du modèle standard. On discute brièvement les modèles les plus populaires, tels que les théories supersymétriques et les théories avec des extra-dimensions universelles.

1. Introduction

There is compelling evidence that the dark matter making up a large fraction of the Universe's density consists of exotic particles [1,2], representing one of the few concrete examples of evidence for physics beyond the Standard Model (SM). The identity of the dark matter is thus an essential ingredient in a complete description of nature at the most fundamental level, and may provide important clues about extensions of the SM.

At this time, little is known for certain about the particle nature of the dark matter. That being said, a number of observations have been interpreted as possible signals of dark matter scattering [3] or annihilation [4]. These include the spectrum and angular distribution of gamma rays from the Galactic Center [5,6], the synchrotron emission from the Milky Way's radio filaments [7], the diffuse synchrotron emission from the Inner Galaxy (known as the "WMAP Haze") [8–10] and low-energy signals from the direct detection experiments DAMA/LIBRA [11], CoGeNT [12,13] and CRESST-II [14]. These observations can each be explained by a relatively light dark matter particle ($m \sim 10$ GeV) with an annihilation cross section

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consistent with that predicted for a simple thermal relic ($\sigma v \sim 10^{-26}$ cm^3/s), and with an elastic scattering cross section with nucleons on the order of 10^{-41} cm^2.

In this short review, we summarize some of the theoretical considerations that have gone into our understanding of dark matter, including how dark matter might interact with the SM, and how such particles may have been created in the early Universe. We then move on to consider some examples of popular particle physics frameworks which include potentially viable candidates for the dark matter.

2. Generic features of a theory of dark matter

Although a great variety of particle theories of dark matter have been proposed, all such theories have certain features in common. Any viable dark matter particle must be electrically neutral, non-relativistic, and be stable or have a lifetime at least of order the age of the Universe itself. That still leaves a number of properties undetermined, including:

- spin;
- self-conjugacy (Majorana fermion or real boson) or not;
- electroweak $SU(2) \times U(1)$ representation.

Engineering renormalizable theories containing massive electrically neutral particles with these desired properties is a relatively straightforward exercise.

Perhaps the most subtle requirement to accommodate is that the dark matter must be both massive and very long-lived. Stability of the dark matter particle, however, can be insured by imposing a symmetry. The simplest example of such a symmetry is a discrete $\mathbb{Z}_2$ dark parity, under which the dark matter (and perhaps other particles in a dark sector) are odd whereas the SM particles are even. Such a symmetry may help explain why precision measurements show very small deviations from SM expectations, by requiring new physics contributions to standard processes to occur at loop level at the lowest order [15]. The stabilization symmetry could also be a larger discrete or continuous group, and may be either exact, or very weakly broken, allowing the dark matter to decay.

2.1. Dark matter interactions with the SM

A theory of dark matter must also specify how the dark matter particles primarily interact with the Standard Model. The evidence for the existence of dark matter requires at least gravitational strength interactions to dominate over large distances, but does not preclude the possibility of much stronger short range interactions. The specific channel through which dark matter makes contact with the SM is typically referred to as a *portal*, the most common of which are the Higgs boson h^0, the photon field strength $F_{\mu\nu}$, the massive electroweak force carriers including the Z boson, and massive colored and/or charged particles. Popular theories often make use of more than one of these options, which can make it complicated to connect limits (or observations) from direct, indirect, and collider searches for dark matter, as different portals may end up dominating each type of search.

Dark matter coupling to the Higgs is the only portal which is potentially renormalizable (for bosonic dark matter) even in the absence of more particles in the dark sector [16]. The Higgs portal results in dark matter which couples most strongly to the massive elements of the SM sector: the W and Z bosons and top and bottom quarks. As a result, indirect detection tends to result in a somewhat softer spectrum of gamma rays. Direct detection through the Higgs portal is iso-spin symmetric, inherited from the heavy quark content of the nucleon. At colliders, the Higgs portal can be a challenge. If the dark matter is light enough, the Higgs may decay into it [17,18], a possibility which the LHC can eventually determine with large data sets, particularly if the Higgs is below the threshold of WW decays [19,20].

The weak bosons are the natural mediators of dark matter which is charged under the SM $SU(2) \times U(1)$ gauge interaction. Such WIMPs naturally appear along with charged states, whose masses will be split apart by electroweak symmetry-breaking effects. For exotic $SU(2)$ representations, the stability of the WIMP may be motivated by gauge invariance forbidding renormalizable interactions allowing the dark matter to decay [21]. Because the Z boson vector current is a particularly efficacious mediator of direct scattering, a WIMP with $\mathcal{O}(1)$ interactions with the Z boson is required to have a mass larger than tens of TeV, or to otherwise have suppressed interactions at low energies, for example as a result of the $SU(2)$ representation (such as a triplet) or by virtue of the vector current vanishing, such as for self-conjugate dark matter.

Dark matter may interact with photons, by virtue of an electric or magnetic multipole moment [22–24]. Such a portal is particularly natural in models with a composite dark matter particle whose constituents are electrically charged [25], and can lead to a somewhat novel spectrum of energy recoils in direct detection by virtue of the massless photon as a mediator [25,26]. Annihilation can proceed into a pair of photons, leading to monoenergetic gamma rays [22,27]. At colliders, production through an off-shell photon (together with an initial state photon or hadronic jet) is challenging to detect, because the signal and background processes have very similar shapes [28]. A related class of theories has interactions mediated primarily by exotic ultralight mediators, such as a ∼ GeV mass dark photon [29–31].

Finally, interactions mediated by massive colored or electrically charged particles by necessity involve new particles beyond those contained in the SM itself which will inevitably also be odd under the stabilization symmetry. Thus, they must be heavier than the dark matter particle, otherwise the dark matter would decay into it plus a light SM state. As a result, in direct scattering the low-energy effect of such a mediator looks like a contact interaction, and this will often be the case for dark matter annihilation as well. At colliders, the phenomena are controlled by the mediator masses. If the masses are light enough that they can be produced copiously, the resulting signature consists of one or more energetic SM particles from the mediator decay, along with missing momentum from the escaping pair of dark matter particles. LHC constraints on colored particles decaying into missing energy plus hadronic jets require the masses of such particles to be larger than roughly TeV in the context of supersymmetric squarks and/or gluinos [32] and several hundred GeV in more generic "simplified models" [33]. If the mediators are too heavy for direct production, they will continue to manifest as contact interactions, which can be probed by searches for missing momentum plus energetic SM initial state radiation [34–38].

2.2. Thermal relic density

A powerful argument for dark matter with stronger than gravitational interactions with the SM is provided by the scenario in which the dark matter is a thermal relic, which allows one to understand its current abundance in the Universe via a mechanism that is rather insensitive to the detailed history of the Universe at early times and rests instead on the microscopic properties of dark matter itself. The key assumption is that both the interactions between dark matter and the thermal bath of SM particles is strong enough that after reheating the dark matter particles were in chemical equilibrium with the SM. As the Universe cools, the density of massive particles drops exponentially, following the Maxwell–Boltzmann distribution. At the same time, the Universe is expanding which will eventually lead to the interactions falling out of equilibrium, and the quantity of dark matter freezing out.

Assuming a standard thermal history for the Universe, the resulting relic density is given by

$$\Omega_{\mathrm{DM}} h^2 \simeq \frac{3.0 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \tag{1}$$

with some weak dependence on the WIMP mass (which in many models also controls the size of $\langle \sigma v \rangle$). In particular, an electroweak scale cross section of $\sim$ pb leads to a relic density which is in the correct ballpark to explain observations. Thus, a weakly interacting massive particle (WIMP) is currently at the forefront of candidates to play the role of dark matter.[1] Since this would seem to point to physics which could easily be related to electroweak symmetry-breaking, this appears to be an amazing coincidence of scales which is usually referred to as the "WIMP miracle". Nonetheless, this coincidence could be a red herring, and any particle with the right relation between mass and coupling can naturally have the right relic density, lead to viable theories making use of the "WIMPless miracle" [39].

3. Supersymmetric dark matter

Supersymmetry is of the best motivated and most throughly studied extensions of the Standard Model. In R-parity conserving supersymmetric models, the lightest supersymmetric particle (LSP) is stable and, if electrically neutral and colorless, can serve as a potentially viable dark matter candidates. Possibilities for the dark matter LSP include neutralinos, sneutrinos, and gravitinos. As gravitinos are not expected to lead to observable signals in direct or indirect detection experiments (though they could decay leading to indirect signals), and sneutrinos are highly constrained by direct detection constraints, we focus on neutralinos as a particularly promising candidate for the dark matter of our Universe.

In the minimal supersymmetric standard model (MSSM), their are four neutralinos, each of which is a mixture of the superpartners of the hypercharge gauge boson, B, the neutral component of the W, and the neutral Higgs bosons, H_1 and H_2. The mass and couplings of the lightest neutralino depend on its composition, which is determined in turn by the parameters[2] M_1, M_2, μ, and $\tan\beta$. Over much of the parameter space of the MSSM, the lightest neutralino is predicted to be produced in the early Universe with an abundance in excess of the observed dark matter density. This problem is avoided, however, in models in which the lightest neutralino efficiently coannihilates with another state (such as a light stau), efficiently annihilates through a heavy Higgs resonance, or has relatively large couplings due to possessing a mixed higgsino–gaugino composition.

Although the MSSM represents a reasonable and viable extension of the Standard Model, there is no strong reason to expect nature to make this simplest of all possible choices. Supersymmetric models with many varieties of extended particle content have been considered, including those with extra Higgs singlets or doublets. These and other possibilities significantly expand the range of phenomenological characterstics that supersymmetric dark matter candidates could possess.

At present, direct detection experiments and the LHC are beginning to significantly constrain the characteristics of supersymmetry and supersymmetric dark matter. Limits on the masses of squarks and gluinos from ATLAS and CMS are currently

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[1] It is worth noting that there is some lack of uniformity in the use of the term WIMP in the literature, with some authors interpreting the term to refer to a particle which literally experiences the SM $SU(2) \times U(1)$ electroweak interaction, and others intending any interaction which is roughly electroweak in size. We will use the term in the latter sense.

[2] M_1 and M_2 are SUSY-breaking masses for the $U(1)$ and $SU(2)$ gauginos, respectively. μ is the (supersymmetric) higgsino mass parameter, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets.

around 700–800 GeV, and will likely exceed 1 TeV in the very near future. Ultimately, the LHC (running at 14 TeV) is expected to be sensitive to such states as heavy as approximately 3 TeV. Constraints from XENON-100 and other direct detection experiments currently require the dark matter's elastic scattering cross section to be below $\sim 10^{-44}$ cm^2 for masses between several ten and several hundred GeV. While such limits do exclude otherwise viable supersymmetric models, a large fraction of the remaining parameter space lies within one to two orders of magnitude of this constraint. By the end of the decade, direct detection experiments are projected to possess the sensitivity required to explore a large majority of the supersymmetric parameter space containing a neutralino LSP.

4. Extra dimensional dark matter

Universal Extra Dimensions (UED) models [40,41] engineer the stabilization symmetry as part of the naturally expanded space–time symmetries of a higher dimensional model. Naively, translational invariance in the extra directions becomes conservation of mode number in the Kaluza–Klein (KK) expansion of bulk fields. In practice, the compactification of the extra dimensions breaks conservation of KK mode number [42], but often a discrete subgroup of the symmetry remains [43,44], and can be enough to insure stability of the lightest KK particle (LKP).

In the simplest five dimensional UED model, the boundary conditions on the bulk fields induce terms living on the boundaries which preserve a $\mathbb{Z}_2$ "KK parity" and split apart the masses of the states at a given KK level. The lightest state is often the first mode of the hyper charge boson, $B_\mu^{(1)}$ [43]. Given the properties of the $U(1)$ boson, the WIMP interactions (and thus its annihilation rates) are essentially determined, and the relic abundance effectively depends on the size of the extra dimension. For compactifications of $L^{-1} \sim 1$ TeV, one obtains the correct relic density [45,46]. As a spin-1 boson, the 5d LKP provides an interesting foil to contrast with the Majorana fermion WIMP of supersymmetric theories, leading to rather different properties in terms of its indirect [45,47–50] and direct [47,51,52] detection.

In models with more than five dimensions, there is more than one viable compactification, and the physics of dark matter is more model-dependent. One attractive 6d option is the chiral square model [53], which identifies adjacent sides of two compact dimensions, and leads to a stable LKP which is scalar [54] and communicates with the SM largely through the Higgs portal [55], leading to the correct relic density for WIMP masses ranging from 200 to 600 GeV, depending on the SM Higgs mass. The chiral square also predicts a rich structure of gamma ray lines from WIMP annihilation, leading to novel prospects for indirect detection [56].

5. Outlook

In this short review, we have discussed a number of examples of dark matter candidates that can appear in TeV-scale extensions of the Standard Model. Over the next decade, a very large fraction of these models will become within the reach of direct and indirect detection experiments, as well as the LHC. While past and current results from these experiments have constrained the properties of dark matter to some extent, it will be over the next several years that the sensitivity of these experiments will finally reach the level required to truly put the WIMP paradigm to the test.

Indirect detection experiments such as Fermi and PAMELA (and AMS-02 in the near future) have become sensitive to WIMPs with annihilation cross sections near the value predicted for a simple thermal relic ($\sigma v \sim 3 \times 10^{26}$ cm^3/s). In particular, Fermi's observations of the Galactic Center [5] and dwarf spheroidal galaxies [57] have each lead to limits on the dark matter's annihilation cross section which are similar to this value for masses on the order of ~100 GeV. PAMELA and BESS POLAR-II have produced similar constraints based on measurements of the cosmic ray antiproton spectrum [58].

Over the past dozen years or so, constraints from direct detection experiments have become more stringent by about an order of magnitude every four years. While many WIMP models predict elastic scattering cross sections which are not currently ruled out by these experiments, the same will not be true a decade from now if this progress continues. In particular, while weak-scale dark matter candidates with order unity couplings to the Standard Model Z (heavy neutrinos, or sneutrinos, for example) have long been ruled by out direct detection, such experiments are now beginning to constrain models in which dark matter scatters with nuclei through the Higgs (i.e. the Higgs portal).

Last, but certainly not least, the LHC over the next decade will continue to explore the TeV-scale. If the dark matter candidate is part of a larger theory which includes new colored particles (such as squarks and gluinos, or KK quarks and gluons) those states will likely be produced in large numbers. By studying the decays of those states, one can infer the mass of the dark matter, and possibly information pertaining to its interactions. And even if no such strongly interacting state exists, the dark matter could be pair produced directly. Searches for mono-jets with missing energy will ultimately be sensitive to dark matter particles with masses as high as several hundred GeV [37,35].

If the dark matter of our Universe does in fact take the form of a weakly interacting massive particle, it will very likely be unable to hide from this onslaught of experimental scrutiny. A decade from now, reviews such as this will disappear and become replaced by articles describing the characteristics of the newly discovered dark matter particle, or by those lamenting the long and fruitless wild-goose chase known as the WIMP paradigm.

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