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Dark Matter searches: A theoretical perspective

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Summary. — In an era of promising experimental searches, Dark Matter theorists are diversifying their portfolio, adding assets different from the time-honored SuperSymmetric neutralino. I pick and briefly discuss a few new directions in model building and in phenomenology: Minimal Dark Matter, Asymmetric Dark Matter and Secluded Dark Matter (Report numbers: CERN-PH-TH/2012-081, SACLAY–T12/026).

PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).
PACS `12.60.-i` – Models beyond the standard model.
PACS `98.80.Cq` – Particle-theory and field-theory models of the early Universe (including cosmic pancakes, cosmic strings, chaotic phenomena, inflationary universe, etc.).

1. – Introduction

At the cost of oversimplifying history, I shall claim that the latest 30 years or so, in the field of particle Dark Matter (DM) phenomenology, have been dominated by one single dispotic ruler: the SuperSymmetric neutralino. Sure, challengers have tried to emerge, sometimes with force (*e.g.*, Kaluza-Klein DM), and a somewhat clandestine subculture has continued to pursue its goals in the dark (axion or sterile neutrino workshippers, for instance). But there is little doubt that SuSy DM is perceived by most of the community as a point of reference and veneration. *E.g.*, it is not uncommon to hear experimentalists or astronomers confuse (or identify in their minds, in a sort of revealing giveaway) the concepts of “particle DM”, “WIMP” and “neutralino”.

Of course, there is nothing surprising in this state of affairs, given that the theoretical community has insisted for decades that i) the neutralino is such a well motivated DM candidate which ii) is just around the corner in your favorite energy/scattering strength/sensitivity scale. And indeed the neutralino *is* such a well-motivated DM candidate, if SuSy is true, and it *is* around the corner, if naturalness motivated and naïve SuSy parameters hold.

However, other possibilities exist.

TABLE I. – *A tentative categorization of some popular DM candidates. In* ***bold****, those picked for an additional discussion in the text, in italic, naturalness-inspired candidates.*

Charge	Candidates	Production	Stability
~~electromagnetic~~	–	–	–
weak	*neutralino…*	thermal freeze-out	R-parity
	Kaluza-Klein DM		KK-parity
	Little Higgs DM		T-parity
	Minimal DM	thermal freeze-out	gauge symmetry
	Inert Doublet DM		$\mathbb{Z}_2$ symmetry
strong(ish)	$\left.\begin{array}{c}\textit{Technicolor DM}\\ \text{mirror DM}\end{array}\right\}$ **asym DM**	‘exhaustion’	T-baryon number $\mathbb{Z}_2$ symmetry
other	“**secluded DM**”	sort of freeze-out	some symmetry
	Wimpless DM		some symmetry
none	singlet scalar	thermal freeze-out	$\mathbb{Z}_2$ symmetry
	sterile ν	mixing	just long lived
	gravitino	thermal or decay	R-parity or long lived
	axion	misalignment?	just long lived

2. – The current panorama and an attempt at widening the perspective

Many DM candidates (including the neutralino, my strawman) arise within the context of comprehensive theories (such as supersymmetry), often aiming at explaining some problem in particle physics (such as the hierarchy problem) other than the DM problem itself. For this reason it is often customary to classify them in terms of the theory in which they originate (SuperSymmetric DM, Kaluza-Klein DM, Technicolor DM…). However, this is not necessarily the only way to proceed. An arguably more democratic and revealing classification could be made in terms of the quantum numbers under which the DM candidate is charged, or in terms of the production mechanism that assures its correct abundance today, or yet in terms of the reason which guarantees its stability (or meta-stability) on cosmological time-scales.

Table I presents such a classification. Bear in mind that it is only partial and that no classification I can come up with would be totally satisfactory (at least to me). This is as good as an attempt can be.

Starting from the left of the table: DM can be charged under different forces. The first possibility is electromagnetism, but this is immediately excluded by the very name of *Dark* Matter (more technically: there exist very stringent constraints on ChaMPs, Charge Massive Particles [1]).

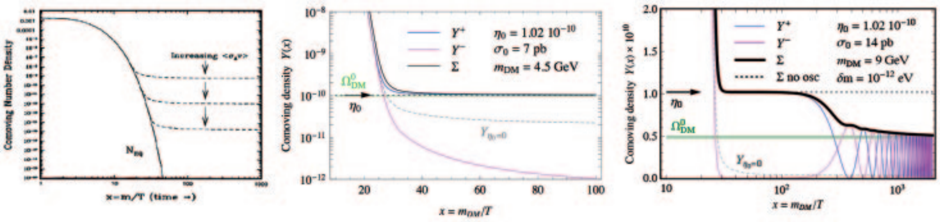

Fig. 1. – Three typical histories of DM abundance production mechanisms: thermal WIMP freeze-out (left, from [2]), asymmetric DM "exhaustion" (center) and talantogenesis (oscillating asymmetric DM, right).

Next come weak interactions (in the sense of the Standard Model $SU(2)$): this is the well known class of WIMPs, Weakly Interacting Massive Particles. In this class lie the candidates which arise within SuSy, extradimensions, Little Higgs, *i.e.* as a byproduct of a more ambitious and comprehensive theory, often addressing the naturalness issue. Here also lie, however, models loosely identified by the fact that they aim at providing a viable DM candidate insisting on introducing the minimal set of new particles beyond the Standard Model, somewhat in opposition to the mainstream direction just discussed. The namesake Minimal Dark Matter (MDM) [7] falls in this class, as well as less fundamentalist theories such as the model in [12], the hidden vector [13], the Inert Doublet Model (IDM) [14,15] and others. I will discuss MDM in sect. **3**˙1.

One of the main compelling features of WIMP candidates is that it is automatically produced in the correct amount in cosmology, thanks to the so called "WIMP miracle", a realization of the thermal freeze-out mechanism which works in the following way. DM particles were as abundant as photons in the beginning, being freely created and destructed in pairs when the temperature of the hot plasma was larger then their mass. Their relative number density started then being suppressed as annihilations proceeded but the temperature dropped below their mass, due to the cooling of the Universe. Finally the annihilation processes also froze out as the Universe expanded further. The remaining, diluted abundance of stable particles constitutes the DM today. As it turns out, particles with weak scale mass ($\sim 100\,\text{GeV}$–$1\,\text{TeV}$) and weak interactions could play the above story remarkably well, and their final abundance would automatically (miraculously?) be the observed Ω_{DM}. This is an enchanting story, but it is certainly not the only possibility, as we will also see below. (See fig. 1.)

Dark Matter can also be subject to strong or simil-strong interactions, such as in Technicolor or Mirror DM motivated models. Here the emphasis is on the existence of some large interaction cross section similar to that of baryons. In this case the production mechanism is completely different from thermal freeze-out and it relies instead on the existence of a primordial asymmetry, as I will discuss in sect. **3**˙2. For this reason, these kinds of models are accomunated in the category of asymmetric DM for my purposes.

Apart from the ordinary interactions discussed so far (and of course apart from gravity), it could be that other new forces exist, under which DM is charged. This is the basic idea underlying models such as "secluded DM" and WIMPless DM (named of course in opposition to weakly interacting DM), which I will briefly discuss in sect. **3**˙3.

Finally, DM could have no charge at all. This does not mean that it needs not interact with ordinary matter at all. It just means that it is sterile under all gauge groups. In this class of candidates one finds singlet scalar DM [3], sterile neutrino DM [4], gravitino DM [5], the axion [6].

The reason by which the DM particle is stable constitutes another aspect of difference among candidates. The most popular solution is to invoke the existence of a (possibly discrete) symmetry that forbids its decay. This symmetry may be imposed in the theory for other purposes (or be the remnant of a larger broken one imposed for other purposes) so that DM "benefits" from it somewhat by chance. Alternatively, it can be put there by hand just to keep DM stable. A notable example in the first class is R-parity in SuSY, while in the second class one can mention KK-parity in ExtraDimensional DM, T-parity in Little Higgs DM etc. The "stabilization symmetry" has become such a household tool for the model builder that often he/she does not even spend time arguing about it: when in a hurry, just say you add a $\mathbb{Z}_2$ symmetry and move on. Recently, however, a couple of different options have emerged. The first one is that DM might be stabilized by the ordinary gauge symmetries of the Standard Model: this is the idea underlying the MDM model, discussed in sect. **3**˙1. The second one is the realization that, after all, DM need not be absolutely stable but just long lived enough to still be around on cosmological timescales: decaying DM has been the subject of much interest lately.

3. – A few new directions

3˙1. *Minimal Dark Matter: the most economical model?* – The MDM model [7-11] is constructed by simply adding on top of the Standard Model a single fermionic or scalar multiplet $\mathcal{X}$ charged under the usual SM $SU_L(2) \times U_Y(1)$ electroweak interactions (that is: a WIMP). Its conjugate $\bar{\mathcal{X}}$ belongs to the same representation, so that the theory is vector-like with respect to $SU_L(2)$ and anomaly-free. The Lagrangian is "minimal":

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}, & \text{for fermionic } \mathcal{X}, \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2, & \text{for scalar } \mathcal{X}. \end{cases} \tag{1}$$

The gauge-covariant derivative D_μ contains the known electroweak gauge couplings to the vectors bosons of the SM (Z, $W^\pm$ and γ) and M is a tree level mass term (the only free parameter of the theory). A host of additional terms (such as Yukawa couplings with SM fields) would in principle be present, but for successful candidates they will be forbidden by gauge and Lorentz invariance, as detailed below. $\mathcal{X}$ is fully determined by the assignments of its quantum numbers under the gauge group: the number of its $SU(2)_L$ components, $n = \{2, 3, 4, 5\ldots\}$ and the hypercharge Y.

For a given assignment of n there are a few choices of the hypercharge Y such that one component of the $\mathcal{X}$ multiplet has electric charge $Q = T_3 + Y = 0$ (where T_3 is the usual "diagonal" generator of $SU(2)_L$), as needed for a DM candidate. For instance, for the doublet $n = 2$, since $T_3 = \pm 1/2$, the only possibility is $Y = \mp 1/2$. For $n = 5$ one can have $Y = \{0, \pm 1, \pm 2\}$, and so on. The list of possible candidates has to stop at $n \leq 5$ (8) for fermions (scalars) because larger multiplets would accelerate the running of the $SU(2)_L$ coupling g_2: demanding that the perturbativity of $\alpha_2^{-1}(E)$ is mantained all the way up to $E \sim M_{\rm Pl}$ (since the Planck scale $M_{\rm Pl}$ is the cutoff scale of the theory) imposes the bound.

The candidates with $Y \neq 0$ have vector-like interactions with the Z boson that produce a tree-level spin-independent elastic cross sections which are 2–3 orders of magnitude above the present bounds from direct detection searches. Unless minimality is abandoned in an appropriate way, such MDM candidates are therefore excluded and I will focus in the following on those with $Y = 0$.

Next I need to inspect which of the remaining candidates are stable against decay into SM particles. For instance, the fermionic 3-plet with hypercharge $Y = 0$ would couple through a Yukawa operator $\mathcal{X}LH$ with a SM lepton doublet L and a Higgs field H and decay in a very short time. This is not a viable DM candidate, unless the operator is eliminated by some *ad hoc* symmetry. For another instance, the scalar 5-plet with $Y = 0$ would couple to four Higgs fields with a dimension 5 operator $\mathcal{X}HHH^*H^*/M_{\rm Pl}$, suppressed by one power of the Planck scale. Despite the suppression, the resulting typical life-time $\tau \sim M_{\rm Pl}^2\,{\rm TeV}^{-3}$ is shorter than the age of the Universe, so that this is not a viable DM candidate.

Now, the crucial observation is that, given the known SM particle content, the large n multiplets cannot couple to SM fields and are therefore automatically stable DM candidates. This is the same reason why known massive stable particles (like the proton) are stable: decay modes consistent with renormalizability and gauge symmetry do not exist. In other words, for these candidates DM stability is explained by an "accidental symmetry", like proton stability. Among the candidates that survived all the previous constraints, only two possibilities then emerge: a $n = 5$ fermion, or a $n = 7$ scalar. But scalar states may have non-minimal quartic couplings with the Higgs field. I will then set the 7-plet aside and focus on the fermionic 5-plet for minimality.

In summary, the "Minimal Dark Matter" construction singles out a

$$\text{fermionic } SU(2)_L \text{ 5-plet with hypercharge } Y = 0$$

as providing a fully viable, automatically stable DM particle. It is called "Minimal DM" since it is described by the minimal gauge-covariant Lagrangian that one obtains adding the minimal amount of new physics to the SM in order to explain the DM problem.

Assuming that DM arises as a thermal relic in the Early Universe, via the standard freeze-out process, we can compute the abundance of MDM as a function of its mass M. In turn, requiring that MDM makes all the observed DM, $\Omega_{\rm DM}h^2 = 0.110 \pm 0.005$, we can univocally determine M. Not surprisingly, its value turns out to be broadly in the TeV range, because MDM is a pure WIMP model for which the "WIMP miracle" applies. The actual value turns out to be 9.6 ± 0.2 TeV, somewhat on the high side because the 5-plet has many components so that coannihilations are important *and* because Sommerfeld corrections (not discussed here) enhance the annihilation cross section.

3˙2. *Asymmetric Dark Matter: a new production paradigm?* – I briefly presented above the thermal freeze-out mechanism, which plays a prominent role for WIMP candidates, including MDM. I now discuss another possibility, which is to assume that DM particles were once in thermal equilibrium *with an initial asymmetry* between particles and antiparticles. This was originally considered in Technicolor-like constructions [16-20] or mirror models [21-27], but also in other contexts [28-33]. In the latest two years, there has been a revival of interest for this scenario, dubbed Asymmetric Dark Matter (aDM) [34-58], with the aim in particular of connecting the DM abundance to the abundance of baryons, *i.e.* to understand the origin of the ratio $\Omega_{\rm B}/\Omega_{\rm DM} \sim 1/5$. A common production history for the dark and visible matter, in fact, provides an elegant explanation of why the two densities are so close to each other. This approach, in its simplest realizations, suggests a rather light particle, $\mathcal{O}(5\,{\rm GeV})$: this does not match the expected scale of new physics, but part of the community has seen in it intriguing connections with some recent hints of signals in various direct detection experiments. Like for the baryonic abundance, if there is an asymmetry in the dark sector, as soon as annihilations have wiped out the density of (say) antiparticles, the number density of particles remains frozen for lack of targets, and is entirely controlled by the primordial asymmetry rather than by the value of the annihilation cross section. This is why this scenario appears rather constraining on the value of the DM mass.

This conclusion changes in the presence of oscillations between DM and anti-DM particles [59,60]. Such oscillations can indeed replenish the depleted population of "targets". Annihilations, if strong enough, can then re-couple and deplete further the DM/anti-DM abundance. The final DM relic abundance is therefore attained through a more complex history than in the standard case of aDM, and in closer similarity to the freeze-out one. So this is an instructive setup in the sense that it fills a gap between the standard thermal freeze out prediction (where $\Omega_{\rm DM}$ does not depend explicitly on the DM mass but only on the annihilation cross section $\langle \sigma v \rangle$), and the aDM prediction where $\Omega_{\rm DM} h^2$ does not depend on $\langle \sigma v \rangle$ but only on the primordial DM asymmetry.

3˙3. *Secluded Dark Matter: new dark forces?* – A model building line which has attracted a *huge* interest in recent years is the one of models with new dark forces or, more generically, a rich Dark Sector. Most of them have been directly stimulated by the rather ephemeral desire of explaining the charged CR excesses in PAMELA, FERMI and HESS [61], but nevertheless they have taught us to look into new interesting directions, and this is a part that will most probably stay.

The model which undoubtedly has most attracted attention and has best spelled out the ingredients is presented in [62], although similar ideas have been proposed before or around the same time [63-69]. The model in [62] features a TeV-ish DM particle which is sterile under the SM gauge group but which interacts with itself via a new force-carrying boson ϕ (with the strength of typical gauge couplings). The DM annihilation therefore proceeds through DM DM $\to \phi\phi$. A small mixing between ϕ and the electromagnetic current assures that ϕ eventually decays. Therefore the process of DM annihilation occurs in 2 steps: first two DMs go into two ϕ's and then each ϕ's, thanks to its mixing with a photon, goes into a couple of SM particles. The crucial ingredient is that the mass of ϕ is chosen to be light, of the order of $\lesssim 1\,\text{GeV}$. This simple assumption, remarkably, kills two birds with a stone. On one side, the exchange of ϕ realizes a Sommerfeld enhancement, thus providing a very large annihilation cross section today but preserving the thermal production of DM in the Early Universe. On the other side, ϕ can only decay into SM particles lighter than a GeV, *i.e.* electrons, muons and possibly pions, but not protons: this assures that the annihilation is leptophilic, for a simple kinematical reason. The model therefore fulfils all the requirements needed to explain charged CR anomalies [61]. The construction can then be complicated *ad libitum*, *e.g.* assuming that the dark gauge group is non-Abelian and the DM sits in a multiplet of such group, with small splitting between the components. This allows to accommodate other experimental anomalies, not discussed here.

The kinematical argument is not the only one available to justify a leptophilic nature for DM. In the literature, variations have been proposed in which DM is coupled preferentially to leptons because it carries a lepton number [70], because it shares a quantum number with a lepton [61, 71], because quarks live on another brane [72] or... "because I say so" [73].

4. – Conclusions

At a historical moment in which conventional DM candidates are facing their "moment of truth" [74], I argue that new alternative directions are gaining momentum. In sect. **2**

I tried to categorize many DM candidates in terms of their "charge", production process or stability mechanism, pointing out that there is a whole panorama outside of the ordinary, naturalness motivated, thermal WIMP candidates. I then picked three ideas for some further discussion: Minimal Dark Matter (sect. **3**˙1, one of the most economic modesl), Asymmetric DM (sect. **3**˙2, an example of alternative production mechanism) and secluded DM (sect. **3**˙3, advocating new dark forces).

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