

Particle dark matter physics: An update

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Abstract. This write-up gives a rather elementary introduction into particle physics aspects of the cosmological dark matter puzzle. A fairly comprehensive list of possible candidates is given; in each case the production mechanism and possible ways to detect them (if any) are described. I then describe detection of the, in my view, most promising candidates, weakly interacting massive particles or WIMPs, in slightly more detail. The main emphasis will be on recent developments.

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1. Introduction: The need for exotic dark matter

Dark matter (DM) is, by definition, stuff that does not emit detectable amounts of electromagnetic radiation. At present its existence can therefore only be inferred [1] from the gravitational pull it exerts on other, visible, celestial bodies. The best evidence of this kind comes from the study of galactic rotation curves. Here one measures the velocity with which globular stellar clusters, gas clouds, or dwarf galaxies orbit around (other) galaxies, including our own milky way. If the mass of these galaxies was concentrated in their visible parts, the orbital velocity at large radii R should decrease like $1/\sqrt{R}$. Instead, in nearly all cases one finds that it remains approximately constant out to the largest radius where it can be measured. This implies that the total mass $M(R)$ felt by an object at radius R must increase linearly with R . Studies of this type imply that 90% or more of the mass of (large) galaxies is dark; this is a lower bound, since it is not known where the growth $M(R) \propto R$ cuts off (as it must, since the total mass of a galaxy is obviously finite).

Cosmologists like to express mass densities averaged over the entire visible Universe in units of the critical density $\rho_c \sim 10^{-29}$ g/cm³; the dimensionless ratio is then called Ω , with $\Omega = 1$ corresponding to a flat Universe. Analyses of galactic rotation curves imply

$$\Omega \geq 0.1. \quad (1)$$

Studies of larger (than galactic) structures tend to favor larger values of the total mass density of the Universe. These include the ‘weighing’ of (super) clusters of galaxies through (weak) gravitational lensing as well as through measurements of their X-ray temperature*, as well as studies of the large-scale streaming of galaxies. A widely,

* These two methods give somewhat different results. Gravitational lensing seems to be a more direct, and hence more reliable, measure of the total mass of a (super)cluster; it favors larger values of Ω .

although not quite universally, accepted lower bound on the total mass density is

$$\Omega \geq 0.3. \quad (2)$$

Note that a putative cosmological constant would not be detectable through such studies, since it does not affect local gravitational fields. Finally, naturalness arguments and (most) inflationary models prefer $\Omega = 1.0$ to high accuracy.

Very recently there have been some claims [2] that observations of type I supernovae at high redshift z disfavor matter density $\Omega = 1$ 'at the 95% confidence level'. Much of this evidence seems to rest on the observation of three supernovae with z between 0.5 and 1.0. Type I supernovae are assumed to be more or less the same ('standard bombs'), in which case their absolute distance can be computed fairly easily from their apparent brightness. Spectral lines allow to determine the redshift precisely. Observations of these three supernovae using the Hubble space telescope give $\Omega = -0.1 \pm 0.5$ for vanishing cosmological constant, so $\Omega = 1.0$ seems to be more than two standard deviations away from the central value. However, if we believe the bound (2), a good part of the region favored by this recent measurement is excluded. Besides, in cosmology the errors are nearly always dominated by systematics, and can therefore not be interpreted in a straightforward statistical manner.[†] In my view it is therefore premature to give up on a total mass density $\Omega = 1.0$, and even more premature to take Einstein's self-described 'worst mistake', a (tiny but non-zero) cosmological constant, seriously. Finally, the requirement that the Universe be at least 10 billion years old (a conservative lower limit on the age of the oldest stars) implies

$$\Omega h^2 \leq 1, \quad (3)$$

where h is the (present) Hubble parameter in units of 100 km/(sec-Mpc). Recent observations indicate $h = 0.65 \pm 0.15$.

The total density of luminous matter only amounts to less than 1% of the critical density [1]. Moreover, analyses of big bang nucleosynthesis determine the total baryonic density to lie in the range [3]

$$0.01 \leq \Omega_{\text{baryon}} h^2 \leq 0.015. \quad (4)$$

Assuming $h \geq 0.5$, the upper bound in (4) implies

$$\Omega_{\text{baryon}} \leq 0.06, \quad (5)$$

in mild conflict with the lower bound (1),[‡] and in blatant conflict with (2). Most dark

[†] There is also a long-running program of ground-based searches for high- z type I supernovae. Recent results also seem to favor $\Omega < 1$ in the absence of a cosmological constant, but I have not been able to find more details in several hours of web browsing.

[‡] There has been a recent claim in the literature [4] that a modification of the assumed mass-to-light ratio would allow to explain galactic rotation curves without introducing exotic DM; this amounts to the assumption that the outer parts of galaxies contain many more small, and hence dim, stars than one finds in the solar neighbourhood. Another recent article [5] claims to have found indirect evidence for the existence of fairly compact, partly ionized gas clouds in the halo of our galaxy, based on the apparent modification of some radio waves emitted by quasars. Finally, yet a third paper [6] claims to have found some indication that the dark halo of our galaxy consists of

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matter must therefore be non-baryonic.[§] This, of course, is where particle physics comes into play; some sort of ‘new physics’ seems to be required to describe this exotic matter, beyond the particles described by the standard model of particle physics (SM). According to the best (post-MACHO) estimate [8], the local density of this mysterious stuff amounts to about

$$\rho_{\text{local}}^{\text{DM}} \simeq 0.3 \text{ GeV/cm}^3 \simeq 5 \cdot 10^{-25} \text{ g/cm}^3. \quad (6)$$

It is assumed to have a Maxwellian velocity distribution with mean $\bar{v} \simeq 300 \text{ km/sec}$. The local flux of DM ‘particles’ χ (which could be very massive, e.g. black holes) is thus

$$\Phi_{\text{local}}^{\text{DM}} \simeq \frac{100 \text{ GeV}}{m_\chi} \cdot 10^5 \text{ cm}^{-2} \text{ s}^{-1}. \quad (7)$$

The task for particle physicists is two-fold. First, one has to identify a particle (or configuration of fields) that has the proper universal relic density. Second, one should find a way to detect these putative relics from the early Universe. As we will see in the following two sections, the first task is easily accomplished; in fact, there is an ‘embarrassment of riches’ of particle DM candidates. Testing these hypotheses experimentally, however, may well prove very difficult; in some cases it seems basically impossible.

2. Dark matter candidates

Particle physicists have come up with a fairly long list of DM candidates. Many of them have been described in other recent reviews [9]. I therefore treat these ‘usual suspects’ comparatively briefly, and instead put somewhat more emphasis on developments in the last year or so.

2.1 Light neutrinos

A light ($m_\nu \leq \text{MeV}$) neutrino contributes [10]

$$\Omega_\nu h^2 \simeq m_\nu / (90 \text{ eV}) \quad (8)$$

to the scaled mass density of the Universe; that is, for $h \simeq 0.6$, neutrinos give $\Omega \simeq 1$ if $\sum_i m_{\nu_i} \simeq 30 \text{ eV}$. This does not violate any direct experimental limits if most of the mass comes from μ or τ neutrinos. However, evidence for neutrino oscillations suggests that mass differences between the three known neutrinos are of order 1 eV or less [11]. Together with the upper bound on the ν_e mass from studies of the tritium β -decay spectrum this seems to indicate that the three known neutrinos cannot contribute $\Omega_\nu \simeq 1$.

Jupiter-sized primordial black holes. Note that, unlike the first two suggestions, this would allow to circumvent the bound (5) if these black holes were formed before the era of nucleosynthesis. It is quite possible, even likely, that these claims will be refuted in due course. Nevertheless one should keep in mind that purely astrophysical solutions may yet contribute to the solution of (part of) the DM puzzle.

[§] Note that the lower bound in (4) implies $\Omega_{\text{baryon}} \geq 0.015$; hence BBN not only allows for, but actually demands, the existence of baryonic DM. Currently MACHOs observed in microlensing experiments [7] seem to be the best candidates for this.

Moreover, light neutrinos constitute ‘hot’ DM, i.e. they were still relativistic at the onset of galaxy formation (after the recombination of electrons and ions, i.e. after the freeze-out of the cosmic background radiation, about $3 \cdot 10^5$ years after the big bang). This seems incompatible with the observed pattern of structure in the Universe, if density inhomogeneities were seeded by quantum fluctuations during the (hypothetical) inflationary epoch. However, neutrino DM still seems to be able to describe structure formation if it is seeded by cosmic strings [12]; and even in the standard inflationary scenario a hot + cold mixture might describe structure formation better than pure cold DM, if the hot component amounts to 20–30% of all DM [1]. It may therefore be premature to exclude neutrinos as (a component of) DM.

Unfortunately light relic neutrinos seem to be almost impossible to detect. Studies of μ and τ decays are not likely to ever tell us whether the μ or τ neutrino carry a mass of a few (tens of) eV. If neutrinos mix, oscillation experiments should eventually be able to tell us the differences of squared neutrino masses; as mentioned above, current evidence suggests that these differences are small. In this case careful studies of tritium β decay and of neutrinoless double beta decay (e.g. of ^{76}Ge) should soon tell us if neutrinos can contribute significantly to DM, if there are only three neutrinos. If sterile neutrinos exist, essentially all bets are off. In this case the only hope seems to be to wait for the next nearby (but not too close, one hopes) supernova; precise measurements of the time structure of the neutrino pulse ought to be able to determine the masses of active neutrinos to a few eV at least [13].

2.2 Axions

Axions [14] are neutral spin-0 CP-odd (pseudoscalar) particles associated with the spontaneous breakdown of a new global $U(1)_{\text{PQ}}$ symmetry introduced by Peccei and Quinn as a solution of the strong CP problem. The basic idea is that the CP violating phase θ_{QCD} is transformed into a dynamical variable; the axion potential is then chosen such that it is minimized for $\theta_{\text{QCD}} = 0$. The axion would be massless except for chiral symmetry breaking in QCD, which gives it a mass of order

$$m_a \simeq 0.6 \text{ meV} \cdot 10^{10} \text{ GeV}/f_a. \quad (9)$$

Here, f_a is the scale where the PQ symmetry is broken. Note that not only the mass of the axion but also its couplings to ordinary matter are proportional to $1/f_a$. A combination of laboratory and cosmological constraints therefore leads to the lower bound [14]

$$f_a \geq 5 \cdot 10^9 \text{ GeV}. \quad (10)$$

On the other hand, the axions’ contribution to the total mass of the Universe increases with f_a . The requirement $\Omega h^2 \leq 1$ therefore implies [15]

$$f_a \leq 10^{12} \text{ GeV}. \quad (11)$$

This upper bound is somewhat soft. If the Universe (after inflation) ever had a temperature exceeding f_a , axionic strings should have formed during the PQ phase transition; these are potent sources of axions, so the bound (11) would be strengthened. On the other hand, if the axion field at the onset of the QCD phase transition ‘happened’ to have had a small value, this bound could be relaxed considerably. Certain supersymmetric axion models also allow to relax this bound by up to three orders of magnitude, if the decay of the

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superpartners of the axion produces a sufficient amount of entropy after the epoch of axion production [16].

The bound (10) implies that axions interact far too weakly for us to be able to detect axions produced in laboratory experiments. Indeed, relic axions seem to be the only ones that might be detectable with current technology. Note that axions are produced athermally; they behave like cold DM, and should thus cluster in our galaxy. Also, the bounds (10) and (11) imply that, if axions exist at all, their relic density ought to be substantial.

Currently two axion search experiments are under way, one in Japan and one in the US. Both attempt to convert relic axions into microwave photons in the presence of a strong magnetic field. The US experiment plans to cover the range $2 \mu\text{eV} \leq m_a \leq 12 \mu\text{eV}$, with moderate sensitivity, while the Japanese experiment intends to search for axions with $m_a \simeq 10 \mu\text{eV}$ with very high sensitivity. The US experiment has just published their first results [17], which exclude one kind of axions with mass between 2.9 and 3.3 μeV . As far as I know, the Japanese experiment [18] has not released any results yet.

2.3 WIMPs

Weakly interacting massive particles (WIMPs) are the most widely studied particle physics DM candidates. Their name derives from a peculiar ‘coincidence’. The relic density of massive particles that were already more or less non-relativistic when they decoupled from the hot bath of SM particles is approximately (up to logarithmic corrections) given by [19]

$$\Omega_\chi h^2 \simeq \frac{C}{\langle \sigma_{\text{ann}}^\chi \cdot v \rangle}, \quad (12)$$

where σ_{ann}^χ is the total annihilation cross section of WIMP pairs into SM particles, v is the relative velocity between the two WIMPs in their cms, and $\langle \dots \rangle$ denotes thermal averaging. The constant C involves factors of Newton’s constant, the temperature of the cosmic background radiation, etc. The ‘coincidence’ mentioned above is that its numerical value is such that $\Omega_\chi h^2$ comes out in the desired range (of order 0.2) if the annihilation cross section is roughly of order of weak scattering cross sections. This hints at a connection between the total mass of the Universe and (generalized) electroweak physics.

The simplest example for a WIMP would have been a massive ($m_\nu \geq \text{GeV}$) neutrino, but this possibility is now nearly excluded by a combination of searches at the e^+e^- collider LEP (specifically, by the upper bound on any non-SM contribution to the invisible width of the Z boson), cosmological arguments, and DM searches (to be described in the next section); the only loophole would be a massive neutrino that is mostly (but not entirely) an $SU(2) \times U(1)_Y$ singlet. It would be very difficult to understand why such a particle should be stable, however.

The by far best motivated WIMP is the lightest supersymmetric particle, specifically the lightest neutralino $\tilde{\chi}_1^0$ [19]. It is stable by virtue of R parity, which is automatically conserved if one only introduces absolutely necessary interactions in the SUSY Lagrangian.* Moreover, there are several regions of parameter space where Ω_χ comes out close to the desired value.

* This minimality argument can be made more rigorous in models with gauged $B-L$ symmetry [20].

This last point deserves a bit more discussion. Assuming minimal particle content, as in the MSSM, $\tilde{\chi}_1^0$ is in general a linear superposition of the fermionic superpartners of the $U(1)_Y$ and neutral $SU(2)$ gauge bosons and of the two neutral Higgs bosons; in the notation of ref. [21]:

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{h}_1^0 + N_{14}\tilde{h}_2^0. \quad (13)$$

Not surprisingly, the properties of the LSP depend quite strongly on which of these four components are large.

A bino- ($|N_{11}| \simeq 1$) or photino-like ($N_{11} \simeq \cos \theta_W$, $N_{12} \simeq \sin \theta_W$) LSP annihilates predominantly through the exchange of a sfermion in the t - or u -channel (unless an s -channel diagram is ‘accidentally’ enhanced; see below). Due to their large (hyper)charges and, in many models, comparatively small masses, the exchange of $SU(2)$ singlet sleptons is especially important. The relic density of a ‘generic’ bino-like LSP can therefore be approximated by [22]

$$\Omega_\chi h^2 \simeq \frac{\Sigma^2}{(1 \text{ TeV})^2 m_\chi^2} \frac{1}{(1 - m_\chi^2/\Sigma)^2 + m_\chi^4/\Sigma^2}, \quad (14)$$

where $\Sigma = m_\chi^2 + m_{\tilde{e}_R}^2$, and three degenerate sleptons have been assumed. This yields interesting relic densities for very reasonable choices of parameters, $m_\chi < m_{\tilde{e}_R} \leq 350 \text{ GeV}$ and $m_{\tilde{e}_R} > 100 \text{ GeV}$. Unfortunately this cannot be translated into a stringent upper bound on slepton masses, since s -channel diagrams can greatly increase the annihilation cross section, i.e. decrease the predicted relic density. This occurs if the LSP mass is very close to, or slightly below, half of the mass of one of the neutral Higgs bosons of the MSSM; such a scenario can be realized even in the framework of ‘minimal supergravity’ models [22, 23], where one postulates a very simple form of the sparticle spectrum at an energy scale not far from the scale of grand unification, $M_X \simeq 2 \cdot 10^{16} \text{ GeV}$. In such cases LSP masses of several TeV, while extremely ugly from the point of view of particle physics, cannot be excluded from cosmology.

The situation is a bit more complicated for a higgsino-like LSP ($|N_{13}|^2 + |N_{14}|^2 \simeq 1$). In the framework of the MSSM this usually implies $|N_{13}| \simeq |N_{14}|$ ($\simeq 1/\sqrt{2}$), which means that the $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling is suppressed (it vanishes in the limit of exact equality [24]). Since the $\tilde{\chi}_1^0 ff$ couplings are now Yukawa couplings, sfermion exchange contributions are small for LSPs that are too light to annihilate into $\bar{t}t$ pairs. The annihilation cross section for light higgsino-like LSPs is therefore small.

Their relic density nevertheless turns out to be quite small [25], due to ‘co-annihilation’ [26] between LSPs and heavier neutralinos or charginos. If $\tilde{\chi}_1^0$ is higgsino-like, so are (usually) $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$; moreover, the masses of these three particles are quite close to each other. Recall that $\tilde{\chi}_1^0$ is already non-relativistic at freeze-out, i.e. its number density is suppressed exponentially (by a Boltzmann factor) compared to those of SM particles. Scattering reactions of the type $\tilde{\chi}_1^0 f \leftrightarrow \tilde{\chi}_2^0 f$ and $\tilde{\chi}_1^0 f \leftrightarrow \tilde{\chi}_1^\pm f'$ therefore occurred much more frequently than annihilation reactions like $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \leftrightarrow f\bar{f}$; here f, f' denote SM (matter) fermions. As a result, the $\tilde{\chi}_1^0, \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ densities remain in *relative* equilibrium long after superparticles have decoupled from ordinary particles. This is important, since the $Z\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $W^\pm\tilde{\chi}_1^0\tilde{\chi}_1^\mp$ couplings are unsuppressed if $\tilde{\chi}_1^0$ is higgsino-like. Hence the cross sections for $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0\tilde{\chi}_1^\pm$ co-annihilation into SM fermion antifermion pairs are

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orders of magnitude larger than those for $\tilde{\chi}_1^0\tilde{\chi}_1^0$ annihilation. This greatly reduces the final $\tilde{\chi}_1^0$ density, to the extent that only a small sliver of parameter space survives where a higgsino-like LSP with mass below M_W makes a good DM candidate; among other things, one has to assume that certain quantum corrections to the masses of the higgsino-like states occur with the correct sign [27].

A higgsino-like LSP with mass $\geq M_W$ has very large annihilation cross sections into W and Z pairs. Even in the absence of co-annihilation one therefore needs LSP masses exceeding 400 GeV to get a cosmologically interesting relic density. (Note that the annihilation cross section must drop at least as $1/m_\chi^2$, due to partial wave unitarity.) Moreover, a recent complete calculation of co-annihilation of heavy higgsino-like states [28] showed that it reduces the predicted relic density significantly. Even though annihilation into W and Z pairs are the biggest single cross sections, the *total* co-annihilation cross sections remain significantly larger than annihilation cross sections, due to the large number of different fermion antifermion final states, which essentially only contribute to the former. This pushes the lower bound on the mass of a cosmologically interesting higgsino-like LSP into the TeV region. Such a heavy LSP is not natural from the particle physics point of view; one would need a significant amount of fine tuning [29] to keep the W and Z bosons as light as they are, if even the lightest superparticle weighs at least a TeV. This would weaken the very motivation for ‘weak scale’ supersymmetry.[†]

Finally, if the LSP is \tilde{W}_3 -like ($|N_{12}| \simeq 1$), its predicted relic density is again very small unless the LSP mass exceeds 1 TeV [30]. The culprit is again co-annihilation; in this case the mass splitting to the lightest chargino often only amounts to a few hundred MeV. Fortunately such a situation appears somewhat unlikely from the model building point of view, since it requires strong violation of the unification of gaugino mass parameters (at the GUT scale, the $U(1)_Y$ gaugino mass must be more than twice as large as the $SU(2)$ gaugino mass); such scenarios do exist, however [31].

While the lightest MSSM neutralino is the by far most widely studied WIMP candidate, other examples also have been suggested. In the NMSSM, where one introduces one $SU(2) \times U(1)_Y$ singlet Higgs superfield, the LSP usually is still the lightest neutralino, but it now also has a ‘singlino’ component [i.e., a fifth term must be added to eq. (13)]. This allows for new solutions with interesting relic density [32]. Similar remarks apply for models with an extra $U(1)$ gauge factor [33].

Another possible WIMP candidate [34] is the lightest ‘messenger sneutrino’ in models where supersymmetry breaking is mediated to the visible sector through gauge interactions. Unlike an ‘ordinary’ sneutrino, such a particle could evade bounds from direct WIMP searches (see § 3.1) if quantum corrections split the CP-even and CP-odd components of the sneutrino field (associated with its real and imaginary part, respectively), so that only one of these components survives to the present time [35]. However, the messenger scale

[†] The authors of ref. [28] also find examples where co-annihilation *increases* the prediction for the LSP relic density. This can happen if there are three nearly degenerate neutralino states, i.e. if the supersymmetry breaking bino mass parameter M_1 is close to the supersymmetric higgsino mass parameter $|\mu|$. Since the cross section for co-annihilation of a gaugino-like and a higgsino-like state is quite small, conversion of the LSP into a heavier neutralino can then enhance its probability to survive until freeze-out. However, this phenomenon only occurs for a narrow strip of parameter space.

would then have to be quite low in order to avoid getting too high a relic density, in violation of the bound (3).[‡] Similarly, the CP-even and CP-odd components of $\bar{\nu}_\tau$ could be split by some new lepton flavor violating interaction [36]; this mechanism would require a ν_τ mass of at least 5 MeV, which might be measurable at the upcoming B -factories.

Several schemes for detecting relic WIMPs have been suggested; these will be discussed in §3.

2.4 Strongly interacting particles

Certain extensions of the SM also contain strongly interacting DM candidates. Note that the ‘strong’ interactions referred to here are a new gauge force, not standard QCD. The oldest example of this kind [37] is a techni-baryon associated with a hypothetical technicolor (TC) gauge group, whose techni-quark condensates are supposed to be responsible for electroweak symmetry breaking. In analogy with QCD one expects the lightest techni-baryon to be stable, but it can annihilate through TC interactions into unstable technipions. Techni-baryons have masses of roughly a few TeV; given their strong annihilation cross sections, the standard formalism described in the previous subsection would then predict too low a relic density to be of cosmological interest. However, it is possible that there is a techni-baryon number asymmetry in the Universe. In fact, mechanisms have been suggested that would generate approximately equal baryon and techni-baryon asymmetries. In this case one would expect

$$\Omega_{\text{TC}} \sim \Omega_{\text{baryon}} \cdot \frac{m_{\text{TC}}}{m_p}, \quad (15)$$

where m_p is the proton mass. Given that $\Omega_{\text{baryon}} > 0.01$, see eq. (4), this is actually too large by at least one order of magnitude, so one has to postulate a ‘model-specific suppression factor’ [37]. Note also that 20 years of effort have not produced a single fully viable technicolor model. Techni-baryons would resemble heavy WIMPs as far as DM searches are concerned [37].

Another strongly interacting DM candidate [34] originates in the ‘secluded sector’ of SUSY models where supersymmetry is broken at relatively low energies, $\mathcal{O}(100\text{TeV})$. Strongly interacting ‘baryons’ of this mass would have $\Omega \sim 1$ if no ‘baryon’ asymmetry exists in this sector. Indeed, from partial wave unitarity one can derive [38] the upper bound

$$m_X \leq 500\text{TeV} \quad (16)$$

for any particle X whose lifetime exceeds the age of the Universe, if this particle has ever been in chemical equilibrium with SM particles (after inflation). An absolutely stable particle of this mass is probably all but undetectable [34] if it is a singlet under the SM gauge group, as is expected for ‘secluded baryons’.

Strongly interacting particles always behave like cold DM.

[‡] One can still construct models with very high messenger scales if one arranges for the lightest messenger particle to be unstable, or for it to be ‘inflated away’. However, it can then no longer be a DM candidate.

2.5 Gravitationally interacting particles

On the other end of the spectrum are DM candidates that only have gravitational interactions. The most prominent example is the gravitino [39]. If it is much lighter than ‘visible’ sparticles (as it has to be in order to make a viable DM candidate), its interactions are actually of ‘enhanced gravitational strength’, since the effective coupling of the spin-1/2 (Goldstino) component of the gravitino is $s/(m_{3/2}M_{\text{Pl}})$, where s is the squared cms energy of the process under consideration, $m_{3/2}$ is the gravitino mass, and M_{Pl} is the Planck mass. This is sufficient for a keV gravitino to have been in thermal equilibrium at temperatures $T \geq 100$ GeV. Gravitinos would have been ultra-relativistic at freeze-out, so the calculation of their relic density resembles that for light neutrinos [10]. One finds [39]

$$\Omega_{\tilde{G}} h^2 \simeq \frac{m_{3/2}}{0.85 \text{ keV}}. \quad (17)$$

These gravitinos would have been ‘warm’ at the onset of structure formation; for most, though not all, purposes this would resemble cold DM. One can also produce an effectively hot (really, athermal) gravitino component if a large number of LSPs decay into gravitinos [39]; however, one needs sfermion masses well in excess of 1 TeV for this component to be significant.

To my knowledge nobody has yet found a way to detect relic gravitinos.

2.6 Superheavy particles

Recently there has been renewed interest in DM candidates whose masses greatly exceed the unitarity bound (16). Recall that this bound assumed that the new particle once was in chemical equilibrium* with SM particles. Stable particles with mass beyond 500 TeV must therefore have sufficiently small annihilation cross sections to never have achieved equilibrium [40]:

$$n_X \langle \sigma_{\text{ann}}^X v \rangle < H, \quad (18)$$

where H is the Hubble parameter and n_X the number density of X particles. Note that this inequality must be satisfied at all times (after the end of the inflationary epoch, if there was one). In the framework of ‘standard’ inflationary models, and assuming $\Omega_X = 1$, this implies [40]

$$m_X \geq 10^{13} \text{ GeV} \cdot \left(\frac{100 \text{ GeV}}{T_{\text{RH}}} \right)^{1/3} \cdot \left(\frac{\langle \sigma_{\text{ann}}^X v \rangle}{m_X^2} \right)^{2/3}. \quad (19)$$

Here T_{RH} is the reheating temperature after inflation, which might have been as high as 10^9 GeV. Also, the annihilation cross section could be (much) smaller than the unitarity limit $\sim 1/m_X^2$. Equation (19) therefore suggests that particles with masses exceeding 10^{13} GeV certainly never were in thermal equilibrium, but (much) lighter particles might also satisfy this criterion.

* This means that reactions that change the number of these heavy particles must have been in equilibrium. This is a far more restrictive constraint than the requirement that the X particles have the same temperature as the bath of SM particles.

By definition the X -particle could not have formed thermally, but several other mechanisms have been suggested [40]. If m_X is less than the mass of the inflaton $m_\phi \simeq 10^{13}$ GeV, it could be formed in inflaton decays. Even if $m_X > m_\phi$ a substantial X density might have been created during a period of ‘pre-heating’ through a ‘parametric resonance’ [41]. Neither of these two mechanisms seems to particularly favor $\Omega_X \sim 1$, though. In contrast, (gravitational) interactions between X -particles and the space-time metric at the end of inflation naturally produce [40] $\Omega_X \sim 1$ (to logarithmic accuracy, anyway) if $m_X \sim m_\phi$ ($\sim 10^{13}$ GeV). Finally, X might be the inflaton itself [42].

Of course, X also has to be very long-lived for it to be a good DM candidate. In particular, its couplings to SM particles must be far weaker than gravity [43]. This probably excludes massive Kaluza–Klein modes, which are expected to exist in superstring (or M) theory. On the other hand, 10^{13} GeV is close to the scale where SUSY is supposed to be broken in the hidden sector of many supergravity (or superstring) theories. Some ‘baryons’ in this hidden sector may be sufficiently long-lived; an explicit example has been suggested in ref. [43].

Stable X -particles of this mass are almost certainly undetectable. On the other hand, if their lifetime is roughly comparable to the age of the Universe, their decay products might be detectable. In fact, it has been suggested [44] that these have been seen already, in form of ultra-high energy cosmic rays ($E \geq 10^{11}$ GeV)!†

2.7 Supersymmetric Q -balls

Q -balls [45] are stable scalar field configurations carrying a global conserved $U(1)$ charge Q . Such objects might exist in supersymmetric models [46], provided the potential is sufficiently flat for large field values; the $U(1)$ charge in question would be the baryon number B . The MSSM has many directions in field space that are both D - and F -flat (i.e. where the potential feels neither gauge nor Yukawa interactions), but SUSY breaking has to be switched off at sufficiently low energies to make the soft breaking terms sufficiently small for large values of the fields. This scenario can therefore only work in models with gauge mediated SUSY breaking, where the soft breaking terms rapidly disappear at scales above the mass of the messenger fields.* In these models the total mass of the B -balls only grows $\propto B^{3/4}$; hence a B -ball becomes stable against decay into nucleons if

$$B > \left(\frac{m_{\bar{q}}}{m_p}\right)^4 \simeq 10^{10} \cdot \left(\frac{m_{\bar{q}}}{300 \text{ GeV}}\right)^4. \quad (20)$$

This implies that their mass would have to be at least 10^9 GeV or so. Kusenko and Shaposhnikov argue [46] that such objects could have been formed abundantly in the decay of a squark field condensate, which is an ingredient of the Affleck–Dine mechanism [48] of baryogenesis. At present it is not clear why this should produce $\Omega \sim 1$, though.

Although fairly heavy, B -balls are actually easy to detect [49], provided only that their flux (7) is high enough for one of them to pass through your detector. If the field

† The origin of these extremely energetic events is very difficult to explain in the framework of the SM.

* In gravity mediated scenarios, B -balls might still be sufficiently long-lived to play a role in the creation of the baryon asymmetry of the Universe [47].

configuration is such that electrons have a large mass inside the B -ball, it will collect a large electric charge by ‘eating’ protons through the reaction $qq \rightarrow \bar{q}q$. Eventually the Coulomb barrier will become too high and this reaction will stop. A fully charged B -ball will interact very strongly with matter through atomic collisions, releasing ~ 100 GeV of energy on each cm of its track. This has to come from the kinetic energy of the B -ball, i.e. eventually it will get stuck in matter. Charged B -balls with $B \leq 10^{13}$ would therefore not reach detectors placed deeper than 1 km water-equivalent [49]. Heavier ones should reach those detectors; their flux is thus limited by unsuccessful searches for highly charged ‘quark nuggets’. On the other hand, if electrons are light or massless inside a B -ball, it can shed its electric charge through $ue \rightarrow d\nu_e$. Such a neutral B -ball also releases ~ 100 GeV/cm $\cdot \rho / (1\text{g/cm}^3)$, but this energy comes from ‘eating’ nucleons, and is released mostly in form of pions. Such an object would therefore look like a magnetic monopole catalyzing nucleon decay as it moves through a detector, so the corresponding search limits apply. Altogether one has [49] $B \leq 10^{13}$ or $B \geq 10^{21}$, for electrically charged B balls; $B \geq 3 \cdot 10^{22}$, for electrically neutral B balls.

Finally, it has been proposed that B -balls might be eating up neutron stars [50]. Eventually an attacked n -star would become too light to remain gravitationally bound, and would be blown apart by its Fermi pressure. This might give rise to the observed gamma ray bursters.

3. WIMP detection

WIMPs are in my view best motivated, and certainly most widely studied, particle DM candidates. I will therefore describe proposals for their detection in somewhat more detail than for the other candidates mentioned in the previous section. Basically three kinds of WIMP signatures have been discussed in the literature [19]: Direct detection through elastic WIMP-nucleus scattering; WIMP annihilation in the center of the Earth or Sun producing high-energy neutrinos; and WIMP annihilation in the halo of our galaxy producing hard gamma rays, positrons, or antiprotons. These methods will be described in the following three subsections.

3.1 Direct WIMP detection

Here one searches simply for the elastic scattering of a WIMP on a nucleus inside a detector; more exactly, one looks for the recoil of the struck nucleus. Recall that WIMPs in the halo are supposed to have velocities of about $10^{-3}c$.[†] The recoil energy of a nucleus with mass m_A can therefore at most be

$$E_{\text{recoil}}^{\text{max}} = 2v_{\chi}^2 m_A \frac{m_{\chi}^2}{(m_A + m_{\chi})^2}. \quad (21)$$

Hence typical recoil energies are $10^{-6}m_A$ or less, in the (tens of) keV range. Detecting this

[†] Cowsik *et al* have argued [51] that the true velocity might be at least two times higher. This has been criticized in [52]. The issue does not yet seem to be entirely settled, though [53].

low an energy is far from easy. One has to use ultrapure materials for both the detector and its immediate shielding to minimize backgrounds from α and β decays. Most advanced detection schemes in addition (plan to) use methods to distinguish between nuclear recoils and β and γ backgrounds, e.g. by using pulse shape information (in scintillator detectors [54]), or by measuring both phonon and ionization energy (in cold semiconductor detectors [55]).

The first experiments of this type [56] have already achieved sufficient sensitivity to exclude massive Dirac neutrinos, or (complex) sneutrinos, as a major component of the galactic halo. The sensitivity limit of these early experiments was tens or hundreds of events per kg and day. The currently best bound has been established by the DAMA collaboration [57], which operates 9 NaI crystals in the Gran Sasso underground laboratory; it improves the bound of ref. [56] by up to a factor of 5.

Unfortunately the predicted counting rate for the most attractive WIMP candidate, the lightest MSSM neutralino, is usually quite low. LSPs can interact with nucleons through the exchange of squarks in the s - or u -channel, or through t -channel exchange of a Z or neutral Higgs boson [19]. Squark exchange is suppressed by the large squark mass ($m_{\tilde{q}} \geq 200$ GeV from searches at the Tevatron $p\bar{p}$ collider [58]). The exchange of Z bosons is suppressed by the smallness of the $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ coupling. Moreover, Z exchange only produces a spin-spin coupling, since the vector current of the Majorana neutralino vanishes identically. Unlike scalar (spin-independent) couplings, such spin-dependent couplings are not enhanced for heavy nuclei, compared to the coupling to a single nucleon.

This leaves Higgs exchange as the (usually) most important contribution to the LSP-nucleus scattering matrix element. The squared Higgs exchange contribution scales like the inverse fourth power of the mass of the corresponding Higgs boson;[‡] the maximal possible cross section is thus getting squeezed by Higgs mass bounds from unsuccessful Higgs searches at LEP and elsewhere. Constraints from radiative $b \rightarrow s\gamma$ decays also play a role. As a result, choices of parameters that give a relic density of the right order of magnitude typically predict [19, 59] LSP detection rates in ^{76}Ge somewhere between 10^{-4} and 10^{-1} evts/(kg-day), although somewhat higher rates may still be possible [60]. This means that one will have to improve the current sensitivity by at least two, and possibly five, orders of magnitude!

The Proceedings of a recent workshop on DM and its direct detection [61] contains contributions from 11 different groups who are looking, or are planning to look, for WIMPs. As already mentioned, the currently best limit comes from NaI scintillator detectors [57]. Their sensitivity is expected to improve significantly through improved pulse shape discrimination, doping, and by reducing the operating temperature [62]. However, among the experiments that are now running, the CDMS experiment will probably achieve the highest sensitivity, at least for spin-independent couplings. They just published [63] first results from a pilot run, where they operated several Si and Ge detector modules at millikelvin temperatures at a shallow site in California; the mass of the modules is of order 100 g each. While not yet competitive, this run indicates that their detectors are working satisfactorily. Once the full experiment is installed in the Soudan mine, it is expected to improve upon current sensitivity by at least two orders of magnitude [63].

[‡]Note that the contribution from exchange of the CP-odd Higgs boson is negligible, since the pseudoscalar LSP current is suppressed by a factor of the LSP velocity $\sim 10^{-3}$.

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This will still not be sufficient to probe much of MSSM parameter space (although it may see a positive signal). Recently there has been a proposal [64] to deploy a large number of enriched ^{76}Ge detectors, for a total mass of (at least!) one ton, in a big tank of liquid nitrogen inside the Gran Sasso laboratory. Preliminary studies indicate that this could indeed cover nearly the entire MSSM parameter space, for material purities that are worse than what has already been achieved for the BOREXINO experiment (not for Ge, however). Besides looking for WIMPs, this experiment could also improve the sensitivity of searches for neutrinoless double- β decays by several orders of magnitude; in fact, the ‘ordinary’ $2\nu\beta\beta$ decay may well give the biggest background to WIMP searches in this experiment! Note that the total target mass so far deployed in the CDMS experiment is less than 1 kg. Clearly 1 ton of ^{76}Ge inside 500m^3 of liquid nitrogen is no longer a ‘table top’ experiment, but it should still be much cheaper to build than a major collider experiment.

One problem of direct WIMP search experiments is that it may be difficult to convince people that a putative signal is in fact due to WIMPs. Neither the NaI nor the semiconductor experiments have any directionality, so at best one can measure a recoil energy spectrum. Since the mass of the WIMP is not known, no clear prediction for the shape of this spectrum can be made. Worse, this shape also depends on the assumed velocity distribution of the WIMPs in the halo. It could, e.g., be changed significantly if the halo had some net rotation [65].

The only fairly robust characteristic WIMP signal that has so far been suggested is based on the annular modulation of the WIMP flux as seen on Earth [66]. This signal occurs because the Earth moves around the Sun with about 30 km/sec. If the DM halo does not rotate in the rest frame of the (visible) galaxy (the standard assumption), a component of about 15 km/sec will add to the Sun’s velocity around the center of our galaxy ($v_{\text{sun}} \simeq 220$ km/sec) in early June, and subtract from it in December. As long as the rotational velocity of the dark halo does not exceed the orbital velocity of the Sun around the galactic center, the phase and frequency of this modulation will not change, although the amplitude might. One thus expects the counting rate to behave like

$$N(t) = N_0 + N_1 \cos[\omega(t - t_0)], \quad (22)$$

where $t_0 = \text{June } 2$ and $\omega = 2\pi/\text{yr}$. Unfortunately N_1/N_0 is expected to be quite small ($\sim 5\%$ for a non-rotating halo), so seeing this modulation will not be easy.

Nevertheless the DAMA collaboration announced last year (1997) that they may have found an effect which is not incompatible with being a signal [67]. However, as pointed out in ref. [68], this ‘not-bound’ is almost certainly not a true signal. For one thing, it only occurs in 3 out of 9 crystals; for the other 6 crystals N_1 is perfectly consistent with 0. Also, even the best fit value of m_χ does not reproduce the observed energy dependence of the excess very well; however, as far as I know they have not tried varying the parameters of the galactic halo model (WIMP velocity distribution and/or bulk halo rotation) in their fits. Finally, the data were taken either in winter or in June; it is therefore not surprising that the fit gave a period compatible with 1 yr.

3.2 Indirect WIMP detection: Neutrinos

Of course, WIMPs (if they exist) do not only scatter off nuclei inside a detector; they can scatter off any nucleus inside the Sun or Earth (or elsewhere). If they lose a sufficient

amount of energy in that scattering, they will become gravitationally bound to the celestial body they hit. After (many) additional scatters, they will eventually spiral into the center of this body. In other words, the WIMP density should be (greatly) enhanced in the centers of massive celestial bodies. WIMPs will then begin to annihilate with significant rates inside these bodies; eventually WIMP capture by and WIMP annihilation in these bodies will reach equilibrium. In case of the Sun this equilibrium should have been reached for all reasonable WIMPs, but this may not be true in case of the Earth if the WIMP mass exceeds 100 GeV or so.

Of course, most particles produced by WIMP annihilation in the Earth or Sun will get stuck in these bodies. The only particles that have a chance to escape are neutrinos. Unfortunately Majorana WIMPs at rest cannot annihilate into a massless $f\bar{f}$ pair (unless CP is violated in the WIMP sector, e.g. due to phases in the neutralino mass matrix in the MSSM [69]). The neutrinos thus have to come from the decay of heavier particles. In case of the LSP, the best sources of neutrinos are usually $\tau^+\tau^-$ and, for heavier LSPs, W^+W^- and ZZ final states [19].

The most easily detected neutrinos are muon (anti-)neutrinos. These can be searched for with so-called neutrino telescopes. The idea is that the neutrino converts into a muon through a charged current reaction in the material surrounding the detector; the muon itself is then easily detected, either using conventional muon chambers, or through the Čerenkov light it emits on its way through (frozen) water. Due to the large background of cosmic ray induced muons, one can only hope to see a signal for WIMP annihilation in upwards going muons. Obviously neutrinos (and hence muons) from WIMP annihilation in the center of the Earth will always come from below, but in case of neutrinos from the center of the Sun this requirement reduces the ‘duty cycle’ (the useful luminosity) by a factor of two.

Note that in equilibrium the annihilation rate is half the capture rate, which in turn is given by the WIMP-nucleus scattering cross section. The expected rates for direct and indirect WIMP detection are therefore correlated [70]. However, the dependence on the WIMP mass is different for the two signals. In case of direct detection, if the WIMP mass is less than or of order of the mass of the target nucleus, increasing m_χ increases the average recoil energy, eq. (21), which makes these events easier to detect.* The increase of the available phase space also increases the total scattering cross section. However, for large WIMP masses the direct detection rate drops like $1/m_\chi$, due to the decrease in flux, eq. (7). On the other hand, both the $\nu_\mu \rightarrow \mu$ conversion probability and the length of the muon track (which determines the effective detector volume) increase more or less linearly with the average neutrino energy, which in turn is proportional to the WIMP mass. One would therefore naively expect the indirect detection rate to increase linearly with m_χ , even after the reduction of the flux (7) has been taken into account.† However, heavier WIMPs are less likely to become gravitationally bound after they scatter [19]. Moreover, at least in case of MSSM neutralinos, heavier LSPs are usually less mixed;

* However, increasing the energy region where a signal can exist might also increase the total background.

† Note also that the angular correlation between the μ and ν_μ directions becomes better at higher energies. Heavier WIMPs would therefore give sources with smaller opening angles, and hence less background. The main physics background comes from atmospheric neutrinos.

note that the $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ Higgs couplings are proportional to the product of higgsino and gaugino components of $\tilde{\chi}_1^0$. Heavier LSPs hence tend to have lower scattering cross sections. The combination of these competing effects means that in the MSSM there is no strong correlation between the expected indirect detection rate from LSP annihilation in the Earth or Sun and the LSP mass [71].

The best bounds on the flux of upward-going muon neutrinos currently come from the Baksan collaboration [72]. Their detector consists of several layers of muon chambers covering $\sim 250 \text{ m}^2$; it has been taking data for about 20 years. This bound gives the best constraint on heavy Majorana neutrinos as DM candidates [73], but it only begins to scratch the MSSM parameter space [71]. One would need to improve sensitivity by 4 or 5 orders of magnitude to probe most of parameter space. The required large increase in detector area is probably only affordable if one instruments a large volume of (frozen) water with photo-multiplier tubes (PMTs), and searches for muon tracks through their Čerenkov light. The so far most promising experiment along these lines is AMANDA, which has been operating successfully at the South pole for a couple of years [74]. They have now demonstrated their ability to distinguish upward going (neutrino induced) events from cosmic ray backgrounds, but currently their threshold energy is still quite high, $E_\mu^{\text{thr}} \simeq 50 \text{ GeV}$; this limits their usefulness for WIMP searches since typically $\langle E_\mu \rangle \leq m_\chi/4$. Currently the effective detector area of AMANDA is about 10^4 m^2 ; they eventually plan to instrument an entire km^3 of ice. Since deep polar ice has proven to be exceptionally transparent, about 5,000 PMTs would be sufficient for this ambitious experiment [74]. At present it is not clear what the ultimate energy threshold of this 'ice cube' detector would be. There are also several proposals to deploy Čerenkov detectors in deep lake or sea water [75].

The energy resolution of most existing or planned neutrino telescopes is quite poor. The only exception I know of is the HANUL experiment in Korea [76], which plans to use large permanent magnets as muon spectrometers. Excellent up-down rejection (required to suppress cosmic ray muon backgrounds) is to be achieved by precise timing, as well as by PMT-instrumented water tanks above and below the magnets (which determine the direction of the Čerenkov cones of the muons, and hence their flight direction). If everything works as planned, this might allow one to do neutrino astronomy above ground. However, the currently foreseen number of modules is probably too small to detect a signal for LSP annihilation.

3.3 Indirect WIMP detection: Annihilation in the halo

Even though the WIMP density in the galactic halo is expected to be far lower than that in the center of celestial bodies, halo WIMPs should still annihilate occasionally. In this case all annihilation products are in principle visible, although it is not a priori clear whether they will be detectable on top of the expected backgrounds. Three channels appear to have some potential for WIMP detection [19]: positrons, antiprotons, and γ lines.

Since positrons are very light, they can again not be produced in Majorana WIMP annihilation at rest, but are expected to originate from the decay products of heavier particles. In particular, annihilation into W and Z pairs might give rise to a prominent feature in the e^+ energy spectrum at $E_{e^+} \sim m_\chi/2$ [19]. In contrast, the background is expected to be a smoothly falling function of the positron energy.

Antiprotons can originate from hadronic decays of WIMP annihilation products. Since these antiprotons will be produced at the end of a fairly long decay and hadronization chain, their momentum is expected to be only a small fraction of the WIMP mass. In contrast, most background antiprotons come from the interaction of energetic cosmic rays with more or less stationary targets, and are therefore expected to be quite energetic due to a Lorentz boost. The best signal for WIMP annihilation in this channel is therefore expected to show up at low energies, well below 1 GeV [19].

Both e^+ and \bar{p} have to be detected near the top of or above the atmosphere. A significant improvement of the current \bar{p} flux measurements (from balloon experiments) is expected to be achieved by the alpha magnetic spectrometer [77], which is scheduled to be flown on a space shuttle this year, and should eventually be installed on the international space station (assuming it ever gets built).

Predictions for both these signals suffer from uncertainties in the modeling of charged particle propagation through the galaxy. Charged particles in the expected energy range will get trapped by the magnetic field of the galaxy; they may thus have spent a lot of time orbiting the galaxy before reaching Earth. In case of the \bar{p} signal the energy is so low that effects of the solar B -field, including its time dependence, also have to be modeled carefully.

These complications do not arise for the γ line signal for WIMP annihilation in the halo, since the produced photons simply travel in a straight line (more exactly, a geodesic). On the other hand, WIMPs by definition have no tree-level couplings to photons. WIMP annihilation into $\gamma\gamma$ or γZ can therefore only occur through loops. The first complete calculations of the corresponding matrix elements in the MSSM have been completed only last year [78]. For gaugino-like LSPs the resulting cross section is small, much less than 1% of the total annihilation cross section. On the other hand, these loop-induced cross sections become quite important for heavy higgsino-like LSPs. Indeed, ref. [78] find constant (m_χ -independent) cross sections in this case, in conflict with partial wave unitarity. Since the calculation for the $\gamma\gamma$ final state has been performed by two independent groups, their result is probably correct. However, multi-loop effects should unitarize the cross section, i.e. restore the required $1/m_\chi^2$ behavior. The results of ref. [78] violate unitarity only for $m_\chi \geq 100$ TeV, which is of no practical interest; however, already for $m_\chi \sim 2$ TeV the loop-induced $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma$ cross section comes out *larger* than the cross section for $\chi_1^+ \chi_1^- \rightarrow \gamma\gamma$, which occurs at tree-level. I find it hard to believe that this result will survive in a more complete calculation.*

The strength of the signal for WIMP annihilation into $\gamma\gamma$ and γZ final states is proportional to the square of the WIMP density, integrated along the line of sight in the direction one is looking. If WIMPs exist, they should be most abundant near the center of our galaxy. Unfortunately the value of the DM density near the galactic center is much less constrained by observation than the local DM density is. Predictions for the strength of this signal using different halo models therefore differ by several orders of magnitude [81]. If the halo density is quite singular near the center, prospects for detecting heavy

* Last year there has been a claim [79] that data from a balloon emulsion experiment and from air shower Čerenkov telescopes show evidence for a line at 3.5 TeV; however, this claim seems to have been based on an incorrect interpretation of the data [80]. Besides, this 'signal' would have been far stronger than what one expects in any known model.

higgsino-like LSPs in this channel may be quite good [81]; recall, however, that higgsinos need to be uncomfortably (from the particle physics point of view) heavy to make good DM candidates. If the LSP is gaugino-like, and/or the halo density varies smoothly near the center of the galaxy, the γ line signal does not appear to be very promising.

We thus see that predictions for all signals for WIMP annihilation in the galactic halo suffer from large astrophysical (or galacto-physical) uncertainties. It will therefore be difficult to translate null results into bounds on parameter space, or positive observations into measurements of cross sections, until we know much more about the dynamics of our galaxy. For the time being the signals discussed in this subsection should therefore be considered to be potential discovery channels, rather than as ways to possibly rule out certain DM candidates.

4. Summary and conclusions

Most of the mass of the Universe is dark. Very likely most of this dark matter is non-baryonic, although baryonic dark matter should also exist, and may have been found in the form of MACHOs. Neutrinos, by themselves, do not appear to make good DM candidates; the DM puzzle therefore strongly hints towards new physics.

Unfortunately knowing the approximate DM density does not allow us to say much about the objects that form it. Even if we restrict ourselves to truly elementary particles, their mass could be anywhere between 10^{-5} eV (axions; see § 2.2) and $\geq 10^{13}$ GeV (§ 2.6). Their interactions with normal (baryonic) matter could be anywhere between essentially non-existent (gravitinos; § 2.5) and extremely violent (*B*-balls; § 2.7).

Out of this zoo of exotic hypothetical DM candidates, the supersymmetric LSP (§ 2.3) remains my personal favorite. The agreement (to logarithmic accuracy) between expected and ‘observed’ relic density, especially for gaugino-like LSPs, seems too close to be a mere coincident. Also, supersymmetry is well motivated quite independent of the DM problem. (However, axions also have a, to my mind weaker, particle physics motivation; and some SUSY models allow for other DM candidates.) The detection of relic neutralinos, while probably far from easy, is at least not hopeless (§ 3). I would be surprised if the necessary sensitivity will be achieved before the turn-on of the LHC experiments, which are almost guaranteed to detect superparticles if they exist ‘at the weak scale’. However, even if SUSY is first discovered at colliders, detecting relic neutralinos (or other DM particles) remains of the greatest importance. For one thing, collider experiments will never be able to prove that the LSP is sufficiently stable to form DM (although they might eliminate it from the list of candidates if it is very short-lived); the best bound on the LSP lifetime from these experiments is expected to be some 24 orders of magnitude less than the age of the Universe. Conversely, once the mass and interaction strength of the LSP (or any other DM candidate) have been determined by collider experiments, and its longevity has been established by any one positive DM signal, various (bounds on) ‘indirect’ signals for WIMP annihilation will allow us to constrain galactic models; a major source of uncertainty in attempts to understand the formation of large scale structures in the Universe will then also have been removed. Accelerator based experiments and dark matter searches should therefore be considered to complement, rather than compete with, each other.

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