The Enigma of the Dark Matter

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Abstract

One of the great scientific enigmas still unsolved, the existence of dark matter, is reviewed. Simple gravitational arguments imply that most of the mass in the Universe, at least 90%, is some (unknown) non-luminous matter. Some particle candidates for dark matter are discussed with particular emphasis on the neutralino, a particle predicted by the supersymmetric extension of the Standard Model of particle physics. Experiments searching for these relic particles, carried out by many groups around the world, are also discussed. These experiments are becoming more sensitive every year and in fact one of the collaborations claims that the first direct evidence for dark matter has already been observed.

1 Why do we need dark matter?

One of the most evasive and fascinating enigmas in physics is the problem of the dark matter in the Universe. Most astronomers, cosmologists and particle physicists are convinced that at least 90% of the mass of the Universe is due to some non-luminous matter, the so called 'dark matter'. However, although the existence of dark matter was suggested 68 years ago, still we do not know its composition.

In 1933 the astronomer Fritz Zwicky provided evidence that the mass of the luminous matter (stars) in the Coma cluster, which consists of about 1000 galaxies, was much smaller than its total mass implied by the motion of cluster member galaxies. But, only in the 1970's the existence of dark matter began to be considered seriously. Its presence in spiral galaxies was the most plausible explanation for the anomalous rotation curves of these galaxies, as we will discuss in detail in the next subsection. In summary, the measured rotation velocity of isolated stars or gas clouds in the outer parts of galaxies was

not as one should expect from the gravitational attraction due to the luminous matter. This lead astronomers to assume that there was dark matter in and around galaxies. Although the nature of this dark matter is still unknown, its hypothetical existence is not so odd if we remember that the discovery of Neptune in 1846 by Galle was due to the suggestion of Le Verrier on the basis of the irregular motion of Uranus.

1.1 Dark matter in galaxies

To compute the rotation velocity of stars or hydrogen clouds located far away from galactic centres is easy. One only needs to extrapolate the Newton's law, which works outstandingly well for nearby astronomical phenomena, to galactic distances. Let us recall e.g. that for an average distance r of a planet from the center of the Sun, Newton's law implies that $v^2(r)/r = GM(r)/r^2$, where $v(r)$ is the average orbital velocity of the planet, $G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2} is the Newton's constant and $M(r)$ is the total mass inside the orbit. Therefore one obtains

$$v(r) = \sqrt{\frac{G\ M(r)}{r}}\ . \tag{1}$$

Clearly, $v(r)$ decreases with increasing radius since $M(r)$ is constant and given by the solar mass $M_\odot = 1.989 \times 10^{30}$ kg. The credibility of this formula can be deduced easily. For example, the mean distance for the Earth to the Sun is 150×10^6 km implying $v = 30$ km s^{-1}. For Neptune whose mean distance is 30 times bigger the velocity is 5.4 km s^{-1}. As it is well known both results for the velocity of the Earth and Neptune are correct.

In the case of a galaxy, if its mass distribution can be approximated as spherical or ellipsoidal, eq.(1) can also be used as a estimate. Thus if the mass of the galaxy is concentrated in its visible part, one would expect $v(r) \sim 1/\sqrt{r}$ for distances far beyond the visible radius. Instead, astronomers, by means of the Doppler effect, observe that the velocity rises towards a constant value about 100 to 200 km s^{-1}. Thus for large distances $M(r)/r$ is generically constant. Hence the mass interior to r increases linearly with r. An example of this can be seen in Fig. 1, where the rotation curve of M33, one of the about 45 galaxies which form our small cluster, the Local Group, is shown. For comparison, the expected velocity from luminous disk is also shown. Using approximation (1) and the visible mass of M33, $4 \times 10^{10} M_\odot$, one can roughly reproduce this curve.

This phenomenon has already been observed for about a thousand spiral galaxies [2], and in particular also for our galaxy, the Milky Way. The most common explanation for these flat rotation curves is to assume that disk galaxies are immersed in extended dark matter halos. While at small distances this dark matter is only a small fraction of the galaxy mass inside those distances, it becomes a very large amount at larger distances. For instance for* $r = 10$ kpc in Fig. 1, since the observed velocity is $v \approx 120$ km s^{-1} and the expected velocity due to the luminous matter is $v_{\rm lum} \approx 40$ km s^{-1}, one obtains using

*The parsec (pc) is a unit of distance, 1 pc = 3.26 light-years $\simeq 30.8 \times 10^{12}$ km. For galactic distances, the kiloparsec (kpc), 1 kpc = 10^3 pc, is used. On the other hand, for cosmological distances, the megaparsec (Mpc), 1 Mpc = 10^6 pc, is preferred. For example the Coma cluster mentioned above measures about 1.5 Mpc across.

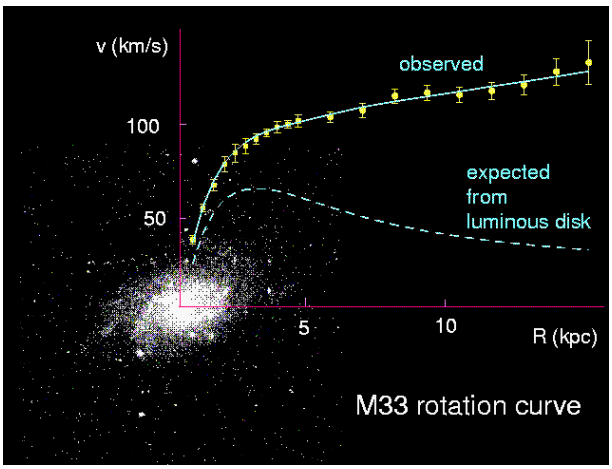

Figure 1: Observed rotation curve of the nearby dwarf spiral galaxy M33, superimposed on its optical image (from ref. [1]).

approximation (1) the following ratio between the total mass and the luminous mass, $M \approx 9 M_{\rm lum}$. Clearly, this type of analyses imply that 90% of the mass in galaxies is dark.

Cosmologists usually express the present-day mass density averaged over the Universe, ρ, in units of the so-called critical density, $\rho_c \approx 10^{-29}$ g cm^{-3}, i.e. they define $\Omega = \rho/\rho_c$. We can understand the critical density much like the notion of escape velocity: $\rho = \rho_c$ ($\Omega = 1$) corresponds to the cancellation of kinetic and (gravitational) potential energies. If $\rho > \rho_c$ ($\Omega > 1$) the Universe expands to a maximum, and then contracts leading to an inverse Big Bang (closed Universe). If $\rho < \rho_c$ ($\Omega < 1$) the Universe will continue expanding forever (open Universe). This is also the situation of the critical case $\Omega = 1$, where moreover the geometry of the Universe is flat. Clearly, the amount of dark matter in the Universe will then determine its future since $\Omega = \Omega_{\rm lum} + \Omega_{\rm dark}$.

Whereas current observations of luminous matter in galaxies determine $\Omega_{\rm lum} \lesssim 0.01$, analyses of rotation curves imply in fact $\Omega \approx 0.1$. The latter is really a lower bound, since almost all rotation curves remain flat out to the largest values of r where one can still find objects orbiting galaxies. We do not really know how much further the dark matter halos of these galaxies extend (see e.g. Fig. 1). The case of the Milky Way, which has a visible size of about 30 kpc across, is controversial but might have a halo as large as 200 kpc. Since the distance between the Milky Way and M31, the Andromeda galaxy, is 350 kpc, the halos of both galaxies might even touch each other. Thus we can conclude that galactic rotation curves imply

$$\Omega \gtrsim 0.1 \ . \tag{2}$$

Let us finally remark two points concerning galaxies. First, although the detection of dark matter is more problematic in galaxies other than spirals, such as ellipticals, dwarf irregulars, dwarf spheroidals, lenticulars, etc., they also possess important amounts of dark matter [3]. Second, it is fair to say that a small number of authors suggest that dark matter is not really necessary to explain rotation curves. Basically their approach consists of modifying the Newton's law at galactic scales. However, these attempts are not

only rather ad hoc in general but also insufficient to account the necessity of dark matter in scales larger than galactic ones. Evidence for dark matter in large scale structures is precisely the aim of our next discussion.

1.2 Dark matter in large scales

The analysis of dark matter in cluster of galaxies becomes more involved than in galaxies. Different techniques have been used to compute the value of Ω [4]. For example, the conventional method of studying the motion of cluster member galaxies seems to point at values of Ω larger than those obtained in galactic scales. The high temperature of the gas detected in clusters through its X-ray emission also points at large amounts of dark matter. Finally, the more reliable method of studying the gravitational lensing confirms the previous conclusions. Here a cluster acts as a lens which distorts the light emitted by quasars and field galaxies in its background, due to the gravitational bending of light. All these analyses favour a value

$$\Omega \approx 0.2 - 0.3 \ . \tag{3}$$

Moreover, measurements of velocity flows at scales larger than that of clusters favour also very large amounts of dark matter [4]:

$$\Omega > 0.3 \ . \tag{4}$$

In fact, theoretical arguments prefer a $\Omega = 1$ flat Universe [5], and therefore even larger amounts of dark matter would be necessary (unless we take seriously the speculative idea of a non-vanishing vacuum energy density $\rho_{\text{c.c.}}$ contribution to the density of the Universe, i.e. a cosmological constant contribution $\Omega = \Omega_{\text{lum}} + \Omega_{\text{dark}} + \Omega_{\text{c.c.}}$.)

1.3 What is dark matter made of?

Nowadays there is overwhelming observational evidence for the presence of dark matter. It not only clusters with stellar matter forming the galactic halos, but also exists as a background density over the entire Universe. Thus the problem is no longer to explain the rotation curves but to decipher the nature of the dark matter. As we will explain in detail below, the search of its solution provides a potentially important interaction between particle physics and cosmology since only elementary particles are reliable candidates for the dark matter in the Universe. The reason being that they are the only candidates which can be present in the right amount to explain the observed density of the Universe. In addition, they are necessary to explain structure formation. Clumps of neutral particles arose first through gravitational attraction and later, when the neutral atoms were formed, these were gravitationally attracted by the dark matter to form the galaxies.

Here we will review first possible candidates for dark matter. In particular we will learn that baryonic objects, i.e. formed from protons and neutrons, such as e.g. gas, brown dwarfs, etc., can be components of the dark matter, but more candidates are needed. Fortunately, particle physics offers various candidates for dark matter. Although

the current Standard Model of particles and interactions [6] does not have non-baryonic particles that can account for the dark matter, several extensions of this model do have. Indeed, detecting non-baryonic dark matter in the Universe would be a signal for new physics beyond the Standard Model.

We will see that very interesting and plausible candidates for dark matter are weakly-interacting massive particles (WIMPs). Long-lived or stable WIMPs can remain from the earliest moments of the Universe in sufficient number to account for a significant fraction of relic dark matter density. This raises the hope of detecting relic WIMPs directly by observing their elastic scattering on target nuclei though nuclear recoils. In fact, recent results from a dark matter experiment of this type at an underground laboratory suggest that the first direct evidence for dark matter has already been observed. Although this could be a great discovery, it is fair to say that this experiment is controversial, mainly because another one reported negative search results.

In any case, due to these and other projected experiments, it seems very plausible that the dark matter will be found in the near future. Assuming that it is a WIMP, the leading candidate in this class is the lightest neutralino, a particle predicted by the supersymmetric extension of the Standard Model. We will discuss why neutralinos are so interesting and will review the current and projected experiments for their detection.

2 Dark matter candidates

Since ordinary matter is baryonic, the most straightforward possibility is to assume also this composition for the evasive dark matter. The contribution from gas is not enough, so astrophysical bodies collectively known as MAssive Compact Halo Objects (MACHOs) are the main candidates. This is the case of brown and white dwarfs, jupiter-like objects, neutron stars, stellar black hole remnants. However, the scenario of Big-Bang nucleosynthesis, which explains the origin of the elements after the Big Bang, taking into account measured abundances of helium, deuterium and lithium sets a limit to the number of baryons that can exists in the Universe, namely

$$\Omega_{\rm baryon} \lesssim 0.04 \ . \tag{5}$$

This density is clearly small to account for the whole dark matter in the Universe (see bounds (2), (3) and (4)). The conclusion is that baryonic objects are likely components of the dark matter but more candidates are needed. This result is also confirmed by observations of MACHOs in our galactic halo through their gravitational lensing effect on the light emitted by stars. Their contribution to the dark matter density is small. Thus non-baryonic matter is required in the Universe.

Particle physics provides this type of candidate for dark matter. The three most promising are 'axions', 'neutrinos' and 'neutralinos' with masses of the order of 10^{-5} eV, 30 eV and 100 GeV, respectively[†]. Although, as mentioned in Section 1, these particles are not present in the current Standard Model of particle physics, they are well motivated

[†]The electronvolt (eV) is a unit of energy, 1 eV $\simeq 1.6\times10^{-19}$ J. Due to Einstein's equation, $E = mc^2$, the masses of particles are given in units of eV/c^2 $\simeq 1.78 \times 10^{-36}$ kg, usually shortened to eV. For

by theories that attempt to unify the forces and particles of Nature, i.e. by extensions of the Standard Model. Perhaps it is not a coincidence that such particles which may solve crucial problems in particle physics, as we will discuss below, also solve the dark matter problem (it could be either a big coincidence or a big hint).

Before analyzing these candidates, let us mention that many others have also been proposed. Some of them are quite exotic and most of them are ephemeral.

2.1 Neutrinos

The only dark matter candidates which are known to exist are neutrinos. They are leptons, i.e. non-strongly-interacting elementary particles, with zero charge and spin 1/2. The Standard Model [6] has three families or flavours of (left-handed) neutrinos ν_L, each associated with an electron-like lepton, i.e. there are electron neutrinos, muon neutrinos and tau neutrinos. These Standard Model neutrinos are strictly massless because there are no (right-handed) neutrinos ν_R that could combine with ν_L to form a Dirac mass term through their interaction with the Higgs doublet.

However, several extensions of the Standard Model do allow neutrinos to have a mass. This is the case for example of grand unified theories where the interactions of the Standard Model, i.e. the strong interaction $SU(3)$ and the electroweak interaction $SU(2) \times U(1)$ are combined as components of a single one, e.g. $SO(10)$ or E_6. Then, ν_R appear in a natural way. Moreover, in recent years, observation of solar and atmospheric neutrinos have indicated that one flavour might change to another. Remarkably, this is a quantum process (neutrino oscillations) which can only happen if the neutrino has a mass. The best evidence for neutrino mass comes from the SuperKamiokande experiment in Japan concerning atmospheric neutrino oscillations. The results of this experiment indicate a mass difference of the order of 0.05 eV between the muon neutrino and the tau neutrino. If there is a hierarchy among the neutrino masses (as it is actually the case not only for quarks where e.g. the top mass is five orders of magnitude bigger than the up mass, but also for electron-like leptons where the electron mass is 0.51 MeV whereas the muon mass is 105.6 MeV and the tau mass is 1777 MeV), then such a small mass difference implies that the neutrino masses themselves lie well below 1 eV. This is not cosmologically significant, as we will show below. On the other hand, there could be near mass degeneracy among the neutrino families. In this case, if neutrino masses $m_\nu \approx 30$ eV, they could still contribute significantly to the non-baryonic dark matter in the Universe.

These neutrinos left over from the Big Bang were in thermal equilibrium in the early Universe and decoupled when they were moving with relativistic velocities. They fill the Universe in enormous quantities and their current number density is similar to the one of photons (by entropy conservation in the adiabatic expansion of the Universe). In particular, $n_\nu = \frac{3}{11}\, n_\gamma$. Moreover, the number density of photons is very accurately obtained from the cosmic microwave background measurements. The present temperature $T \approx 2.725\ K$ implies $n_\gamma \approx 410.5\ \mathrm{cm}^{-3}$. Thus one can compute the neutrino mass density

example, the mass of the electron is 0.51 MeV, where the megaelectronvolt (MeV), 1 MeV=10^6 eV, is used. The mass of the proton is of the order of 1 GeV, where the gigaelectronvolt (GeV), 1 GeV = 10^9 eV, is used.

$\rho_\nu = m_{tot}\ n_\nu$, where m_{tot} is basically the total mass due to all flavours of neutrino. Hence,

$$\Omega_\nu \approx \frac{m_{tot}}{30\ \text{eV}}\ . \tag{6}$$

Clearly, neutrinos with $m_\nu \lesssim 1$ eV cannot solve the dark matter problem, but a neutrino with $m_\nu \approx 30$ eV would give $\Omega_\nu \approx 1$ solving it. Unfortunately, due to the small energies involved, detection of these cosmological neutrinos in the laboratory is not possible.

On the other hand, there is now significant evidence against neutrinos as the bulk of the dark matter. Neutrinos belong to the so-called 'hot' dark matter because they were moving with relativistic velocities at the time the galaxies started to form. But hot dark matter cannot reproduce correctly the observed structure in the Universe. A Universe dominated by neutrinos would form large structures first, and the small structures later by fragmentation of the larger objects. Such a Universe would produced a 'top-down' cosmology, in which the galaxies form last and quite recently. This time scale seems incompatible with our present ideas of galaxy evolution. This might be solved if galaxies were formed through topological defects such as cosmic strings, but still is difficult to explain how neutrinos could form the dark matter halos in dwarf galaxies.

This lead to fade away the initial enthusiasm for a neutrino-dominated Universe. Hence, many cosmologists now favour an alternative model, one in which the particles dominating the Universe are 'cold' (non-relativistic) rather than hot. This is the case of the axions and neutralinos which we will study below.

2.2 Axions

The theory of the strong interaction, Quantum Chromodynamics (QCD), may include in its Lagrangian the following invariant term formed from the field strength $F^a_{\mu\nu}$, $\frac{\theta}{16\pi^2} tr(F_{\mu\nu}\tilde{F}^{\mu\nu})$, where the parameter $(\theta/16\pi^2)$ describes the strength of this term and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$. In principle, this invariant can be reduced to a total divergence, hovewer, it cannot be dropped because non-perturbative effects in QCD require such a term. The presence of this term is potentially dangerous since it violates parity and CP, and therefore there are important experimental bounds against it. In particular, the stringent upper limit on neutron dipole electric moment implies the bound $\theta < 10^{-9}$. This is the so-called strong CP problem. Why is this value so small, when a strong interaction parameter would be expected to be $\mathcal{O}(1)$?

The most plausible solution to this naturalness problem is to show that θ is effectively zero, and this was in fact the proposal made by Peccei and Quinn in 1977. They increased the number of Higgs bosons so that QCD together with the electroweak theory has a global $U(1)$ symmetry. Since the vacuum expectation values of the Higgses must be nonzero to generate fermion masses, this symmetry is spontaneously broken giving rise to a Goldstone boson, the so-called axion. On the other hand, the CP violating phase becomes a dynamical variable which is vanishing at the minimum of the axion potential, as required.

In summary, axions are spin 0 particles with zero charge associated with the spontaneous breaking of the global $U(1)$ Peccei-Quinn symmetry, which was introduced to

dynamically solve the strong CP problem. Although axions are massless at the classical level they pick up a small mass by non-perturbative effects. The mass of the axion, m_a, and its couplings to ordinary matter, g_a, are proportional to $1/f_a$, where f_a is the (dimensionful) axion decay constant which is related to the scale of the symmetry breaking. In particular, the coupling of an axion with two fermions of mass m_f, is given by $g_a \sim m_f/f_a$. Likewise, $m_a \sim \Lambda^2_{\rm QCD}/f_a$, i.e.

$$m_a \sim 10^{-5}\ \text{eV} \times \frac{10^{12}\ \text{GeV}}{f_a}\ . \tag{7}$$

A lower bound on f_a can be obtained from the requirement that axion emission does not over-cool stars. The supernova SN1987 put the strongest bound, $f_a \gtrsim 10^9$ GeV. On the other hand, since coherent oscillations of the axion around the minimum of its potential may give an important contribution to the energy density of the Universe, the requirement $\Omega \lesssim 1$ puts a lower bound on the axion mass implying $f_a \lesssim 10^{12}$ GeV. The combination of both constraints, astrophysical and cosmological, give rise to the following window for the value of the axion constant

$$10^9\ \text{GeV} \lesssim f_a \lesssim 10^{12}\ \text{GeV}\ . \tag{8}$$

The lower bound implies an extremely small coupling of the axion to ordinary matter and therefore a very large lifetime, larger than the age of the Universe by many orders of magnitude. As a consequence, the axion is a candidate for dark matter. Axions would have been produced copiously in the Big Bang, they were never in thermal equilibrium and are always nonrelativistic (i.e. they are cold dark matter). In addition the upper bound implies that $m_a \sim 10^{-5}$ eV if the axion is to be a significant component of the dark matter.

Since the axion can couple to two photons via fermion vacuum loops, a possible way to detect it is through conversion to photon in external magnetic field. Unfortunately, due to the small couplings to matter discussed above, we will not be able to produce axions in the laboratory. On the other hand, relic axions are very abundant (as we will show in Section 4, the density of dark matter particles around the Earth is about 0.3 GeV cm^{-3}, since $m_a \sim 10^{-5}$ eV there will be about 10^{13} axions per cubic centimeter) and several experiments are trying already to detect axions or are in project. For example, an experiment at Lawrence Livermore National Laboratory (California, US) has reported in 1998 its first results excluding a particular kind of axion of mass 2.9×10^{-6} eV to 3.3×10^{-6} eV as the dark matter in the halo of our galaxy.

2.3 WIMPs

As discussed in Section 1, weakly interacting massive particles, the so-called WIMPs, are very interesting candidates for dark matter in the Universe. They were in thermal equilibrium with the Standard Model particles in the early Universe, and decoupled when they were non-relativistic. The process was the following. When the temperature T of the Universe was larger than the mass of the WIMP, the number density of WIMPs and

photons was roughly the same, $n_{\rm WIMP} \propto T^3$, and the WIMP was annihilating with its own antiparticle into lighter particles and vice versa. However, shortly after the temperature dropped below the mass of the WIMP, m, its number density dropped exponentially, $n_{\rm WIMP} \propto e^{-m/T}$, because only a small fraction of the light particles mentioned above had sufficient kinetic energy to create WIMPs. As a consequence, the WIMP annihilation rate dropped below the expansion rate of the Universe. At this point WIMPs came away, they could not annihilate, and their density is the same since then. Following these arguments, the relic density of WIMPs can be computed with the result

$$\Omega_{\rm WIMP} \simeq \frac{7 \times 10^{-27}\ {\rm cm}^3\ {\rm s}^{-1}}{< \sigma_{ann}\ v >}\ , \tag{9}$$

where σ_{ann} is the total cross section for annihilation of a pair of WIMPs into Standard Model particles, v is the relative velocity between the two WIMPs, $< .. >$ denotes thermal averaging, and the number in the numerator is obtained using the value of the temperature of the cosmic background radiation, the Newton's constant, etc. As expected from the above discussion about the early Universe, the relic WIMP density decreases with increasing annihilation cross section.

Now we can understand easily why WIMPs are so good candidates for dark matter. If a new particle with weak interactions exists in Nature, its cross section will be $\sigma \simeq \alpha^2/m^2_{\rm weak}$, where $\alpha \simeq \mathcal{O}(10^{-2})$ is the weak coupling and $m_{\rm weak} \simeq \mathcal{O}(100\ {\rm GeV})$ is a mass of the order of the one of the W gauge boson, which is associated to the $SU(2)$ gauge group of the Standard Model. Thus one may obtain $\sigma \approx 10^{-9}\ {\rm GeV}^{-2}$. Since at the freeze-out temperature v is close to the speed of light, one obtains[‡] $< \sigma_{ann}\ v > \approx 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}$. For our surprise, this number is remarkably close to the value that we need in eq.(9) in order to obtain the observed density of the Universe. This is a possible hint that new physics at the weak scale provides us with a reliable solution to the dark matter problem. This is a qualitative improvement with respect to the axion dark matter case, where a small mass for the axion about 10^{-5} eV has to be postulated. As we will discuss in the next section, supersymmetry is a theory that introduce new physics precisely at the weak scale, and that predict a new particle, the neutralino, which could be stable and therefore the sought-after dark matter.

On the other hand, since WIMPs interact with ordinary matter with roughly weak strength, their presence in galactic scales, and in particular in our galaxy, raises the hope of detecting relic WIMPs directly in a detector by observing their scattering on target nuclei through nuclear recoils.

3 Neutralino dark matter

Although supersymmetry was proposed 27 years ago, and despite the absence of experimental verification, it is still today (together with string theory which anyway needs probably supersymmetry) the most convincing theory in order to unify the physical laws [7]. Relevant theoretical arguments can be given in its favour.

[‡]Here we are using natural units, where $1\ {\rm GeV}^{-2} = 0.389 \times 10^{-27}\ {\rm cm}^2$.

First of all, supersymmetry is a new type of symmetry since relates bosons and fermions. We know from the past that symmetries are crucial in particle physics but in addition supersymmetry introduces a new kind of unification between particles of different spin. In this sense, the Higgs scalar is no longer a mysterious particle as it stands in the Standard Model, where it is introduced just in order to break the electroweak symmetry, the Supersymmetric Standard Model is naturally full of fundamental scalars (squarks, sleptons and Higgs) related through supersymmetry with their fermionic partners (quarks, leptons and Higgsino). On the other hand, supersymmetry ensures the stability of the hierarchy between the weak and the Planck scales. Since any fundamental theory must contain gravity, due to quantum corrections the masses of the scalar particles turn out to be proportional to the natural scale of the theory $M_{Planck} \simeq 1.2 \times 10^{19}$ GeV. However, since these mass terms contribute to the Higgs potential, they should be of the order of the electroweak scale (100-1000 GeV) in order to avoid any type of fine-tuning when breaking the electroweak symmetry. This problem of stabilizing the scalar masses against quantum corrections is solved in supersymmetry since now the scalar masses and the masses of their superpartners are related. As a consequence, the dangerous contributions of Standard Model particles to quantum corrections are canceled with new ones which are present due to the existence of the additional superpartners. Furthermore, the joining of the three gauge coupling constants of the Standard Model at a single unification scale, in agreement with experimental results from the LEP accelerator at CERN laboratory (Geneve, Switzerland), can only be obtained assuming supersymmetry. Last, but not least, the local version of supersymmetry leads to a partial unification of the Standard Model with gravity, the so-called supergravity, which is the low-energy limit of superstrings.

The price we have to pay for these marvellous properties, is the introduction of a plethora of new particles. Not only the ones already mentioned (together with one more Higgs and Higgsino in order to cancel anomalies), but also the spin-1/2 superpartners of the gauge bosons, gluons, W's and B, i.e. the so-called gluinos, winos and bino. All of them form the so-called Minimal Supersymmetric Standard Model, the most simple supersymmetric extension of the Standard Model. This is the most widely studied potentially realistic supersymmetric model.

Since ordinary particles and their superpartners only differ in spin, supersymmetry would imply e.g. that the masses of gluinos are vanishing as the masses of gluons, that the masses of squarks and sleptons are the same as the ones of quarks and leptons respectively, and therefore there would be selectrons with a mass of 0.51 MeV, smuons with a mass of 105.6 MeV, etc. However there is no experimental evidence for such particles with those masses. Thus, in order for supersymmetry to play a realistic role in quark-lepton physics, it must be a broken symmetry. Fortunately, one can introduce consistently terms in the Lagrangian, the so-called 'soft' terms, which explicitly break supersymmetry giving masses, for example, to scalars. Moreover, these terms do not to spoil the supersymmetric solution to the hierarchy problem (hence the name soft). It is important to remark that, as mentioned above, these mass terms should be of the order of the electroweak scale. Several accelerator experiments are in preparation in order to detect these predicted supersymmetric partners, e.g. LHC at CERN will start operations in 2005 producing

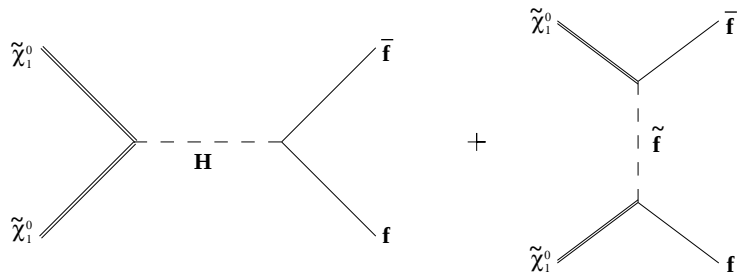

Figure 2: Feynman diagrams contributing to early-universe neutralino ($\tilde{\chi}_1^0$) annihilation into fermions through Higgses (H) and squarks and sleptons ($\tilde{f}$).

energies about 1000 GeV. It is worth recalling here that new physics at the electroweak scale was the crucial assumption for WIMPs in order to obtain the observed density of the Universe.

On the other hand, in the simplest supersymmetric model, the Lagrangian contains interactions between one standard-model particle and (always) two supersymmetric particles. For example, a quark-squark-gluino interaction, which has in natural units the required dimension 4, is allowed. It is true that there are other possible interactions with dimension 4 and only one supersymmetric particle, as e.g. quark-quark-squark or squark-quark-lepton. However they should be forbidden in order to avoid fast proton decay. This yields important phenomenological implications. Supersymmetric particles are produced or destroyed only in pairs and therefore the lightest supersymmetric particle is absolutely stable, implying that it might constitute a possible candidate for dark matter, as first suggested by Goldberg in 1983. So supersymmetry, whose original motivation has nothing to do with the dark matter problem, fulfils the two crucial requirements: new physics at the electroweak scale with a stable particle. In fact, since the lightest supersymmetric particle is stable, another signature of major importance for this supersymmetric model will be obtained in colliders. One will be able to detect events with supersymmetric particle decays which produce lots of missing energy (for instance, $e^+e^- \to \text{jet} + \text{missing energy}$).

It is remarkable that in most of the parameter space of the Minimal Supersymmetric Standard Model the lightest supersymmetric particle is an electrically neutral (also with no strong interactions) particle, called neutralino. This is welcome since otherwise it would bind to nuclei and would be excluded as a candidate for dark matter from unsuccessful searches for exotic heavy isotopes.

As a matter of fact there are four neutralinos, $\tilde{\chi}_i^0$ $(i = 1, 2, 3, 4)$, since they are the physical superpositions of the fermionic partners of the neutral electroweak gauge bosons, bino and wino, and the fermionic partners of the two neutral Higgs bosons, Higgsinos. Therefore the lightest neutralino, $\tilde{\chi}_1^0$, will be the dark matter candidate. The experimental limit on its mass due to the negative searches at LEP is $m_{\tilde{\chi}_1^0} > 37$ GeV.

Concerning the annihilation cross section contributing to the density of the Universe in eq.(9), there are numerous final states into which the neutralino can annihilate. The most important of these are the two body final states which occur at the tree level. Specially these are fermion-antifermion pairs, as shown in Fig. 2. Many regions of the parameter

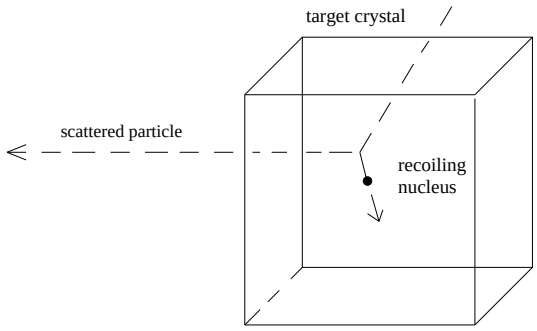

Figure 3: Elastic scattering of a dark matter particle with an atomic nucleus in a detector.

space of the Minimal Supersymmetric Standard Model produce values of the annihilation cross section in the interesting range mentioned below eq.(9). Therefore the neutralino is a very good candidate to account for the dark matter in the Universe.

4 The search for dark matter particles

4.1 Direct detection

As discussed in Section 1, if neutralinos, or WIMPs in general, are the bulk of the dark matter, they will form not only a background density in the Universe, but also will cluster gravitationally with ordinary stars in the galactic halos. In particular they will be present in our own galaxy, the Milky Way. This raises the hope of detecting relic WIMPs directly, by experiments on the Earth. In fact general studies of the possibility of dark matter detection began around 1982. Since the detection will be in the Earth we need to know the properties of our galaxy in order to be sure that such a detection is feasible.

As a matter of fact, rotation curves are much better known for external galaxies than for ours, due to the position of the Earth inside the galaxy. In any case analyses have been carried out with the conclusion that indeed the Milky Way contains large amounts of dark matter [8]. Besides, some observational evidence seems to point at a roughly spherical distribution of dark matter in the galaxy. At the position of the Sun, around 8.5 kpc away from the galactic center, the mean density of elementary particles trapped in the gravitational potential well of the galaxy is expected to be $\rho_{\rm dark} \approx 5 \times 10^{-24}$ gr cm^{-3} $\simeq 0.3$ GeV cm^{-3}. For WIMPs with masses about 100 GeV this means a number density $n_{\rm WIMP} \approx 3 \times 10^{-3}$ cm^{-3}. In addition, their velocity will be similar to the one of the Sun since they move in the same gravitational potential well, $v \approx 300$ km s^{-1}, implying a flux of dark matter particles $J_{\rm WIMP} = n_{\rm WIMP}\ v \approx 10^5$ cm^{-2} s^{-1} incident on the Earth. Although this number is apparently large, the fact that WIMPs interact weakly with matter makes the neutralino detection very difficult. Most of them will pass through matter without prevention.

In any case, as suggested first by Goodman and Witten in 1985, direct experimental

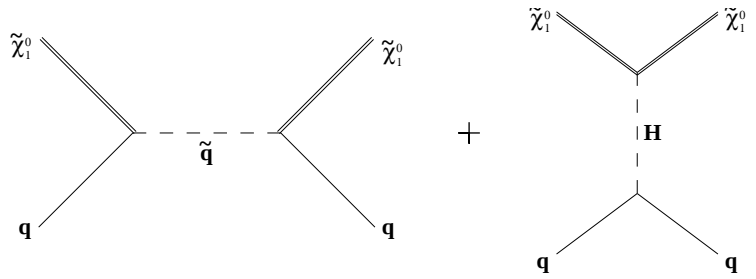

Figure 4: Feynman diagrams contributing to neutralino ($\tilde{\chi}_1^0$)–quark (q) cross section.

detection through elastic scattering with nuclei in a detector, as shown schematically in Fig. 3, is in principle possible. A very rough estimate of the rate R in a detector is the following. A particle with a mass of the order of 100 GeV and electroweak interactions will have a cross section $\sigma \approx 10^{-9}$ GeV^{-2}, as discussed in Subsection 2.3. Thus for a material with nuclei composed of about 100 nucleons, i.e. $m_N \sim 100$ GeV, one obtains $R \sim J_{\rm WIMP}\ \sigma/m_N \approx 10$ events kg^{-1} yr^{-1}. This means that every day a few WIMPs, the precise number depending on the number of kilograms of material, will hit an atomic nucleus in a detector. Of course the above computation is just an estimate and one should take into account in the exact computation the interactions of WIMPs with quarks and gluons, the translation of these into interactions with nucleons, and finally the translation of the latter into interactions with nuclei. In the case of neutralinos as WIMPs, diagrams contributing to neutralino-quark cross section are shown in Fig. 4. This scattering is elastic since the nucleus recoils as a whole, giving billiard-ball collisions. It is possible to check that many regions of the parameter space of the Minimal Supersymmetric Standard Model produce values of the neutralino-nucleus cross section as those mentioned above, and therefore giving rise to a reasonable number of events (10^{-5} to 10 events per day per kilogram).

4.2 Experimental techniques

Experimentalists use three main techniques in order to detect the nuclear recoil energy [9]. The technique of measuring ionization in solids, since the recoiling nucleus from a neutral particle collision is itself charged and can also produce some electron-hole excitation by collision with electrons. The alternative technique of measuring ionization through the emission of photons in scintillation crystals. Finally, a small temperature rise. For example when a 1 cm^3 of Silicon (Si) crystal is cooled to a very low temperature (≈ 120 mK) in a dilution refrigerator, the heat capacity ($\propto T^3$) is so low that even a few keV of deposited energy raises the temperature by a measurable amount ($\sim 10^{-6}$ K). This can be observed since the recoiling nucleus (or more accurately the recoiling atom, since at $v \sim 300$ km s^{-1} most of the atomic electrons will remain bound to the moving nucleus) is stopped within $10^{-7} - 10^{-6}$ cm ($\sim 10^{-14}$ s) releasing phonons. Which method is better depends on the target material, and in fact in many materials more than one of these effects may be observed.

On the other hand, for a slow moving (~ 300 km s^{-1}) and heavy ($\sim 100 - 1000$ GeV) particle forming the dark matter halo, the kinetic energy is very small, around 100 keV. The largest recoil energy transfer to a nucleus in the detector is obtained when the mass of the WIMP and its mass are equal, $m_N \sim 100$ GeV, but in any case it will only be a few keV . Since cosmic rays with energies $\sim$ keV-MeV bombard the surface of the Earth, the experiments must have an extremely good background discrimination. In particular, neutrons coming from collisions between cosmic-ray muons and nuclei produce nuclear recoils similar to those expected from WIMPs at a rate $\sim 10^3$ events kg^{-1} day^{-1}. Thus it is convenient to carry the experiments out in the deep underground, in order to reduce the background by orders of magnitude in comparison with the sea level intensity.

In fact, this is still not enough since the detector has to be protected also against the natural radioactivity from the surroundings (e.g. the rocks) and the materials of the detector itself. This produces again neutrons but also X rays, gamma rays and beta rays giving rise to electron recoils. The latter may be a problem for detectors based only on ionization or scintillation light since nuclear recoils with energies of a few keV are much less efficient in ionizing or giving light than electrons of the same energy. Various protections aim to reduce these backgrounds. In particular, low radioactive materials, such as e.g. high-purity copper or aged lead, are used for the shielding. In addition, high-purity materials for the detector are also used.

4.3 Experiments around the world

Germanium is a very pure material and has been used for many years for detecting 'neutrinoless double beta decay'. Double beta decay is a process where two neutrons decay into protons, electrons and antineutrinos. However if neutrinos are massive they cannot be produced. These searches have reached extremely low background levels and therefore are very interesting for detecting dark matter particles. In fact, ^{76}Ge ionization detectors has been applied to WIMP searches since 1987 [10]. The best combination of data from these experiments, together with the last data from the Heidelberg-Moscow [11] and IGEX experiments [12] located at the Gran Sasso (L'Aquila, Italy) and Canfranc (Huesca, Spain) underground laboratories, respectively, have been able to exclude a WIMP-nucleus cross section larger than 10^{-6} GeV^{-2} for masses of WIMPs ~ 100 GeV, due to the negative search result. Although this is a very interesting bound, it is still well above the expected weak-interaction value $\sim 10^{-9}$ GeV^{-2}.

A generic problem of these type of detectors with germanium crystals, given the small expected event rates, is that only small masses ($\lesssim$ 10 kg) can be assembled. However, this problem disappears when sodium-iodide (NaI) scintillation detectors are used. In addition, NaI gives good sensitivity over a wide range of WIMP masses, since the mass of Na is small ($\sim$ 23 GeV) and the mass of I is large ($\sim$ 127 GeV).

Very intriguing results have been obtained in two experiments [13] using NaI detectors. The UK Dark Matter Collaboration (UKDMC) [14] has a scintillation detector located 1100 metres below ground at the Boulby salt mine (Yorkshire, UK) which comprises several NaI crystals ranging from 1 to 10 kg. It started taking data in 1997, and a number of anomalous events have emerged in the data since the autumn of 1998. Although

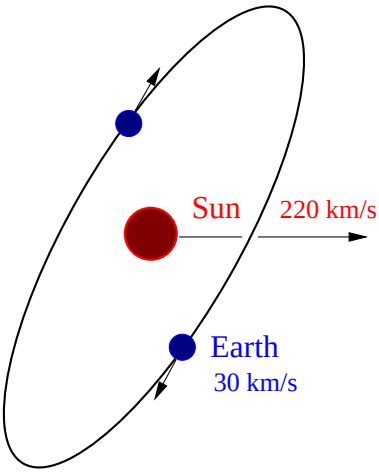

Figure 5: Earth's motion around the Sun.

spurious events due to several usual sources, as e.g. gamma rays, neutrons, etc., have been investigated and dismissed, a WIMP origin of the nuclear recoils is uncertain since they were faster than the neutron calibrations used to simulate the WIMP interactions. Other (atypical) sources of the events are currently under investigation.

A different method for discriminating a dark matter signal from background is the one used by the DAMA collaboration, the so-called annual modulation signature. As it is shown schematically in Fig. 5, as the Sun orbits the galaxy with velocity ≈ 220 km s^{-1}, the Earth orbits the Sun with velocity ≈ 30 km s^{-1} and with the orbital plane inclined at an angle of 60° to the galactic plane. As a consequence the dark matter flux will be larger in June (when the Earth's rotation velocity adds to the Sun's velocity through the halo) than in December (when the two velocities are in opposite directions). This fluctuation produces a rate variation $\approx 7\%$ between the two extreme conditions. The DAMA experiment [15] investigates the annual modulation of this signature. It involves physicists from Italy and China, and consists of about 100 kg of material (nine 9.70 kg NaI crystal scintillators to be precise) located at the Gran Sasso laboratory built 1400 metres below ground. Remarkably, they found that their detectors flashed more times in June than in December. The data collected over four yearly cycles, since November 1996, strongly favour the presence of a yearly modulation. Besides, this signal is consistent with a WIMP with mass $\approx 30 - 200$ GeV and a WIMP-nucleus cross section $\sigma \approx 10^{-6} - 10^{-7}$ GeV^{-2}, corresponding at a rate of about 1 event per kg per day. DAMA group is confident about this result since they claim to have ruled out other possible explanations, as e.g. temperature changes. It is worth noticing that although the above values for the cross section are still above the expected weak-interaction value, they can be obtain in some regions of the parameter space of supersymmetric models with neutralino dark matter.

However the DAMA result is controversial, mainly because the negative search result obtained by the Cryogenic Dark Matter Search (CDMS) experiment in the US [16]. This is located just 10 metres below ground at Stanford University in California, and therefore it must discriminate WIMPs signals against interactions of background particles. Two

of the three detection techniques described above are used for this discrimination, both the ionization and the temperature rise produced during a recoil are measured. This allows to discriminate electron recoils caused by interactions of background particles from WIMP-induced nuclear recoils. The ratio of deposited energies heat/ionization would be $\sim 2-3$ for the former and larger than 10 for the latter. However, although neutrons are moderated by a 25-cm thickness of polyethylene between the outer lead shield and cryostat, an unknown fraction of them still survives. Two data sets are used in this analysis: one consisting of 33 live days taken with a 100-g Si detector between April and July 1998, and another consisting of 96 live days taken with three 165-g Ge detectors between November 1998 and September 1999. Although four nuclear recoils are observed in the Si data set, they cannot be due to WIMPs, they are due in fact to the unvetoed neutron background. On the other hand, in the Ge detector thirteen nuclear recoils are observed per 10.6 kg per day, which is a similar rate to that expected from the WIMP signal claimed by DAMA. However, the CDMS group concludes that they are also due to neutrons. These data exclude much of the region allowed by the DAMA annual modulation signal.

5 Future dark matter searches

Due to this controversy between DAMA and CDMS experimental results, we cannot be sure whether or not the first direct evidence for the existence of dark matter has already been observed. Fortunately, the complete DAMA region will be tested by current dark matter detectors. This is for example the case of the IGEX experiment [12] mentioned above, which is located at the Canfranc Tunnel Astroparticle Laboratory (2450 metres of water equivalent (m.w.e.)), with an additional 1 kg-year of exposure, i.e. a few months of operation with two upgraded IGEX detectors. Likewise the Heidelberg Dark Matter Search (HDMS) experiment [17], which operates two ionization Ge detectors in a unique configuration, was installed at Gran Sasso in August 2000 and will also be able to test the DAMA region in the future.

In addition, DAMA and CDMS collaborations plan to expand their experiments. The DAMA collaboration will increase the amount of NaI crystals in its detector from 100 to 250 kg, which will make the experiment more sensitive to the annual modulation signal. On the other hand, the CDMS collaboration is planning to move its detector to the abandoned Soudan mine in Minnesota (approximately 700 metres below ground), increasing also the mass of its Ge/Si targets to 10 kg. Of course this will clarify completely whether or not the thirteen events found by the current experiment at Stanford are due to neutrons. This experiment will be able to test a WIMP-nucleus cross section $\sigma > 10^{-9}$ GeV^{-2}

In the light of the polemical results from the DAMA and CDMS collaborations, a new generation of very sensitive experiments have been proposed all over the world. For instance only in the Gran Sasso laboratory there will be five experiments searching for WIMPs. Apart from the two already discussed DAMA and HDMS, there are three other experiments in prospect, CRESST, CUORE and GENIUS. For example, the Cryogenic

Rare Event Search using Superconducting Thermometers (CRESST) experiment [18], which involves the Max Planck Institute for Physics, the Technical University in Munich, the Gran Sasso, and the University of Oxford, measures simultaneously phonons and scintillation light distinguishing the nuclear recoils from the electron recoils cause by background radioactivity. In contrast to other experiments, CRESST detectors allow the employment of a large variety of target materials, such as e.g. sapphire or tungsten. This allows a better sensitivity for detecting the WIMPs. In the long term the present CRESST set-up permits the installation of a detector mass up to 100 kg, which will test a WIMP-nucleus cross section slightly smaller than the CDMS Soudan one discussed above.

But the most sensitive detector will be the GErmanium in liquid NItrogen Underground Setup (GENIUS) [17], which will be able to test a WIMP-nucleus cross section as low as $\sigma \approx 10^{-10}$ GeV^{-2}. Indeed such a sensitivity covers almost the full range of the parameter space of supersymmetric models with neutralinos as dark matter. The GENIUS project is based on the idea to operate an array of 100 kg of Ge crystals directly in liquid nitrogen. The latter, which is very clean with respect to radiopurity, can act simultaneously as cooling medium and shield against external activities, using a sufficiently large tank $\sim$ 12 metres in diameter at least. It has been shown using Monte Carlo simulations that with this approach the unwanted background is reduced by three to four orders of magnitude. In order to demonstrate the feasibility of the GENIUS project a GENIUS Test-Facility (GENIUS-TF) has been approved [17].

In addition to these Gran Sasso experiments, there is also the French experiment EDELWEISS which is being carried out at Modena underground laboratory, the French project MACHe3 at the Joseph Fourier University, the PICASSO project at the University of Montreal, the ORPHEUS project at the University of Bern, and the ZEPLIN project at the Boulby mine. For example, the latter is an experiment carried out between the UKDMC collaboration, the University of California at Los Angeles, the Institute of Theoretical and Experimental Physics in Moscow, CERN and the University of Torino in Italy. It consists of a series of xenon detectors where the nuclear recoil produces both an ionization and a scintillation signal, giving a discrimination power 10–100 times better than for NaI.

Efforts to build detectors sensitive to the directional dependence, i.e. recoil away from direction of Earth motion, are also being carried out. This is an extension of the idea of annual modulation. To reconstruct such a three-dimensional direction is not simple, but UKDMC collaboration together with Temple University in Philadelphia, Occidental College in Los Angeles and the University of California at San Diego, are studying the possibility of using an ionization xenon-gas detector, the so-called DRIFT, for this issue. The arrival time of the ionization signal will be used to reconstruct the event in three dimensions.

Let us finally mention that there are other promising methods for the (indirect) detection of WIMPs in the halo [19]. For example WIMPs passing through the Sun and/or Earth may be slowed below escape velocity by elastic scattering. Thus they will accumulate and annihilate in the center producing neutrinos. These can be detected in underground experiments, specially through the muons produced by their interactions in the rock. Another way of detecting WIMPs indirectly is through anomalous cosmic rays

produced by their annihilations in the galactic halo.

6 Conclusions

Nowadays there is overwhelming evidence that most of the mass in the universe (90% and probably more) is some (unknown) non-luminous 'dark matter'. At galactic and cosmological scales it only manifests through its gravitational interactions with ordinary matter. However, at microscopical scales it might manifest through weak interactions, and this raises the hope that it may be detected in low-energy particle physics experiments.

One of the most interesting candidates for dark matter is the so-called neutralino, a particle predicted by the supersymmetric extension of the Standard Model. These neutralinos are stable and therefore may be left over from the Big Bang. Thus they will cluster gravitationally with ordinary stars in the galactic halos, and in particular they will be present in our own galaxy, the Milky Way. As a consequence there will be a flux of these dark matter particles on the Earth.

Many experiments have been carried out around the world in order to detect this flux. One of them even claims to have detected it. Unfortunately, this result is controversial because of the negative search result obtained by another experiment in the same range of parameters. Thus we will have to wait for the next generation of experiments, which are already starting operations or in project, to be sure whether or not the neutralino, or generically, a weakly interacting massive particle, is the evasive dark matter filling the whole Universe.

In summary, underground physics as the one discussed here is crucial in order to detect dark matter. Even if neutralinos are discovered at future particle accelerators such as LHC, only their direct detection due to their presence in our galactic halo will confirm that they are the sought-after dark matter of the Universe.

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