22. DARK MATTER

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22.1. Theory

22.1.1. *Evidence for Dark Matter* :

The existence of Dark (*i.e.*, non-luminous and non-absorbing) Matter (DM) is by now well established. The earliest [1], and perhaps still most convincing, evidence for DM came from the observation that various luminous objects (stars, gas clouds, globular clusters, or entire galaxies) move faster than one would expect if they only felt the gravitational attraction of other visible objects. An important example is the measurement of galactic rotation curves. The rotational velocity v of an object on a stable Keplerian orbit with radius r around a galaxy scales like $v(r) \propto \sqrt{M(r)/r}$, where $M(r)$ is the mass inside the orbit. If r lies outside the visible part of the galaxy and mass tracks light, one would expect $v(r) \propto 1/\sqrt{r}$. Instead, in most galaxies one finds that v becomes approximately constant out to the largest values of r where the rotation curve can be measured; in our own galaxy, $v \simeq 220$ km/s at the location of our solar system, with little change out to the largest observable radius. This implies the existence of a *dark halo*, with mass density $\rho(r) \propto 1/r^2$, *i.e.*, $M(r) \propto r$; at some point ρ will have to fall off faster (in order to keep the total mass of the galaxy finite), but we do not know at what radius this will happen. This leads to a lower bound on the DM mass density, $\Omega_{\rm DM} \gtrsim 0.1$, where $\Omega_X \equiv \rho_X/\rho_{\rm crit}$, $\rho_{\rm crit}$ being the critical mass density (*i.e.*, $\Omega_{\rm tot} = 1$ corresponds to a flat Universe).

The observation of clusters of galaxies tends to give somewhat larger values, $\Omega_{\rm DM} \simeq 0.2$. These observations include measurements of the peculiar velocities of galaxies in the cluster, which are a measure of their potential energy if the cluster is virialized; measurements of the *X-ray* temperature of hot gas in the cluster, which again correlates with the gravitational potential felt by the gas; and—most directly—studies of (weak) gravitational lensing of background galaxies on the cluster.

A particularly compelling example involves the bullet cluster (1E0657-558) which recently (on cosmological time scales) passed through another cluster. As a result, the hot gas forming most of the clusters' baryonic mass was shocked and decelerated, whereas the galaxies in the clusters proceeded on ballistic trajectories. Gravitational lensing shows that most of the total mass also moved ballistically, indicating that DM self–interaction are indeed weak [2].

The currently most accurate, if somewhat indirect, determination of $\Omega_{\rm DM}$ comes from global fits of cosmological parameters to a variety of observations; see the Section on Cosmological Parameters for details. For example, using measurements of the anisotropy of the cosmic microwave background (CMB) and of the spatial distribution of galaxies, Ref. 3 finds a density of cold, non–baryonic matter

$$\Omega_{\rm nbm} h^2 = 0.110 \pm 0.006 \ , \tag{22.1}$$

where h is the Hubble constant in units of 100 km/(s·Mpc). Some part of the baryonic matter density [3],

$$\Omega_{\rm b} h^2 = 0.0227 \pm 0.0006 \ , \tag{22.2}$$

may well contribute to (baryonic) DM, *e.g.*, MACHOs [4] or cold molecular gas clouds [5].

The DM density in the "neighborhood" of our solar system is also of considerable interest. This was first estimated as early as 1922 by J.H. Jeans, who analyzed the motion of nearby stars transverse to the galactic plane [1]. He concluded that in our galactic neighborhood, the average density of DM must be roughly equal to that of luminous matter (stars, gas, dust). Remarkably enough, the most recent estimates, based on a detailed model of our galaxy, find quite similar results [6]:

$$\rho_{\rm DM}^{\rm local} \simeq 0.3 \frac{\rm GeV}{\rm cm^3} \ ; \tag{22.3}$$

this value is known to within a factor of two or so.

22.1.2. *Candidates for Dark Matter* :

Analyses of structure formation in the Universe [7] indicate that most DM should be "cold," *i.e.*, should have been non-relativistic at the onset of galaxy formation (when there was a galactic mass inside the causal horizon). This agrees well with the upper bound [3] on the contribution of light neutrinos to Eq. (22.1),

$$\Omega_\nu h^2 \leq 0.0067 \quad 95\% \text{ CL} \ . \tag{22.4}$$

Candidates for non-baryonic DM in Eq. (22.1) must satisfy several conditions: they must be stable on cosmological time scales (otherwise they would have decayed by now), they must interact very weakly with electromagnetic radiation (otherwise they wouldn't qualify as *dark* matter), and they must have the right relic density. Candidates include primordial black holes, axions, and weakly interacting massive particles (WIMPs).

Primordial black holes must have formed before the era of Big-Bang nucleosynthesis, since otherwise they would have been counted in Eq. (22.2) rather than Eq. (22.1). Such an early creation of a large number of black holes is possible only in certain somewhat contrived cosmological models [8].

The existence of axions [9] was first postulated to solve the strong *CP* problem of QCD; they also occur naturally in superstring theories. They are pseudo Nambu-Goldstone bosons associated with the (mostly) spontaneous breaking of a new global "Peccei-Quinn" (PQ) U(1) symmetry at scale f_a; see the Section on Axions in this *Review* for further details. Although very light, axions would constitute cold DM, since they were produced non-thermally. At temperatures well above the QCD phase transition, the axion is massless, and the axion field can take any value, parameterized by the "misalignment angle" θ_i. At $T \lesssim 1$ GeV, the axion develops a mass m_a due to instanton effects. Unless the axion field happens to find itself at the minimum of its potential ($\theta_i = 0$), it will begin to oscillate once m_a becomes comparable to the Hubble parameter H. These coherent

oscillations transform the energy originally stored in the axion field into physical axion quanta. The contribution of this mechanism to the present axion relic density is [9]

$$\Omega_a h^2 = \kappa_a \left(f_a / 10^{12} \text{ GeV} \right)^{1.175} \theta_i^2 \ , \tag{22.5}$$

where the numerical factor κ_a lies roughly between 0.5 and a few. If $\theta_i \sim \mathcal{O}(1)$, Eq. (22.5) will saturate Eq. (22.1) for $f_a \sim 10^{11}$ GeV, comfortably above laboratory and astrophysical constraints [9]; this would correspond to an axion mass around 0.1 meV. However, if the post-inflationary reheat temperature $T_R > f_a$, cosmic strings will form during the PQ phase transition at $T \simeq f_a$. Their decay will give an additional contribution to Ω_a, which is often bigger than that in Eq. (22.5) [10], leading to a smaller preferred value of f_a, *i.e.*, larger m_a. On the other hand, values of f_a near the Planck scale become possible if θ_i is for some reason very small.

Weakly interacting massive particles (WIMPs) χ are particles with mass roughly between 10 GeV and a few TeV, and with cross sections of approximately weak strength. Within standard cosmology, their present relic density can be calculated reliably if the WIMPs were in thermal and chemical equilibrium with the hot "soup" of Standard Model (SM) particles after inflation. In this case, their density would become exponentially (Boltzmann) suppressed at $T < m_\chi$. The WIMPs therefore drop out of thermal equilibrium ("freeze out") once the rate of reactions that change SM particles into WIMPs or vice versa, which is proportional to the product of the WIMP number density and the WIMP pair annihilation cross section into SM particles σ_A times velocity, becomes smaller than the Hubble expansion rate of the Universe. After freeze out, the co-moving WIMP density remains essentially constant; if the Universe evolved adiabatically after WIMP decoupling, this implies a constant WIMP number to entropy density ratio. Their present relic density is then approximately given by (ignoring logarithmic corrections) [11]

$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle} \ . \tag{22.6}$$

Here T_0 is the current CMB temperature, $M_{\rm Pl}$ is the Planck mass, c is the speed of light, σ_A is the total annihilation cross section of a pair of WIMPs into SM particles, v is the relative velocity between the two WIMPs in their cms system, and $\langle \ldots \rangle$ denotes thermal averaging. Freeze out happens at temperature $T_F \simeq m_\chi/20$ almost independently of the properties of the WIMP. This means that WIMPs are already non-relativistic when they decouple from the thermal plasma; it also implies that Eq. (22.6) is applicable if $T_R > T_F$. Notice that the 0.1 pb in Eq. (22.6) contains factors of T_0 and $M_{\rm Pl}$; it is, therefore, quite intriguing that it "happens" to come out near the typical size of weak interaction cross sections.

The seemingly most obvious WIMP candidate is a heavy neutrino. However, an SU(2) doublet neutrino will have too small a relic density if its mass exceeds $M_Z/2$, as required by LEP data. One can suppress the annihilation cross section, and hence increase the relic density, by postulating mixing between a heavy SU(2) doublet and some "sterile"

SU(2) $\times$ U(1)$_Y$ singlet neutrino. However, one also has to require the neutrino to be stable; it is not obvious why a massive neutrino should not be allowed to decay.

The currently best motivated WIMP candidate is, therefore, the lightest superparticle (LSP) in supersymmetric models [12] with exact R-parity (which guarantees the stability of the LSP). Searches for exotic isotopes [13] imply that a stable LSP has to be neutral. This leaves basically two candidates among the superpartners of ordinary particles, a sneutrino, and a neutralino. Sneutrinos again have quite large annihilation cross sections; their masses would have to exceed several hundred GeV for them to make good DM candidates. This is uncomfortably heavy for the lightest sparticle, in view of naturalness arguments. Moreover, the negative outcome of various WIMP searches (see below) rules out "ordinary" sneutrinos as primary component of the DM halo of our galaxy. (In models with gauge-mediated SUSY breaking, the lightest "messenger sneutrino" could make a good WIMP [14].) The most widely studied WIMP is therefore the lightest neutralino. Detailed calculations [15] show that the lightest neutralino will have the desired thermal relic density Eq. (22.1) in at least four distinct regions of parameter space. χ could be (mostly) a bino or photino (the superpartner of the U(1)$_Y$ gauge boson and photon, respectively), if both χ and some sleptons have mass below $\sim$ 150 GeV, or if m_χ is close to the mass of some sfermion (so that its relic density is reduced through co-annihilation with this sfermion), or if $2m_\chi$ is close to the mass of the *CP*-odd Higgs boson present in supersymmetric models. Finally, Eq. (22.1) can also be satisfied if χ has a large higgsino or wino component.

Many non–supersymmetric extensions of the Standard Model also contain viable WIMP candidates. Examples are the lightest $T-$odd particle in "Little Higgs" models with conserved $T-$parity [16], or "techni–baryons" in scenarios with an additional, strongly interacting ("technicolor" or similar) gauge group [17].

Recently there has been a flurry of developments of models where the DM particles, while interacting only weakly with ordinary matter, have quite strong interactions within an extended "dark sector" of the theory. These were spurred by measurements by the PAMELA, ATIC and Fermi satellites indicating excesses in the cosmic e^+ and/or e^- fluxes at high energies. However, these excesses are relative to background estimates that are clearly too simplistic (*e.g.*, neglecting primary sources of electrons and positrons, and modeling the galaxy as a homogeneous cylinder). Moreover, the excesses, if real, are far too large to be due to usual WIMPs, but can be explained by astrophysical sources. It therefore seems unlikely that they are due to Dark Matter [18].

Although thermally produced WIMPs are attractive DM candidates because their relic density naturally has at least the right order of magnitude, non-thermal production mechanisms have also been suggested, *e.g.*, LSP production from the decay of some moduli fields [19], from the decay of the inflaton [20], or from the decay of "$Q-$balls" (non-topological solitons) formed in the wake of Affleck-Dine baryogenesis [21]. Although LSPs from these sources are typically highly relativistic when produced, they quickly achieve kinetic (but not chemical) equilibrium if T_R exceeds a few MeV [22](but stays below $m_\chi/20$). They therefore also contribute to cold DM.

Primary black holes (as MACHOs), axions, and WIMPs are all (in principle) detectable with present or near-future technology (see below). There are also particle physics DM

candidates which currently seem almost impossible to detect, unless they decay; the present lower limit on their lifetime is of order 10^{25} to 10^{26} s for 100 GeV particles. These include the gravitino (the spin-3/2 superpartner of the graviton) [23], states from the "hidden sector" thought responsible for supersymmetry breaking [14], and the axino (the spin-1/2 superpartner of the axion) [24].

22.2. Experimental detection of Dark Matter

22.2.1. *The case of baryonic matter in our galaxy* :

The search for hidden galactic baryonic matter in the form of MAssive Compact Halo Objects (MACHOs) has been initiated following the suggestion that they may represent a large part of the galactic DM and could be detected through the microlensing effect [4]. The MACHO, EROS, and OGLE collaborations have performed a program of observation of such objects by monitoring the luminosity of millions of stars in the Large and Small Magellanic Clouds for several years. EROS concluded that MACHOs cannot contribute more than 8% to the mass of the galactic halo [25], while MACHO observed a signal at 0.4 solar mass and put an upper limit of 40%. Overall, this strengthens the need for non-baryonic DM, also supported by the arguments developed above.

22.2.2. *Axion searches* :

Axions can be detected by looking for $a \to \gamma$ conversion in a strong magnetic field [26]. Such a conversion proceeds through the loop-induced $a\gamma\gamma$ coupling, whose strength $g_{a\gamma\gamma}$ is an important parameter of axion models. There currently are two experiments searching for axionic DM. They both employ high quality cavities. The cavity "Q factor" enhances the conversion rate on resonance, *i.e.*, for $m_a c^2 = \hbar\omega_{\rm res}$. One then needs to scan the resonance frequency in order to cover a significant range in m_a or, equivalently, f_a. The bigger of the two experiments, the ADMX experiment [27], originally situated at the LLNL in California but recently moved to the University of Washington, started taking data in the first half of 1996. It now uses SQUIDs as first–stage amplifiers; their extremely low noise temperature (1.2 K) enhances the conversion signal. Their first published results [28], obtained with conventional amplifiers, exclude axions with mass between 1.9 and 3.3 μeV, corresponding to $f_a \simeq 4 \cdot 10^{13}$ GeV, as a major component of the dark halo of our galaxy, if $g_{a\gamma\gamma}$ is near the upper end of the theoretically expected range. Later, the experiment achieved [29] an about five times better limit on $g_{a\gamma\gamma}$ for 1.98 μeV $\leq m_a \leq$ 2.18 μeV, if a large fraction of the local DM density is due to a single flow of axions with very low velocity dispersion. The ADMX experiment is being upgraded by reducing the cavity temperature from the current 1.2 K to about 0.1 K. This should increase the frequency scanning speed for given sensitivity by more than two orders of magnitude, or increase the sensitivity for fixed observation time.

The smaller "CARRACK" experiment now being developed in Kyoto, Japan [30] uses Rydberg atoms (atoms excited to a very high state, $n = 111$) to detect the microwave photons that would result from axion conversion. This allows almost noise-free detection of single photons. Their ultimate goal is to probe the range between 2 and 50 μeV with sensitivity to all plausible axion models, if axions form most of DM.

22.2.3. *Basics of direct WIMP search* :

As stated above, WIMPs should be gravitationally trapped inside galaxies and should have the adequate density profile to account for the observed rotational curves. These two constraints determine the main features of experimental detection of WIMPs, which have been detailed in the reviews [31].

Their rms velocity inside our galaxy relative to its center is expected to be similar to that of stars, *i.e.*, a few hundred kilometers per second at the location of our solar system. For these velocities, WIMPs interact with ordinary matter through elastic scattering on nuclei. With expected WIMP masses in the range 10 GeV to 10 TeV, typical nuclear recoil energies are of order of 1 to 100 keV.

The shape of the nuclear recoil spectrum results from a convolution of the WIMP velocity distribution, usually taken as a Maxwellian distribution in the galactic rest frame, shifted into the Earth rest frame, with the angular scattering distribution, which is isotropic to first approximation but forward-peaked for high nuclear mass (typically higher than Ge mass) due to the nuclear form factor. Overall, this results in a roughly exponential spectrum. The higher the WIMP mass, the higher the mean value of the exponential. This points to the need for low nuclear energy threshold detectors.

On the other hand, expected interaction rates depend on the product of the local WIMP flux and the interaction cross section. The first term is fixed by the local density of dark matter, taken as 0.3 GeV/cm^3 (see above), the mean WIMP velocity, typically 220 km/s, and the mass of the WIMP. The expected interaction rate then mainly depends on two unknowns, the mass and cross section of the WIMP (with some uncertainty [6] due to the halo model). This is why the experimental observable, which is basically the scattering rate as a function of energy, is usually expressed as a contour in the WIMP mass–cross section plane.

The cross section depends on the nature of the couplings. For non-relativistic WIMPs, one in general has to distinguish spin-independent and spin-dependent couplings. The former can involve scalar and vector WIMP and nucleon currents (vector currents are absent for Majorana WIMPs, *e.g.*, the neutralino), while the latter involve axial vector currents (and obviously only exist if χ carries spin). Due to coherence effects, the spin-independent cross section scales approximately as the square of the mass of the nucleus, so higher mass nuclei, from Ge to Xe, are preferred for this search. For spin-dependent coupling, the cross section depends on the nuclear spin factor; used target nuclei include ^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, and ^{133}Cs.

Cross sections calculated in MSSM models induce rates of at most 1 evt day^{-1} kg^{-1} of detector, much lower than the usual radioactive backgrounds. This indicates the need for underground laboratories to protect against cosmic ray induced backgrounds, and for the selection of extremely radio-pure materials.

The typical shape of exclusion contours can be anticipated from this discussion: at low WIMP mass, the sensitivity drops because of the detector energy threshold, whereas at high masses, the sensitivity also decreases because, for a fixed mass density, the WIMP flux decreases $\propto 1/m_\chi$. The sensitivity is best for WIMP masses near the mass of the recoiling nucleus.

22.2.4. *Status and prospects of direct WIMP searches* :

The first searches have been performed with ultra-pure semiconductors installed in pure lead and copper shields in underground environments [32]. Combining a priori excellent energy resolutions and very pure detector material, they produced the first limits on WIMP searches (Heidelberg-Moscow, IGEX, COSME-II, HDMS) [32]. Without positive identification of nuclear recoil events, however, these experiments could only set limits, *e.g.*, excluding sneutrinos as major component of the galactic halo. Still, planned experiments using several tens of kg to a ton of Germanium (many of which were designed for double-beta decay search)—GERDA, MAJORANA—are based on only passive reduction of the external and internal electromagnetic and neutron background by using segmented detectors, minimal detector housing, close electronics, and large liquid nitrogen shields. Their sensitivity to WIMP interactions will depend on their ability to lower the energy threshold sufficiently, while keeping the background rate small.

New results have recently been obtained with non–cryogenic detectors with sub–keV thresholds. The TEXONO collaboration has operated four ultra low energy Germanium 5 g detectors, in a reactor environment, with threshold of order of 200 eV [33]. The CoGENT collaboration has operated a 475 g Germanium detector with point contact electrode, with a very small capacitance which allowed to reach an effective threshold of 500 eV in a physics run performed in rather shallow site [34]. Both results allowed to set best limits for spin independent coupling WIMPs in the 5 to 8 GeV WIMP mass range, at a cross section around 10^{-4} pb, a bit below the allowed range for the low WIMP mass DAMA solution without channeling (see below).

To make further progress, in particular at higher masses, active background rejection and signal identification questions have to be addressed. This has been the focus of many recent investigations and improvements. Active background rejection in detectors relies on the relatively small ionization in nuclear recoils due to their low velocity. This induces a reduction—quenching—of the ionization/scintillation signal for nuclear recoil signal events relative to e or γ induced backgrounds. Energies calibrated with gamma sources are then called "electron equivalent energies" (eee). This effect has been both calculated and measured [32]. It is exploited in cryogenic detectors described later. In scintillation detectors, it induces in addition a difference in decay times of pulses induced by e/γ events vs nuclear recoils. Due to the limited resolution and discrimination power of this technique at low energies, this effect allows only a statistical background rejection. It has been used in NaI(Tl) (DAMA, LIBRA, NAIAD, Saclay NaI), in CsI(Tl)(KIMS), and Xe (ZEPLIN I) [32]. No observation of nuclear recoils has been reported by these experiments.

Two experimental signatures are predicted for true WIMP signals. One is a strong daily forward/backward asymmetry of the nuclear recoil direction, due to the alternate sweeping of the WIMP cloud by the rotating Earth. Detection of this effect requires gaseous detectors or anisotropic response scintillators (stilbene). The second is a few percent annual modulation of the recoil rate due to the Earth speed adding to or subtracting from the speed of the Sun. This tiny effect can only be detected with large masses; nuclear recoil identification should also be performed, as the much larger background may also be subject to seasonal modulation.

After the report of an observed annual modulation with a statistical significance of 6.3 σ, through operation of 100 kg of NaI(Tl) in Gran Sasso for 7 years, the DAMA collaboration has reported a new result with the LIBRA phase, involving 250 kg of detectors and an exposure of 0.53 t·y [35]. The modulation signal phases are compatible in both sets of data with the phase expected for a homogenous halo. The significance of the combined sets of data, corresponding to an exposure of 0.82 t·y, is between 8.3 and 8.9 σ depending on the width of the analyzed energy window. If interpreted within the standard halo model described above, it would require a WIMP with $m_\chi \simeq 50$ GeV and $\sigma_{\chi p} \simeq 7 \cdot 10^{-6}$ pb (central values) or at low mass, in the 6 to 10 GeV range with $\sigma_{\chi p} \sim 10^{-3}$ pb, and lower if there is a significant channeling effect. Such solutions would induce a sizeable fraction of nuclear recoils in the total measured rate in the 2 to 6 keV bin. No pulse shape analysis has been reported by the authors to check whether the signal was detectable this way. The shape of the residual e/γ-induced, background is also an unresolved issue [36]. Concerning compatibility with other experiments, there is now severe tension for the high mass solution (see below) and a small phase space available for the low mass solution (according to [36] this loophole is closed if the energy spectrum measured by DAMA/LIBRA is taken into account). The reported large significance of the signal has triggered new activity with non minimal WIMP models to reconcile DAMA result with limits from other experiments [35].

No other annual modulation analysis with comparable sensitivity has been reported by any experiment. KIMS, an experiment operating 12 crystals of CsI(Tl) with a total mass of 104.4 kg in the Yang Yang laboratory in Korea, has now accumulated 1 year of continuous operation. They should be able to set an upper limit on annual modulation amplitude lower than DAMA value if no annual modulation is present, and would need 2 years of running to confirm the DAMA value at 3 σ. They currently provide the best limit on pure proton spin-dependent couplings [37] above 30 GeV.

The simultaneous measurement of the phonon signal and the ionization signal in semiconductor detectors permits event by event discrimination between nuclear and electronic recoils down to 5 to 10 keV recoil energy. Currently the largest such experiment is the Cryogenic Dark Matter Search (CDMS). They reject surface detector interactions, which can mimic nuclear recoils, using timing information. New limits on the spin-independent coupling of WIMPs were obtained by this collaboration, which has operated 19 Ge cryogenic detectors at the Soudan mine, during new runs involving total exposure of around 400 kg·d (121 kg·d fiducial) [38], without any event in the pre-defined signal region. Combined with earlier data sets, these data provide an upper limit on the spin-independent cross section for the scattering of a 60 GeV/c^2 WIMP on a nucleon of 4.6×10^{-8} pb, at 90% CL. This experiment has achieved the best sensitivity for WIMP masses above 44 GeV/c^2.

Assuming conventional WIMP halo parameters described above, and spin-independent coupling WIMP interactions, the CDMS limit and DAMA signal are clearly incompatible. Varying the halo parameters, and/or including spin-dependent interactions compatible with the neutrino flux limit from the Sun, does not allow reconciliation of both results without fine tuning [36,39].

EDELWEISS, who is using similar technqiue as CDMS, but with different sensors has

shown substantial instrumental progress with an interleaved electrodes scheme prototype able to reject surface interactions at the level of one in 100 000. They are building and going to operate these new detectors [41] in the Modane underground lab. Other cryogenic experiments like CRESST and ROSEBUD [40] use the scintillation of $CaWO_4$ or other inorganic scintillators as second variable for background discrimination. They set weaker limits than the best current experiments. The cryogenic experimental programs of CDMS II, EDELWEISS II, and CRESST II [40] intend to increase their sensitivity by a factor of 10, by operating from a few to 40 kg of detectors.

Noble gas dual (liquid and gas) phase detectors allow one to measure both the primary scintillation and the ionization electrons drifted through the liquid and amplified in the gas, which can be used for background rejection. The limit obtained by XENON-10, an experiment involving 5.4 kg of fiducial mass of Xenon, run at the Gran Sasso laboratory, on spin-independent couplings of WIMPs is still the best for masses lower than 44 GeV/c^2 [42]. This was obtained thanks to a very low threshold of 4 keV recoil energy and the high A of Xenon nuclei. Xenon10, by exploiting the presence of ^{129}Xe and ^{131}Xe isotopes in natural Xenon has set the best limit for spin-dependent WIMPs with pure neutron couplings at all masses [43]. Xenon100, the next stage of the experiment with a fiducial mass of 30 to 50 kg and lower radioactivity components, has been operated and calibrated, and is expected to take data in 2010.

ZEPLIN III, using a similar principle and with an active mass of 12 kg of Xenon, operated in the Boulby laboratory for 83 days, reports a lower sensitivity. XMASS in Japan has operated a single-phase 100 kg detector (few kg fiducial mass) at the SuperKamiokande site, and demonstrated the self-shielding effect to lower the background [44]. They are currently building the 800 kg (100 kg fiducial mass) detector, installed in a large pure water shield.

The WARP collaboration is now installing a 100 l Argon detector at the Gran Sasso laboratory. They have demonstrated that, thanks to a double-background rejection method based on the asymmetry between scintillating and ionizing pulses and pulse shape discrimination of scintillating pulses, they could achieve very high background rejection, even in the presence of the radioactive isotope ^{39}Ar, although with a final sensitivity still lower than that of CDMS or XENON. The ArDM project will use a similar technique with a much larger (1,100 kg) volume. Many other projects (CLEAN, DEAP, HPGS, and SIGN) are developing with the aim of using Argon, Xenon, or Neon in liquid, double-phase, or high-pressure gas form [44].

There is also continuous development of the low pressure Time Projection Chamber technique, the only convincing way to measure the direction of nuclear recoils [45]. DRIFT, a 1 m^3 volume detector, has been operated underground, but suffered high background due to internal radon contamination. A background rejection technique has been developed, the recoil track head tail effect has been demonstrated, but no new operation underground was reported. A sub-keV energy threshold gaseous detector using Helium 3, the Mimac project, is being investigated for WIMP searches [45]. Very sensitive measurements of quenching factor of Helium nuclei have been performed recently down to 1 keV and are shown to depend on the pressure of the gas [46]. Other groups developing similar techniques are DMTPC in the US and NewAge in Japan.

A bubble chamber like detector, COUPP, run at Fermilab [47], has provided the best limits for spin-dependent proton-coupling WIMPs for masses lower than 30 GeV. The performance was limited by alpha background from radon internal contamination. Other exotic techniques include the superheated droplet detectors SIMPLE and PICASSO, which has obtained interesting but not competitive limits on spin-dependent couplings. An ultra cold pure ^{3}He detector (ULTIMA) has been operated with a very small sensitive mass.

Sensitivities down to $\sigma_{\chi p}$ of 10^{-10} pb, as needed to probe large regions of MSSM parameter space [48], can be reached with detectors of typical masses of 1 ton [40], assuming nearly perfect background discrimination capabilities. More and more projects are envisaged such EURECA (European multi-array, multi-target 1 ton cryogenic set up), Xenon1T (Extension of Xenon100), LUX/LZ (US 300 kg liquid Xenon, then multiton project), DARWIN European consortium (liquid Xe and Ar multiton project) [40,44]. Note that the expected WIMP rate is then 5 evts/ton/year for Ge. The ultimate neutron background will only be identified by its multiple interactions in a finely segmented or multiple-interaction-sensitive detector, and/or by operating detectors containing different target materials within the same set–up. Information on various neutron background calculations and measurements can be found in [49]. With an intermediate mass of 10 to 30 kg, and therefore less efficient multiple interaction detection, a muon veto seems mandatory in most existing underground laboratories.

22.2.5. *Status and prospects of indirect WIMP searches* :

WIMPs can annihilate and their annihilation products can be detected; these include neutrinos, gamma rays, positrons, antiprotons, and antinuclei [50]. These methods are complementary to direct detection and can explore higher masses and different coupling scenarios. "Smoking gun" signals for indirect detection are neutrinos coming from the center of the Sun or Earth, and monoenergetic photons from WIMP annihilation in space.

WIMPs can be slowed down, captured, and trapped in celestial objects like the Earth or the Sun, thus enhancing their density and their probability of annihilation. This is a source of muon neutrinos which can interact in the Earth. Upward going muons can then be detected in large neutrino telescopes such as MACRO, BAKSAN, SuperKamiokande, Baikal, AMANDA, ANTARES, NESTOR, and the large sensitive area IceCube [50]. The best upper limits, of $\simeq$ 1000 muons/km^2/year, have initially been set by SuperKamiokande [51]. A new limit has been set by AMANDA and IceCube22 (using 22 strings) at around few hundreds of muons/km^2/year for muons from the sun [52]. In the framework of the MSSM and with standard halo velocity profiles, only the limits from the Sun, which mostly probe spin-dependent couplings, are competitive with direct WIMP search limits. IceCube80 will increase this sensitivity by a factor $\simeq$ 5 at masses higher than 200 GeV while IceCube Deep Core will allow one to reach masses down to 50 GeV.

WIMP annihilation in the halo can give a continuous spectrum of gamma rays and (at one-loop level) also monoenergetic photon contributions from the $\gamma\gamma$ and γZ channels. These channels also allow to search for WIMPs for which direct detection experiments have little sensitivity, *e.g.*, almost pure higgsinos. However, the size of this signal depends

very strongly on the halo model, but is expected to be most prominent towards the galactic center. Existing limits come from the EGRET satellite below 10 GeV, and from the WHIPPLE ground based telescope above 100 GeV [53]. The FERMI/LAT apparatus, now taking data, will soon bring new quality data in the galactic center region. Atmospheric Cherenkov Telescopes like MAGIC, VERITAS, and H.E.S.S. did not claim so far any significant excess which could be attributed to Dark Matter annihilation.

Diffuse continuum gammas could also give a signature due to their anisotropic distribution tracking the halo density as seen from Earth. According to [54], a re-analysis of EGRET data shows an excess in the energy spectrum at the GeV range, if one normalizes the experimental spectrum to that expected from model calculations at lower energies, assuming that the cosmic ray spectrum has the same shape (but different normalization) everywhere in our galaxy. The excess has be explained in terms of WIMP annihilation, with WIMP mass near 80 GeV, only if one assumes a rather clumpy halo. However, with newly accumulated high accuracy data [55] the FERMI/LAT instrument has found agreement with a pure secondary production model (from CR interactions), and does not confirm the EGRET excess.

Antiprotons arise as another WIMP annihilation product in the halo. The signal is expected to be detectable above background only at very low energies. The BESS balloon-borne experiment indeed observed antiprotons below 1 GeV [56]. However, the uncertainties in the calculation of the expected signal and background energy spectra are too large to reach a firm conclusion. PAMELA measurement of the antiproton spectrum between 2 and 20 GeV [57], of higher accuracy, shows a good agreement with secondary production and propagation models.

Positrons arise as well as another WIMP annihilation product in the halo. A cosmic-ray positron flux excess at around 8 GeV measured by HEAT [58] has given rise to numerous calculations and conjectures concerning a possible WIMP interpretation. New positron /(electron+positron) ratio measurement performed by PAMELA [59] between 1 and 100 GeV showed a rather marked rise between 10 and 100 GeV. The observed spectrum falls within the one order of magnitude span (largely due to differences in the propagation model used) of positron fraction values predicted by secondary production models [60]. Measurements of the total electron+positrons energy spectrum by ATIC [61], FERMI/LAT [62] and HESS [63] between 100 and 1000 GeV also exceed the predicted purely secondary spectrum, but with very large dispersion of the magnitude of these excesses. While it has been recognized that astrophysical sources may account for all these features, many ad-hoc Dark Matter models have been built to account for these excesses. As mentioned in section 1, given the amount of jerking and twisting needed to build such models not to contradict any observation, it seems very unlikely that Dark Matter is at the origin of these excesses.

Last but not least, an antideuteron signal [64], as potentially observable by AMS2 or PAMELA, could constitute a signal for WIMP annihilation in the halo.

An interesting comparison of respective sensitivities to MSSM parameter space of future direct and various indirect searches has been performed with the DARKSUSY tool [65]. A web-based up-to-date collection of results from direct WIMP searches, theoretical predictions, and sensitivities of future experiments can be found in Ref. 66. Also, a new

web page, initiated by ILIAS [67], a European underground science and infrastructure network, allows to make predictions for WIMP signals in various experiments, within a variety of SUSY models. Its long-term goal is to propose an interactive integrated analysis of all relevant data. These should ultimately include not only data from direct and indirect WIMP detection experiments, but also from high-energy colliders such as the LHC. If a positive WIMP signal is found anywhere, such a comprehensive approach will be required to fully unravel the mysteries of dark matter.

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