PHYSICS AT UNDERGROUND LABORATORIES: DIRECT DETECTION OF DARK MATTER

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Underground laboratories host two kind of experiments at the frontier of our knowledge in Particle Physics, Astrophysics and Cosmology: the direct detection of the Dark Matter of the Universe and the search for the Neutrinoless Double Beta Decay of the nuclei. Both experimental quests pose great technical challenges which are being addressed in different ways by an important number of groups. Here a updated review of the efforts being done to detect Dark Matter particles is presented, emphasizing latest achievements.

1 Introduction

Since first suggested by Zwicky in the 1930s, the existence of an invisible and non-conventional matter as a dominant part of our Universe has been supported by an ever increasing body of observational data. The latest precision cosmology measurements \[123\] further constrain the geometry of the Universe to be flat \((\Omega \sim 1 \pm 0.04)\), and its composition to be mostly dark energy \((\Omega_{\Lambda} = 74 \pm 3\%)\) and non-baryonic cold dark matter \((\Omega_c \sim 21.4 \pm 3\%)\), leaving about \(\sim 4.4\%\) for ordinary baryonic matter. Dark energy is a theoretical concept related to Einstein’s cosmological constant, the nature of which is essentially unknown. Dark matter, on the contrary, could be composed by elementary particles with relatively known properties, and which could be searched for by a variety of means. These particles must have mass, be electrically neutral and interact very weakly with the rest of matter. They must provide a way of being copiously produced in the early stages of the Universe life, so they fill the above-mentioned \(\sim 23\%\) of the Universe contents. Neutrinos are the only standard particles fitting in that scheme, but the hypothesis of neutrinos being the sole component of dark matter fails to reproduce part of the cosmological observations, in particular the current structure of the universe. The dark matter problem is therefore solved only by going into models beyond the standard model of elementary particles, among which two generic

\[\text{\*Although the talk at the conference included also a brief review of double beta decay experiments, due to space and time constraints, this written version is focused only on dark matter.}\]
categories emerge as the best motivated for the task: WIMPs and axions.

WIMP is a generic denomination for any Weakly Interacting Massive Particle. A typical example of WIMP is the lightest supersymmetric particle (LSP) of SUSY extensions of the standard model, usually the neutralino. They would have been thermally produced after the Big Bang, cooled down and then frozen out of equilibrium providing a relic density. The interesting mass window for the WIMPs spans from a few GeV up to the ~ TeV scale, but can be further constrained for specific models and considerations.

Axions, on the contrary, are light pseudoscalar particles that are introduced in extensions of the Standard Model including the Peccei-Quinn symmetry as a solution to the strong CP problem. This symmetry is spontaneously broken at some unknown scale $f_a$, and the axion is the associated pseudo-Goldstone boson. The axion framework provides several ways for them to be produced copiously in the early stages of the Universe, which makes it a leading candidate to also solve the dark matter problem.

The hypothesis of axions or WIMPs composing partially or totally the missing matter of the Universe is specially appealing because it comes as an additional bonus to what these particles were originally thought for, i.e. they are not designed to solve the dark matter problem, but they may solve it. In addition, the existence of WIMPs or axions could be at reach of the sensitivity of current or near future experiments, and this has triggered a very important experimental activity in the last years. The detection of WIMPs by direct means, i.e. aiming at their direct interaction with terrestrial detectors is being pursued by a large variety of techniques. All of them, however, share the feature that they are carried out in underground sites, to reduce backgrounds induced by cosmic rays. In fact, WIMP experiments are, together with double beta decay, one of the main pillars of underground physics. In the following pages a review is given of the current experimental efforts to directly detect these particles. Axions, on the other hand, are not necessarily searched in underground labs (although some axion detection techniques do use underground setups), and because of this they are sometimes dropped out of dark matter reviews. The fact that the ”dark matter community” is substantially polarized towards WIMPs (probably due to the boost of underground physics in the last years) should not be regarded as a justification to ignore or minimize the importance of the axion as a potential candidate for dark matter. Much on the contrary, for many the existence of the axion is better motivated by theory arguments other than being a good dark matter candidate. Axions are in fact being searched for in experiments per se, without the assumption of them composing the dark matter, something that does not happen with
WIMPs (excepting supersymmetry searches in accelerators). To compensate a bit this prejudice, and in spite of this review being focused on underground physics, we will devote a section on axion searches at the end of it.

Finally, indirect methods, like those looking for the decay products of WIMPs or axions in astronomical or cosmic rays observations may also put constraints on the properties of these particles, although they suffer from extra degrees of uncertainties, like the phenomenology driving the accumulation of dark matter particles in astrophysical bodies and their decay into other particles, and they are left out of the scope of the present review.

2 WIMP searches

If WIMPs compose the missing matter of the universe, and are present at galactic scales to explain the observed rotation curves of the galaxies, the space at Earth location is supposed to be permeated by a flux of these particles characterized by a density and velocity distribution that depend on the details of the galactic halo model. A common estimate (although probably not the best one) gives a local WIMP density of 0.3 GeV/cm$^3$ and a maxwellian velocity distribution of width $v_{rms} \simeq 270$ km/s, truncated by the galactic escape velocity $v_{esc} \simeq 650$ km/s and shifted by the relative motion of the solar system through the galactic halo $v_0 = 230$ km/s.

The direct detection of WIMPs relies on measuring the nuclear recoil produced by their elastic scattering off target nuclei in underground detectors. Due to the weakness of the interaction, the expected signal rates are very low ($1 - 10^{-6}$ c/kg/day). In addition, the kinematics of the reaction tells us that the energy transferred to the recoiling nuclei is also small (keV range), which in ionization and scintillation detectors may be further quenched by the fact that only a fraction of the recoil energy goes to ionization or scintillation. These generic properties determine the experimental strategies needed. In general, what makes these searches uniquely challenging is the combination of the following requirements: thresholds as low as possible, and at least in the keV range; ultra low backgrounds, which implies the application of techniques of radiopurity, shielding and event discrimination; target masses as large as possible; and a high control on the stability of operation over long times, as usually large exposures are needed.

Even if these strategies are thoroughly pursued, one extra important consideration is to be noted. The small WIMP signal falls in the low-energy region of the spectrum, where the radioactive and environmental backgrounds accumulate at much faster rate and with similar spectral shape. Several calculated WIMP spectra are shown in figure 1 for several target nuclei and some...
selected input parameters. The pseudo-exponential shape of these spectra makes WIMP signal and background practically indistinguishable by looking at their spectral features. If a clear positive detection is aimed for, then more sophisticated discrimination techniques and specially more WIMP-specific signatures are needed. Several positive WIMP signatures have been proposed, although all of them pose additional experimental challenges. The first one is the annual modulation\(^{18}\) of the WIMP signal, reflecting the periodical change of relative WIMP velocity due to the motion of the Earth around the Sun. The variation is only of a few % over the total WIMP signal, so even larger target masses are needed\(^{19}\) to be sensitive to it. This signal may identify a WIMP in the data, provided a very good control of systematic effects is available, as it is not difficult to imagine annual cycles in sources of background. A second WIMP signature is the \(A\)-dependence signature\(^{17}\), based on the fact that WIMPs interact differently (in rate as well as in spectral shape) with different target nuclei. This signature should be within reach of set-ups composed by sets of detectors of different target materials, although the technique must face the very important question of how to assure the background conditions of all detectors are the same. Finally, the directionality signature\(^{20}\) is based on the possibility of measuring the nuclear recoil direction, which in galactic coordinates would be unmistakably distinguished from any terrestrial background. This option supposes an important experimental challenge and it is reserved to gaseous detectors, where the track left by a nuclear recoil, although small, may be measurable.

Most of the past and current experiments having given the most competitive results are not sensitive to any of these positive WIMP signatures, and their reported results are usually exclusion plots in the \((\sigma_N, M)\) plane, obtained by comparing the total spectra measured directly with the nuclear recoil spectrum expected for a WIMP (where \(\sigma_N\) is WIMP-nucleon cross section and \(M\) the the WIMP mass). These exclusion plots, like the ones in fig. 2, are usually calculated assuming the standard properties for the halo model previously mentioned, and a spin independent WIMP-nucleus interaction. But this is an oversimplification, justified only in part by the need to agree on some reasonable values for the calculation’s unknown inputs for the sake of comparison between different experiment’s sensitivities. The use of other halo model assumptions, the introduction of spin-dependent WIMP-nucleus interaction or, eventually, the invocation of very specific exotic theoretical frameworks for the WIMP may alter significantly the obtained exclusion plots.\(^{13}\)\(^{14}\)\(^{15}\) The study of these effects become especially important in the case of comparing a positive signal from one experiment with negative results from others.
This is a hot topic in dark matter conferences, object of much of the discussion regarding the controversial positive result of the DAMA collaboration (that will be discussed later). Unfortunately, these problems are inherent to the model-dependence of exclusion plots and can only be solved by pursuing experiments capable of getting identifying signals (as model-independent as possible), like the ones mentioned before. Fortunately, recent progress in the experimental techniques promises that experiments in the near future will hopefully have wider access to these.

In the following section a review of the current status of the experimental WIMP searches is done. Although some historical notes are given, it is not aimed at providing an exhaustive and historical listing of experiments, and it is focussed mainly on the most relevant detection techniques used with stress in the latest results and developments. However, the division done in the first five subsections keep also some chronological dimension as each of the techniques described has shown their emergence in the field and sometimes preponderance over the rest for some period of time in the past. We briefly
start with the pioneer ionization detectors (subsection 2.1), which set a benchmark in radiopurity and low background techniques, to continue with the pure scintillators (subsection 2.2) which have up-to-now reached the largest target masses. Bolometers (subsection 2.3) provided a breakthrough in the quest for WIMPs in the late 90s by exploiting very effectively the electron-nuclear recoil discrimination, although the current lead corresponds to noble liquid techniques (subsection 2.4), which apart from equaling bolometers in the discrimination capabilities, they seem to provide better scaling-up prospects. The fifth subsection is devoted to the gaseous TPCs, a category of experiment that, although not yet implemented into successful experimental prototypes is the only one offering access to the WIMP direccionality signal, and is attiring a renewed attention lately. The two last subsections are devoted not to different detection techniques, but to searches specially focused to a specific subset of WIMP models, like the case of low mass WIMPs, or the spin-dependent interaction.

Let us finish by saying that for a review containing an historical listing of the older experiments we refer to 21, 22, 23, which, although outdated with respect to the latest results, they contain a very complete and exhaustive listing of experiments up to their date.

### 2.1 The pioneers: ionization detectors

The experimental field of dark matter direct detection was born out of the important advances in background reduction, radiopurity and shielding techniques exhaustively applied to germanium detectors in the last 2 decades of the last century, motivated by the search for the neutrinoless double beta decay of Ge-76. Nowadays, ionization germanium detectors represent the conventional approach of a well-known technology, where radiopurity and shielding techniques have been optimized. In the last years, their interest for WIMP searches have been reduced in favor of techniques, discussed in next sections, that exploit advanced detection features to discriminate between electron and nuclear recoils, and therefore allowing to go much beyond the best background levels achieved by Ge detectors. Germanium ionization detectors remain however a benchmark of the level of raw background achieved, i.e. only by radiopurity/shielding techniques, without strong event discrimination techniques, which may still make them relevant in some specific situations where the latter are not available, like for example the quest for very low mass WIMPs discussed in section 2.7.

The result released by the IGEX collaboration already 8 years ago 24, shown in fig. 2 exemplifies the state-of-the-art in raw background reduction
Figure 2. Exclusion plots for several experiments commented in the text, as well as the positive region of the DAMA experiment (only first 4 annual cycles). Standard assumptions for the halo model and a pure spin-independent WIMP-nucleon interaction have been considered. See text for more details.

techniques. The result was obtained with a setup in the Canfranc Underground Laboratory composed by an ultrapure germanium detector of 2.1 kg, surrounded by a shielding of ultrapure components, including an innermost core of 2.5 tons of 2000-year-old archaeological lead forming a 60 cm side cube, flushed with clean N\textsubscript{2} to remove radon and followed by an extra 20 cm of radiopure lead, a cadmium sheet, muon vetos and 40 cm of neutron moderator. The achieved threshold was 4 keV, and the background level was 0.21 c/keV/kg/d between 4-10 keV (0.10 in 10-20 keV, 0.04 in 20-40 keV), the lowest raw background level achieved up-to-date in this energy range.

2.2 Scintillation detectors

Scintillation detectors have been extensively used for WIMP detection, specially because they are the technique which provided the easiest way to large
target masses. It was in fact a setup of NaI scintillators which first looked for
the annual modulation signature. With no so good prospects concerning
low background capabilities as germanium detectors, scintillation may how-
ever provide a way—although limited—to discriminate between nuclear recoils
and electron recoils, due to their slightly different scintillation decay times.

Currently, the DAMA group gathers the expectation of the field with its
claim of observation of an annual modulation signal of unexplained origin and
perfectly compatible with a WIMP of \( \sim 52 \) GeV and \( \sim 7.2 \times 10^{-6} \) pb (and
standard assumptions for the halo model). The DAMA experiment in the
Gran Sasso Laboratory, now completed, operated 9 radiopure NaI crystals
of 9.7 kg each, viewed by two PMTs in coincidence having gathered 107731
kg day of statistics and obtaining evidence for the modulation along 7 annual
cycles. The experimental setup was subsequently enlarged up to 250 kg of
target mass in 2005, the so-called DAMA/LIBRA experiment, whose first
results were released in 2007. The DAMA/LIBRA data confirms the annual
modulation seen by DAMA, in intensity, frequency and phase, and increases
its overall statistical significance up to 8.2\( \sigma \) CI.

The DAMA positive signal has been ruled out by other experiments in
the standard scenario represented by the exclusion plots of fig. 2. However, in
view of the important uncertainties in the underlying theoretical frameworks
and in the galactic halo models, it is unclear, and a matter of hot discus-
sion, whether all results are compatible once all uncertainties are taken into
account. It seems that one can always concentrate on a specific theoretical
framework that allows to accommodate both DAMA positive result and the
other exclusion plots. An additional result using the same target seems to
be needed to solve the controversy. An independent result will come from the
ANAIS experiment, currently in the way of instrumenting its \( \sim 100 \) kg of
NaI in the Canfranc Underground Laboratory.

Other promising scintillating material for WIMP searches is CsI, used by
the KIMS experiment in the Yangyang Underground Laboratory in Ko-
rea. This material offers a higher potential of discrimination between nuclear
and electron recoils when compared with NaI, due to the enhanced difference
between the scintillation pulse time pattern of the two kind of events. The
latest KIMS result includes 10 kg-y of data taken with a 36 kg setup,
and represent the best exclusion plot by a pure scintillation setup, excluding
WIMP-nucleus cross sections down to \( 2 \times 10^{-42} \) cm\(^2\) for WIMP masses
around 50-100 GeV, and excluding (always under the standard assumptions)
the DAMA result. This result is especially relevant when compared to the
DAMA positive result, as both experiments share one of the target nuclei:
2.3 Cryogenic detectors

Nuclear recoils can also be detected through the heat (phonons) created in the detector by the recoiling nucleus. This signal is detectable in bolometers operating at cryogenic temperatures, to which a suitable thermometer is attached. At those temperatures, the released heat produces a temperature raise that can be measurable.

The main advantage of this technique is that most of the energy of the interaction is visible and therefore no quenching factor must be applied. Besides, the phonon signal potentially provides the best energy resolution and thresholds. On the other hand, however, the operation of cryogenic detectors is a relatively complex technique facing many challenges when going for larger exposure times and masses. For the same reason, radiopurity techniques are also more difficult to apply.

A reference point in pure cryogenics detectors is the pioneering work of the Milano group, now leading the CUORE/CUORICINO experiment in the Gran Sasso Laboratory. The CUORE project, designed to search for the neutrinoless double beta decay of $^{130}$Te, intends the construction of an array of 988 TeO$_2$ cryogenic crystals, summing up $\sim$ 750 kg of bolometric mass. A first step of the project, CUORICINO, is already in operation and involves 62 ($\sim$40.7 kg) crystals, by far the largest cryogenic mass in operation underground. Although background levels are still too high to provide competitive limits in WIMP detection, important progress is being made and CUORE may have good sensitivity to WIMP annual modulation.

However, cryogenic detectors took the lead in WIMP searches in the beginning of the 2000s because of the possibility of operating in hybrid mode. Due to the relatively large choice of target materials available to the cryogenic techniques, and when the material in question is a semiconductor or a scintillator, the detector could in principle be operated in hybrid mode, measuring simultaneously the heat and charge or the heat and light respectively. This strategy has proven to be very competitive and efficient in discriminating nuclear recoils from electron recoils. Pioneers in this concept are the cryogenic ionization experiments, like CDMS in the Soudan Underground Laboratory and EDELWEISS in the Modane Underground Laboratory. CDMS took the lead of the race in the standard WIMP exclusion plot since they provided their first results underground in 2003, with only 19.4 kg-days of effective exposure, and which went substantially beyond any other exclusion obtained up-to-date. Further improved in 2005 with data from 2 towers, it was not
challenged until the publication of the first XENON experiment results (discussed in next section) in 2006. Their most recent published results, this year, adds data from the full 30-detector setup (19 of them Ge, and 11 Si, amounting to 4.75 kg of Ge) between October 2006 and July 2007, excluding WIMPs down to $4.6 \times 10^{-44}$ cm$^2$ for a WIMP mass of 60 GeV, and improving slightly beyond the XENON exclusion limit for WIMP masses above 44 GeV (see Fig. 2).

The EDELWEISS collaboration presented similar early results, but it has not been able to later improve its sensitivity to the same levels of CDMS mainly due to the problem of surface events. However, the latest advances in their detectors seem to show prospects to reduce these events in the current physics runs that the new setup, EDELWEISS II composed by 4 kg of Ge mass (to be extended to 9 kg next year), is already preforming in the Modane Underground Laboratory.

Although currently less competitive than heat-and-charge, the simultaneous measurement of heat and light has shown very interesting prospects. The ROSEBUD group first applied it underground (in the Canfranc Lab) and subsequently the CRESST collaboration presented a competitive exclusion plot obtained with two 300 g CaWO$_4$ prototypes. The CRESST setup, installed at Gran Sasso has been improved and enlarged (CRESST II) to accommodate up to 33 modules of such size working in cryogenic temperatures (10 mK) and fully shielded. Preliminary results from the commissioning run still with only 2 such modules (total of 600 g of CaWO$_4$) show already a sensitivity down to $4.8 \times 10^{-7}$ pb, only one order of magnitude away from CDMS and XENON, as seen in Fig. 2.

A very relevant feature of these results is that tungsten recoils can be distinguished -with some efficiency- from O or Ca recoils by virtue of their different ratio heat/light. This improves substantially the sensitivity of the experiment, as neutrons are expected to interact more with lighter nuclei, unlike WIMPs. In addition, recent scintillation studies have shown that a large variety of scintillating crystals are available. This opens the way to use sets of different crystals operating in this mode to look for the $A$-dependence WIMP signature. While the use of this signal in conventional detectors suffers from large uncontrolled systematics derived from the fact that one cannot assure the background to be the same for different crystals, light/heat hybrid detectors, sensitive only to neutrons, may overcome this difficulty. In this line, the ROSEBUD collaboration has successfully operated underground a set of 3 different bolometers in the same setup, sharing similar external background conditions.
The main challenge in general for hybrid bolometric detectors is how to cope with the complexity of the technique when going to larger scales, keeping the ever stronger constraints on radiopurity and shielding that future setups will have. Present setups, as mentioned, have achieved target masses at the 1–10 kg scale. In order to successfully accomplish the next step in scale (\(\sim 100\) kg and more) a joint effort is needed. In Europe a new protocollaboration has been established, EURECA\(^{[35]}\) which gathers all European groups mentioned above, EDELWEISS, CRESST and ROSEBUD plus cryogenic expertise from CERN, as well as new interested groups. EURECA will work towards a large scale cryogenic facility (up to 1 ton target mass) that will tentatively be located in the future extension of the Modane Laboratory, with the goal of solving all related technical aspects and reaching sensitivities down to \(\sim 10^{46}\) cm\(^2\). In America, the CDMS collaboration have similar plans (SuperCDMS\(^{[16]}\)) of evolving towards a ton-scale facility that would be installed in a deeper location that the current Soudan site (like SNOLAB for example).

2.4 Noble liquid experiments

Experiments using liquid noble gases, especially Argon or Xenon, should be classified halfway between ionization and scintillation. The scintillation mechanism in noble gases is very different than in the previous cases, and allows for an improved discrimination capability by exploiting the different time patterns of the scintillation pulses of nuclear and electron recoils or, more efficiently, by using the ratio charge/light when operating in hybrid mode. This second possibility is available in two-phase prototypes, where an electric field is applied to prevent recombination and to drift the electrons to the gaseous phase where they are detected, either via the secondary luminescence or by charge amplification.

Several groups are developing and using noble liquid detectors for WIMP searches. They have proven that this technique provides good prospects of radiopurity and background discrimination and relatively easy scaling-up. DAMA/Xe\(^{[17,18]}\) is among the pioneers of the technique, originally motivated for double beta decay searches. The ZEPLIN collaboration working in the Boulby Mine Laboratory in UK has also a long-standing program on liquid Xenon for WIMP searches that has given a series of prototypes of increasing mass: ZEPLIN I, in pure ionization mode\(^{[19]}\), which gave a first competing exclusion plot in 2004, and ZEPLIN-II and -III working in double phase mode. But the breakthrough in the field was given by the XENON collaboration in 2007 when the first 58.6 live days of the XENON10 prototype of 5.4 kg
fiducial mass operating in the Gran Sasso National Laboratory were released. The data excluded WIMP-nucleon cross sections down to $4.5 \times 10^{-44}$ cm$^2$ at WIMP masses of 30 GeV, and in general a factor 2 to 10 (depending on the WIMP mass) better than the best exclusion at the time, that of CDMS$^a$. The reasons of such good sensitivity are the good levels of radiopurity achieved by the detector, the shielding and self-shielding, but especially the enhanced discrimination capability that was achieved even at relatively low energies (XENON10 was claimed to have significant discrimination down to 4.5 keV nuclear recoil energy). In fact, the behavior of the ionization of both nuclear and electron recoils in liquid Xenon is not yet fully understood from fundamental reasons, but, although this sometimes has been used as a kind of criticism, it is true that the collaboration has carefully calibrated the effect. The latest addition of the liquid Xenon scenario are the results released this same year by the ZEPLIN collaboration, including the first physics run of the ZEPLIN-III setup$^{[50]}$, which has provided an exclusion plot only a factor of 2 to 4 close to that of XENON10.

The XMASS Japanese collaboration is trying a different approach to the detection in liquid Xenon. Their prototype is simplified with respect the previous experiments in the sense that only the scintillation in the liquid is measured by a set of photomultipliers that surrounds the Xe mass in all directions (no double phase operation). The key question beneath this is the self-shielding concept, consisting in performing fiducial cuts of the detector to achieve the maximum signal-to-background ratio, exploiting the fact that external background will interact primarily in the outer parts of the detector volume. A 100 kg prototype has been successfully built and operated$^{[51]}$ with levels of background in the fiducial volume compatible with Monte Carlo simulations, although still not enough to provide competitive exclusion plots. The collaboration is quickly moving towards the construction of a 800 kg prototype that should be able to achieve much lower backgrounds in the fiducial volume and get sensitivities$^{[51]}$ down to $\sim 10^{-45}$ cm$^2$. This detector will be located in the Kamioka mine. Finally, in US a recent collaboration, LUX, has been formed with most american groups participating in XENON10 and ZEPLIN-II experiments in order to build a 350 kg detector using double phase Xenon technology$^{[52]}$.

At this moment, both germanium bolometers and liquid Xenon detectors, exemplified by CDMS and XENON respectively, are providing the best sensitivities for WIMPs, with successful prototypes at the $\sim 5$ kg of fiducial mass

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$^a$as mentioned in the previous section, however, the latest CDMS result, in 2009, has reached a similar level as that of XENON10
scale. Liquid Xenon, however, have some features that a priori will play a very important role in the subsequent phases of scaling-up. The complexity of the liquid Xenon detector does not scale with detector size as much as in the case of bolometers. One could say that in the case of bolometers to increase the total size means, in first approximation, to increase the number of crystal-modules, and therefore the complexity of the detector (mechanics, readout, electronics,...) increase linearly with size. In case of liquid Xenon, the volume of the vessel increases but the readout is associated to one size of the vessel, and therefore its complexity scales less than linearly. In addition, the sensitive volume is a monolithic one in the case of liquid Xenon, and not in the case of bolometers, which the drawback, for the latter, of the material needed in between modules and the advantage, for the former, of a more efficient background reduction strategies based on multi-site topologies and self-shielding, both concepts of increasing importance in future bigger detectors. All these arguments are confirmed in practice by the relatively rapid emergence and success of the XENON experiment, which has already built the next prototype XENON100, which will operate between 30 to 50 kg of fiducial mass, and it is currently being commissioned in the Gran Sasso Laboratory. In conclusion, short term prospects seem to favor liquid Xenon technology to lead the quest for WIMPs in the coming years, at least as long as no irreducible backgrounds (or signals!) are found.

Apart from liquid Xenon, other noble liquid are being considered. In spite of the current advantage of Xenon results, the use of liquid Argon or even liquid Neon as proposed by the following collaborations could emerge as a competitive option with certainly very interesting scaling-up prospects if the next generation of prototypes show themselves successful. The detection process of these detectors is similar to that of the liquid Xenon ones, although the discrimination power of the ratio light/ionization seems to be less powerful than in Xenon. In compensation, the scaling-up prospects, cost and ease of manipulation of Argon surpasses those of Xenon. In Europe two collaborations are building and testing liquid Argon prototypes for dark matter. Both collaborations inherit experience in large liquid Argon TPCs from the ICARUS experiment, which certainly supposes a guarantee of know-how as it was composed of TPC modules of 600 tons of liquid Argon. The WARP collaboration is for now the only one having produced an exclusion plot which goes down to $10^{-42}$ cm$^2$ at 100 GeV, obtained with a test chamber of only 2.3 l of liquid Argon accumulating a fiducial exposure of 100 kg-d in the Gran Sasso Laboratory and also shown in Fig. 2. The collaboration is currently commissioning a second generation prototype of 140 kg in the Gran Sasso Laboratory also shown in Fig. 2. On the other hand, the ArDM collaboration has chosen to build a relatively
large TPC, of 850 kg of liquid Argon mass, right from the start. Currently it is being commissioned at surface level\(^55\) at CERN, and it will be transported underground at a later stage, probably at the Canfranc Underground Laboratory. Finally, the DEAP/CLEAN collaboration, composed by groups from US and Canada are building small scale prototypes of both liquid Argon and Neon. The CLEAN program\(^56\) has a broader scope that includes solar neutrino detection and has recently proved the feasibility of liquid Neon for such purpose.

### 2.5 Directional detectors

Detectors aiming at measuring the direction of the nuclear recoil must be put in a different special category. Being extremely challenging, they have not reached the level of operative prototypes with any significant sensitivity and remain at an R&D phase. However they could have access to the only unmistakable signature of a WIMP. Many believe that the ultimate identification of a WIMP as a dark matter component (maybe after its detection in another non-discrimination experiment) will come from a directionality experiment. Moreover, the technical advances achieved in the last years have increased the interest for these experiments and nowadays a growing community actively explores the different technological options.

As mentioned in section 1, such signal would suppose a definitive positive signature of a WIMP and would in addition give information about how they are distributed in the halo. The preferred detection medium is gas, where nuclei of \(\sim 10 - 100\) keV could leave tracks in the mm–cm range (depending on the pressure and nature of the gas), although proposals to scan the tiny recoils in solid materials (in high resolution nuclear emulsions) exist\(^57\). The pioneer collaboration exploring Gaseous Time Projection Chambers (TPCs) for WIMP directionality is DRIFT\(^58\). DRIFT is developing the low pressure negative ion TPC concept\(^59\)\(^60\). Low pressure (40 Torr) makes the tracks to be relatively long (few cm), and the addition of electronegative gas (CS\(_2\)) makes the electrons to be captured, so the negative ions drift to the avalanche region (a multiwire proportional chamber) with much smaller diffusion and no magnetic field is needed. Since 2001, DRIFT has successfully operated 1 m\(^3\) prototypes in the Boulby Mine Laboratory, and especially with the second generation of prototypes DRIFT-IIa-d since 2006 has achieved important milestones in terms of underground operation, background understanding and in particular the demonstration of sensitivity to the recoil direction sense (head-tail discrimination)\(^61\).

Despite this progress, sensitivity to nuclear recoil’s direction (especially
of low energies, i.e. below 100 keV) is still challenging, and target masses operated up to now are very small (few tens of grams), due to the low pressures involved, making difficult an appropriate strategy towards large scale detector. Recently, novel readouts based on micropattern technologies are emerging as an alternative option that could in principle outdo MWPCs in several aspects, especially in terms of spatial resolution. In these novel readouts, metallic strips or pads, precisely printed on plastic supports with photolithography techniques (much like printed circuit boards), substitute the traditional wires to receive the drifting charge produced in the gas. The simplicity, robustness and mechanical precision are much higher than those of the conventional planes of wires.

Around this basic principle, first introduced by Oed already in 1988\textsuperscript{62}, several different designs have been developed, which differ in the way the multiplication structure is done, and that in general are referred to as Micro Pattern Gas Detectors (MPGD). One of the first clear initiatives to apply this to WIMP directionality was the the Japanese NEWAGE collaboration, which explores since 2003 the use of a MPGD (a microdot structure) as readout of its first prototype of micro-TPC of $20 \times 25 \times 31$ cm$^3$ with low pressure CF4 gas. Since 2007 tests continue underground in the Kamioka Underground Observatory\textsuperscript{63}, studying aspects like background, gas purity, scaling-up (bigger prototypes are under construction) and detector characterization. Up to now, a threshold of 100 keV has been achieved and an angular resolution of 55° at 128 torr of pressure, but better numbers are expected in future prototypes.

Although probably the most promising MPGD concept for WIMP searches (and rare event searches in general\textsuperscript{64,65}) is the so-called Micromesh Gas Structure or Micromegas\textsuperscript{66}, created about 14 years ago and actively developed since them by the CEA/Saclay group led by I. Giomataris. It consists of the use of a micromesh, suspended over the strip plane by some isolator pillars, defining a high electric field gap of only 50-100 microns. In this gap, an electron avalanche is produced like the one in parallel plate chambers, inducing signals in both the mesh and the strips. Depending on the strip (or pixels) design, the spatial/topology information of the event can be imaged with unprecedented precision. Nowadays, the Micromegas concept is already being used in many particle physics experiments achieving unique results in terms of temporal, spatial and energy resolution. In the field of rare events, the use of Micromegas readouts have been pioneered by the CEA/Saclay and University of Zaragoza groups, in the CAST experiment\textsuperscript{67} at CERN. CAST is equipped with a low background Micromegas detector since 2002\textsuperscript{70}, and 2 additional ones were installed in 2007 substituting the former multi-
wire TPC. CAST has been a test ground for Micromegas technology, and the continuous efforts to improve the detectors have given rise to 3 generation of detector setups (regarding the fabrication method, the detector materials, their shielding and their electronics and data reduction treatment), yielding continuously improving background levels.

Micromegas readouts are being used already by the French MIMAC collaboration, which proposes the use of a multi-chamber setup composed by microTPCs operating with $^4\text{He}$ or, alternatively, CF$_4$ at low pressure. The use of light nuclei facilitates the imaging of low energy recoils and the use of odd-nuclei provides sensitivity of spin-dependent interaction (see next section) and relaxes the requirement of going to very large masses needed to compete with the experiments searching for spin-independent interaction. MIMAC has successfully operated a small microTPC module equipped with Micromegas in $^4\text{He}$, has measured ionization quenching factor down to 1 keV, and has recently obtained first 3D tracks. On the other hand, the DRIFT collaboration has shown interest in the Micromegas readouts, having successfully tested the negative ion concept with them.

More recently, the American collaboration DMTPC has proposed an optical readout, based on a CCD camera coupled to some appropriate optics in order to register the scintillation light produced by the CF$_4$ in the avalanche. They have succeeded in operating a first prototype and demonstrate 2D imaging of nuclear recoils down to 100 keV. Future plans include test underground (at WIPP) as well as development to extract the third dimension.

Although one cannot deny that the construction of a detector with directional sensitivity at the required mass scale and performance is still a big challenge, a large and growing development activity and interest is going on in the last years. This interest is crystallized in the creation of an international series of workshops (CYGNUS, Cosmology with Nuclear Recoils) which gathers the whole emerging community worldwide. One of the outcomes of the last gathering has been the preparation of a white paper presenting the physics case for directional WIMP detectors, the latest picture of the developments and the justification that the realization of a directional detector may be realistic in the near future.

### 2.6 Spin-dependent WIMP interactions

The prejudice of assuming spin-independent (SI) interaction for the WIMP comes because in that case the interaction for the total nucleus sums coher-
ently over all the nucleons, giving a very appealing enhancement factor with the mass of the target nuclei $\sim A^2$. This reasoning, used in all the experiments mentioned up to now, leads to the preferred use of heavy nuclei like Xe of Ge. However, an important (or even dominant) spin-dependent (SD) component in the WIMP-nucleus interaction is not at all excluded. In fact, in the case of the WIMP being the lightest supersymmetric particle (LSP), this is the case for some particular compositions of the neutralino. In these cases, the WIMP-nucleus is not any more coherent, as the couplings with nucleons of opposite spins interfere destructively. The target mass does not play any more a special role, being the nucleus spin (the presence of unpaired neutrons or protons) what matters to determine the interaction rate, and the sensitivity of the experiment. Experiments sensitive to the standard SD interaction may be also sensitive to SI models if they contain spin-odd isotopes, like in the case of CDMS, XENON, KIMS and others. These experiments have published by-products results excluding SD WIMPs, even if they consider their SI result as the main goal of the experiment\textsuperscript{72,73}.

However, some experiments are being carried out which are specifically focused on SD WIMPs. Modest mass of SD sensitive material can explore neutralino models that are out of reach of large SD detectors, if the SD interaction is severely suppressed. This is the argument of experiments like MIMAC, planning to use light nuclei like $^3$He of CF$_4$ (fluorine). Other experiments providing primarily SD limits are PICASSO\textsuperscript{74} using superheated C$_4$F$_{10}$ droplets as the active material, or COUPP\textsuperscript{75} using the bubble chamber technique with superheated CF$_3$ as active material.

2.7 The case for low mass WIMPs

The sensitivity of standard WIMP searches like the ones commented in the previous pages peaks at WIMP masses around $\sim$100 GeV, as kinematics favors equal masses of projectile and target. These masses are also the preferred ones for most popular supersymmetry models. Lighter neutralinos, however, are not excluded\textsuperscript{76} but the sensitivity of usual experiments to them drops substantially as can be seen in Fig. 2. Because of this, they have been in fact invoked to explain the DAMA positive result and reconcile it with all other limits.

Light (<10 GeV) WIMPs would leave very small energy deposits in the detectors, so sub-keV thresholds are needed to detect them. Even if such thresholds are achieved, the discrimination mechanisms that have pushed down the sensitivity of the experiments during the last decade are not available at such energies. The search for light WIMPs relies again on pure raw background
reduction, by means of radiopurity and shielding. Results from "standard" experiments like CRESST or CDMS (but using data below the discrimination threshold) have been used to extract limits for low mass WIMPs. However, recently specific setups with low-threshold detectors have been used to improve limits on light WIMPs, mainly motivated by the DAMA signal issue.

The TEXONO experiment has operated a $4 \times 5$ g Ge detector in a shallow depth site. The smallness of the detectors allow for thresholds as low as 220 eV, although this strategy will be difficult to scale-up. More recently, the CoGENT collaboration has developed a new type of Ge detector, the p-type point contact (PPC) detector which, profiting from a low-capacity geometry, allows for both larger masses and low threshold.

3 What if there are axions?

Axion phenomenology depends mainly on the scale of the PQ symmetry breaking, $f_a$. In fact, the axion mass is inversely proportional to $f_a$, as well as all axion couplings. The proportionality constants depend on particular details of the axion model considered and in general they can be even zero. An interesting exception is the coupling axion-photon $g_{a\gamma}$, which arises in every axion model from the necessary Peccei-Quinn axion-gluon term. This coupling allows for the conversion of axion into photons in the presence of (electro)magnetic fields, a process usually called Primakoff effect and that is beneath all the detection techniques described in the following.

3.1 Galactic axions

Axions could be produced at early stages of the Universe by the so-called misalignment (or realignment) effect. Extra contributions to the relic density of non-relativistic axions might come from the decay of primordial topological defects (like axion strings or walls). There is not a consensus on how much these contributions account for, so the axion mass window which may give the right amount of primordial axion density (to solve the dark matter problem) spans from $10^{-6}$ eV to $10^{-3}$ eV. For higher masses, the axion production via these channels is normally too low to account for the missing mass, although its production via standard thermal process increases. Thermal production yields relativistic axions (hot dark matter) and is therefore less interesting from the point of view of solving the dark matter problem, but in principle axion masses up to $\sim 1$ eV, are not in conflict with cosmological observation.

The best technique to search for low mass axions composing the galactic
dark matter is the microwave cavity originally proposed in 80. In a static background magnetic field, axions will decay into single photons via the Primakoff effect. The energy of the photons is equal to the rest mass of the axion with a small contribution from its kinetic energy, hence their frequency is given by $hf = m_a c^2 (1 + O(10^{-6}))$. At the lower end of the axion mass window of interest, the frequency of the photons lies in the microwave regime. A high-Q resonant cavity, tuned to the axion mass serves as high sensitivity detector for the converted photons.

The Axion Dark Matter Experiment (ADMX) 81, 82 has implemented the concept using a cylindrical cavity of 50 cm in diameter and 1 m long. The $Q$ is approximately $2 \times 10^5$ and the resonant frequency (460 MHz when empty) can be changed by moving a combination of metal and dielectric rods. The cavity is permeated by a 8 T magnetic field to trigger the axion-photon conversion, produced by a superconducting NbTi solenoid.

So far the ADMX experiment has scanned a small axion mass energy, from 1.9 to 3.3 $\mu$eV 82 with a sensitivity enough to exclude a KSVZ axion, assuming that thermalized axions compose a major fraction of our galactic halo ($\rho_a = 450$ MeV/c$^2$). An independent, high-resolution search channel operates in parallel to explore the possibility of fine-structure in the axion signal 83.

Current work focuses on the upgrade of the experimental set-up, which means basically to reduce the noise temperature of the amplification stage. This is being done by newly developed SQUID amplifiers and in a later stage by reducing the temperature of the cavity from the present 1.5 K down to below 100 mK by using a dilution refrigerator. These improvements will allow ADMX to increase the sensitivity to lower axion-photon coupling constants and also to larger axion masses.

3.2 Solar axions

Axions or other hypothetical axion-like particles with a two-photon interaction can also be produced in the interiors of stars by Primakoff conversion of the plasma photons. This axion emission would open new channels of stellar energy drain. Therefore, energy loss arguments constrain considerable axion properties in order not to be in conflict with our knowledge of solar physics or stellar evolution 84.

In particular, the Sun would offer the strongest source of axions being a unique opportunity to actually detect these particles. The solar axion flux can be estimated within the standard solar model. The expected number of solar axions at the Earth surface is $\Phi_a = (g_{a\gamma}/10^{-10} \text{GeV}^{-1})^2 3.54 \times$
10^{11} \text{ cm}^{-2} \text{s}^{-1} and their energies follow a broad spectral distribution around \sim 4 \text{ keV}, determined by solar physics (Sun’s core temperature). Solar axions, unlike galactic ones, are therefore relativistic particles.

These particles can be converted back into photons in a laboratory electromagnetic field. Crystalline detectors may provide such fields, giving rise to very characteristic Bragg patterns that have been looked for as byproducts of dark matter underground experiments. However, the prospects of this technique have been proved to be rather limited, and do not compete with the experiments called “axion helioscopes” which use magnets to trigger the axion conversion. This technique was first experimentally applied in 1979 and later on by the Tokyo helioscope, which provided the first limit to solar axions which is ”self-consistent”, i.e, compatible with solar physics. Currently, the same basic concept is being used by the CAST collaboration at CERN with some original additions that provide a considerable step forward in sensitivity to solar axions.

The CAST experiment is making use of a decommissioned LHC test magnet that provides a magnetic field of 9 Tesla along its two parallel pipes of 2\times14.5 \text{ cm}^2 area and 10 m length, increasing the corresponding axion-photon conversion probability by a factor 100 with respect to the previous best implementation of the helioscope concept. The magnet is able to track the Sun by about 3 hours per day, half in the morning and half in the evening. At its two ends x-ray detectors are placed, at the ”sunrise” side, a Micromegas detector and a CCD, and at the ”sunset” side two additional Micromegas detectors, installed in 2007 replacing the former TPC. All of the detector setups are conceived following low background techniques (shielding, radiopure materials). The CCD is coupled to a focusing X-ray device (X-ray telescope) that enhances its signal-to-background ratio by two orders of magnitude. Both the CCD and the X-ray telescope are prototypes developed for X-ray astronomy.

The experiment already released its phase I results form data taken in 2003 and 2004 with vacuum in the magnet bores. No signal above background was observed, implying an upper limit to the axion-photon coupling \( g_{\alpha\gamma} < 8.8 \times 10^{-11} \text{ GeV}^{-1} \) at 95% CL for the low mass (coherence) region \( m_{\alpha} \lesssim 0.02 \text{ eV} \). Since 2006 the experiment runs its second phase, which makes use of a buffer gas inside the magnet bores to recover the coherence of the conversion for specific axion masses matching the effective photon mass defined by the buffer gas density. The pressure of the gas is changed in discrete small steps to scan the parameter space above \( m_{\alpha} \sim 0.02 \text{ eV} \). The \(^4\text{He Run taken in 2006} \), allowed to scan axion masses up to 0.39 eV, for axion-photon couplings down to about \( 2.2 \times 10^{-10} \text{ GeV}^{-1} \), entering into the QCD axion
model band. Due to gas condensation, in order to go to higher pressures, the experiment switched to $^3$He as buffer gas in 2007. The experiment is currently immersed in the $^3$He Run since beginning of 2008. It should last until end of 2010 and should allow us to explore up to 1.2 eV in axion mass approximately, overlapping with the CMB upper limit on the axion mass discussed above. At the moment of writing this paper, the experiment has explored a region of axion masses up to about $m_a \sim 0.70$ eV. Everyday a new thin slice of untouched parameter space is being explored. Due to the sharp coherence effect, and to the fact that the parameter space to which we are sensitive now is populated by realistic QCD axion models and not excluded by previous experiments, a clear positive signal in CAST may appear at any moment.

4 Conclusions

A review of the current status of the experimental searches for WIMPs and axions has been given. The field lives a moment of great activity, triggered by the fact that very well motivated theoretical candidates could be within reach of present technologies. The next years will witness the results of many very interesting developments currently ongoing to define and operate a new generation of experiments, well into the region of interest for both WIMPs and axions.

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