Direct Detection of Nonbaryonic Dark Matter

Laura Baudis 1
H. V. Klapdor-Kleingrothaus 2

Max–Planck–Institut für Kernphysik,
P.O.Box 10 39 80
D–69029 Heidelberg, Germany

Abstract. Weakly Interacting Massive Particles (WIMPs) are leading candidates for the dominant part of the mass density of the Universe. Here we will review direct WIMP detection techniques by giving examples of currently running experiments, and present the status of the most promising future projects.

1. Introduction

There is strong observational and theoretical evidence that dark, nonbaryonic matter accounts for about a third of the critical density of the Universe (for a recent review see [1] and references therein). Many candidates have been proposed and some of them (cosmions, heavy Dirac neutrinos) have already been rejected. Slow thermal relics born in an early phase of the Universe, stable or very long lived, are excellent candidates for nonbaryonic dark matter [2]. These weakly interacting ($\sigma \leq \sigma_{\text{weak}}$), massive (1 GeV - 1 TeV) particles (WIMPs) arise independently from cosmological considerations in supersymmetric models as neutralinos - the lightest supersymmetric particles. Direct detection of neutralinos can occur in very low background experiments, where the elastic neutralino scattering off target nuclei is exploited.

1 E-mail: Laura.Baudis@mpi-hd.mpg.de
2 E-mail: klapdor@daniel.mpi-hd.mpg.
In the following, after giving a short overview on the principles of direct detection, we will describe existing or planned experimental techniques aiming at direct WIMP detection, illustrated by examples of currently running experiments and of future projects. We do not intend a complete coverage of all direct detection experiments, but rather present some of the most promising ones.

2. Principles of direct detection

The differential rate for WIMP elastic scattering off nuclei is given by

\[
\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_W} \int_{v_{\text{min}}}^{v_{\text{max}}} d\tilde{v} f(\tilde{v}) \tilde{v} \frac{d\sigma}{dE_R}, \tag{1}
\]

where \(N_T\) represents the number of the target nuclei, \(m_W\) is the WIMP mass and \(\rho_0\) the local WIMP density in the galactic halo, \(\tilde{v}\) and \(f(\tilde{v})\) are the WIMP velocity and velocity distribution function in the Earth frame and \(d\sigma/dE_R\) is the WIMP-nucleus differential cross section.

The nuclear recoil energy is given by

\[E_R = m_N^2 \frac{\tilde{v}^2(1 - \cos \theta)}{2 m_N} \]

where \(\theta\) is the scattering angle in the WIMP-nucleus center-of-mass frame, \(m_N\) is the nuclear mass and \(m_t\) is the WIMP-nucleus reduced mass. The velocity \(v_{\text{min}}\) is defined as

\[v_{\text{min}} = \left( \frac{m_N E_{\text{th}}}{2 m_t^2} \right)^{\frac{1}{2}}\]

where \(E_{\text{th}}\) is the energy threshold of the detector, and \(v_{\text{max}}\) is the escape WIMP velocity in the Earth frame.

The standard lore assumes a Maxwell-Boltzmann distribution for the WIMP velocity in the galactic rest frame, with a velocity dispersion of \(v_{\text{rms}} \approx 270 \text{ km s}^{-1}\) and an escape velocity of \(v_{\text{esc}} \approx 650 \text{ km s}^{-1}\).

The differential WIMP-nucleus cross section can be divided into two separate parts: an effective scalar coupling between the WIMP and the nucleus (proportional to \(A^2\), where \(A\) is the target atomic mass) and an effective coupling between the spin of the WIMP and the total spin of the nucleus. In general the coherent part dominates the interaction (for neutralinos) and the cross section can be factorized as

\[\frac{d\sigma}{dE_R} \propto \sigma_0 F^2(E_R),\]

where \(\sigma_0\) is the point-like scalar WIMP-nucleus cross section and \(F(E_R)\) denotes the nuclear form factor, expressed as a function of the recoil energy.

The left side of equation (1) is the measured quantity in a detector, the right side represents a theoretical WIMP spectrum (see Figure 1 for an example of a measured spectrum and a calculated WIMP spectrum for \(m_W = 100 \text{ GeV}\)). It includes the WIMP properties which are completely unknown, like the WIMP mass \(m_W\) and elastic cross section \(\sigma_0\), quantities accessible from astrophysics, like the density of WIMPs in the halo, \(\rho_0\), the WIMP velocity distribution and the escape velocity (which are however prone to large uncertainties) and detector specific parameters, like mass of target nucleus, energy threshold and nuclear form factor.
It is straightforward to see that a WIMP with a typical mass between a few GeV and 1 TeV will deposit a recoil energy below 100 keV in a terrestrial detector. As for the predicted event rates, scans of the MSSM parameter space under additional assumptions (GUT, mSUGRA, etc) and accounting for accelerator and cosmological constraints, yield about $10^{-5}$ to 10 events per kilogram detector material and day [5].

Evidently, in order to be able to measure a WIMP spectrum, low energy threshold, low background and high mass detectors are required.

In such a WIMP detector, the recoil energy of the scattered nucleus is transformed into a measurable signal, like ionization, scintillation or lattice excitations and at least one of the above quantities is detected.

An additional information is given by the pulse shape of the interaction, which can lead to background reduction in some cases (see Section 3).

A low background can be achieved in both passive and active ways. Passive methods range from high material selection of detector components to various specific shieldings against the natural radioactivity of the environment and against cosmic rays and secondary particles produced in cosmic ray interactions. Active background reduction implies either an active shielding surrounding the detector (against gammas and/or muons)
and/or the recording of two of the above mentioned quantities (ionization and phonon, scintillation light and phonon or ionization and scintillation signals), since in general the amount of energy shared between two observables is different for nuclear recoils and photon induced interactions. Consequently, a discrimination between WIMPs (or neutron) induced recoils and gamma- or electron induced events becomes possible.

Identifying the measured spectrum as a WIMP induced one is by far not trivial, since both background (radioactive and noise) and WIMP signal are exponentially decreasing shaped. For this purpose an additional quantity, a WIMP signature is requested.

The Earth's motion through the galaxy induces both a seasonal variation of the total event rate \[6, 7\] and a forward-backward asymmetry in a directional signal \[8, 9\].

The annual modulation of the WIMP signal arises due to the Earth motion in the galactic frame, which is a superposition of the Earth rotation around the Sun with that of the Sun around the galactic center:

\[
v_E = v_\odot + v_{\text{orb}} \cos \gamma \cos \omega (t - t_0), \tag{2}\]

where \(v_\odot = v_0 + 12 \text{ km s}^{-1} (v_0 \approx 220 \text{ km s}^{-1})\), \(v_{\text{orb}} \approx 30 \text{ km s}^{-1}\) denotes the Earth orbital speed around the Sun, the angle \(\gamma \approx 60^\circ\) is the inclination of the Earth orbital plane with respect to the galactic plane and \(\omega = 2\pi/1\text{yr}, t_0 = \text{June 2}^{\text{nd}}\).

The expected time dependence of the count rate can be approximated by a cosine function with a period of \(T = 1\) year and a phase of \(t_0 = \text{June 2}^{\text{nd}}\):

\[
S(t) = S_0 + S_m \cos \omega (t - t_0), \tag{3}\]

where \(S_0, S_m\) are the constant and the modulated amplitude of the signal, respectively. In reality, an additional contribution to \(S(t)\) from the background (B) must be considered, which is supposed to be constant in time.

The expected seasonal modulation effect is very small (of the order of \(v_{\text{orb}}/v_0 \approx 0.07\)), requiring large masses and/or large counting times and an excellent long-term stability of the experiment.

A much stronger signature would be given by the ability to detect the axis and direction of the recoil nucleus. In \[8\] it has been shown, that the WIMP interaction rate as a function of recoil energy and angle \(\theta\) between the WIMP velocity and recoil direction (in the galactic frame) is:

\[
\frac{d^2 R}{dE_R d\cos \theta} \propto \exp \left[ -\frac{(v_\odot \cos \theta - v_{\text{min}})^2}{v_0^2} \right], \tag{4}\]
where $v_{min}^2 = (m_N + m_W)^2 E_R / 2m_N m_W$ and $v_0^2 = 3v_0^2 / 2$.

The forward-backward asymmetry yields thus a large effect of the order of $O(v_0/v_0) \approx 1$ and much less events are needed to discover a WIMP signal than in the case of the seasonal modulation.

3. Existing experiments

After the seminal paper of Goodman & Witten in 1985, first limits on WIMP-nucleon cross sections were derived from at that time already existing Germanium double beta decay experiments. Since then, more than a dozen of dedicated WIMP dark matter experiments were built up and are delivering data, while even more are planned for the future (see for example [11, 12]).

Dark matter experiments can be classified by the employed technique or by their ability to distinguish between nuclear recoils and other types of interactions.

Another type of classification would be by the ability of the experiments to detect a WIMP signature, which however is basically equivalent (with one exception, i.e. DAMA) to our subdivision in currently running experiments and in future projects. The annual modulation signature can in principle be looked for in any kind of experiment. However, as it has been shown, there exist statistical limitations for extracting a periodic signal from the data for low background experiments and depending on the signal/noise ratio a minimal target mass is required. Consequently, only high mass experiments are well suited and will have a realistic chance to detect a seasonal variation of the WIMP rate with high statistical significance.

To detect a forward-backward asymmetry, a directional sensitive detector is required. Because of the inherent difficulties in conceiving such a detector, only one realistic project exists up to now (the DRIFT project, see section 4).

Low mass experiments with no directional information can set stringent limits on the WIMP-nucleon cross section and thus test (and exclude) supersymmetric models and eventual “evidence regions” in SUSY parameter spaces found by high mass experiments, under the condition that their radioactive background is low enough.

The lowest background obtained from raw data up to now comes from the Heidelberg-Moscow experiment, which uses an enriched $^{76}$Ge detector of 2.758 kg active mass in an extreme low level environment in the Gran Sasso Underground Laboratory (LNGS). After a total measuring period of more than 550 d, the background in the energy region 9-40 keV is about 0.05 events/kg d keV. The obtained limits for the spin-independent
Figure 2. WIMP-nucleon cross section limits as a function of the WIMP mass for spin-independent interactions. The hatched region is excluded by the Heidelberg-Moscow \cite{20} and the DAMA experiment \cite{21}, the plain black curve is the new limit of the CDMS experiment \cite{22}. The dashed lines are expectations for recently started or future experiments, like HDMS \cite{23}, CRESST \cite{24}, CDMS (Soudan) \cite{25} and GENIUS \cite{26}. The filled contour represents the 2σ evidence region of the DAMA experiment \cite{27}. The experimental limits are compared to expectations (scatter plot) for WIMP-neutralinos calculated in the MSSM parameter space at the weak scale (without any GUT constraints) under the assumption that all superpartner masses are lower than 300 GeV - 400 GeV \cite{28}.

WIMP-nucleon cross section are very close to the present best ones (from DAMA, see below), and are the most stringent ones (for m_W \geq 13 GeV) for using only raw data (see Figure 2).

HDMS \cite{23} is conceived to further reduce the already very low background of the Heidelberg-Moscow experiment. A small (200 g) Ge-crystal (natural Ge for the prototype, isotopically enriched 73Ge for the second stage) is surrounded by a well-type Ge-crystal, the anticoincidence between them acting as an effective suppression of multiple scattered photons (see Figure 3). After a measuring period of 362.9 d, the background of the prototype was close to the level of the Heidelberg-Moscow experiment (the
Figure 3. Schematic view of the HDMS experiment. A small Ge crystal is surrounded by a well type Ge-crystal, the anticoincidence between them is used to suppress background created by external photons.

background reduction factor through anticoincidence is 4) [19]. After replacement of the detector holder by a low radioactive copper system and of the inner detector by an enriched $^{73}$Ge crystal, the full scale experiment will start to take data in the course of the year 2000.

More complex Ge experiments, measuring not only the ionization, but also the phonon signal are CDMS [25] and EDELWEISS [29]. Nuclear recoils deposit only about 25% of their energy as ionization (see [30] and references therein), while gamma- and electron interactions ionize much more efficiently. Measuring the total energy deposition provides not only the means to achieve a low energy threshold but also a powerful background rejection method (with exception of neutron interactions, which also induce nuclear recoils). CDMS employs both thermal (the temperature change of a detector is measured) and athermal (the fast phonons are detected) phonon-mediated detectors. Based on a 10.6 kg d exposure of thermal Ge detectors ($3 \times 165$ g) at the SUF (Stanford Underground Facility, 16 m.w.e.), new stringent limits on WIMP-nucleon scattering cross sections have been derived [22] (see Figure 2). These exclude also the region allowed by the DAMA annual modulation signature (see below) at 84% C.L. [22]. The limitations of CDMS up to now were mainly surface events, especially electrons, with low ionization yield (leading to confusion of these events with nuclear recoils). While the ionization yield of Ge de-
tectors could be increased by improved charge contacts, it was realized that the fast phonon sensors of the Si detectors allow to measure the event position, and thus to identify surface events based on their rise-time. Recently this technique has been developed also for Ge detectors \[31\]. CDMS will move to the Soudan mine (2070 m.w.e.), where the muon induced neutron background will be considerably decreased. The expected sensitivity at the Soudan site is shown in Figure 4. EDELWEISS operates two natural Ge detectors of 70 g each in the MODANE underground laboratory. While a test measurement with one of the detectors resulted in a background level of 0.345 events/kg d keV, new data from the two detectors are expected soon \[32\]. The plans are to operate a total of 1.2 kg of Ge detectors during this year and, because of currently limited cryostat space, to construct a new cryostat system with a 100 l detector volume \[32\].

Other cryogenic experiments, which however measure only the phonon signal and thus do not discriminate nuclear recoils are CRESST \[24\] and ROSEBUD \[33\] (at Gran Sasso and Canfranc respectively, using sapphire - Al\(_2\)O\(_3\) - detectors), the Milano experiment \[34\] (at Gran Sasso, using TeO\(_2\) bolometers) and the Tokyo experiment \[35\] (at Nokogiriyama, using LiF bolometers). CRESST achieved the lowest energy threshold with 262 g sapphire detectors (500 eV) and the highest energy resolution (133 eV at 1.5 keV) up to now. They are thus particularly sensitive in the low WIMP mass region (1 GeV to 10 GeV), for non-coherent interactions. The expected sensitivity for two different exposures (0.1 kg y and 1 kg y) and a background of 1 event/kg d keV is shown in Figure 4. The expected sensitivity of ROSEBUD, which plans to operate 25 - 100 g of sapphire detectors at 2450 m.w.e. is very similar to CRESST \[33\].

The Milano group operates an array of 20 TeO\(_2\) crystals of 340 g each, mainly for double beta decay searches \[34\]. One of the bolometers, with an energy threshold of 13 keV and a background level of about 1.9 events/keV d is used for a dark matter analysis, the limits on WIMP-proton cross sections however are not yet competitive to other running experiments. Tokyo reported results from a measurement of eight 21 g LiF bolometers at 15 m.w.e. for axially coupled WIMPs \[35\]. Although their spectra seem to be dominated by microphonics below 10 keV (4 detectors) and 40 keV (2 detectors), they improve existing limits for spin-dependent WIMP interactions for WIMP masses below 5 GeV (see Figure 5).

Cryogenic experiments are presently (and in the near future) limited by low masses. Given the complexity of the employed technology, it is by far not trivial to operate a large amount of bolometers at mK temperatures. The first high mass dark matter detectors were conventional scintillators (mostly NaI(Tl) and liquid Xenon). Their advantage is the low cost/mass-factor (rendering masses of tens of kg feasible) and the possibility of background discrimination. Although their absolute background
Figure 4. Expectation for the WIMP-proton cross section limits for spin dependent interactions for the CRESST sapphire detectors with a total mass of 1 kg, an energy threshold of 0.5 keV, a background of 1 count/(kg keV day) and an exposure of 0.1 and 1 kg year. The present limits from the DAMA [36] and UKDMC [37] NaI experiments are also shown (from [24]).

is still at least a factor of ten higher than in Ge diodes, low backgrounds were achieved by severe selection and chemical purification of the used materials. Background discrimination in NaI detectors relies on the shorter decay times of nuclear recoil than of electron induced pulses. The difference at low energies being small, the discrimination occurs statistically, rather than on an event by event basis [38] (compared are the distributions of the decay time constants for nuclear recoils and for electron interactions).

The pulse shape analysis requires a large temperature stability of an underground experiment. For example, in order to detect a 10% component of recoils in a Compton background, the T-stability has to be better than 1°C [39].

Scintillator experiments which apply pulse shape analysis are DAMA (NaI, CaF, Xe, in Gran Sasso) [21], UKDM (NaI, Xe, at the Boulby mine) [40] and the Saclay experiment (NaI, in Frejus) [39].

The DAMA experiment gives the at present most stringent limits on WIMP-nucleon cross sections (see Figures 2 and 3). A large target mass (about 100 kg of NaI detectors), enables DAMA to search for the WIMP
annual modulation signature. In fact, an analysis of (undiscriminated) data with a combined exposure of 159 kg yr is consistent with the presence of an annual modulation, favouring a WIMP mass of $m_W = (52^{+10}_{-8})$ GeV, and a WIMP-proton scalar cross section of $\xi\sigma = (7.2^{+0.4}_{-0.9})$ pb (where $\xi = \rho_W/0.3$ GeV) [27] (see Figure 4 for the $2\sigma$ confidence region). These news have caused excitement, mainly among theorists [41], and criticism at the same time [42]. Being however an experimental issue, it will most likely be solved in the near future.

Measurements of the UKDM group with a 5 kg crystal of NaI with improved sensitivity [39] and of the Saclay group with a 10 kg crystal of NaI [40] revealed the existence of a small population of pulses with a shorter decay time even than for nuclear recoils, with up to now unknown origin. While the observed effect is limiting the pulse shape analysis method, it is currently strongly investigated. Other limitations to pulse shape analysis in NaI detectors are surface interactions induced by X-rays or betas from outside the detector, with pulse shapes very similar to nuclear recoils [39].

A proposal for a large liquid Xenon detector, with the aim to detect both scintillation and ionization signal, is the ZEPLIN experiment [40].
The plan is to drift the ionization electrons in a uniform electric field and detect the current via proportional scintillation and/or induced electrical pulses. After test measurements with a small TPC at CERN, a 5 kg target mass liquid Xe detector is now under construction. The final TPC will have a total mass of 20-30 kg.

A different type of experiments with potential to go to large detector masses and owning an excellent background rejection technique are superheated droplet detectors (PICASSO, SIMPLE). These pure counting experiments (no energy information) use small drops of a superheated liquid (freon) uniformly dispersed in an elastic gel as detectors. While the droplets remain in a metastable, superheated condition at ambient temperatures and pressures, an energy deposition by a particle with large dE/dx causes them to expand to bubbles after a phase transition. The bubbles remain fixed in the gel and can be counted as an acoustic signal by piezo-electric sensors. By adjusting the operational temperature and pressure, the droplet detectors can be made sensitive only to nuclear recoils, the energy threshold can be varied by changing the temperature alone. First limits from SIMPLE (15 g active mass) and from PICASSO (5 g active mass) for spin-dependent interaction are promising, although not yet competitive to other running experiments. The main limitations at the moment are the U/Th intrinsic background of the counters as well as their small active masses.

4. Future projects

The aim of future dark matter experiments lies not only in setting more and more stringent limits to WIMP-nucleon cross sections, but in eventually detecting a WIMP-specific signature, thus bringing an exact study of WIMP properties on a concrete ground. The up to now proposed strategies are either to scale up existing technologies to large mass experiments and thus be sensitive to the predicted seasonal variation of the event rate or to build up a directional sensitive detector.

The most sensitive directional technique proposed so far, ionization in a low pressure TPC, is followed by the DRIFT collaboration (see Figure 6 for a schematic view of the TPC). Resolving the ionization tracks in the target gas would provide not only a directional information but also a recoil discrimination method based on dE/dx and on the track length. The challenge is to minimize the electron diffusion, in order to obtain a sufficiently high track resolution (less than 1 mm). While an initial small Ar test chamber (1m × 0.4 m) was placed in a superconducting magnet, this solution is ruled out for a ten times larger experiment mainly on costs reasons. A solution was found by adding a small electronegative gas admixture (which would attach the ionized electrons) and drift the negative ions,
for which both longitudinal and transversal diffusion is suppressed. While small TPC prototypes are currently under test, the goal of the DRIFT project is to operate a 20 m$^3$ detector by the year 2001 in the Boulby mine.

The CUORE project to be built up at Gran Sasso plans to install 1000 TeO$_2$ crystals (about 750 g each) in one dilution refrigerator operating at a temperature below 10 mK. They plan to improve their current background level (which is, with 1.9 events/keV d for a 340 g crystal, by a factor of about 100 higher than the one of the Heidelberg-Moscow experiment) by material selection and anticoincidence between the bolometers. It still has to be demonstrated however, that a stable low-energy threshold with the large TeO$_2$ crystals is feasible.

The CRESST collaboration recently developed a nuclear recoil discrimination method, by measuring both scintillation light and phonon signal in a CaWO$_4$ crystal. A small light detector is placed near the scintillating absorber, which has a tungsten superconducting phase transition thermometer on it, both being operated at 12 mK. Figure 7 shows the discrimination between electron and neutron recoils down to an energy of 10 keV.

While a first CaWO$_4$ crystal will be installed in Gran Sasso in the course of the year 2000, the long-term plans are to develop and install up to 100 kg of diverse detector materials (CaWO$_4$, PbWO$_4$, BaF, BGO) in the cold box, thus to be sensitive to the annual modulation signature and, in case of a positive signal, to extract the WIMP properties through the dependence of the recoil spectrum on the target nucleus mass. The expected sensitivity for an exposure of 100 kg y, a background suppression of 99.9% above 15 keV and a background level of 1 event/kg d keV is shown in Figure 2.
Figure 7. Scatter plot of the pulse heights observed in a CRESST light detector versus the pulse height in the phonon detector, measured with a photon and a neutron source. The lower, neutron induced band (nuclear recoils) can be clearly distinguished from the electron induced upper band.

For an almost complete covering of the relevant MSSM parameter space for neutralinos as dark matter candidates, an increase in sensitivity by more than three orders of magnitude relative to running experiments is required. This is precisely the aim of the GENIUS project [16, 20], which will operate about 40 HPGe-detectors (100 kg) immersed directly in liquid nitrogen (see Figure 8 for a schematic view). GENIUS will use conventional ionization in a Ge crystal as detection technique, without discrimination of nuclear recoils. The large step in background reduction would be achieved by removing (almost) all materials from the immediate vicinity of the detectors (crystal holder, cryostat system, which were the main background sources so far) and operate the crystals directly in a cold liquid of extreme purity.

GENIUS could be realized favourably in the Gran Sasso or WIPP underground laboratories.

In three consecutive technical studies it was demonstrated that HPGe detectors work reliably under such conditions; low-energy thresholds (2.5 keV) and good energy resolutions (1 keV at 300 keV) were achieved with 300 g - 400 g crystals [47, 13, 20]. Monte Carlo simulations and back-
ground estimations showed, that achieving such a low absolute background level is feasible if the liquid shielding amounts to 12 m in diameter and if low activation times of the crystals at sea level (< 10 d) are ensured [47, 19]. Figure 3 shows the expected sensitivity for an exposure of 100 kg y and a background level of $10^{-2}$ events/kg y keV. The clear advantages of GENIUS would be the well studied detection technique and the possibility to increase the amount of target material (detectors made of enriched $^{73}$Ge material could be used to study the spin-dependent interaction). Already the first step with 100 kg of natural Ge would allow not only to set stringent limits on WIMP-nucleon cross sections, but to be highly sensitive for the annual modulation signature (see also [48]). Currently a smaller test phase,
GENINO, is under study [49]. GENINO would already operate 100 kg of Ge crystals, but in a smaller liquid nitrogen tank of 5 m diameter and 5 m height. Due to the increased influence of the natural environmental radioactivity, the suppression in background would be only a factor 20 with respect to the currently lowest value of about 0.05 events/kg d keV [20]. However, the complete DAMA evidence region could be tested in the near future, not only by exclusion, but by directly looking for the modulation signature.

5. Conclusions

Doubtless the present situation in the field of direct dark matter detection is exciting.

A plenitude of experiments using very different detection techniques have reached sensitivities which for the first time start to probe the supersymmetric parameter space. A well motivated WIMP candidate from supersymmetry, the neutralino, might thus reveal its presence in the near future. While the report of evidence for a WIMP signal by one experiment has raised an equal amount of interest and criticism, confirmation or exclusion by other experiments is expected soon.

The goal of future projects has shifted from merely setting limits on the WIMP interaction strength to the ability of detecting a distinctive WIMP signature. The experimentally explored WIMP signatures up to now, leading to unambiguous WIMP identification, are caused by the Earth’s motion with respect to the galactic rest frame.

The hope is that future dark matter experiments will not only unveil the major composition of matter in the Universe, but will possess the aptitude to study its inherent features, thus opening the avenue towards discerning between different galactic halo models. Needless to say, direct detection of dark matter would have striking implications for particle physics and cosmology.

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