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Understanding the Dark Universe

Direct detection of WIMPs

Détection directe des WIMPs

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A R T I C L E   I N F O

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A B S T R A C T

To test the hypothesis according to which Weakly Interacting Massive Particles are a major constituent of Dark Matter, direct detection experiments aim at detecting the spectrum of nuclear recoils induced by WIMPs from the Milky Way halo within a target material. While the detection concept is already more than 20 years old, recent experimental developments have allowed fast progress, which up to now have lead to constrain electroweak theories beyond the standard model in a complementary way to collider experiments.

R É S U M É

Afin de tester l'hypothèse selon laquelle les WIMPs (particules massives interagissant faiblement) sont des constituants importants de la Matière Noire, les expériences de détection directe cherchent à mesurer le spectre des reculs nucléaires induits par les WIMPs du halo de la Voie Lactée dans une cible matérielle. Alors que le principe de détection date déjà de plus de 20 ans, les développements expérimentaux récents ont permis de rapides progrès, qui ont fourni des contraintes sur les théories électrofaibles au-delà du modèle standard de manière complémentaire des expériences sur collisionneurs.

1. Motivations

Knowing the nature of non-baryonic dark matter is one of the major challenges that modern cosmology is facing [1]. The more and more precise determination of cosmological parameters may remain sterile if this "substance", which drives the dynamics of galaxies and clusters and generates the growth of large-scale structures, is not understood. Among the various models that were put forward to describe dark matter [2], we focus here on the so-called Weakly Interacting Massive Particles (WIMPs) and in particular those associated to the electroweak scale. Their expected mass is typically 100 GeV and they interact only through gravitational and weak forces.

In addition to being one of the best-motivated dark matter candidates from theoretical and phenomenological points of view, the WIMP is also a testable hypothesis with existing technologies. The direct detection of WIMPs consists in measuring the spectrum of nuclear recoils generated in a detector by WIMP–nucleus scattering, making use of WIMPs from the local halo of our Milky Way [3]. The orders of magnitude of local WIMP density and velocity are roughly known from measurements of stellar motions in the Milky Way. For WIMPs of mass ~ 100 GeV, the recoil energy is of the order of tens

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of keV, and interaction rates span over a wide range of magnitudes, but are detectable with currently existing or foreseen technologies.

Information about WIMP dark matter may also come from colliders and so-called indirect dark matter searches. On the one hand, colliders, and especially now experiments at the LHC, may demonstrate the existence of new particles which could be dark matter candidates. Still they would not definitely prove that these particles constitute dark matter. On the other hand, several astrophysical observatories may detect fluxes of secondary particles generated by WIMP dark matter interactions (e.g. annihilation) at various locations. However, these indirect detection channels are often in competition with astrophysical backgrounds, making it difficult for them to provide compelling evidence for the existence of particle dark matter. As a consequence, provided the technologies develop as foreseen, direct detection is a particularly clean way to test the hypothesis according to which dark matter is mostly made of GeV–TeV WIMPs.

In the following, we briefly review the general features of WIMP direct detection before describing a few experimental strategies and results.

2. Phenomenology of WIMP direct detection

2.1. Basic formalism

We sketch here very briefly the steps to calculate the interaction rate of galactic WIMPs on a terrestrial detector. More details may be found for example in [4,5].

We consider a WIMP of mass M_χ diffusing elastically on a nucleus with mass M_N. The nucleus recoils with an angle θ_r with respect to the initial WIMP velocity. Since the WIMP velocity v relative to the detector is of the order of the galactic rotation velocity ~ 200 km/s, the kinematics is non-relativistic. The recoil energy reads

$$E_r = \left(\frac{m_\chi}{2}v^2\right)\frac{4M_N M_\chi}{(M_N + M_\chi)^2}\cos^2\theta_r$$

Typical recoil energies are in the range 1–100 keV. We parametrize the WIMP–nucleon interaction cross-section as a function of momentum transfer:

$$\frac{d\sigma}{dq^2} = \frac{\sigma_0}{4m_r^2 v^2}F^2(q)$$

where m_r is the reduced mass of the system, and $F(q)$ is a dimensionless "form factor" such that $F(0) = 1$. Since the maximum momentum transfer for a given (v, m_r) is $q_{\max} = 2vm_r$, the parameter σ_0 corresponds to the total cross-section in the case of $F(q) = 1$. Concerning the local WIMP distribution, we note ρ_0 the local WIMP mass density. We define $f_1(v)$ as the local distribution of WIMP velocities relative to the terrestrial detector. The interaction rate per unit mass of detector for WIMPs in the velocity range $[v; v + dv]$ is then given by:

$$dR = \left(\frac{\rho_0}{M_\chi M_N}\right)v\frac{d\sigma}{dq^2}f_1(v)\,dv\,dq^2 \tag{1}$$

After integration over the velocity distribution, this gives as a function of recoil energy $E_r = q^2/2M_N$:

$$\frac{dR}{dE_r} = \frac{\sigma_0\rho_0}{2M_\chi m_r^2}F^2(q)\int_{v_{\min}}^{\infty} dv\,\frac{f_1(v)}{v}$$

where $v_{\min} = \sqrt{\frac{M_N E_r}{2m_r^2}}$. This formula can be numerically integrated given any WIMP velocity distribution function. The benchmark model, generally used to estimate the sensitivities of different experiments, consists in a truncated Maxwellian velocity distribution in the rest frame of the Milky Way halo. For a detector which would also be at rest with respect to the galactic halo and $f_1(v) \propto \frac{v^2}{v_0^3}e^{-v^2/v_0^2}$ ($v_0 \sim 220$ km/s), the integration is straightforward and one finds

$$\frac{dR}{dE_r} \propto \exp\left(-\frac{M_N E_r}{2m_r^2 v_0^2}\right)$$

An approximately exponential recoil spectrum is expected: as a consequence, no really precise spectral signature such as a peak may be used as a smoking gun, and in addition most of the signal in a detector is expected at low recoil energies, which requires the energy threshold of WIMP detectors to be well understood experimentally. The complete WIMP signal calculation in the benchmark model takes into account the galactic escape velocity, whose conventional value is now $v_{\rm esc} = 544$ km/s, and more importantly the influence of the Earth velocity with respect to the WIMP halo. This velocity can be written $v_e = v_0(1.05 + 0.07\cos\omega t)$ where $1.05v_0$ is the rotation velocity of the Sun around the galactic center and $\omega = 2\pi/1$ year. The 7% modulation is due to the rotation of the Earth around the Sun. In the former calculation, $f_1(v)$ must be replaced by $f_1(|\mathbf{v}-\mathbf{v_e}|)$ and the instantaneous differential rate of WIMP interaction becomes (neglecting the additional correction due to finite v_{esc}):

$$\frac{dR}{dE_r}(t)=\frac{\sigma_0\rho_0}{4v_e M_\chi m_r^2}F^2(q)\left[\mathrm{erf}\left(\frac{v_{min}+v_e(t)}{v_0}\right)-\mathrm{erf}\left(\frac{v_{min}-v_e(t)}{v_0}\right)\right] \tag{2}$$

The variation of v_e due to Earth rotation around the Sun induces an annual variation of the spectrum. At a given recoil energy, the interaction rate undergoes a sinusoidal modulation. The amplitude of the modulation depends on the recoil energy and is typically $\lesssim 10\%$. In addition, the average relative velocity of the Solar System with respect to the halo generates a strong anisotropy in the expected WIMP-induced nuclear recoil distribution in the direction opposite to the Solar System velocity [6]. We note ϕ the angle of the nuclear recoil with respect to the direction $(\ell,b)=(90°,0°)$ in galactic coordinates, towards which the Solar System is moving and which is roughly located in the Cygnus region. With the same notations as before, the angular distribution of recoils is:

$$\frac{dR}{dE_r\,d\cos\phi}\propto \exp\left(-\frac{(v_e\cos\phi-v_{min})^2}{v_0^2}\right)$$

Since the Solar System velocity is of the same order of magnitude than v_0, the modulation amplitude is large, of the order of $\sim 80\%$ at appropriate recoil energies.

2.2. Model predictions

The generic formulas given above yield different predictions depending on astrophysical [7] and particle physics [4] parameters.

The dependance of the interaction rate as a function of local WIMP density ρ_0 is a straightforward linear function. The canonical value used to predict WIMP signals is $\rho_0=0.3\ \mathrm{GeV\,cm^{-3}}$. While some astrophysical determinations of ρ_0 have $\sim 10\%$ errors, other analyses quote a more conservative range $\rho_0=0.2$–$0.4\ \mathrm{GeV\,cm^{-3}}$. It has also been suggested that the density at Earth may be boosted if the Solar System were located in a dark matter clump by chance, but simulations indicate that it is quite unlikely. Another potential boost factor would come in some models which predict the existence of a dark matter disk in the same plane as the Milky Way disk [8], with a density of the order of $(0.25$–$1)\rho_0$.

The exact shape of the WIMP velocity distribution changes the recoil spectrum, annual modulation and directional signals in experiments. Moderate excursions from the canonical truncated Maxwellian model only slightly change the expected WIMP signals in most cases. However, if $f_1(v)$ is strongly distorted by the presence of streams, more significant changes may happen, boosting for example the annual modulation signal [9]. Furthermore, in some conditions the WIMP signal in a given detector may be due only to the tail of the velocity distribution, i.e. only WIMPs in the upper end of $f_1(v)$ have enough energy to generate detectable recoils. In that case, unavoidable uncertainties in the tail of $f_1(v)$ imply that the signal intensity and annual modulation are less predictable.

The strongest theoretical uncertainty by far in the WIMP recoil signal comes from the interaction model between the WIMP and the nucleus. By definition, these interactions are of electroweak nature (exchanges of Z, Higgs, squarks, etc.), but the WIMP–quark coupling may vary a lot depending on the exact WIMP model. For a given electroweak model, effective non-relativistic WIMP–quark couplings may be derived. The calculation of WIMP–nucleus cross-section on a given target depends then on QCD and nuclear physics effects, which also have non-negligible uncertainties.

If the WIMP is a Majorana fermion χ, as is the case for supersymmetric neutralinos, the effective Lagrangian describing the coupling with nucleons (n) is the sum of an axial term, $\mathcal{L}\sim a_{(n)}(\bar\chi\gamma^\mu\gamma_5\chi)(\bar n\gamma_\mu\gamma_5 n)$, and a scalar term $\mathcal{L}\sim f_{(n)}(\bar\chi\chi)(\bar n n)$. Axial couplings result in a so-called spin-dependent interaction cross-section with nuclei. For a nucleus of spin J, we note $\langle S_p\rangle$ and $\langle S_n\rangle$ the average spins carried by protons and neutrons respectively. The elastic diffusion cross-section at null momentum transfer then writes

$$\frac{d\sigma}{dq^2}\left(q^2=0\right)=\frac{8}{\pi v^2}G_F^2\Lambda^2 J(J+1)\quad \text{where } \Lambda=\frac{a_p\langle S_p\rangle+a_n\langle S_n\rangle}{J}$$

Depending on the target nucleus, the effective WIMP–nucleon couplings a_p and a_n can be probed. On the other hand, scalar couplings generate a cross-section of the form

$$\frac{d\sigma}{dq^2}\left(q^2=0\right)=\frac{1}{\pi v^2}\left[Zf_p+(A-Z)f_n\right]^2$$

It appears that the spin-independent couplings to proton f_p and to neutron f_n are often close to each other (in particular for neutralinos) [4], leading to the isospin invariance of the interaction $f_n\simeq f_p$. As a consequence, in the spin-independent channel, all experiments measure approximately the same WIMP–nucleon cross-section called σ_{SI}. The interaction cross-section for a given nucleus is proportional to σ_{SI}, and a strongly increasing function of the target mass A. This boosts the interaction rate on heavy nuclear targets, so that most detectors use such heavy targets when possible. As a consequence, for most WIMP models the spin-independent channel is currently the most sensitive one. In the following, we therefore almost exclusively focus on this channel, and when not specified, the “WIMP–nucleon cross-section” will refer to σ_{SI}.

More exotic scenarios were also explored, in particular when confronting positive experimental hints with other null search results. As an example, WIMPs may diffuse inelastically on nuclei, with a transition to an excited state $\chi^\star$ and a possible later deexcitation [10]. The spin-independent coupling may also be isospin violating, so that experimental sensitivities may strongly depend on the target, especially in the case when f_p and f_n are of opposite signs [11].

Model scans are used to predict the values of a_p, a_n and σ_{SI} as a function of different model parameters. This is exemplified in scans of some supersymmetric model, such as CMSSM or also now models with more free parameters [12]. Unfortunately, the predicted values of σ_{SI} span over a quite large number of orders of magnitude (typically from 10^{-5} to 10^{-12} pb) and its probability distribution depends strongly on the models, on their imposed parameter priors, and on constraints from both particle physics and cosmology. This imposes to envisage experimental strategies that are able to probe this wide range of cross-sections.

The WIMP mass is also strongly model-dependent. In the specific scenario of CMSSM, LEP searches for new charged particles impose the bound $M_\chi \gtrsim 40$ GeV. A more generic constraint for fermions, based on the relic density calculation, gives the much looser Lee–Weinberg bound [13] $M_\chi > 2$ GeV. On the opposite side, WIMPs with masses larger than the TeV scale would not help a lot to solve the fine-tuning problem for the Higgs mass. Recently, constraints from both the Fermi satellite [14] and early LHC results would tend to favor relatively large WIMP masses.

3. Experimental strategies: principle

From the previous discussion, we see that in order to measure WIMP-induced nuclear recoils, detectors with massive targets, low detection thresholds, and low backgrounds must be developed. We summarize the expected signatures of WIMP interactions:

– The interactions generate nuclear recoils with typical energies of ~ 1–100 keV;
– The recoil spectrum has an approximately exponential shape;
– Due to the small interaction rate, only single interactions will be observed (no multiple interactions);
– For the same reason, WIMP interactions are uniformly distributed in the detector volume;
– For the spin-independent channel, the interaction rate varies approximately as the square of the target nucleus: the use of several nuclear targets can serve as a first cross-check for a potential signal;
– The distribution of recoil directions is highly anisotropic in the galactic frame;
– The recoil rate is annually modulated, with an expected modulation $\lesssim 10\%$.

The main challenge is the removal of environmental backgrounds due to radioactivity or cosmic-ray-induced signals. Among all the backgrounds encountered, the followings are found in most WIMP searches:

(i) Gamma-ray and beta-ray radioactivities, due to the intrinsic radioactivity of the surrounding materials as well as of the detector itself. As an example, photomultiplier radioactivity is a major source of background for scintillating detectors. Another example is the radioactivity from long-lived isotopes due to the cosmic activation of e.g. Argon (^{39}Ar with a 269-year lifetime) or Germanium (^{65}Zn, ^{68}Ge with lifetimes of the order of a year), which generate an intrinsic γ background for these nuclear targets.
(ii) Diffusion of fast neutrons. Fast neutrons are generated by interactions of cosmic-ray-induced muons in the rocks and materials surrounding the detectors. They also originate from intrinsic radioactivity of the rock and surrounding materials, due to (α, n) processes and fission reactions from U/Th traces. Neutrons with kinetic energy of a few MeV generate typical ~ 10 keV nuclear recoils after elastic diffusion, with also an exponential-like spectral shape.

In addition, the coherent diffusion of solar neutrinos in the detectors is expected to be relevant for the future extremely large exposures achieved with at least ton-scale detectors [15]. The observation of this background would constitute an interesting by-product of WIMP searches.

There are several strategies to attenuate background intensities by several orders of magnitude. The intensity of gamma, beta and neutron backgrounds may be reduced by a careful selection of all materials in the experiment as well as by the use of shielding strategies. The experiments are installed in deep underground environments with reduced neutron fluxes. High-Z shields surrounding the detectors, like lead, reduce the external gamma backgrounds, while polyethylene or water shields thermalize the residual flux of fast neutrons. If the reconstruction of the interaction position is possible within the detector, then the self-shielding effect can also strongly reduce the residual external backgrounds, as is the case for gamma radioactivity in Xenon and for the surface beta radioactivity in Germanium sensors. The detector segmentation also favors the rejection of multiple interactions.

Finally, most experiments currently use an active discrimination, taking advantage of the fact that WIMPs generate nuclear recoils while the gamma and beta backgrounds consist in electron recoils. This discrimination may rely on the pulse shape analysis of a single channel, or on the comparison between signals from distinct channels (e.g. ionization versus scintillation signals).

In this context, a large panel of experimental strategies has been developed over the years, each one with different backgrounds and different approaches to reduce them. Dark matter searches are therefore a wonderful playground to develop

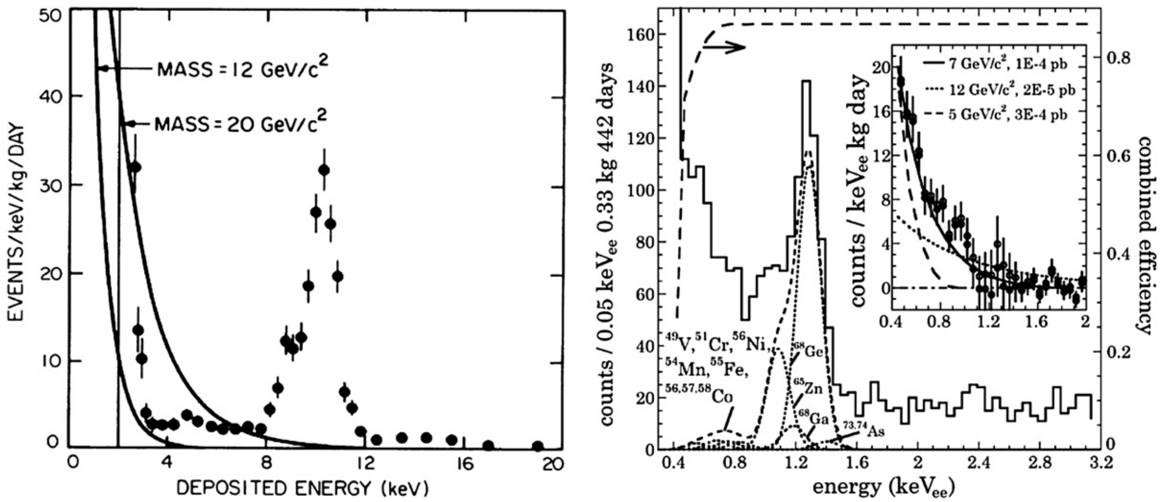

Fig. 1. A comparison between the background spectra measured by the Oroville experiment (left) and more recently by CoGeNT (right). The energy scales correspond to electron recoils. For CoGeNT, the spectrum in the inset is the residual obtained after subtraction of the known cosmogenic internal gamma-ray lines plus a flat Compton component. Example WIMP spectra are overlaid.

innovative particle detectors with outstanding performances in terms of low-energy thresholds and background identification.

4. A few experimental results

We now describe some of the strategies that have already been undertaken. We do not intend to be exhaustive at all, and focus mostly on a few experiments.

4.1. Germanium diodes

In the end of the 1980s, first searches for WIMP–nucleon scatterings were conducted using ultra-pure, semiconducting Germanium detectors with an ionization channel. The low-energy background spectrum obtained by the Oroville experiment [16] is shown in Fig. 1 (left). These ionization-only experiments are severely limited by their inability to reject the background of γ-ray-induced electronic recoils. However, recently the CoGeNT experiment instrumented a specific HPGe detector in a low-background environment and obtained a good sensitivity to low-mass WIMPs ($M_\chi \sim 5$–10 GeV) [17]. This is due to both a low intrinsic noise of ~ 70 eV and the ability to identify near-surface interactions with pulse shape analysis. We show in Fig. 1 (right) the corresponding background spectrum down to the threshold of 0.4 keV in electron recoil energy scale – which translates to ~ 2 keV for nuclear recoils.

A significant interest was raised by this later data, since a low-energy exponential rise of unclear origin appears. This potential ~ 7 GeV WIMP spectrum is further supported by the 2.5σ hint of annual modulation obtained thanks to the one-year statistics accumulated [18]. However, caution should be raised since, apart from apparently contradicting constraints from other experiments, the observed exponential may be due to other plausible effects, such as the inefficiency of pulse shape rejection at low energies. Furthermore, the significance of the observed modulation seems to be mostly driven by events above 0.9 keV, while most of the WIMP exponential spectrum is below 1 keV.

4.2. Solid scintillators

Other classical particle physics detectors used for WIMP search are solid scintillators such as NaI or CsI crystals, equipped with ultra-pure photomultipliers. The low threshold and large target mass achievable are exemplified in the DAMA experiment, which used 100 kg, and in a later stage 250 kg of ultra-pure NaI(Tl) to search specifically for an annual modulation in its low-energy background spectrum [19]. A statistically compelling modulation was indeed found for $2 \lesssim E \lesssim 4$ keV (electron recoil energy scale), as shown in Fig. 2. The signal is compatible with a WIMP interpretation, in particular in terms of event multiplicity – the modulation appears only in the rate of single interactions – and observed phase – the modulation has a maximum in the beginning of June. The standard WIMP parameter space compatible with this signal can be seen in Fig. 4 (right). However, more than ten years after the first claim, this result remains highly controversial. The observed spectrum must be the sum of a slightly modulated WIMP signal and a background of electron recoils (in particular the ^{40}K line at 3 keV), which seems currently difficult to fully understand. It has also been remarked that the modulation signal seems to decrease over the years of data-taking.

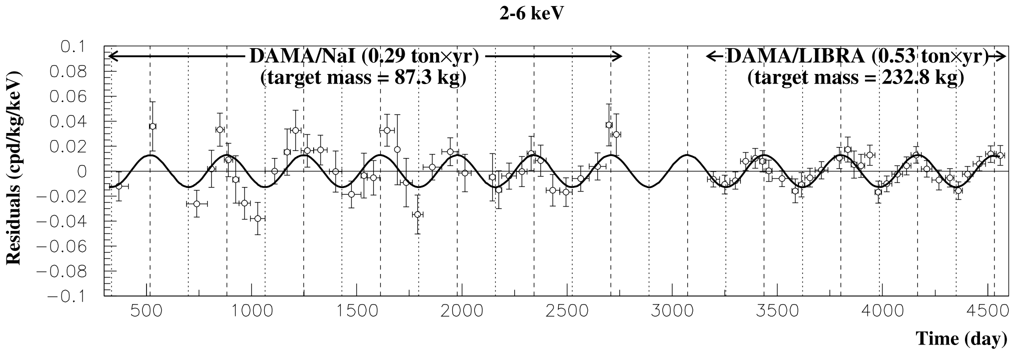

Fig. 2. Annual modulation of the low-energy background as seen by DAMA over several years.

Although no event-by-event discrimination of electron recoils is currently possible with these detectors, the falltimes of scintillation pulses are different on average depending on whether the initial recoil in the crystal is nuclear or electronic. A statistical discrimination against gamma-rays can therefore reduce the effective background. The KIMS experiment [20] uses this feature in CsI crystal and has in particular put limits on the spin-dependent WIMP–proton cross-section of the order of 0.2 pb for $M_\chi \sim 100$ GeV.

4.3. Bolometric detectors

The use of cryogenic bolometers for WIMP search, as well as in other subjects such as the search for neutrinoless double-beta decay, is motivated by the ability to combine a calorimetric measurement of energy depositions with another detection channel whose response differs according to the nature of the interactions.

- A cryogenic bolometer is made of an absorber (a crystal with heat capacitance C) in contact with a thermal bath, and a phonon detector associated to the absorber. Since the instantaneous energy deposition E_0 in the absorber generates a temperature rise $\Delta T = E_0/C$, and C is an increasing function of T, low-energy depositions can be measured only at ultra-low temperatures, typically $T \sim 10$–100 mK. Several phonon sensor technologies are used, from semiconducting materials such as Neutron Transmutation Doped Germanium to Transition-Edge Sensors working at the temperature of their supraconducting transition.
- The second measurement channel may be ionization or scintillation. For each recorded interaction within the absorber, the measurement of ionization or scintillation yields provides a discriminating variable between electronic and nuclear recoils, therefore enabling a strong rejection of several radioactive backgrounds.

Arrays of heat-and-ionization bolometers are used by the EDELWEISS and CDMS experiments. The absorber is a Germanium monocrystal with a mass ranging from ~ 100 g to ~ 1 kg, cooled down to 20 mK or 40 mK. Electrodes covering the crystal are used to apply differential voltages of a few volts and at the same time collect the charges created during an interaction. The ionization yield measurement results in a remarkable discrimination of γ-ray-induced interactions within the absorber, since it is more than a factor three lower for nuclear recoils in the relevant energy range. However, interactions taking place near the crystal surface must be discriminated independently because, for these interactions, the charge collection mechanism cannot be fully completed, which results in a loss of ionization signal.

The phonon sensors used in CDMS-II detectors enable the rejection of such surface events, thanks to their sensitivity to athermal phonons: surface events generate fast, athermal phonons which yield a different pulse shape from volume interactions. Surface events can then be rejected at the price of a $\sim 50\%$ WIMP efficiency loss. The complete WIMP search by CDMS-II [21], carried out over several years, resulted in a "null result", excluding cross-sections down to 3.8×10^{-8} pb for $M_\chi = 70$ GeV. Two potential WIMP candidates were present in the final dataset but their number is fully consistent with the expected backgrounds.

More recently, the EDELWEISS-II experiment implemented another way to reject surface events. The electrodes used to measure the ionization yield were segmented in the so-called "Interdigit" design: by applying alternate voltages to different interleaved electrodes, surface events are easily recognized as their charge deposition pattern differs from the one of volume events [22]. A one-year WIMP search carried out in 2009–2010 also resulted in a null result, excluding a cross-section of 4.4×10^{-8} pb for $M_\chi = 85$ GeV [23]. The EDELWEISS-II sensitivity is similar to CDMS-II for large WIMP mass, but degrades below 50 GeV due to a higher recoil energy threshold (20 keV instead of 10 keV) and to the presence of four near-threshold WIMP candidates compatible with the expected backgrounds – see Fig. 3 (left). Since both experiments use the same target and yielded similar results, a combination of both datasets was carried out [24]. The obtained sensitivity is presented in Fig. 3 (right). With a total effective exposure of 614 kg days, a cross-section of 3.3×10^{-8} pb for $M_\chi = 90$ GeV is currently excluded by the Germanium bolometric technology.

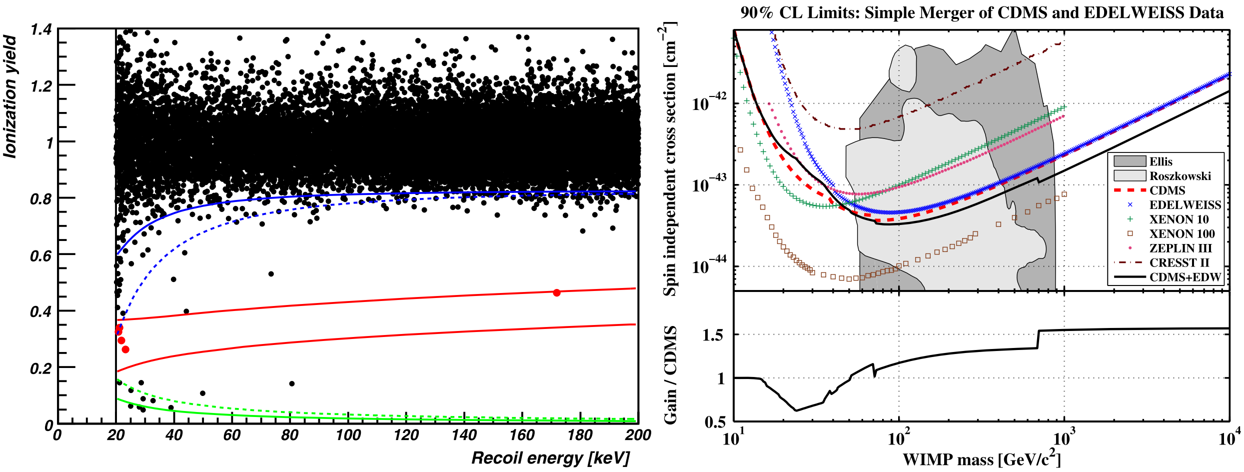

Fig. 3. Left: scatterplot of measured ionization yield versus energy for the fiducial events in the whole EDELWEISS-II dataset. By construction, the average ionization yield of gamma events is one. Nuclear recoil candidates are highlighted in red, within the nuclear recoil band centered on ionization yields ~ 0.3. Right: 90% CL limit on σ_{SI} as a function of WIMP mass obtained from the combined datasets of EDELWEISS-II and CDMS-II.

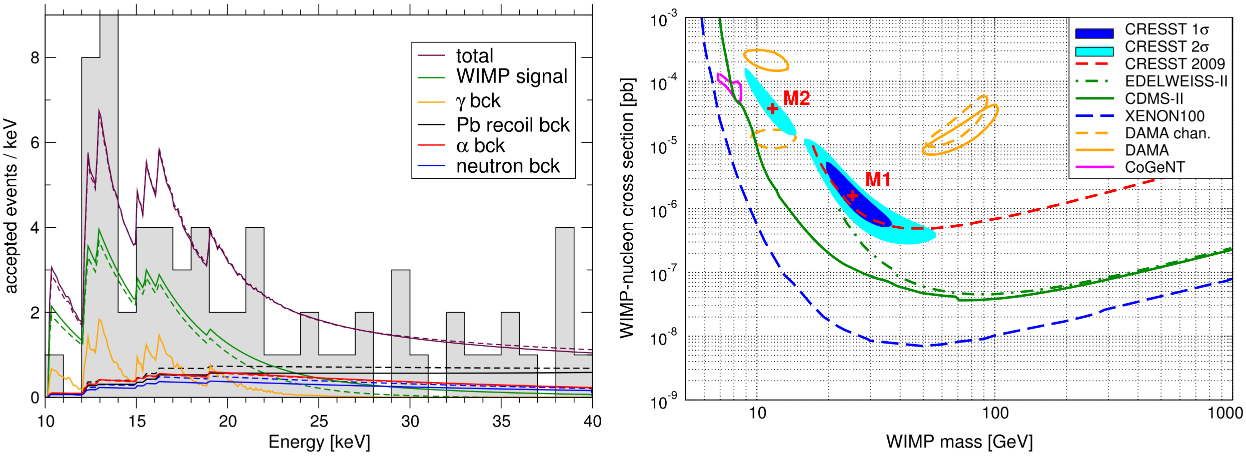

Fig. 4. Left: energy distribution of CRESST WIMP candidates, together with a possible fit by the sum of several known backgrounds and a WIMP signal. The "multi-spike" shape of fit components is due to the different energy thresholds of the stacked detectors. Right: contours of WIMP parameter space compatible with the possible CRESST signal. Also shown are the DAMA and CoGeNT contours.

We now turn to another type of bolometers tested for WIMP search: in heat-and-scintillation detectors, the absorber is a scintillating material instrumented with a thermometer. A second, much lighter calorimeter faces the main absorber in order to detect the photons created during an interaction in the target detector. The scintillation yield is therefore measured on an event-by-event basis, and is used as a discrimination variable in a similar way to the ionization yield: in appropriate crystals, nuclear recoils generate a very weak scintillation light with respect to electron recoils. Recently the CRESST experiment carried out a WIMP search with an array of scintillating $CaWO_4$ bolometers [25]. The results are ambiguous, since 67 WIMP interaction candidates were recorded over an exposure of 730 kg days, while the total expected background amount to ~ 45 events. Known WIMP-like background events originate at the same time from gamma-rays, neutrons, alpha radioactivity and lead recoils. The observed spectrum is shown in Fig. 4 (left). The corresponding excess may be adjusted to a WIMP signal. The allowed WIMP parameters are shown in Fig. 4 (right), where we see that relatively low-mass WIMPs are privileged. On the other hand, such an interpretation may be disputable since quantifying all the aforementioned backgrounds is a difficult task, especially near the detector-dependent energy thresholds.

4.4. Noble liquid detectors

Noble liquid scintillators provide an alternative to bolometers for WIMP search with a strong, active background reduction. Their main advantage is the ability to scale a single target to large masses, with an increasing self-shielding effect against external backgrounds as a function of target mass. In addition, the operating temperature is less demanding than for bolometers, although still requiring complex cryogenic systems: 165 K for Xenon and 88 K for Argon. Low recoil thresholds

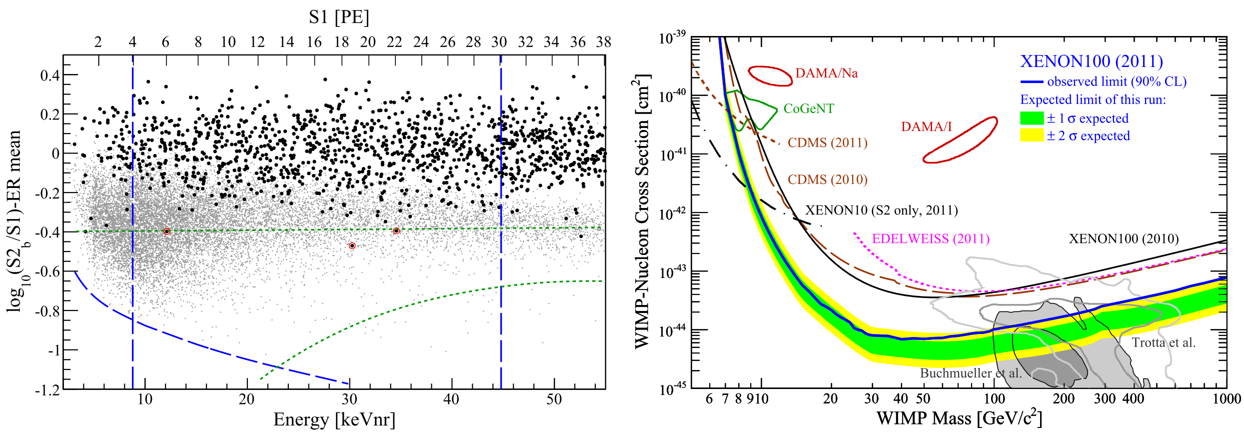

Fig. 5. Results of the 100-day XENON100 WIMP search. Left: scatterplot of the "S2/S1"-based discrimination variable as a function of energy for all fiducial events. By construction, this variable is null on average for electron recoils. Overlaid in grey are events from a neutron calibration which mimics WIMP-induced recoils. Three potential WIMP candidates are highlighted in red. Right: limit obtained from a likelihood analysis of this dataset. The sensitivity in the ~ 10 GeV region is disputed since it is driven by data near the detector energy threshold.

can be reached and additional background rejections can be achieved depending on the chosen technology. As for bolometers, there are experimental strategies employed by different collaborations.

- Choice of target nucleus. Both Xenon and Argon targets are currently used in dark matter searches. Apart from the obvious difference in nuclear mass, several features give different advantages to each one. For Argon, the scintillation from triplet state may be discriminated from the singlet state with pulse shape analysis thanks to a slow decay time. Since the singlet/triplet ratio depends on the ionizing power of incident particles, this opens the way to the reject electron recoils. On the other hand, natural Argon contains the ^{39}Ar radioactive isotope which generates an abundant internal electron recoil background. Xenon detectors must also face the less abundant internal beta radioactivity from ^{85}Kr.
- Choice of detector instrumentation. The conceptually simplest way of instrumenting these detectors is to surround a spherical volume of scintillator by photomultipliers. On the other hand, an additional discrimination against all sources of electron recoils can be achieved if one also measures the ionization signal generated by each interaction. This has been implemented in particular in dual-phase TPCs, which work as follows: the Xenon or Argon is kept in thermodynamical equilibrium between a large liquid volume and a small volume of gas phase on top of it. A strong, vertical electric field of the order of 1 kV/cm is applied within the whole volume. An interaction within the liquid phase generates free electrons in addition to the direct scintillation "S1" light signal. The electrons drift vertically up to the liquid surface and are extracted into the gas. Electrons traveling through the gas stimulate a second "S2" scintillation signal. Both "S2" and "S1" can be detected by PMTs. Since the ionization yield is smaller on average for nuclear recoils, the S2/S1 ratio is used as a discriminating parameter between electronic and nuclear recoils.

The best sensitivities obtained so far with a noble liquid target were obtained by the XENON100 experiment at the Gran Sasso Laboratory [26]. It consists in a dual-phase TPC with 62 kg of target liquid Xenon. After a 100-day WIMP search within the innermost 48 kg fiducial volume, no evidence for WIMP interactions was found, resulting in a 90% CL exclusion limit on the cross-section of 7×10^{-9} pb for $M_\chi = 50$ GeV [27], as shown in Fig. 5 (right). The residual background in the WIMP-search region is dominated by internal beta-rays from ^{85}Kr: although the intensity of this electron recoil background is very low compared to other experiments (less than 2×10^{-2} events/keV kg days), the rejection based on the S2/S1 parameter is not complete since, as we see in Fig. 5 (left), populations of electron recoils (black) and nuclear recoils (grey) partly overlap. In addition, the energy scale depends on the Xenon light yield for nuclear recoils, which is not yet measured with high precision.

A similar dual-phase Xenon TPC program is also developed by the LUX-ZEPLIN Collaboration. On the other hand, the currently ongoing XMASS experiment at the Kamioka mine consists in a single-phase 900-kg Xenon sphere completely surrounded by low-radioactivity PMTs to measure the scintillation signal: the lack of discrimination against electron recoils will be compensated by a large Xenon mass which, with full PMT coverage, will enable a strict fiducial cut to reject all external radioactivity. Sophisticated purification systems will strongly reduce the intensity of internal backgrounds.

The use of Argon instead of Xenon for WIMP search was demonstrated by the WArP experiment, based on the dual-phase TPC concept [28]. The conjugated use of the "S2/S1" measurement and pulse shape discrimination enabled an efficient rejection of the relatively intense gamma backgrounds.

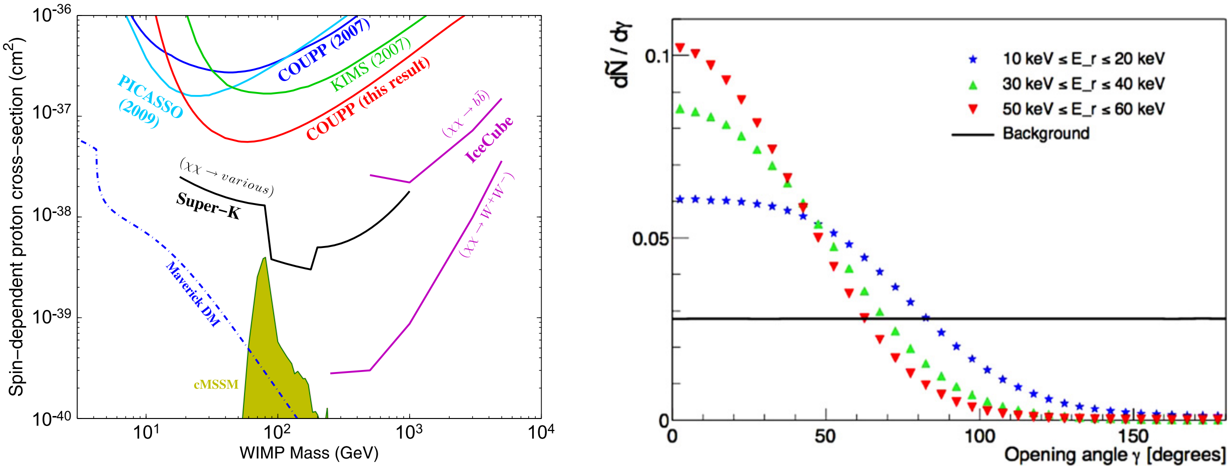

Fig. 6. Left: summary of current sensitivities of direct and indirect detection experiments to the spin-dependent WIMP–proton coupling. For large WIMP masses, direct detection experiments are still less sensitive than large neutrino detectors which constrain the VHE neutrino flux from the Sun. Right: predicted cumulative angular distribution of WIMP-induced recoils with respect to the Cygnus direction, for different recoil energy bands. The target is ^{19}F and the WIMP mass is 100 GeV.

4.5. Bubble chambers

The technique of superheated liquid detectors is undergoing a revival in the context of WIMP search: in appropriate temperature and pressure conditions, low-energy nuclear recoils in these detectors create bubbles in the target volume. The liquid targets used are for example CF_3I (COUPP) or ^{19}F (PICASSO experiment). A major advantage of this technology is that electron recoils do not generate such events, so that gamma and beta radioactivities are not expected to limit the WIMP sensitivity of bubble chambers. The remaining backgrounds for WIMP searches are therefore internal alpha radioactivity and neutron interactions. The PICASSO [29] and COUPP [30] experiments have shown that alpha signals can be rejected by measuring the ultrasonic acoustic emission from bubble nucleation, whose power spectrum depends on the nature of the interaction. Finally, while individual energy depositions cannot be measured with these detectors, their nuclear recoil energy threshold depends strongly on thermodynamical conditions. Therefore, temperature or pressure scans are carried out to constrain the energy distribution of the observed remaining nuclear recoils in a WIMP search. Currently, bubble chambers are mostly competitive in the proton spin-dependent channel as can be seen in Fig. 6 (left).

4.6. Gaseous TPCs

The directional distribution of WIMP-induced nuclear recoils is expected to be strongly anisotropic in galactic coordinates. Direction-sensitive WIMP detectors would therefore be able to confirm the extraterrestrial origin of a potential WIMP signal with high confidence, and in addition on to provide astrophysical informations on the local dark matter velocity distribution. As an example, Fig. 6 (right) shows the expected angular distribution of recoils with respect to the direction of solar motion for the standard WIMP halo model [31].

To reach the goal of building a directional WIMP detector, the experimental challenge is to be able to observe nuclear recoil traces down to keV-scale energies, which requires a gaseous TPC with high-granularity readout. At the same time, a very large instrumented volume is needed to provide enough sensitivity. The ability to observe the direction of the traces in addition to their axis (using the so-called head–tail effect) would also be an advantage. Several R&D developments are currently ongoing (e.g. DRIFT, NEWAGE, MIMAC, DMTPC), exploring different detection schemes ranging from micropattern TPCs to optical readouts [32].

5. Perspectives

While vertiginous progress was accomplished over the past decades towards understanding the composition and history of the observable Universe, the basic nature of Dark Matter remains an enigma. WIMPs are long-standing, plausible candidates which deserve to be fully tested. The direct detection of WIMPs is therefore a clear, well-motivated research path.

On the other hand, the extraordinarily low backgrounds and low-energy thresholds required to detect WIMPs imply strong R&D efforts, which are carried out in diverse technological directions. The experimental progresses made over the recent years are huge. The sensitivity to spin-independent WIMP–nucleon cross-sections improved by two orders of magnitude from 2004 to 2011, with a similar perspective for the coming years. The sensitivity of direct detection experiments is currently driven by both Germanium bolometers and noble liquid detectors.

– Cryogenic bolometers remain competitive, and new detectors with larger masses and improved background discrimination are under preparation. Both the EDELWEISS-III and SuperCDMS experiments will use arrays of massive Ge bolometers with improved ionization readouts to reject both bulk gamma-rays and surface interactions.
– The most impressive recent progresses were accomplished with dual-phase liquid Xenon detectors. While the final XENON100 results to come should improve again its already world-leading sensitivity by a factor ~ 3, more massive detectors such as LUX and XENON1t are in preparation for the next years. Results are also expected to come from single-phase Xenon (XMASS) and Argon (DEAP-3600) detectors. On a longer timescale, multiton-scale noble liquid detectors are considered.

While existing experiments have achieved sensitivities to cross-sections of the order of 10^{-8} pb, these foreseen ton- or multiton-scale experiments should reach sensitivities down to 10^{-10}–10^{-12} pb. Other technologies, such as bubble chambers, may also well progress at such a pace that they reach the sensitivity of the currently leading experiments in the spin-independent channel.

Currently, there is no hint of WIMPs with mass above 50 GeV and standard couplings, but a few orders of magnitude remain to be covered by future experiments before one can reasonably exclude the WIMP hypothesis. On the other hand, we have seen that some experiments, namely DAMA, CoGeNT and CRESST, have more or less recently found possible indications of low-mass WIMPs, with typical masses ~ 10 GeV and relatively large cross-sections $\sigma_{SI} \sim 10^{-4}$ pb. These surprising findings are driving a lot of interest for this previously poorly explored mass range, both from the experimental and theoretical points of view. However, let us remind that there are experimental questions on the potential signals from the three experiments. In addition, other experiments using complementary technologies did not confirm these signals: both the small-size XENON10 TPC and specific CDMS Germanium bolometers were used in conditions adapted to this range of WIMP signal, by lowering their threshold at the price of less background discrimination, and did not find a signal [33,34]. The currently existing low-mass WIMP hints therefore appear quite questionable, but there is anyway a real interest for future detectors to also explore deeper this region of parameter space.

References

[1] G. Bertone, D. Hooper, J. Silk, Phys. Rep. 405 (2004) 144.
[2] J.L. Feng, Ann. Rev. Astron. Astrophys. 48 (2010) 495.
[3] M. Goodman, E. Witten, Phys. Rev. D 31 (1985) 3059.
[4] G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267 (1996) 195–373.
[5] J. Lewin, P. Smith, Astropart. Phys. 6 (1996) 87–112.
[6] D. Spergel, Phys. Rev. D 37 (1988) 1353.
[7] A. Green, arXiv:1112.0524.
[8] T. Bruch, et al., Astrophys. J. 696 (2009) 920–923.
[9] C. Savage, K. Freese, P. Gondolo, Phys. Rev. D 74 (2006) 27.
[10] D. Smith, N. Weiner, Phys. Rev. D 64 (2001) 43502.
[11] J. Feng, et al., Phys. Lett. B 703 (2011) 124–127.
[12] O. Buchmueller, et al., arXiv:1102.4585.
[13] B. Lee, S. Weinberg, Phys. Rev. Lett. 39 (1977) 165–168.
[14] M. Ackermann, et al., Phys. Rev. Lett. 107 (2011) 241302.
[15] J. Monroe, P. Fisher, Phys. Rev. D 76 (2007) 033007.
[16] D. Caldwell, et al., Phys. Rev. Lett. 61 (1988) 510–513.
[17] C. Aalseth, et al., Phys. Rev. Lett. 106 (2011) 131301.
[18] C. Aalseth, et al., Phys. Rev. Lett. 107 (2011) 141301.
[19] R. Bernabei, et al., Eur. Phys. J. C 56 (2008) 333–355.
[20] H. Lee, et al., Phys. Rev. Lett. 99 (2007) 091301.
[21] Z. Ahmed, et al., Science 327 (2010) 1619–1621.
[22] A. Broniatowski, et al., Phys. Lett. B 681 (2009) 305–309.
[23] E. Armengaud, et al., Phys. Lett. B 702 (2011) 329–335.
[24] Z. Ahmed, et al., Phys. Rev. D 84 (2011) 011102.
[25] G. Angloher, et al., arXiv:1109.0702.
[26] E. Aprile, et al., arXiv:1107.2155.
[27] E. Aprile, et al., Phys. Rev. Lett. 107 (2011) 131302.
[28] P. Benetti, et al., Astropart. Phys. 28 (2008) 495–507.
[29] S. Archambault, et al., Phys. Lett. B 682 (2009) 185–192.
[30] E. Behnke, et al., Phys. Rev. Lett. 106 (2011) 021303.
[31] J. Billard, et al., Phys. Lett. B 691 (2010) 156–162.
[32] G. Sciolla, C. Martoff, New J. Phys. 11 (2009) 105018.
[33] J. Angle, et al., Phys. Rev. Lett. 107 (2011) 051301.
[34] Z. Ahmed, et al., Phys. Rev. Lett. 106 (2011) 131302.