DARK MATTER: DIRECT AND INDIRECT DETECTION

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Supersymmetric remnant particles are the best motivated candidates to fill the Dark Matter gap, and are actively hunted by a number of competing experiments. Direct and indirect detection experiments are complementary and begin to test for the first time SUSY models compatible with accelerator constraints. The CDMS, CRESST and EDELWEISS experiments together contradict the DAMA candidate for all WIMP mass < 5 GeV or > 13 GeV. The ZEPLIN-I result is critically discussed. The sensitivities of direct and indirect detection techniques for both present experiments and future projects are compared.

1 Introduction: motivations

The case for non baryonic dark matter has become compelling over the last few years. After the recent satellite WMAP precision measurements of the Cosmological Microwave Background (CMB) [1], the precision on the Universe density is now a few percent, with $\Omega \sim 1.02 \pm 0.02$. On the other hand, the recent apparition in the cosmological landscape of a non-zero cosmological constant or some other "quintessential" component has brought some uneasiness to an emerging "concordance" model: our Universe appears to be a strange mixture of $\sim 72\%$ of some cosmological repulsive component, $\sim 28\%$ of matter, with only $\sim 4.4 \pm 0.2\%$ of baryonic matter: 95% of the universe content is of unknown nature. Generically predicted by supersymmetric (SUSY) theories, Weakly Interacting Massive Particles (WIMPs) then appear as the best motivated candidate to solve the missing matter enigma.

2 WIMP direct detection: initial results and the DAMA candidate

For WIMPs virialized in our galaxy and interacting weakly with nuclei, typical nuclear recoil energies range from a few keV to a few tens of keV, and interaction cross-sections range from a few 10^{-6} to less than 10^{-11} picobarn. Initial direct detection experiments were unable to reach such small cross-sections and used detectors mainly dedicated to other purposes, e.g. double–beta decay search, using conventional germanium detectors [2,3]. Sodium iodide NaI scintillating crystals [4,5,6], with larger target mass but much lower resolutions and higher background rates, have also been used.

The main significant achievement of these experiments, using a set of ultrapure isotopically enriched ^{76}Ge crystals, was the experimental demonstration that massive Dirac neutrinos could not be the solution to Dark Matter over essentially all the cosmologically relevant mass interval [2,3]. Further improvements in the sensitivity of these experiments were mostly due to the passive reduction of internal ^{68}Ge cosmogenic activation by deep–underground storage [7]. Attempts to use an anti–Compton strategy resulted in the dedicated Heidelberg Dark Matter Search (HDMS), using a well–type germanium detector protecting a smaller 200 g germanium inner detector [8]. Although efficient at MeV energy, this technique resulted in only a factor two gain at the lowest energies (a few keV) relevant for WIMP searches and is not yet competitive at larger WIMP mass with the previous result of the Heidelberg-Moscow experiment. The International Germanium Experiment (IGEX) [9] is reaching a better sensivitivy over most of the WIMP mass range but remains above the sensitivity level required to test the first SUSY models.

2.1 The DAMA annual modulation candidate

Alternatively, massive sodium iodide crystals have been used, notably by the DAMA, the UKDMC and the Saclay groups, to reach sensitivities of the order of 10^{-5} picobarn. Despite the NaI inefficient discrimination at low energies, where the number of collected photons is small and the scintillation time constants for electron and nuclear recoils are less separated, the DAMA experiment, using a total mass of $\sim$ 100 kg of high purity NaI crystals, reported in 2000 the observation of an annual modulation involving a 160 kg $\times$ year data sample recorded over three annual cycles [10].

Recently, the group has published the analysis of three additional annual cycles [11] and the DAMA observation, taken at face value, presents a 6.2σ statistical significance, with both phase and amplitude consistent over a period of more than six years with a WIMP signature, using a 107 800 kg $\times$ day total data sample. Assuming standard halo parameters [12] and interpreted in terms of a WIMP candidate, the annual modulation would correspond to a WIMP mass $\sim$ (52$\pm$10) GeV and WIMP–nucleon cross–section $\sim$ $(7\pm1)10^{-6}$ picobarn. Using these parameters, the allowed region, delimited by a three sigma contour, is represented in Fig. 1 together with the constraints of the presently most sensitive experiments. The DAMA group has recently started operating a larger mass detector for WIMP search using a new 250 kg NaI setup, LIBRA.

2.2 Cryogenic detector experiments

Much of the progress in recent direct detection experiments is related to cryogenic detectors and their background discrimination performances, with real event-by-event identification capabilities between electron recoils, associated with the gamma, beta and alpha radioactive background, and nuclear recoils, observed in neutron and WIMP interactions. The CDMS [14], CRESST [15] and EDELWEISS [16] experiments have built detectors capable of the simultaneous detection of two signals: ionization and phonons for CDMS and EDELWEISS, scintillation and phonons for the CRESST experiment.

In 2000, the CDMS experiment [17,18], set in the shallow Stanford Underground Facility, had already excluded a large fraction of the 3-σ DAMA zone. However, CDMS suffered from a significant neutron background (27 events were observed for a 15.8 kg $\times$ day exposure) and the contradiction between DAMA and CDMS was not model-independent. EDELWEISS [19,20,21], in three data takings with a total exposure of 30 kg $\times$ day was the first experiment testing and excluding a first sample of supersymmetric models. Under the assumption of spin-independent

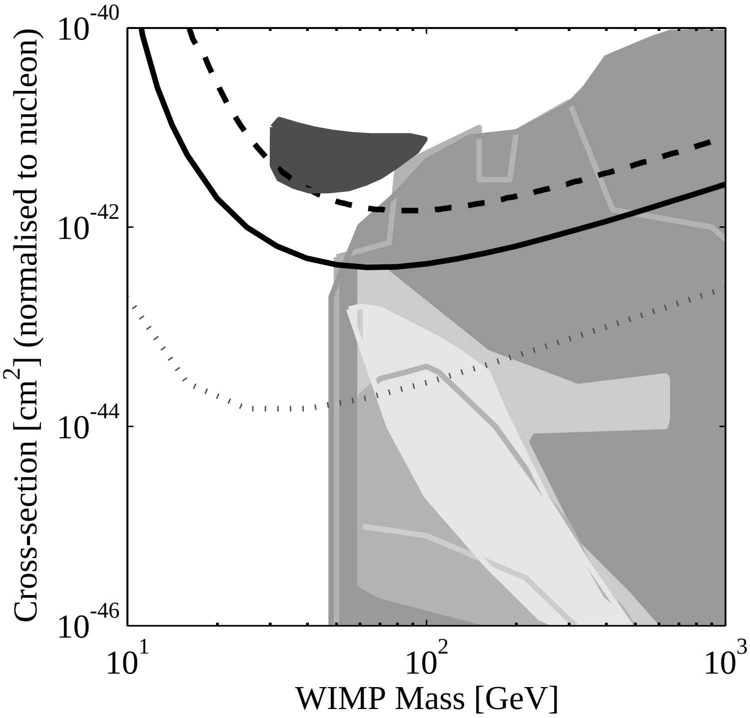

Figure 1: Experimental sensitivities of the present most sensitive WIMP direct detection experiments (after Ref. [13]). The CDMS-II result (full black line), excludes the full 3-σ zone of the DAMA signal (dark grey, upper left corner) compatible with accelerator constraints, independently of the WIMP halo model parameters. The EDELWEISS and CRESST experiments have rather similar sensitivities approximated by the black dashed line. The expected sensitivity of the next generation of cryogenic direct detection experiments is represented by the dotted line. Regions allowed by various SUSY models are represented by the shaded regions, with WIMP-nucleon cross-sections extending down to $\sim 10^{-12}$ pbarn

interactions, the CDMS and EDELWEISS results together excluded the whole DAMA region compatible with accelerator constraints.

There remained the possibility that a mixture of spin-dependent and spin-independent couplings could be used to reconcile the conflicting experimental results. But in a recent publication [22], the CDMS-II experiment has presented its analysis of a 55 kg $\times$ day raw data sample (19.2 kg $\times$ day after cuts) recorded in the Soudan underground laboratory (Minnesota, USA), with a much reduced neutron background compared to the Stanford site. The absence of nuclear recoil candidates for the whole data sample (one event in the unblind analysis), with an energy threshold of 10 keV (recoil energy) for three detectors (Fig. 2) results in a sensitivity, for WIMP mass $\approx$ 60 GeV, $\approx 4\times10^{-7}$ picobarn, more than one order of magnitude lower than the preferred value reported by the DAMA experiment.

Recently, the CRESST-II experiment [23] has used two 300 gram $CaWO_4$ light-phonon detectors as a test for its full 32-detector stage. On $CaWO_4$, WIMPs can *a priori* interact with oxygen, calcium or tungsten nuclei, but the scintillation quenching (suppression) factor, measured relative to an electron recoil, is $\approx$ 10 for an oxygen recoil, while it is $>\approx$ 40 for a calcium or a tungsten nuclear recoil. For this reason, oxygen recoils provide interactions emerging distinctly from the thermal noise of the light detector, while calcium and tungsten recoils give rise to extremely small light signals.

The present CRESST-II sensitivity, although limited by the neutron background originating from the rock, is now comparable to that of EDELWEISS. The CRESST-II is upgrading its setup to incorporate a plastic scintillator muon veto and a polethylene shield against neutrons. Its new 66-SQUID system will allow the acquisition of $\approx$ 10 kg of $CaWO_4$ crystal target.

Overall, Kurylov and Kamionkowski [24] and Savage et al. [25] have then shown that it is impossible to reconcile the DAMA result with other negative results for all WIMP with mass < 5 GeV or > 13 GeV. The sensitivities of the most significant direct detection experiments are represented in Fig. 1, showing that a first sample of optimistic SUSY models are now tested and excluded by the CDMS, CRESST and EDELWEISS results. It is significant to note that the three most sensitive Dark Matter direct detection experiments, CDMS, EDELWEISS and CRESST, are now using cryogenic detectors, with sensitivities nearly one order of magnitude better than their present competitors.

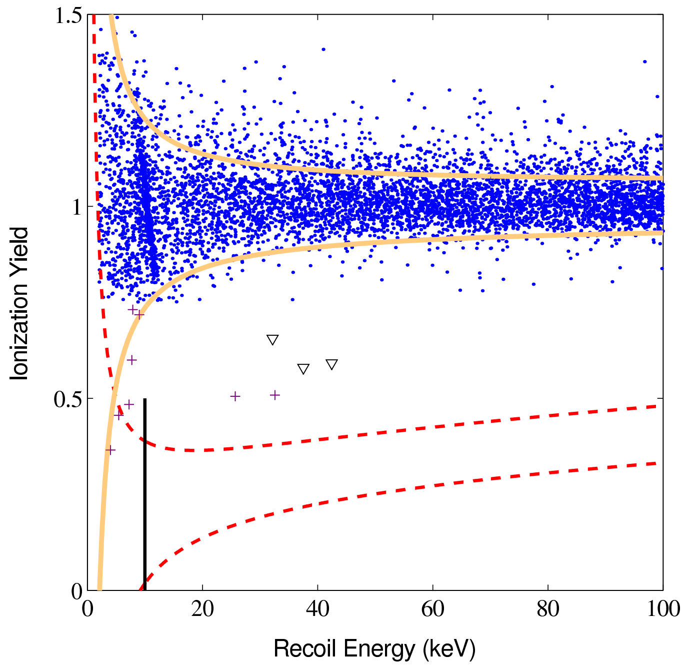

Figure 2: Scatter diagram of the ionisation efficiency, normalized to electron recoils, as a function of recoil energy for all events with energy < 100 keV recorded by the CDMS experiment using three 250 gram Ge detectors (after Ref. [22]). With a fiducial mass 300 times smaller than the DAMA NaI crystals, and an exposure 5 000 times shorter, the CDMS experiment exceeds by a factor > 10 the sensitivity of the DAMA experiment.

2.3 Rare gas target experiments

Several projects (XENON, XMASS, WARP, ZEPLIN) are developing detectors using rare gas targets such as liquid xenon or liquid argon.

The ZEPLIN-I experiment has attempted using the different scintillation time constants for nuclear and electron recoils to identify and reject the radioactive background. Using a 290kg $\times$ day data sample from a 4.5 kg liquid cell (3.1 kg fiducial), ZEPLIN is claiming a maximum sensitivity of $\sim 1.0 \times 10^{-6}$ picobarn for WIMP masses of ~ 60 GeV.

However, this sensitivity appears subject to important systematic uncertainties, according to conference proceedings [26], in the absence of refereed publications :

- with the present background level of 100 events/kg/keV/day [26], nearly two orders of magnitude higher than the germanium experiments, the claimed sensitivity requires a factor > 1000 in background rejection at low energies
- there exists no reliable calibration of the quenching factor and scintillation time constants for nuclear recoils below ~ 40 keV recoil energy [27] ; this calibration indicated a vanishing difference of scintillation time constants at low energies, similarly to the behavior of other scintillators such as NaI or CsI

- most surprisingly, according to the ZEPLIN observations, almost no low-energy nuclear recoils are detected when a neutron source irradiates the detector, in strong contrast with the expected exponential shape of the neutron recoil spectrum ; there is no indication that the "ambient neutron" population used to justify the discrimination at low energies is indeed related to neutron interactions.

Therefore, it cannot be excluded at present that nuclear recoils are indistinguishable from electron recoils at the energies where WIMP interactions are expected. The sensitivity of the ZEPLIN experiment would then be $\sim 10^{-3}$ picobarn, a factor 1000 higher than the claimed sensitivity.

2.4 WIMP direct detection: future projects

The CDMS, CRESST and EDELWEISS experiments are presently upgrading to detector mass between ~10 kg for CDMS and CRESST, to 35 kg for EDELWEISS, promising to reach a target sensitivity of $\sim 2 \times 10^{-8}$ pbarn and sampling more realistic SUSY models [28,29]. Beyond this second generation of discriminating experiments, in Europe, in the US and in Japan, tonne–scale cryogenic and xenon detectors are considered with the SuperCDMS, EURECA, XENON and XMASS projects. Clearly, the scientific impact of a positive WIMP detection will be more robust if complementary information is recorded using at least two target nuclei.

3 WIMP indirect detection

Since neutralinos are massive Majorana particles, they must annihilate and release copious fluxes of particles and antiparticles. Detection of these annihilation products —positrons, antiprotons, antideuterons, γ-rays and neutrinos— is the basis of indirect WIMP detection. A two-body process, WIMP annihilation is strongly enhanced in high density regions such as the center of stars, of the Earth, or the galactic center.

3.1 WIMP indirect detection: charged antiparticles

With mass in the typical range 100 GeV-1 TeV, WIMPs are expected to produce antiparticles in large quantities when they annihilate, but the directional information of annihilation source is lost after a short distance since propagation in the galactic magnetic field acts as a diffusion process. Therefore, an excellent comprehension of the cosmic-ray production of antiparticles must be achieved to be able to use the global diffuse emission of positrons and antiprotons as the signature of WIMP annihilations [30].

Antideuterons have been proposed as a less ambiguous signature, since their secondary production by cosmic-ray interactions is expected to be negligible. The AMS-2 experiment [31], on board the International Space Station, will measure both the positron, antiproton and antideuteron signals as potential WIMP signatures. But with a detection surface in the meter-squared range, the antideuteron rate appears discouragingly low.

3.2 WIMP indirect detection: gamma-rays

The cosmological diffuse emission resulting from WIMP annihilation in the halo might be observable [32,33] by future generation experiments, looking for a "knee" in the γ-ray spectrum. The GLAST satellite experiment [34] at energies from GeV to a few hundred GeV and a meter-squared detection area, together with atmospheric Cerenkov telescopes at ground level, with much larger detection areas of $\sim 10^4$ m^2 are looking for such signatures. The problem is not so much the intensity of the γ-ray flux expected from WIMP annihilation that the ambiguity of an excess. Recent observations illustrate this difficulty.

In 2003, the CANGAROO collaboration [35] reported an excess of γ-rays from the galactic center with a steeply falling spectrum, which could, if confirmed, indicate the presence of a WIMP of a mass of ~ 1 TeV. This observation is not confirmed by the HESS experiment [36], with a much better angular resolution: although HESS does observe an excess of gamma-rays, the energy spectrum appears much flatter. Interpreting the excess in terms of WIMP annihilation favors a WIMP mass > 12 TeV, hardly compatible with a SUSY WIMP. But the excess could also be interpreted more conventionally, e.g. interactions of cosmic-rays in the high-density region of the Galactic Center. Similarly, an excess of γ-rays in the EGRET data has been interpreted [37] in terms of a WIMP annihilation, with a mass in the 50-100 GeV range and an excellent adjustment of the observed spectrum, at the expense of a boost factor of 50-70. These two observations illustrates the difficulty of interpreting inambiguously an excess in the γ-ray spectrum, even when a "knee" structure is observed.

3.3 WIMP indirect detection: neutrinos

Using the neutrino signal emitted in WIMP annihilations may constitute a powerful signature as the signal is directional and sources opaque to γ-ray emission can be observed. Three main potential sources have been studied: the Earth, the Sun and the Galactic Center region. The overwhelming muon background coming from the above horizon hemisphere imposes to have a detector with directional capabilities, to distinguish upward going muons, associated with neutrino interactions, from the huge background of down–going cosmic–ray remnants. Water or ice Cerenkov detectors provide an elegant solution to this experimental challenge, with large and unexpensive target mass.

The AMANDA [38], Baksan [39], MACRO [40] and Super-Kamiokande [41] under-ice or underground experiments have published sensitivity limits to WIMP disintegrations derived from the observation of high-energy neutrino interactions. The presently most sensitive indirect search experiment for spin–independent WIMP interactions is SuperKamiokande, using a 3.5 years data sample and a 50 kiloton target. AMANDA–B and Baksan are reaching somewhat lesser but similar sensitivities. The degraded sensitivity of AMANDA at lower energies can be attributed to its higher energy threshold.

Future experiments include ICECUBE [42], a km^2 extension of the AMANDA-B detector, together with ANTARES [43], a European collaboration in the Mediterranean sea. NESTOR and NEMO are two other projects based in the Mediterranean sea, with sensitivities similar to ANTARES. ANTARES, in its 0.1 km^2 version, plans to increase the present indirect detection sensitivity by a factor ~ 3 and ICECUBE is expected to increase the ANTARES sensitivity by a further factor ~ 5, at least for high WIMP mass. Figure 3 compares the sensitivities expected from the forthcoming generation of direct and indirect detection experiments.

Whereas ICECUBE itself, when using neutrino emission from the Earth, can hardly compete with the sensitivity of present direct detection experiments, indirect searches using neutrinos from the Sun remain competitive when compared to the next generation of direct searches for a limited fraction [29] of predominantly axial, or spin–dependent, couplings.

4 Conclusions

WIMP direct and indirect detection experiments are finally reaching sensitivities allowing to sample optimistic SUSY models compatible with accelerator constraints. The first WIMP candidate proposed in 2000 by the DAMA experiment appears impossible to reconcile with the CDMS, CRESST and EDELWEISS results for all WIMPs with mass > 12 GeV.

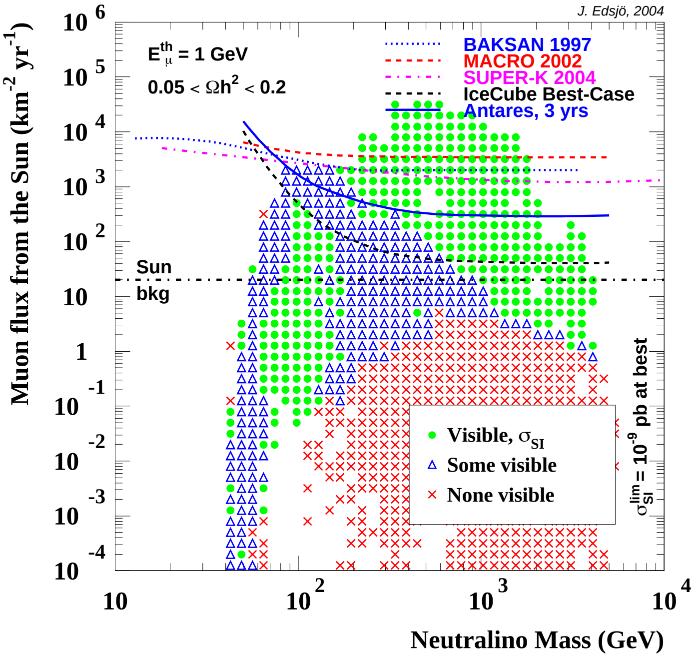

Figure 3: Sensitivities of the present indirect searches (three upper curves) using interactions of neutrinos produced in WIMP annihilations in the Sun (after Ref.[44]) compared with the sensitivity obtained by future direct search (noted SI (spin-independent), region represented by full grey dots). The target sensitivities of the future ICECUBE and ANTARES experiments are presented on the figure as the two curves above the ultimate background from interactions of cosmic-rays in the Sun (dot-dashed lower curve).

Over the next few years, a second generation of discriminating experiments, using target mass in the 10–30 kg range, intend to reach sensitivities of a few 10^{-8} picobarn, allowing them to test more favored SUSY models. Direct searches with a detector mass of the order of one ton should be able to test most of the SUSY parameter space, assuming outstanding background discrimination capabilities and excellent control of the fast neutron background.

Indirect detection experiments, notably the future ICECUBE experiment, being more sensitive to the spin–dependent part of the interaction, may help determine the nature of a WIMP candidate. Improvements in sensitivity by WIMP direct and, more marginally, indirect detection experiments will hopefully allow the identification of Dark Matter within the next few years.

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