WIMPS : DIRECT AND INDIRECT DETECTION, STATUS AND PERSPECTIVES

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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. Status of the current performances of the complementary direct and indirect WIMP detection experiments are given together with the perspectives in the coming years. Reached sensitivities allow to test for the first time SUSY models compatible with accelerator constraints. The first WIMP candidate reported by the DAMA experiment is now excluded by the limits set by the CDMS and EDELWEISS experiments unless contrived mixed models are used. Signals from various indirect detection experiments are dicussed.

1. Introduction, motivations

The case for non baryonic Dark Matter has become compelling over the last few years. After the satellite WMAP precision measurements of the Cosmological Microwave Background (CMB) [1], the universe density is now known to few percent and $\Omega \sim 1.02 \pm 0.02$. On the other hand, the recent evidence for a non-zero cosmological constant or some other quintessential component leads to a new model of our universe: a mixture of 2/3 of some cosmological repulsive component, 1/3 of exotic matter, and only a few percent of ordinary matter: 95% of the universe content is unknown. As the baryonic density, Ω_{baryon}, is strongly constrained by primordial nucleosynthesis [2] and cosmological measurements to be $\sim 4.4 \pm 0.2\%$, the matter component is then composed of nearly 85% of a mostly unobserved and non-interacting component.

Experimental constraints impose that neutrinos contribute at most to 10% of the missing mass. Then, the majority of Dark Matter is unknown, but however the candidates should fulfill several conditions : they must be stable on cosmological time scales (otherwise they would have decayed by now), they must interact very weakly with electromagnetic radiation (otherwise they wouldn't qualify as *dark* matter), and they must have the right relic density. Candidates include primordial black holes, axions, and weakly interacting massive particles (WIMPs). While creation of large number of primordial black holes is only possible in constrived cosmological models, axion and WIMPs are good candidates with a wide range of parameters to explore.

Weakly Interacting Massive Particles (WIMPs) are particularly attractive for two reasons : 1) with mass roughly between 10 GeV and a few TeV, and with cross sections of approximately weak strength, they provide a good "cold" DM candidate to satisfy the requirements for structure formation in the Universe, 2) on the particle physics side, the supersymmetric (SUSY) theories provide an ideal candidate, the lightest supersymetric particle : the neutralino, stable and massive. In a large range of allowed parameters, the right relic density is obtained.

In the following, we will summarize the important effort undertaken by many groups, in both direct and indirect searches, to test a larger, if possible exhaustive, sample of SUSY parameter space.

2. WIMP direct detection

Locally, WIMPs should be gravitationally trapped inside our galaxy and should have the adequate density profile to account for the local DM density, measured to be about 0.3 Gev/cm3. These two constraints determine the main features of experimental detection of WIMPs. With typical velocities around 220 km/s, WIMPs interact with ordinary matter through elastic scattering on nuclei. Expected 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.

2.1. *Experiments without discrimination*

The first searches have been performed with ultra–pure semiconductors installed in pure lead and copper shields in underground environments [3]. Combining a priori excellent energy resolutions and very pure detector material, they produced the first limits on WIMP searches and until recently had the best performance (Heidelberg-Moscow, IGEX, COSME-II, HDMS) [3]. Without positive identification of nuclear recoil events, however, these experiments could only set limits, e.g. excluding sneutrinos as major component of the galactic halo. Attempts to use an anti–Compton strategy resulted in the dedicated Heidelberg Dark Matter Search (HDMS) [4].

However, this technique resulted in only a factor two gain at the energies relevant for WIMP searches.

Planned experiments using several tens of kgs to a ton of Germanium (many of which were designed for double–beta decay search) – GENIUS TF, GEDEON, MAJORANA – are based on passive reduction of the external and internal electromagnetic and neutron background by using segmented detectors, minimal detector housing, close electronics, and large liquid nitrogen shields.

To make further progress, background reduction and signal identification questions have to be addressed. This has been the focus of many recent investigations and improvements.

2.2. *Experiments with discrimination*

Background reduction in detectors relies on the relatively small ionisation produced by nuclear recoils due to their low velocity. This induces a reduction – quenching – of the ionisation/scintillation signal for nuclear recoil signal events relative to e or γ induced backgrounds. Energies calibrated with gamma sources are then called "electron equivalent energies" (eee). This effect is exploited in cryogenic detectors described later. In scintillation detectors, it induces in addition a difference in decay times of pulses induced by e/γ events vs nuclear recoils. Due to the limited resolution and discrimination power of this technique at low energies, this effect allows only a statistical rejection. It has been used in NaI(Tl) (DAMA, NAIAD, Saclay NaI), in CsI(Tl)(KIMS), Xe (ZEPLIN) [3]. No observation of nuclear recoils has been reported by these experiments.

There are two experimental signatures of WIMP detection that would prove its astrophysical origin. One is the measurement of the strong daily forward/backward asymmetry of the nuclear recoil direction, due to the alternate sweeping of the WIMP cloud by the rotating Earth. The second is the few % annual modulation of the recoil rate due to the Earth speed adding to or subtracting from the speed of the Sun. This tiny effect can only be detected with large masses; nuclear recoil identification should also be performed, as the much larger background may also be subject to modulation.

The DAMA experiment operating 100 kg of NaI(Tl) in Gran Sasso has observed, with a statistical significance of 6.3 σ, an annually modulated signal with the expected phase from an isothermal halo, over a period of 7 years with a total exposure of around 100 000 kg·d , in the 2 to 6 keV (eee) energy interval [5]. This effect is attributed to a WIMP signal by the authors. If interpreted within the standard halo model described above, it would require a WIMP with $m_\chi \simeq 50$ GeV and $\sigma_{\chi p} \simeq 7 \cdot 10^{-6}$ pb (central values). This interpretation has however several unadressed implications. The expected nuclear recoil rate from WIMPs should be of the order of 50 % of the total measured rate in the 2-3 keV (eee) bin and 7 % in the 4-6 keV (eee) bin. This rather large WIMP signal should be detectable by the pulse shape analysis. Moreover, the remaining, presumably e/γ induced background, would have to rise with energy and the spectrum shape would be marginally consistent with the expected resolution; no explanation for this is given by the authors.

The DAMA group has started operating the largest mass NaI detector for WIMP search using a new 250 kg NaI setup, LIBRA.

The best current limit for a WIMP mass above 60 GeV has been produced in the two last years by Ge cryogenics detectors first by EDELWEISS in the deep underground Fréjus lab [6] and more recently by CDMS now operated in the Soudan mine [7](Fig. 1). They superceded the earlier CDMS results obtained at the much shallower Stanford site, with its large cosmic ray induced neutron flux [8]. The simultaneous measurement of the phonon signal and the ionisation signal in such semiconductor detectors, operated at few tens of mK, permits event by event discrimination between nuclear and electronic recoils down to 10 keV recoil energy. Assuming conventional WIMP halo parameters, EDELWEISS and CDMS, at lower WIMP mass, exclude the DAMA signal at more than 99.9 % CL. Varying the parameters of the halo parameters within realistic limits do not allow to reconcile both results [9] [10]. The obtained sensitivity of $\sigma_{\chi p} \simeq 4.10^{-7}$ pb for the first time tests cross sections that can be accommodated in the MSSM [11]. The sensitivities of the most significant direct detection experiments are represented in Fig. 2, showing that a first sample of optimistic SUSY models are tested and excluded by the CDMS and EDELWEISS results.

Other cryogenic experiments like CRESST and ROSEBUD [3] use the scintillation of CaWO4 as second variable for background discrimination, while CUORECINO will use TeO2 in the purely thermal mode. Recently, the CRESST-II experiment has used two 300 gram $CaW0_4$ light-phonon detectors as a test for its full 32-detector stage. WIMPs can *a priori* interact with oxygen, calcium or tungsten nuclei, but the scintillation quenching

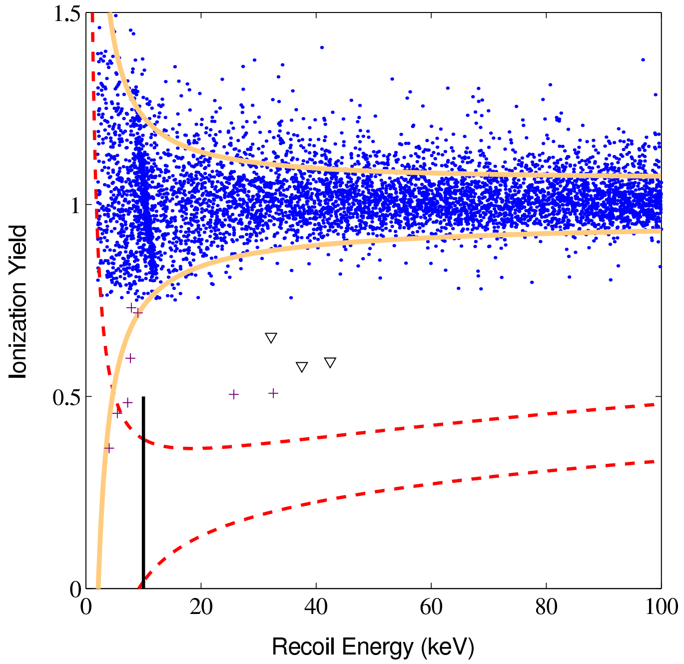

Figure 1. Scatter diagram of the ionisation efficiency, normalized to electron recoils, as a function of recoil energy for all events with energy $<$ 100 keV recorded by the CDMS experiment using three 250 gram Ge detectors [7].

(suppresssion) factor, measured relative to an electron recoil, is $\approx$ 10 for an oxygen recoil, while it is $\approx$ 40 or larger for a calcium or a tungsten nuclear recoil. No events were observed in the expected tungsten recoil zone, which allowed to produce an exclusion limit a factor 2 above the last EDELWEISS one.

In the coming years, the cryogenic experimental programs of CDMS II, EDELWEISS II, CRESST II, CUORICINO and ROSEBUD [3] hope to increase their sensitivity by a factor 100, by operating from few to 40 kg of detectors.

Liquid and two–phase Xenon detectors are coming rapidly on line. ZEPLIN has been operating 6 kg of liquid Xe in the Boulby laboratory for about 1 year, by measuring the scintillation light. By using the different scintillation time constants for nuclear and electron recoils, they announced a sensitivity close to the EDELWEISS limit. However, this sensitivity ap-

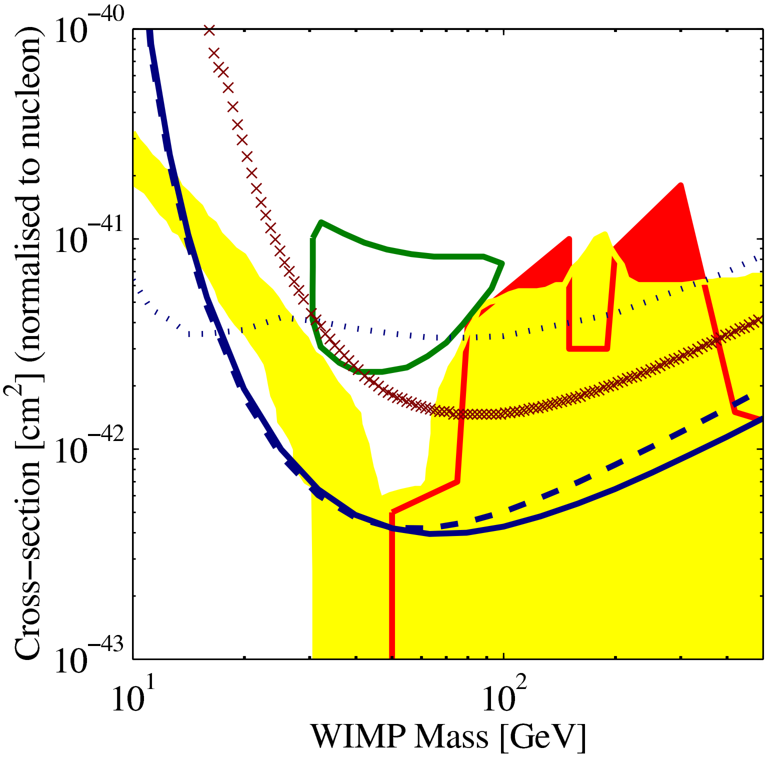

Figure 2. Experimental sensitivities of the present most sensitive WIMP direct detection experiments [7]. The CDMS (full and dotted lines) and EDELWEISS (crosses) results, without background subtraction, exclude the full 3-σ zone of the DAMA signal (heart-shaped region), unless unconventional halos and/or interactions are invoked. Yellow and red regions show SUSY models predictions [11].

pears subject to important systematic uncertainties, according to the informations delivered in the conference proceedings [12], and in the absence of publications. With only 1.5 photoelectron/keV (eee), and a three–fold coincidence, searching for the WIMP signal in the 2-10 keV (eee) region is quite challenging. On the other hand, the neutron calibration realized on the ZEPLIN-I detector itself suffers from strong weaknesses. When a neutron source irradiates the detector, no low-energy nuclear recoils are detected at energies below 10 keV, while when leaving the detector at the surface with no neutron source, a population with lower time constants is ascribed to "ambient neutron". From the time constants of this population of events is deduced an increasing discrimination towards lowest energies, a really unexpected feature as compared to dedicated calibration above 10 keV [13] and to other scintillators such as NaI or CsI. The hypothesis of a vanishing discrimination power below 10 keV cannot be excluded, which would result in a sensitivity a factor 1000 lower than the claimed one.

With masses of 7 to 30 kg, ZEPLIN II, III, and then IV aim at sensitivities down to 10^{-8} pb. XMASS in Japan has recently operated successfully a 100 kg at the SuperKamiokande site, and have demonstrated that self–shielding is indeed working and allows to reach very low counting rates in the very central part of the detector. Their goal is to operate in the coming years a 800 kg total Xe mass with a 100 kg fiducial mass.

There is also growing interest towards low pressure Time Projection Chamber, the only convincing technique to measure the direction of nuclear recoils [14]. DRIFT, a 1m^3 volume detector is currently taking data. The small active mass of 200 g precludes competitive results. The sub–keV energy threshold gazeous detector MICROMEGAS is being investigated for WIMP search [14]. Other exotic techniques include the superheated droplet detectors SIMPLE, PICASSO, ORPHEUS and ultra cold pure ^{3}He detector MacHe3 [3].

Beyond the second generation of discriminating experiments, in Europe, in the US and in Japan, tonne–scale cryogenic and xenon detectors are considered with the CryoArray, 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. Status and prospects of indirect WIMP searches

WIMPs can annihilate and their anihilation products be detected; these include neutrinos, gamma rays, positrons, antiprotons, and antinuclei [15]. These methods are complementary to direct detection, can explore higher masses, different coupling scenarii and are sensitive to different regions of the WIMP velocity distribution. ”Smoking guns” signals for indirect detection are neutrinos coming from the center of the Sun or Earth, and monoenergetic photons from the halo.

WIMPs can be slowed down, captured and trapped in celestial objects like the Earth or the Sun, thus enhancing their density and their probability of annihilation. This is a source of muon neutrinos which can interact in the Earth. Upward going muons can then be detected in large neutrino telescopes such as MACRO, BAKSAN, SuperKamiokande, Baikal, AMANDA, ANTARES, NESTOR and the future large sensitive area IceCube [15]. The best upper limits, of $\simeq$ 3000 muons/km2/year, have been set by MACRO and BAKSAN [16]. However, at least in the framework of the MSSM, only the limits from the Sun are competitive with direct WIMP search limits. ANTARES (IceCube) will increase this sensitivity respectively by $\simeq$ one (two) order(s) of magnitude. Figure 3 compares the sensitivities reached by the forthcoming generation of direct and indirect detection experiments.

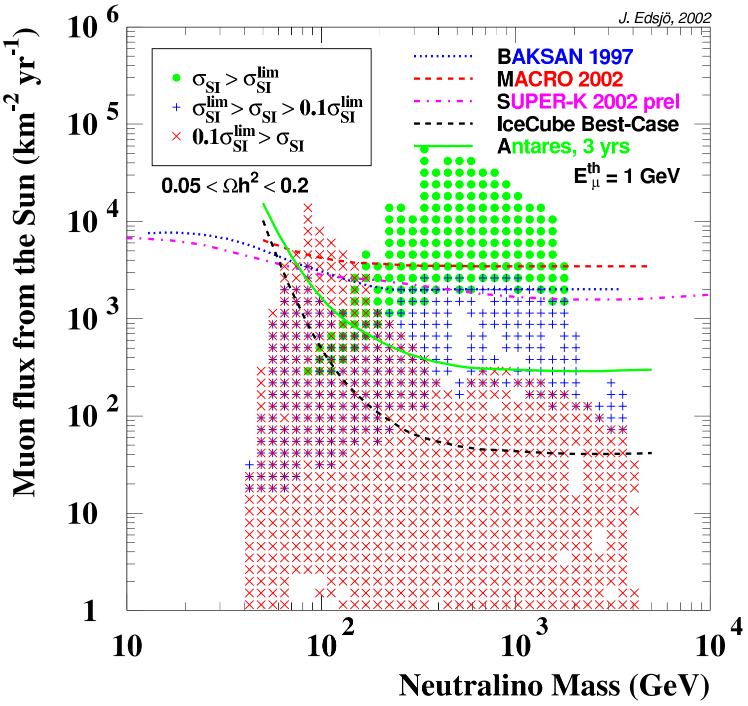

Figure 3. Sensitivities of the present and future indirect searches using interactions of neutrinos produced in WIMP annihilations in the Sun (after Ref. [17]) compared with the sensitivity obtained by future direct search (noted SI (spin-independent), region represented by full grey dots). The target sensitivities of the future ICECUBE and ANTARES experiments are also presented on the figure as the two lower curves.

WIMP annihilation in the halo can give a continuous spectrum of gamma rays and (at one–loop level) also monoenergetic photon contributions from the $\gamma\gamma$ and γZ channels. The size of this signal depends very strongly on the halo model, but is expected to be most prominent towards the galatic center and from high density clumpped regions of Dark Matter. Existing limits come from the EGRET satellite below 10 GeV, and from the WHIPPLE ground based telescope above 100 GeV [18]. However, only the planned space mission GLAST will be able to provide competitive SUSY sensitivities in both the continuous and γ line channels. Also, Air Cherenkov Telescopes like MAGIC, VERITAS and HESS should be able to test some SUSY models, at large WIMP mass, for halo models showing a significant WIMP enhancement at the galactic center [15].

Diffuse continuum gammas could also give a signature due to their isotropic halo origin. The excess of GeV gamma-rays observed by EGRET [18] and attributed to a possible WIMP signal could however be due to classical sources.

CANGAROO has also recently observed a point-like 7-sigma excess of γ-ray in the direction of the Galactic center. HESS should be able to confirm with high statistics the CANGAROO excess.

The antiproton signal arises as another WIMP annihilation product in the halo. The signal is expected to be detectable above background only at very low energies. The BESS balloon–borne experiment indeed observed antiprotons below 1 GeV [19]. However, the uncertainties in the calculation of the expected signal and background energy spectra are too large to reach a firm conclusion. Precision measurements by the future experiments BESS, AMS2 and PAMELA may allow to disentangle signal and background [15].

A cosmic–ray positron flux excess at around 8 GeV measured by HEAT [20] has given rise to numerous calculations and conjectures concerning a possible SUSY interpretation. The need for an ad–hoc "boost" of expected flux to match the observed one and the failure to reproduce the energy shape by including a component from WIMP annihilation are illustrative of the difficulty to assign a Dark Matter origin to such measurements.

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

An interesting comparison of respective sensitivities to MSSM parameter space of future direct and various indirect searches has been performed with the DARKSUSY tool [21].

4. Conclusions

WIMP direct and indirect detection experiments are reaching sensitivities allowing to sample SUSY models compatible with accelerator constraints. The first WIMP candidate proposed in 2000 by the DAMA experiment appears impossible to reconcile with the CDMS and EDELWEISS results without a high degree of fine-tuning.

Over the next few years, a second generation of discriminating experiments, using target mass in the 10–35 kg range, intend to reach the sensitivity of 10^{-8} picobarn, allowing to test a larger fraction of realistic SUSY models. Direct searches with a detector mass of the order of one tonne should be able to test most of the SUSY parameter space. Reaching a sensitivity of 10^{-10} picobarn will require outstanding background discrimination capabilities, as well as an accurate control of the fast neutron background.

Indirect detection experiments, such as the pioneering AMANDA experiment, or the future ICECUBE or ANTARES experiments, being more sensitive to the spin–dependent part of the interaction, are complementary to direct detection experiments and may help determine the nature of a WIMP candidate. Improvements in sensitivity by WIMP direct and indirect detection experiments will hopefully allow the detection of Dark Matter and the identification of its nature.

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