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Direct dark matter searches - recent highlights

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Abstract. The experimental search for cold dark matter particles has seen significant progress over the last few years. A number of new results have been announced which are now feeding back interesting constraints on particular types of particle and their interaction strengths, even though no convincing positive detection has yet been made. The range of promising techniques (and named experiments) continues to grow to the point where it is no longer feasible to overview the whole field in a digestible way within a single talk; hence this report will focus on some of the key experimental highlights from the last two years. Before doing that a reminder of the motivation and general requirements for such direct search will be given. As a conclusion the short-term prospects for more exciting results over the next two years will be outlined. both.

1. Introduction

There has been a relentless increase over the past several decades in the evidence from straightforward astrophysical observations for deeper gravitational potentials associated with visible matter than expected. In addition to this there has been the growth of a standard cosmological model which uses a different set of observations together with n-body simulations to put bounds on a number of key parameters within such cosmological models. One of the key parameters is the matter density in the Universe and not only does that parameter come out to be significantly in excess of that considered acceptable from big-bang nucleo-synthesis models, it comes out with a value which is also consistent with that needed to explain all of the individual pieces of more direct observational evidence from specific astrophysical objects/systems. Together these make the case for the existence of systematically enhanced gravitational potentials throughout and encompassing the Universe itself. Some clue as to the nature of the dark matter comes out of the n-body simulations which only convincingly produce results close to reality if the dark matter is ‘cold’; i.e. non-relativistic. If this cold dark matter is in the form of elementary particles this argues for heavy weakly interacting particles, which is now seen to preclude neutrinos as being a dominant contribution. However there are another candidate particles which come naturally out of unification schemes, such as supersymmetry, which naturally predict additional undiscovered heavy weakly interacting particles, and what is more there is a ‘naturalness’ about the expected annihilation interaction cross-sections which would lead to a cosmologically relevant residual density from the big-bang.

1.1. Astrophysical Observations

Direct probes of the depth of gravitational potentials come from the balance between kinetic and potential energy in bound systems. This type of study has been done for a variety of different systems of very different scale sizes. Apart from the solar system, one of the earliest studies was of the motion of nearby disk stars applying the virial theorem to estimate the required mass in the local disk to bind the stars to the disk given their measured velocity distribution [1]. Since then observations on larger and larger scale-lengths have come from rotation curves of galaxies [2], dynamics of galaxy clusters [3], hot gas associated with clusters [4], gravitational lensing by clusters [5] and large scale streaming motions [6].

1.2. Cosmological Models

To understand the observed properties of our Universe requires three components: (i) the starting perturbations in the very early universe, (ii) the subsequent expansion rate, and (iii) the growth of structure through the action of gravity. These ingredients then go into computer models with typically some 11 parameters describing a universe [7]. Remarkable success has been achieved in reconciling the output predictions of these models in respect of a number of observable parameters, such as the cosmic microwave background anisotropy, high-redshift supernova data and large-scale structure, and this has put values and error bars on the 11 or so parameters. The key one in relation to dark matter is the overall matter density within the universe which comes out to be 5-6 times higher than what is thought allowable from big-bang nucleo-synthesis models. Moreover the width in the distribution of values is very small and precludes models without any dark matter at the several σ level [8]. Other parameters relate to the properties of the matter content and differentiate between 'hot' and 'cold' matter according to its initial velocity distribution; essentially whether it is relativistic or not. Only a small component is allowed as 'hot' and the natural candidate filling that role is the neutrino. The dominant component seems to be required in the 'cold' form, and moreover must not have any interaction with normal matter beyond gravity and possibly a weak force. Another outcome of the universe modelling is that there seems to be the need also for an additional unknown energy content which has been dubbed 'dark energy'. The consensus model of the Universe is then called the ΛCDM model.

1.3. Dark Matter Particles

Many different types of object have been postulated as possible dark matter candidates [9]. The best motivated of these are particles which also serve other purposes; for example the natural partners to existing particles coming out of unification frameworks (such as weakly interacting massive particles (WIMPs) from supersymmetry or Kaluza-Klein models) or axions invoked to solve the strong CP violation problem. If it is to be demonstrated that dark matter is in the form of one or other of these particles then detection schemes must target the specific interaction mechanisms available to those particles [10]. For axions there are a number of experiments searching for their conversion in magnetic fields to microwaves [11] and for evidence of axion production in the Sun [12]. For WIMPs there is the possibility of direct scattering of WIMPs with nuclei (via a weak interaction) producing a measurable energy deposit and of seeing the products from WIMP/anti-WIMP annihilations [13, 14]. There is also the prospect, of course, that beam collisions at LHC may artificially produce some new unknown particles likely to have some linkage to dark matter [15]. Here the focus will be on the direct detection of WIMP-like particles using underground experiments.

The direct detection of a new particle species constituting the dark matter of our Galaxy would have enormous scientific impact. Not only would it confirm that the dark matter in the Universe is indeed in a particle form, it would also enable the study of the particles to find out if they existed within a framework leading to supersymmetry or not. Finally, if their velocity distribution could be determined, using some of the new directional technologies coming on line, this would provide information about our galaxy dynamics.

This review will now focus on direct detection results which have come out over past few years and the emphasis will be on implications for the dark matter itself rather than more specific technological issues.

2. Recent Direct Detection Highlights

A number of new results have been announced over the past few years impacting on many aspects of direct dark matter detection. A significant number relate to the claimed positive detection of an annual modulation from the DAMA experiment and these will be summarised first. In addition to these there has then been further progress on sensitivity of experiments looking for elastic WIMP scattering with both spin-independent and spin-dependent couplings. There have even been some first results on spin-dependent limits from directional detectors

2.1. The DAMA annual modulation

In 2010 the DAMA collaboration announced their latest results bringing the total combined exposure of their NaI experiment to 1.17 ton.years with 13 annual cycles [16]. Their observed annual modulation has persisted through a number of experiment stages and upgrades and is now claimed at the 8.9σ confidence level and its phase is consistent with that expected for dark matter particles. However if the signal is due to dark matter particles it is clear that they can not be the standard 'WIMPs' otherwise a number of the other direct search experiments would already have confirmed their presence. There are two popular variants which have been put forward and these are low-mass WIMPs [17] and WIMPs showing predominantly inelastic scattering [18].

2.1.1. Low-mass WIMPs The elastic scattering of low-mass WIMPs transfers relatively small amounts of energy partly due to the mass mismatch with the target nuclei and partly as they carry less kinetic energy in the first place. Hence the most sensitive experiments are those with the lowest energy thresholds. In the DAMA experiment using NaI scintillators the annual modulation is only seen in their lowest energy channels between $2-6\,\mathrm{keV}$. Recently three other experiments have claimed signals which seem broadly consistent with low-mass WIMP scattering from Na as an interpretation of the DAMA signal. The three experiments are CDMS-II whose most recent result has two events within the WIMP search box [19], CoGent which is showing an unexplained background continuum in its germanium detectors in the low energy region [20], and CRESST which has been reporting unexplained oxygen nuclear recoil events in its calcium tungstate crystals. Figure 1, taken from [21], shows how all these results compare with each other. In addition to the results already mention the figure has a few others which are presented as *upper* limits. These are from an earlier data set from CDMS [22] and a new result from XENON100 [23]. However these rely on fairly extensive extrapolations to very low recoil energies where calibrations are much less secure particularly when there is a quenching mechanism for the primary signal [24] as is the case for xenon-based two-phase detectors using both a primary scintillation signal and a secondary ionisation signal. The remaining curve shown in the figure is from XENON10 and this uses an analysis avoiding use of the primary signal by relying only on the secondary ionisation channel [25]. It can be seen from Fig. 1 and discussion within [21] that the evidence is not definitive either way given both the nature of the experimental data and their confidence limits and the systematic uncertainties introduced by uncertain astrophysical parameters. Low-mass WIMPs remain on the list of possibilities and it is clear that more focus will come to bear on them as new data are acquired with more emphasis on studying this part of the WIMP parameter space.

2.1.2. Inelastic WIMP scattering Another variant on the 'standard' neutralino WIMP was introduced in an attempt to reconcile the DAMA data with other experiments, and this variant

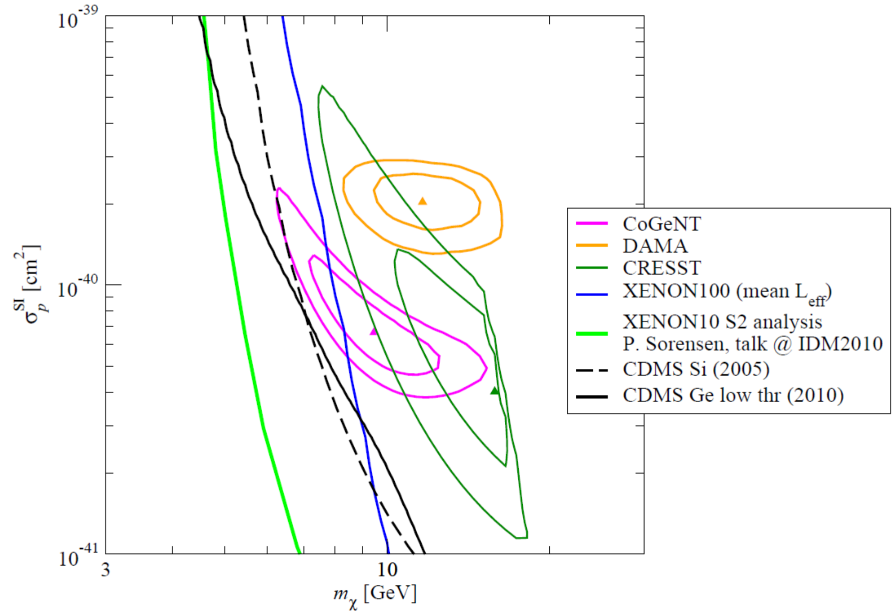

Figure 1. Summary of results relevant to low-mass WIMPs, taken from [21].

allowed for inelastic scattering by incorporating an energy level structure within the WIMP. This inelastic Dark Matter (iDM) [18] can only scatter in a process that leaves it in the excited state and this changes the energy and momentum conservation such that only the highest energy WIMPs from the quasi-Maxwellian distribution can be scattered and the recoiling nucleus then shows a peaked spectrum at higher energies than expected for elastic scattering [26]. The energy deposits are still expected to be from the nuclear recoils, at least in the standard iDM scenario. The latest results to have been published on searches for iDM signatures have been from CDMS [19], XENON10 [27], and ZEPLIN-III [28], together with an analysis based on CRESST data [29]. Only upper limits (exclusion plots) have been obtained so far and there are three important parameters which are allowed to vary in the analyses. These are the escape velocity for WIMPs in our Galaxy, the WIMP mass and its energy splitting. Figure 2 shows the exclusion plot from ZEPLIN-III for the most unfavourable choice of escape velocity, 600 km/s. It can be seen that over the full range of mass and splitting which is consistent with the DAMA data (filled area within the plot) the ZEPLIN-III data exclude iDM at least at the 88% level. The analysis based on CRESST data claims an even higher significance of exclusion but for a nuclear species less similar to the Iodine implicated in the DAMA results and hence subject to more systematic uncertainties. Hence it would seem that the iDM scenario is effectively ruled out. However some recent 'escape clauses' have been put forward which include a suggestion that it is actually the thallium doping in the DAMA crystals which is scattering the WIMPs [30] and/or that maybe the WIMPs have some level of magnetic coupling which particularly favours iodine [31]. In this last case an electromagnetic WIMP decay mode would be expected with a time constant of several tens of microseconds which is within the measurement time window of many existing experiments and could have caused many events to fail cuts, but on the other hand can be searched for relatively easily.

2.2. SUSY WIMP searches

The detection principle of most direct search experiments is still predicated on WIMPs which generically come out of frameworks such as supersymmetry and the assumption is that there will be some elastic scattering probability with target nuclei. Two situations are considered; one in which the scattering adds coherently from all the nucleons in the nucleus and the other

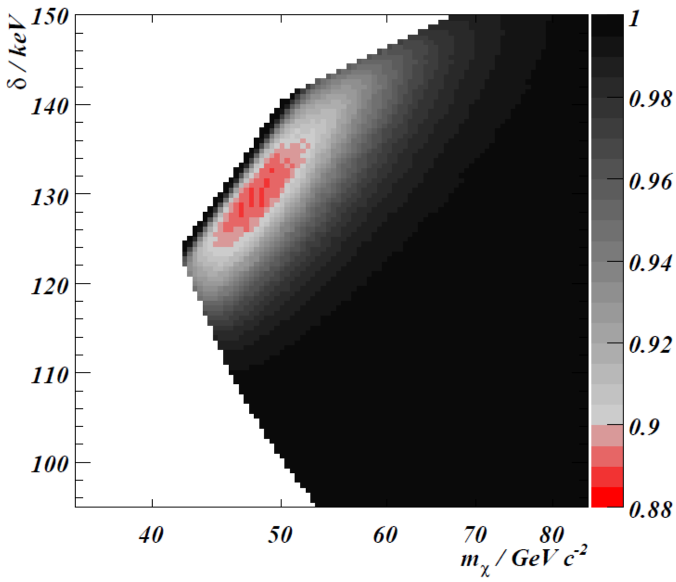

Figure 2. Exclusion plot from ZEPLIN-III provided most stringent iDM limits, taken from [28].

in which it is only from the unpaired nucleons. These are often referred to as spin-independent (SI) and spin-dependent (SD) respectively and results are displayed in terms of cross-sections per nucleon in the case of SI and cross-sections per proton or neutron for SD.

2.2.1. Spin-independent elastic scattering The past few years have been extremely active and there have been new results announced from ZEPLIN-III [32], CRESST [33], CDMS [19], EDELWEISS-II [34] and XENON100 [23]. All of the new results have been upper limits and Fig. 3 shows a compilation of results. Also shown in the figure are shaded areas which are ascribed some theoretical favouritism within a constrained minimal supersymmetry model (CMSSM) [35]. This gives the experimental teams some target to aim for and some of the existing upper limit curves are now within an order of magnitude or so of significantly impacting on these areas.

2.2.2. Spin-dependent elastic scattering New SD upper limits have been published by ZEPLIN-III [36], SIMPLE-II [37], COUPP [38], PICASSO [39], NEWAGE [40], DMTPC [41] and DRIFT-II [42]. Figure 4 shows compilations of some of these data. On the left-hand side is a plot taken from [36] which shows a relatively recent summary of results for both WIMP-proton and WIMP-neutron upper limits, with the DAMA detection region also shown if interpreted as a SD WIMP scattering signal. The shaded region at the bottom of both plots indicates where the favoured CMSSM areas lie on these plots. The curve labelled 'SuperK' is an indirect detection upper limit which is model dependent and should not really be compared with the direct detection limits. On the right-hand side is shown a more recent plot with the new limits for WIMP-proton SD scattering coming from COUPP and PICASSO. Still not shown are the new WIMP-proton result from SIMPLE-II which is roughly a factor of 2 better than the latest COUPP curve and with a minimum at slight lower mass. Significantly the directional detectors NEWAGE, DMTPC and DRIFT-II have also recently announced SD WIMP-proton upper limits. Whilst these are not yet competitive with the best it is encouraging to see this technology making good progress as a very powerful diagnostic/study tool in the longer term. The DRIFT-II upper limit is just above the COUPP (2007) curve for masses above 100 GeV/c^2 . The NEWAGE and DMTPC are about 4 orders of magntidue above that.

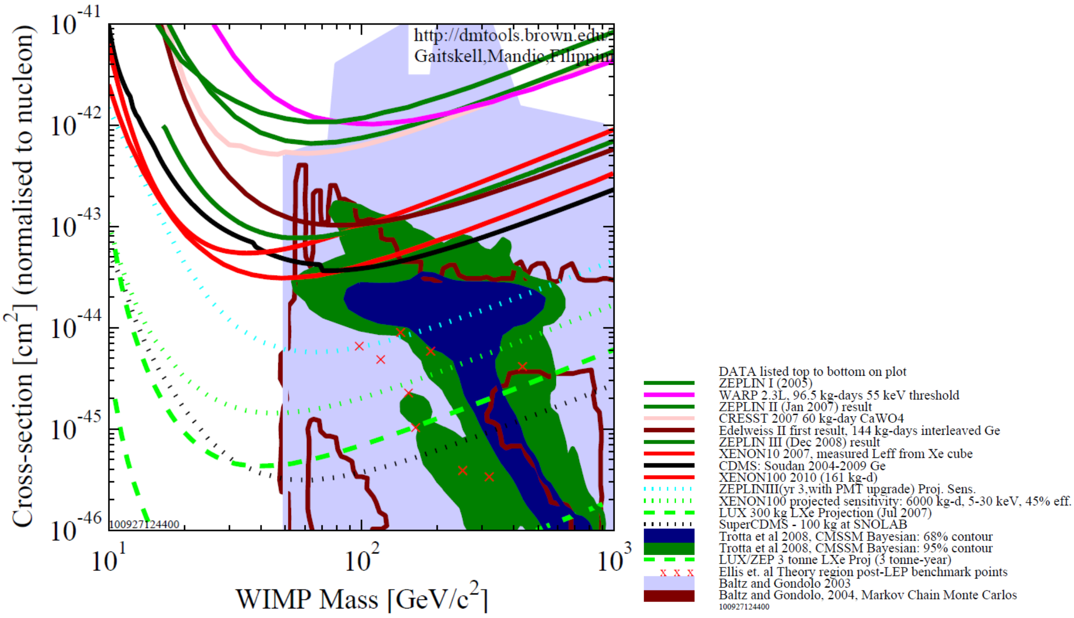

Figure 3. Current experimental upper limits to WIMP-nucleon spin-independent cross-section.

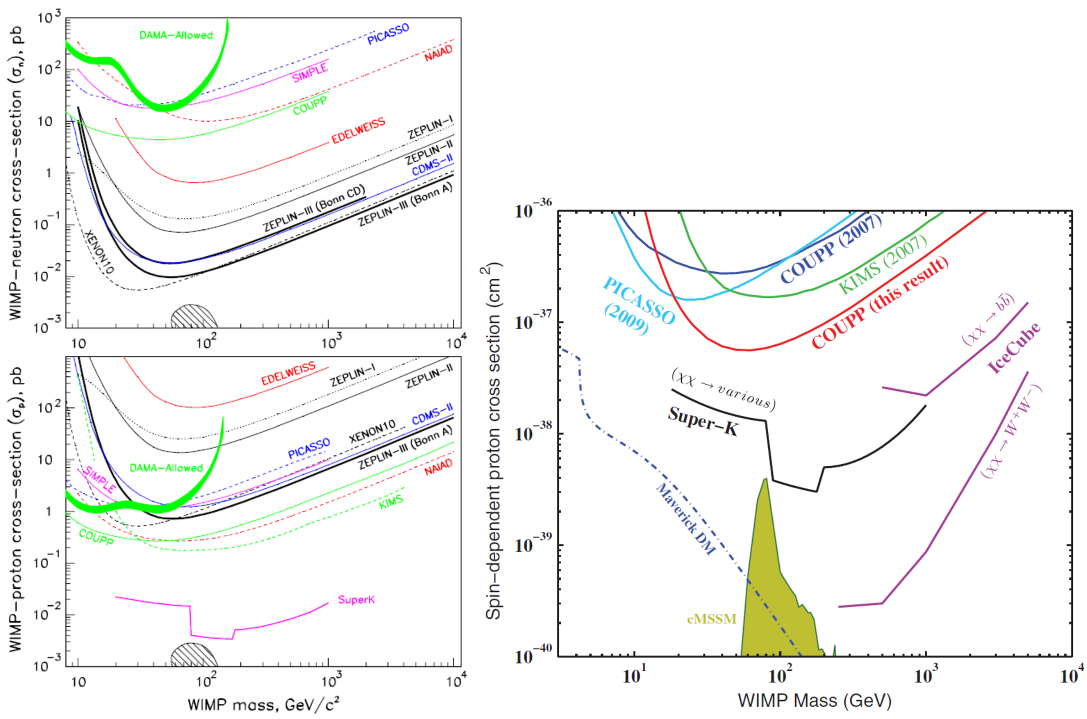

Figure 4. Current experimental upper limits to WIMP-nucleon spin-dependent cross-section. On the left is shown a recent compilation taken from [36] for both WIMP-proton and WIMP-neutron cross-sections. On the right is an updated plot showing some of the more recent progress made for WIMP-proton cross-sections taken from [38]

3. A Medium-Term Forward Look

A number of new experimental runs are underway or about to start with the likelihood that sensitivities will improve significantly over the next few years. Experiments which are currently taking new data with the short-term prospect of improvements include an upgraded ZEPLIN-III with lower background photomultipliers and a veto system [43] and XENON100 [23]. Other new experiments with significant mass targets which will come on-line shortly include XMASS [44] and LUX350 [45]. The COUPP experiment will run underground with a larger successor in preparation [46]. In addition a number of new experiments are in advanced states of build including DEAP3600 [47] and MiniCLEAN [48]. Figure 3 has projected sensitivity curves for the two running experiments, ZEPLIN-III and XENON100, as well LUX350. Between them they promise up to 2 orders of magnitude improvement in sensitivity which will explore the greater fart of the CMSSM favoured parameter space. The prospects of a positive detection are very bright and with first results now trickling from the LHC [49], candidate events from LHC together with events from direct experiments would make a very persuasive argument that Dark Matter is indeed in particle form.

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