

Part 15

Direct Detection of Elementary Particles

WIMP direct detection and halo structure

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Abstract. Weakly Interacting Massive Particle (WIMP) direct detection experiments are just reaching the sensitivity required to detect Galactic dark matter in the form of neutralinos (or indeed any stable weakly interacting particle). Detection strategies and data analyses are often based on the simplifying assumption of a standard spherical, isothermal halo model, but observations and numerical simulations indicate that galaxy halos are in fact triaxial and anisotropic, and contain substructure. The annual modulation and direction dependence of the event rate (due to the motion of the Earth) provide the best prospects of distinguishing WIMP scattering from background events, however these signals depend sensitively on the local WIMP velocity distribution. I briefly review the status of WIMP direct detection experiments before discussing the dependence of the annual modulation signal on astrophysical input, in particular the structure of the Milky Way halo, and the possibility that the local WIMP distribution is not smooth.

1. WIMPs a (very) brief introduction

Any stable weakly interacting massive particle (WIMP) in thermal equilibrium in the early universe will generically have an interesting present day density, $\Omega_{\text{WIMP}} \sim \mathcal{O}(\Omega_{\text{CDM}}) \approx 0.3$. Furthermore supersymmetry provides a natural WIMP candidate, the lightest supersymmetric particle, the neutralino. There are basically two methods of detecting WIMPs: indirect detection, which involves detecting the products of WIMP annihilation (γ , ν , \bar{p} , e^+), and direct detection, which involves detecting the energy deposited in a detector due to elastic scattering of WIMPs on the detector nuclei. I will focus on WIMP direct detection. For a review of particle dark matter see e.g. Bergström (2000).

2. Direct detection signals

Direct detection experiments are just reaching the sensitivity required to detect WIMPs. The expected event rates are very small ($\mathcal{O}(10^{-5} - 10)$ counts $\text{kg}^{-1} \text{day}^{-1}$) and distinguishing a putative Weakly Interacting Massive Particle (WIMP) signal from backgrounds, such as neutrons from cosmic-ray induced muons or natural radioactivity, is crucial. The event rate depends on the velocity of the detector relative to the Galactic rest frame and the Earth's motion (as

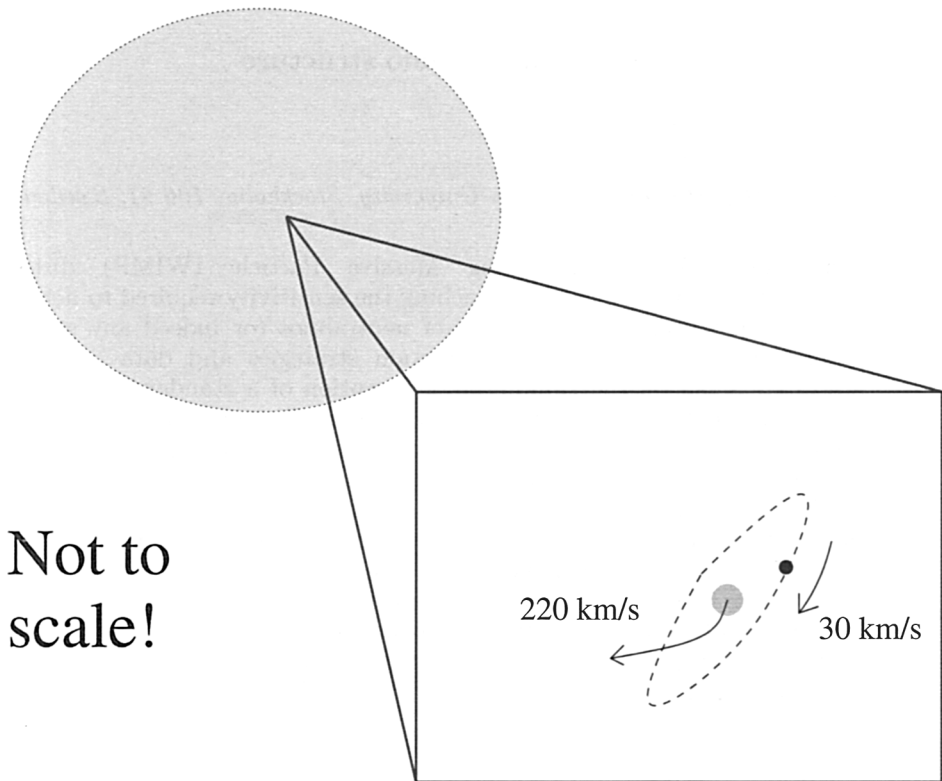


Figure 1. A sketch of the motion of the Earth. The Sun moves about the Galactic centre with circular velocity $v_c \approx 220 \text{ km s}^{-1}$, while the Earth orbits the Sun with speed $v_e = 30 \text{ km s}^{-1}$ in a close to circular orbit, inclined at an angle of roughly 60° to the Galactic plane.

shown in Fig. 1) provides two potential WIMP smoking guns. Firstly the event rate is direction dependent, being greatest in the forward direction (Spergel 1988). Secondly the Earth's velocity, and hence the event rate, varies annually due to the Earth's orbit about the Sun (Drukier, Freese & Spergel 1986). If the local WIMP velocity distribution is isotropic then the annual modulation is roughly sinusoidal with a maximum in early June (when the Earth's speed with respect to the Galactic rest frame is largest) and amplitude of order a few percent.

There are currently more than 20 WIMP direct detection experiments being carried out around the world. I will focus on those currently producing the most interesting results. The DAMA collaboration, using NaI with an exposure of 108 000 kg-days at Gran Sasso, have detected an annual modulation with the properties described above which they interpret as a WIMP signal (Bernabei et al. 2003). Assuming a standard halo model with a Maxwellian velocity

distribution with dispersion $\sigma = 270 \text{ km s}^{-1}$ (corresponding to an asymptotic halo circular velocity of $v_c = 220 \text{ km s}^{-1}$, they find a best fit WIMP mass $m_\chi \approx 50 \text{ GeV}$ and scattering cross-section $\zeta\sigma \approx 7 \times 10^{-46} \text{ m}^2 \text{ s}^{-1}$. Also of interest are three other experiments using different targets and a different strategy: Cryogenic Dark Matter Search (Ge target, 28 kg-days exposure at the Stanford Underground Facility (Akerib et al. 2003)), Edelweiss (Ge, 32 kg-days at Modane (Benoit et al. 2002)) and Zeplin I (liquid Xe, 230 kg-days at Boulby (Barton et al. 2002)). With their smaller exposures these experiments aim to constrain the mean WIMP scattering rate, rather than attempting to detect the annual modulation signal. The full DAMA allowed region of WIMP mass cross-section parameter space is shown in Fig. 2, along with the exclusion limits from the CDMS, Edelweiss and Zeplin I experiments. The allowed region and the exclusion limits are all calculated assuming the standard halo model as described above and, taken at face value, the allowed region appears to be incompatible with the exclusion limits.

3. Local velocity distribution

The differential elastic scattering rate depends on the local WIMP density, ρ_χ , and the normalised WIMP speed distribution, in the rest frame of the detector, f_v , as

$$\frac{dR}{dE} \propto \rho_\chi \int_{v_{\min}}^{\infty} \frac{f_v}{v} dv, \quad (1)$$

where v_{\min} is the minimum WIMP velocity which can kinematically produce a nuclear recoil of energy E .

As discussed above, data analyses usually assume that WIMPs have an isotropic Maxwellian velocity distribution (i.e. that the Milky Way halo is an isothermal sphere), but observed and simulated halos are triaxial, anisotropic and contain substructure. Exclusion limits, which depend on the time averaged speed distribution, vary by of order tens of percent when triaxial and anisotropic halo models (with parameters chosen to match the properties of observed and simulated halos) are considered, with the shift being experiment dependent (Green 2002).

The annual modulation signal is far more sensitive to the WIMP velocity distribution, and Belli et al. (2002) found that considering “non-standard” halo models led to a large increase in the size of the region of $m_\chi - \sigma$ parameter space consistent with the DAMA annual modulation signal. Accurate calculation of the shape and phase of the annual modulation signal requires all three components of the Earth’s velocity with respect to the Sun, and also the Sun’s motion with respect to the Local Standard of Rest, to be taken into account (Green 2003). Significantly, if the velocity distribution is not close to isotropic then the phase and shape of the annual modulation change and become incompatible with the DAMA annual modulation signal (Copi & Krauss 2003; Fornengo & Scopel 2003; Green 2003).

¹ $\zeta = \rho_\chi / (0.3 \text{ GeV cm}^{-3})$ parameterizes the uncertainty in the local WIMP density ρ_χ .

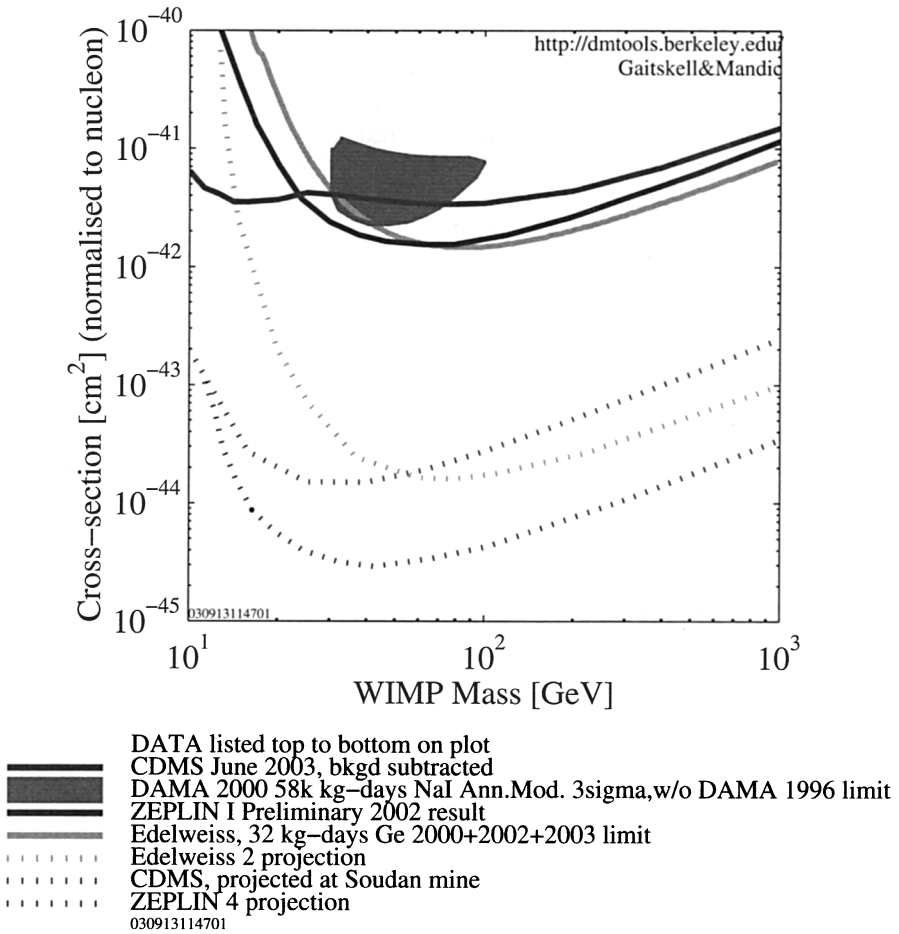


Figure 2. Selected experimental results, plotted using the interactive limit plotter at <http://dmttools.berkeley.edu/limitplots>, which assumes the standard halo model. The solid region is the allowed region corresponding to the DAMA annual modulation signal, the solid lines the current exclusion limits from the CDMS, Edelweiss and Zeplin I experiments and the dotted lines the projected future sensitivities of these experiments.

4. (Very) Small scale structure

The velocity distributions of analytic halo models are derived via the Jeans equations, which assume that the phase space distribution function has reached a steady state. In Cold Dark Matter (CDM) cosmologies structure forms hierarchically, with galaxy halos forming from the merger and accretion of smaller subhalos (which themselves formed from even smaller subhalos), and the local velocity distribution may not have reached a steady state. Helmi, White & Springel (2001) examined the velocity distribution of particles within a 4 kpc box located 8 kpc from the centre of a simulated Milky Way-like halo and found that, apart from a stream of fast moving particles from a late accreting subhalo, the velocity distribution was well approximated by a multi-variate gaussian. The WIMP direct detection event rate, however, depends on the dark matter distribution on sub-mpc scales, many orders of magnitude smaller than the scales probed by even the highest resolution galaxy simulations. Moore et al. (2001) argued that the local velocity distribution will depend sensitively on the structure and merger history of the first halos to form, while Stiff & Widrow (2003) have used a novel reverse technique to probe the velocity distribution at a single point in a simulation, finding that it appears to consist of a series of discrete peaks.

The power spectrum on very small scales is an essential input for any attempt to study the fate of the first subhalos to form and the dark matter distribution on very small scales. For neutralino CDM, collisional damping and free-streaming erase power on comoving scales smaller than of order a pc (Hofmann, Schwarz & Stöcker 2001; Green, Hofmann & Schwarz 2003), and the first subhalos to form have mass of order $10^{-6} M_{\odot}$ (Green et al. 2003), 12 orders of magnitude lighter than the smallest subhalos resolved in galaxy simulations.

Streams of WIMPs with small velocity dispersion (from late accreting subhalos which pass through the solar neighbourhood or from the remnants of the first dense subhalos to form, should they survive to the present day) will produce steps in the differential event rate, the position and amplitude of which vary annually.

5. Summary

Direct detection of WIMPs would confirm the existence of Cold Dark Matter (and probe particle physics beyond the standard model). Accurate astrophysical input (not just the local WIMP velocity distribution, but also the motion of the detector with respect to the Galactic rest frame) is required when calculating the WIMP annual modulation signal. Analyzing data assuming a sinusoidal modulation with fixed phase could lead to erroneous constraints on, or best fit values, for the WIMP mass and cross-section; even worse, a WIMP signal could be overlooked. On the other hand using unrealistic halo models or parameter values could lead to overly restrictive exclusion limits or a misleadingly large range of allowed values of the WIMP mass and cross-section. Finally if WIMPs are directly detected then we will be able to probe the local velocity distribution and perhaps learn about the (sub-)structure of the Milky Way halo.

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