ON THE USE OF THE ESCAPE SPEED ESTIMATES IN SETTING DARK MATTER DIRECT DETECTION LIMITS

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The knowledge of the high velocity tail of the WIMP velocity distribution has a strong impact on the way direct detection (DD) may constrain or discover light WIMPs in the GeV mass range. Recently, there have been important observational efforts to estimate the so-called Galactic escape speed at the position of the Earth, for instance the analysis published in early 2014 by the RAVE Collaboration [1], which is of interest in the perspective of reducing the astrophysical uncertainties in DD. Nevertheless, these new estimates cannot be used blindly as they rely on assumptions in the dark halo modeling, which induce tight correlations between the escape speed and other local astrophysical parameters (e.g. the local circular speed and dark matter density). We make a self-consistent study of the implications of the RAVE results on DD assuming isotropic DM velocity distributions, both Maxwellian and ergodic. Taking as reference the experimental sensitivities currently achieved by LUX, CRESST2, and SuperCDMS, we show that the DD constraints on WIMPs (and associated uncertainties) are slightly stronger (moderate).

1 Introduction

DD aims at detecting WIMPs via their scattering off nuclei. A careful investigation of the physics affecting the low WIMP mass region of the parameter space for the spin-independent interpretation of this scattering is fundamental, because at around 10 GeV signal-like events reported by some experiments (e.g. DAMA), are at odds with limits. Different effects impact DD limits at low WIMP masses, particularly relevant are the local escape speed from the Milky Way (MW) and the local circular speed, as the sum of both defines the maximum speed in the observer's frame. While the latter has been studied in depth by many authors, this is not the case for the former. A method to measure it is to use nearby high-velocity stars, that are supposed to trace the high velocity tail of the stars speed distribution, which should vanish at the escape speed. Following this approach, the RAVE collaboration published in 2014 the latest estimate of this quantity [1] (P14). Directly using those results to compute DD limits is straightforward, but this would lead to inconsistent results because neglecting the hypotheses these estimates rely upon. In our work [2] we analyzed these assumptions and derived a self-consistent model for the local phase-space of the DM, which consistently takes into account the correlations between the astrophysical parameters. We computed the corresponding exclusion curves, with associated uncertainties, for the most constraining experiments at the moment of writing.

2 Milky Way Mass Model from Rave analysis

P14 analysis is based on a sample of $\sim$ 100 stars mostly from the RAVE catalog. The escape speed for a star in $\vec{r}$ is defined as $v_{\rm esc}(\vec{r}) \doteq \sqrt{2\left|\Phi(\vec{r})\right|}$, $\Phi(\vec{r})$ being the gravitational potential GP of the MW. To derive observational constraints on $v_{\rm esc}$ from stellar velocities P14 needed to make an assumption on the shape of the high velocity tail of the stars speed distribution, namely $f_\star(v) \propto (v_{\rm esc} - v)^k$, with k calibrated from cosmological simulations. To estimate $v_{\rm esc}$ at the position of the Sun, P14 rescaled the $v_{\rm esc}$ of the observed stars using the GP of the MW, for which a particular MW mass model (MWM) had to be assumed and where only the DM halo parameters were left free. They thus transformed the line of sight velocity $v_{||}(\vec{r})$ of each star according to $v'_{||}(\vec{r}) = v_{||}(\vec{r}) \times \sqrt{\left|\Phi(\vec{r}_\odot)/\Phi(\vec{r})\right|}$ ($\vec{r}_\odot$ being the position of the Sun) before performing a likelihood analysis. This introduces a dependence on the MWM and thus correlations in the astrophysical parameters relevant to DD, that one must take into account when using P14 results.

P14 fixed the Sun's distance from the Galactic center $r_\odot = 8.28$ kpc [3], the peculiar motion of the Sun [4], and repeated the analysis for 3 cases: $v_{\rm c} = 220$ km/s, $v_{\rm c} = 240$ km/s and $v_{\rm c}$ free. Their MWM is based on a fixed baryonic model (disk and bulge), and on an NFW profile for the dark halo, the parameters of which were left free (the scale density ρ_s and radius r_s).

The speed of a body which is on a circular orbit on the Galactic plane can be computed from the GP of the MW as $v_{\rm c}^2(R,0) = R\frac{d\Phi(R,z)}{dR}\big|_{z=0}$ (here in cylindrical coordinates). The escape speed is set by the kinetic energy an object needs to get unbound, i.e. to reach a certain $R_{\rm max}$, it is thus defined as: $v_{\rm esc}(r_\odot) \doteq \sqrt{2\left|\Phi(r_\odot) - \Phi(R_{\rm max})\right|}$. To take into account the presence of nearby galaxies, the above distance is chosen to be $R_{\rm max} = 3R_{340}$ (where R_{340} is the radius at which the average DM density is 340 times the critical one). Since the assumed MWM has only two free parameters, a pair of ρ_s, r_s (or equivalently a pair of M_{340}, c_{340}) converts into a pair of $v_{\rm c}$, $v_{\rm esc}$. P14 results for the 3 cases mentioned above (prior or not on $v_{\rm c}$) can thus be converted in that plane, more relevant to DD; this is shown in Fig.1. It is clear from this figure that, because of the assumed MWM, the results of P14 induces strong correlations among $v_{\rm c}$, $v_{\rm esc}$ and the local DM density $\rho_\odot \doteq \rho_{DM}(r_\odot)$.

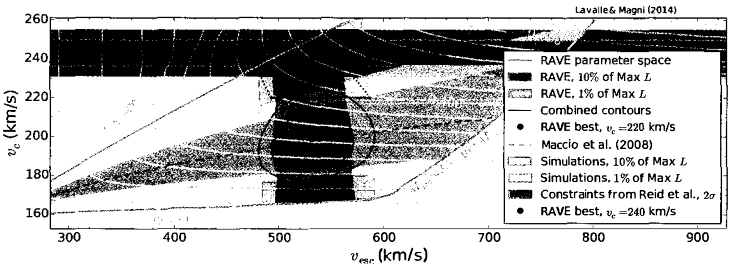

Figure 1 – P14 parameter space (yellow contours), with the regions where their likelihood for free $v_{\rm c}$ decreases down to the 10% (blue) and 1% (cyan) of its maximum, the best-fit P14 results for fixed $v_{\rm c} = 220$ km/s and $v_{\rm c} = 240$ km/s (with 90% C.L. error bars) and the curves of constant $\rho_\odot$ (in GeV/cm^3, in gray).

3 DD limits from P14 results and related astrophysical uncertainties

We translated the P14 estimates into DD limits, focusing on the spin-independent interpretation of the elastic scattering of a WIMP (mass m_χ) off a nucleus (atomic number A, mass m_A), and no isospin violation. The differential event rate per atomic target mass in an experiment is:

$$\frac{dR}{dE_r}(E_r) = \frac{\rho_\odot \sigma_{pSI} A^2}{2 m_\chi \mu_{\rm p}^2} F^2(E_r) \int_{|\vec{v}|>v_{min}(E_r)} d^3\vec{v}\frac{f_\oplus(\vec{v},t)}{|\vec{v}|}\ , \qquad (1)$$

with μ_p the WIMP-proton reduced mass, E_r the recoil energy, σ_p the WIMP-nucleon cross section, $F(E_r)$ the nuclear form factor (assumed of the Helm type), and $v_{min} = \sqrt{m_A E_r/(2\mu_p)}$ the minimal velocity that a WIMP needs to transfer to a nucleus the recoil energy E_r. $f_\oplus(\vec{v}, t)$ is the DM velocity distribution in the Earth reference frame. In addition, we take into account the experimental efficiency, energy resolution of the detector, fractions of atomic targets, isotopic compositions for each target element, and we take the time average of Eq. 1.

Usually, DD limits are computed by means of the Standard Halo Model (SHM), a set of assumptions in which the WIMP velocity distribution is a truncated Maxwell-Boltzmann (MB), $f(\vec{v}) \doteq \left[\exp(-|\vec{v}|^2/v_c^2) - \exp(-v_{esc}^2/v_c^2)\right] \bullet (v_{esc} - |\vec{v}|) / \left(N_{esc}\pi^{3/2}v_c^3\right)$, where N_{esc} is the normalization and $\bullet$ the Heaviside step function. The SHM also fixes $\rho_\odot^{SHM} = 0.3$ GeV/cm^3, $v_c^{SHM} = 220$ km/s and $v_{esc}^{SHM} = 544$ km/s. Because of the by-hand cutoff at the escape speed, the MB distribution is no more a solution of the Jeans equation, so it is not even self-consistent.

In order to build a self-consistent velocity distribution, we are going to consider functions of integrals of motion, which automatically satisfy the Jeans equation. Assuming spherical symmetry and velocity isotropy, the phase-space distribution becomes a function of the total energy $E = m\Phi + \frac{1}{2}mv^2$ only, which is an integral of motion. Such systems are called ergodic [5]. Under these assumptions we can use the Eddington equation [6], which allows to compute the phase-space distribution for the DM directly from the assumed GP of the Milky Way Φ and the DM density profile ρ. This equation reads:

$$f(\epsilon) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^\epsilon \frac{d^2\rho}{d\Psi^2}\frac{d\Psi}{\sqrt{\epsilon - \Psi}} + \frac{1}{\sqrt{\epsilon}}\left(\frac{d\rho}{d\Psi}\right)_{\Psi=0}\right], \tag{2}$$

where $\Psi = -\Phi + \Phi_0$ is the relative GP of the MW, $\epsilon = -E/m + \Phi_0$ the relative energy per unit mass and Φ_0 a constant. The local velocity distribution for the DM is given by $f_{erg}(v, r_\odot) = f(\epsilon)/\rho(r)$. This procedure can be applied only to spherically symmetric systems, and the assumed MWM is not, because of the disk, but since this does not dominate it can be shown that we can force spherical symmetry while not affecting the circular velocity at the Sun position.

4 Results and discussion

We converted P14 results and used them to derive DD limits, focusing on LUX [7] (Xe), SuperCDMS [8] (Ge) and CRESST II [9] (multi-target). The changes with respect to the SHM are both in the WIMP velocity distribution and in $\rho_\odot$. Eq. 1 tells us how the astrophysical parameters affect the exclusion curves. The sum $v_{esc} + v_c$ impacts on the position of the asymptote of the limit at low WIMP mass and v_c on the position of the maximum of sensitivity of the experiment on the m_χ axis, while $\rho_\odot$ produces a linear vertical translation of the entire curve.

We considered the best-fit point with prior $v_c = 240$ km/s, likely the most motivated given recent estimates (e.g. [10]). Fig.2 shows the exclusion curves with associated 90% C.L. uncertainties for this configuration. Comparing our results with those obtained for the SHM, we find that the former are more constraining by $\sim 40\%$ in a wide range of high WIMP masses, due to the P14-inferred value of $\rho_\odot = 0.43 \pm 0.05$ GeV/cm^3, higher than the SHM one. We also show the effect of using a MB velocity distribution (instead of a more consistent ergodic one). This impacts especially at low WIMP masses, because of significant differences between the high-velocity tail of the two distributions. The uncertainties saturate at $\sim \pm 10\%$ at high WIMP masses, value set by the allowed range in $\rho_\odot$, and they degrade toward very low WIMP masses, where the maximum possible recoil energy approaches the threshold energy. Some of the bumps in Fig.2 in the case of CRESST2 come from the presence of more than one target nucleus (the others from applying the Maximum Gap Method). This shows that employing different target nuclei in a detector helps to reduce the astrophysical uncertainties (as well as combining different experiments).

We consider also the v_c free analysis of P14. We do not use the same prior on the concentration of the DM halo of P14 (pink in Fig.1) but instead we combine the region provided by the v_c free analysis of RAVE in the plane of Fig.1, with the constraint on v_c published in [10], independent on any MWM. That work obtained $v_c = 243 \pm 12$ km/s at 2σ (the green band in Fig.1). In the above region the allowed values of the local DM density reach up to $\rho_\odot = 0.57$ GeV/cm^3, i.e. they are higher than those of the SHM, but in agreement with those found in recent studies [11]. These results, translated into DD limits, have a behavior qualitatively similar to the one already described for the $v_c = 240$ km/s, but with uncertainties that saturates at values of $\pm 20\%$, due to the allowed range of $\rho_\odot \in [0.37, 0.57]$ GeV/cm^3.

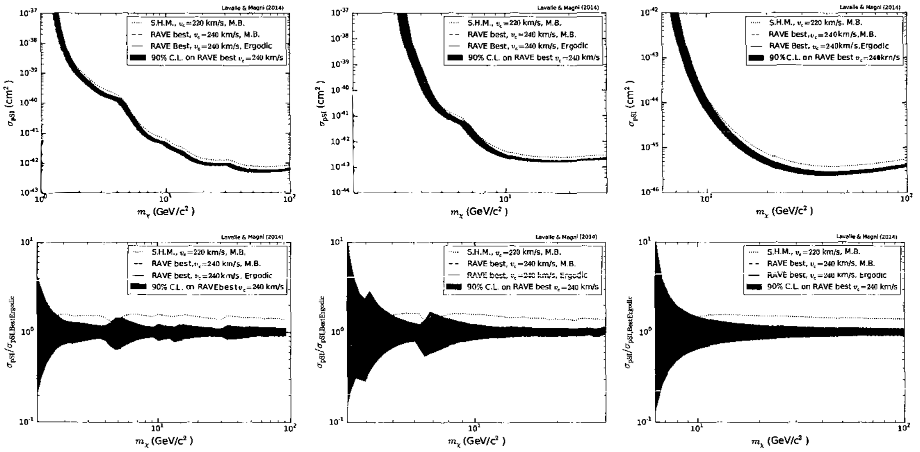

Figure 2 – Experimental 90% C.L. exclusion curves, calculated using the P14 result for the $v_c = 240$ km/s analysis (upper: absolute, lower: relative). From left to right: CRESST2, SuperCDMS, LUX.

5 Conclusions

We presented a method to use the local escape speed estimates of P14 in deriving DD limits. A naive use of these estimates would neglect the underlying assumptions, and thus the correlations they induce among the astrophysical parameters and the DM velocity distribution. We found that a consistent use of these estimates implies large values for $\rho_\odot$, so more constraining exclusion curves, and evaluated the associated uncertainties. We are generalizing this work to anisotropic velocity distributions and testing our methods on cosmological simulations.

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