A review on the discovery reach of Dark Matter directional detection

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Abstract. Directional detection of galactic Dark Matter offers a unique opportunity to identify Weakly Interacting Massive Particle (WIMP) events as such. Depending on the unknown WIMP-nucleon cross section, directional detection may be used to: exclude Dark Matter, discover galactic Dark Matter with a high significance or constrain WIMP and halo properties. We review the discovery reach of Dark Matter directional detection.

Several projects of directional detectors [1–9] are being developed for Dark Matter search. There is in particular a worldwide effort toward the development of a large TPC devoted to this goal [1–7]. Since the pioneer paper of D. N. Spergel [10], the contribution of directional detection to the field of Dark Matter has been addressed through a wealth of studies [11–34]. Depending on the unknown WIMP-nucleon cross section, directional detection may be used to: exclude Dark Matter [13,17], discover galactic Dark Matter with a high significance [12,15,25] or constrain WIMP and halo properties [14,26,27].

1. Directional framework

Dark Matter directional detection aims at measuring both the energy (\(E_r\)) and the 3D track (\(\Omega_r\)) of a recoiling nucleus following a WIMP (Weakly Interacting Massive Particle) scattering. The double-differential spectrum is given by

\[
\frac{d^2 R}{dE_r d\Omega_r} = \frac{\rho_0}{4\pi m_\chi m_r^2} \left[ \sigma_0^{SI} F_{SI}^2 (E_r) + \sigma_0^{SD} F_{SD}^2 (E_r) \right] \hat{f}(v_{\text{min}}, \hat{q})
\]

where \(m_\chi\) is the WIMP mass, \(\rho_0\) the local WIMP density, \(m_r\) the reduced WIMP-nucleus mass, \(\sigma_0^{SI}\) (resp. \(\sigma_0^{SD}\)) the spin independent (resp. dependent) WIMP-nucleus cross section at zero momentum transfer, \(F_{SI}\) (resp. \(F_{SD}\)) the spin independent (resp. dependent) form factor, \(v_{\text{min}}\) the WIMP minimal velocity to produce a recoil and \(\hat{f}\) the three-dimensional Radon transform of the WIMP velocity distribution \(f(\vec{v})\), given by [34]

\[
\hat{f}(v_{\text{min}}, \hat{q}) = \int \delta(v_{\text{min}} - \vec{v} . \hat{q}) f(\vec{v}) \, d^3 v
\]
The expression of the WIMP velocity distribution \( f(\vec{v}) \) depends on the Milky Way halo model. For an isotropic isothermal sphere, it reads

\[
f(\vec{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp\left(\frac{- (\vec{v} + \vec{v}_\odot)^2}{2\sigma_v^2}\right)
\]  

where \( \vec{v}_\odot \) is the Sun velocity vector and \( \sigma_v \) is the WIMP velocity dispersion.

It follows that the WIMP event distribution is expected to present an excess in the direction of motion of the Solar system \(-\vec{v}_\odot\), which happens to be roughly in the direction of the constellation Cygnus \((\ell_\odot = 90^\circ, b_\odot = 0^\circ\) in galactic coordinates). As shown in [12], the WIMP-induced recoil distribution presents a dipole-feature (fig. 1) while the background distribution [35] is expected to be isotropic in the galactic rest frame. In fact, several directional features provide a clear and unambiguous difference between the WIMP signal and the background one, e.g. dipole [12], ring-like\(^1\) [28], aberration\(^2\) [29] and daily modulation of the WIMP direction.

The event spectrum (1) depends on the particle model \((m_\chi, \sigma_{SI}^0 \text{ and } \sigma_{SD}^0)\) and on the Dark Matter halo model \((\rho_0, f(\vec{v}))\). For direction-insensitive Dark matter search \((dR/dE_r)\), this high number of free parameters may induce a bias due to wrong halo model assumption when constraining the WIMP properties (mass and cross section), see e.g. [36]. Thanks to the measurement of the double-differential spectrum (1), directional detection may either account for astrophysical uncertainties [15,16] or even constrain astrophysical parameters [14,26,27].

Low pressure TPC cannot be arbitrarily large and are hence exposure-limited. This is the reason why most directional detectors are using a target made of a light nucleus with non-vanishing spin, that makes them sensitive to the spin dependent interaction \((\sigma_{SD}^0)\) for which current limits are weaker. As shown in [12], all target nuclei present\(^3\) an equivalent directional signal, when adjusting the energy range. For low pressure TPC, \(^{19}\)F is usually considered as the golden target for SD directional detection.

2. Dark Matter exclusion

Two dedicated exclusion methods have been developed for directional detection [13, 17]. S. Henderson et al. have proposed [17] a 2D generalization of the maximum gap [37], first proposed for direction-insensitive Dark Matter detection in order to deal with an unknown background contamination. It is based on the double-differential spectrum (1) and allows to account for all information given by a directional detector. However, the energy spectrum of the

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\(^1\) maximum of the recoil rate in a ring around the mean recoil direction.

\(^2\) annual variation of the mean recoil direction.

\(^3\) at sufficiently low recoil energy when the form factor can be approximated to unity.
background is unknown, while its angular spectrum is expected to be isotropic in the galactic rest frame. J. Billard et al. have taken advantage on this point [13] by proposing a likelihood method that deals only with the angular part of the spectrum in a given recoil energy range. This way, no assumption on the background energy dependence is needed and conservative exclusion limits may be provided. As shown in [13] a 30 kg.year CF$_4$ directional detector would be able to exclude spin dependent Dark Matter down to $\sim 10^{-6}$ pb in the background free case and $\sim 10^{-5}$ pb with a background rate of 10 events/kg/year (with sense recognition).

3. Dark Matter discovery

Beyond the exclusion strategy, directional detection may be used to discover Dark Matter [12, 15, 25]. First, one may prove that the directional data are not compatible with the background, by rejecting the isotropy hypothesis. With the help of unbinned likelihood methods [22] or non-parametric statistical tests on unbinned data [24], it has been shown that a few number of events $O(10)$ is required to reject the isotropy hypothesis. These methods [18] are based on a generic test of isotropy following the mean recoil deviation $<\cos \theta>$. For instance, the significance of an observed anisotropy can be evaluated by computing the distributions of $<\cos \theta>$ for both $H_0$ corresponding to the isotropic background hypothesis and $H_1$ the background plus signal hypothesis. The use of the variable $<\cos \theta>$ is particularly interesting in the case of directional detection of Dark Matter as the expected signal exhibits a dipole feature [12] hence maximizing the deviation between $H_0$ and $H_1$. One may also show that the data favor the background plus signal hypothesis ($H_1$). The method proposed in [12] is a blind likelihood analysis, that allows to identify a genuine WIMP signal as such. The proof of discovery is the fact that the recovered main recoil direction is pointing towards Cygnus, within a few degrees at 95% CL (see fig. 2), even with a sizeable background contamination and in the case of non standard Dark Matter halo models. This outlines the robustness of this parameter as an observable to prove a positive detection of Dark Matter with a directional detector. Even at low exposure, a high significance discovery is achievable for various detector configurations [15]. Moreover, it is possible to go beyond the standard Dark Matter halo paradigm [15] by accounting for most astrophysical uncertainties [38]. This is a key advantage for directional detection with respect to direction-insensitive strategy. Indeed, as the velocity dispersions are set as free parameters, induced bias due to wrong model assumption...
should be avoided. This is for instance the effect observed in [36], with a systematic downward shift of the estimated cross section, when assuming a standard isotropic velocity distribution fitting model whereas the input model is a triaxial one [39].

4. Dark Matter identification
For high WIMP-nucleon cross section, it is also possible to go further by constraining the WIMP and halo properties [14] thanks to a high dimensional multivariate analysis. Indeed, a 30 kg.year CF$_4$ directional detector would allow us to constrain the WIMP properties, both from particle physics (mass and cross section) and galactic halo (velocity dispersions). Figure 3 presents the constrains on $m_\chi$, $\sigma_n$ and $\beta$, the velocity anisotropy parameter, that may be obtained with a single 30 kg.year directional detector. Hence, directional detection may allow to constrain models beyond the standard model of particle physics as well as to discriminate between various halo models.

In a so-called post-discovery era, meaning the WIMP mass is supposed to be known to sufficient precision, it has been shown that directional detection may be used to infer Dark Matter phase space distribution in the solar neighborhood [26]. In particular, a parametrization of the functional form of the Dark Matter distribution is proposed, avoiding to rely on ansatzes. In this case, the coefficients of its moment decomposition on a model independent basis are the measurable quantities in a directional experiment. The conclusion of [26] is that about 1000 events are required for a good measurement of the underlying Dark Matter distribution.

5. Constraining Dark Matter and supersymmetry models
As shown in [11], directional detection provides a powerful tool to explore neutralino Dark Matter models as most MSSM configurations, and to a lesser extent for NMSSM ones, with a neutralino lighter than 200 GeV/c$^2$ would lead to a significance greater than $3\sigma$ (90\% CL) in a 30 kg.year CF$_4$ directional detector. No signal with such an exposure would lead to an exclusion of neutralinos up to 600 GeV/c$^2$.

The use of directional detection to constrain the astrophysical properties of Dark Matter has received much interest in the past years. Beyond the constraint on the Dark Matter halo properties [14] (e.g. velocity dispersions of the local WIMP velocity distribution), directional detection may be sensitive to the presence of substructures in the Milky Way halo, such as Dark Matter tidal streams (spatially localized), debris flow (spatially homogenized but with
velocity substructures) and a co-rotating dark disk. Such components of the local Dark Matter distribution may lead to distinctive features in the expected directional signal [16,27,31,32,40], although the conclusion depends strongly of their unknown properties. As a matter of fact, constraining their properties remains however a challenging task requiring a very low threshold and/or a large exposure, depending on the type of substructure.

6. Conclusion
Dark Matter directional detectors with large exposure (∼ 30 kg.years) offer a unique opportunity as they may lead, depending on the value of the unknown WIMP-nucleon cross section, either to a conclusive exclusion, a high significance discovery of galactic Dark Matter or even to an estimation of the WIMP properties. For larger exposures, directional detection may be a way to break the neutrino floor that stands as the ultimate limit for direct Dark Matter detection [41].

References
[1] S. Ahlen et al., Int. J. Mod. Phys. A 25 (2010) 1
[2] F. Mayet and D. Santos (Eds), Proceedings of the third workshop on Directional Detection of Dark Matter (CYGNUS 2011) : Aussois, France, June 8-10, 2011, EAS Publ. Ser. 53 (2012) pp.1.
[3] S. Ahlen et al., Phys. Lett. B695 (2011) 124-129
[4] E. Daw et al., Astropart.Phys. 35 (2012) 397-401
[5] S. E. Vahsen et al., EAS Publications Series 53 (2012) 43-50
[6] D. Santos et al., EAS Publications Series 53 (2012) 25-31
[7] K. Miuchi et al., Phys. Lett. B 686 (2010) 11
[8] A. Drukier, K. Freese, D. Spergel, C. Cantor, G. Church and T. Sano, arXiv:1206.6809
[9] T. Naka et al., EAS Publ. Ser. 53 (2012) 51
[10] D. N. Spergel, Phys. Rev. D 37 (1988) 1353
[11] D. Albornoz Vásquez, G. Belanger, J. Billard and F. Mayet, Phys. Rev. D 85 (2012) 055023
[12] J. Billard, F. Mayet, J. F. Macias-Perez and D. Santos, Phys. Lett. B 691 (2010) 156-162
[13] J. Billard, F. Mayet and D. Santos, Phys. Rev. D 82 (2010) 055011
[14] J. Billard, F. Mayet and D. Santos, Phys. Rev. D 83 (2011) 075002
[15] J. Billard, F. Mayet and D. Santos, Phys. Rev. D 85 (2012) 055006
[16] J. Billard, Q. Riffard, F. Mayet and D. Santos, Phys. Lett. B 718 (2013) 1171
[17] S. Henderson, J. Monroe and P. Fisher, Phys. Rev. D 63 (2001) 043507
[18] B. Morgan and A. M. Green, Phys. Rev. D 72 (2005) 123501
[19] B. Morgan, A. M. Green and N. J. C. Spooner, Phys. Rev. D 71 (2005) 103507
[20] C. J. Copi and L. M. Krauss., Phys. Rev. D 63 (2001) 043507
[21] C. J. Copi et al., Phys. Rev. D 75 (2007) 023514.
[22] C. J. Copi and L. M. Krauss, Phys. Lett. B 461 (1999) 43
[23] A. M. Green and B. Morgan, Phys. Rev. D 77 (2008) 023703
[24] A. M. Green and B. Morgan, Astroparticle Physics 27 (2007) 142
[25] A. M. Green and B. Morgan, Phys. Rev. D 81 (2010) 061301
[26] D. S. Alves, S. E. Hedri and J. G. Wacker, arXiv:1204.5487 [astro-ph.GA].
[27] S. K. Lee and A. H. G. Peter, Phys. Rev. D 71 (2005) 023501
[28] N. W. Evans, C. M. Carollo and P. T. de Zeeuw, Mon. Not. Roy. Astron. Soc. 318 (2000) 1131
[29] A. M. Green, JCAP 1010 (2010) 034