Astronomy for WIMPs: the direct detection of dark matter

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The Dark Matter Problem

Observations on cosmological scales indicate that roughly 84% of mass in the universe must be in the form of so-called **Dark Matter** which can only be detected gravitationally. [1] A popular class of candidates for this dark matter is the **WIMP** - or **W**eakly **I**nteracting **M**assive **P**article. These occur in many theories of particle physics and have small but non-zero couplings to ordinary matter. Experiments looking for these interactions provide one of few windows into the particle physics and astrophysics of dark matter. *But what can we actually measure from such experiments?*

Direct Detection

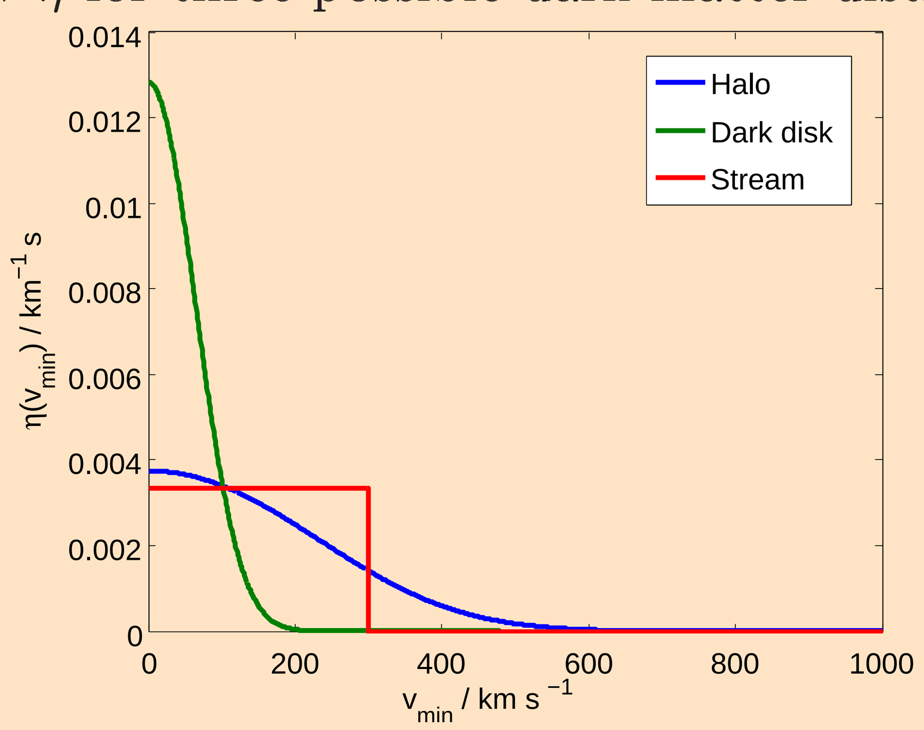
WIMP detectors aim to measure nuclear recoils caused by WIMPs passing through detectors in the lab. The fundamental - but unknown - interaction cross-section σ determines the probability of an interaction and therefore the total number of events observed. The WIMP mass m_χ and speed v determine the typical energy E_R of the nuclear recoils.

The event rate R per unit recoil energy can be written: [3]

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \eta(v_{\mathrm{min}}) = \int_{v_{\mathrm{min}}}^{\infty} \frac{f(v)}{v}\,\mathrm{d}v\,,$$

where $v_{\mathrm{min}}(E_R)$ is the minimum speed required by a particle to cause a nuclear recoil of energy E_R.

Below we show η for three possible dark matter distributions.

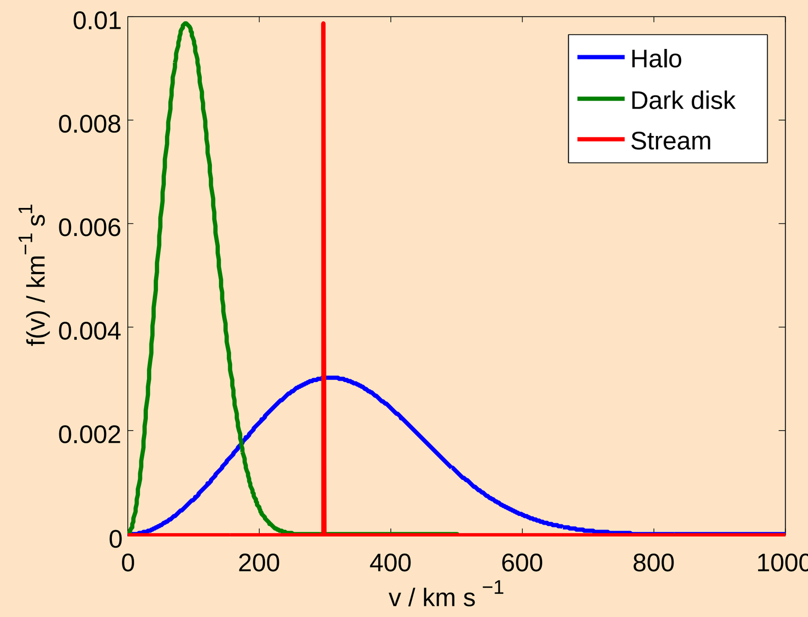


Different speed distributions can lead to significantly different event rates. How does this affect parameter reconstruction?

Dark Matter Distribution

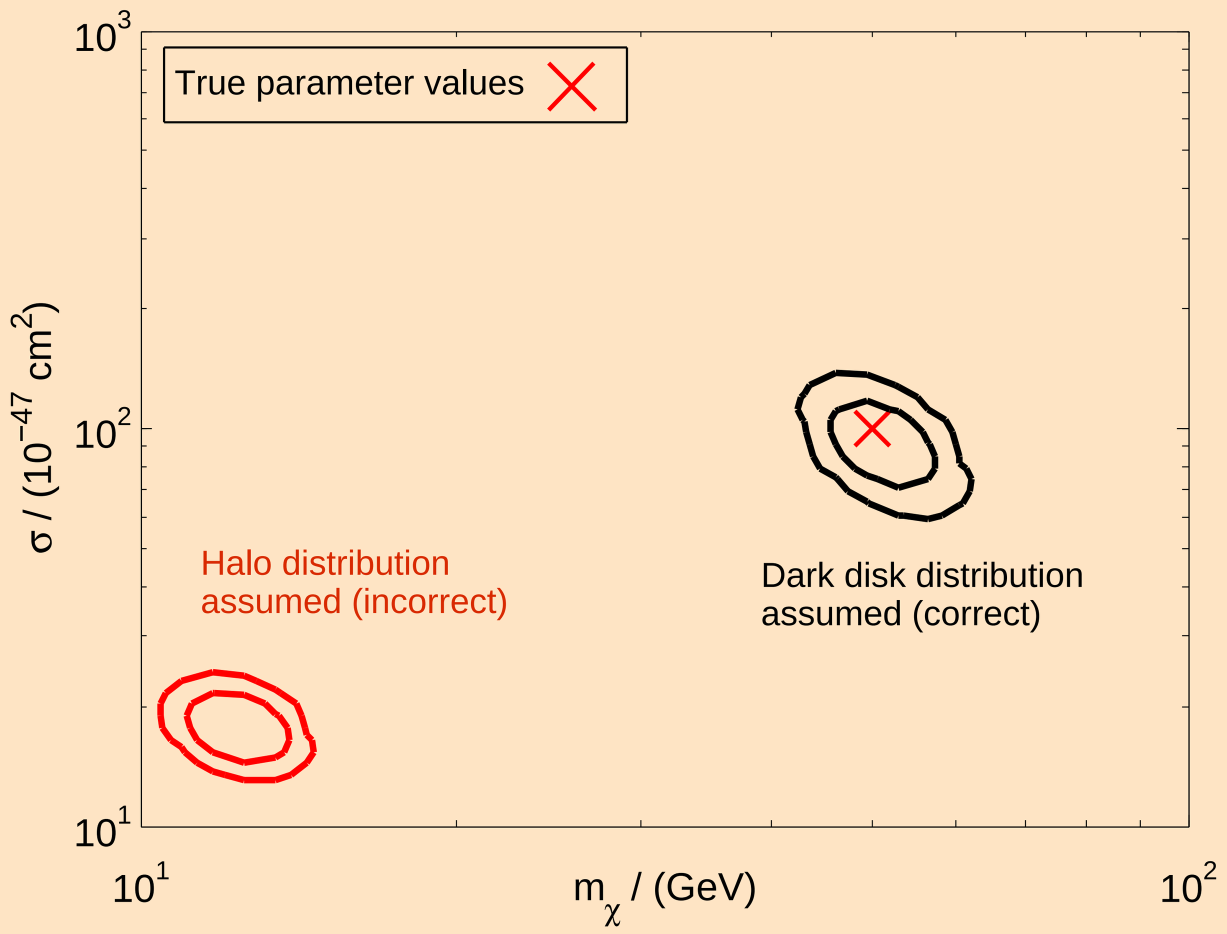
The distribution of dark matter in the galaxy is not well understood. It may be in equilibrium: distributed in a sphere, or **halo**, whose density decays with radius. However, strong tidal forces can create a **dark disk** which co-rotates with the galactic disk (see e.g. [2]). In extreme cases, the WIMP distribution could be dominated by a single **stream** of dark matter, tidally stripped from another halo. There is also uncertainty about the **speed distribution** of WIMPs, $f(v)$: the fraction of WIMPs having speed v to $v+\mathrm{d}v$. Here, we show three possible speed distributions for dark matter near Earth.

But how does this uncertainty affect the detection of dark matter?



Parameter Reconstruction

We generate mock data for several different hypothetical detectors, then attempt to reconstruct the underlying input parameters (shown as a red cross below) using **M**arkov **C**hain **M**onte **C**arlo (**MCMC**). We generate data using a dark disk distribution function and investigate how our assumptions about $f(v)$ impact our ability to recover σ and m_χ. Shown are the 68% and 95% confidence contours for the mass and cross-section.



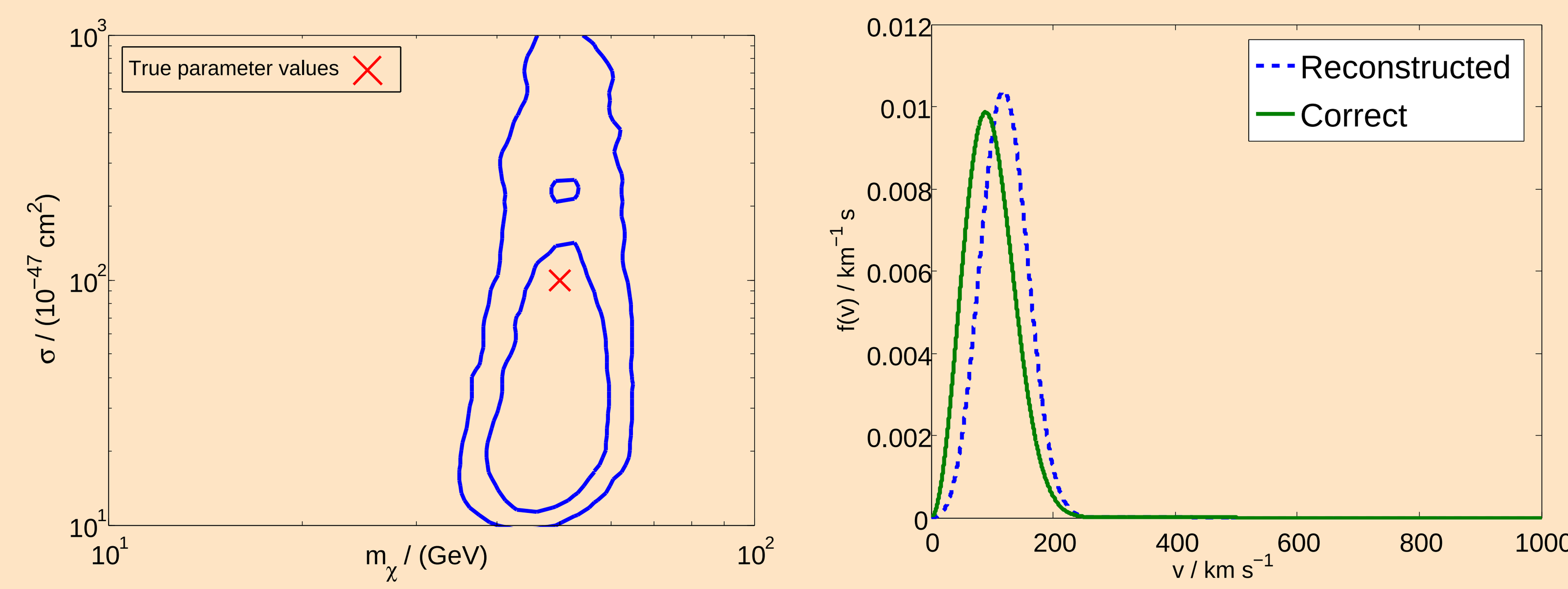
Clearly, if our assumptions about the speed distribution are poor, the values we 'measure' for the WIMP parameters may be incorrect. But how can we deal with this?

Improving Reconstructions

In order to incorporate astrophysical uncertainties, we can fit the speed distribution simultaneously, by writing:

$$f(v) = v^2 \exp\left[a_0 + a_1 v + a_2 v^2 + \ldots\right]\,,$$

and fitting the parameters $\{a_i\}$. This parametrisation ensures that $f(v) \geq 0$ and is well suited to distributions which decay to zero for large v. Shown below are the 68% and 95% confidence contours and reconstructed speed distribution obtained using this method.



The reconstructed contours are now much wider, reflecting the additional uncertainty in $f(v)$. However, the contours now enclose the true parameter values and the mass is accurately recovered. We have also been able to obtain a close approximation to the speed distribution itself.

Making ***no assumptions*** *about the WIMP speed distribution, we have been able to reconstruct the underlying particle- and astrophysics reliably.*

Conclusions

- The dark matter speed distribution influences the direct detection event rate but is *a priori* unknown.
- Poor assumptions about the DM speed distribution can lead to large biases in reconstructed WIMP parameters.
- By carefully parametrising $f(v)$, we can accurately reconstruct the WIMP mass, cross-section and speed distribution - **without the need for astrophysical assumptions.**

References

[1] G. Hinshaw et al. (2012), arXiv:1212.5226
[2] A. M. Green (2009), arXiv:1009.0916
[3] G. Jungman et al. (1995), hep-th/9506380