Harnessing astrophysical uncertainties in the direct detection of dark matter

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The Problem

The standard analysis of **Dark Matter (DM)** direct detection experiments requires assumptions about the speed distribution of **Weakly Interacting Massive Particles (WIMPs)** in the galactic halo. Poor assumptions can lead to a bias in the reconstruction of the WIMP mass and interaction cross section [1]. **But can we *measure* the dark matter speed distribution** rather than assuming it? Can we avoid bias in the WIMP parameters and look for features which may provides hints about the formation history of the Milky Way?

DM direct detection

Aim to measure rate R of WIMP-induced nuclear recoils of energy E_R at a DM direct detector. For purely spin-independent interactions [2]:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\sigma_p^{SI}}{2m_\chi \mu_{\chi p}^2} A^2 F^2(E_R) \rho_0 \int_{v_{\mathrm{min}}}^{\infty} \frac{f(v)}{v} v^2 \mathrm{d}v \,, \qquad (1)$$

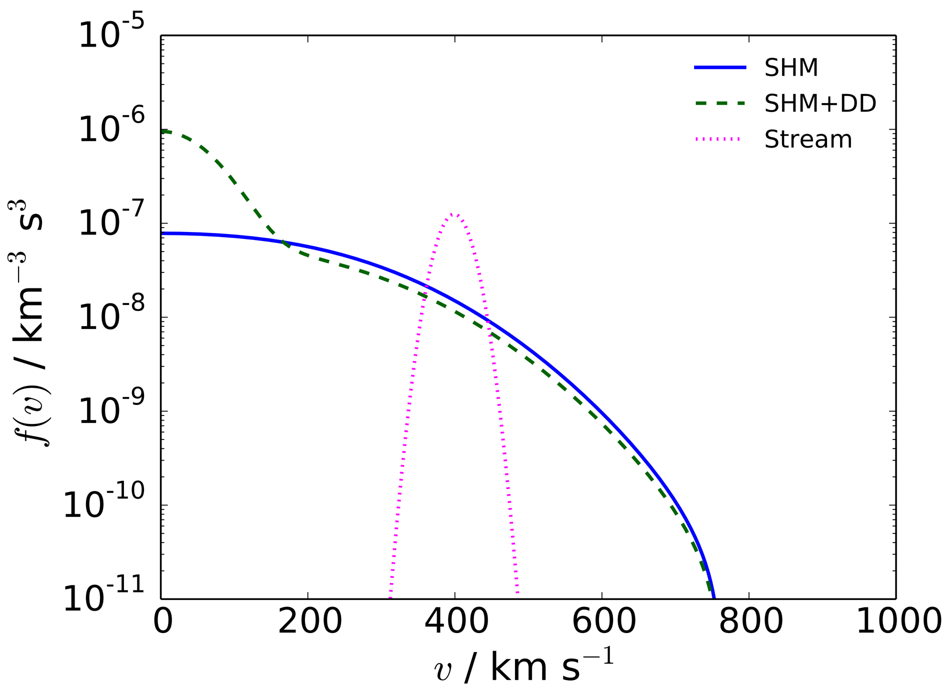
- WIMP mass, m_χ, and cross section, σ_p^{SI}
- Response for a nucleus of mass number A: $A^2 F^2(E_R)$
- Local WIMP density, ρ_0
- Need to integrate speed distribution, $f(v)$, over all WIMPs with sufficient speed to scatter with energy E_R.

But what form does $f(v)$ have?

DM speed distribution $f(v)$

Formation history of the Milky Way is inprinted in the speed distribution:

- Halo may be fully equilibrated and smooth - typically assumed Standard Halo Model (SHM).
- Tidal stripping of subhaloes may form a dark disk (DD) which corotates with the stellar disk [3, 4, 5].
- Local substructure such as streams [6, 7] may contribute to the local DM population.



Can we analyse data without choosing a particular form for $f(v)$?

Parametrising the Speed Distribution - arXiv:1303.6868

We introduce a general parametrisation for the speed distribution. **We parametrise the *logarithm* of the speed distribution** in order to ensure that $f(v)$ is everywhere positive:

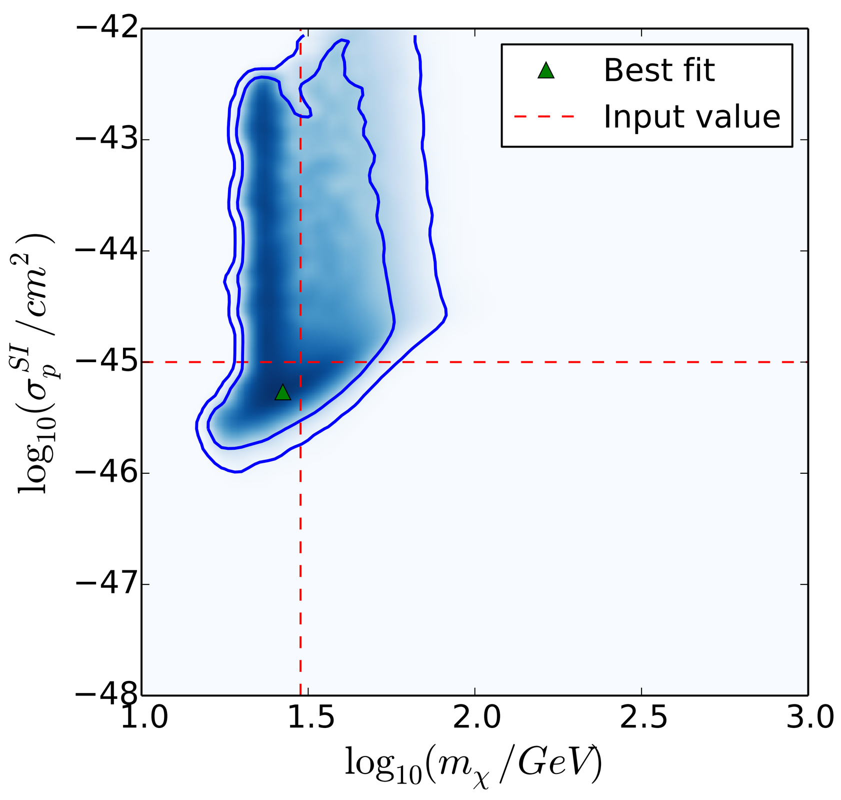
$$f(v) = \exp\left\{ \sum_{k=0}^{N-1} a_k P_k \left(\frac{v}{v_{\mathrm{max}}} \right) \right\} . \qquad (2)$$

We use an orthogonal basis of Chebyshev polynomials P_k, impose a conservative cut off at $v_{\mathrm{max}} = 1000$ km s^{-1} and use $N = 6$ basis functions.
We can now analyse mock data from future experiments by fitting WIMP parameters *and* speed distribution parameters, $\{a_k\}$.

Using direct detection data only

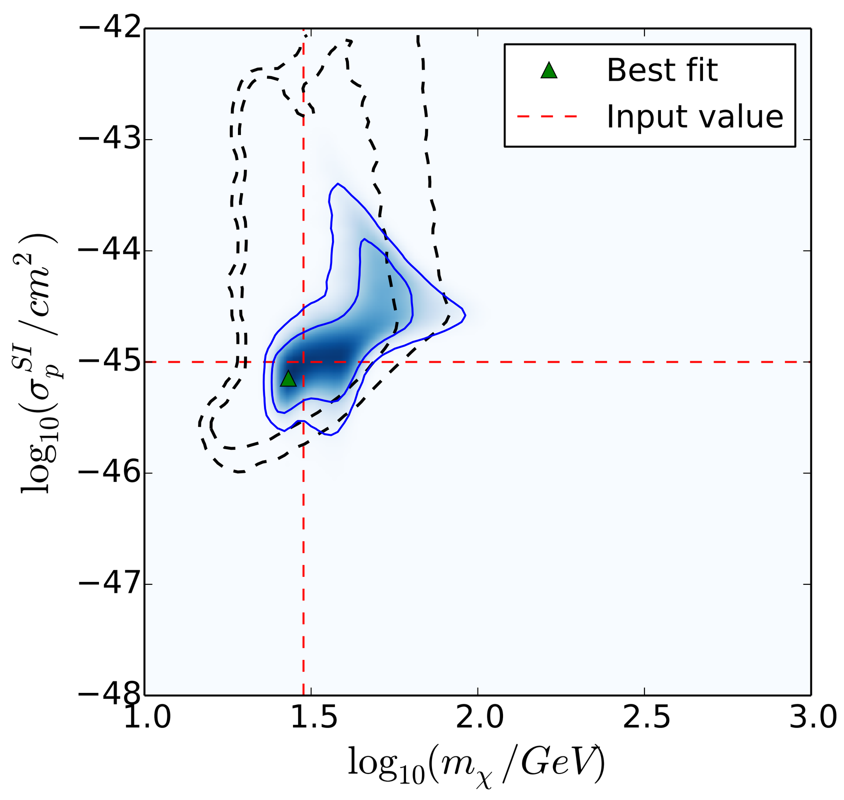
Generate mock data **assuming SHM+DD distribution**, then construct 68% and 95% confidence contours (in blue) **using the above parametrisation** (Eq. (2)):

- DM mass is correctly reconstructed without assuming a specific shape for $f(v)$.
- Finite energy thresholds of direct detection experiments mean we are insensitive to low speed WIMPs. Large degeneracy in the cross section, as we do not know the fraction of WIMPs below threshold [8].



Note: Spin-dependent (SD) interactions are included, but are not shown in these figures.

Including IceCube data - arXiv:1410.8051



- IceCube detector is sensitive to neutrinos from DM particles captured in the Sun.
- **Slow moving particles preferentially captured** - sensitivity to low speed WIMPs.
- Compare contours *without IceCube* (black dashed) to contours *with IceCube* (solid blue).
- WIMP mass reconstructed more precisely and cross section degeneracy is broken.

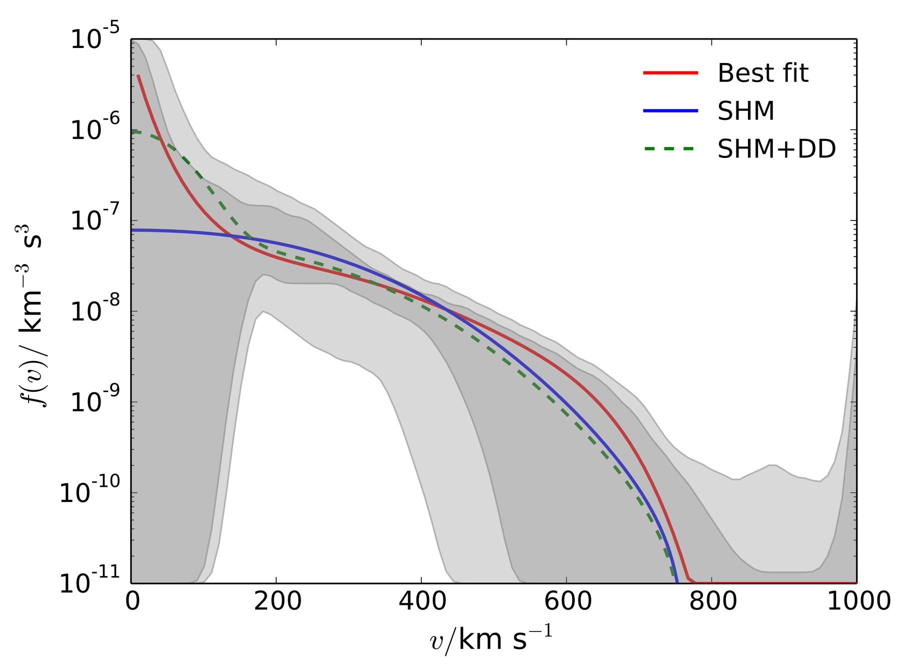
Both the WIMP mass *and* cross section can be reconstructed. But what about the speed distribution?

Reconstructing $f(v)$

We can also use reconstructed values of parameters $\{a_k\}$ to reconstruct $f(v)$ from combined direct detection and IceCube data. We show the 68% and 95% confidence intervals on $f(v)$ as grey bands:

- Best fit distribution function traces underlying SHM+DD distribution.
- $f(v)$ constrained to within a factor of ~ 4 for $v \sim 200-400$kms^{-1}.
- Tightest constraints near direct detection thresholds - where sensitivity is greatest.

Full likelihood analysis allows SHM distribution to be rejected at 3σ using 3-5 years of data.



References

[1] Peter (2011) [arXiv:1103.5145]
[2] Jungman et al. (1995) [hep-ph/9506380]
[3] Read et al. (2009) [arXiv:0902.0009]
[4] Read et al. (2010) [arXiv:0901.2938]
[5] Kuhlen et al. (2013) [arXiv:1308.1703]
[6] Vogelsberger et al. (2007) [arXiv:0711.1105]
[7] Purcell et al. (2012) [arXiv:1203.6617]
[8] Kavanagh et al. (2012) [arXiv:1207.2039]

WIMP astronomy in the future

- The shape of $f(v)$ encodes information about Milky Way's merger history and is important in the analysis of direct detection experiments.
- Using a completely **general parametrisation** for $f(v)$ we can reconstruct the WIMP mass **without astrophysical assumptions**.
- Including IceCube data allows us to probe the full range of WIMP speeds and constrain the WIMP (SI & SD) cross sections.
- Direct detection and neutrino telescope experiments (such as IceCube) can be used together to **directly measure** the WIMP speed distribution.
- With 3-5 years of data, deviations from the Standard Halo Model could potentially be detected at the 3σ level, beginning the era of **WIMP astronomy**.