Probing the nature of particle dark matter

(and worrying about astrophysics)

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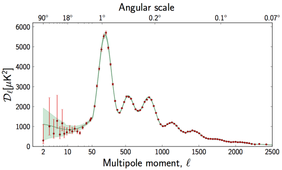
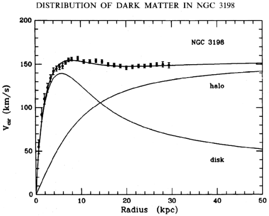
Outline

- Introduction
- Dark matter (DM) detectors and detection
- Current limits
- Astrophysical uncertainties
- Parametrising the DM speed distribution
- Results (from 'future' data sets)
- Problems - and how we hope to solve them
- Future Work

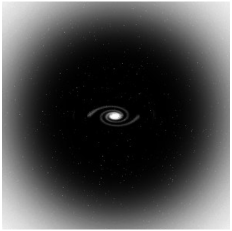
Dark matter (DM) on all scales

Strong evidence for dark matter on scales from cosmological right down to galactic...



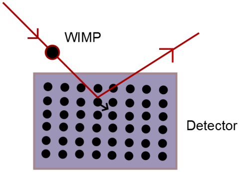


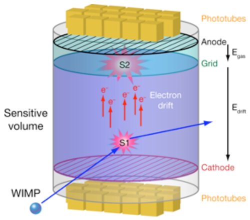
We expect the Milky Way to be embedded in a roughly spherical dark matter halo.



DM Detectors

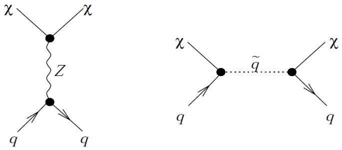
- Aim to detect interactions of Weakly Interacting Massive Particles (WIMPs) in the halo with nuclei in detectors on Earth.
- Look for nuclear recoils of energy ($O(\mathrm{keV})$)
- **Very low** event rate (10s of events per year), so need to understand experimental background very well
- Run detectors underground and use shielding to reduce nuclear recoil backgrounds
- Use multiple channels to distinguish between nuclear and electronic recoils: Ionisation, Phonons, Scintillation, ...
- Two broad classes of detector:
  - Cryogenic detectors - CDMS, CoGeNT, CRESST-II, ...
  - Liquid Noble detectors - Xenon, Argon, ...





DM-nucleon interactions

- Many possible diagrams could contribute to WIMP-quark scattering e.g.



- Need to consider low momentum-transfer ($v \approx 10^{-3}c$) effective interactions between DM χ and nucleons n
- Simple 4-point interactions dominate:

$$\mathcal{L}_{eff} \supset g_S(\bar{\chi}\chi)(\bar{n}n) + g_A(\bar{\chi}\gamma^{\mu}\gamma_5\chi)(\bar{n}\gamma_{\mu}\gamma_5 n)$$

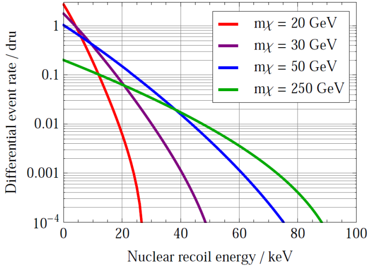
- For now, restrict only to spin-independent interactions (i.e. assume g_S dominates)
- We can then calculate the scattering cross section as a function of momentum (but because we don't know g_S, we don't know the strength cross section at zero momentum-transfer σ_p)

Direct Detection Event Rate

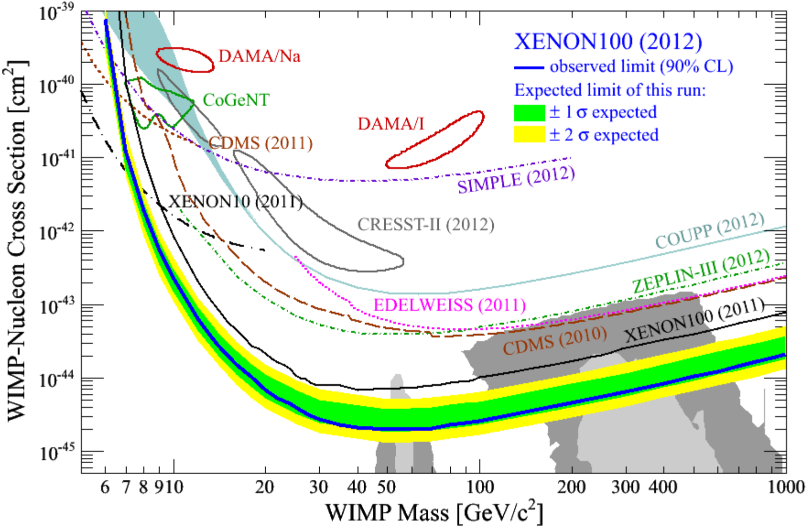
- For a WIMP of mass m_χ and cross section σ_p, rate of nuclear recoils R per unit recoil energy E_R given by:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \underbrace{\frac{\sigma_p}{2 m_\chi \mu_{\chi p}^2}}_{\text{Particle Physics}} \times \underbrace{A^2 F^2(E_R)}_{\text{Nuclear Physics}} \times \underbrace{\rho_\chi \int_{v_{\min}}^{\infty} \frac{f(\mathbf{v})}{v} \mathrm{d}^3\mathbf{v}}_{\text{Astrophysics}}$$

- The nuclear physics is very well understood
- The astrophysics is assumed
- The particle physics - m_χ and σ_p - is constrained from experiments



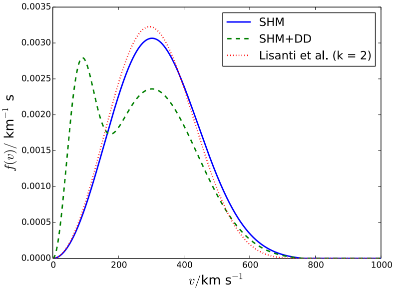
Current constraints (and claimed signals...)



Xenon100 Collaboration [arXiv:1207.5988]

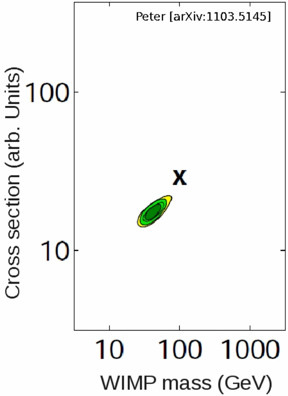
WIMP speed distribution $f(v)$

- Speed distribution describes fraction of WIMPs with speeds in range $v \to v + \mathrm{d}v$
- Analysis typically assumes a particular, simple form for the WIMP speed distribution: the Standard Halo Model (SHM)
- True distribution is almost certainly NOT the Standard Halo Model.
- N-body simulations suggest deviations from SHM, including the presence of a dark disk



What could go wrong?

- Different distributions produce different event rates
- Assuming the incorrect distribution can lead to bias in reconstructed mass and cross section
- There have been attempts to fit the speed distribution too, but typically still assume a particular functional form (e.g. Pato et al. [arXiv:1211.7063])
- If functional form is incorrect, it can still lead to significant bias in reconstruction



A General Parametrization

- We want to analyse direct detection data while making as *few* assumptions as possible about the speed distribution.
- We want to parametrize an arbitary function - the only constraints are (a) $f(v)$ should be normalised, and (b) $f(v)$ should be everywhere positive.
- Instead parametrize the **logarithm** of $f(v)$:

$$f(v) = v^2 \exp\left(a_0 + a_1 v + a_2 v^2 + ...\right)$$

- Then, we can fit m_χ, σ_p *and* the speed parameters $\{a_k\}$.

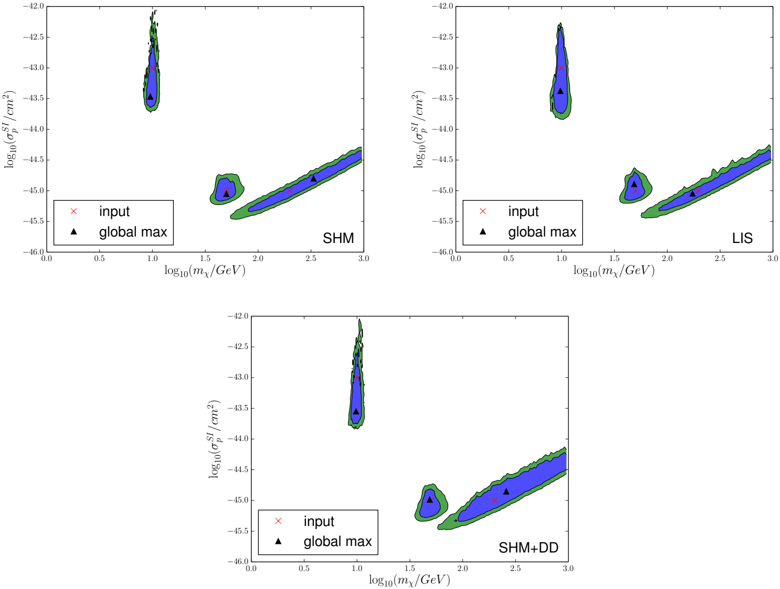
NB: In practice, we impose a conservative cut off speed of $v_{\mathrm{max}} = 1000 \ \mathrm{km} \ \mathrm{s}^{-1}$ and we pick a more sensible polynomial basis.

Parameter Reconstruction - testing the method

In order to test how well the method works:

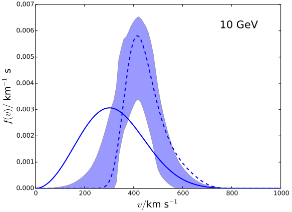
- Pick values for m_χ, σ_p and choose a form for $f(v)$
- Generate mock data from a set of proposed experiments
- Attempt to reconstruct parameters by exploring the posterior likelihood using MultiNest
- Repeat for several WIMP masses/speed distributions

Results - mass and cross section

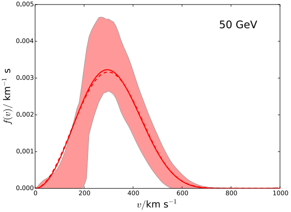


Results - speed distribution

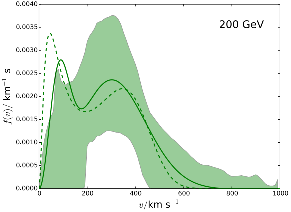
10 GeV
SHM



50 GeV
N-body



200 GeV
SHM + Dark disk

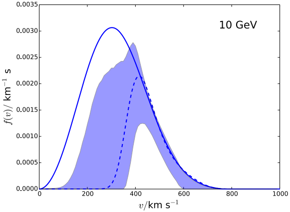


True distribution: ——
Bestfit distribution: – – –

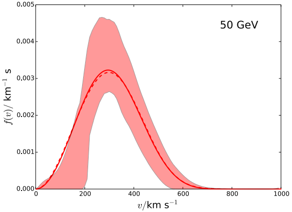
For a given set of experiments, the range of speeds which are probed depends on the mass of the dark matter particle: $E_R \approx m_\chi v^2$.

Results - speed distribution

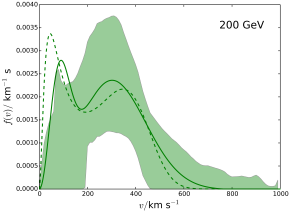
10 GeV
SHM [rescaled by σ_p]



50 GeV
N-body



200 GeV
SHM + Dark disk



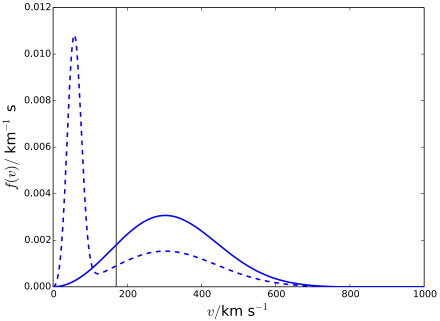
True distribution: ——

Bestfit distribution: – – –

For a given set of experiments, the range of speeds which are probed depends on the mass of the dark matter particle: $E_R \approx m_\chi v^2$.

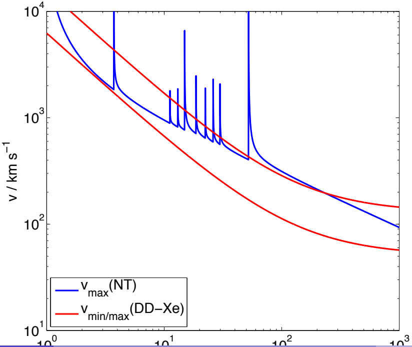
Degeneracy in the cross section

- Due to finite energy thresholds, experiments cannot probe the entire range of v
- Cannot distinguish between (a) small interaction cross section, and (b) small number of WIMPs within sensitivity of detector
- This is an unavoidable problem if we make no assumptions about the speed distribution



Breaking the cross section degeneracy

- We need a way to probe right down to $v = 0$ - WIMP solar capture
- WIMPs scatter with nuclei in the Sun, lose energy and are captured
- Eventually annihilate into neutrinos, which we can detect at IceCube
- Neutrino rate at IceCube can probe capture rate and therefore interaction cross section
- Slower WIMPs are more likely to be captured - complementarity with direct detection



Work in progress

- Incorporating (hypothetical) IceCube data into the analysis
- In-depth analysis - realistic experiments, more benchmarks, how many terms in expansion?
- Extending the analysis to *directional* experiments - parametrizing $f(\mathbf{v})$
- Ultimately aim to reconstruct the entire velocity distribution - the best constraints on local distribution will eventually come from direct detection
- Velocity distribution can be used to probe formation and merger history of Milky Way

Conclusions

- The dark matter mass m_χ can reliably be reconstructed from direct detection data...
- ...as long as you worry about astrophysics
- We can even reconstruct the WIMP speed distribution - within the range of sensitivity of the experiments
- The cross section σ_p can not be constrained so well
- Need to incorporate information about Solar capture (which probes low v)
- Towards WIMP astronomy - measuring the speeds (and directions) of dark matter particles, we can learn a lot about structure formation and particle physics

Thank You