Astrophysical uncertainties in direct detection experiments

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Based on work with A M Green and M Fornasa:
arXiv:1303.6868, arXiv:1312.1852, arXiv:1410.8051

Outline

- Direct detection of dark matter
- The problem of astrophysical uncertainties
- What goes wrong?
- A method of controlling astrophysical uncertainties
- Combining direct detection and neutrino telescopes

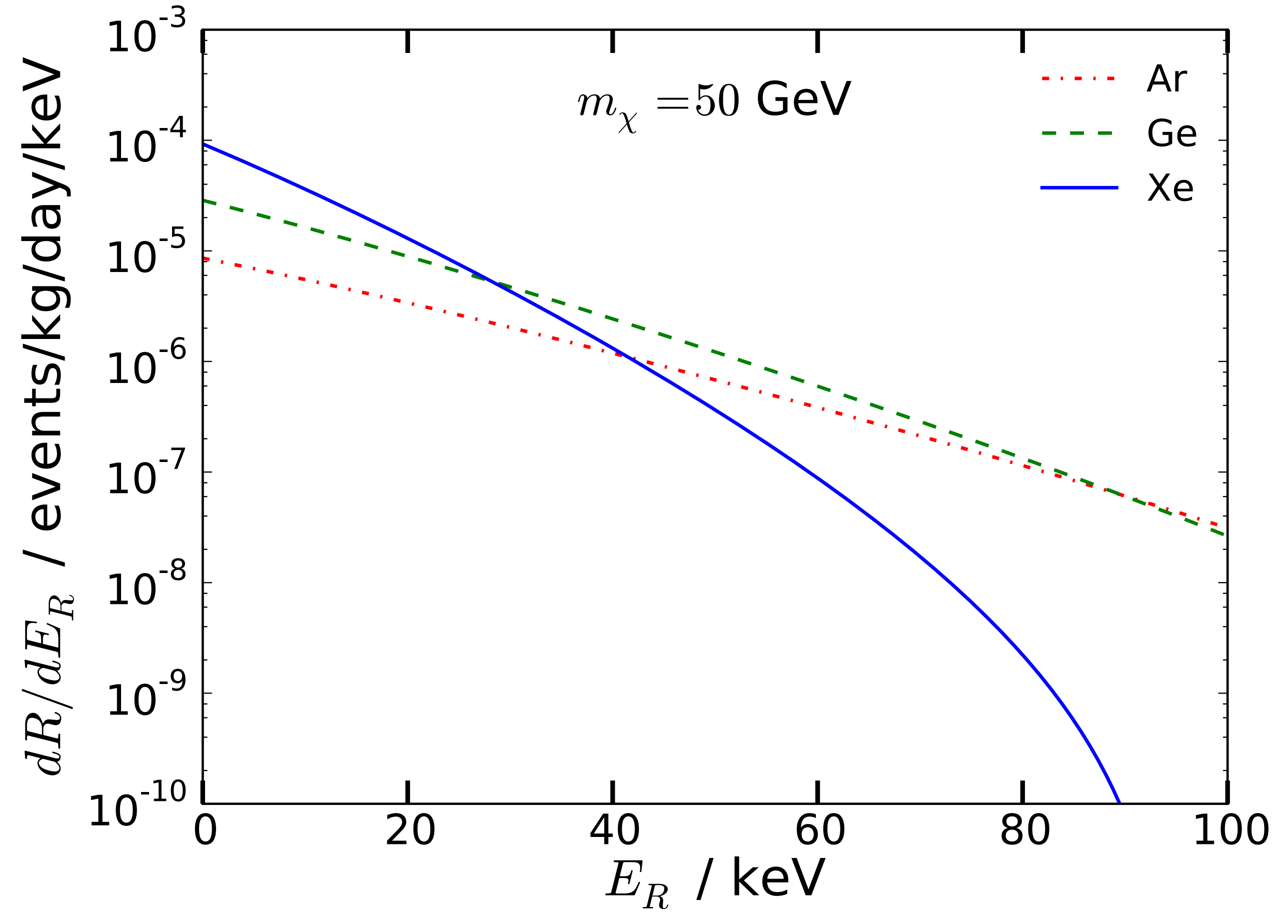
Direct detection

Aim to measure recoil spectrum as a function of recoil energy, E_R

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\boxed{\rho_0}}{m_\chi m_N} \int_{v_{\min}}^{\infty} \boxed{v f_1(v)} \boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}} \mathrm{d}v$$

Astrophysics

Particle physics



$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Typically $\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \propto 1/v^2$

Astrophysical uncertainties

Need to know:

- DM density, ρ_0, controls overall normalisation of rate

$$\rho_0 \sim 0.2 - 0.6\,\mathrm{GeV\,cm}^{-3}$$

Read (2014) [arXiv:1404.1938]

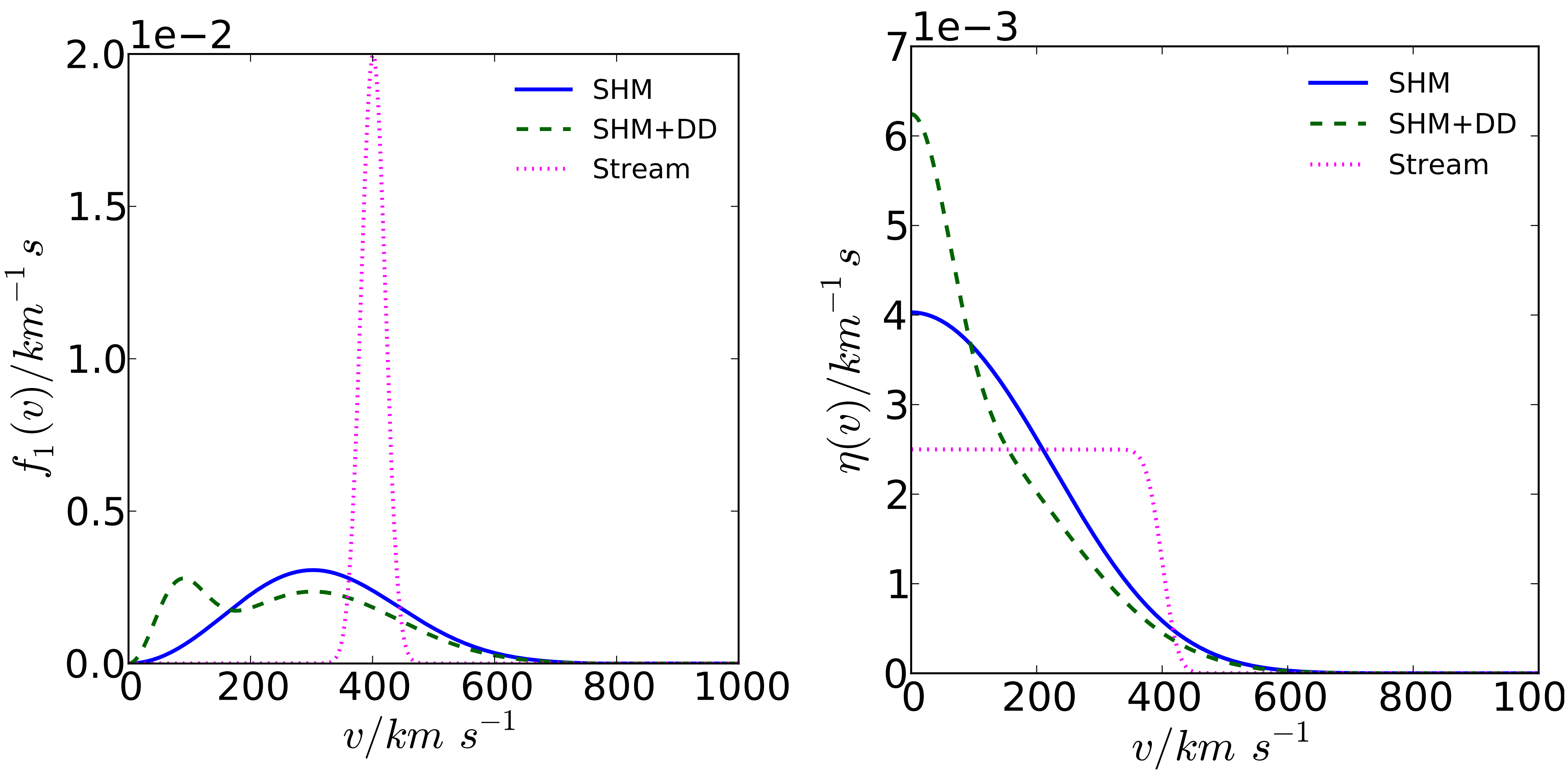
- Speed distribution, $f_1(v)$, controls shape of recoil spectrum and is degenerate with DM mass m_χ

  A given nuclear recoil could be caused by a slow-moving, heavy DM particle, or a fast-moving, light particle.

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sigma\,\eta(v_{\mathrm{min}}) \qquad \eta(v_{\mathrm{min}}) = \int_{v_{\mathrm{min}}}^{\infty} \frac{f_1(v)}{v}\,\mathrm{d}v$$

Uncertainties in $f_1(v)$

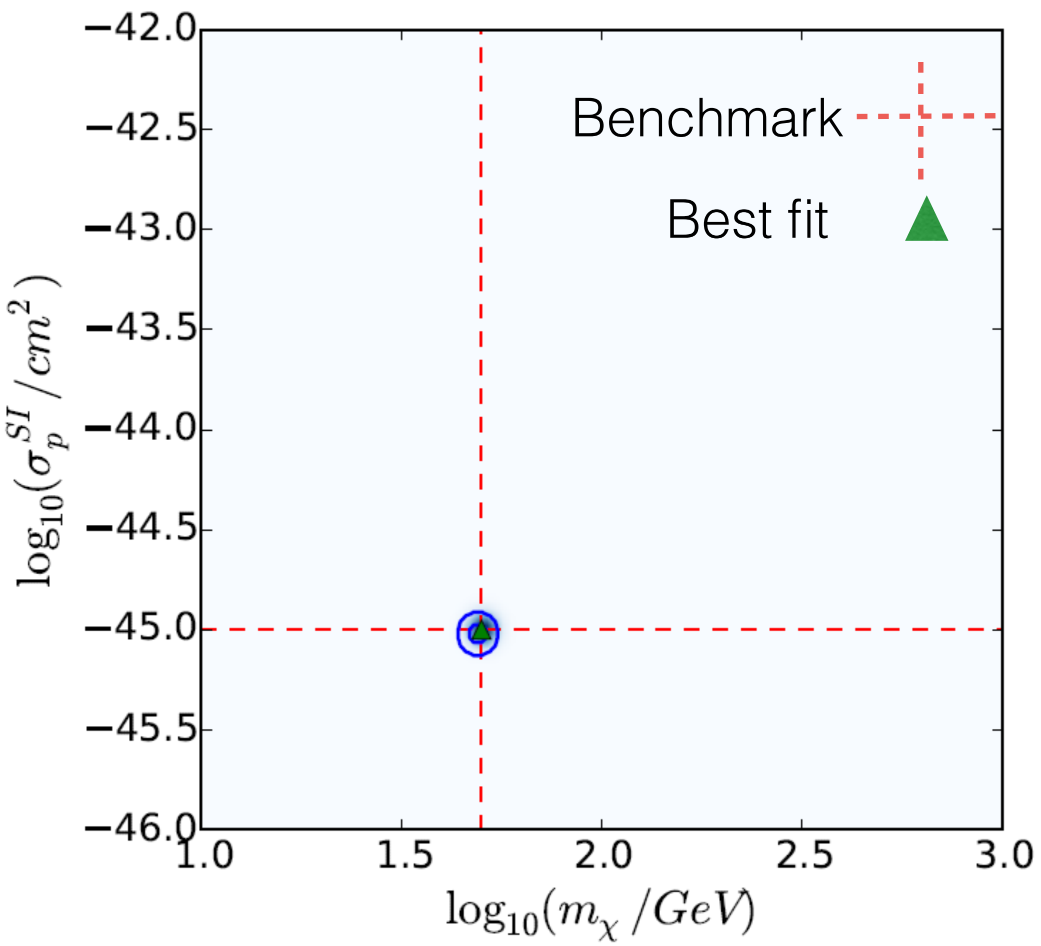
Typically assume Standard Halo Model (SHM) - a smooth, equilibrated halo with $\rho(r) \propto r^{-2}$. However, there could be a contribution from a dark disk (DD), streams, tidal flows…



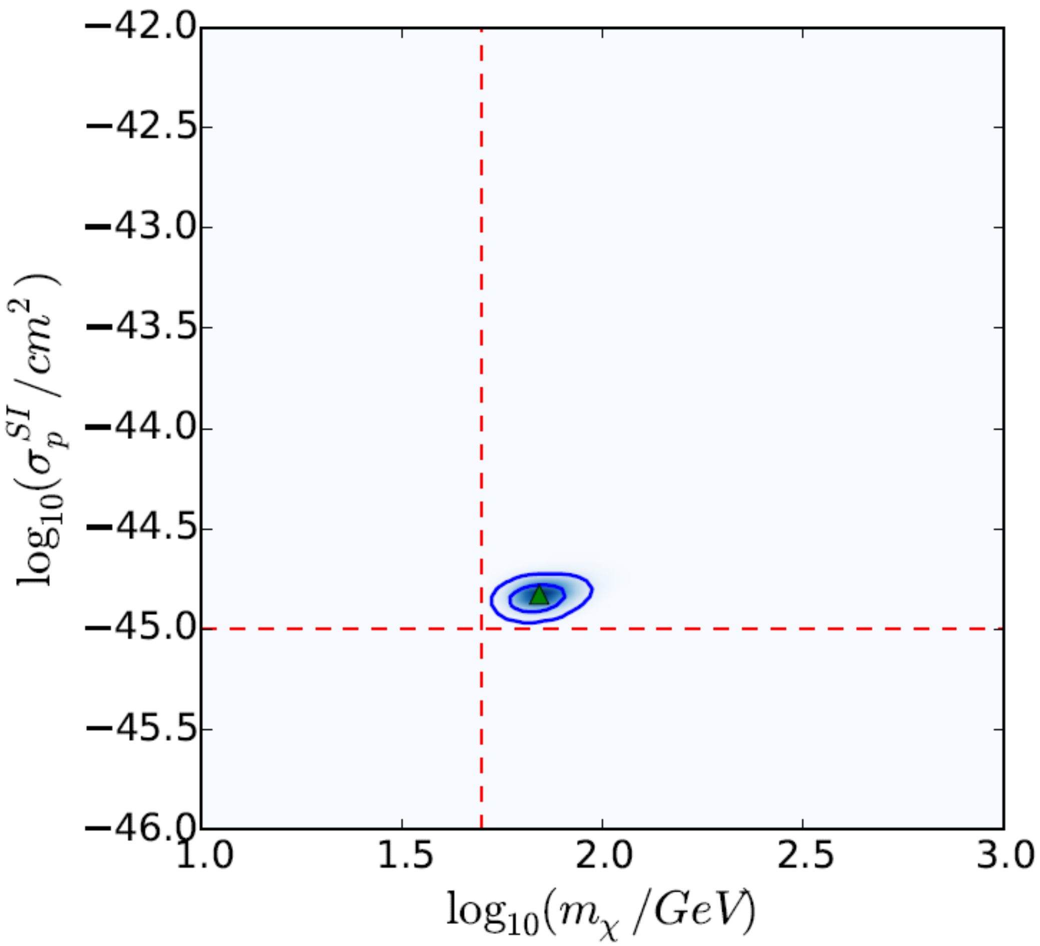
What could *possibly* go wrong?

Generate mock data for 3 future experiments (Xe, Ge, Ar) assuming a stream distribution function. Reconstruct (m_χ, σ_p^{SI}) assuming:

(correct) stream distribution



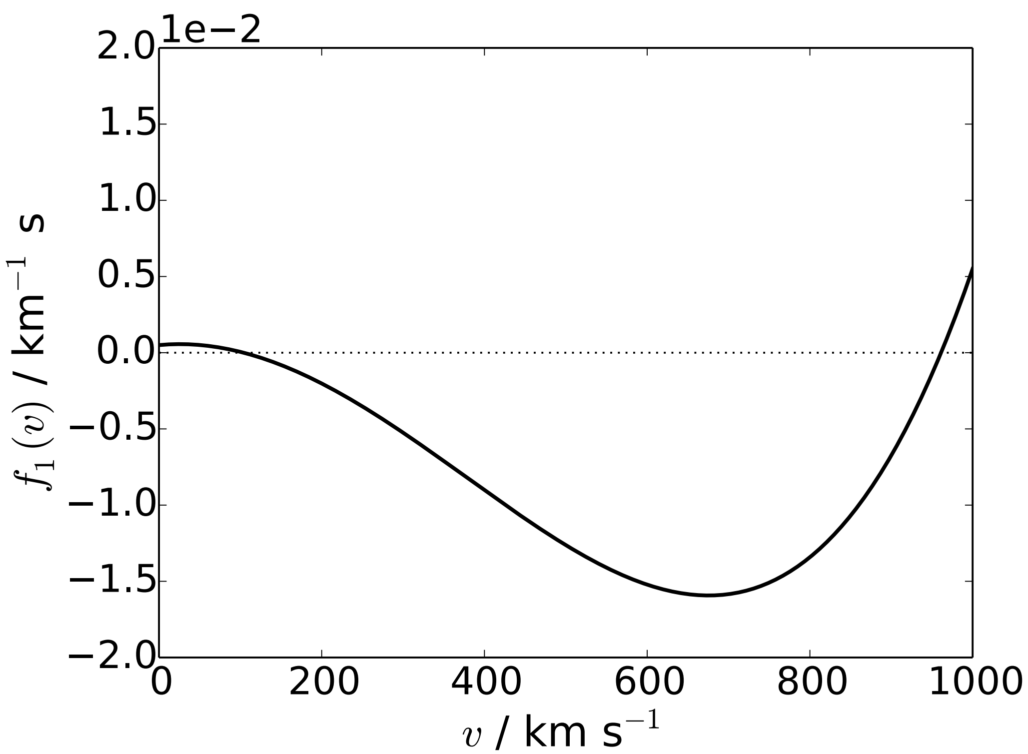
(incorrect) SHM distribution



Trying to fix the problem

We want to be able to write down a *general* form for the speed distribution. Try:

$$f_1(v) = \sum_{k=0}^{N-1} a_k v^k = a_0 + a_1 v + a_2 v^2 + \ldots$$



But negative values cannot correspond to physical distribution functions…

Many other approaches have also been proposed: Strigari & Trotta, Fox et al., Frandsen et al., Peter, Feldstein & Kahlhoefer…

Parametrising $f_1(v)$

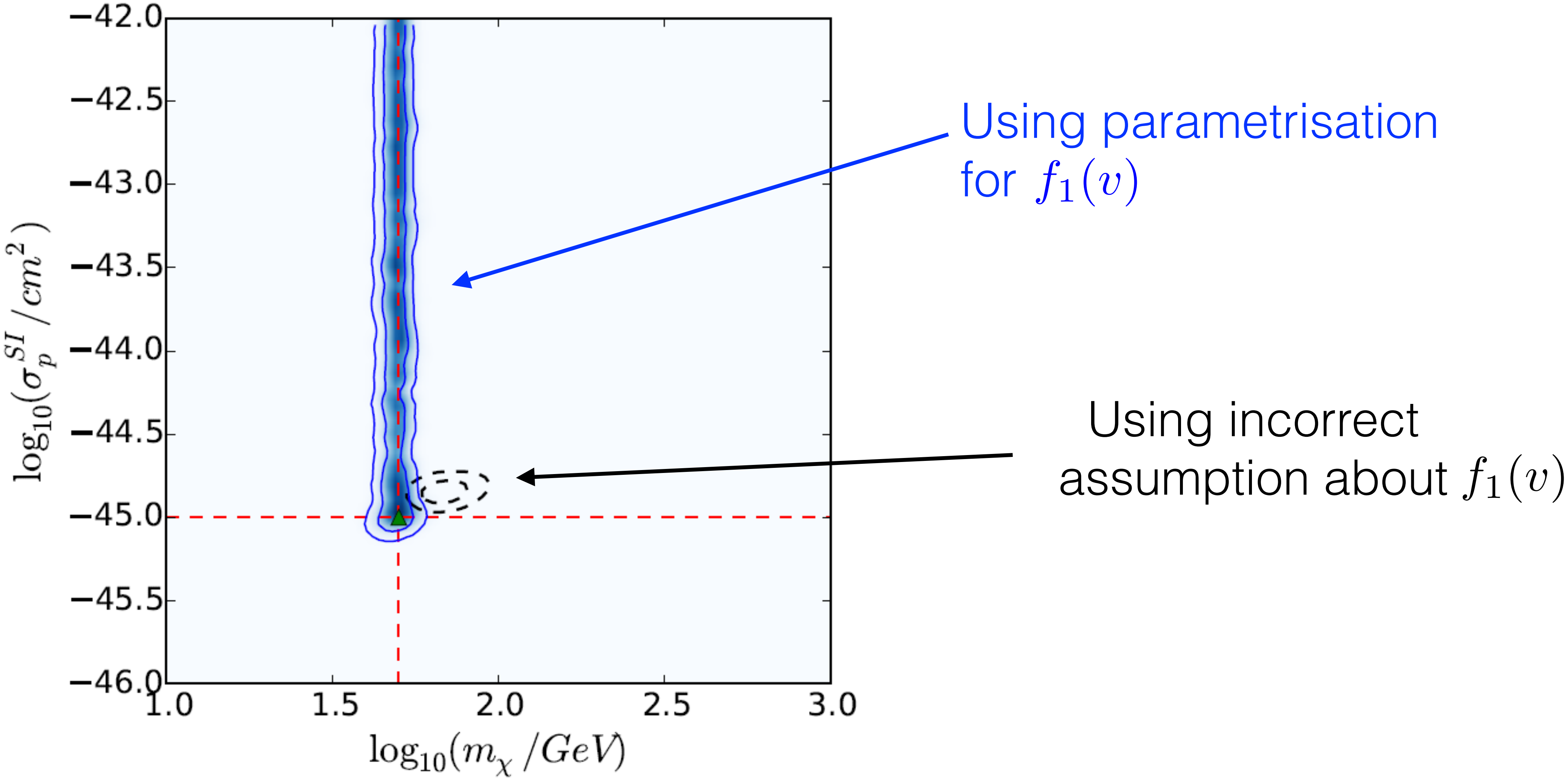
We want to be able to write down a *general* form for the speed distribution which is *everywhere positive*.

$$f_1(v) = v^2 \exp\left(\sum_{k=0}^{N-1} a_k v^k\right)$$

Note: factor of v^2 comes from volume element of the distribution function d^3v

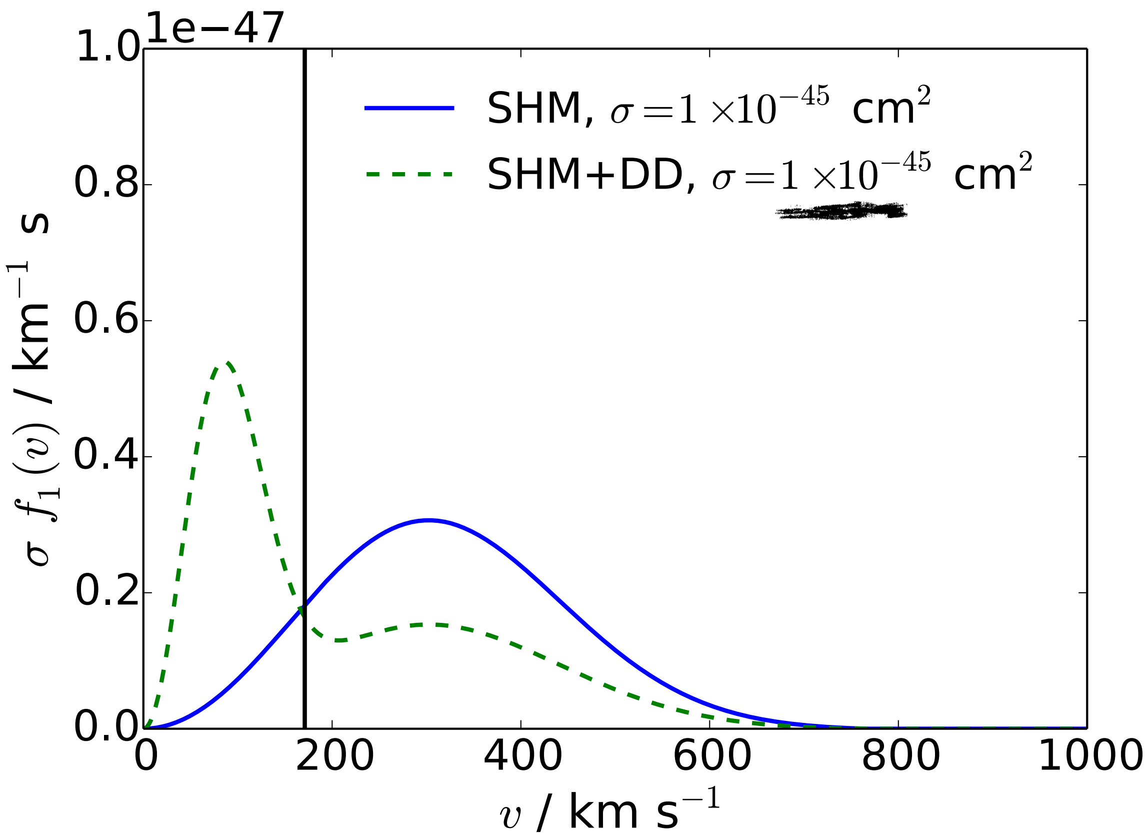
Now we can fit not only (m_χ, σ_p^{SI}) but also the speed distribution parameters $\{a_k\}$

Result

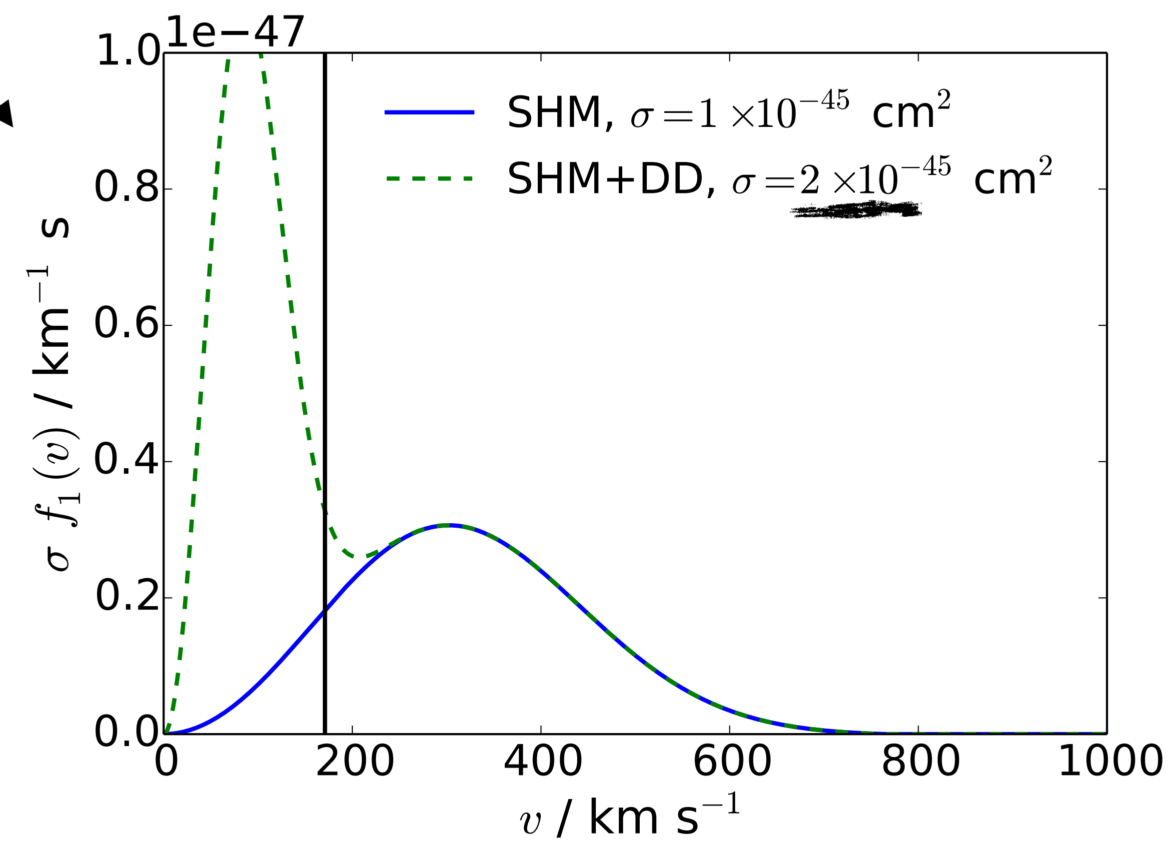


Tested over a range of WIMP masses and distribution functions [arXiv:1312.1852]

Cross section degeneracy



$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sigma \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v}\, \mathrm{d}v$$



This is a problem for *any* astrophysics-independent method!

Including IceCube data

IceCube is sensitive to neutrinos from WIMP annihilations in the Sun

Solar capture occurs preferentially for *low speed* WIMPs - they have less energy to begin with

Combining IceCube and direct detection mock data should give us complementary information about WIMPs of *all* speeds

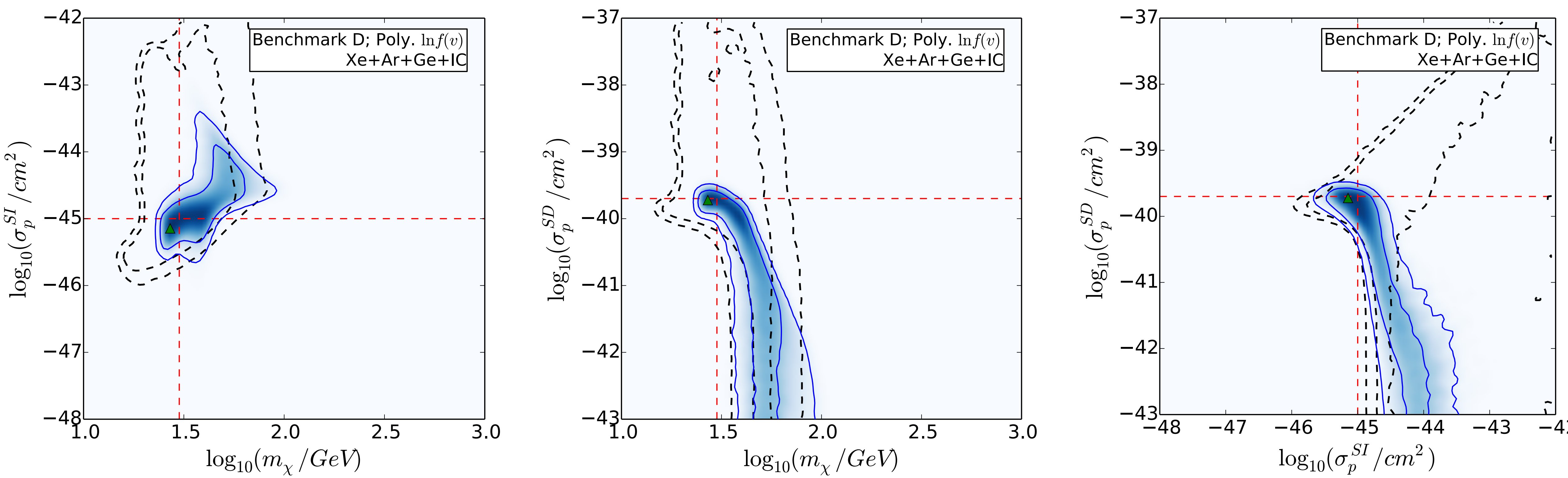
Sun is mostly spin-1/2 Hydrogen - so also need to include spin-*dependent* interactions

Complementarity

Consider a single benchmark:

$$m_\chi = 30\,\mathrm{GeV};\;\; \sigma^p_{SI} = 10^{-45}\,\mathrm{cm}^2;\;\; \sigma^p_{SD} = 2\times 10^{-40}\,\mathrm{cm}^2$$

annihilation to $\nu_\mu \bar{\nu}_\mu$, SHM+DD distribution



Benchmark

Best fit

Direct detection only

Direct detection + IceCube

Conclusions

- Poor astrophysical assumptions can lead to biased results for the WIMP mass and cross sections
- Demonstrated a general parametrisation which allows us to *fit* the speed distribution, along with other parameters
- Allows an unbiased measurement of the WIMP mass from future direct detection data
- Lack of sensitivity to low speed WIMPs means cross section would remain unknown - a problem faced by any method which makes no assumptions
- Introducing future IceCube data can break this degeneracy and allows us to pin down the WIMP mass and cross section - and even reconstruct $f_1(v)$ itself!

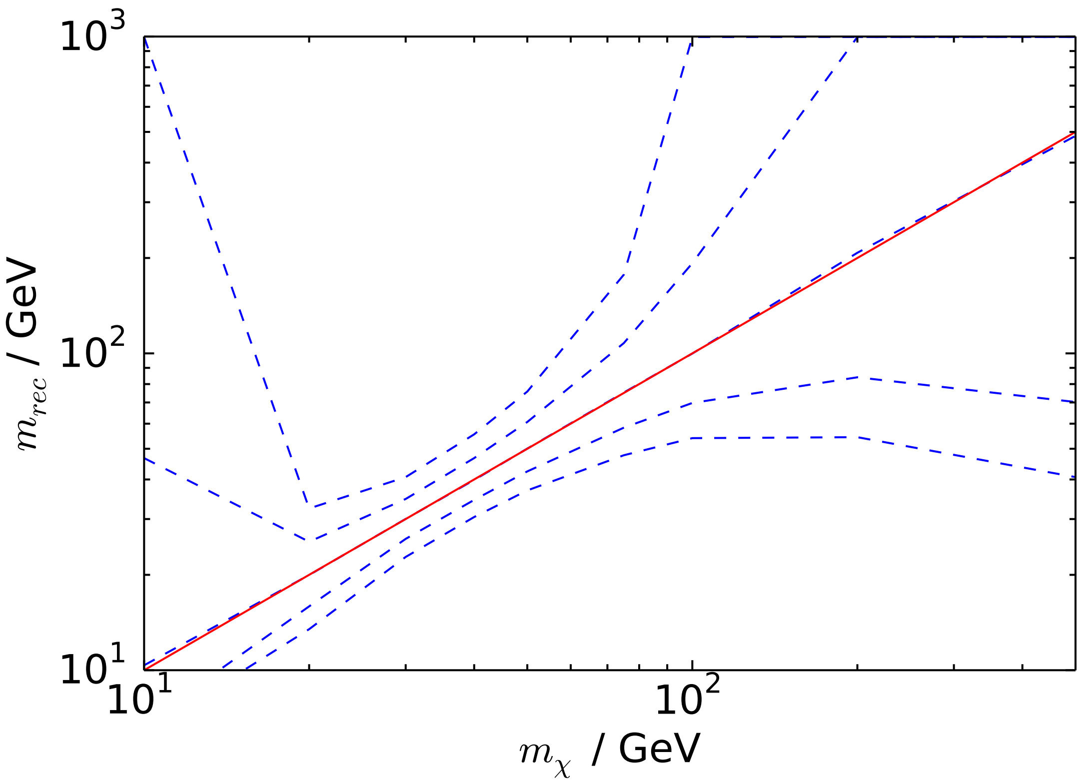
Thank you

Questions?

Backup Slides

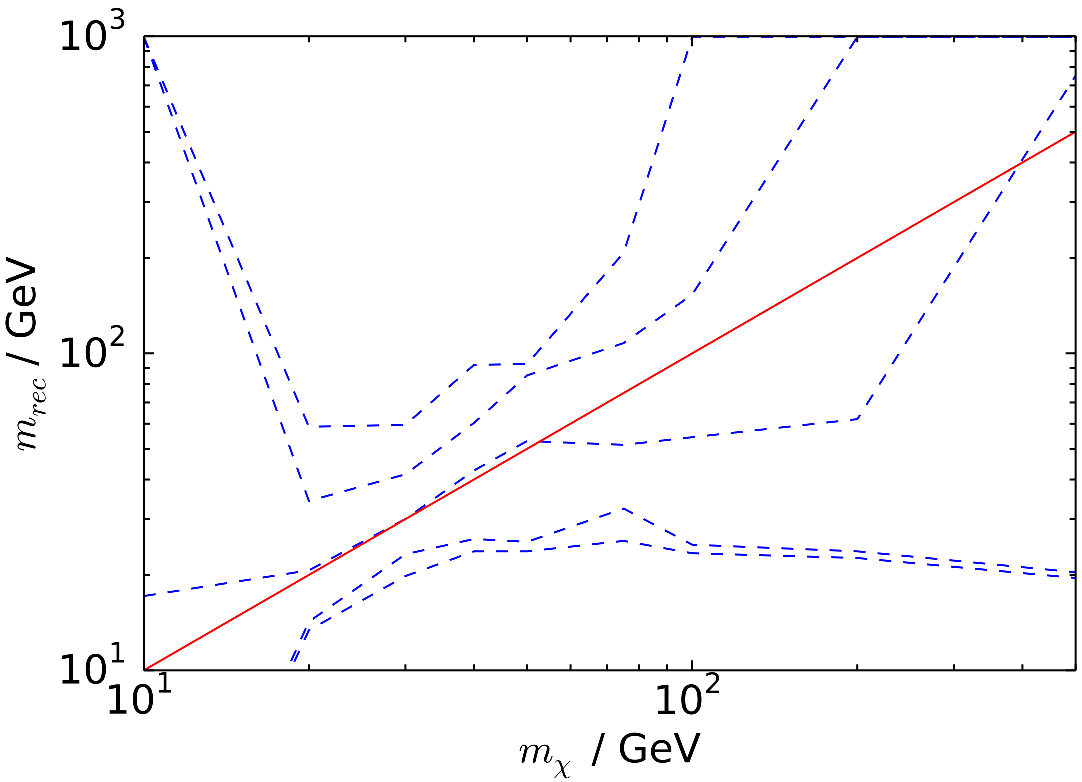
Mass reconstruction

Ideal experiments



Background-free
Perfect energy resolution

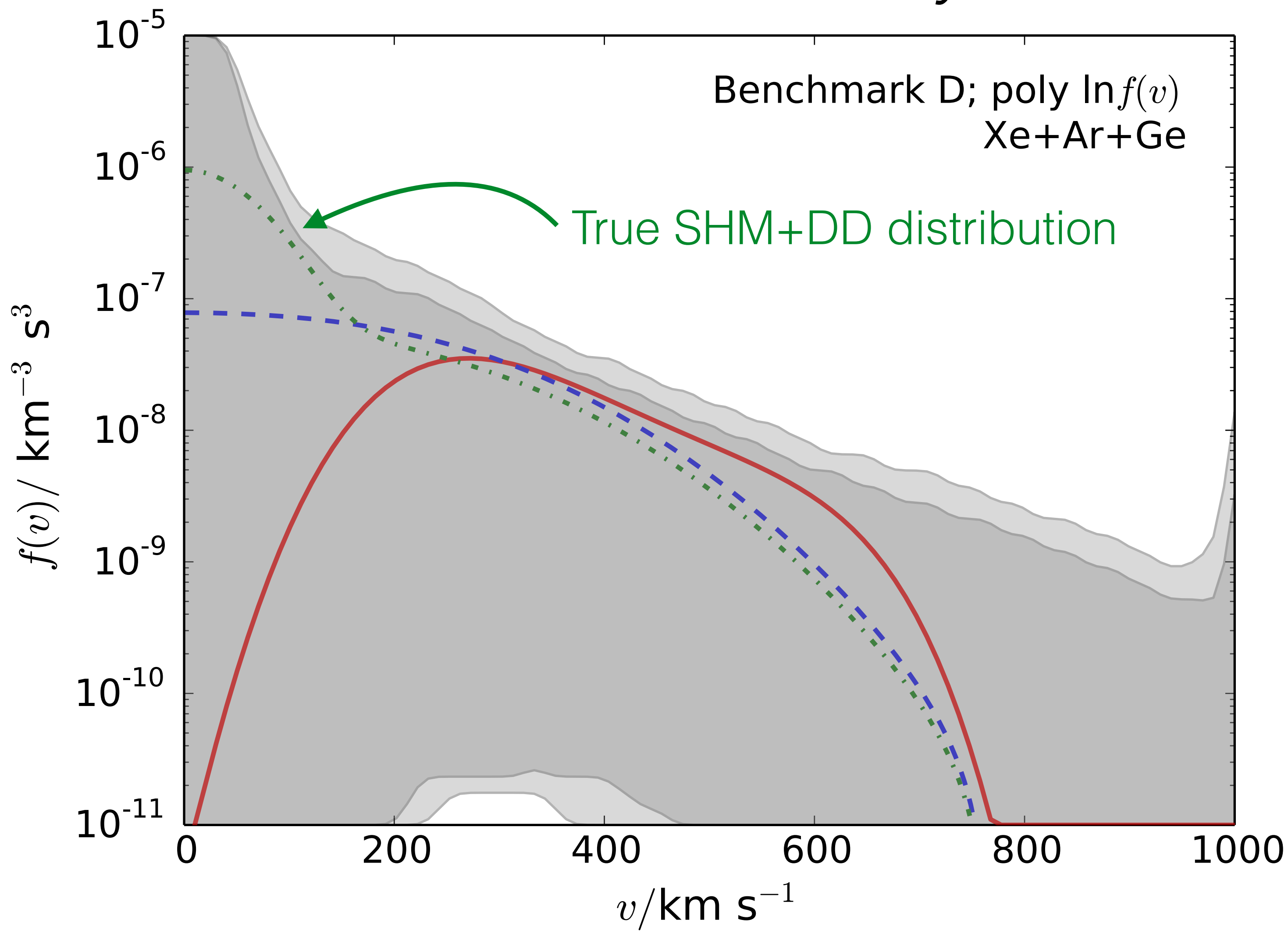
Realistic experiments



Non-zero backgrounds
Finite energy resolution

Reconstructing the speed distribution

Direct detection *only*

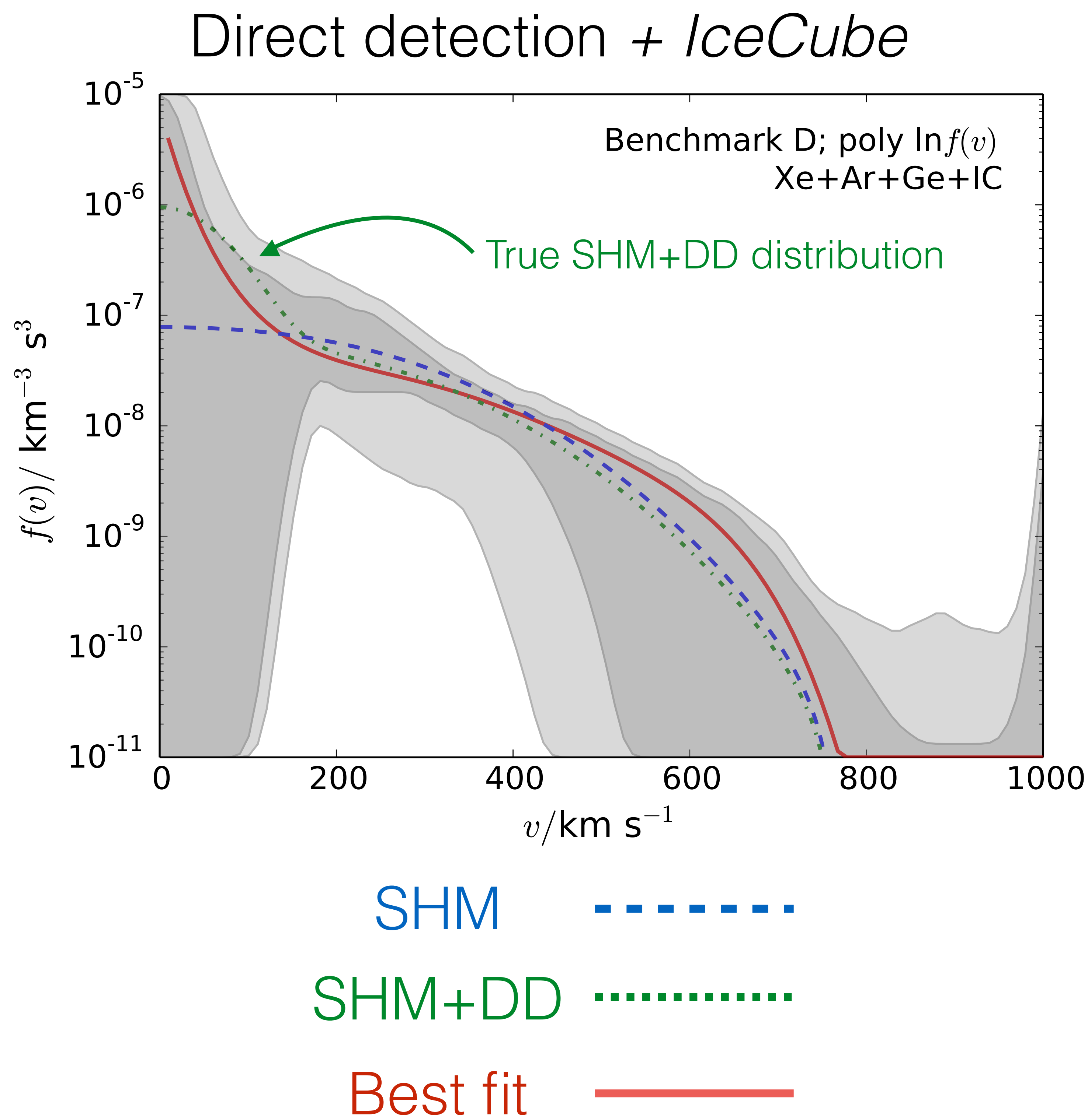


SHM

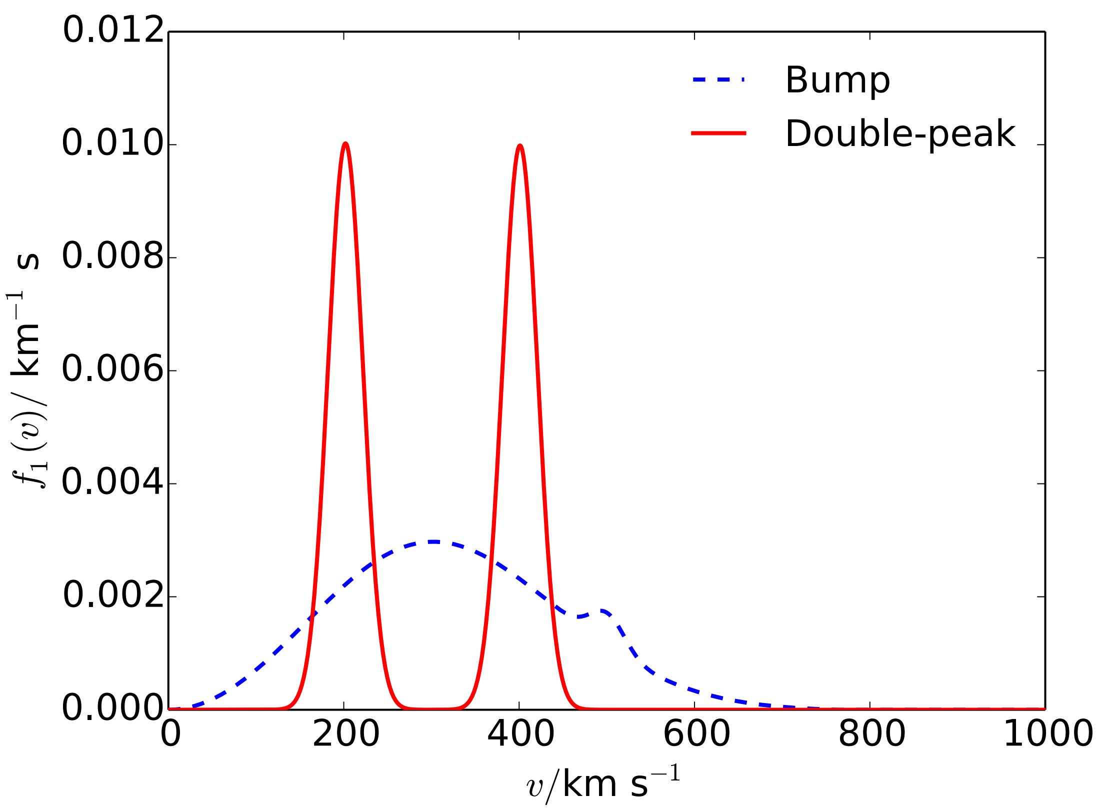
SHM+DD

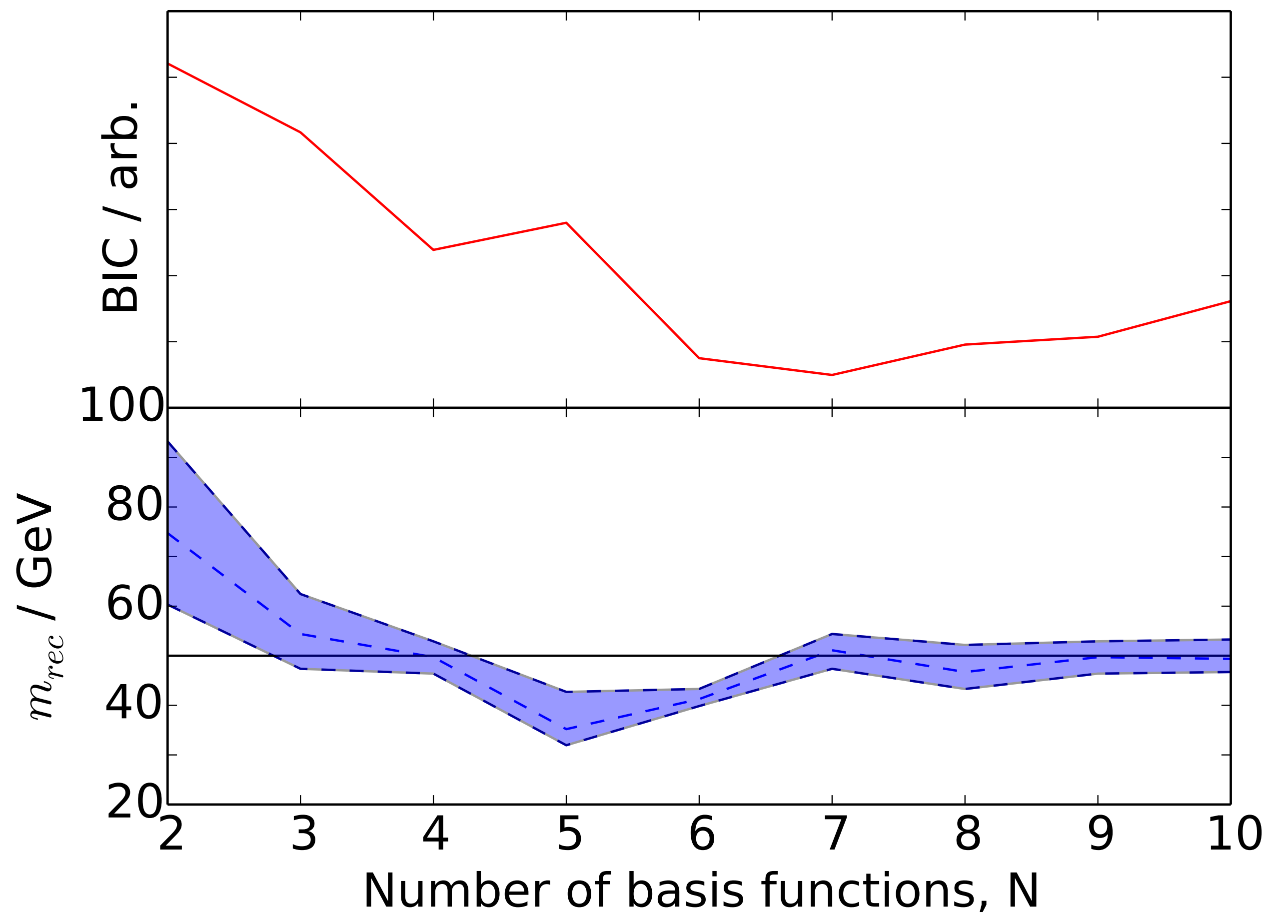
Best fit

Reconstructing the speed distribution



How many terms?





`Shapes' of the speed distribution