Parameterising the WIMP speed distribution for direct detection experiments

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Work with **Bradley Kavanagh** and Mattia Fornasa.

- Why are uncertainties in f(v) important?
- Strategies: i) build a self-consistent model
  ii) integrate out
  iii) marginalize over
- How to parameterise f(v)?

‘Model independent determination of the dark matter mass from direct detection experiments’, Kavanagh & Green, PRL, arXiv:1303.6868

‘Parameterizing the local dark matter speed distribution: a detailed analysis’, Kavanagh, PRD, arXiv:1312.1852

+ IceCube, Kavanagh, Fornasa & Green, in prep.

see also

‘WIMP physics with ensembles of direct detection experiments’, Peter, Gluscevic, Green, Kavanagh, Lee, arXiv:1310.7039.

Why are uncertainties in f(v) important?

Direct detection differential event rate depends on both particle physics parameters (WIMP mass and cross-section) and astrophysical input (local DM density and speed distribution).

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\rho_0 \sigma_{\mathrm{p}}}{2 m_\chi \mu_{\chi \mathrm{p}}^2} A^2 F^2(E) g(v_{\mathrm{min}})$$

$$g(v_{\mathrm{min}}) = \int_{v > v_{\mathrm{min}}} \frac{f(\mathbf{v})}{v} \, \mathrm{d}^3\mathbf{v}$$

$$v_{\mathrm{min}} = \left(\frac{E (m_{\mathrm{A}} + m_\chi)^2}{2 m_{\mathrm{A}} {m_\chi}^2} \right)^{1/2}$$

Experimental constraints on σ-m_χ plane usually calculated using 'standard halo model' (isotropic, isothermal sphere, with Maxwell-Boltzmann speed distribution).

Simulations suggest this is unlikely to be a great approximation to the real Milky Way halo (shape of f(v) different, and there may be features e.g. dark disc, streams, tidal flows).

Incorrect assumptions about the WIMP local density and speed distribution will lead to biased determinations of/constraints on the WIMP mass & cross-section.

Strategies: i) build a self-consistent model

e.g. Evans, Carollo & de Zeeuw; Strigari & Trotta; Catena & Ullio; Bozorgnia; Catena & Schwetz; Fornasa & Green

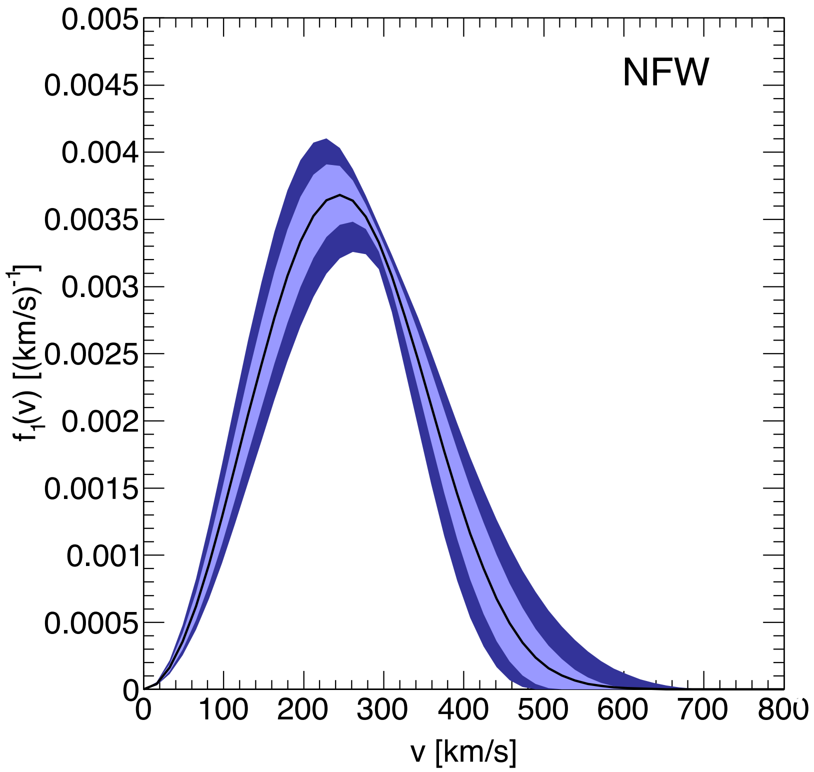
Build a mass model of the Milky Way (density profile of halo and luminous components).

Constrain parameters using astronomical data (e.g. rotation curve, velocity dispersion of halo stars etc.).

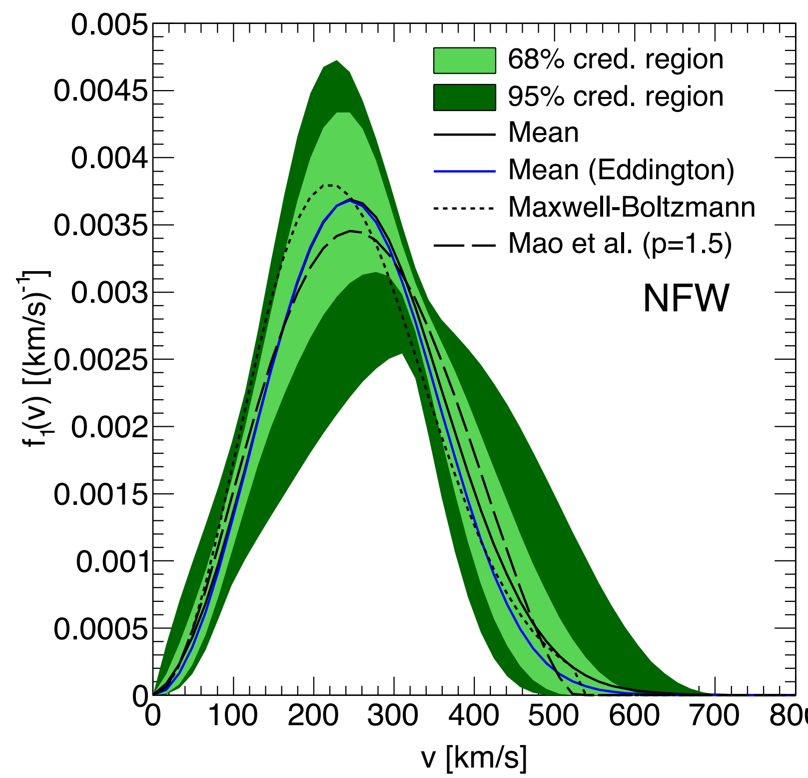
Calculate corresponding f(v) (with assumptions about spherical symmetry & form of anisotropy).

f(v) for Navarro, Frenk, White 'cuspy' density profile

Isotropic



Anisotropic



Fornasa & Green

ii) integrate out

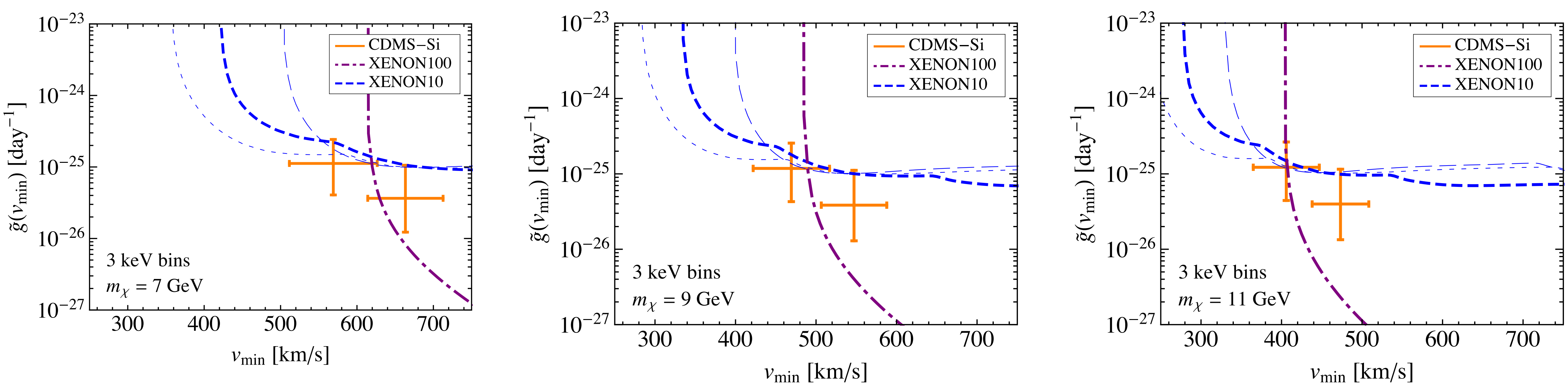
Fox, Liu & Weiner, Gondolo & Gelmini; Frandsen, Kahlhoefer, McCabe, Sarkar, Schmidt-Hoberg; Herrero-Garcia, Schwetz & Zupan; Fox, Kahn & McCullough; Borzognia, Herrero-Garcia, Schwetz & Zupan; Del Nobile, Gelmini, Gondolo & Huh

Compare experiments in terms of the renormalised velocity integral:

$$\tilde{g}(v_{\rm min}) = \frac{\rho_0 \sigma_{\rm p}}{m_\chi} \int_{v > v_{\rm min}} \frac{f(\mathbf{v})}{v} \, {\rm d}^3\mathbf{v} \qquad v_{\rm min} = \left(\frac{E(m_A + m_\chi)^2}{2 m_A m_\chi^2} \right)^{1/2}$$

Extremely useful for checking consistency of signals and exclusion limits.

v_{min} values probed by each experiment depend on, unknown, WIMP mass, therefore need to do comparison for each mass of interest.



Frandsen, Kahlhoefer, McCabe, Sarkar, Schmidt-Hoberg

iii) marginalise over

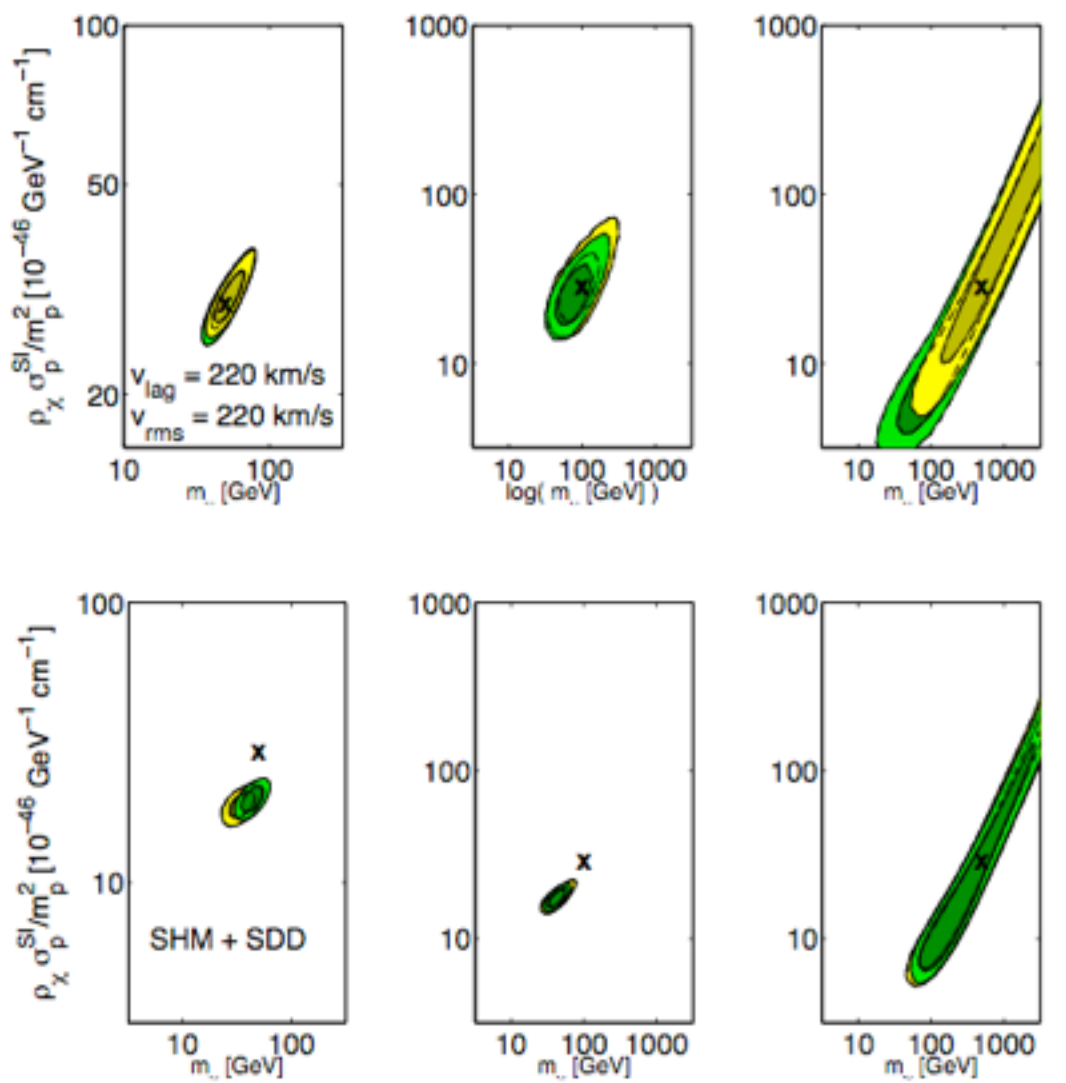
Parameterize f(v) and marginalise over these parameters.

Strigari & Trotta; **Peter x2;** Pato et al. x2; Lee & Peter; Billard, Meyet & Santos; Alves, Hedri & Wacker; Kavanagh & Green x2; Friedland & Shoemaker; Kavanagh

If actual shape of f(v) is similar to assumed shape marginalisation approach works well, but if not can get significant biases:

$m_\chi = 50\,\mathrm{GeV}$ $\quad 100\,\mathrm{GeV}$ $\quad 500\,\mathrm{GeV}$

$$D = \frac{\rho_0 \sigma_{\mathrm{p}}}{m_\chi^2}$$



m_χ

Peter simulated data from future tonne scale Xe, Ar & Ge expts, analysed assuming standard halo model (allowing v_{lag} & v_{rms} to vary).

standard halo model in

standard halo model + dark disc in

How to parameterise f(v)?

Kavanagh & Green; Kavanagh; Fornasa, Green & Kavanagh

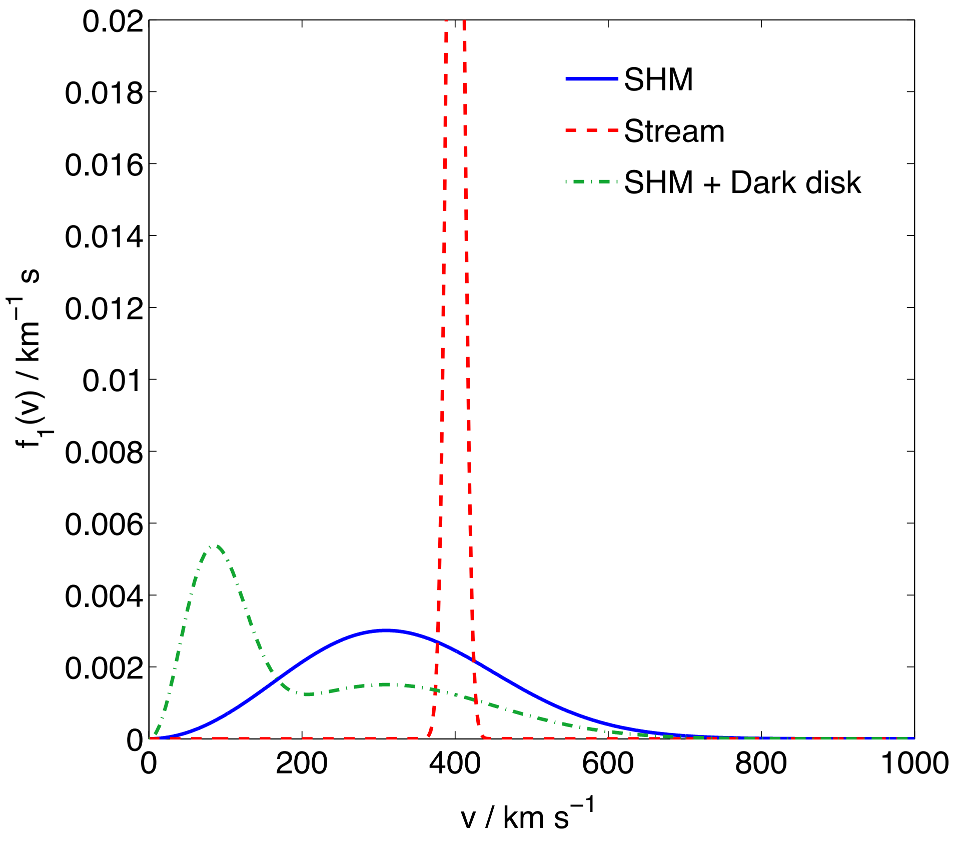
Parameterise log of 1d speed distribution in terms of Legendre or Chebyshev polynomials.

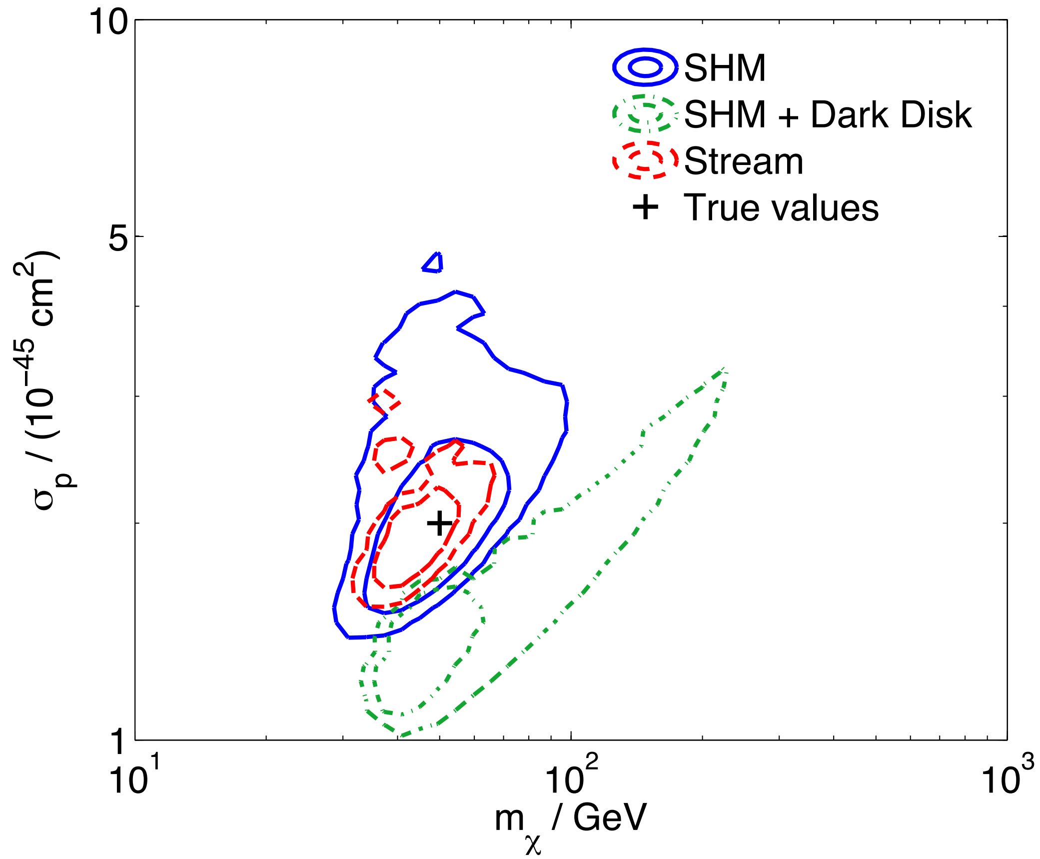
Gives unbiased reconstruction of WIMP mass even for extreme input f(v) (stream or large density small dispersion dark disc).

input speed distributions

reconstructed m_χ and σ
68% & 95% cls from 2d profile likelihood

SHM
Stream
SHM
+ dark disc





And combining direct detection & IceCube data allows unbiased measurement of cross-section and reconstruction of f(v).

BACKUP SLIDES

Methodology

Experimental parameters

Experiment	Target Mass, A	Detector Mass (fid.), $m_{\rm det}$/kg	Efficiency, ϵ	Energy Range/keV
Xenon	131	1100 [48]	0.7 [49]	7-45 [50]
Argon	40	1000	0.9 [51]	30-100 [52]
Germanium	73	150 [53]	0.6 [54]	8-100 [54]

$$t_{\rm exp} = 2\,{\rm years}$$

Priors

Parameter	Prior type	Prior range
m_χ/ GeV	log-flat	$[10^0, 10^3]$
σ_p/ cm^2	log-flat	$[10^{-46}, 10^{-42}]$
$\{a_k\}$	linear-flat	$[-50, 50]$
R_{BG}/dru	log-flat	$[10^{-12}, 10^{-5}]$

Multinest sampling parameters

Parameter	Value
$N_{\rm live}$	10000
efficiency	0.25
tolerance	10^{-4}

Asimov data, binned likelihood:
(1 keV bins)

$$\mathcal{L}_{\rm b} = \prod_{i=1}^{N_{\rm b}} \frac{N_{\rm e,i}^{N_{\rm o,i}} \exp\left(-N_{\rm e,i}\right)}{N_{\rm o,i}!}$$

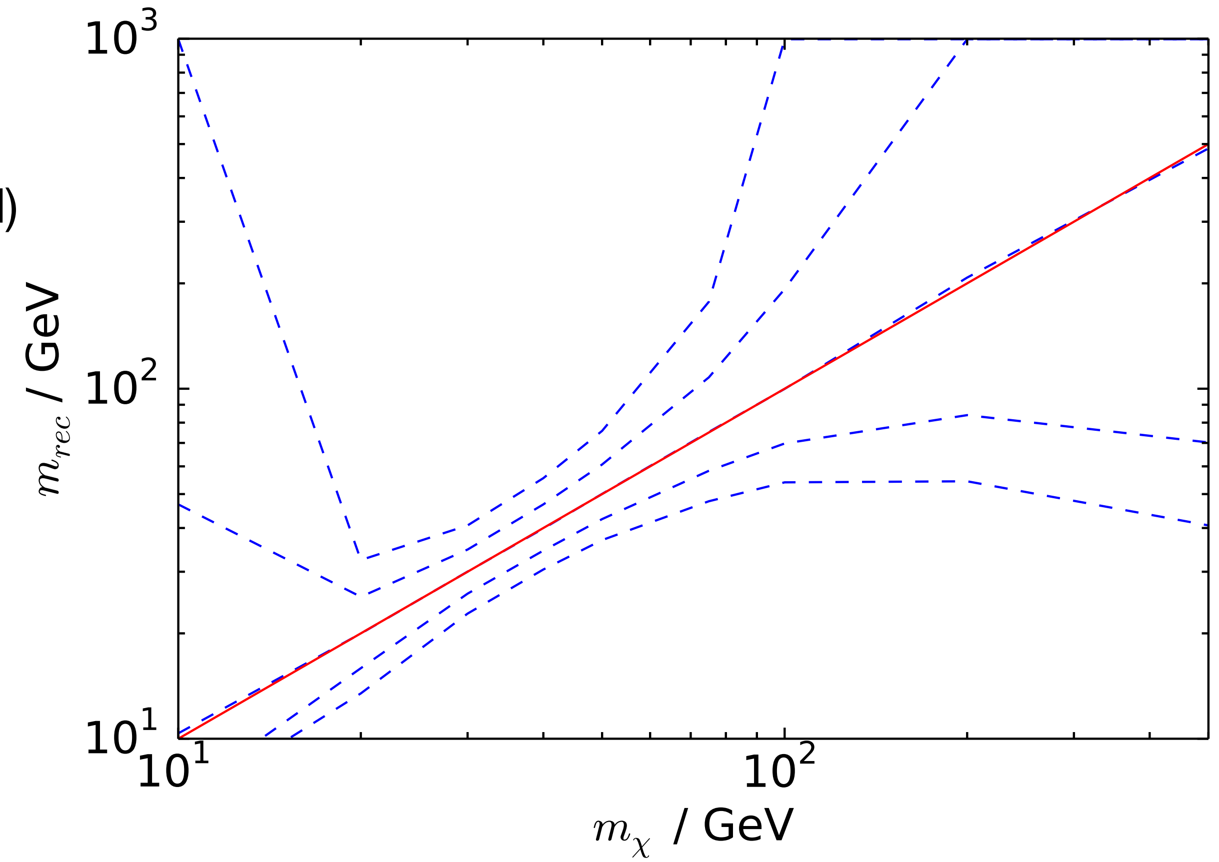
Realisations with Poisson noise, extended Likelihood:

$$\mathcal{L} = \frac{N_{\rm e}^{N_{\rm o}} \exp\left(-N_{\rm e}\right)}{N_{\rm o}!} \prod_{i=1}^{N_{\rm b}} P(E_{\rm i})$$

IceCube: 86 string configuration including DeepCore array, calculate number of events using DarkSUSY, following Arina et al.

Dependence on underlying WIMP mass

reconstructed mass
(central value + 68%
& 95% intervals
from profile likelihood)



input mass

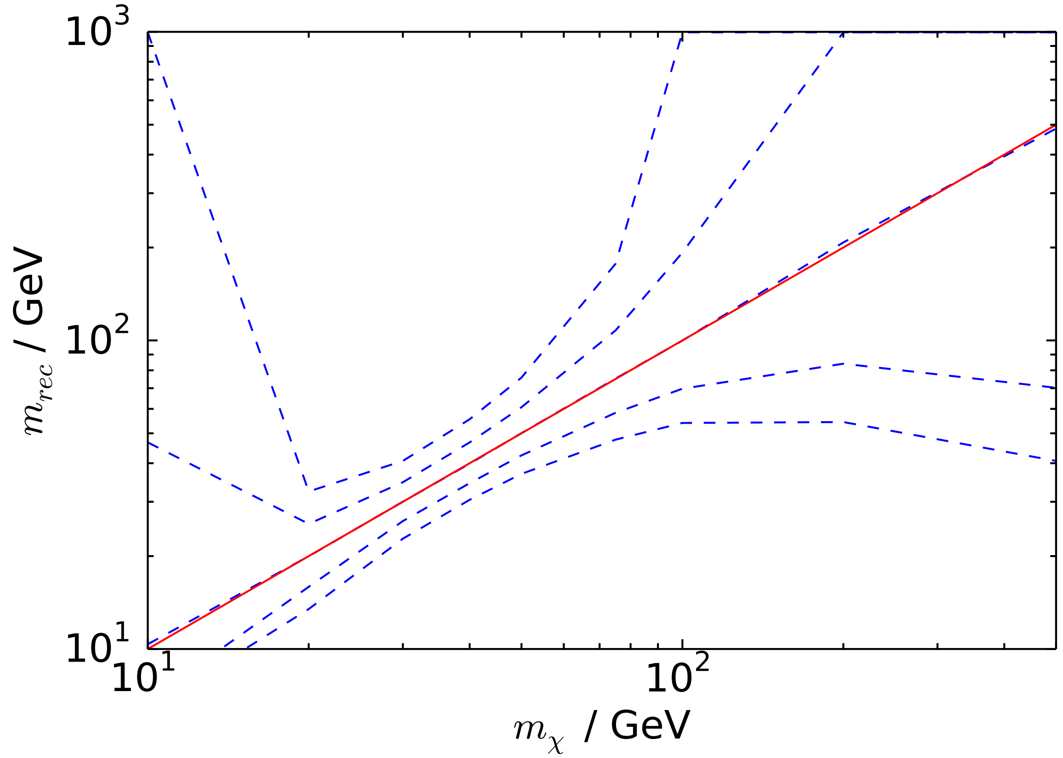
Inherent limitations in determining the mass:

at low masses event rates above thresholds small

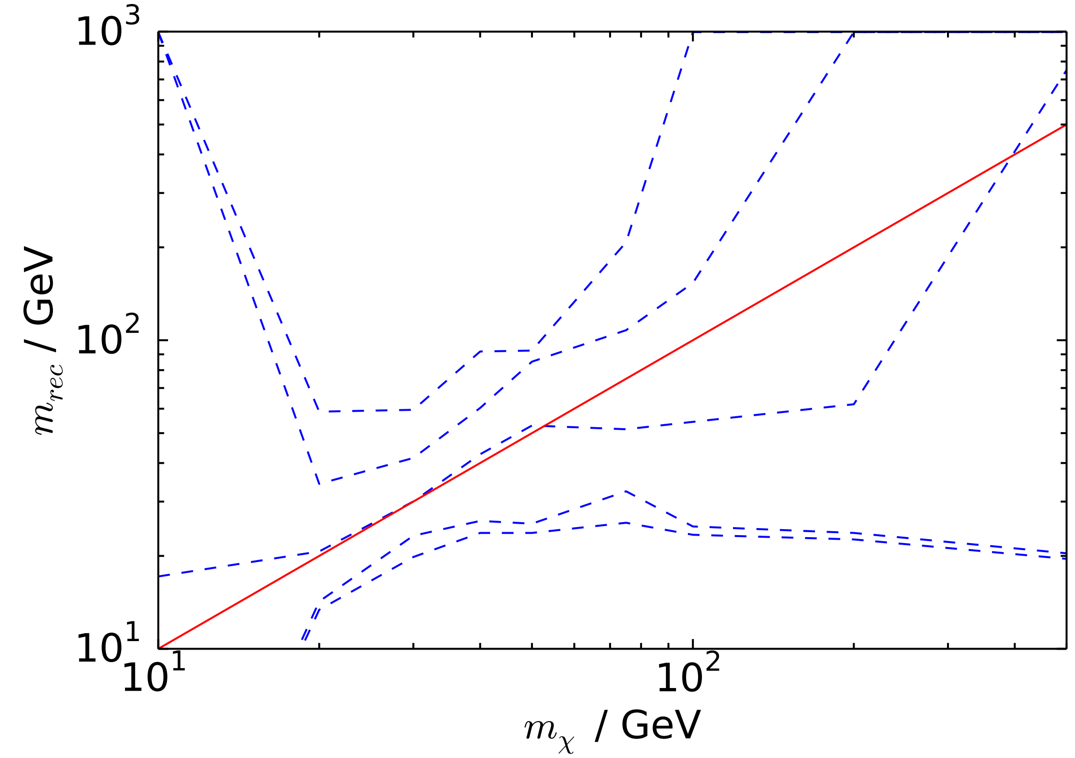
at high masses energy spectrum independent of mass

Finite background & energy resolution

Idealised experiments



1keV energy resolution
flat background, 1 /kg/day/keV



At high masses: finite resolution means shape is less well-determined

flat background spectrum can mimic heavy WIMP

Statistical fluctuations

Results from 250 realisations, including Poisson fluctuations.

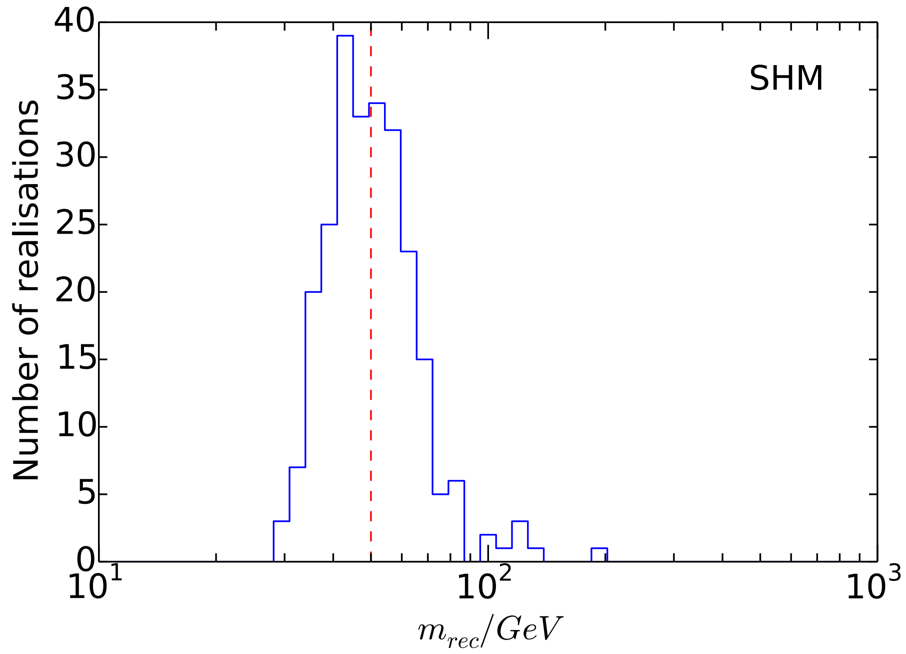
Bias: $b = \ln(m_{\rm rec}/{\rm GeV}) - \ln(m_\chi/{\rm GeV})$

Coverage: fraction of realisations in which true parameter lies within given interval

$$\langle b \rangle = 0.002 \pm 0.008$$

$$68\% \text{ coverage: } (71 \pm 3)\%$$

$$95\% \text{ coverage: } (94 \pm 3)\%$$

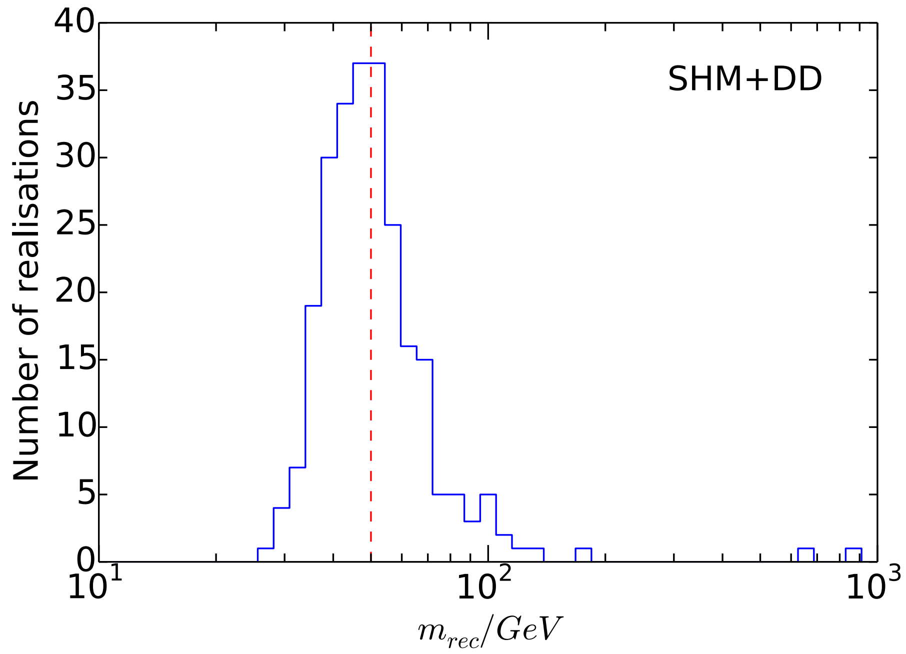


SHM

$$\langle b \rangle = 0.005 \pm 0.007$$

$$68\% \text{ coverage: } (68 \pm 3)\%$$

$$95\% \text{ coverage: } (91 \pm 4)\%$$



SHM+DD

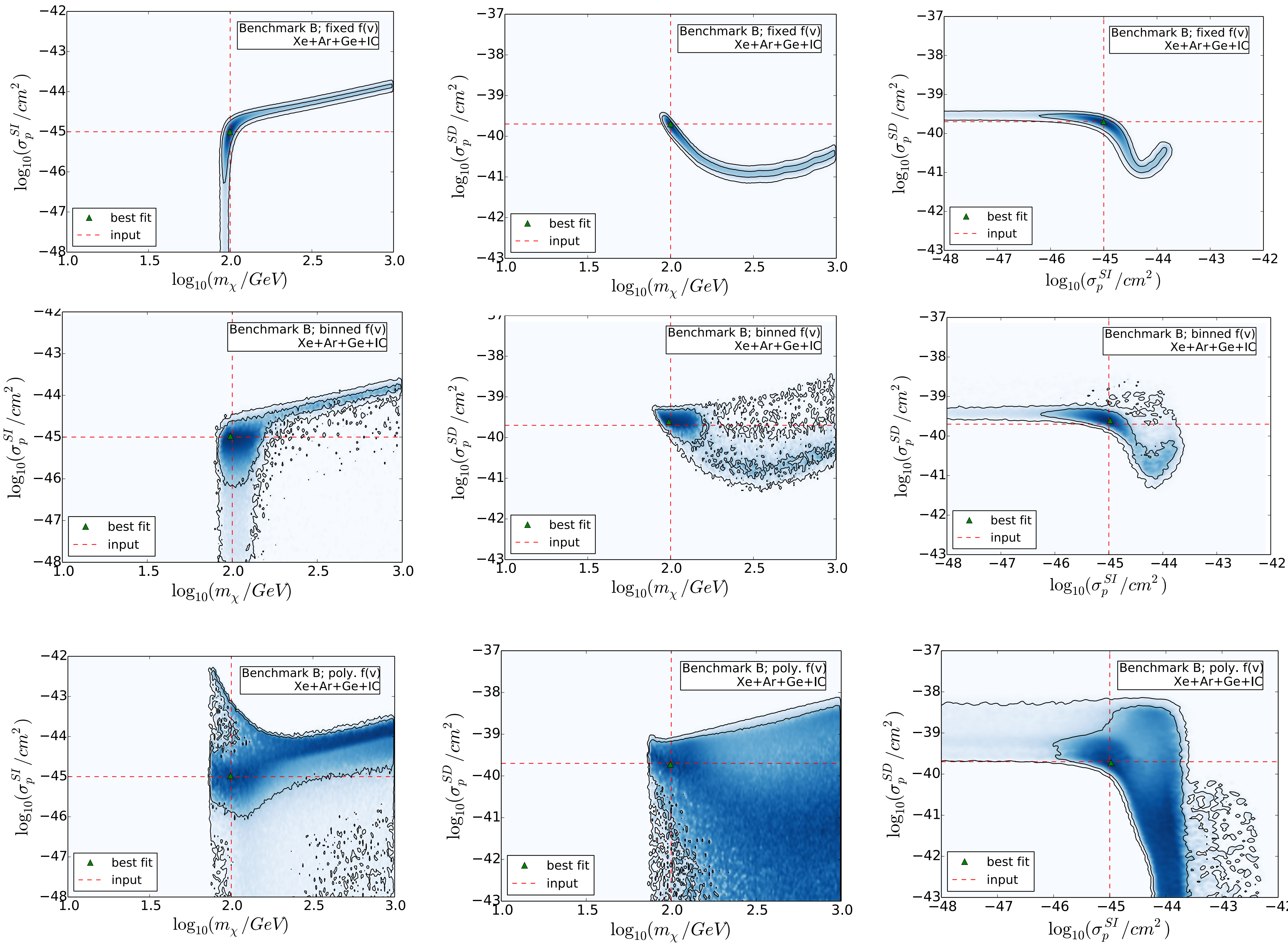
Same particle physics benchmark as Arina et al. (100 GeV WIMP annihilating predominantly into W^+W^-) but with f(v) = SHM + DD.

Simulated data from Xe, Ar & Ge direct detection experiments + IceCube.

assuming SHM+DD

binned f(v)

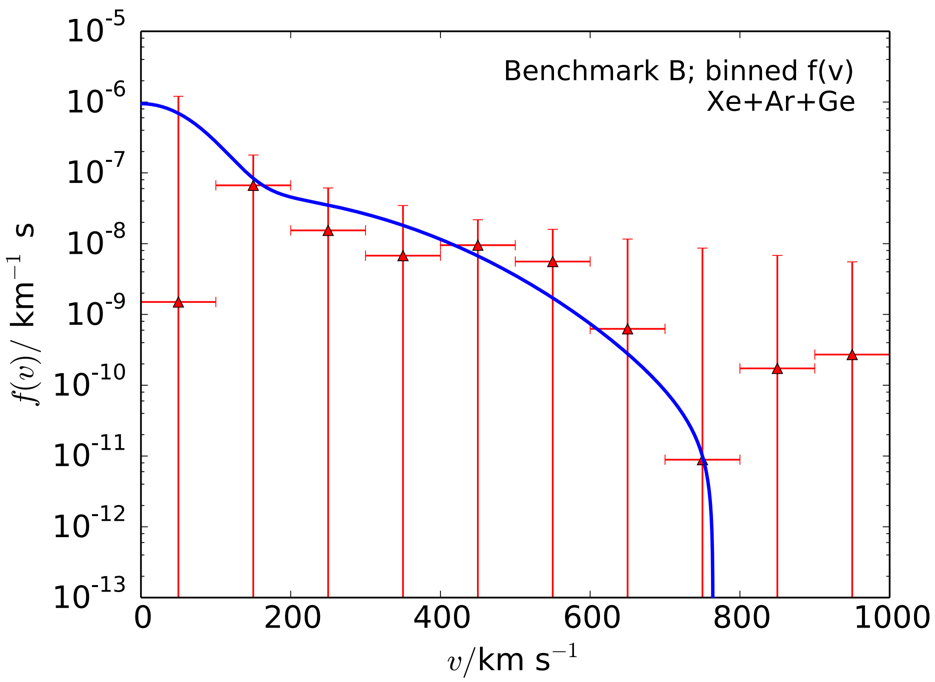
polynomial f(v)

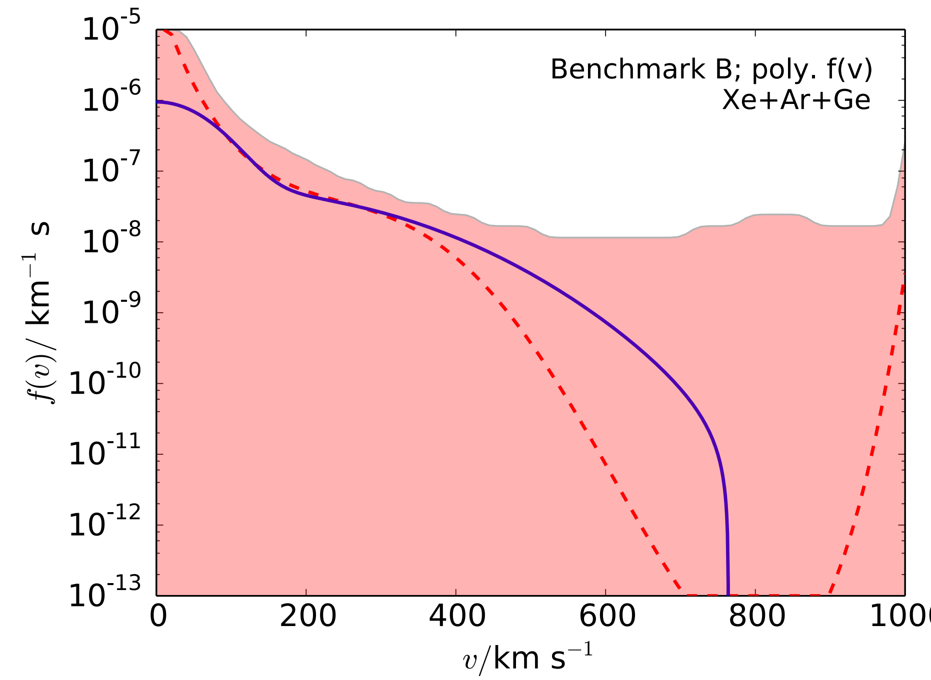


Reconstructed speed distribution

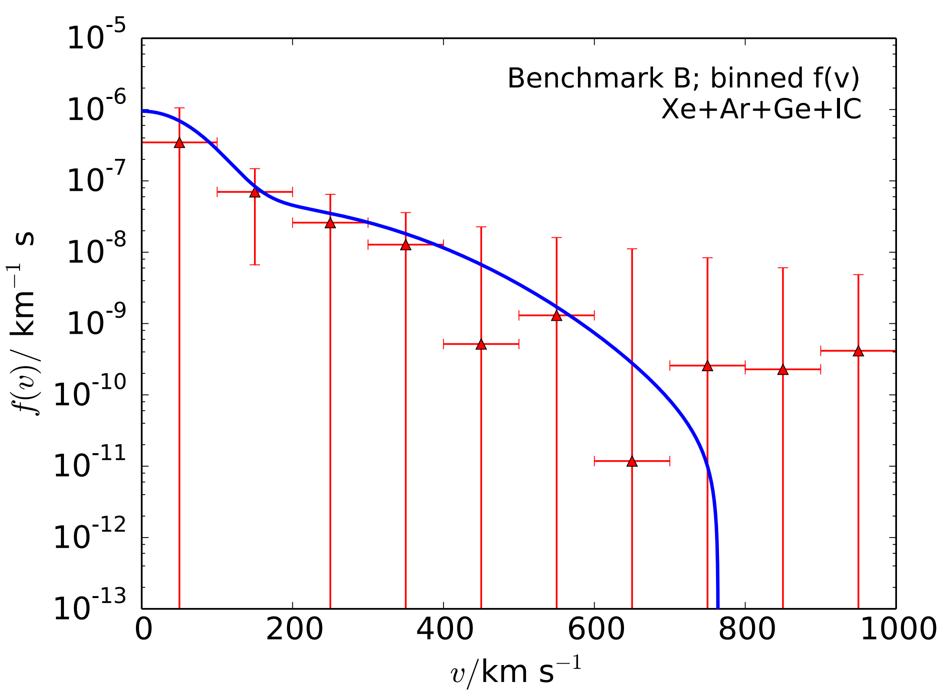
binned f(v) | polynomial f(v)

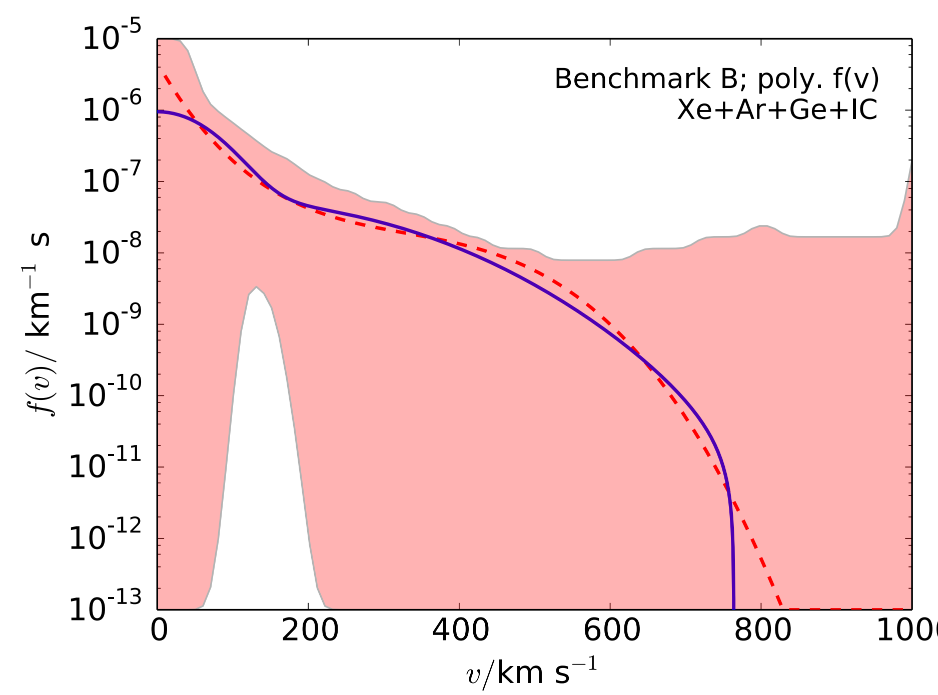
direct detection only





direct detection + IceCube





Preliminary results using 5 polynomials (may not be enough → flat likelihood function → wide contours).

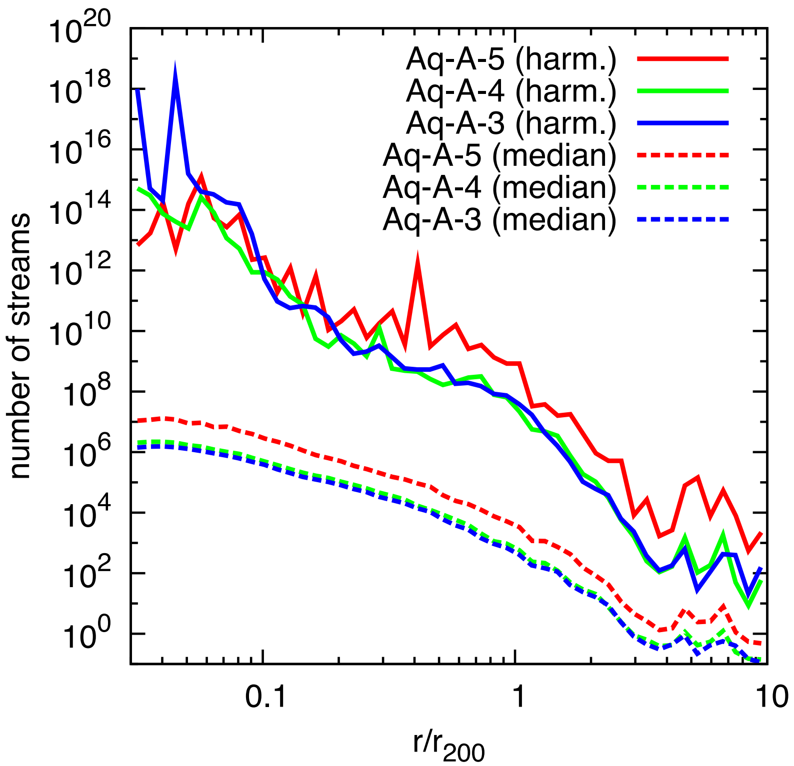
fine structure in ultra-local DM velocity distribution?

Vogelsberger & White:

Follow the fine-grained phase-space distribution, in Aquarius simulations of Milky Way like halos.

From evolution of density deduce ultra-local DM distribution consists of a huge number of streams (but this assumes ultra-local density= local density).

At solar radius <1% of particles are in streams with $\rho > 0.01\rho_0$.



number of streams as a function of radius

calculated using harmonic mean/median stream density

Schneider, Krauss & Moore:

Simulate evolution of microhalos. Estimate tidal disruption and heating from encounters with stars, produces 10^2-10^4 streams in solar neighbourhood.