Impact of astrophysical uncertainties on WIMP direct detection

Anne Green
University of Nottingham

- Observations
- Simulations
- Strategies for handling astrophysical uncertainties
    i. integrate out
    ii. model Milky Way
    iii. parameterise and marginalise

Intro

Differential event rate (for spin independent elastic scattering with f_p=f_n):

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

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

minimum speed that can cause a recoil with energy E

Particle physics parameters: WIMP mass and cross-section m_χ σ_{p}

Astrophysical input: local DM density and speed distribution ρ_0 $f(v)$

Normalization: σ and ρ are degenerate.

Shape of energy spectrum: depends on m_χ and f(v) (with a single experiment can't probe m_χ without making assumptions about f(v), but with multiple experiments can break this degeneracy Drees & Shan; Peter)

Experimental constraints on σ-m_χ plane usually calculated using 'standard halo model':

isotropic, isothermal sphere, with Maxwell-Boltzmann speed distribution

$$f(\mathbf{v}) \propto \exp\left(-\frac{3|\mathbf{v}|^2}{2\sigma^2} \right) \qquad \sigma = \sqrt{\frac{3}{2}} v_{\mathrm{c}}$$

with v_c=220 km s^{-1} and local density ρ_0=0.3 GeV cm^{-3}

Observations

Local density: see Read review

Use multiple data sets (rotation curve, velocity dispersions of halo stars, local surface mass density, total mass...) and model for the MW (luminous components and halo).

For a fixed halo density profile can get high precision determination:

Catena & Ullio NFW & Einasto profiles: $\rho_0 = (0.39 \pm 0.03)\,\mathrm{GeV\,cm^{-3}}$

Model independent/minimal assumption methods give larger errors:

e.g. Salucci et al. eqn of centrifugal eqm $\rho_0 = (0.43 \pm 0.11 \pm 0.10)\,\mathrm{GeV\,cm^{-3}}$

Garbari et al. solve Jeans-Poisson eqns $\rho_0 = 0.85^{+0.57}_{-0.50}\,\mathrm{GeV\,cm^{-3}}$

Pato et al. DM density in stellar disc of simulated halos is ~ 20% larger than the shell average determined by observations.

Summary

i) standard value of 0.3 GeV cm^{-3} is probably a bit low.

ii) recent determinations have ~10% statistical errors, but systematic uncertainties from modelling are still significantly larger.

Local circular speed:

IAU/Kerr & Linden-Bell compilation of measurements: $v_{\rm c} = (220 \pm 20)\,{\rm km\,s^{-1}}$

Proper motion of Sgr A* Reid & Brunthaler and maser data Reid et al: $v_{\rm c} \sim (250 \pm 10)\,{\rm km\,s^{-1}}$

Bovy et al. if non-random phases of masers modelled only get weak constraint combined with Sgr A* & GD-1 stellar stream, assuming flat rotation curve: $v_{\rm c} = (236 \pm 11)\,{\rm km\,s^{-1}}$

Bovy et al. APOGEE data (l.o.s. v of 3000 stars): $v_{\rm c} = (218 \pm 6)\,{\rm km\,s^{-1}}$

McMillan & Binney allowing non-flat rotation curve: $v_{\rm c} = (200 - 280)\,{\rm km\,s^{-1}}$

Modelling uncertainties larger than statistical uncertainties here too.

n.b. Standard halo has one-to-one relationship between circular speed and velocity dispersion, $\sqrt{2}\sigma = v_{\rm c}$, but in general relationship depends on density profile and velocity anisotropy, β :

$$\frac{1}{\rho}\frac{{\rm d}(\rho\sigma_r^2)}{{\rm d}r} + 2\frac{\beta\sigma_r^2}{r} = -\frac{v_c^2}{r}$$

Also for non-standard halos peak velocity, v_0, isn't equal to circular speed.

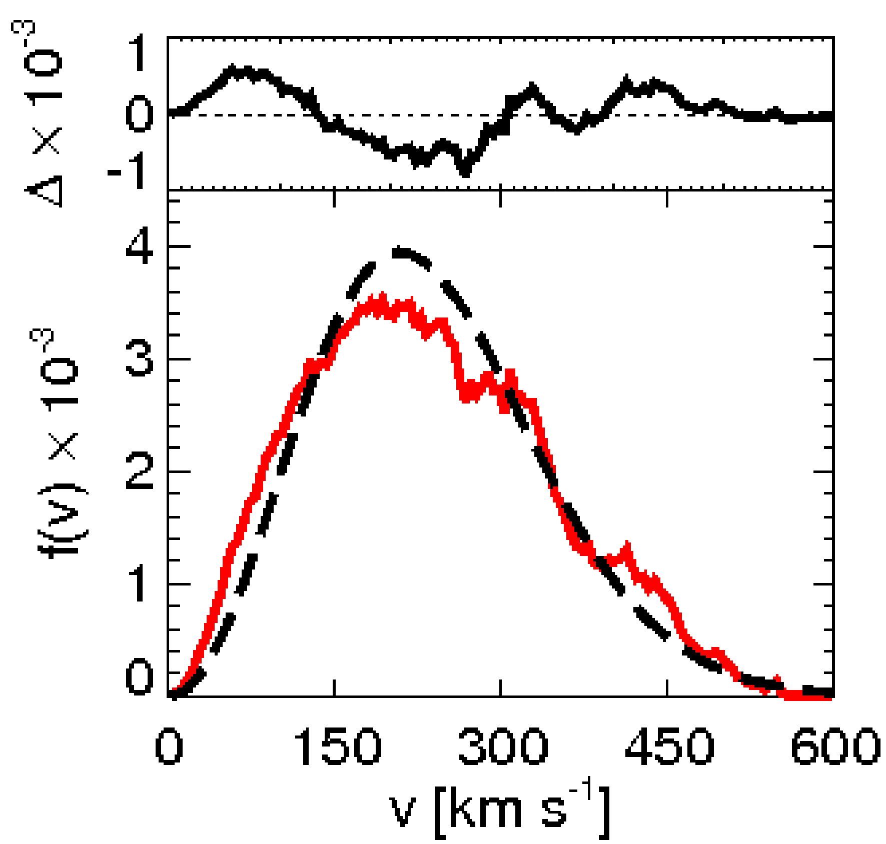
Simulations i) N-body (DM only)

Systematic deviations from multi-variate gaussian: more low speed particles, peak of distribution lower/flatter → Mao et al. fitting function

Features in tail of dist, 'debris flows', incompletely phased mixed material. Lisanti & Spergel; Kuhlen, Lisanti & Spergel

Deviations less pronounced in lab frame than Galactic rest frame.

Vogelsberger et al.

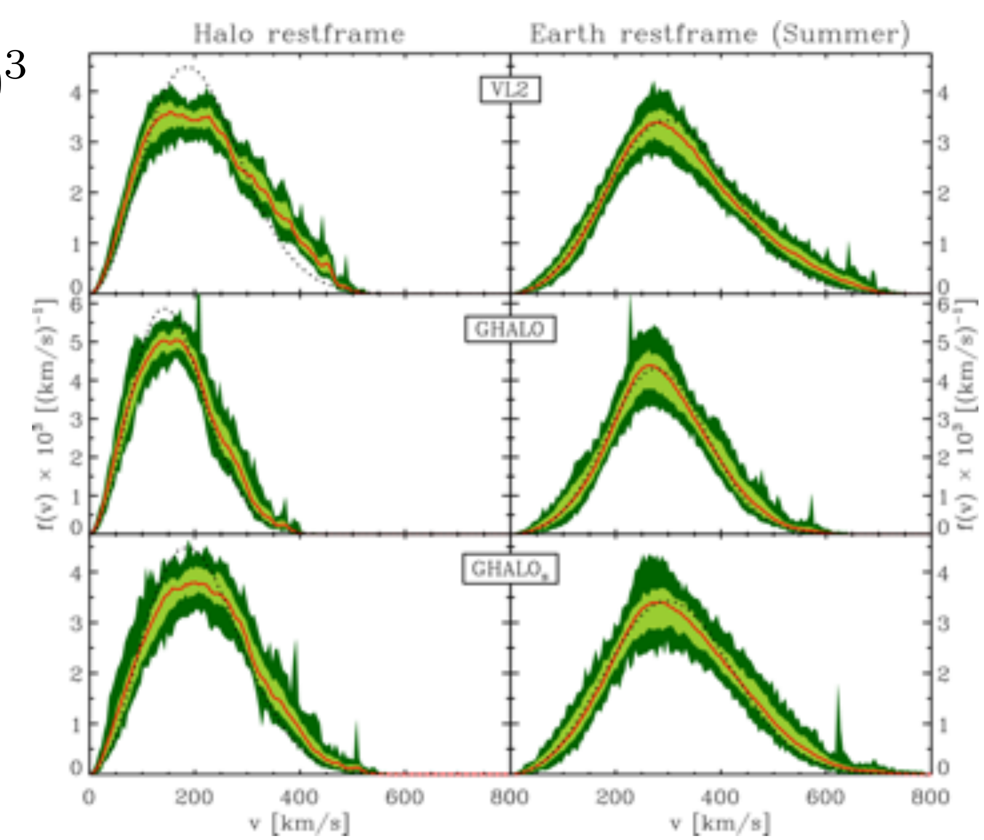


Aquarius simulation data,
best fit multi-variate Gaussian

Kuhlen et al.

halo rest frame Earth rest frame

$f(v) \times 10^3$



$v[\mathrm{km/s}]$

Simulations ii) SPH (including baryons)

Ling et al; Eris: Pillepich et al: NIHAO: Butsky et al.

early 2016: Sloane et al.; EAGLE/APOSTLE: Borzognia et al.; MaGICC Kelso et al,.

Use different prescriptions for sub-grid physics and different criteria for selecting MW-like galaxies.

Adding baryons deepens potential and increases average speed of particles.

Borzognia et al. and Kelso et al.:

Maxwellian (with larger v_0) is a good fit to f(v) of hydro simulations (since baryonic contraction means logarithmic slope of density list is closer to -2 at Solar radius??).

Sloane et al.:

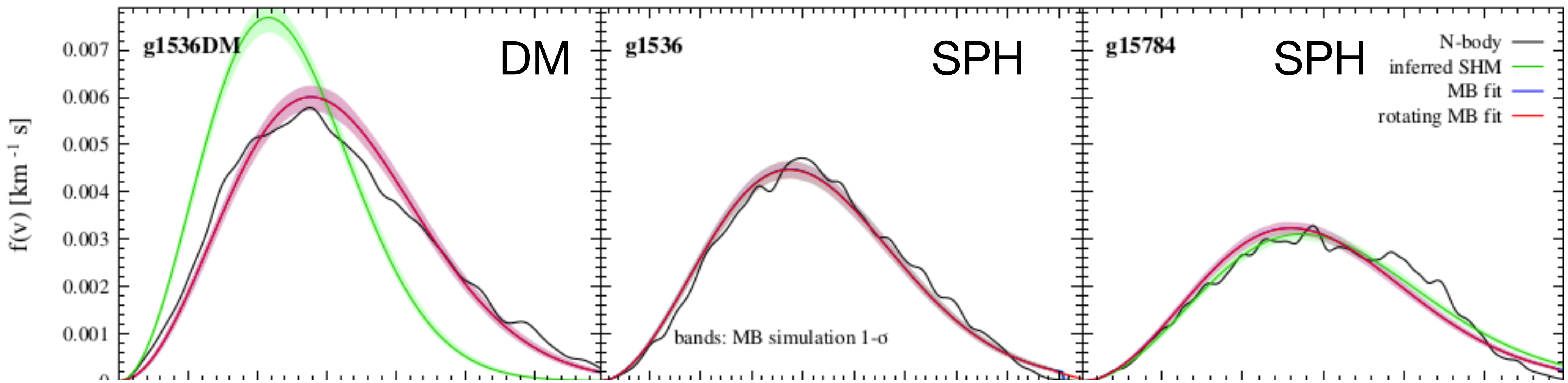
Maxwellian better fit to hydro sims for 3/4 galaxies, but not a good fit (sims have deficit of high v particles).

See features in Earth frame in hydro sims.

Most galaxies have no sign of a dark disc.

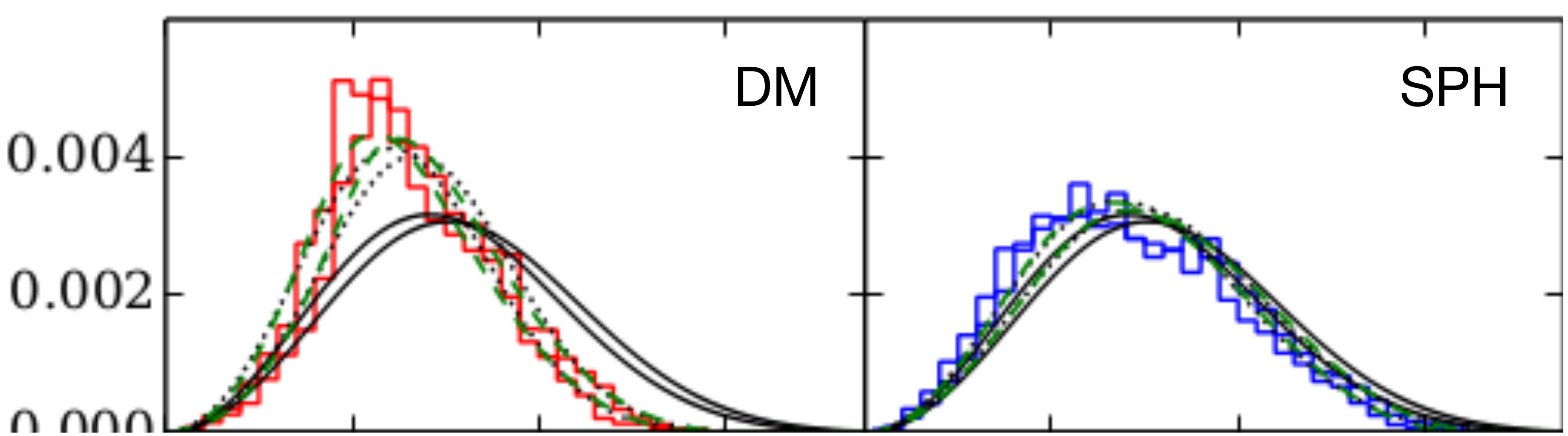
Speed distributions in Earth frame:

Kelso et al.:



SHM Maxwellian

Sloan et al.:



Mao Maxwellian

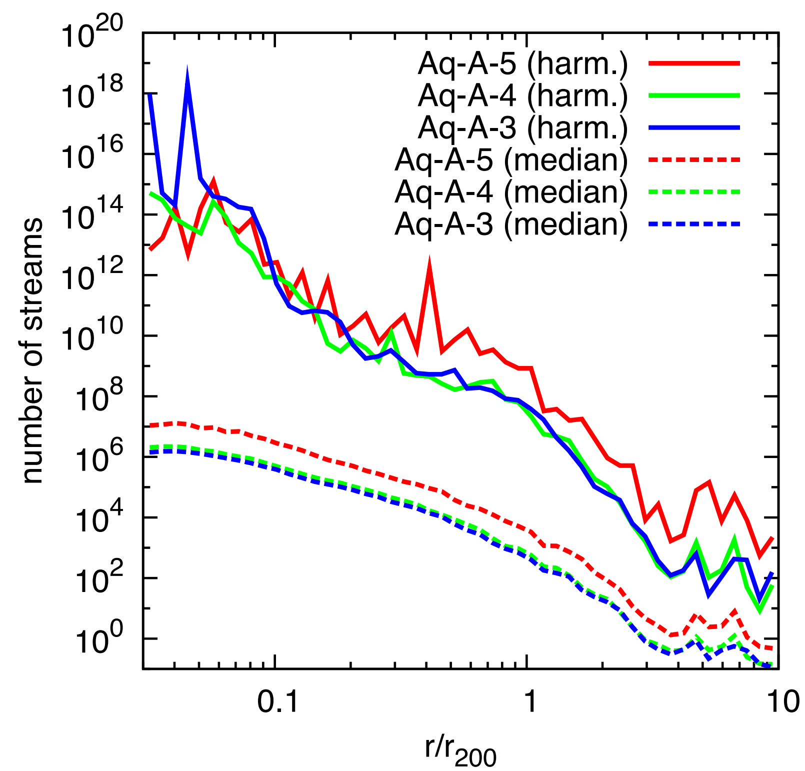
the resolution of simulations is many orders of magnitude larger than the mpc scales probed by direct detection experiments: is there fine structure in ultra-local DM velocity distribution?

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

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.

NO

Deviations from the standard halo model are almost certainly not as large as (I) once feared.

However, the standard halo model may well not be a great approximation to the real Milky Way halo.

Strategy: i) integrate out

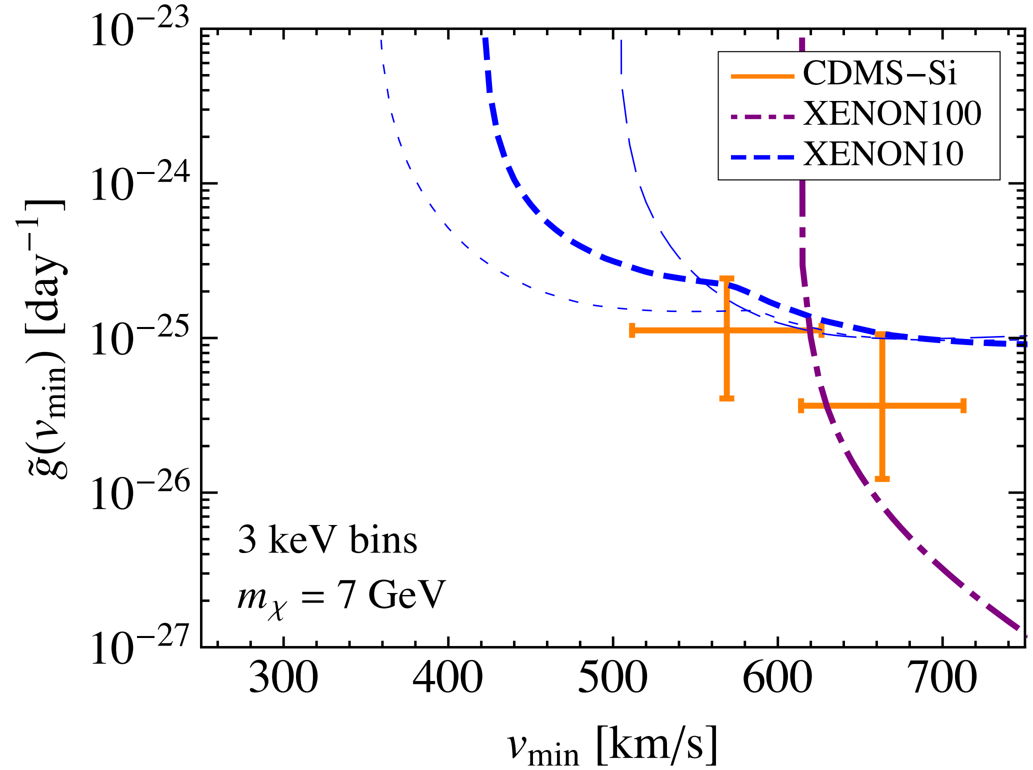
Fox, Liu & Weiner

Compare experiments in terms of the renormalised velocity integral:

Frandsen et al.

$$\tilde{g}(v_{\rm min}) = \frac{\rho_0 \sigma_{\rm p}}{m_\chi} \int_{v>v_{\rm min}} \frac{f(\mathbf{v})}{v} \, {\rm d}^3\mathbf{v}$$

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



Approach has been extended to incorporate experimental energy resolution and efficiency, annual modulation, unbinned data, inelastic scattering, non-standard interactions etc. etc.

Useful for checking consistency of signals and exclusion limits.

$v_{\rm min}$ values probed by each experiment depend on, unknown, WIMP mass, therefore need to do comparison for each mass of interest (or do comparison in terms of recoil momentum Anderson, Fox, Kahn & McCullough).

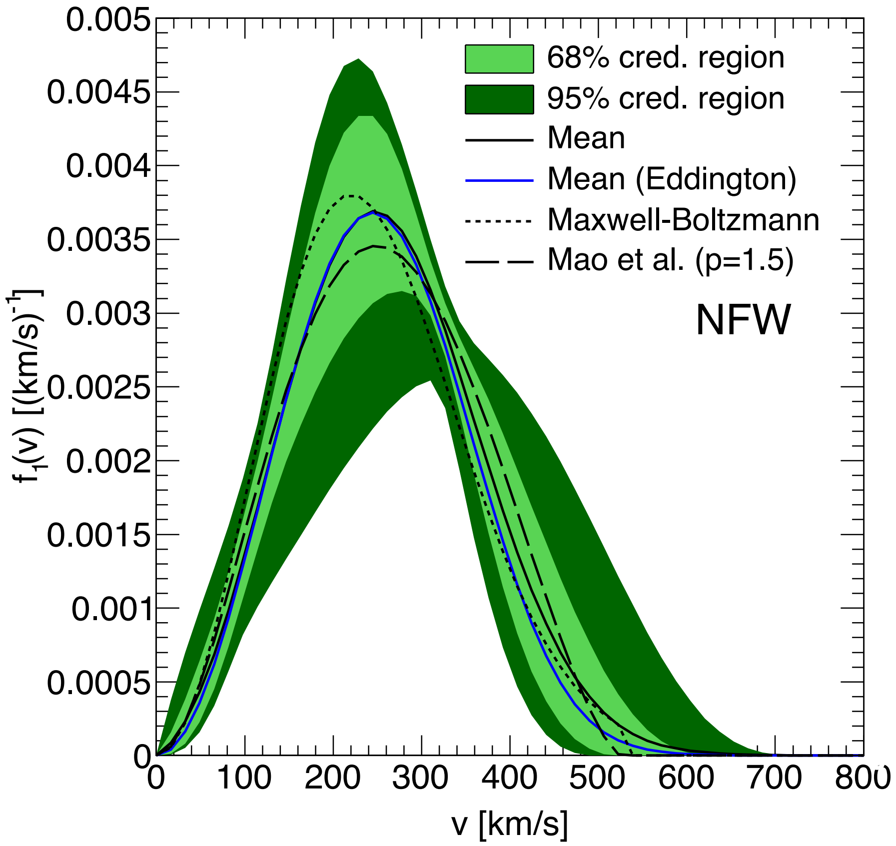
ii) model the MW

Catena & Ullio

Build a mass model of the Milky Way (stellar disk, bulge/bar, ISM + DM halo) and constrain parameters using various observational data sets (local circular speed, local surface density, terminal velocities, microlensing, proper motions of masers, velocity dispersion of halo stars).

Use Eddington formalism to calculate speed distribution f(v), including uncertainties.

Extensions to drop assumption of isotropic f(v). [Bozorgnia, Catena & Schwetz;Fornasa & Green]



.... Maxwell-Boltzmann

_ _ _ _ Mao et al. parameterisation (good fit to DM only simulations)

For a given ρ(r) uncertainty on f(v) is a factor of ~4-5, and high-speed tail is more with anisotropy.

iii) parameterise and marginalise

Peter

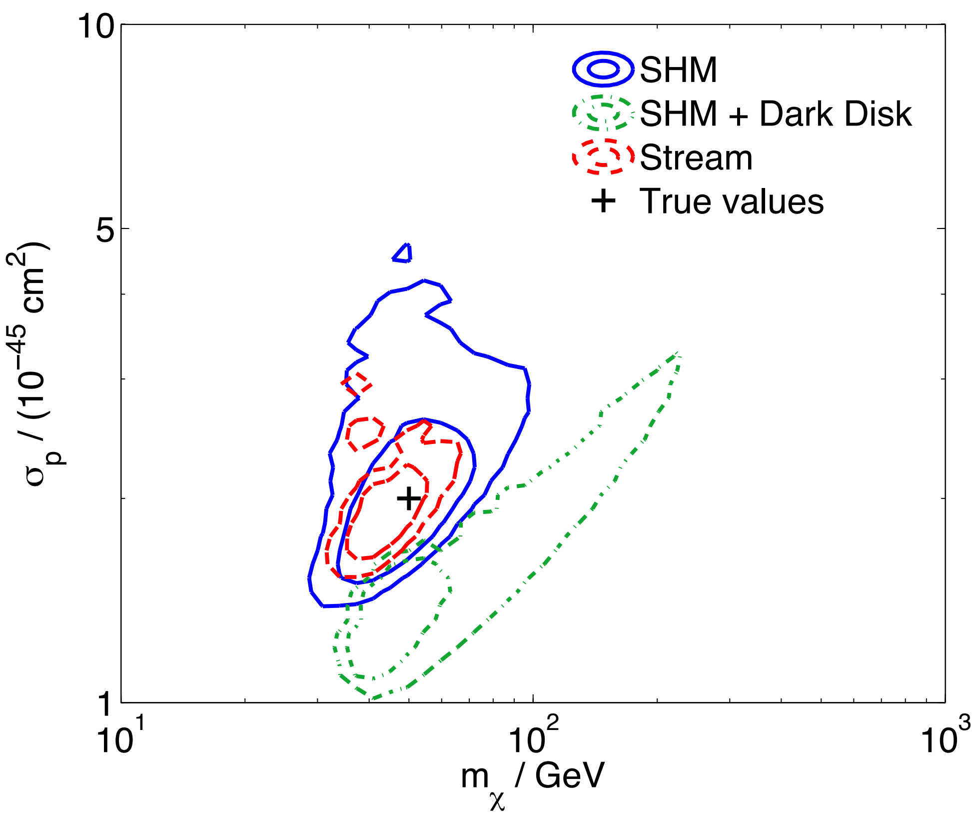
Parameterize f(v) and marginalise over these parameters.

With direct detection data only:

Cross-section can be biased, as an unknown fraction of the WIMPs are below threshold.

Binned parameterisation Peter leads to biased mass (reducing mass reduces width of bins in E, and enables better fit Kavanagh & Green).

(Legendre or Cheyshev) polynomial parameterisation gives good reconstruction of mass, even for extreme f(v) Kavanagh & Green.



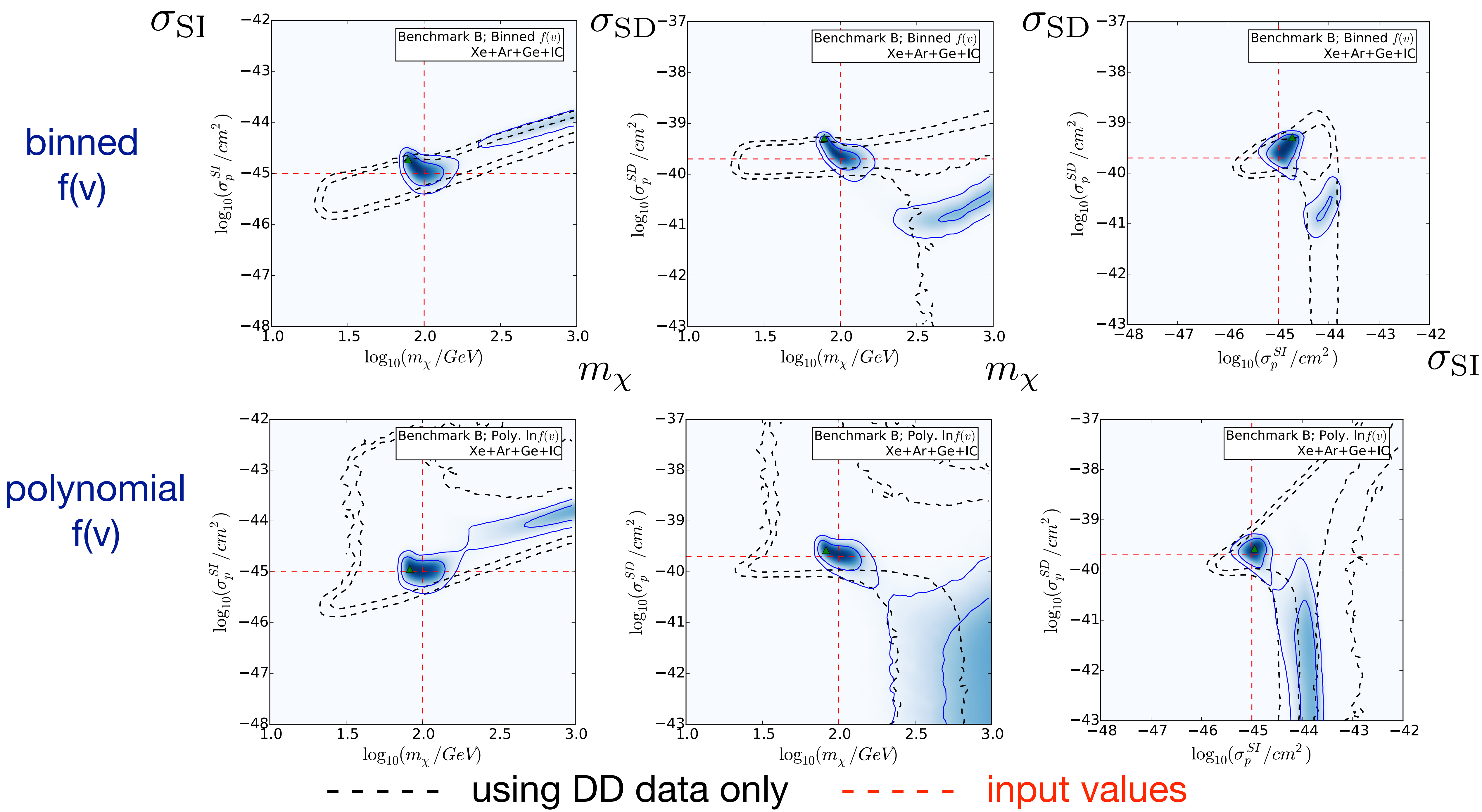
reconstructed m_χ and σ from simulated data from next gen experiments

SHM
Stream
SHM + dark disc

Flux of neutrinos due to WIMP annihilation in Sun is sensitive to low speed tail of f(v).

Therefore by combining direct & indirect data probe full range of f(v) and can make unbiased measurements of mass and cross-sections. Kavanagh, Fornasa & Green

Reconstructed mass and cross-sections for a 100 GeV WIMP annihilating into W^+W^- using simulated data from Xe, Ar & Ge direct detection experiments + IceCube.



Summary

- The direct detection energy spectrum depends on both f(v) and the WIMP mass (with a single experiment can't probe the mass without making assumptions about f(v), with multiple experiments can break this degeneracy).

- Observational determinations of the local density and circular speed have ~10% errors, but systematic errors are larger

- Simulations: with baryons Maxwellian is a better fit than without, but not clear whether it's a **good** fit.

- Can assess compatibility of signals/exclusion limits in speed integral, $g(v_{min})$, space ('integrating out the astrophysics').

- Can make an unbiased mass measurement from multiple data sets using a suitable empirical parameterisation (e.g. shifted Legendre or Chebyshev polynomials).

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

Local escape speed:

Piffl et al: high velocity stars from the RAVE survey,

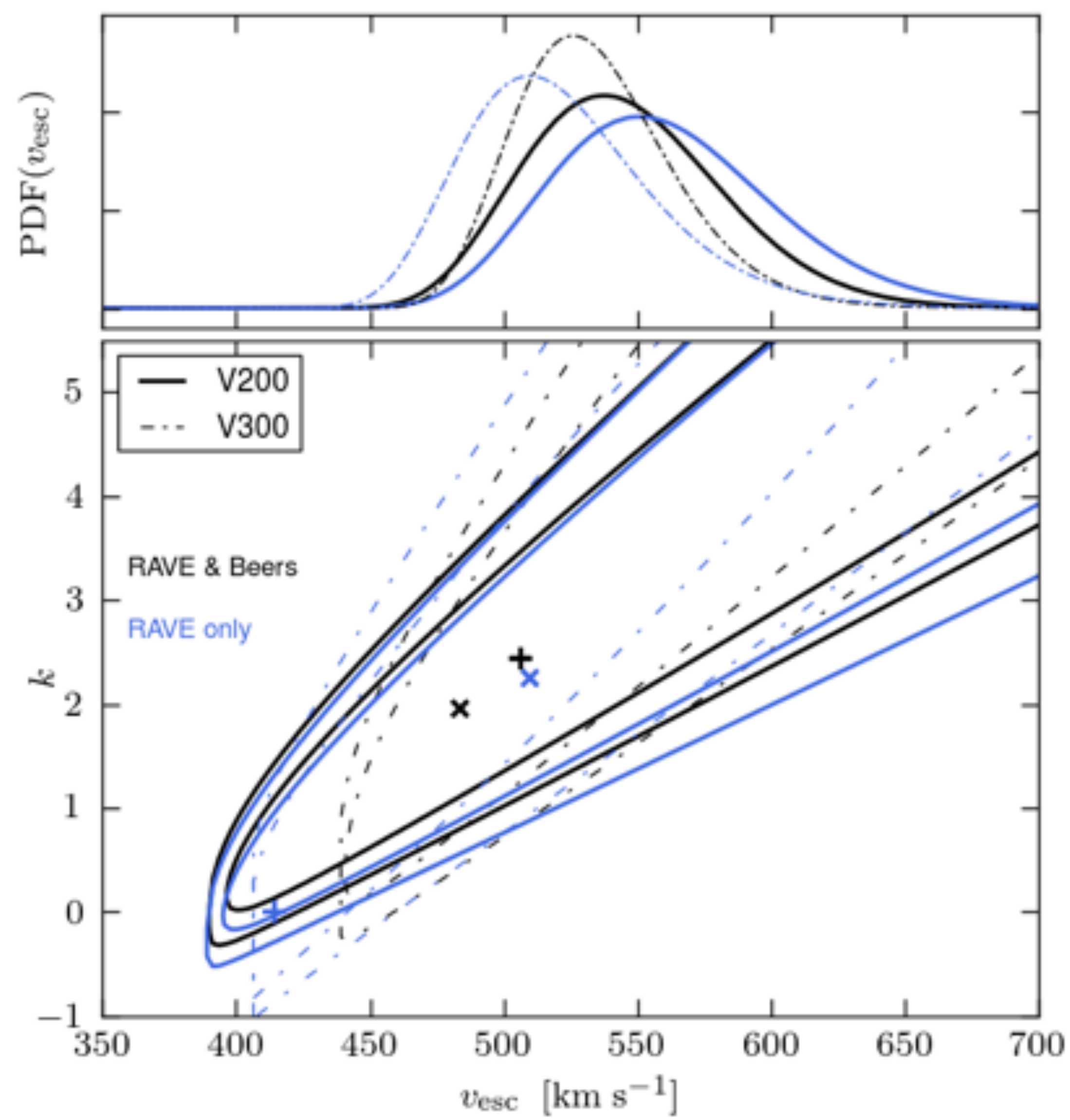
assume $f(|\mathbf{v}|) \propto (v_{\rm esc} - |\mathbf{v}|)^k$

with k in range 2.3 to 3.7 (motivated by numerical simulations):

$$v_{\rm esc} = 533^{+54}_{-41}\,{\rm km\,s^{-1}}$$

$P(v_{\rm esc})$

k

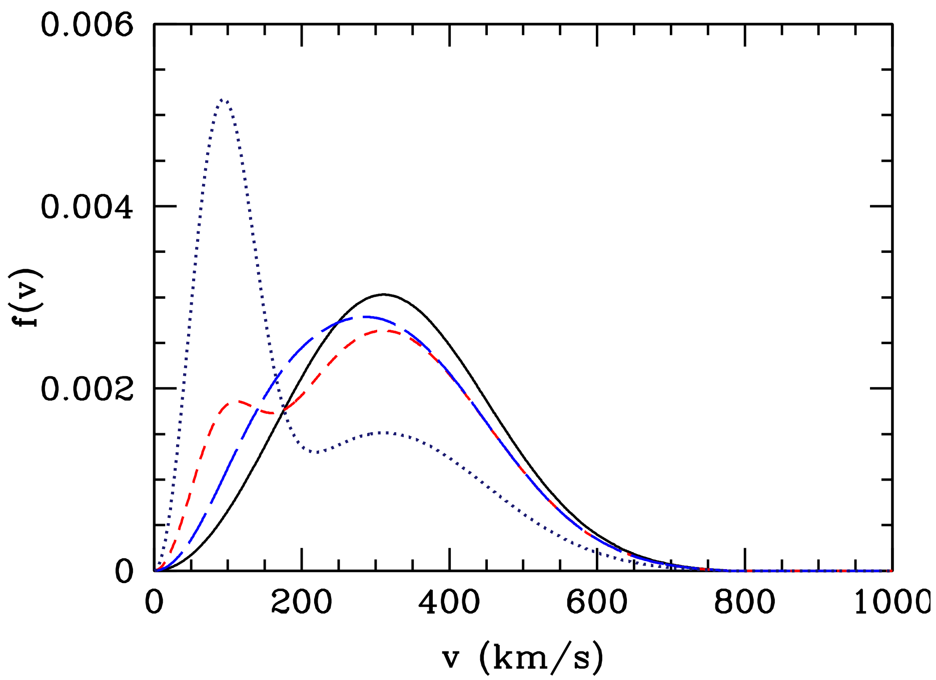


$v_{\rm esc}$

dark-disc:

Sub-halos merging at $z<1$ preferentially dragged towards disc, where they're destroyed leading to the formation of a co-rotating dark disc. Read et al., Bruch et al., Ling et al.

Could have a significant effect on f(v) if density is high and velocity dispersion low.



SH

SH + high density $\rho_D=\rho_H$, low dispersion DD

SH + lower density $\rho_D=0.15\rho_H$, low dispersion DD

SH + lower density, high dispersion DD

However:

Eris simulation (Guedes et al.): dark disc contributes ~10% of local density.

Ruchti et al.: no sign of stellar component in GAIA data.

DM component of Sagittarius leading **stream** may pass through the solar neighbourhood

Purcell, Zentner & Wang (as originally suggested by Freese, Gondolo & Newberg).