Reconstructing the local dark matter velocity distribution from direct detection experiments

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ICAP@IAP - 29th September 2016

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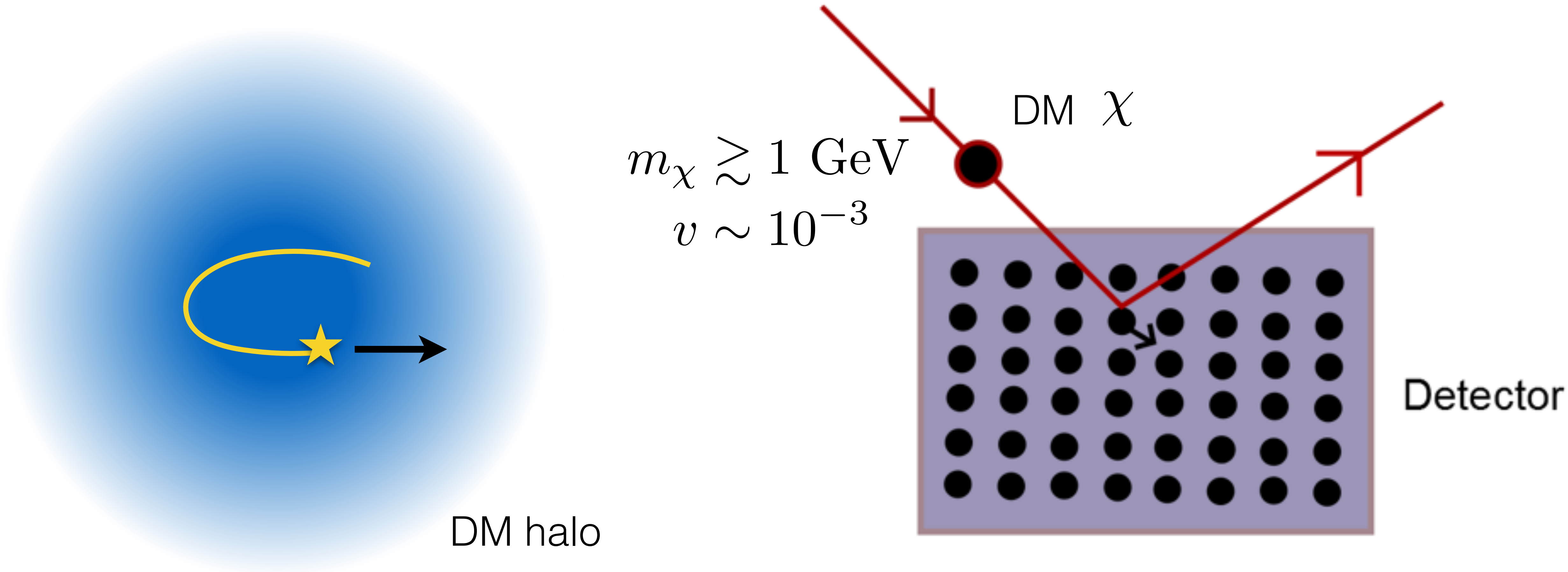
Direct detection experiments



I've been worrying about the DM velocity distribution for a while now…

Improved determination of the WIMP mass from direct detection data
B. J. Kavanagh and A. M. Green
Phys. Rev. D 86, 065027 (2012), arXiv:1207.2039

Model independent determination of the dark matter mass from direct detection
B. J. Kavanagh and A. M. Green
Phys. Rev. Lett. 111, 031302 (2013), arXiv:1303.6868

Parametrizing the local dark matter speed distribution: a detailed analysis
B. J. Kavanagh
Phys. Rev. D 89, 085026 (2014), arXiv:1312.1852

Probing WIMP particle physics and astrophysics with direct detection and neutrino telescope data
B. J. Kavanagh, M. Fornasa, A. M. Green
Phys. Rev. D. 91, 103533 (2015), arXiv:1410.8051

Discretising the velocity distribution for directional dark matter experiments
B. J. Kavanagh
JCAP 07 (2015) 019, arXiv:1502.04224

Reconstructing the three-dimensional local dark matter velocity distribution
B. J. Kavanagh, C. A. J. O'Hare
arXiv:1609.08630

The problem

When we observe a nuclear recoil with energy E_R
we cannot distinguish between:

Heavy, slow DM

Light, fast DM

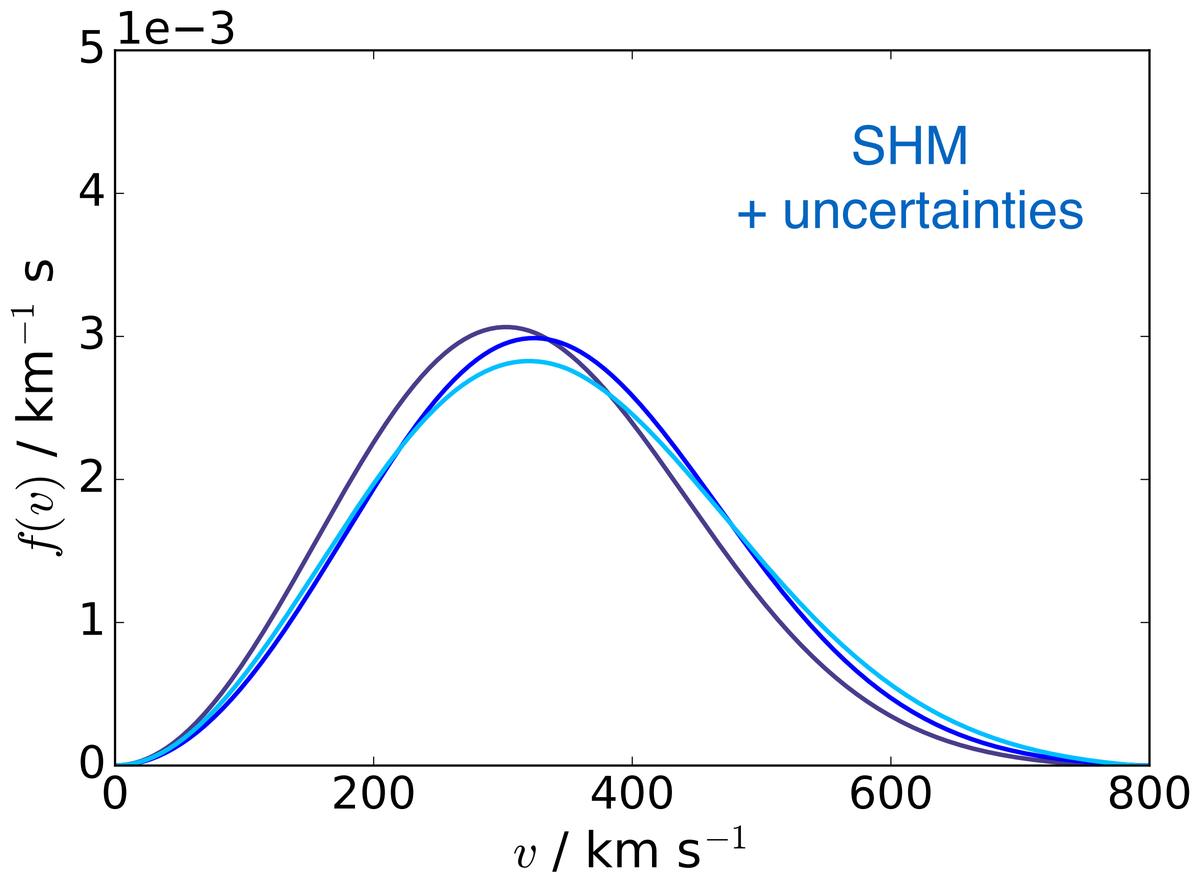
What can we do?

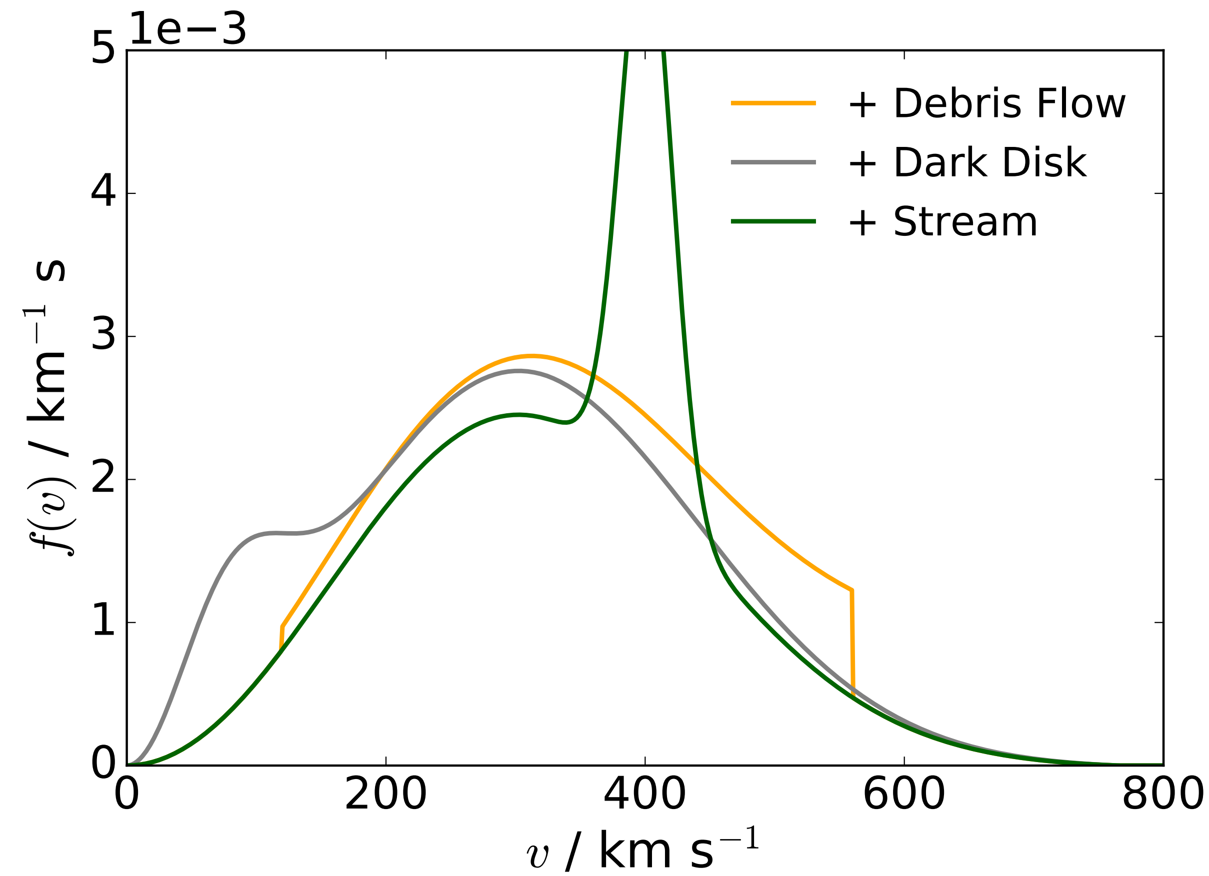
Typically, aim to fix DM speeds (or rather the *speed distribution* $f(v)$) and measure DM mass

In reality, we don't know $f(v)$ precisely, and we would ideally like to measure it!

Astrophysical uncertainties

Typically assume an isotropic, isothermal halo leading to a smooth Maxwell-Boltzmann distribution - the Standard Halo Model (SHM)





But simulations suggest there could be substructure:

Debris flows Kuhlen et al. [1202.0007]

Dark disk Pillepich et al. [1308.1703], Schaller et al. [1605.02770]

Tidal stream Freese et al. [astro-ph/0309279, astro-ph/0310334]

Reconstructing the *speed* distribution

Write a *general parametrisation* for the speed distribution:

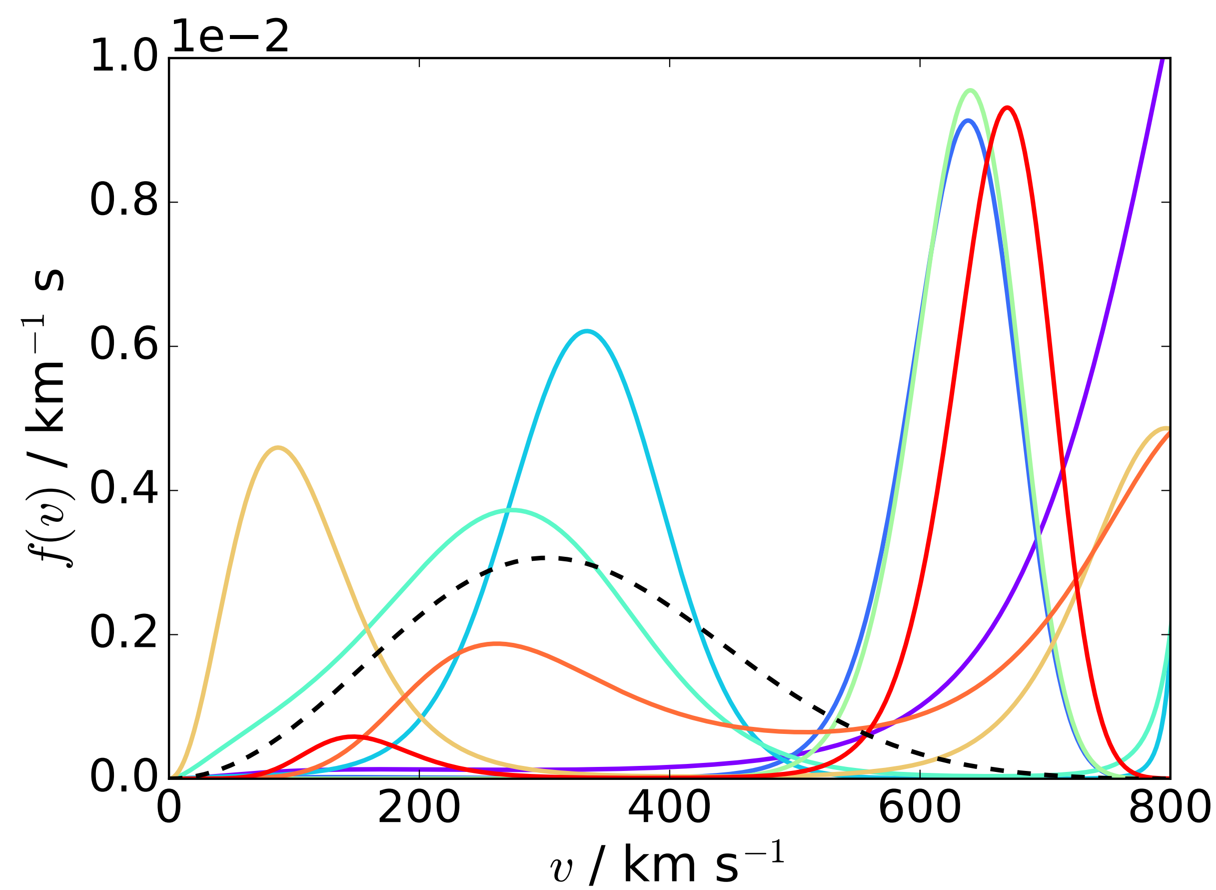
Peter [1103.5145]

$$f(v) = v^2 \exp\left(-\sum_{m=0}^{N-1} a_m v^m\right)$$

BJK & Green [1303.6868,1312.1852]

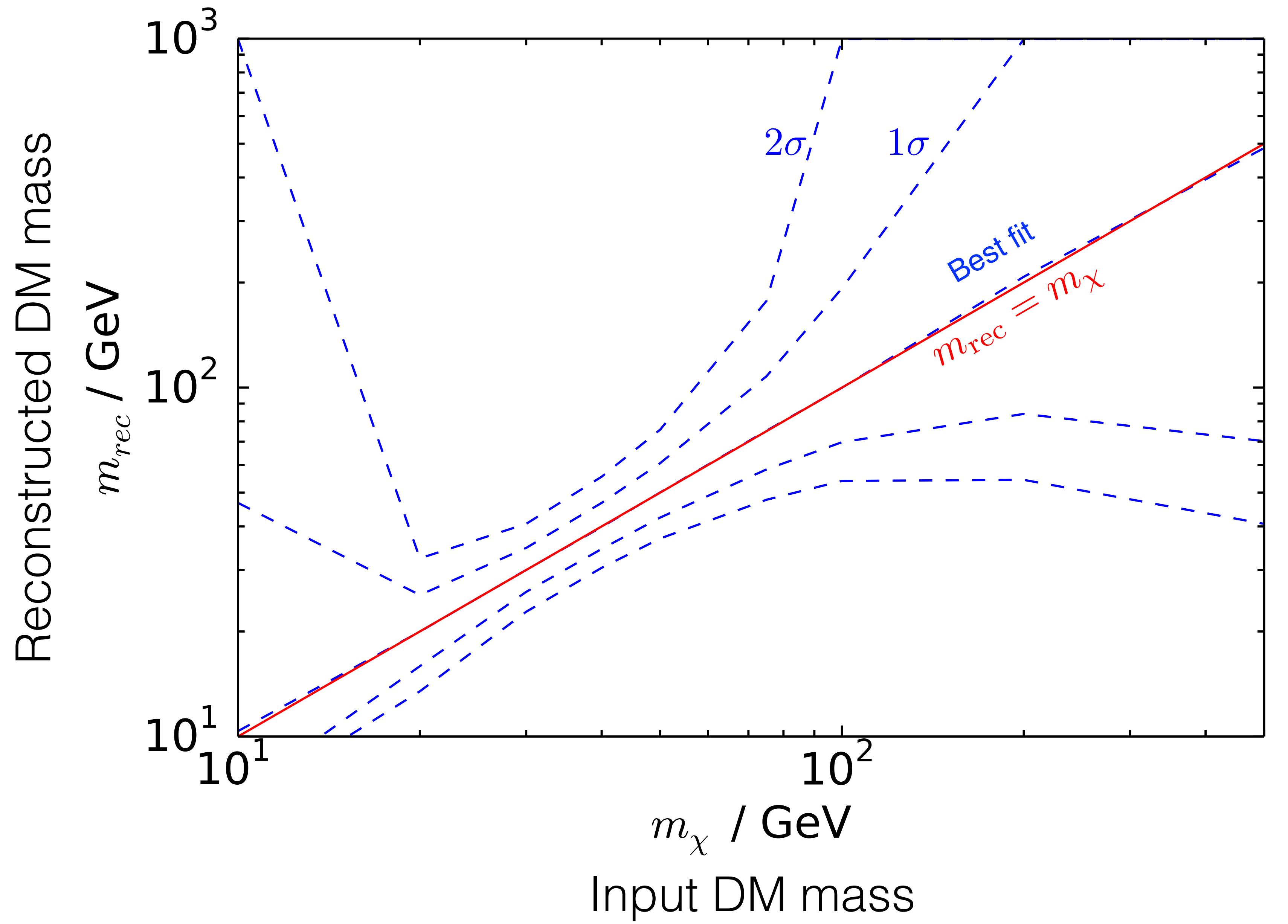
This form guarantees a positive distribution function.

Now we attempt to fit the particle physics parameters (m_χ, σ^p), as well as the astrophysics parameters $\{a_m\}$.



Testing the parametrisation

Generate mock data in *multiple experiments* and attempt to reconstruct the DM mass:

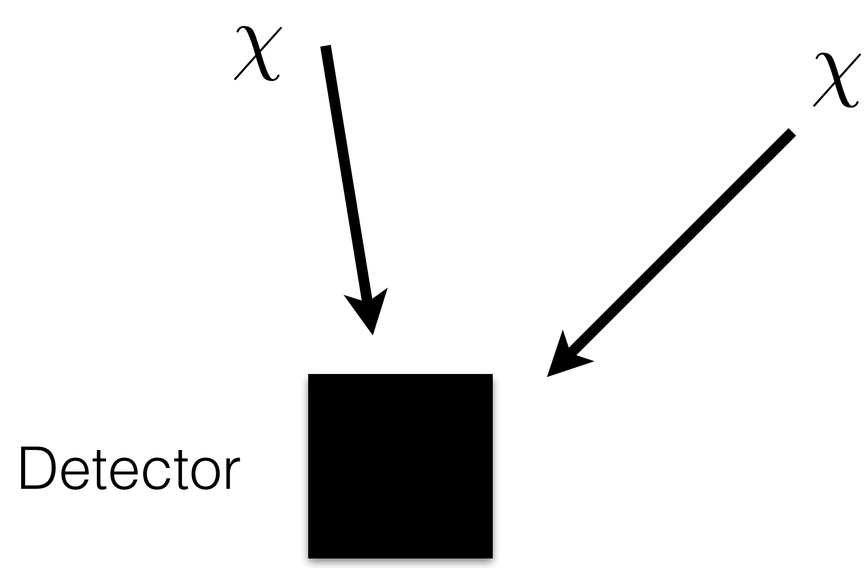


Tested for a number of underlying velocity distributions
(but we'll save the reconstructed distributions until later…)

DM velocity distribution

Experiments which are sensitive to the *direction* of the nuclear recoil can give us information about the full 3-D distribution of the *velocity vector* $\mathbf{v} = (v_x, v_y, v_z)$, not just the speed $v = |\mathbf{v}|$

Mayet et al. [1602.03781]



But, we now have an *infinite* number of functions to parametrise (one for each incoming direction (θ, ϕ))!

If we want to parametrise $f(\mathbf{v})$, we need some *basis functions* to make things more tractable:

$$f(\mathbf{v}) = f^1(v)A^1(\hat{\mathbf{v}}) + f^2(v)A^2(\hat{\mathbf{v}}) + f^3(v)A^3(\hat{\mathbf{v}}) + \ldots.$$

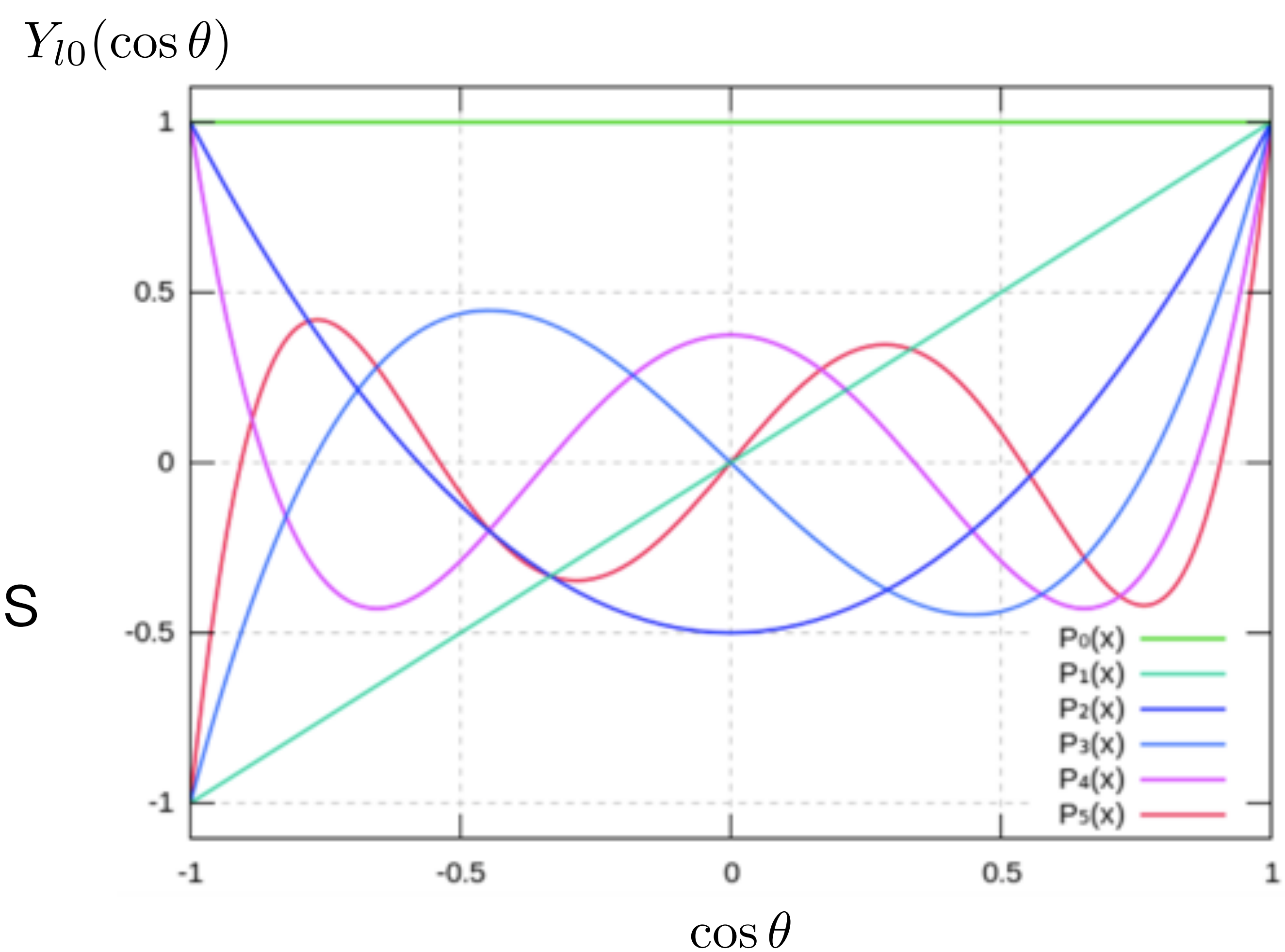
Basis functions

$$f(\mathbf{v}) = f^1(v)A^1(\hat{\mathbf{v}}) + f^2(v)A^2(\hat{\mathbf{v}}) + f^3(v)A^3(\hat{\mathbf{v}}) + \ldots .$$

One possible basis is spherical harmonics:

Alves et al. [1204.5487], Lee [1401.6179]

$$f(\mathbf{v}) = \sum_{lm} f_{lm}(v) Y_{lm}(\hat{\mathbf{v}})$$



However, they are not strictly positive definite.

Physical distribution functions must be positive!

A discretised velocity distribution

Divide the velocity distribution into N = 3 angular bins…

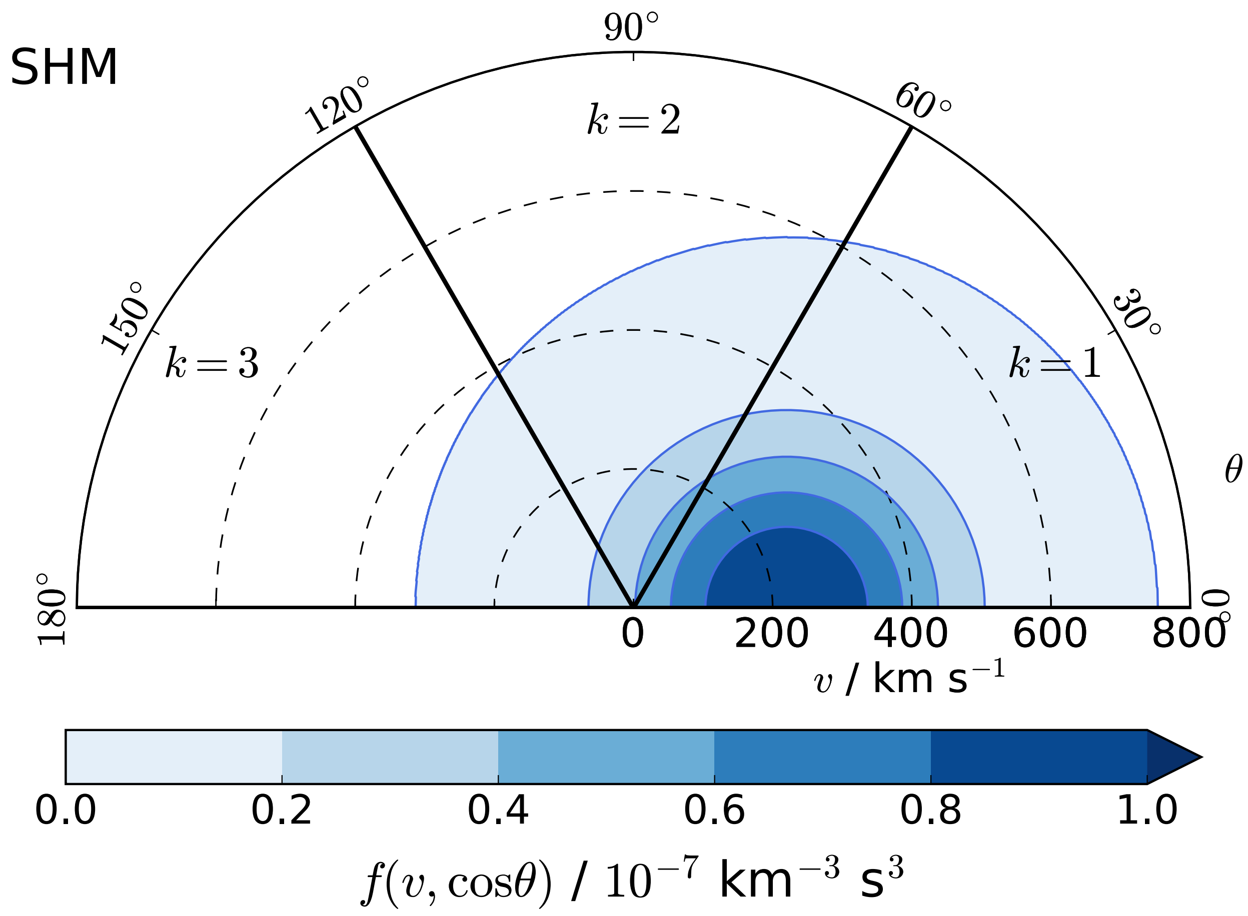
$$f(\mathbf{v}) = f(v, \cos\theta, \phi) = \begin{cases} f^1(v) & \text{for } \theta \in [0°, 60°] \\ f^2(v) & \text{for } \theta \in [60°, 120°] \\ f^3(v) & \text{for } \theta \in [120°, 180°] \end{cases}$$

BJK [1502.04224]

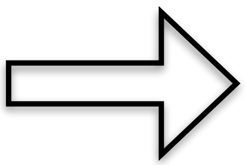
…and then parametrise $f^k(v)$ within each angular bin.

Calculating the event rate from such a distribution (especially for arbitrary N) is non-trivial. But not impossible.

An example: the SHM



DM wind



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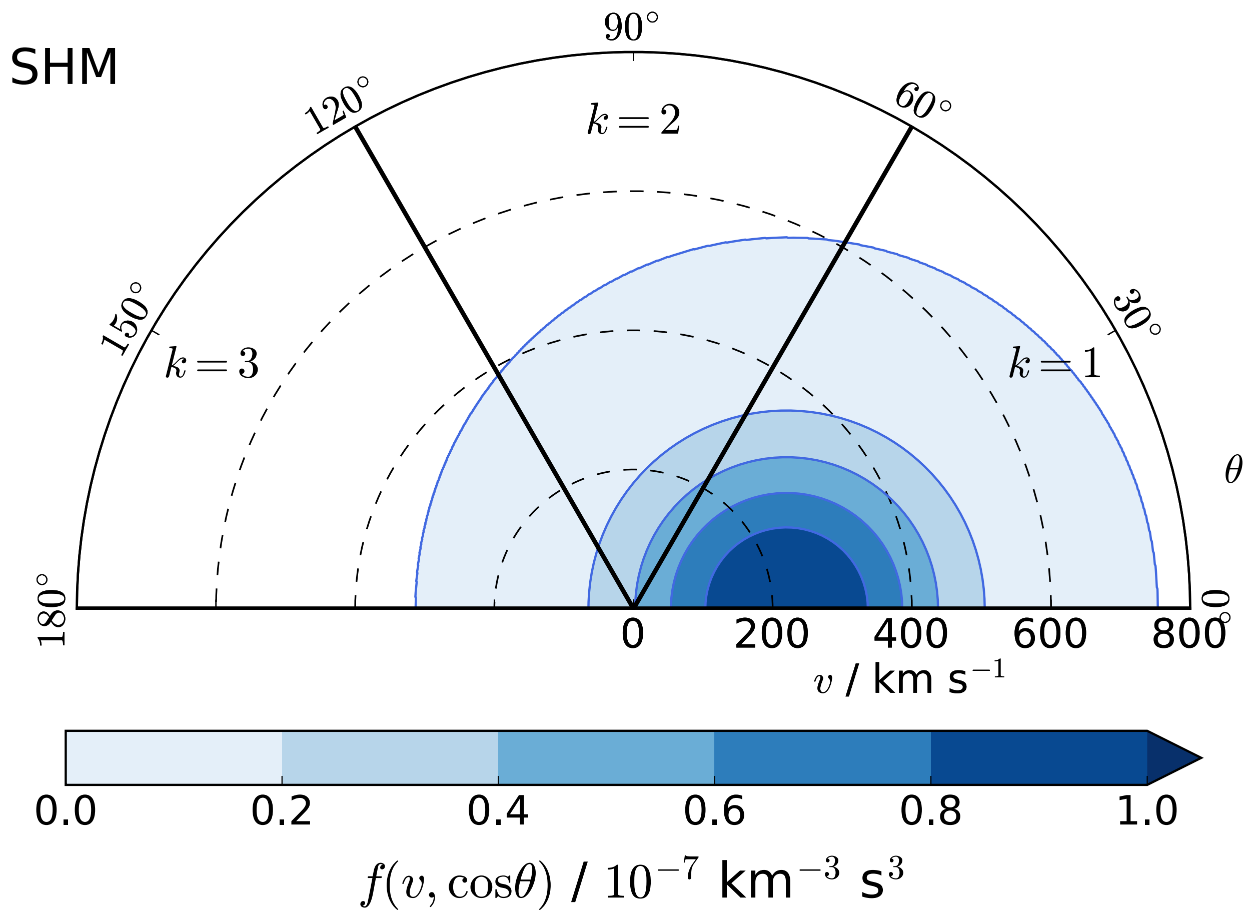
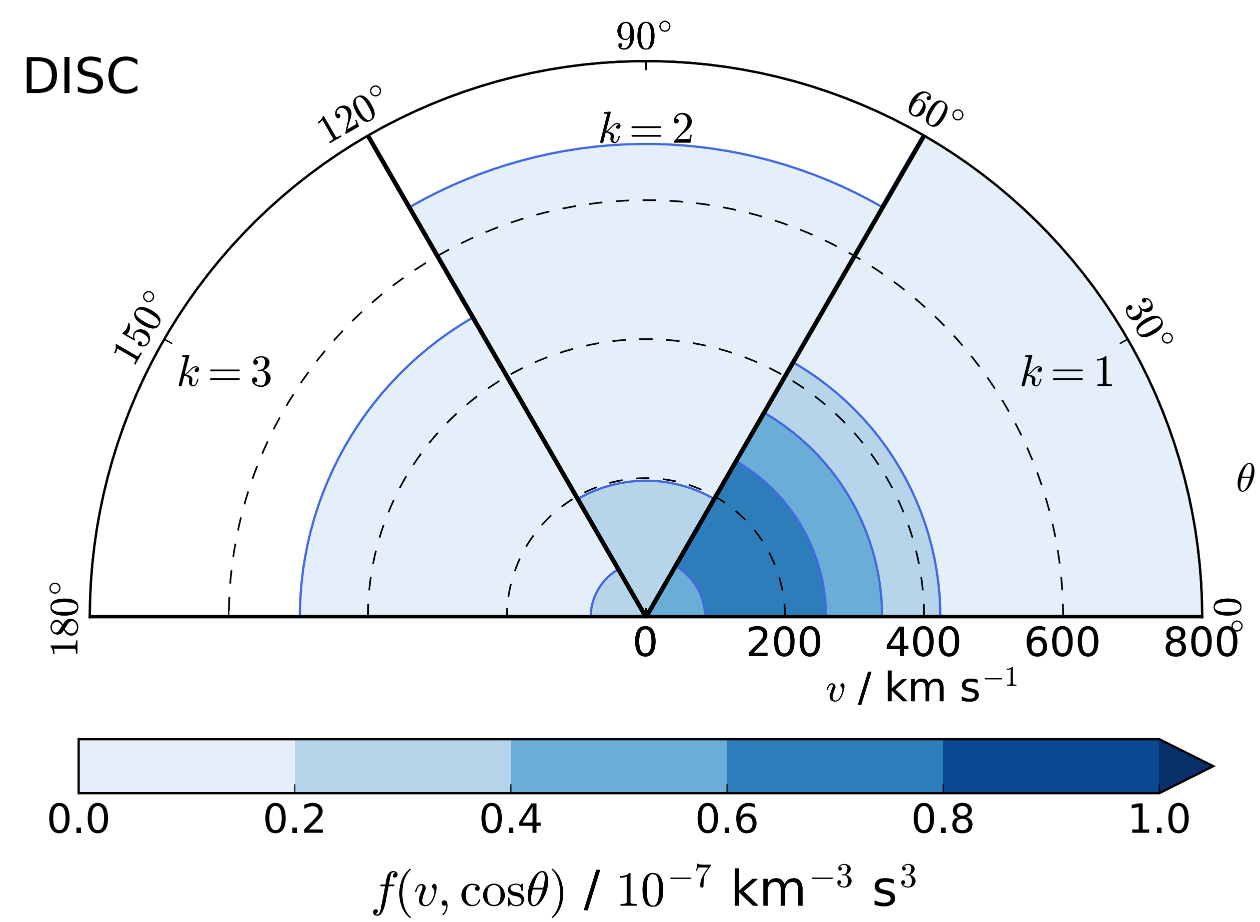
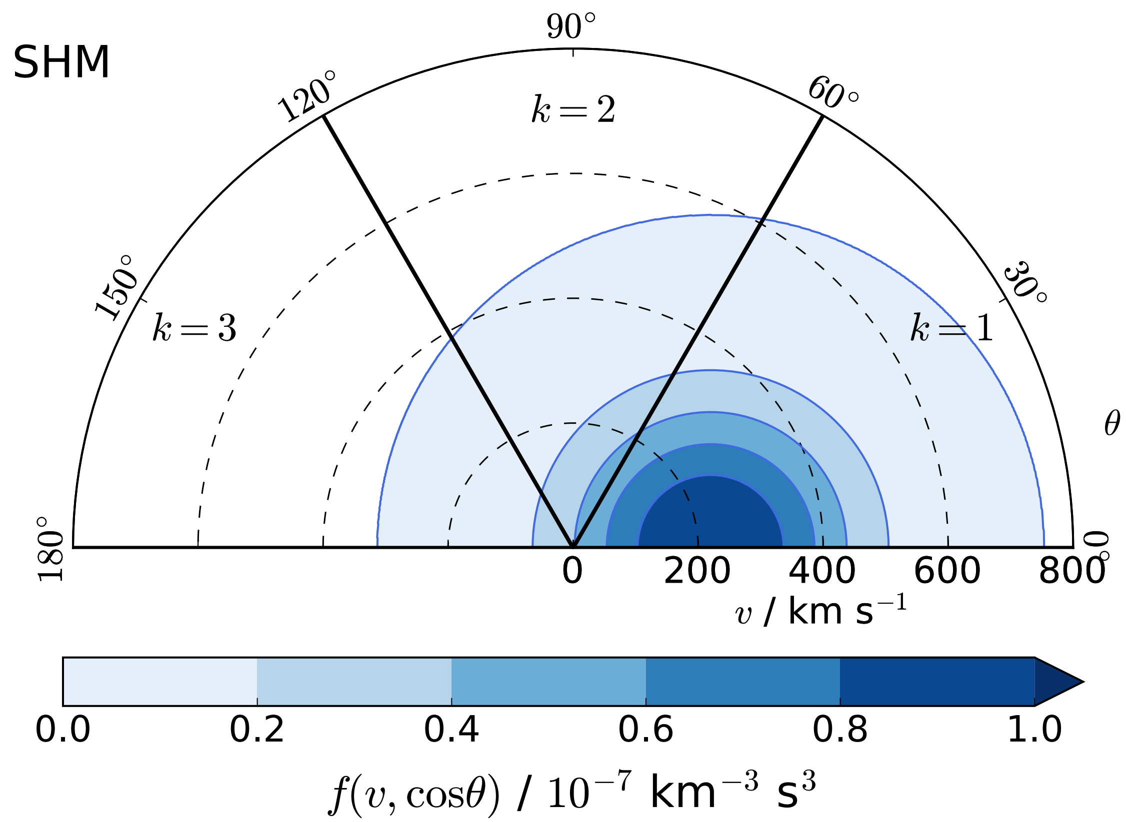
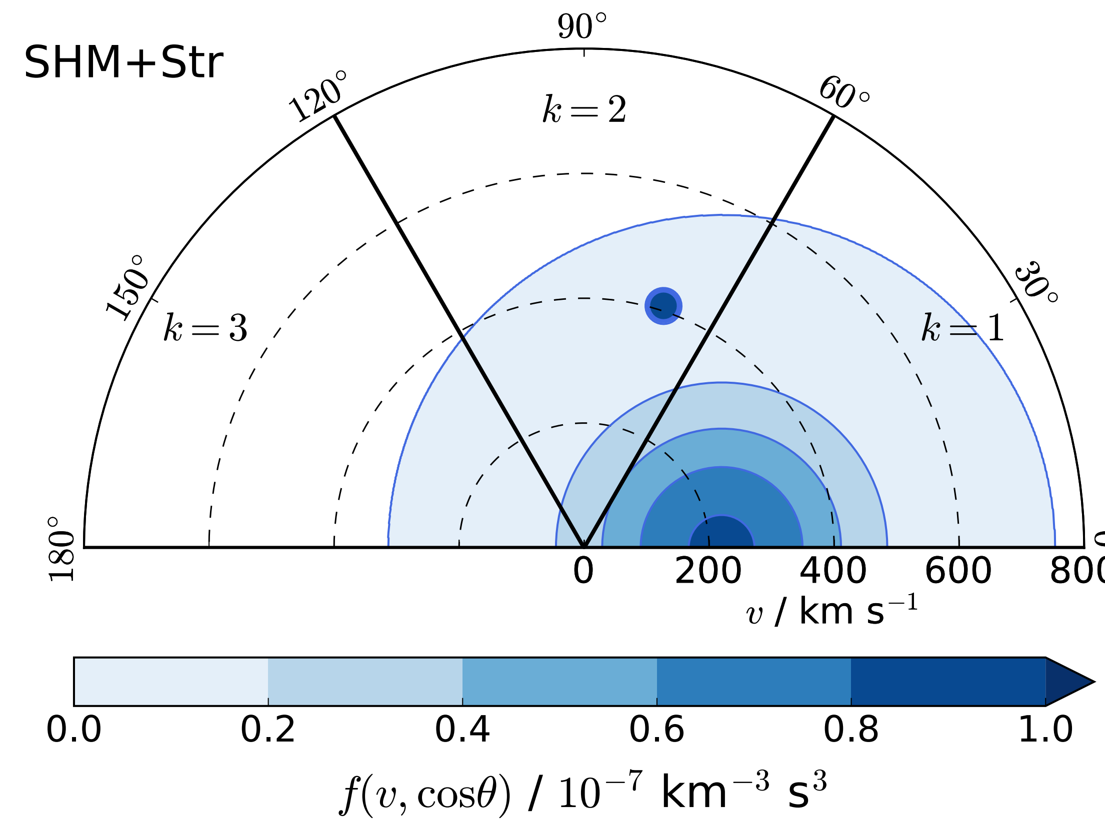


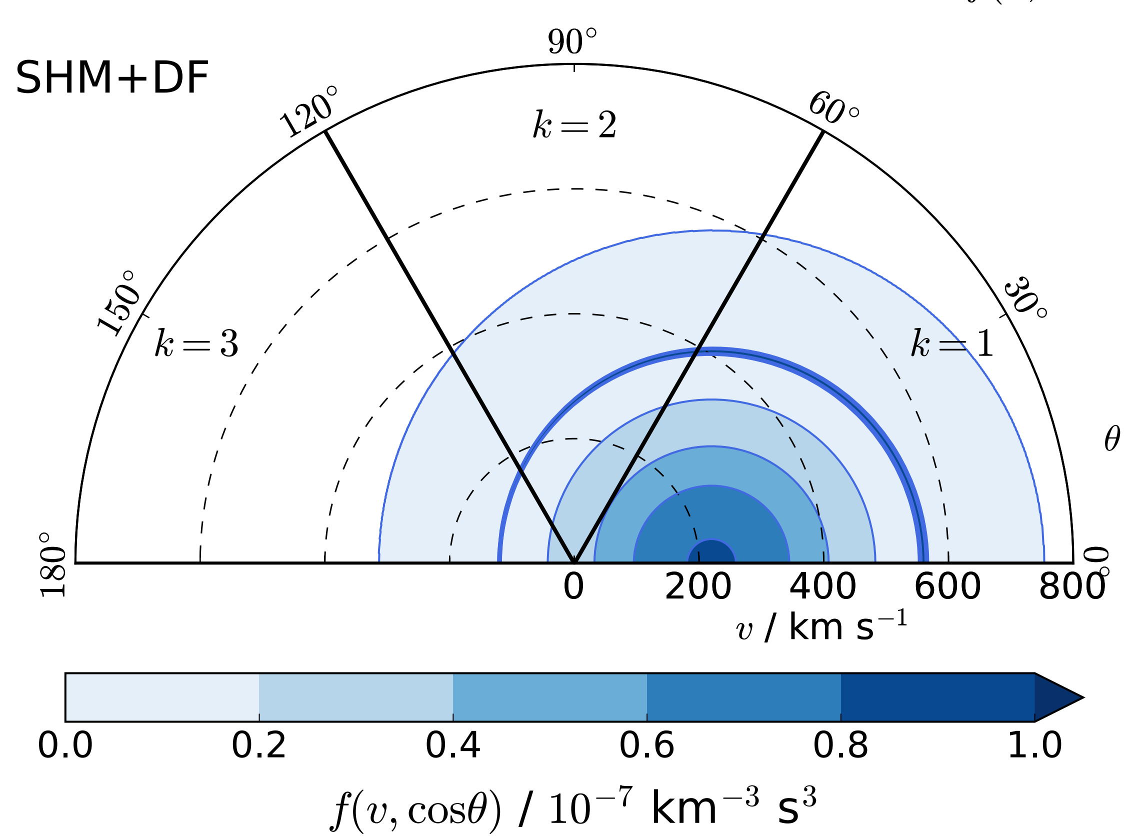
DM wind



Benchmarks


SHM
90°
120°
60°
150°
30°
180°
0°
$k=1$
$k=2$
$k=3$
θ
0
200
400
600
800
v / km s^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
$f(v, \cos\theta)$ / 10^{-7} km^{-3} s^3


SHM+Str
90°
120°
60°
150°
30°
180°
0°
$k=1$
$k=2$
$k=3$
θ
0
200
400
600
800
v / km s^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
$f(v, \cos\theta)$ / 10^{-7} km^{-3} s^3


SHM+DF
90°
120°
60°
150°
30°
180°
0°
$k=1$
$k=2$
$k=3$
θ
0
200
400
600
800
v / km s^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
$f(v, \cos\theta)$ / 10^{-7} km^{-3} s^3

Reconstructions

BJK, CAJ O'Hare[1609.08630]

For a single particle physics benchmark (m_χ, σ_p),
generate mock data in two *ideal* future directional detectors:
Xenon-based [1503.03937] and Fluorine-based [1410.7821]

Then fit to the data (~1000 events) using 3 methods:

Method A:
Best Case

Assume underlying velocity distribution is known exactly.

Fit m_χ, σ_p

Method B:
Reasonable Case

Assume functional form of underlying velocity distribution is known.

Fit m_χ, σ_p and theoretical parameters

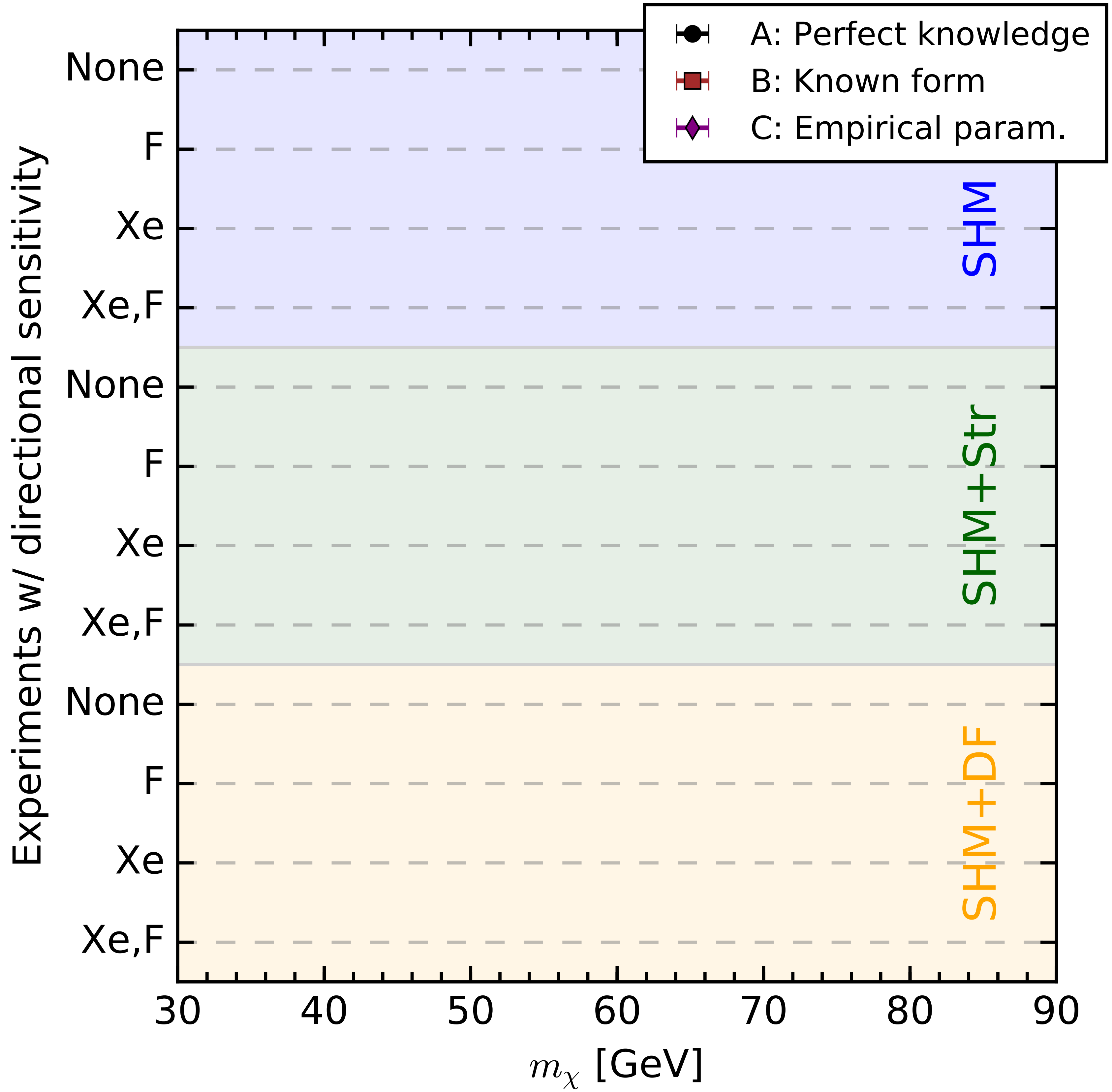
Method C:
Worst Case

Assume nothing about the underlying velocity distribution.

Fit m_χ, σ_p and empirical parameters

Lee at al. [1202.5035]
Billard et al. [1207.1050]

Reconstructing the DM mass



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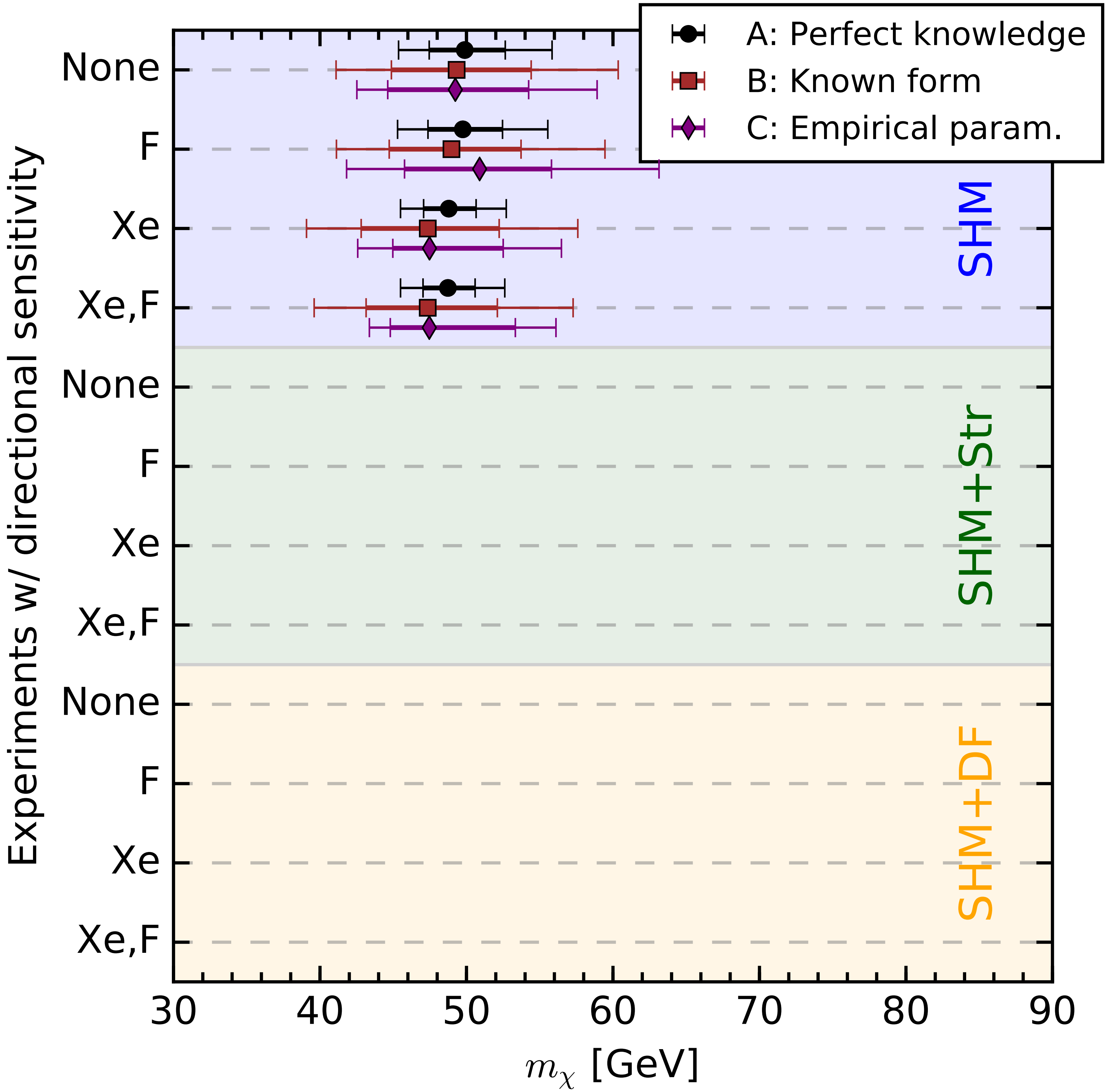

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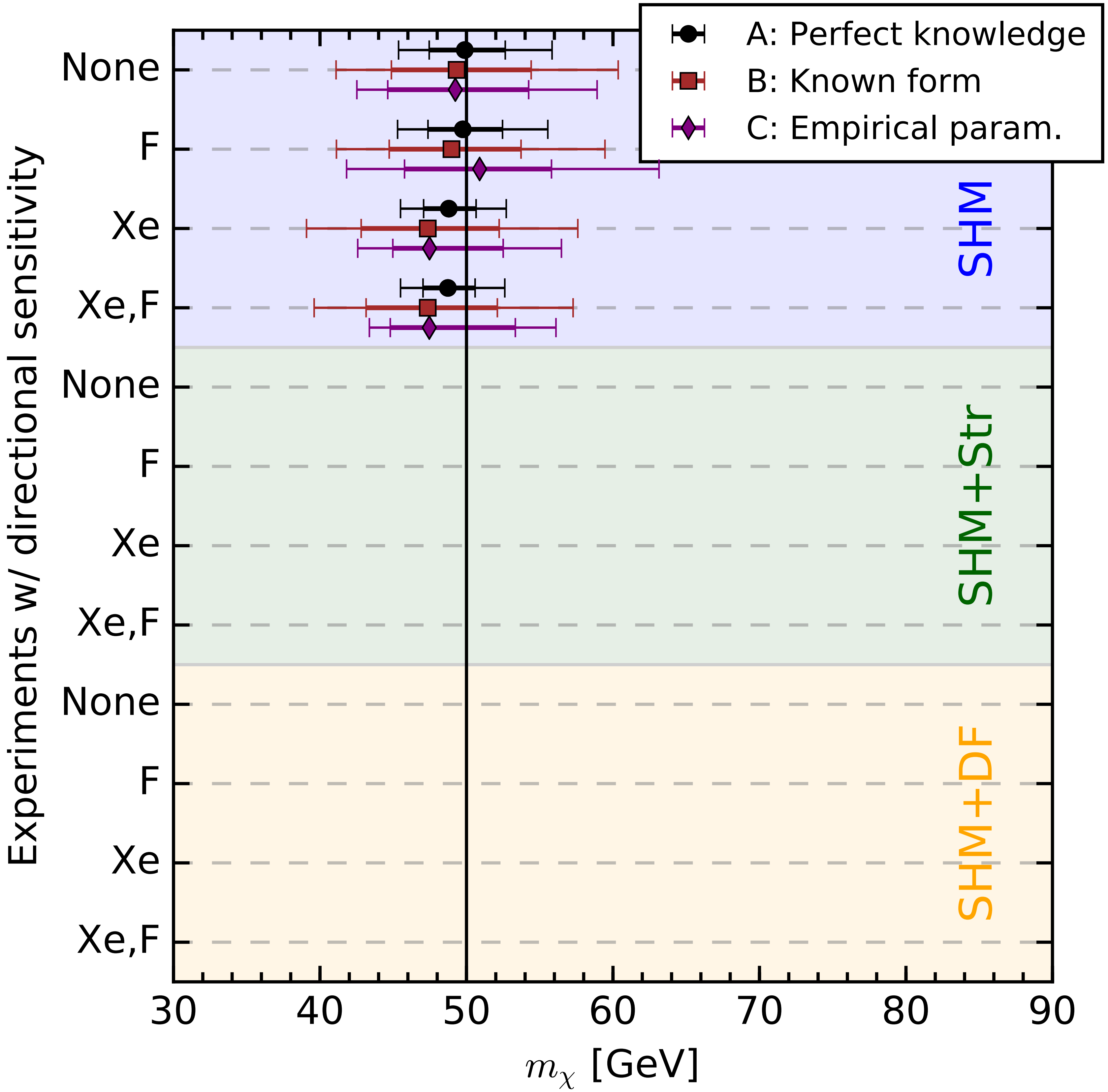
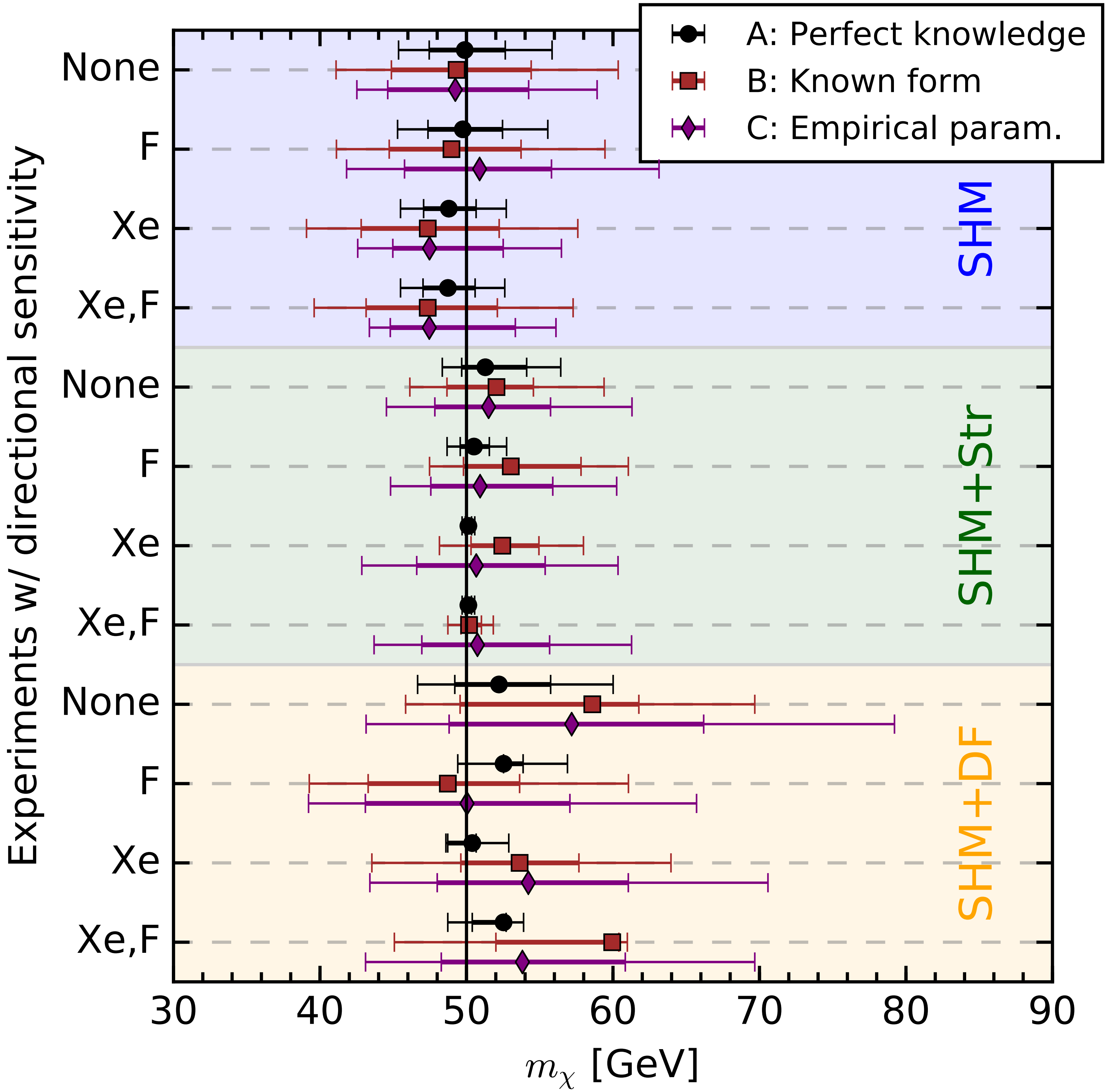


Reconstructing the DM mass



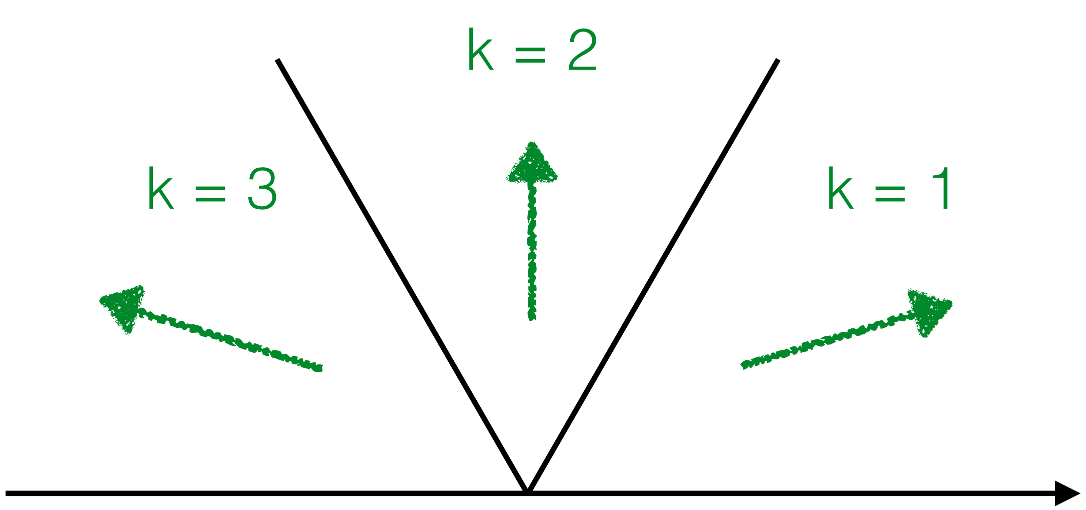
Shape of the velocity distribution

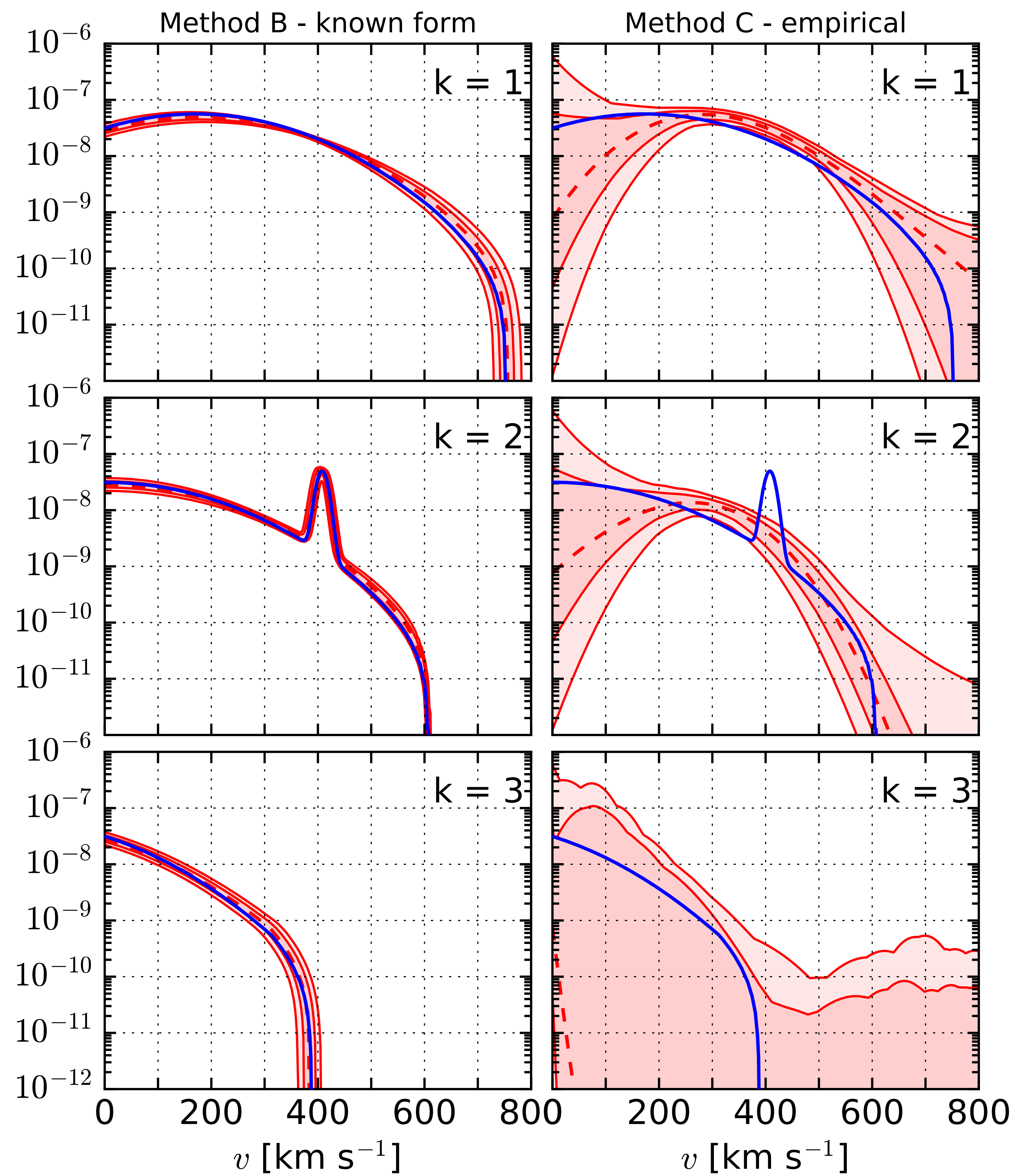
SHM+Stream distribution with directional sensitivity in Xe and F

‘True’ velocity distribution

Best fit distribution

(+68% and 95% intervals)





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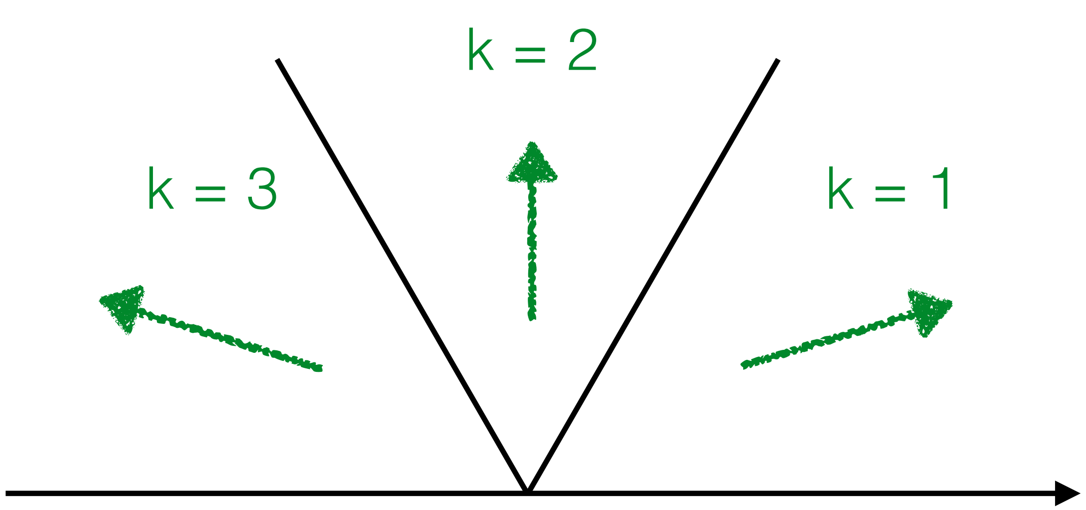
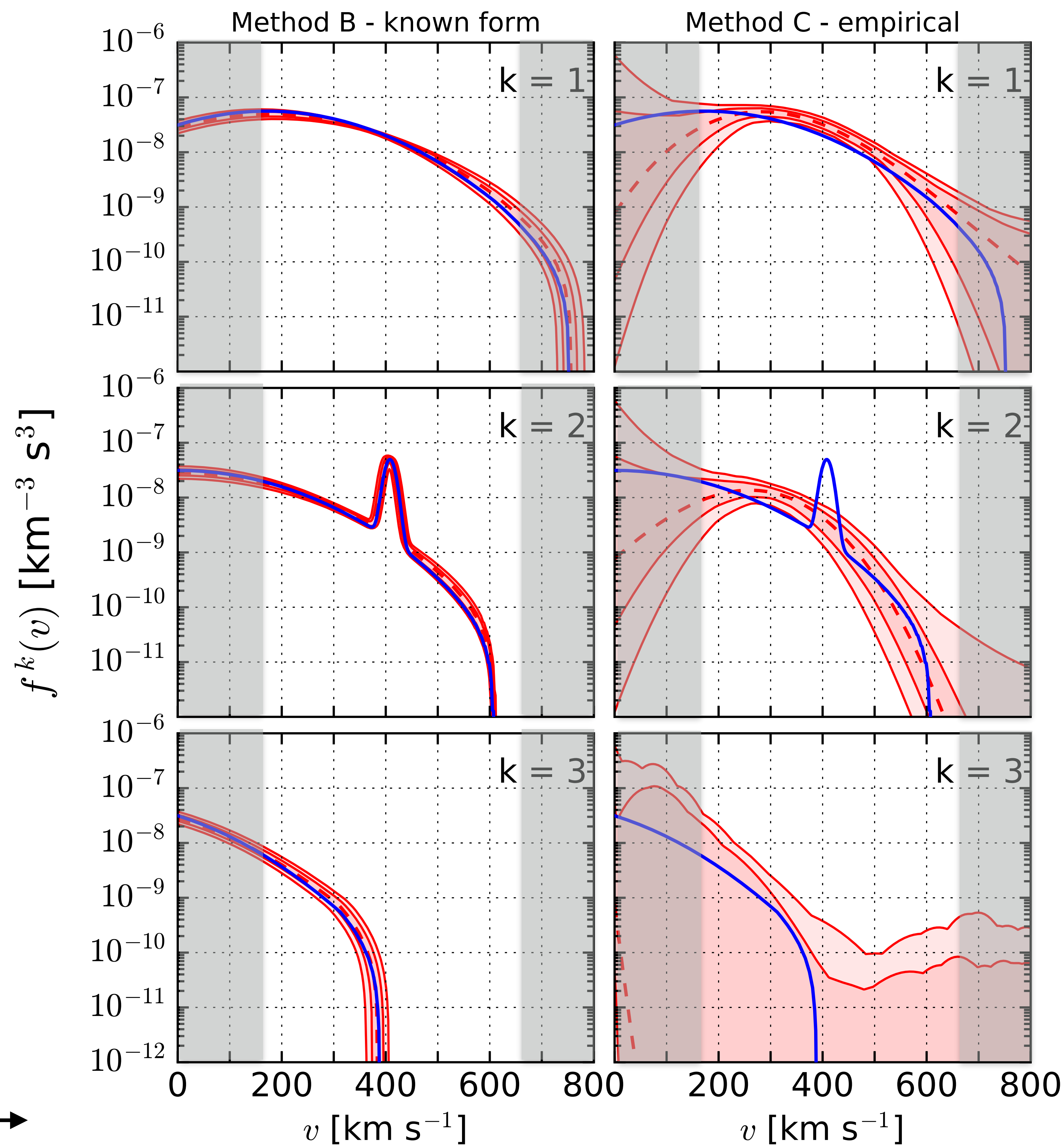


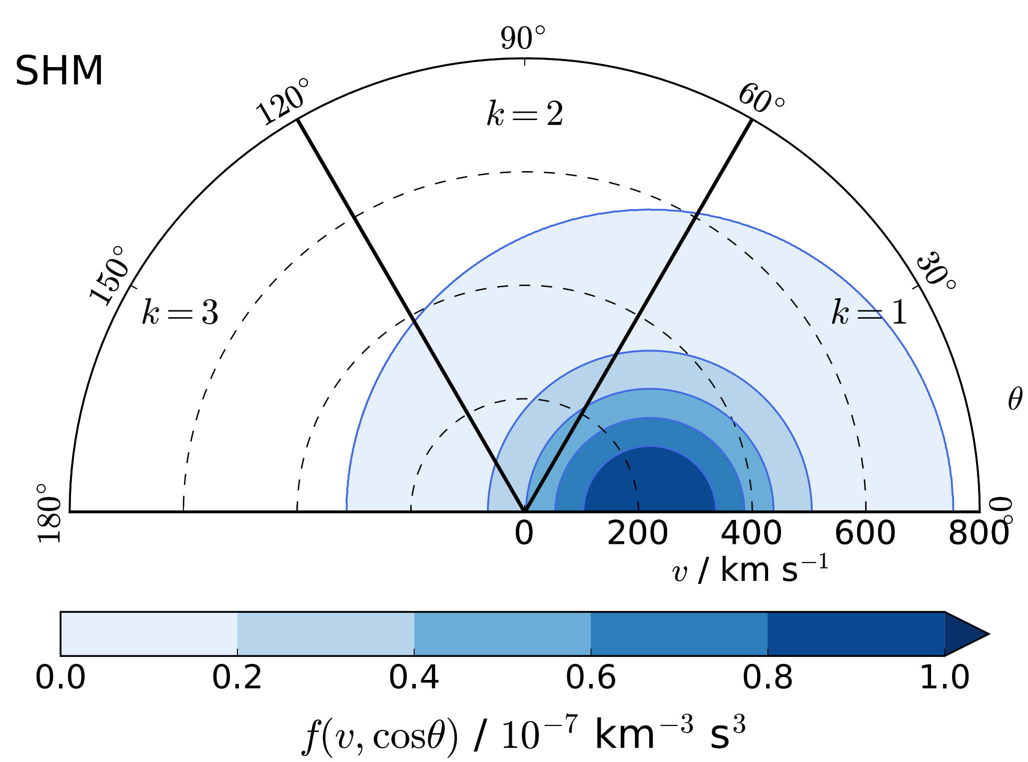


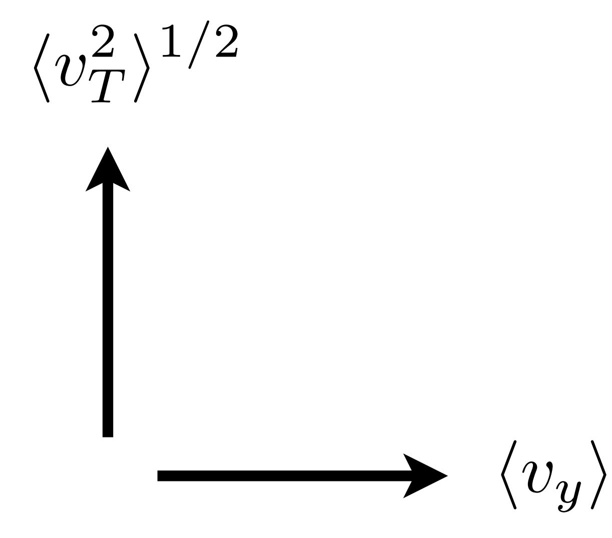
Velocity parameters

In order to compare distributions, calculate some derived parameters:

Average DM velocity *parallel* to Earth's motion → $$\langle v_y \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v\cos\theta) \, v^2 f(\mathbf{v})$$

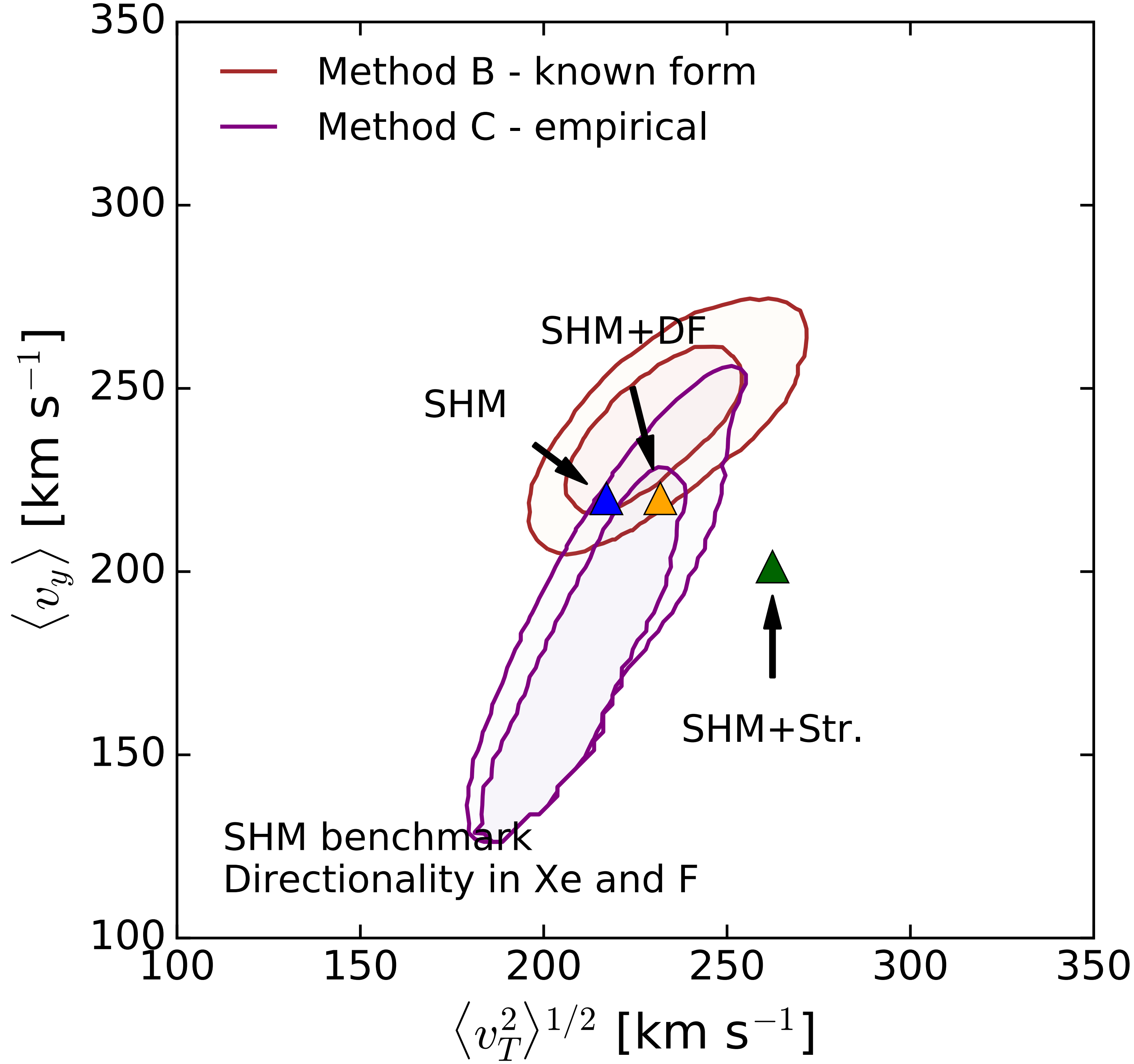
Average DM velocity *transverse* to Earth's motion → $$\langle v_T^2 \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v^2\sin^2\theta) \, v^2 f(\mathbf{v})$$

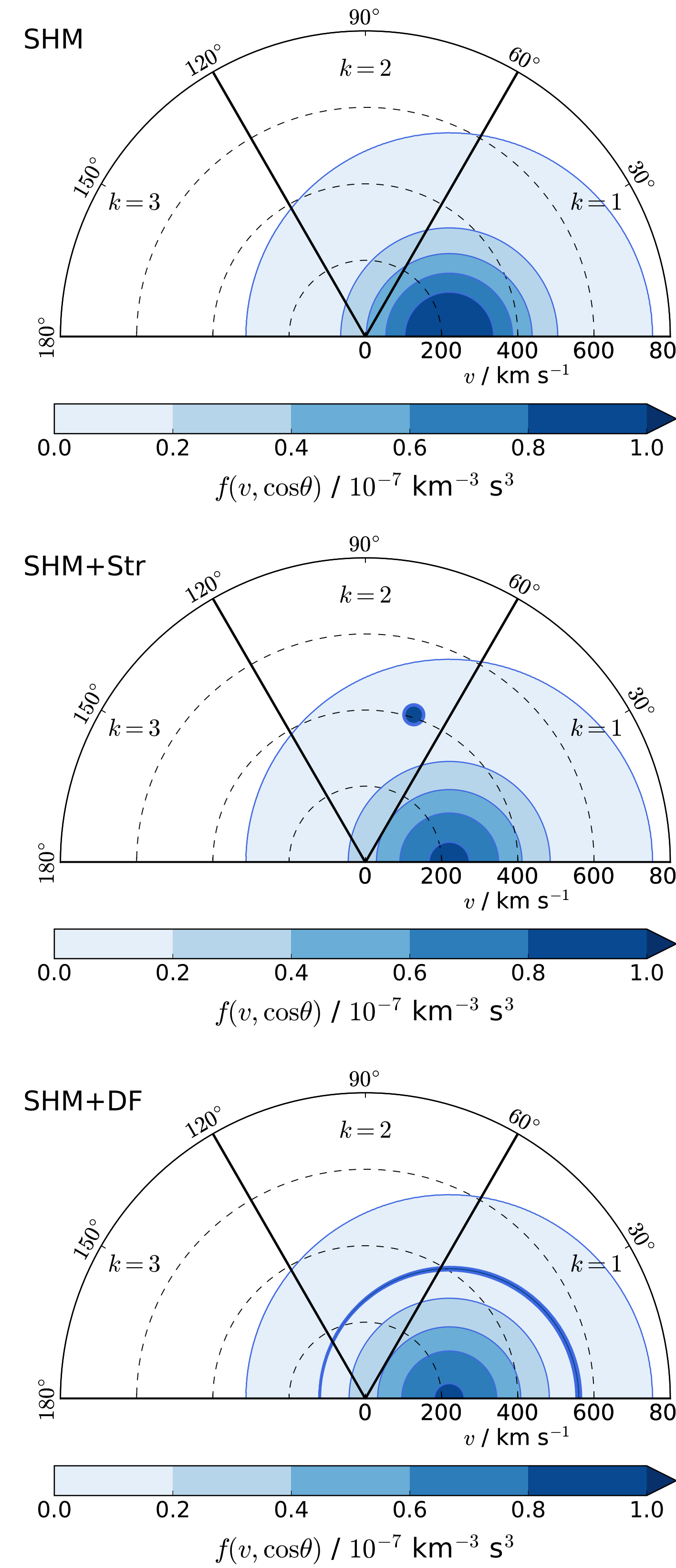




Comparing distributions

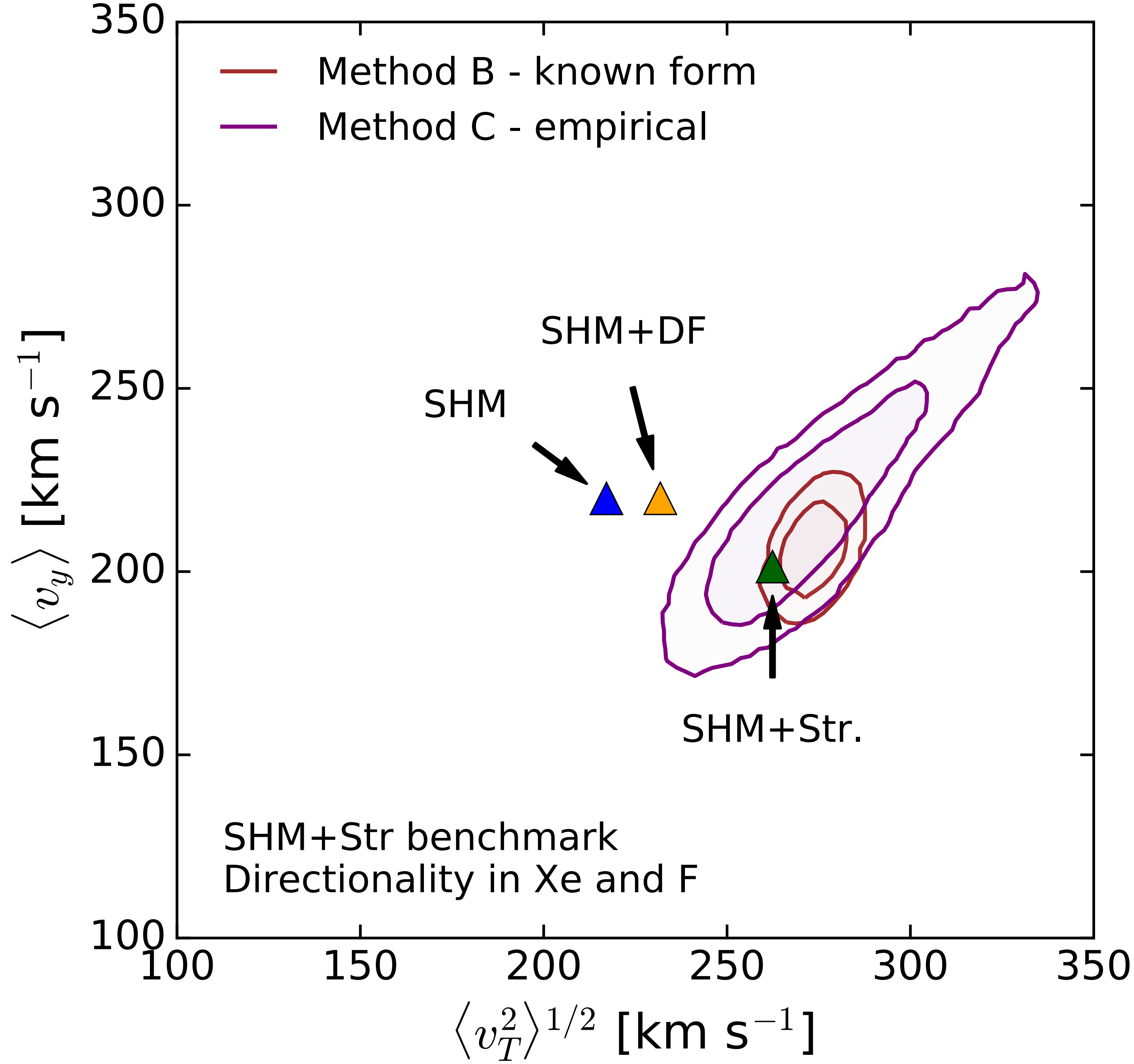
Input distribution: SHM

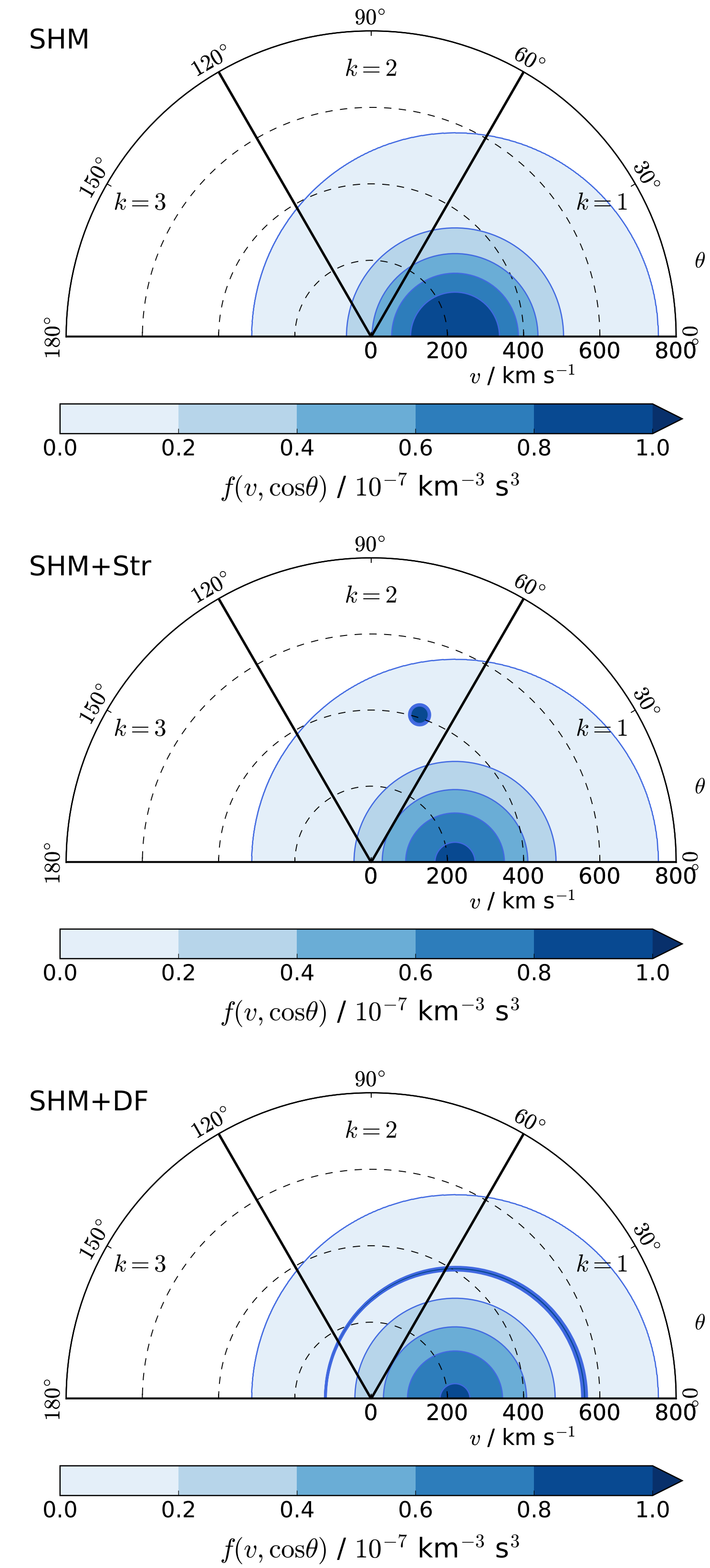




Comparing distributions

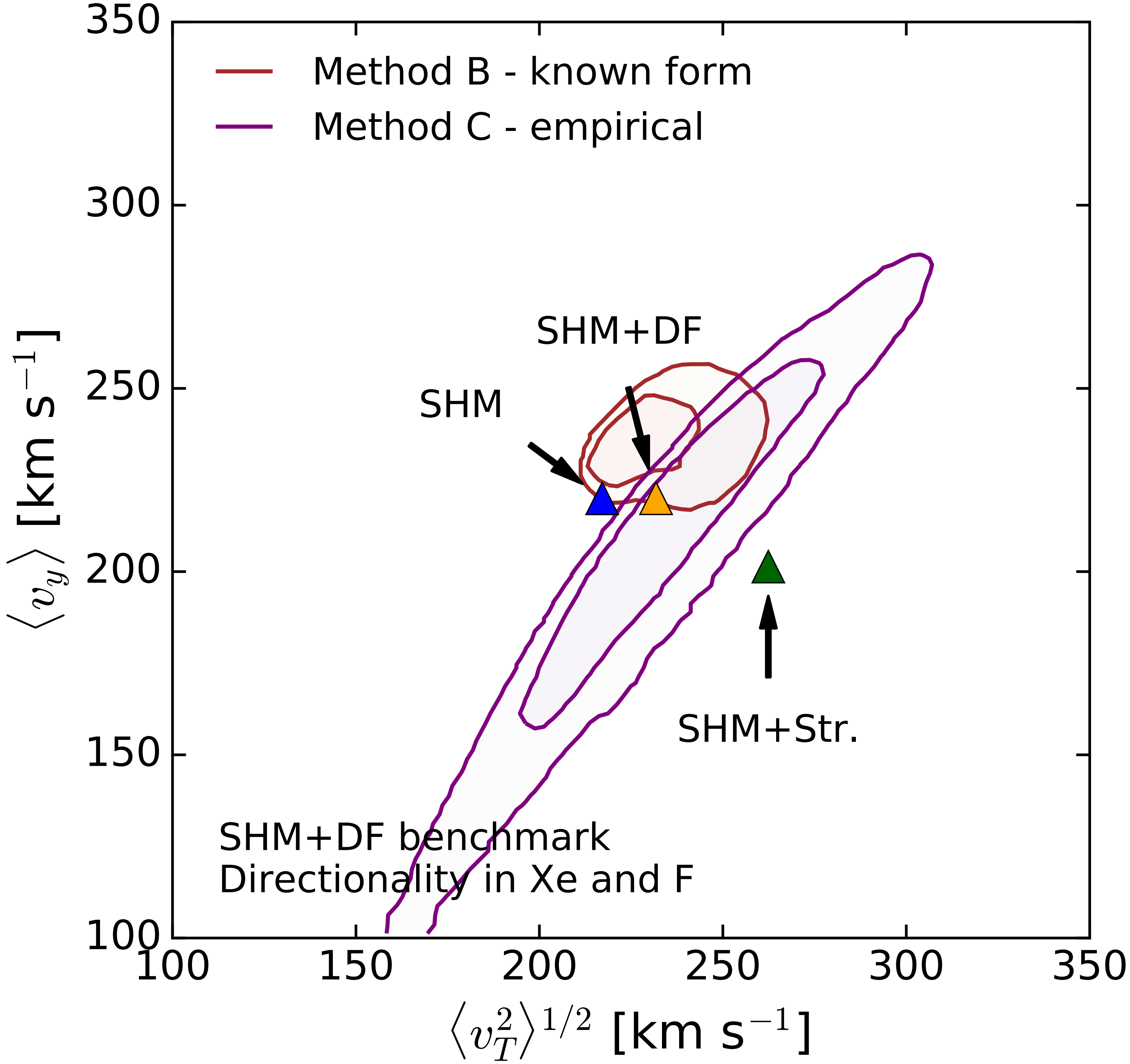
Input distribution: SHM + Stream

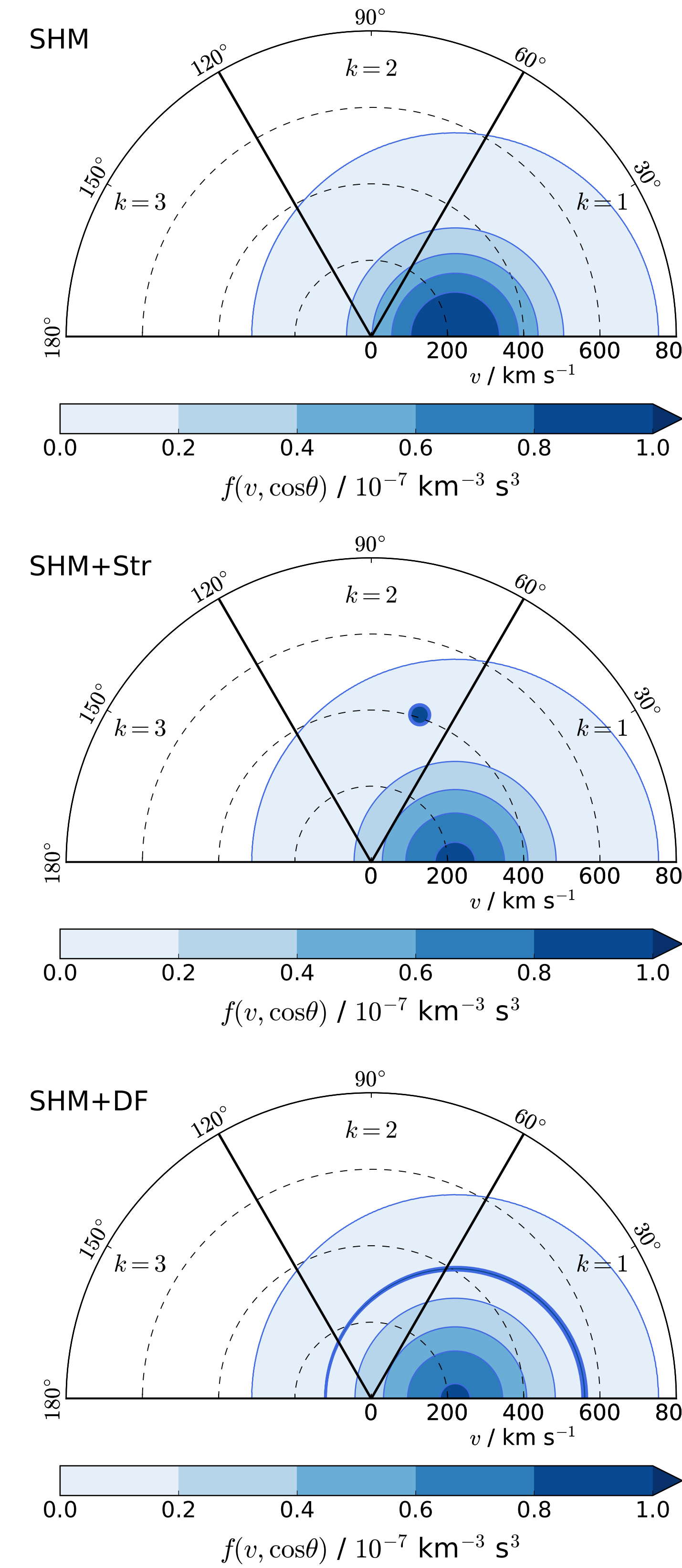




Comparing distributions

Input distribution: SHM + Debris Flow





The strategy

In case of signal break glass

Perform parameter estimation using two methods: 'known' functional form vs. empirical parametrisation

→ Compare reconstructed particle parameters

Calculate derived parameters (such as $\langle v_y \rangle$ and $\langle v_T^2 \rangle^{1/2}$)

→ Check for consistency with SHM

In case of inconsistency, look at reconstructed shape of f(v)

→ Hint towards unexpected structure?

Conclusions

Proof of concept for reconstructing the DM properties from *ideal* directional detectors

→ Extend halo-independent, general parametrisation to the velocity distribution

Angular discretisation of the velocity distribution makes the problem tractable

No large loss of precision or accuracy compared with knowing the functional form of the underlying distribution

→ Reconstruction of the DM mass without assumptions about the halo

May allow us to distinguish different velocity distributions (and tell us something about the Milky Way)

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Thank you

Backup Slides

Directional recoil spectrum

$$\frac{\mathrm{d}R}{\mathrm{d}E_R \mathrm{d}\Omega_q} = \frac{\rho_0}{4\pi\mu_{\chi p}^2 m_\chi} \sigma^p \mathcal{C}_\mathcal{N} F^2(E_R) \hat{f}(v_{\mathrm{min}}, \hat{\mathbf{q}})$$

$$v_{\mathrm{min}} = \sqrt{\frac{m_\mathcal{N} E_R}{2\mu_{\chi\mathcal{N}}^2}}$$

Enhancement for nucleus $\mathcal{N}$:

$$\mathcal{C}_\mathcal{N} = \begin{cases} |Z + (f^p/f^n)(A - Z)|^2 & \text{SI interactions} \\ \frac{4}{3}\frac{J+1}{J} |\langle S_p \rangle + (a^p/a^n)\langle S_n \rangle|^2 & \text{SD interactions} \end{cases}$$

NB: May get interesting directional signatures from other operators BJK [1505.07406]

Form factor: $F^2(E_R)$

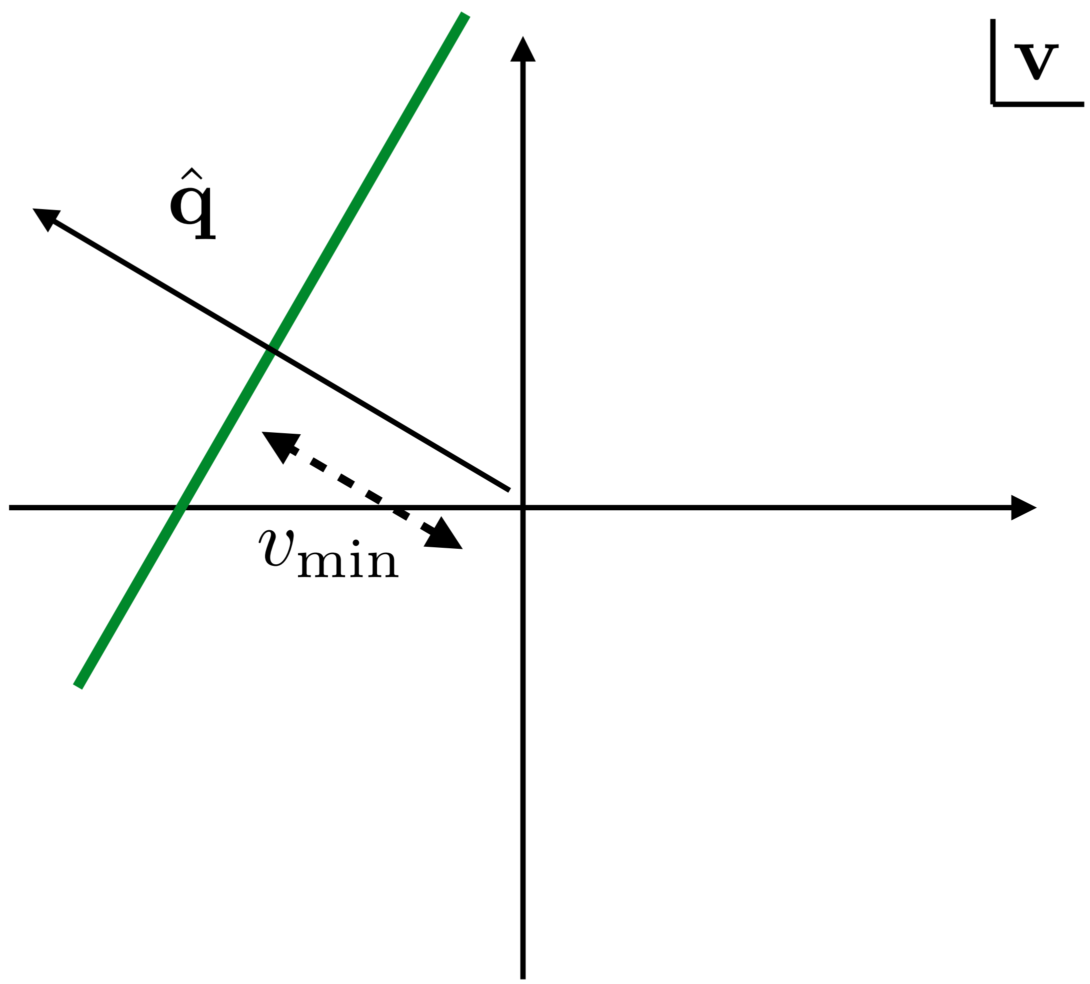
Radon Transform (RT):

$$\hat{f}(v_{\mathrm{min}}, \hat{\mathbf{q}}) = \int_{\mathbb{R}^3} f(\mathbf{v}) \delta\left(\mathbf{v} \cdot \hat{\mathbf{q}} - v_{\mathrm{min}}\right) \mathrm{d}^3\mathbf{v}$$

Radon Transform

Radon Transform (RT):

$$\hat{f}(v_{\mathrm{min}}, \hat{\mathbf{q}}) = \int_{\mathbb{R}^3} f(\mathbf{v}) \delta\left(\mathbf{v} \cdot \hat{\mathbf{q}} - v_{\mathrm{min}}\right) \mathrm{d}^3\mathbf{v}$$



Reconstructing f(v)

Many previous attempts to tackle this problem:

Numerical inversion ('measure' f(v) from the data)

Fox, Liu, Weiner [1011.915], Frandsen et al. [1111.0292], Feldstein, Kahlhoefer [1403.4606]

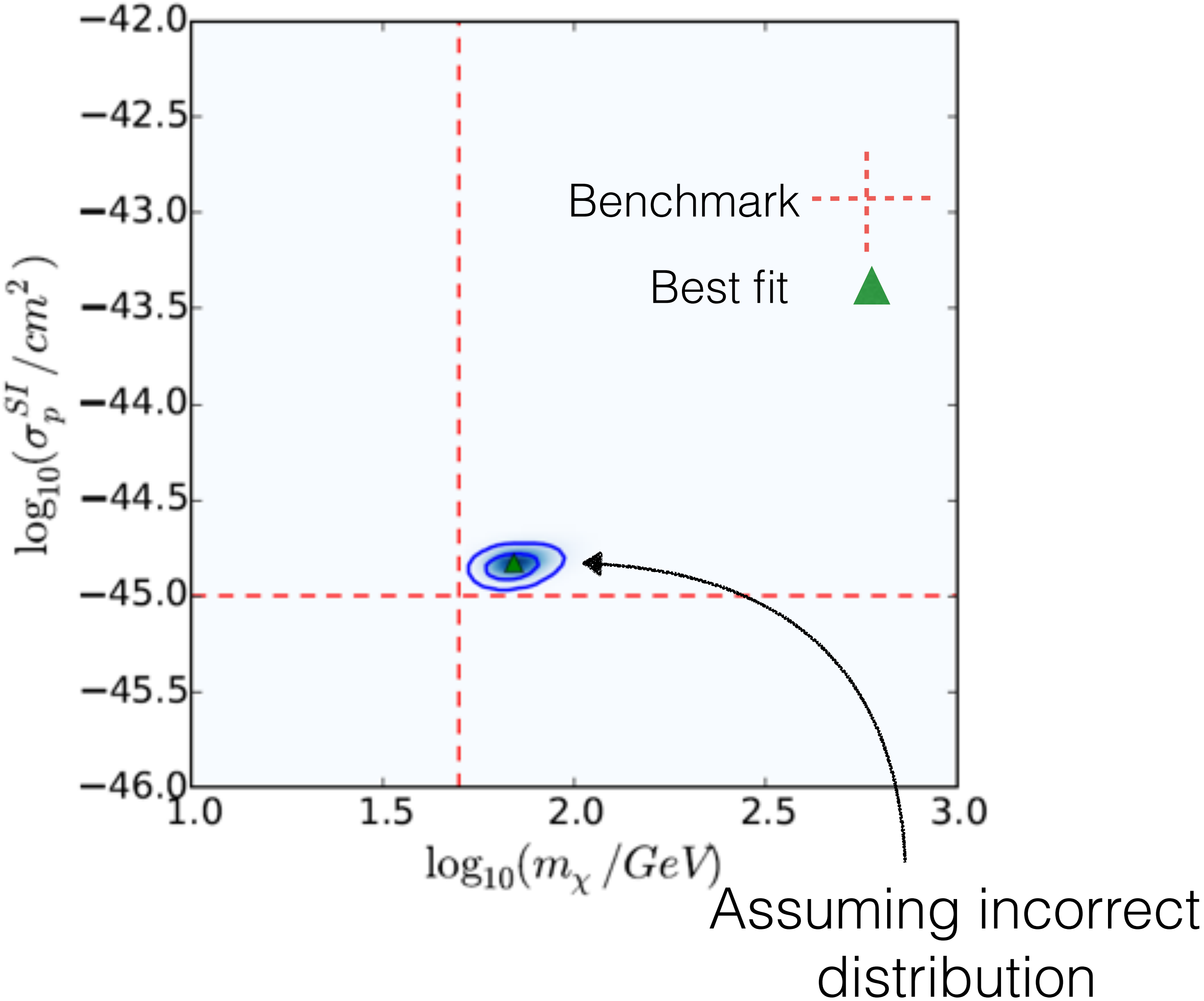
Include uncertainties in SHM parameters in the fit

Strigari, Trotta [0906.5361]

Add extra components to the velocity distribution (and fit)

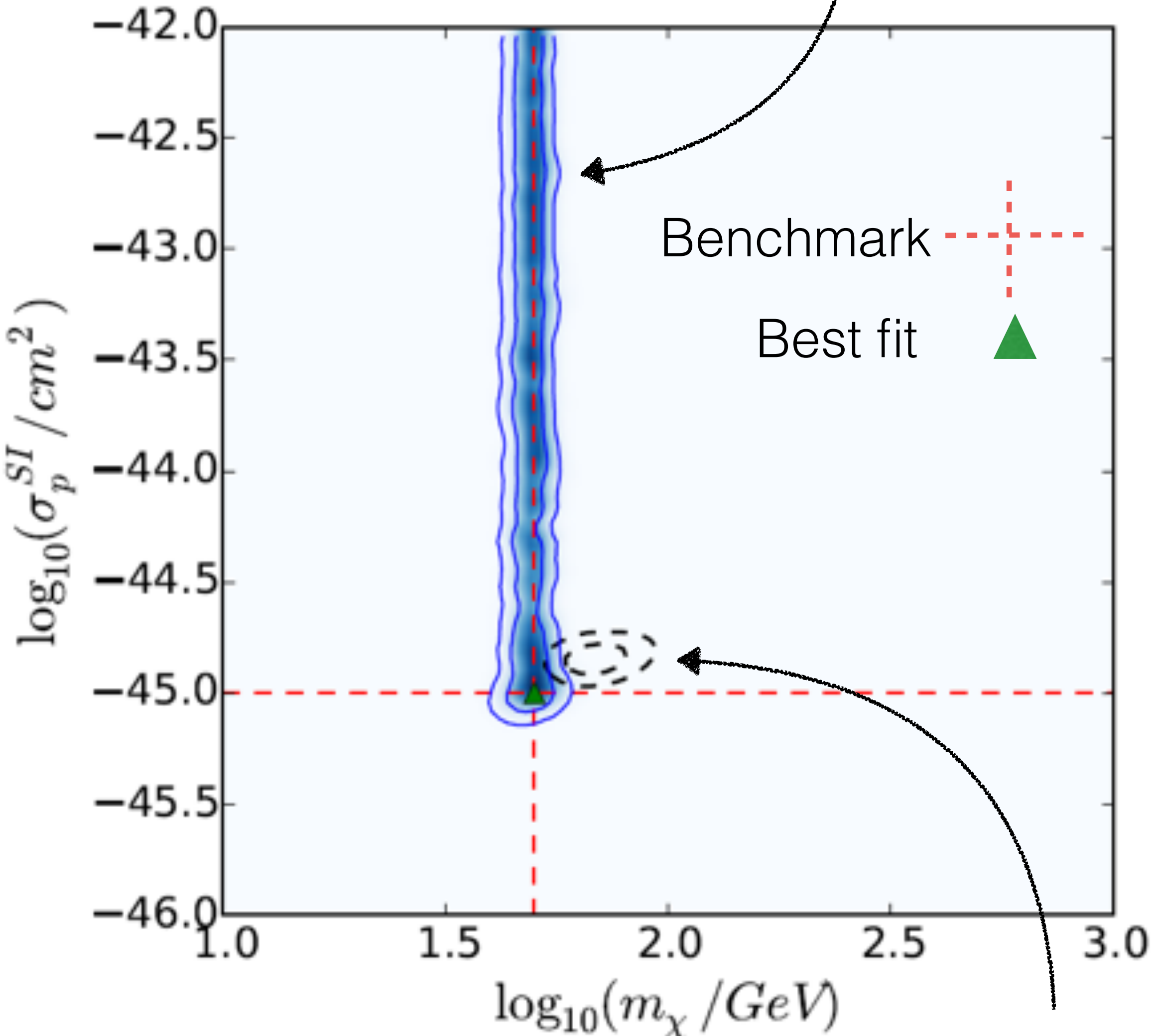
Lee, Peter [1202.5035], O'Hare, Green [1410.2749]

Cross section degeneracy



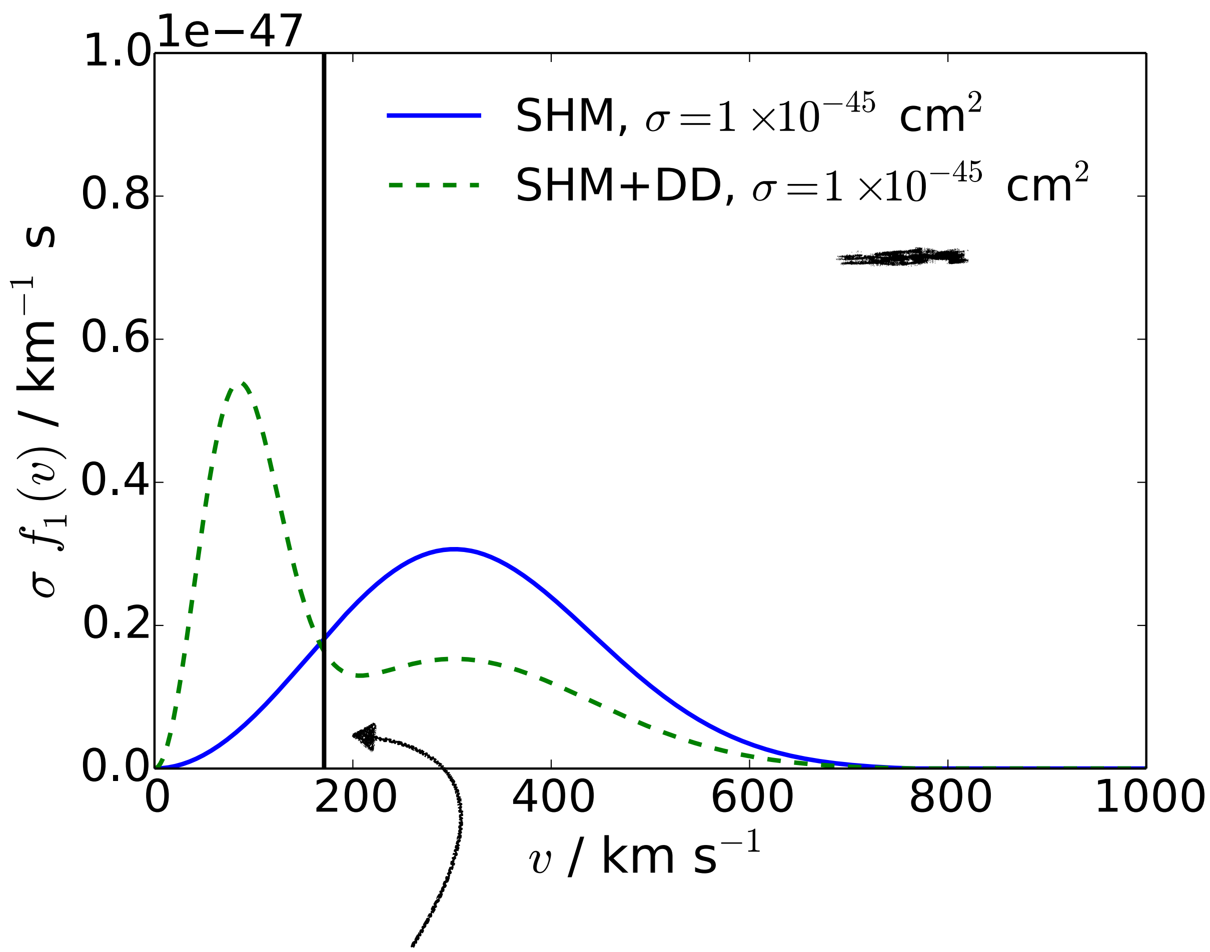
Cross section degeneracy

Using our parametrisation



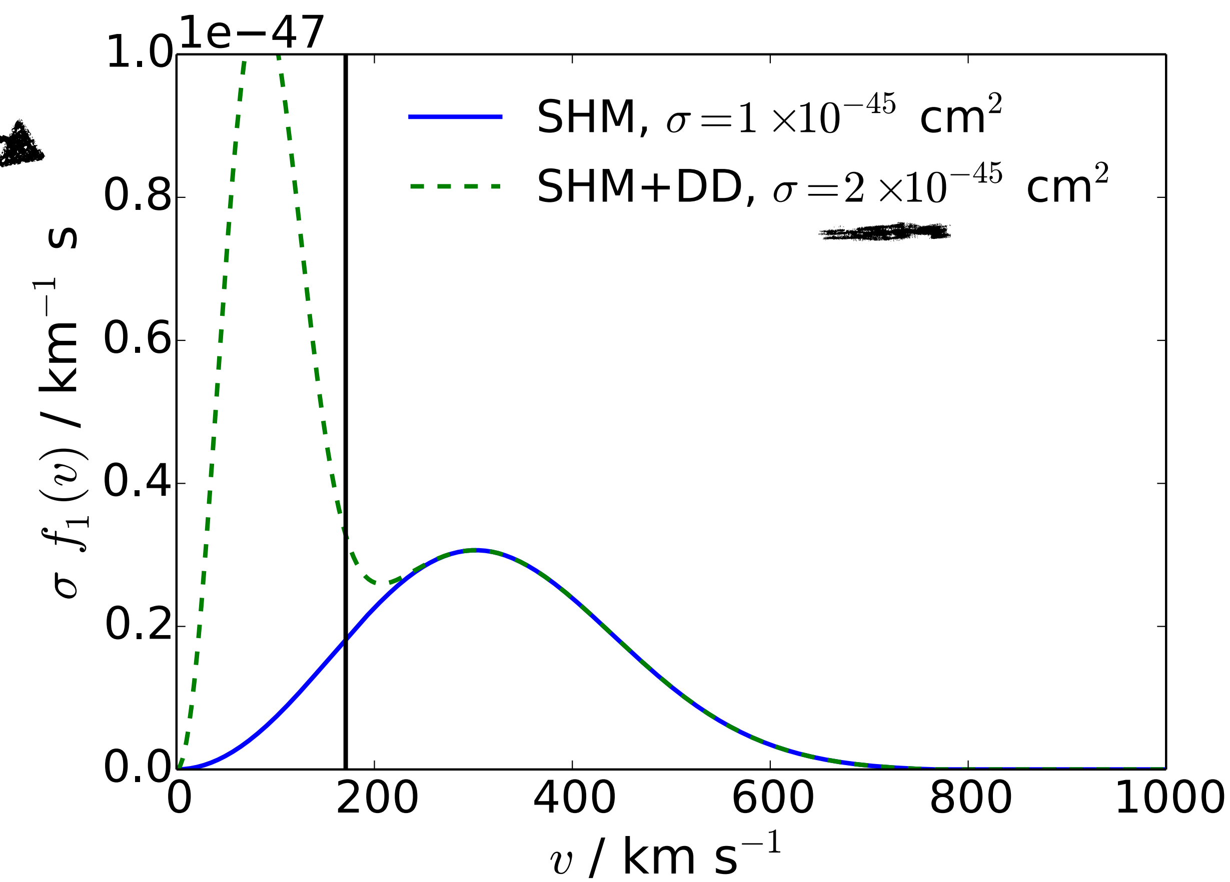
Assuming incorrect distribution

Cross section degeneracy



Minimum DM speed probed by a typical Xe experiment

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



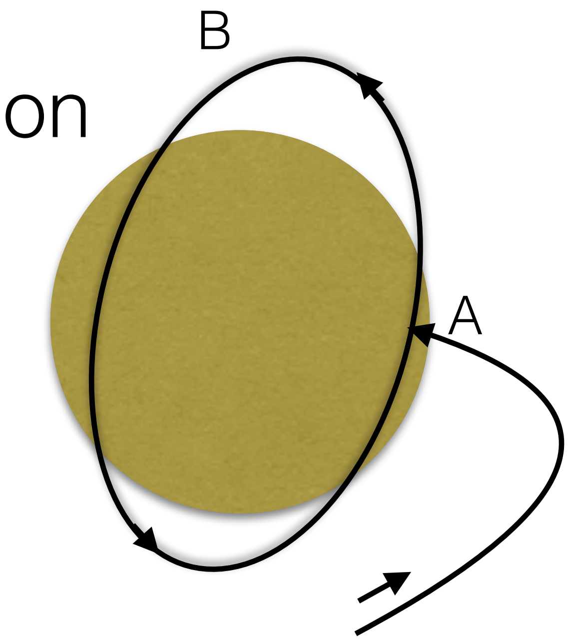
This is a problem for *any* astrophysics-independent method!

Can be solved by including data from Solar Capture of DM - sensitive to low speed DM particles

BJK, Fornasa, Green [1410.8051]

Incorporating IceCube

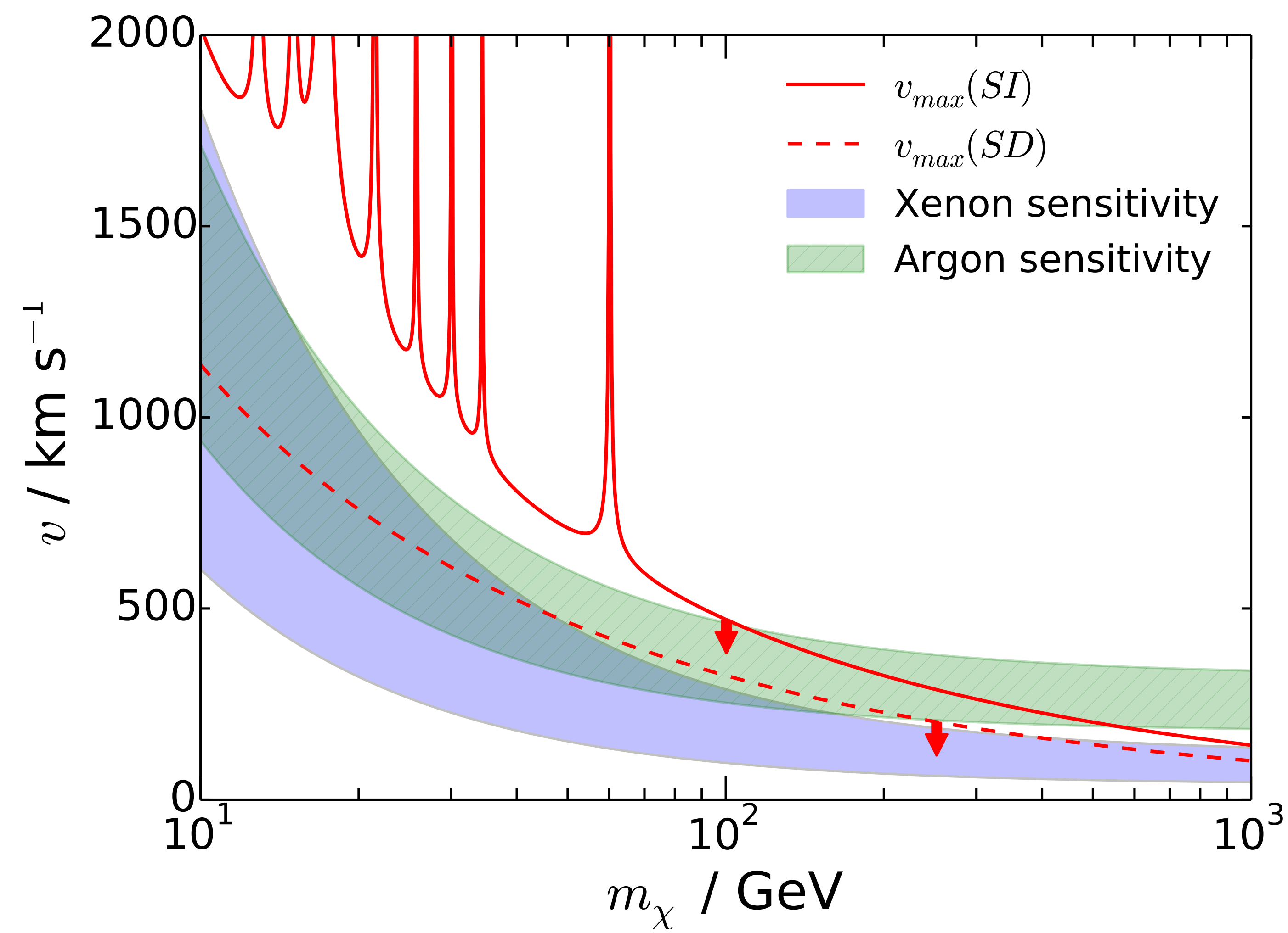
IceCube can detect neutrinos from DM annihilation in the Sun



Rate driven by solar capture of DM, which depends on the DM-nucleus scattering cross section

Crucially, only low energy DM particles are captured:

$$\frac{\mathrm{d}C}{\mathrm{d}V} \sim \sigma \int_0^{v_{\mathrm{max}}} \frac{f_1(v)}{v}\,\mathrm{d}v$$



But Sun is mainly spin-1/2 Hydrogen - so we need to include SD interactions…

Detectors Parameters

Xe detector

$E_{\rm th} = 5$ keV

1000 kg yr

~ 900 events

Mohlabeng et al. [1503.03937]

Mock data from 2 ideal experiments

Consider with and without directionality

F detector

$E_{\rm th} = 20$ keV

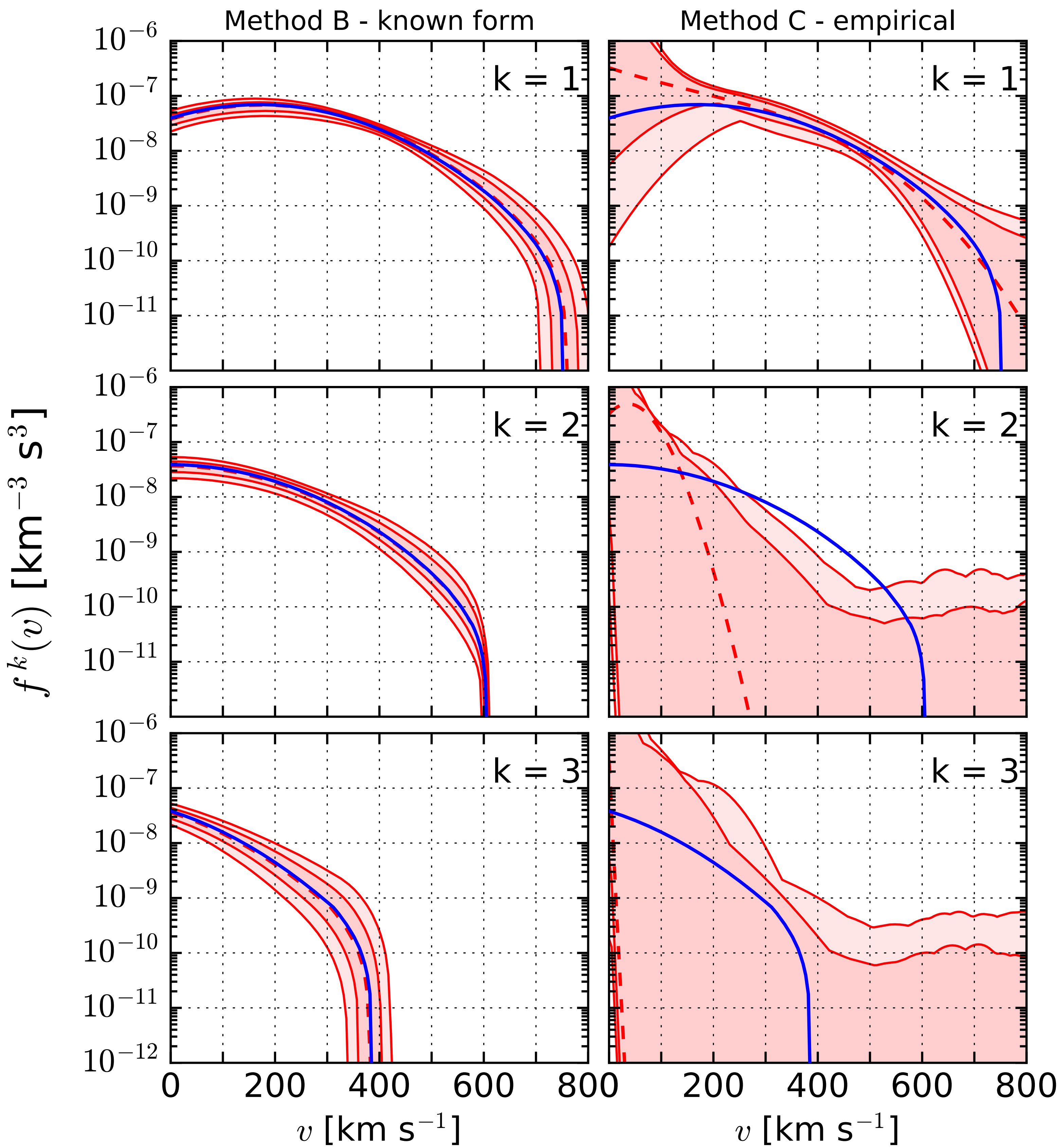
10 kg yr

~ 50 events

DRIFT [1010.3027]

SHM reconstructions

Directionality in Fluorine but *not* in Xenon



SHM reconstructions

Directionality in both Fluorine and Xenon