Dark Matter Particle Astronomy

Bradley J. Kavanagh
LPTHE (Paris)

GRAPPA Institute - 10th October 2016

bradley.kavanagh@lpthe.jussieu.fr
@BradleyKavanagh

Selected for a Viewpoint in *Physics*

PRL **113,** 101101 (2014) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2014

Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data

M. G. Aartsen,[2] M. Ackermann,[45] J. Adams,[15] J. A. Aguilar,[23] M. Ahlers,[28] M. Ahrens,[36] D. Altmann,[22] T. Anderson,[42]

The Era of Neutrino Astronomy Has Begun

NOVEMBER 21, 2013 SHARE EMAIL PRINT Recommend 31 Tweet

Contacts: Heather Dewar 301-405-9267

has been named the "2013 Breakthrough of the Year" by
d more here.

ng a telescope embedded in Antarctic ice have succeeded in a

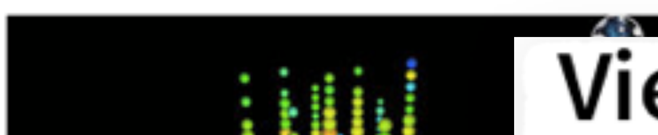
Space.com > Science & Astronomy

Neutrino Telescopes Launch New Era of Astronomy

By Tanya Lewis, Staff Writer | January 20, 2014 07:01am ET

150

56



Viewpoint: The Beginning of Extra-Galactic Neutrino Astronomy

Eli Waxman, Particle Physics & Astrophysics Department, Weizmann Institute of Science, Israel

September 2, 2014 • *Physics* 7, 88

What can high-energy neutrinos tell us about astrophysical objects beyond our galaxy?

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

THE SCIENCES

The Future of Gravitational Wave Astronomy

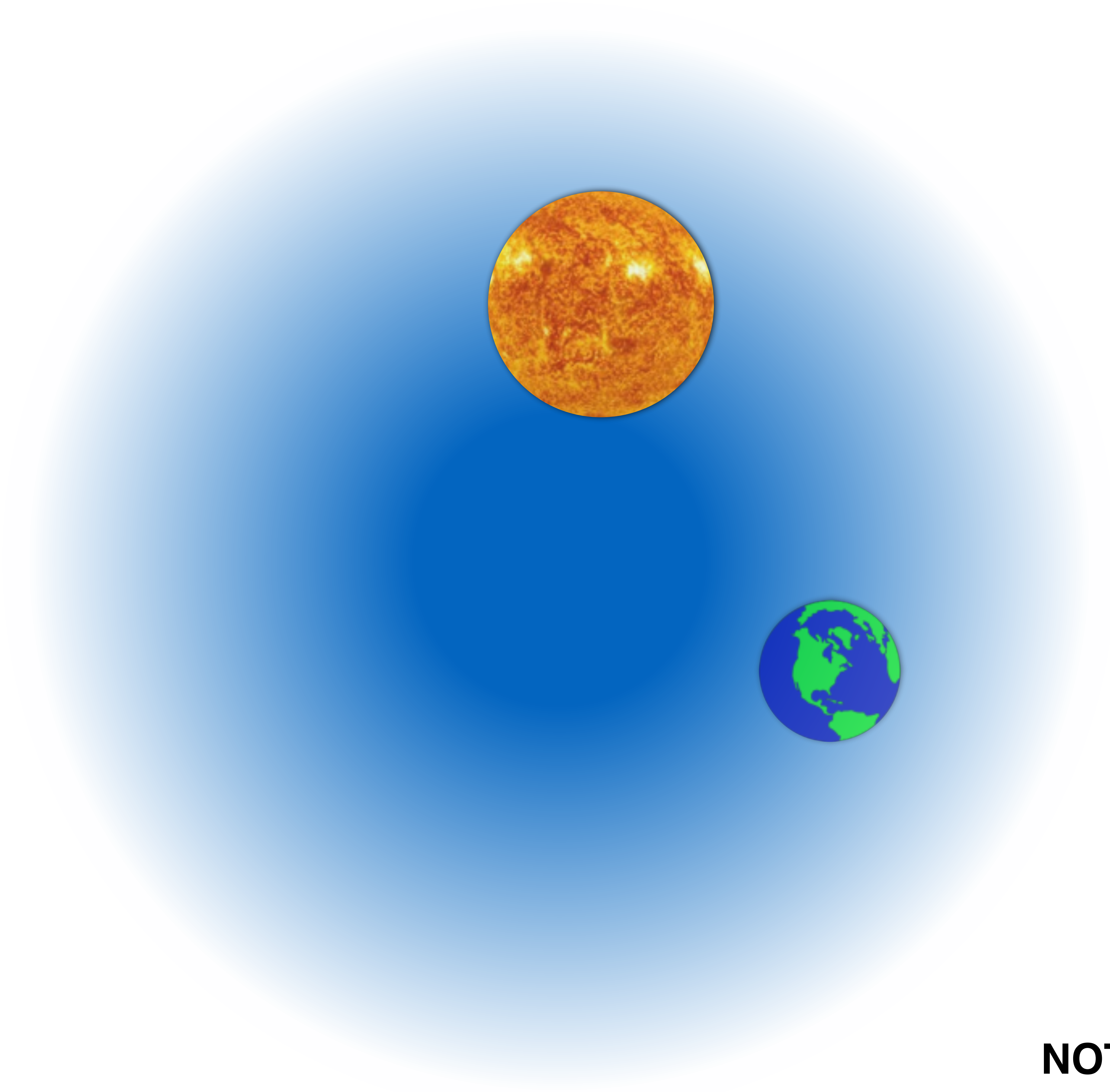
Fully opening this new window on the universe will take decades—even centuries

Why gravitational wave astronomy has physicists so damn excited

Updated by Brian Resnick · @B_resnick · brian@vox.com · Jun 21, 2016, 10:55a

Second detection heralds the era of gravitational wave astronomy

June 17, 2016 by Paul Lasky, The Conversation



NOT TO SCALE

Overview

Dark Matter (DM)

Direct detection of DM

Overcoming halo uncertainties in direct detection

BJK, Green [1207.2039, 1303.6868,1312.1852]

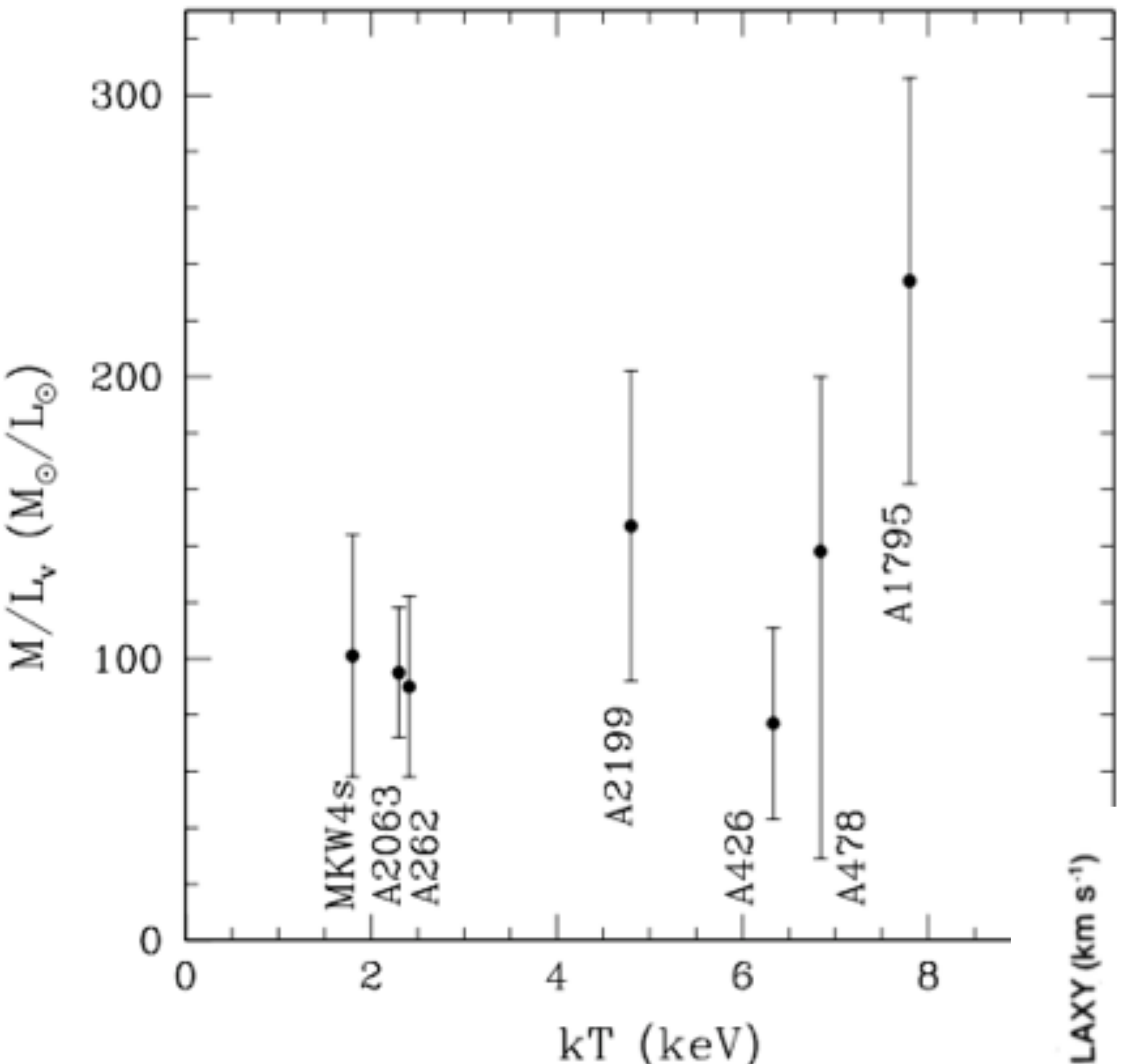
Probing low speed DM with neutrino telescopes

BJK, Fornasa, Green [1410.8051]

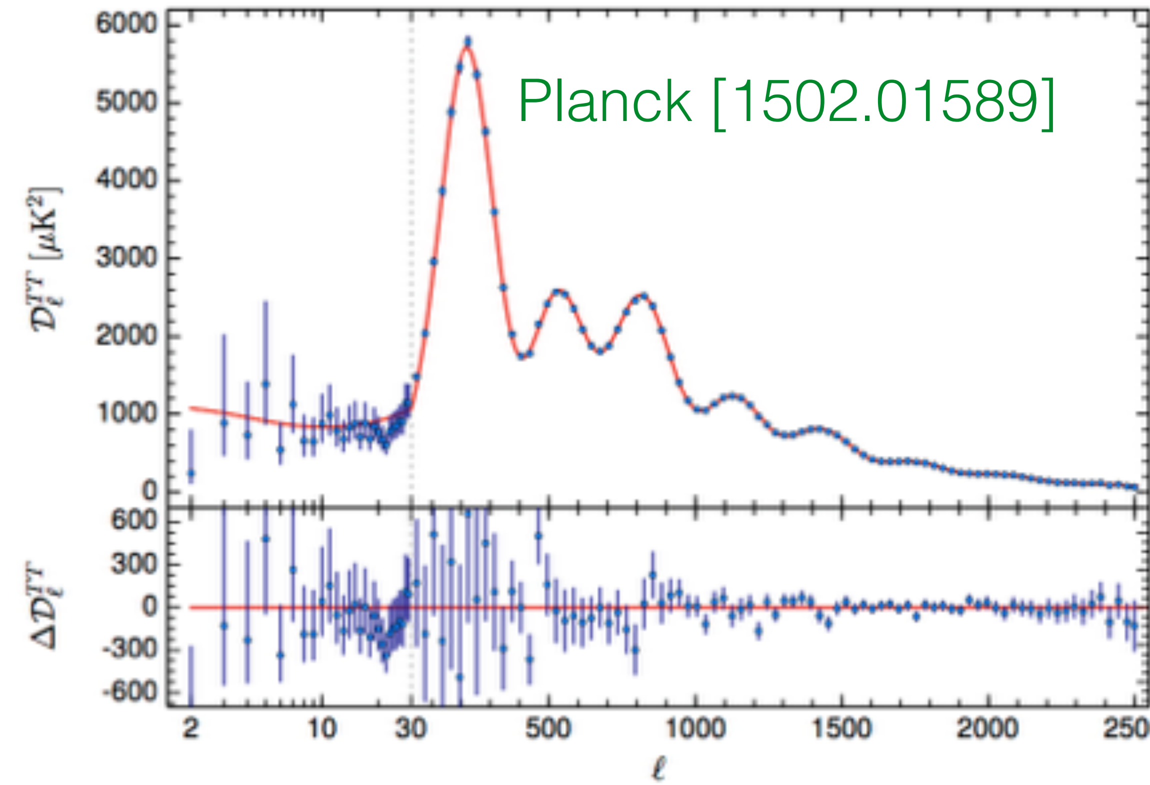
Measuring the DM velocity distribution
with directional experiments

BJK [1502.04224]; BJK, O'Hare [1609.08630]

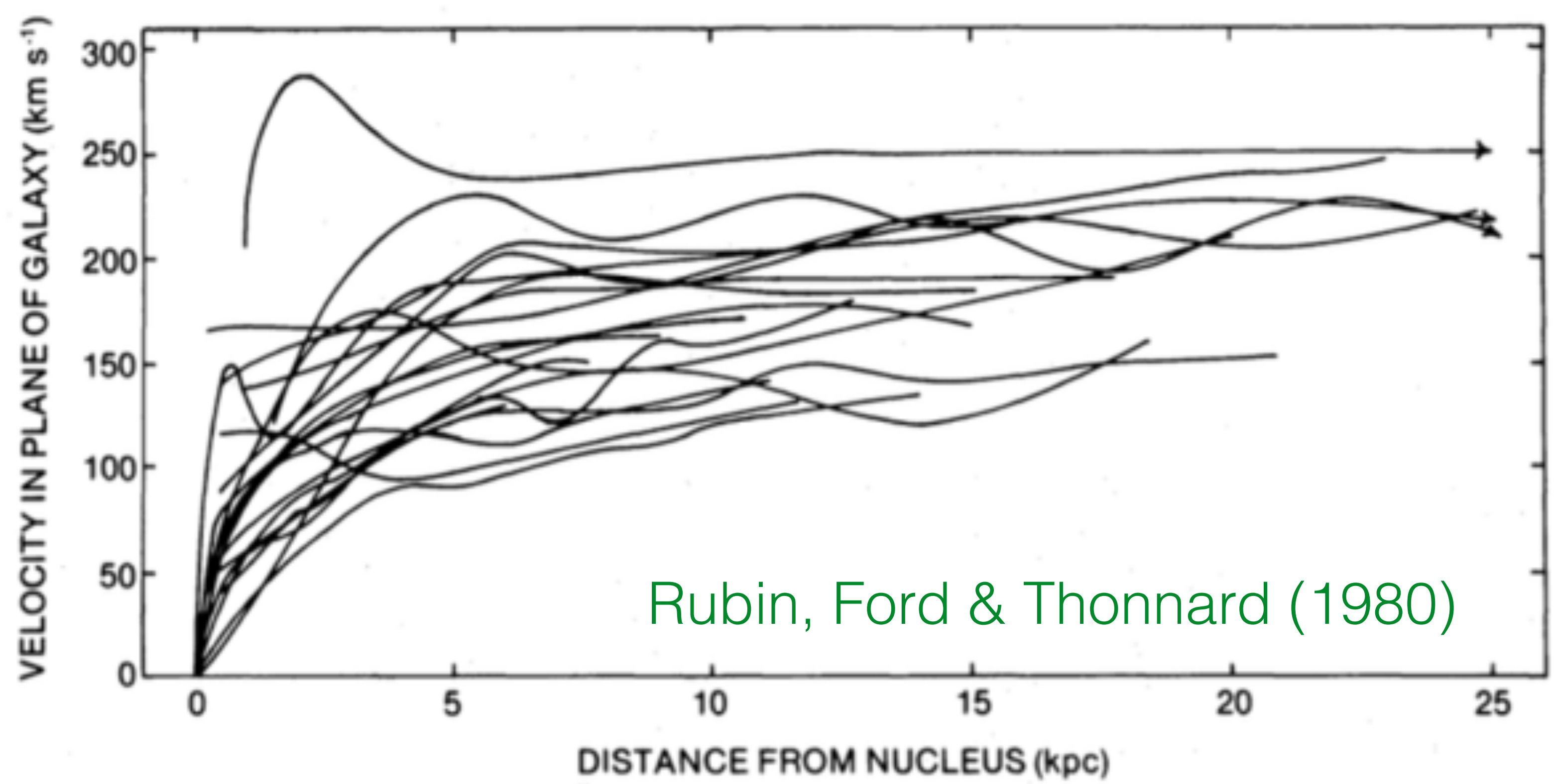
Dark Matter



Hradecky et al. [astro-ph/0006397]



Planck [1502.01589]



Rubin, Ford & Thonnard (1980)

Dark Matter at the Sun's Radius

Global

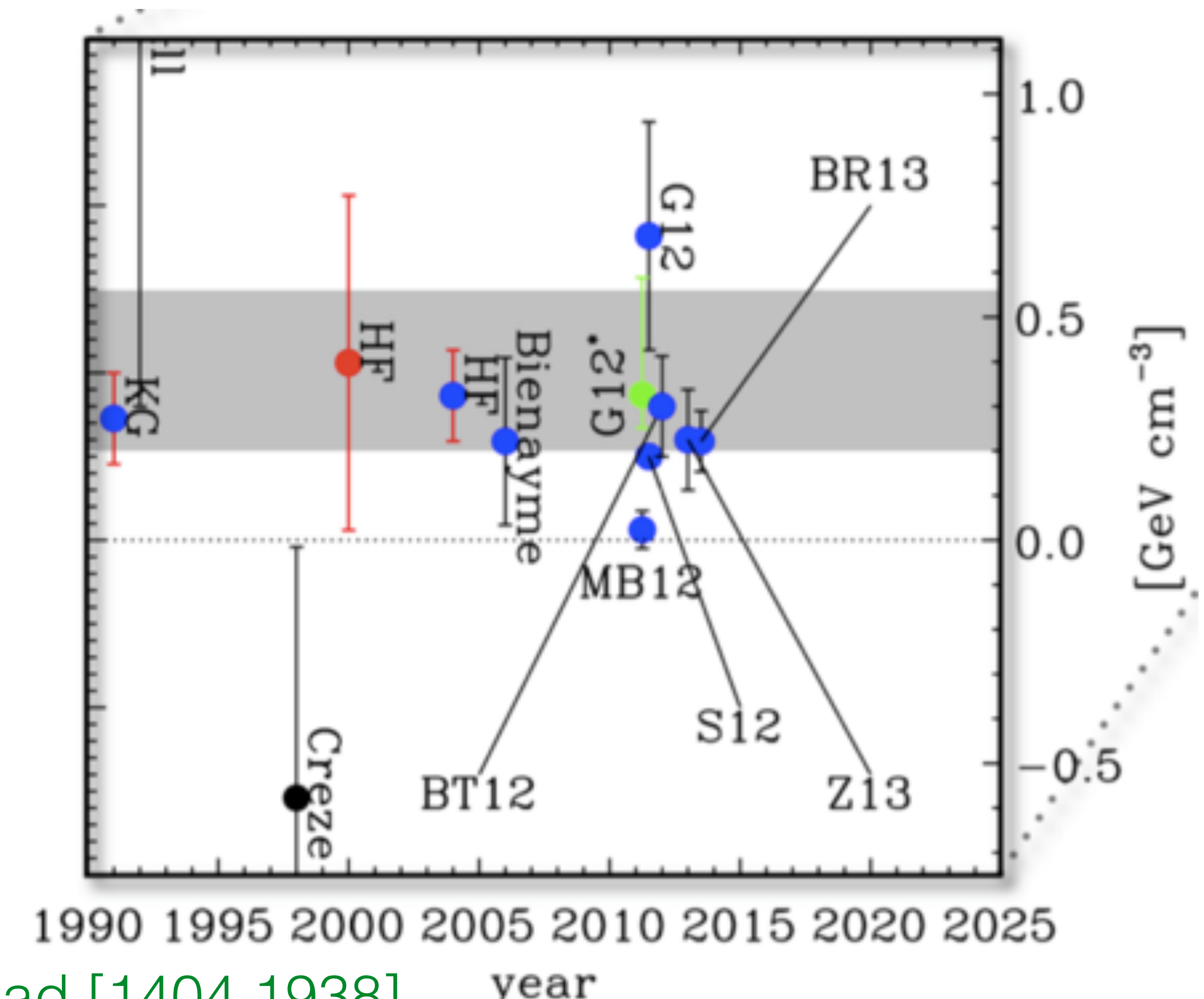
Model total mass distribution in Milky Way and extract DM density at Solar Radius (~8 kpc)

E.g. Iocco et al. [1502.03821]

Local

Estimate local DM density from kinematics of local stars (assuming local disk equilibrium)

E.g. Garbari et al. [1206.0015]



Read [1404.1938]

Values in the range:

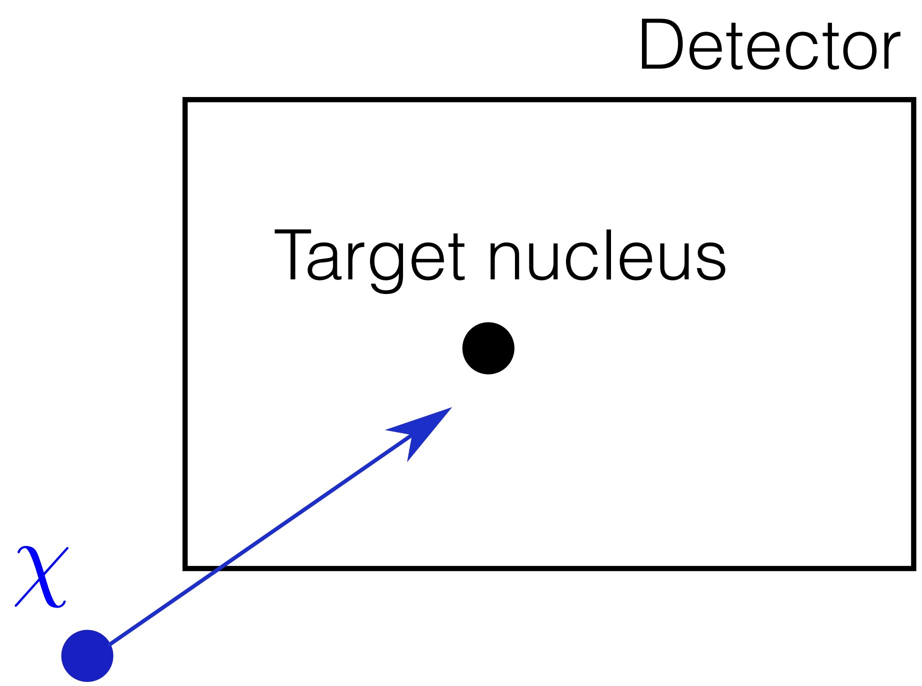
$$\rho_\chi \sim 0.2\text{–}0.8 \text{ GeV cm}^{-3}$$

But **not** zero!

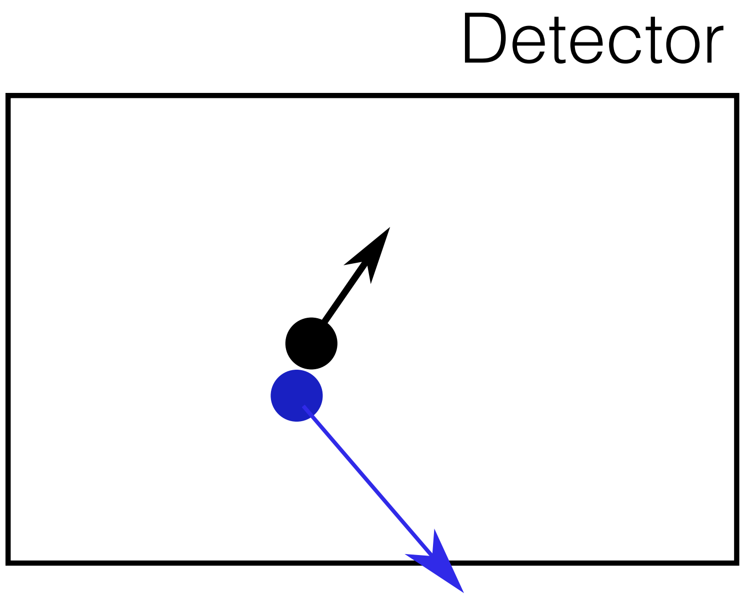
c.f. Garbari et al. [1204.3924]

Direct detection

$$m_\chi \gtrsim 1\ \mathrm{GeV}$$
$$v \sim 10^{-3}$$



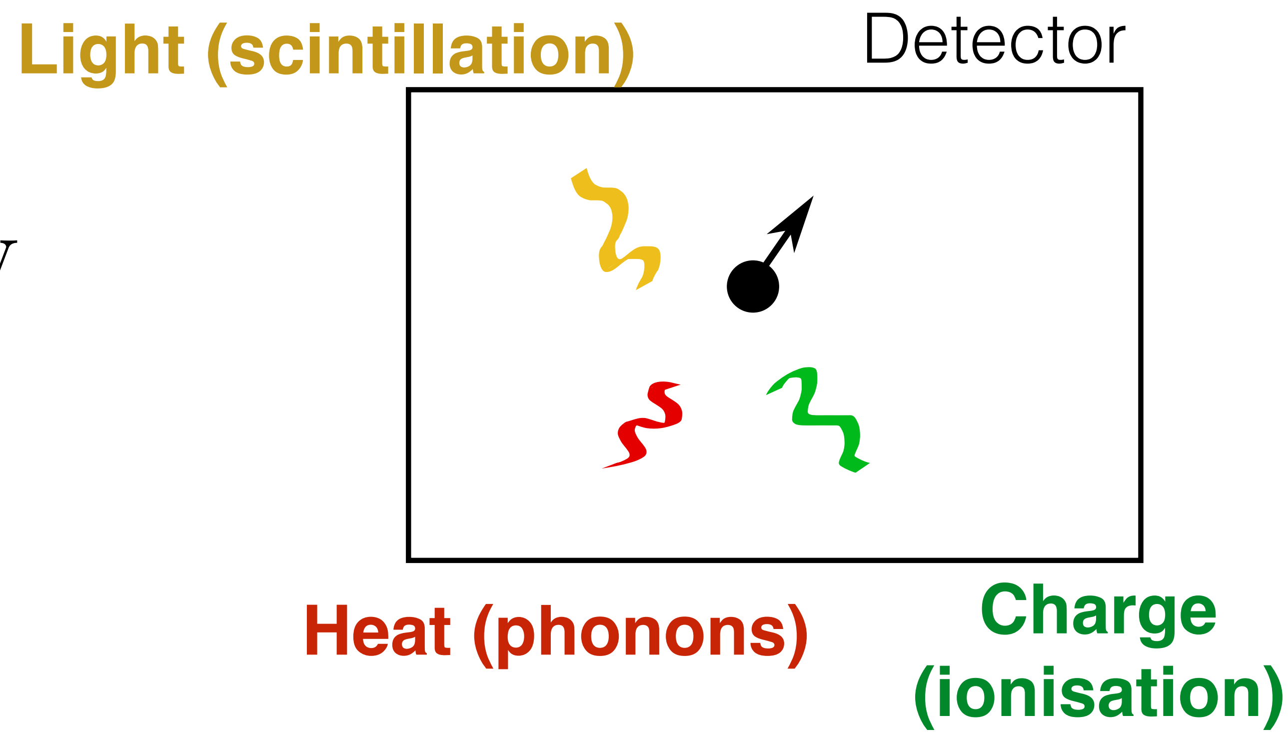
Direct detection



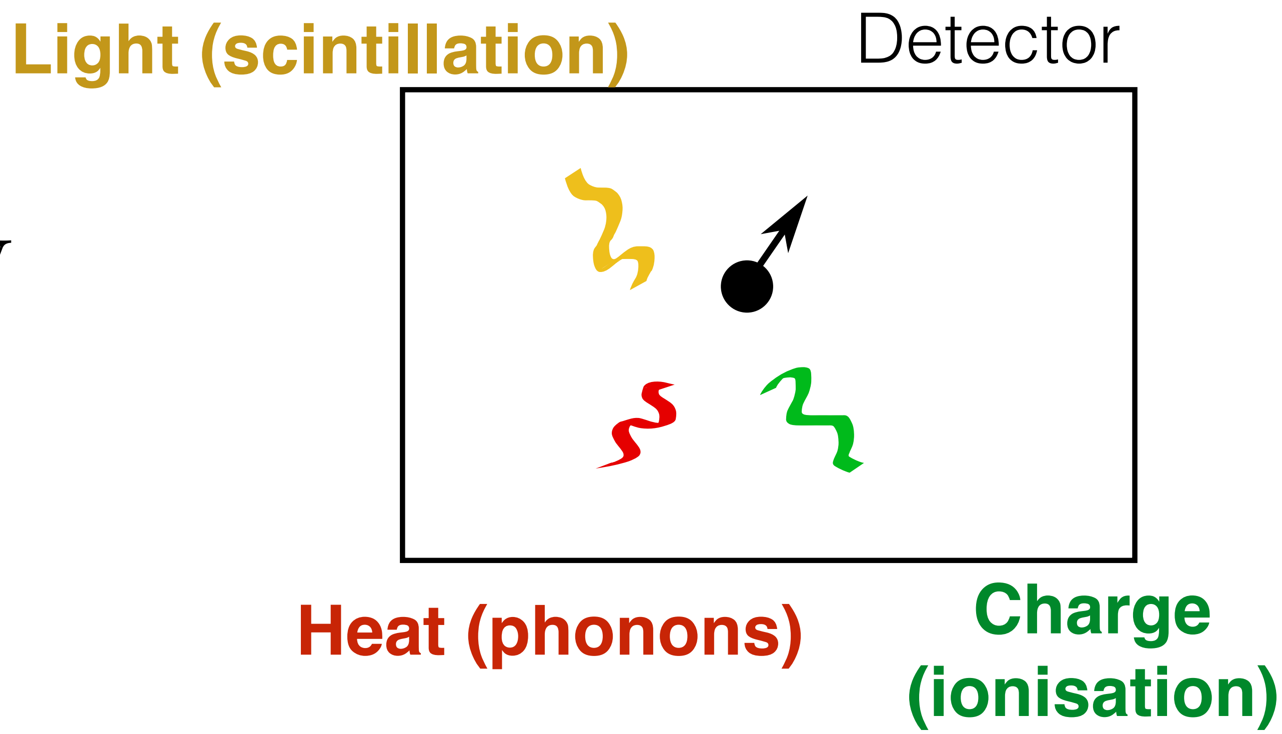
$m_\chi \gtrsim 1 \text{ GeV}$
$v \sim 10^{-3}$

Direct detection

$$m_\chi \gtrsim 1 \text{ GeV}$$
$$v \sim 10^{-3}$$



Direct detection



$$m_\chi \gtrsim 1\ \mathrm{GeV}$$
$$v \sim 10^{-3}$$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{\min}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \, \mathrm{d}^3\mathbf{v}$$

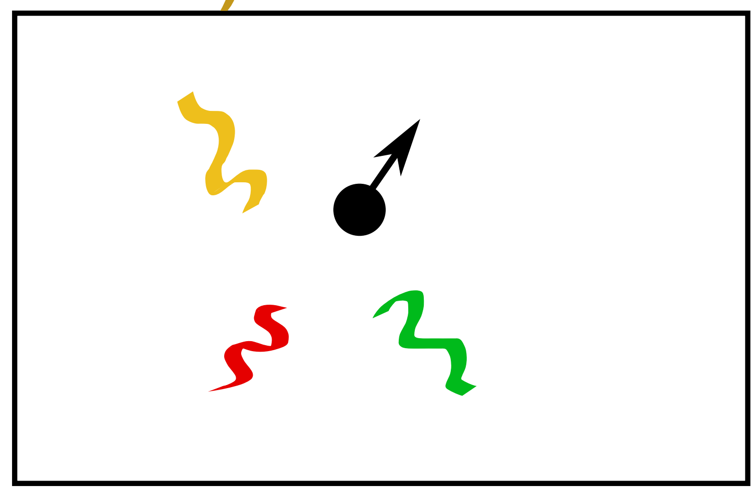
Include all particles with enough speed to excite recoil of energy E_R:

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

Direct detection

Light (scintillation)

Detector



Heat (phonons)

Charge (ionisation)

$$m_\chi \gtrsim 1\ \mathrm{GeV}$$
$$v \sim 10^{-3}$$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\boxed{\rho_\chi}}{m_\chi m_A} \int_{v_{\mathrm{min}}}^{\infty} \boxed{v f(\mathbf{v})} \boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}} \mathrm{d}^3\mathbf{v}$$

Astrophysics

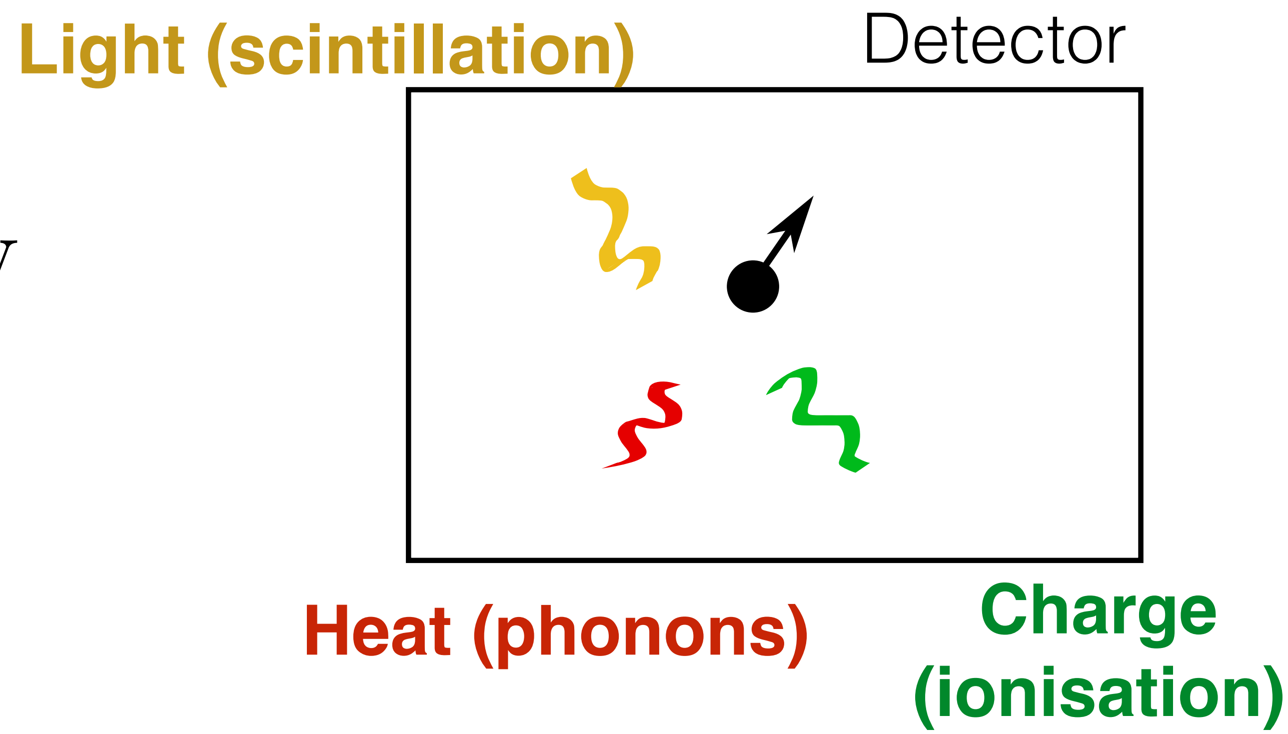
Particle and nuclear physics

Include all particles with enough speed to excite recoil of energy E_R:

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

Direct detection

$$m_\chi \gtrsim 1 \text{ GeV}$$
$$v \sim 10^{-3}$$



$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\boxed{\rho_\chi}}{m_\chi m_A} \int_{v_{\min}}^{\infty} \boxed{v f(\mathbf{v})} \boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}} \mathrm{d}^3\mathbf{v}$$

Astrophysics

Particle and nuclear physics

Include all particles with enough speed to excite recoil of energy E_R:

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

But plenty of alternative ideas:
DM-electron recoils [1108.5383]
Superconducting detectors [1504.07237]
Axion DM searches [1404.1455]

Astrophysics of DM (the simple picture)

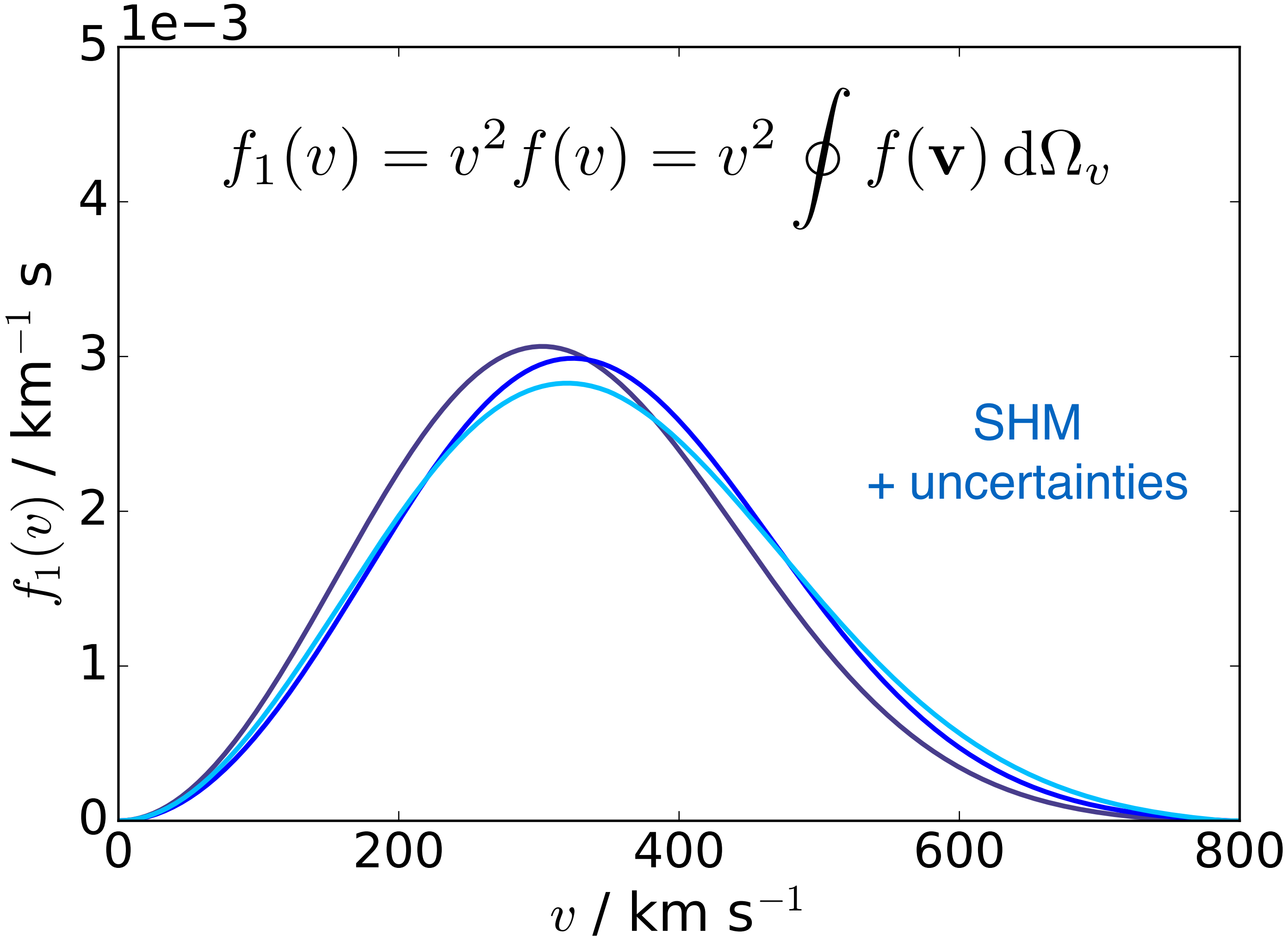
Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

Leads to a Maxwell-Boltzmann (MB) distribution,

$$f_{\mathrm{Lab}}(\mathbf{v}) = (2\pi\sigma_v^2)^{-3/2} \exp\left[-\frac{(\mathbf{v}-\mathbf{v}_\mathrm{e})^2}{2\sigma_v^2}\right] \Theta(|\mathbf{v}-\mathbf{v}_\mathrm{e}| - v_\mathrm{esc})$$

which is well matched in some hydro simulations.

[1601.04707, 1601.04725, 1601.05402]



$\mathbf{v}_e$ - Earth's Velocity

$v_e \sim 220 - 250\,\mathrm{km\,s^{-1}}$

$\sigma_v \sim 155 - 175\,\mathrm{km\,s^{-1}}$

Feast et al. [astro-ph/9706293], Bovy et al. [1209.0759]

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

Piffl et al. (RAVE) [1309.4293]

Particle Physics of DM (the simple picture)

Typically assume contact interactions (heavy mediators).
In the non-relativistic limit, obtain two main contributions.
Write in terms of DM-proton cross section σ^p:

$$\frac{\mathrm{d}\sigma^A}{\mathrm{d}E_R} \propto \frac{\sigma^p}{\mu_{\chi p}^2 v^2} \mathcal{C}_A F^2(E_R)$$

Form factor accounts for loss of coherence at high energy

Enhancement factor different for:

spin-independent (SI) interactions - $\mathcal{C}_A^{\mathrm{SI}} \sim A^2$

spin-dependent (SD) interactions - $\mathcal{C}_A^{\mathrm{SD}} \sim (J+1)/J$

Interactions which are higher order in v are possible. See the non-relativistic EFT of Fitzpatrick et al. [1203.3542]

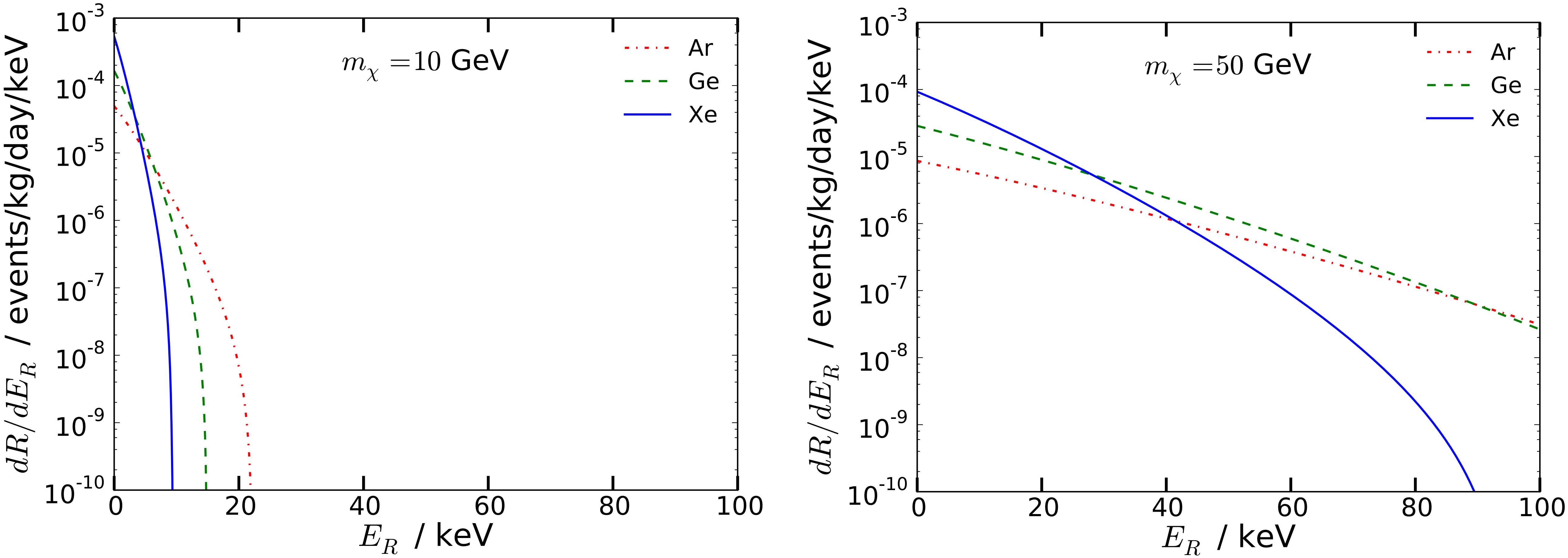
The final event rate

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \sim \int_{v_{\min}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\,\mathrm{d}^3\mathbf{v} \quad + \quad \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \propto \frac{1}{v^2} \quad \longrightarrow \quad \frac{\mathrm{d}R}{\mathrm{d}E_R} \sim \frac{\rho_\chi}{m_\chi}\mathcal{C}_A \eta(v_{\min})$$

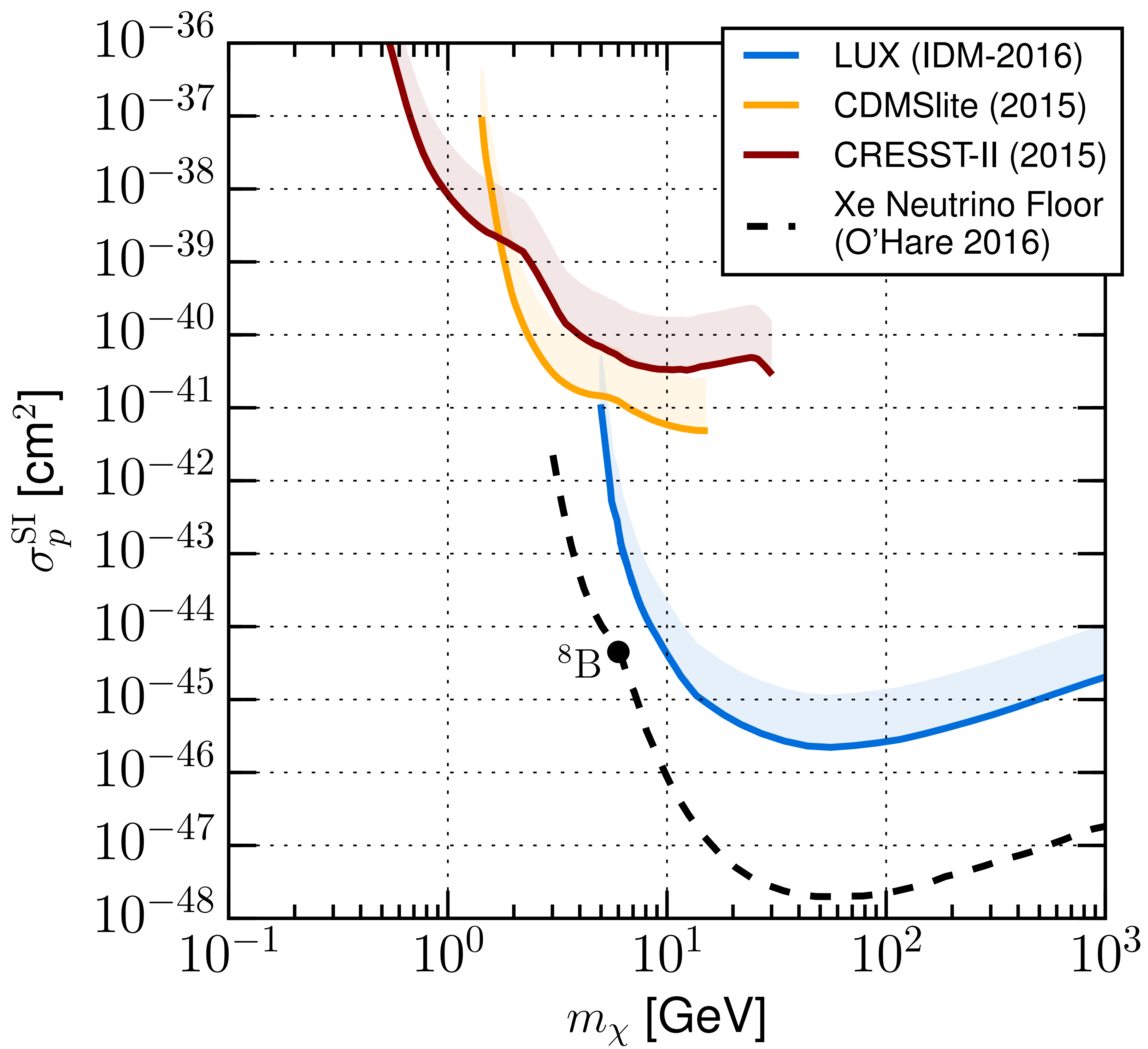
The 'velocity integral': $\boxed{\eta(v_{\min}) \equiv \int_{v_{\min}}^{v_{\mathrm{esc}}} \frac{f_1(v)}{v}\,\mathrm{d}v}$ where

$$f_1(v) = v^2 \oint f(\mathbf{v})\,\mathrm{d}\Omega_v$$

SI interactions, SHM distribution



The current landscape

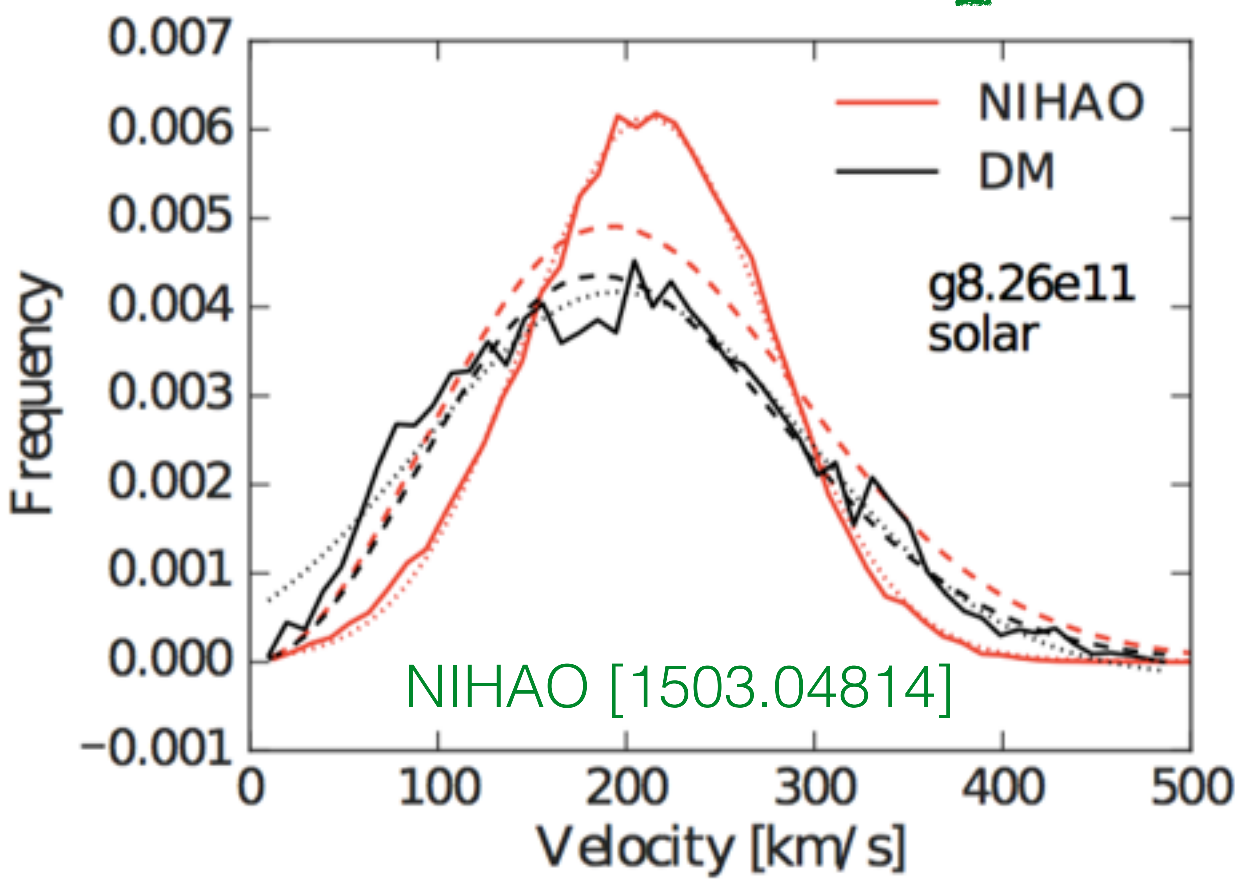


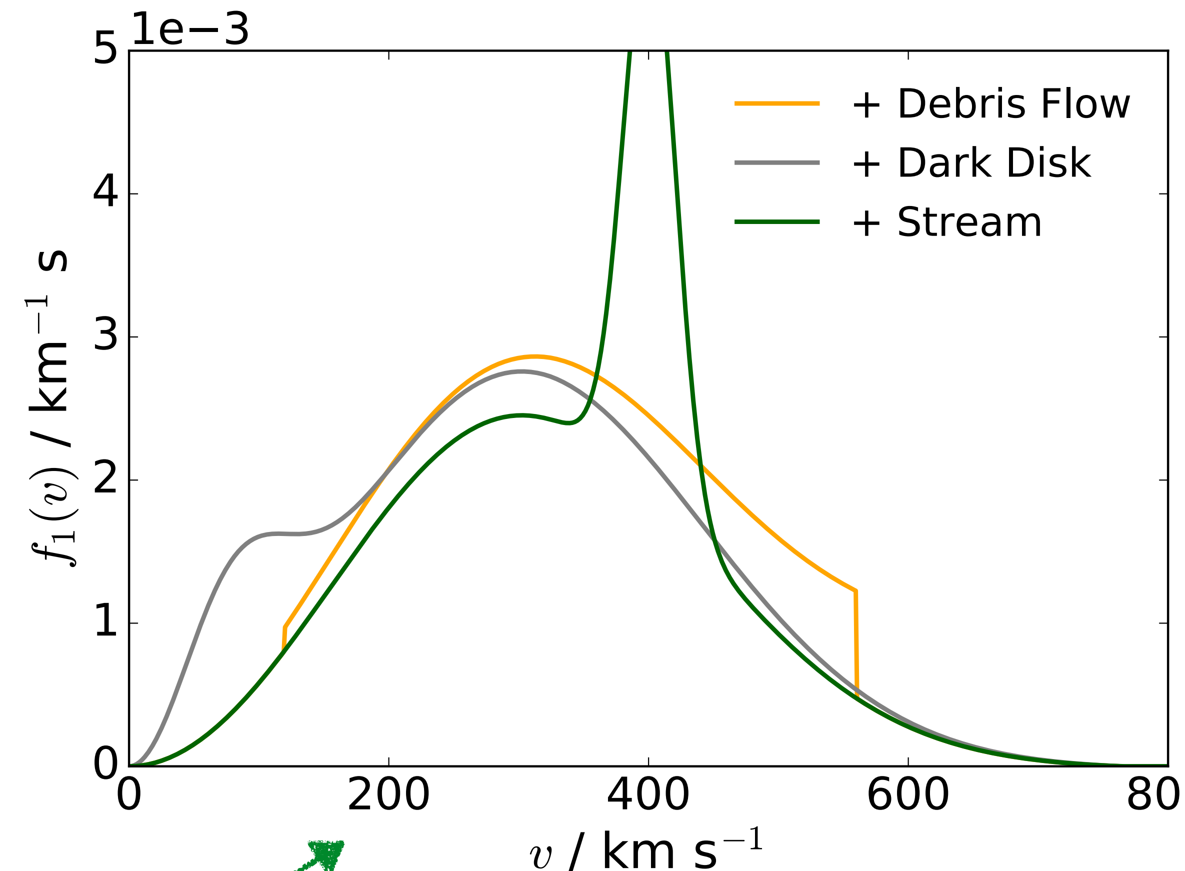
Assuming the Standard Halo Model…

Overcoming halo uncertainties in direct detection

Astrophysical uncertainties

The Standard Halo Model (SHM) has some inherent uncertainties.
But there could also be deviations from MB form:





But simulations suggest there could be also substructure:

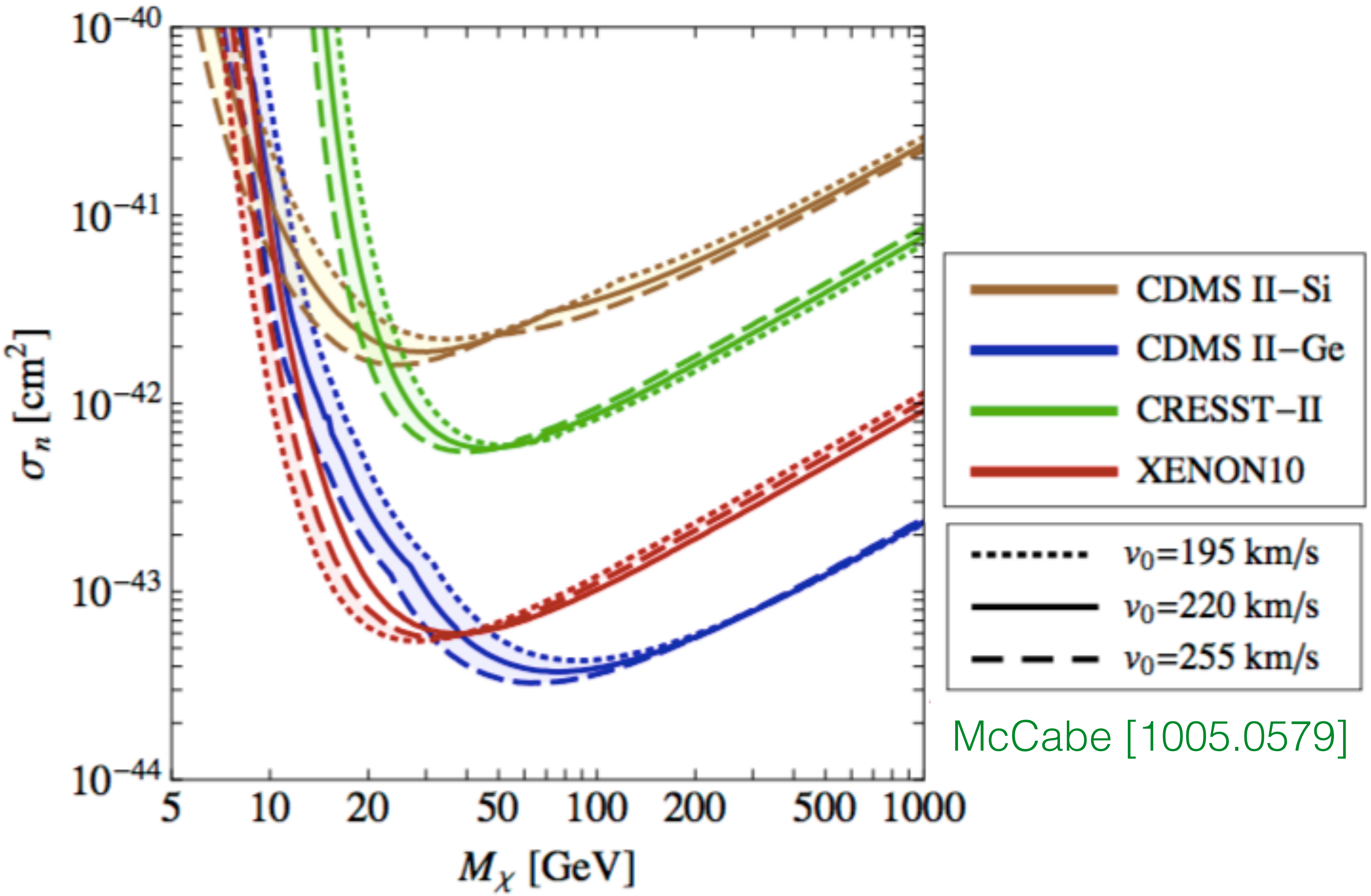
Debris flows	Kuhlen et al. [1202.0007]
Dark disk	Pillepich et al. [1308.1703], Schaller et al. [1605.02770]
Tidal stream	Freese et al. [astro-ph/0309279, astro-ph/0310334]

What could go wrong? (1)

Compare direct detection limits, incorporating SHM uncertainties

may affect proper comparison/compatibility of results

e.g. March-Russell at al. [0812.1931]

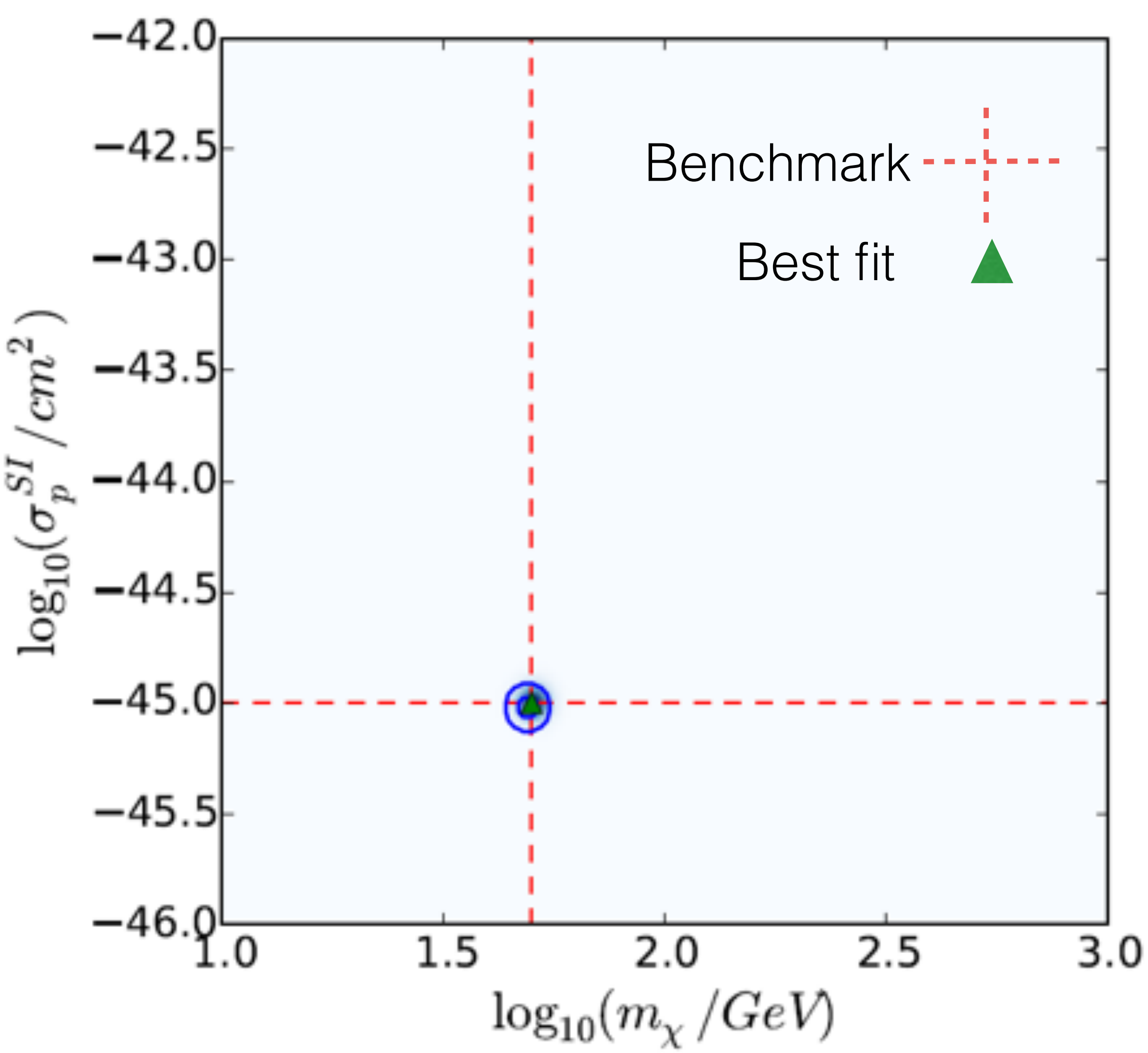


McCabe [1005.0579]

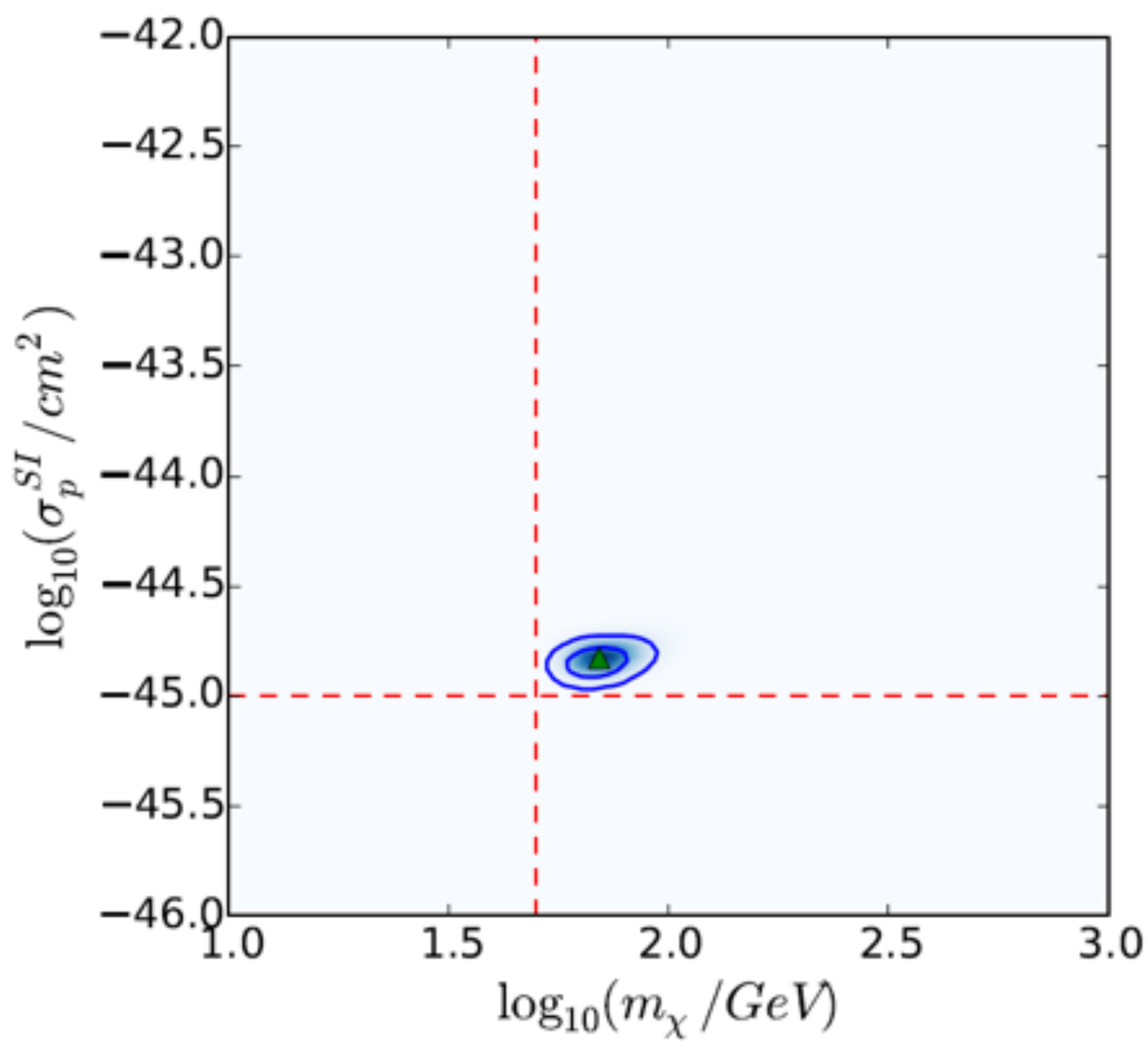
What could go wrong? (2)

Generate mock data for several experiments, assuming a stream distribution, then try to reconstruct the mass and cross section assuming:

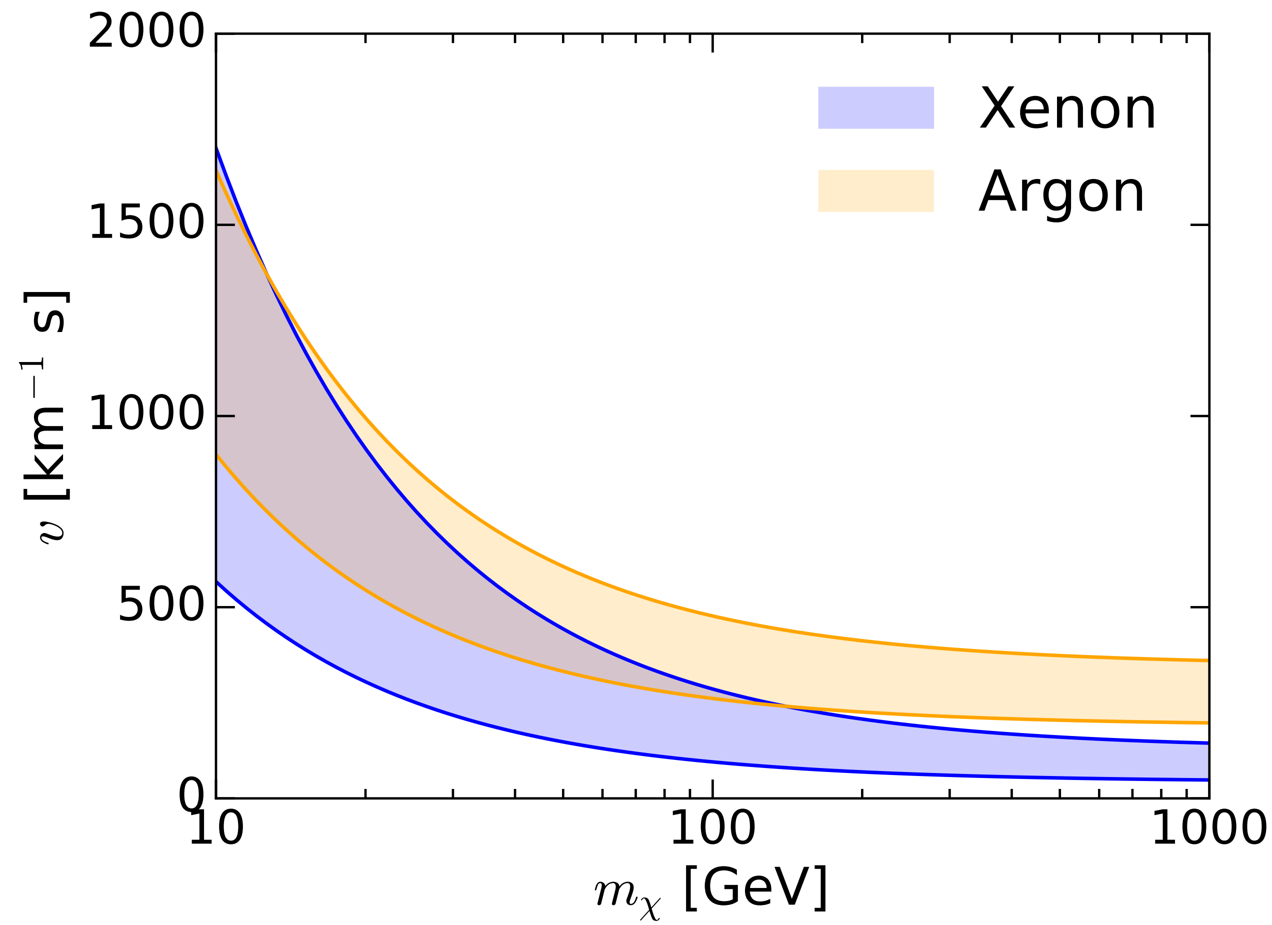
(correct) stream distribution



(incorrect) SHM distribution



Halo-independent methods



Experiments sensitive to a fixed range of recoil energies and therefore (through $v_{\min}(E_R)$) a fixed range of speeds

Ask whether results are consistent over the range of speeds where two experiments overlap

Compare $\eta(v_{\min}) \equiv \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v}\,\mathrm{d}v$ (inferred from rate) over this limited range

Fox et al. [1011.1915,1011.1910], but see also [1111.0292, 1107.0741, 1202.6359, 1304.6183, 1403.4606, 1403.6830, *1504.03333*, 1607.02445, 1607.04418 and more…]

But ideally we want to fit $f_1(v)$, the speed distribution.

Reconstructing the speed distribution

Write a *general parametrisation* for the speed distribution:

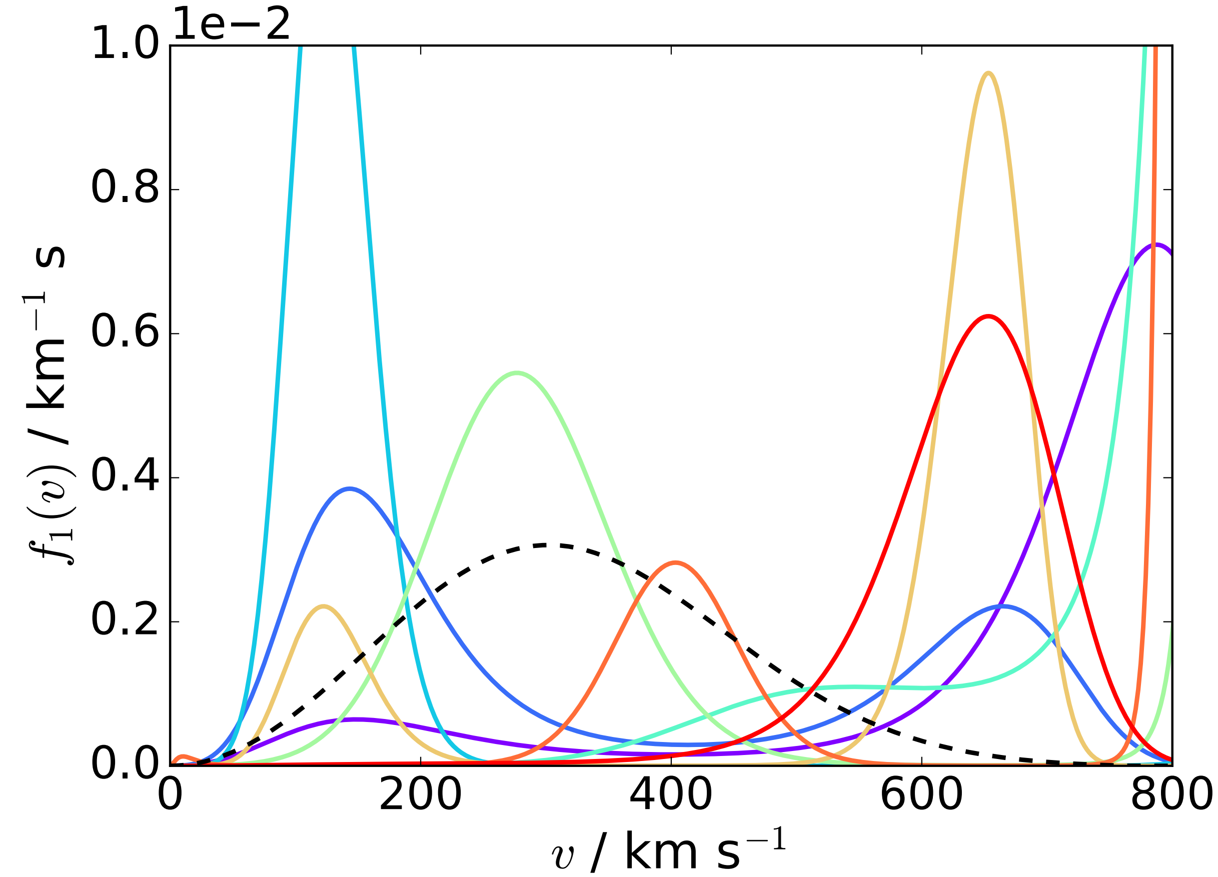
Peter [1103.5145]

$$\boxed{f_1(v) = v^2 \exp\left(-\sum_{m=0}^{N-1} a_m v^m\right)}$$

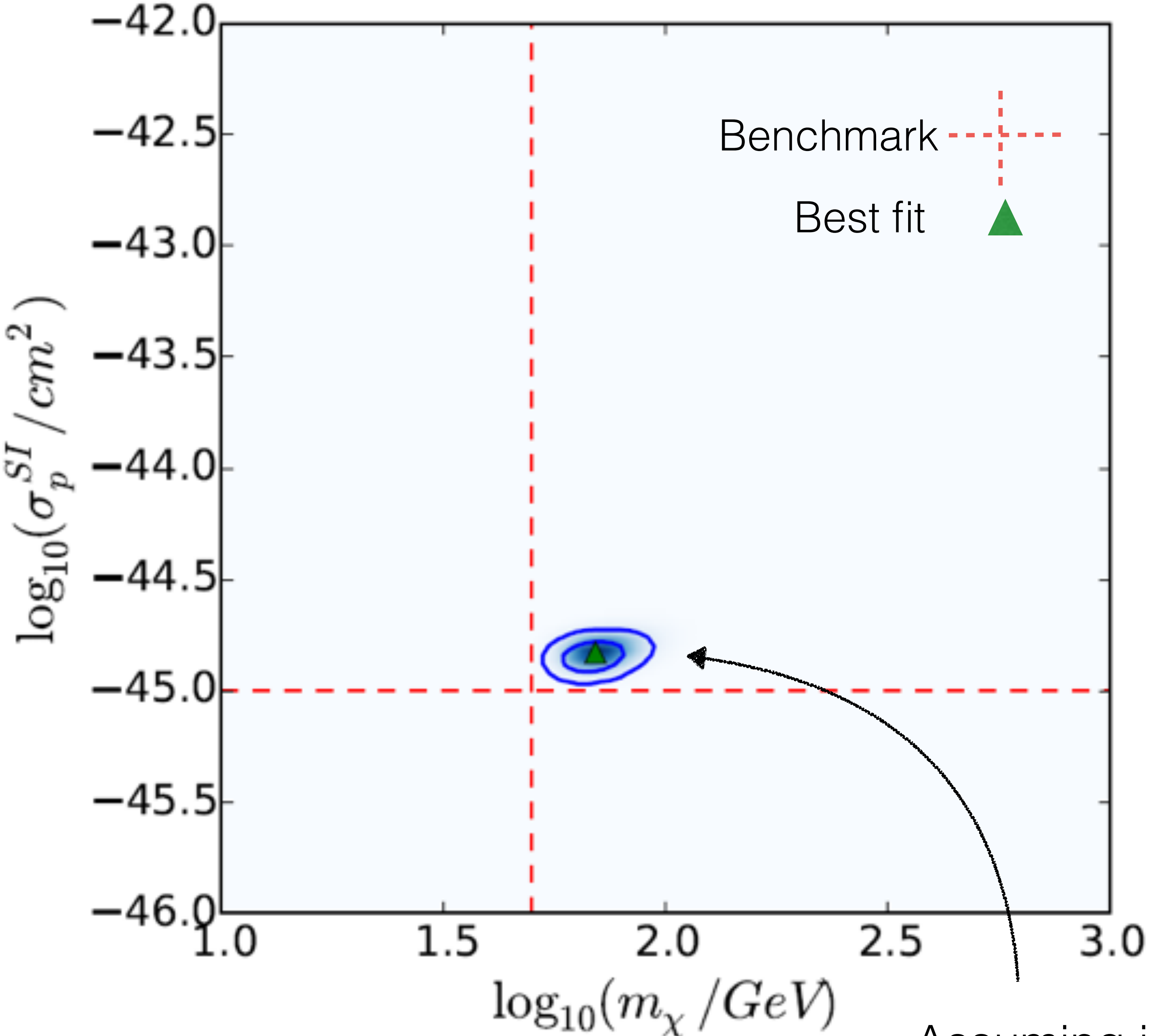
BJK & Green [1303.6868]

This form guarantees a distribution function which is *everywhere positive.*

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

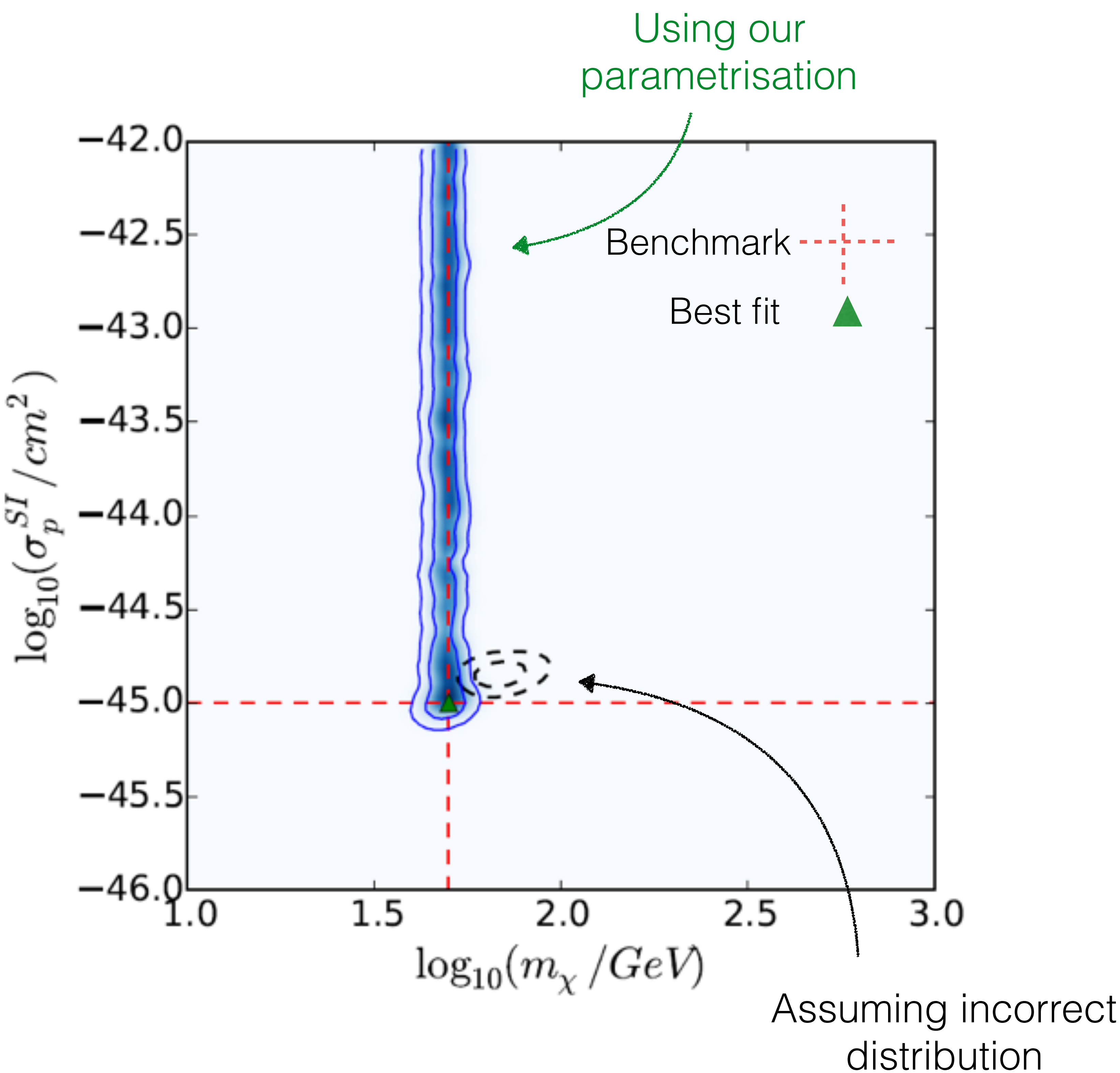


Testing the parametrisation

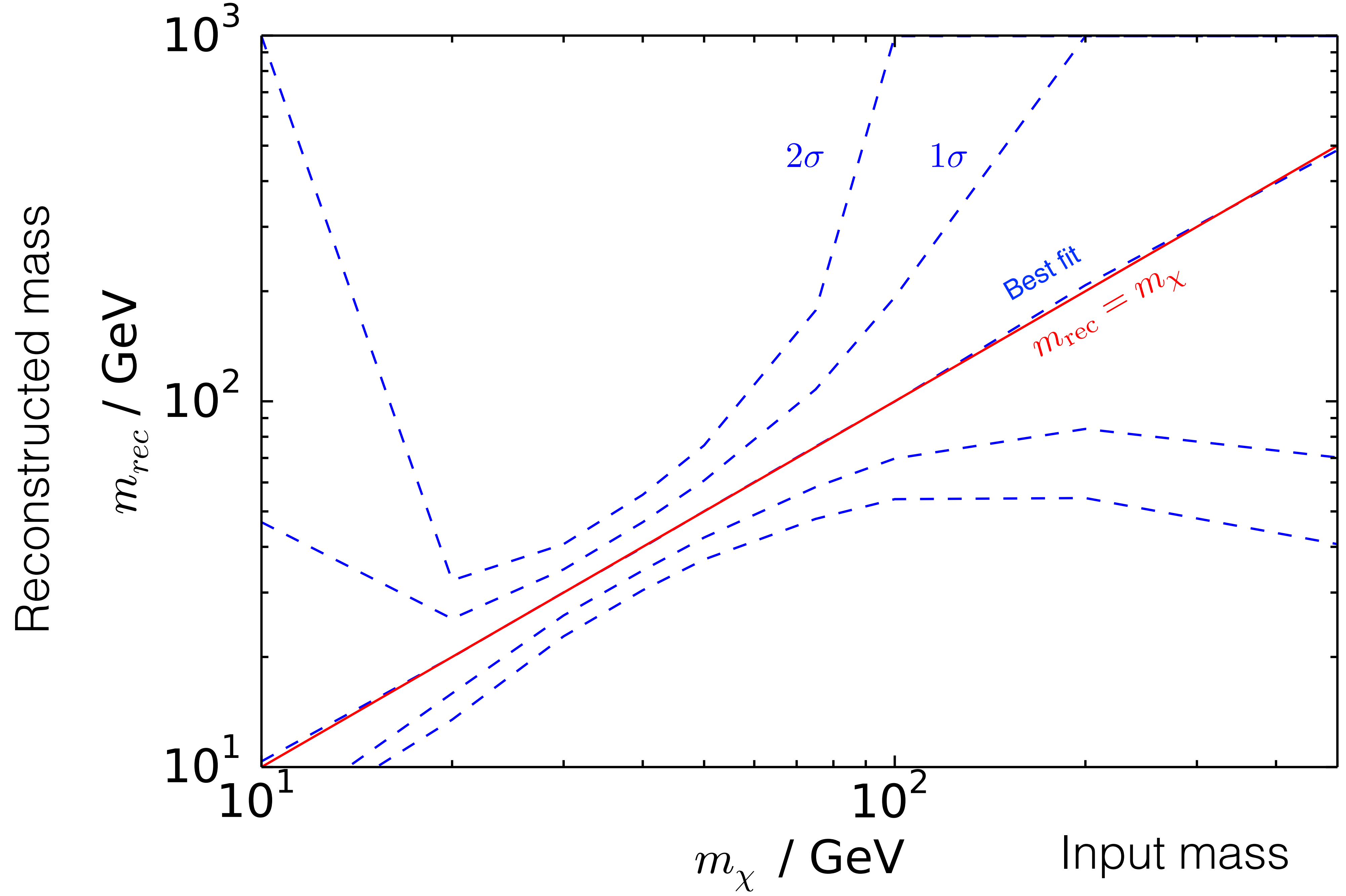


Assuming incorrect distribution

Testing the parametrisation

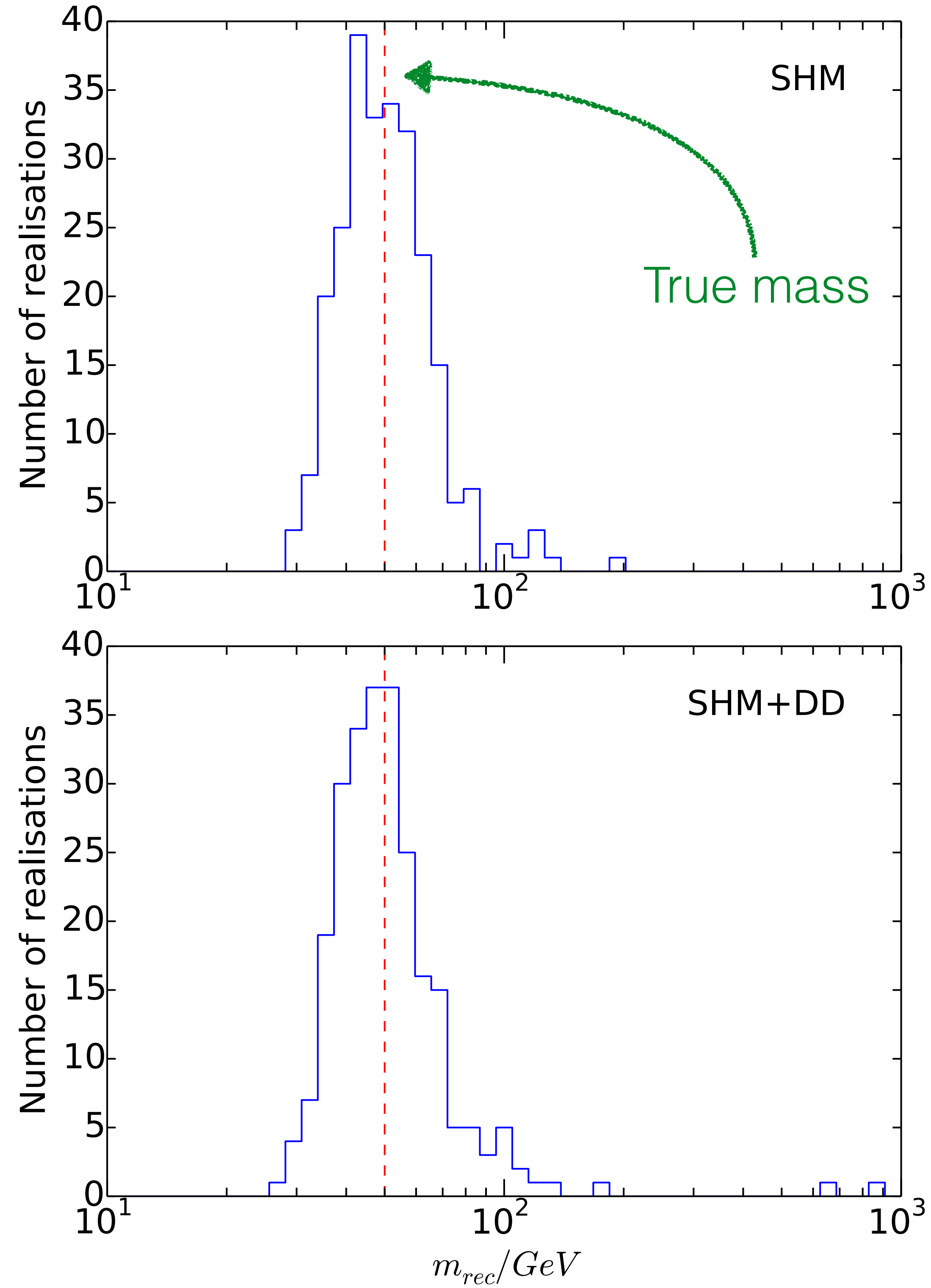


Testing the parametrisation



BJK [1312.1852]

Testing the parametrisation



Reconstructed mass

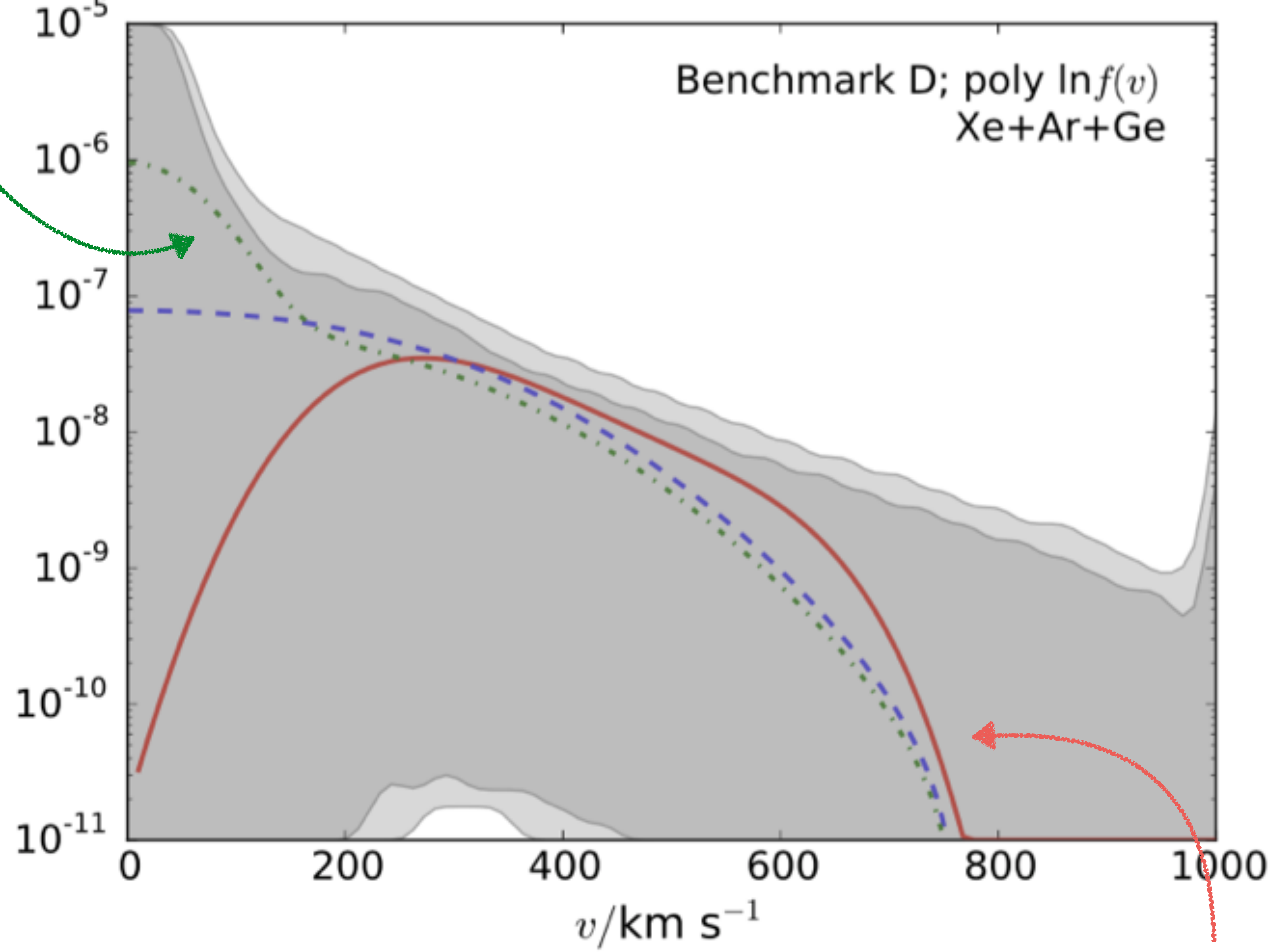
BJK [1312.1852]

Reconstructing the speed distribution

$m_\chi = 30$ GeV

SHM+DD distribution

'True' speed distribution

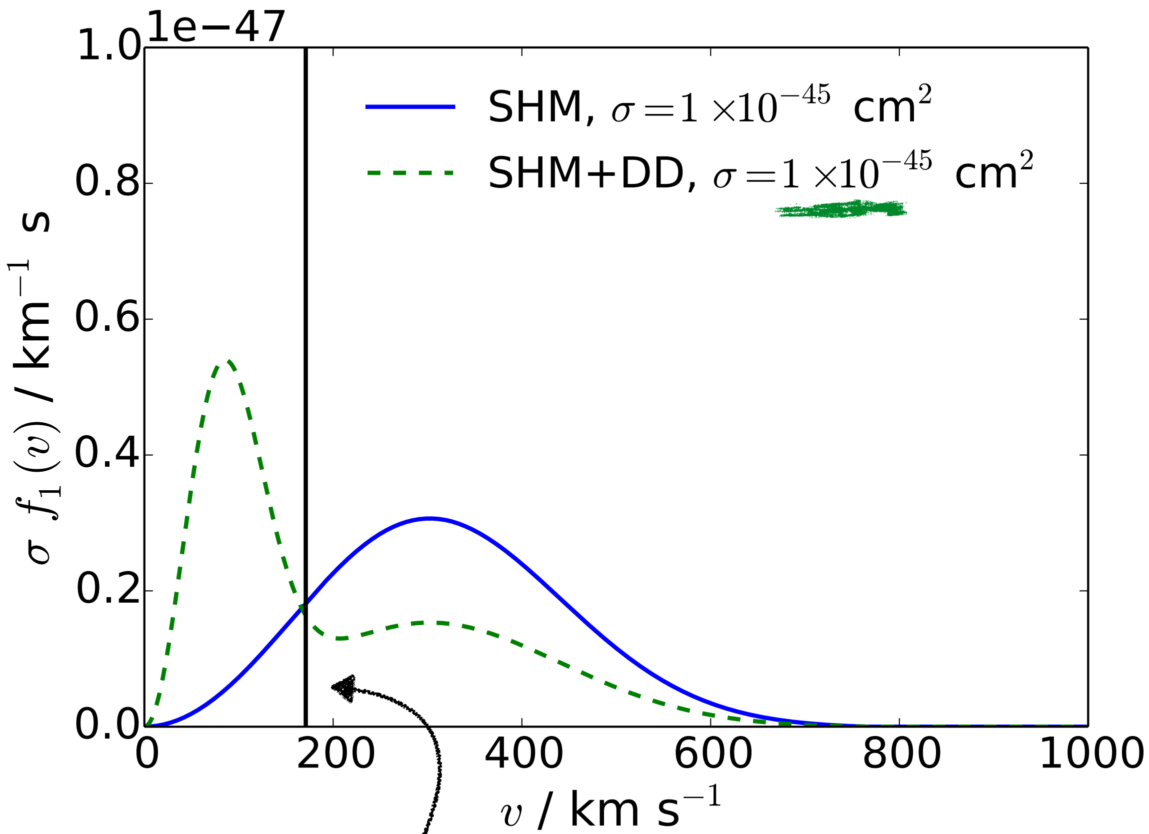


$$f(v) = \oint f(\mathbf{v})\,\mathrm{d}\Omega_v$$

Best fit distribution

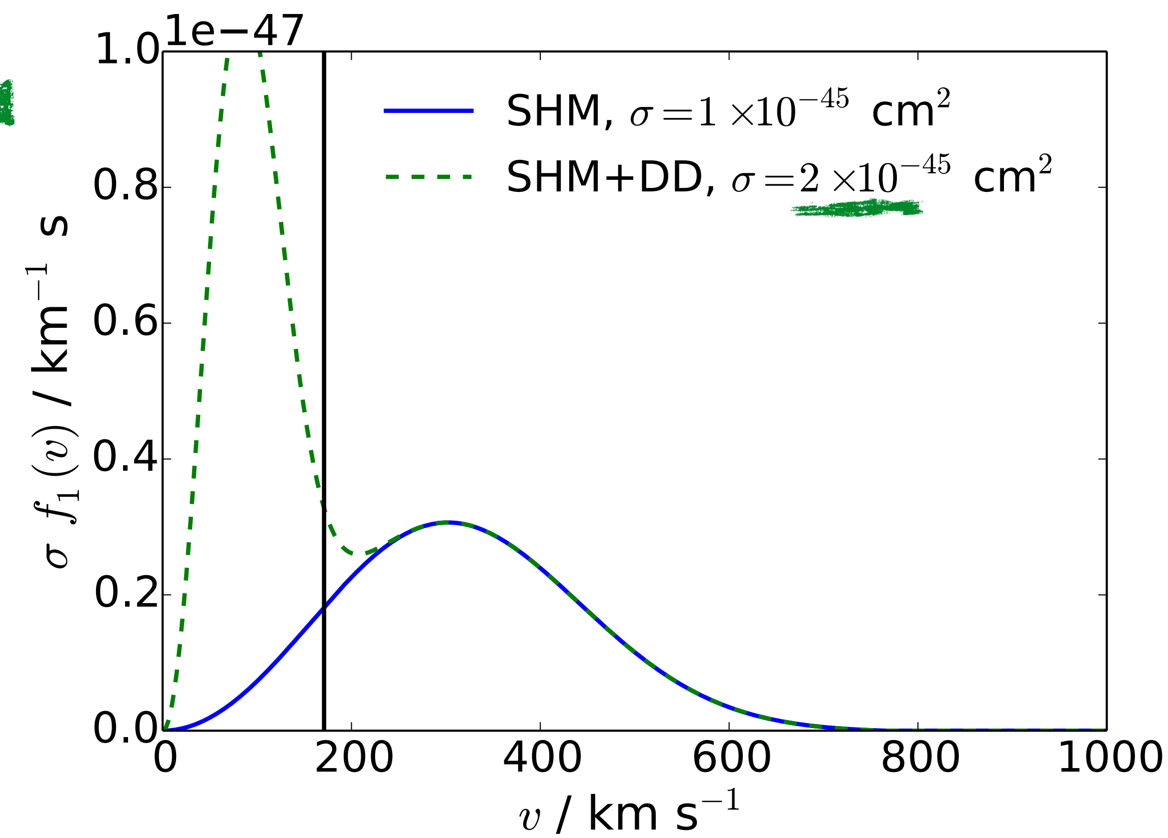
BJK, Fornasa, Green [1410.8051]

Cross section degeneracy



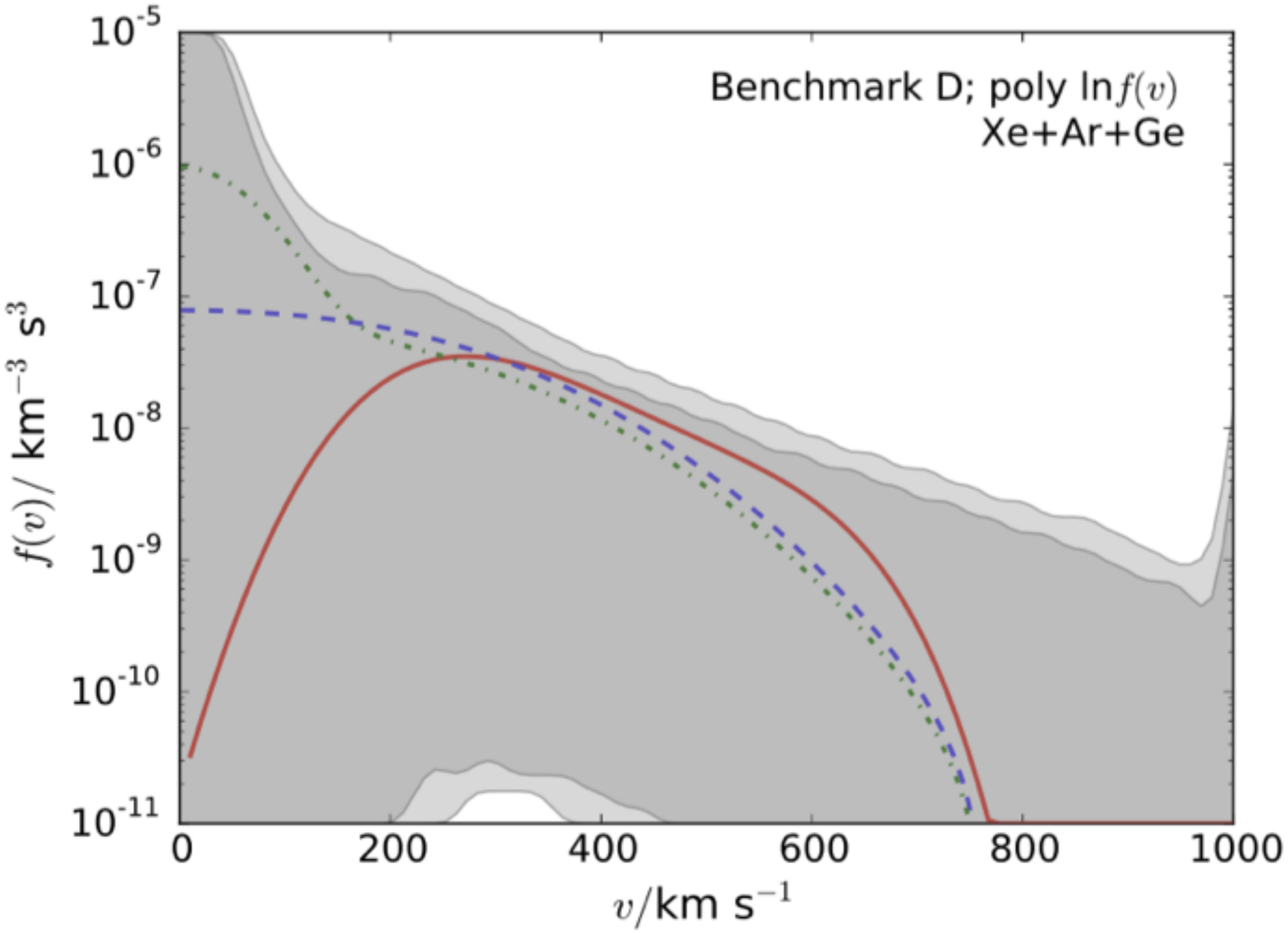
Minimum DM speed probed by a typical Xe experiment

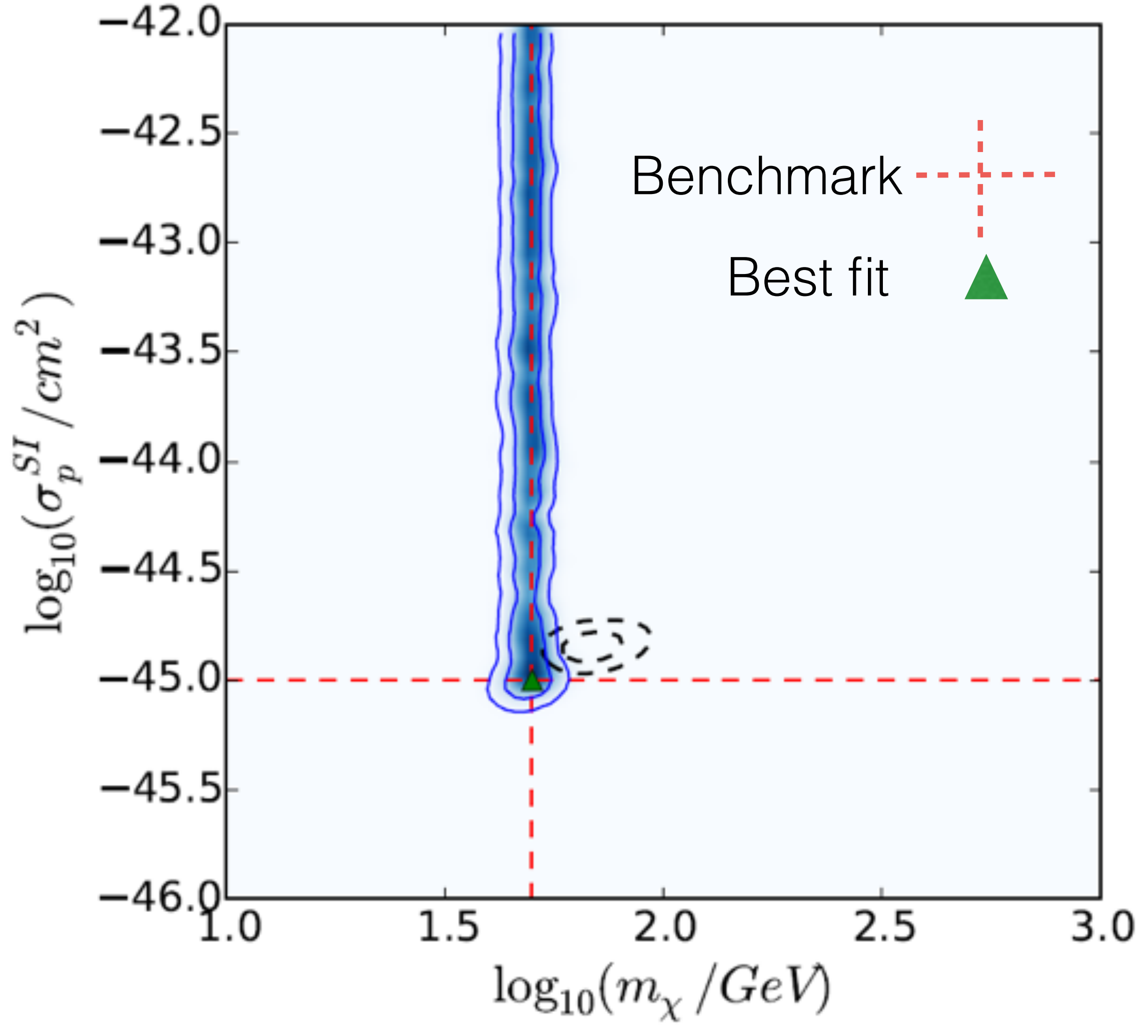
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sigma \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v}\,\mathrm{d}v$$



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

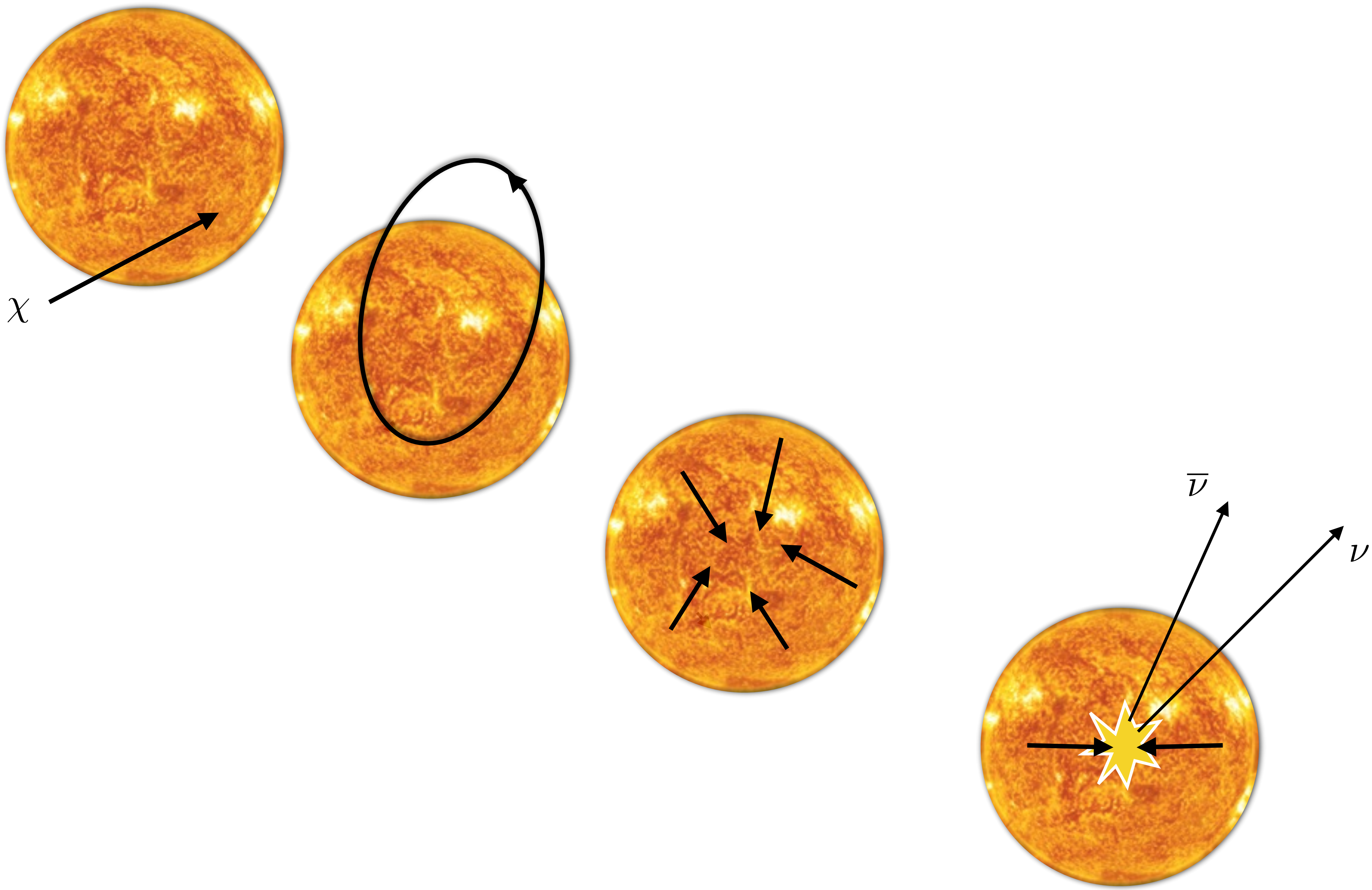
Cross section degeneracy





Neutrino telescopes

DM capture in the Sun



Incorporating IceCube

IceCube can detect the neutrinos from DM annihilation in the Sun

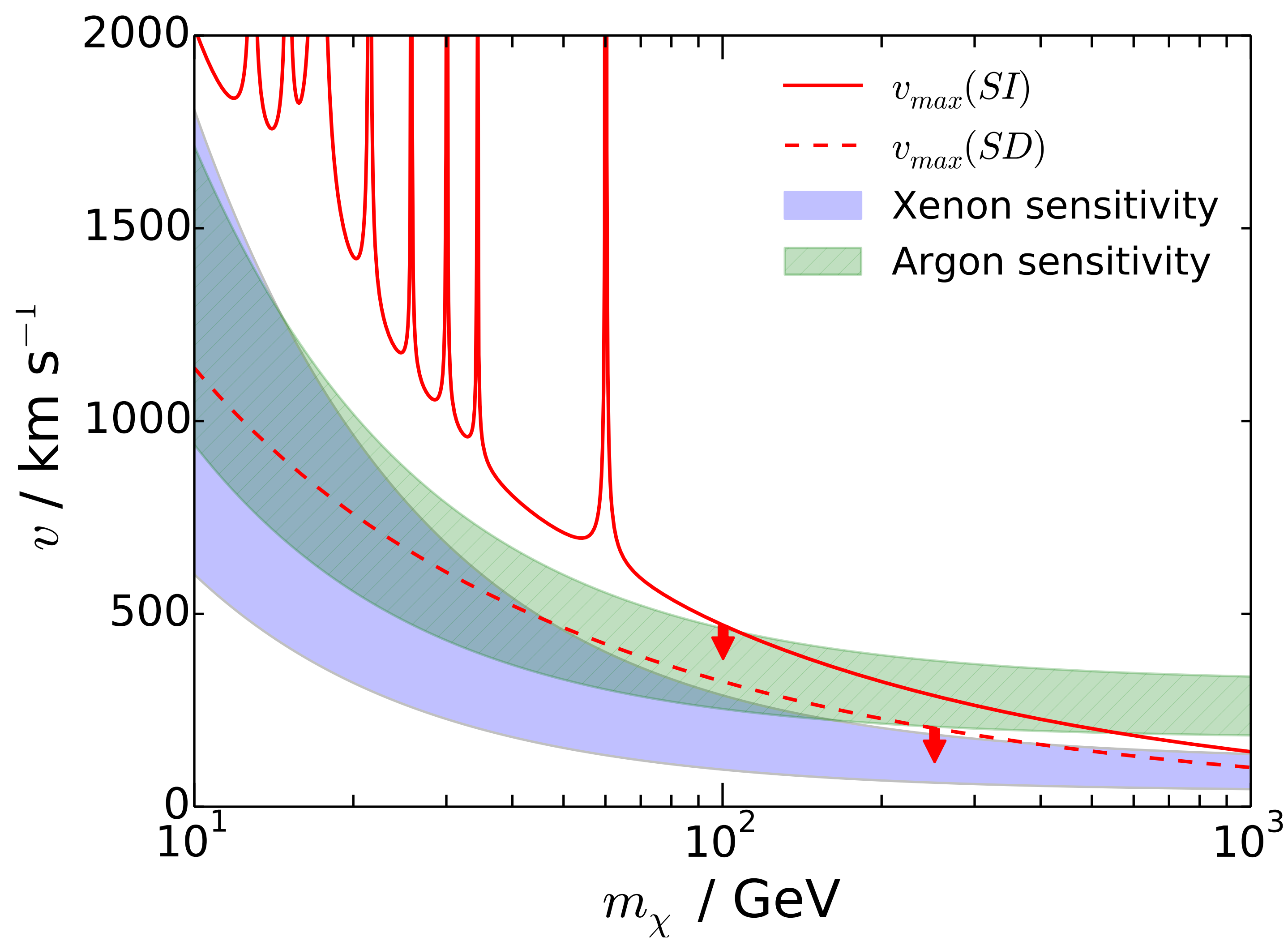
Assuming equilibrium in the Sun, rate is driven by solar capture of DM, which depends on the DM-nucleus scattering cross section

Crucially, only low energy DM particles are captured:

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

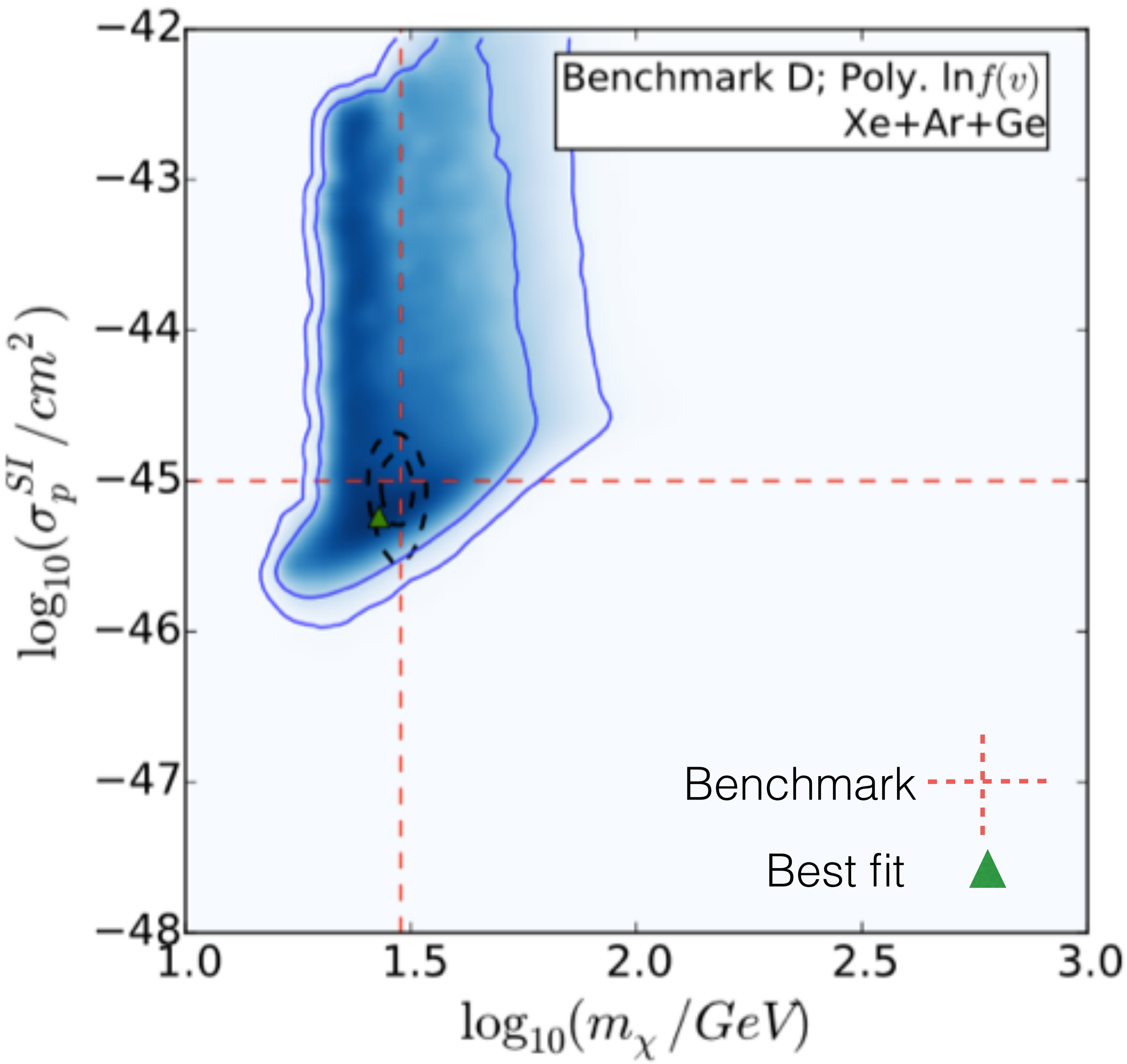
Gould (1991)

If we also had a signal in IceCube, what could we do then?



Reconstructions without IceCube

Mass and cross section reconstruction using three different direct detection experiments



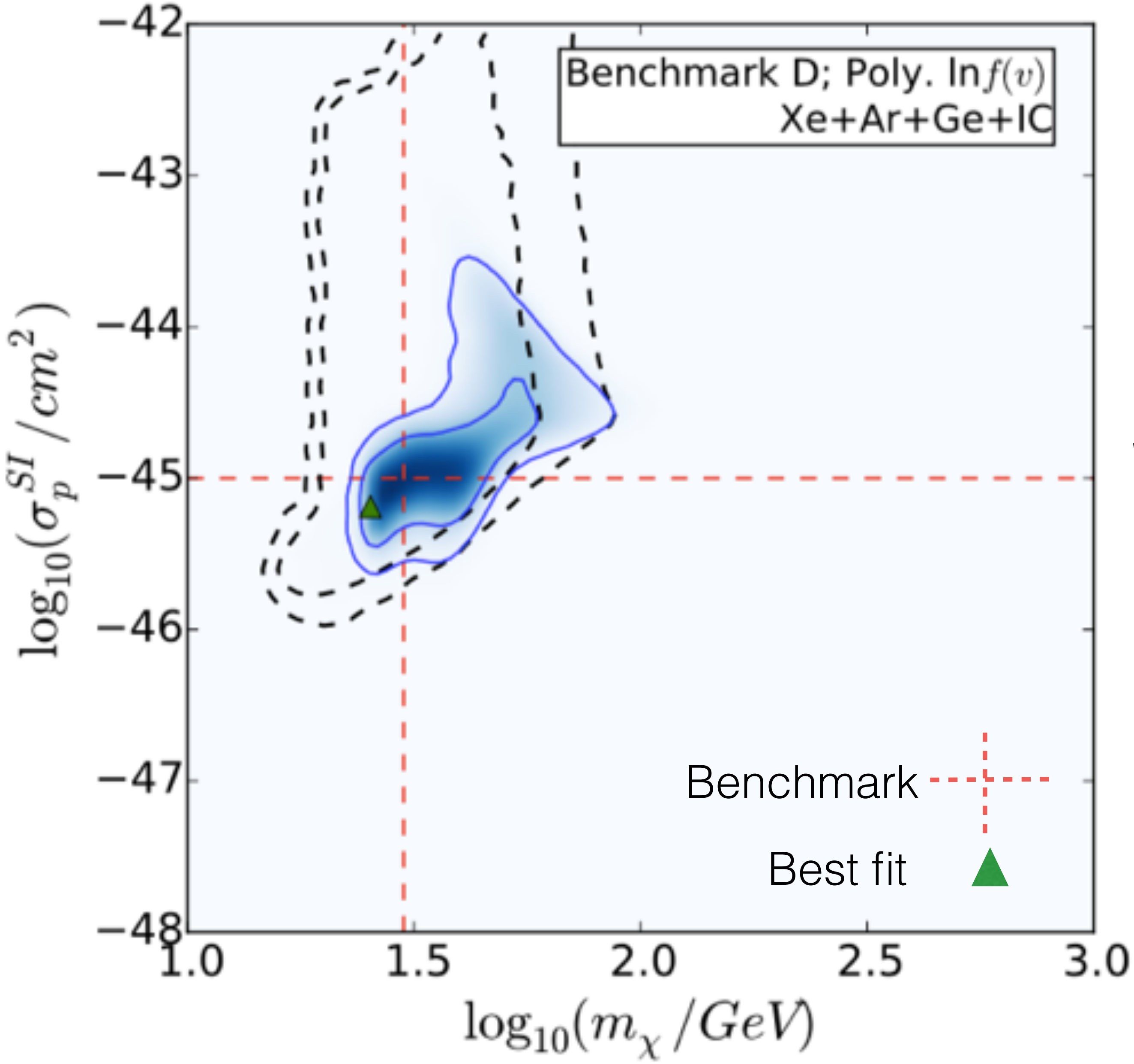
$m_\chi = 30\ \mathrm{GeV}$

SHM+DD distribution

BJK, Fornasa, Green [1410.8051]

Reconstructions *with* IceCube

Mass and cross section reconstruction using three different direct detection experiments and an IceCube signal



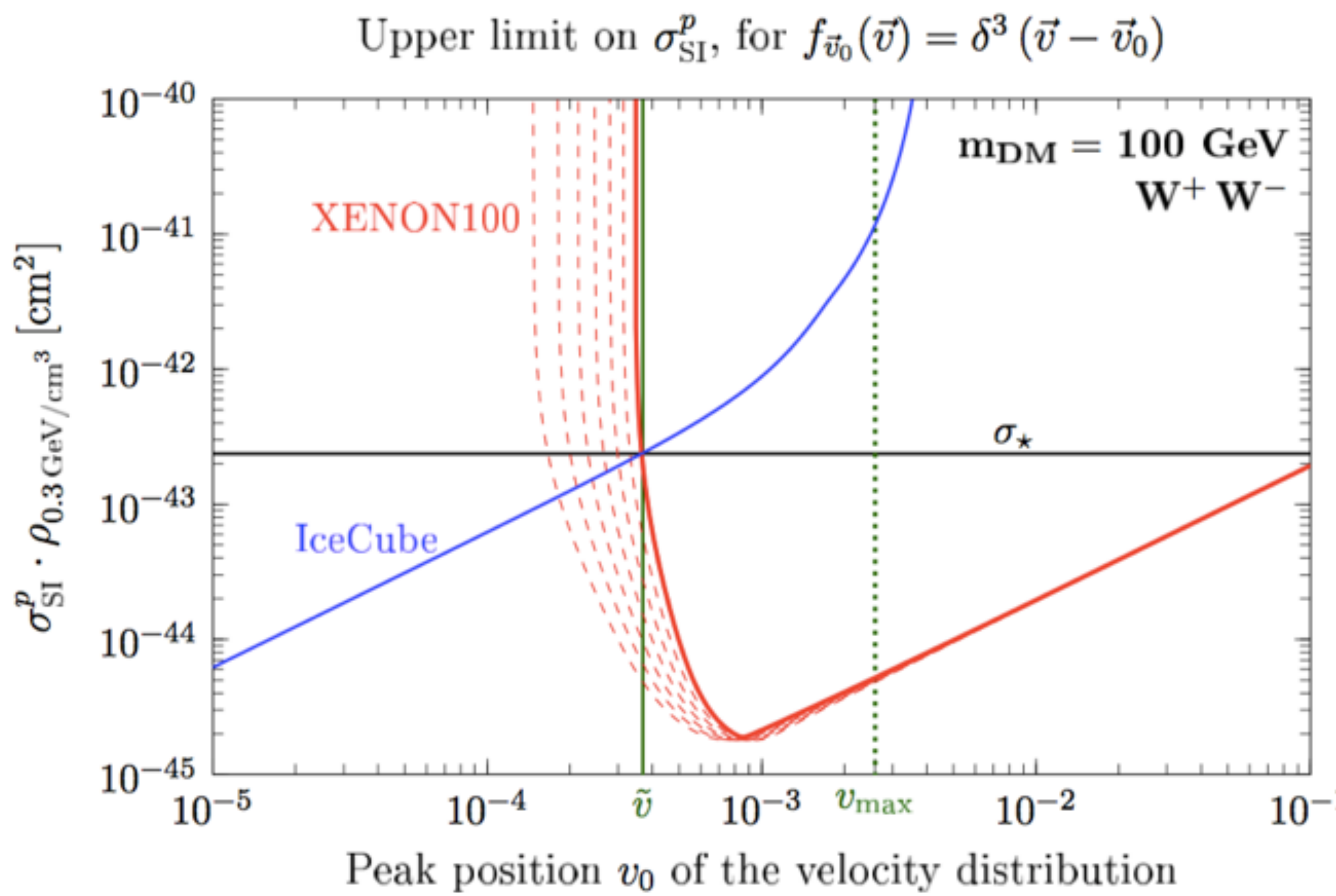
$m_\chi = 30$ GeV
SHM+DD distribution
Annihilation to $\nu_\mu \bar{\nu}_\mu$

Also works for other channels…almost everything produces neutrinos

BJK, Fornasa, Green [1410.8051]

Halo-independent constraints

Combining limits from DD and IceCube also allows you to place halo-independent constraints on the DM-nucleon cross section



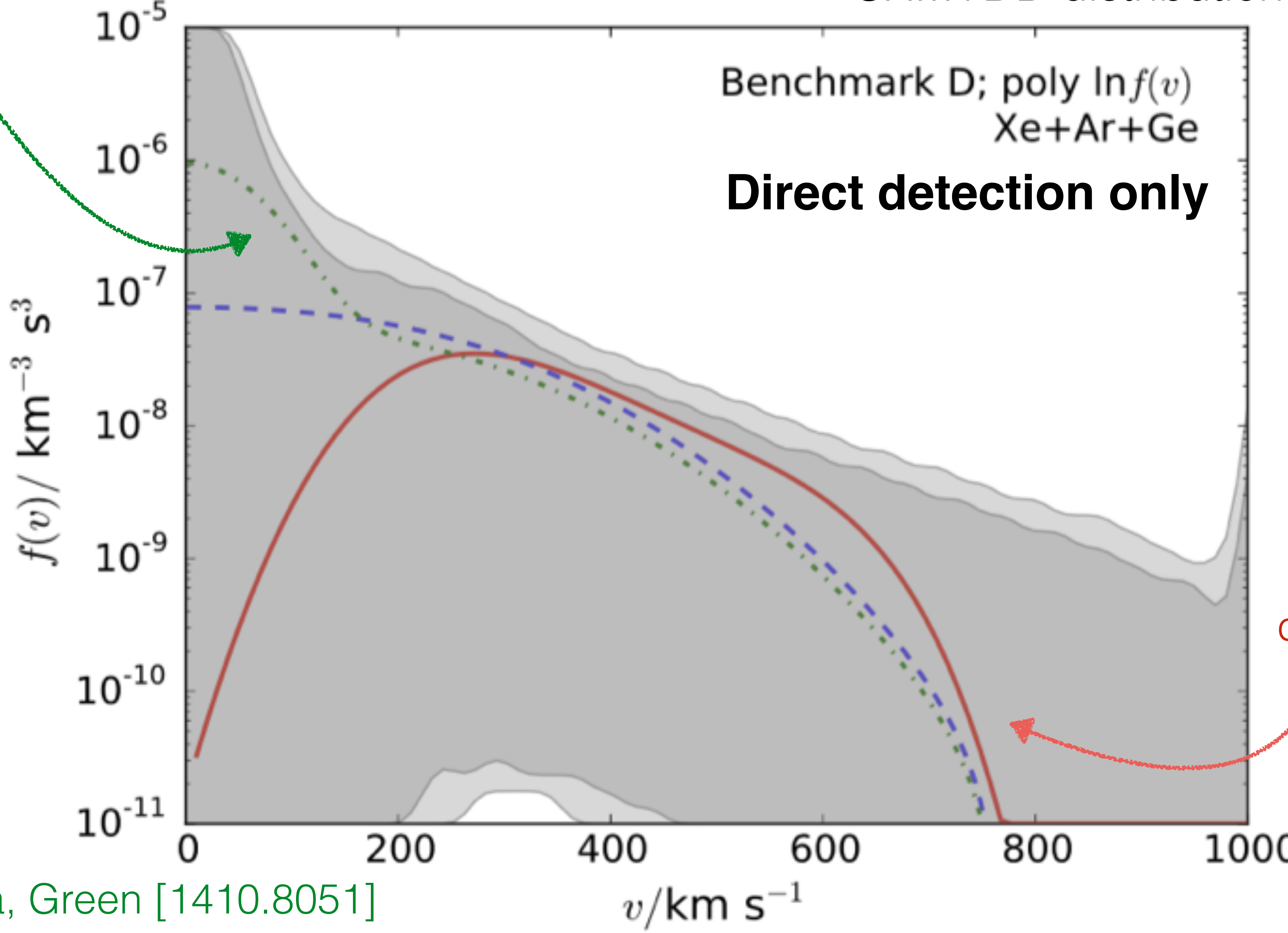
Ferrer et al. [1506.03386]

But see also Blennow et al. [1502.03342]

Reconstructing the speed distribution

$m_\chi = 30$ GeV
Annihilation to $\nu_\mu \bar{\nu}_\mu$
SHM+DD distribution

'True' speed distribution



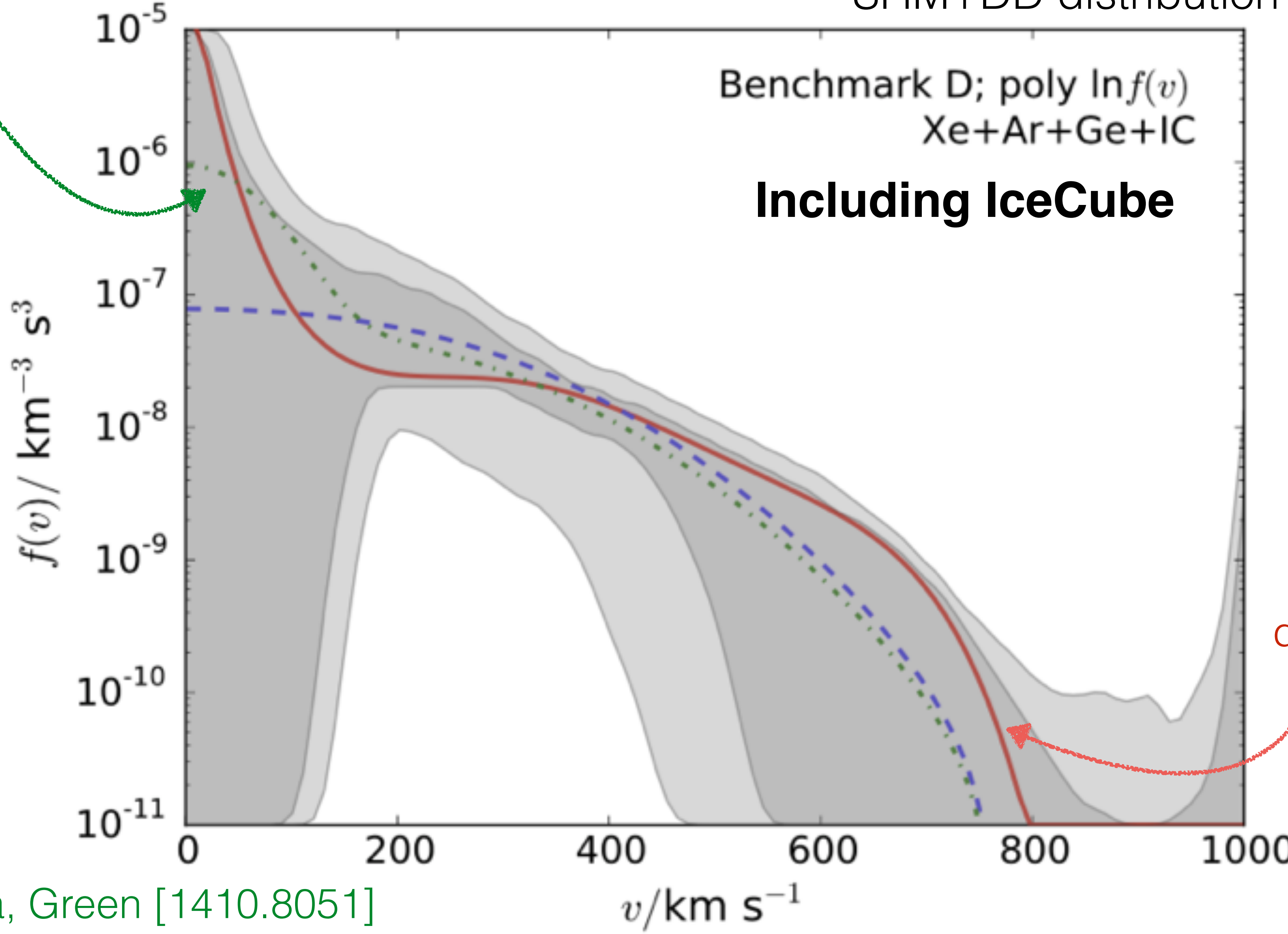
Best fit distribution

BJK, Fornasa, Green [1410.8051]

Reconstructing the speed distribution

$m_\chi = 30\ \mathrm{GeV}$
Annihilation to $\nu_\mu \bar{\nu}_\mu$
SHM+DD distribution

'True' speed distribution



Best fit distribution

BJK, Fornasa, Green [1410.8051]

Constraints improved, but still difficult to distinguish underlying distributions…

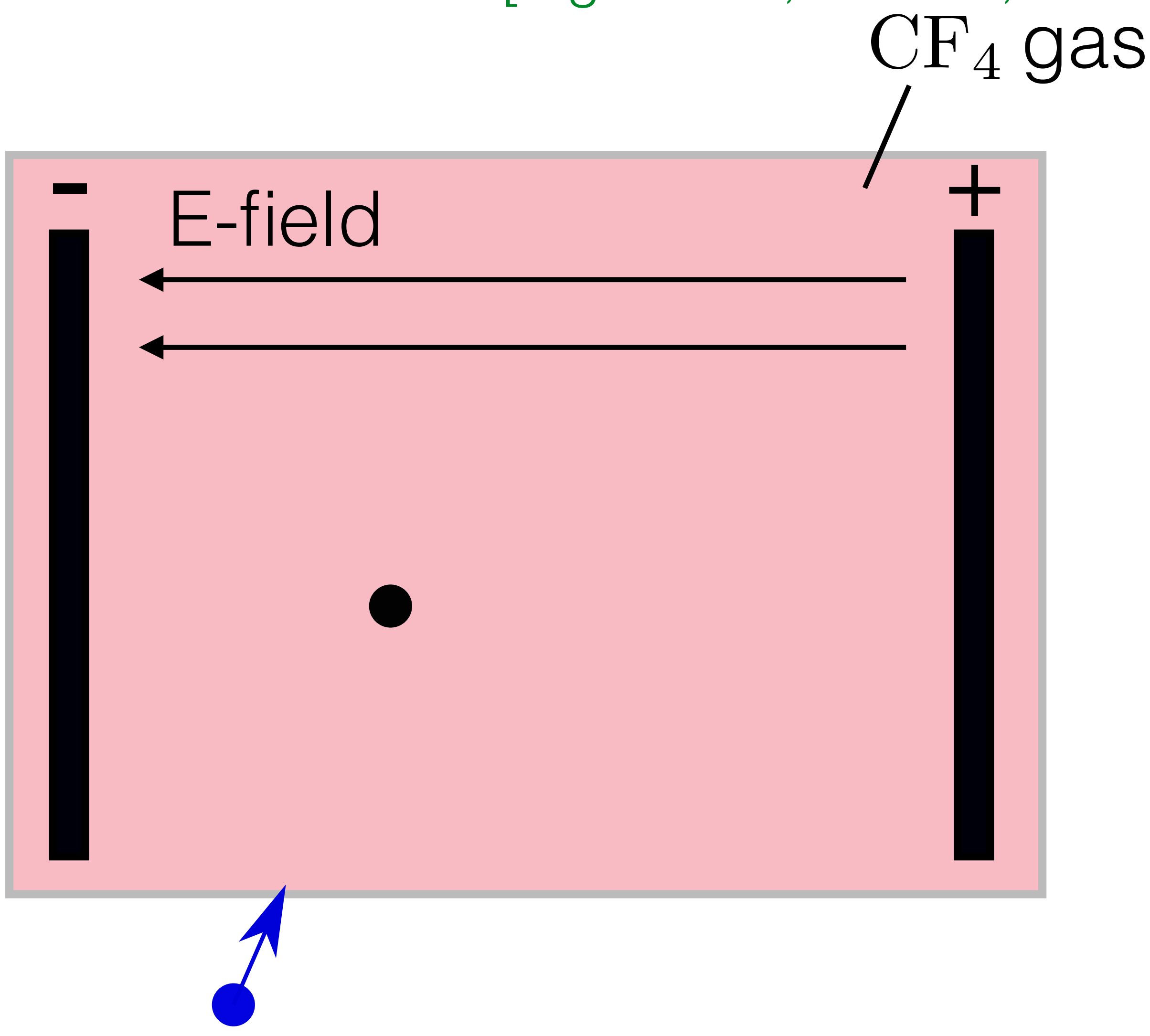
Directional Detection

Directional Detection

Try to measure both the energy *and the direction* of the recoil

Most mature technology is the gaseous Time Projection Chamber (TPC)

[e.g. DRIFT, MIMAC, DMTPC, NEWAGE, D3]

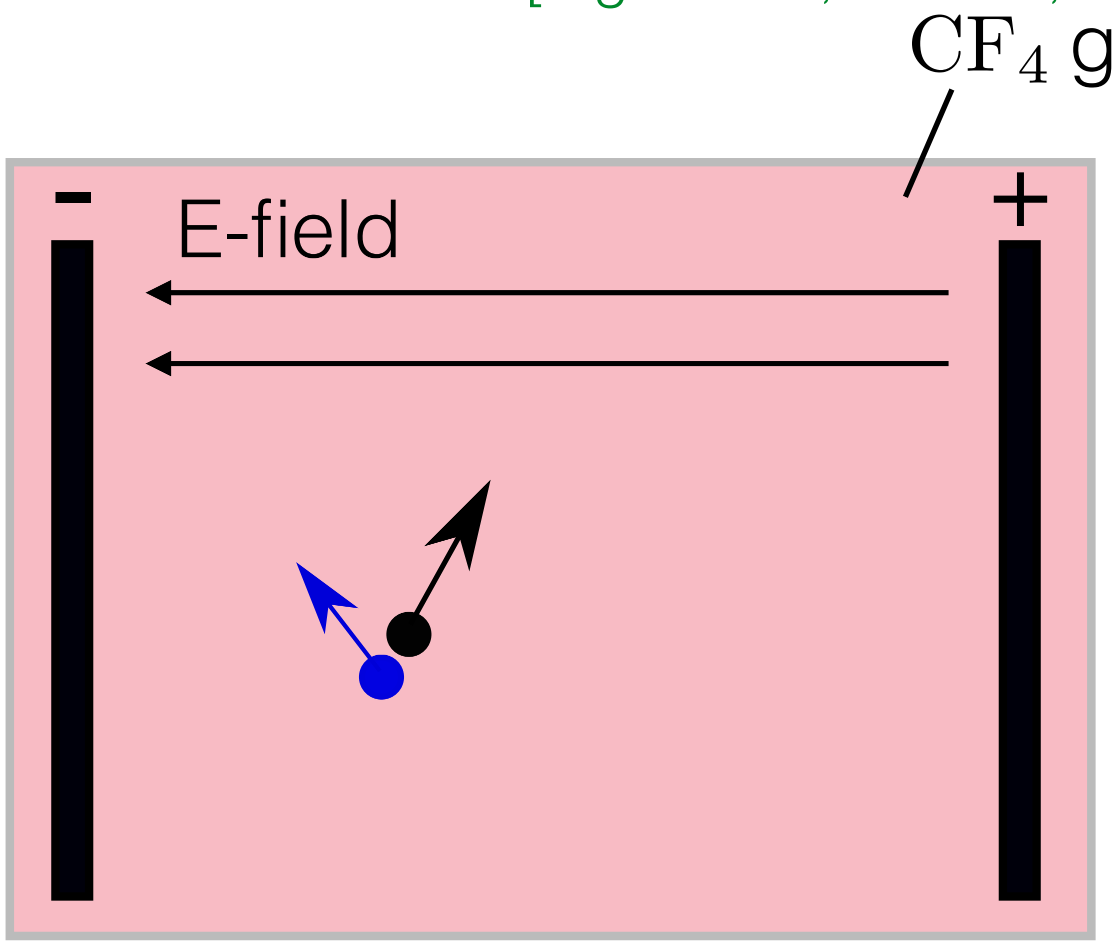


Directional Detection

Try to measure both the energy *and the direction* of the recoil

Most mature technology is the gaseous Time Projection Chamber (TPC)

[e.g. DRIFT, MIMAC, DMTPC, NEWAGE, D3]

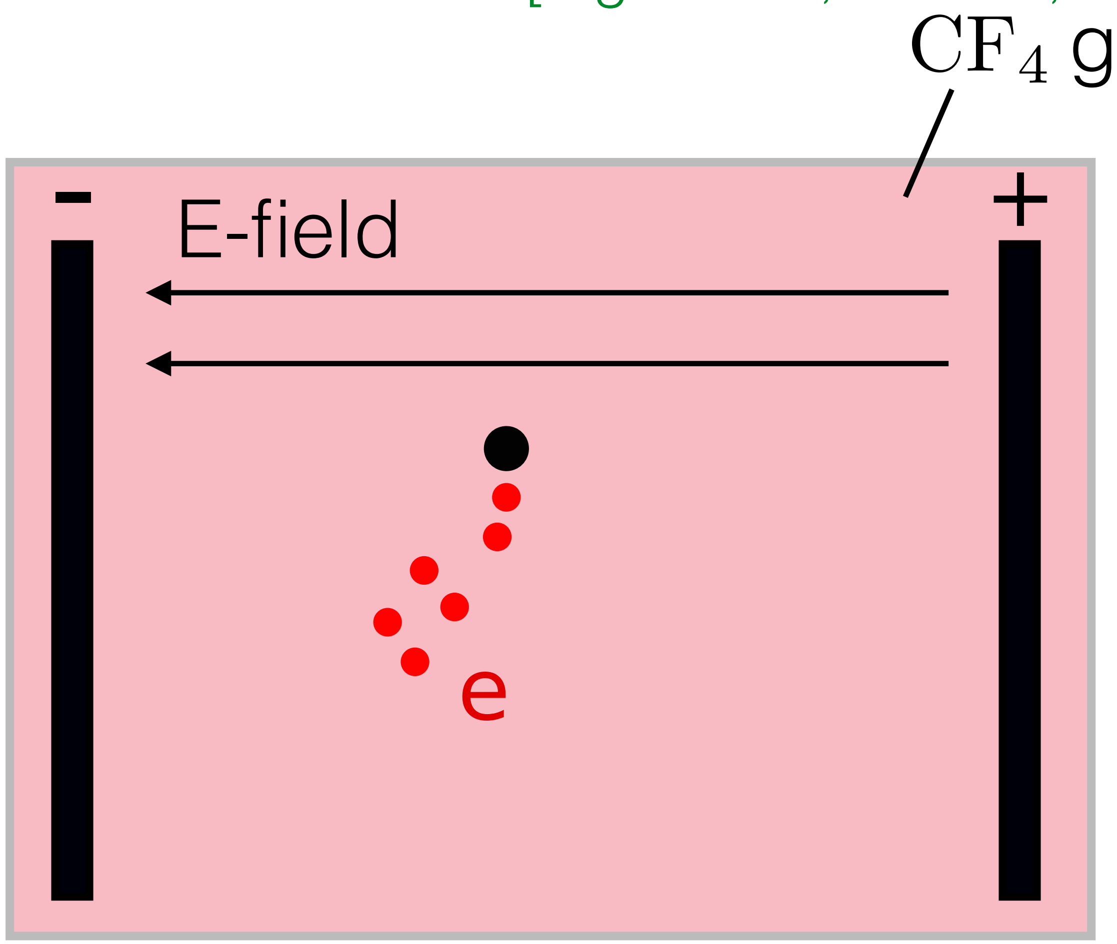


Directional Detection

Try to measure both the energy *and the direction* of the recoil

Most mature technology is the gaseous Time Projection Chamber (TPC)

[e.g. DRIFT, MIMAC, DMTPC, NEWAGE, D3]

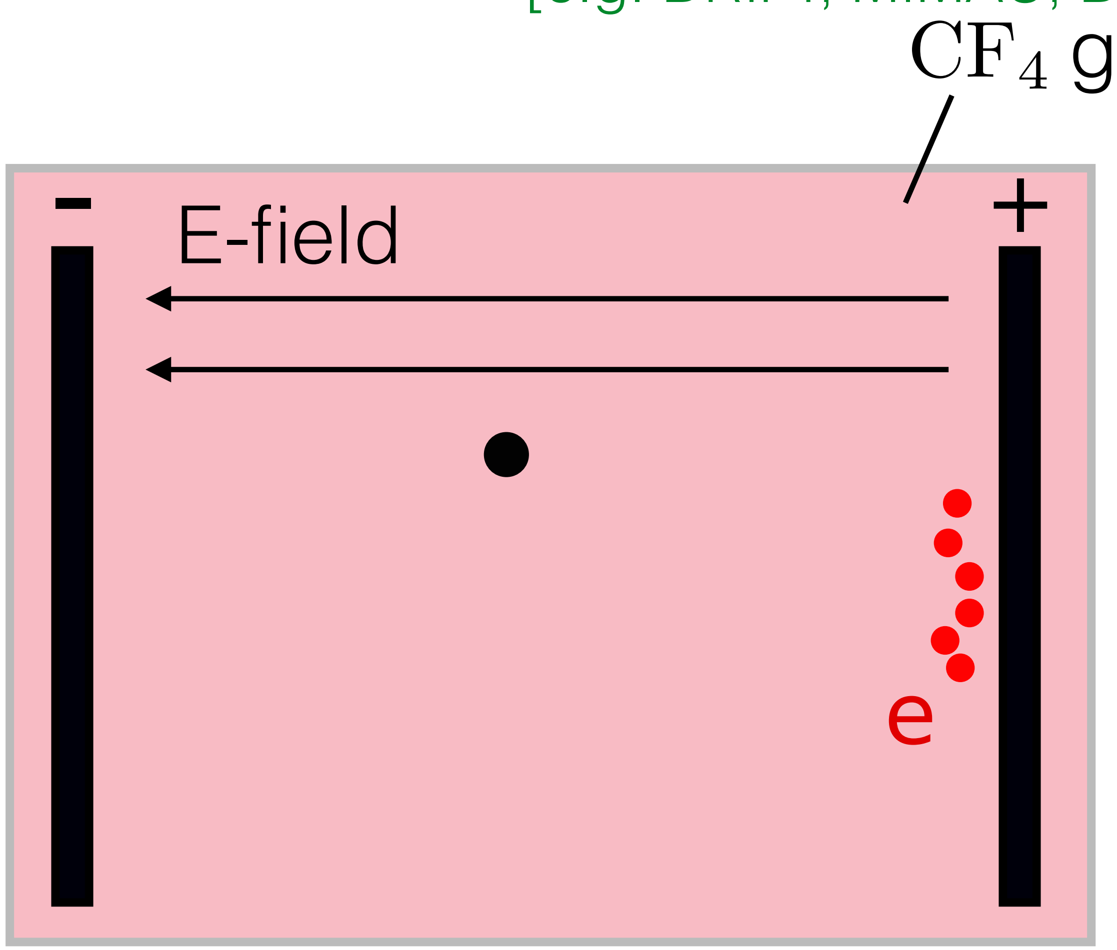


Directional Detection

Try to measure both the energy *and the direction* of the recoil

Most mature technology is the gaseous Time Projection Chamber (TPC)

[e.g. DRIFT, MIMAC, DMTPC, NEWAGE, D3]



Get x,y of track from distribution of electrons hitting anode

Get z of track from timing of electrons hitting anode

Directional recoil spectrum

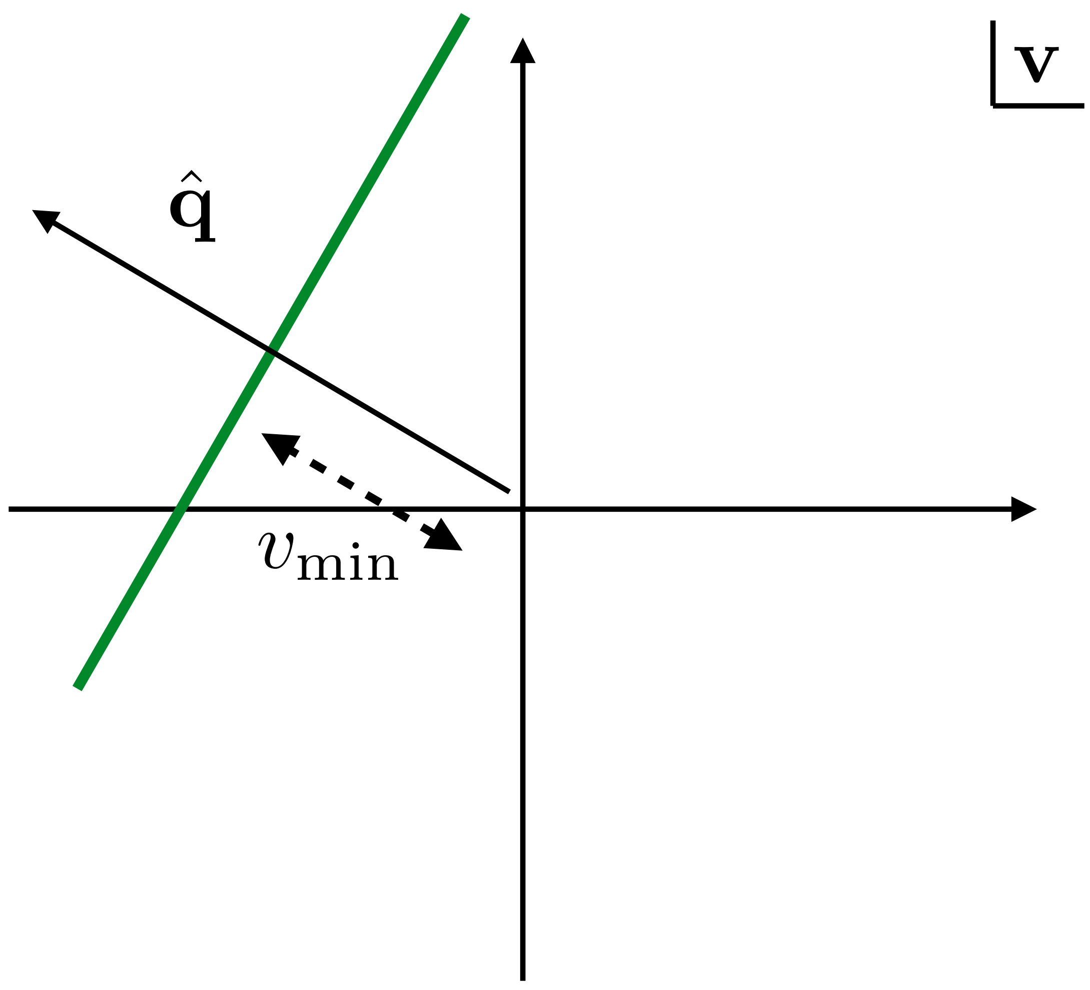
$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

Rate of recoils in direction $\hat{\mathbf{q}}$:

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

Radon Transform (RT):

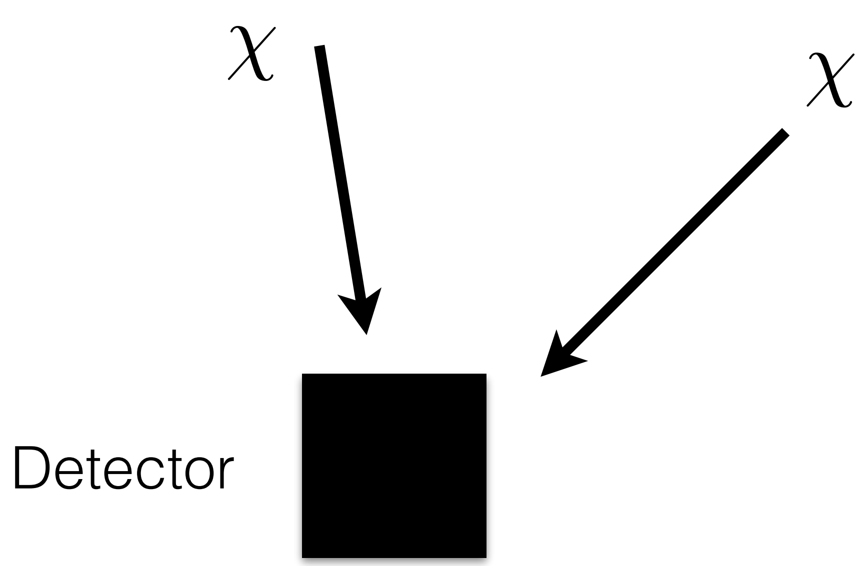
$$\hat{f}(v_{\min}, \hat{\mathbf{q}}) = \int_{\mathbb{R}^3} f(\mathbf{v}) \delta\left(\mathbf{v}\cdot\hat{\mathbf{q}} - v_{\min}\right) \mathrm{d}^3\mathbf{v}$$



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 $(\theta,\, \phi)$)!

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

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

One possible basis is spherical harmonics:

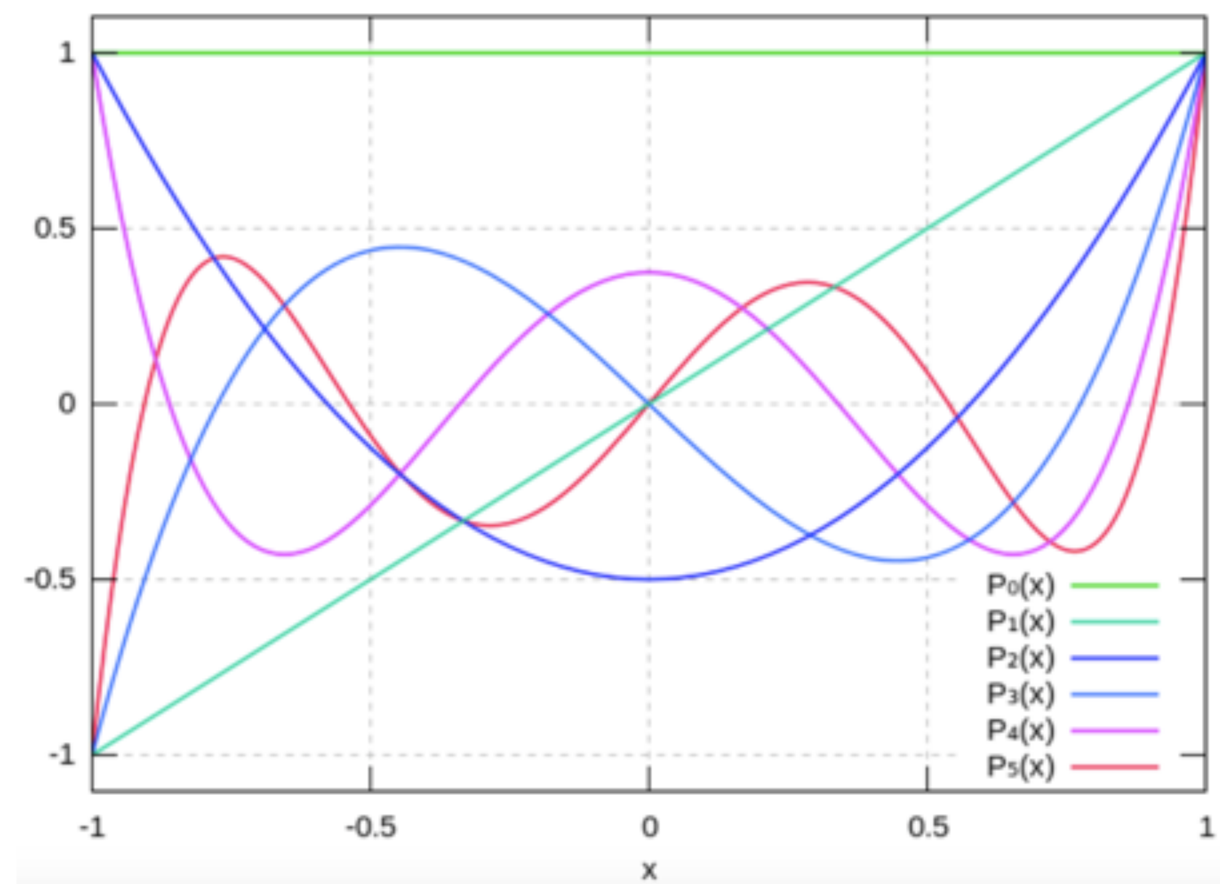
Alves et al. [1204.5487], Lee [1401.6179]

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

However, they are not strictly positive definite.

Physical distribution functions must be positive!

$Y_{l0}(\cos\theta)$



A discretised velocity distribution

Divide the velocity distribution into N = 3 angular bins…

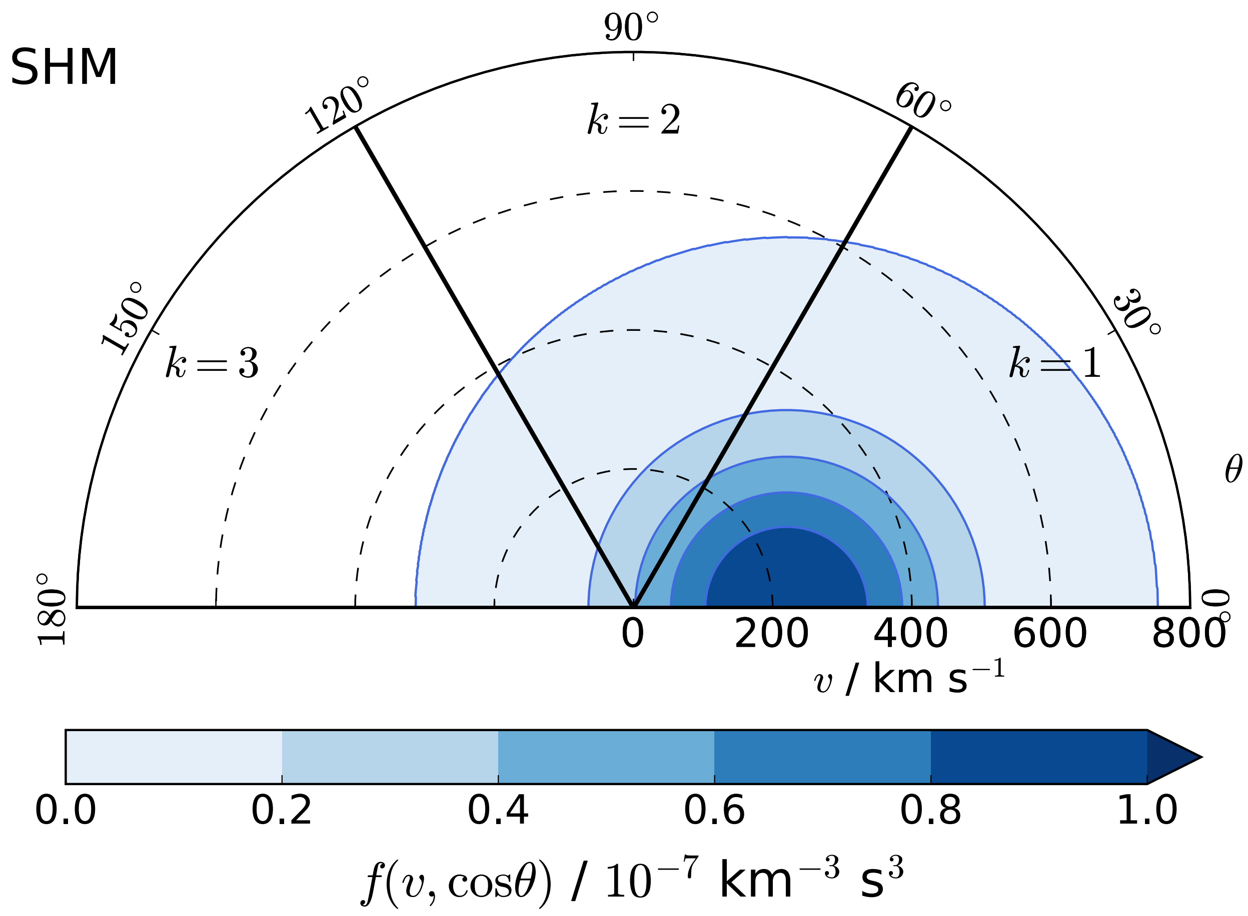
$$f(\mathbf{v}) = f(v, \cos\theta, \phi) = \begin{cases} f^1(v) & \text{for } \theta \in [0°, 60°] \\ f^2(v) & \text{for } \theta \in [60°, 120°] \\ f^3(v) & \text{for } \theta \in [120°, 180°] \end{cases}$$

BJK [1502.04224]

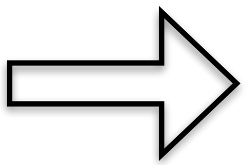
…and then parametrise $f^k(v)$ within each angular bin (using the parametrisation we've already discussed)…

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

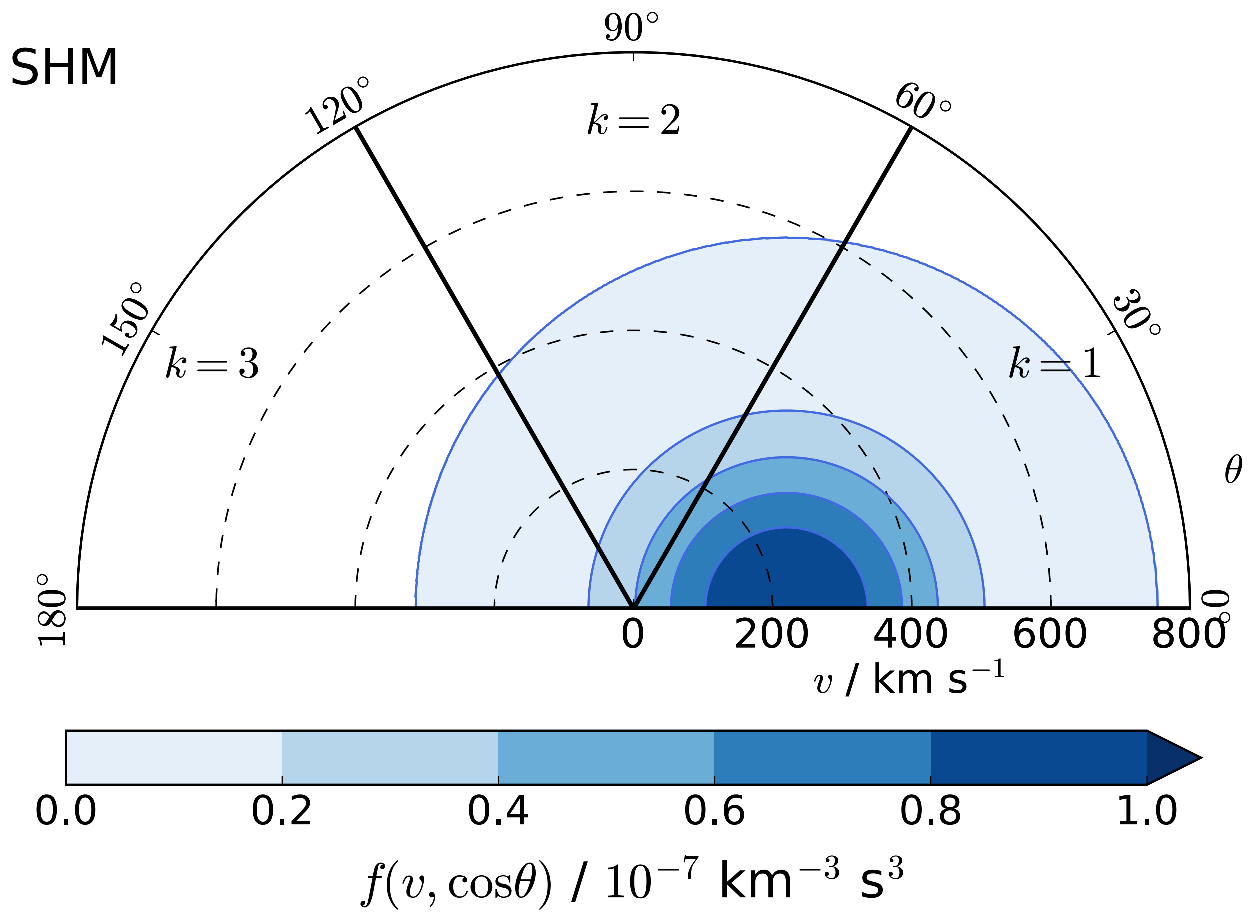
An example: the SHM



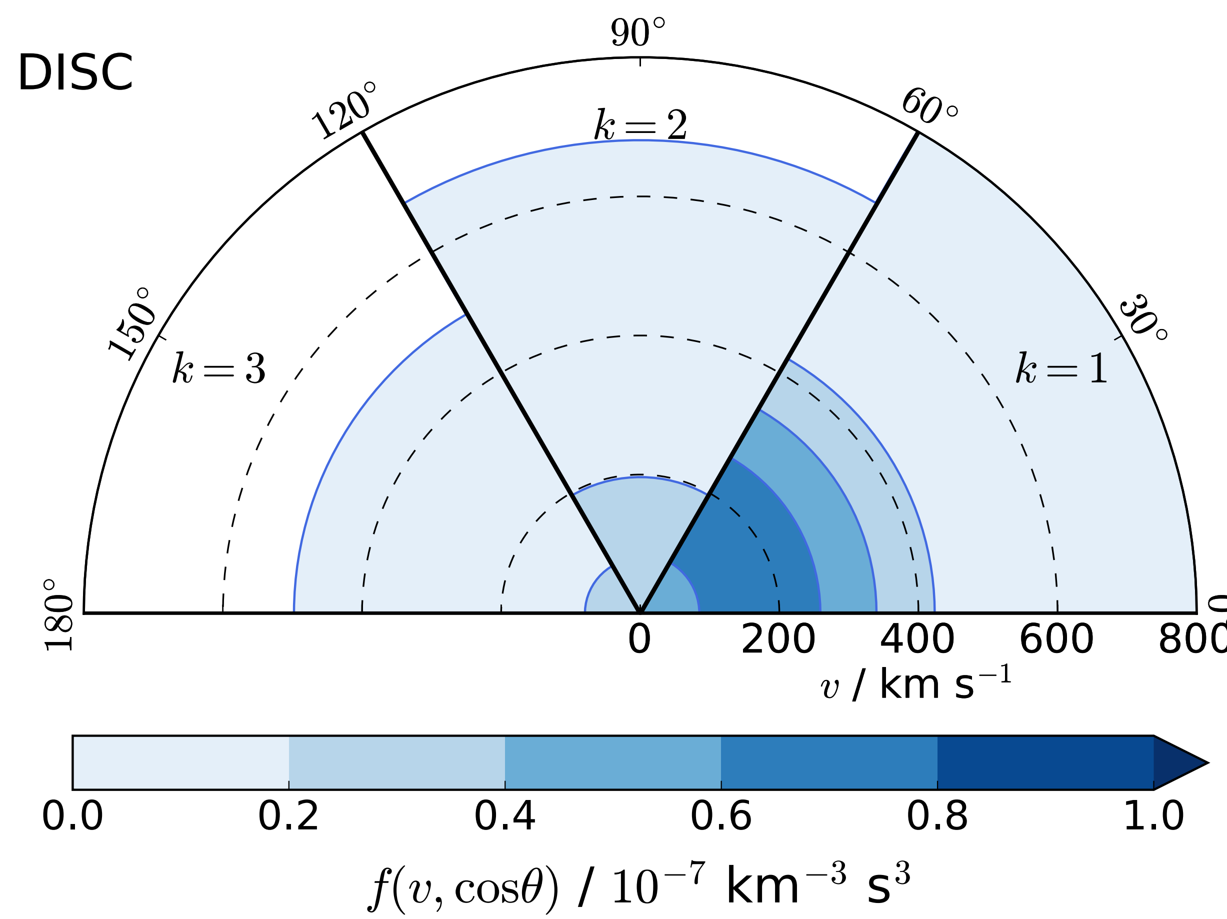
DM wind



An example: the SHM

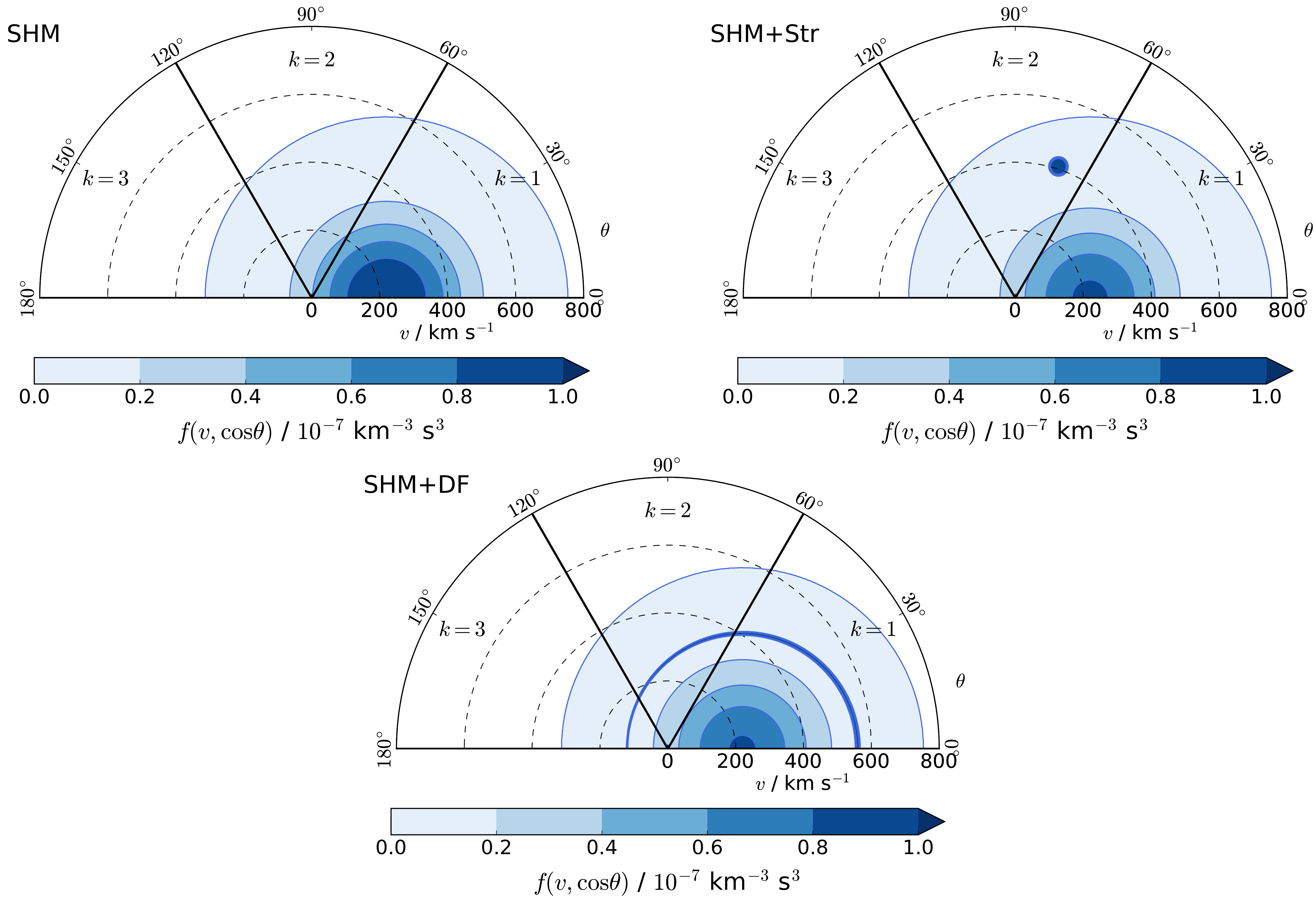


DM wind



But how well will this work?

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
SHM+DF

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

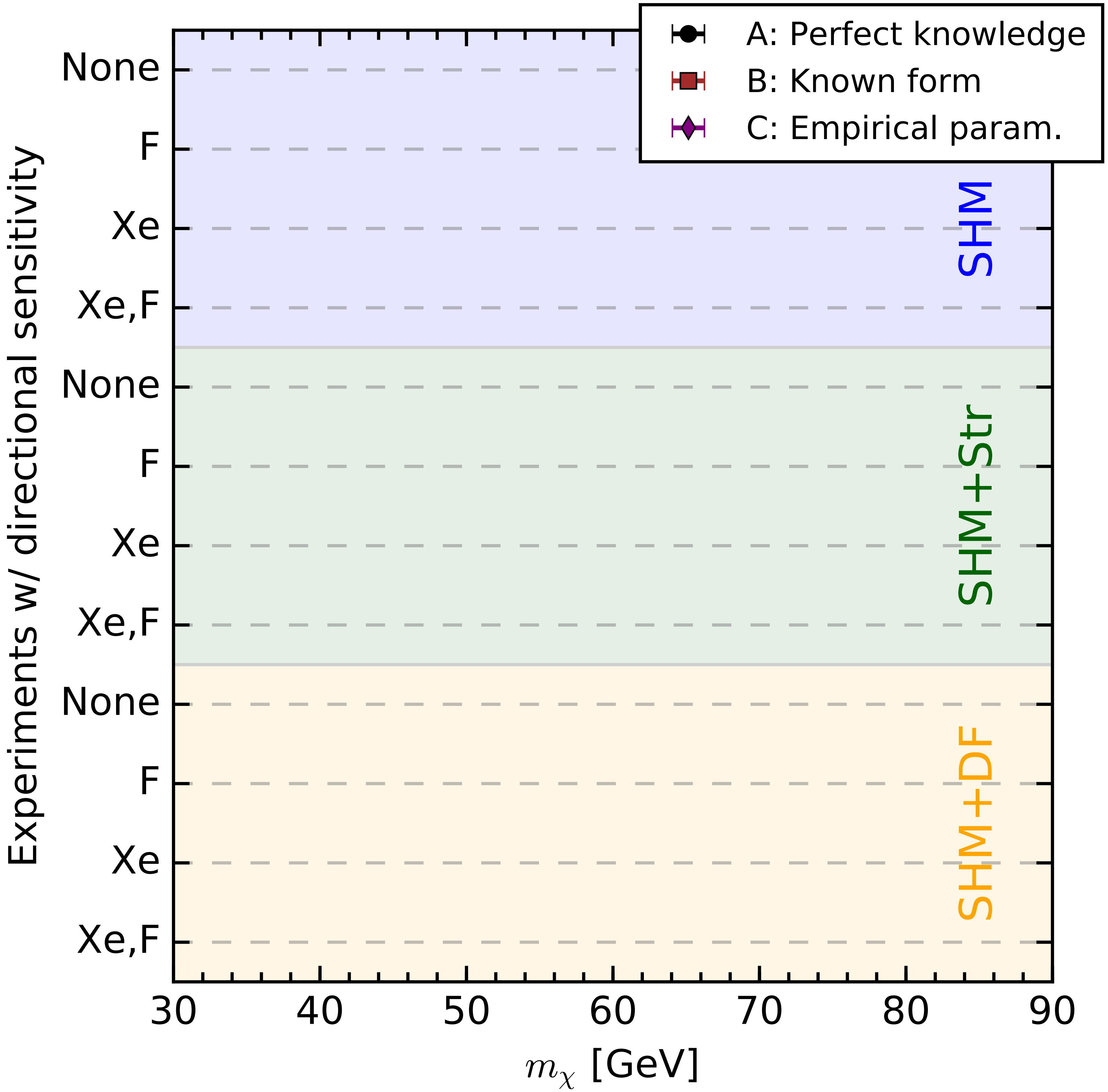
Method C:
Worst Case

Assume nothing about the underlying velocity distribution.

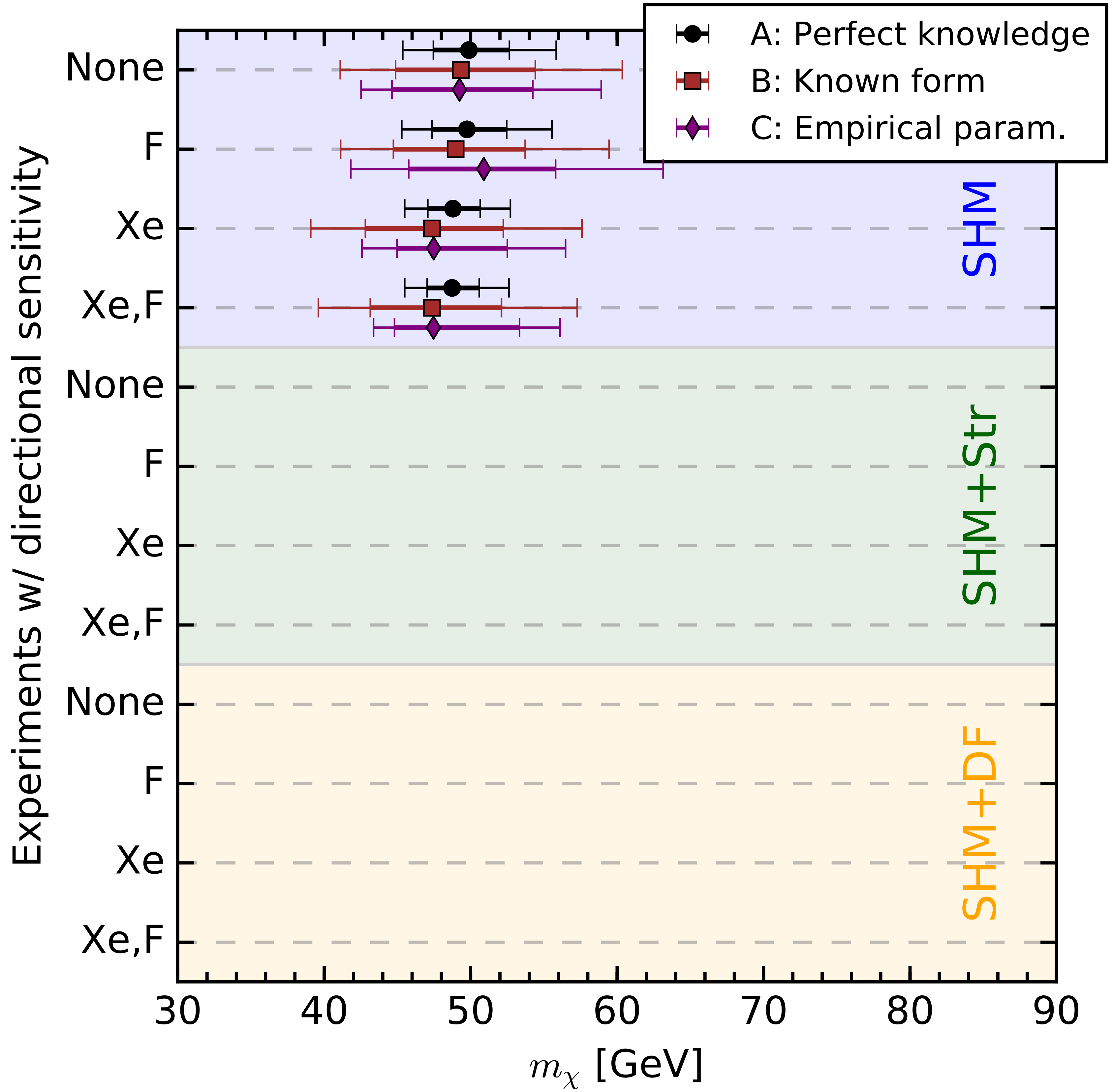
Fit m_χ, σ_p and empirical parameters

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

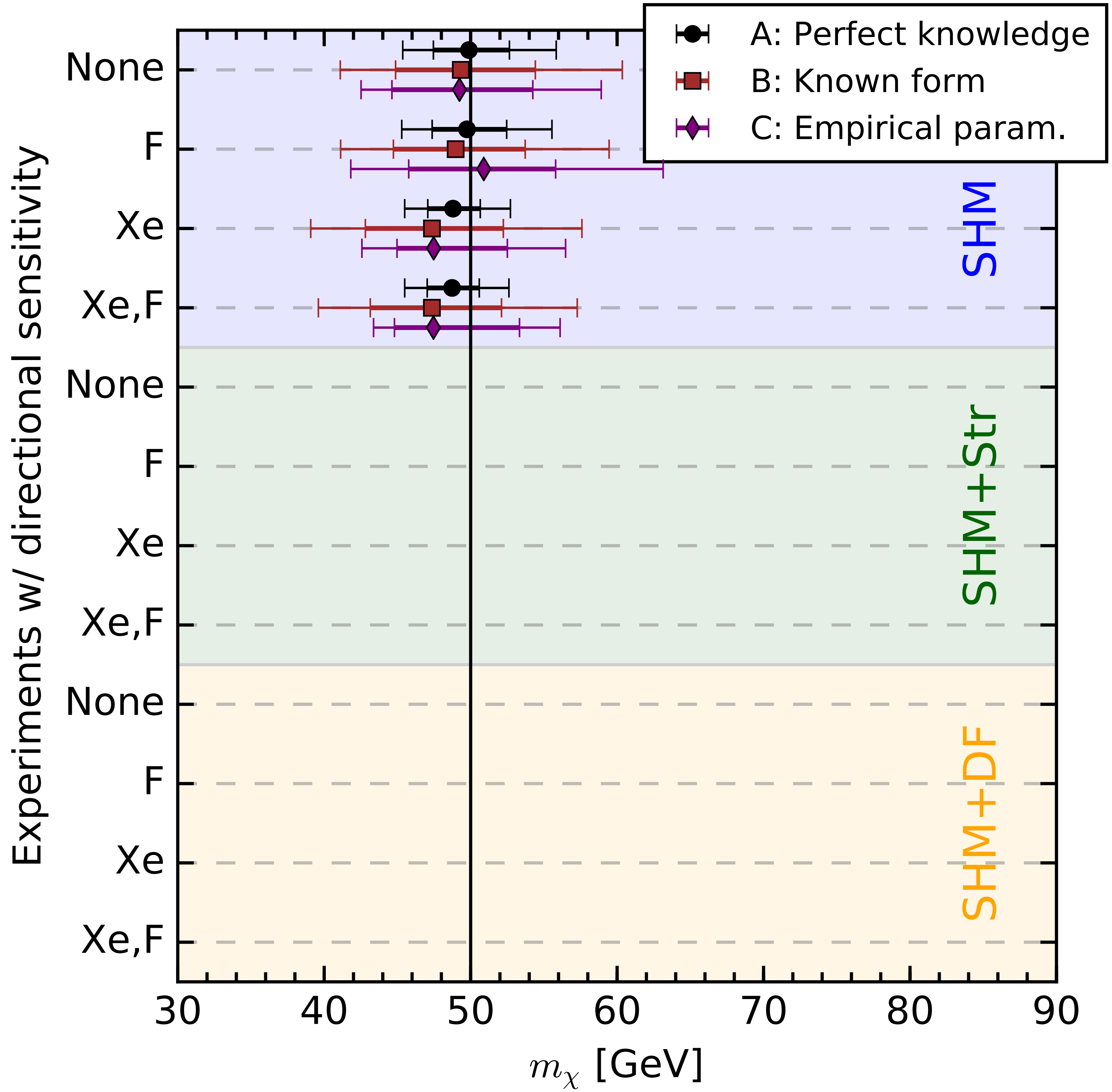
Reconstructing the DM mass



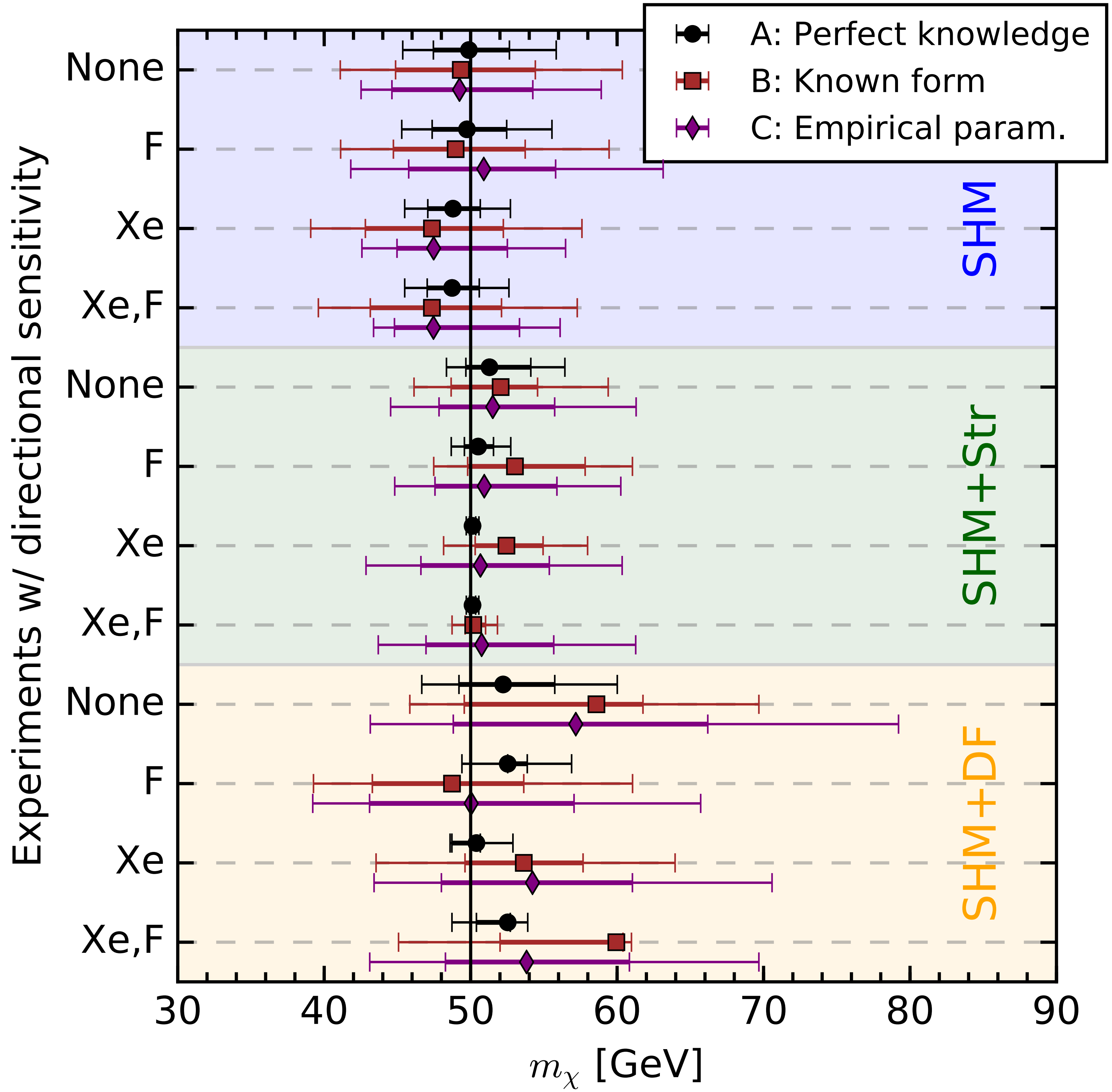
Reconstructing the DM mass



Reconstructing the DM mass



Reconstructing the DM mass



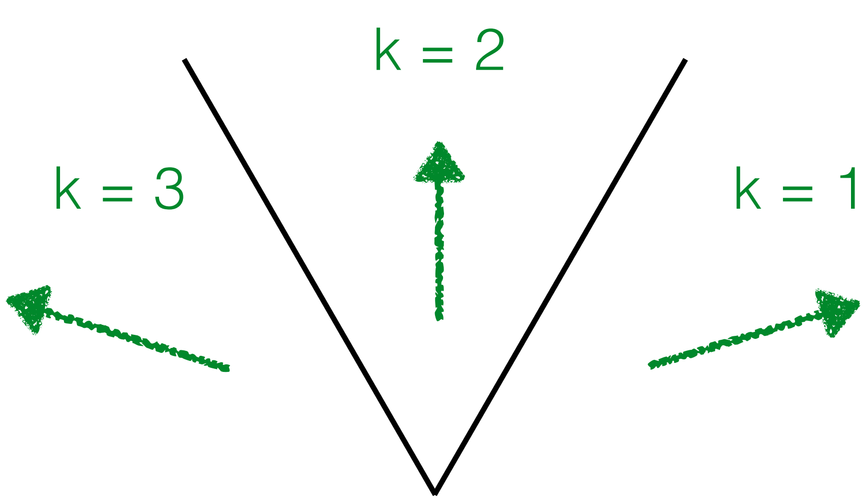
Shape of the velocity distribution

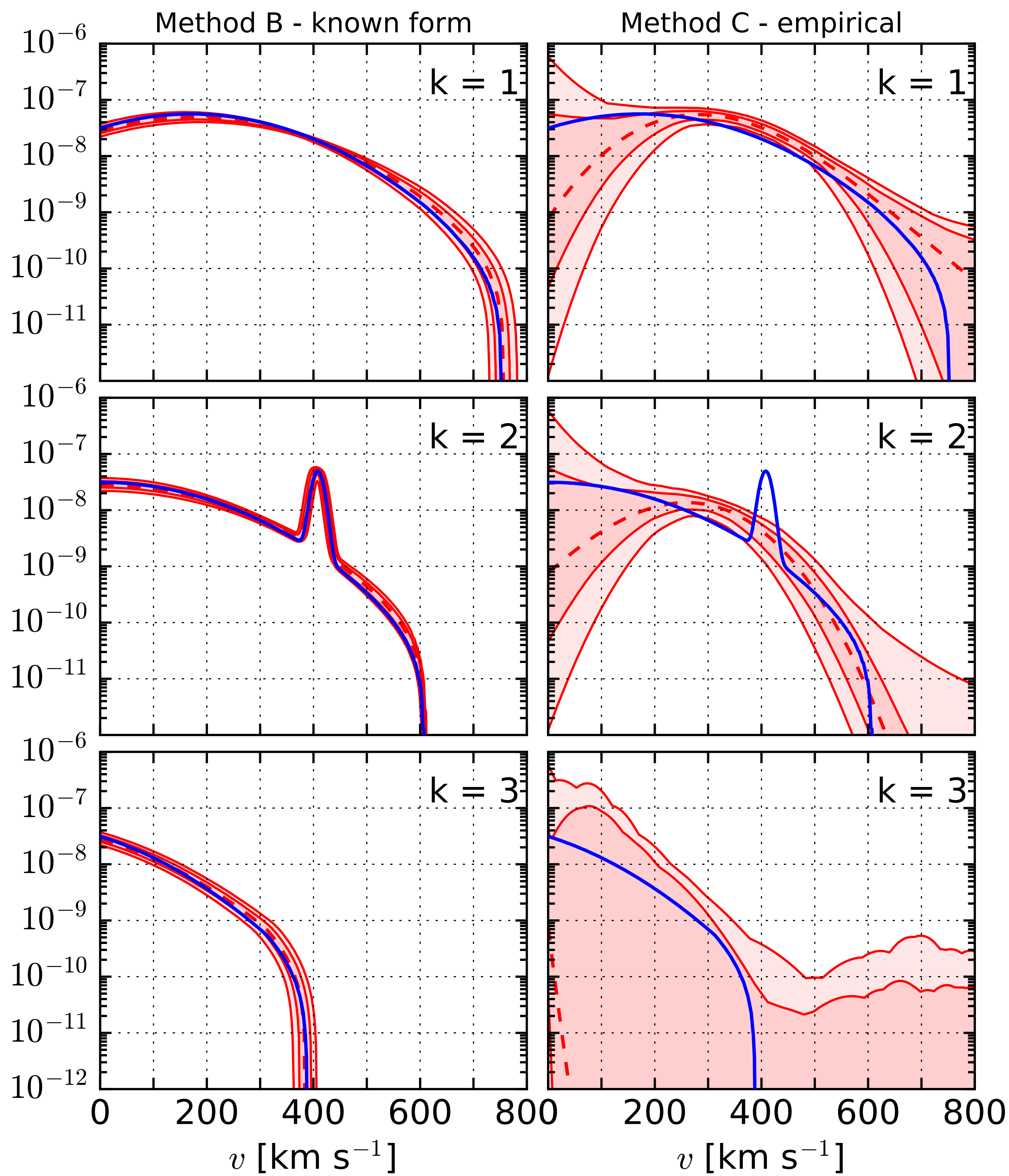
SHM+Stream distribution
with directional sensitivity in
Xe and F

'True' velocity distribution

Best fit distribution

(+68% and 95% intervals)





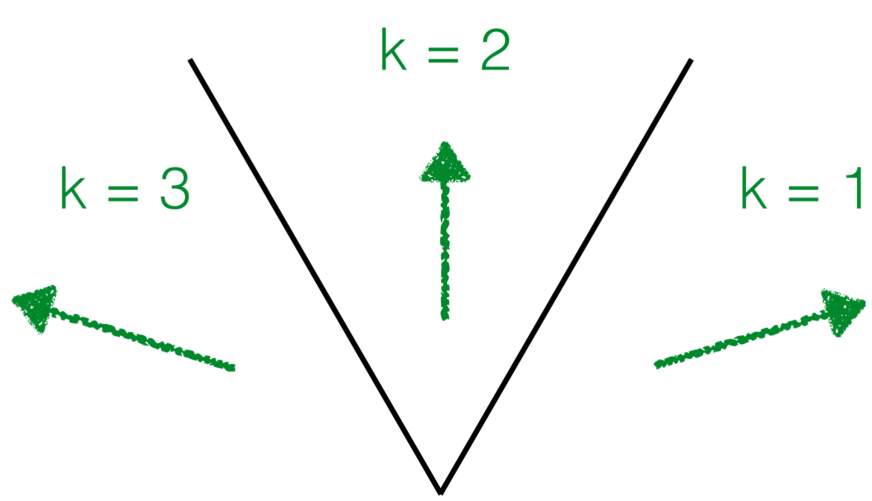
Shape of the velocity distribution

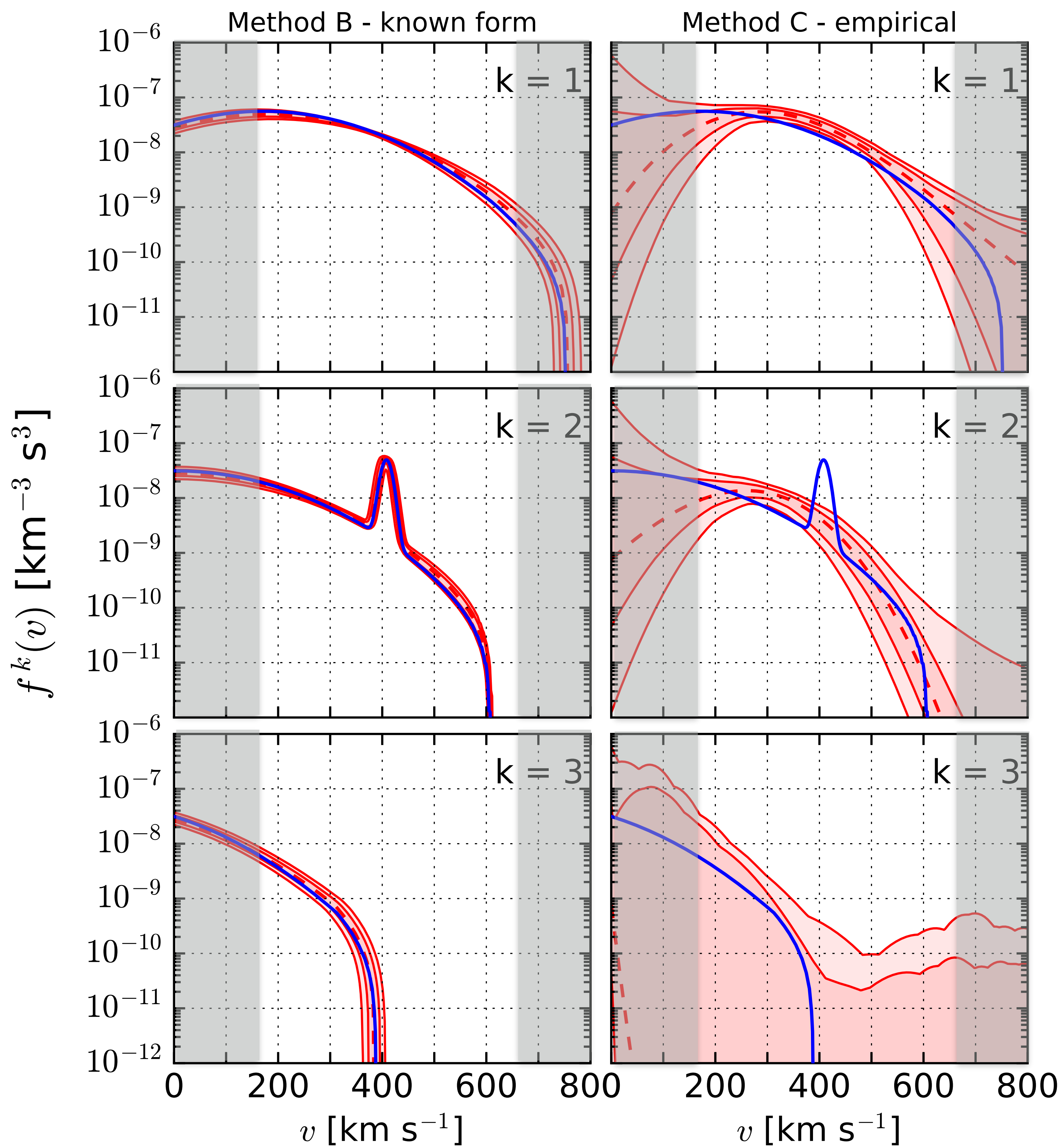
SHM+Stream distribution with directional sensitivity in Xe and F

'True' velocity distribution

Best fit distribution

(+68% and 95% intervals)



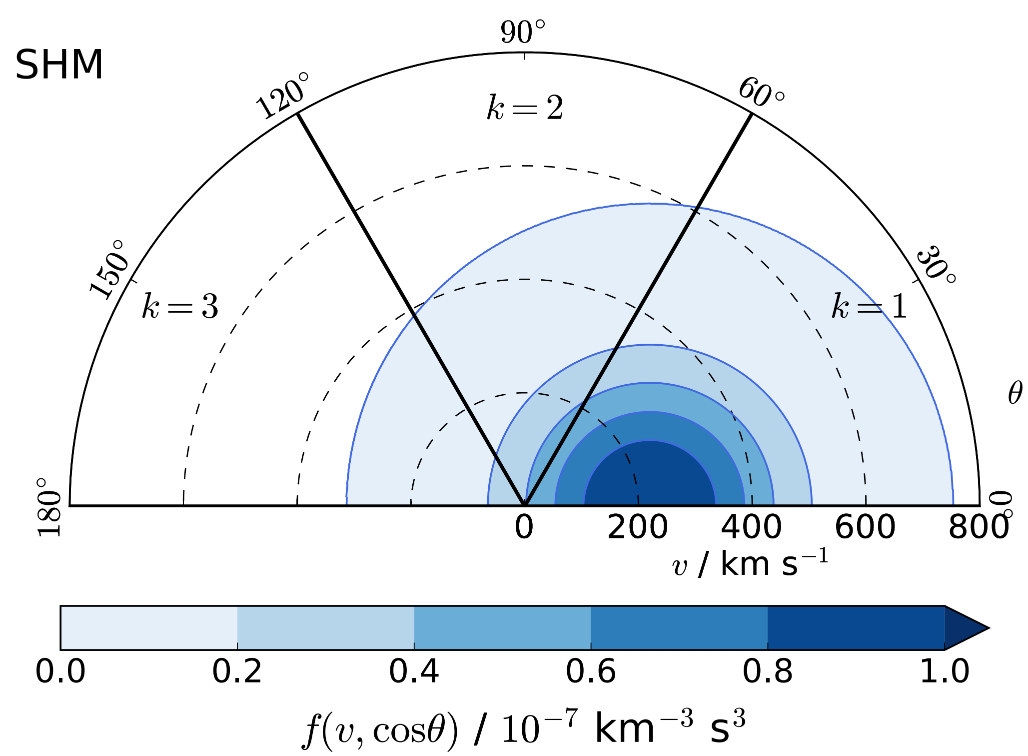


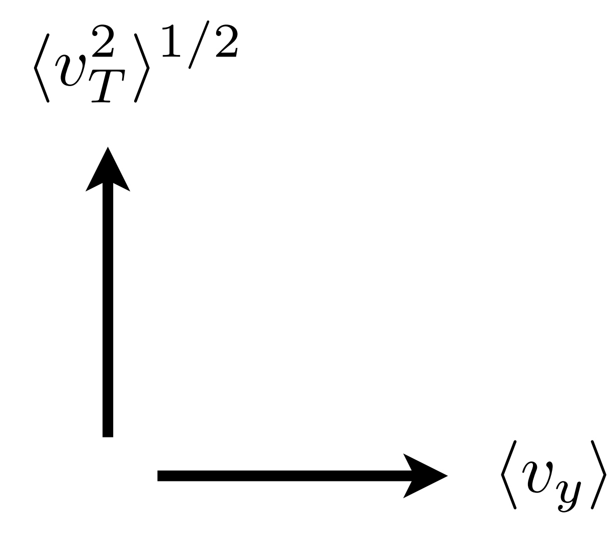
Velocity parameters

In order to compare distributions, calculate some derived parameters:

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

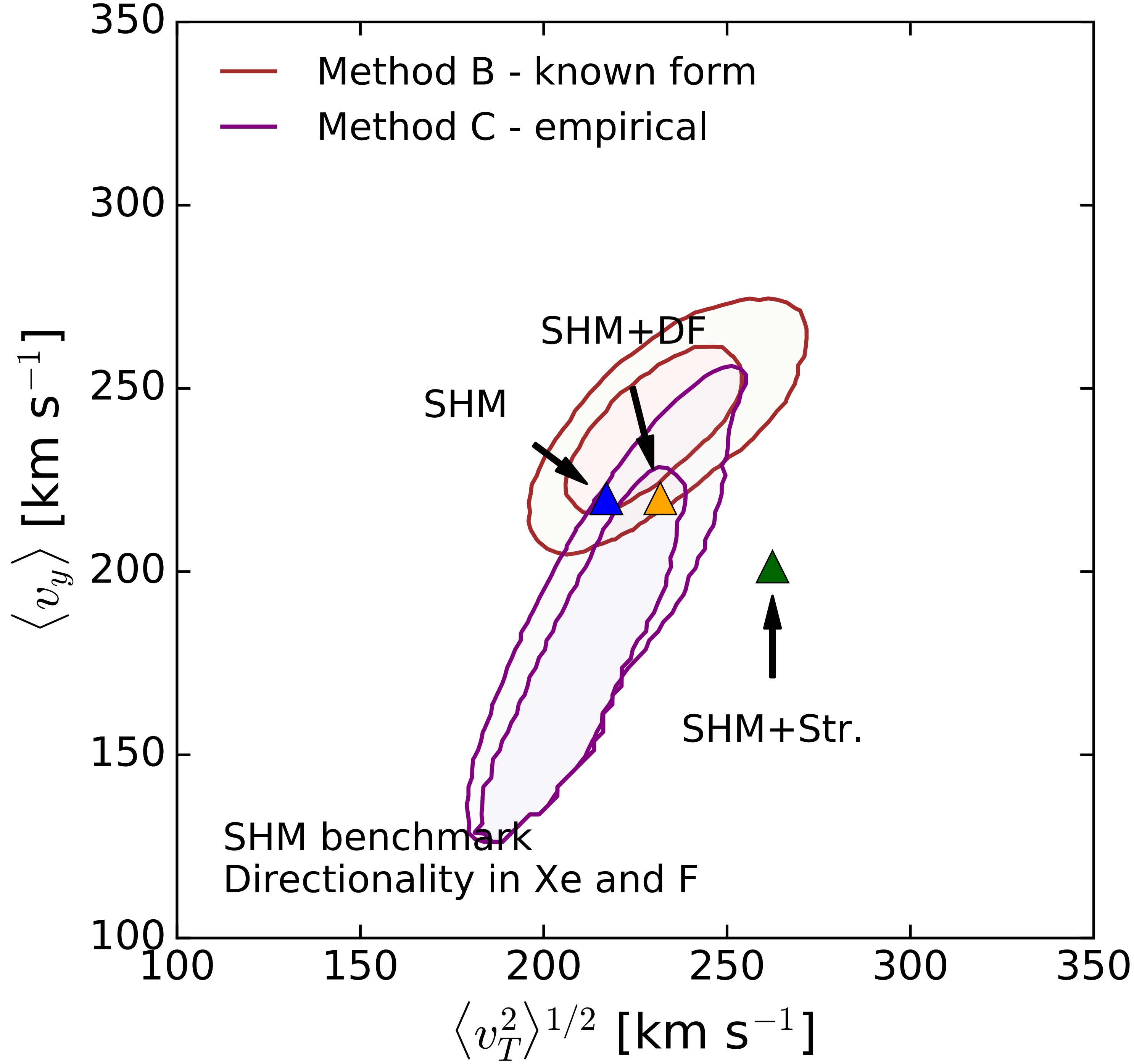
Average DM velocity *transverse* to Earth's motion → $$\langle v_T^2 \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v^2\sin^2\theta) \, v^2 f(\mathbf{v})$$

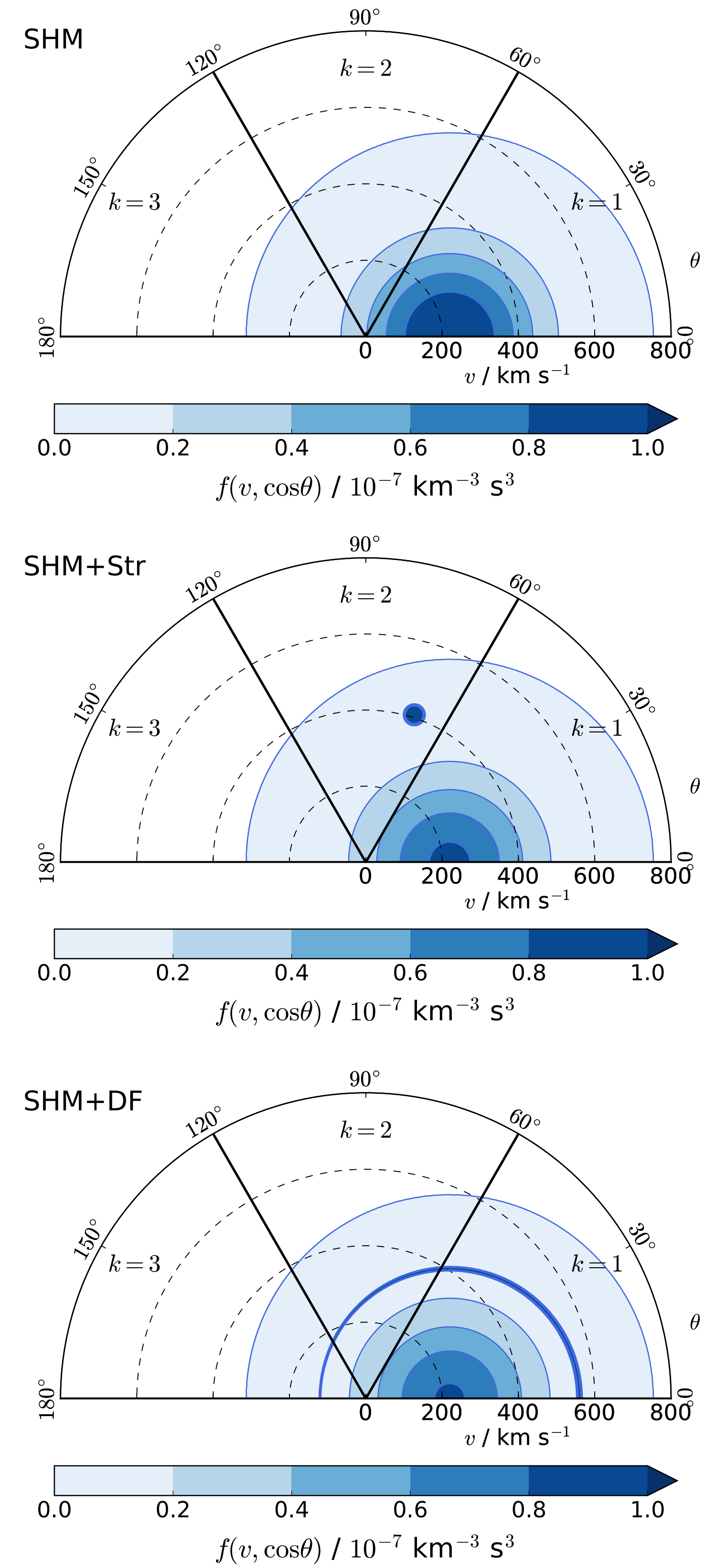




Comparing distributions

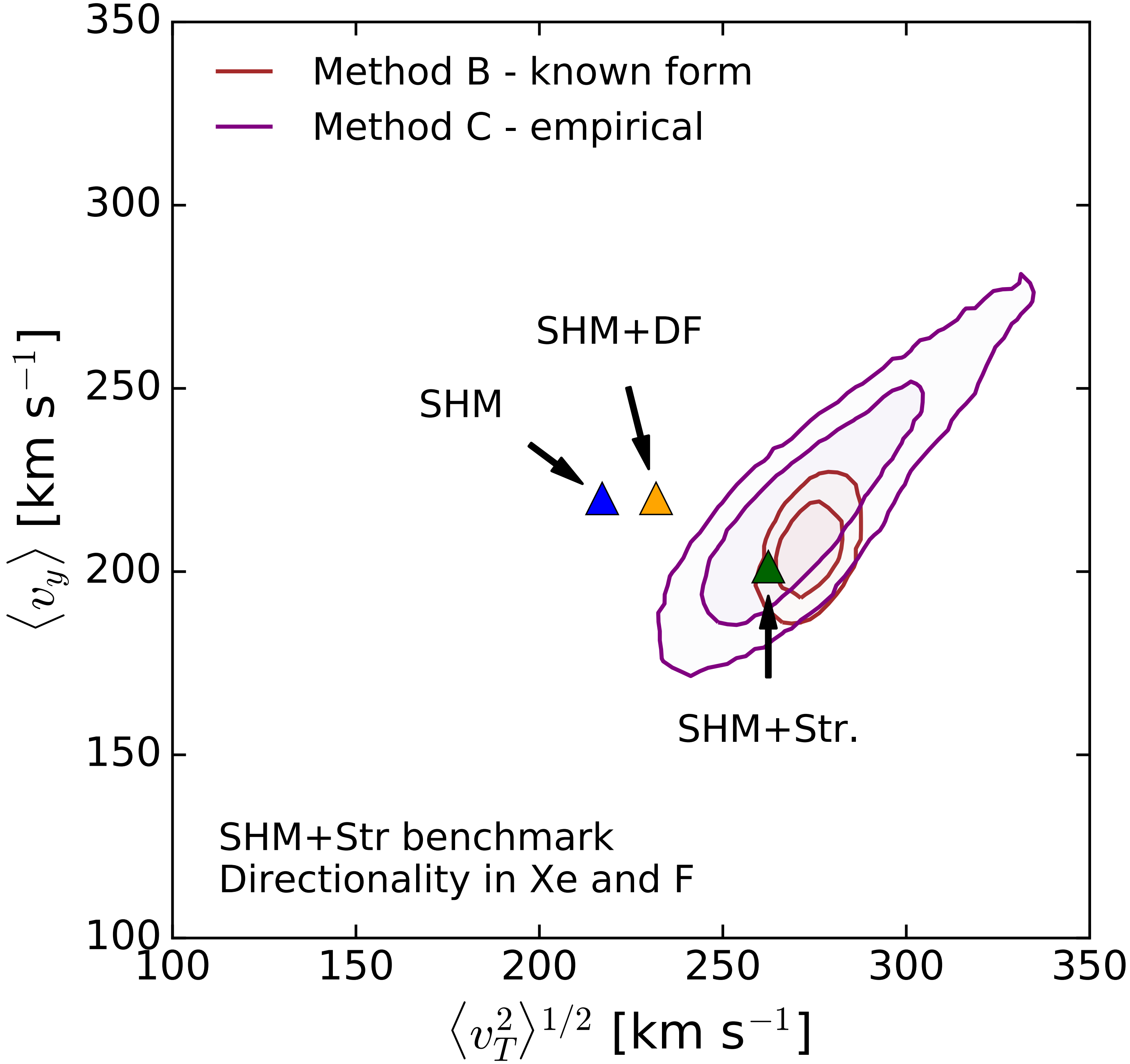
Input distribution: SHM

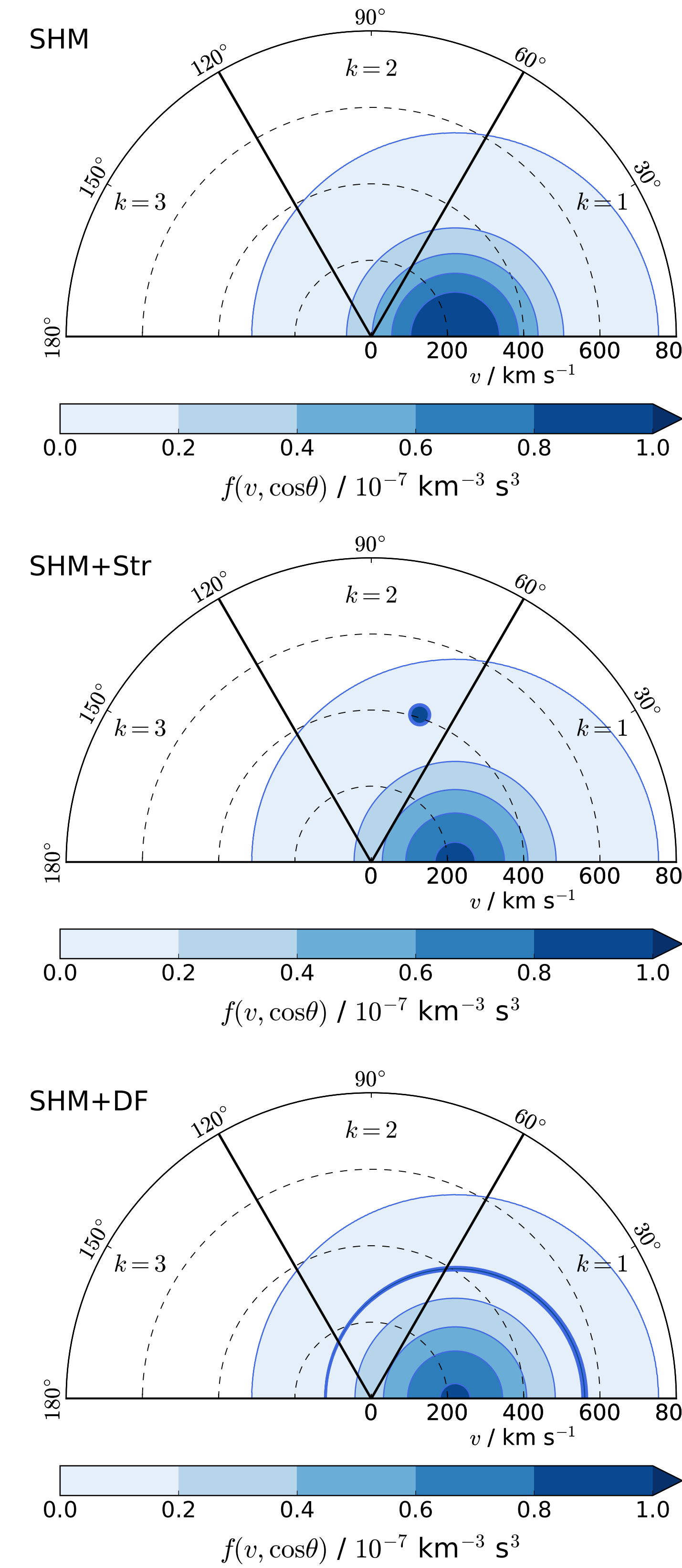




Comparing distributions

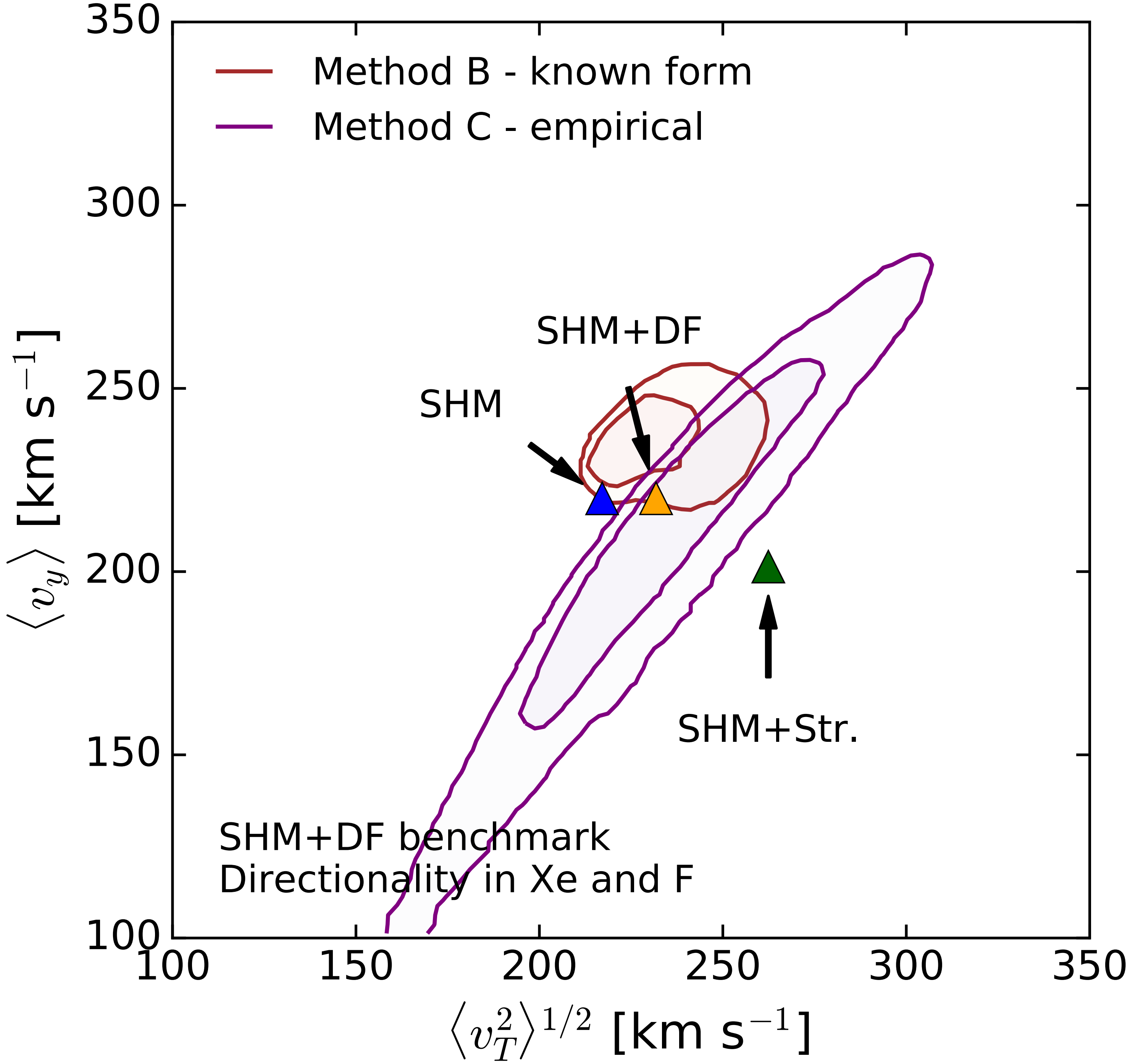
Input distribution: SHM + Stream

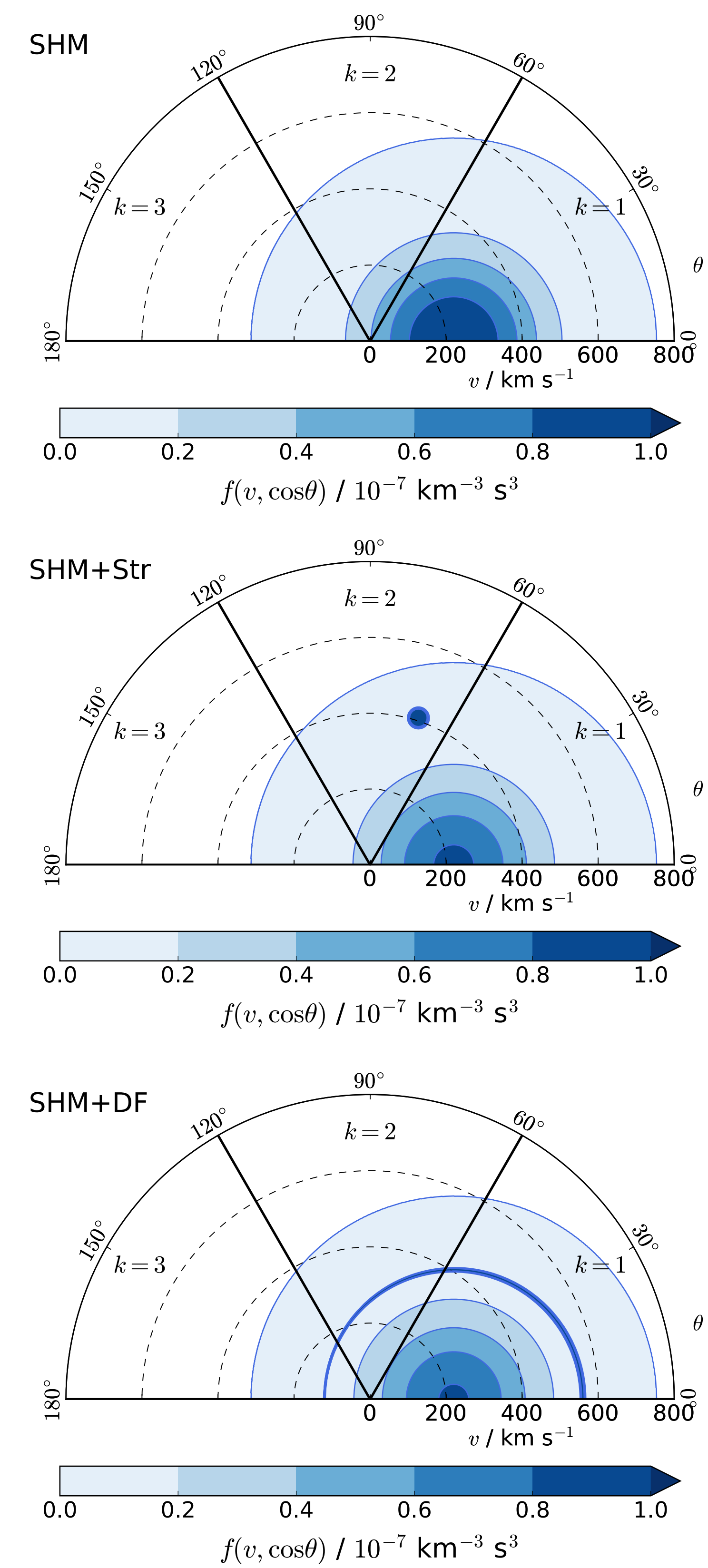




Comparing distributions

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?

Fantin et al. [1108.4411], Fan et al. [1303.1521]

Summary

With multiple direct detection experiments, astrophysical uncertainties can be overcome

Reconstruct DM mass *and* shape of speed distribution using a general empirical parametrisation

Information from solar capture and neutrino telescopes tells us about low speed DM particles

Recover full speed distribution & DM-nucleon cross section

Methods can be extended to directional detection without spoiling nice properties

Towards reconstructing full velocity distribution and helping discriminate different halo models

Summary

With multiple direct detection experiments, astrophysical uncertainties can be overcome

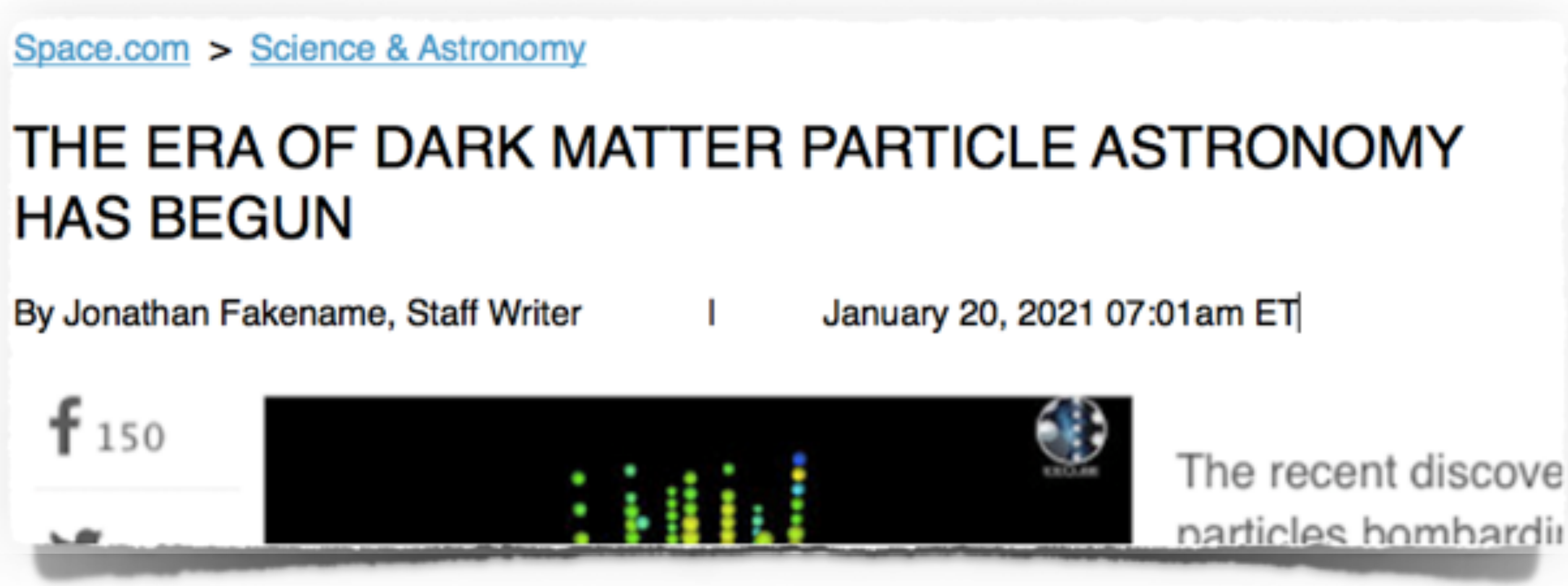
Reconstruct DM mass *and* shape of speed distribution using a general empirical parametrisation

Information from solar capture and neutrino telescopes tells us about low speed DM particles

Recover full speed distribution & DM-nucleon cross section

Methods can be extended to directional detection without spoiling nice properties

Towards reconstructing full velocity distribution and helping discriminate different halo models


Space.com > Science & Astronomy

THE ERA OF DARK MATTER PARTICLE ASTRONOMY HAS BEGUN

By Jonathan Fakename, Staff Writer | January 20, 2021 07:01am ET

150

The recent discove