Directional Dark Matter Detection:
a window into DM astrophysics and particle physics

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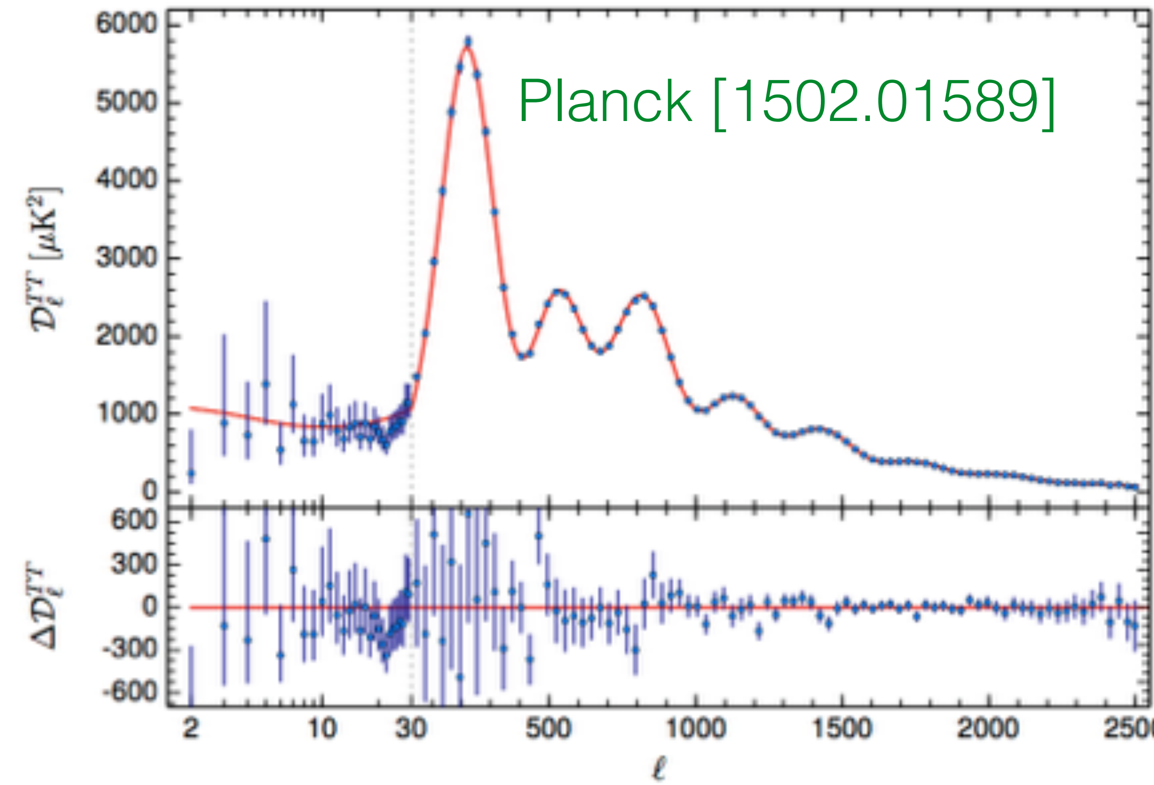
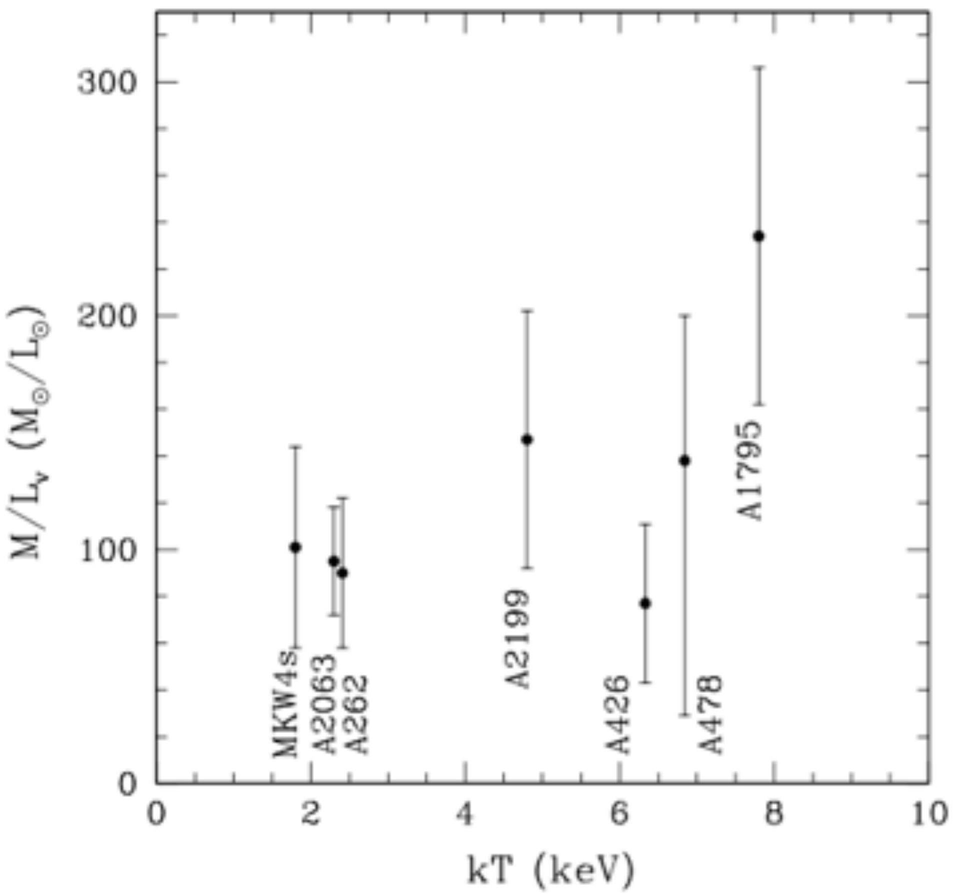
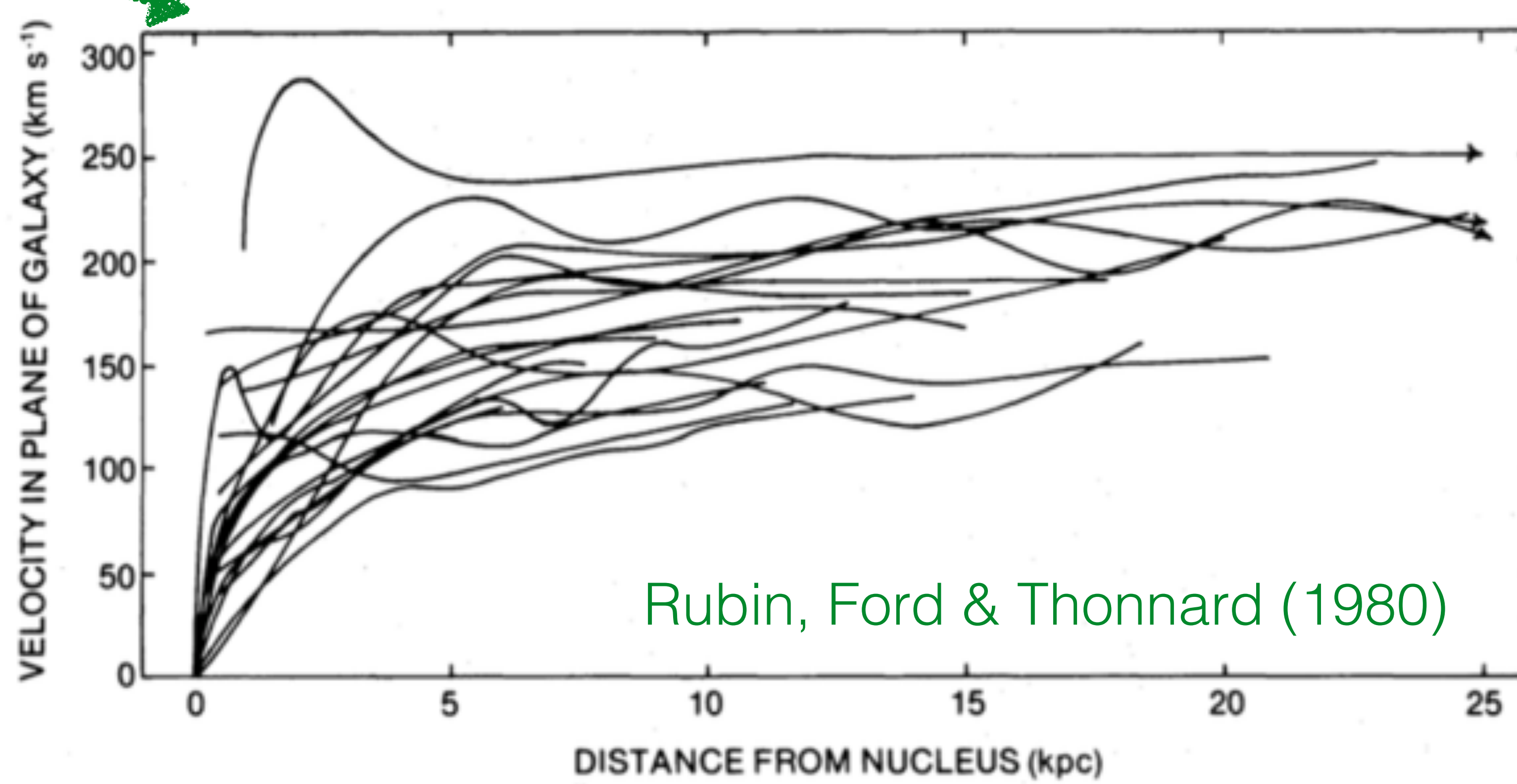
Dark Matter





Hradecky et al. [astro-ph/0006397]



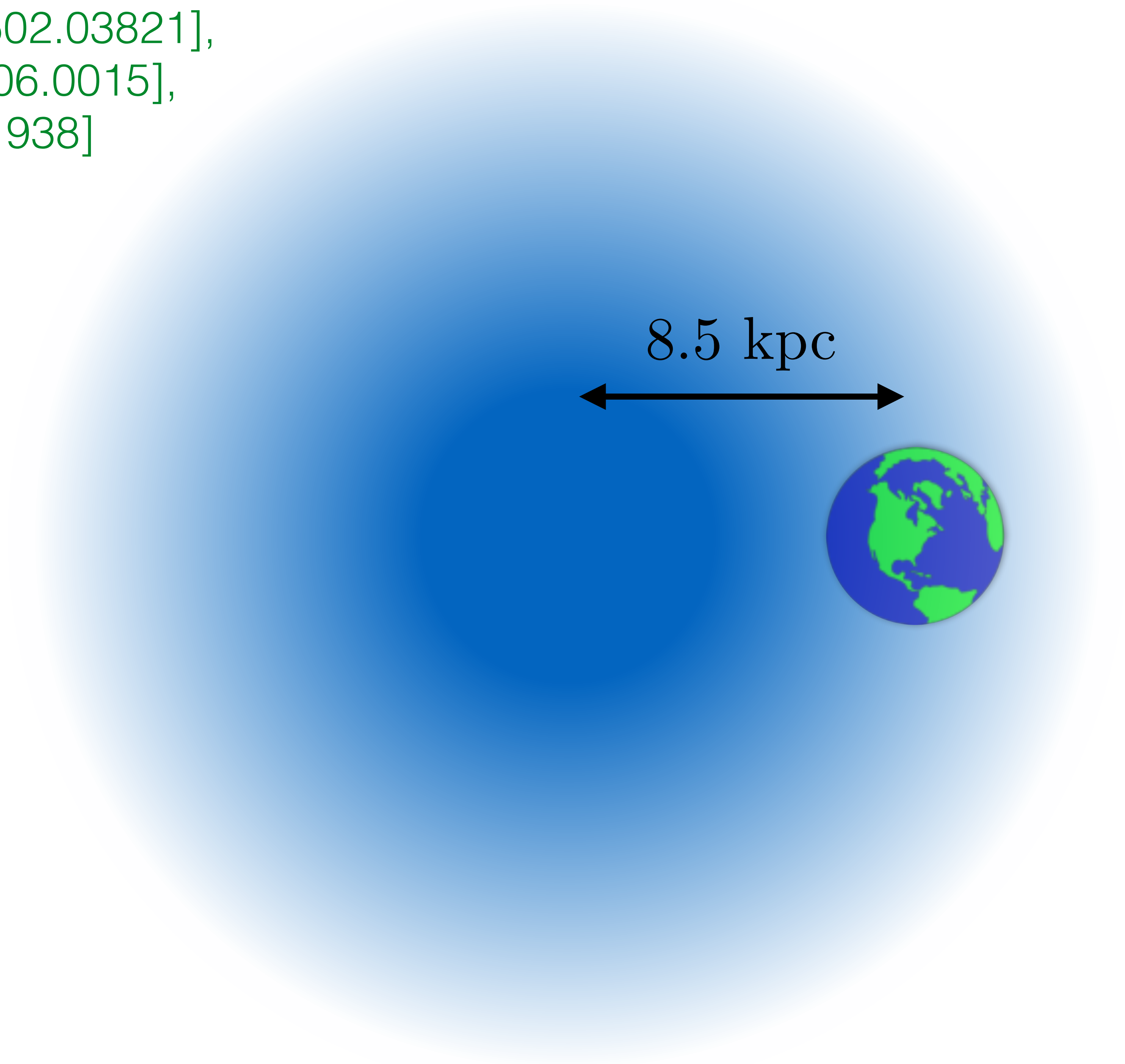
Rubin, Ford & Thonnard (1980)

Dark Matter at the Earth's Location

Global and local estimates of DM at Solar radius give:

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

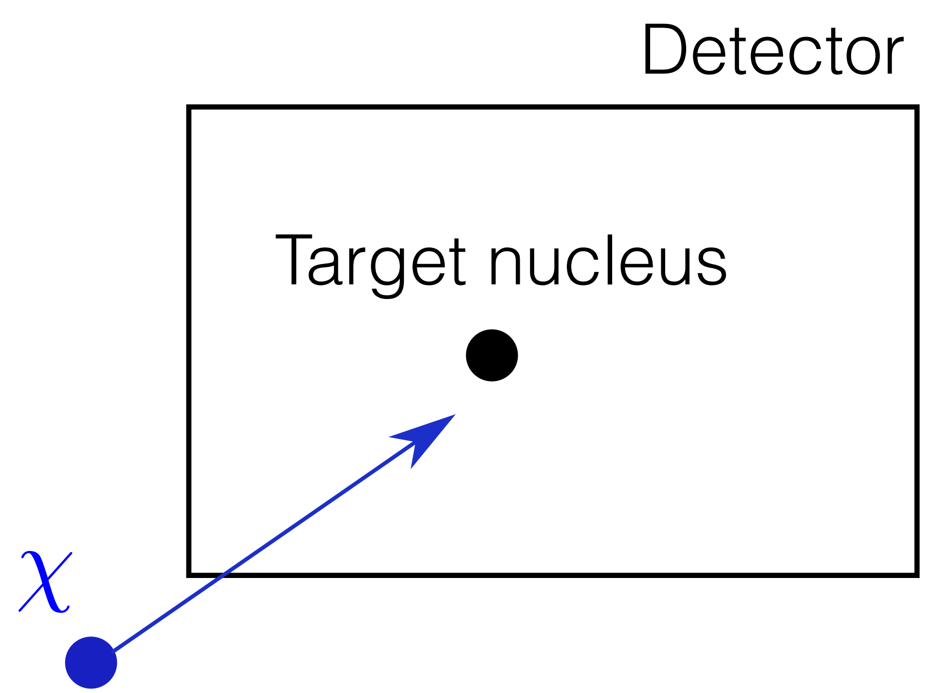
E.g. Iocco et al. [1502.03821],
Garbari et al. [1206.0015],
Read [1404.1938]



NOT TO SCALE

Direct detection

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



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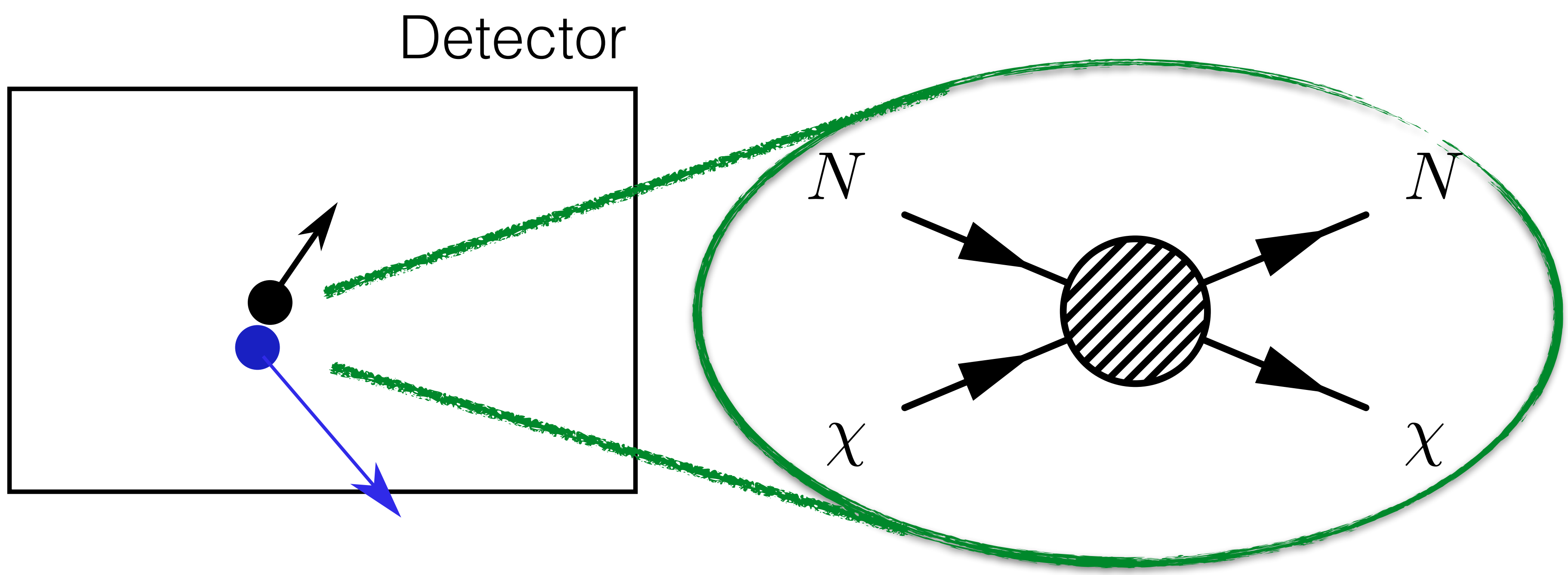

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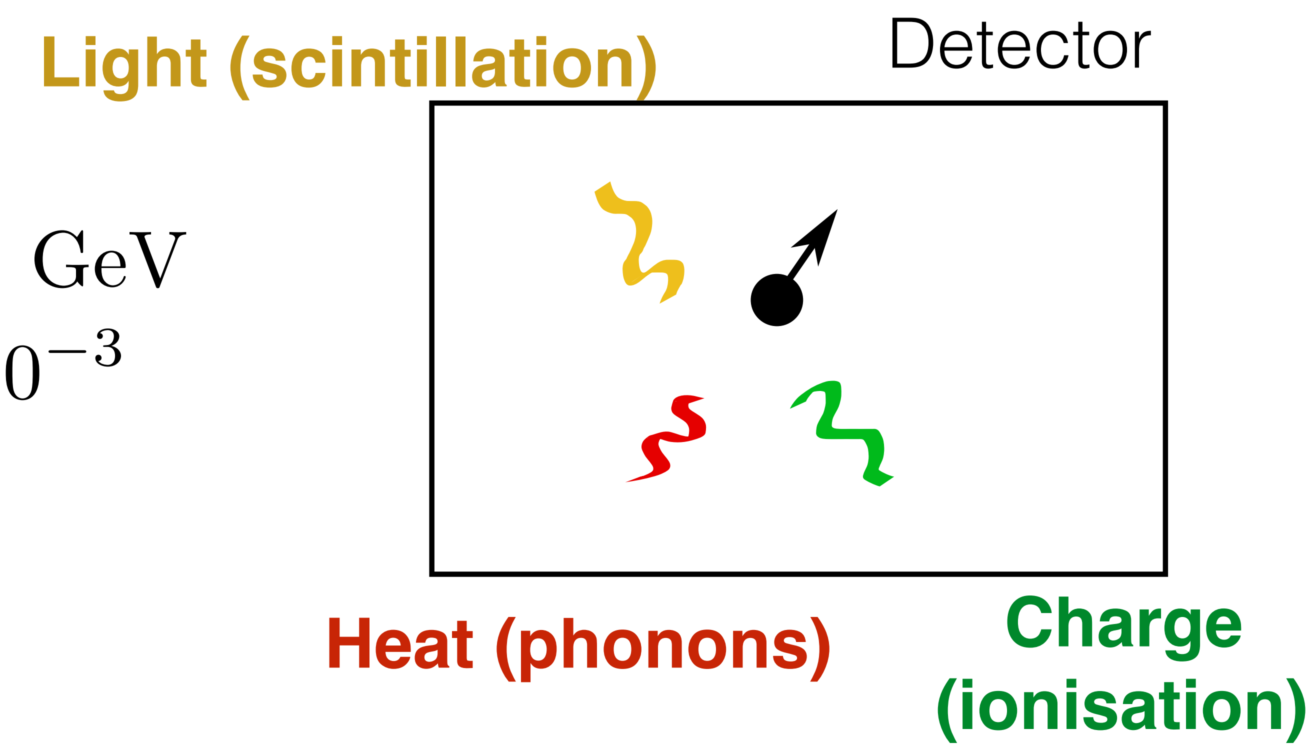


Measure energy and possibly direction of recoiling nucleus

Reconstruct the properties of DM (mass, cross section, etc.)

Outline

Directional detection - experimental approaches

Directional detection in the *pre*-discovery era

Directional detection in the *post*-discovery era

Astrophysics

Measuring the DM velocity distribution with directional experiments

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

Particle Physics

Distinguishing DM-nucleon interactions with directional experiments

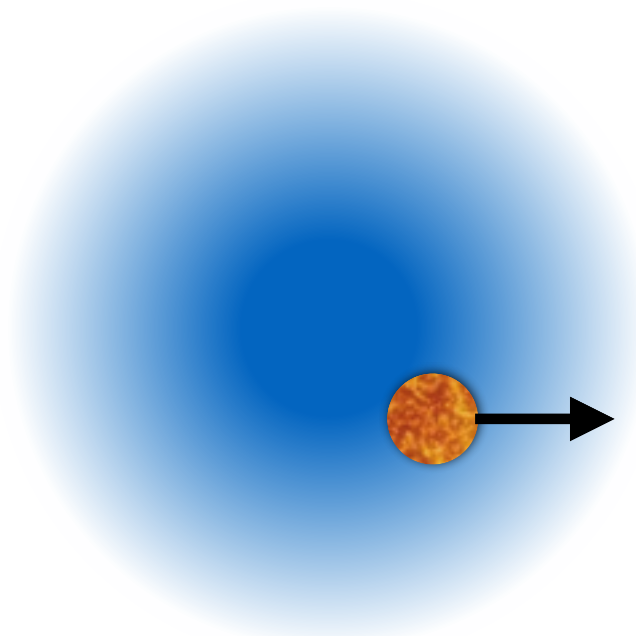
BJK [1505.07406]

Review of Directional Dark Matter Detection: Mayet et al. [1602.03781]

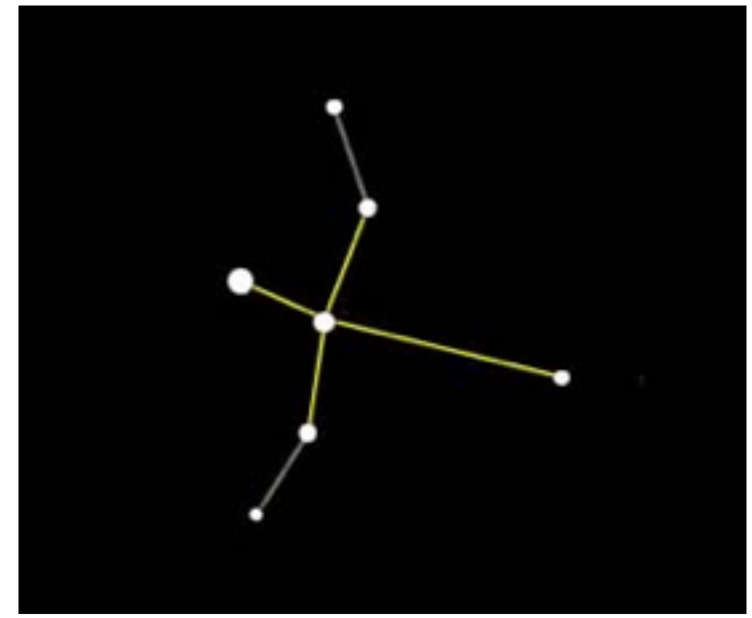
WIMP 'wind'

WIMP: Weakly Interacting Massive Particle

In the halo:



$v_{\rm sun} \sim 220\ {\rm km\,s^{-1}}$

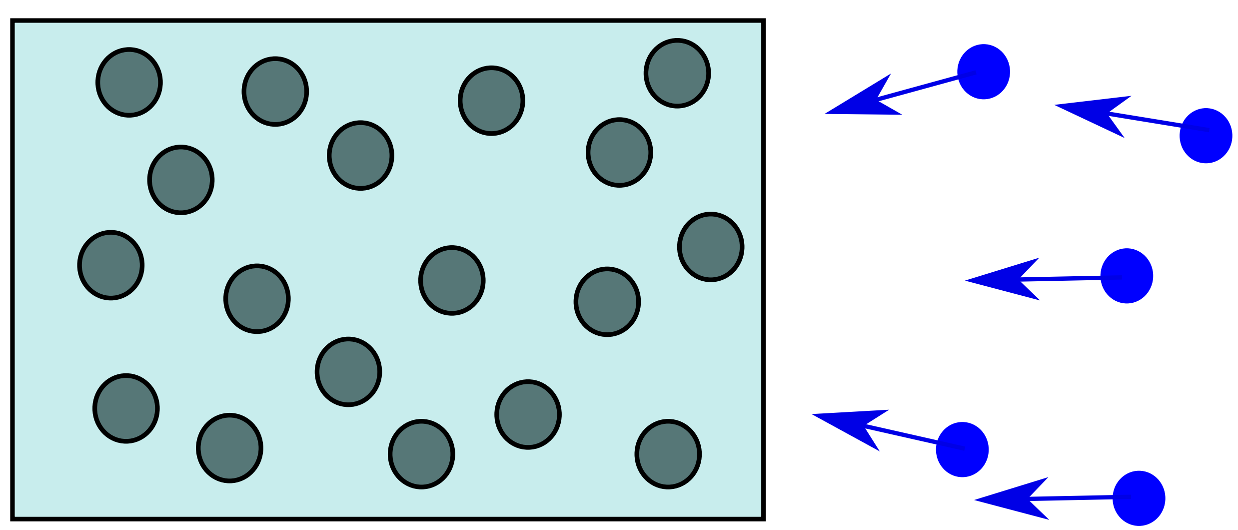


Cygnus constellation

In the lab:

Detector

$v_{\rm DM} \sim 220\ {\rm km\,s^{-1}}$



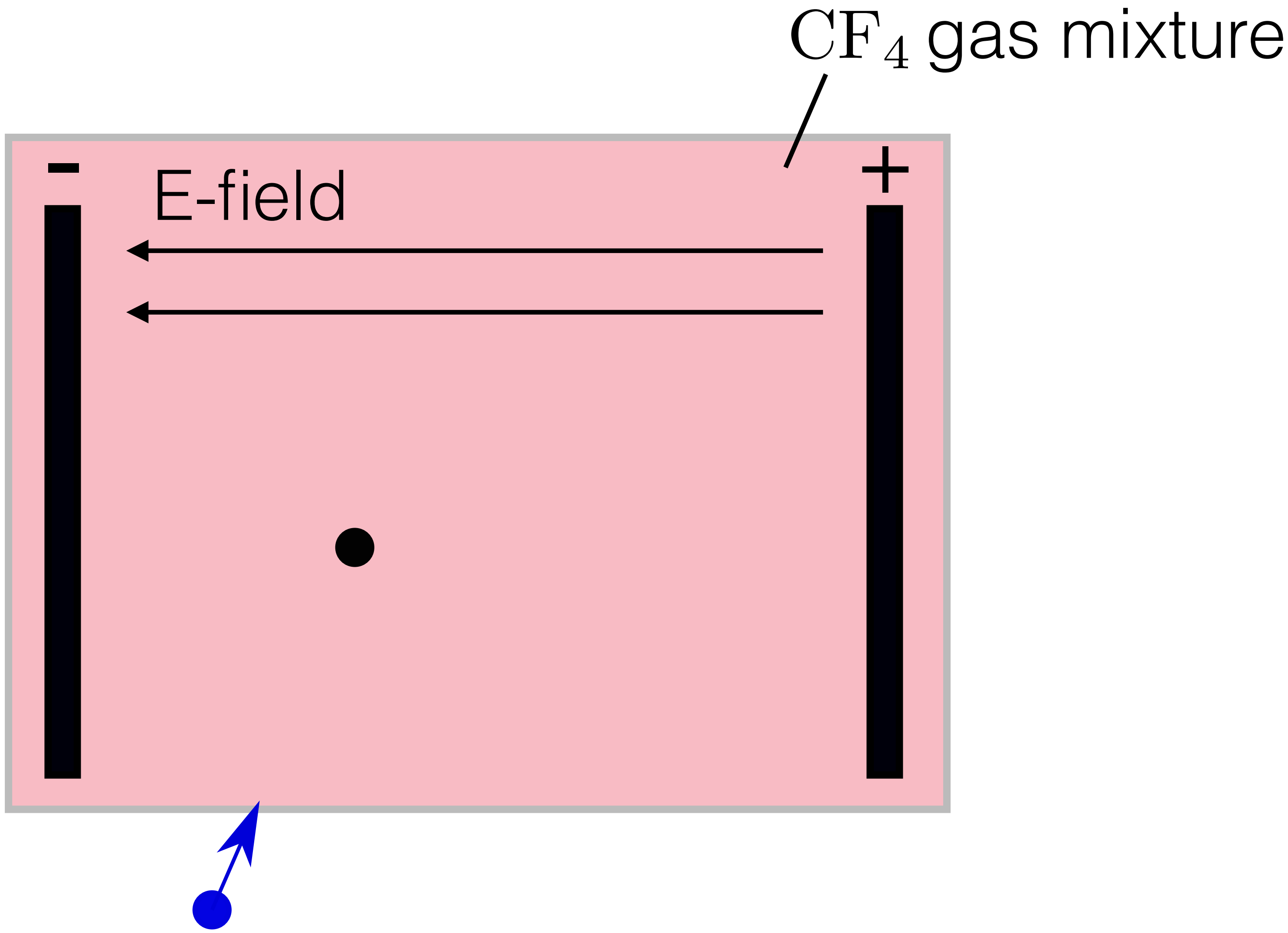
'WIMP wind from Cygnus'

Directional experiments

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]



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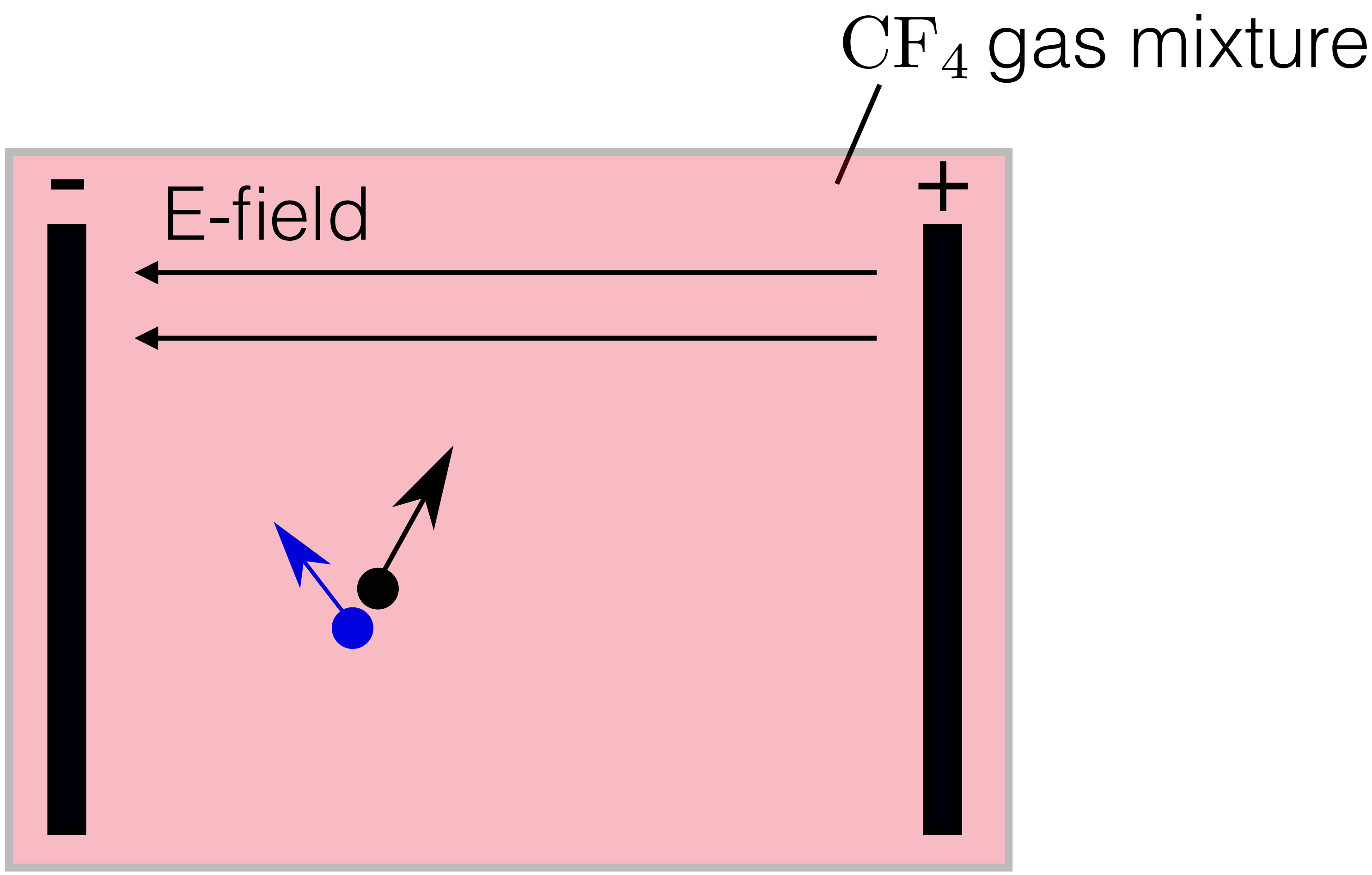

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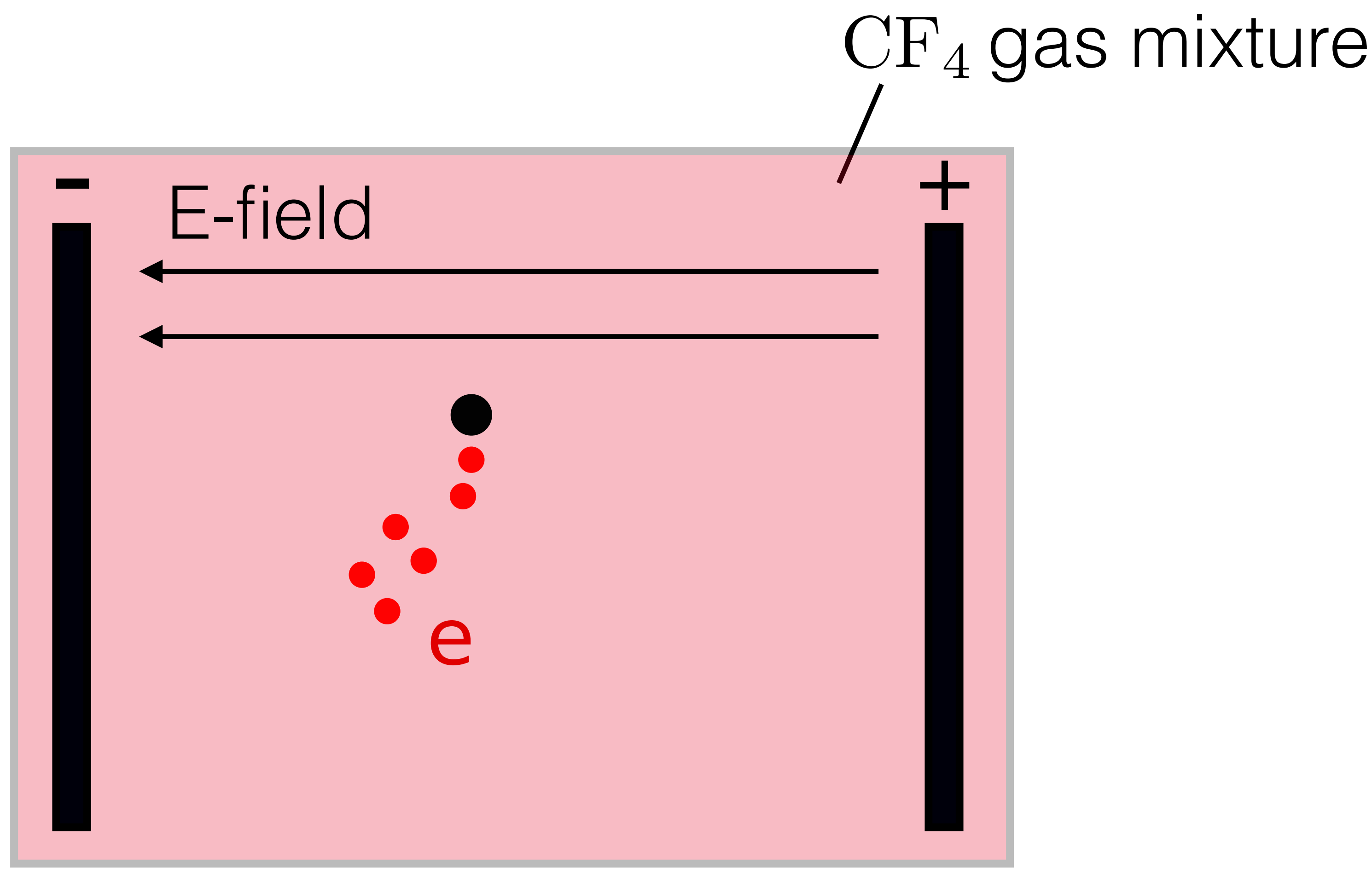

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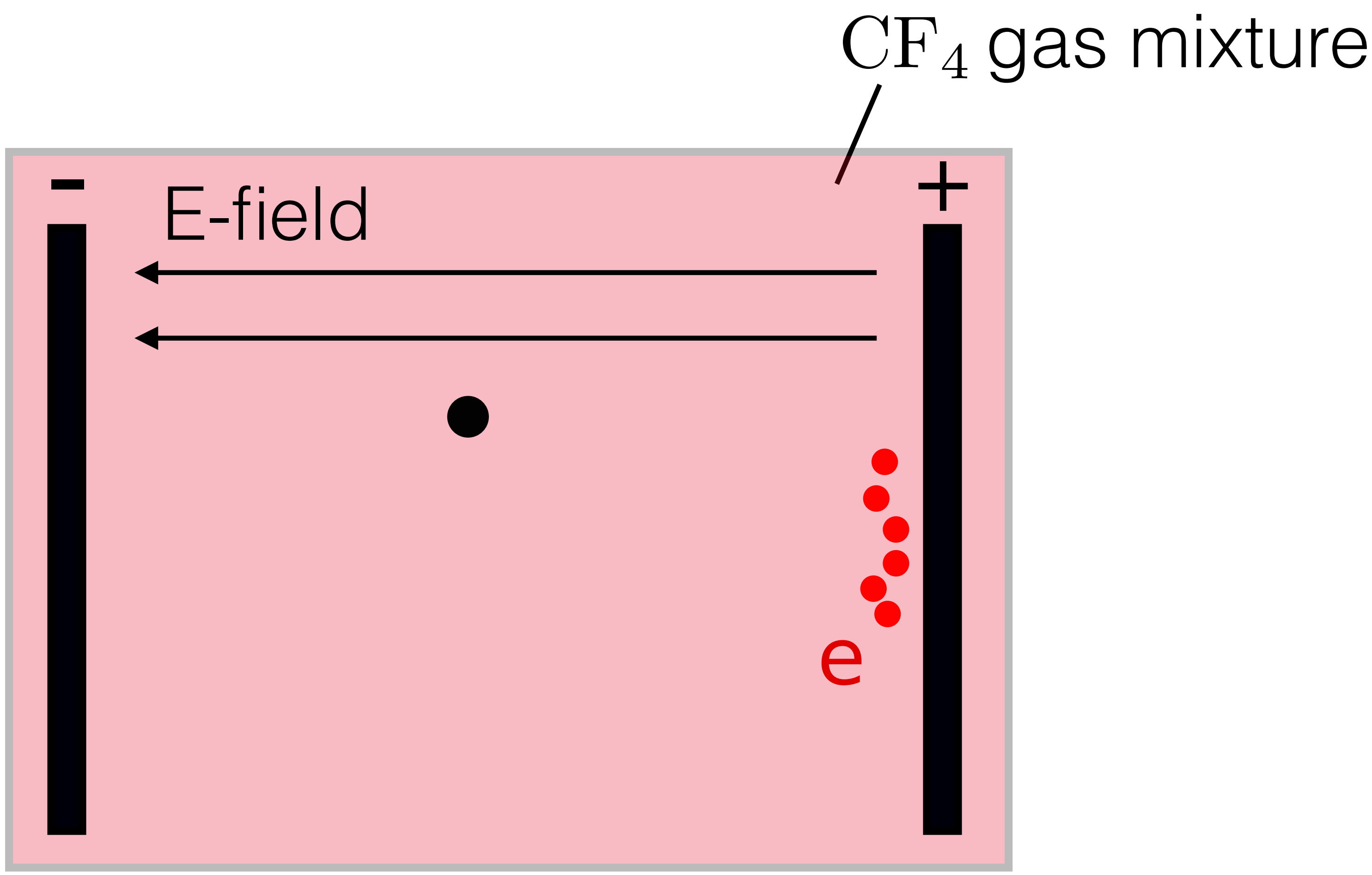
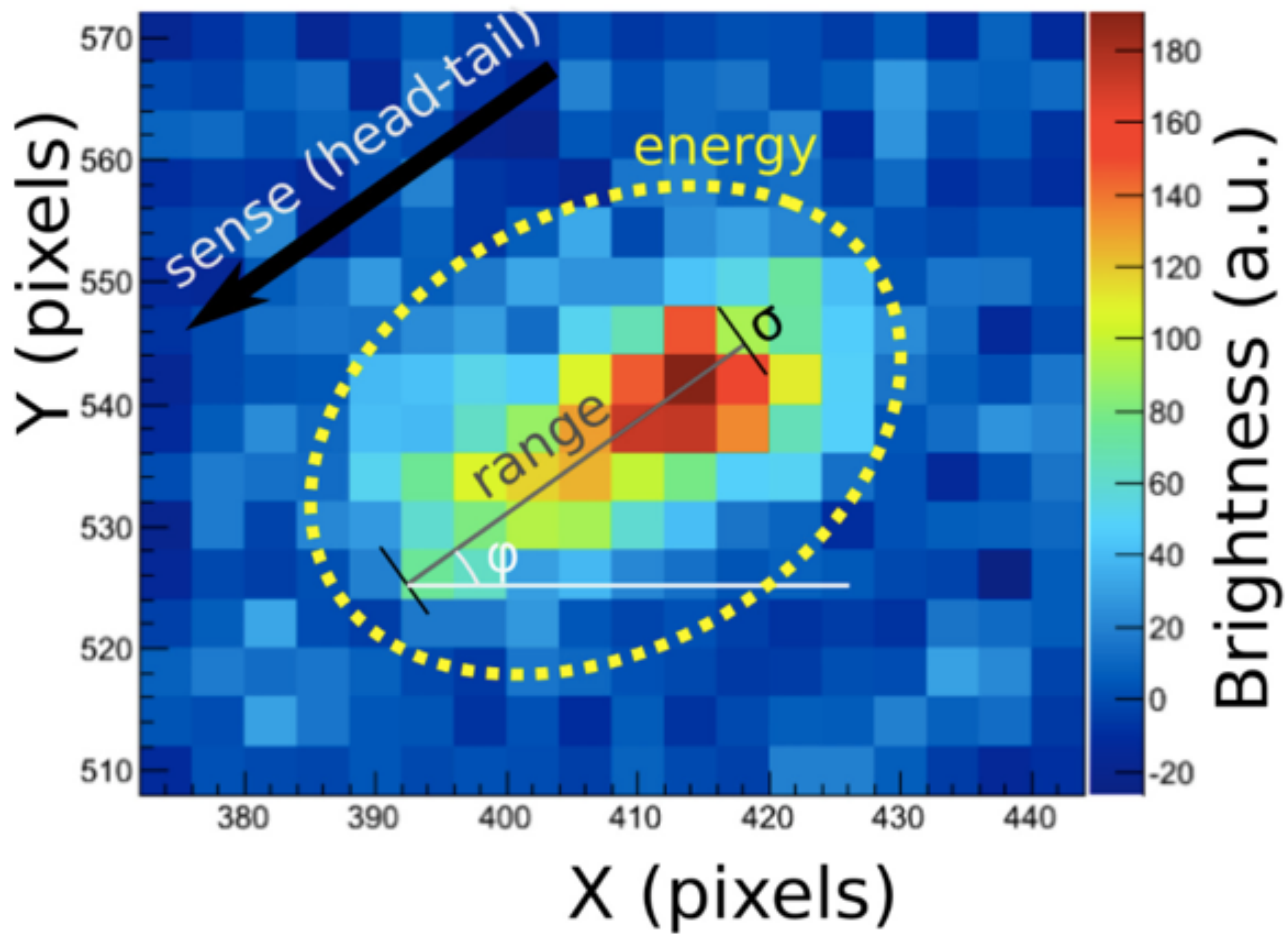


Get x,y of track from distribution of electrons hitting anode

Get z of track from timing of electrons hitting anode

A 'real' signal

Deaconu et al. (DMTPC, 2015)

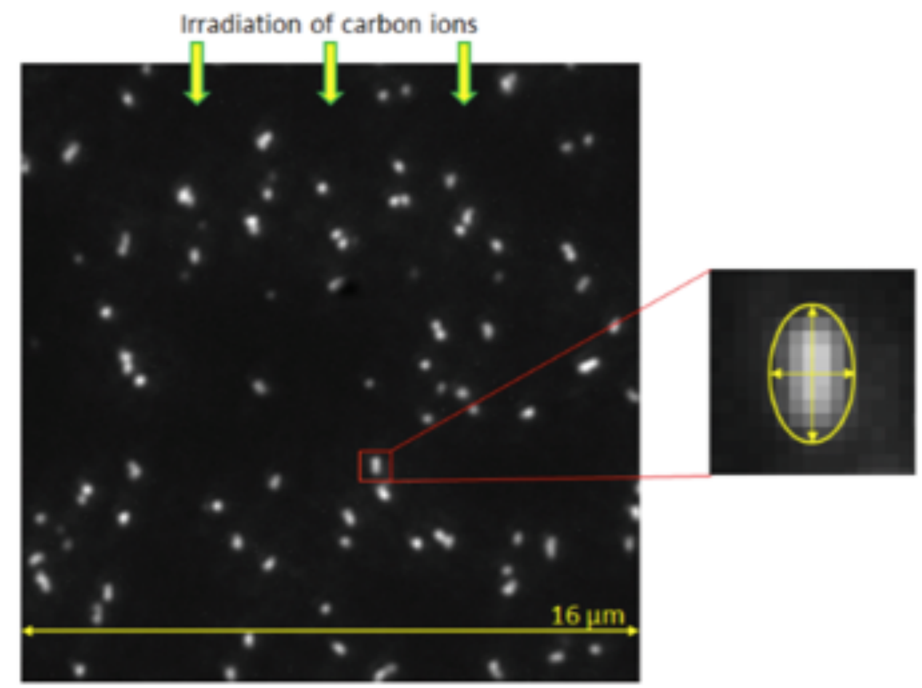


- Finite angular resolution - $\Delta\theta \sim 20^\circ - 80^\circ$
- May not get full 3-D track information
- May not get head-tail discrimination

Other approaches to directionality

Detecting recoil tracks in nuclear emulsion (e.g. NEWS experiment)

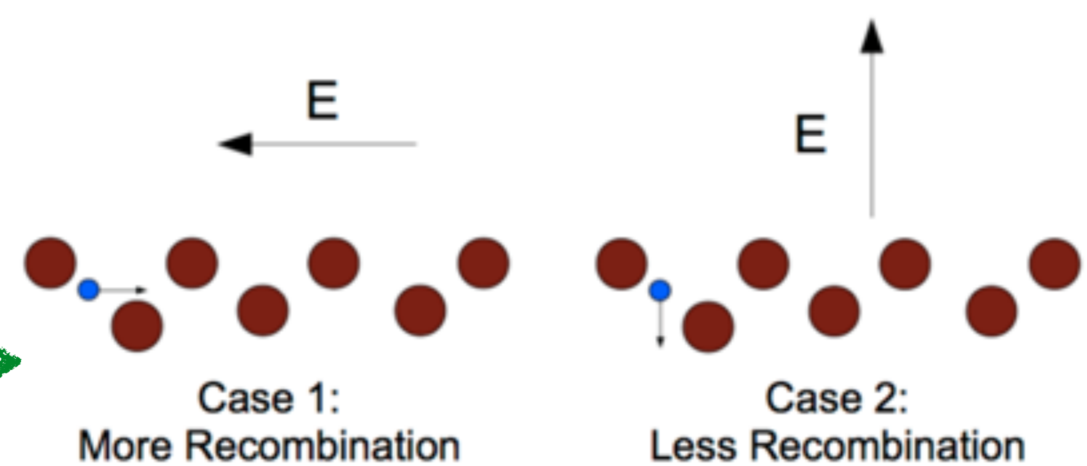
Aleksandrov et al. [1604.04199]



Anisotropic materials such as ZnWO4 crystals or Carbon nanotubes

"Columnar recombination" in Xenon (possible anisotropic response depending on E-field orientation)

Li [1503.07320]



Long & Goldschmidt

Directional Dark Matter Rate

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

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

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

Enhancement for nucleus $\mathcal{N}$:

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

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

Form factor (encoded nuclear structure): $F^2(E_R)$

Radon Transform (RT) of the velocity distribution $f(\mathbf{v})$:

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

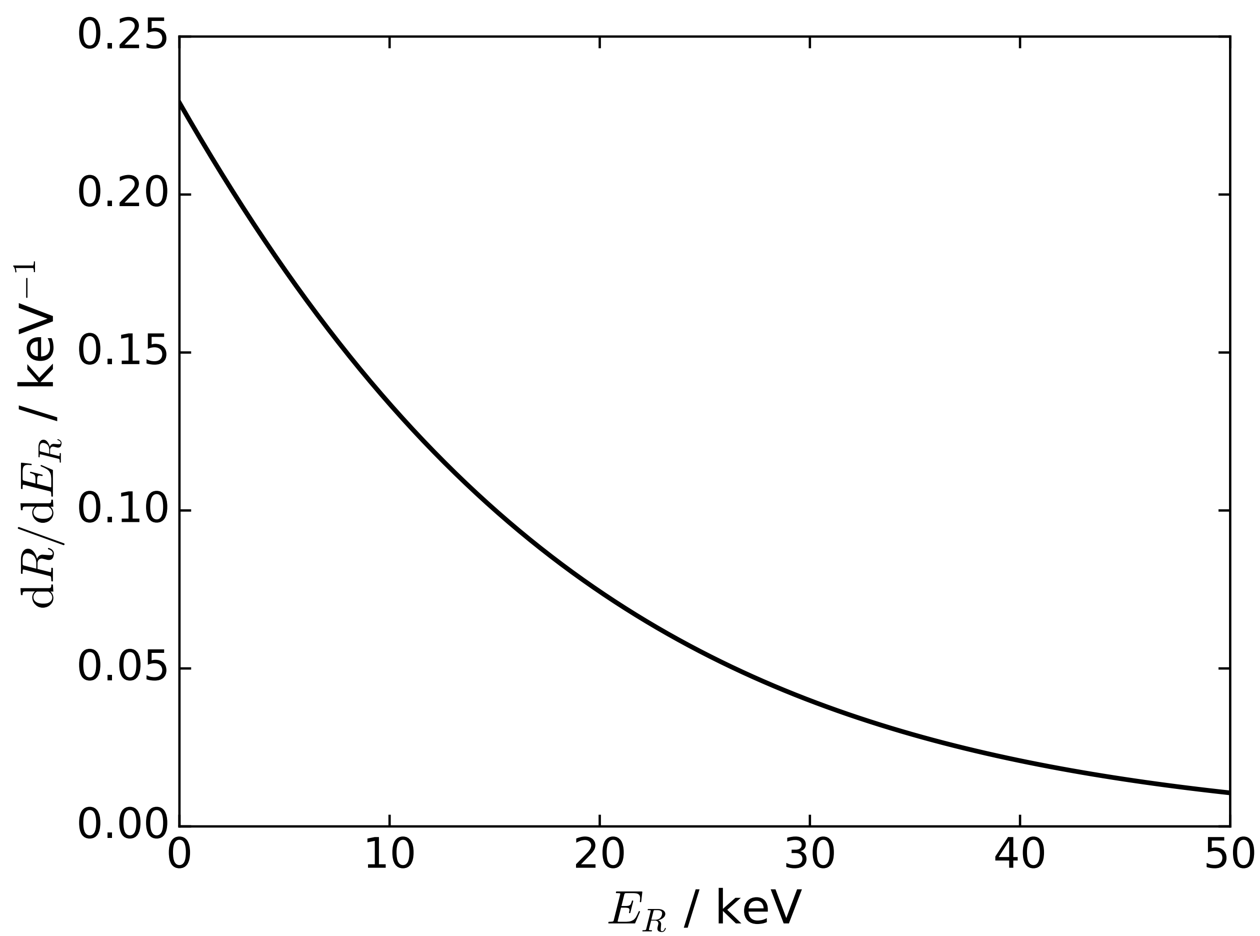
Gondolo [hep-ph/0209110]

Directional Dark Matter Rate

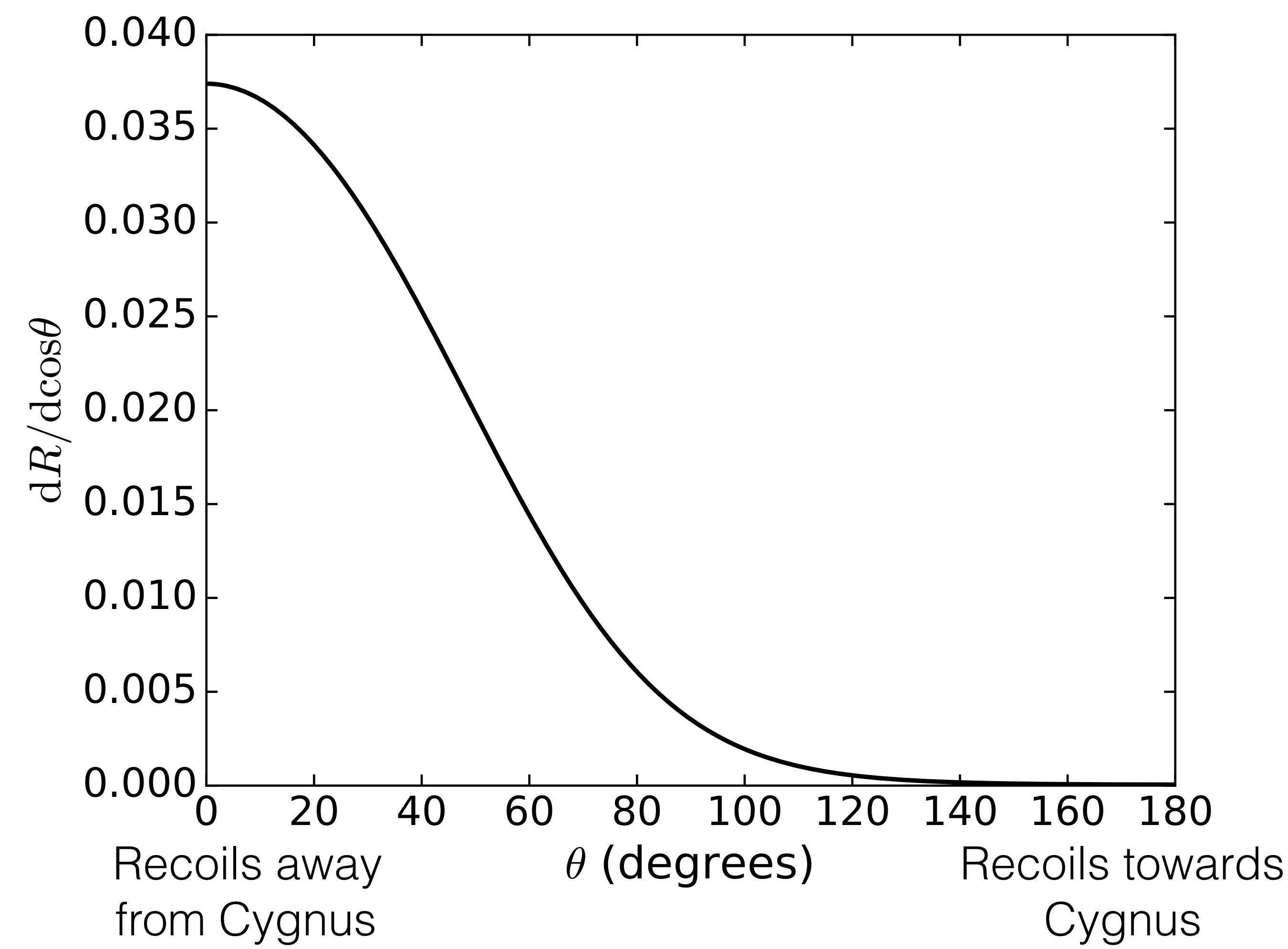
Under some standard assumptions for the astro- and particle-physics (SD interactions, SHM distribution):

We'll talk about relaxing those assumptions later…

Energy spectrum

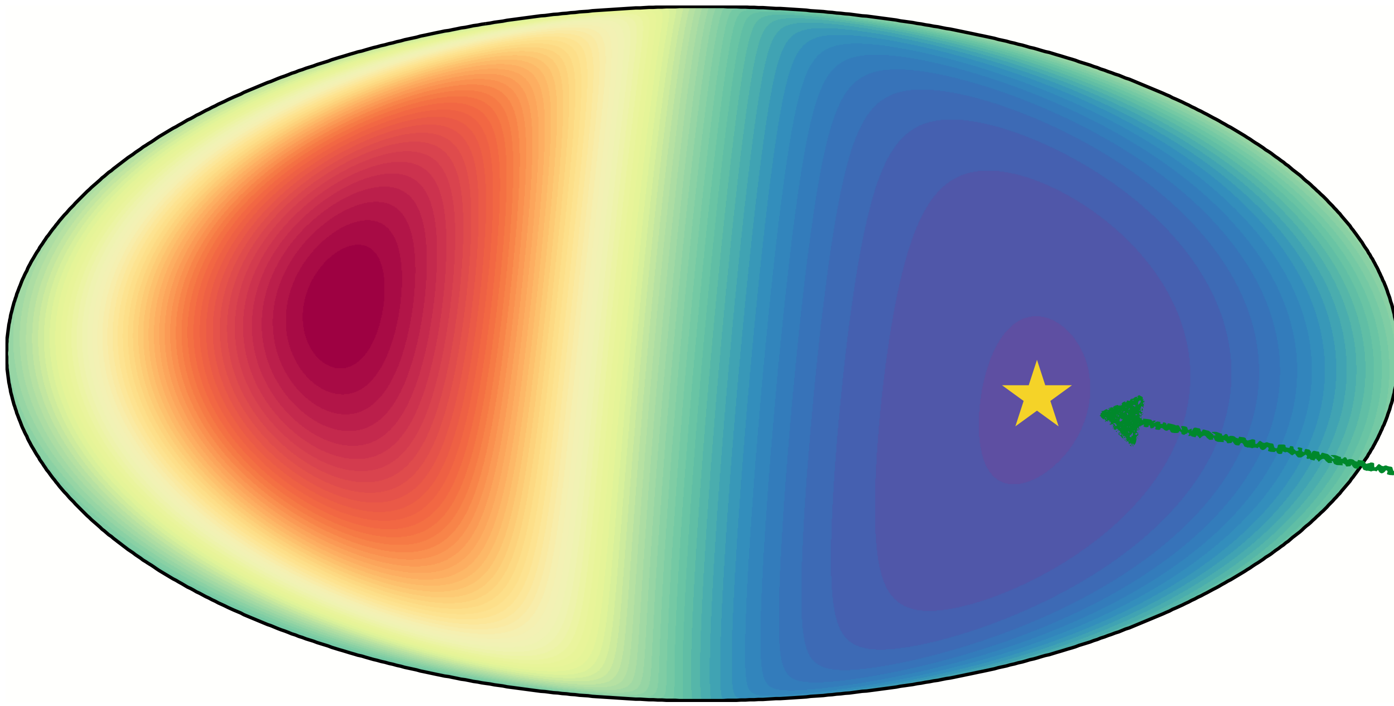


Directional spectrum



Directionality in the *pre*-discovery era

Dipole Signature

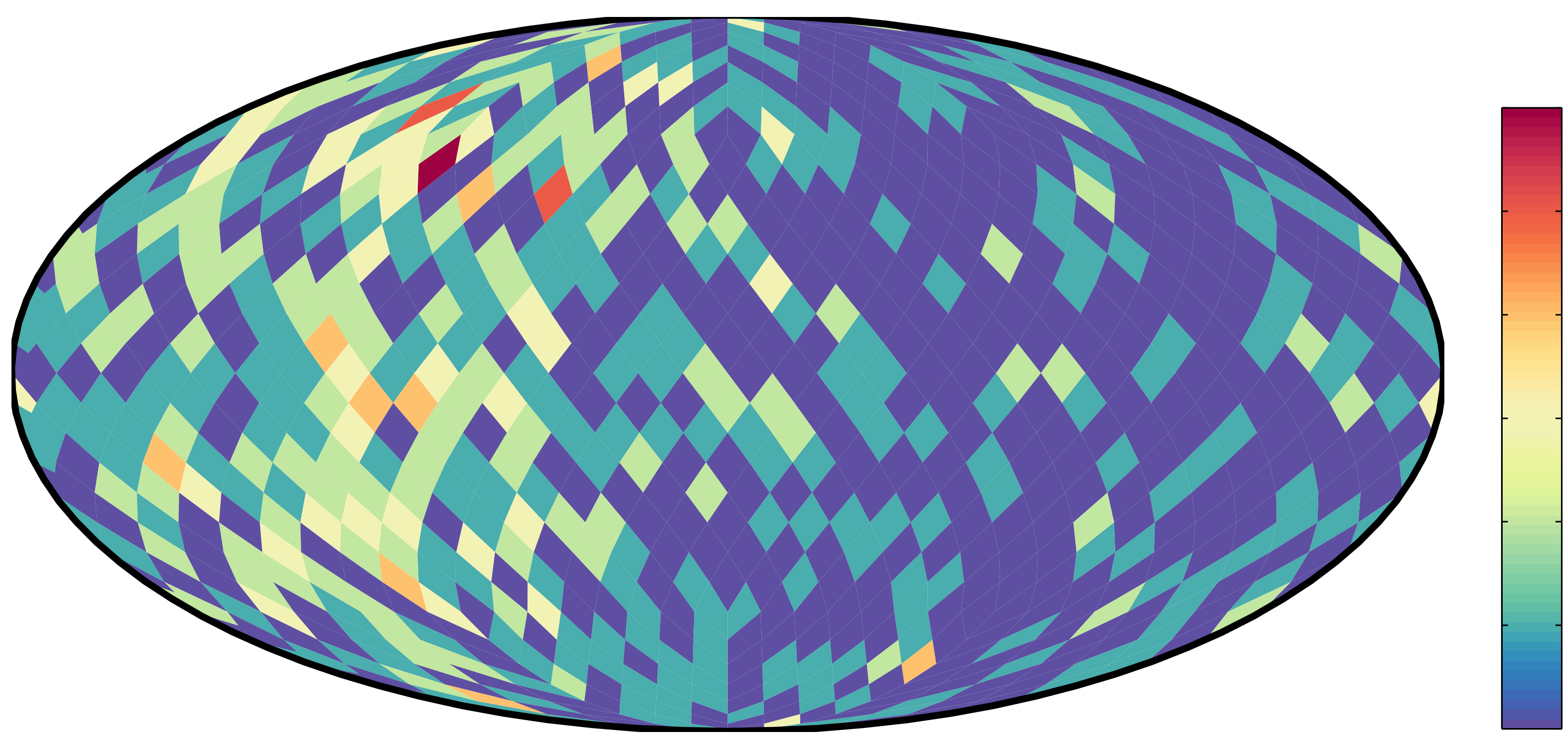


Recoil rate map

$m_\chi = 50 \text{ GeV}$

Cygnus direction

Count rate map



O'Hare & Green [1410.2749]

Background discrimination

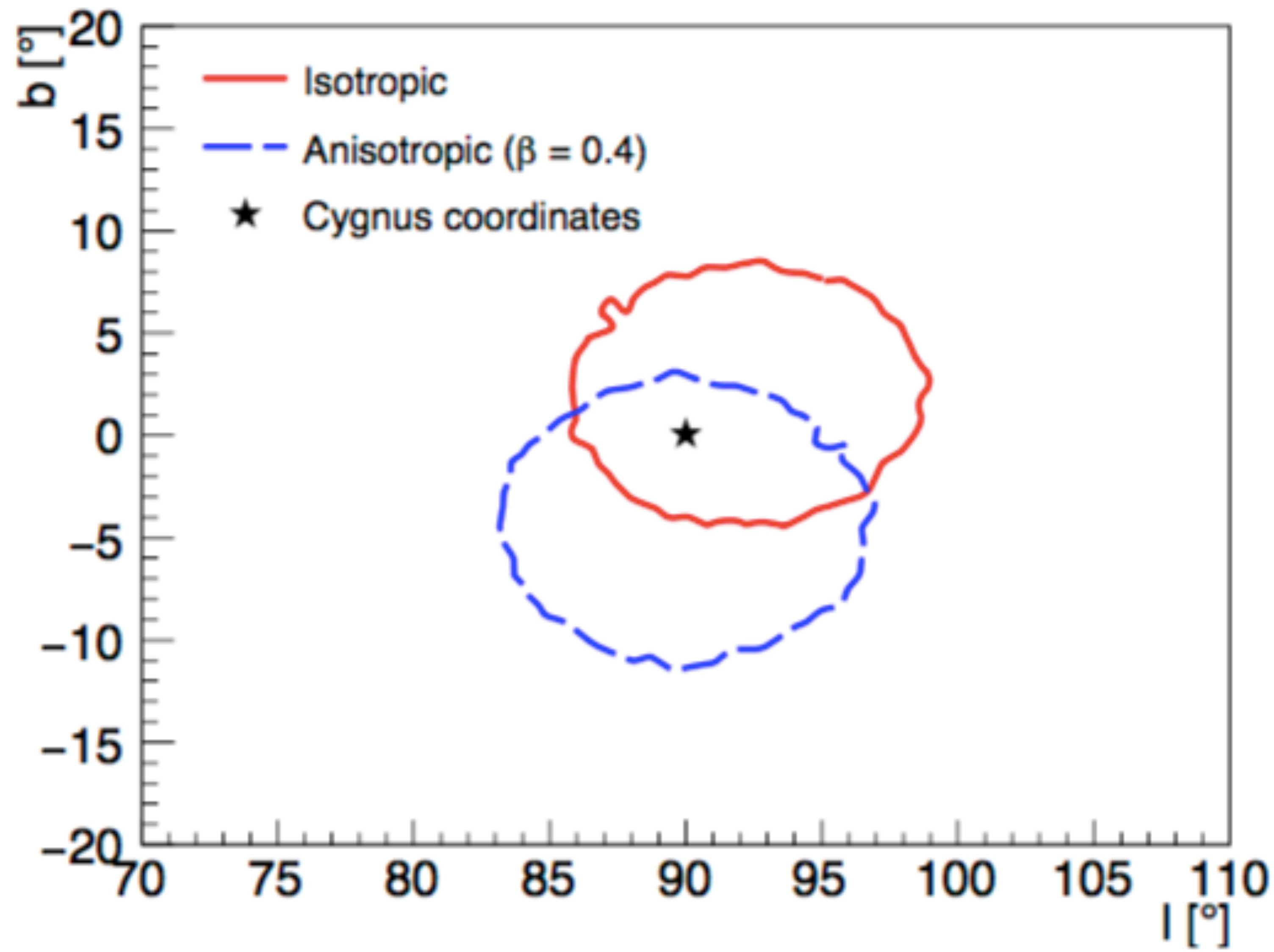
Powerful method of confirming DM origin of signal
(and rejecting backgrounds):

Can reject signal isotropy with O(10) signal events

Copi et al. [hep-ph/9904499], Morgan et al. [astro-ph/0408047]

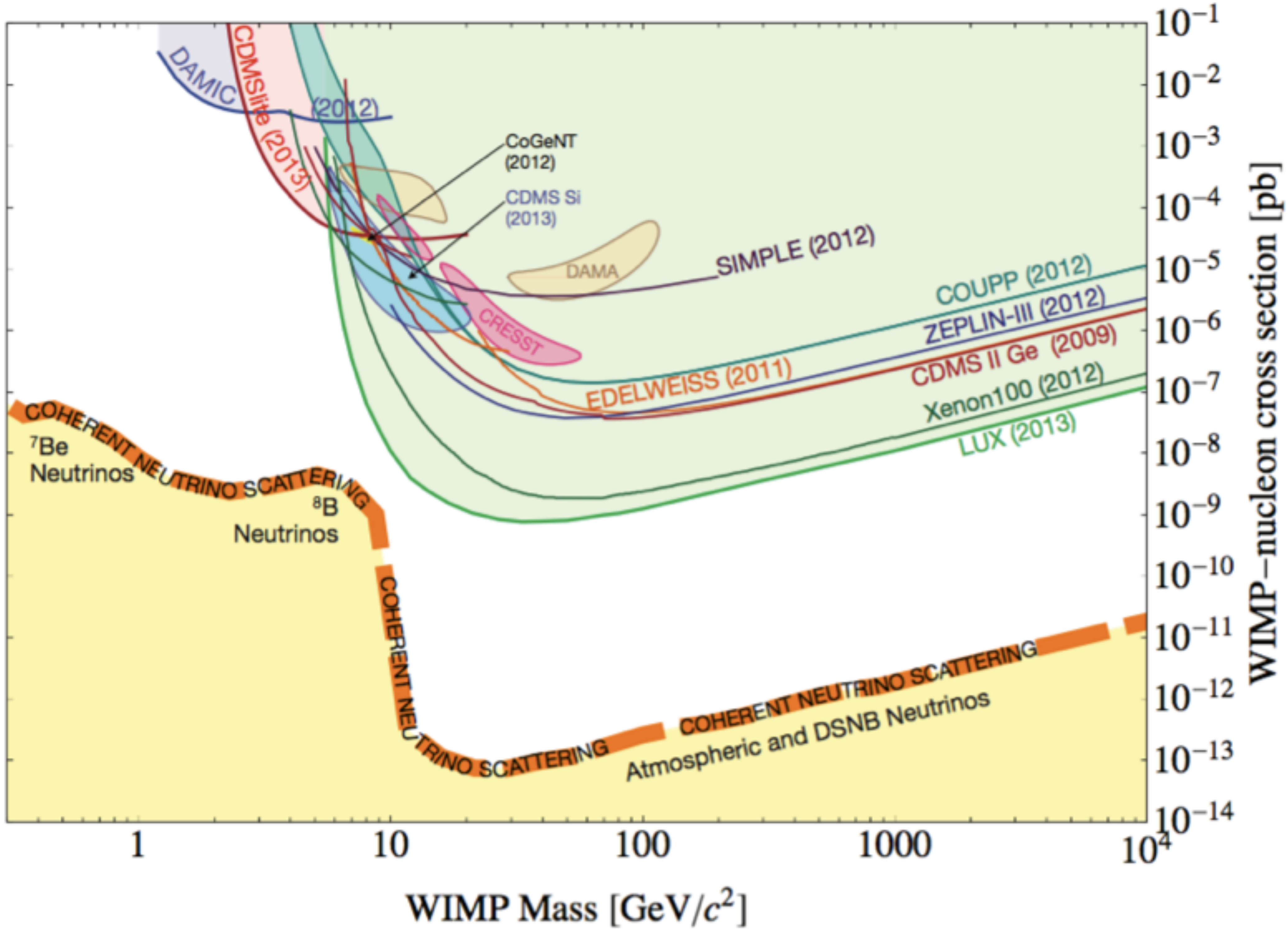
Can confirm median recoil direction with O(30) events

Green & Morgan [1002.2717], Billard et al. [1012.3960]



Mayet et al. [1602.03781]

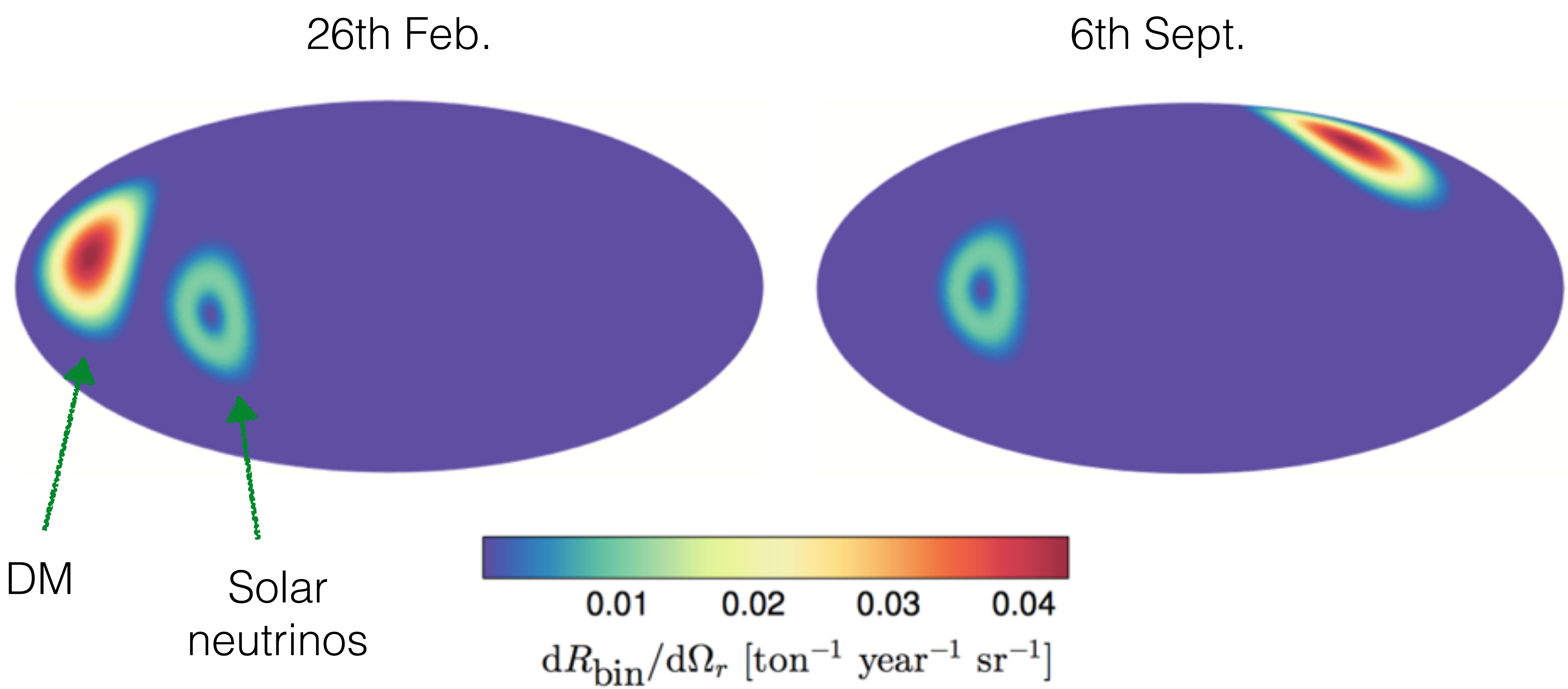
Neutrino Background



Billard et al. [1307.5458]

Directionality and the neutrino background

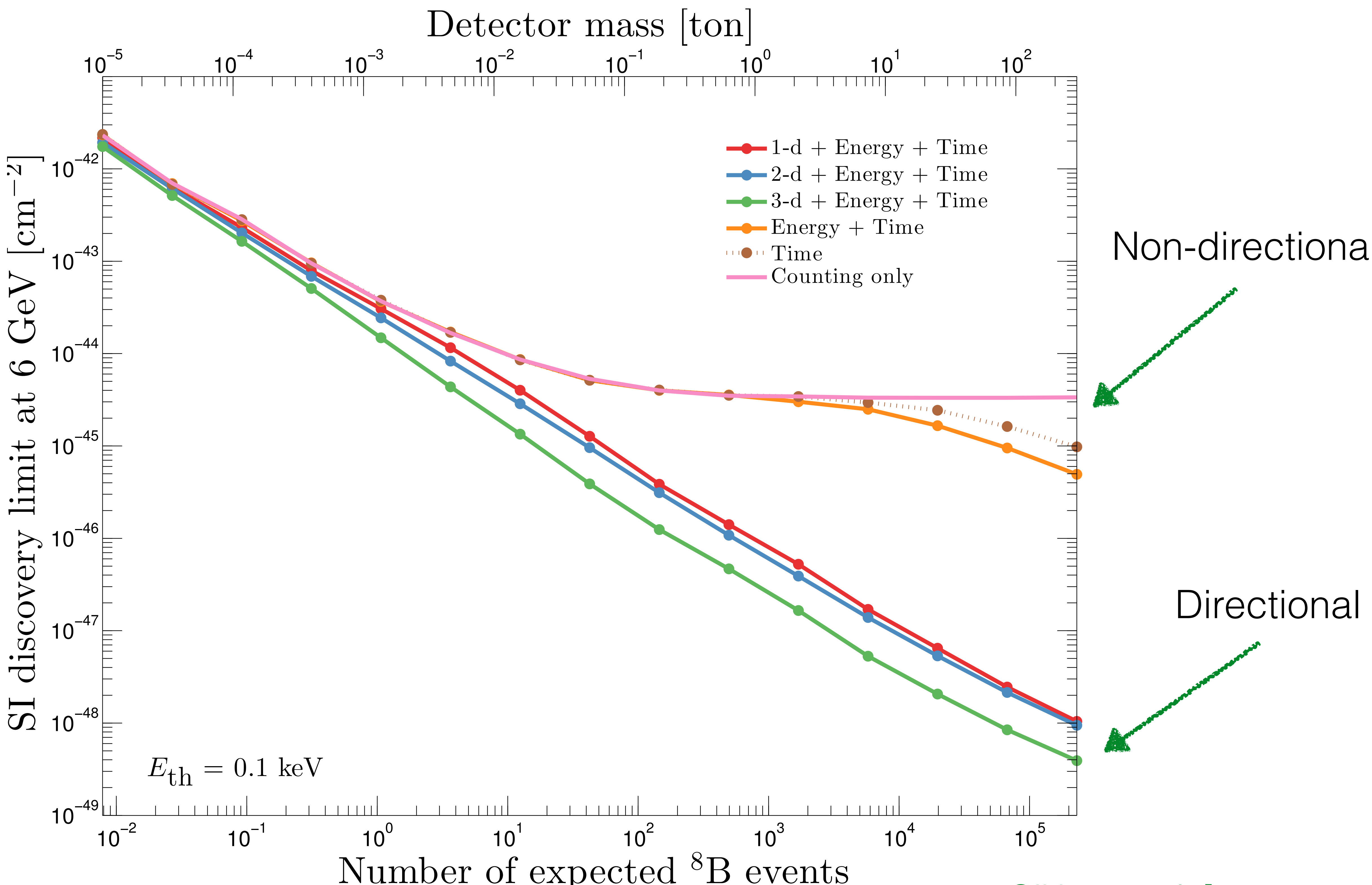
$m_\chi = 6 \text{ GeV}$



O'Hare et al. [1505.08061]

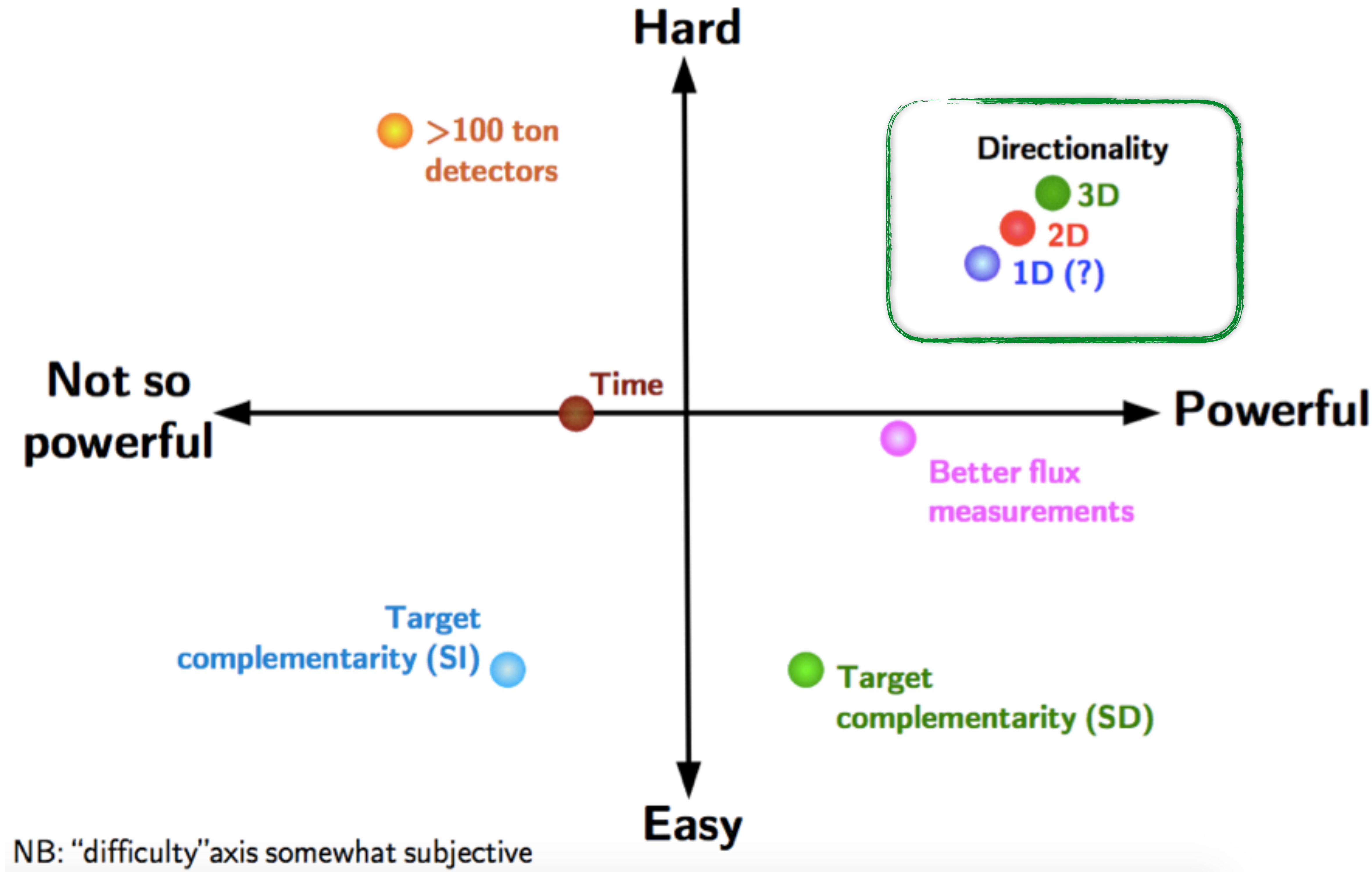
See also Grothaus et al. [1406.5047]

Directionality and the neutrino background



O'Hare et al. [1505.08061]

Strategies for the neutrino floor

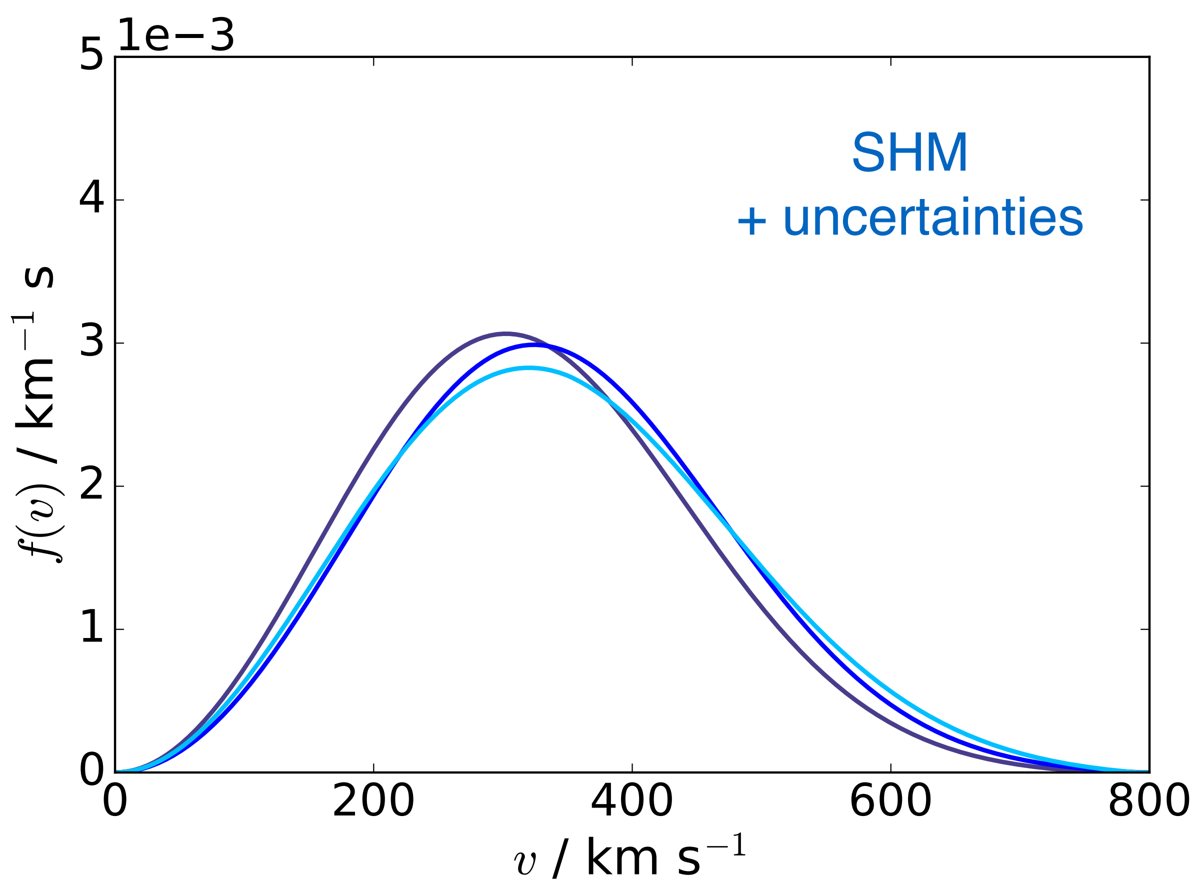


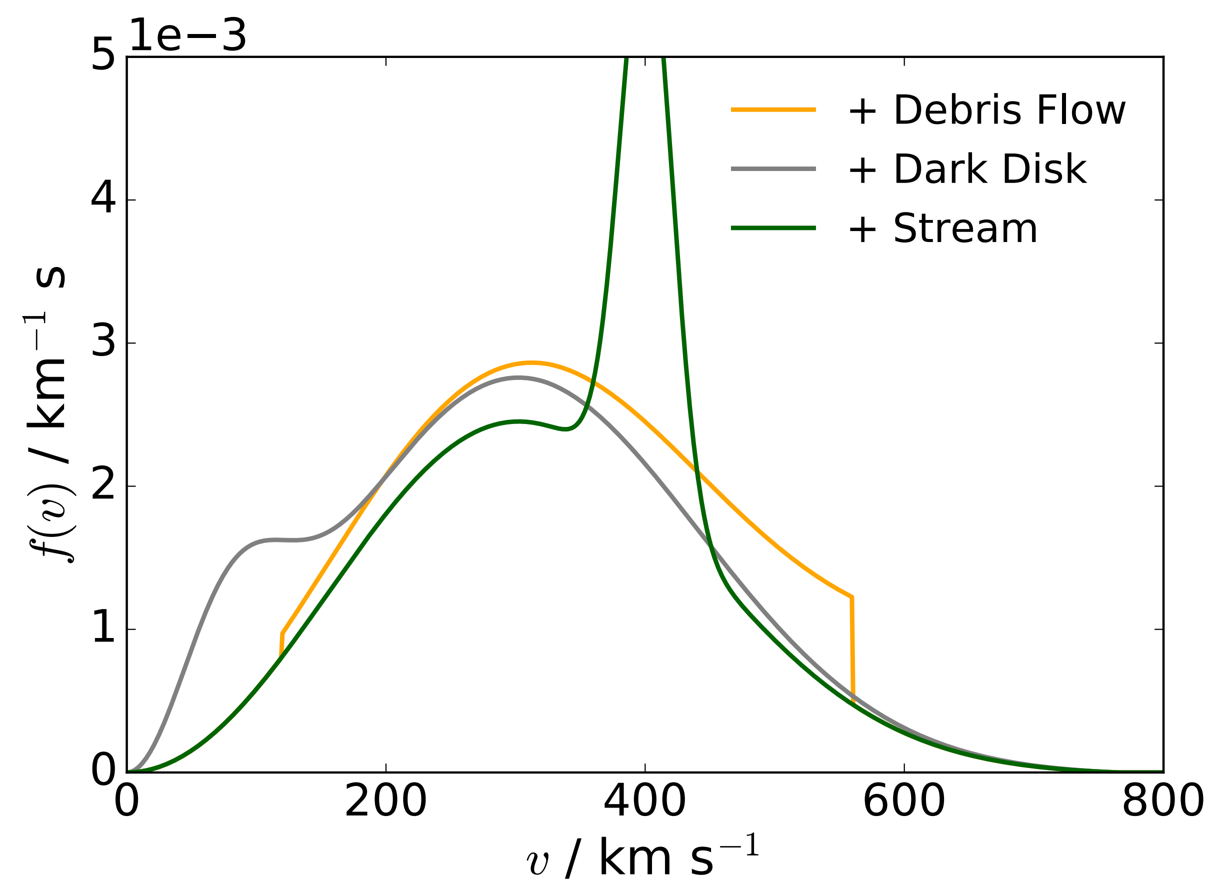
Ciaran O'Hare [IDM 2016]

Directionality in the *post*-discovery era:
Probing DM astrophysics

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]

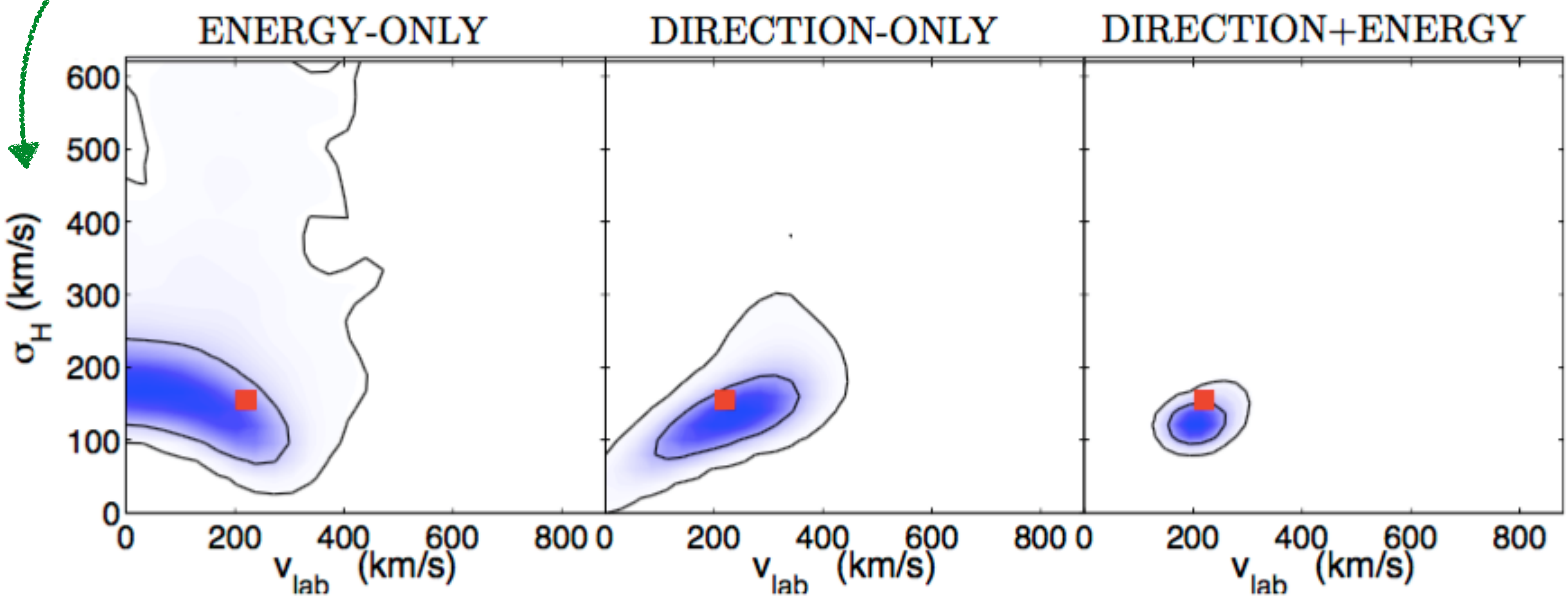
Dark disk — Pillepich et al. [1308.1703], Schaller et al. [1605.02770]

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

Modelling the DM halo

Assume SHM and fit the parameters (using mock data):

Halo dispersion



Earth's speed through halo

Lee & Peter [1202.5035]

Reconstructing the *speed* distribution

Write a *general parametrisation* for the speed distribution:

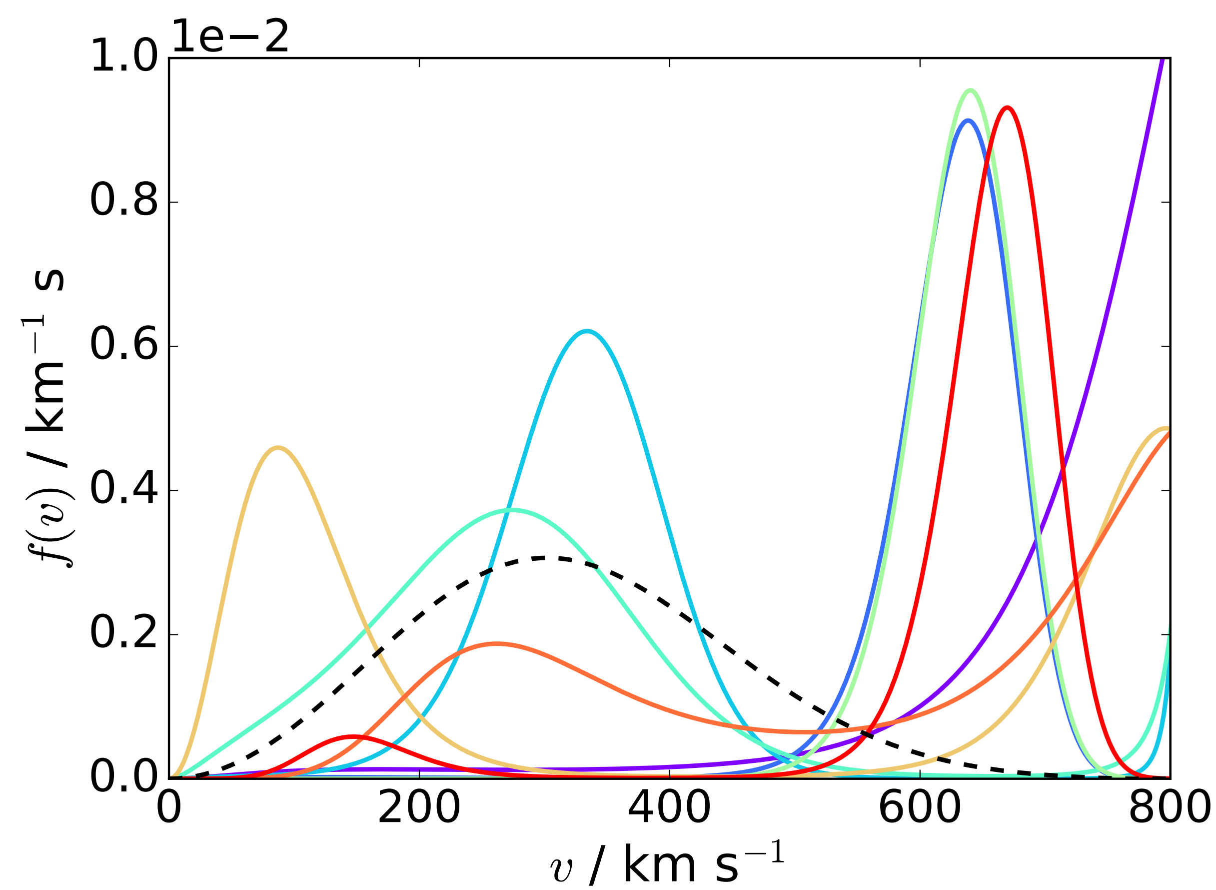
Peter [1103.5145]

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

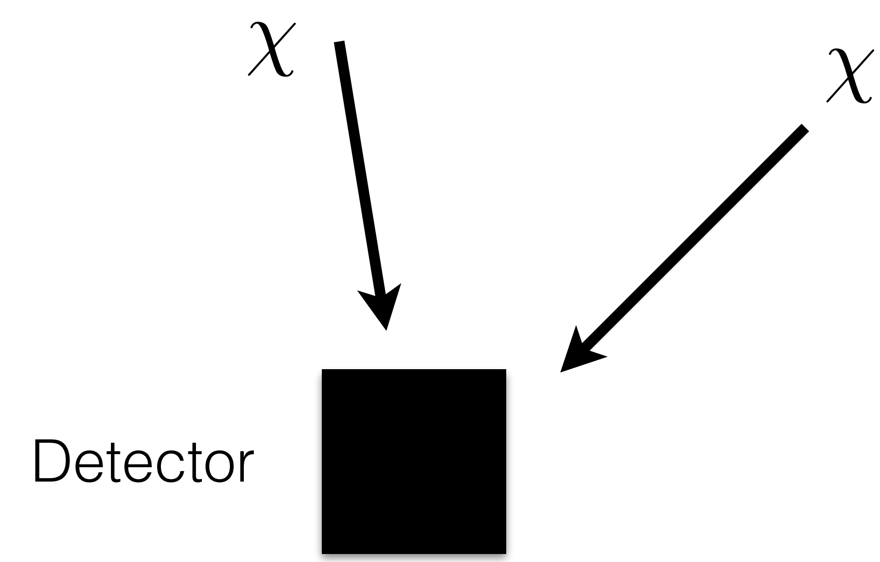
BJK & Green [1303.6868], BJK [1312.1852]

This form guarantees a positive distribution function.

Now we can fit the particle physics parameters $\{m_\chi, \sigma^p\}$, as well as the astrophysics parameters $\{a_m\}$.



DM *velocity* distribution



If we want to fit the *velocity* distribution, we now have an *infinite* number of functions to parametrise (one for each incoming direction (θ, ϕ))!

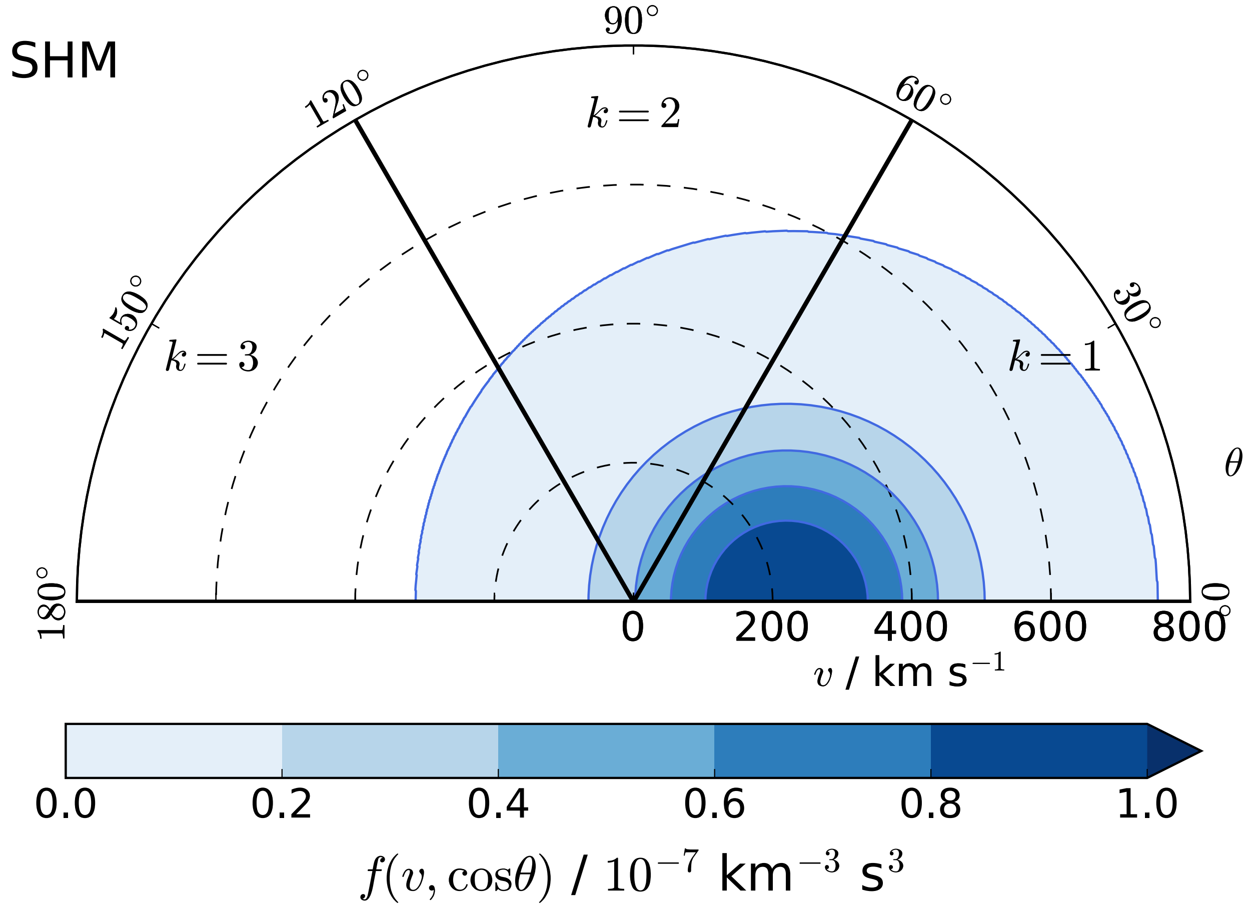
Make the problem more tractable: divide $f(\mathbf{v})$ into N = 3 angular bins…

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

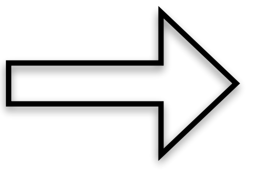
BJK [1502.04224]

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

An example: SHM



DM wind



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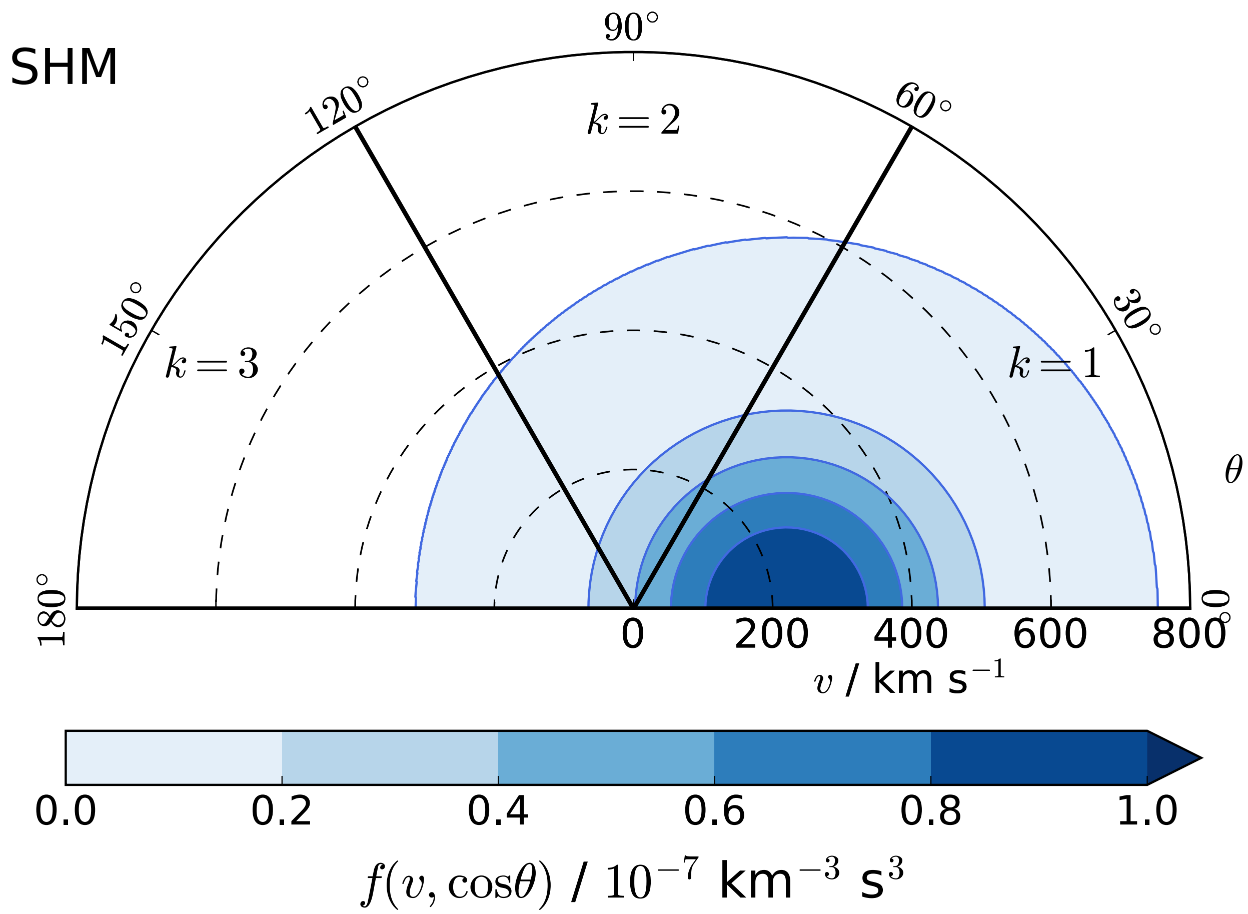
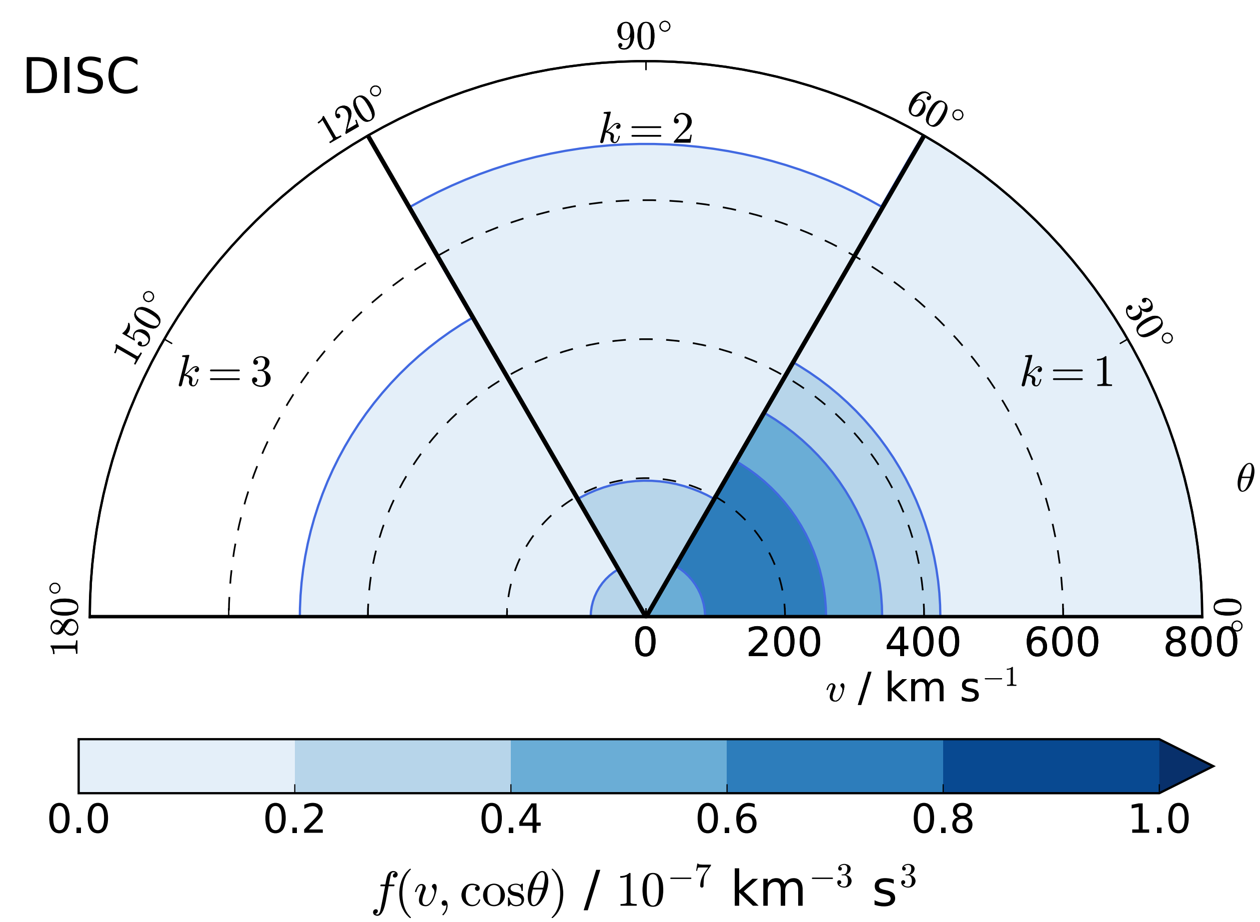
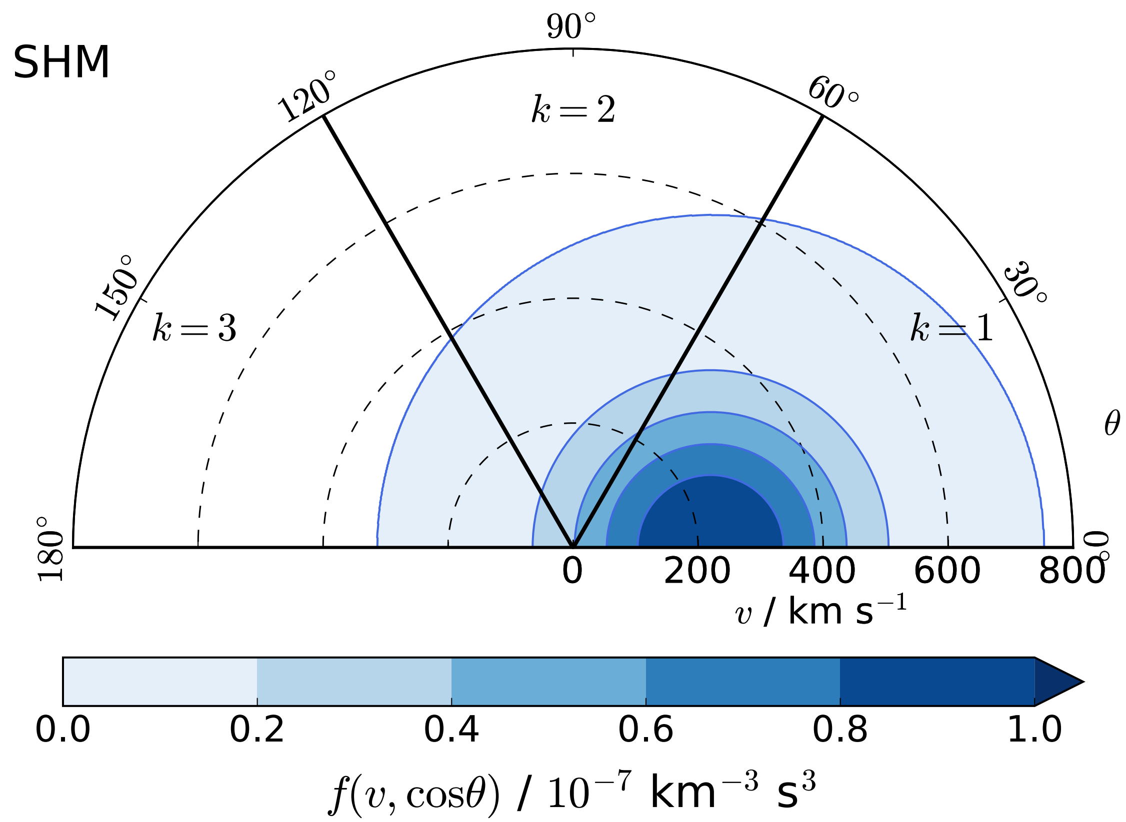
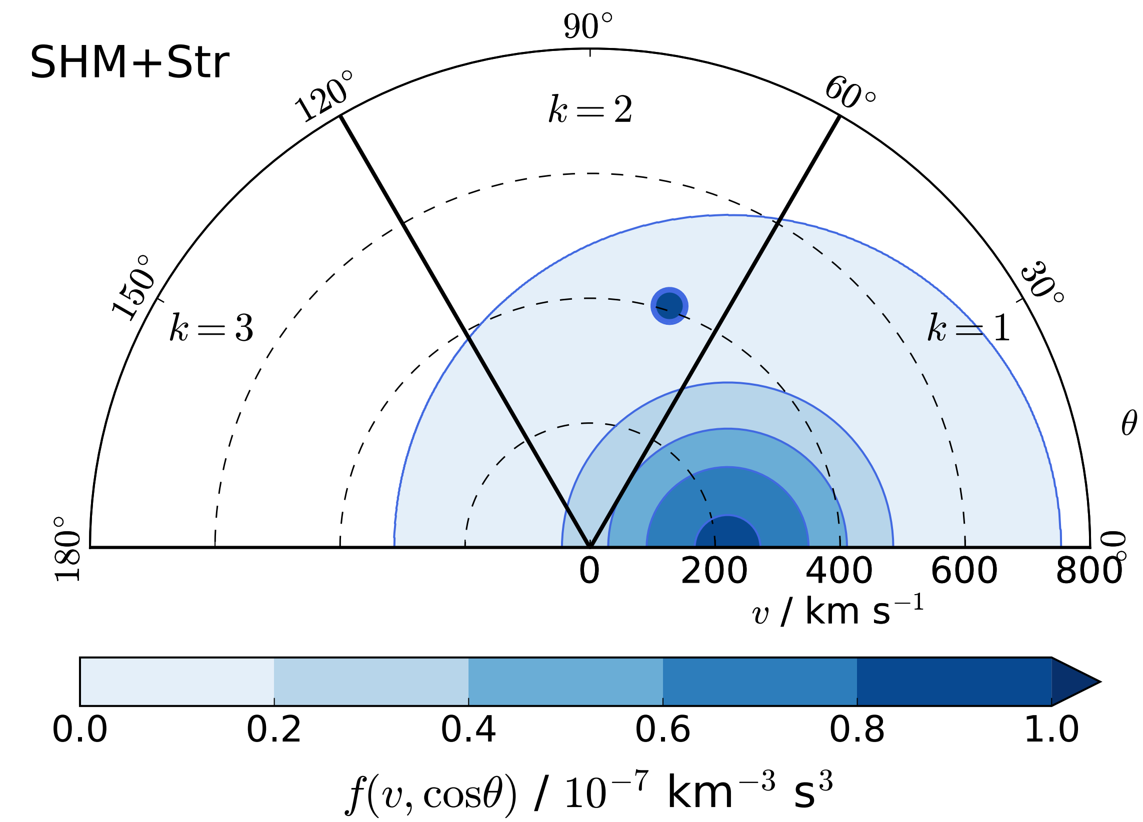


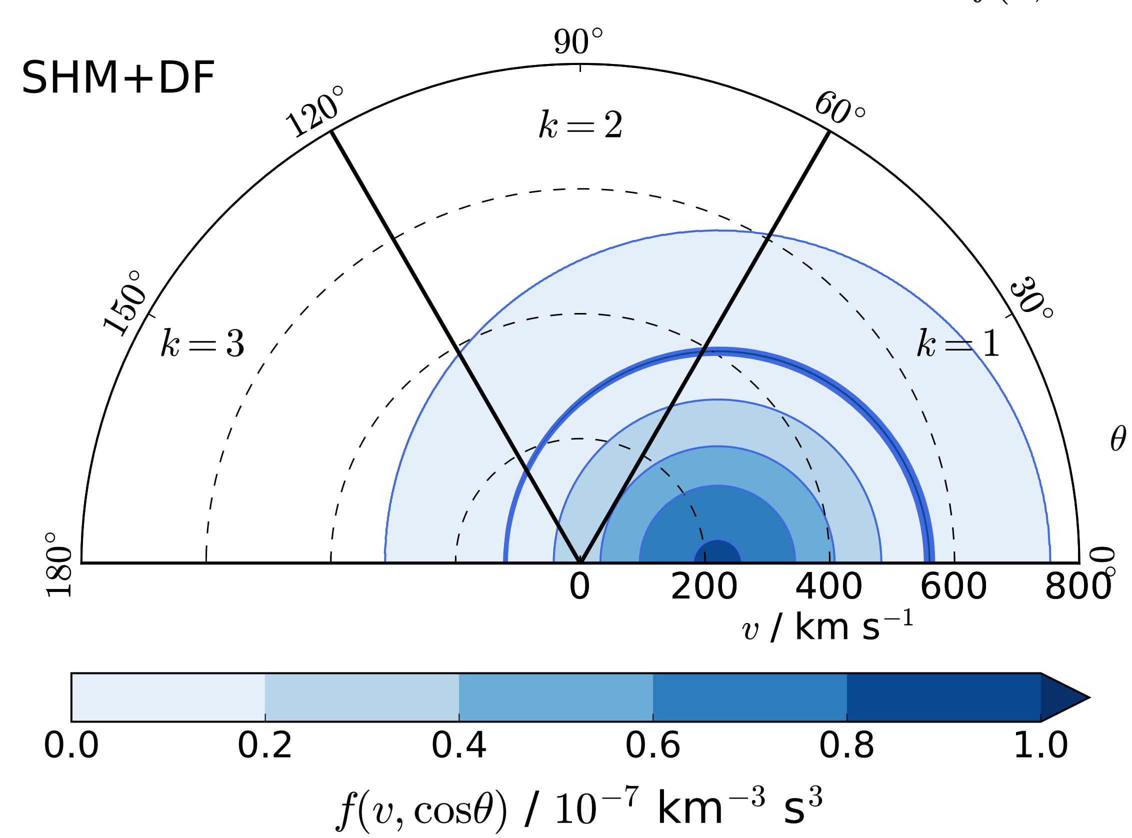
DM wind



Benchmarks

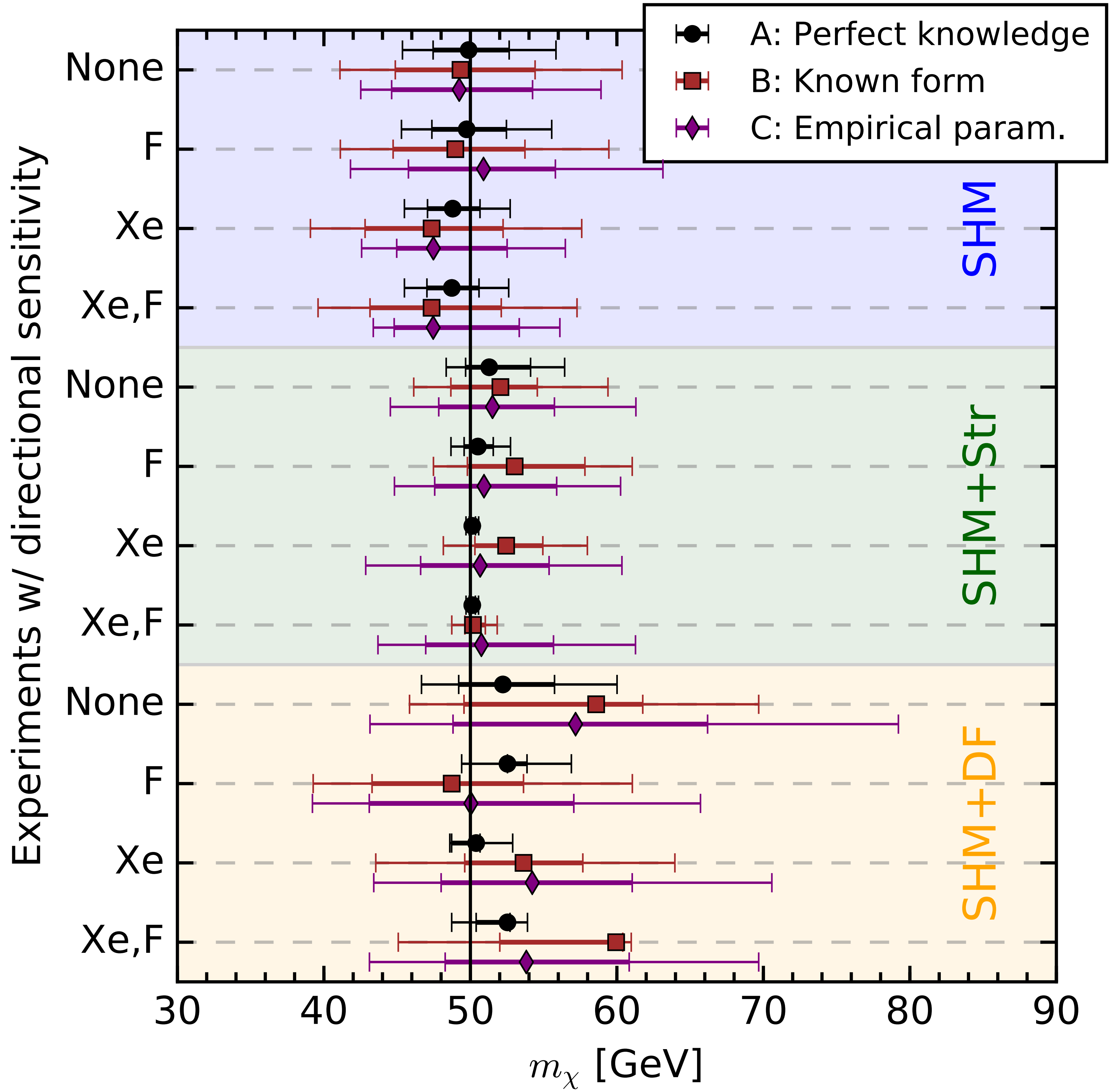

SHM
90°
60°
120°
30°
150°
180°
0°
$k=1$
$k=2$
$k=3$
θ
0
200
400
600
800
v / km s^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
$f(v, \cos\theta)$ / 10^{-7} km^{-3} s^{3}


SHM+Str
90°
60°
120°
30°
150°
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°
60°
120°
30°
150°
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}

Reconstructing the DM Mass

Use mock data for Xenon and Fluorine experiments to reconstruct the DM mass (along with the halo velocity distribution)



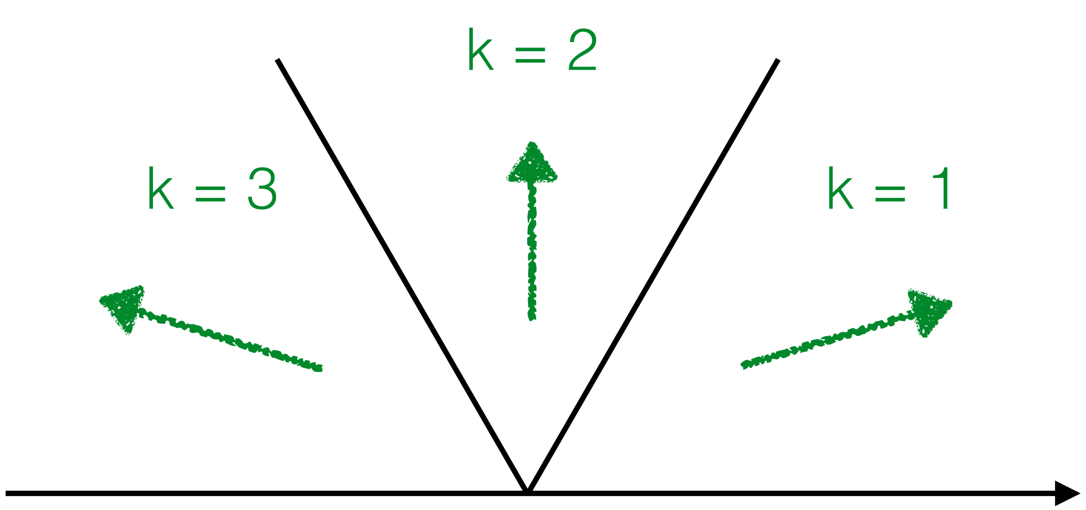
Shape of the velocity distribution

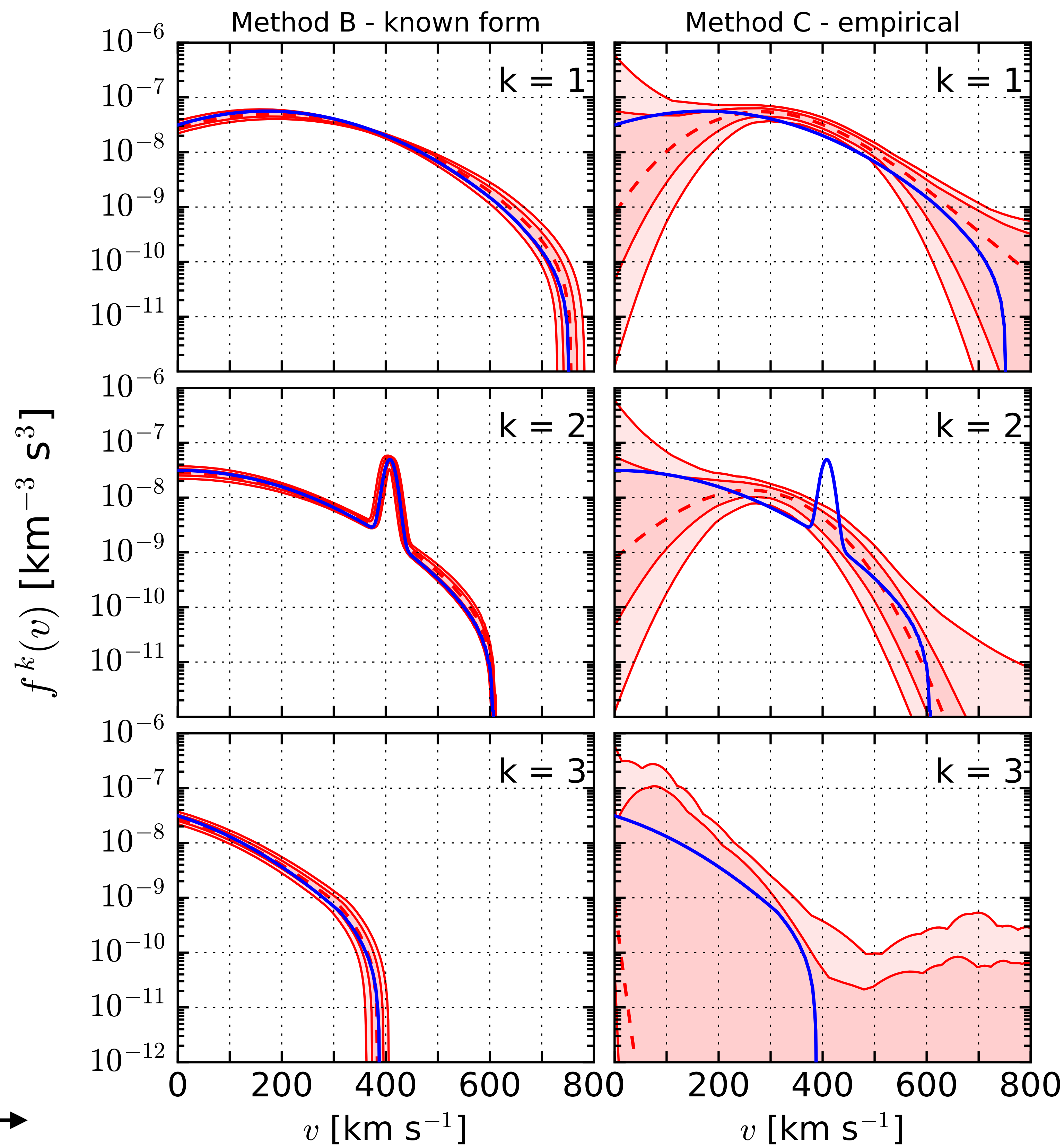
SHM+Stream distribution
with *directional sensitivity in Xe and F*

‘True’ velocity distribution

Best fit distribution

(+68% and 95% intervals)



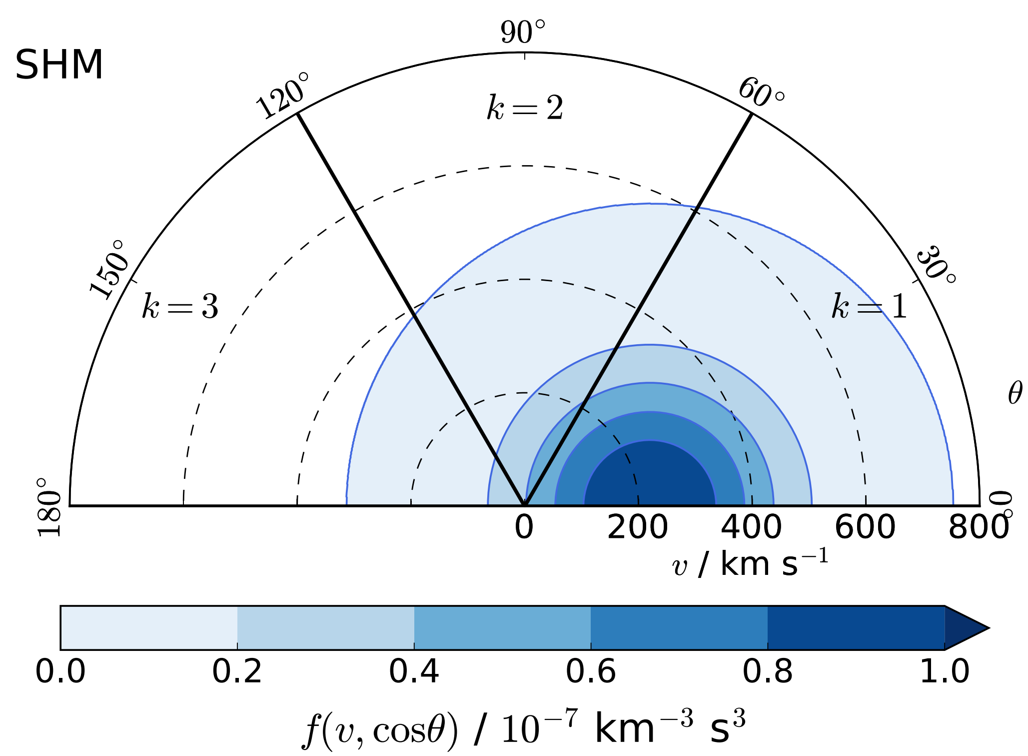


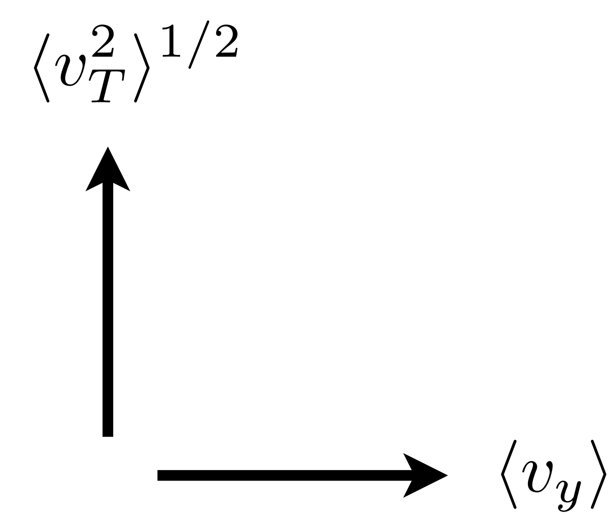
Velocity Parameters

In order to compare distributions, calculate some derived parameters:

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

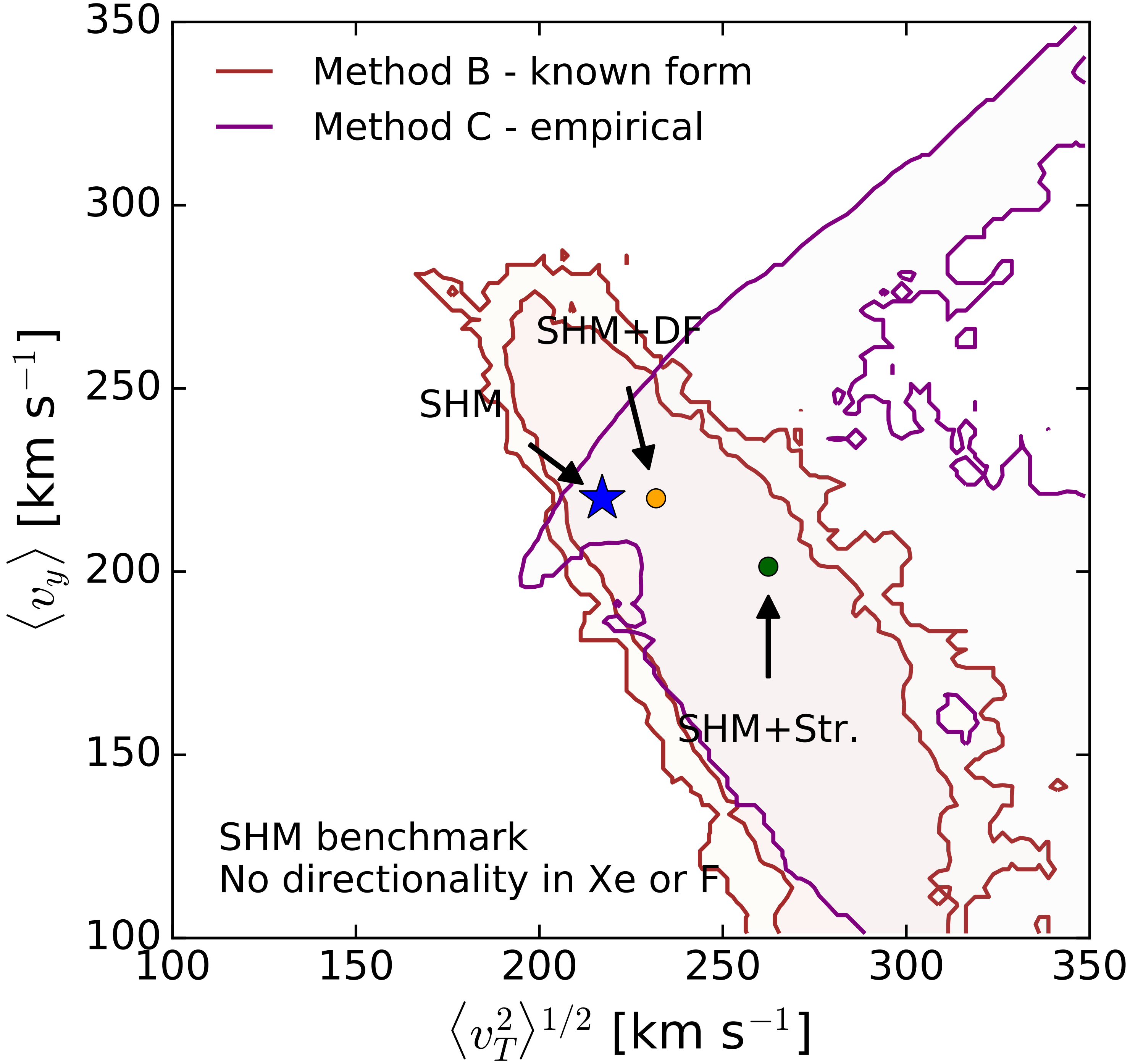
Average DM velocity *transverse* to Earth's motion $\longrightarrow$ $$\langle v_T^2 \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v^2\sin^2\theta)\, v^2 f(\mathbf{v})$$

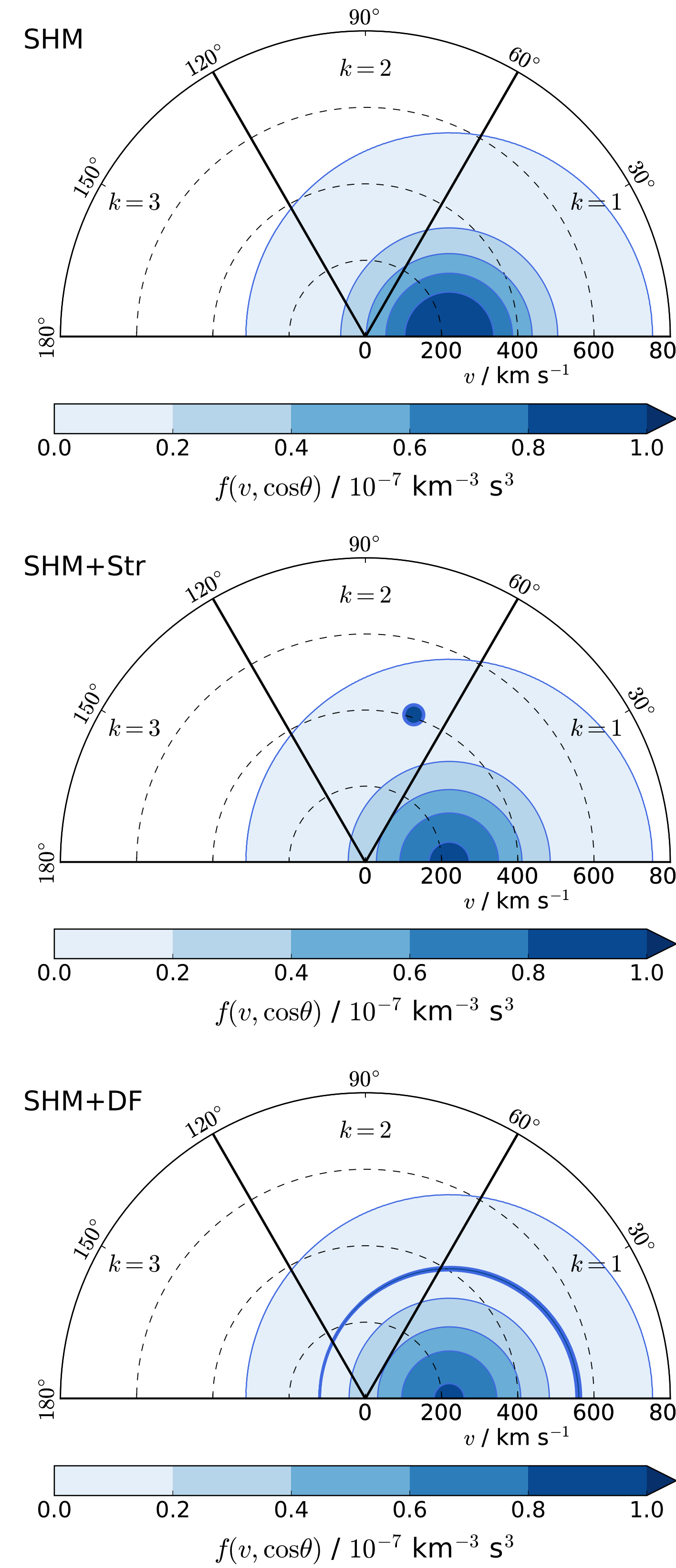




Comparing distributions - no directionality

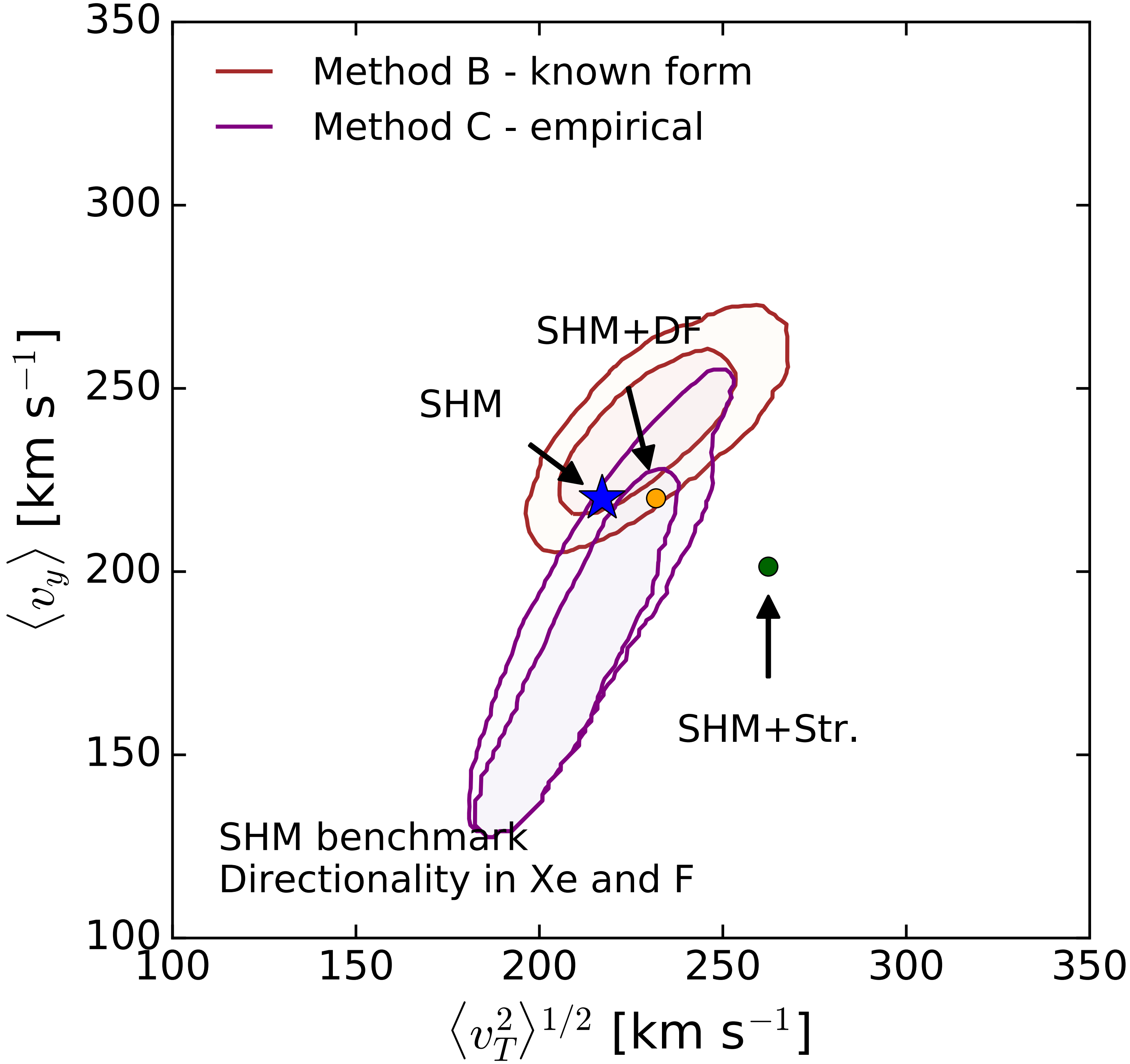
Input distribution: SHM

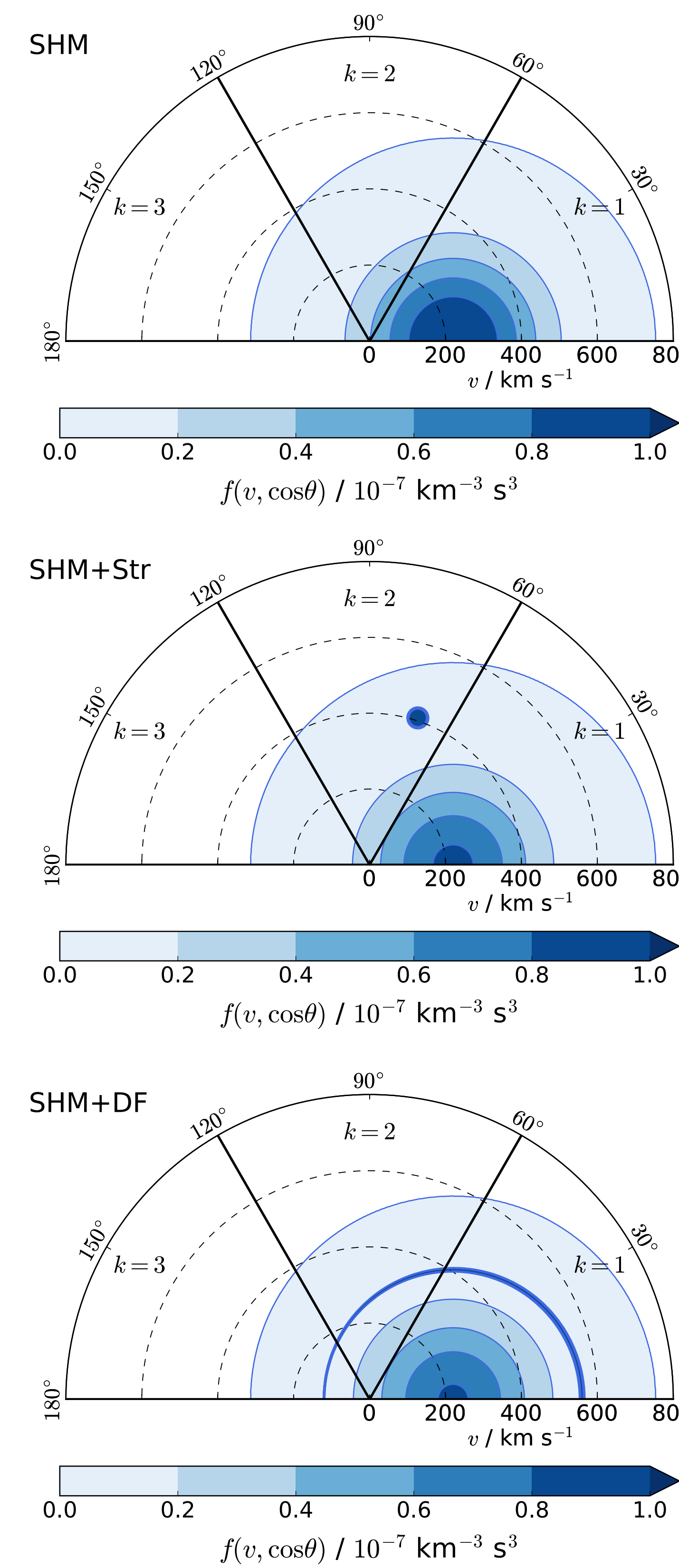




Comparing distributions - with directionality

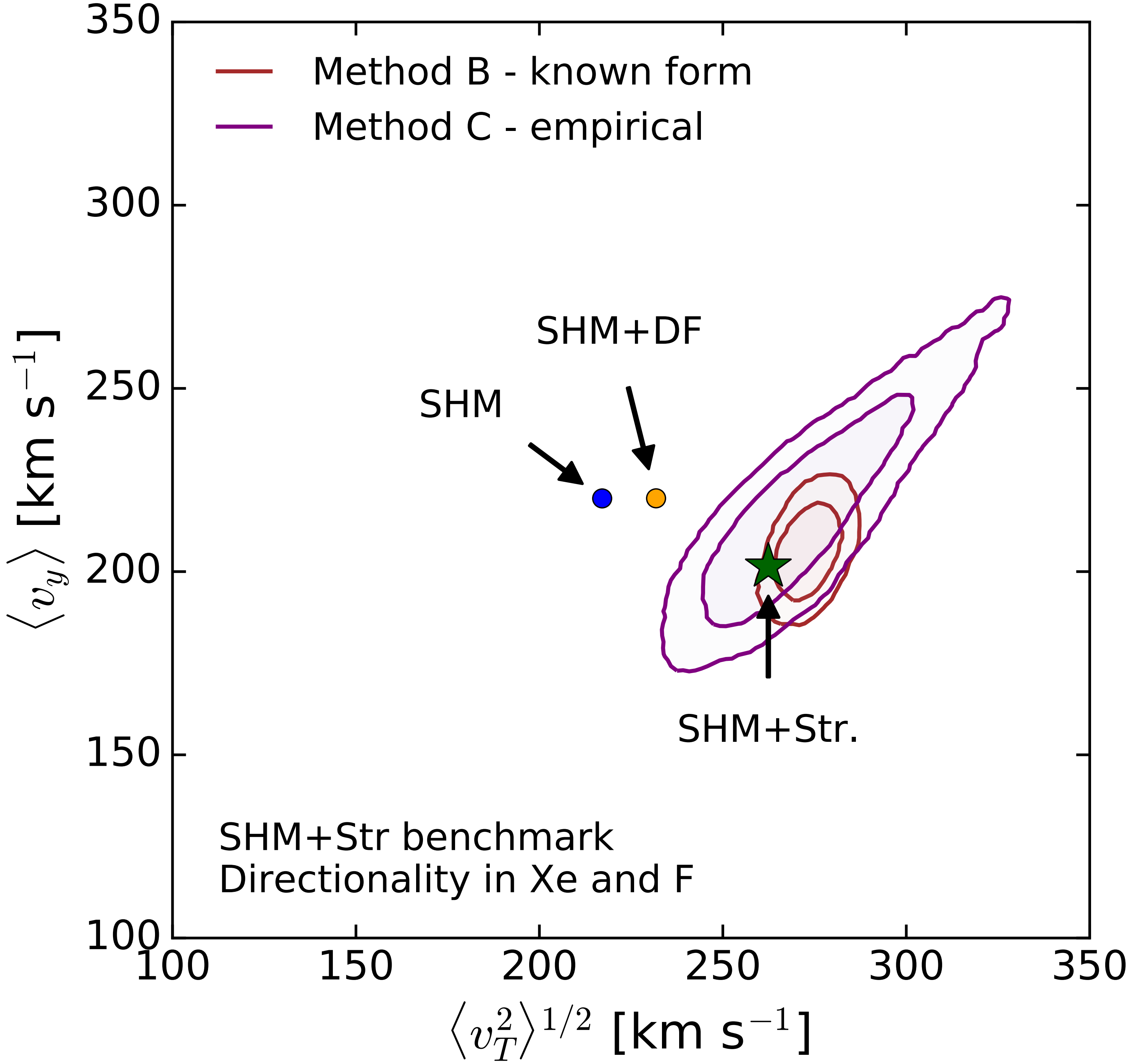
Input distribution: SHM

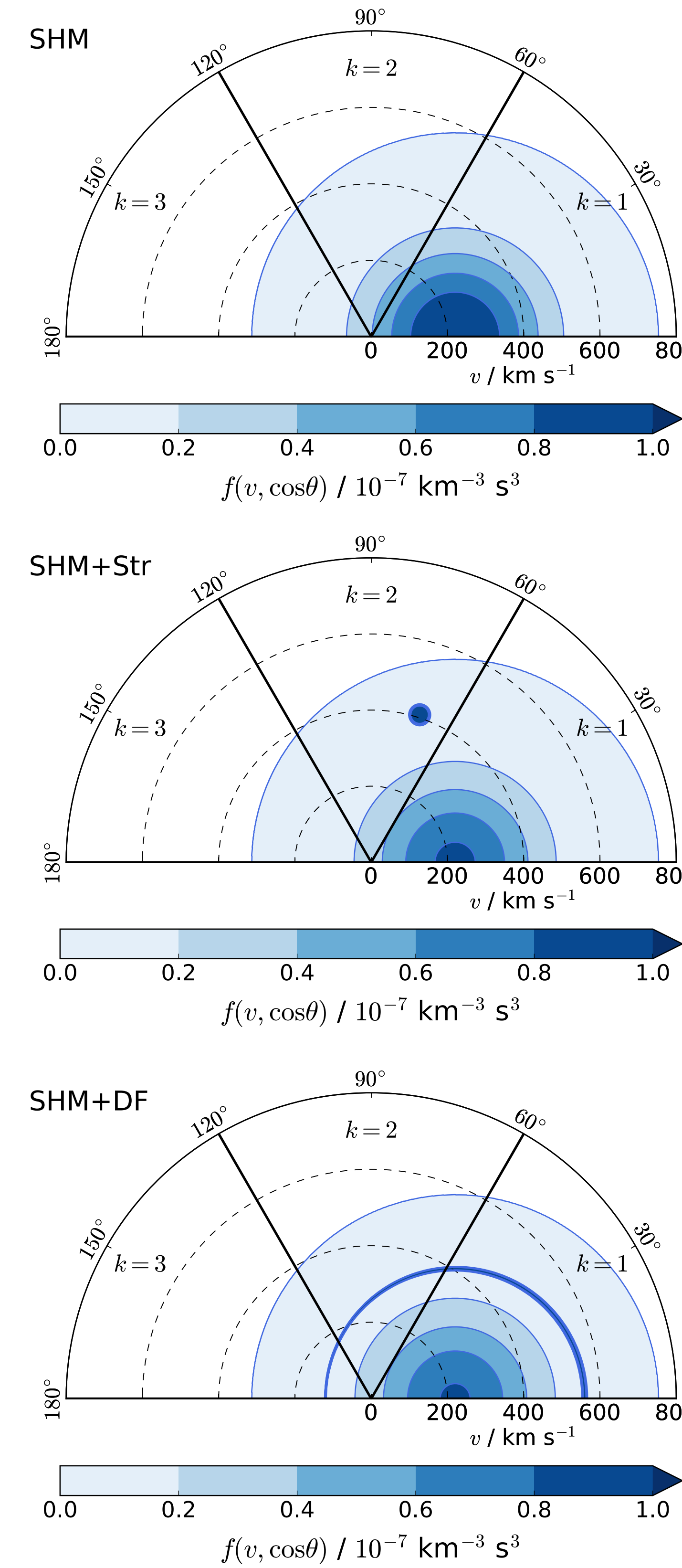




Comparing distributions - with directionality

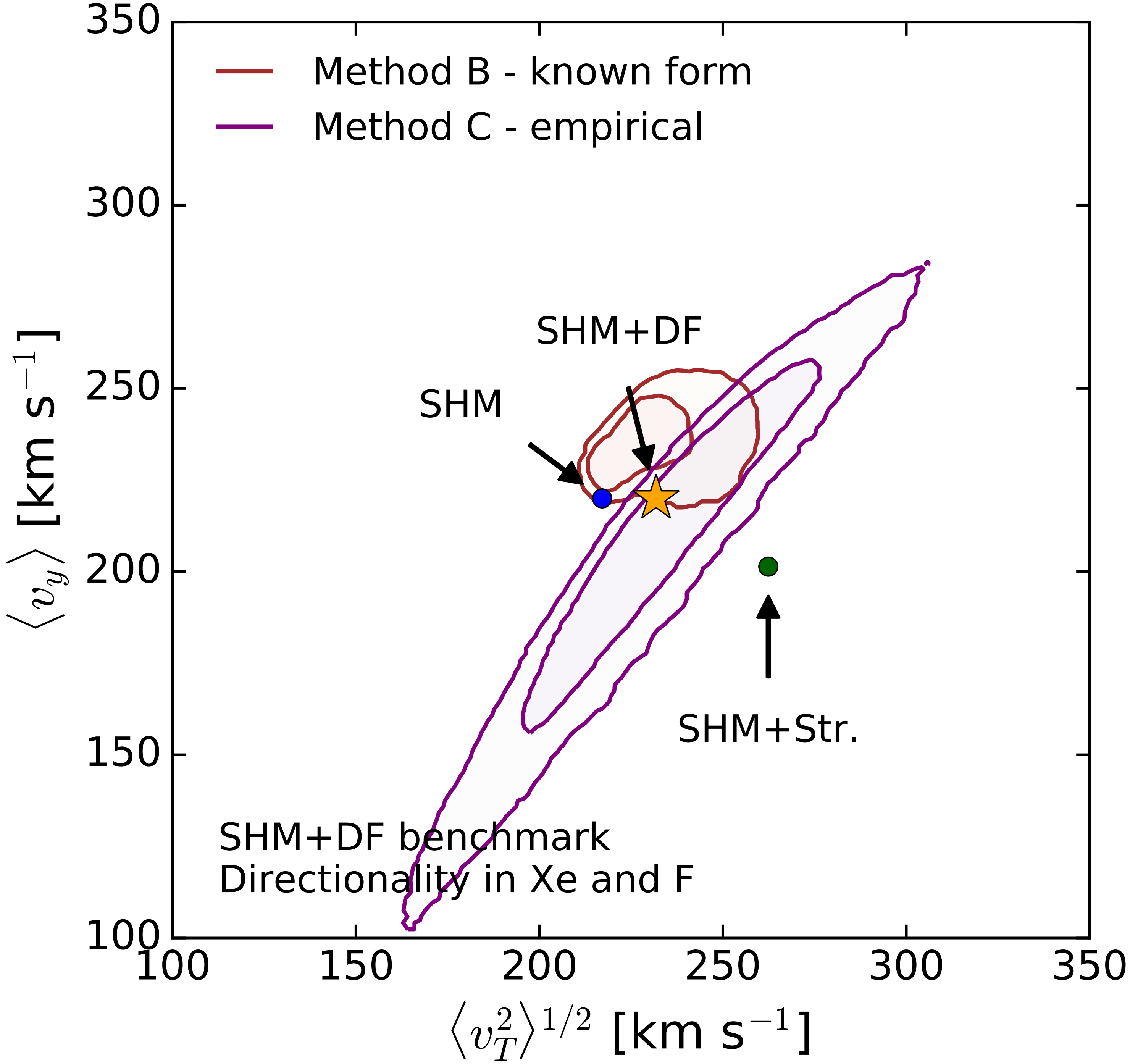
Input distribution: SHM + Stream

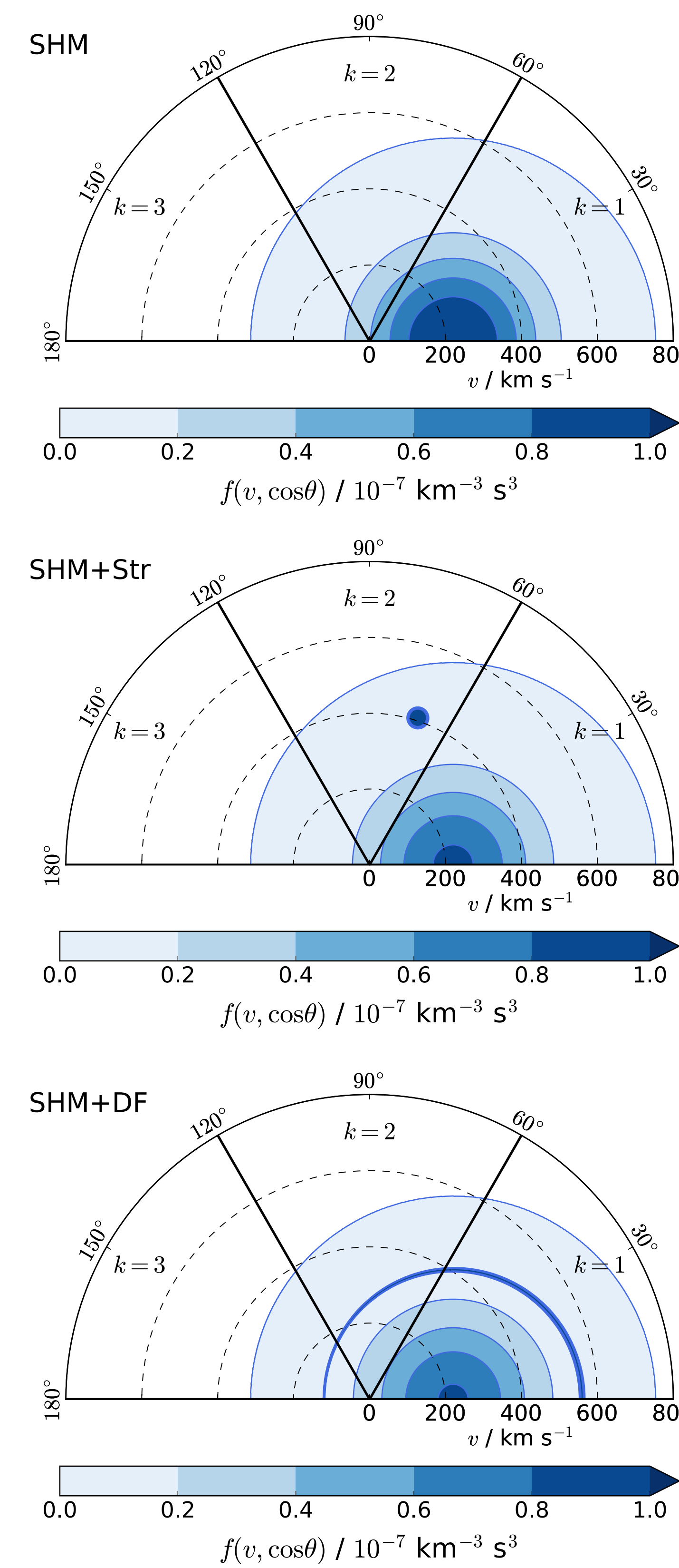




Comparing distributions - with directionality

Input distribution: SHM + Debris Flow

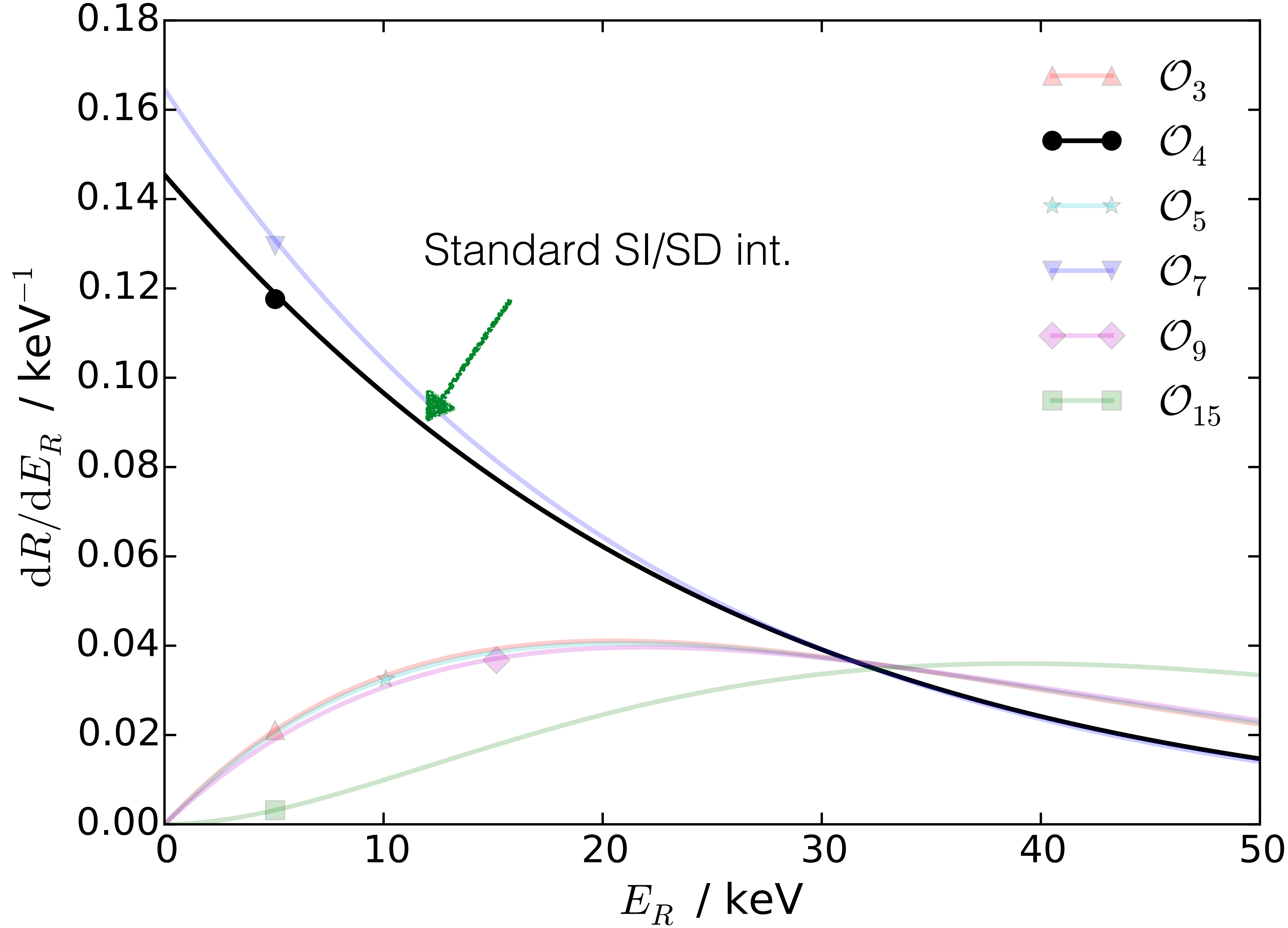




Directional detection may help us discriminate different halo models and probe the DM halo in a model-independent way, but what about…

Directionality in the *post*-discovery era: Probing DM particle physics

Standard Interactions



CF_4 detector,
$m_\chi = 100$ GeV

More general interactions

Can write non-relativistic (NR) DM-*nucleon* Lagrangian as an expansion in:

[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

Recoil momentum - $\vec{q}$

DM velocity - $\vec{v}$

$$\mathcal{L} \supset \boxed{\mathcal{L}_0} + \boxed{\mathcal{L}_1(\vec{v}) + \mathcal{L}_2(\vec{q}) + \mathcal{L}_3(\vec{v}, \vec{q}) + \ldots}$$

'Standard' interactions
(zeroth order)

'Non-standard' interactions
(higher order)

More general interactions

Can write non-relativistic (NR) DM-*nucleon* Lagrangian as an expansion in:
[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

Recoil momentum - $\vec{q}$

Transverse DM velocity - $\vec{v}_\perp$

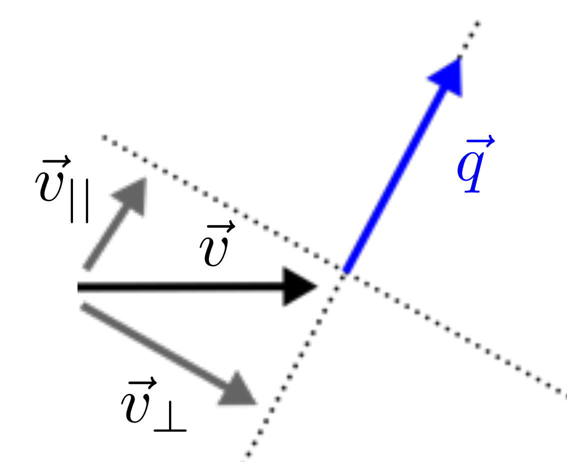
$$\mathcal{L} \supset \boxed{\mathcal{L}_0} + \boxed{\mathcal{L}_1(\vec{v}_\perp) + \mathcal{L}_2(\vec{q}) + \mathcal{L}_3(\vec{v}_\perp, \vec{q}) + ...}$$

'Standard' interactions
(zeroth order)

'Non-standard' interactions
(higher order)

The DM velocity operator is not Hermitian, so it can appear only through the Hermitian *transverse velocity*:

$$\vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}} \qquad \Rightarrow \vec{v}_\perp \cdot \vec{q} = 0$$



Non-relativistic Effective Field Theory (NREFT)

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI

$$\boxed{\mathcal{O}_1 = 1}$$

SD

$$\boxed{\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N}$$

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

Non-relativistic Effective Field Theory (NREFT)

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI

SD

$$\boxed{\mathcal{O}_1 = 1}$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)/m_N$$

$$\boxed{\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N}$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)/m_N$$

$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})/m_N^2$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})/m_N$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}/m_N$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}/m_N$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})/m_N$$

$$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)/m_N$$

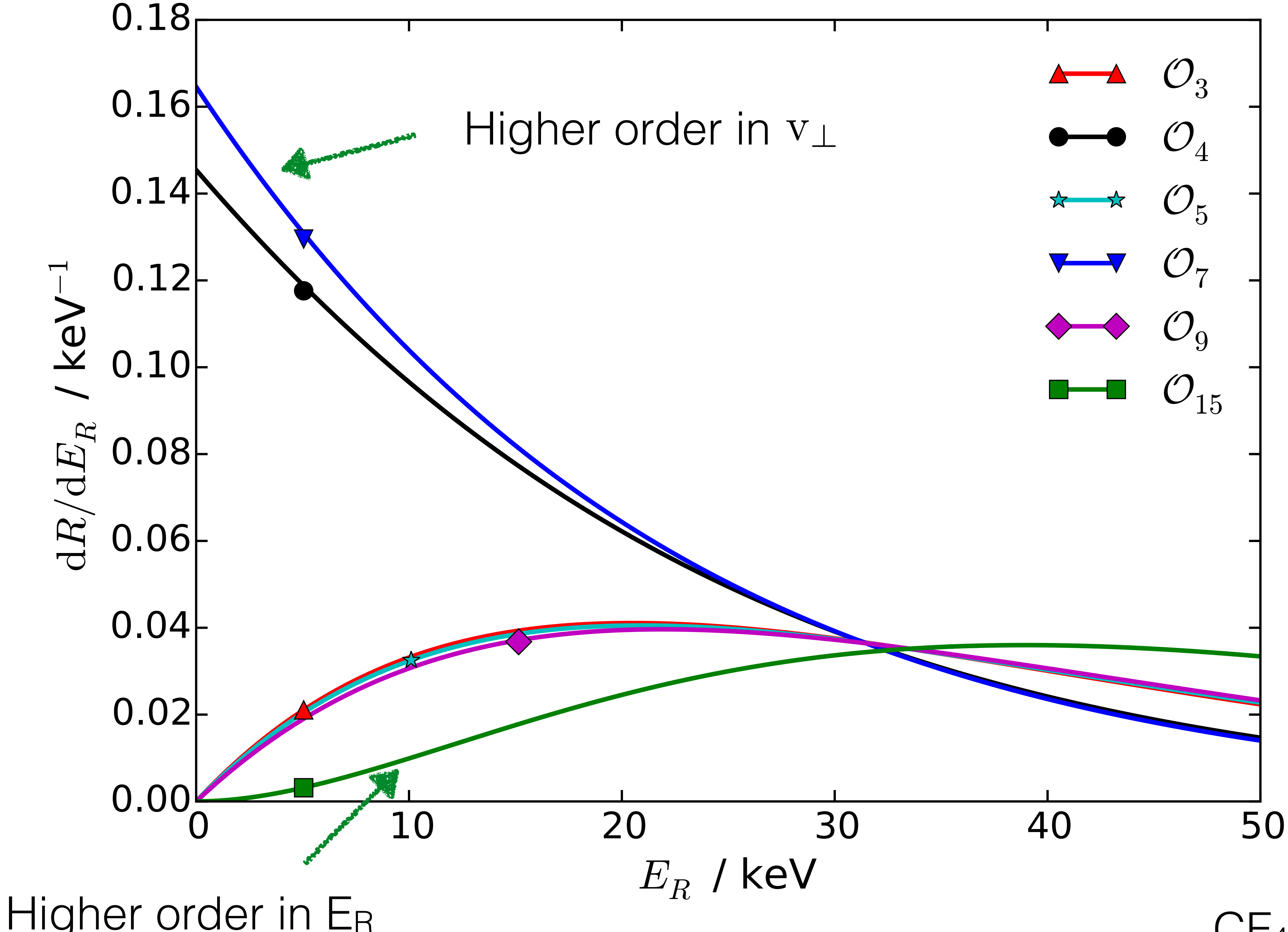
$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q}/m_N^2$$

$$\vdots$$

Whole list of new operators, higher order in $\mathrm{v}_\perp$ and $E_R \sim q^2$

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

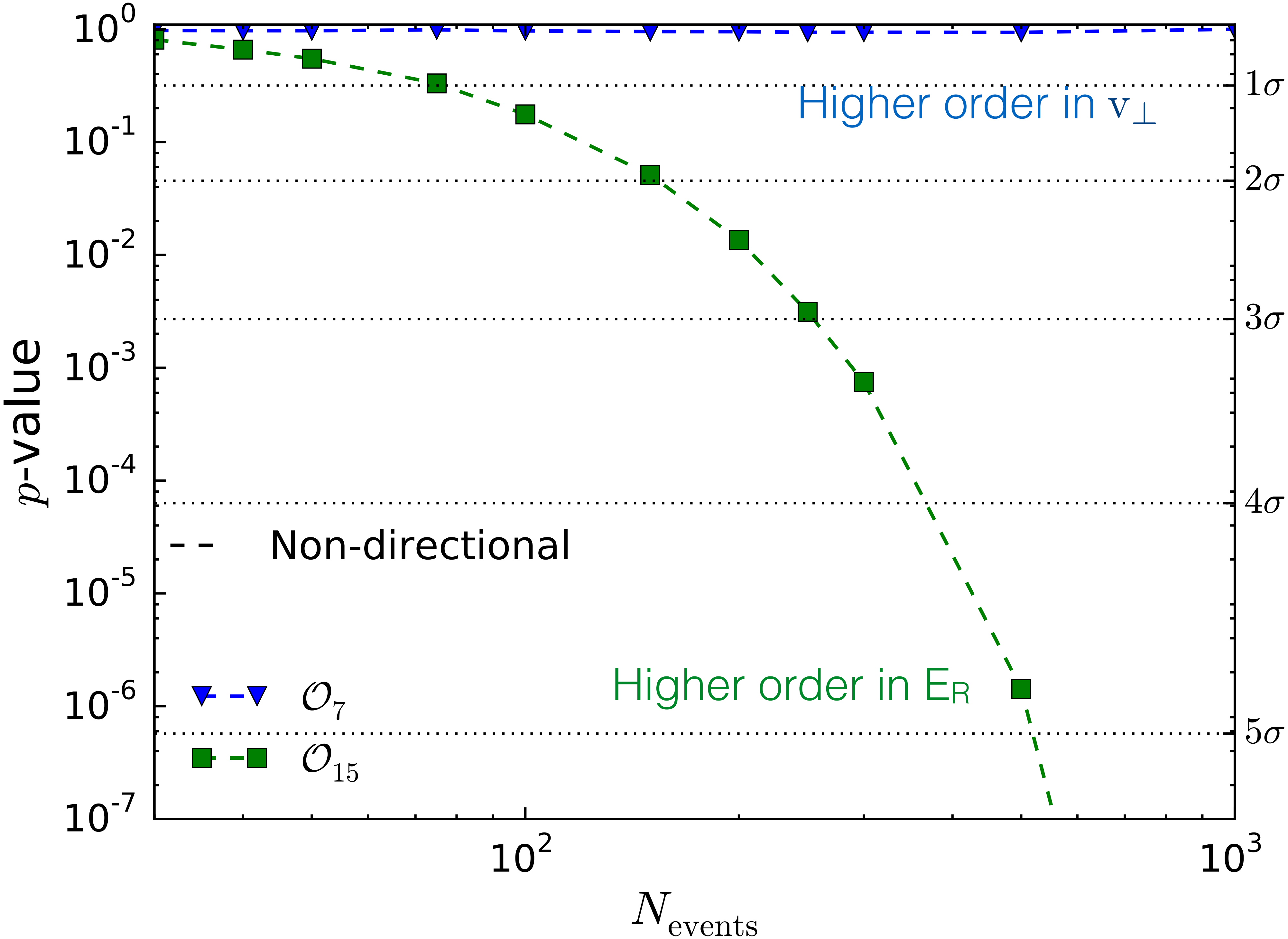
Non-standard Interactions



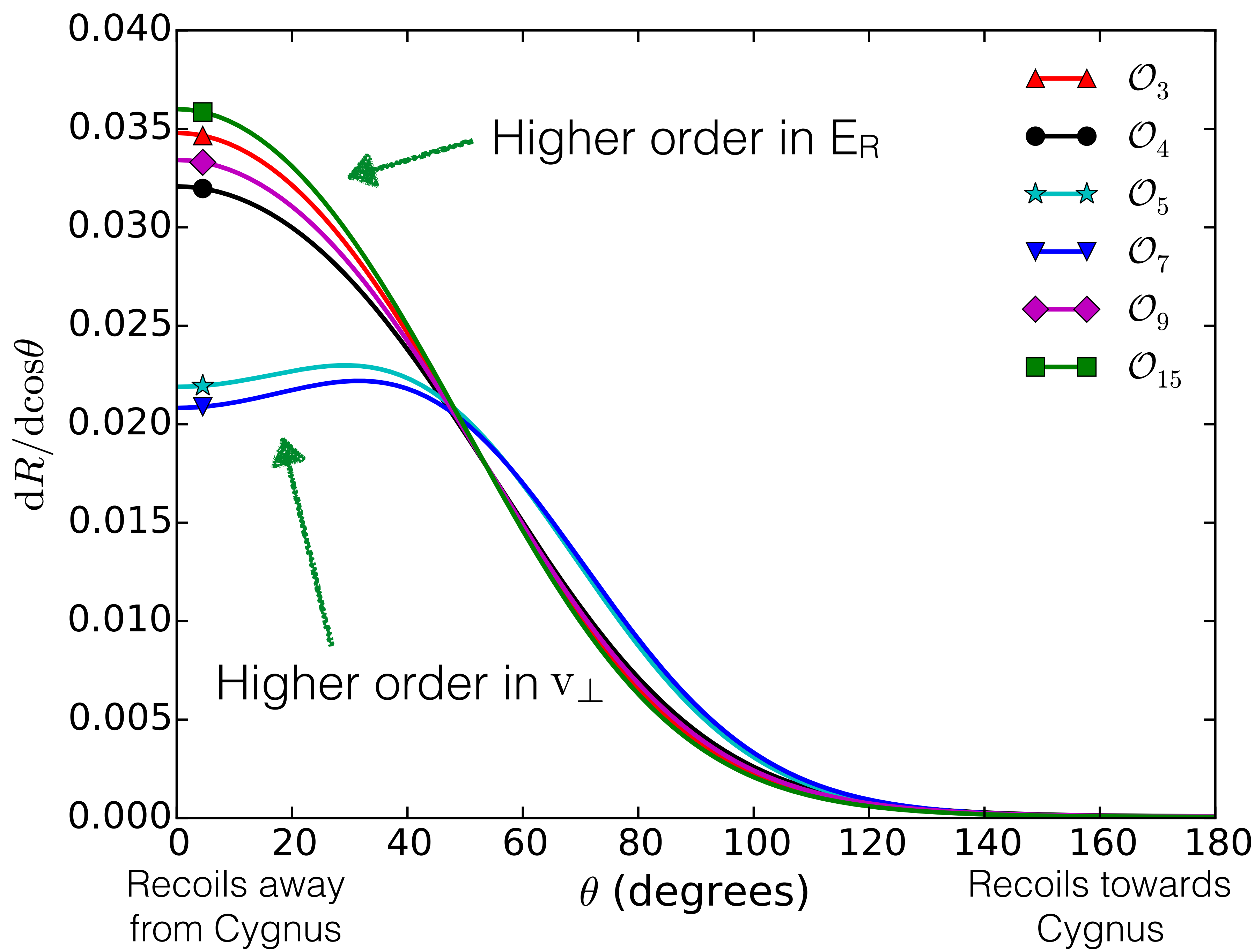
CF_4 detector,
$m_\chi = 100$ GeV

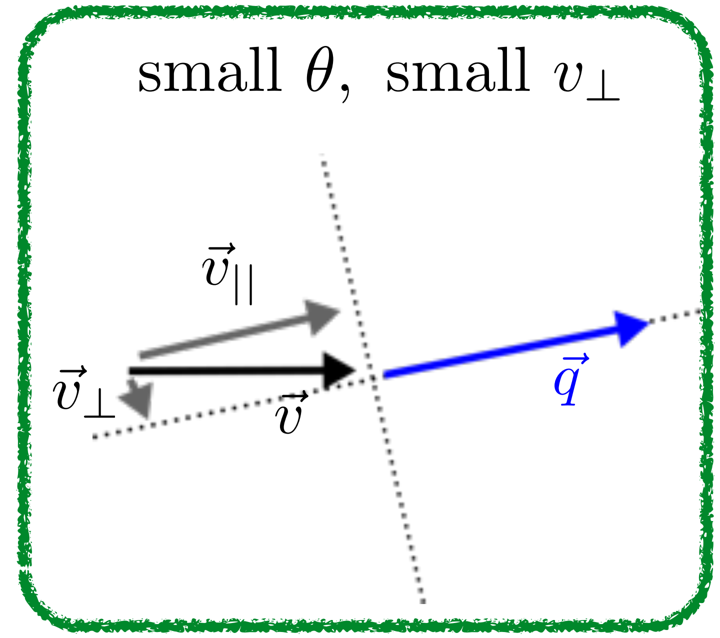
Distinguishing interactions - energy-only

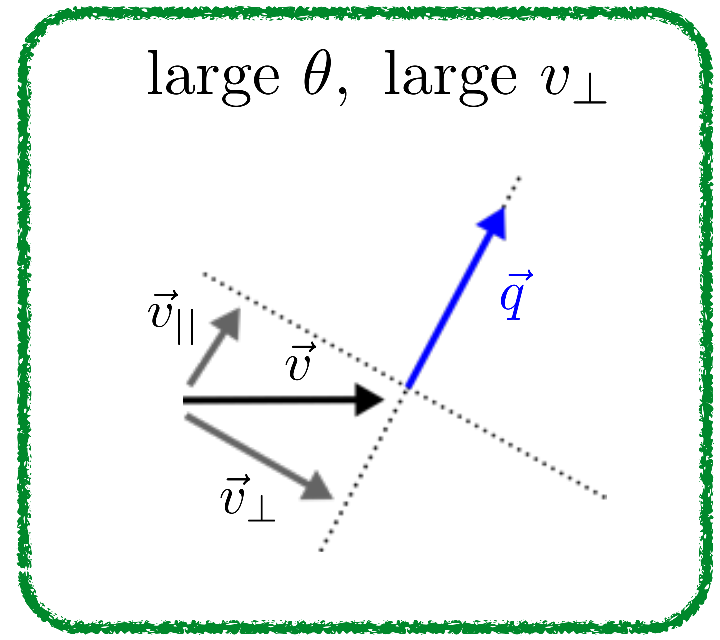
How many events are required to detect the effect of a 'non-standard' interaction?



Directional Spectrum



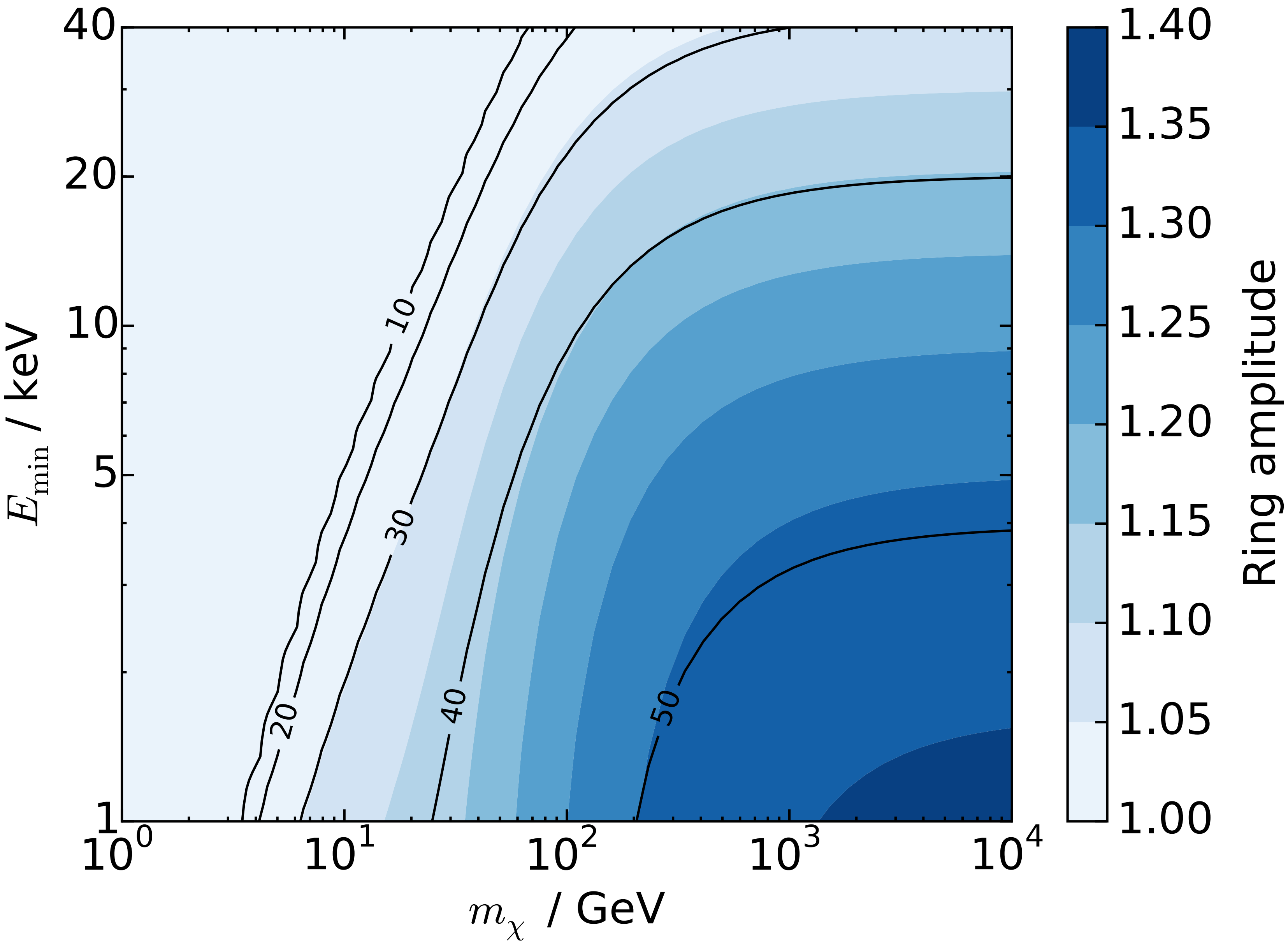




Also note: $q = 2\mu_{\chi N}\vec{v}\cdot\hat{q}$
$= 2\mu_{\chi N} v\cos\theta$

Ring feature

For operators which are higher order in $v_\perp$:



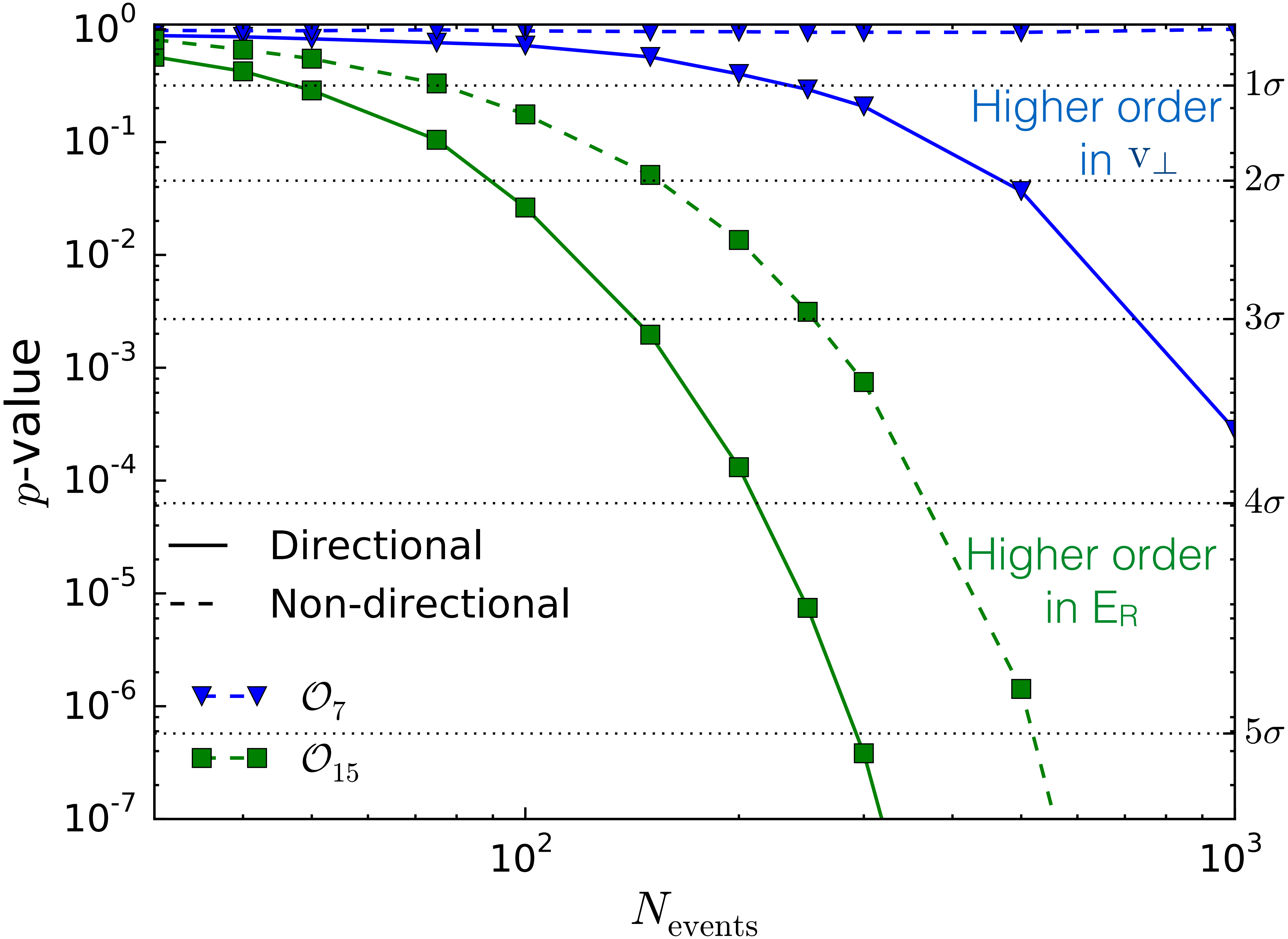
Contours:
ring opening angle
in degrees

Shading:
ring amplitude (ratio
of ring to centre)

A ring in the standard rate has been previously studied [1111.6361], but *this* ring occurs for lower WIMP masses and higher threshold energies.

Distinguishing interactions - directionality

How many events are required to detect the effect of a 'non-standard' interaction?

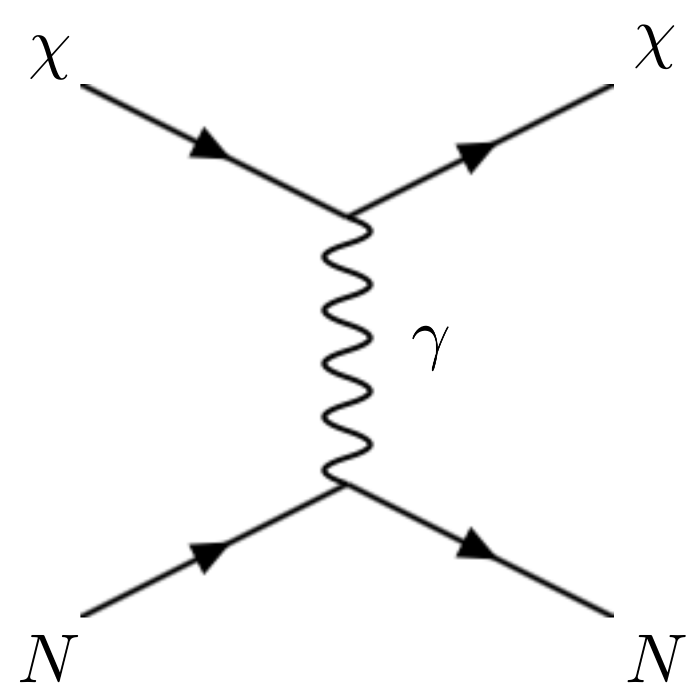


Example: Anapole DM

[1211.0503, 1401.4508, 1506.04454]

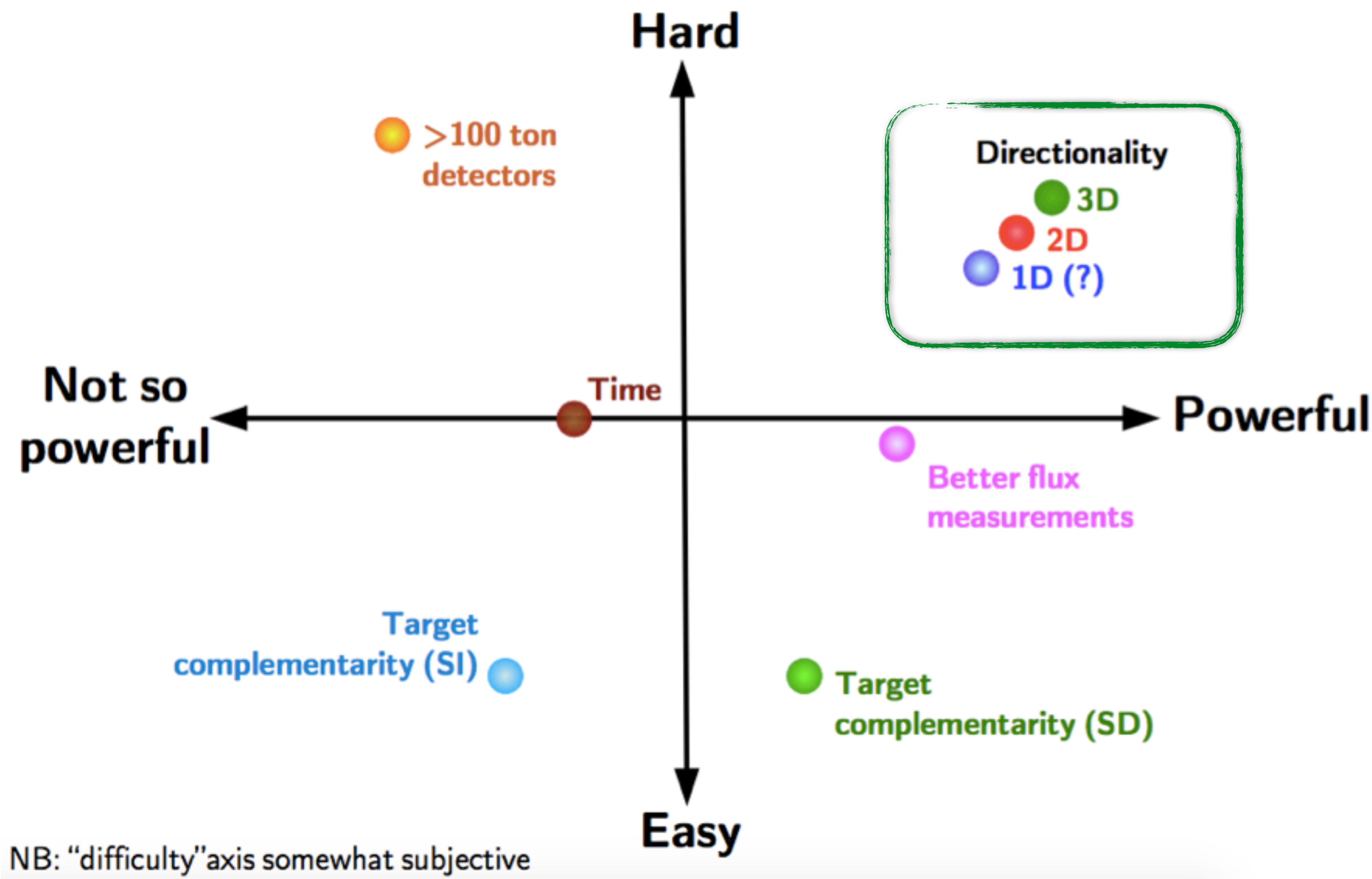
If DM has an 'anapole' moment
(lowest order EM moment possible for a Majorana fermion),
the interaction with nucleons is higher order in $v_\perp$.

$$\mathcal{O}_A = \bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$



In a single experiment, this interaction can only be discriminated
from standard interactions with *directionality*!

Strategies for the neutrino floor



Ciaran O'Hare [IDM 2016]

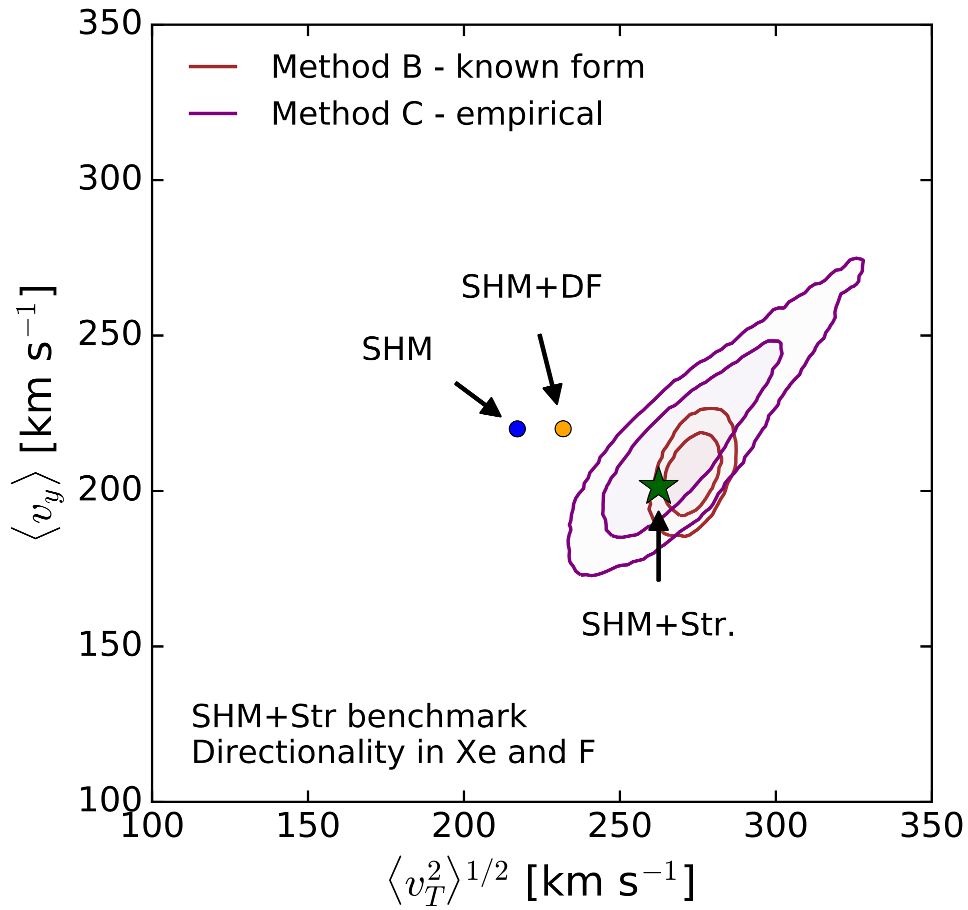
Summary

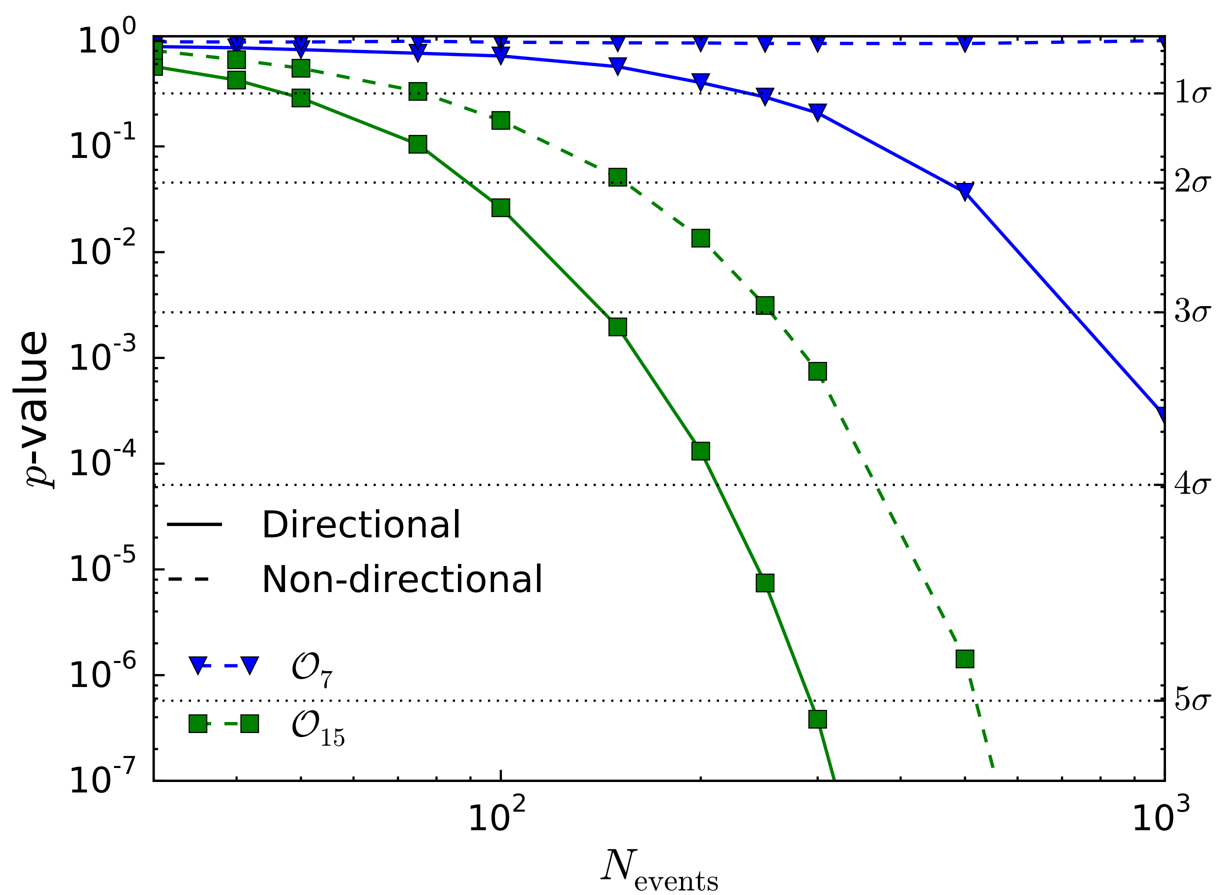
Directional detection is **HARD**. But it is also very **POWERFUL**.

In the discovery era, it provides a smoking gun signal (the dipole) and a method of beating the neutrino background.

In the post-discovery era, it will allow us to probe both the…

Astrophysics of DM + Particle Physics of DM





Summary

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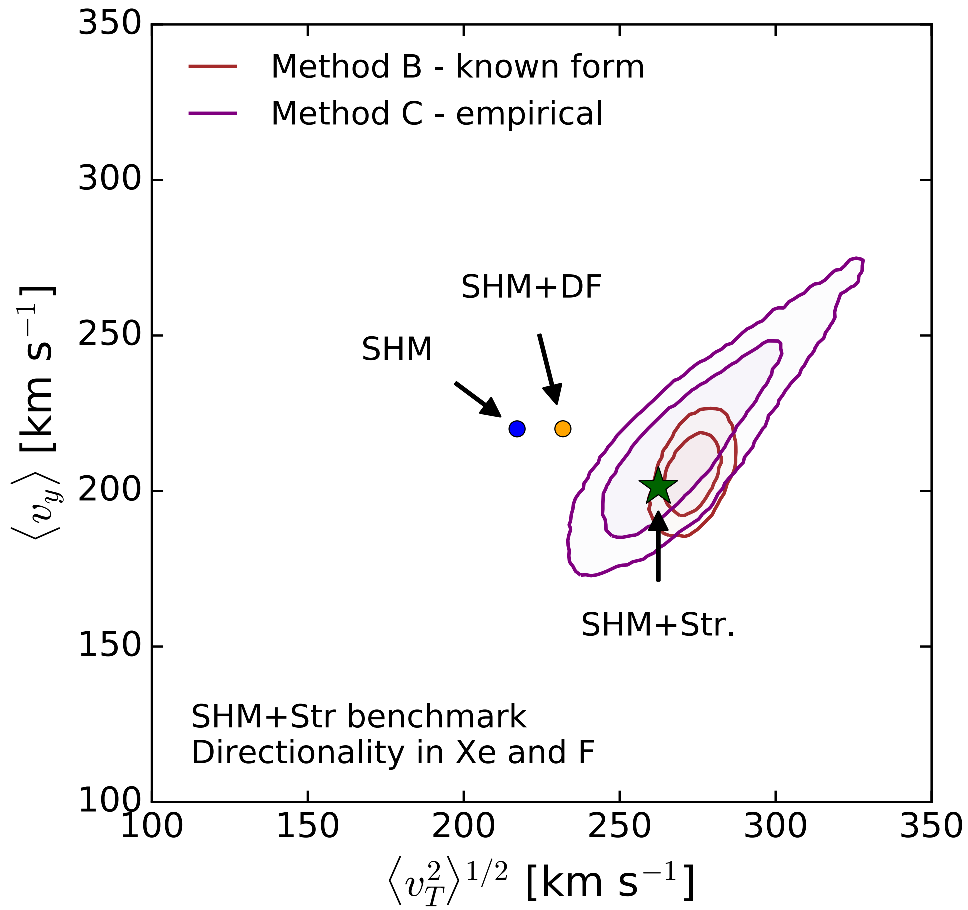
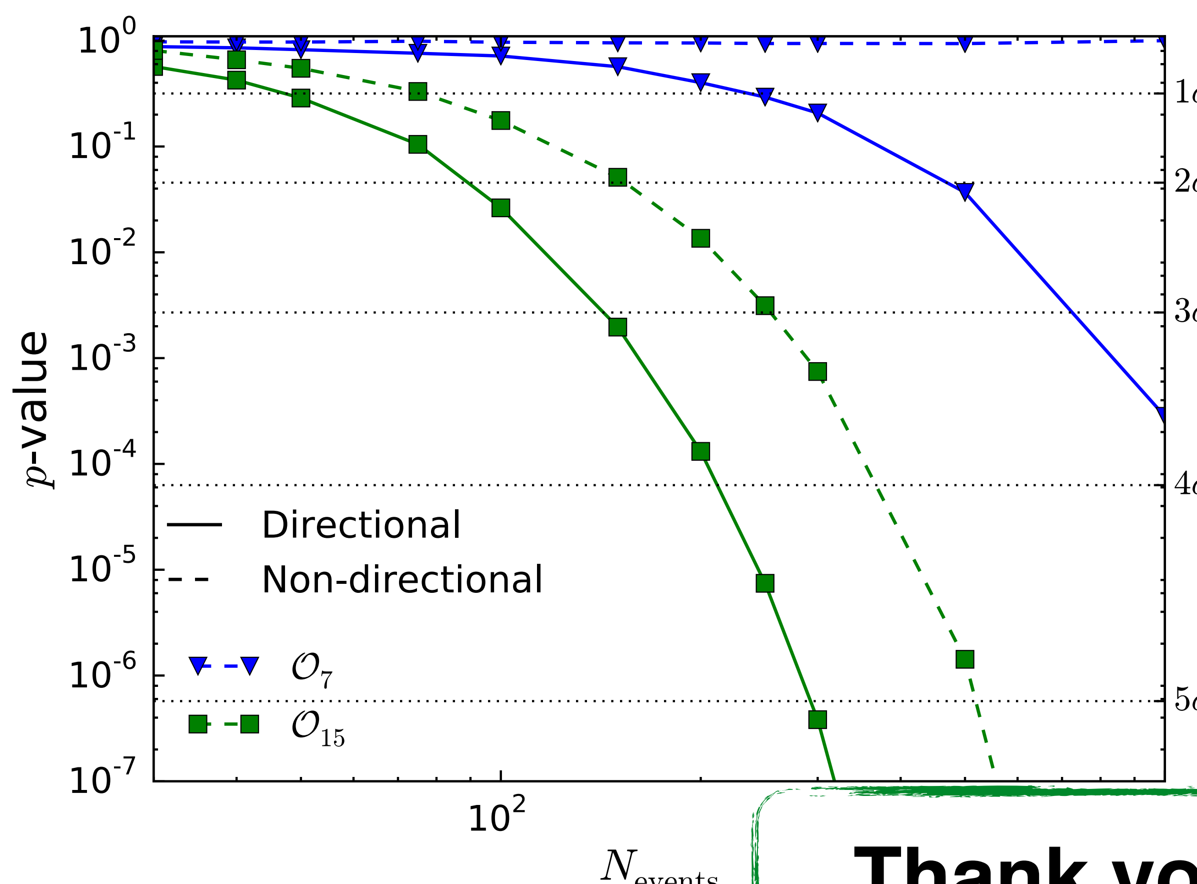
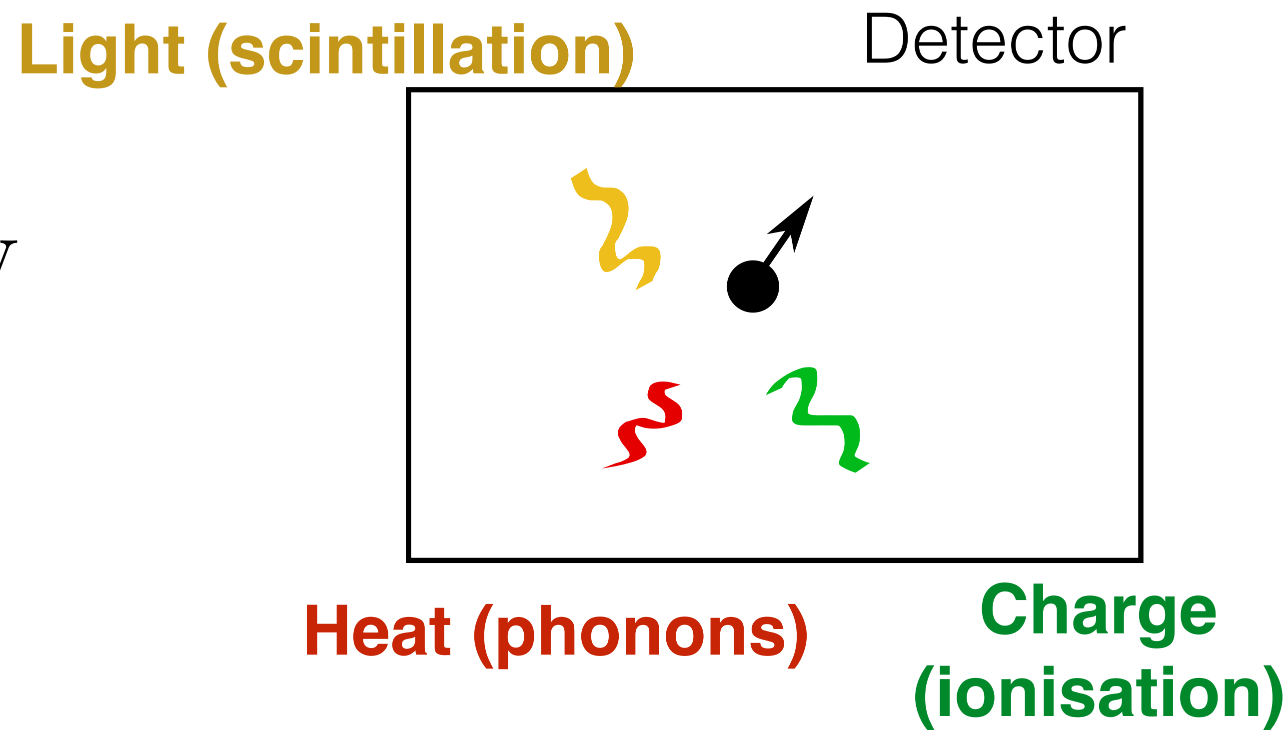




Thank you!

Back-up Slides

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)

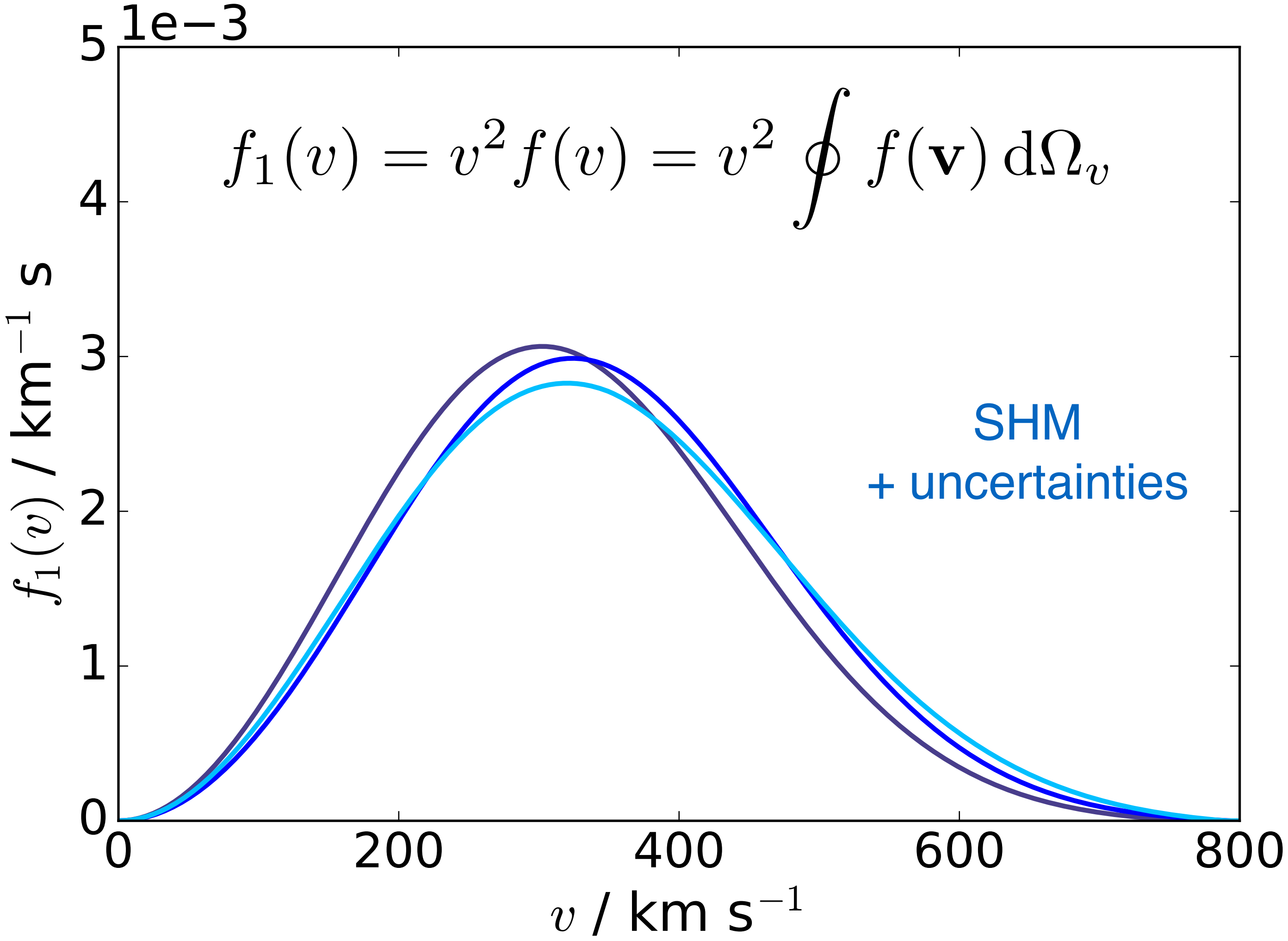
Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

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]

The final event rate

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

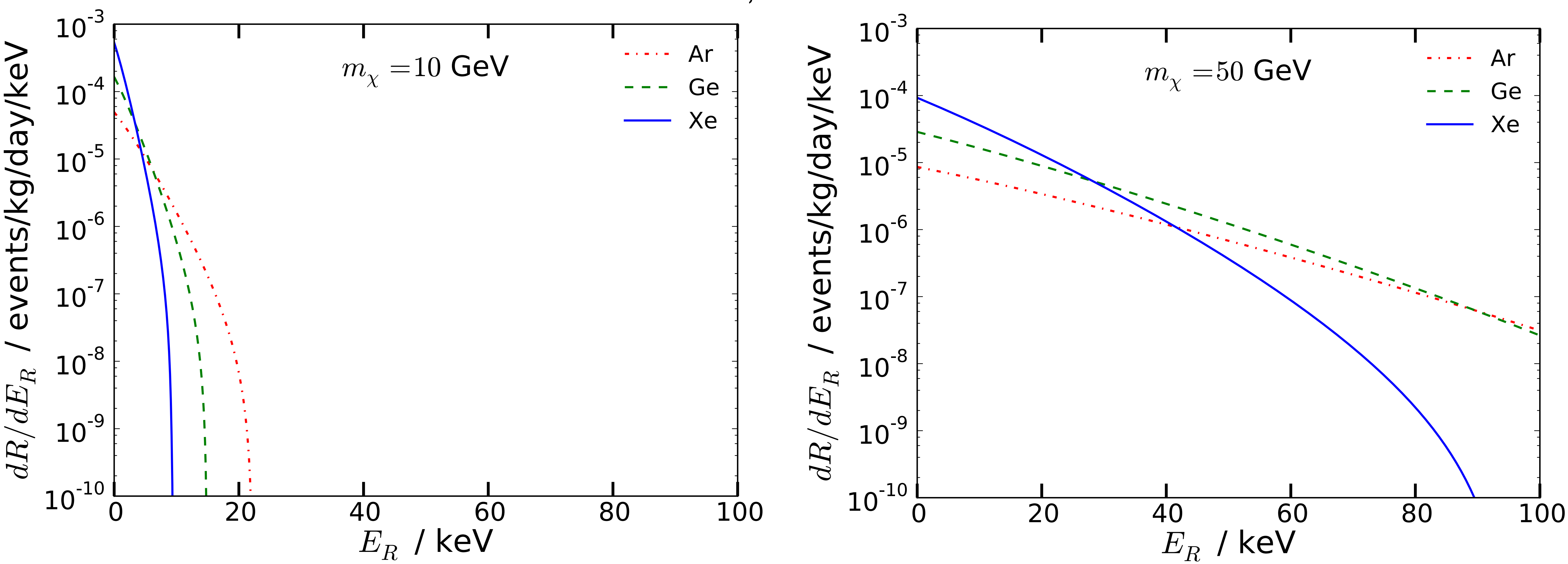
The 'velocity integral':

$$\boxed{\eta(v_{\mathrm{min}}) \equiv \int_{v_{\mathrm{min}}}^{v_{\mathrm{esc}}} \frac{f_1(v)}{v} \,\mathrm{d}v}$$

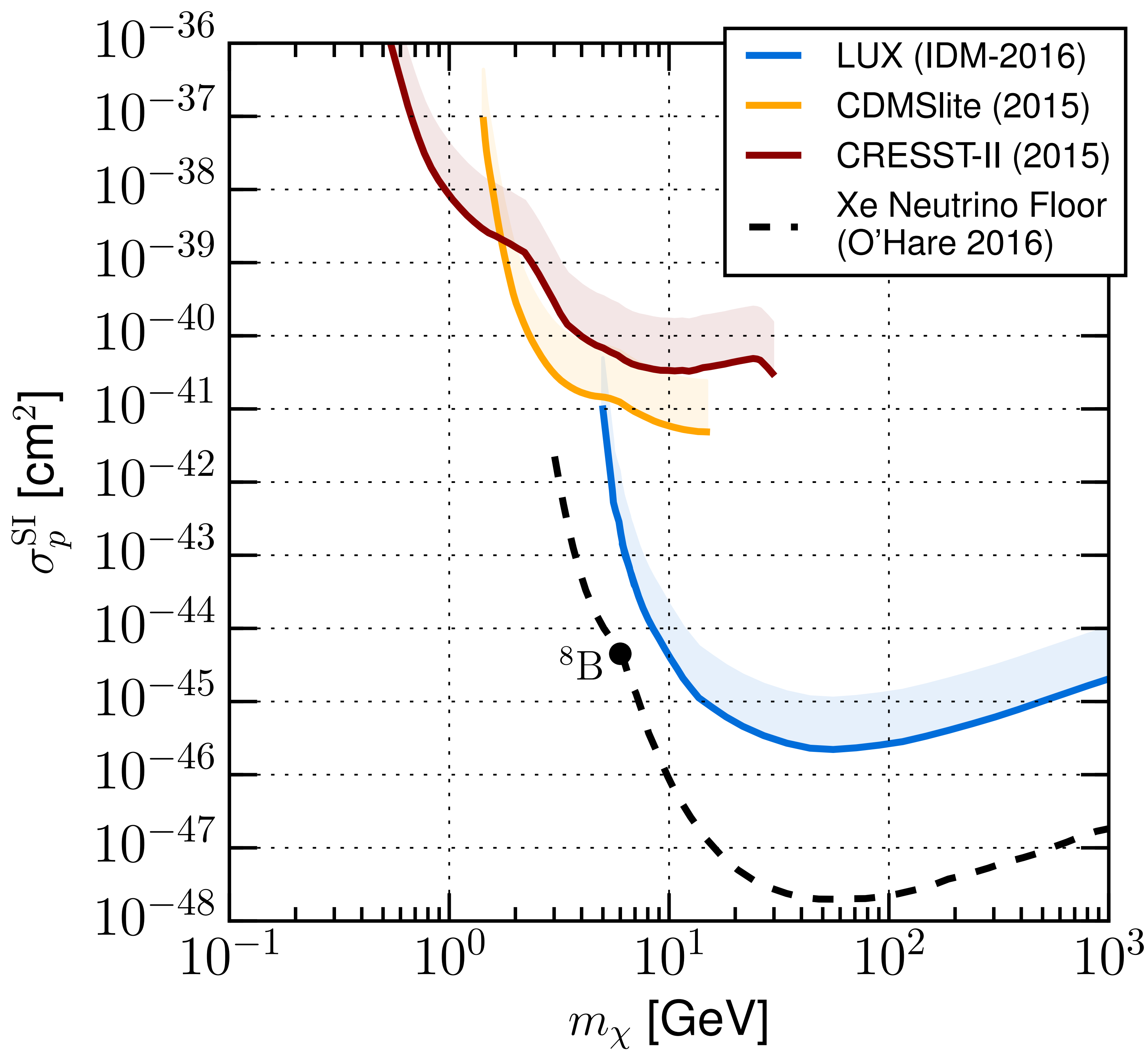
where

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

SI interactions, SHM distribution

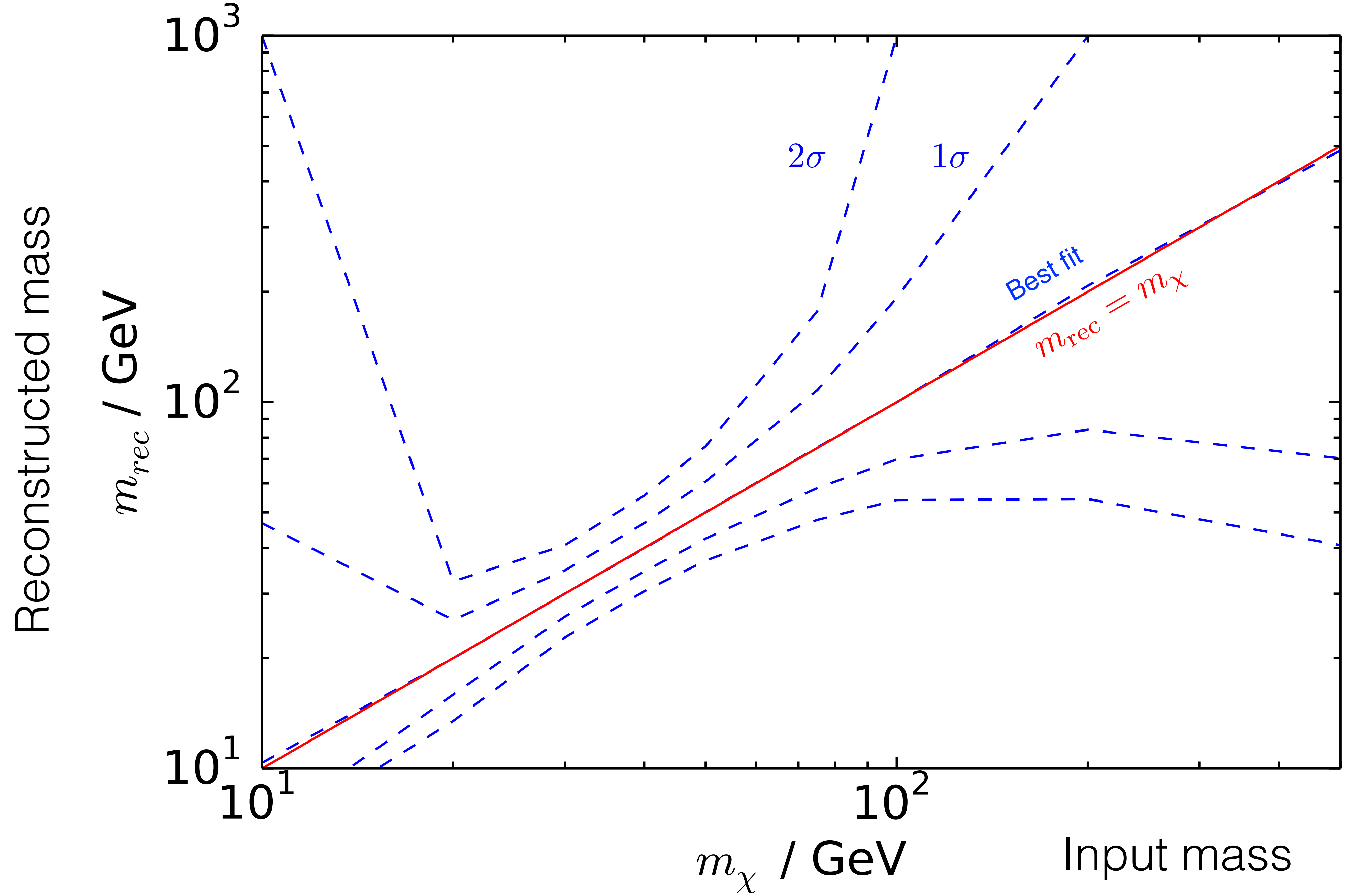


The current landscape



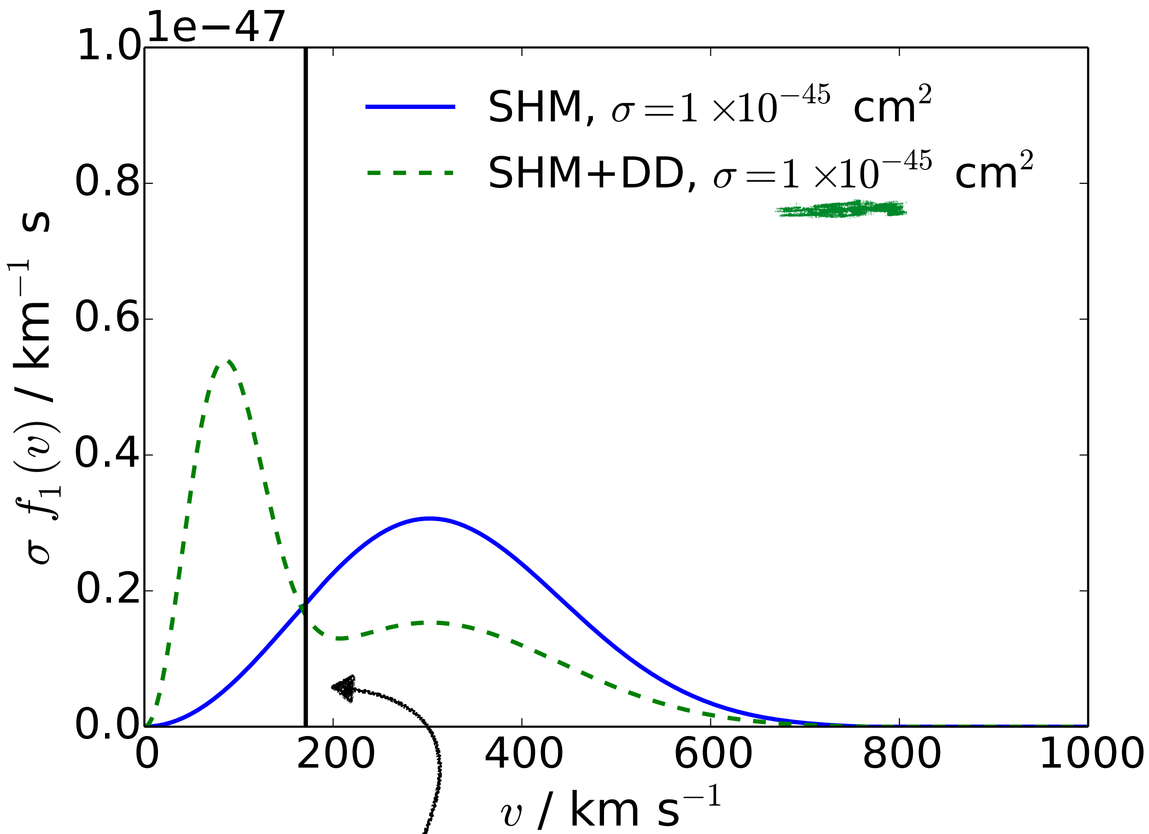
Assuming the Standard Halo Model…

Testing the parametrisation



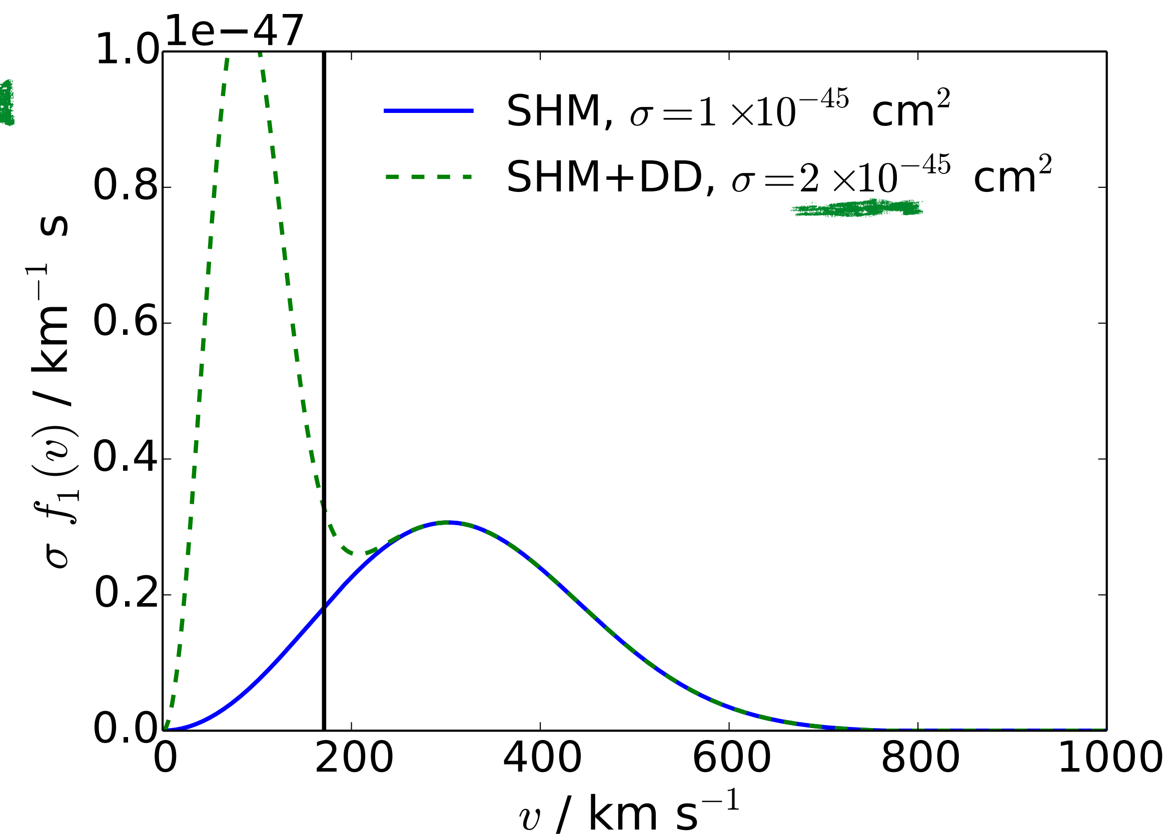
BJK [1312.1852]

Cross section degeneracy



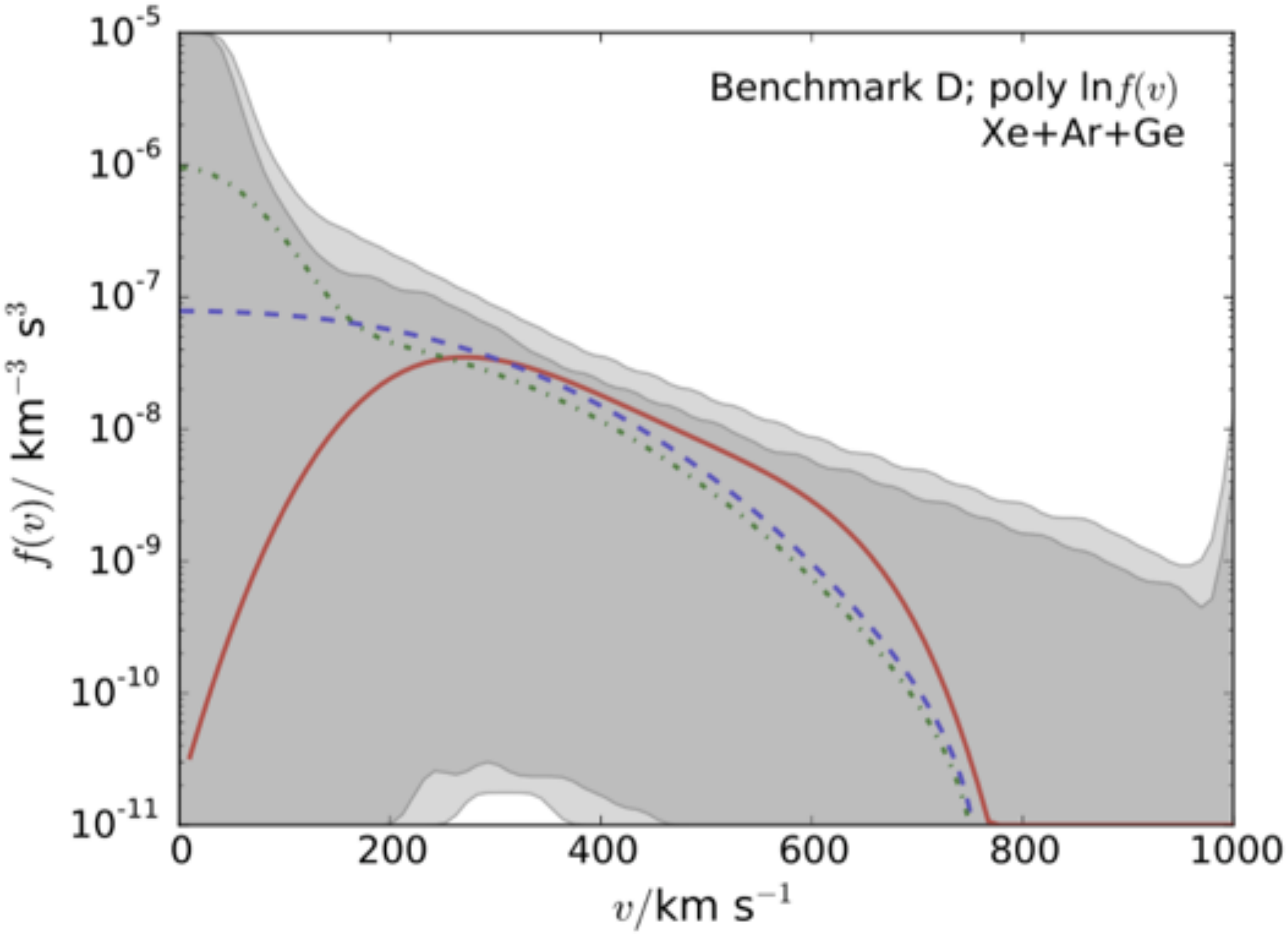
Minimum DM speed probed by
a typical Xe experiment

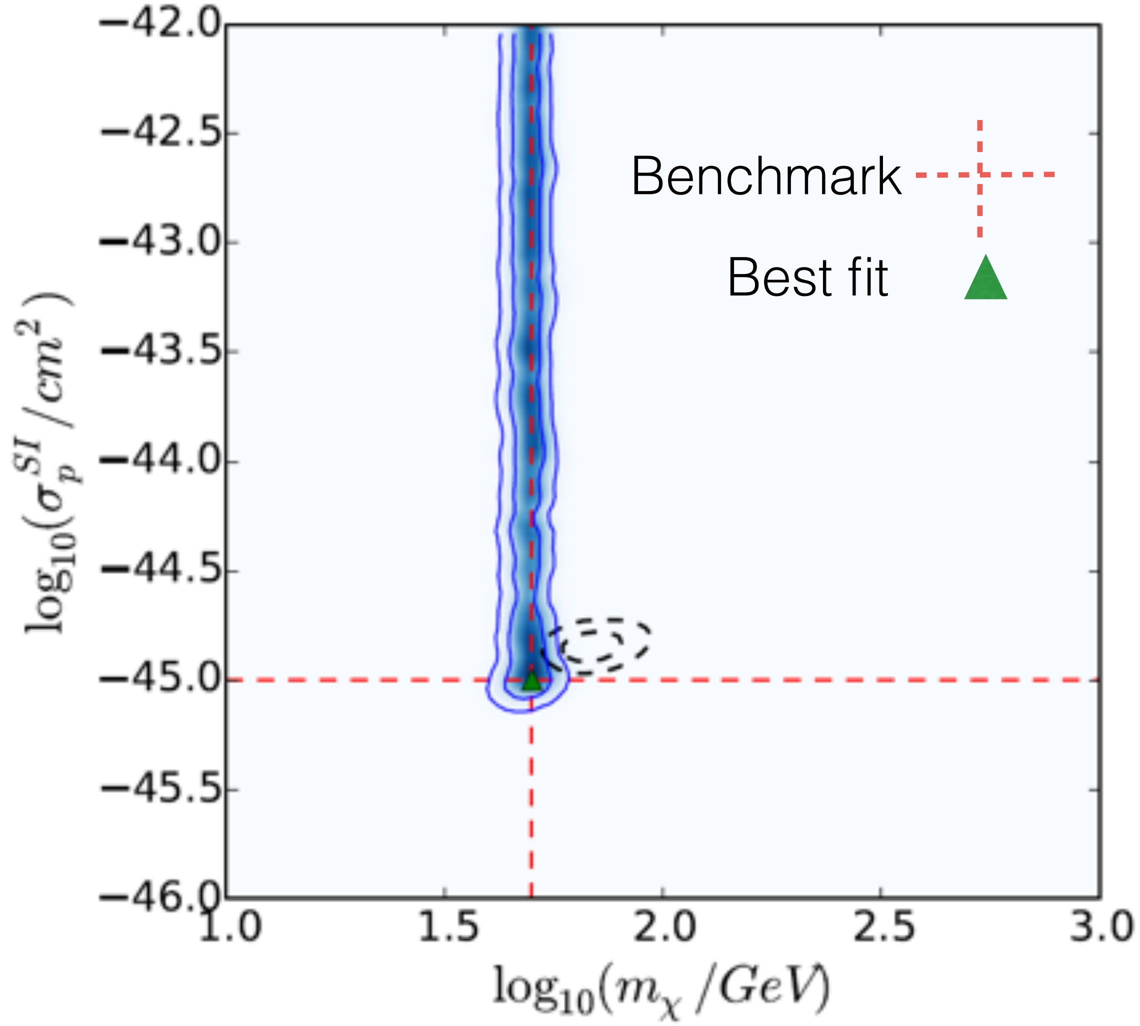
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sigma \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v}\, \mathrm{d}v$$



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

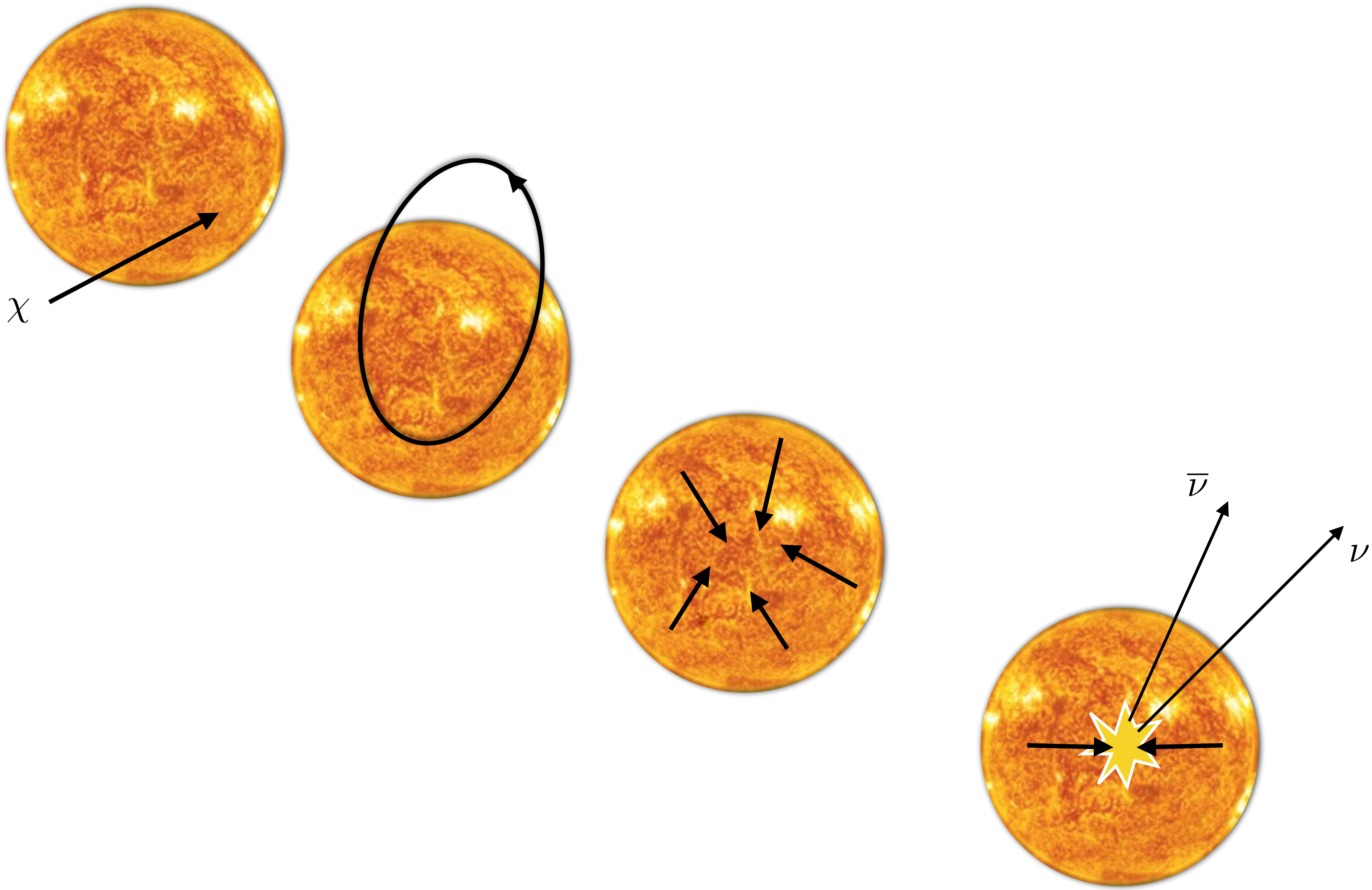
Cross section degeneracy





Neutrino telescopes

DM capture in the Sun



Incorporating IceCube

IceCube can detect the neutrinos from DM annihilation in the Sun

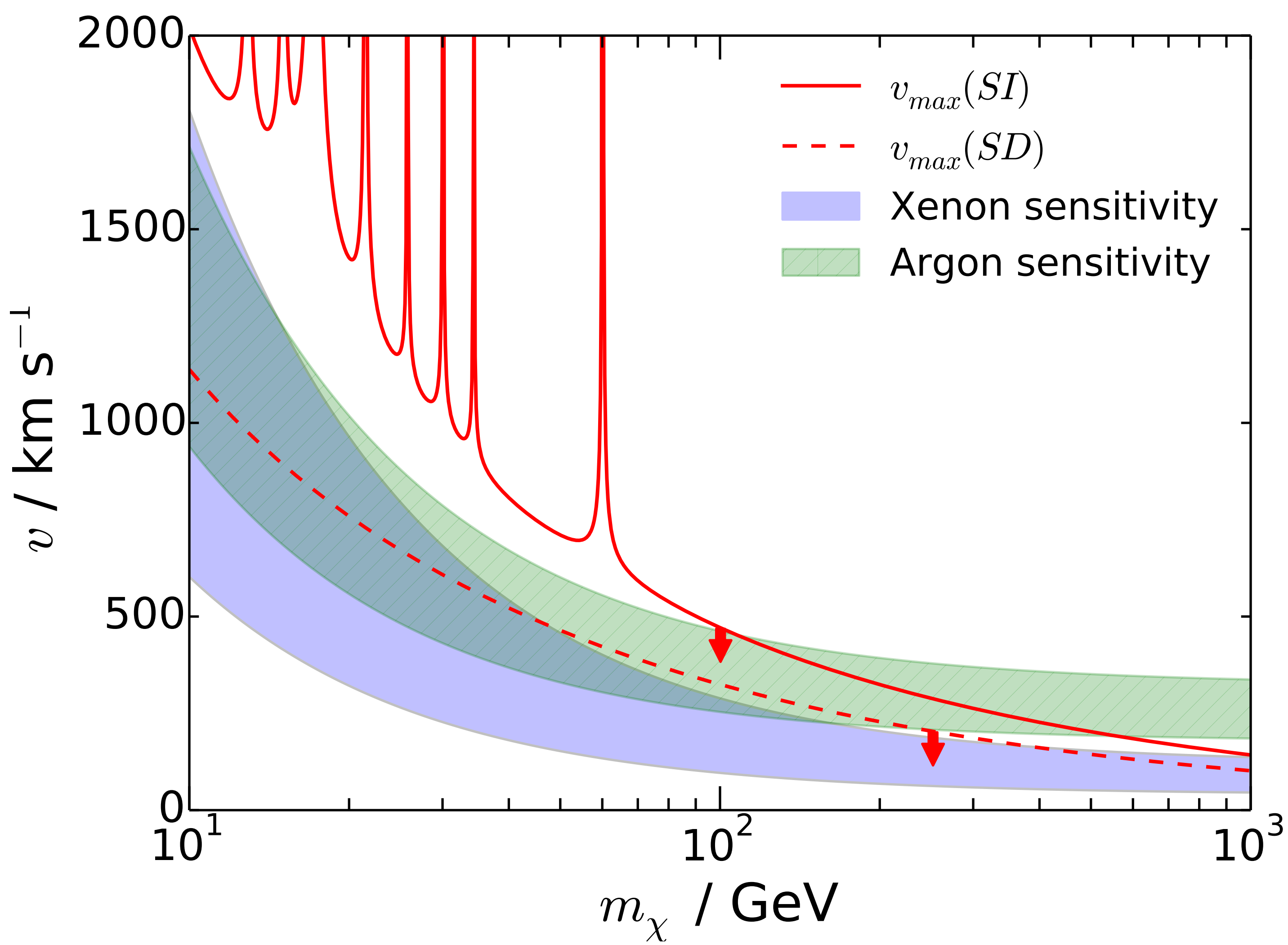
Assuming equilibrium in the Sun, rate is driven by solar capture of DM, which depends on the DM-nucleus scattering cross section

Crucially, only low energy DM particles are captured:

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

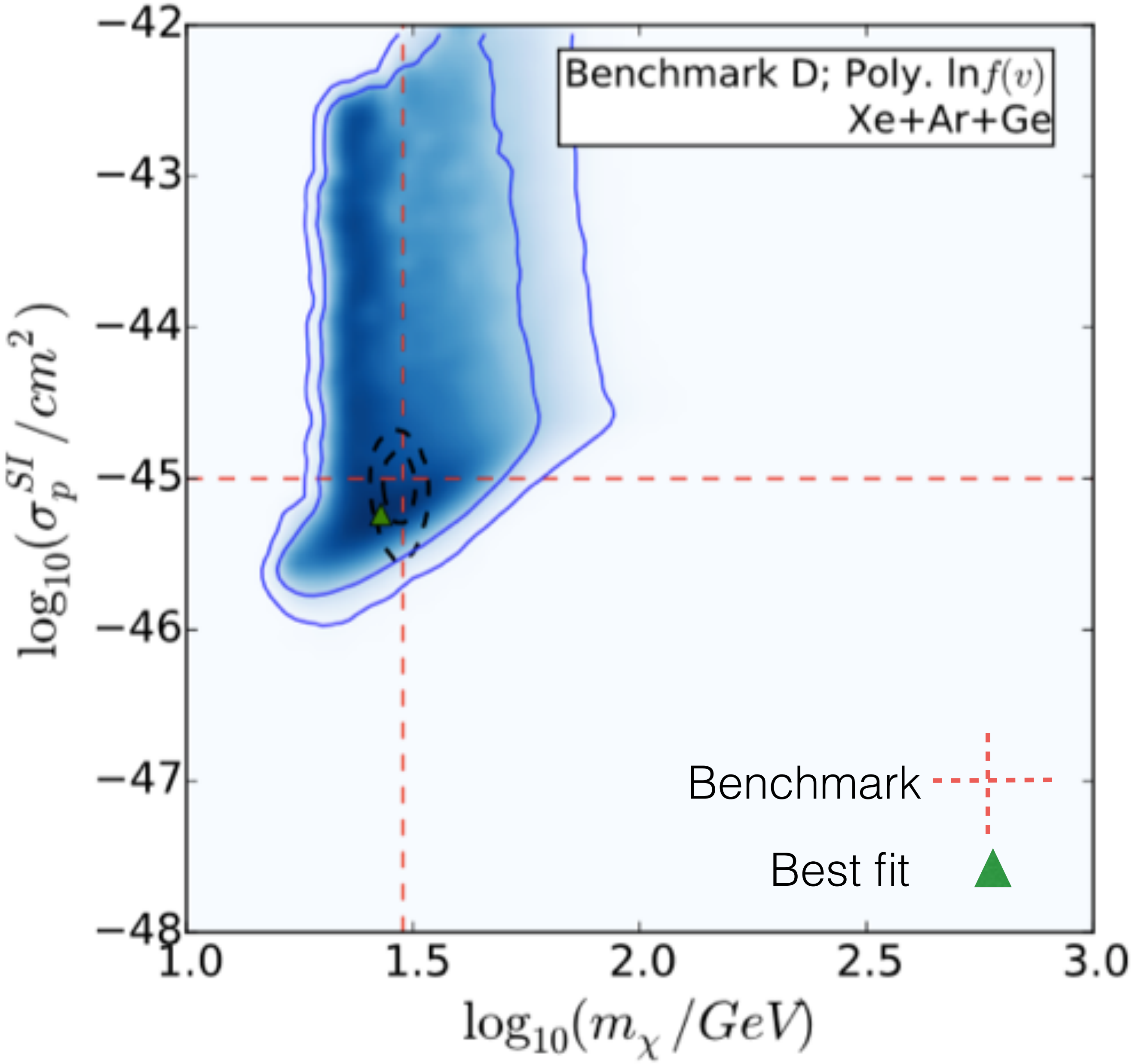
Gould (1991)

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

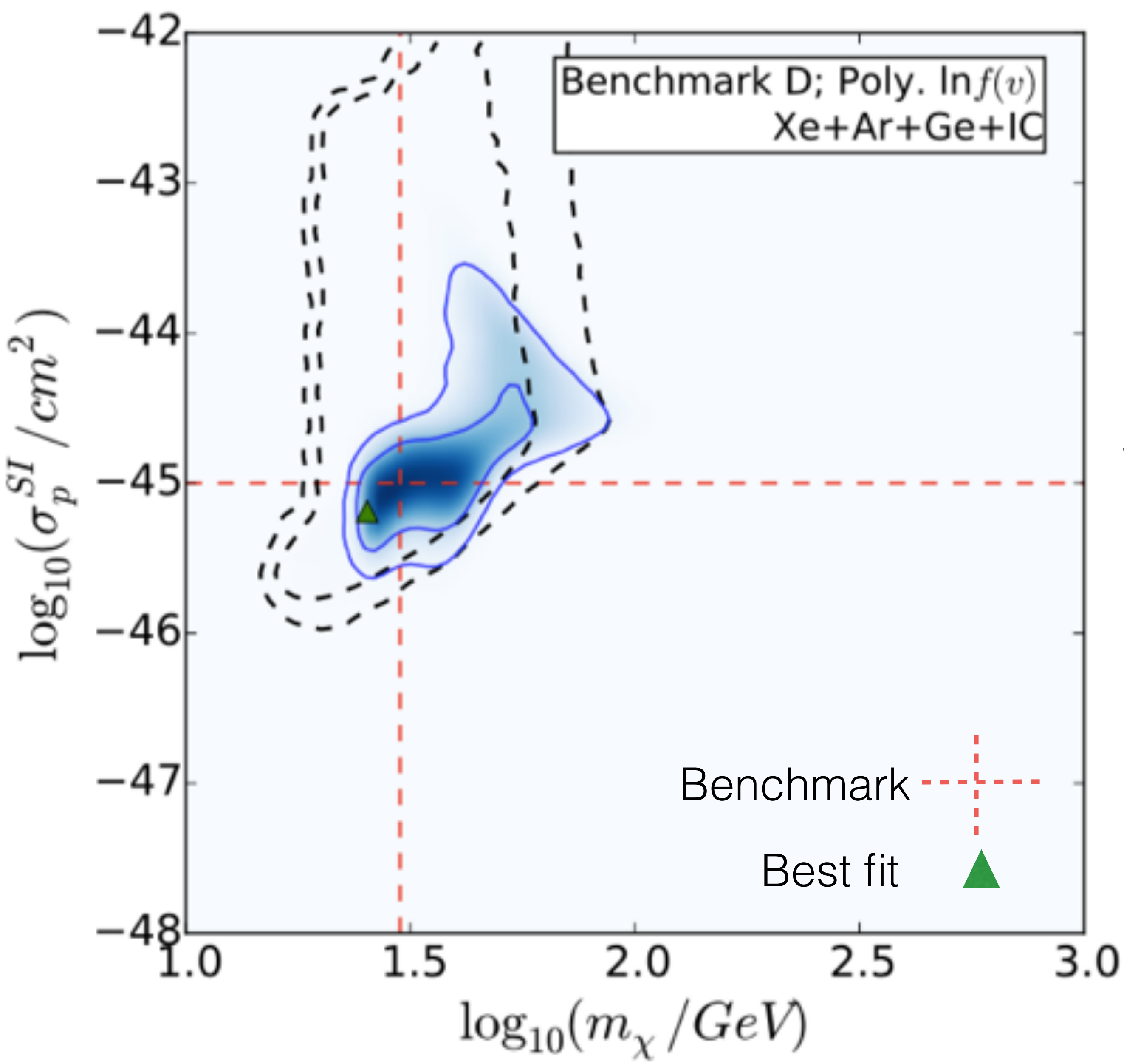


$m_\chi = 30$ GeV
SHM+DD distribution

BJK, Fornasa, Green [1410.8051]

Reconstructions *with* IceCube

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



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

SHM+DD distribution

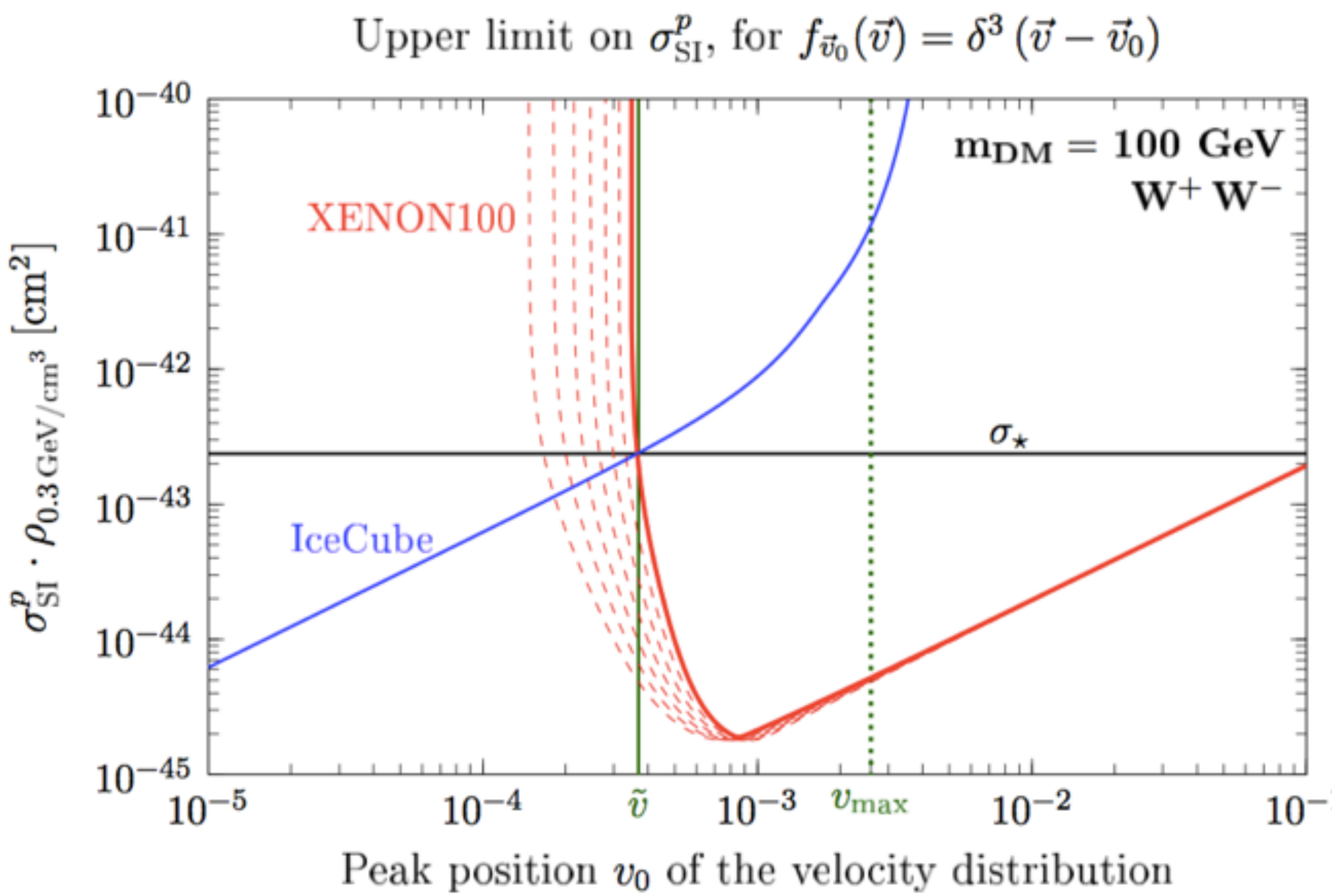
Annihilation to $\nu_\mu \bar{\nu}_\mu$

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



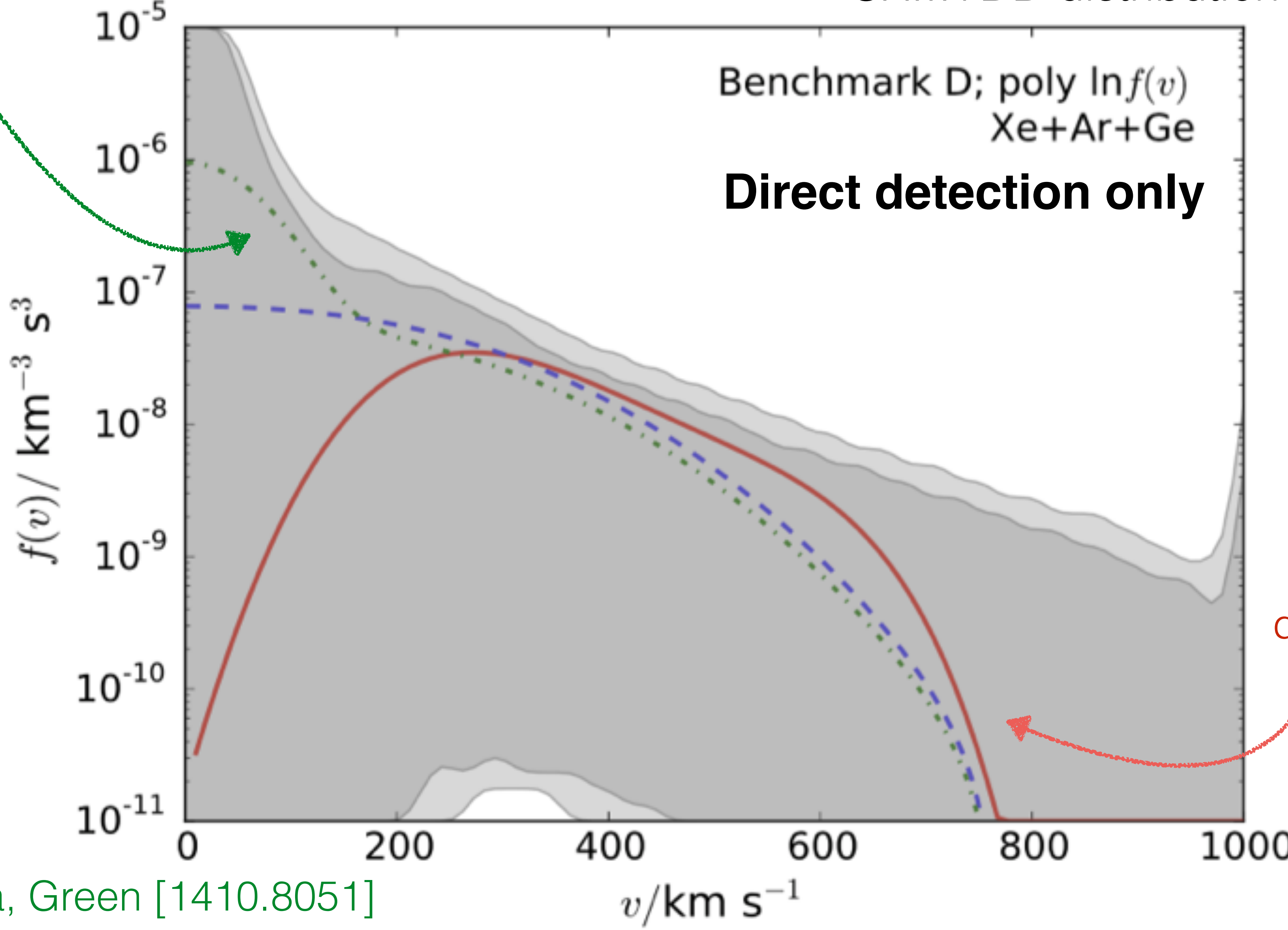
Ferrer et al. [1506.03386]

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

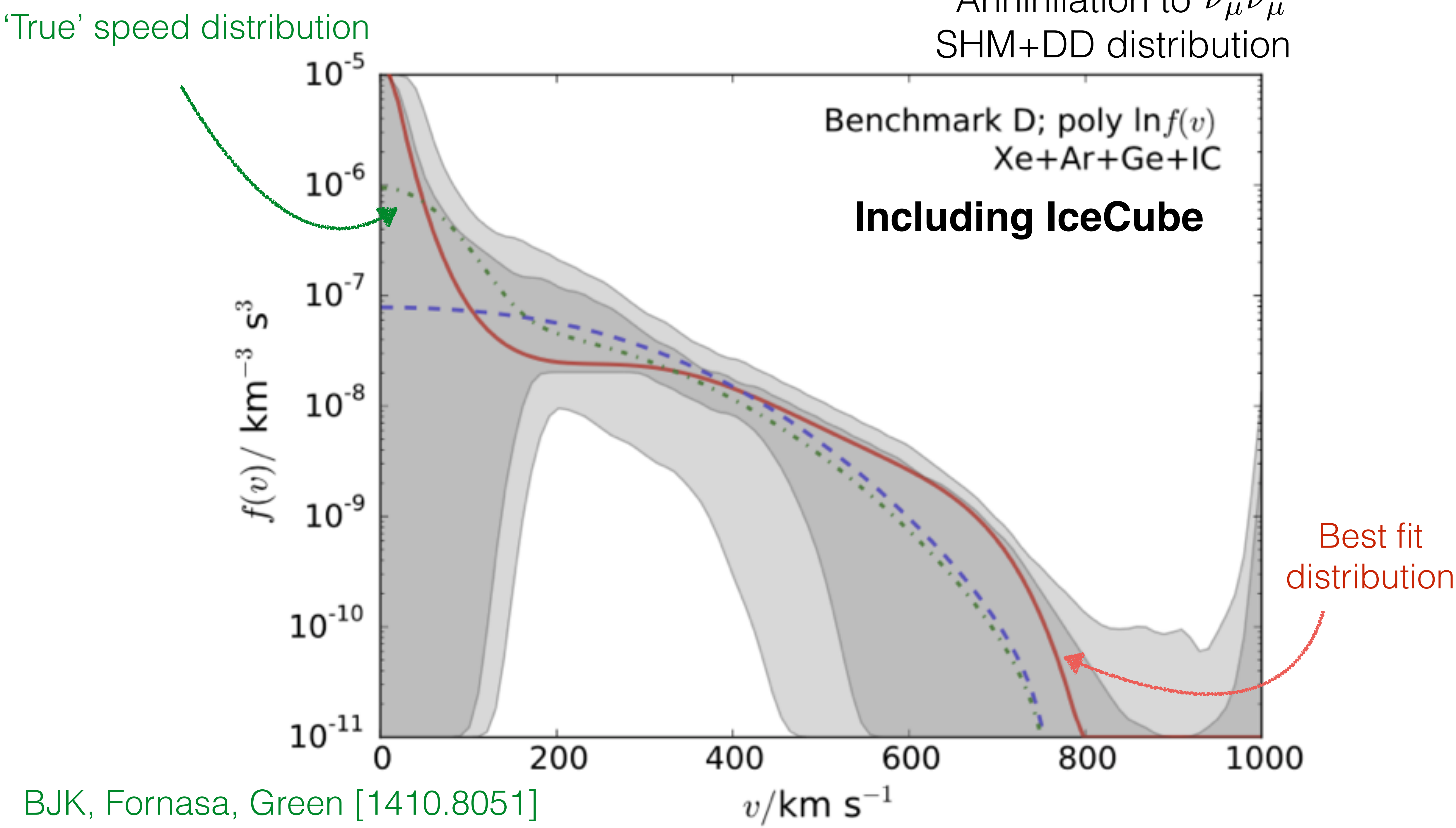


Best fit distribution

BJK, Fornasa, Green [1410.8051]

Reconstructing the speed distribution

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



BJK, Fornasa, Green [1410.8051]

Constraints improved, but still difficult to distinguish underlying distributions…

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.

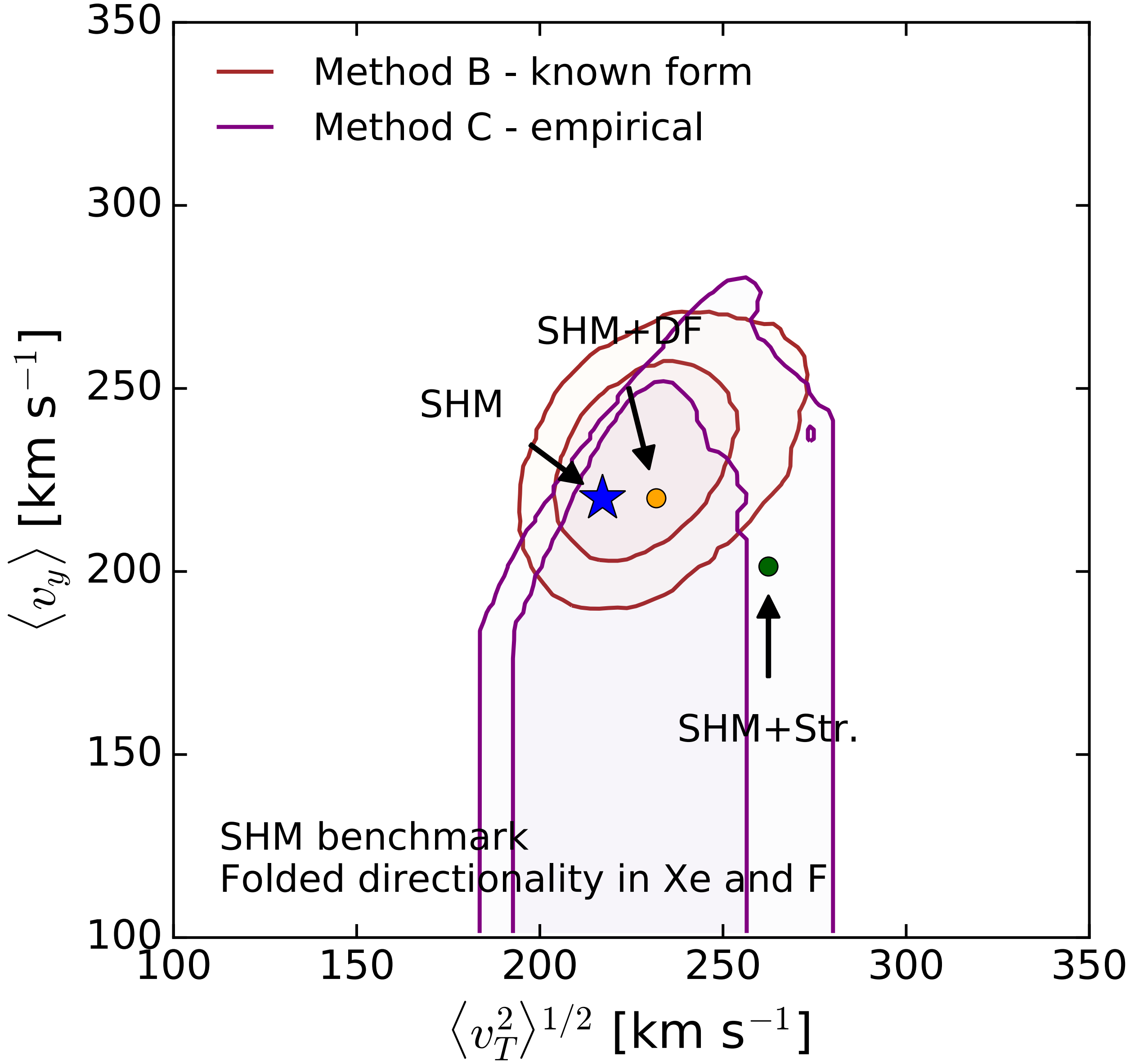
Fit m_χ, σ_p and empirical parameters

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

Comparing distributions - no head-tail

What if we can't measure the *sense* of the recoil?

Input distribution:
SHM



Input distribution:
SHM + Stream