Taming astrophysics and particle physics in the direct detection of dark matter

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Based on…

arXiv:1207.2039
arXiv:1303.6868
arXiv:1312.1852
arXiv:1410.8051

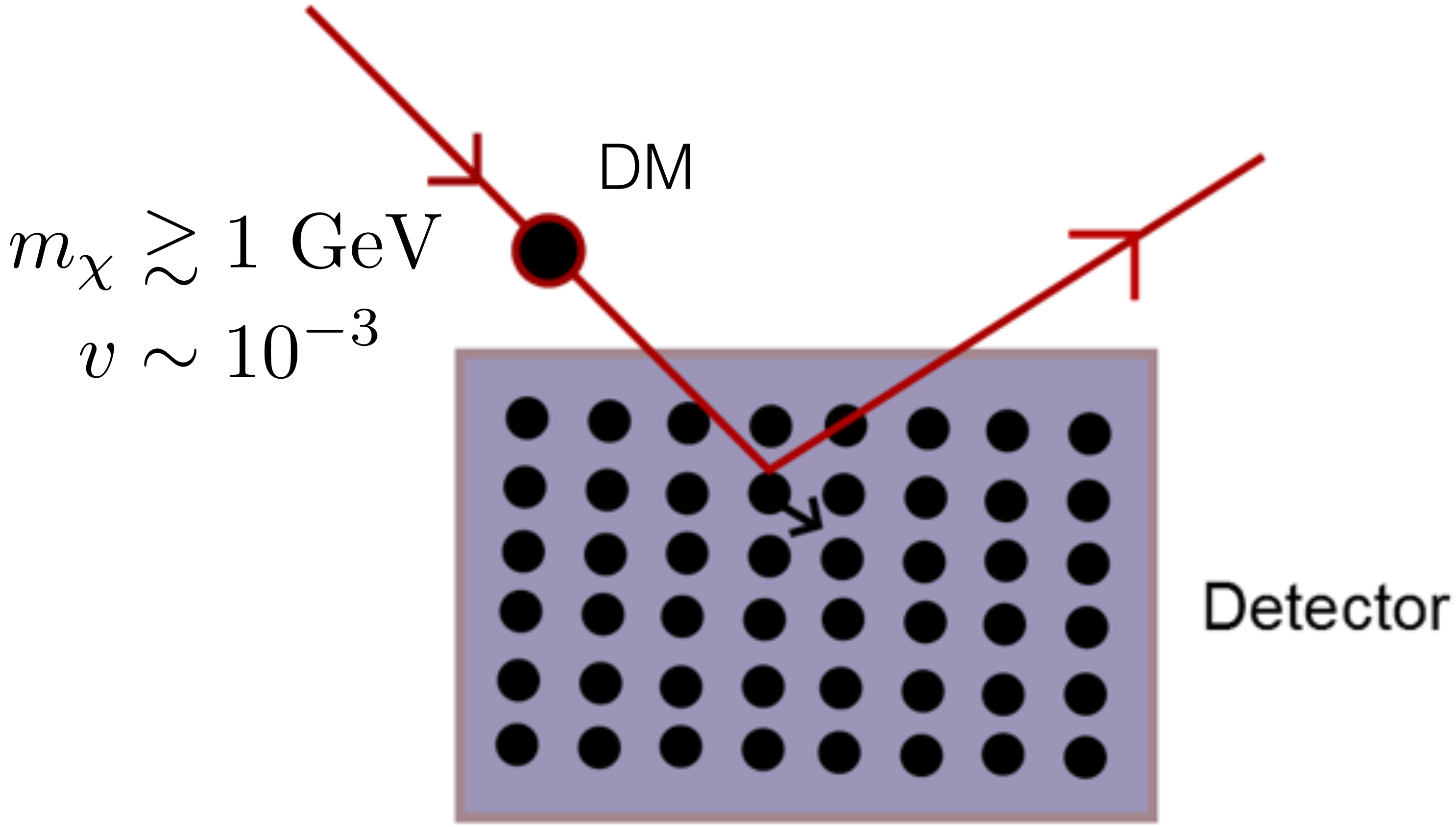
in collaboration with Anne Green and Mattia Fornasa,

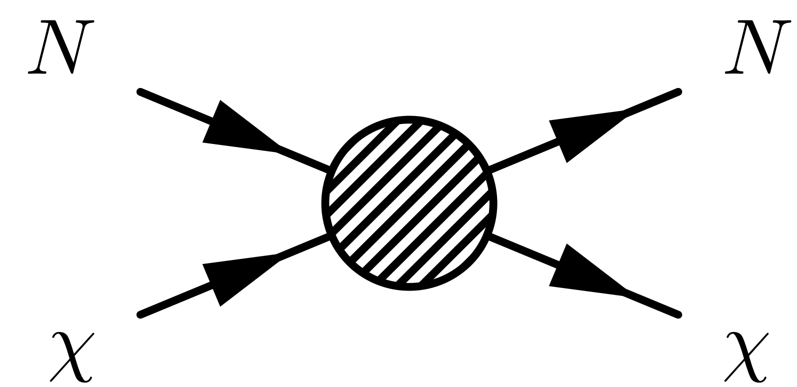
and…

arXiv:1505.07406

as well as ongoing work with Chris Kouvaris, Riccardo Catena and Ciaran O'Hare.

Direct detection of dark matter





Measure energy (and possibly direction) of recoiling nucleus

Reconstruct the mass and cross section of DM

However, we don't know what speed v the DM particles have and we don't know how they interact with nucleons!

Overview

Direct detection event rate

Astro uncertainties:

N-body simulations

What can go wrong?

How to solve it

Particle uncertainties:

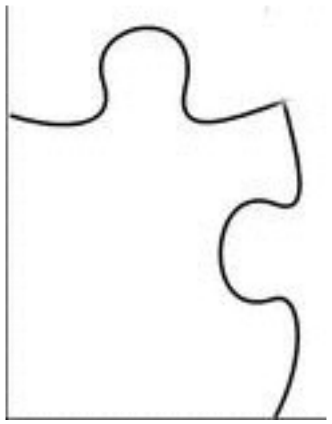
Non-relativistic operators

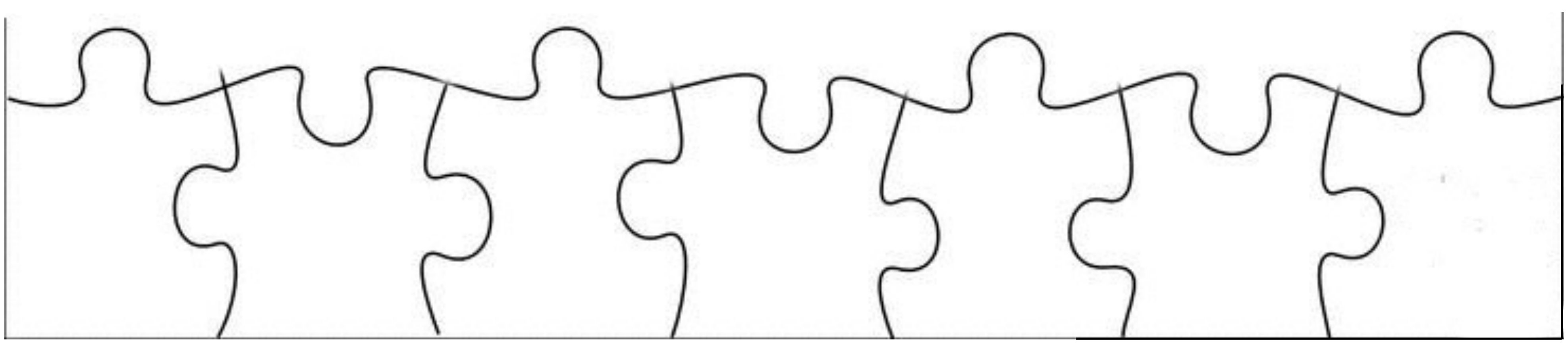
Different signals

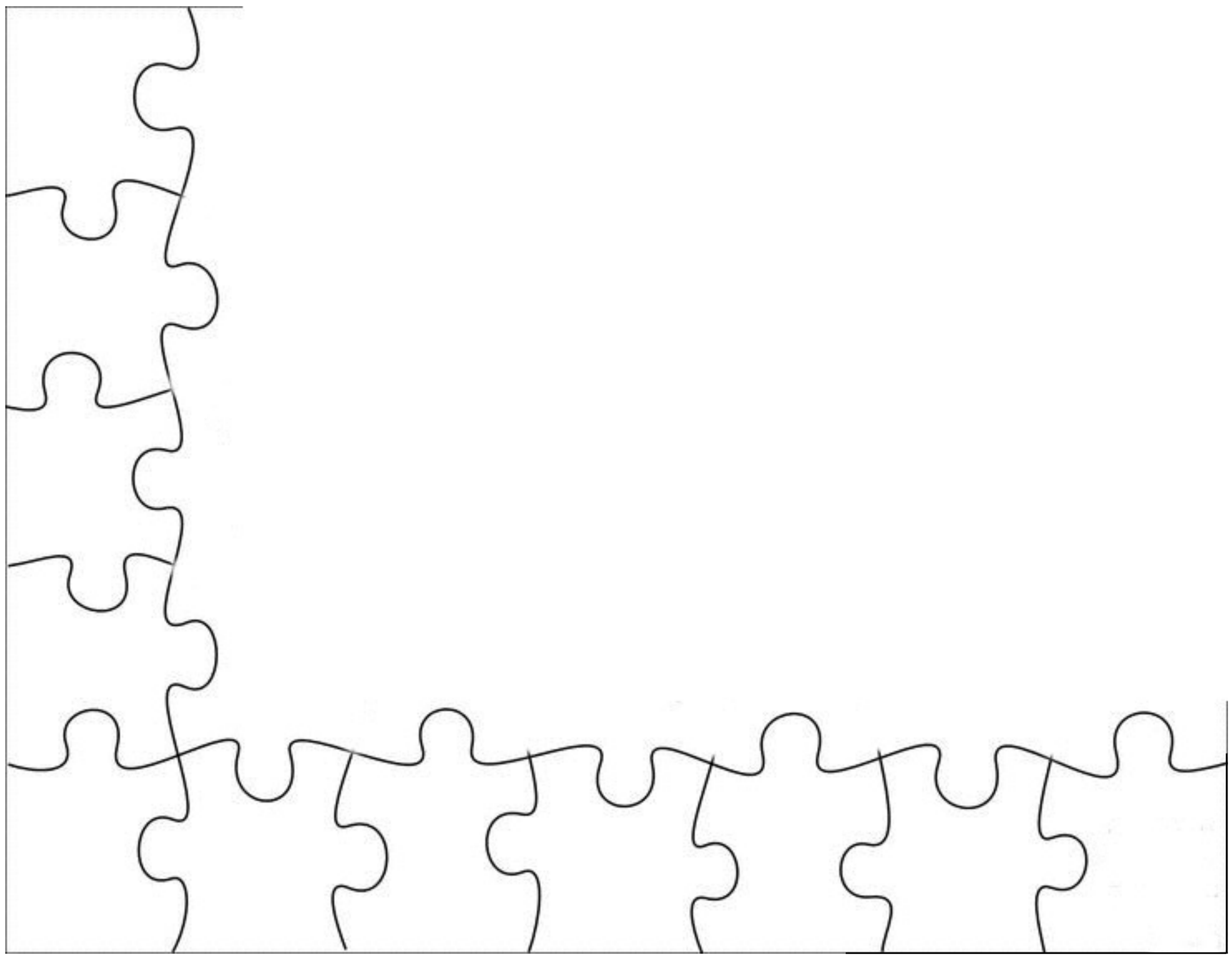
How to distinguish them

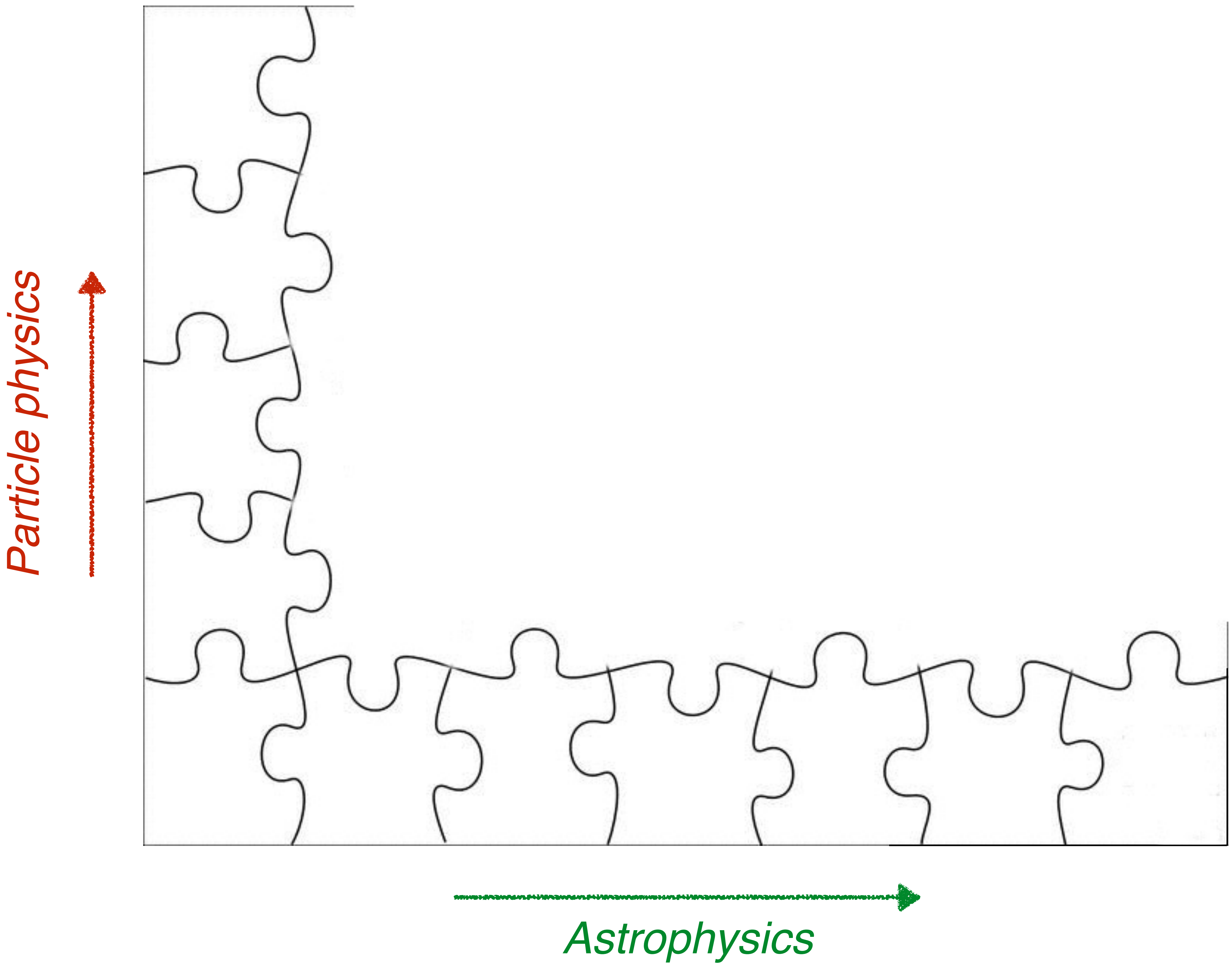
Combining uncertainties

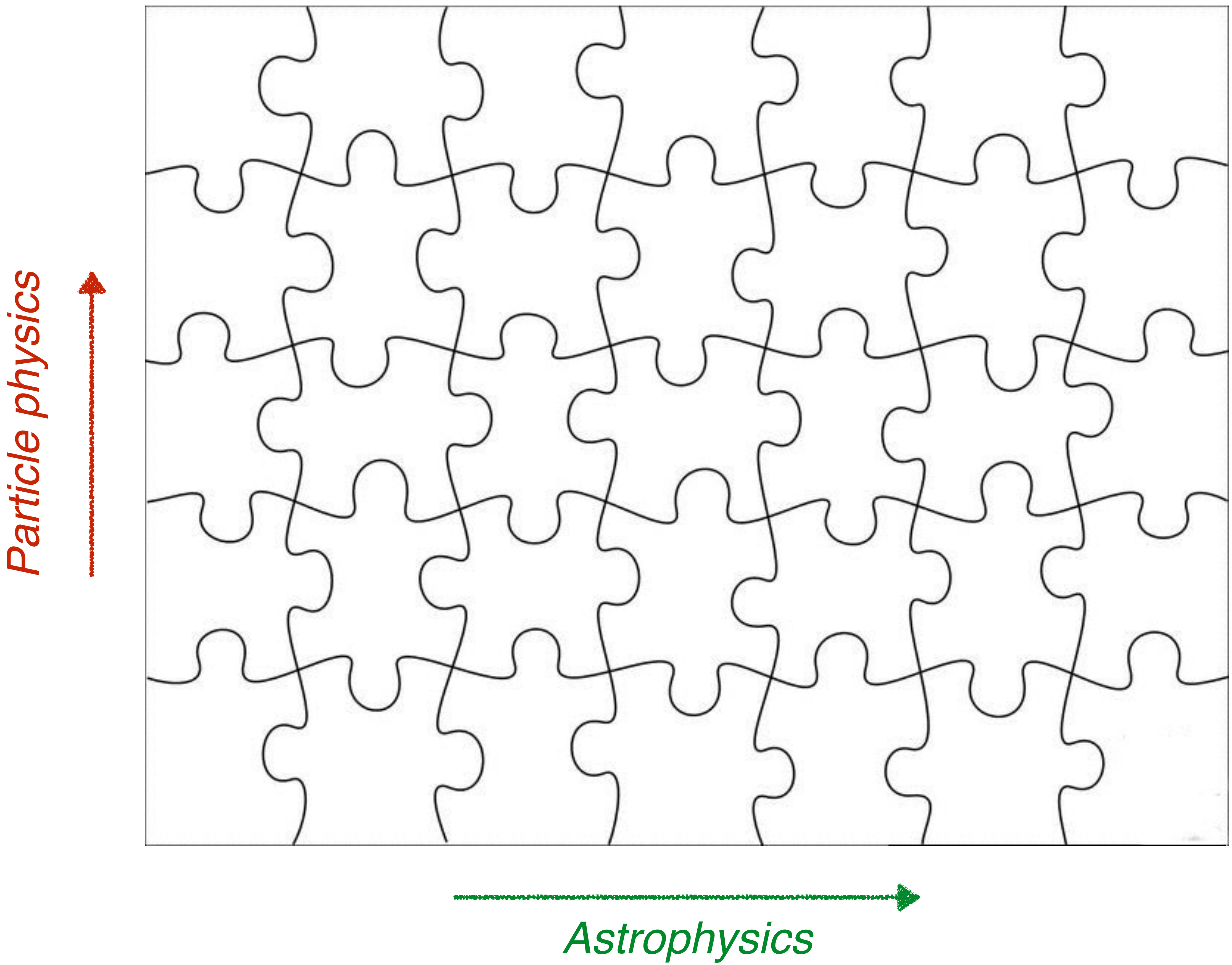
Future work





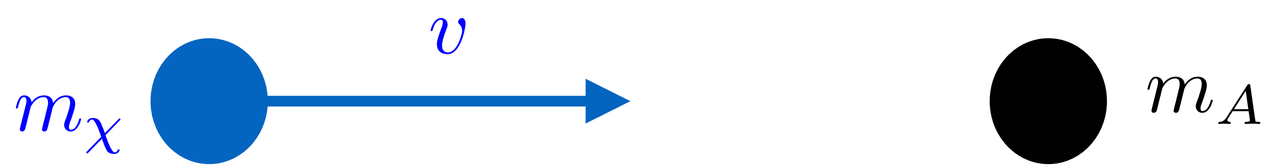



Particle physics
Astrophysics


Particle physics
Astrophysics

Direct detection event rate

Event rate



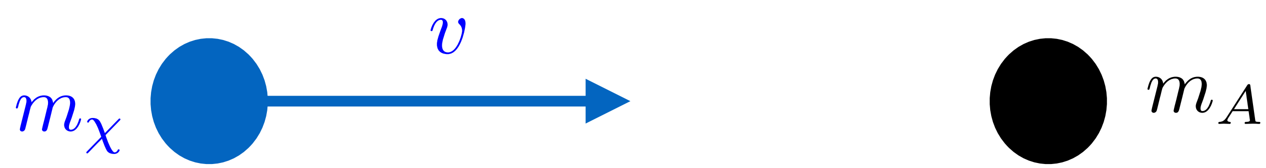
- Flux of DM particles with speed v is $v\left(\frac{\rho_\chi}{m_\chi}\right) f_1(v)\,\mathrm{d}v$
- Minimum speed required to excite a recoil of energy E_R in a nucleus of mass m_A is:

$$v_{\mathrm{min}} = v_{\mathrm{min}}(E_R) = \sqrt{\frac{m_A E_R}{2\mu_{\chi A}^2}}$$

- Event rate per unit detector mass is then

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_A}\int_{v_{\mathrm{min}}}^{\infty} v f_1(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\,\mathrm{d}v$$

Event rate



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$$v_{\mathrm{min}} = v_{\mathrm{min}}(E_R) = \sqrt{\frac{m_A E_R}{2\mu_{\chi A}^2}}$$

$\rho_\chi \sim 0.2\text{--}0.6 \mathrm{~GeV~cm}^{-3}$

Read (2014) [arXiv:1404.1938]

- Event rate per unit detector mass is then

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{\mathrm{min}}}^{\infty} v f_1(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \mathrm{d}v$$

Astrophysics

Particle and nuclear physics

Standard Halo Model (SHM)

Speed distribution obtained for a spherical, isotropic and isothermal Galactic halo, with density profile $\rho(r) \propto r^{-2}$.

Leads to Maxwell-Boltzmann distribution:

$$f(\mathbf{v}) \propto \exp\left(-\frac{(\mathbf{v} - \mathbf{v}_e)^2}{2\sigma_v^2}\right) \Theta(v_\mathrm{esc} - |\mathbf{v} - \mathbf{v}_e|)$$

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

with $v_e \approx \sqrt{2}\sigma_v \approx 220 \, \mathrm{km \, s^{-1}}$.

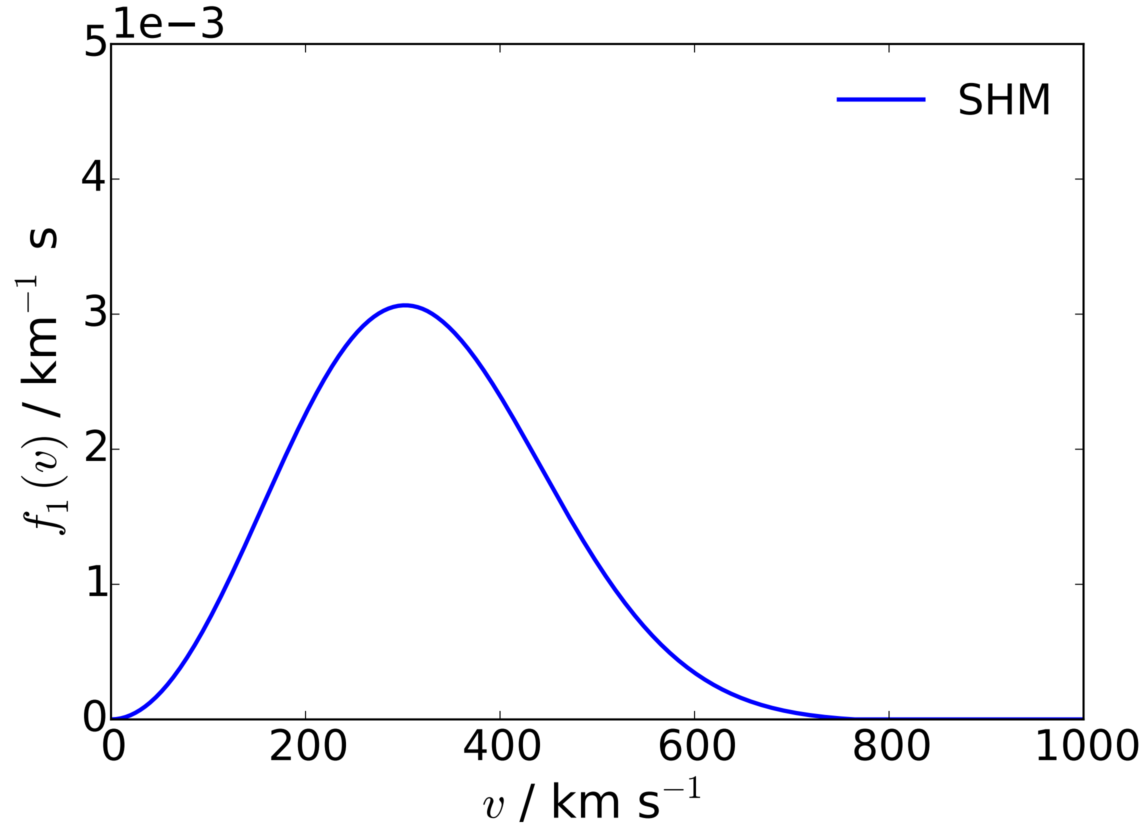
$$v_e \sim 220 - 250 \, \mathrm{km \, s^{-1}}$$

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

E.g. Feast et al. (1997) [astro-ph/9706293], Bovy et al. (2012) [arXiv:1209.0759]

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

Piffl et al. (RAVE, 2013) [arXiv:1309.4293]



Cross section

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 :

Spin-independent (SI)

$$\bar{\chi}\chi\bar{N}N \quad \longrightarrow \quad \frac{\mathrm{d}\sigma^A_{SI}}{\mathrm{d}E_R} \propto \frac{\sigma^p_{SI}}{\mu^2_{\chi p} v^2} A^2 F^2_{\mathrm{SI}}(E_R)$$

Nuclear physics

Spin-dependent (SD)

$$\bar{\chi}\gamma_5\gamma_\mu\chi\,\bar{N}\gamma_5\gamma^\mu N \quad \longrightarrow \quad \frac{\mathrm{d}\sigma^A_{\mathrm{SD}}}{\mathrm{d}E_R} \propto \frac{\sigma^p_{SD}}{\mu^2_{\chi p} v^2} \frac{J+1}{J} F^2_{SD}(E_R)$$

We'll look at more general interactions in the second half of the talk…

The final event rate

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi \sigma_i^p}{m_\chi \mu_{\chi p}^2} \mathcal{C}_i F_i^2(E_R) \eta(v_{\mathrm{min}}) \qquad i = \mathrm{SI}, \mathrm{SD}$$

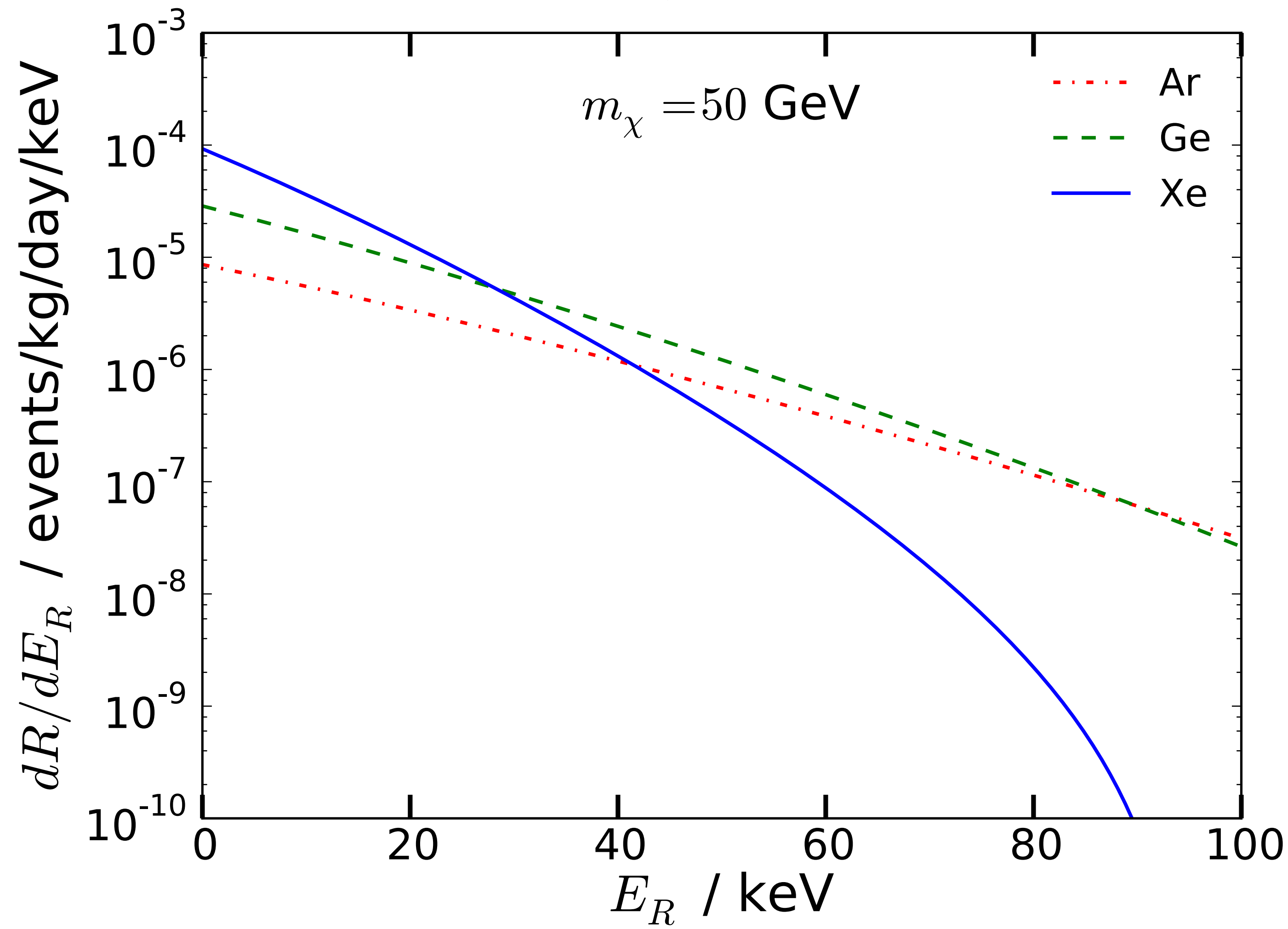
Enhancement factor, $\mathcal{C}_i$

Form factor, $F_i^2(E_R)$

Mean inverse speed,

$$\eta(v_{\mathrm{min}}) = \int_{v_{\mathrm{min}}}^{\infty} \frac{f_1(v)}{v} \, \mathrm{d}v$$

SI interactions, SHM distribution



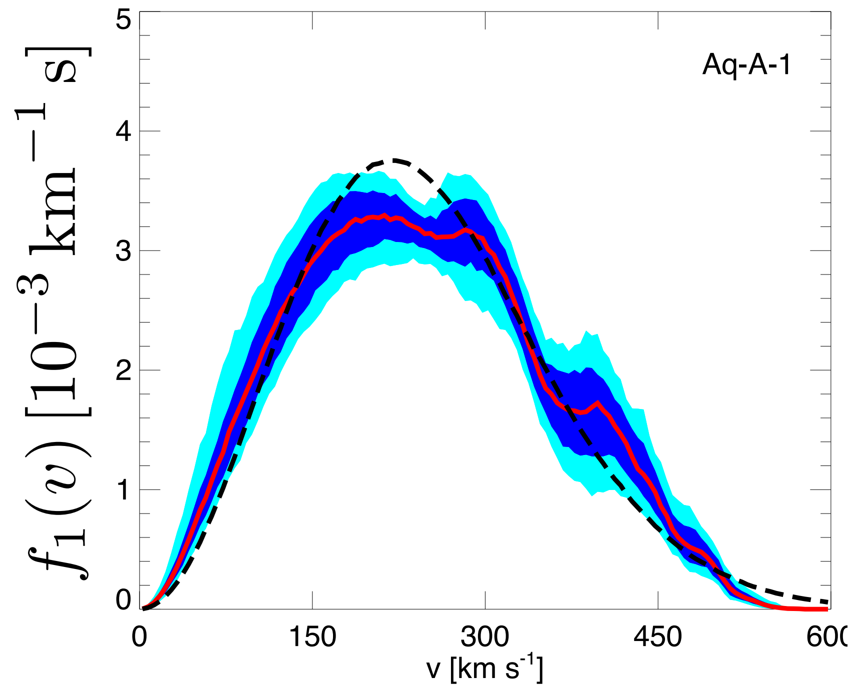
Astrophysical uncertainties

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{\mathrm{min}}}^{\infty} v f_1(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \, \mathrm{d}v$$

N-body simulations

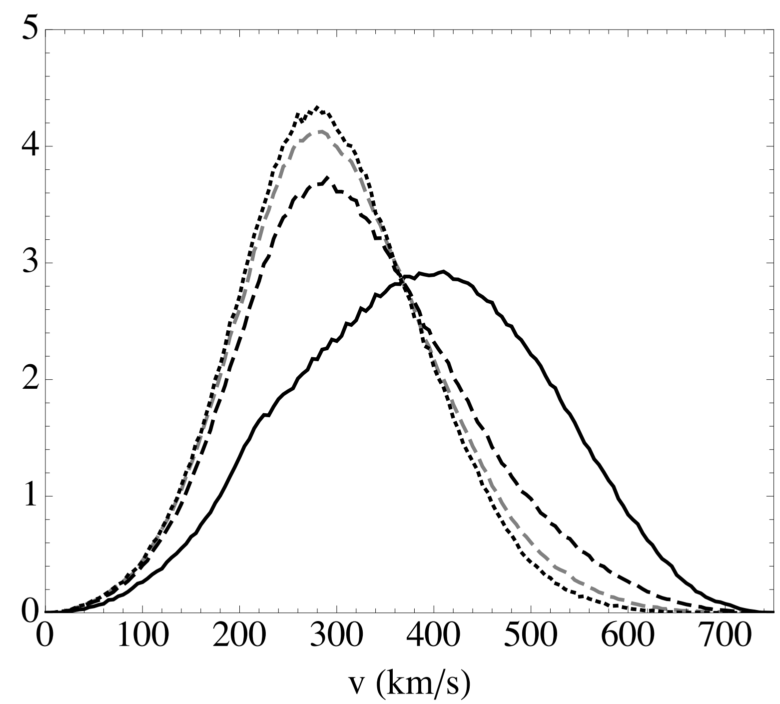
High resolution N-body simulations can be used to extract the DM speed distribution

Non-Maxwellian structure



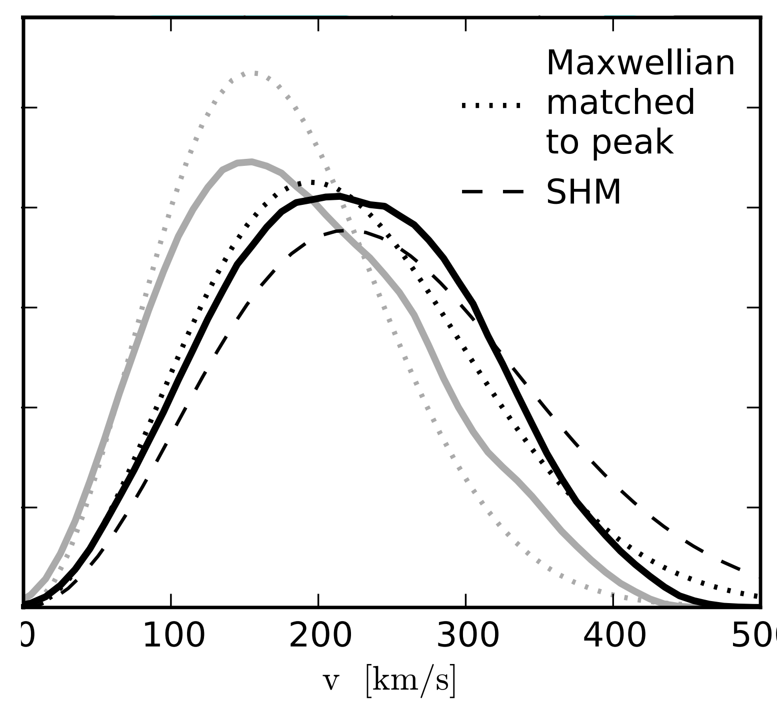
Vogelsberger et al. (2009) [arXiv:0812.0362]

Debris flows



Kuhlen et al. (2012) [arXiv:1202.0007]

Dark disk



Pillepich et al. (2014) [arXiv:1308.1703]

However, N-body simulations cannot probe down to the sub-milliparsec scales probes by direct detection…

Local substructure

May want to worry about ultra-local substructure - subhalos and streams which are not completely phase-mixed.

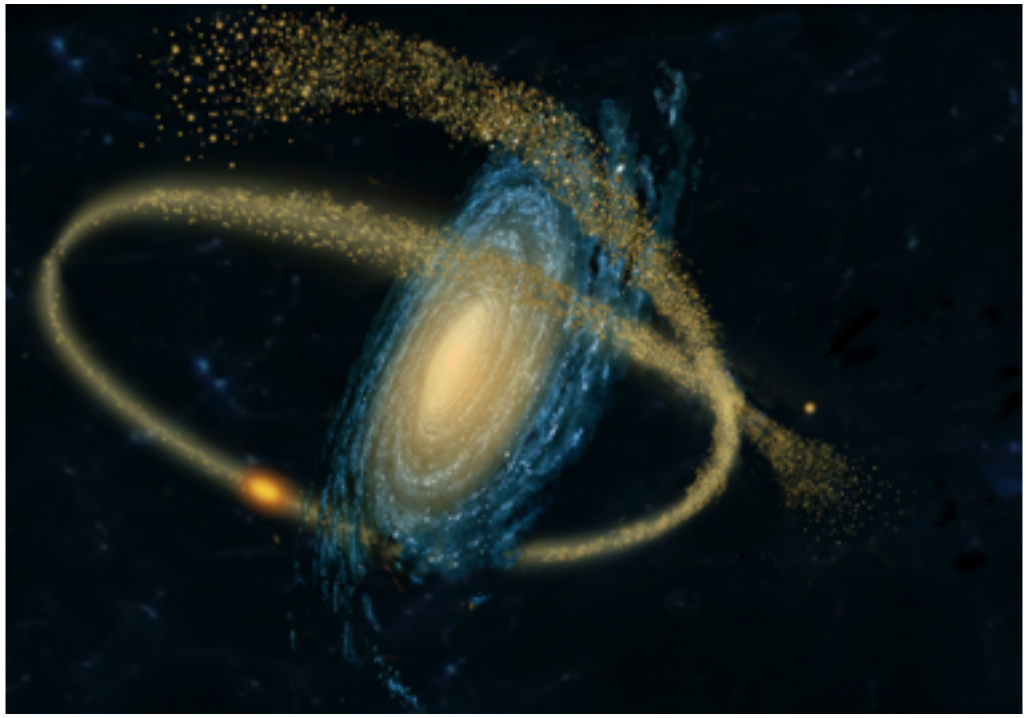
Analysis of N-body simulations indicate that it is unlikely for a single stream to dominate the local density - lots of different 'streams' contribute to make a smooth halo.

Helmi et al. (2002) [astro-ph/0201289]

Vogelsberger et al. (2007) [arXiv:0711.1105]

However, this does not exclude the possibility of a stream - e.g. due to the ongoing tidal disruption of the Sagittarius dwarf galaxy.

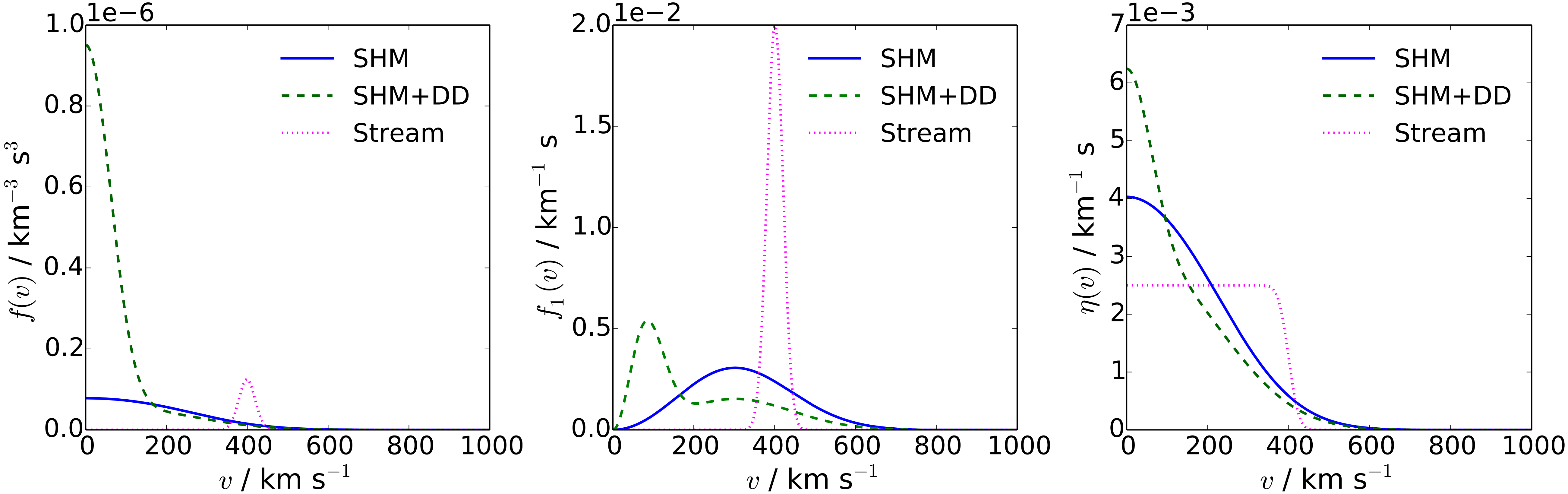
Freese et al. (2004) [astro-ph/0309279]



www.cosmotography.com

Examples

$$f(v) = \oint f(\mathbf{v})\,\mathrm{d}\Omega_v \qquad f_1(v) = v^2 f(v) \qquad \eta(v) = \int_v^\infty \frac{f_1(v')}{v'}\,\mathrm{d}v'$$

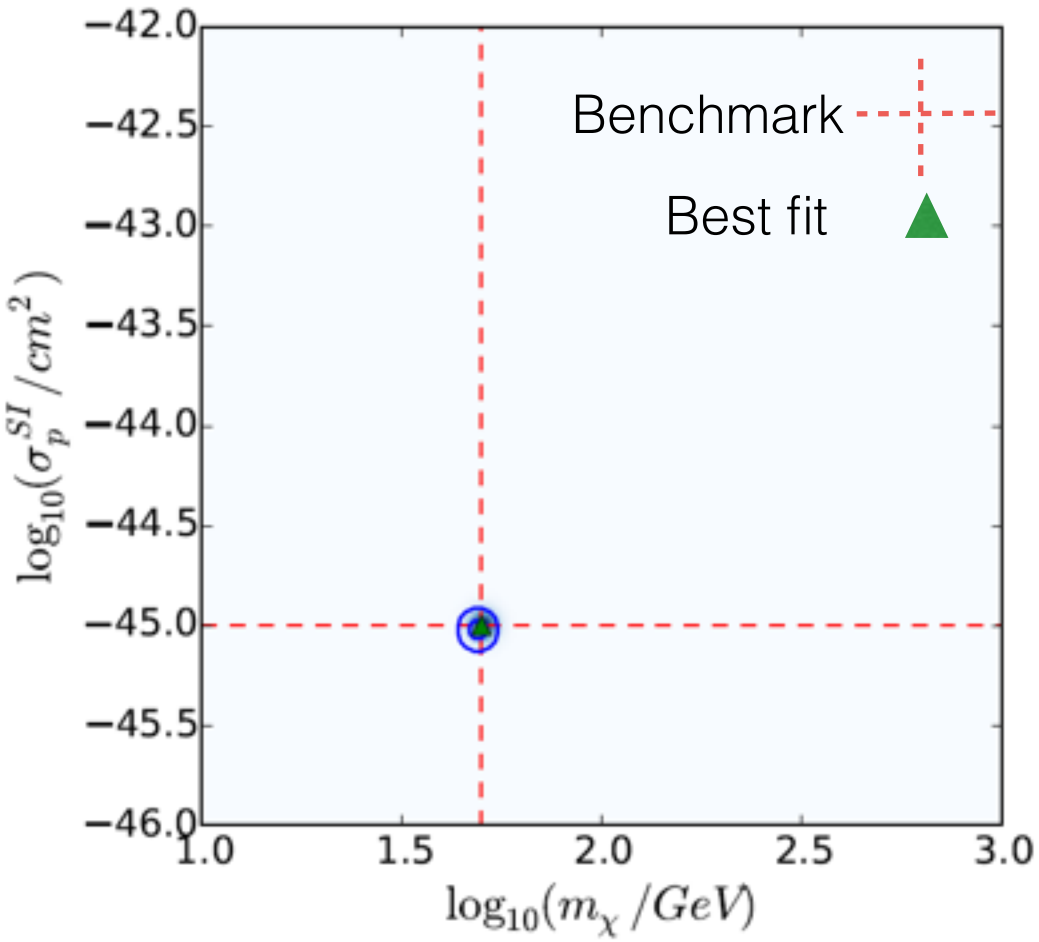


What happens if we assume the wrong speed distribution?

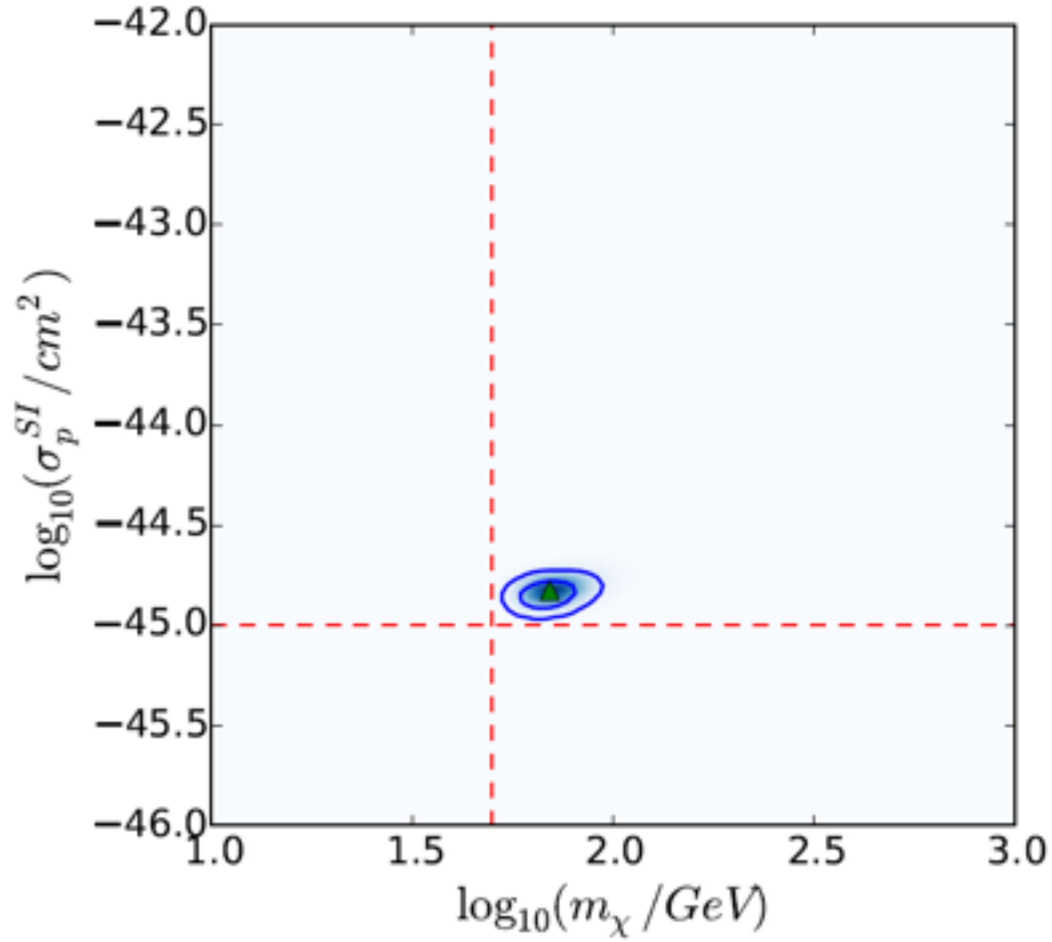
What could possibly go wrong?

Generate mock data for 3 future experiments - Xe, Ar, Ge - for a given (m_χ, σ_{SI}^p) assuming a stream distribution function. Then construct confidence contours for these parameters, assuming:

(correct) stream distribution



(incorrect) SHM distribution



A solution

Many previous attempts to tackle this problem

Strigari & Trotta [arXiv:0906.5361]; Fox, Liu & Weiner [arXiv:1011.915]; Frandsen et al. [arXiv:1111.0292]; Feldstein & Kahlhoefer [arXiv:1403.4606]

Write a *general parametrisation* for the speed distribution:

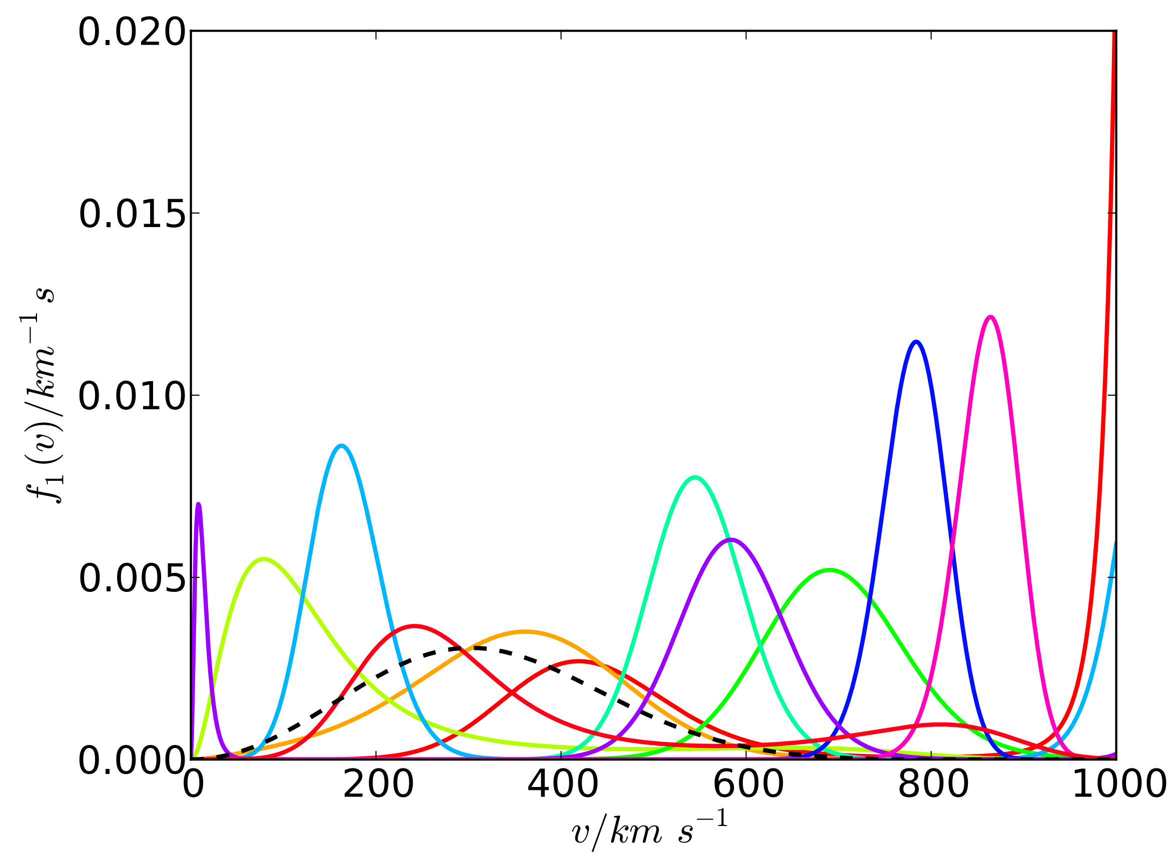
Peter [arXiv:1103.5145]

$$f(v) = \exp\left(-\sum_{k=0}^{N-1} a_k v^k\right)$$

BJK & Green [arXiv:1303.6868]

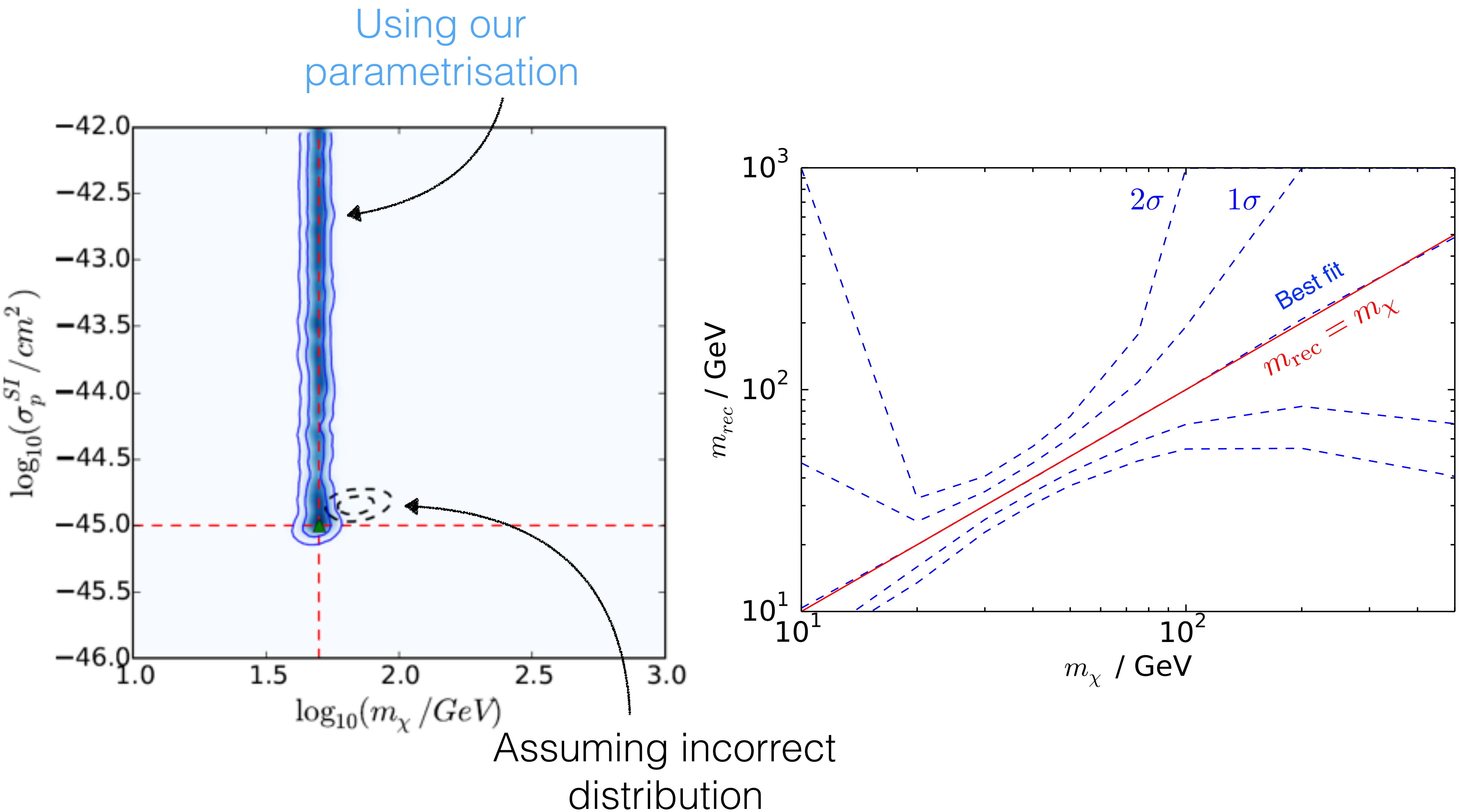
This form guarantees a positive distribution function.

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



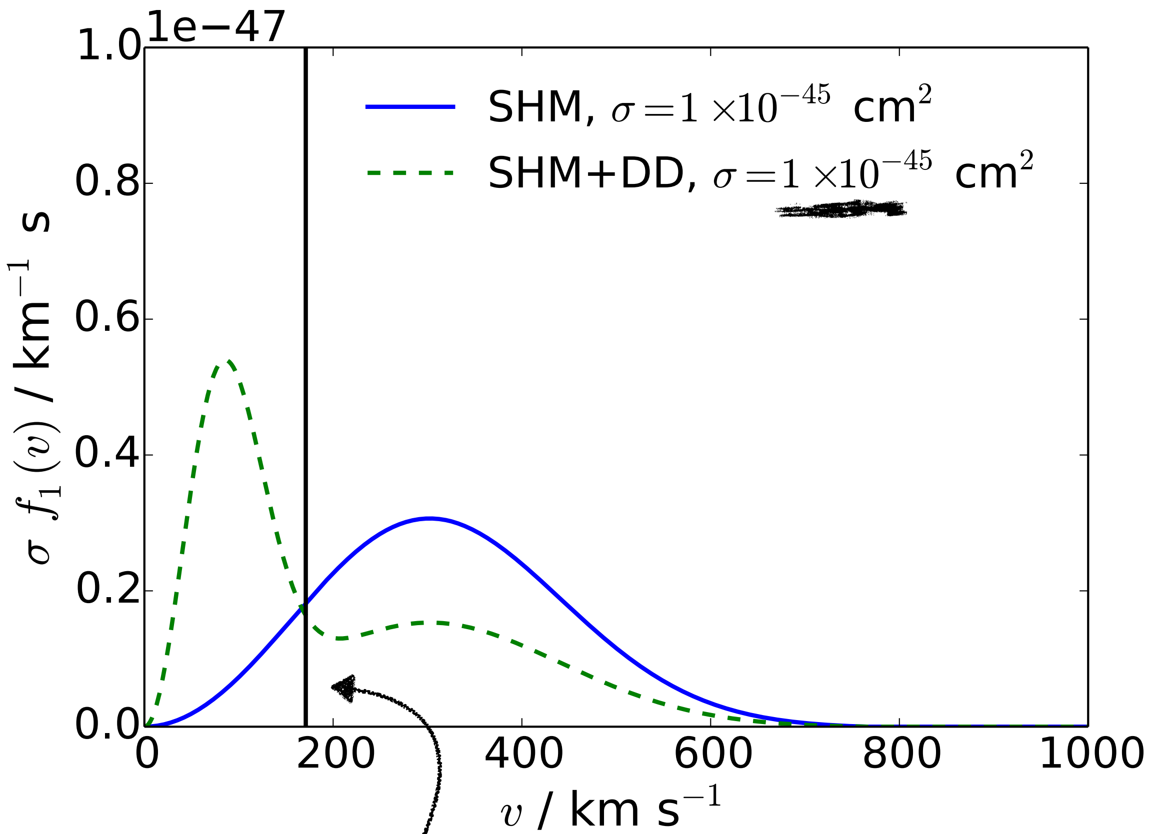
$$f_1(v) = v^2 f(v)$$

Results



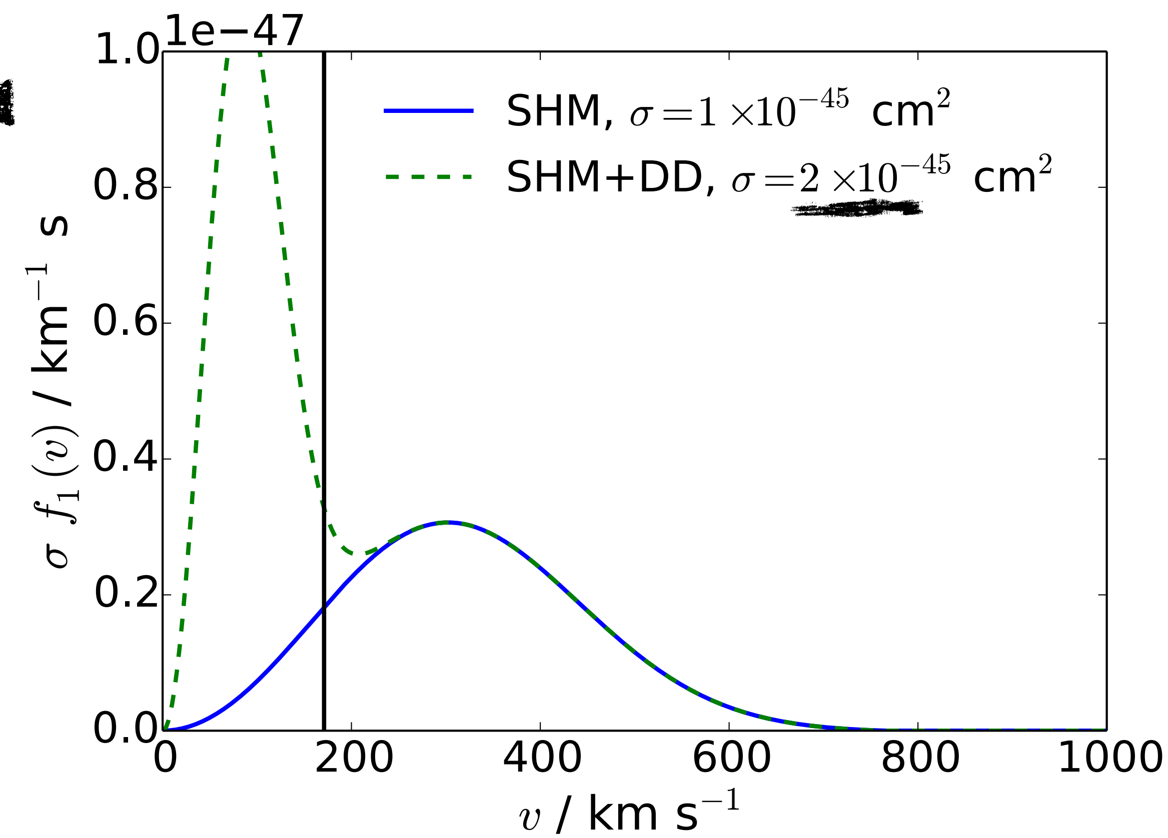
But, there is now a strong degeneracy in the reconstructed cross section…

Cross section degeneracy



Minimum DM speed probed by a typical Xe experiment

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

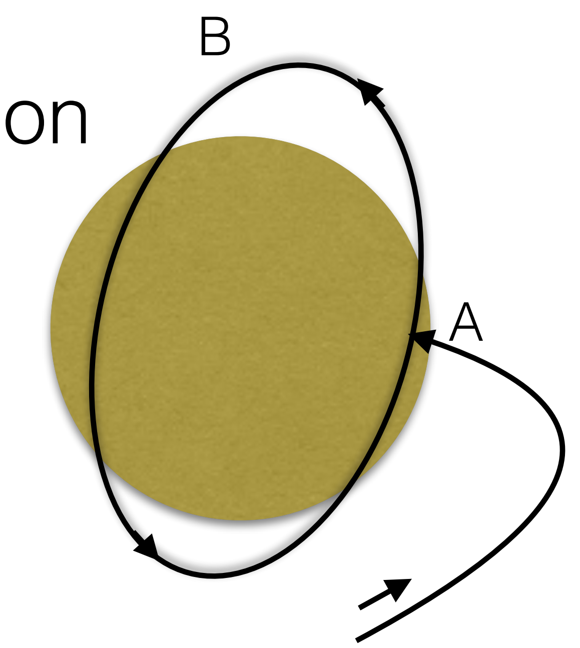


This is a problem for *any* astrophysics-independent method!

Incorporating IceCube

IceCube can detect neutrinos from DM annihilation in the Sun

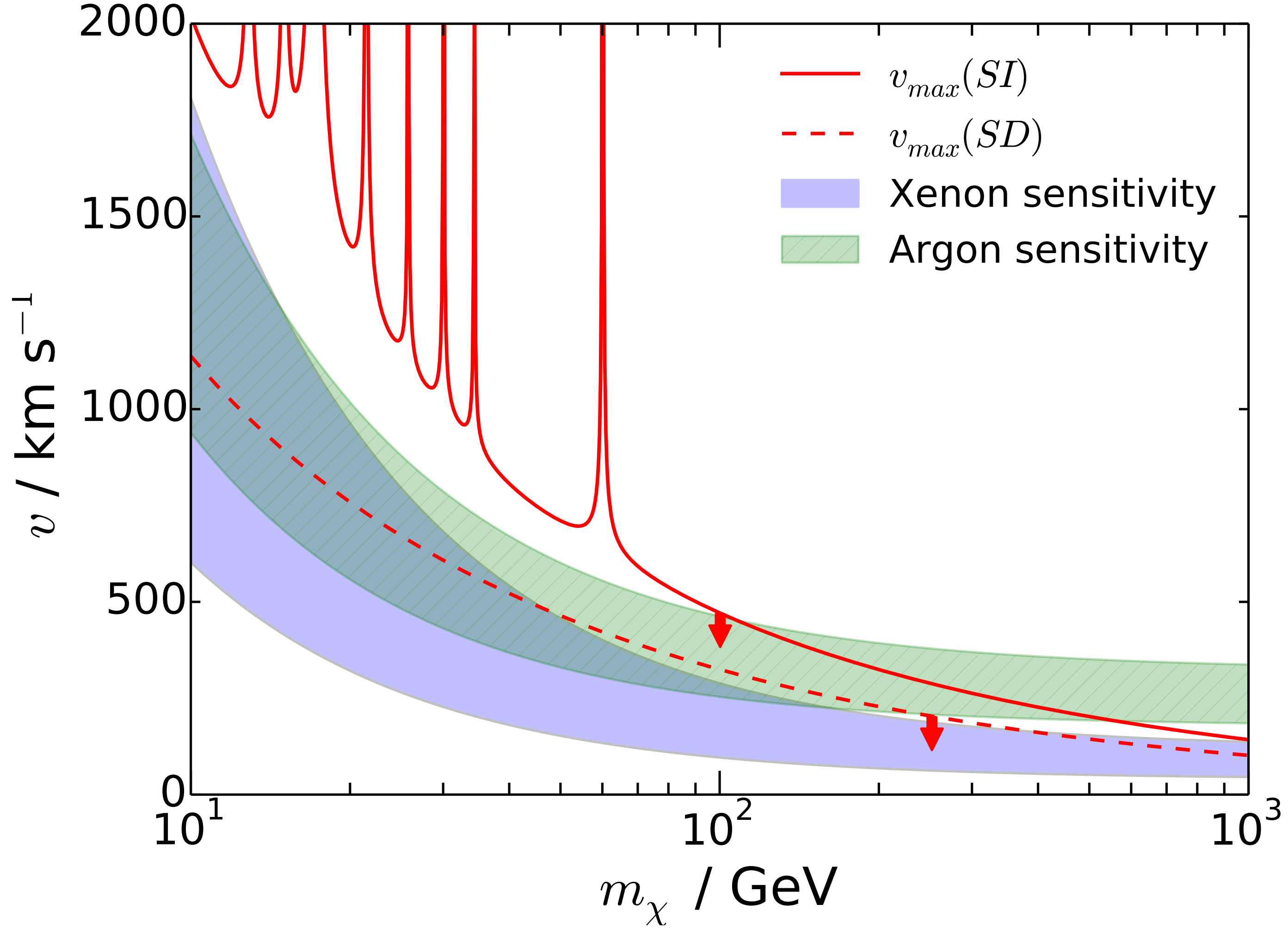
Rate driven by solar capture of DM, which depends on the DM-nucleus scattering cross section



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…

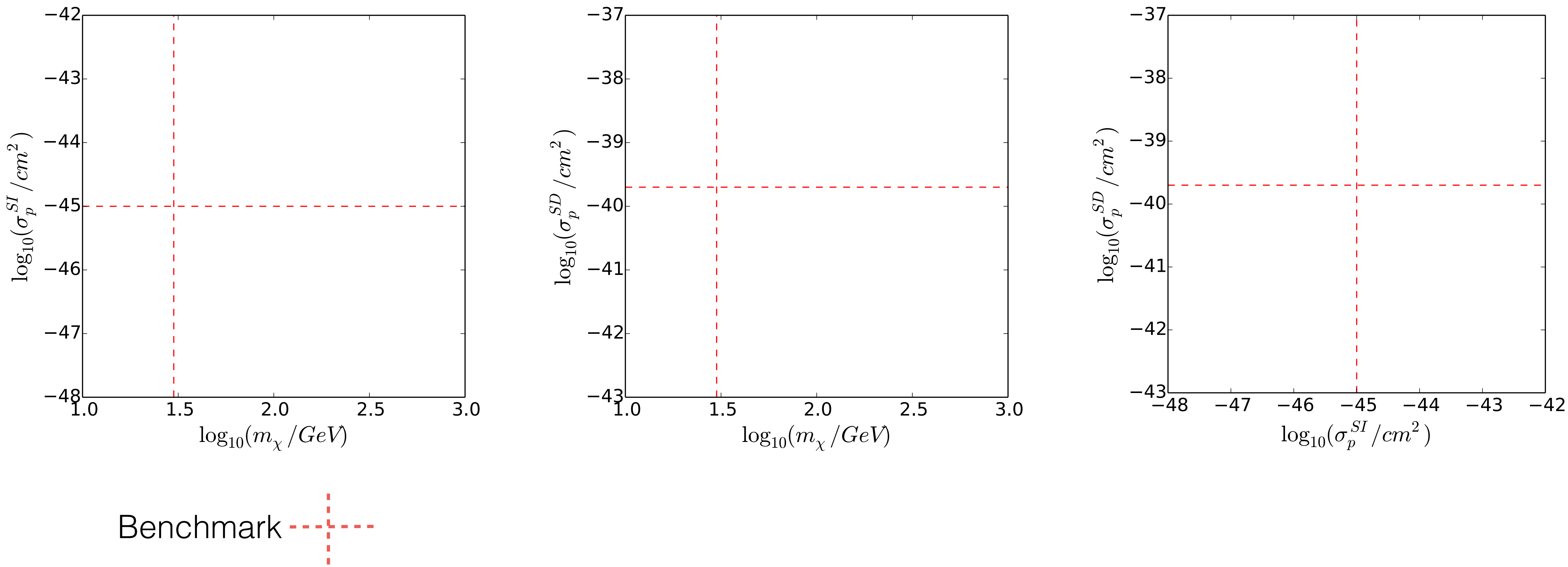


Direct detection only

Consider a single benchmark:

$$m_\chi = 30\,\mathrm{GeV};\;\; \sigma_{SI}^{p} = 10^{-45}\,\mathrm{cm}^2;\;\; \sigma_{SD}^{p} = 2\times 10^{-40}\,\mathrm{cm}^2$$

annihilation to $\nu_\mu \bar{\nu}_\mu$, SHM+DD distribution



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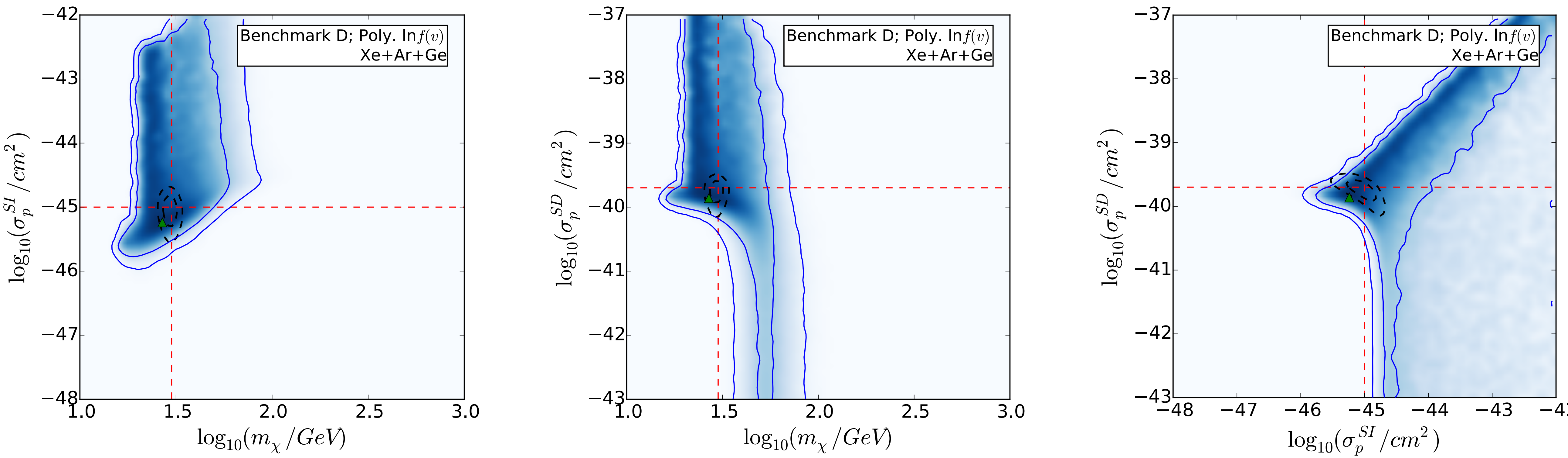

Benchmark

Best fit

Fixed (correct) speed distribution

Our parametrisation

Direct detection + IceCube

Consider a single benchmark:

$$m_\chi = 30\,\mathrm{GeV};\;\; \sigma_{SI}^{p} = 10^{-45}\,\mathrm{cm}^2;\;\; \sigma_{SD}^{p} = 2\times 10^{-40}\,\mathrm{cm}^2$$

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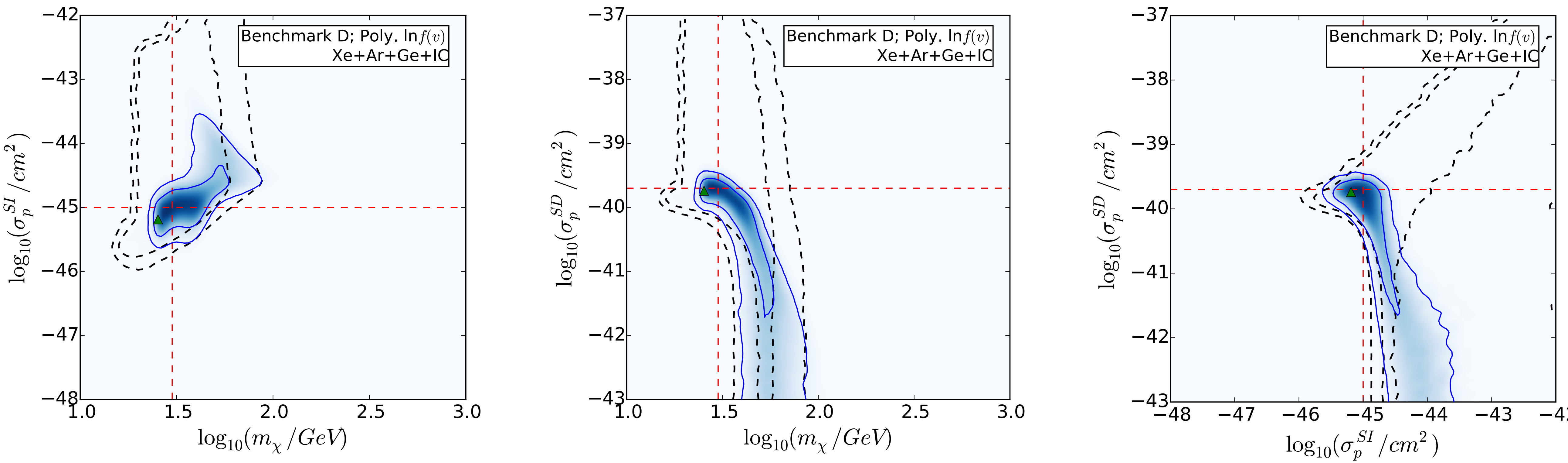


Benchmark

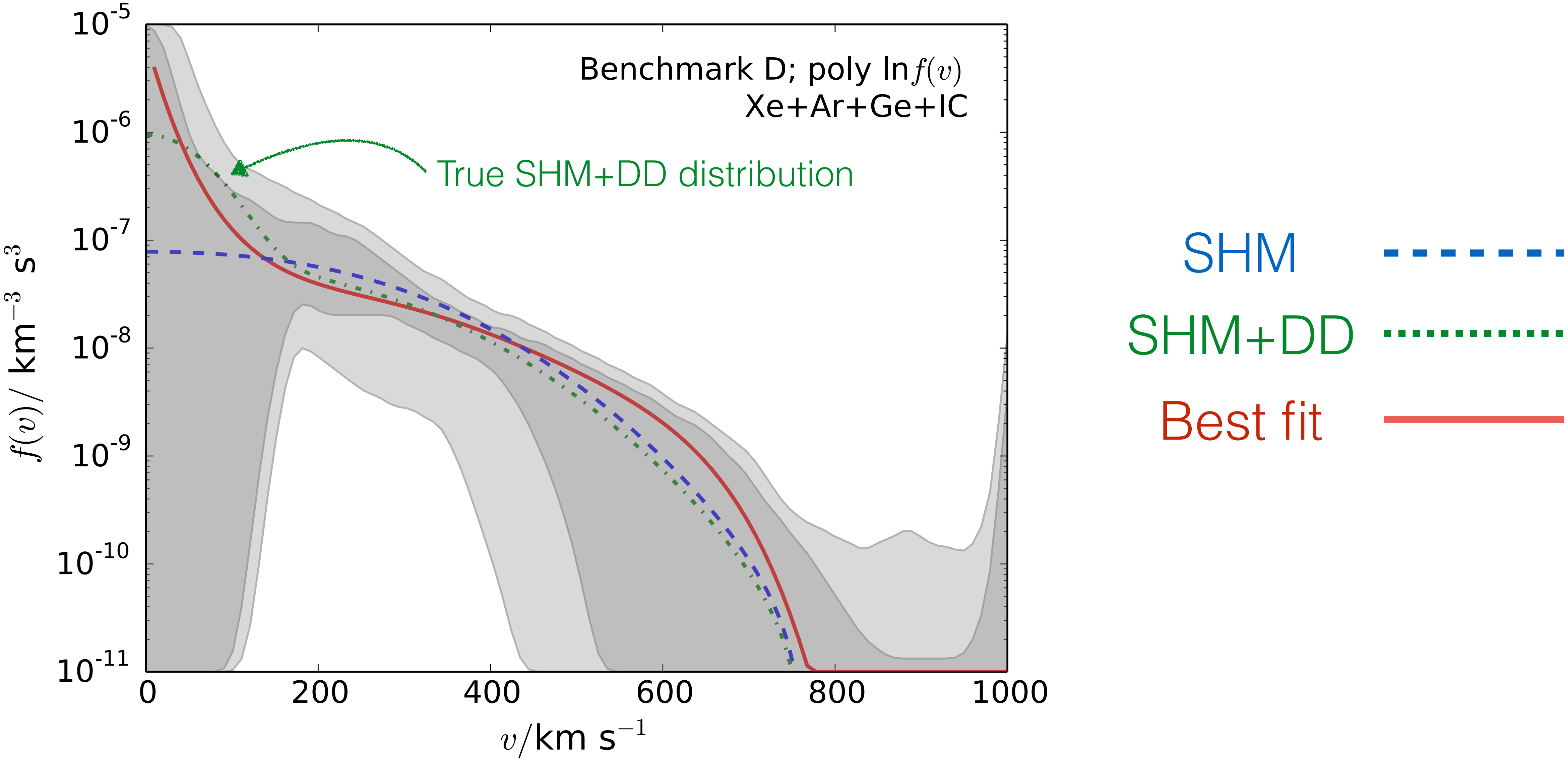
Best fit

Direct detection only (our param.)

Direct detection + IceCube (our param.)

Reconstructing the velocity distribution

Use constraints on $\{a_k\}$ to construct confidence intervals on $f(v)$.



Astrophysical uncertainties

If we take a very general approach to the DM velocity distribution, we can combine results from multiple experiments to reconstruct m_χ *without assumptions*.

If we include neutrino telescope data (e.g. IceCube), we can probe the full range of DM velocities and therefore also constrain the DM cross sections: $(m_\chi, \sigma_{\mathrm{SI}}^p, \sigma_{\mathrm{SD}}^p)$

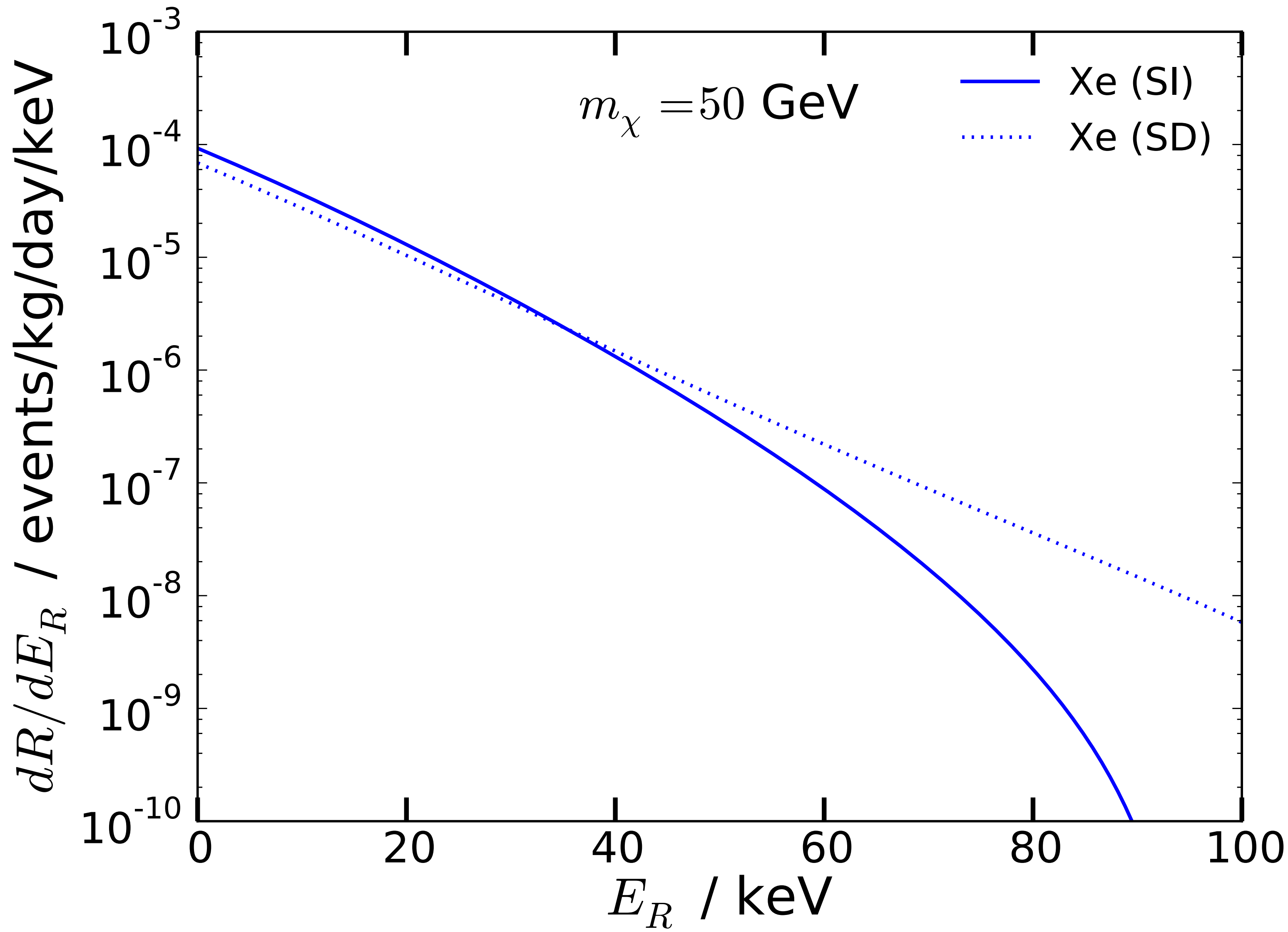
We also simultaneously fit the DM velocity distribution, so we can hope to distinguish different distributions and thus probe DM and Galactic astrophysics.

Particle physics uncertainties

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{\mathrm{min}}}^{\infty} v f_1(v) \boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}} \mathrm{d}v$$

Spin-dependent or spin-independent

Compare SI and SD event rates for a Xenon target:



$$\sigma_{\mathrm{SI}}^p = 10^{-45}\ \mathrm{cm}^2$$

$$\sigma_{\mathrm{SD}}^p = 10^{-40}\ \mathrm{cm}^2$$

assuming equal coupling to protons and neutrons

Need a number of experiments to distinguish SI and SD interactions…

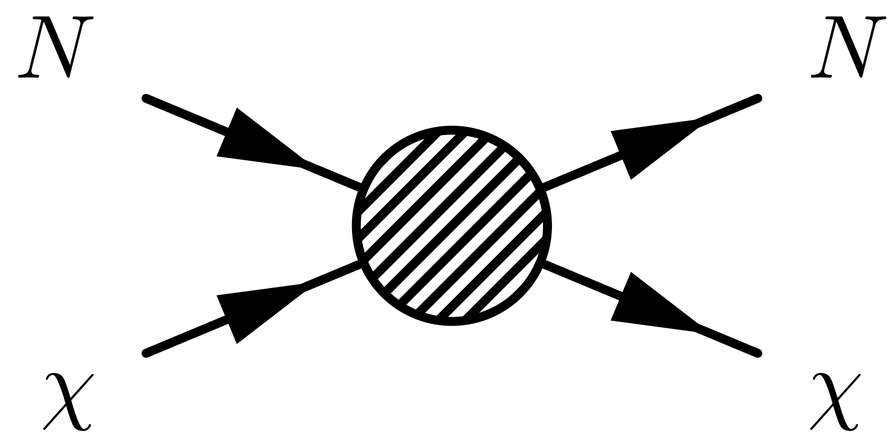
…but it gets worse…

[arXiv:1304.1758, arXiv:1507.08625]

Possible WIMP-nucleon operators

Direct detection:

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

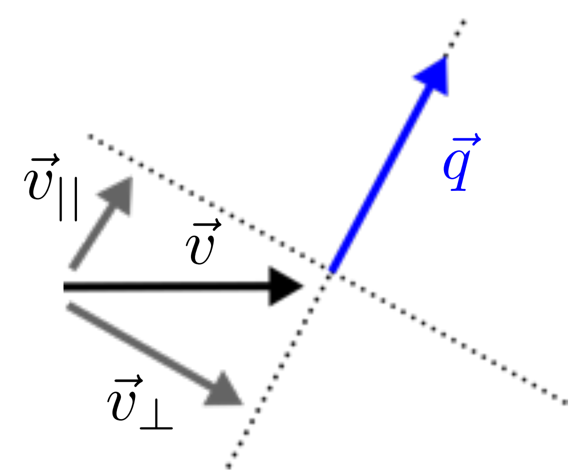


$$q \lesssim 100\,\text{MeV} \sim (2 \text{ fm})^{-1}$$

Relevant non-relativistic (NR) degrees of freedom:

$$\vec{S}_\chi\,, \quad \vec{S}_N, \quad \frac{\vec{q}}{m_N}\,, \quad \vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}}$$

Fitzpatrick et al. [arXiv:1203.3542]



Non-relativistic effective field theory (NREFT)

Require Hermitian, Galilean invariant and time-translation invariant combinations:

SI → $\mathcal{O}_1 = 1$

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

[arXiv:1008.1591, arXiv:1203.3542, arXiv:1308.6288, arXiv:1505.03117]

Non-relativistic effective field theory (NREFT)

Require Hermitian, Galilean invariant and time-translation invariant combinations:

SI → $\boxed{\mathcal{O}_1 = 1}$

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

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

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

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

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

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

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

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

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

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

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

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

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

$\vdots$

[arXiv:1008.1591, arXiv:1203.3542, arXiv:1308.6288, arXiv:1505.03117]

Calculating the cross section

'Dictionaries' are available which allow us to translate from relativistic interactions to NREFT operators:

[e.g. arXiv:1211.2818, arXiv:1307.5955, arXiv:1505.03117]

E.g. $\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma^5 N \longrightarrow 8m_N(m_N\mathcal{O}_9 - m_\chi\mathcal{O}_7)$

Then calculating the scattering cross section is straightforward:

$$\frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} = \frac{1}{32\pi}\frac{m_A}{m_\chi^2 m_N^2}\frac{1}{v^2}\sum_{N,N'=p,n} c_i^N c_i^{N'} F_i^{(N,N')}(v_\perp^2, q^2)$$

Nuclear response functions: $F_i(v_\perp^2, q^2)$

So how can we distinguish these different cross sections?

Distinguishing operators: approaches

Materials signal - compare rates obtained in different experiments [1405.2637, 1406.0524, 1504.06554, 1506.04454, 1504.06772]

→ May require a large number of experiments

Energy spectrum - look for an energy spectrum which differs from the standard SI/SD case in a single experiment [1503.03379]

Examples

Consider three different operators: $\mathcal{O}_1, \mathcal{O}_5, \mathcal{O}_7$

SI operator → $\mathcal{O}_1 = 1$ $\quad F_1 \sim q^0 v^0$

'Non-standard' operators →

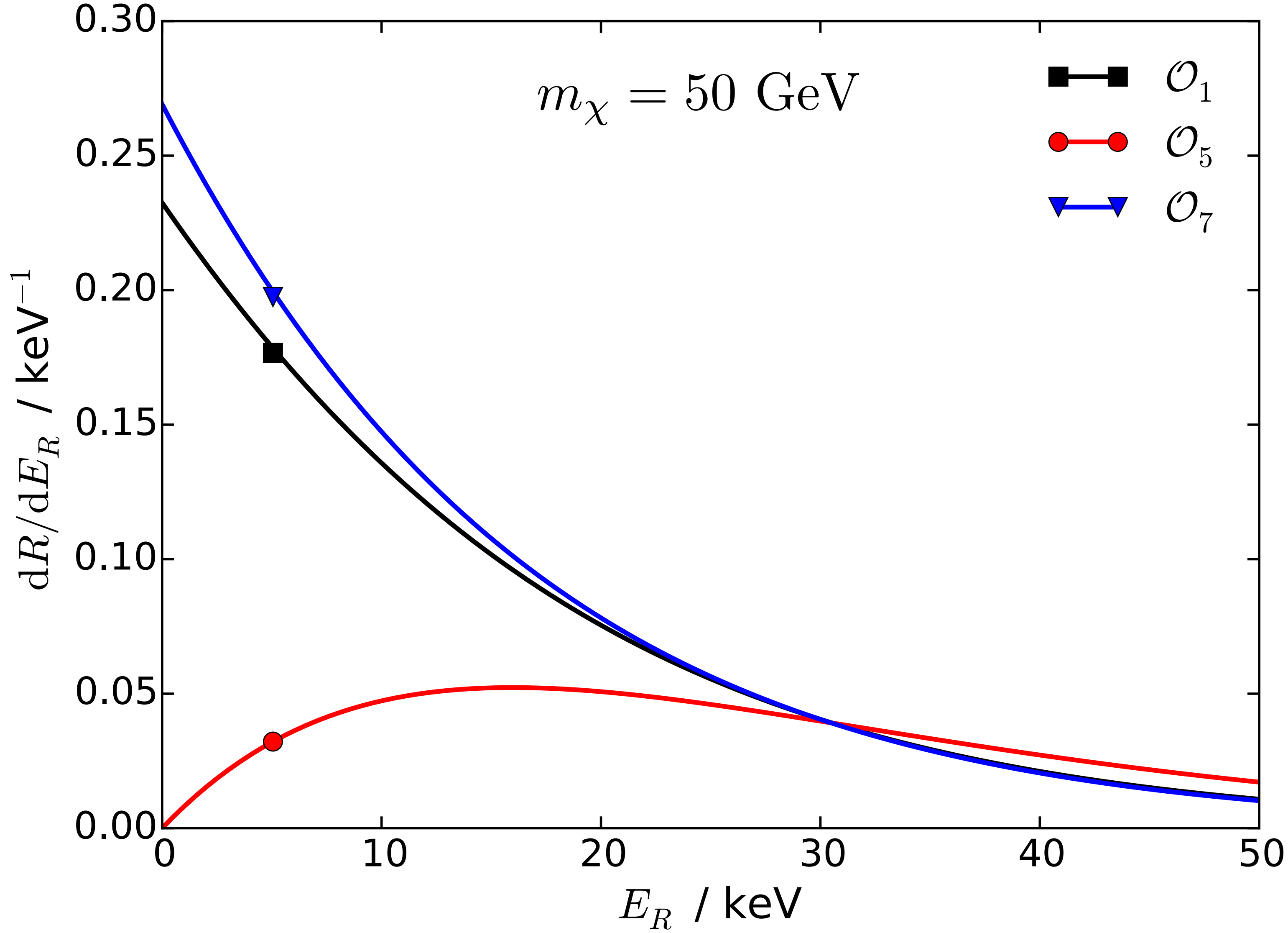
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$ $\quad F_5 \sim q^2(v_\perp^2 + q^2)$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$ $\quad F_7 \sim v_\perp^2$

Different q^2 and $v_\perp^2$ dependence should lead to different energy spectra:

$$\frac{\mathrm{d}R_i}{\mathrm{d}E_R} \sim c_i^2 \int_{v_{\min}}^{\infty} \frac{f(\vec{v})}{v} F_i(q^2, v_\perp^2)\, \mathrm{d}^3\vec{v}\,.$$

Comparing energy spectra



CF$_4$ detector

SHM distribution

$F_1 \sim q^0 v^0$

$F_5 \sim q^2 (v_\perp^2 + q^2)$

$F_7 \sim v_\perp^2$

Energy spectrum differences between $\mathcal{O}_1$ and $\mathcal{O}_7$ are smoothed out once we integrate over (smooth) DM velocity distribution.

True of any operators whose cross-sections differ only by $v_\perp^2$.

Distinguishing operators: Energy-only

Generate mock data assuming either $\mathcal{O}_5$ or $\mathcal{O}_7$.

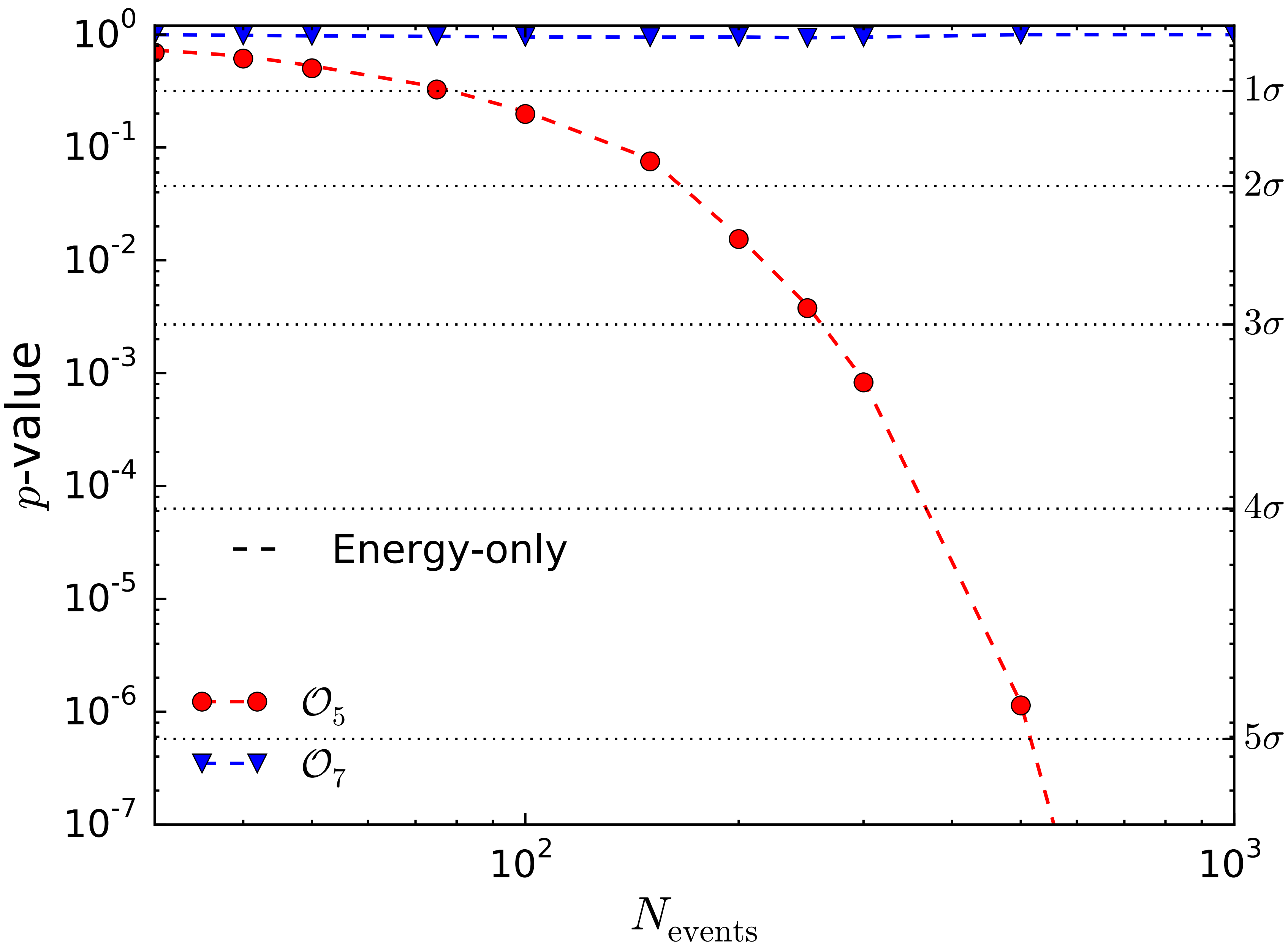
Assume the data is a mixture of events due to $\mathcal{O}_1$ and the 'non-standard' operator (either $\mathcal{O}_5$ or $\mathcal{O}_7$).

Fit values of m_χ and A, fraction of events due to 'non-standard' interactions.

With what significance can we reject the SI-only scenario?

Distinguishing operators: Energy-only

With what significance can we reject 'standard' SI/SD interactions in 95% of experiments?



'Perfect' CF_4 detector

$E_R \in [20, 50]$ keV

Input WIMP mass: $m_\chi = 50$ GeV

SHM velocity distribution

$F_1 \sim q^0 v^0$

$F_5 \sim q^2(v_\perp^2 + q^2)$

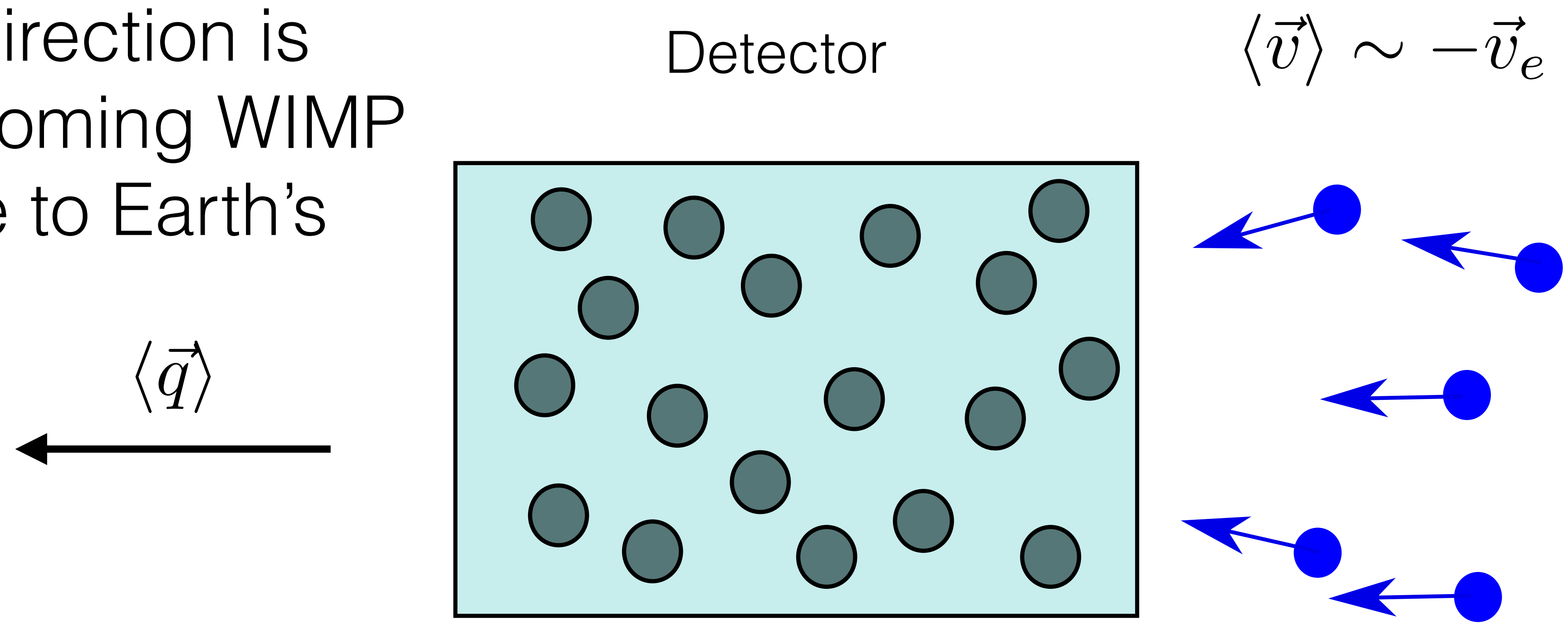
$F_7 \sim v_\perp^2$

Directional detection

Different v-dependence could impact *directional* signal.

e.g. Drift-IId [arXiv:1010.3027]

Mean recoil direction is parallel to incoming WIMP direction (due to Earth's motion).

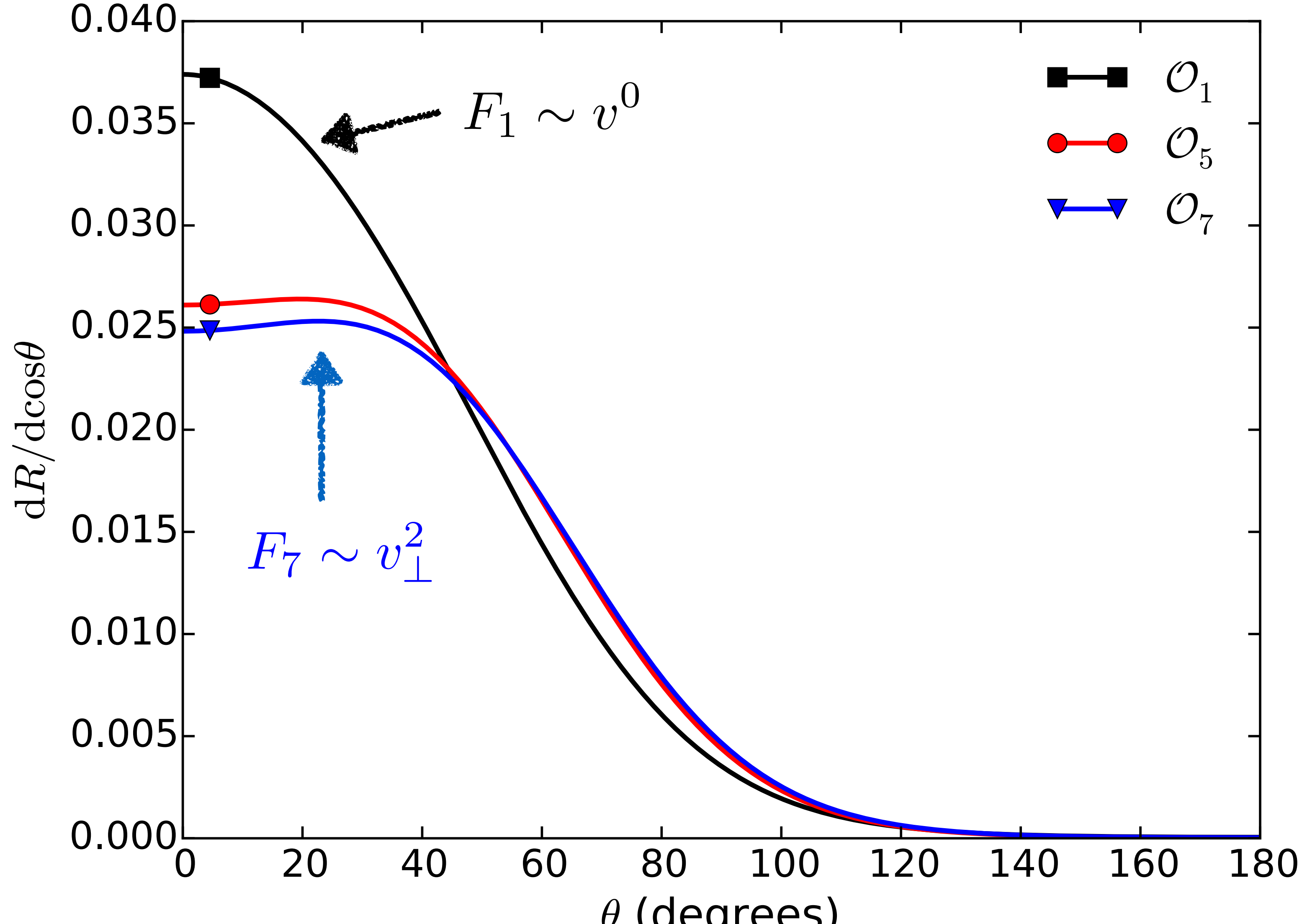


Convolve cross section with velocity distribution to obtain directional spectrum, as a function of θ , the angle between the recoil and the mean DM velocity.

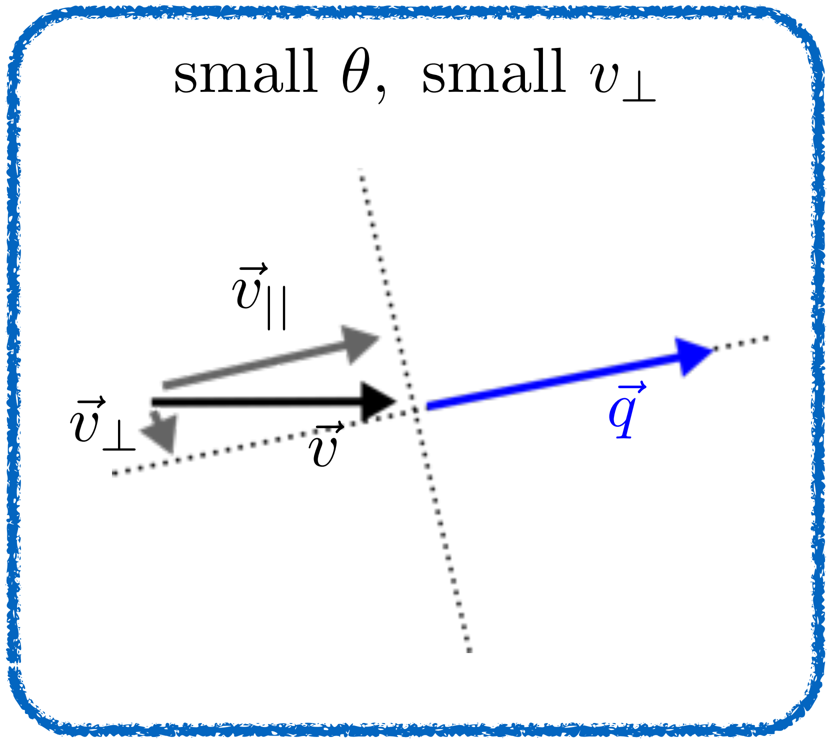
So, what does the directional spectrum look like?

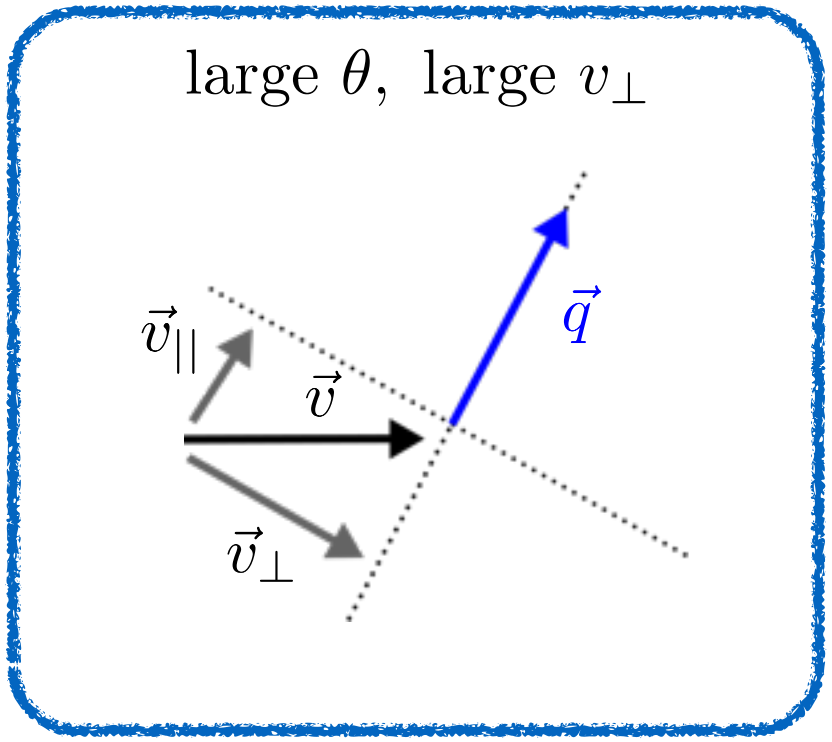
Directional spectra of NREFT operators

Total distribution of recoils as a function of θ:



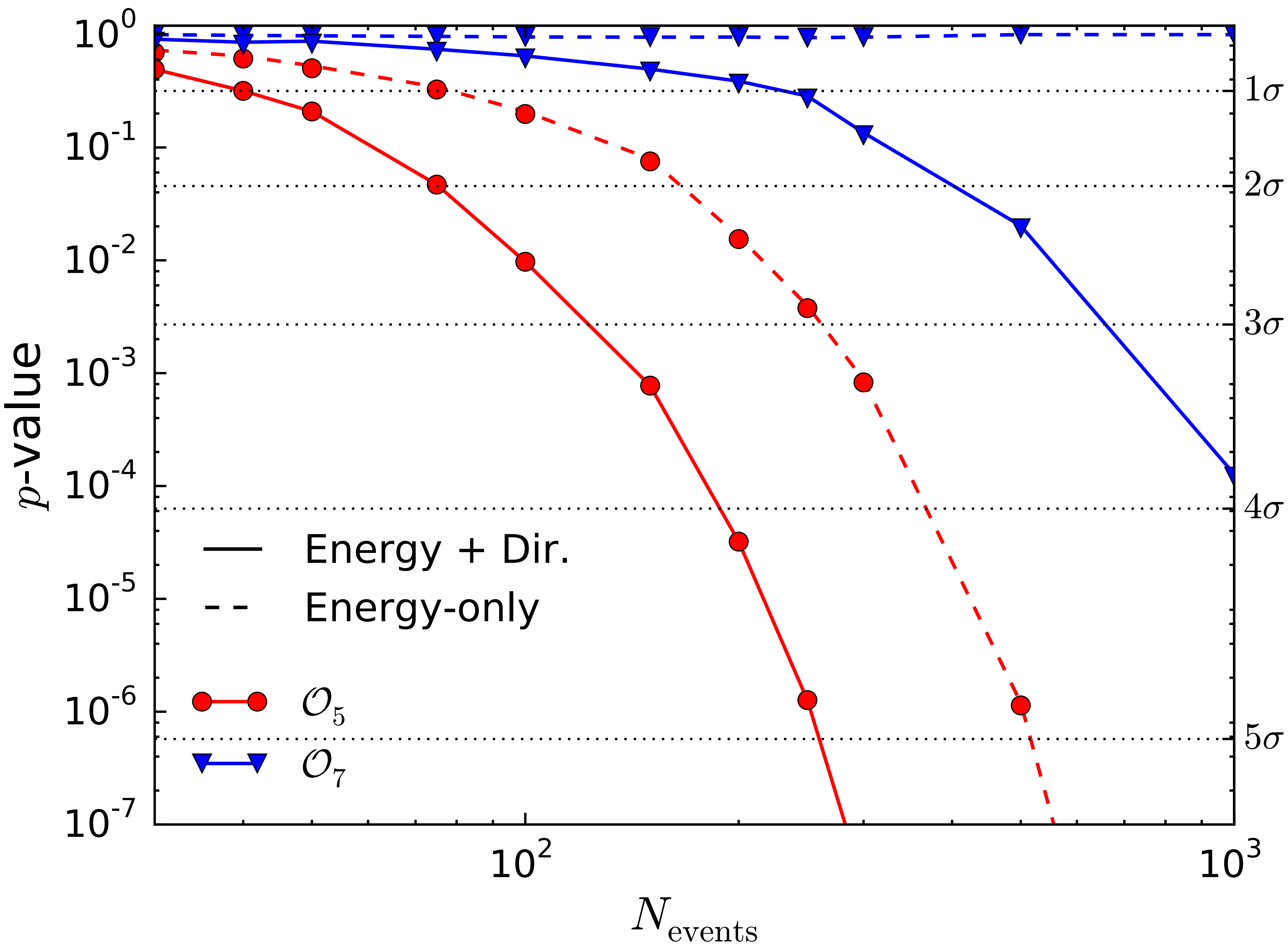
Spectra of all operators given in [1505.07406, 1505.06441].





Distinguishing operators: Energy + Directionality

With what significance can we reject 'standard' SI/SD interactions in 95% of experiments?



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Particle physics uncertainties

Some operators can be distinguished in a single experiment from their energy spectra alone (e.g. if the form factor goes as $F \sim q^n$)

But, this is not true for all operators. Consider:

$$\mathcal{L}_1 = \bar{\chi}\chi\bar{N}N \longrightarrow F \sim v^0$$

$$\mathcal{L}_6 = \bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu N \longrightarrow F \sim v_\perp^2$$

These operators *cannot* be distinguished in a single non-directional experiment.

Could combine multiple experiments (*materials signal*) and directional information to pin down DM-nucleon interactions.

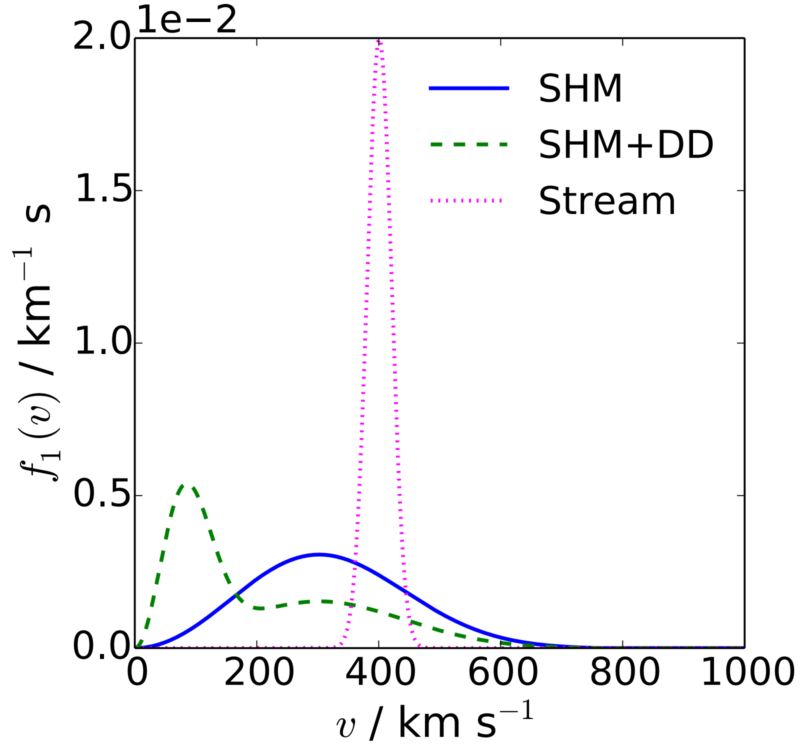
Combining uncertainties

Energy spectra

$F_1 \sim q^0 v^0$

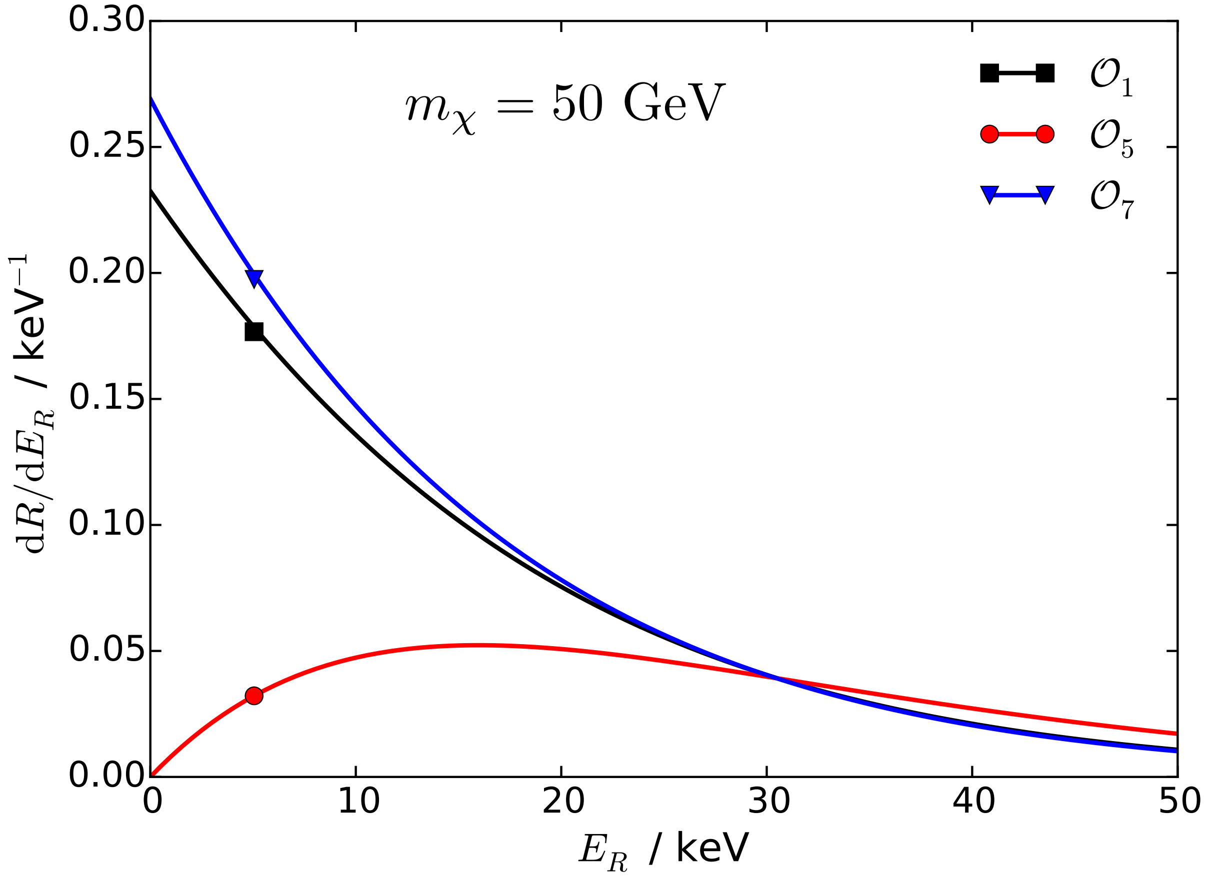
$F_5 \sim q^2 (v_\perp^2 + q^2)$

$F_7 \sim v_\perp^2$

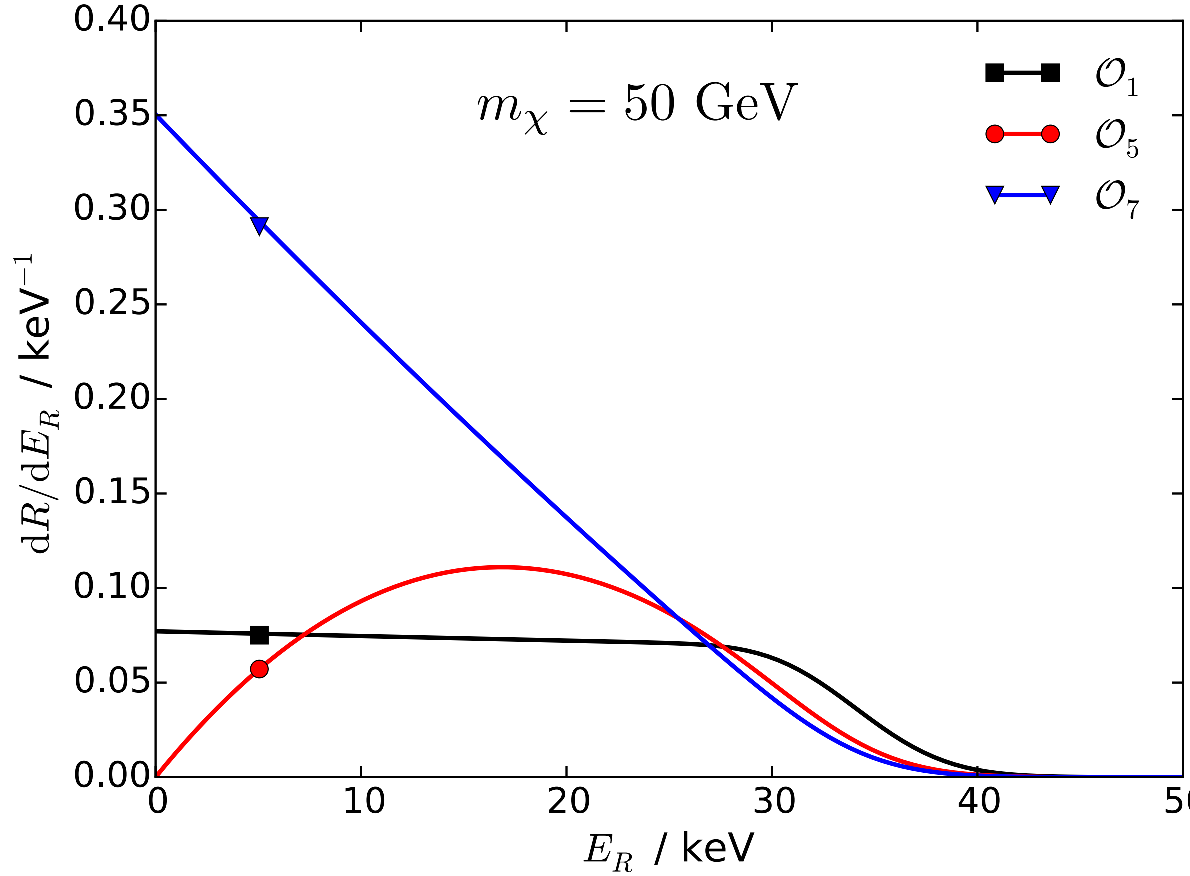


CF_4 detector

SHM



Stream



Directional spectra

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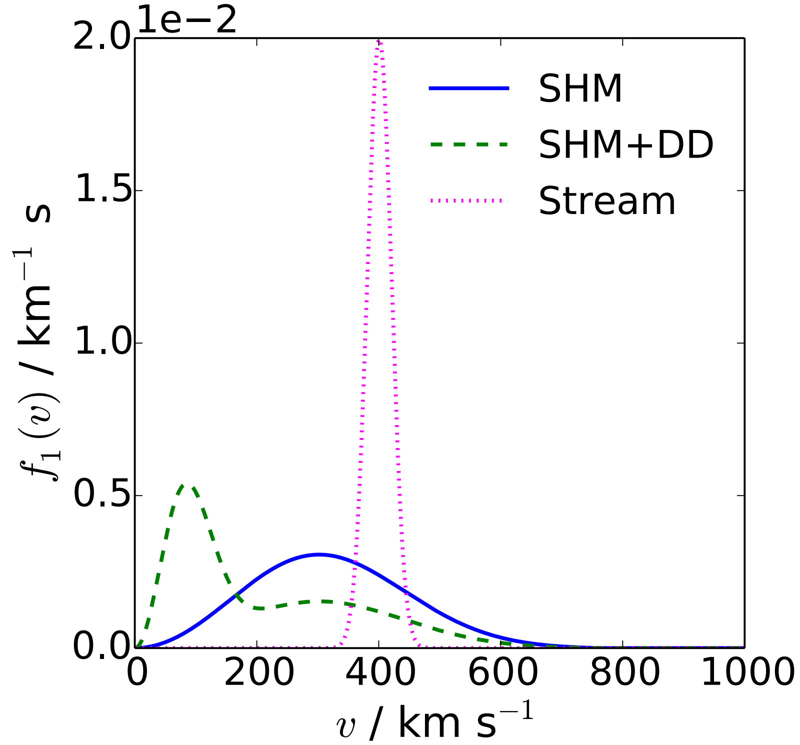
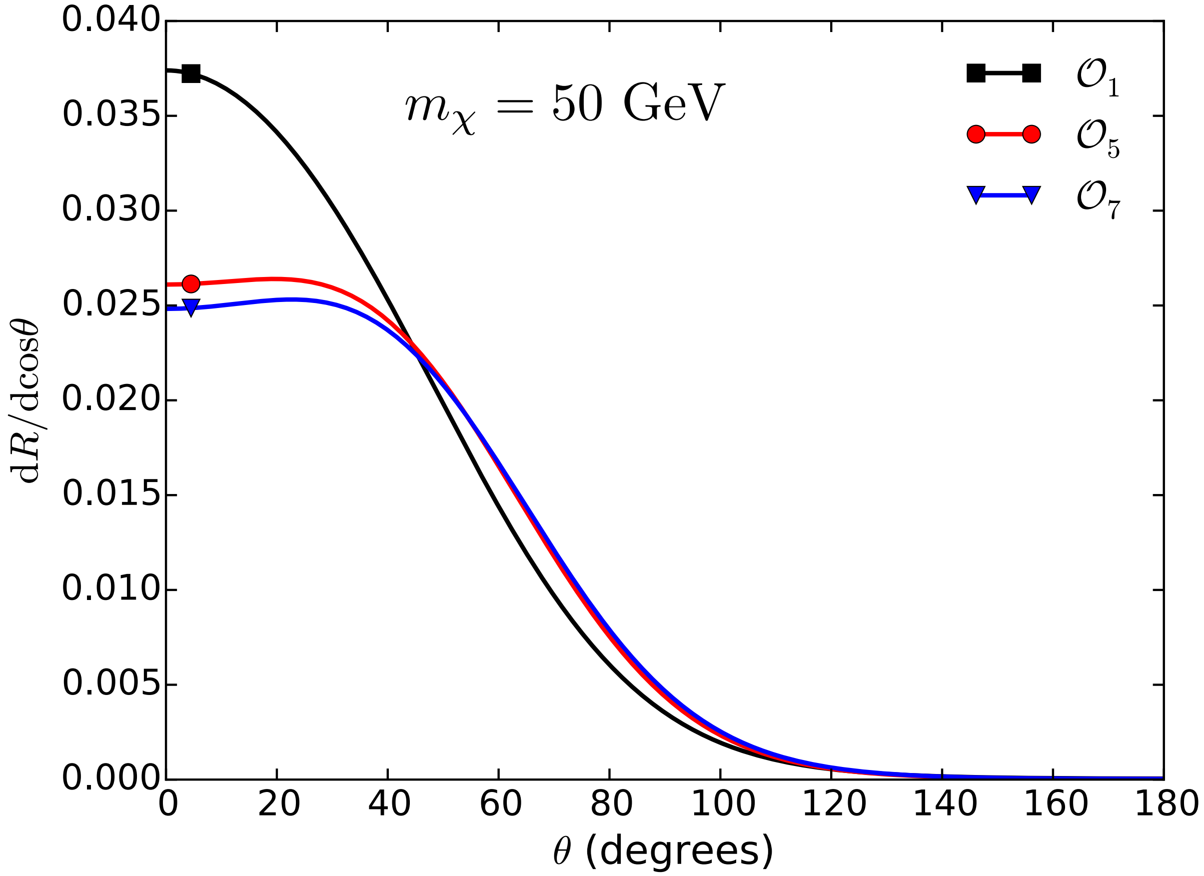
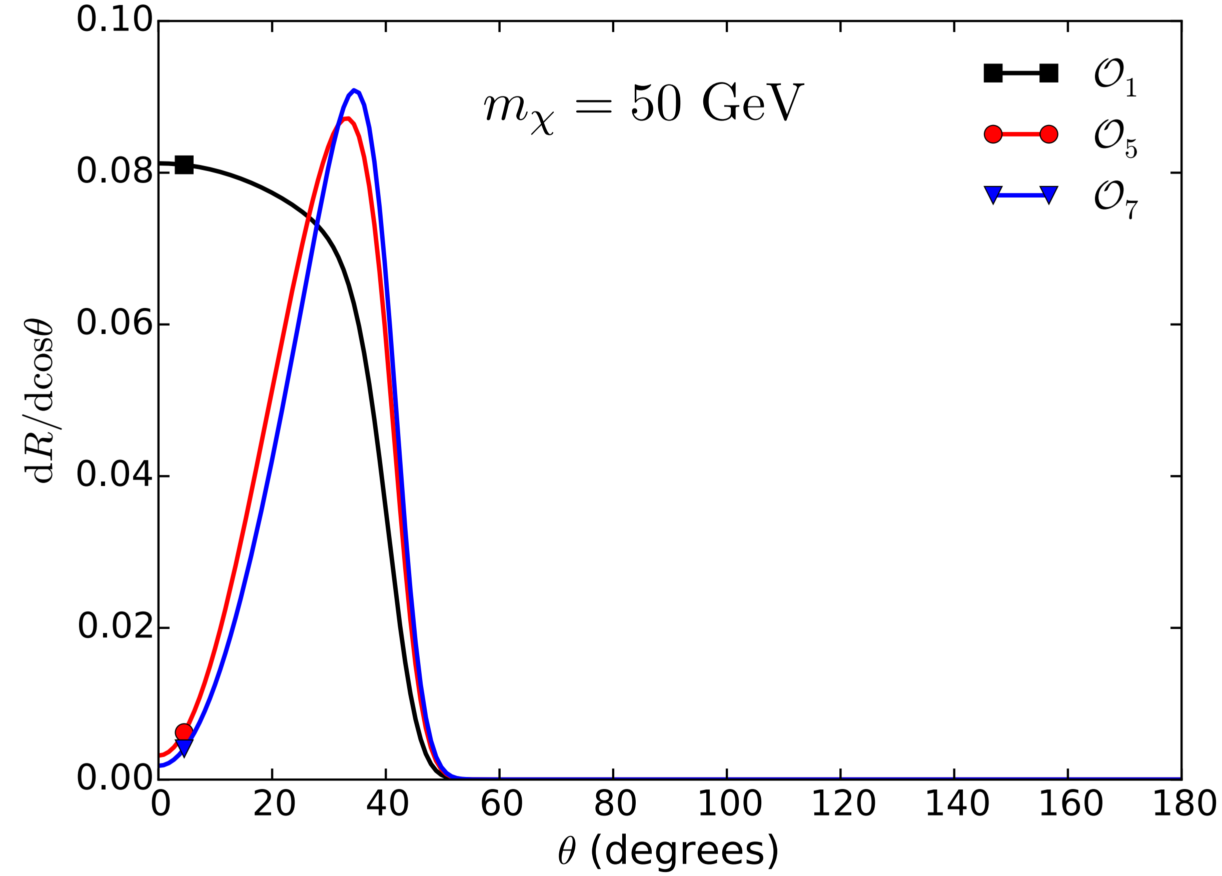


SHM

Stream





Future work

Astro uncertainties:

Reconstructing the full velocity distribution from *directional* experiments

Particle uncertainties:

Classifying which operators can be distinguished

Prospects for discriminating operators using directionality *and* multiple targets

Combining uncertainties:

Prospects for discriminating DM-nucleon operators, assuming a general parametrisation for the DM velocity distribution

Conclusions

- Astrophysical uncertainties can affect our reconstruction of the DM mass and cross section
- But we can fit the DM velocity distribution at the same time
- Including neutrino telescope data gives us access to the full spectrum of the DM halo distribution

- Similarly, particle physics uncertainties can lead to a range of different energy spectra
- We can use multiple targets to distinguish different NR operators
- But directional detection may be the most promising approach - and shouldn't be spoiled by astro uncertainties

Rather than worrying about these uncertainties - we can use them!

Conclusions

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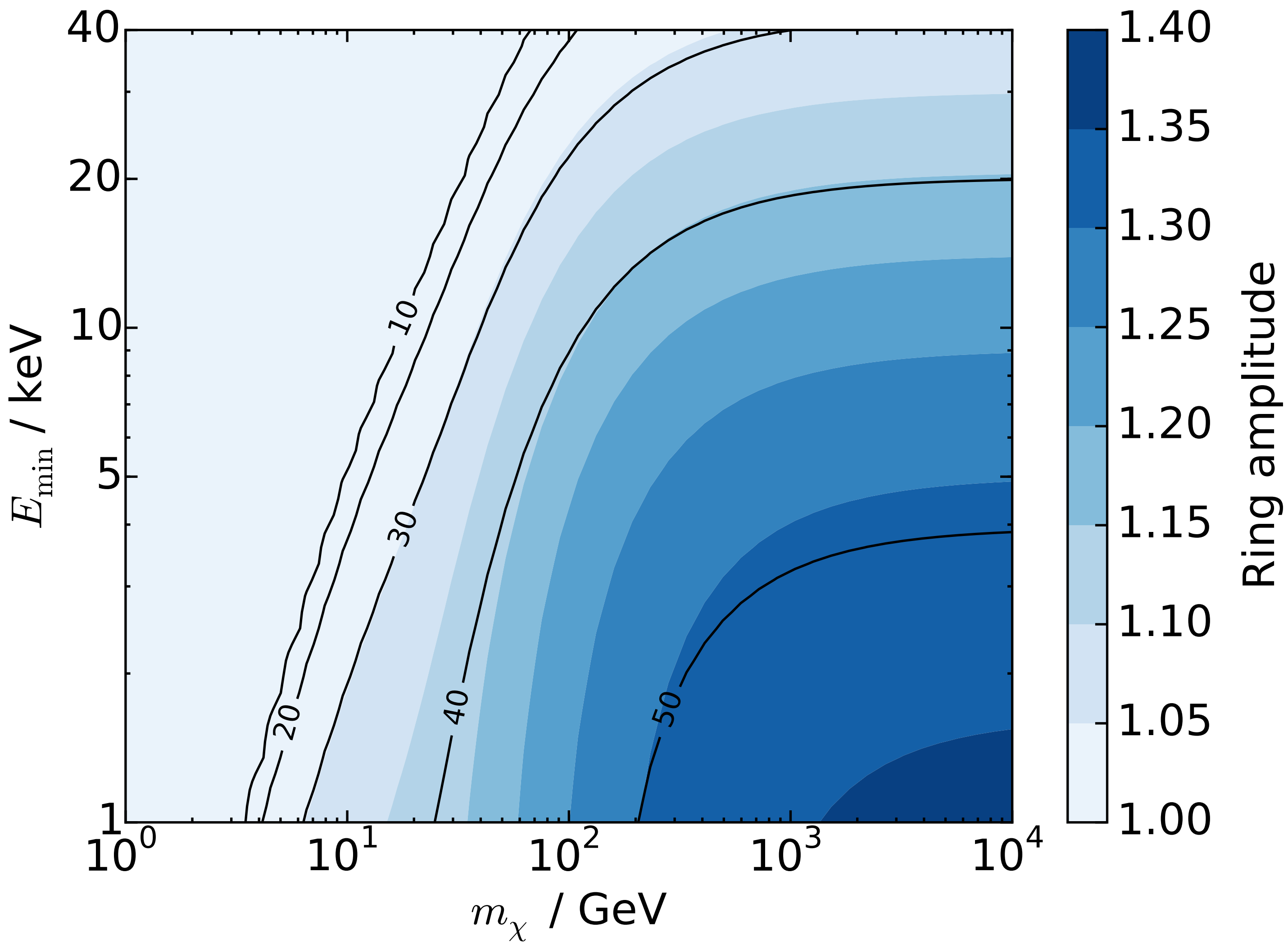
Thank you!

Backup Slides

A (new) ring-like feature

Operators with $\langle|\mathcal{M}|^2\rangle \sim (v_\perp)^2$ lead to a 'ring' in the directional rate.



Contours:
ring opening angle in degrees

Shading:
ring amplitude (ratio of ring to centre)

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

Statistical tests

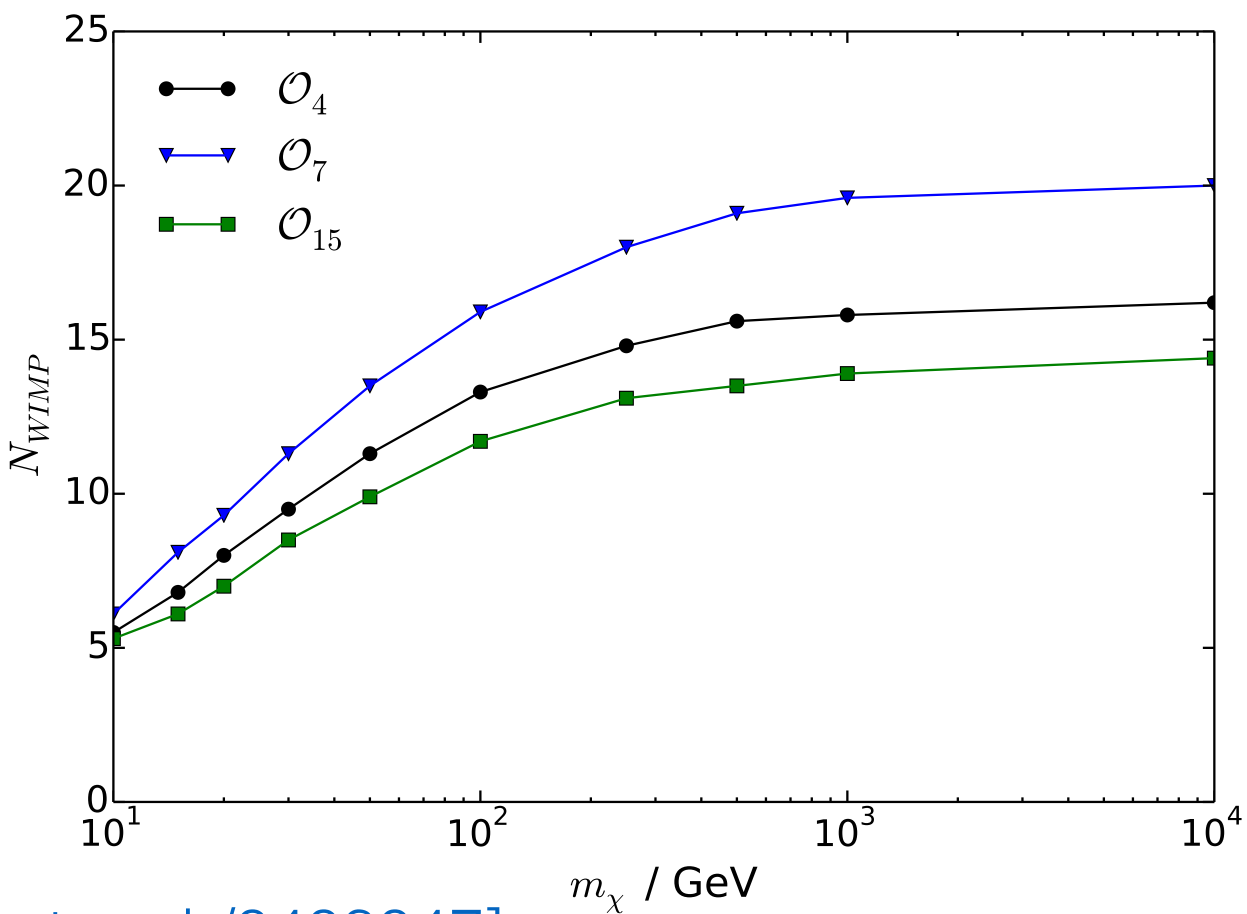
$F_{4,4} \sim 1$

$F_{7,7} \sim v_\perp^2$

$F_{15,15} \sim q^4(q^2 + v_\perp^2)$

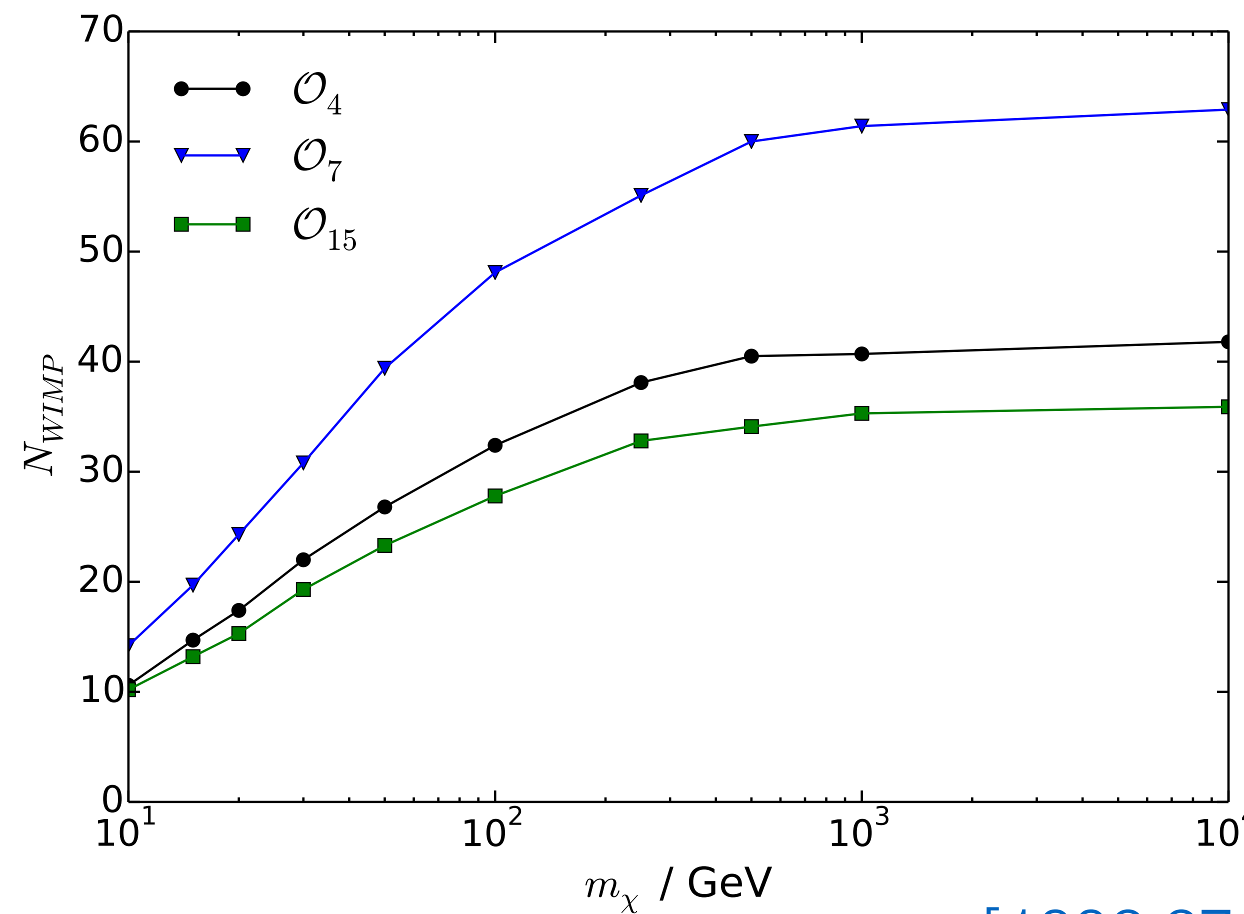
Calculate the number of signal events required to…

…reject isotropy…



[astro-ph/0408047]

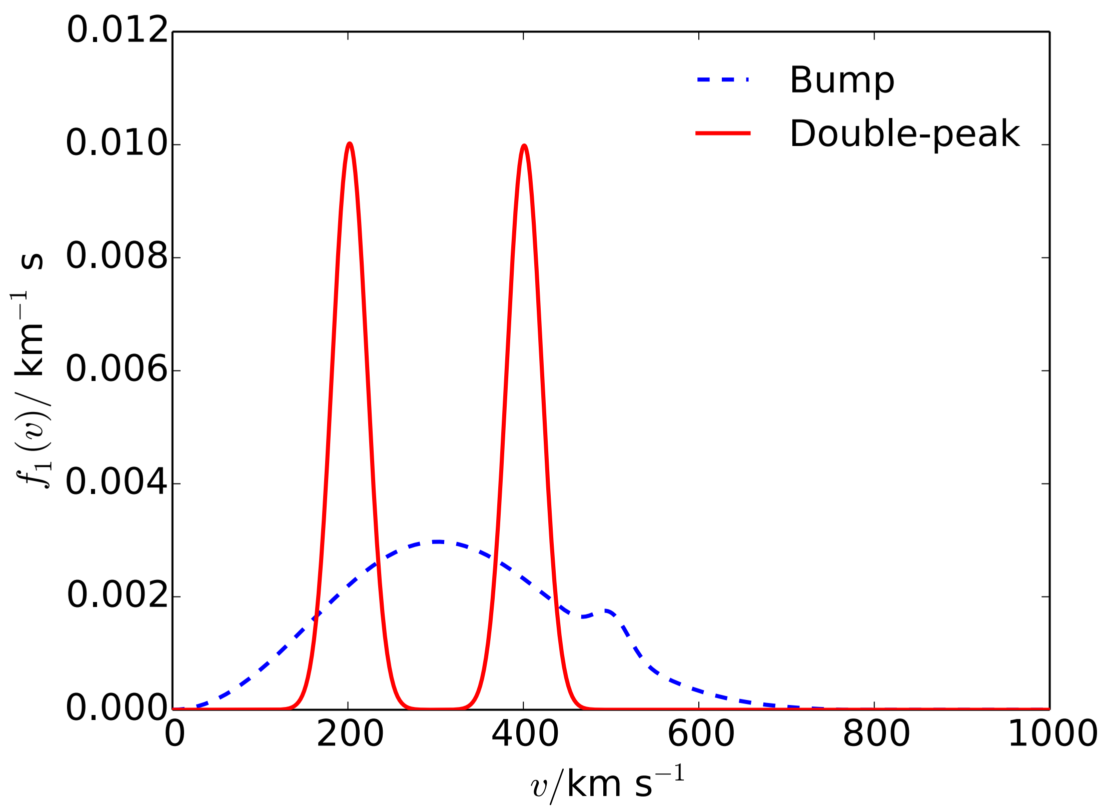
…confirm the median recoil dir…

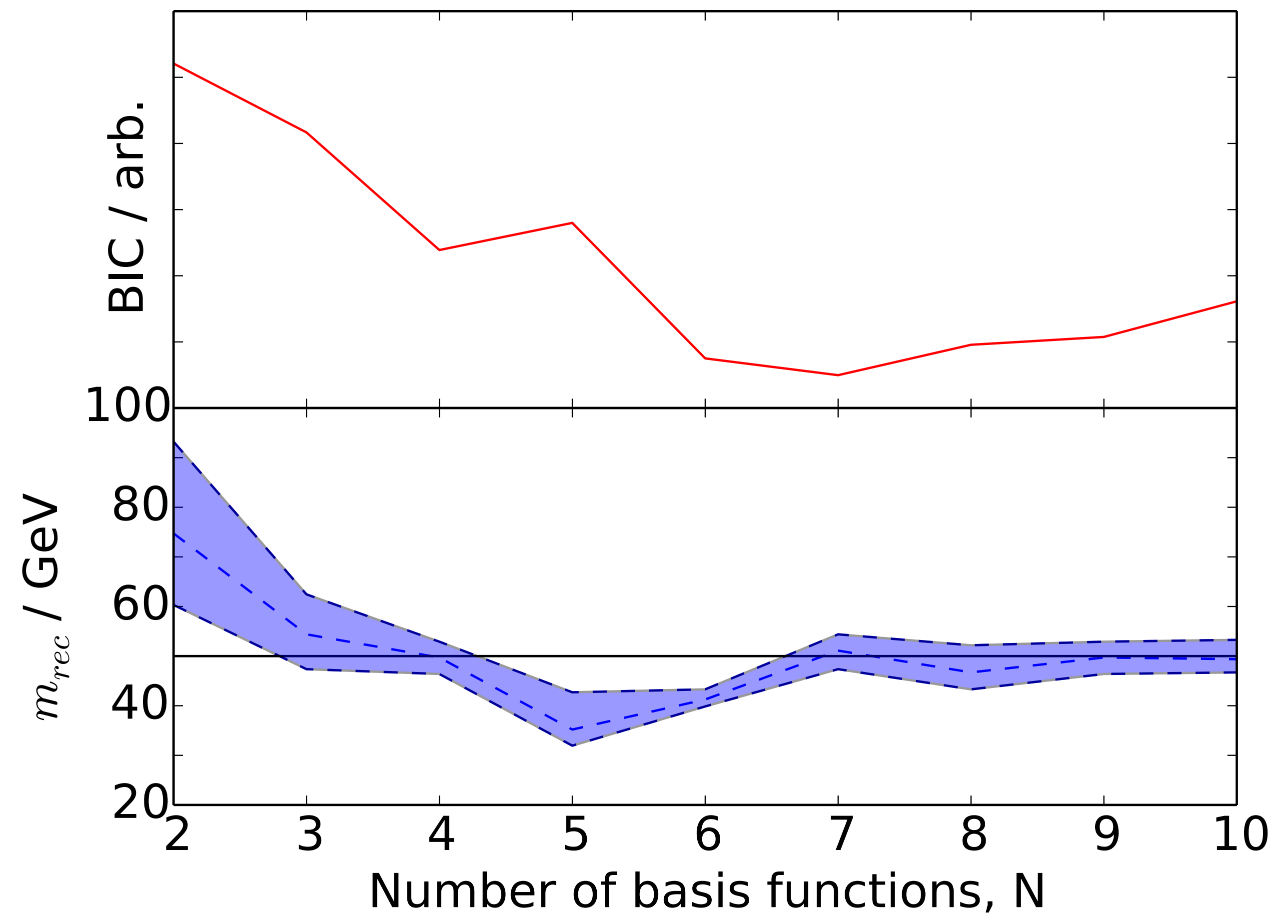


[1002.2717]

…at the 2σ level in 95% of experiment.

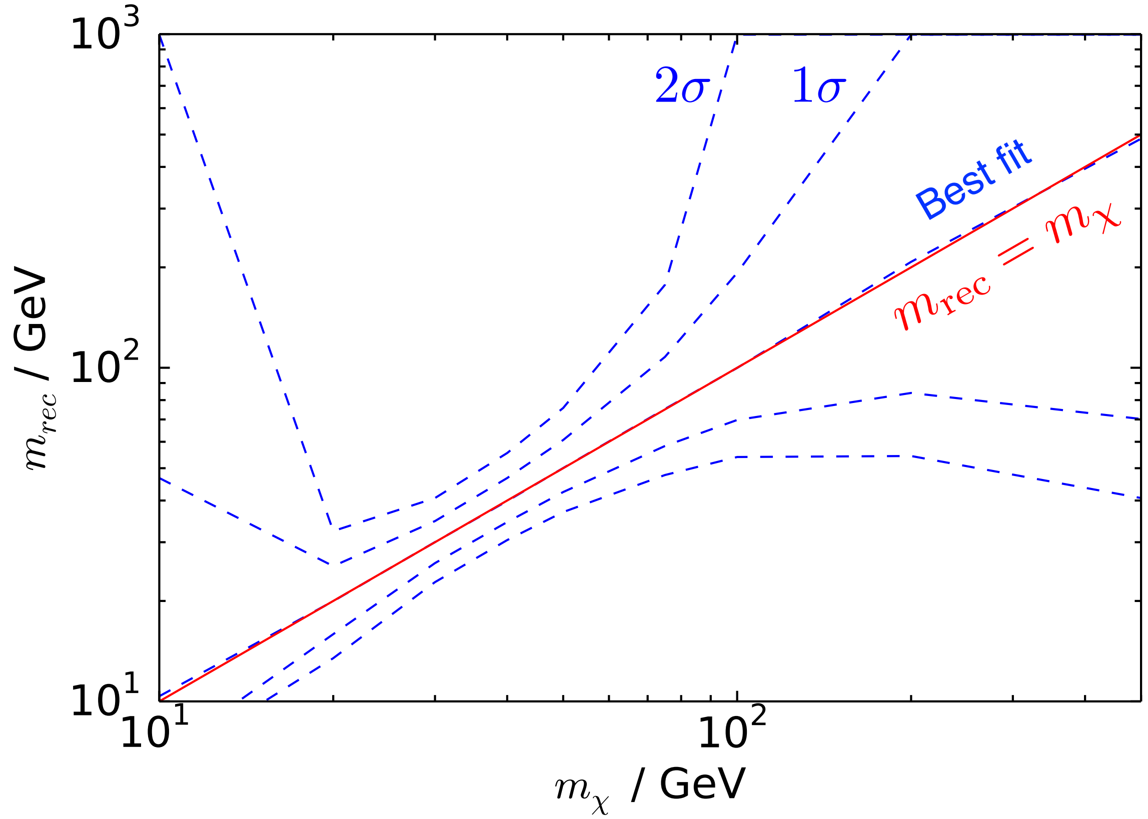
How many terms in the expansion?



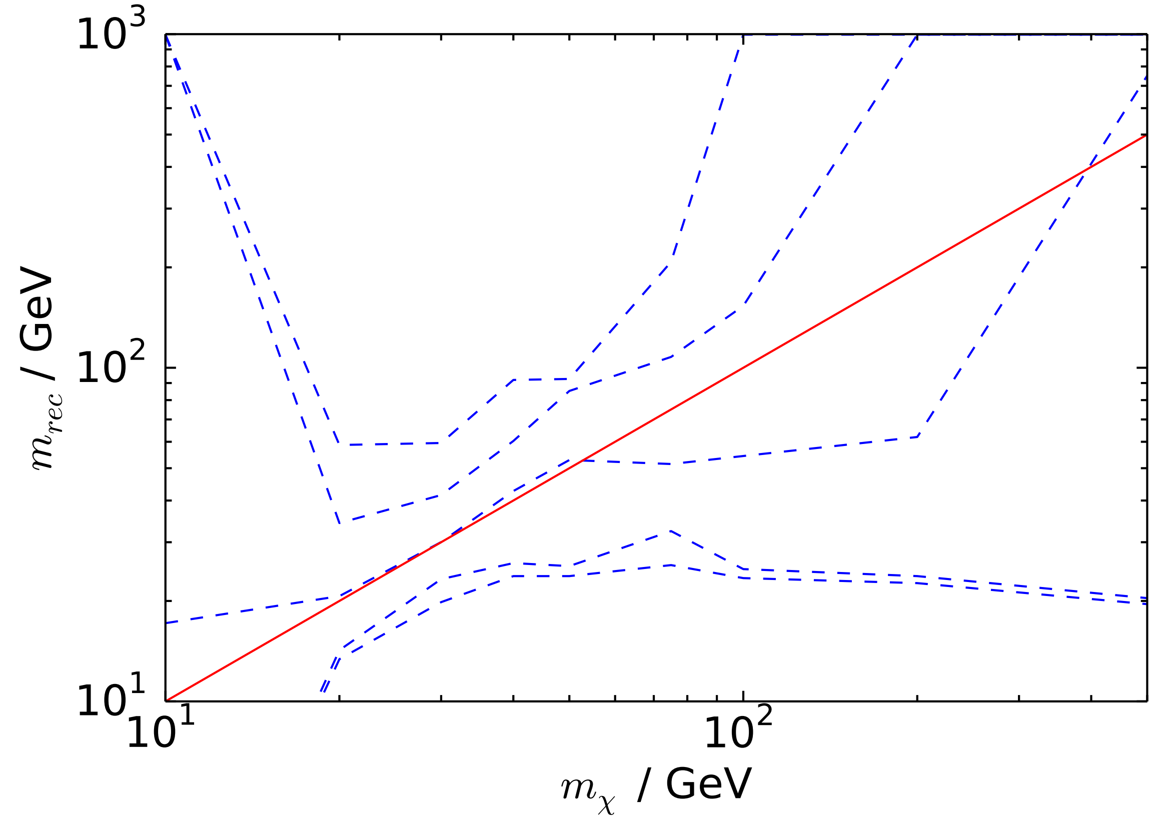


Reconstructing the WIMP mass

Ideal experiments



'Real' experiments



Different velocity distributions

- Generate 250 mock data sets
- Reconstruct mass and obtain confidence intervals for each data set
- True mass reconstructed well (independent of speed distribution)
- Can also check that 68% intervals *are really 68% intervals*