New directional signatures from the non-relativistic EFT of dark matter
or
'Who ordered all these operators?'

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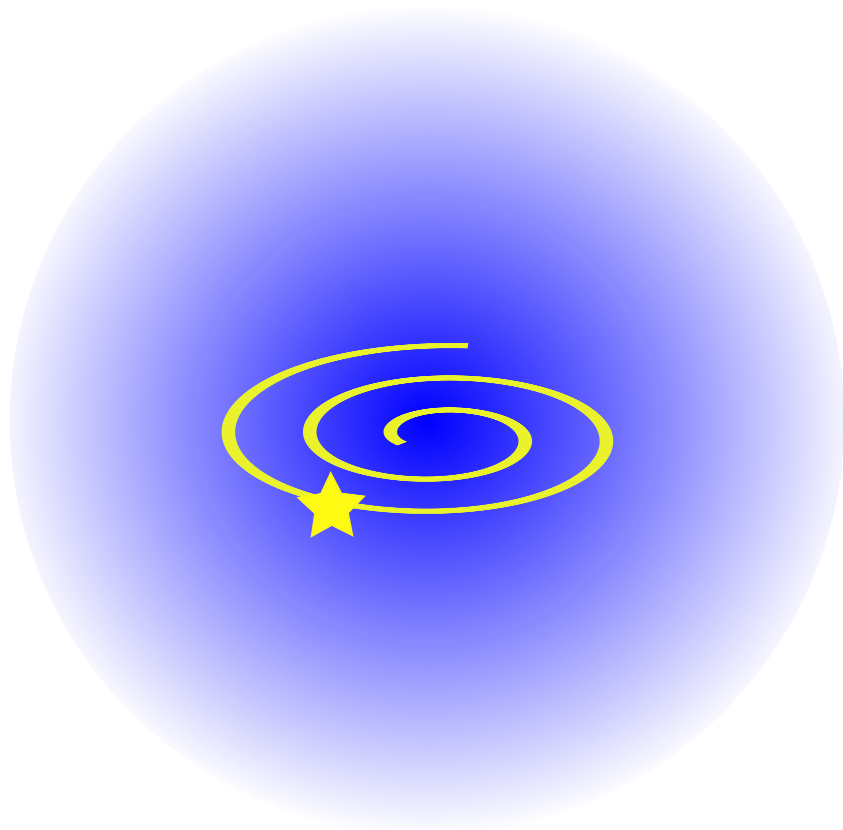
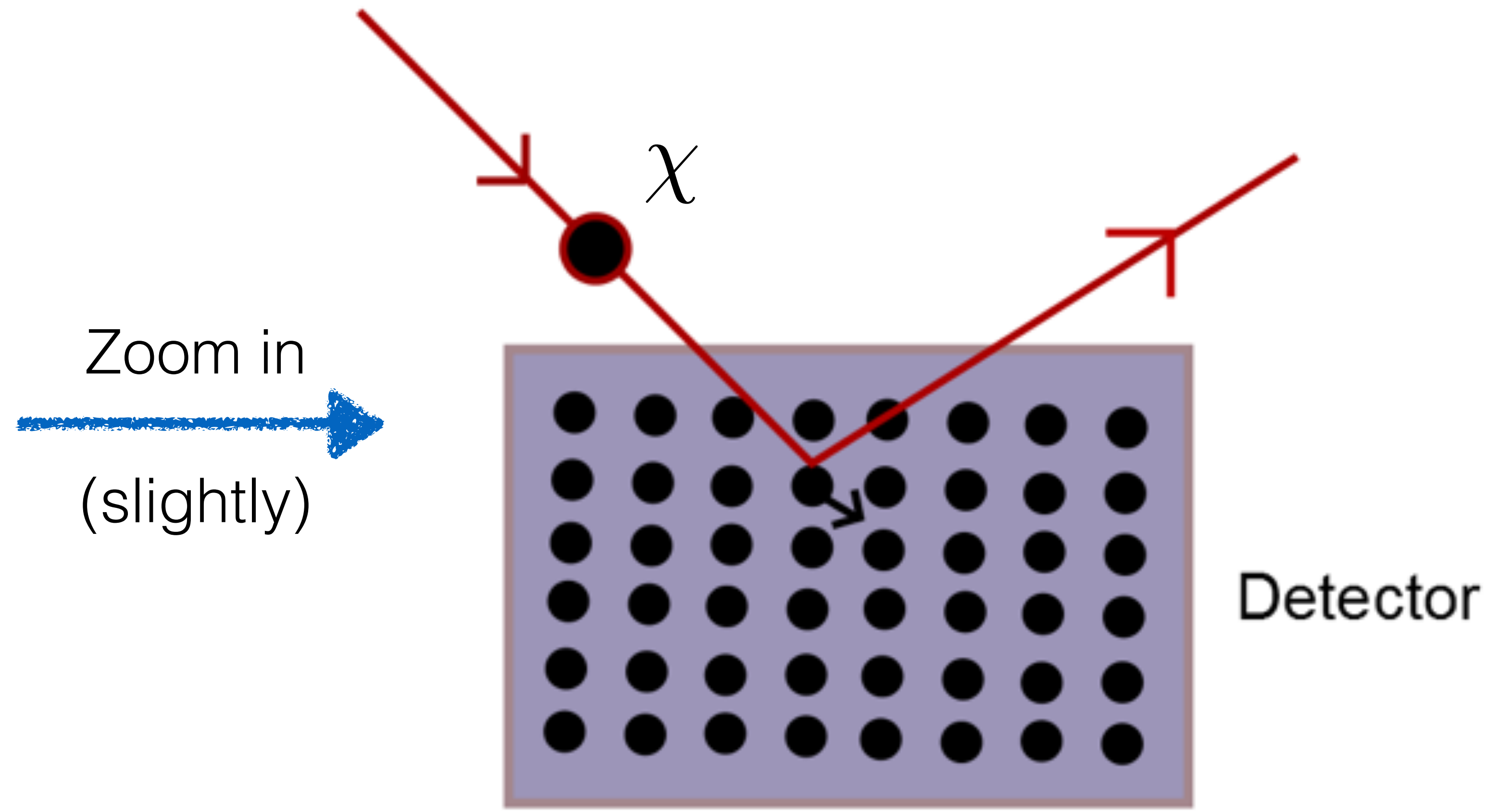
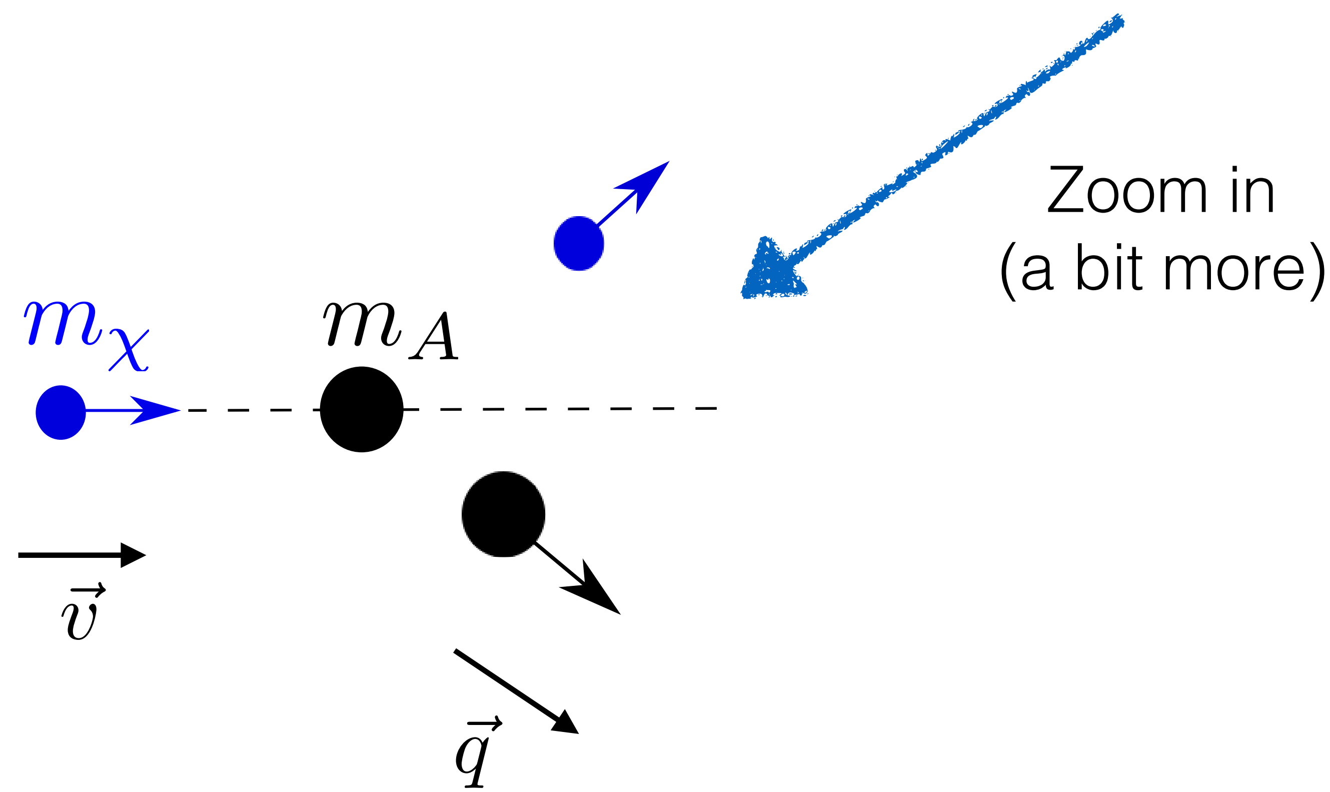
RPP 2016, Annecy - 25th Jan. 2016

Based on
arXiv:1505.07406

Direct detection of Dark Matter





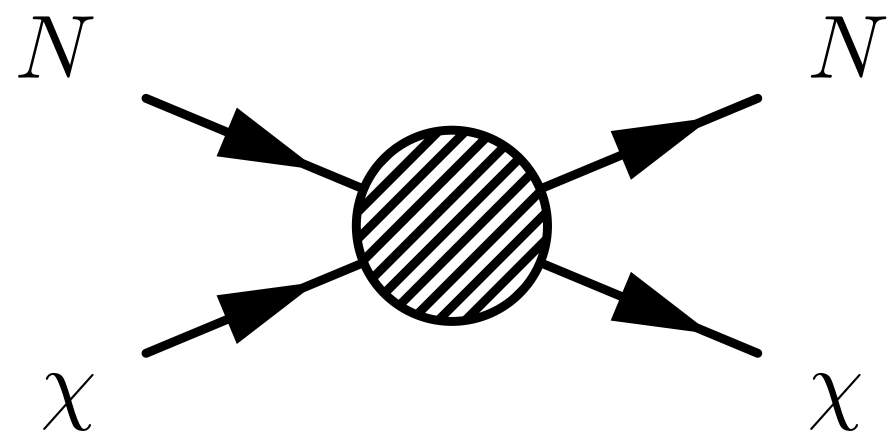


$$m_\chi \gtrsim 1 \text{ GeV}$$
$$v \sim 10^{-3}$$

DM-nucleon interactions

Direct detection:

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

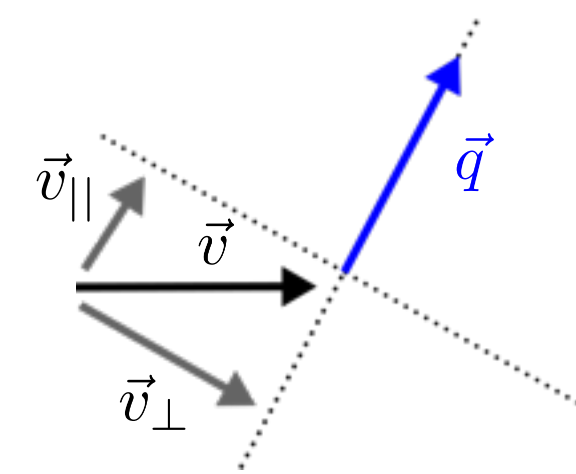


$$q \lesssim 100\,\text{MeV} \sim (2 \text{ fm})^{-1}$$

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)

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

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

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

Non-relativistic effective field theory (NREFT)

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SD

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\vdots$$

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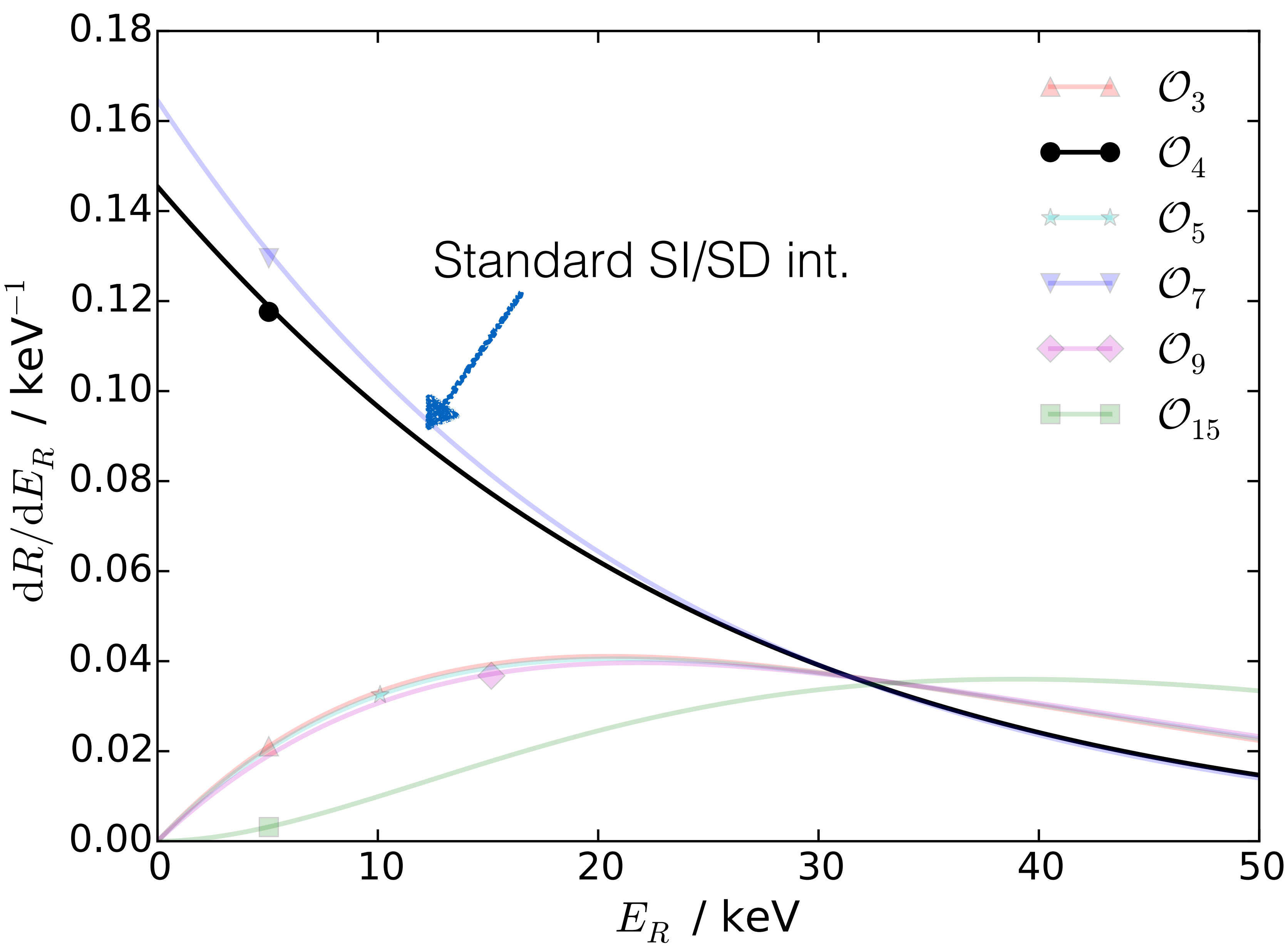
$$\vdots$$

$$\boxed{\frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} \sim \frac{1}{v^2} F_i(v_\perp^2, q^2)}$$

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

Standard energy spectrum



'Perfect' CF_4 detector

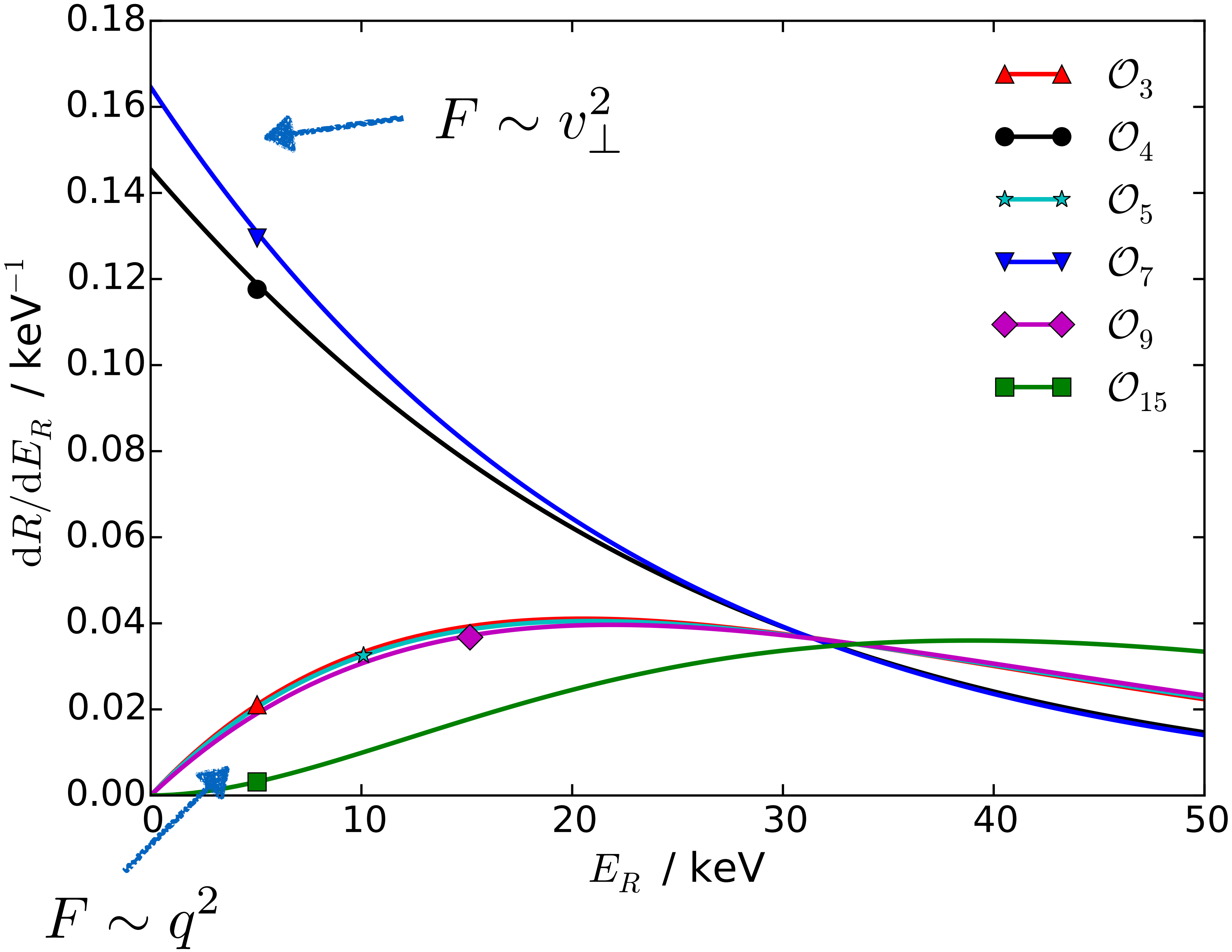
$E_R \in [20, 50]$ keV

Input WIMP mass:

$m_\chi = 100$ GeV

SHM velocity distribution

NREFT energy spectrum



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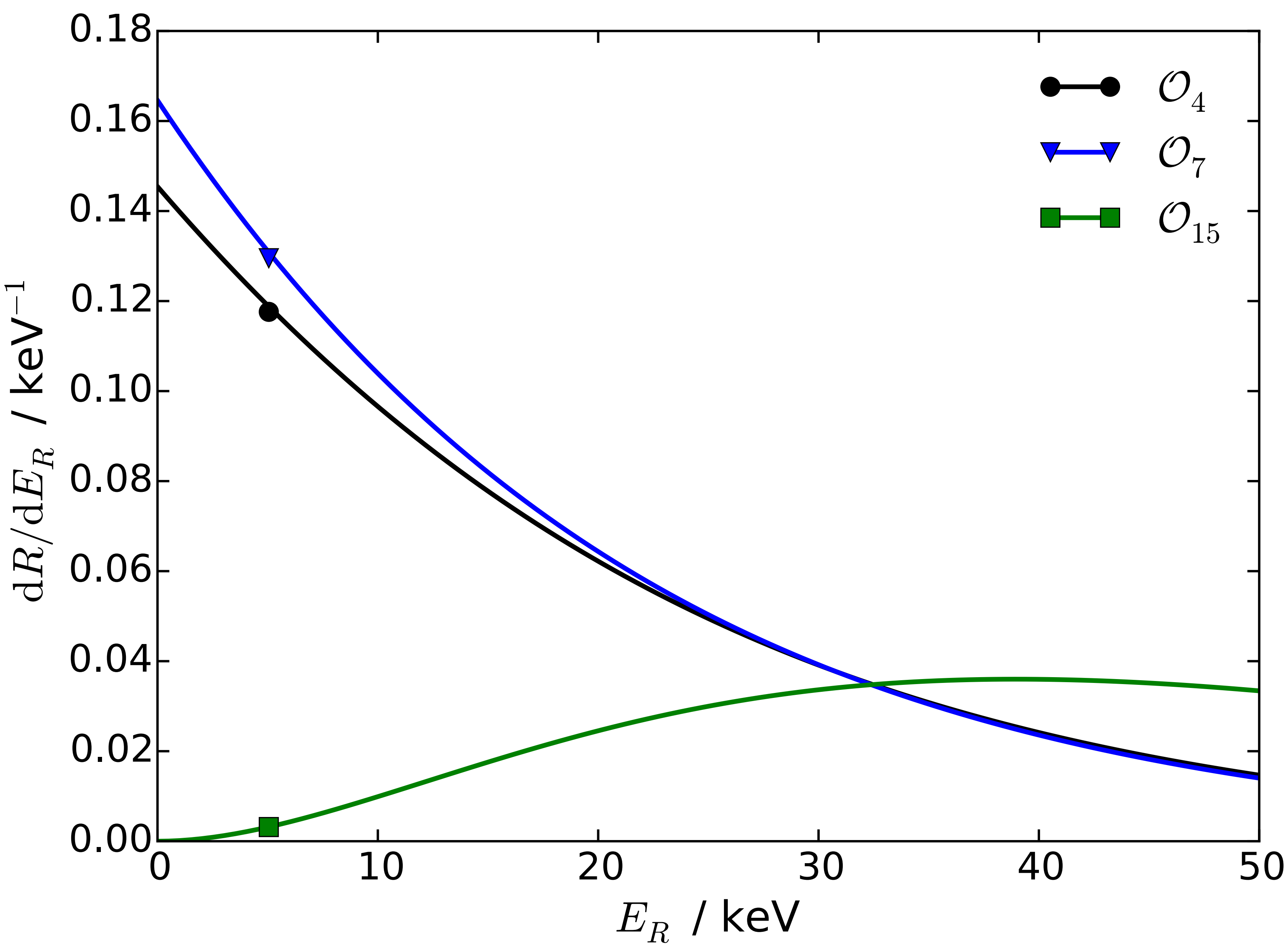

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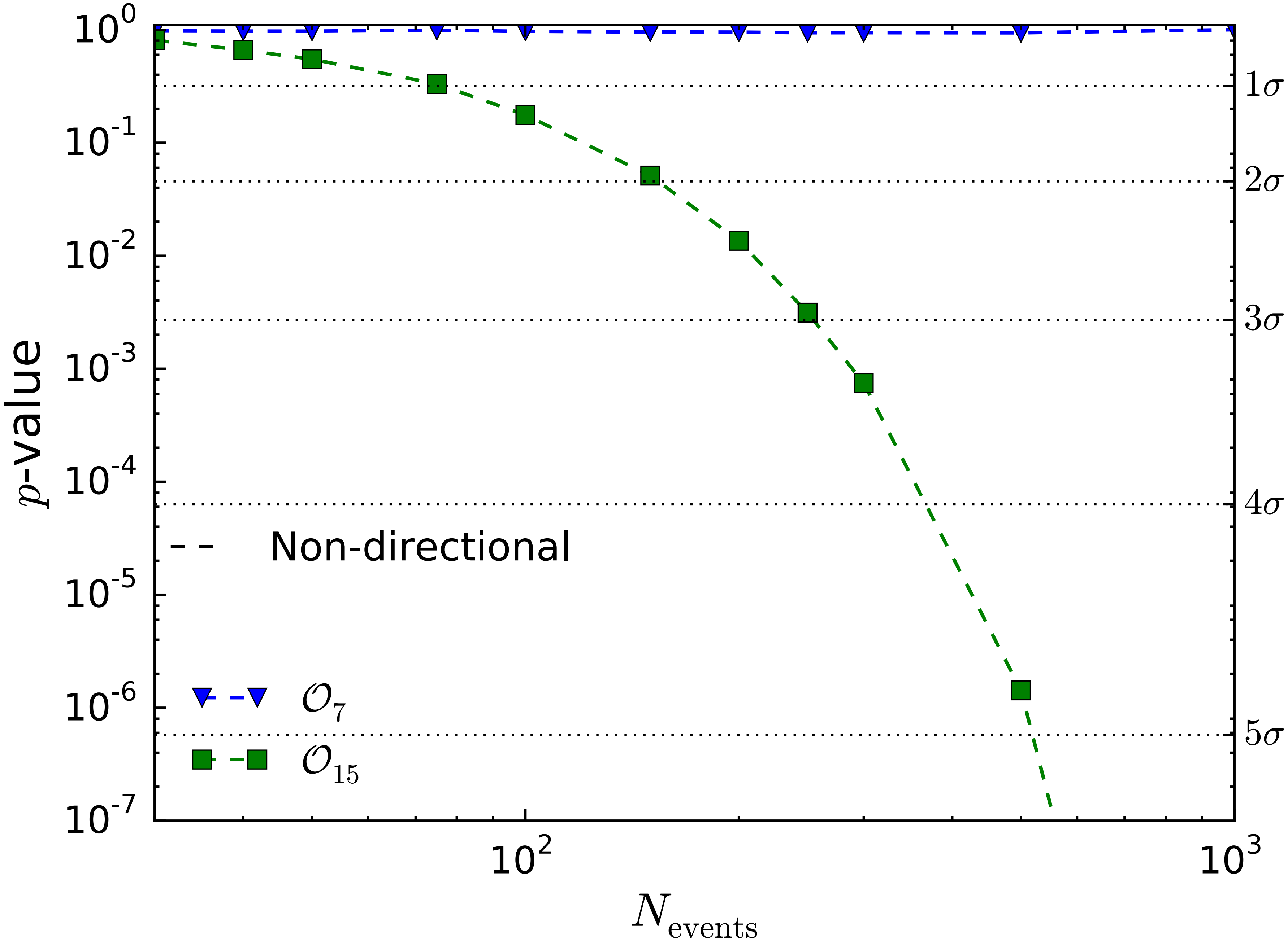
$F_4 \sim 1$ $\quad$ $F_7 \sim v_\perp^2$ $\quad$ $F_{15} \sim q^2(q^2 + v_\perp^2)$

Distinguishing operators: Energy-only

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



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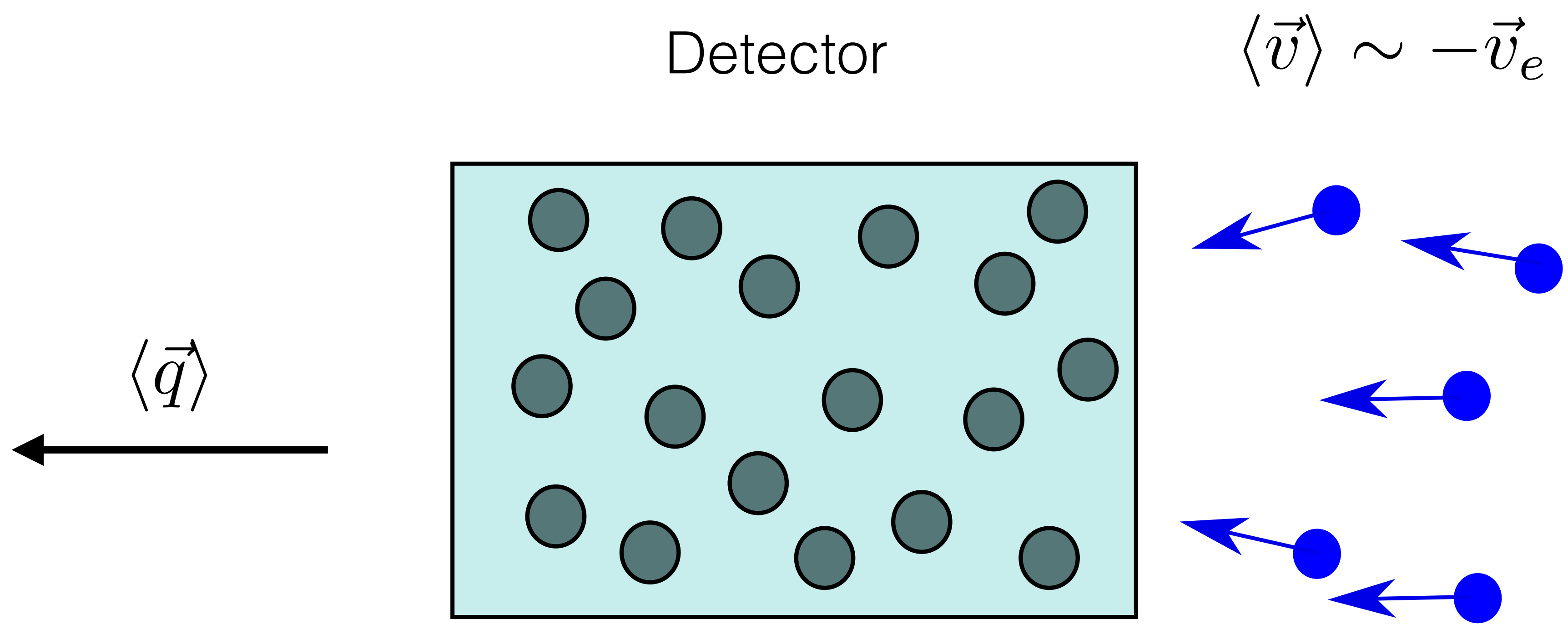
Directional Detection

Different v-dependence could impact *directional* signal.

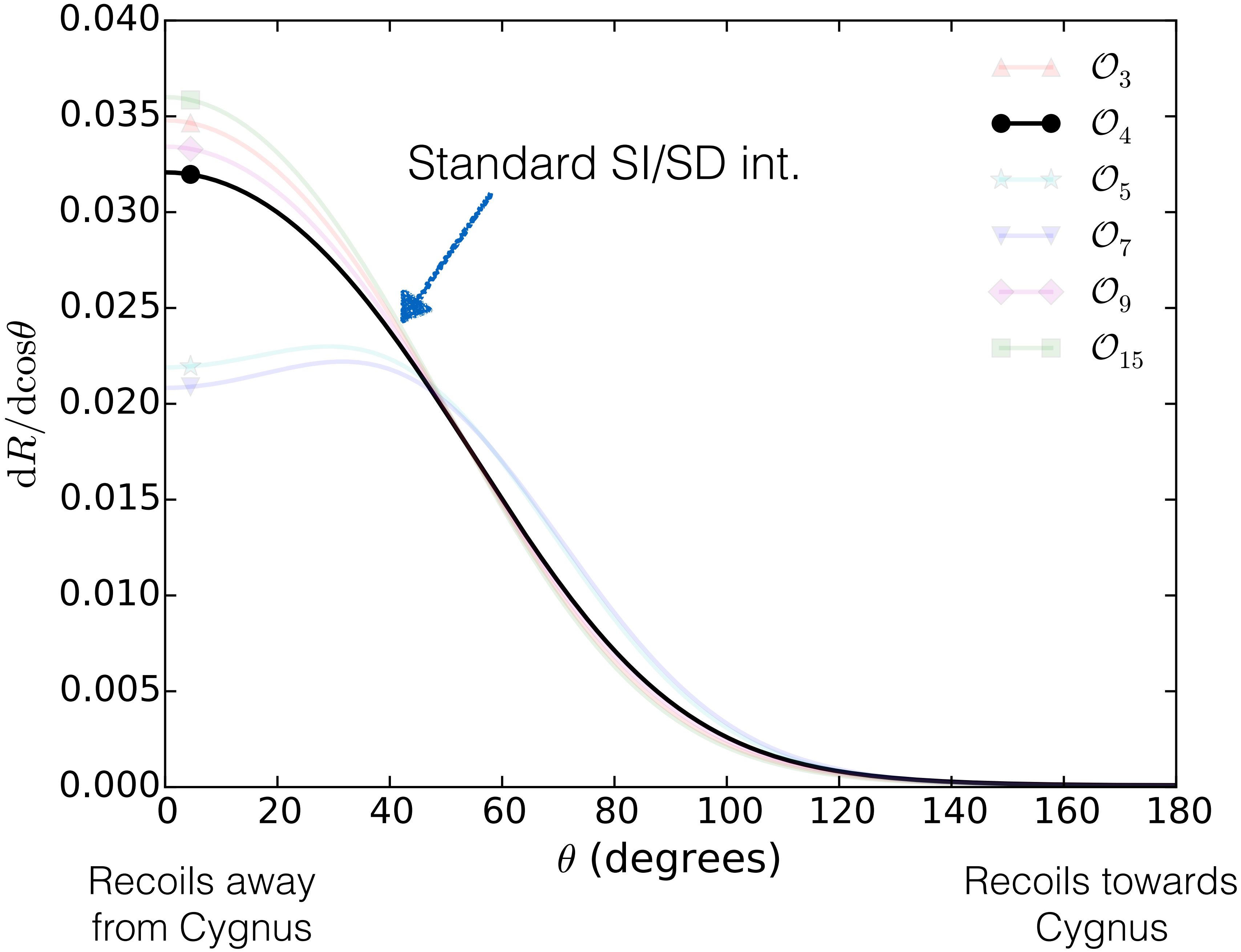
e.g. Drift-IId [arXiv:1010.3027]

Mean recoil direction should point away from constellation Cygnus, due to Earth's motion.



Look at recoil rate, as a function of θ, the angle between the recoil and the mean recoil direction.

Standard directional spectrum



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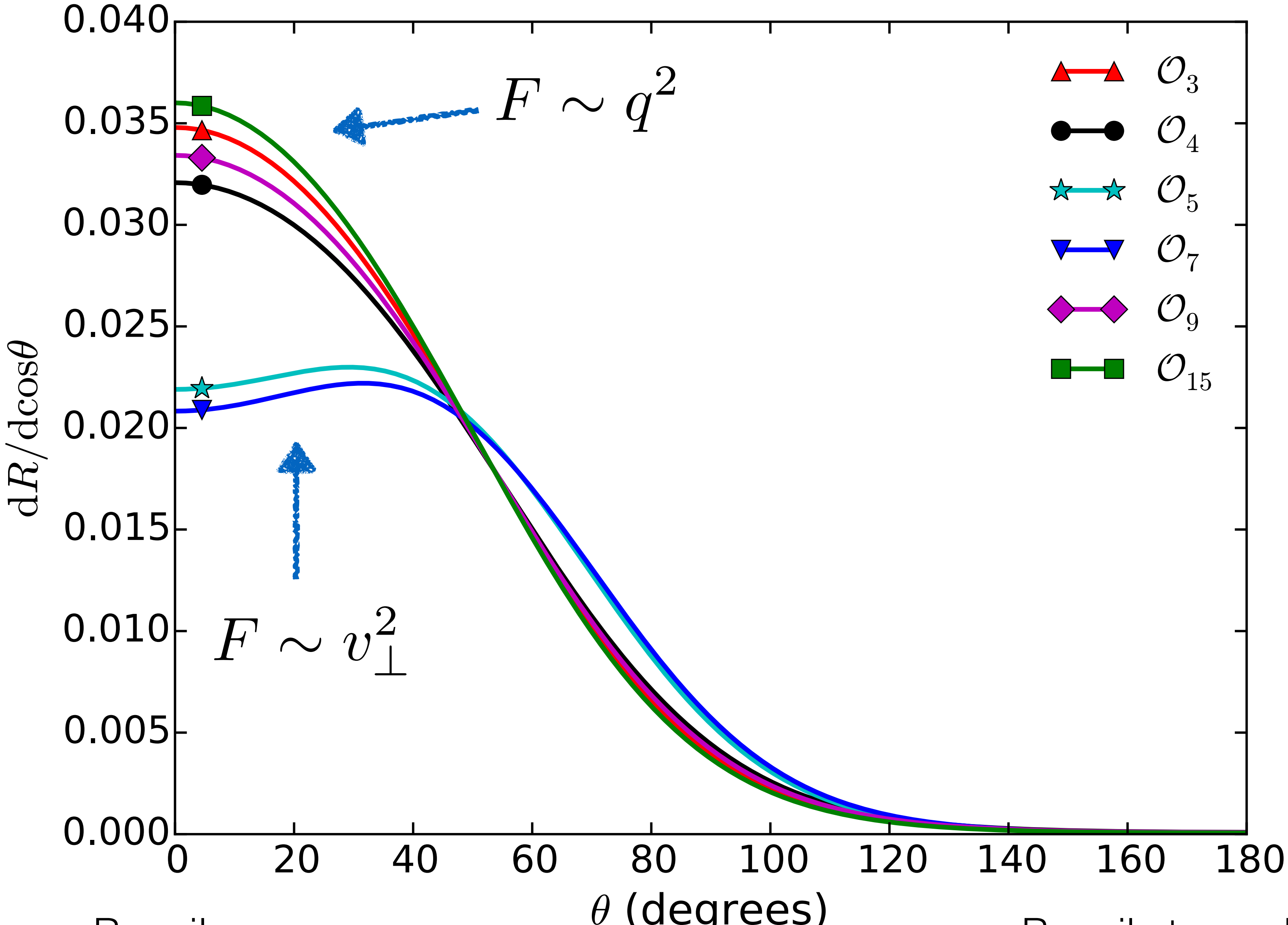
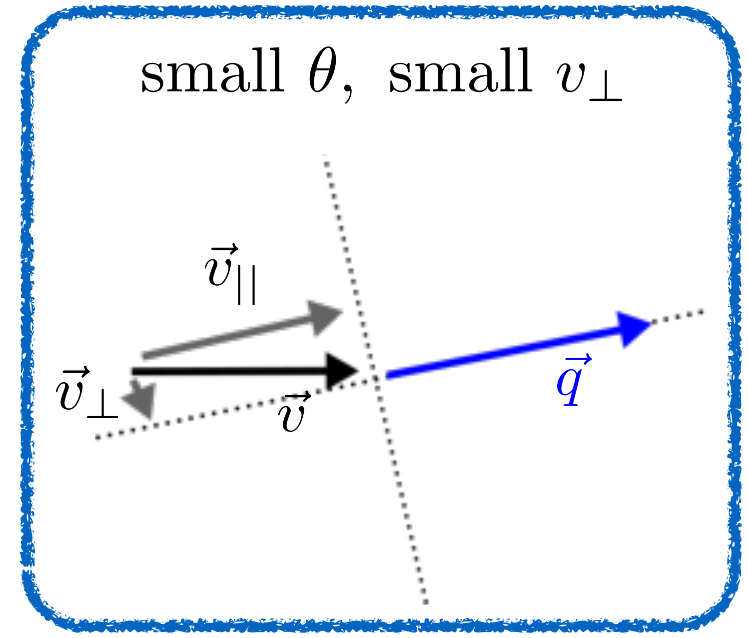
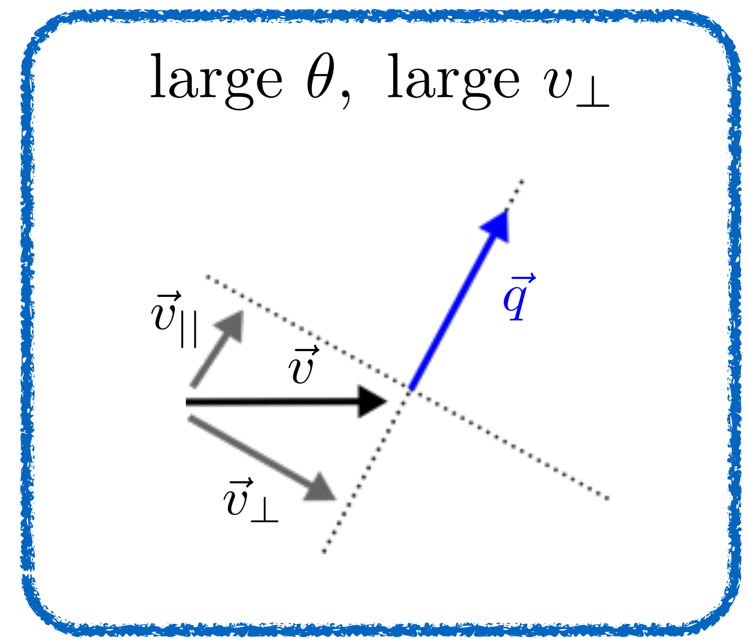
NREFT directional spectrum



Recoils away from Cygnus

Recoils towards Cygnus

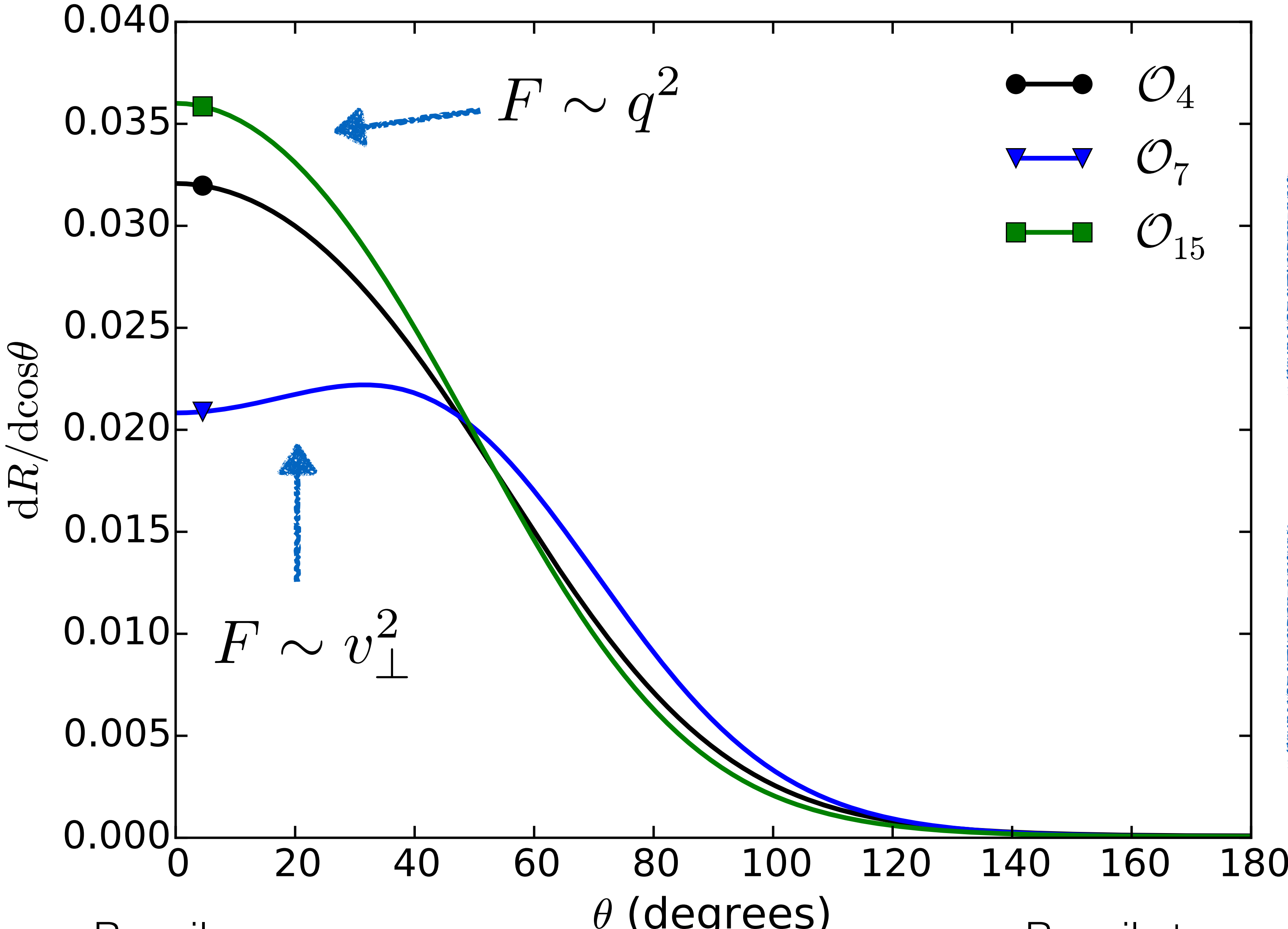




Also note: $q = 2\mu_{\chi N}\vec{v}\cdot\hat{q}$

$= 2\mu_{\chi N} v\cos\theta$

NREFT directional spectrum



Recoils away from Cygnus

Recoils towards Cygnus

Most isotropic: $\mathcal{O}_7$

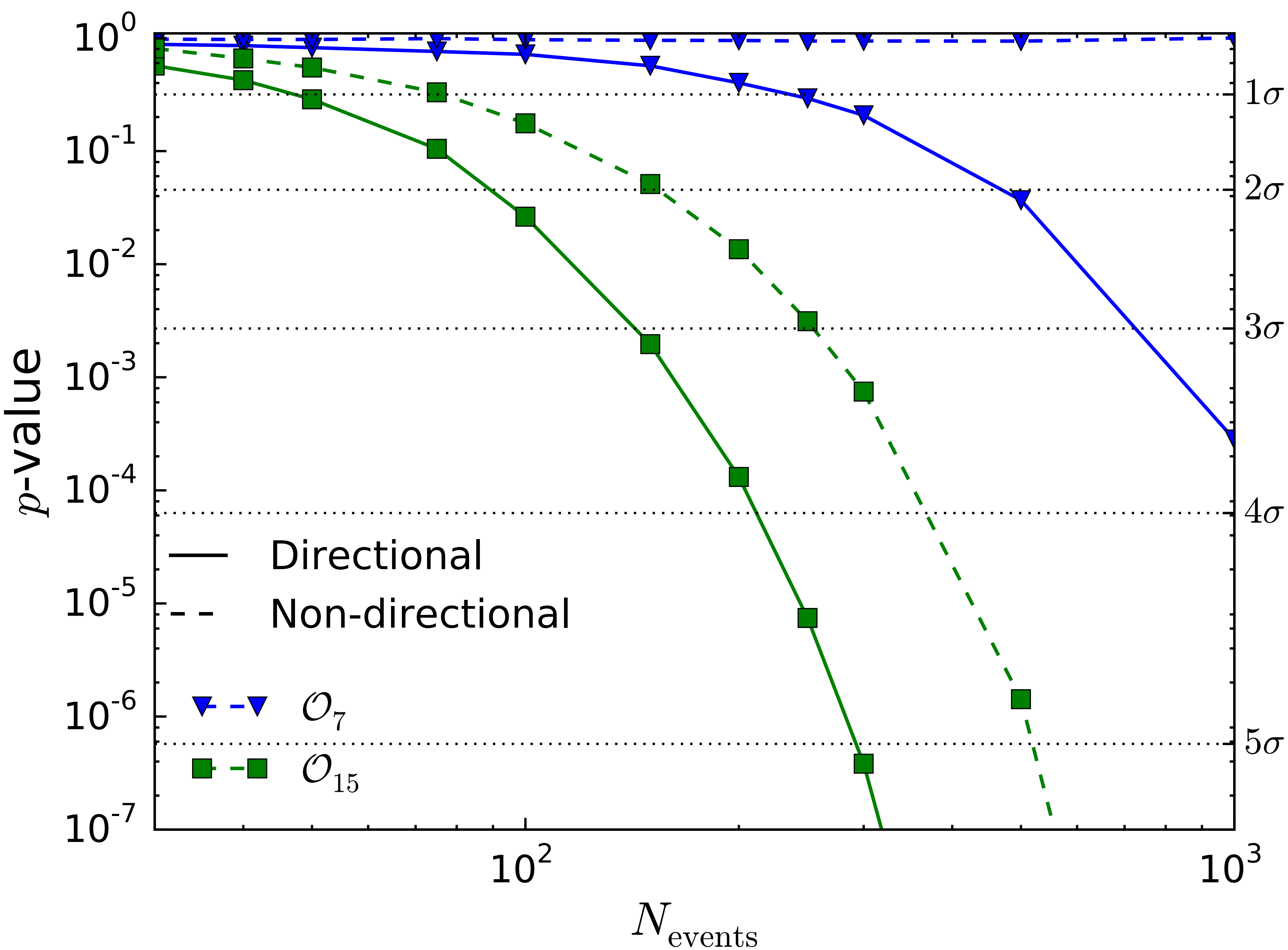
$F_7 \sim v_\perp^2$

Most anisotropic: $\mathcal{O}_{15}$

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

Distinguishing operators: Energy and direction

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



$F_4 \sim 1$

$F_7 \sim v_\perp^2$

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

Conclusions

Direct detection is a unique probe of the different possible interactions between DM and nucleons.

However, not all operators can be distinguished in an energy-only experiment. E.g.:

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

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

But, many operators have interesting *directional* signatures and directional sensitivity may allow us to detect the effects of 'non-standard' operators with only a few hundred events.

Directional detection allows us to probe otherwise inaccessible particle physics of Dark Matter!

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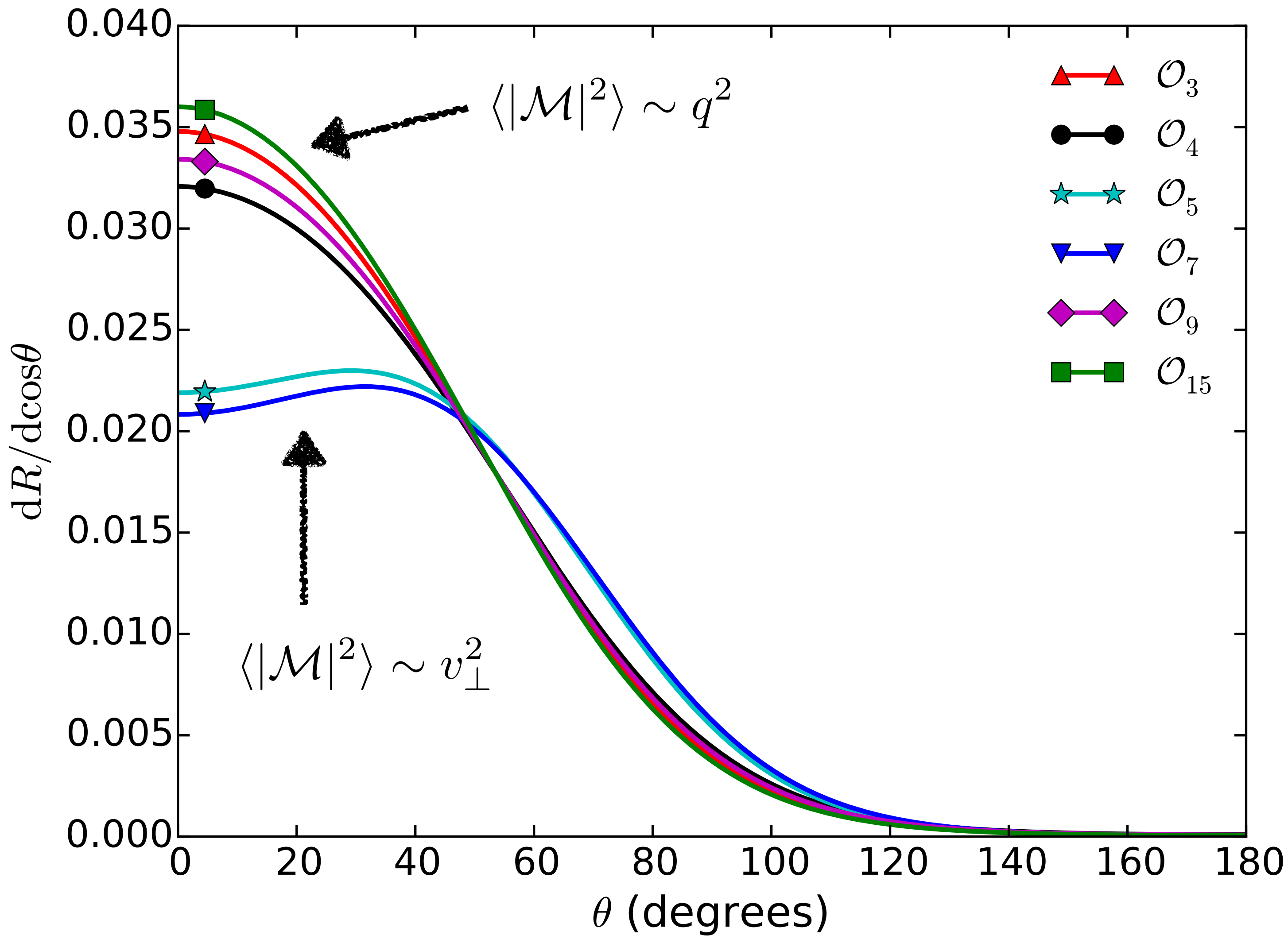
Directional detection allows us to probe otherwise inaccessible particle physics of Dark Matter!

Thank you

Backup Slides

Directional Spectra



Note: $q = 2\mu_{\chi N}\vec{v}\cdot\hat{q}$

$= 2\mu_{\chi N} v\cos\theta$

$$\langle|\mathcal{M}|^2\rangle \sim \begin{cases} 1 & : \mathcal{O}_1, \mathcal{O}_4\,, \\ v_\perp^2 & : \mathcal{O}_7, \mathcal{O}_8\,, \\ q^2 & : \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_{11}, \mathcal{O}_{12}\,, \\ v_\perp^2 q^2 & : \mathcal{O}_5, \mathcal{O}_{13}, \mathcal{O}_{14}\,, \\ q^4 & : \mathcal{O}_3, \mathcal{O}_6\,, \\ q^4(q^2+v_\perp^2) & : \mathcal{O}_{15}\,. \end{cases}$$

Most isotropic:

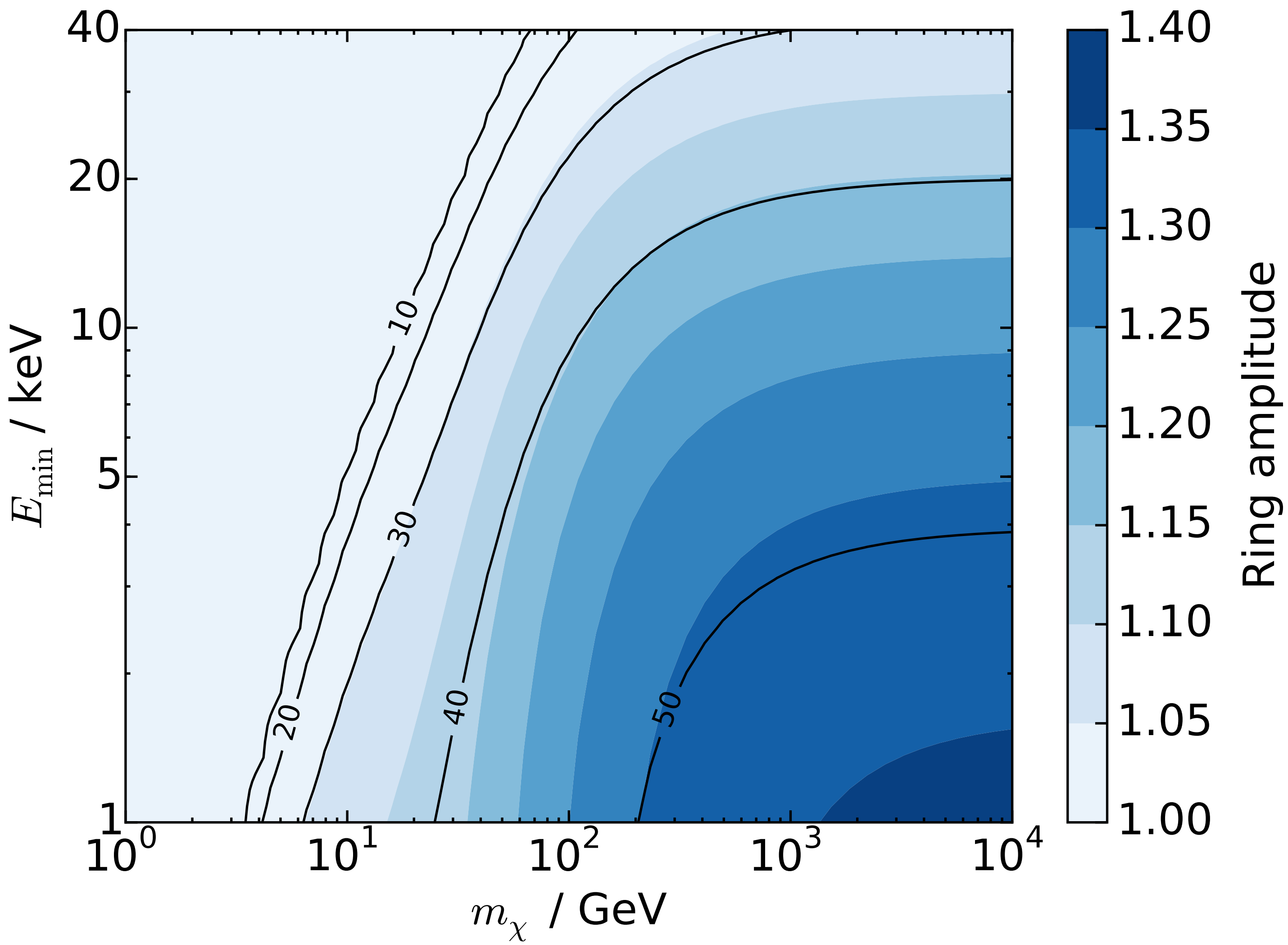
$\mathcal{O}_7 = \vec{S}_n \cdot \vec{v}_\perp$

Least isotropic:

$\mathcal{O}_{15} = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_n})((\vec{S}_n \times \vec{v}_\perp)\cdot\frac{\vec{q}}{m_n})$

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)

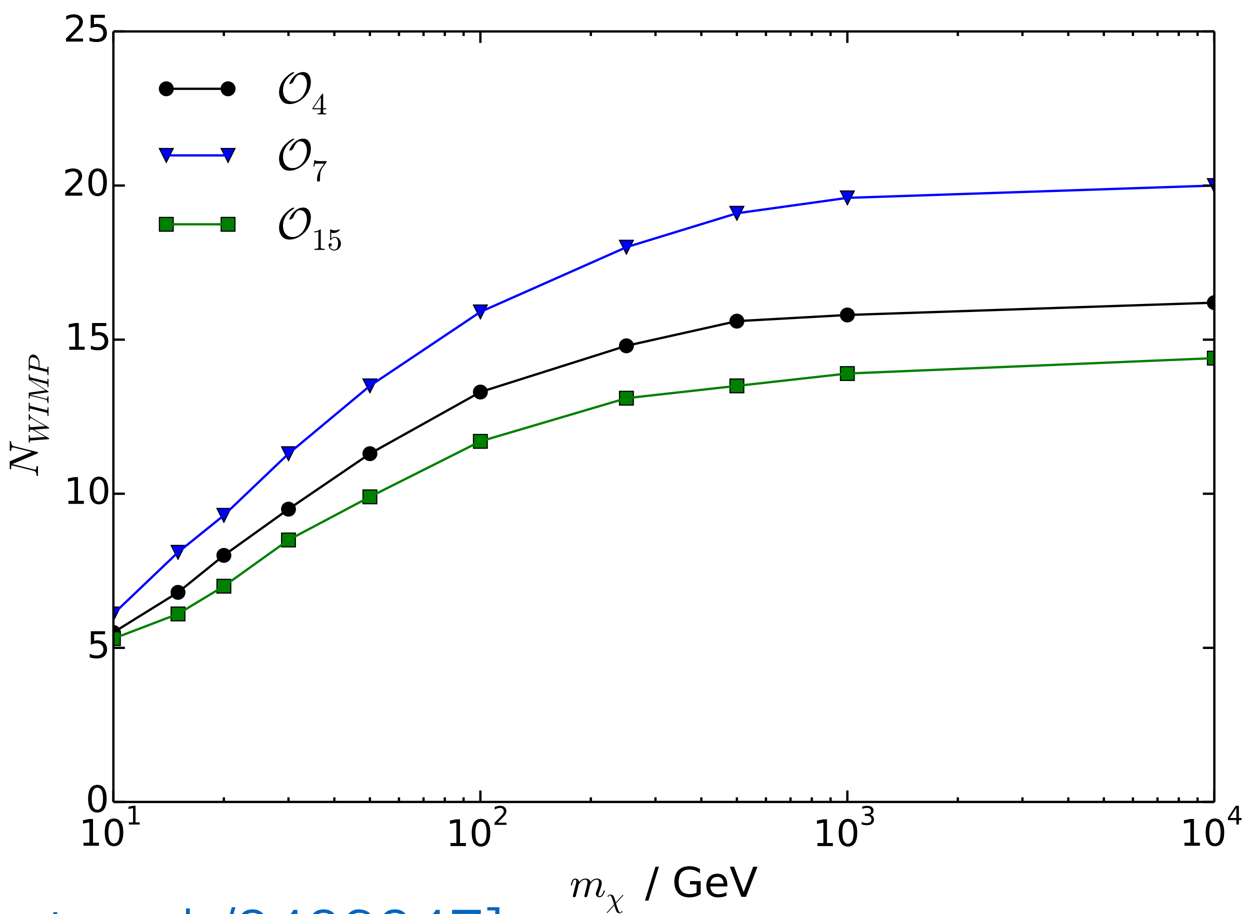
A ring in the standard rate has been previously studied [Bozorgnia et al. - 1111.6361], but *this* ring occurs for lower WIMP masses and higher threshold energies.

Statistical tests

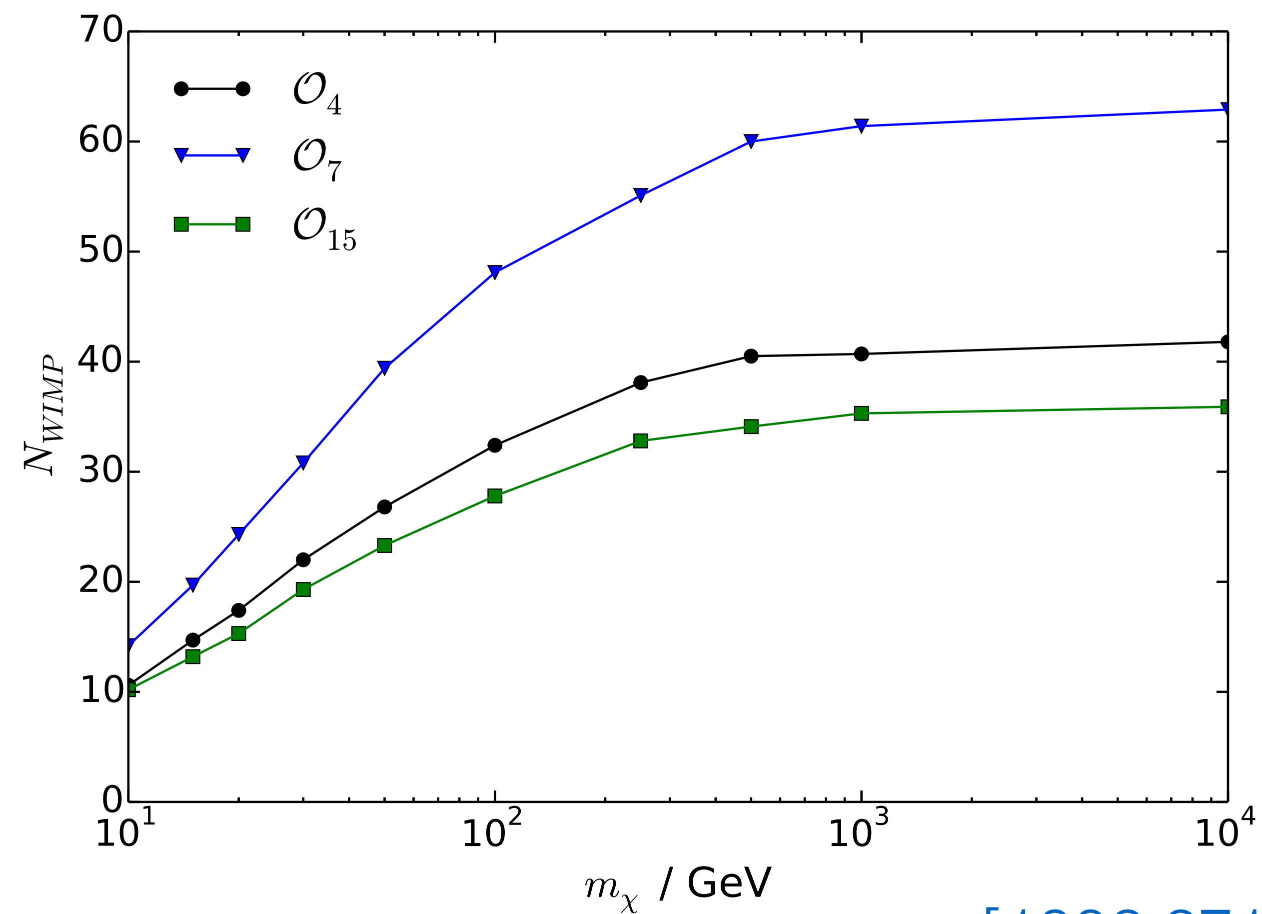
$$F_{4,4} \sim 1$$
$$F_{7,7} \sim v_\perp^2$$
$$F_{15,15} \sim q^4(q^2 + v_\perp^2)$$

Calculate the number of signal events required to…

…reject isotropy…



…confirm the median recoil dir…



[astro-ph/0408047] [1002.2717]

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

Distinguishing operators

Generate data assuming an NREFT operator ($\mathcal{O}_7$ or $\mathcal{O}_{15}$).

Assume data is a combination of standard SI/SD interaction and non-standard NREFT operator. Fit to data with two free parameters m_χ and A .

A : fraction of events which are due to non-standard NREFT interaction.

Perform likelihood ratio test (in 10000 pseudo-experiments) to determine the significance with which we can reject SD-only interactions:

Null hypothesis, **H$_0$**: all events are due to SD interactions, A = 0

Alt. hypothesis, **H$_1$**: there is some contribution from NREFT ops, A $\neq$ 0

Consequences for relativistic theories

Many ‘dictionaries’ are available which allow us to translate from relativistic interactions to NREFT interactions [e.g. 1211.2818, 1307.5955, 1505.03117]

$$\mathcal{L}_1 = \bar{\chi}\chi\bar{n}n \quad \Rightarrow \quad \langle \mathcal{L}_1 \rangle = 4 m_\chi m_n \mathcal{O}_1$$

$$\rightarrow \quad \langle |\mathcal{M}|^2 \rangle \sim F_M(q^2)$$

$$\mathcal{L}_6 = \bar{\chi}\gamma^\mu\gamma^5\chi\bar{n}\gamma_\mu n \quad \Rightarrow \quad \langle \mathcal{L}_6 \rangle = 8 m_\chi (m_n \mathcal{O}_8 + \mathcal{O}_9)$$

$$\rightarrow \quad \langle |\mathcal{M}|^2 \rangle \sim v_\perp^2 F_M(q^2)$$

These two relativistic operators cannot be distinguished without directional detection.

Open issues

- We have assumed an *ideal* detector - lower limits on the event numbers (need to be convolved with detector effects…)
- Different signatures possible for different target materials - see (very) recent paper by Catena [1505.06441]
- Astrophysical uncertainties are expected to be comparable with particle physics uncertainties
    - inability to distinguish different operators depends on SHM-type distribution (may be different for sharp stream-like distributions)
- May be possible to distinguish operators using other methods - measuring annual modulation [1504.06772]

In the future, it would be interesting to examine astrophysical uncertainties in detail, and to compare different approaches to distinguishing NREFT operators.