New directional signatures from the non-relativistic effective field theory of dark matter

Bradley J. Kavanagh (IPhT - CEA/Saclay)

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Based on arXiv:1505.07406

Overview

Directional searches for DM in the lab:

- Why search for a directional signal?
- The standard signal

New signatures [arXiv:1505.07406]:

- Non-relativistic DM-nucleon interactions
- The new signals
- Discovery potential

Full Disclosure

Dark matter directional detection in non-relativistic effective theories

1 [hep-ph] 24 May 2015

[arXiv:1505.06441]

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Abstract. We extend the formalism of dark matter directional detection to arbitrary one-body dark matter-nucleon interactions. The new theoretical framework generalizes the one currently used, which is based on 2 types of dark matter-nucleon interaction only. It includes 14 dark matter-nucleon interaction operators, 8 isotope-dependent nuclear response functions, and the Radon transform of the first 2 moments of the dark matter velocity distribution. We

[arXiv:1505.07406]

SACLAY-t15/093

New directional signatures from the non-relativistic effective field theory of dark matter

27 May 2015

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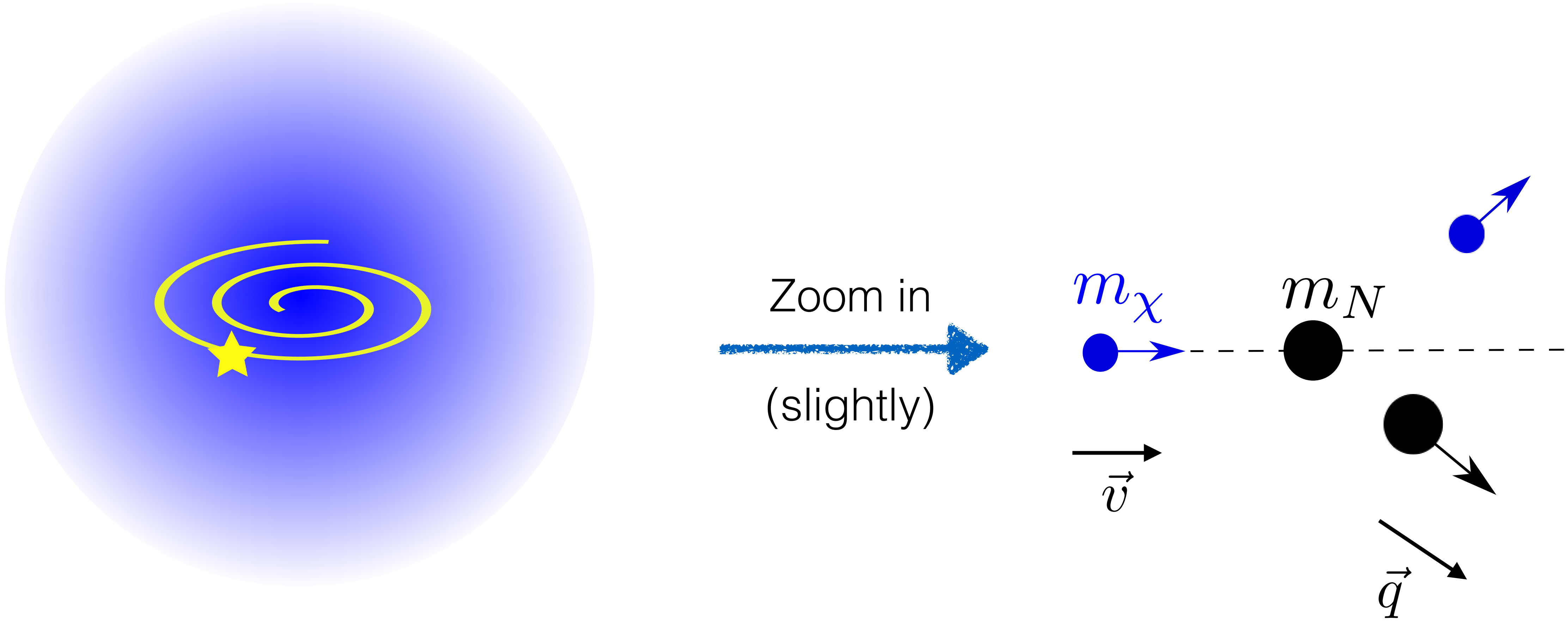
The framework of non-relativistic effective field theory (NREFT) aims to generalise the standard analysis of direct detection experiments in terms of spin-dependent (SD) and spin-independent (SI) interactions. We show that a number of NREFT operators lead to distinctive new directional signatures, such as prominent ring-like features in the directional recoil rate, even for relatively low mass WIMPs. We discuss these signatures and how they could affect the interpretation of future results from directional detectors. We demonstrate that considering a range of possible operators introduces a factor of 2 uncertainty in the number of events required to confirm the median recoil direction of the signal. Furthermore, using directional detection, it is possible to distinguish the more general NREFT interactions from the standard SI/SD interactions at the 2σ level with $\mathcal{O}(100-500)$ events. In particular, we demonstrate that for certain NREFT operators, directional sensitivity provides the only method of distinguishing them from these standard operators, highlighting the importance of directional detectors in probing the particle physics of dark matter.

I. INTRODUCTION

for DM-nucleus interactions. The non-relativistic effective field theory (NREFT; introduced by Fan et al. [22]

Directional detection

Direct detection

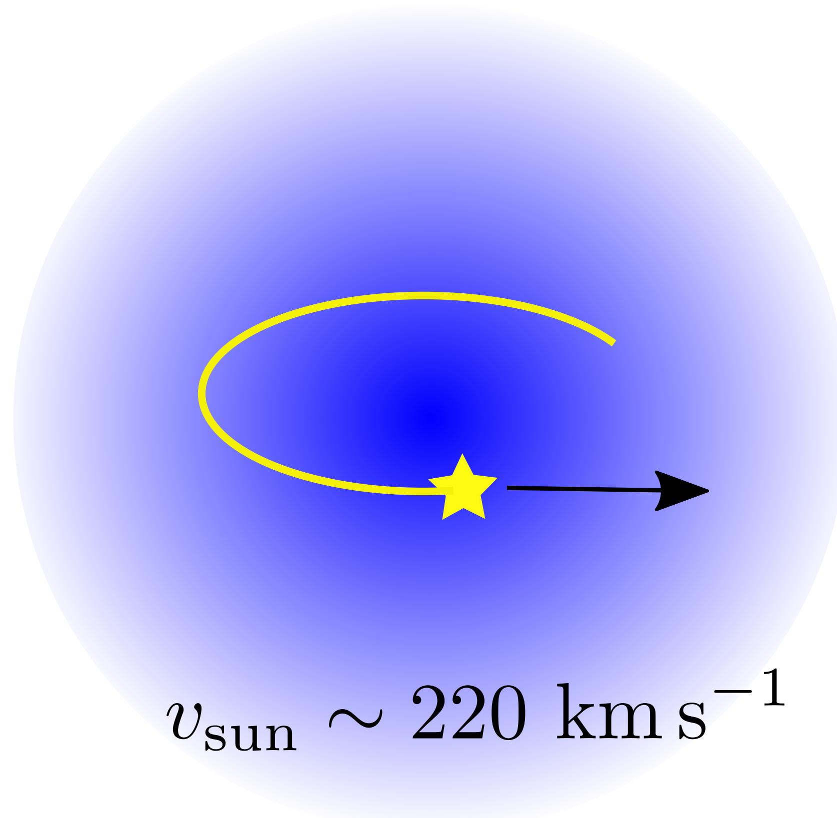


Look for interactions of DM particles from the halo with nuclei in a detector - measure **energy** of the recoiling nucleus.

Expect lots of low energy backgrounds —> background discrimination can be…*problematic…*

The WIMP Wind

In the halo:



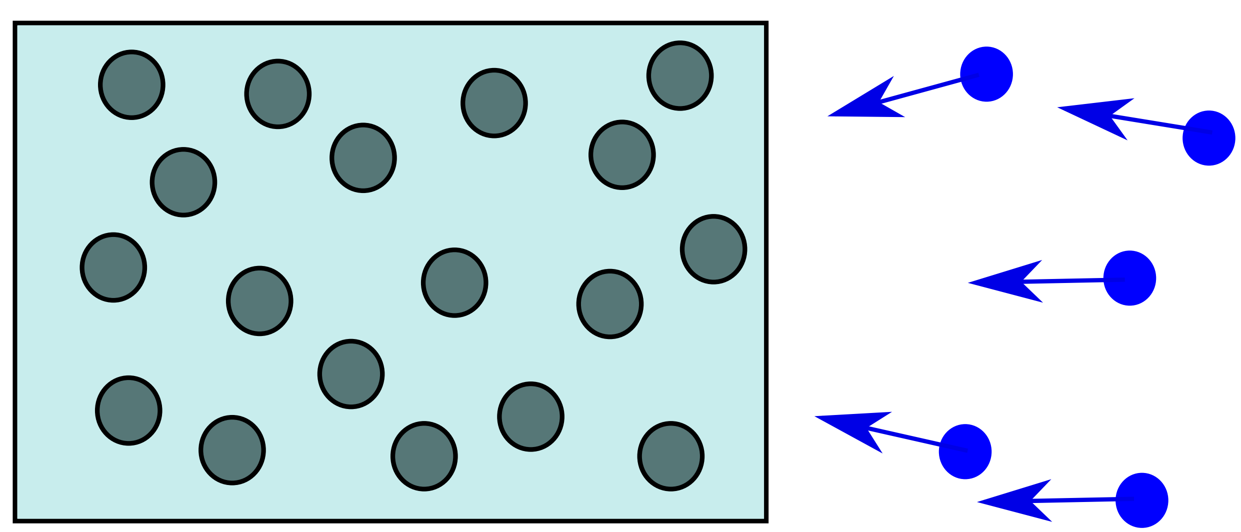
WIMP: Weakly Interacting Massive Particle

Cygnus constellation

In the lab:

Detector

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



'WIMP wind from Cygnus'

Radon Transform

For standard SI/SD, for fixed DM speed:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R\mathrm{d}\Omega_q} \propto \delta\left(\vec{v}\cdot\hat{q} - v_{\mathrm{min}}\right)$$

So integrating over all DM speeds:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R\mathrm{d}\Omega_q} \propto \int_{\mathbb{R}^3} f(\vec{v})\delta\left(\vec{v}\cdot\hat{q} - v_{\mathrm{min}}\right)\,\mathrm{d}^3\vec{v} \equiv \boxed{\hat{f}(v_{\mathrm{min}},\hat{q})}$$

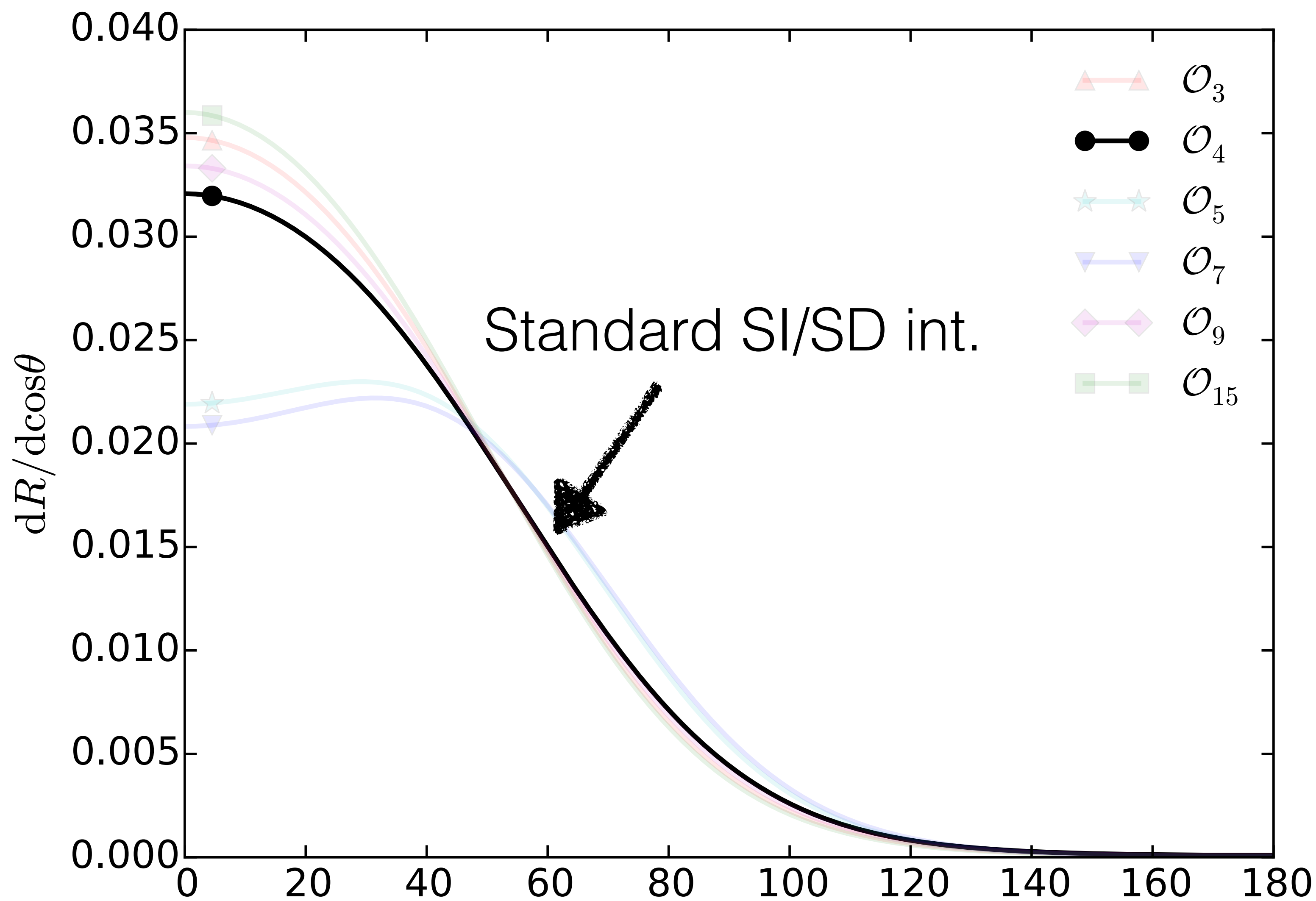
'Radon Transform' (RT)

For the SHM:

$$f(\vec{v}) = \frac{1}{(2\pi\sigma^2)^{3/2}}\exp\left[-\frac{(\vec{v}-\vec{v}_{\mathrm{lag}})^2}{2\sigma_v^2}\right]$$

$$\hat{f}(v_{\mathrm{min}},\hat{q}) = \frac{1}{\sqrt{2\pi\sigma_v^2}}\exp\left[-\frac{(v_{\mathrm{min}}-\vec{v}_{\mathrm{lag}}\cdot\hat{q})^2}{2\sigma_v^2}\right]$$

Directional Spectra



Recoils away from Cygnus

Recoils towards Cygnus

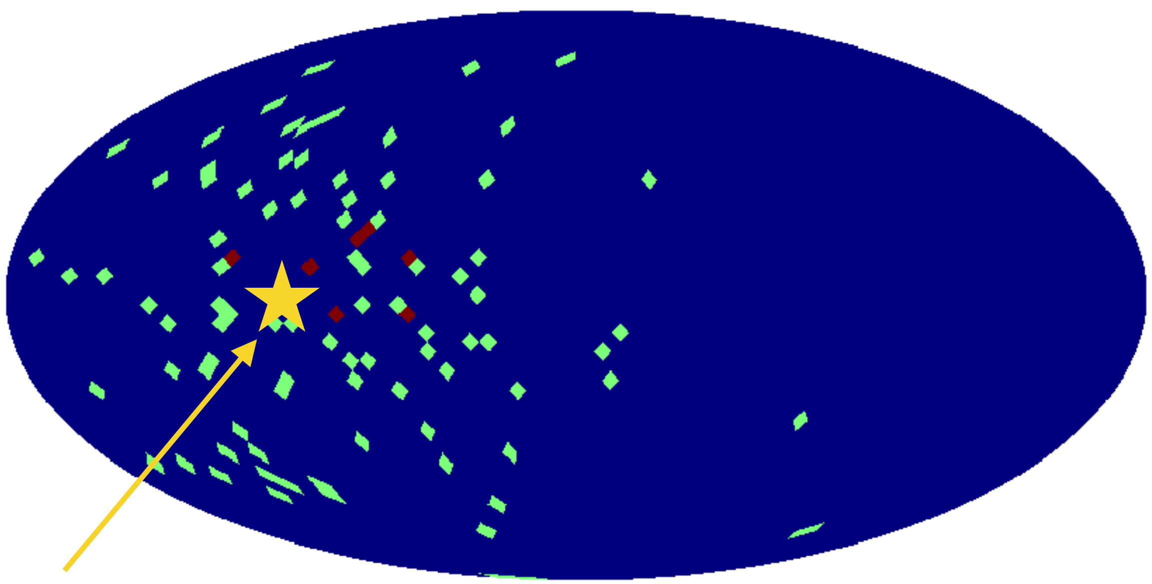
'Perfect' CF_4 detector

$E_R \in [20, 50]\,\mathrm{keV}$

$m_\chi = 100\ \mathrm{GeV}$

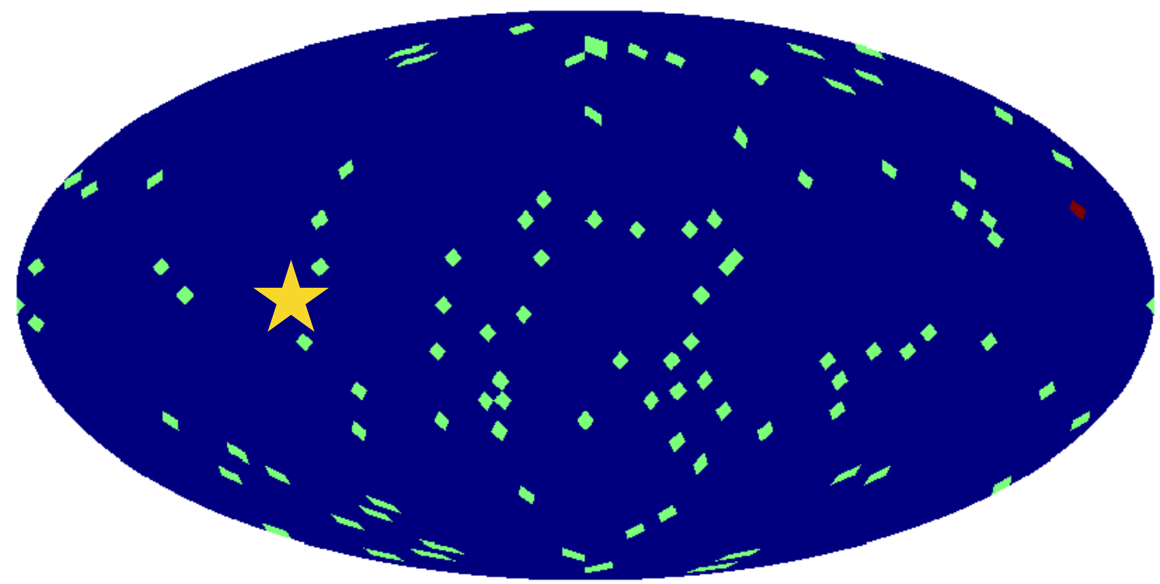
The Smoking Gun

Aim to measure the **energy** and **direction** of the recoiling nucleus.



Away from Cygnus

WIMP signal



Backgrounds

Only need around 10 events to distinguish signal from background, and around 30 events to confirm the median direction of the flux [astro-ph/0408047,1002.2717].

Can also exploit time-dependence of the signal due to the motion of the Earth around the Sun [1205.2333].

New Dark Matter Signatures

DM-nucleon interactions

Need to assume a particular interaction between DM and nucleons.

DM speed highly non-relativistic $(v \sim 220 \mathrm{~km\,s}^{-1} \sim 10^{-3}\,\mathrm{c})$ so consider (contact) operators which are zeroth order in v and q.

Spin-independent (SI) coupling of DM and nucleon densities:

$$\mathcal{O}_{\mathrm{SI}} = 1$$

Spin-dependent (SD) coupling of DM and nucleon spins:

$$\mathcal{O}_{\mathrm{SD}} = \mathbf{S}_\chi \cdot \mathbf{S}_N$$

Interaction cross-sections roughly independent of v and q.

Non-relativistic effective field theory (NREFT)

But, not all relativistic theories give rise to $\mathcal{O}_{\mathrm{SI}}$ and $\mathcal{O}_{\mathrm{SD}}$ as dominant operators. Consider operators higher order in v and q —> **NREFT**.

[Fan et al - 1008.1591,
Fitzpatrick et al. - 1203.3542]
See Paolo's talk this morning…

The building blocks of these operators are:

$$\vec{S}_n \qquad \vec{S}_\chi \qquad \frac{\vec{q}}{2m_n} \qquad \vec{v}_\perp$$

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

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

NREFT Operators

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

SI

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

$$\mathcal{O}_3 = i\vec{S}_n \cdot (\frac{\vec{q}}{m_n} \times \vec{v}^\perp)$$

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

SD

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

$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_n \cdot \vec{q})$$

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

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

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

$$\mathcal{O}_{10} = i\vec{S}_n \cdot \vec{q}$$

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

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

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

$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_n \cdot \frac{\vec{q}}{m_n})$$

$$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_n})(\vec{S}_n \cdot \vec{v}^\perp)$$

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

NB: two sets of operators, one for protons and one for neutrons…

[1308.6288]

NREFT event rate

The matrix element for operator *i* can now be written as:

$$\langle|\mathcal{M}_i|^2\rangle = |\langle c_i \mathcal{O}_i \rangle_{\mathrm{nucleus}}|^2 = c_i^2 F_{i,i}(v_\perp^2, q^2)$$

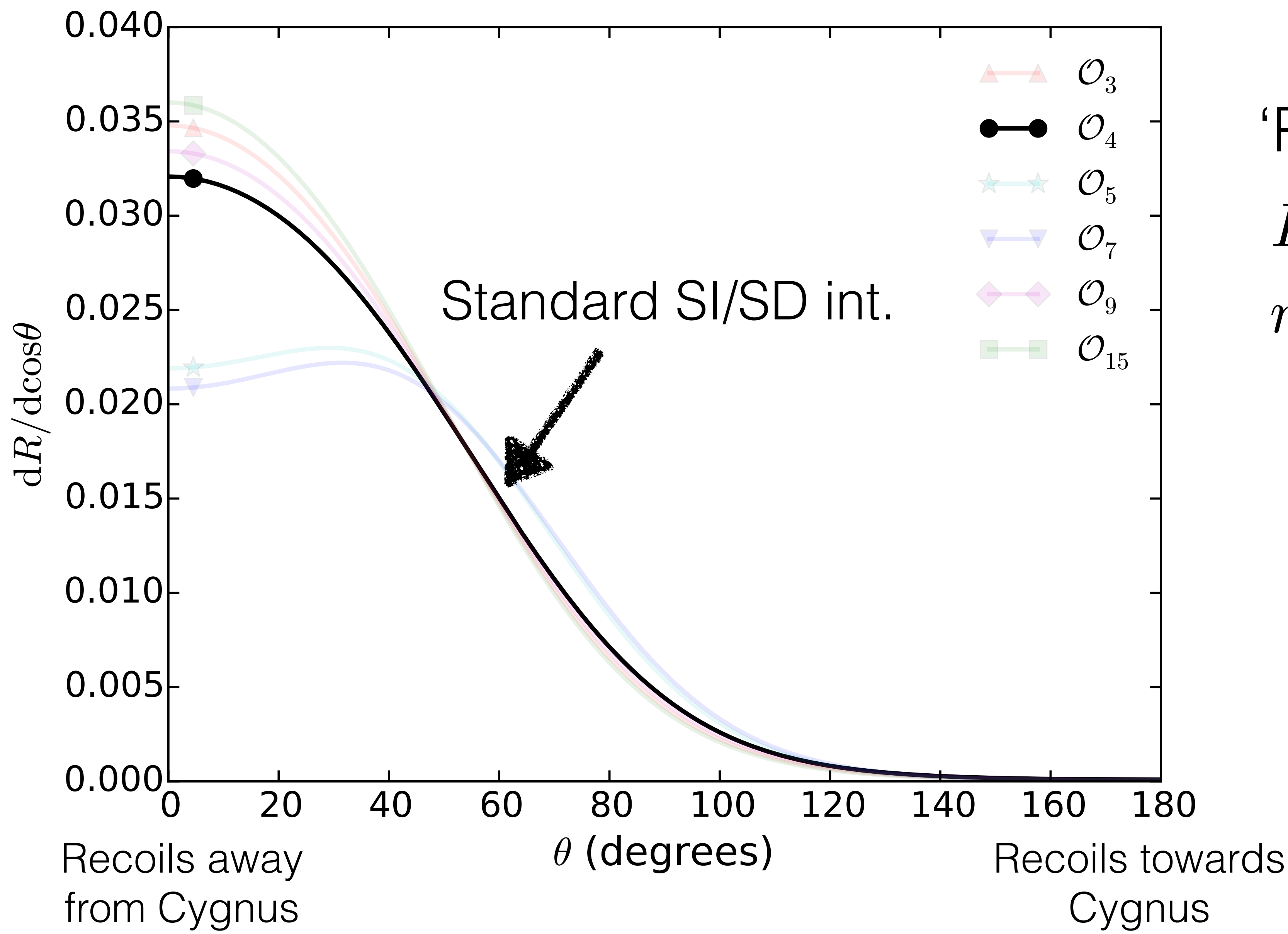
[Assuming for now: $c^p = c^n$]

The nuclear response functions $F_{i,i}(v_\perp^2, q^2)$ are the expectation values of the operators summed over all nucleons in the nucleus. They are proportional to $(v_\perp)^0$ or $(v_\perp)^2$.

$$\frac{\mathrm{d}R_i}{\mathrm{d}E_R \mathrm{d}\Omega_q} = \frac{\rho_0}{64\pi^2 m_N^2 m_\chi^3} c_i^2 \int_{\mathbb{R}^3} F_{i,i}(v_\perp^2, q^2) f(\vec{v})\, \delta\left(\vec{v}\cdot\hat{q} - v_{\mathrm{min}}\right)\, \mathrm{d}^3\vec{v}$$

Framework previously applied to non-directional direct detection and solar capture [1211.2818, 1406.0524, 1503.03379, 1503.04109 and others].

Directional Spectra

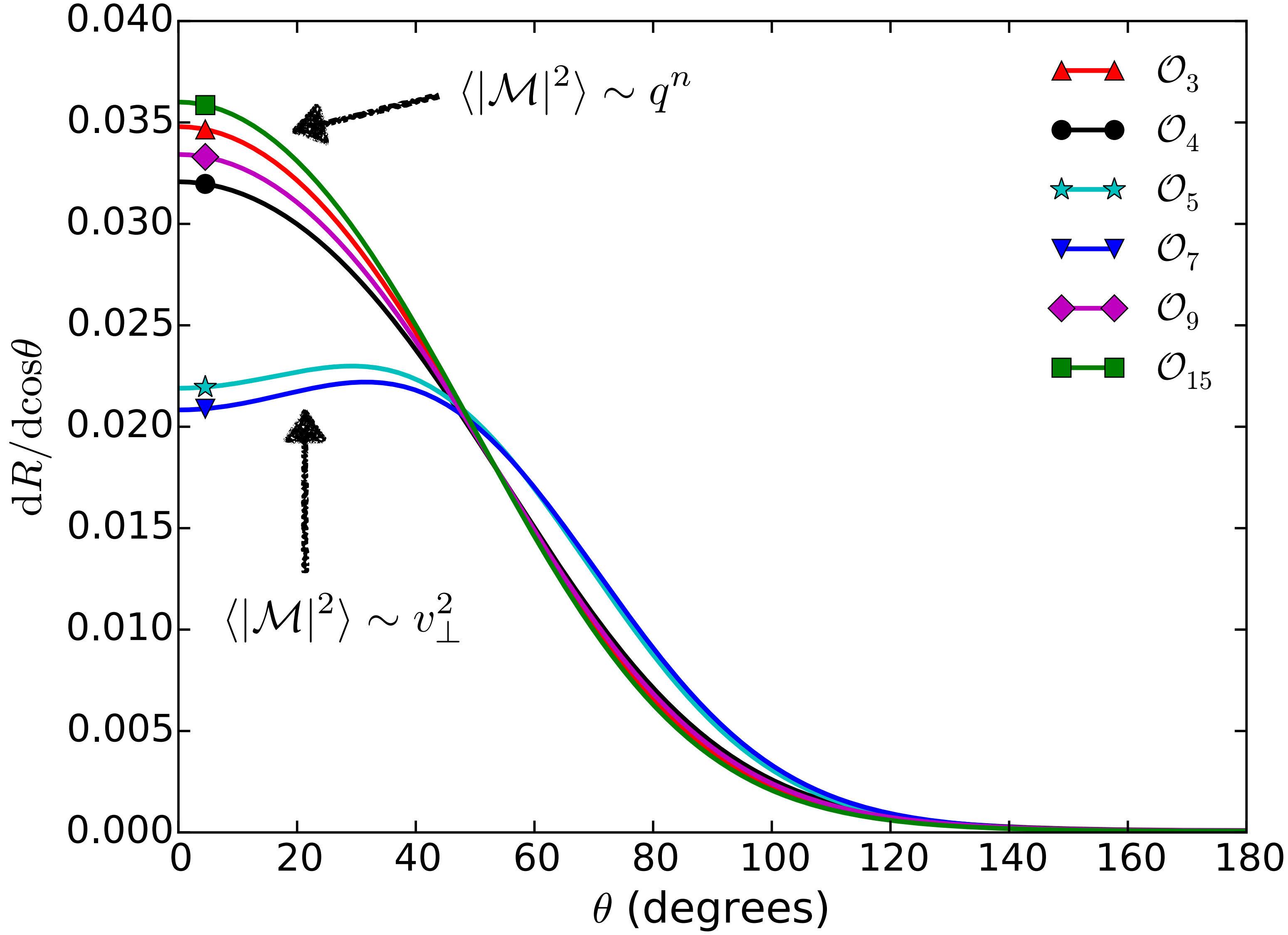


'Perfect' CF_4 detector

$$E_R \in [20, 50]\,\mathrm{keV}$$

$$m_\chi = 100\ \mathrm{GeV}$$

Directional Spectra



'Perfect' CF_4 detector

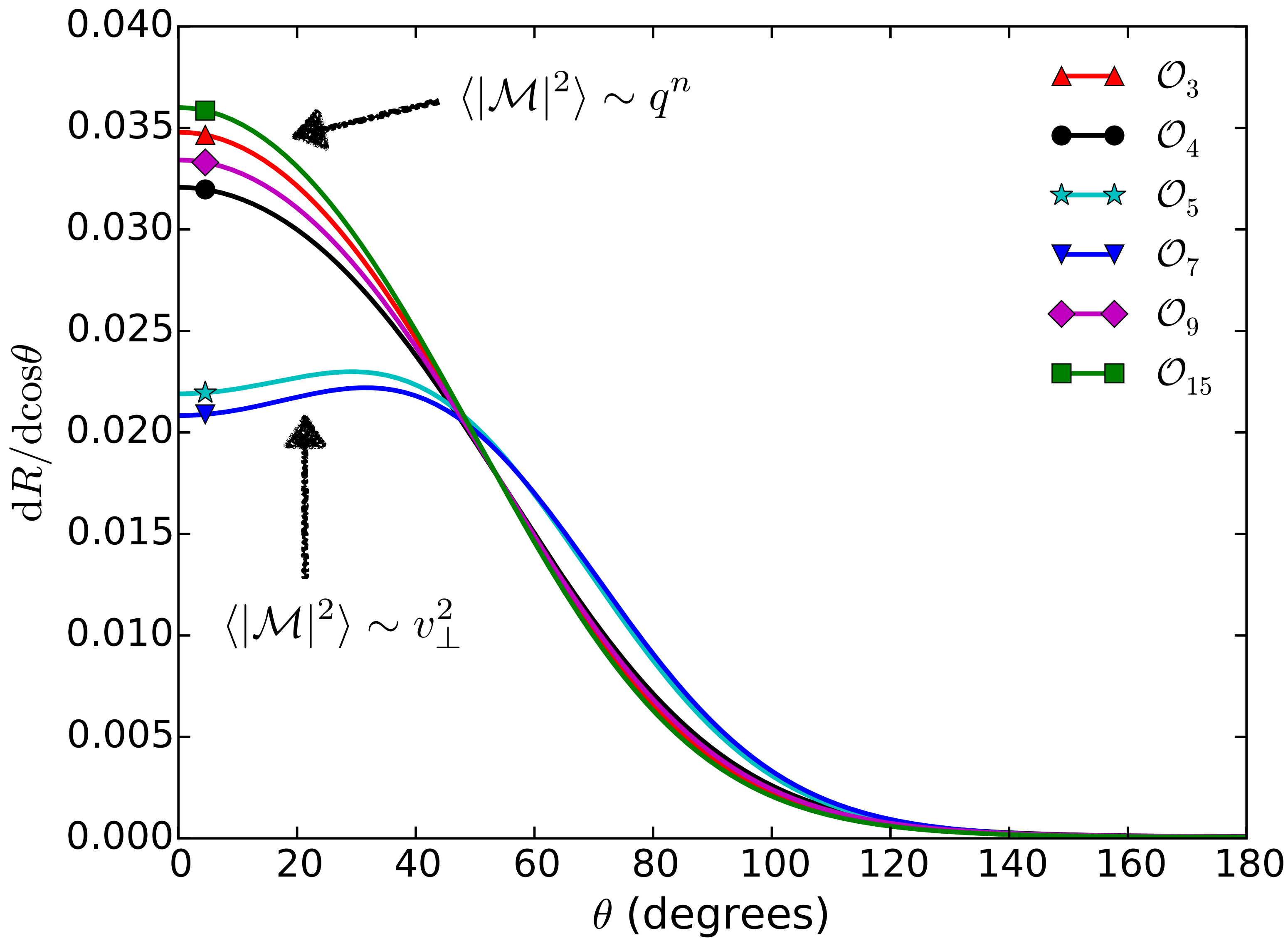
$E_R \in [20, 50]\,\mathrm{keV}$

$m_\chi = 100\ \mathrm{GeV}$

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

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

Directional Spectra



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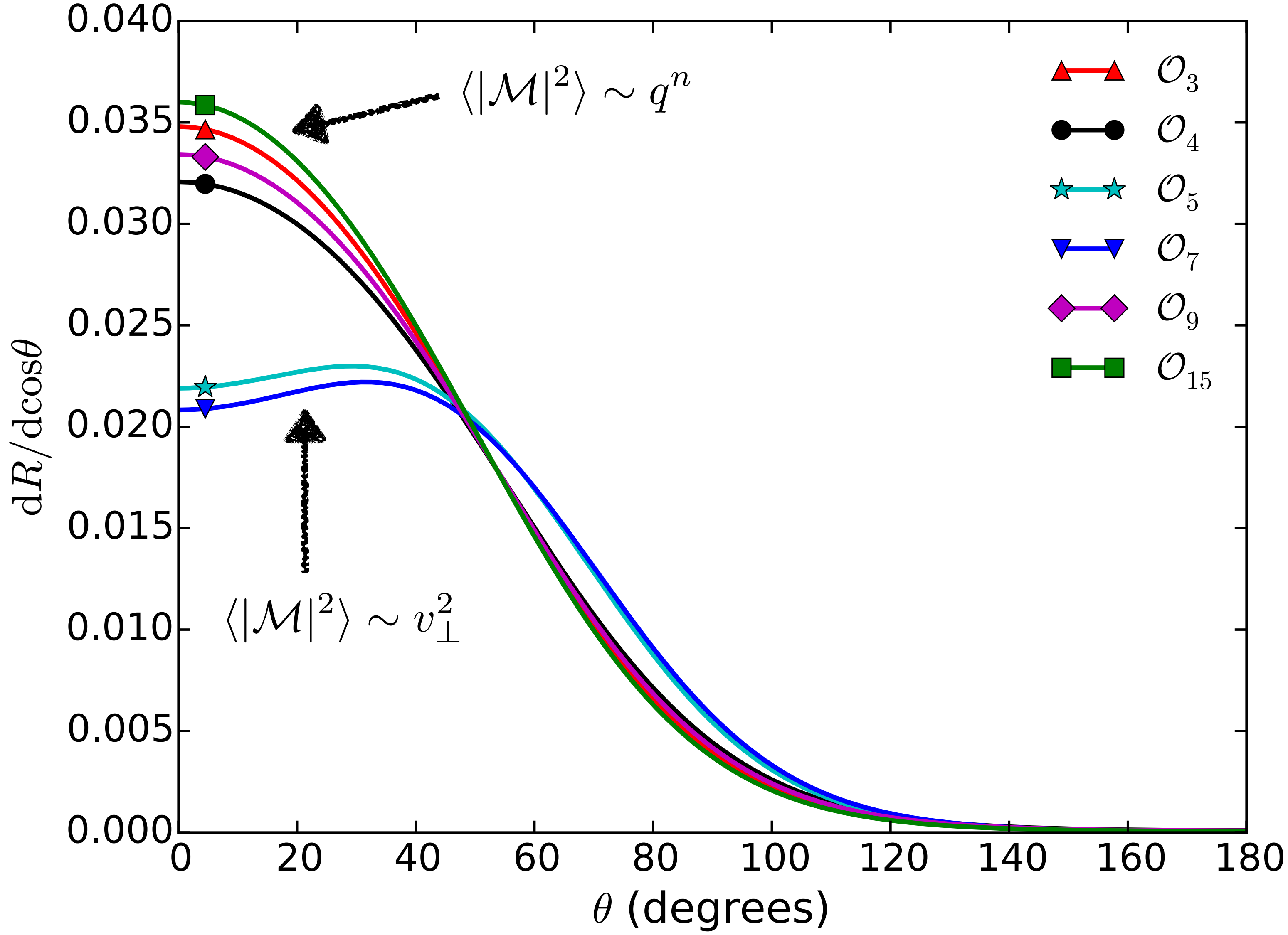
$= 2\mu_{\chi N} v\cos\theta$

Most isotropic: $\mathcal{O}_7 = \vec{S}_n \cdot \vec{v}_\perp \quad \rightarrow \sigma_7 \sim v_\perp^2$

Least isotropic: $\mathcal{O}_{15} = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_n})((\vec{S}_n \times \vec{v}_\perp)\cdot\frac{\vec{q}}{m_n}) \quad \rightarrow \sigma_{15} \sim q^4(q^2 + v_\perp^2)$

A (new) ring-like feature



Operators which give

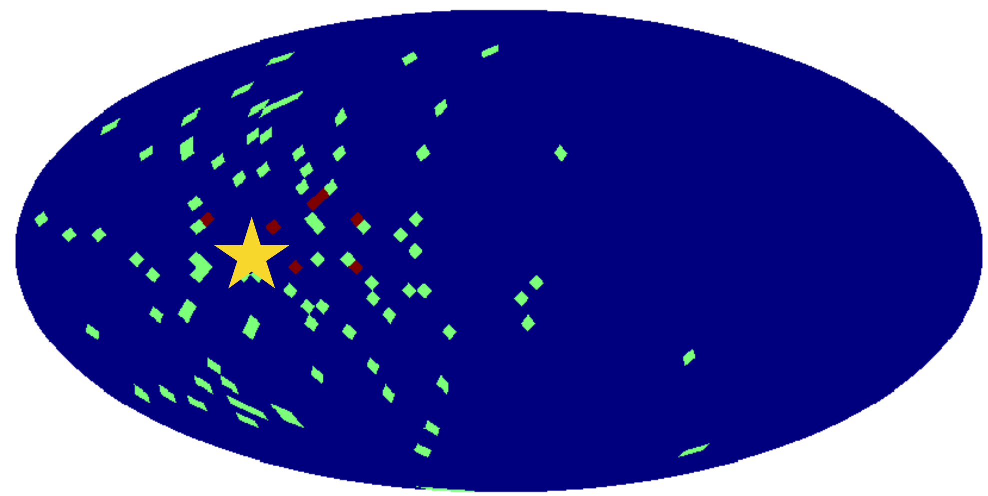
$$\langle|\mathcal{M}|^2\rangle \sim (v_\perp)^2$$

lead to a 'ring' in the directional rate.

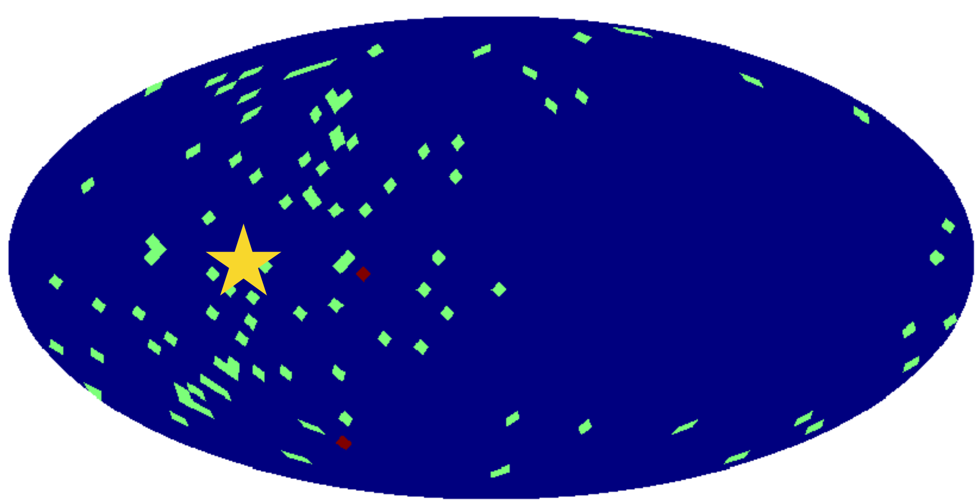
A ring in the standard rate has been previously studied [Bozorgnia et al. - 1111.6361], but *this* ring occurs for lower WIMP masses (down to 10 GeV) and higher threshold energies (up to 10 keV).

Comparing operators

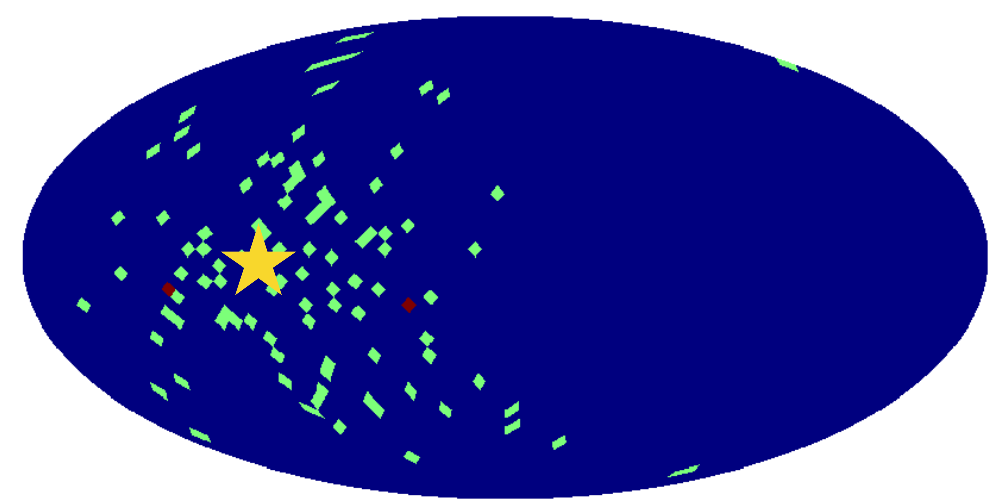
Standard signal



Signal due to $\mathcal{O}_7$



Signal due to $\mathcal{O}_{15}$



Can we distinguish these different operators?

Need to perform a full likelihood analysis…

Likelihood Analysis

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

Assume data is a combination of standard SD interaction and non-standard NREFT interaction. 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 to determine the significance with which we can reject SD-only interactions (i.e. reject A = 0) in 95% of pseudo-experiments.

Plot as a function of the number of signal events N_{WIMP}.

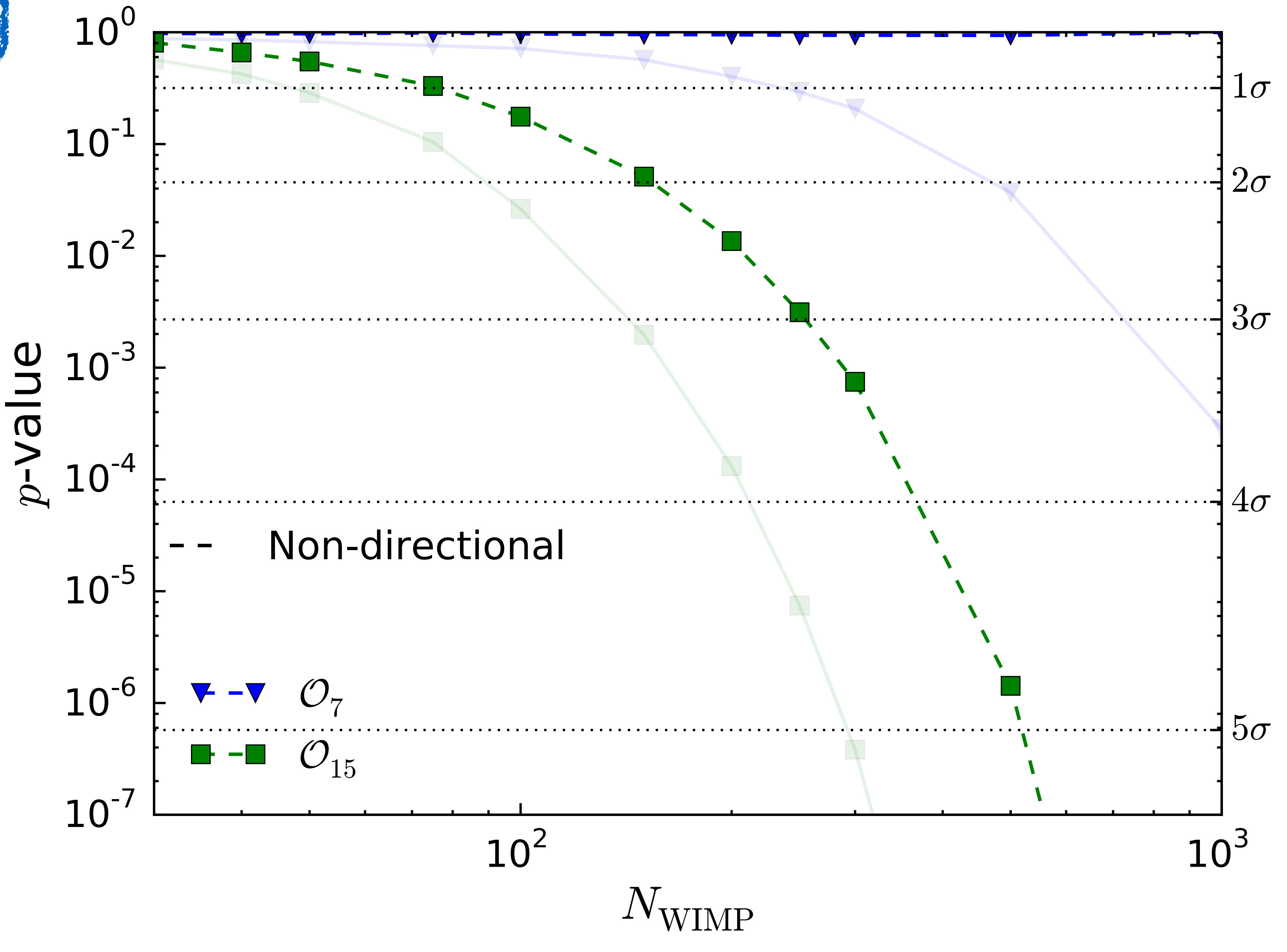
Distinguishing operators: Energy-only

$\sigma_{SI} \sim q^0 v^0$

$\sigma_7 \sim v_\perp^2$

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

How many events are required to reject 'standard' SI/SD interactions?

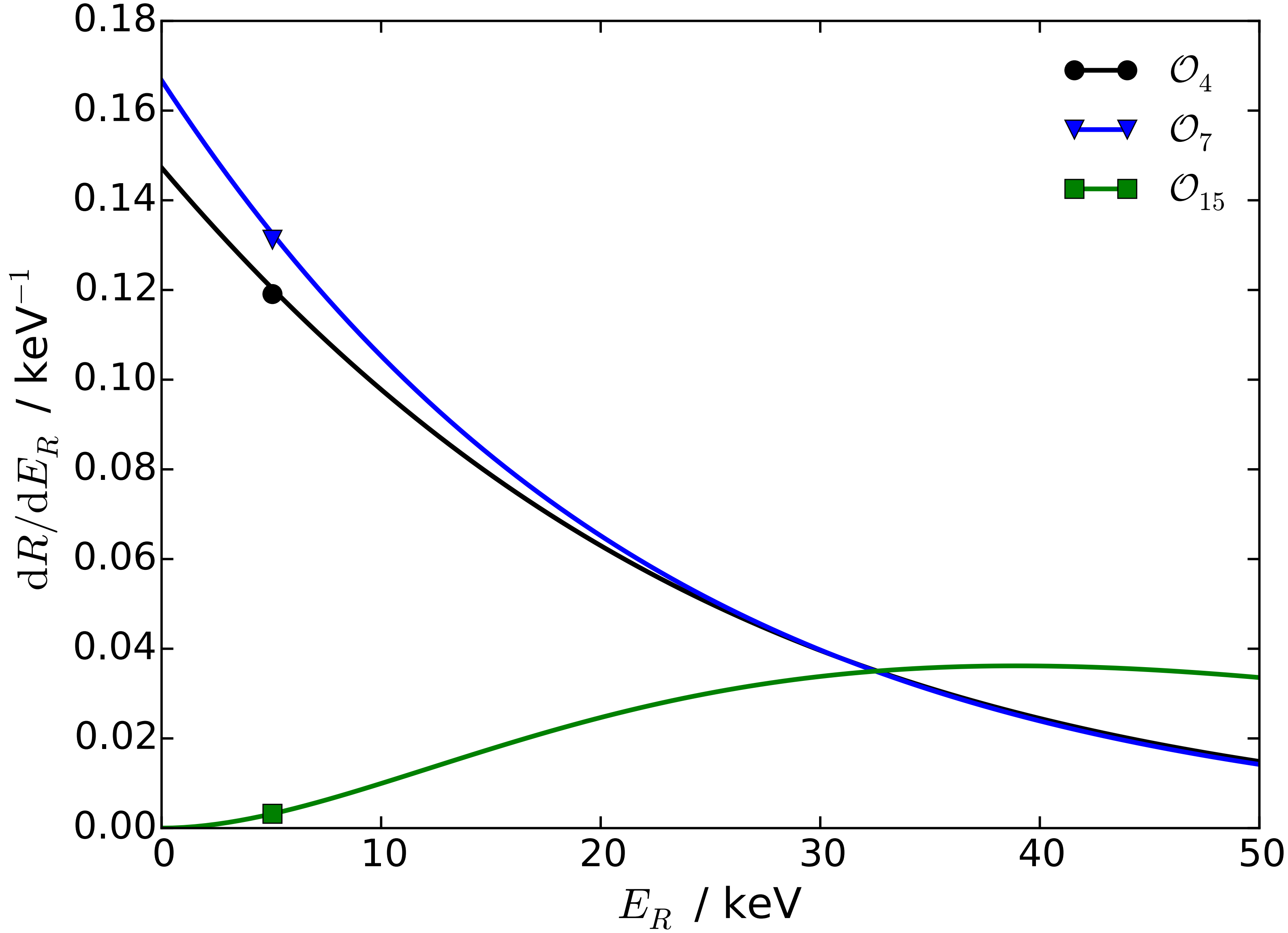


Comparing energy spectra

$\sigma_{SI} \sim q^0 v^0$

$\sigma_7 \sim v_\perp^2$

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



Energy spectra for $\mathcal{O}_4$ *and* $\mathcal{O}_7$ *are indistinguishable*:
Forward recoils are suppressed, but transverse recoils are enhanced.
For slowly varying distributions, these two effects roughly cancel.

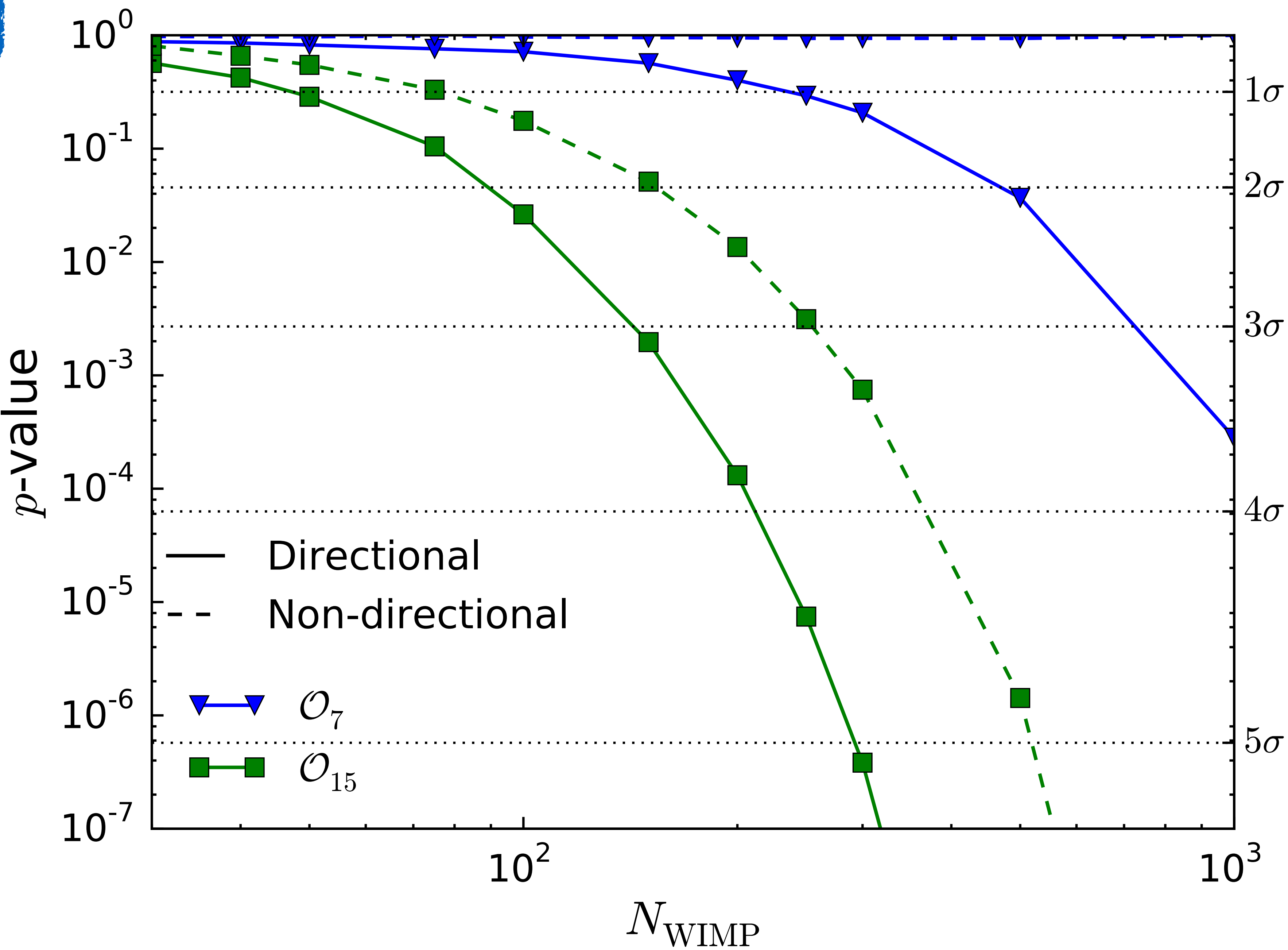
Distinguishing operators: Energy + Directionality

$\sigma_{SI} \sim q^0 v^0$

$\sigma_7 \sim v_\perp^2$

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

How many events are required to reject 'standard' SI/SD interactions?



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]

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

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

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

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

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

Conclusions

Need to be careful to include detector uncertainties, as well as astrophysical uncertainties, but we can say:

- NR operators lead to new directional signatures:
  - Operators coupling to q^2 lead to more directional rates
  - Operators coupling to $v_\perp^2$ lead to more isotropic rates
  - Possible enhanced ring-like signature

- With $\mathcal{O}(100 - 500)$ events it should be possible to distinguish NREFT operators from standard operators at the 2σ level (may not be possible in energy-only experiments).

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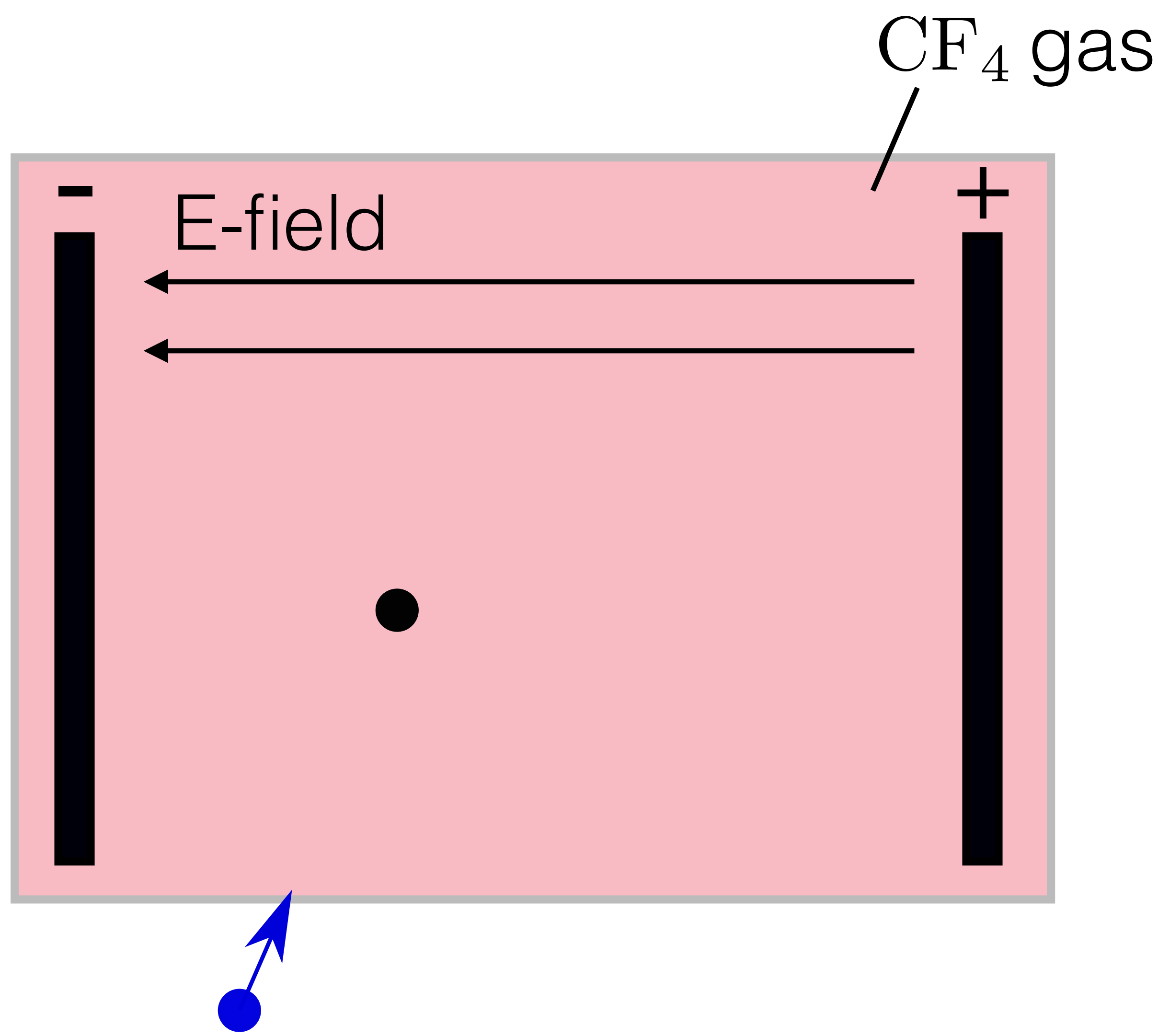
Directional detection allows us to probe otherwise inaccessible particle physics of Dark Matter!

Back-up slides

Directional detection - TPCs

Most advanced technology is the gaseous Time Projection Chamber (TPC) : [e.g. DRIFT, MIMAC, DMTPC, NEWAGE, D3]



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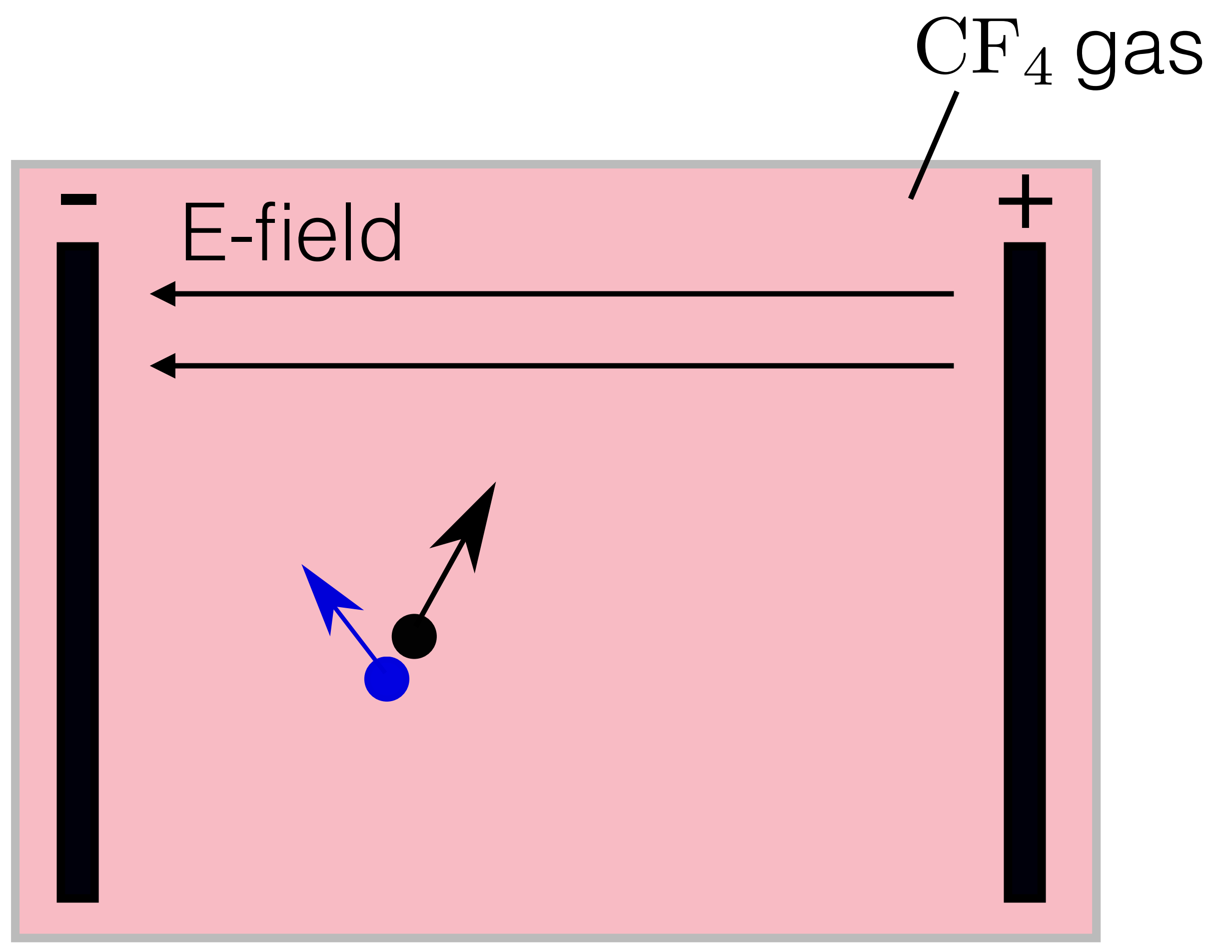

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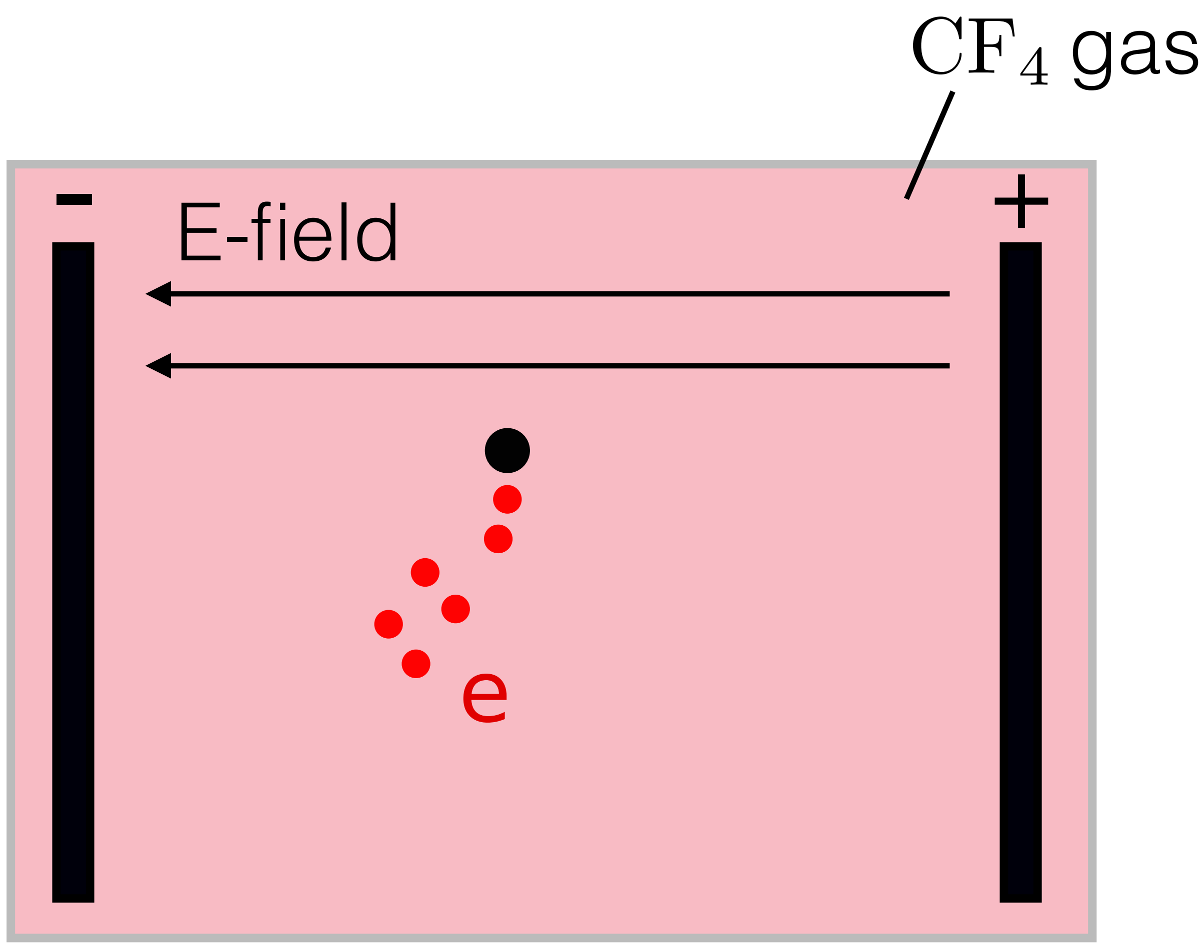

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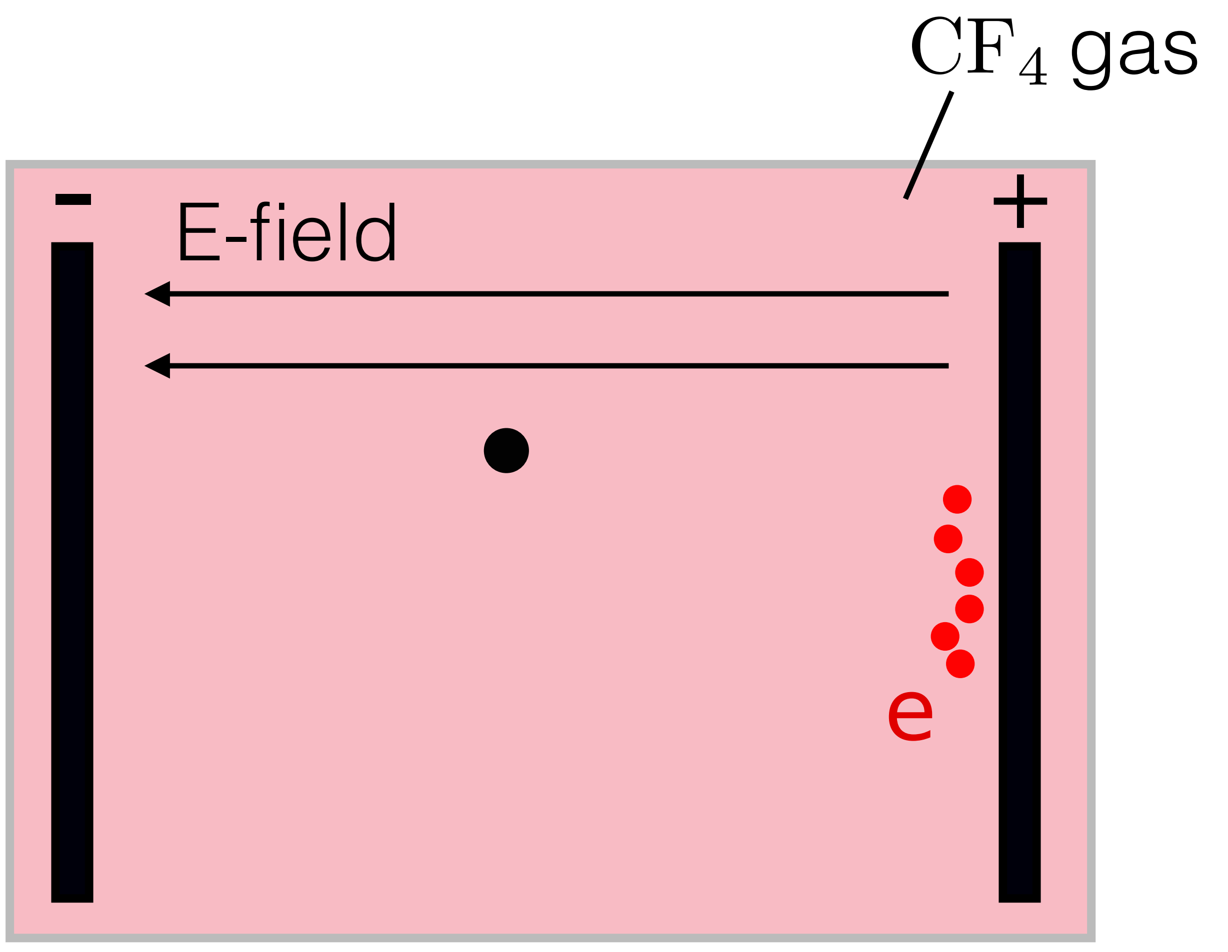
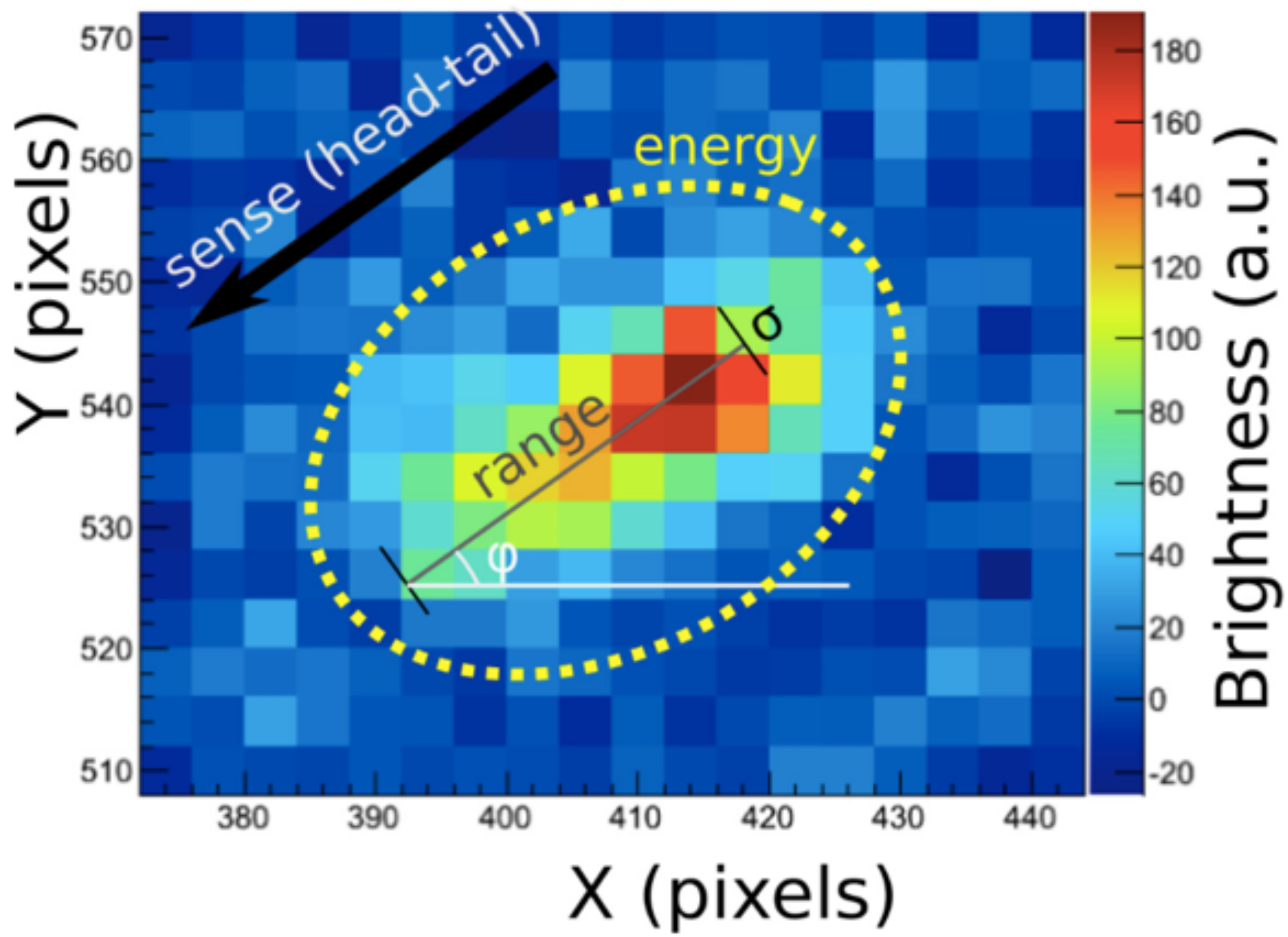


Get x,y of track from distribution of electrons hitting anode

Get z of track from timing of electrons hitting anode

A ‘Real’ Signal

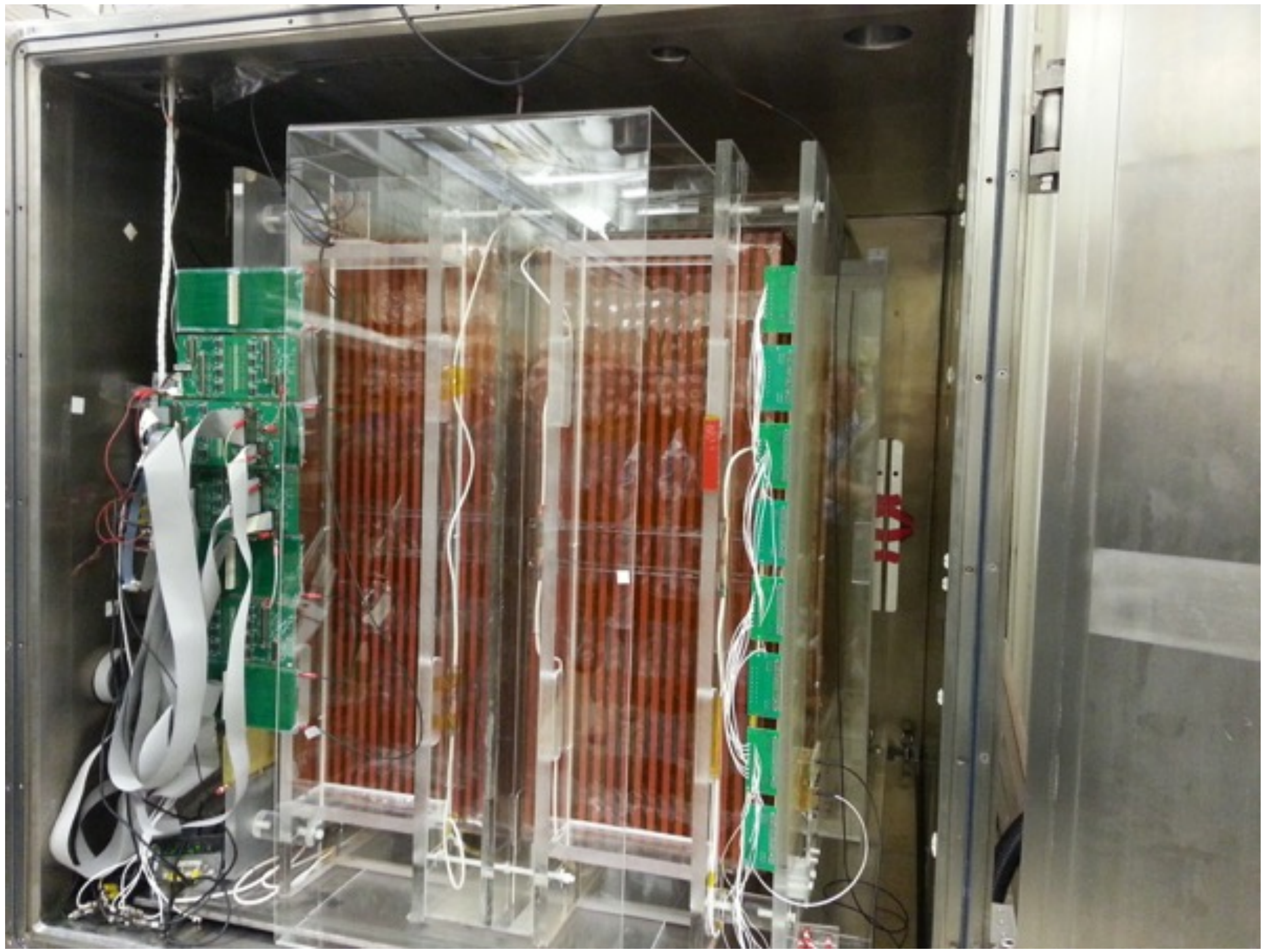
Deaconu et al. (DMTPC, 2015)



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

A Real TPC

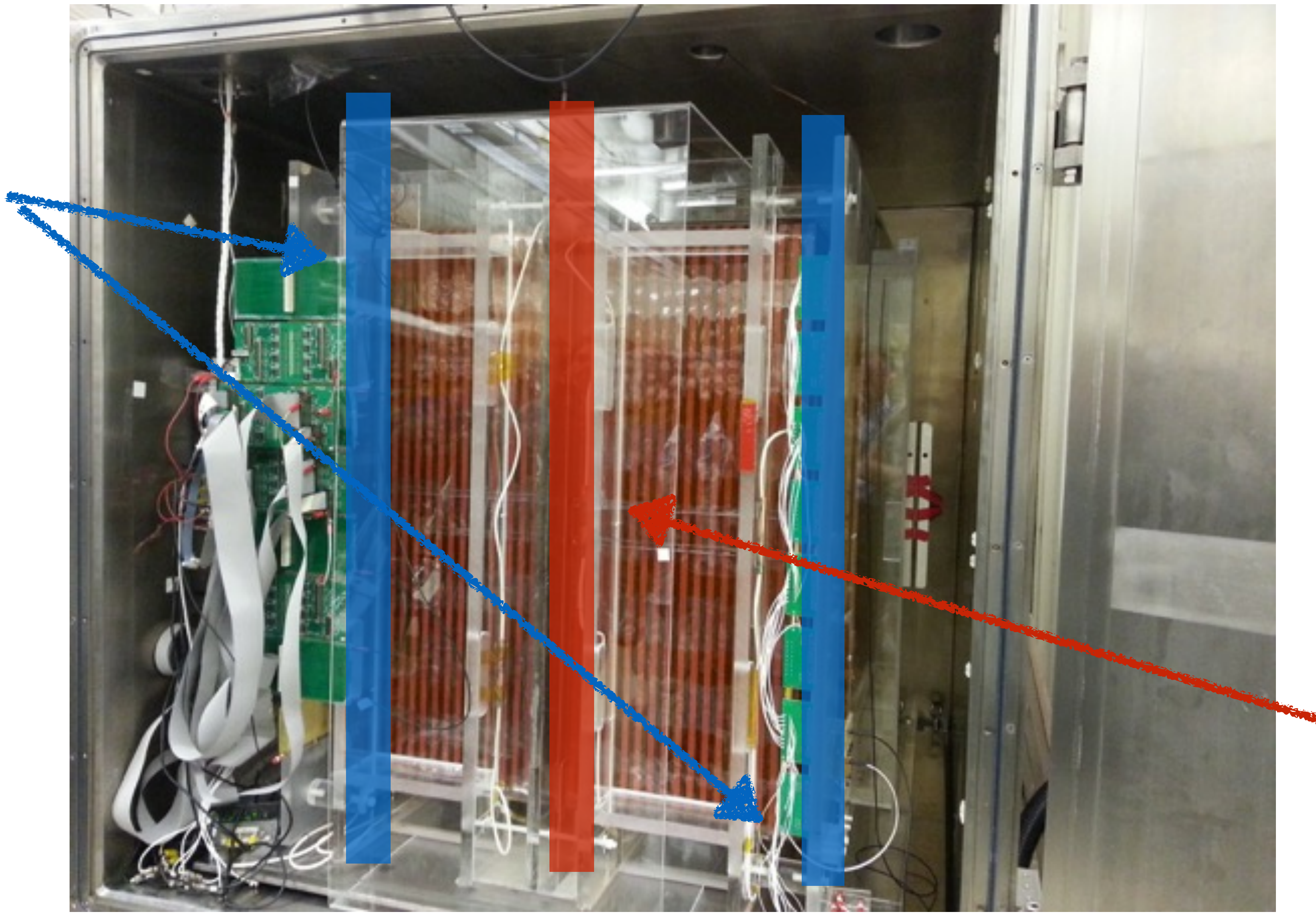
DRIFT-IIe prototype detector @ Occidental College, LA



Two back-to-back TPCs

A Real TPC

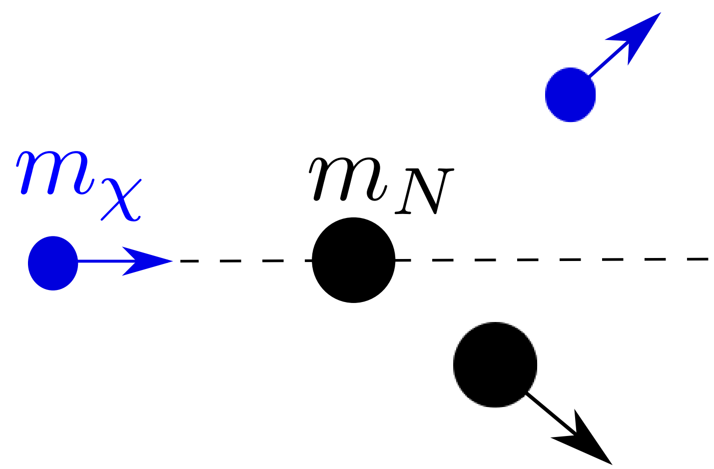
DRIFT-IIe prototype detector @ Occidental College, LA



Two back-to-back TPCs

The Directional Spectrum

Recoil distribution for WIMP-nucleus recoils in direction $\hat{q}$ with fixed WIMP speed $\vec{v}$:



$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$$

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

$$\frac{\mathrm{d}R}{\mathrm{d}E_R \mathrm{d}\Omega_q} = \underbrace{\boxed{\frac{\rho_0 v}{m_\chi}}}_{\text{WIMP flux}} \underbrace{\boxed{\frac{\langle |\mathcal{M}|^2 \rangle}{32\pi m_N^2 m_\chi^2 v^2}}}_{\text{Cross section}} \underbrace{\boxed{\frac{v\,\delta\left(\vec{v}\cdot\hat{q} - v_{\min}\right)}{2\pi}}}_{\text{Kinematics}}$$

For standard SI and SD interactions: $\langle |M|^2 \rangle \sim v^0 q^0$

Nuclear response functions

$$F_{1,1} = F_M$$

$$F_{3,3} = \frac{1}{8}\frac{q^2}{m_n^2}\left(v_\perp^2 F_{\Sigma'} + 2\frac{q^2}{m_n^2}F_{\Phi''}\right)$$

$$F_{4,4} = \frac{C(j_\chi)}{16}\left(F_{\Sigma'} + F_{\Sigma''}\right)$$

$$F_{5,5} = \frac{C(j_\chi)}{4}\frac{q^2}{m_n^2}\left(v_\perp^2 F_M + \frac{q^2}{m_n^2}F_\Delta\right)$$

$$F_{6,6} = \frac{C(j_\chi)}{16}\frac{q^4}{m_n^4}F_{\Sigma''}$$

$$F_{7,7} = \frac{1}{8}v_\perp^2 F_{\Sigma'}\,,$$

$$F_{8,8} = \frac{C(j_\chi)}{4}\left(v_\perp^2 F_M + \frac{q^2}{m_n^2}F_\Delta\right)$$

$$F_{9,9} = \frac{C(j_\chi)}{16}\frac{q^2}{m_n^2}F_{\Sigma'}$$

$$F_{10,10} = \frac{1}{4}\frac{q^2}{m_n^2}F_{\Sigma''}$$

$$F_{11,11} = \frac{1}{4}\frac{q^2}{m_n^2}$$

$$F_{12,12} = \frac{C(j_\chi)}{16}\left(v_\perp^2\left(F_{\Sigma''} + \frac{1}{2}F_{\Sigma'}\right) + \frac{q^2}{m_n^2}\left(F_{\tilde{\Phi}'} + F_{\Phi''}\right)\right)$$

$$F_{13,13} = \frac{C(j_\chi)}{16}\frac{q^2}{m_n^2}\left(v_\perp^2 F_{\Sigma''} + \frac{q^2}{m_n^2}F_{\tilde{\Phi}'}\right)$$

$$F_{14,14} = \frac{C(j_\chi)}{32}\frac{q^2}{m_n^2}v_\perp^2 F_{\Sigma'}$$

$$F_{15,15} = \frac{C(j_\chi)}{32}\frac{q^4}{m_n^4}\left(v_\perp^2 F_{\Sigma'} + 2\frac{q^2}{m_n^2}F_{\Phi''}\right)$$

$F_{M,\Sigma',\Sigma'',\tilde{\Phi}',\Phi'',\Delta}(q^2)$ are standard form factors encoding the distribution of nucleons in the nucleus - suppression at high q.

Coupling to q^2 *does not affect the intrinsic directional rate.*

But, each term in the response function is proportional to either $(v_\perp)^0$ *or* $(v_\perp)^2$.

Transverse Radon Transform

For response functions coupling to $(v_\perp)^2$ we need to calculate the *Transverse* Radon Transform (TRT):

$$\hat{f}^T(v_{\rm min}, \hat{q}) = \int_{\mathbb{R}^3} \frac{(v_\perp)^2}{c^2} f(\vec{v})\, \delta\left(\vec{v}\cdot\hat{q} - v_{\rm min}\right)\, \mathrm{d}^3\vec{v}$$

In the case of a Maxwell-Boltzmann distribution (e.g. SHM):

$$\hat{f}^T(v_{\rm min}, \hat{q}) = \frac{\left(2\sigma_v^2 + v_{\rm lag}^2 - (\vec{v}_{\rm lag}\cdot\hat{q})^2\right)}{\sqrt{2\pi}\sigma_v c^2} \exp\left[-\frac{(v_{\rm min} - \vec{v}_{\rm lag}\cdot\hat{q})^2}{2\sigma_v^2}\right]$$

If we measure recoil angles θ from the mean recoil direction $\vec{v}_{\rm lag}$:

$$\hat{f}^T(v_{\rm min}, \hat{q}) = \frac{\left(2\sigma_v^2 + v_{\rm lag}^2 \sin^2\theta\right)}{\sqrt{2\pi}\sigma_v c^2} \exp\left[-\frac{(v_{\rm min} - v_{\rm lag}\cos\theta)^2}{2\sigma_v^2}\right]$$

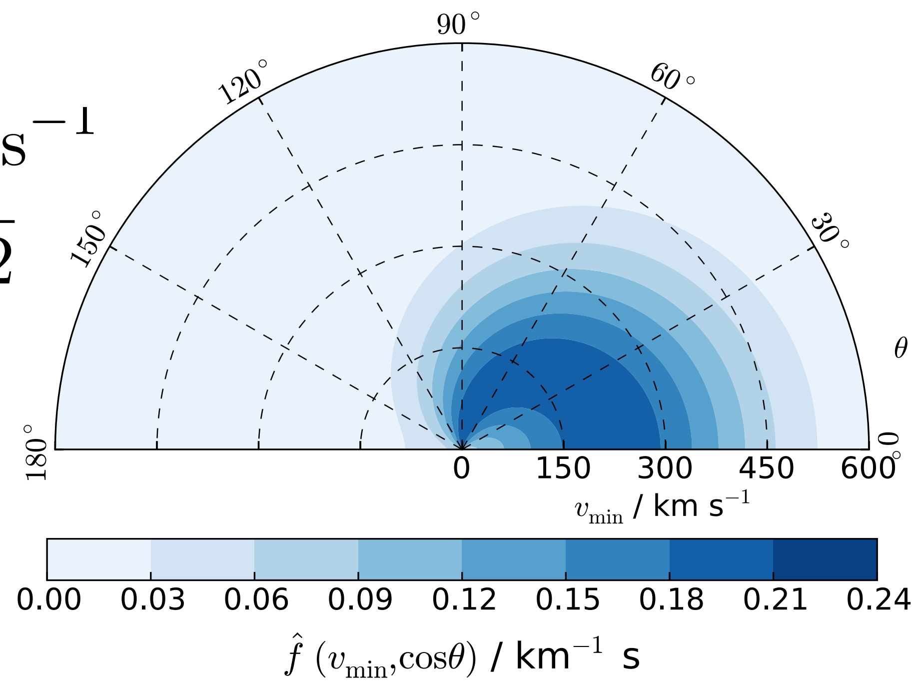
Transverse Radon Transform (examples)

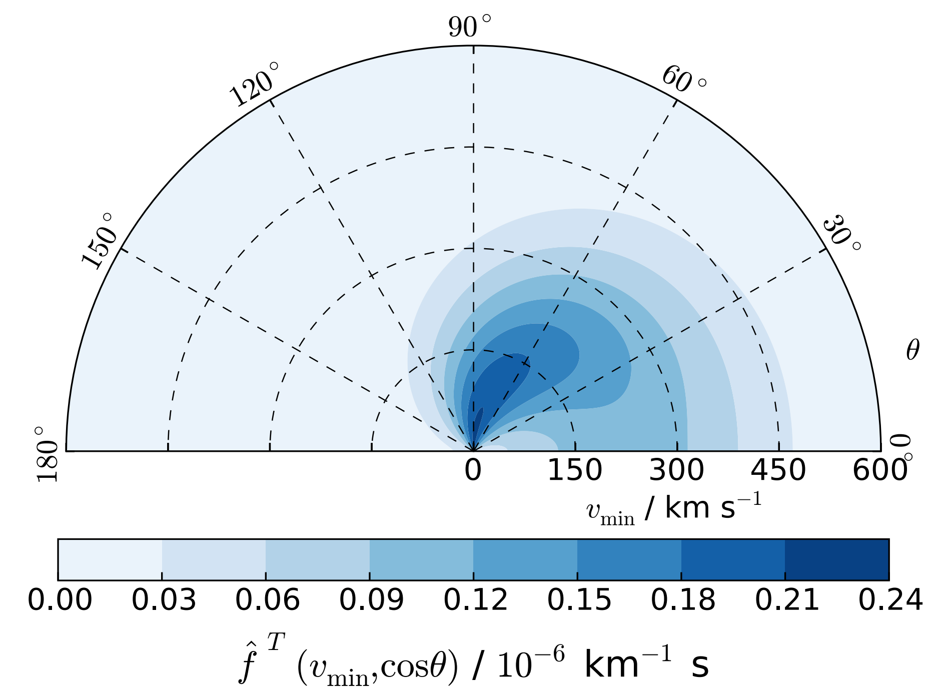
$\hat{f}(v_{\min}, \hat{q})$ $\hat{f}^T(v_{\min}, \hat{q})$

SHM:

$v_{\mathrm{lag}} = 220\,\mathrm{km\,s^{-1}}$

$\sigma_v = v_{\mathrm{lag}}/\sqrt{2}$

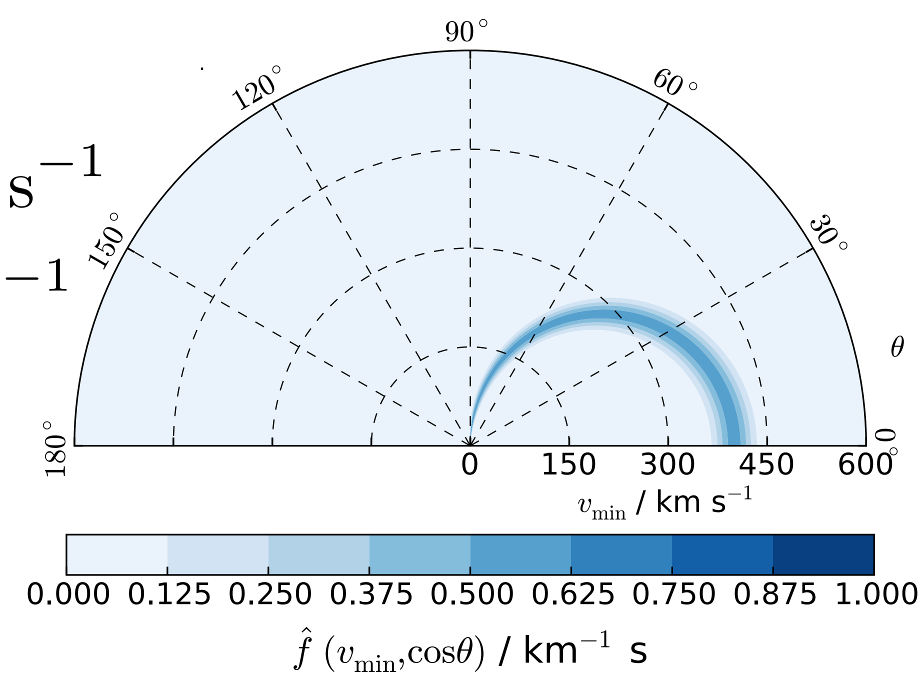


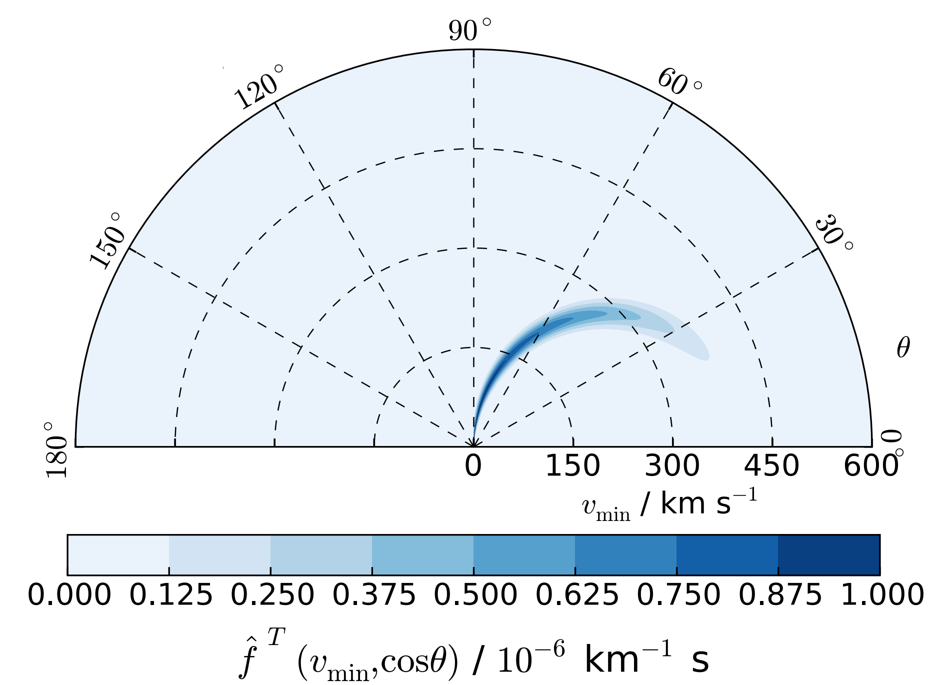


Stream:

$v_{\mathrm{lag}} = 400\,\mathrm{km\,s^{-1}}$

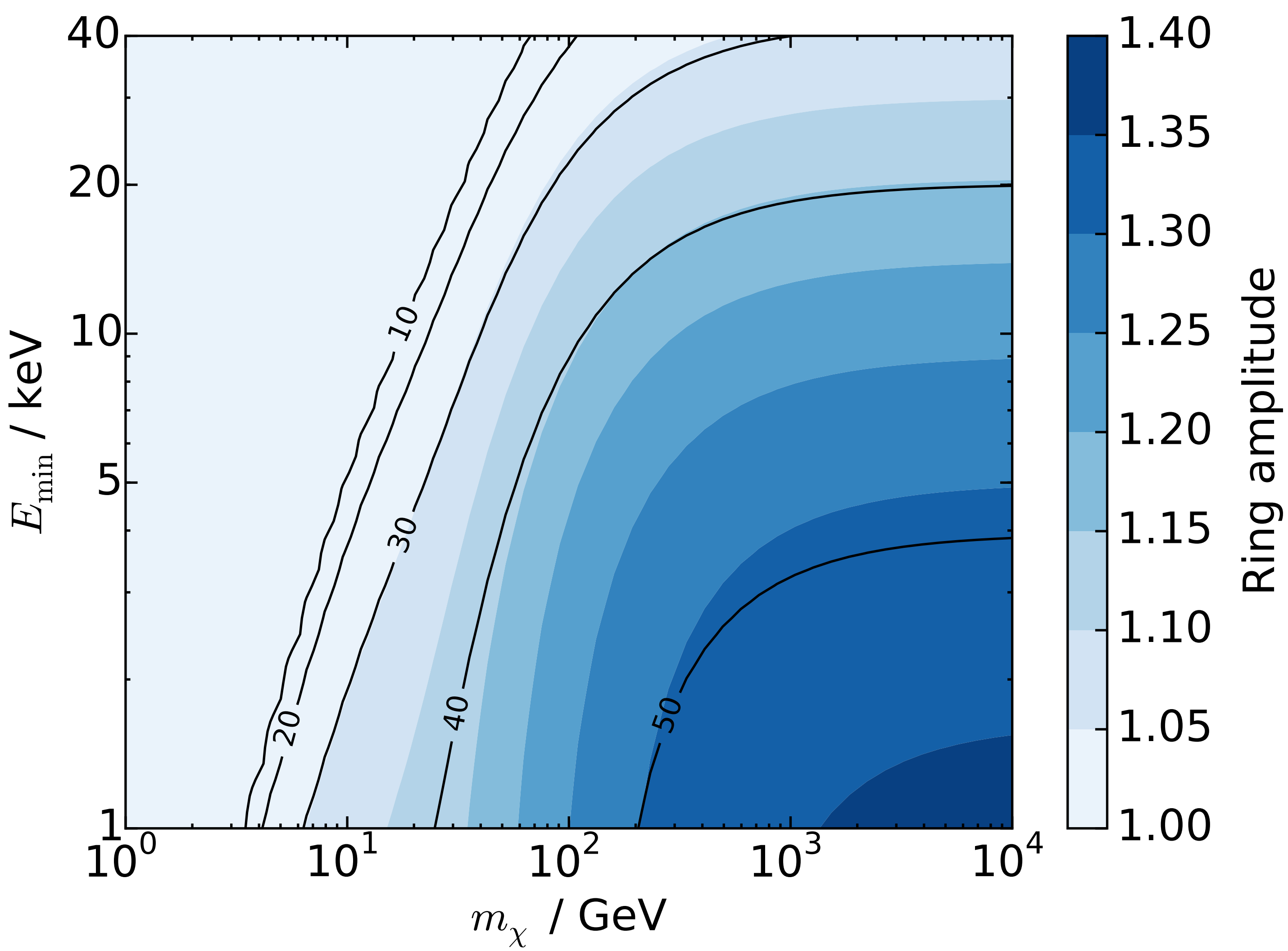
$\sigma_v = 20\,\mathrm{km\,s^{-1}}$





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

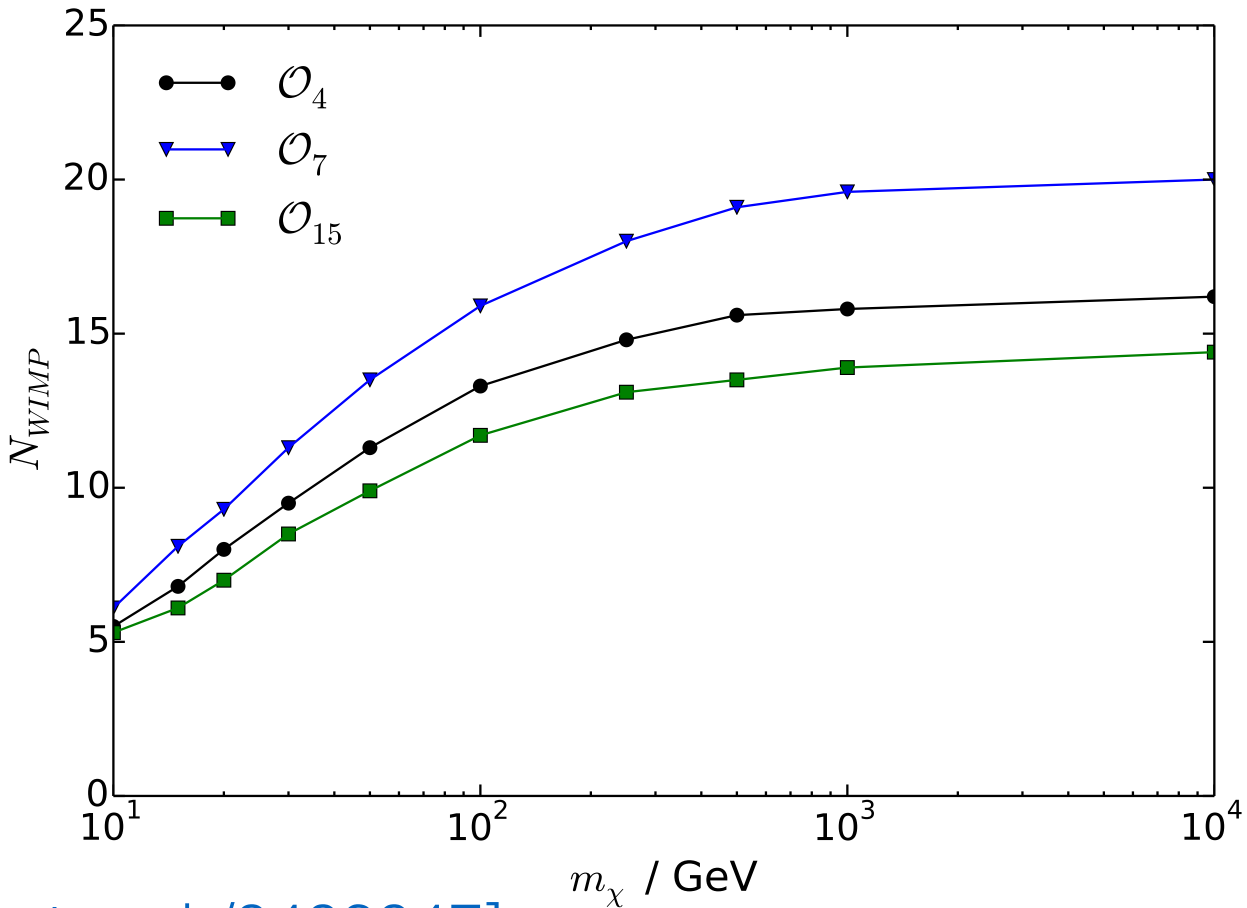
$F_{4,4} \sim 1$

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

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

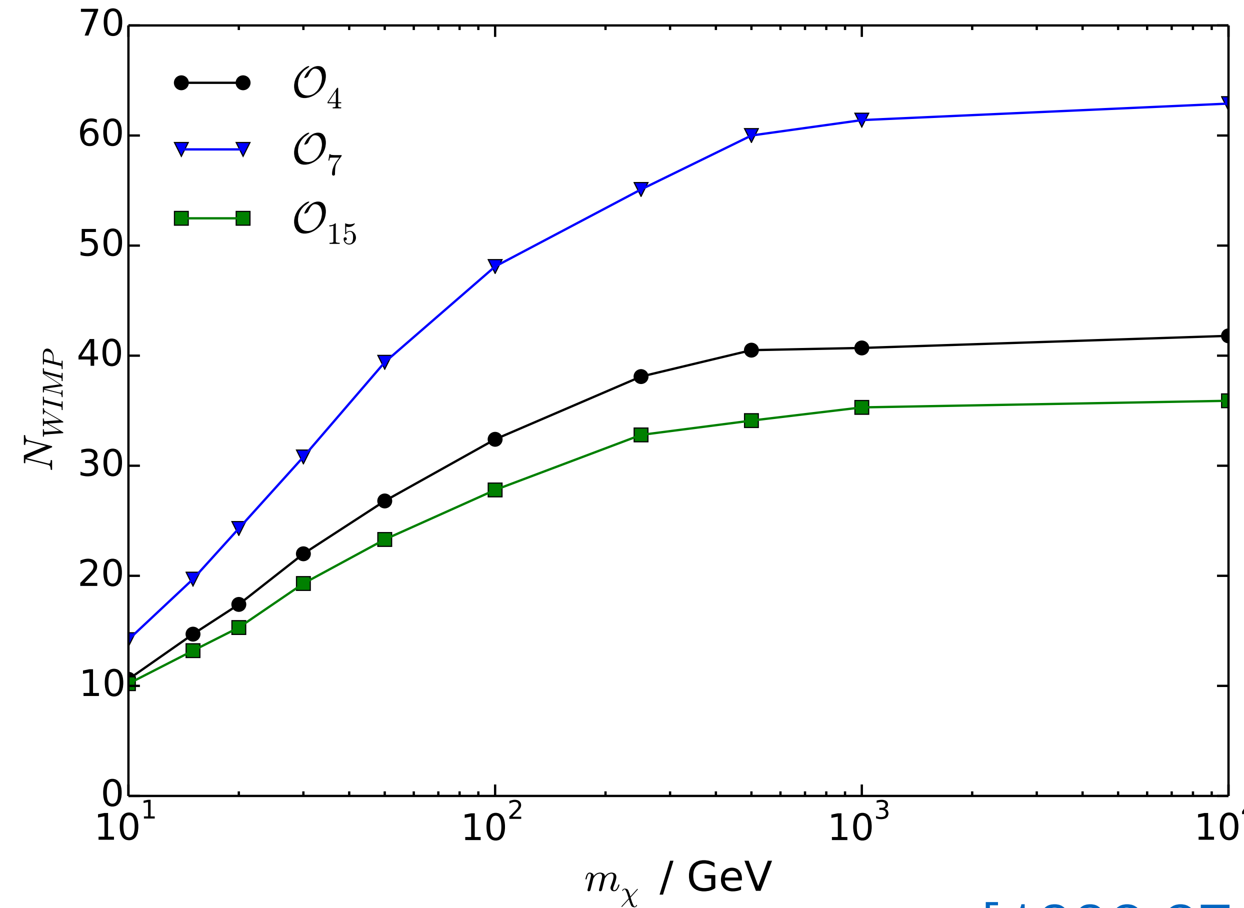
Calculate the number of signal events required to…

…reject isotropy…



[astro-ph/0408047]

…confirm the median recoil dir…



[1002.2717]

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

Distinguishing NREFT operators

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, $\mathbf{H_0}$: all events are due to SD interactions, A = 0

Alt. hypothesis, $\mathbf{H_1}$: there is some contribution from NREFT ops, $A \neq 0$