Distinguishing WIMP-nucleon interactions with directional dark matter experiments

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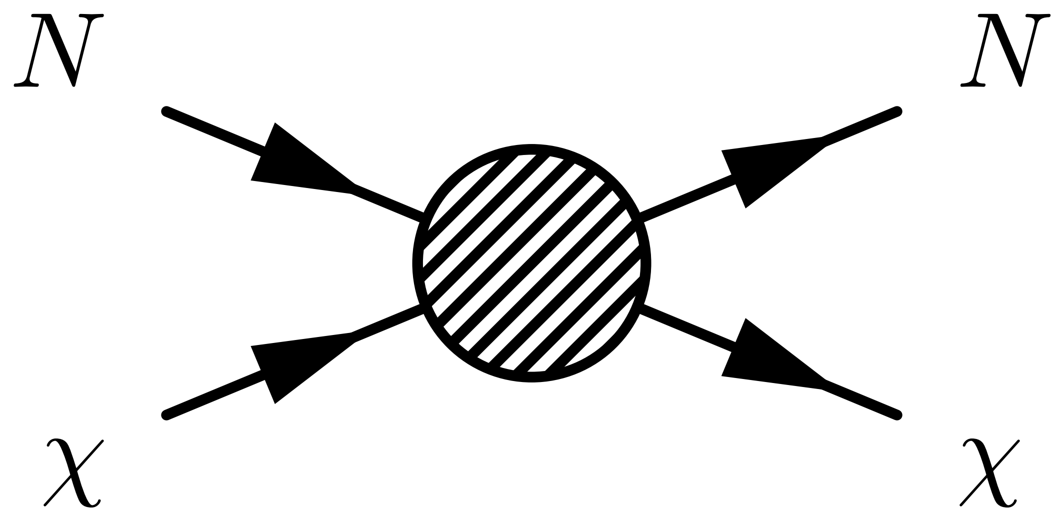
Based on arXiv:1505.07406

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:

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

Non-relativistic effective field theory (NREFT)

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

SI → $\mathcal{O}_1 = 1$

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

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

Non-relativistic effective field theory (NREFT)

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

SI → $\mathcal{O}_1 = 1$

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

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

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

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

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

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

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

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

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

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

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

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

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

$\vdots$

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

Calculating the cross section

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

[e.g. 1211.2818, 1307.5955, 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]

  → May require a large number of experiments

- *Annual modulation* - due to different v-dependence annual modulation rate and phase can be different [1504.06772]

  → Annual modulation is a small effect

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

Distinguishing operators: Energy-only

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

SI operator → $F_1 \sim q^0 v^0$

'Non-standard' operators → $F_5 \sim q^2 (v_\perp^2 + q^2)$; $F_7 \sim v_\perp^2$

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

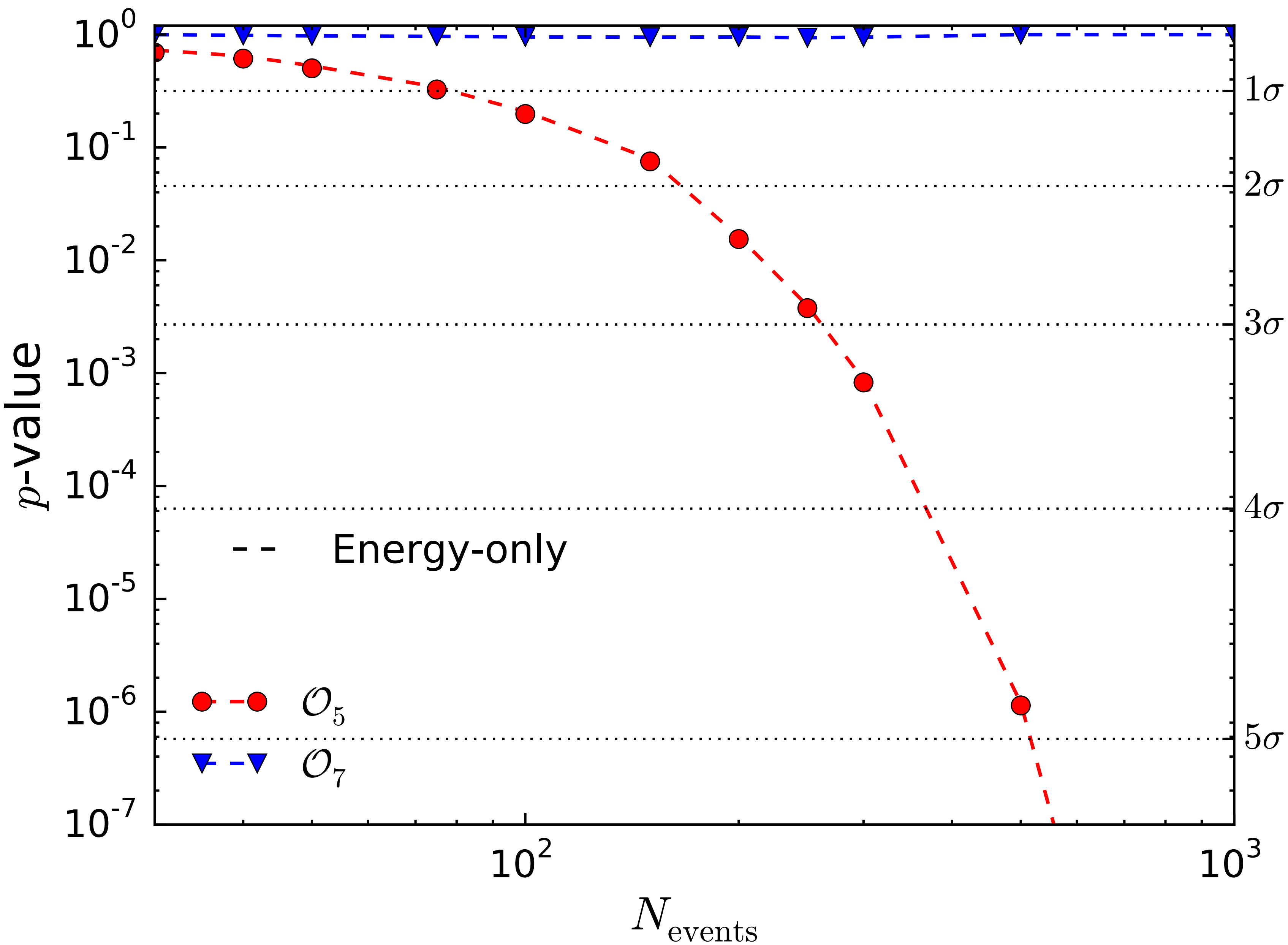
Assume the data is a mixture of events due to $\mathcal{O}_1$ and the 'non-standard' operator (either $\mathcal{O}_5$ or $\mathcal{O}_7$).

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

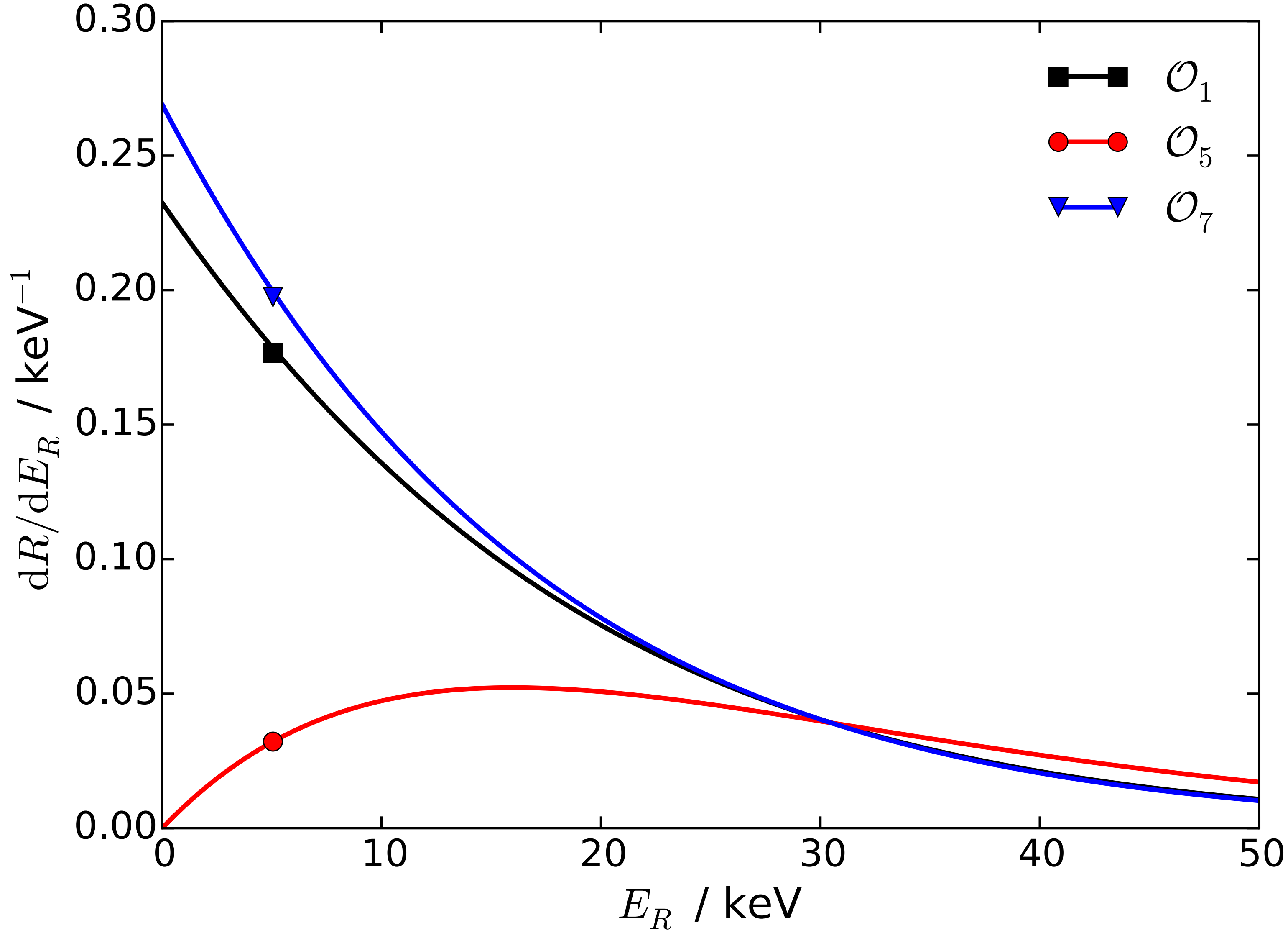
SHM velocity distribution

$F_1 \sim q^0 v^0$

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

$F_7 \sim v_\perp^2$

Comparing energy spectra



$F_1 \sim q^0 v^0$

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

$F_7 \sim v_\perp^2$

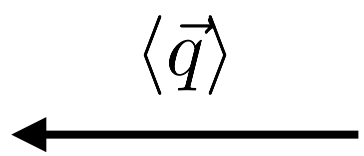
Energy spectrum differences between $\mathcal{O}_1$ and $\mathcal{O}_7$ are smoothed out once we integrate over (smooth) DM velocity distribution.

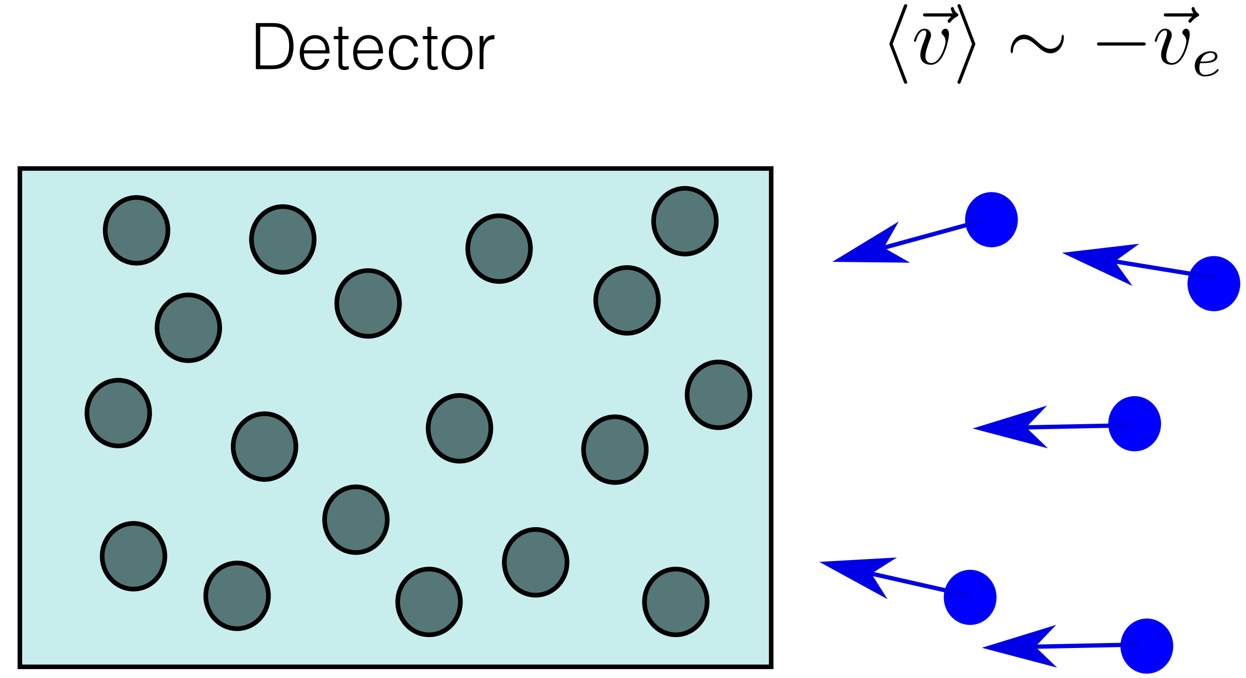
True of any operators whose cross-sections differ only by $v_\perp^2$.

Directional detection

Different v-dependence could impact *directional* signal.

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



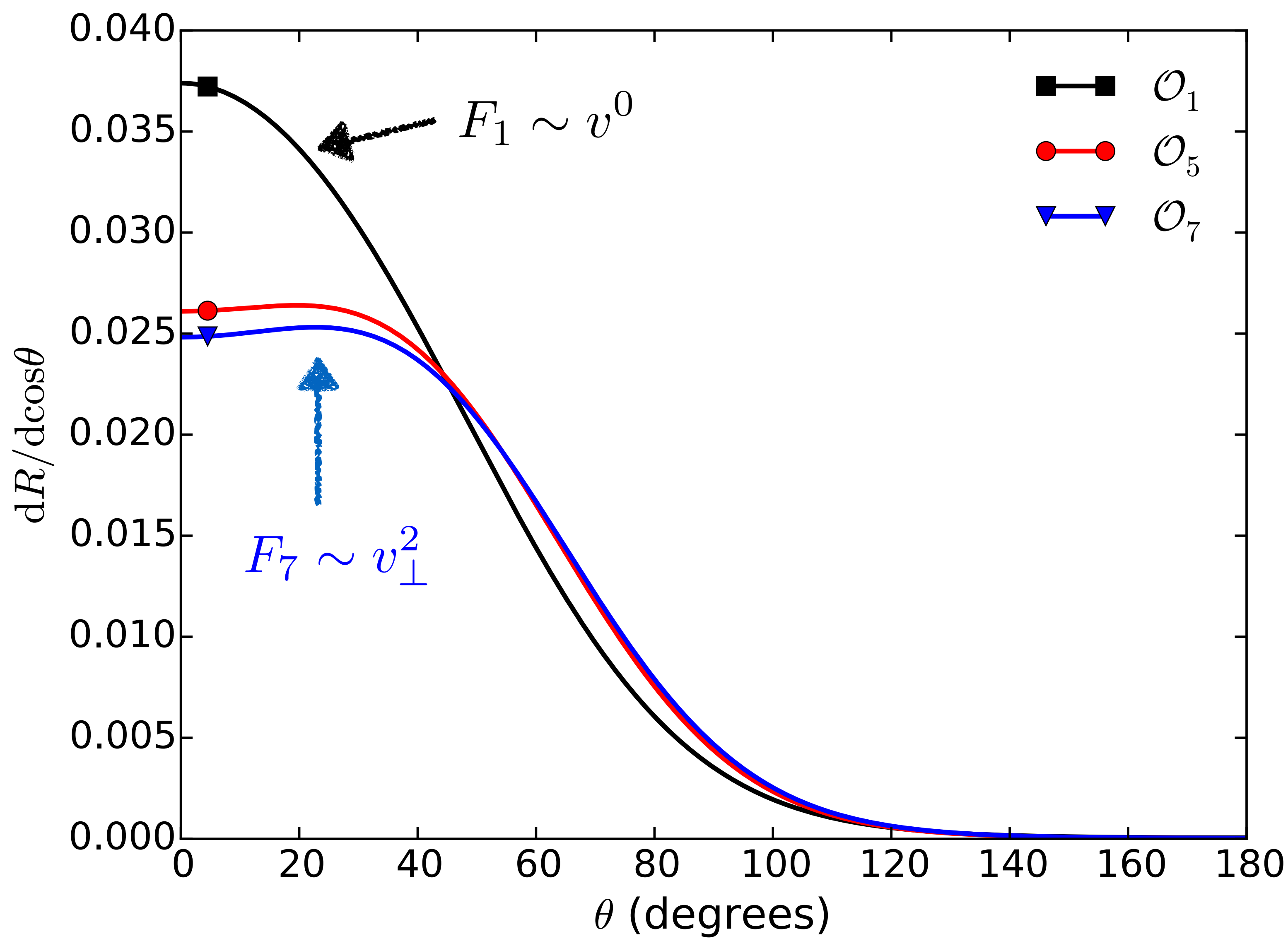


Convolve cross section with velocity distribution to obtain directional spectrum, as a function of θ , the angle between the recoil and the peak direction.

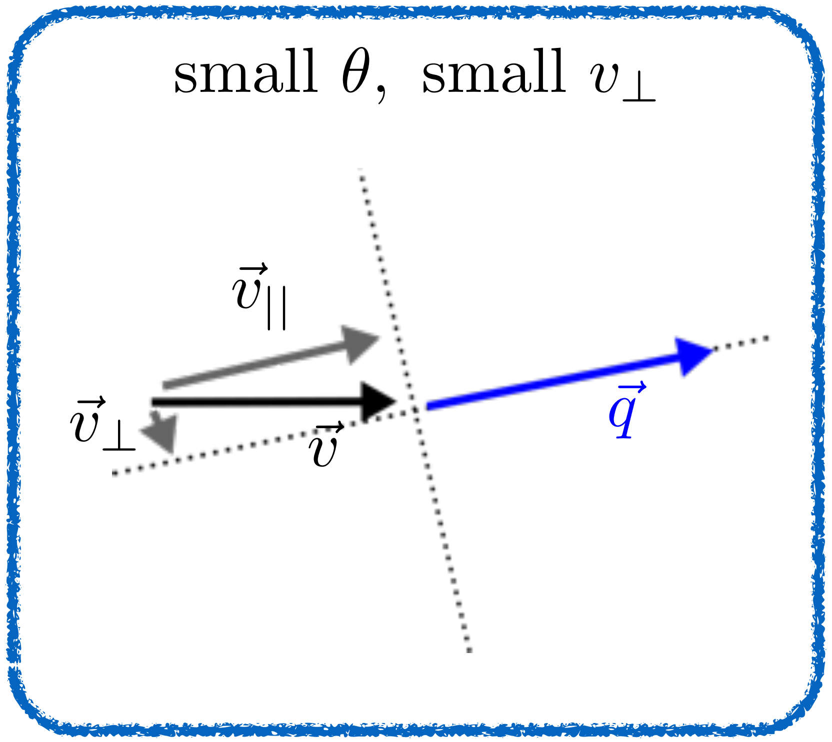
So, what does the directional spectrum look like?

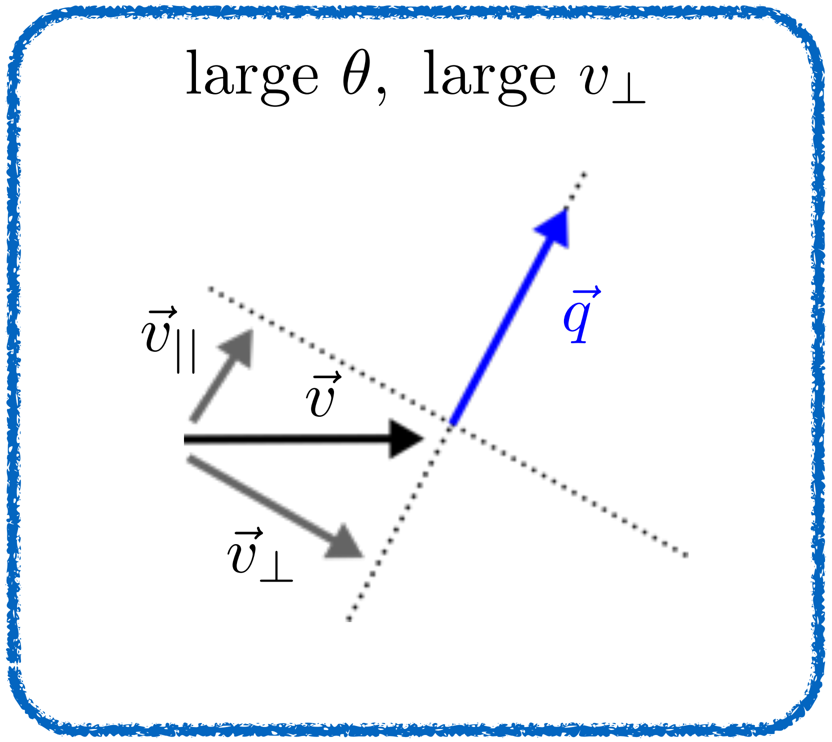
Directional spectra of NREFT operators

Total distribution of recoils as a function of θ:



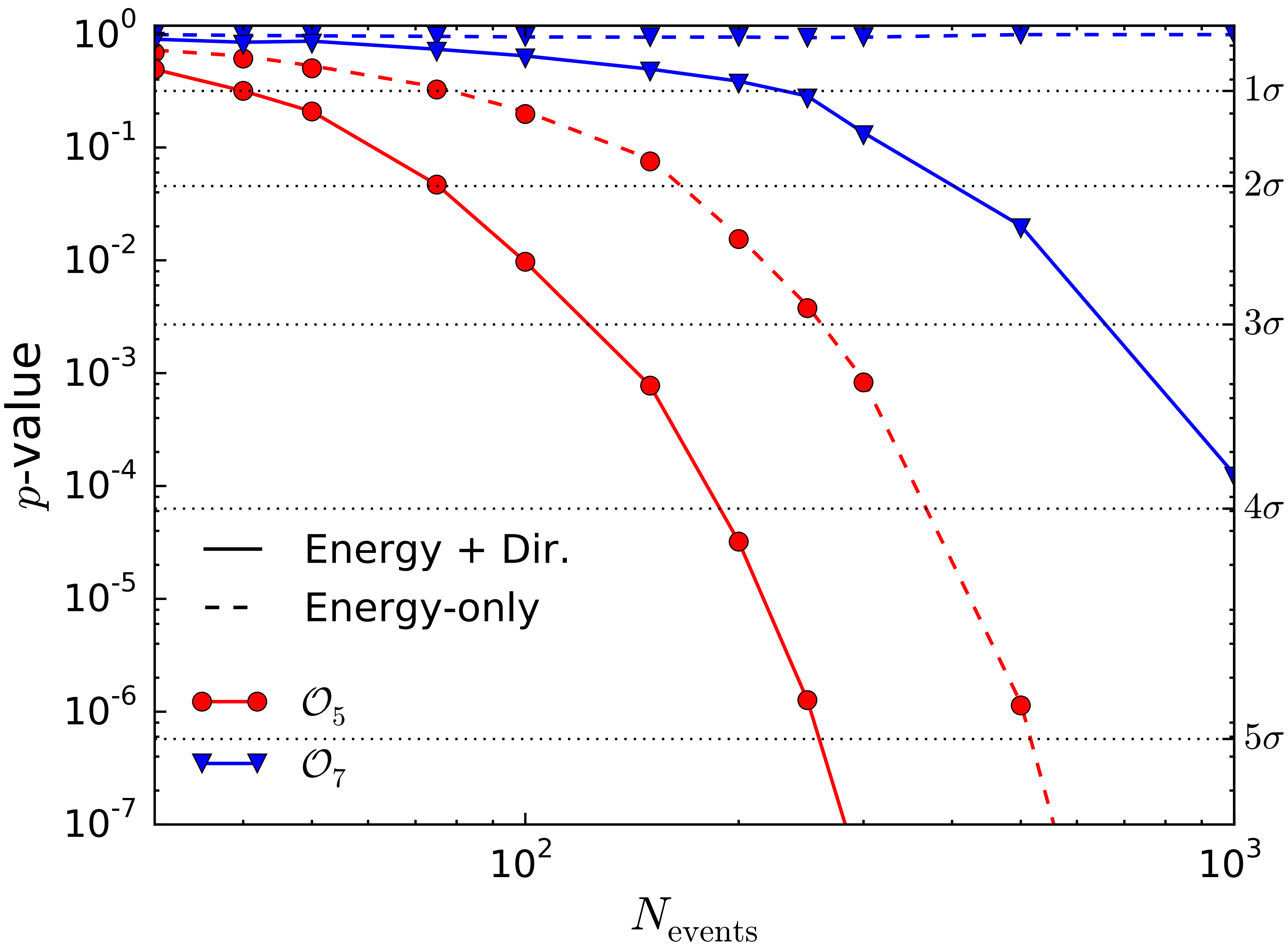
Spectra of all operators given in [1505.07406, 1505.06441].





Distinguishing operators: Energy + Directionality

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



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$F_7 \sim v_\perp^2$

Summary: a final example

NREFT framework allows us to compare the different possible direct detection signals.

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:

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

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

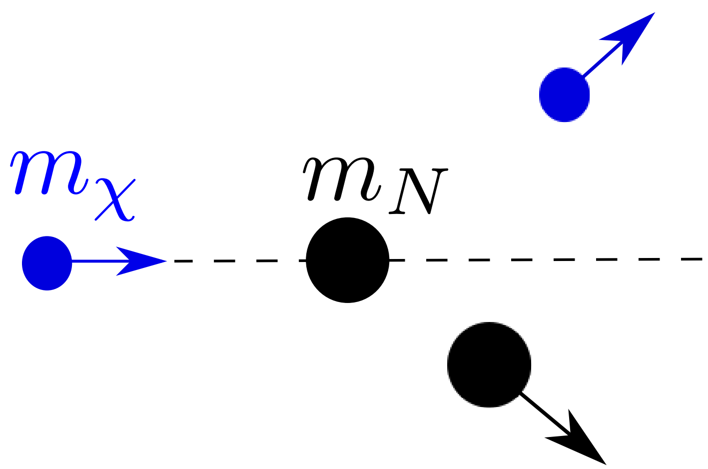
These operators cannot be distinguished in a single non-directional experiment.

Directional detection will be powerful and crucial tool for determining how DM interacts with the Standard Model!

Backup Slides

The Directional Spectrum

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



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

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

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

WIMP flux — Cross section — Kinematics

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

NREFT event rate

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

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

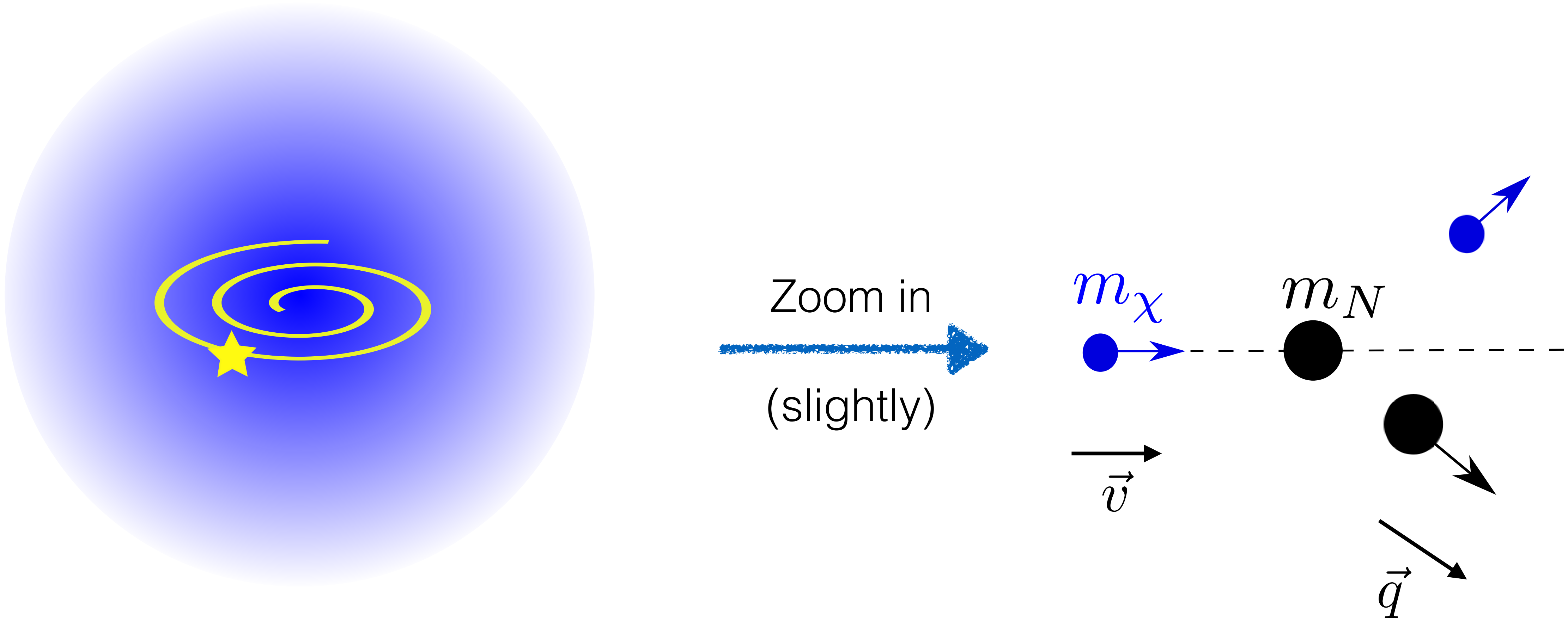
[Assuming for now: $c^p = c^n$]

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].

Direct detection



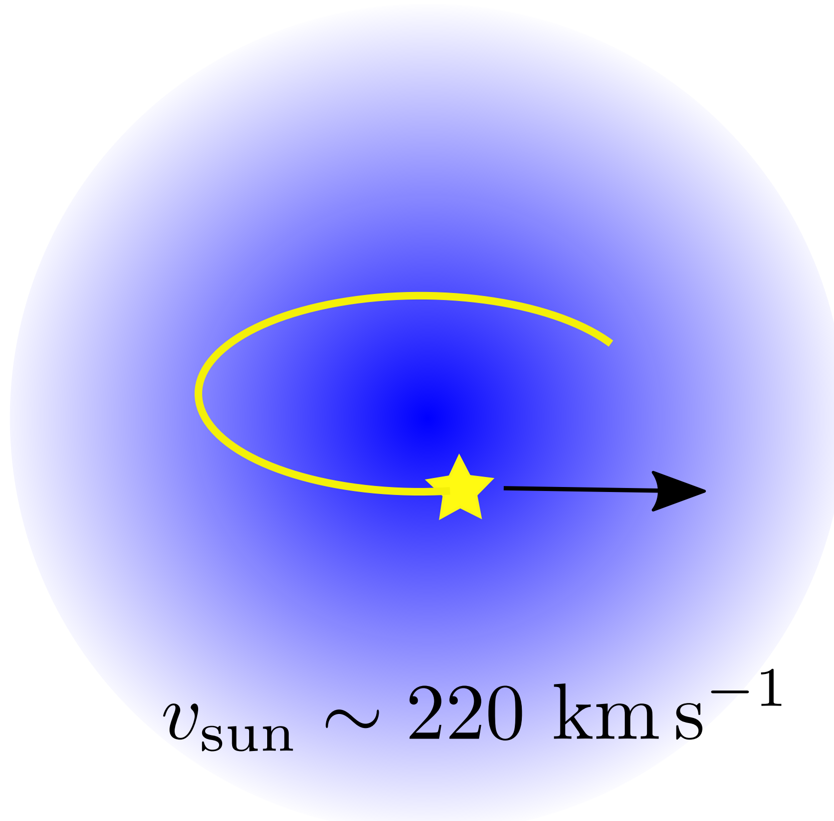
Look for interactions of DM particles from the halo with nuclei in a detector - measure **energy** of the recoiling nucleus.

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

The WIMP Wind

WIMP: Weakly Interacting Massive Particle

In the halo:

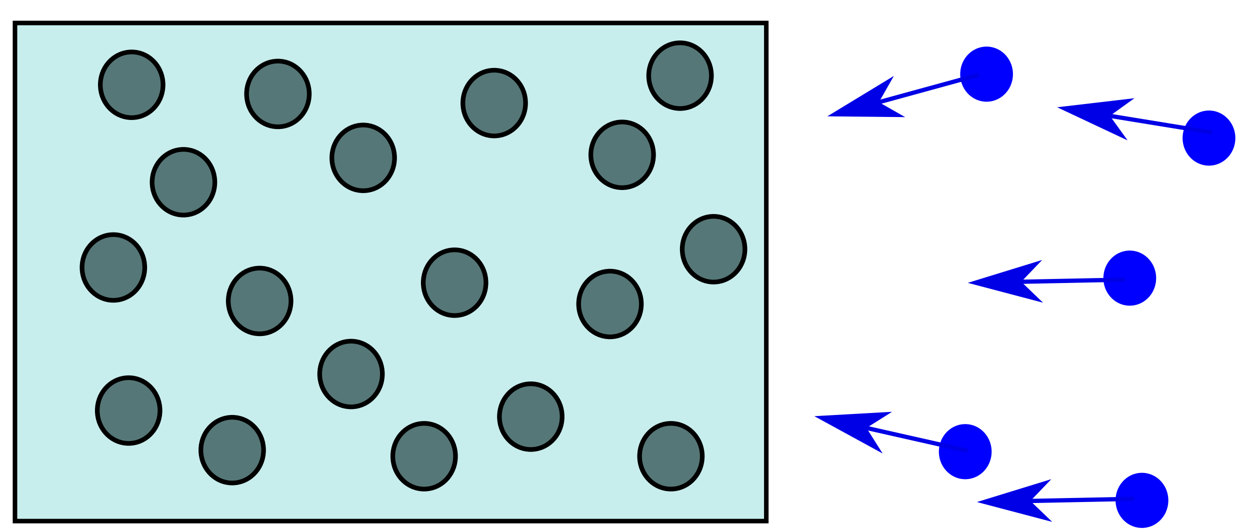


Cygnus constellation

In the lab:

Detector

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



'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:

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

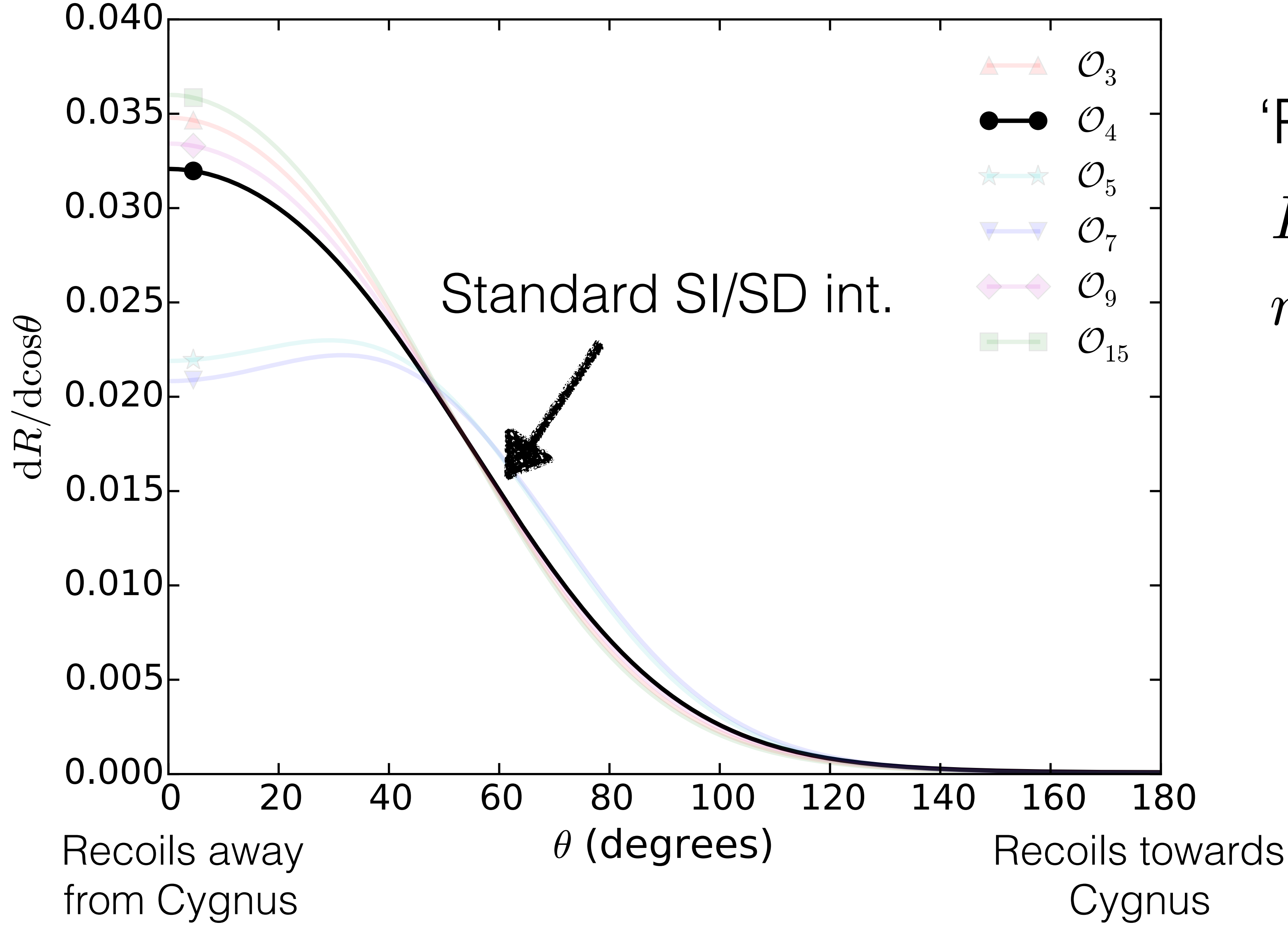
'Radon Transform' (RT)

For the SHM:

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

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

Directional Spectra



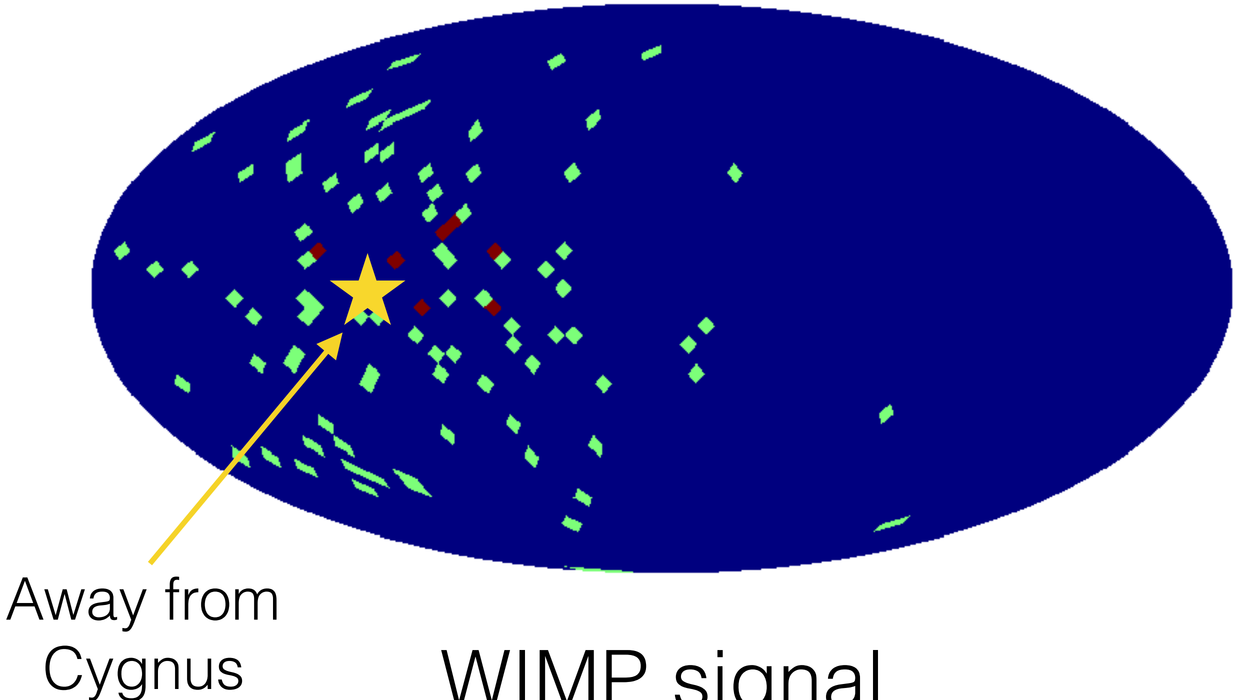
'Perfect' CF_4 detector

$E_R \in [20, 50]$ keV

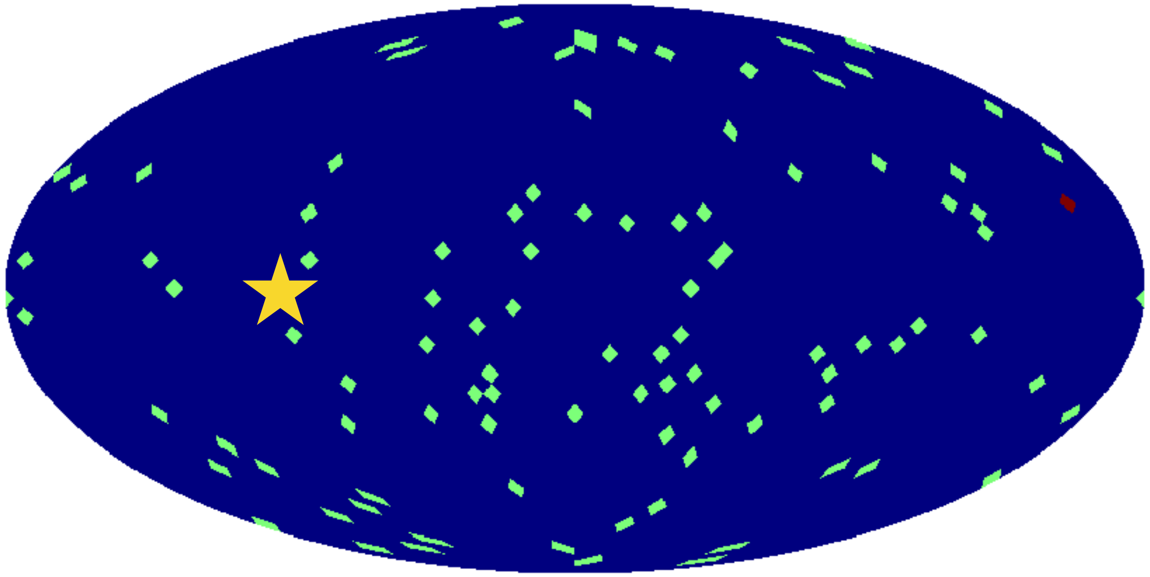
$m_\chi = 100$ GeV

The Smoking Gun

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



WIMP signal

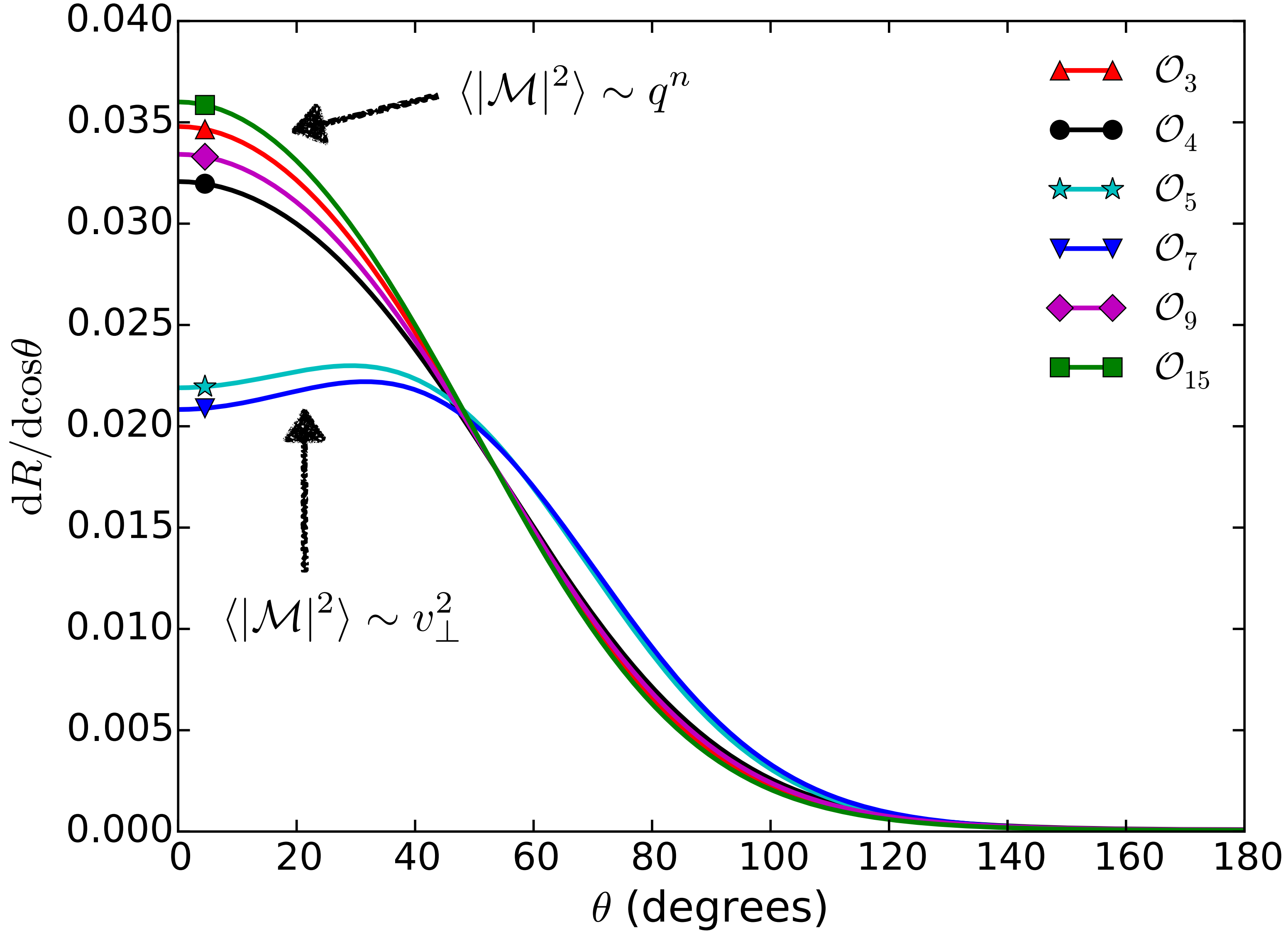


Backgrounds

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].

Directional Spectra



'Perfect' CF_4 detector

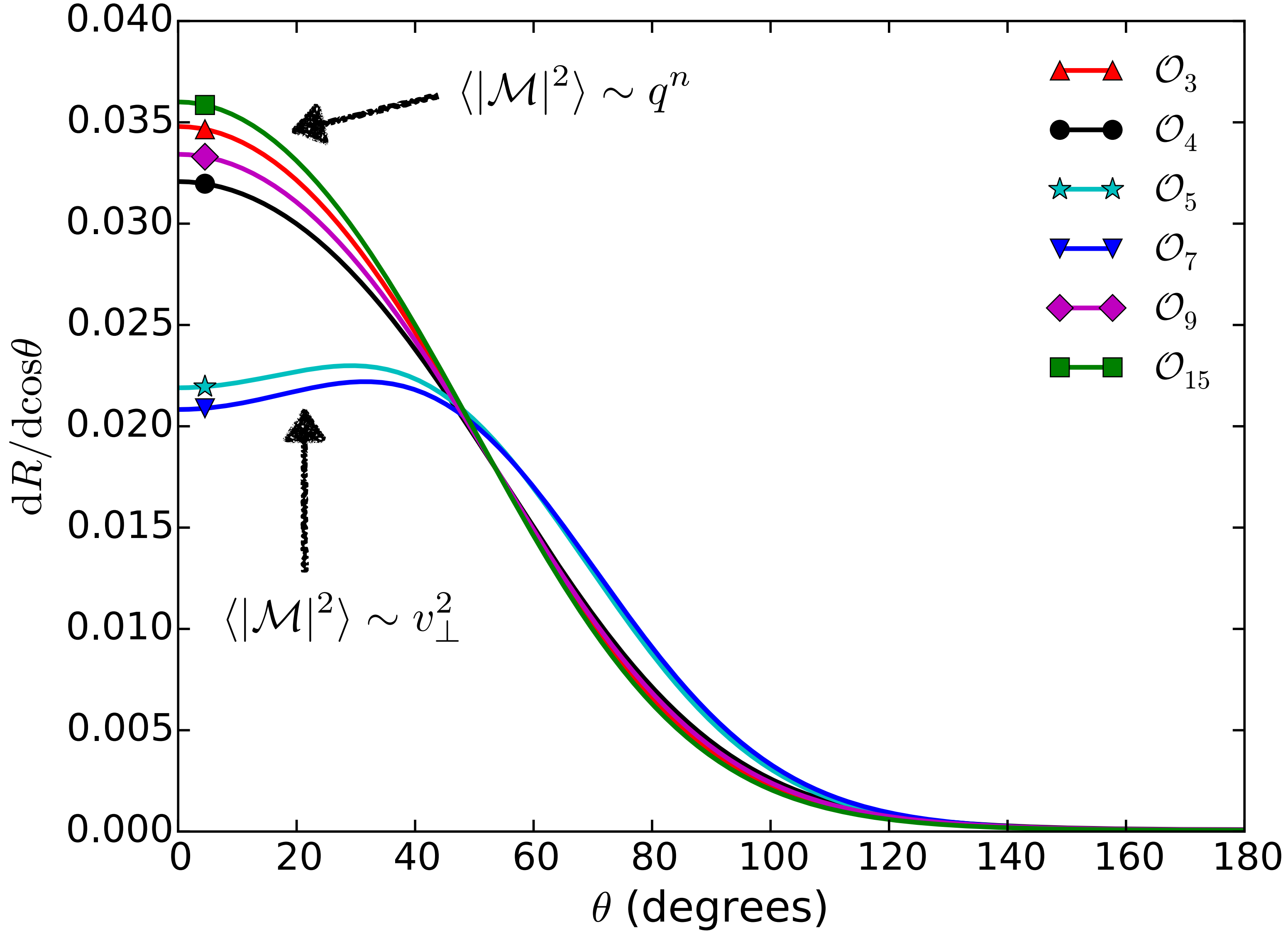
$E_R \in [20, 50]\,\mathrm{keV}$

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

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

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

Directional Spectra



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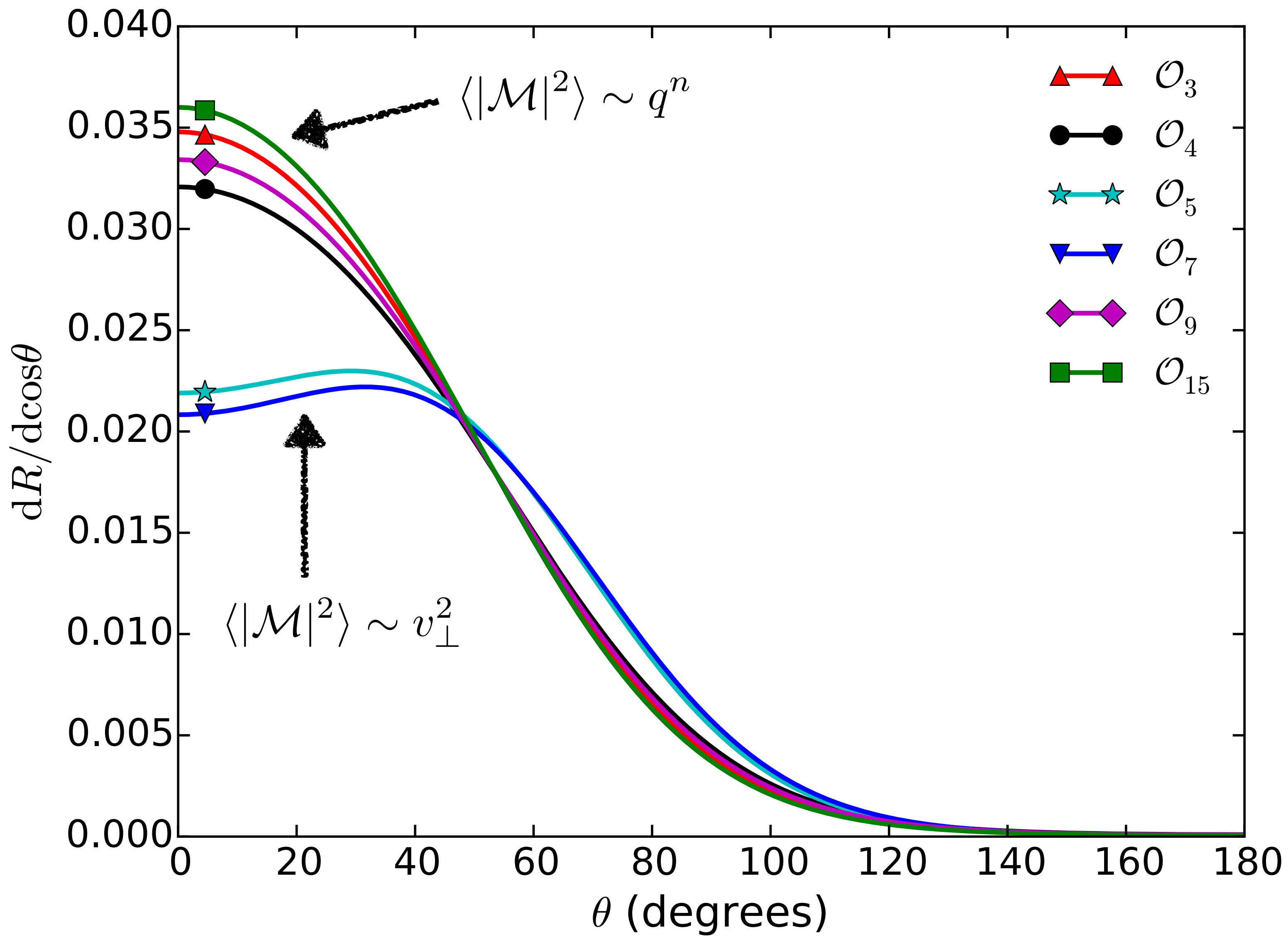
$= 2\mu_{\chi N} v \cos\theta$

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).

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 .

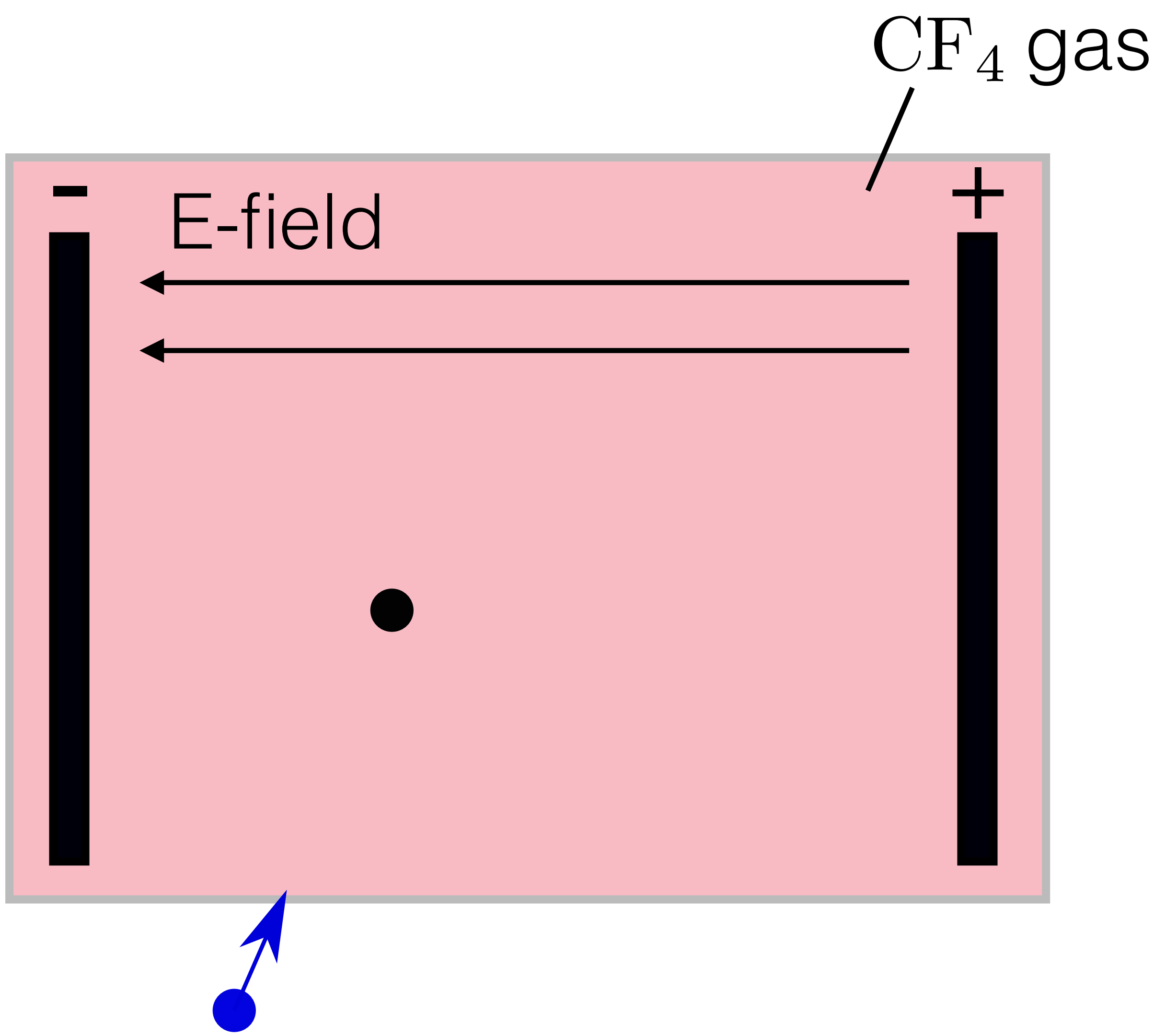
A : fraction of events which are due to non-standard NREFT interaction.

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}.

Directional detection - TPCs

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



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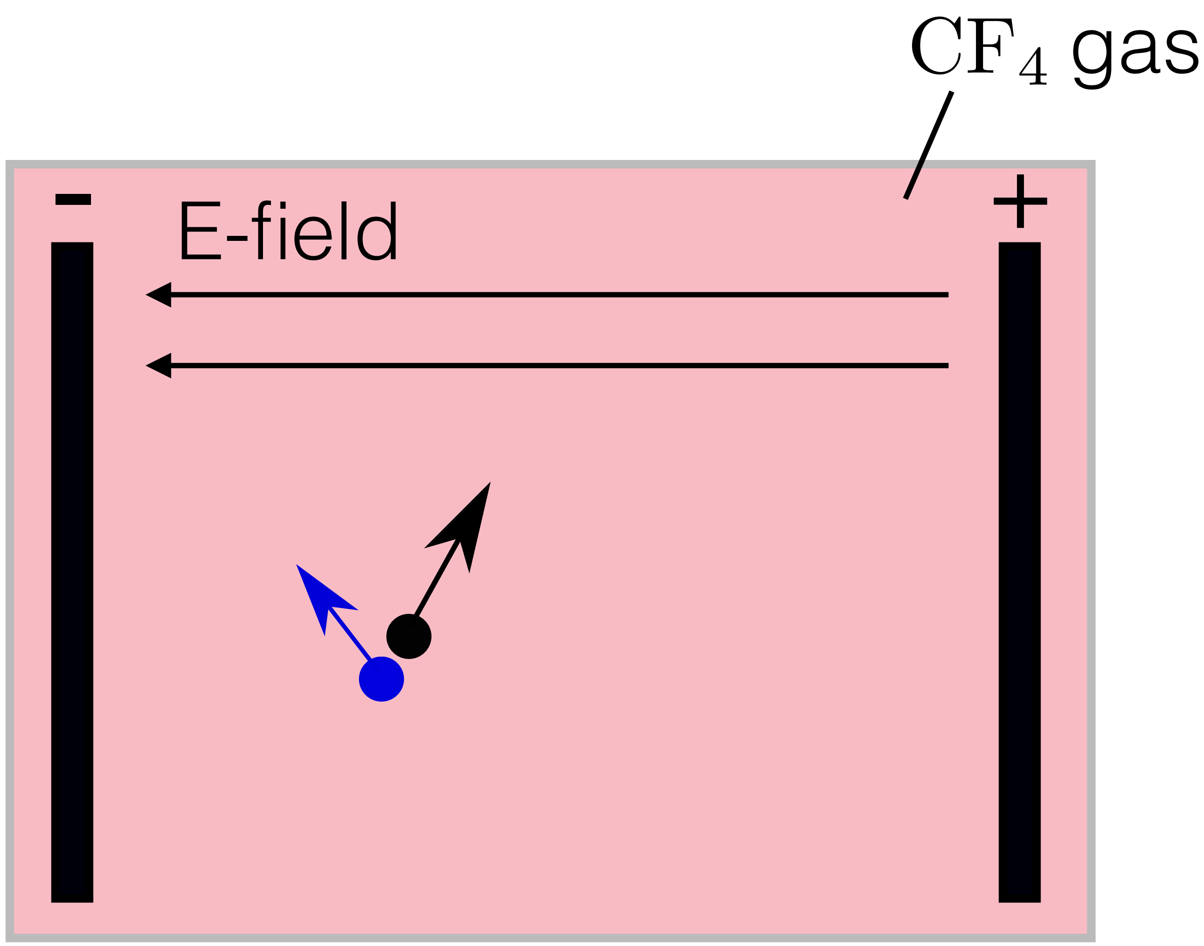

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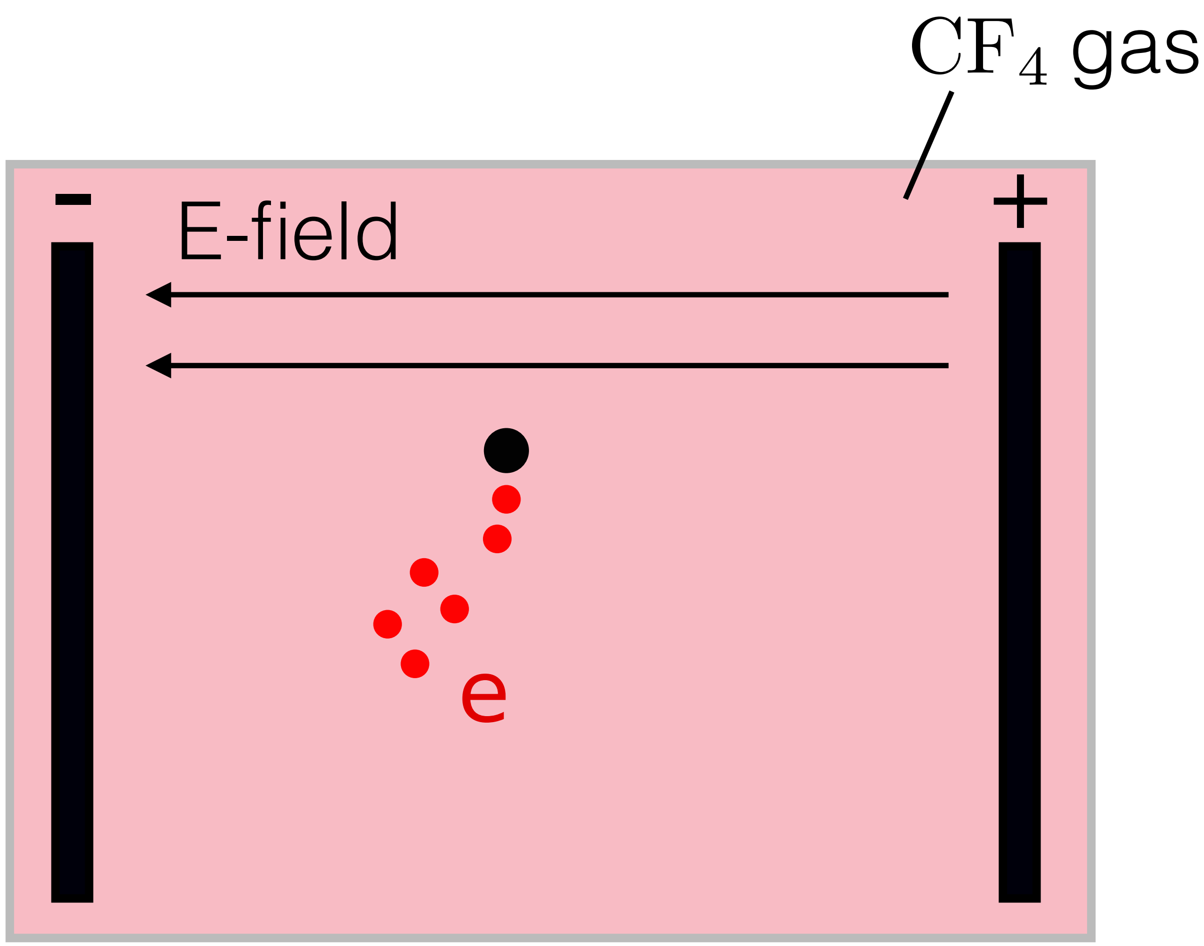

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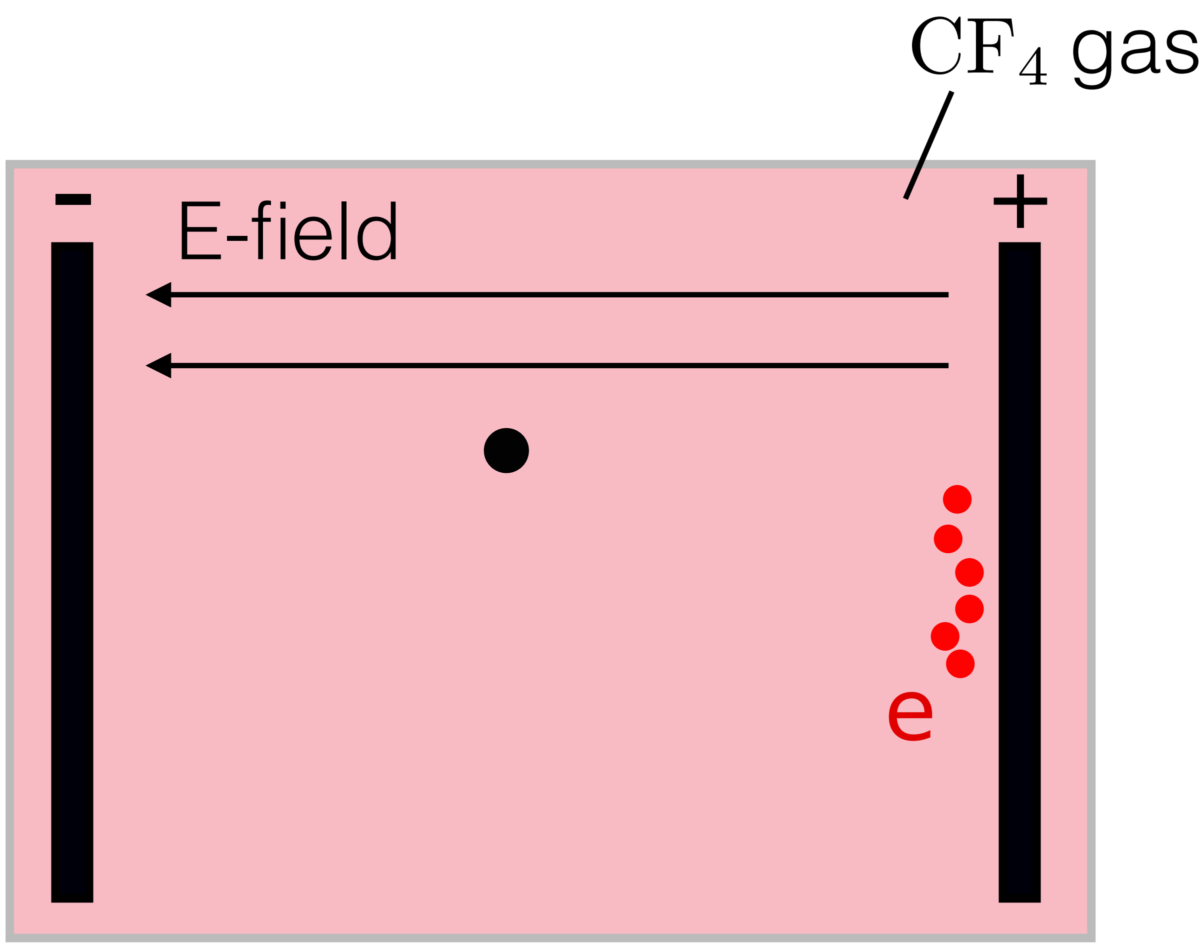
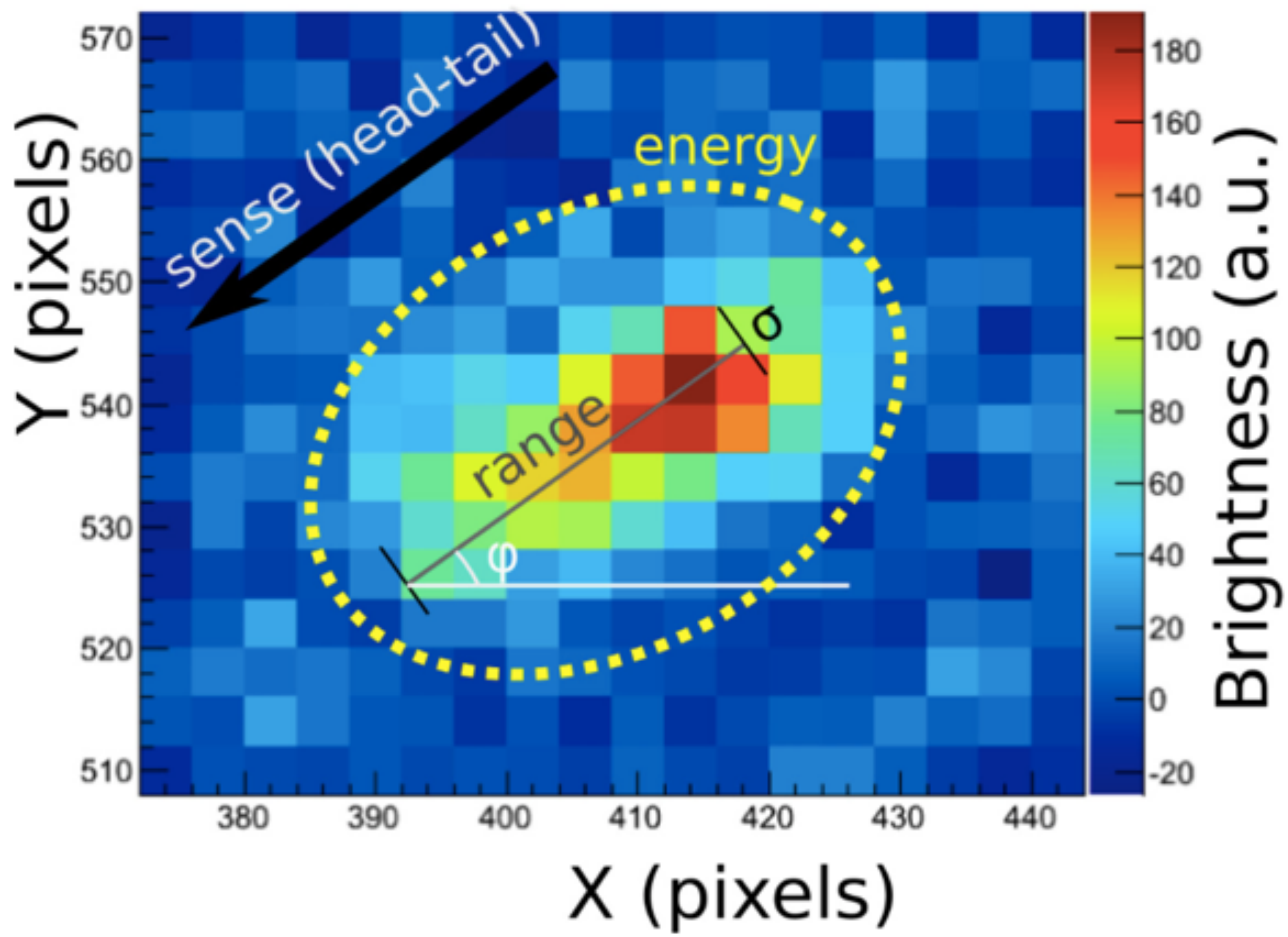


Get x,y of track from distribution of electrons hitting anode

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

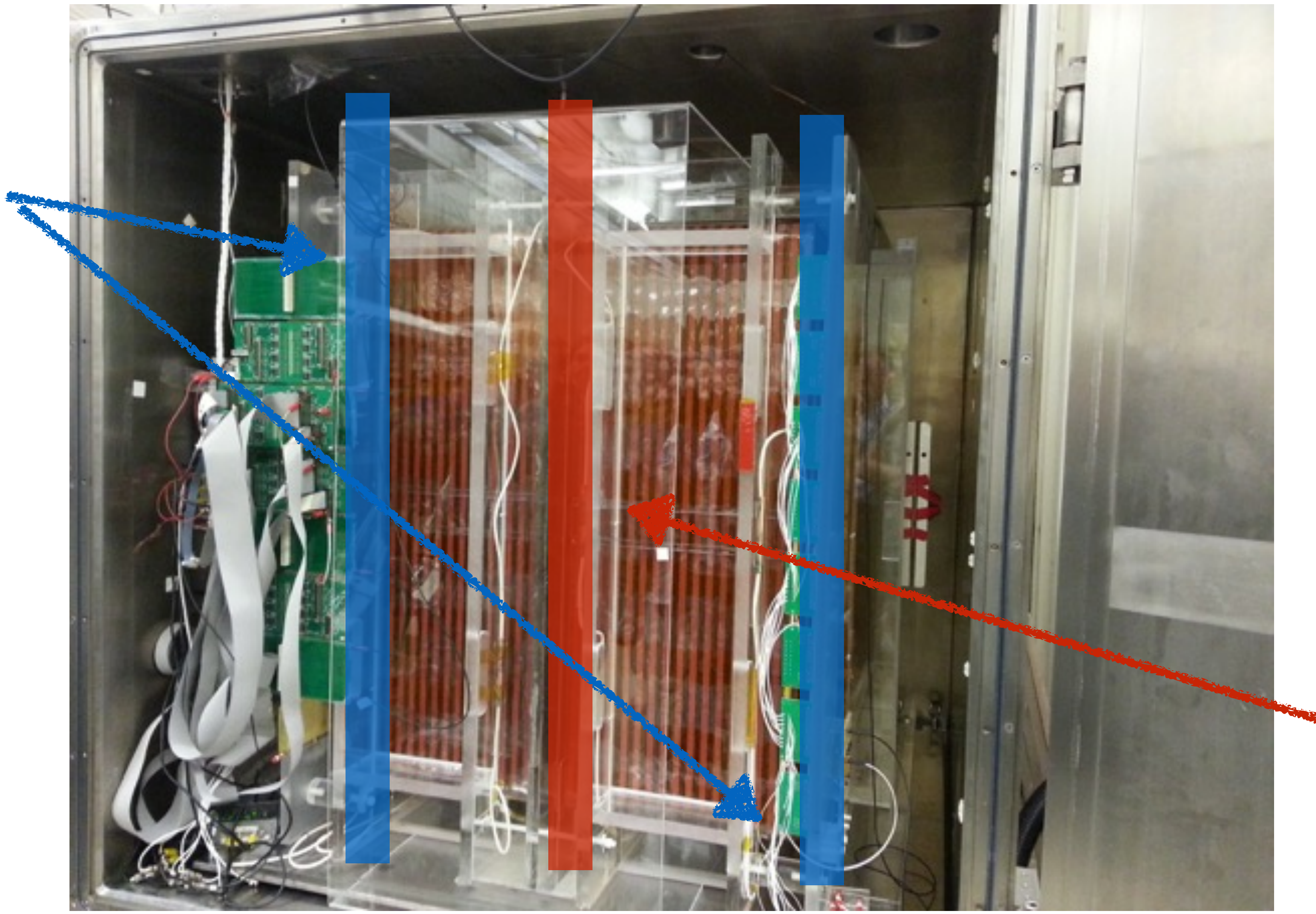
A Real TPC

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

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 $\vec{v}_{\rm lag}$:

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

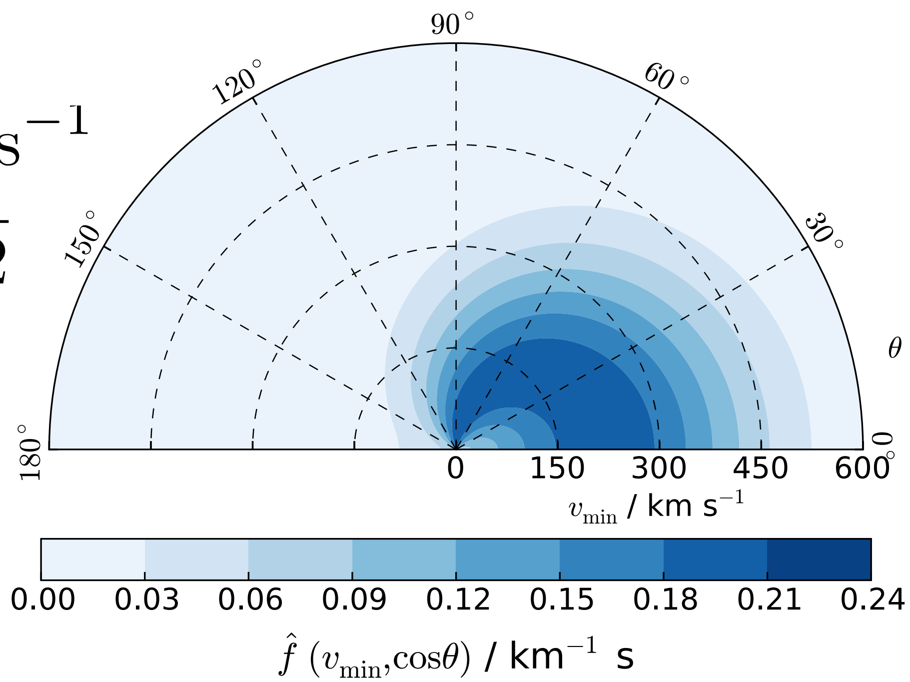
Transverse Radon Transform (examples)

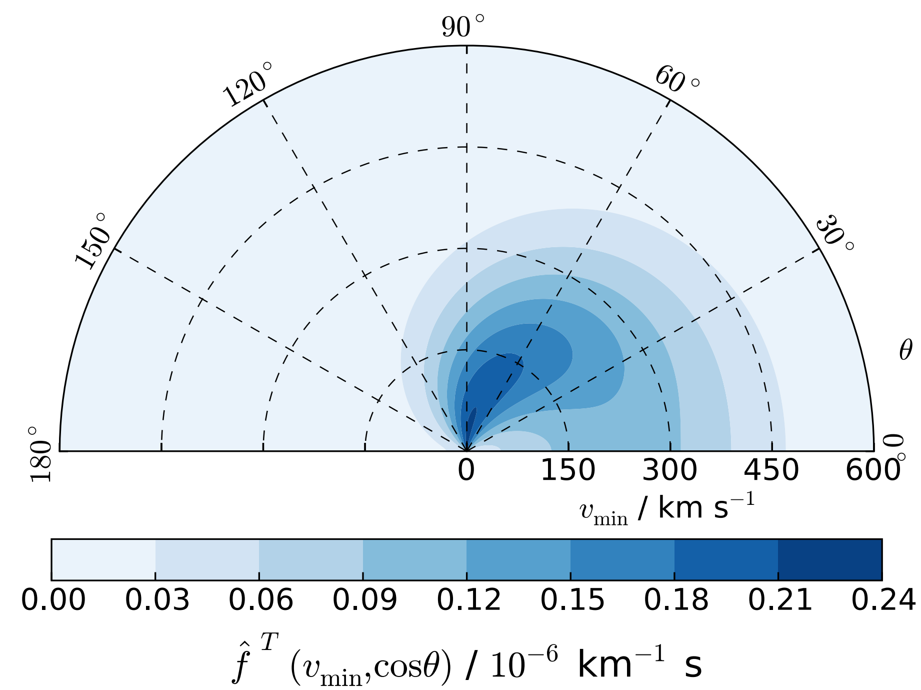
$\hat{f}(v_{\min}, \hat{q})$ $\hat{f}^T(v_{\min}, \hat{q})$

SHM:

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

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

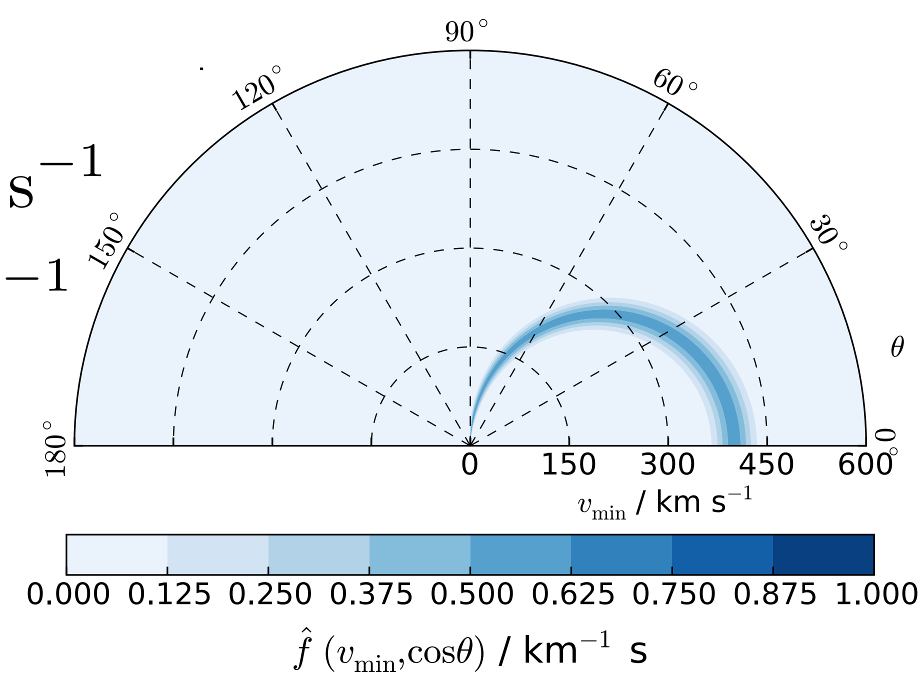


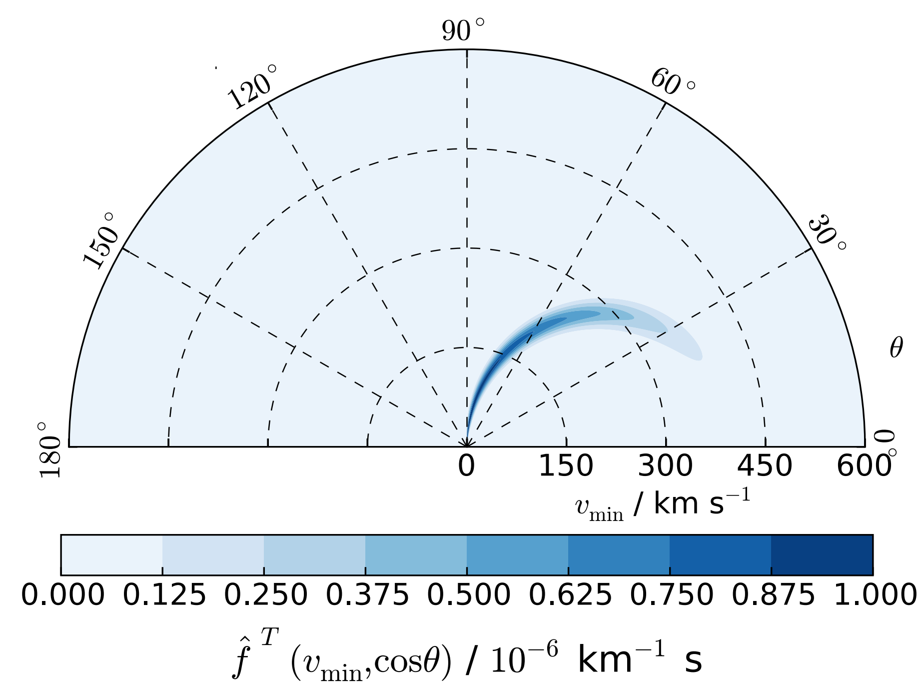


Stream:

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

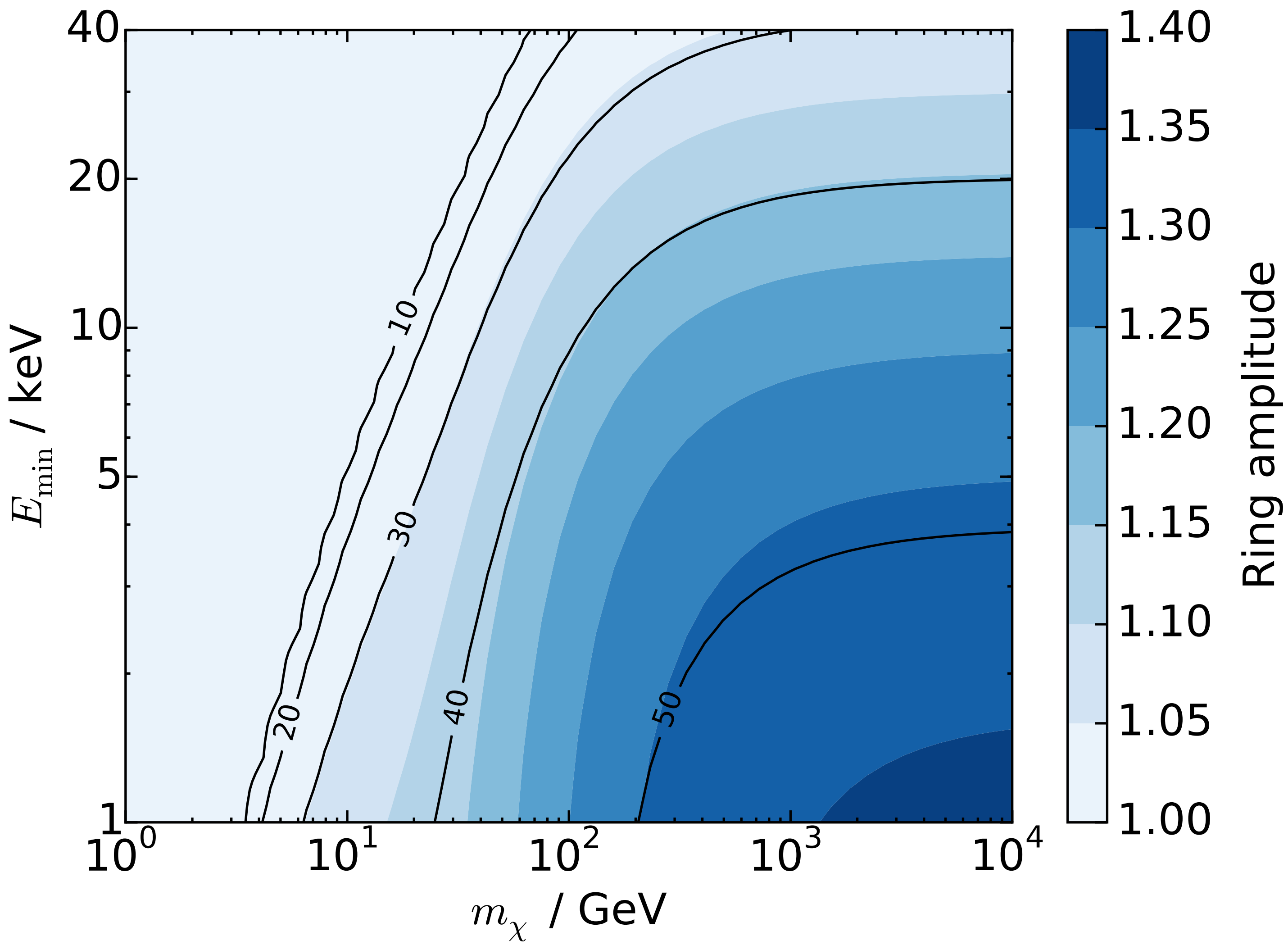
$\sigma_v = 20\,\mathrm{km\,s^{-1}}$





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

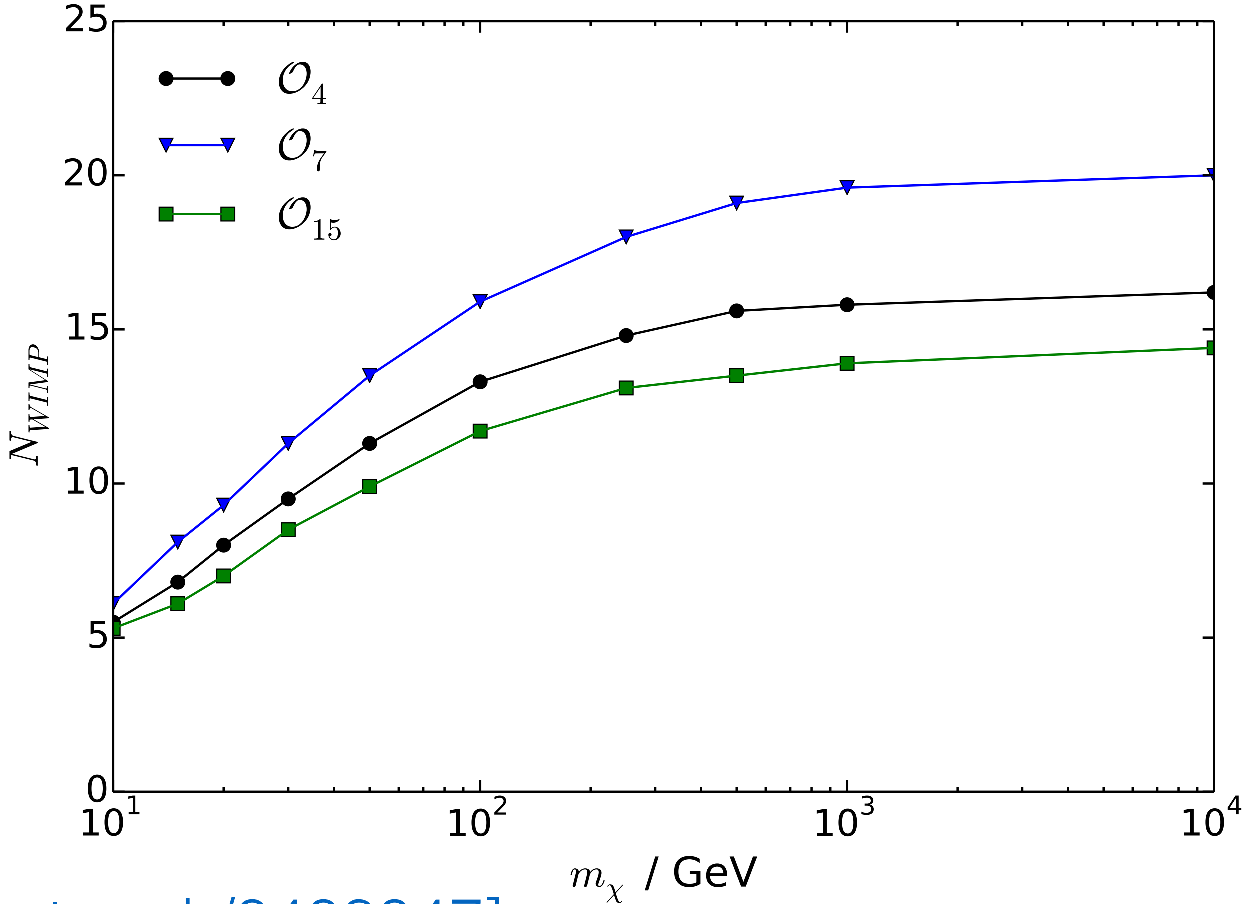
$F_{4,4} \sim 1$

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

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

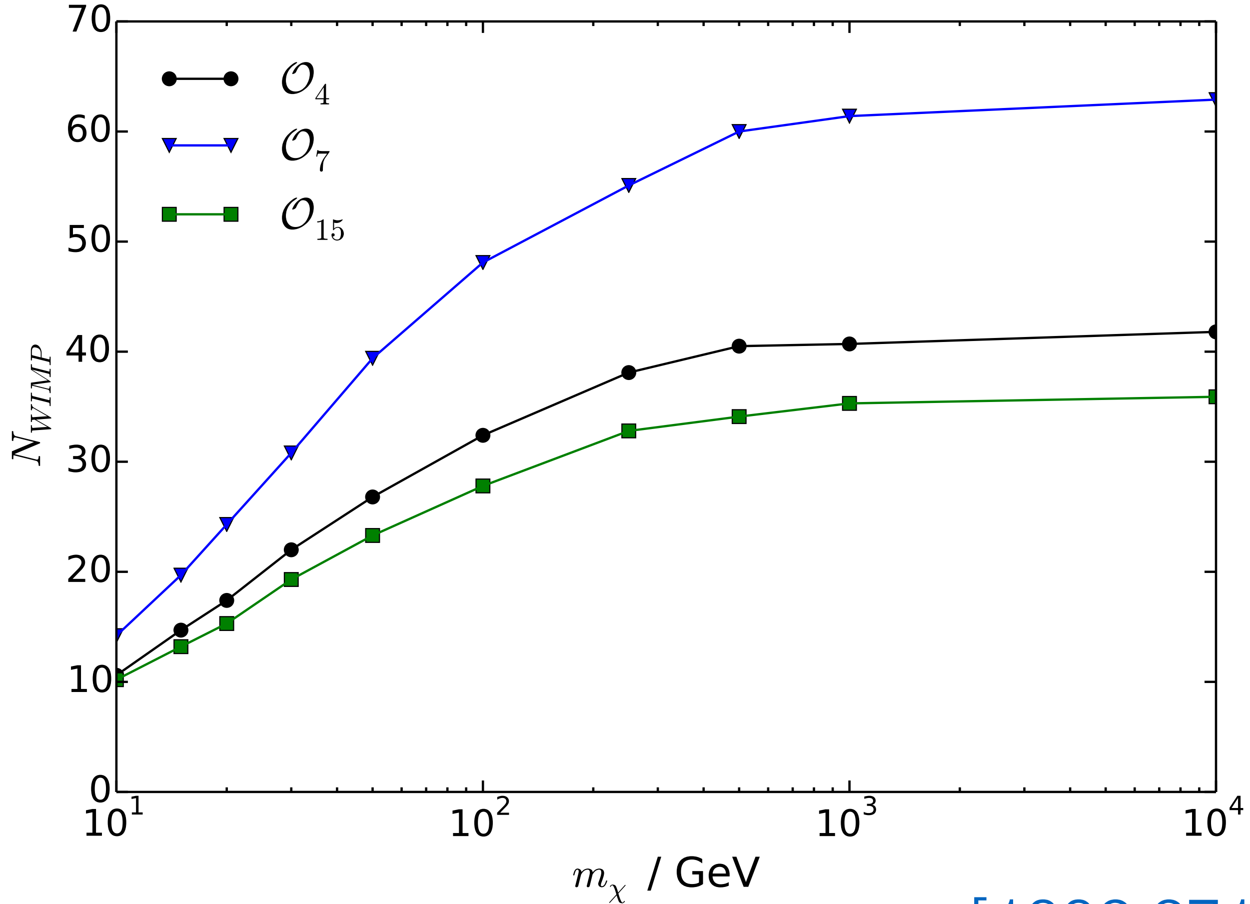
Calculate the number of signal events required to…

…reject isotropy…



[astro-ph/0408047]

…confirm the median recoil dir…



[1002.2717]

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