# Theoretical prospects for directional WIMP detection

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**Based on** arXiv:1410.2749
arXiv:1505.08061

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The University of Nottingham

# Outline

- **Intro to directional detection**
  - Origin of directionality
  - Expected signals
  - Discovery reach
  - Experiments

- **The neutrino floor**
  - Neutrino backgrounds to direct detection
  - Circumventing the neutrino floor with directionality

## Based on

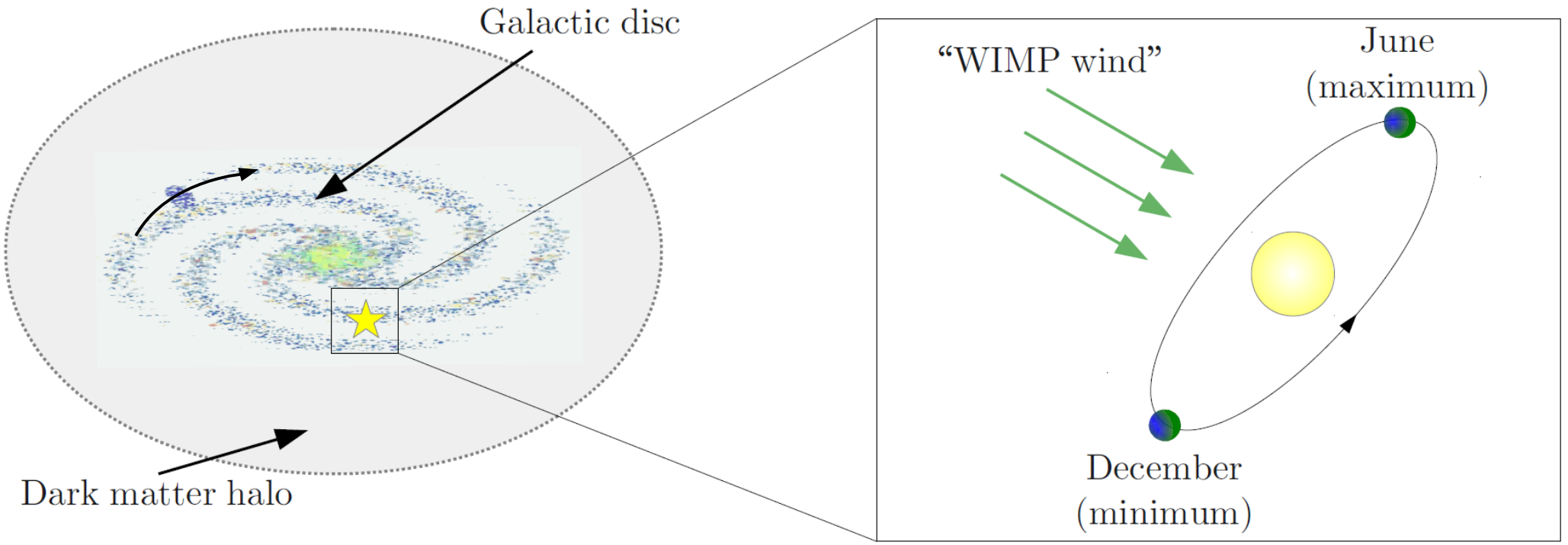
- **C. A. J. O'Hare**, A. M. Green [arXiv:1410.2749]

- **C. A. J. O'Hare**, A. M. Green, J. Billard, E. Figueroa-Feliciano, L. E. Strigari [arXiv:1505.08061]

- J. Billard, N. Bozorgnia, A. M. Green, S. Vahsen, J. Battat, J. Monroe, D. Loomba, P. Gondolo, G. Gelmini, B. Morgan, A. H. G. Peter, N. Phan, **C. A. J. O'Hare**, B. J. Kavanagh, F. Mayet [*Directional review, in prep.*]

# Directional detection

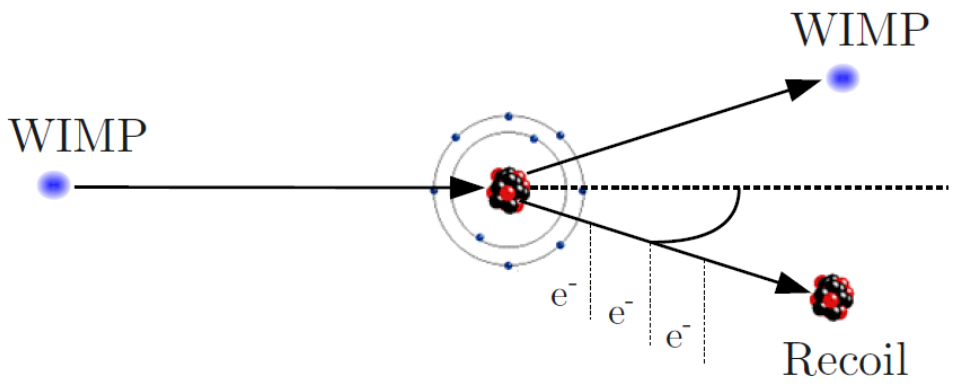
- Rotating Galactic disc embedded in non-rotating DM halo




## WIMP direct detection

- keV-scale nuclear recoils
- Annual modulation of event rate
- Incoming direction towards Cygnus

# Directional WIMP-nucleus elastic scattering rate




- Energy
- Direction $\{E_r, \Omega_r, t\}$
- Time

Rate per unit target mass

$$\frac{\mathrm{d}^3 R}{\mathrm{d}E_r \mathrm{d}\Omega_r \mathrm{d}t} = \frac{\sigma_{\chi-n}}{m_\chi \mu_{\chi n}^2} \times A^2 F^2(E_r) \times \frac{\rho_0}{4\pi \Delta t} \int \delta(\mathbf{v}\cdot\hat{\mathbf{q}} - v_{\mathrm{min}})\, f(\mathbf{v}+\mathbf{v}_{\mathrm{lab}}(t))\, \mathrm{d}^3 v$$

**WIMP properties**
- WIMP mass
- WIMP-nucleon cross-section

**Nuclear physics**
- Nucleus mass
- Nuclear form factor

**Astrophysics**
- Galactic DM density
- Velocity distribution
- Lab frame velocity

# Laboratory frame velocity

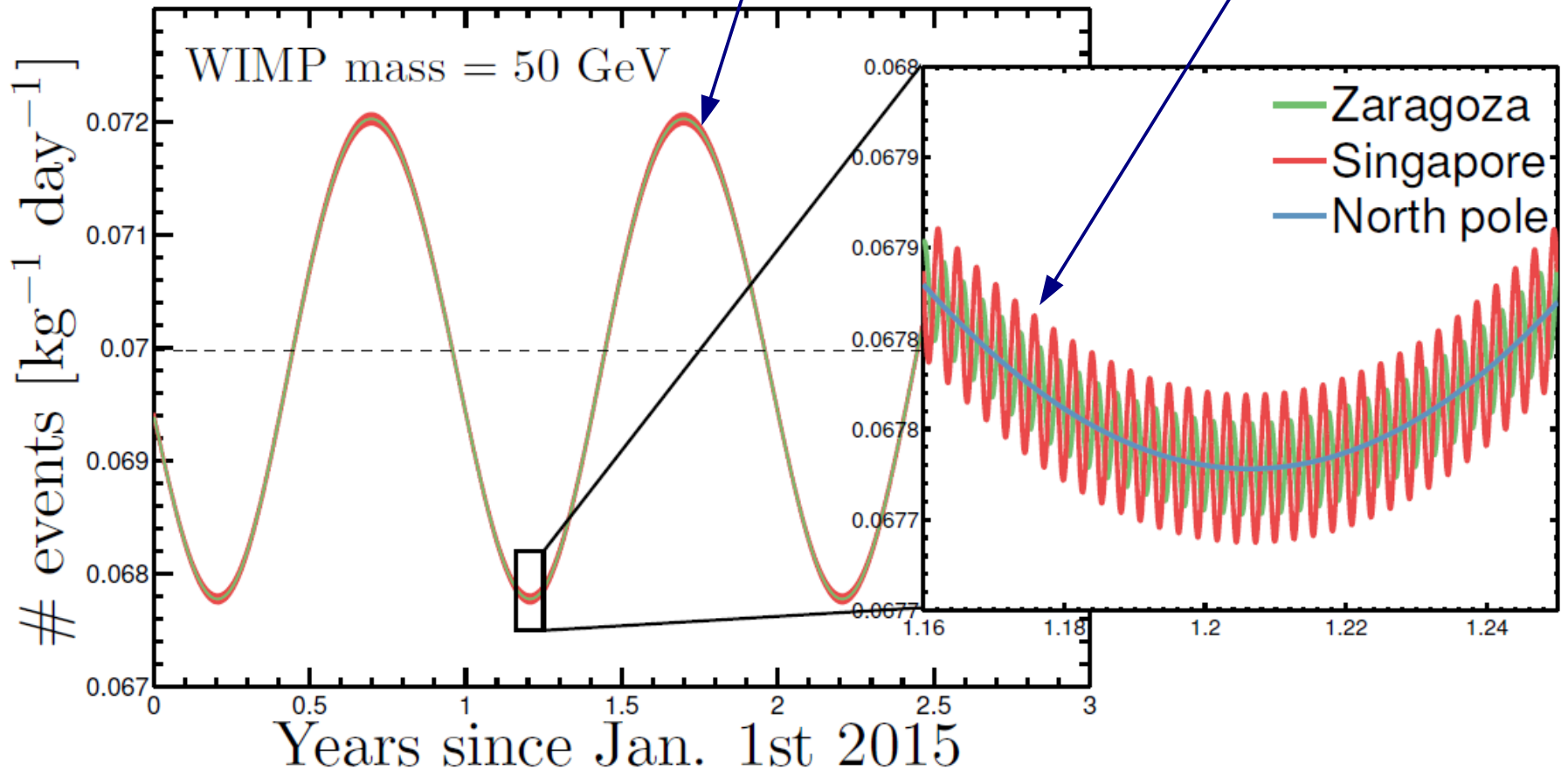
$$\mathbf{v}_{\rm lab} = \mathbf{v}_{\rm GalRot} + \mathbf{v}_{\rm SunPec} + \mathbf{v}_{\rm EarthRev}(\text{time}) + \mathbf{v}_{\rm EarthRot}(\text{time, location})$$

Galactic rotation (220 km/s)

Solar peculiar motion (20 km/s)

Earth's orbit (30 km/s) (annual modulation)

Earth's rotation (0.4 km/s) (diurnal modution)



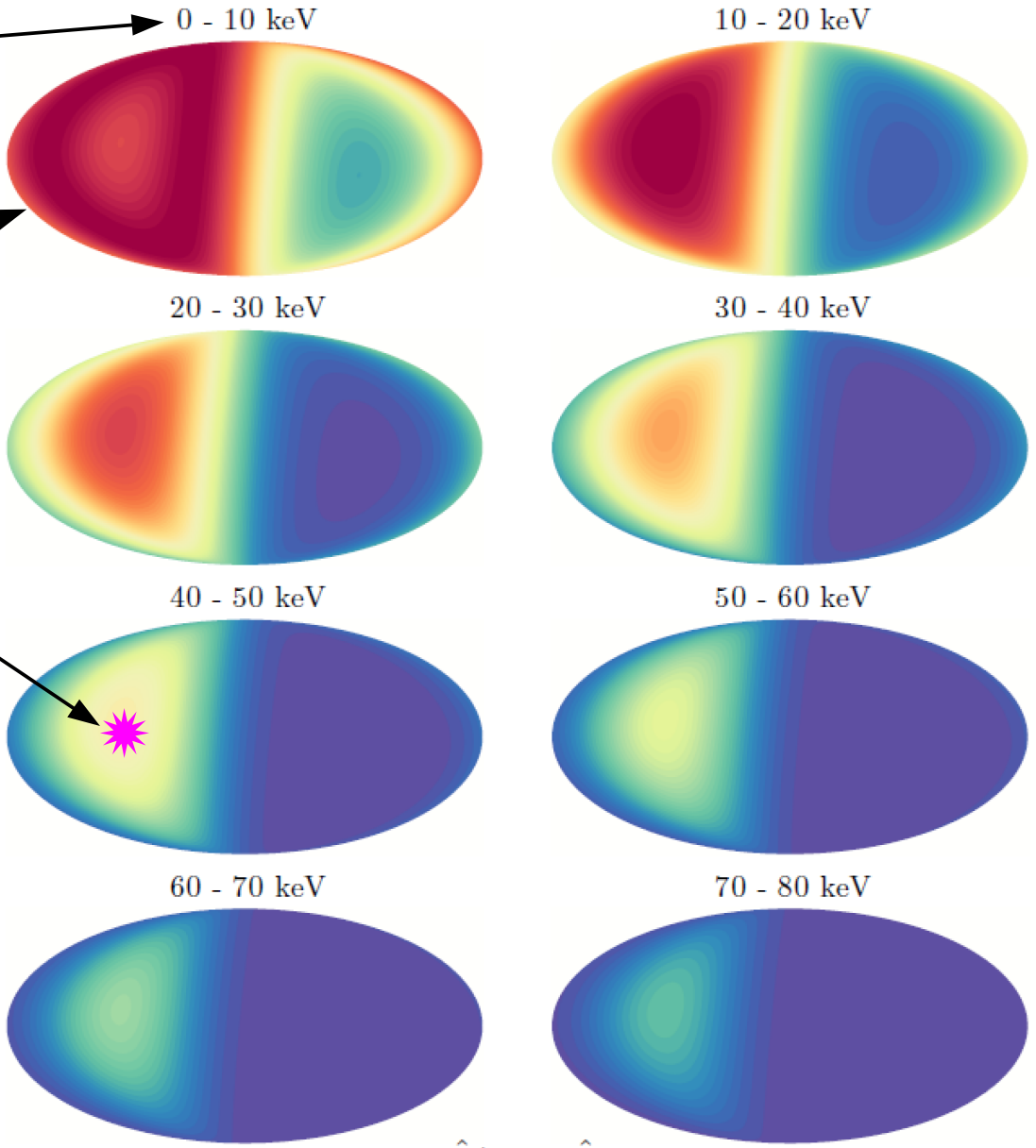
# Direction dependence

- 100 GeV WIMP

$^{19}$F recoil energy range

Mollweide projection of recoil direction

Peak direction toward $-\mathbf{v}_{\text{lab}}$

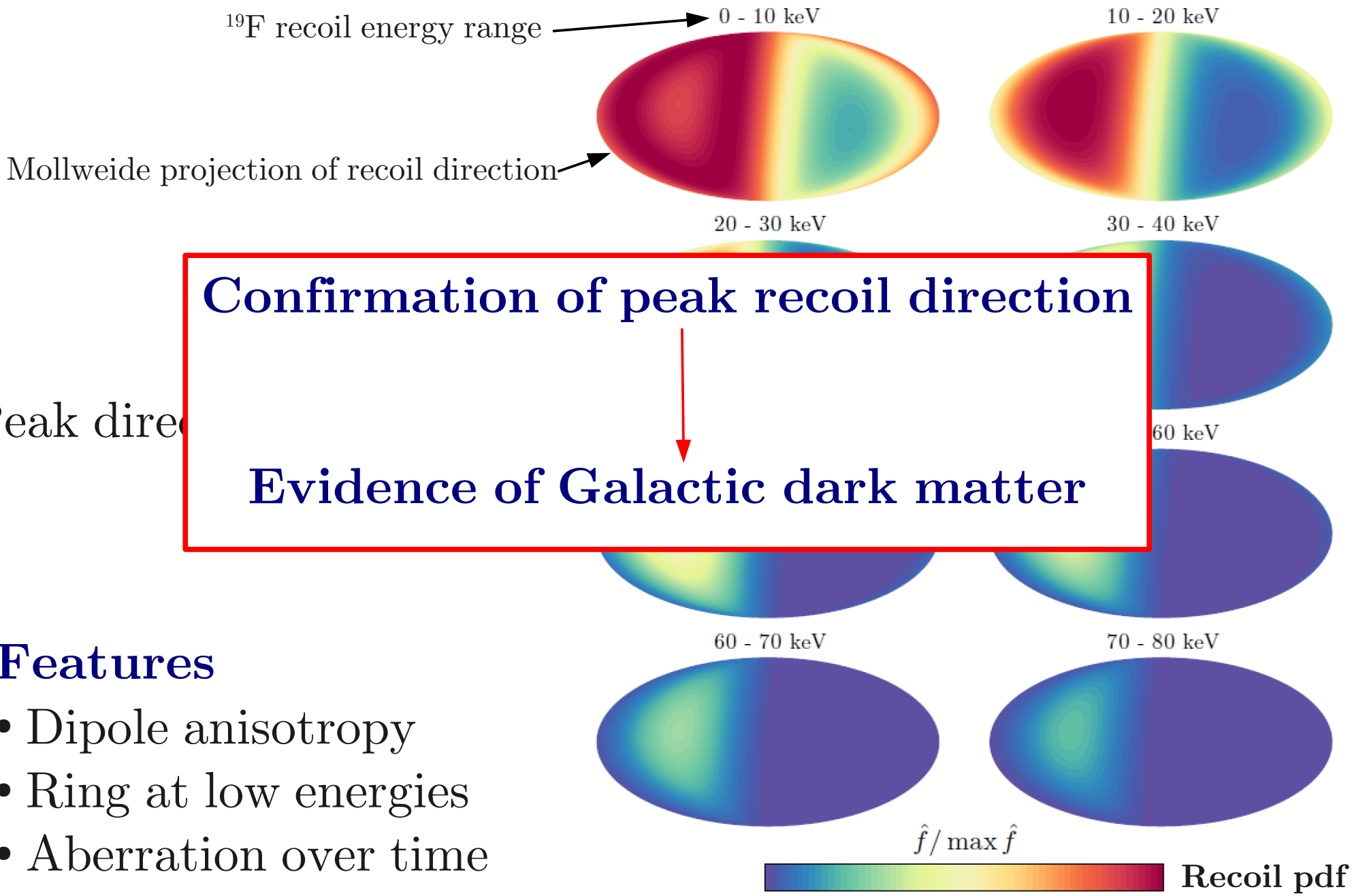



## Features

- Dipole anisotropy
- Ring at low energies
- Aberration over time

# Direction dependence

- 100 GeV WIMP




Peak direc

**Confirmation of peak recoil direction**

↓

**Evidence of Galactic dark matter**

## Features

- Dipole anisotropy
- Ring at low energies
- Aberration over time

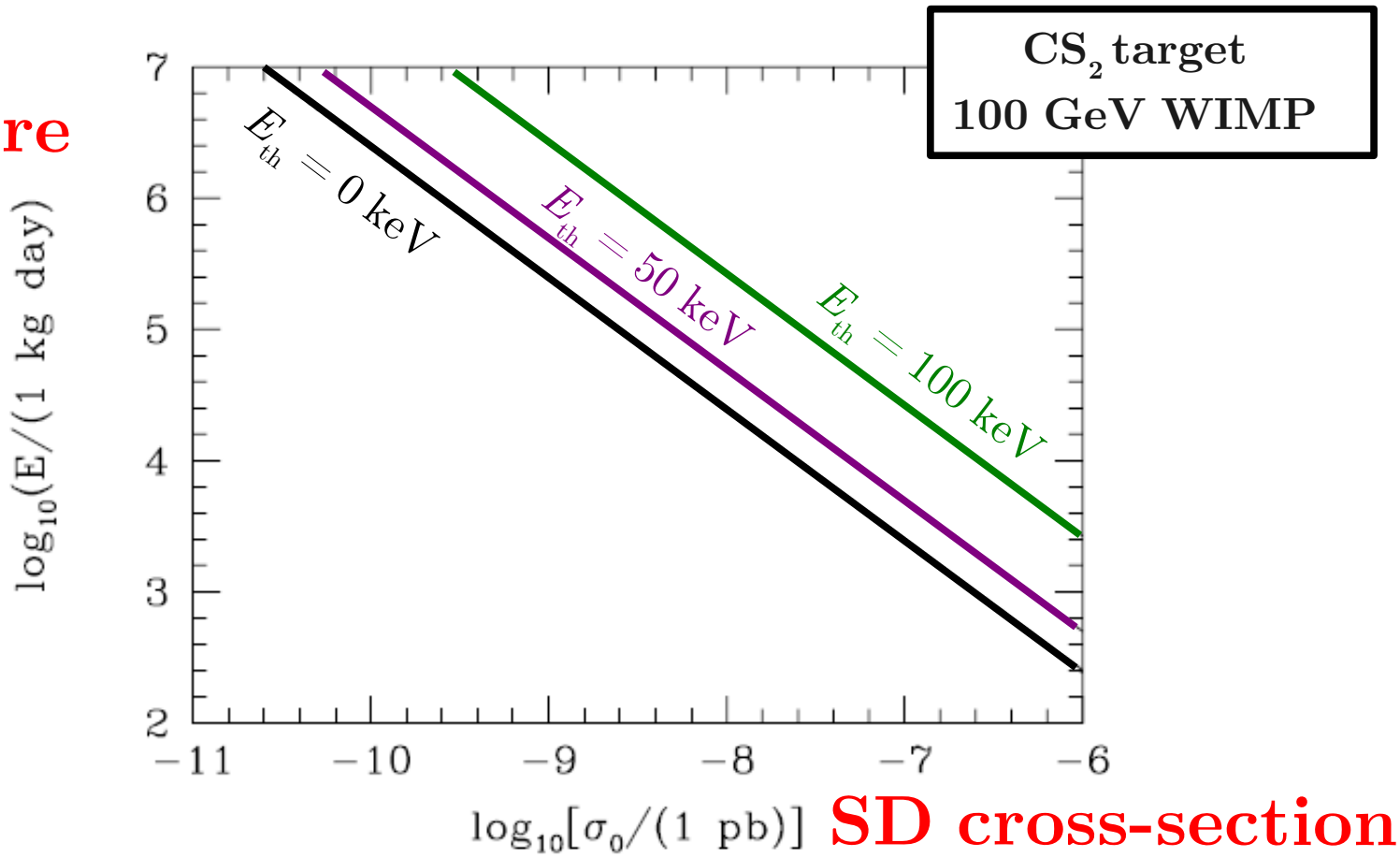
# Discovery reach

## 1. Rejection of isotropy

- Reject isotropic background at 95% CL in 95% of experiments
- O(10) WIMP events using non-parametric directional tests

Green & Morgan [astro-ph/0609115]

**Exposure**



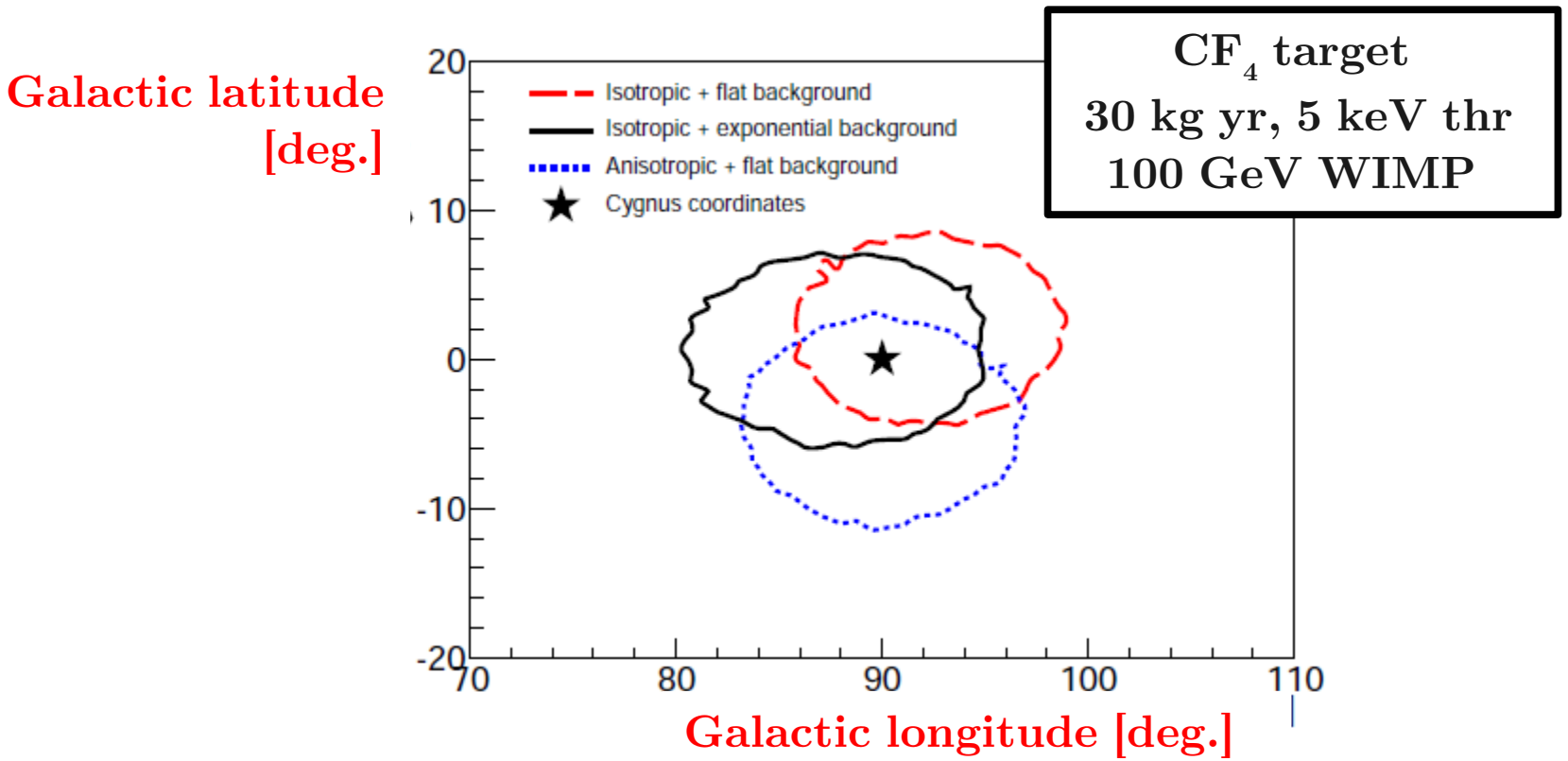

**SD cross-section**

# Discovery reach

## 2. Proof of discovery

- Discovery: direction consistent with Solar motion ($3\sigma$ at 90% CL)
- O(30) WIMP events with non-parametric tests Green & Morgan [arXiv:1002.2717]
- Probe down to SD cross-sections $10^{-4} - 10^{-5}$ pb with 30 kg yr of $CF_4$ detector with 5 keV threshold

**Billard, Mayet, Santos [arXiv:1110.6079]**



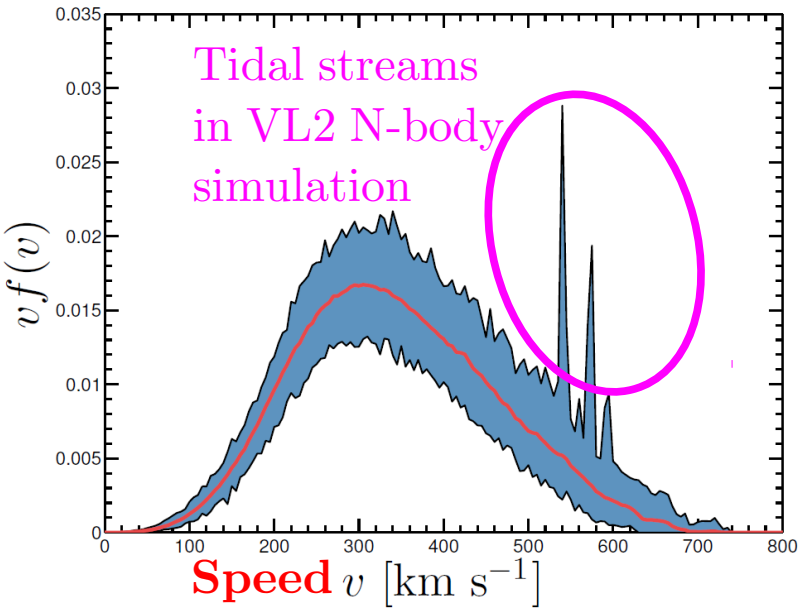
# Discovery reach

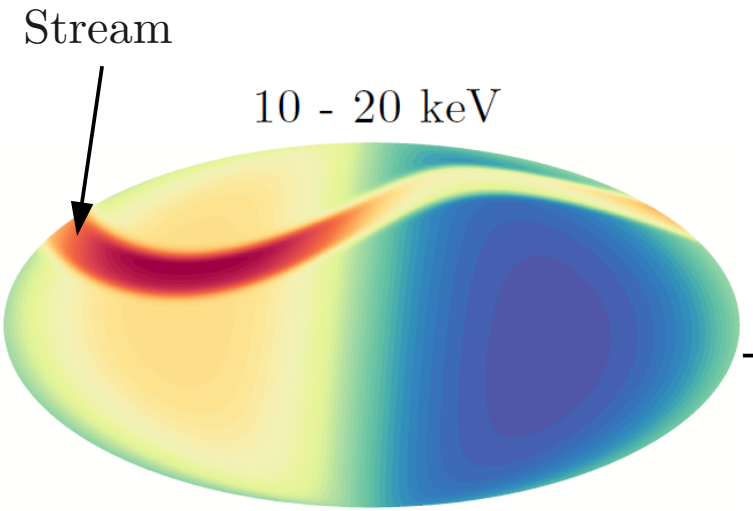
## 3. Post-discovery: astrophysics

- Study *velocity* distribution
  - Non-standard distributions
  - Substructure e.g., tidal streams, dark disk...

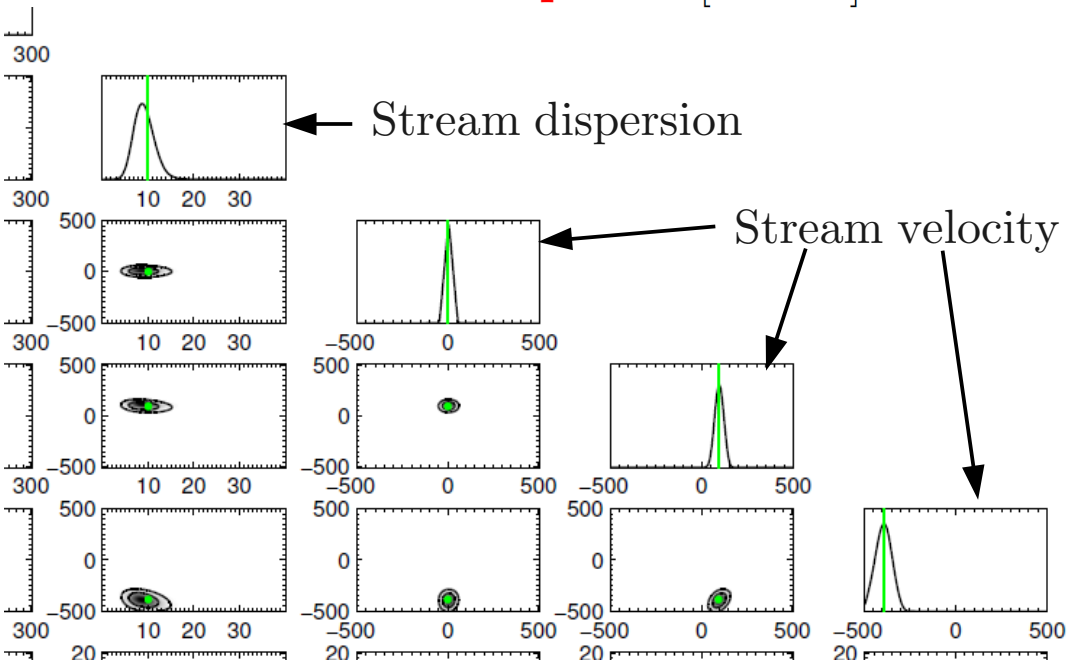
**O'Hare & Green [arXiv:1410.2749]**

**Incoming WIMP flux at "Earth"**



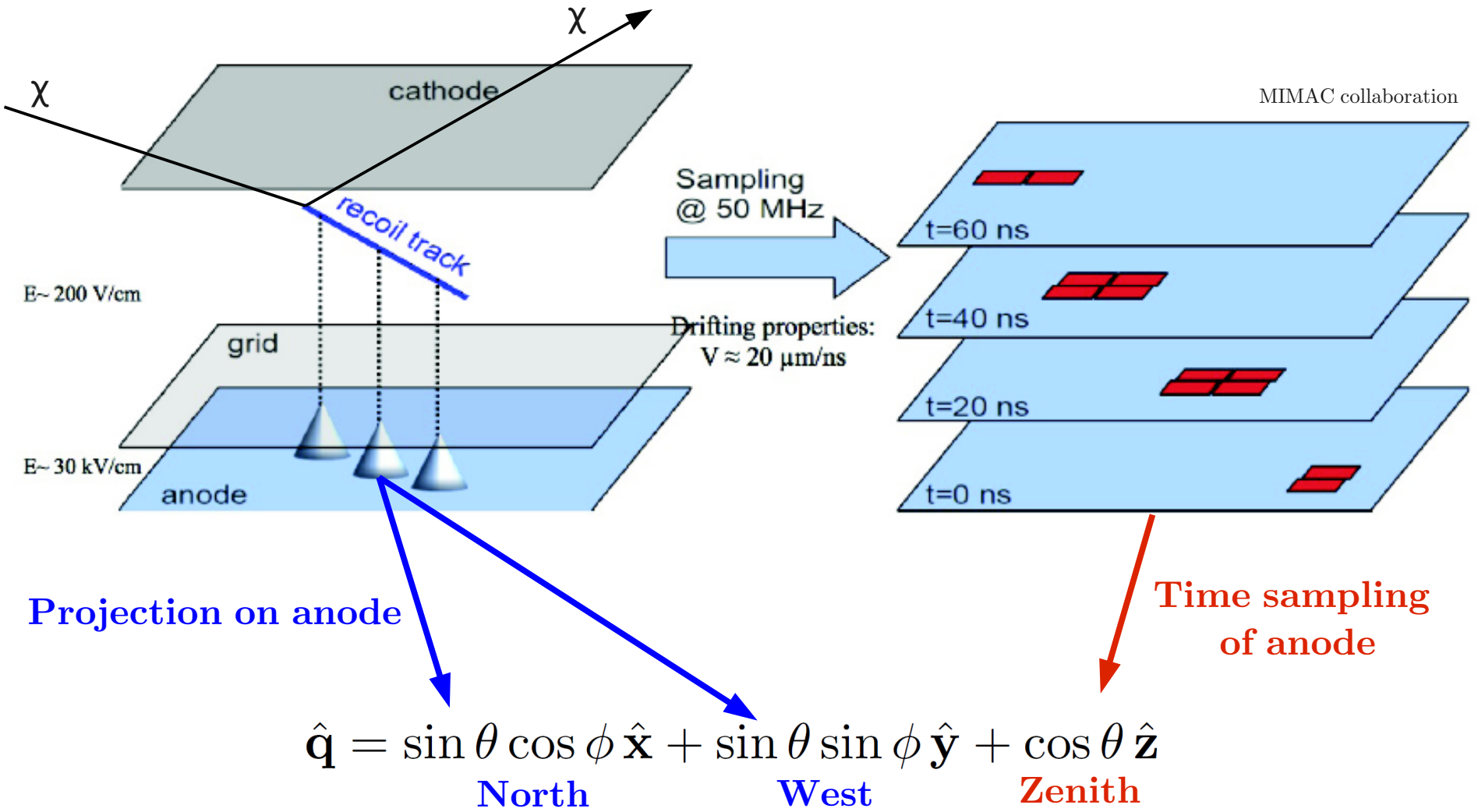

3-d recoil direction pdf



# Directional detection in practice

## Standard approach – low pressure gaseous TPC:

- keV scale recoils = a few mm recoil tracks




$$\hat{\mathbf{q}} = \sin\theta\cos\phi\,\hat{\mathbf{x}} + \sin\theta\sin\phi\,\hat{\mathbf{y}} + \cos\theta\,\hat{\mathbf{z}}$$

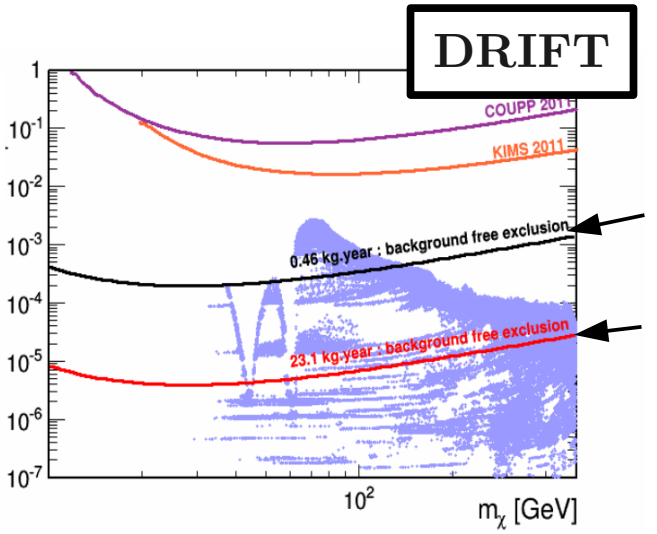
North West Zenith

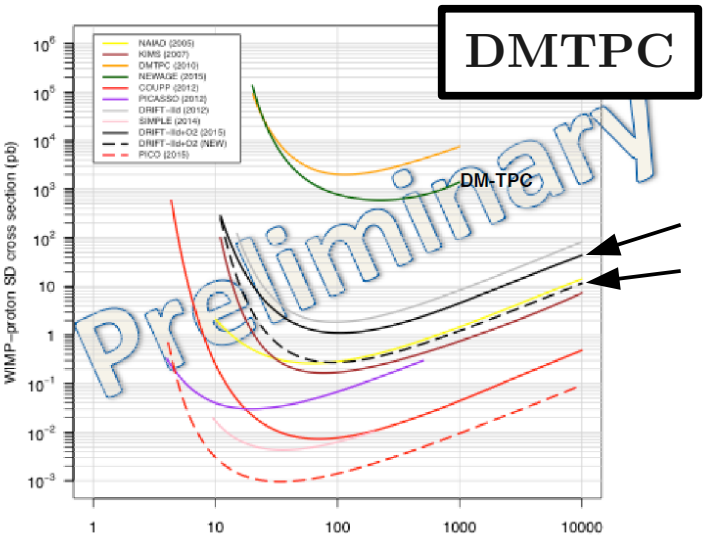
# Directional detection experiments

## Current TPC experiments:

- $CF_4$
  - DMTPC (USA)
  - MIMAC (France)
- $CS_2$
  - DRIFT (UK)

SD cross-section (pb)




## Major limitations

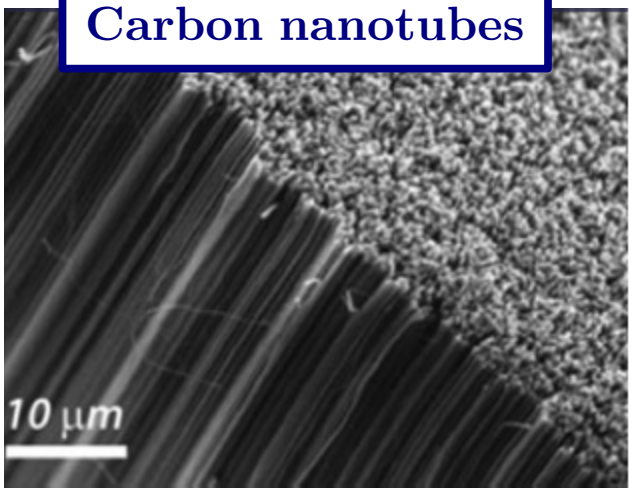
- Finite angular resolution
- Head-tail recognition i.e., $(+\hat{\mathbf{q}}$ or $-\hat{\mathbf{q}})$
- Low mass

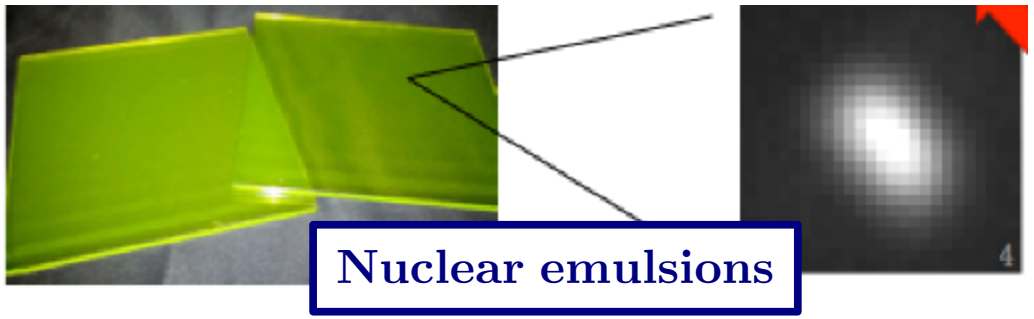
# The future

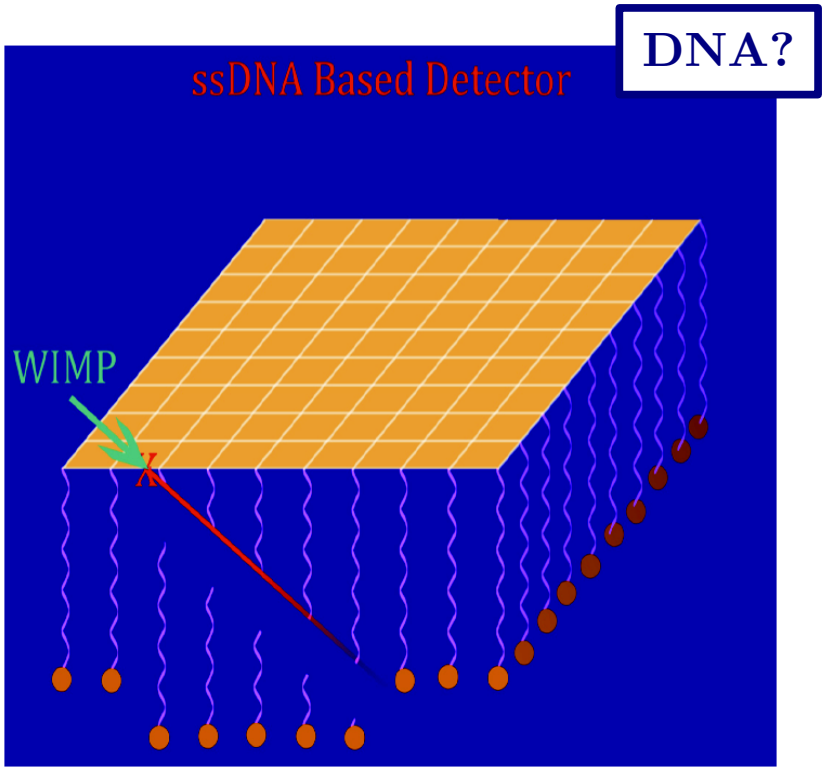
## Possible ways forward

- **Compromise on 3-d recoil track reconstruction**
  - 2-d readout (e.g., TPC with no time sampling of anode)
  - 1-d readout (e.g., columnar recombination in dual phase liquid Xe detector)

- **New strategies?**

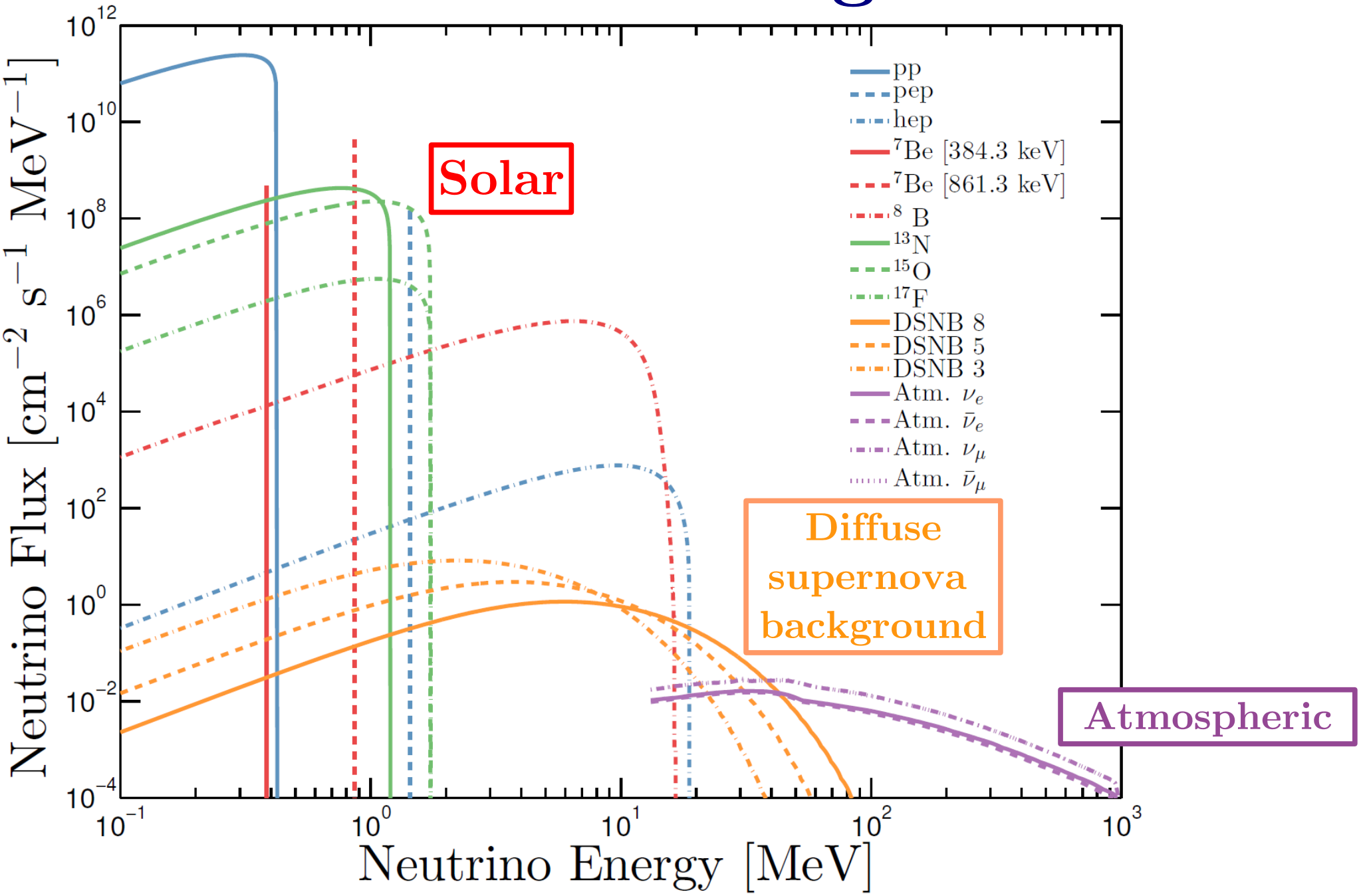


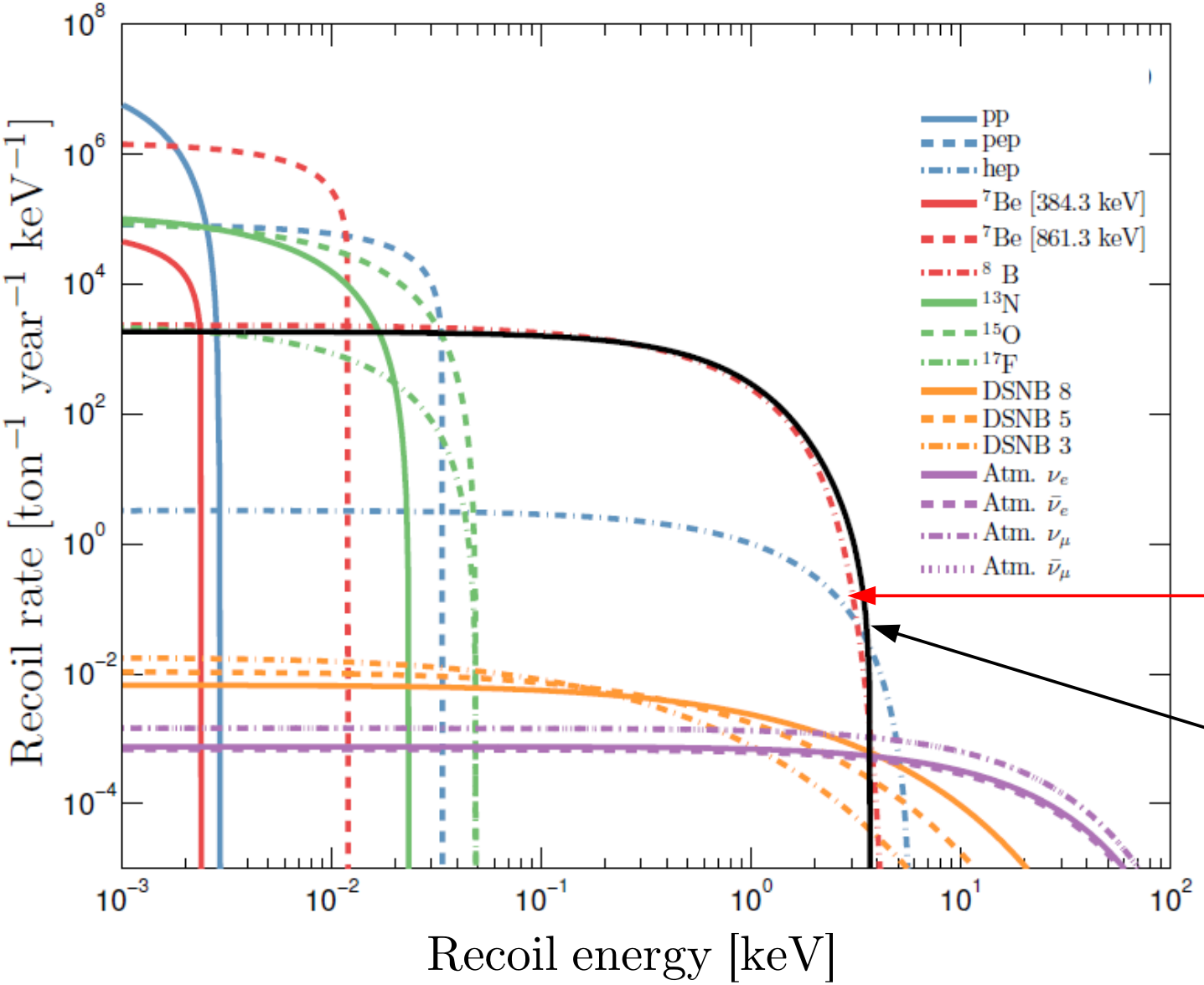
# Neutrino Backgrounds

# Neutrino backgrounds



# Neutrino backgrounds

- Coherent neutrino-nucleus scattering (CNS) rate on a Xenon target:




**$^{8}$B neutrinos**

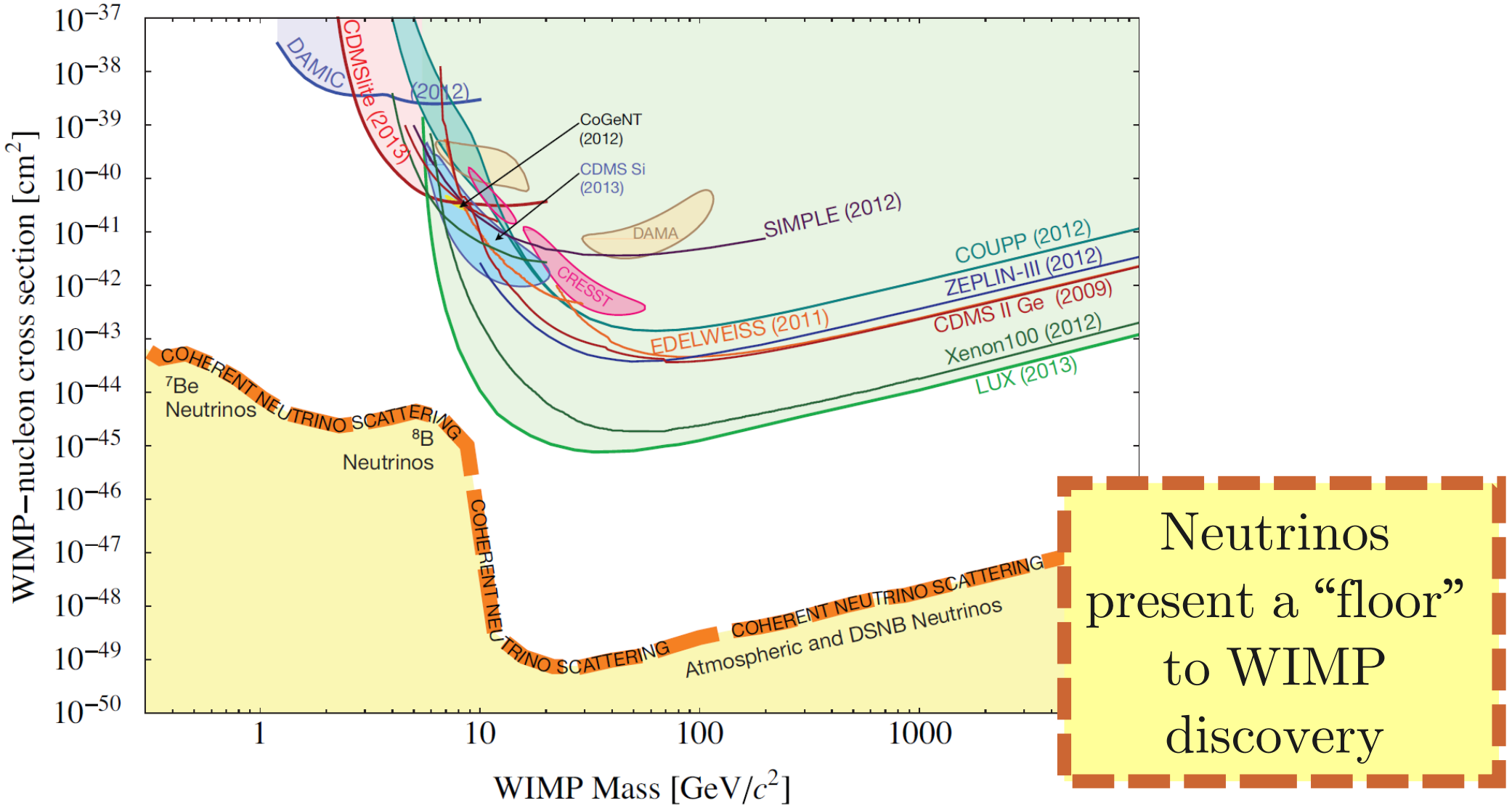
**6 GeV WIMP**

$\sigma_p = 4.9 \times 10^{-45}\,\mathrm{cm}^2$

# Neutrino floor

## SI discovery limits

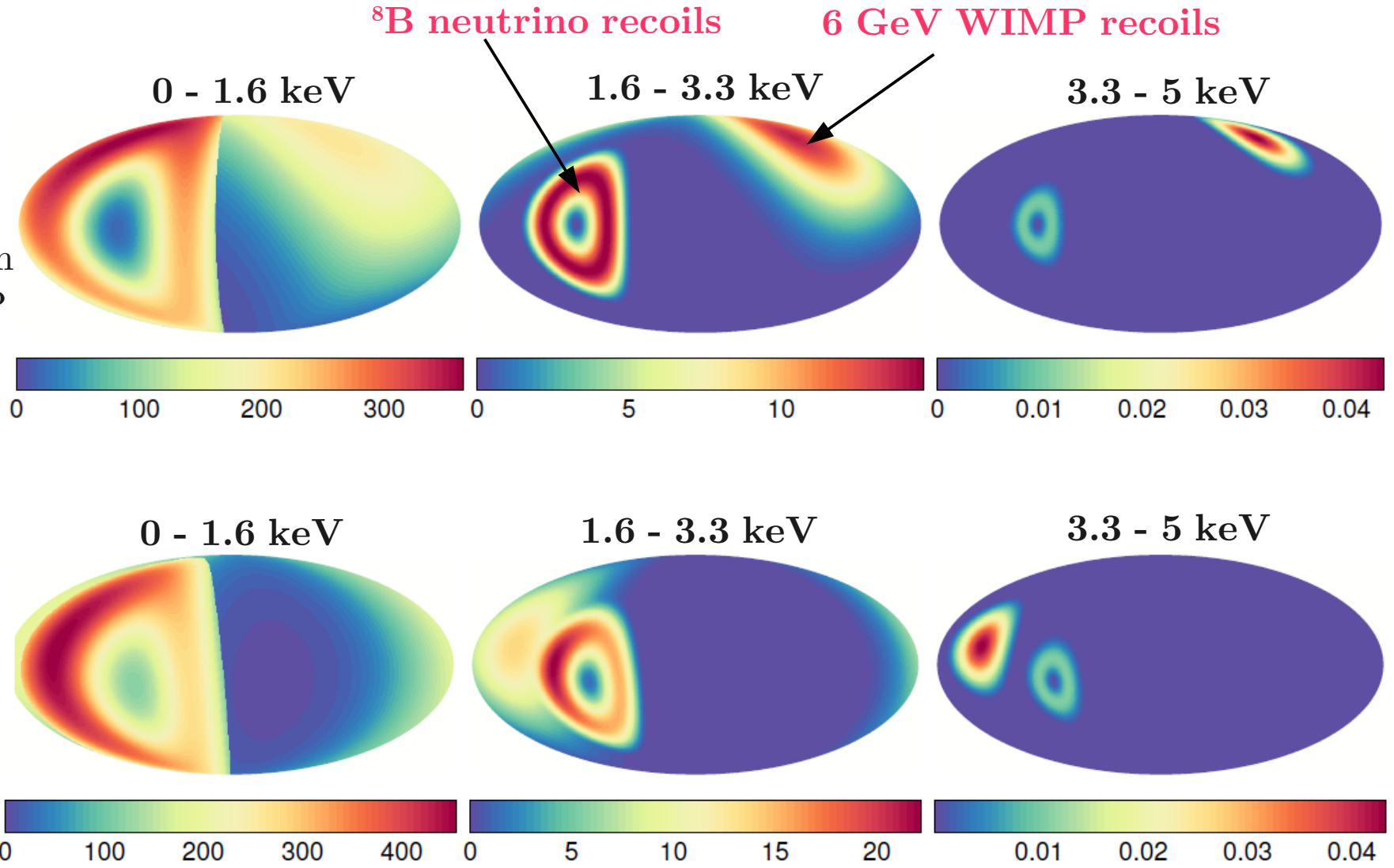
J. Billard *et al* [arXiv:1307.5458]




Neutrinos present a "floor" to WIMP discovery

# Directional signatures

- Sun does not pass through Cygnus
- It should be possible to disentangle WIMP and neutrino signals

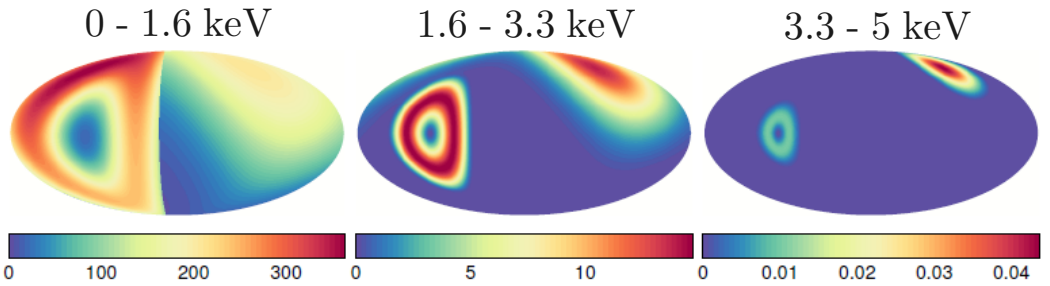


# Readout strategies

- Is there a neutrino floor with only 1-d or 2-d projections of the recoil track?

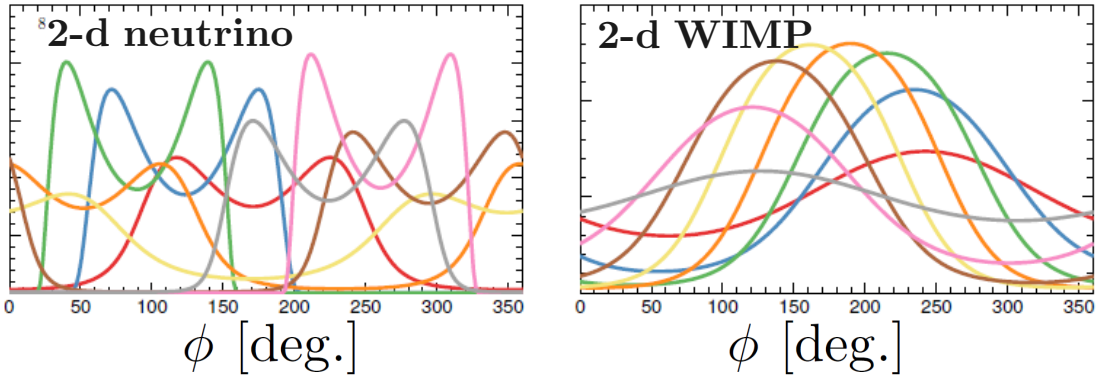
**3-d readout:** e.g., low pressure gas TPC

$\{E_r, \theta, \phi, t\}$



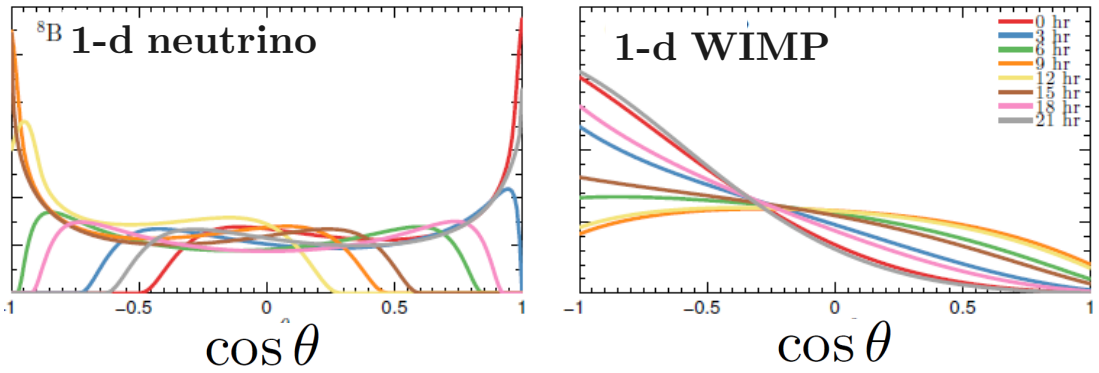

**2-d readout:** e.g., low pressure gas TPC (without time-sampling of anode)

$\{E_r, \phi, t\}$



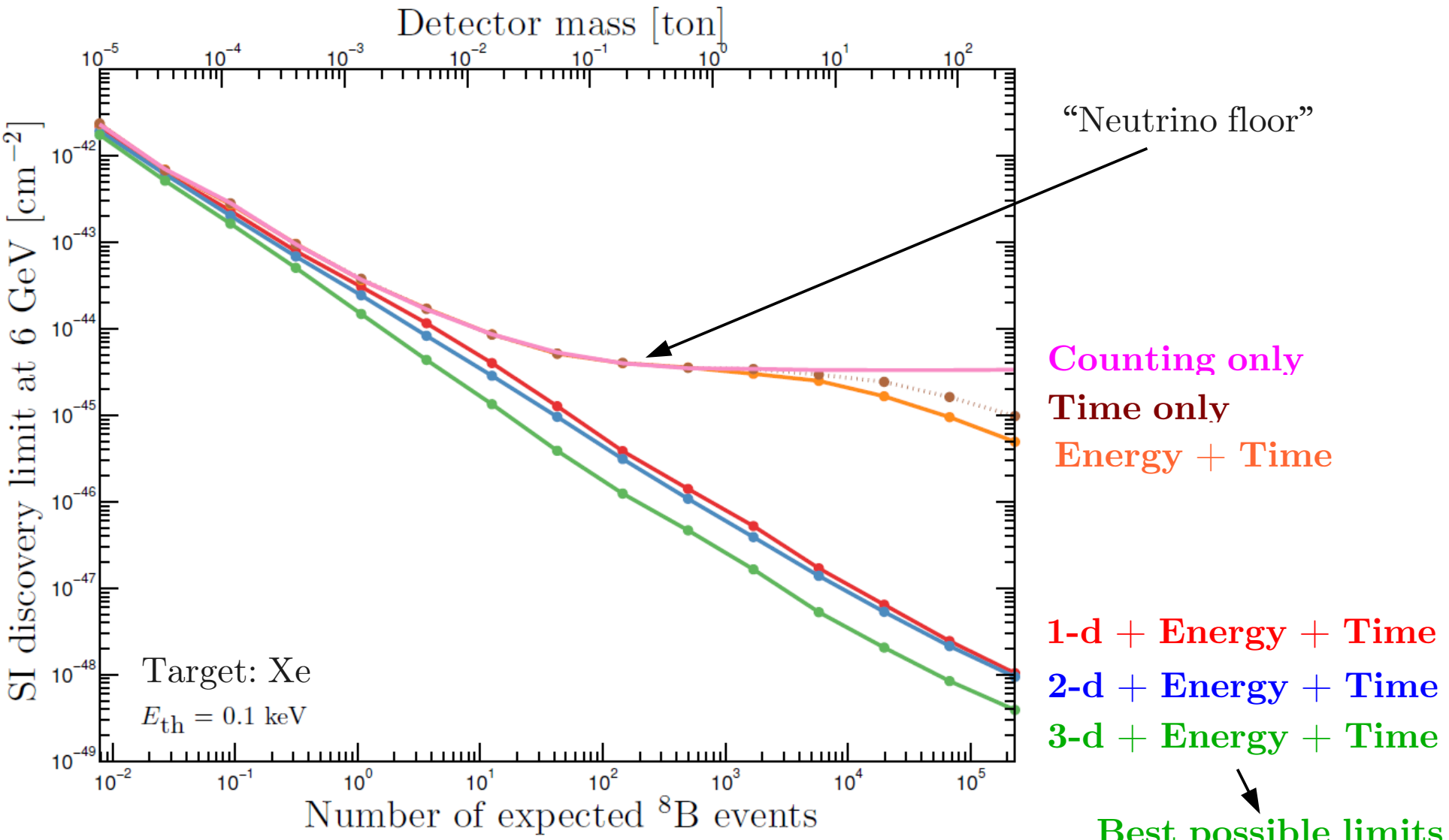

**1-d readout:** e.g., columnar recombination (D. Nygren) see arXiv:1503.03937

$\{E_r, \theta, t\}$



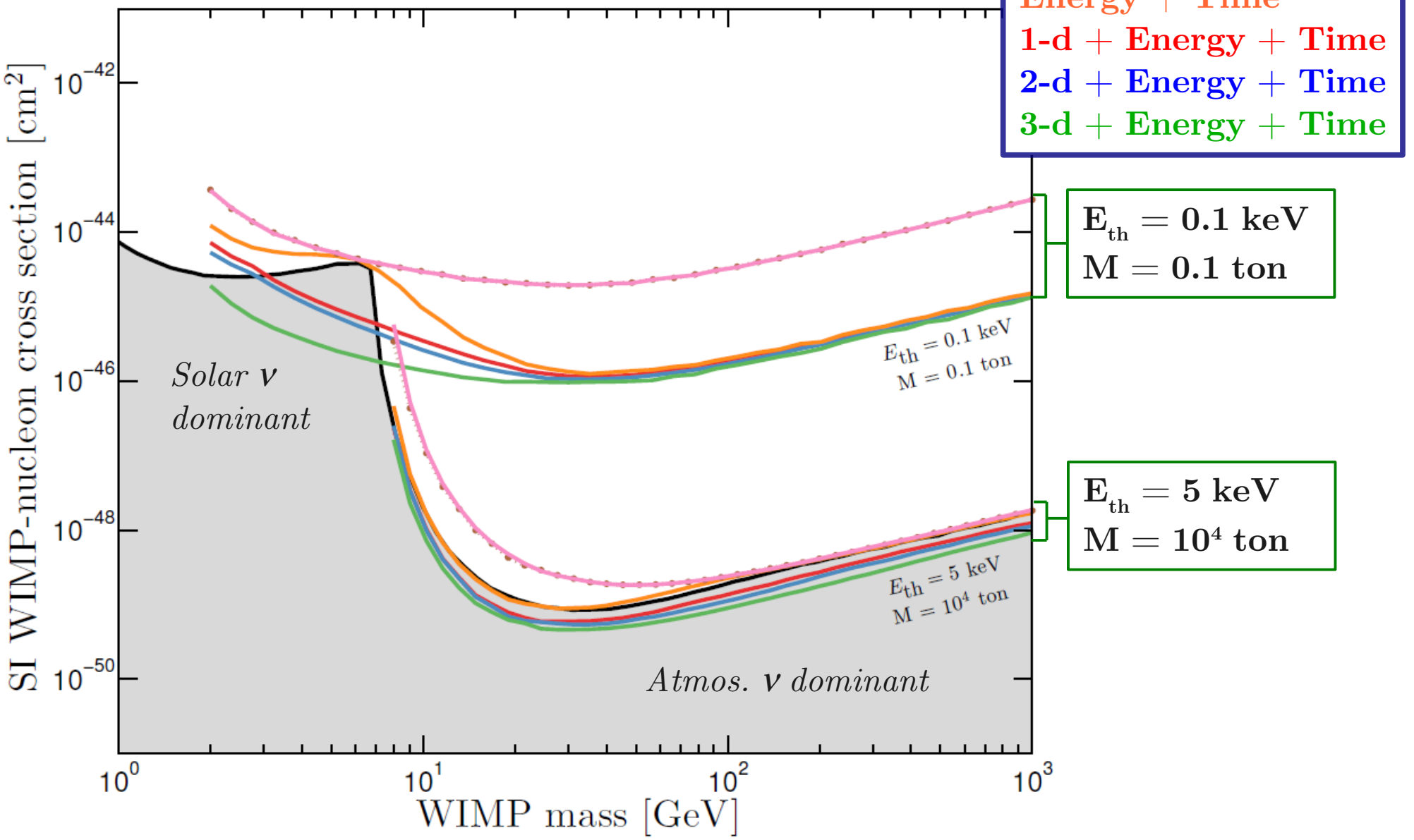
# Discovery limits

- Directional readout strategies penetrate the neutrino floor
- Discovery limit ($3\sigma$ at 90% CL) for 6 GeV WIMP as a function of detector mass



# Discovery limits

- SI discovery limits as a function of WIMP mass



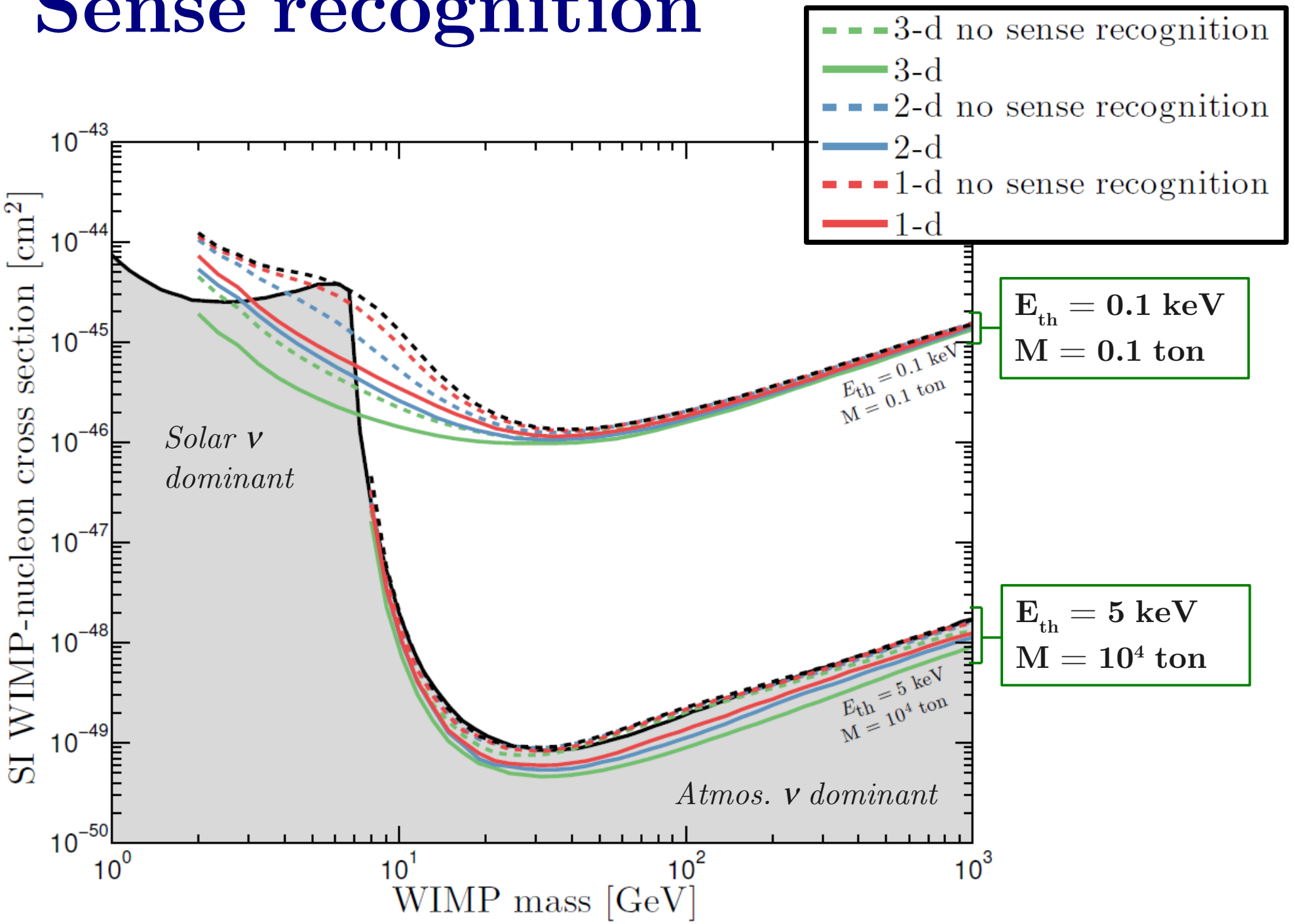
# Summary

## Directionality is a powerful tool for subtracting neutrino backgrounds

- **Directional detection**
  - Reject isotropy with ***O(10)*** events
  - Discovery with ***O(30)*** events
  - Can study astrophysics e.g., detect tidal streams with ***O(100)*** events
  - Need construction of large directional detectors
- **Neutrino floor**
  - With Energy+Time information only neutrino backgrounds can only be subtracted for prohibitively large detectors/exposures.
  - Directional experiments can cut into the neutrino floor
  - Even with only 1-d or 2-d readout

# Extra slides

# Sense recognition



# Angular resolution