UNITED KINGDOM · CHINA · MALAYSIA

# Directly detecting the Milky Way halo

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**Kings College London Dec 2016**

# Outline

## Astrophysical uncertainties in dark matter detection

- C. A. J. O'Hare [1604.03858]

## Observing the local Milky Way dark matter distribution

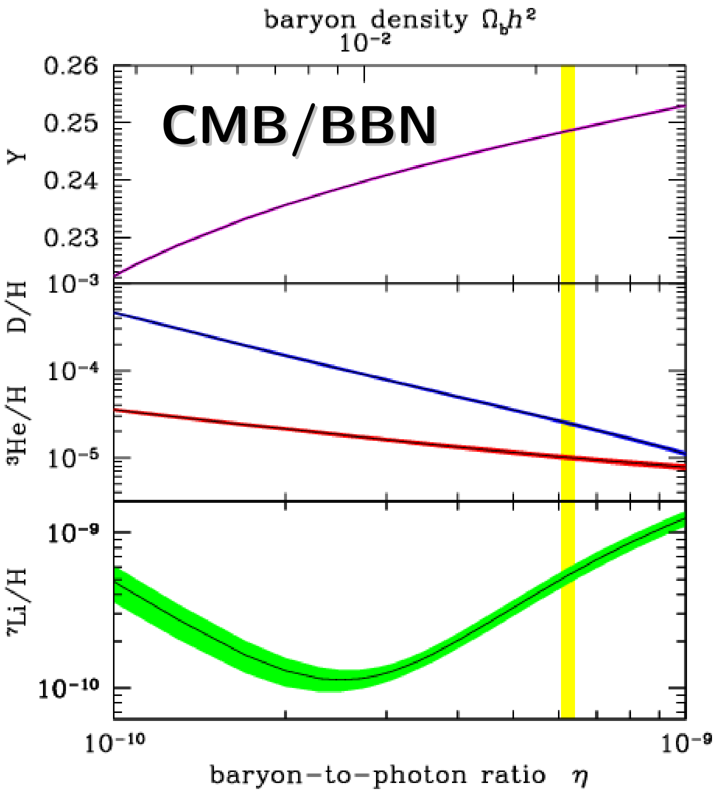
## WIMP directional detectors

- C. A. J. O'Hare & A. M. Green [1410.2749]
- B. J. Kavanagh & C. A. J. O'Hare [1609.08630]

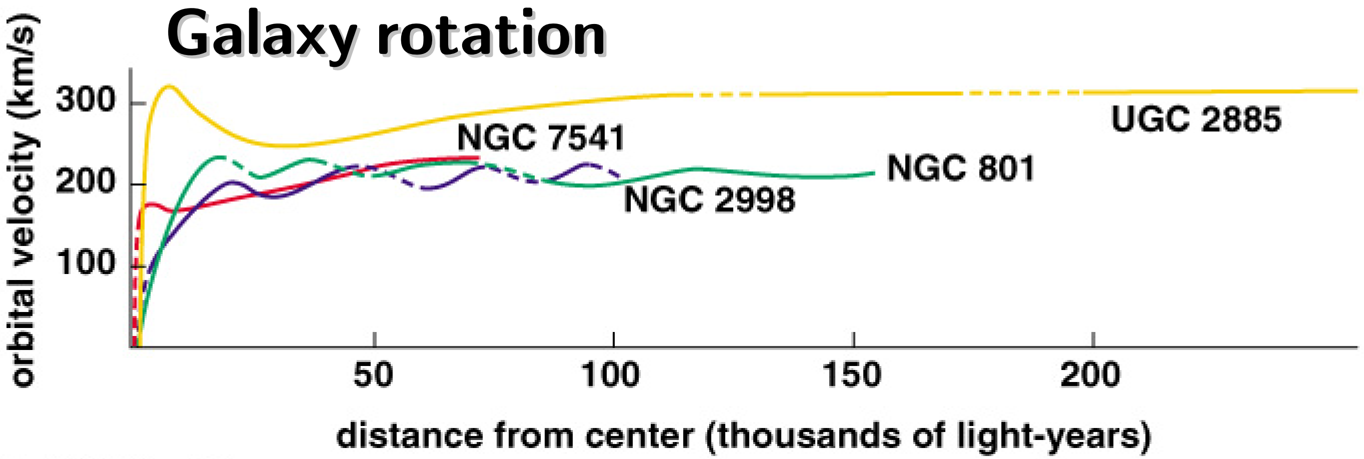
## Axion haloscopes

- C. A. J. O'Hare & A. M. Green [in prep.]

# We haven't enough baryons...

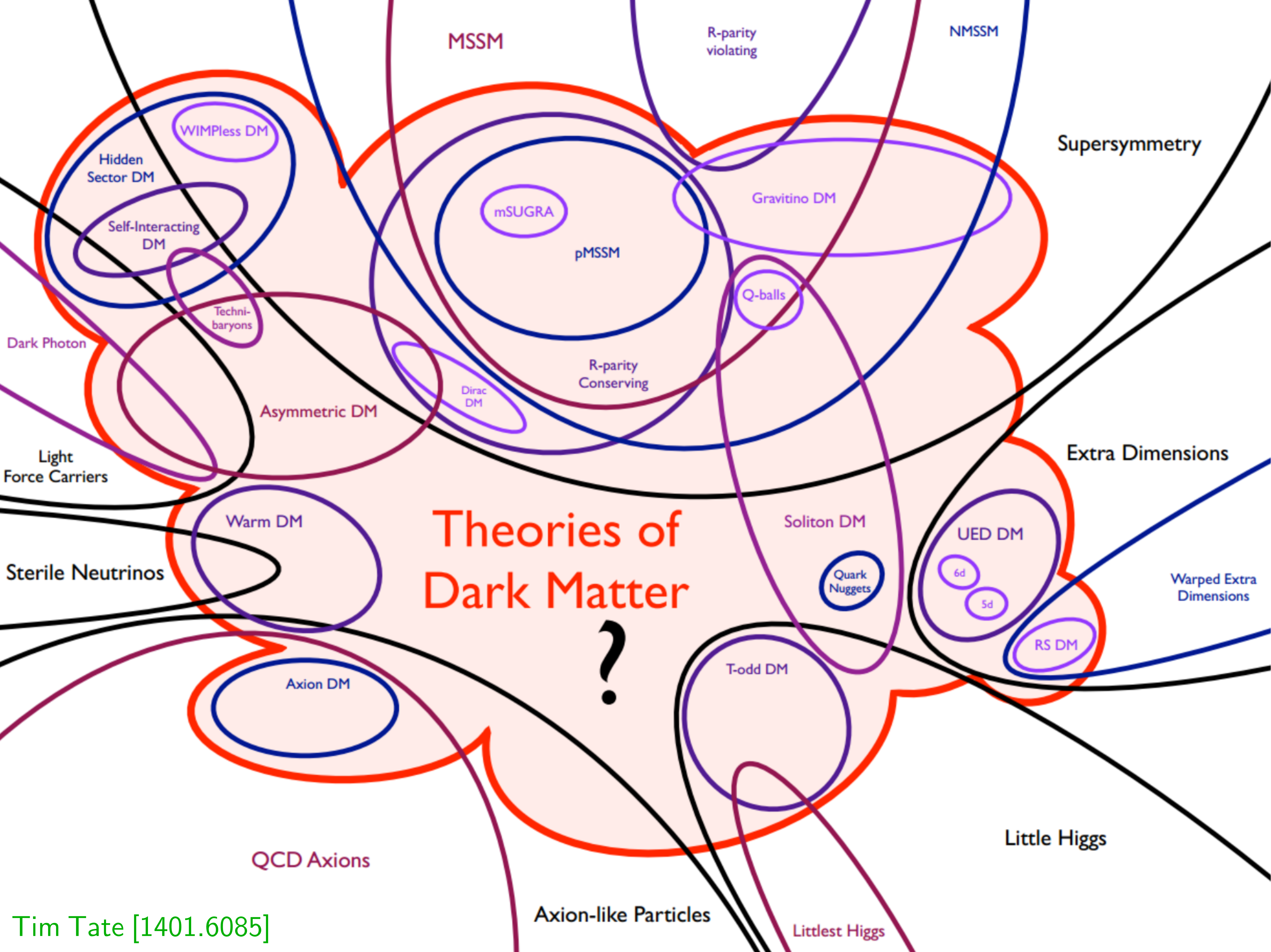




Planck [1502.01589]
Cyburt [1505.01076]




(c) Addison Wellsley (2009)

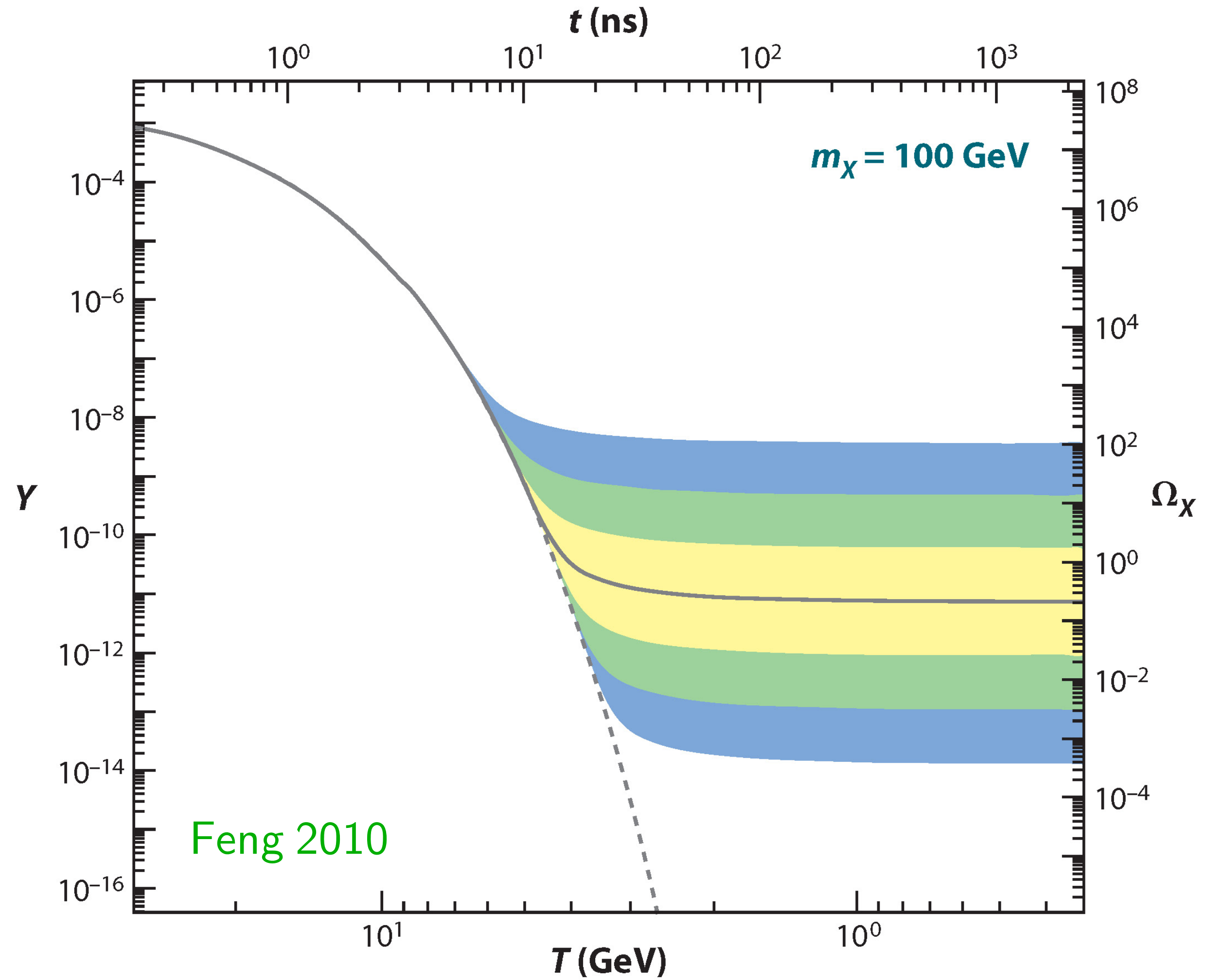
## ...dark matter is there and it's probably a particle




Tim Tate [1401.6085]

# WIMPs

Assuming new particle is initially in thermal equilibrium → freeze-out with relic density proportional to 1/annihilation cross section



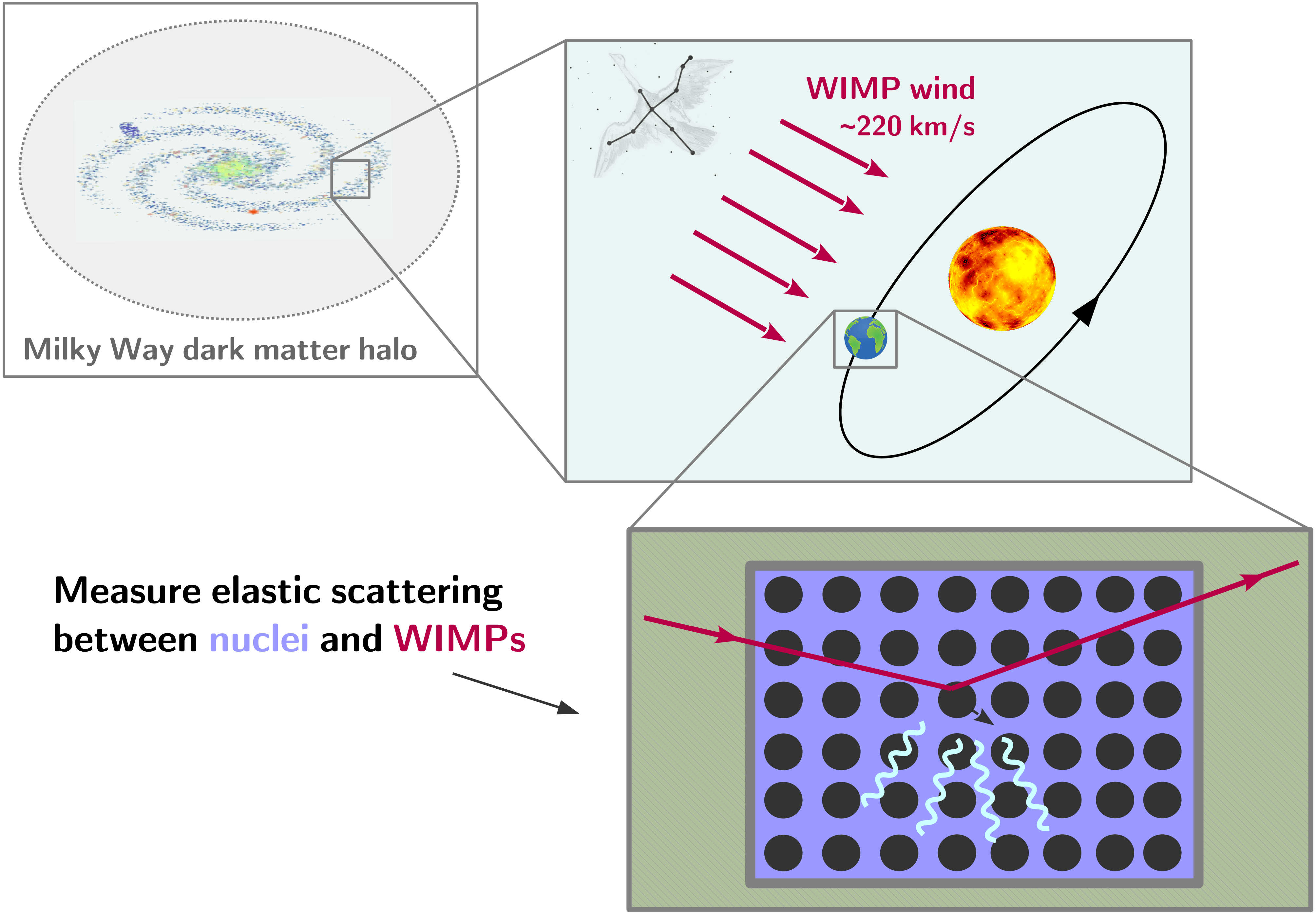

$$\Omega_{\rm dm} h^2 \simeq 0.1196 \implies \langle \sigma v \rangle \simeq 3 \times 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$$

→ Observed relic density would imply weak-scale annihilations

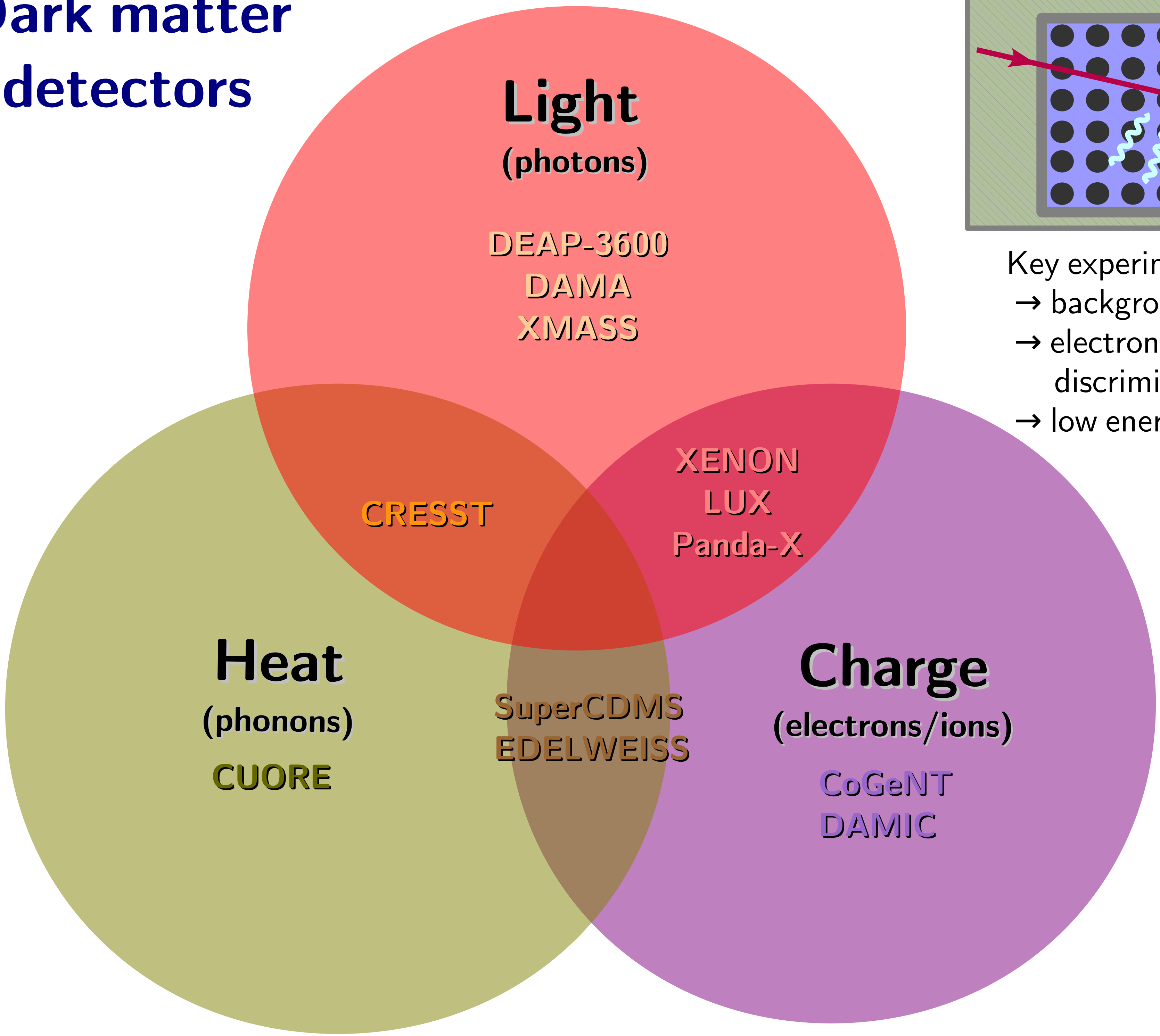
→ WIMPs show up in BSM physics

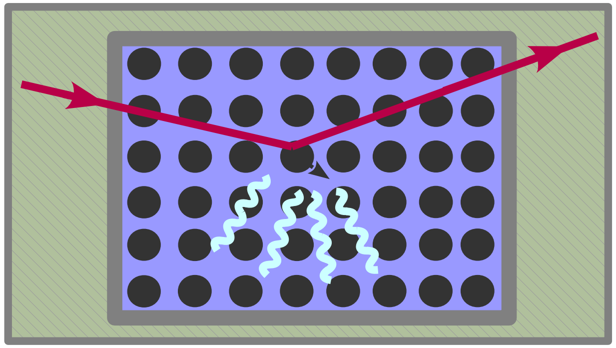
**WIMP** = **W**eakly **I**nteracting **M**assive **P**article

# Direct detection



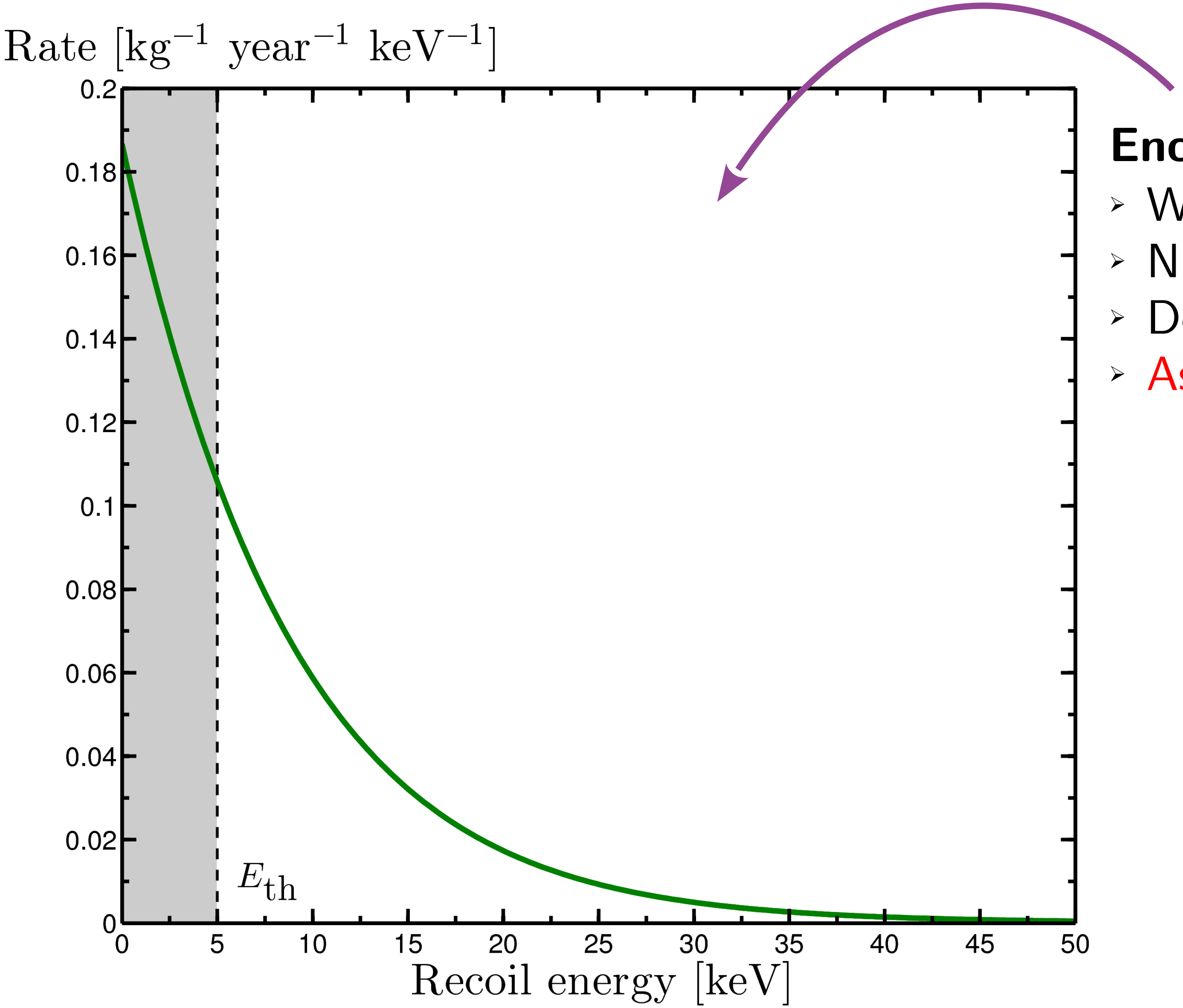
# Dark matter detectors



Key experimental problems
→ background shielding
→ electron/nuclear recoil discrimination
→ low energy thresholds

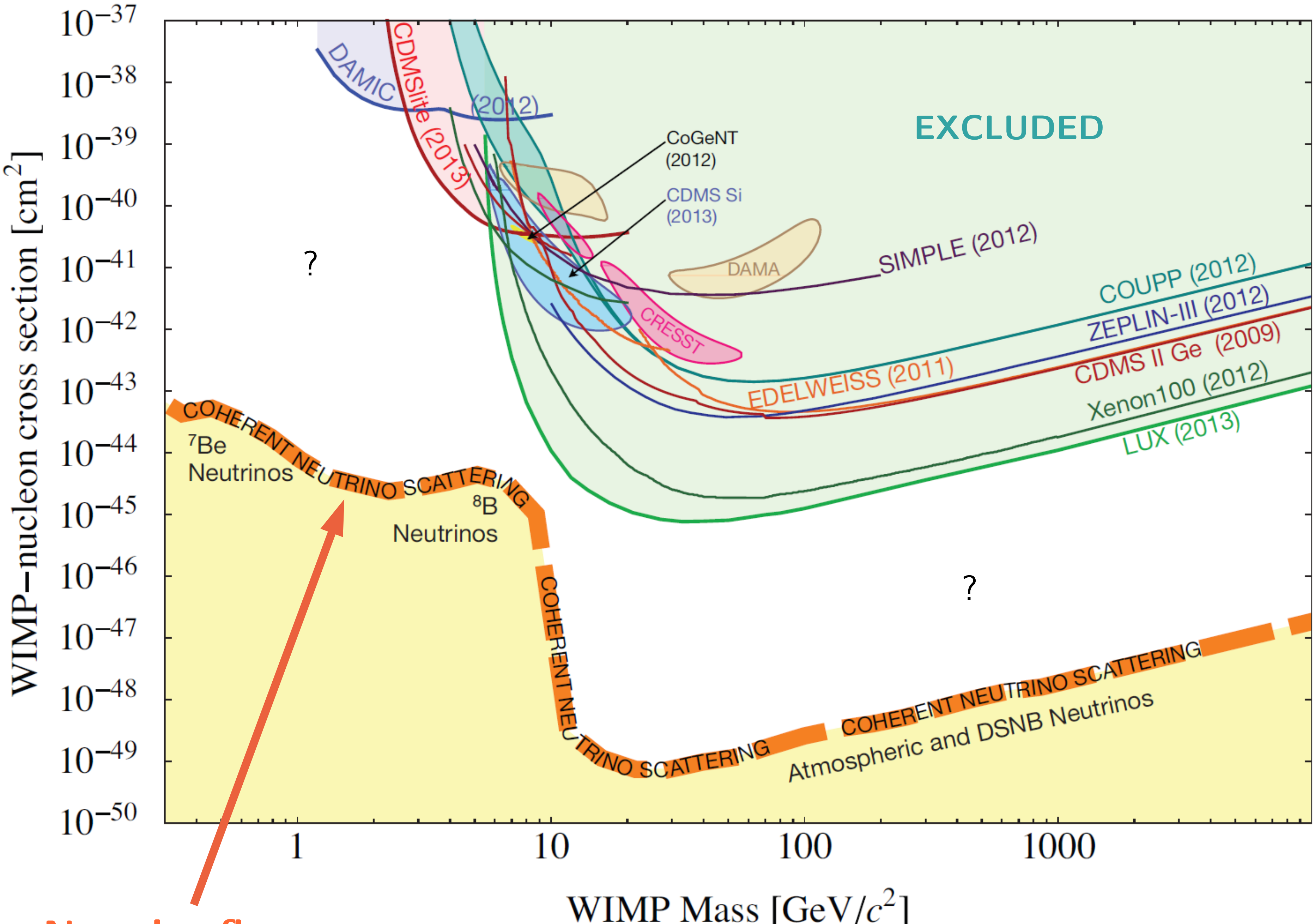
# Direct dark matter detection




**Encodes:**

- WIMP mass & cross section
- Nuclear response
- Detector effects
- Astrophysical information...

J Billard, L Strigari, E Figueroa-Feliciano [1307.5458]




Neutrino floor

# WIMP-nucleus scattering

Double differential event rate (recoil energy $E_r$ and direction $\mathbf{q}$)

$$\frac{\mathrm{d}R}{\mathrm{d}E_r \mathrm{d}\Omega_q} = \frac{\sigma_p \mathcal{C}_N}{4\pi\mu_{\chi p}^2 m_\chi} \times F^2(E_r) \times \rho_0 \hat{f}(v_{\min}, \hat{\mathbf{q}})$$

**Particle physics**

- WIMP-nucleus interaction
  - → spin-independent: $\mathcal{C}_N^{\mathrm{SI}} \propto A^2$
  - → spin-dependent: $\mathcal{C}_N^{\mathrm{SD}} \propto (J+1)/J$

**Nuclear physics**

- Form factor $F^2(E_r)$

**Astrophysics**

- Local DM density $\rho_0$
- Radon transform of velocity distribution:

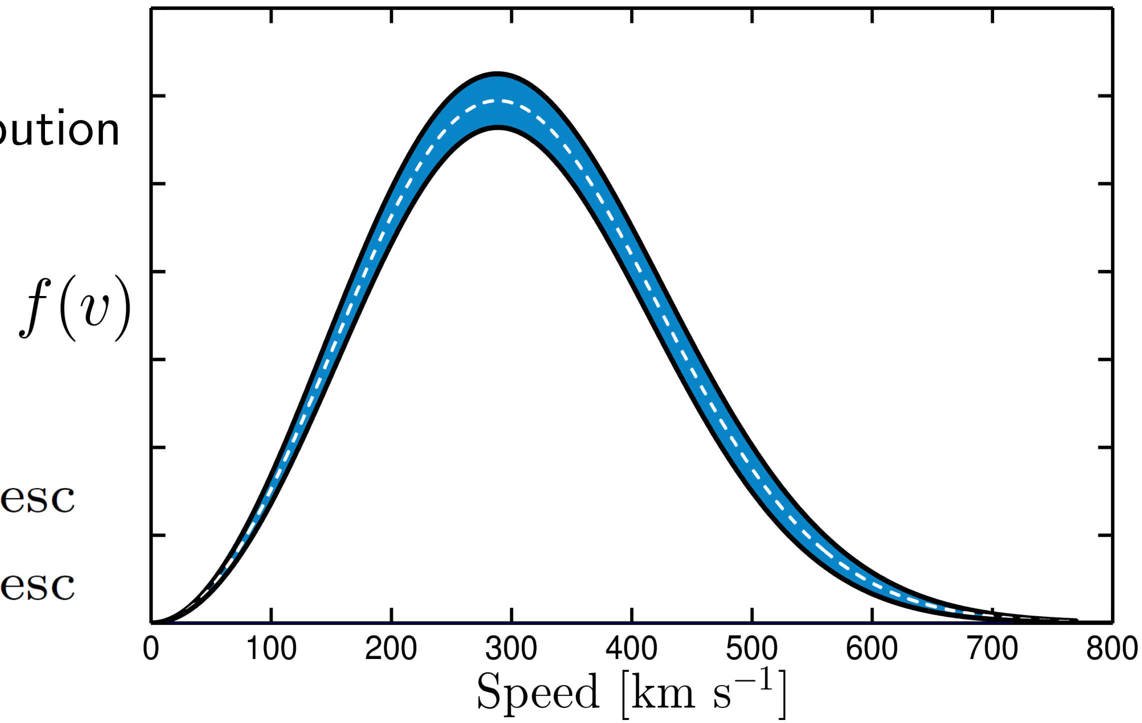
$$\hat{f}(v_{\min}, \hat{\mathbf{q}}) = \int f_{\mathrm{lab}}(\mathbf{v}, t)\delta(\mathbf{v}\cdot\mathbf{q} - \hat{v}_{\min})\mathrm{d}^3\mathbf{v}$$

# Astrophysical uncertainties

- Experimental analyses typically assume **Standard Halo Model (SHM)**

- Smooth isothermal sphere (cow)
  → Maxwell-Boltzmann velocity distribution

$$f(\mathbf{v}) = \begin{cases} \frac{1}{N} e^{-v^2/v_0^2} & |\mathbf{v}| < v_{\rm esc} \\ 0 & |\mathbf{v}| \geq v_{\rm esc} \end{cases}$$



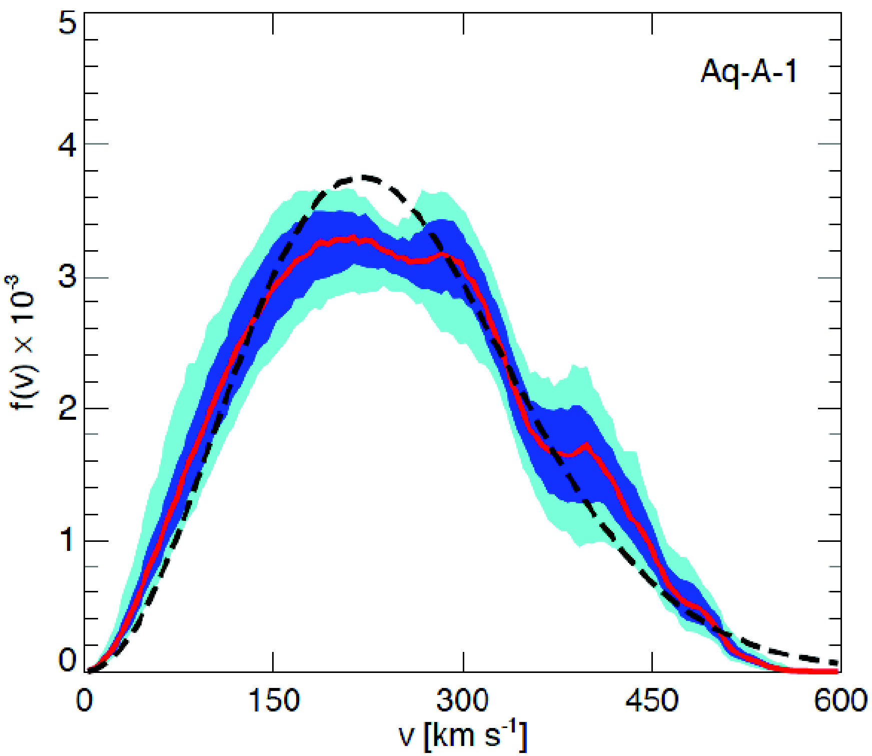

**Free parameters:**

- Rotation speed, $v_0 = 180 – 240$ km s$^{-1}$ Lavalle & Magni [1411.1325]
- Escape velocity, $v_{\rm esc} = 533 \pm 50$ km s$^{-1}$ Piffl et al [1309.4293]
- Local density, $\rho_0 = 0.2$ - $0.8$ GeV cm$^{-3}$ Read et al [1404.1938] ...

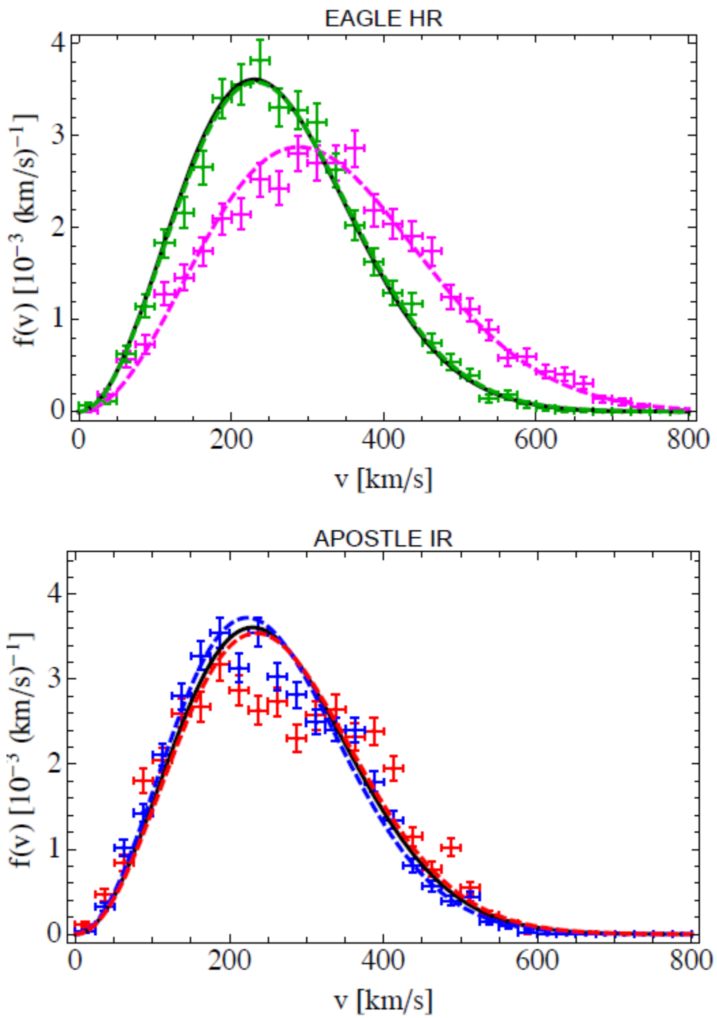
# Halo simulations

- N-body/hydrodynamic simulations persistently exhibit non-Maxwellian structure

*Although adding baryons can improve Maxwellian fit




Vogelsberger [0812.0362]

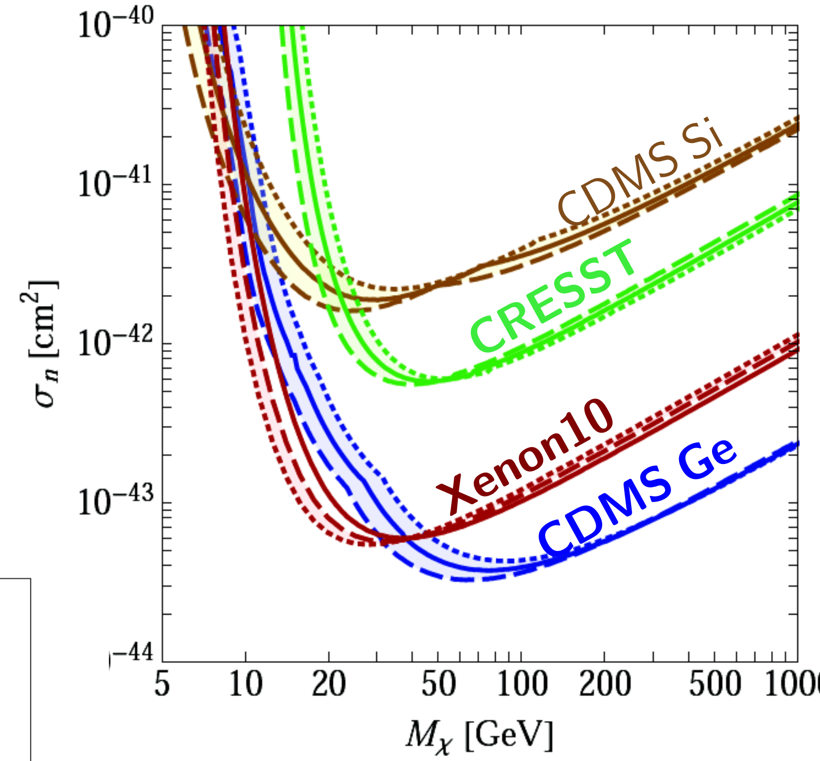


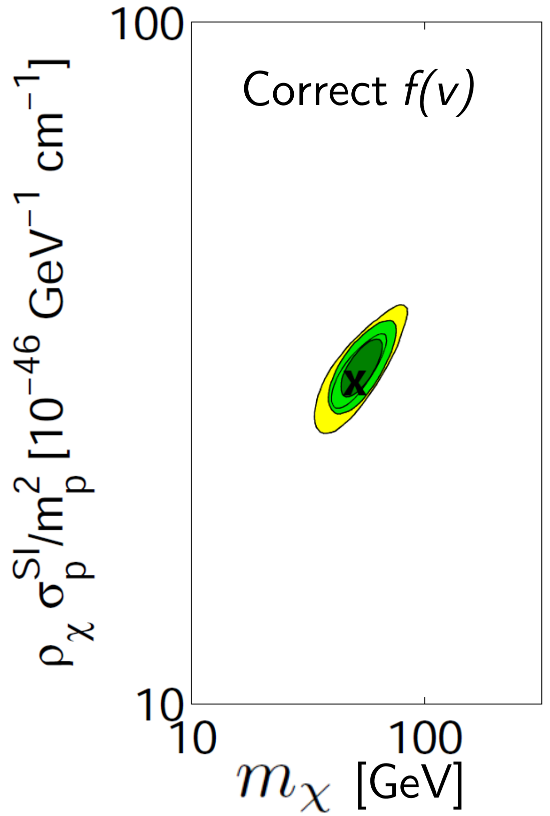

Calore [1509.02164] Bozorgnia [1601.04707]

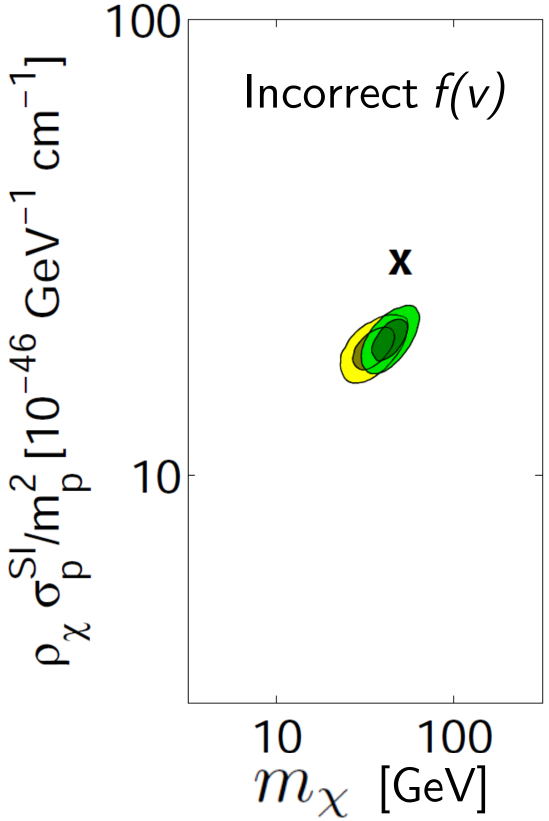
# Effect of astrophysical uncertainties

Uncertainty in exclusion limits →

e.g. McCabe [1005.0579]



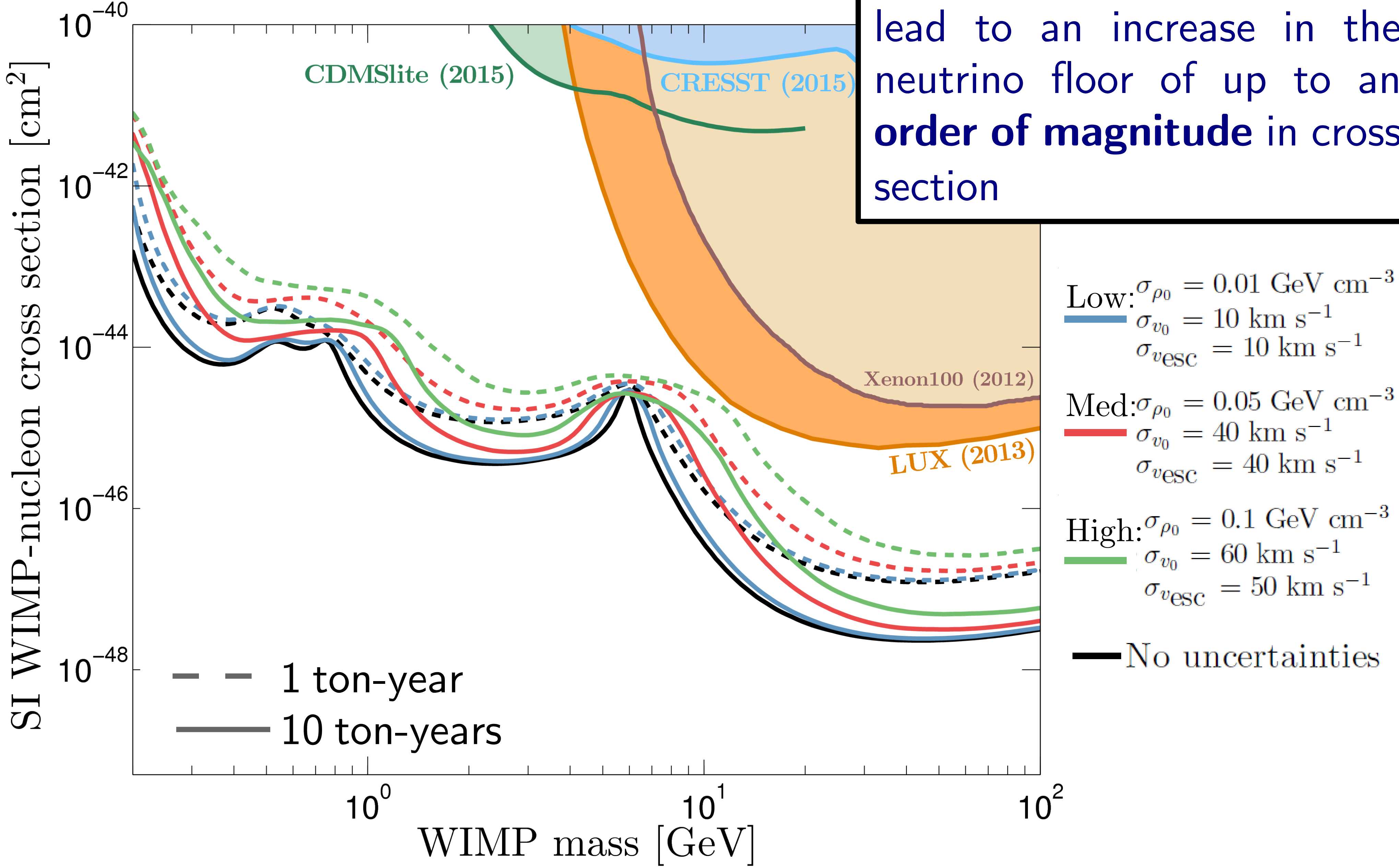

← Biased parameter estimation

e.g. Peter [1103.5145]

# The neutrino floor

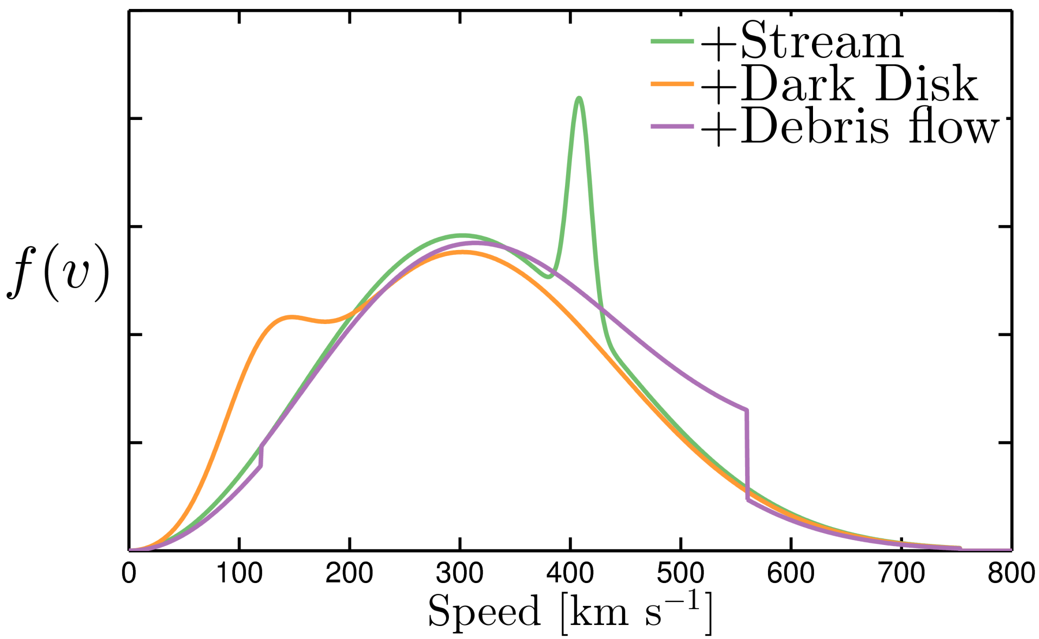
CAJ O'Hare [1604.03858]

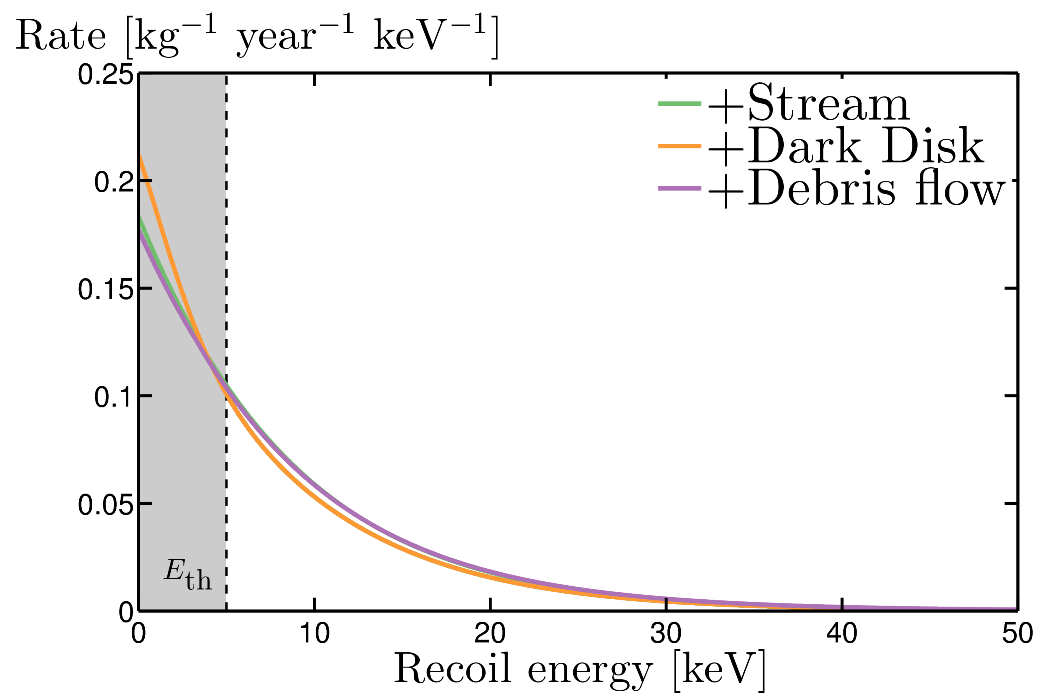
Astrophysical uncertainties lead to an increase in the neutrino floor of up to an **order of magnitude** in cross section



# Dark matter substructure

**Observations/simulations suggest possible substructure in local MW**



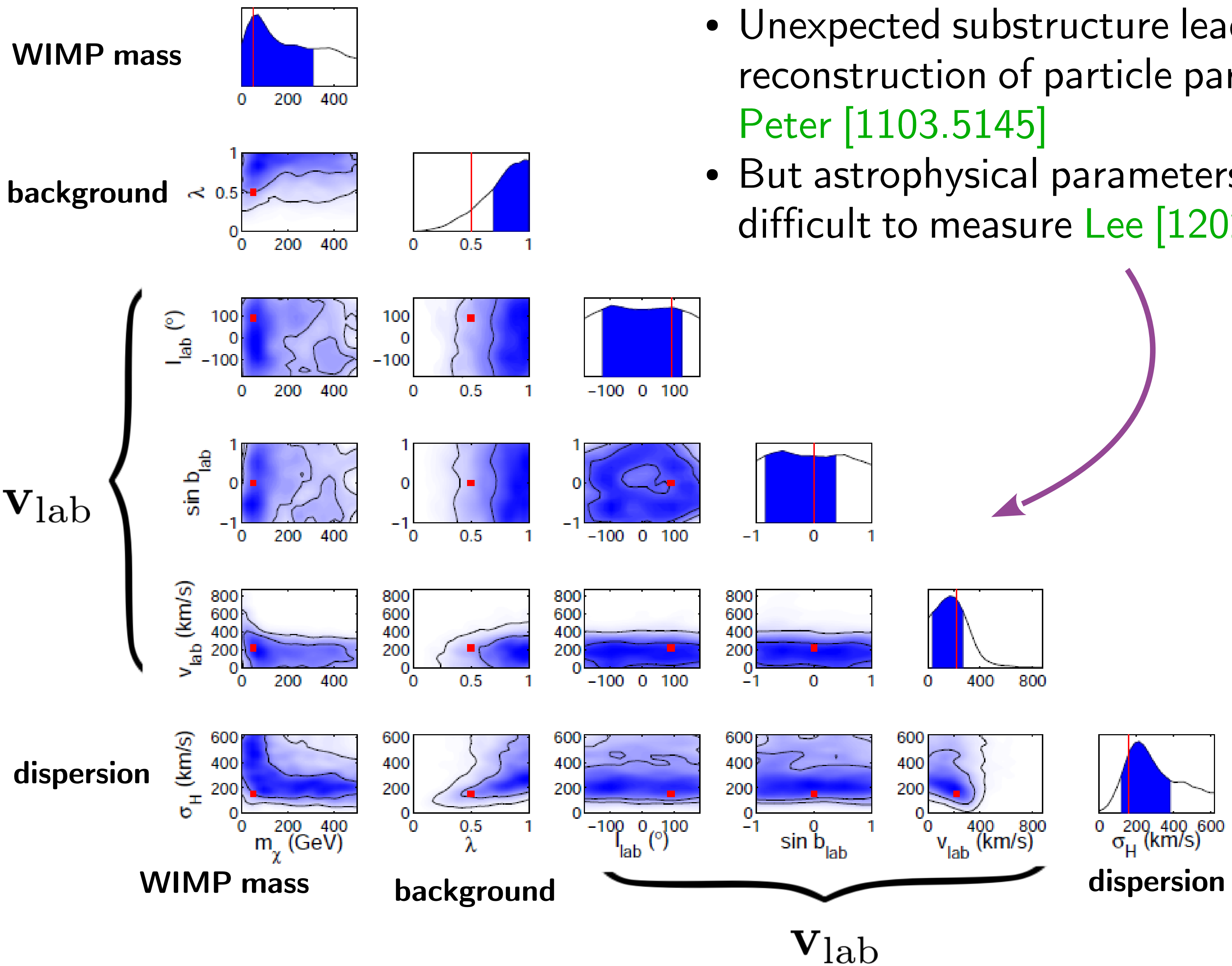




**Speed distribution → Scattering rate**

**Possible substructures**

- Tidal streams Purcell *et al.* [1203.6617]
- Dark disk Pillepich *et al.* [1308.1703], Schaller *et al.* [1605.02770]
- Debris flows Kuhlen *et al.* [1202.0007]

# Measuring astrophysical parameters




- Unexpected substructure leads to biased reconstruction of particle parameters Peter [1103.5145]
- But astrophysical parameters are difficult to measure Lee [1202.5035]

# Astrophysical uncertainties cause problems for direct detection:

→ Uncertainty in experimental limits
→ Neutrino floor higher
→ Degeneracy with particle physics parameters
→ Possible presence of substructure

## Solution: go and measure the local Milky Way halo directly

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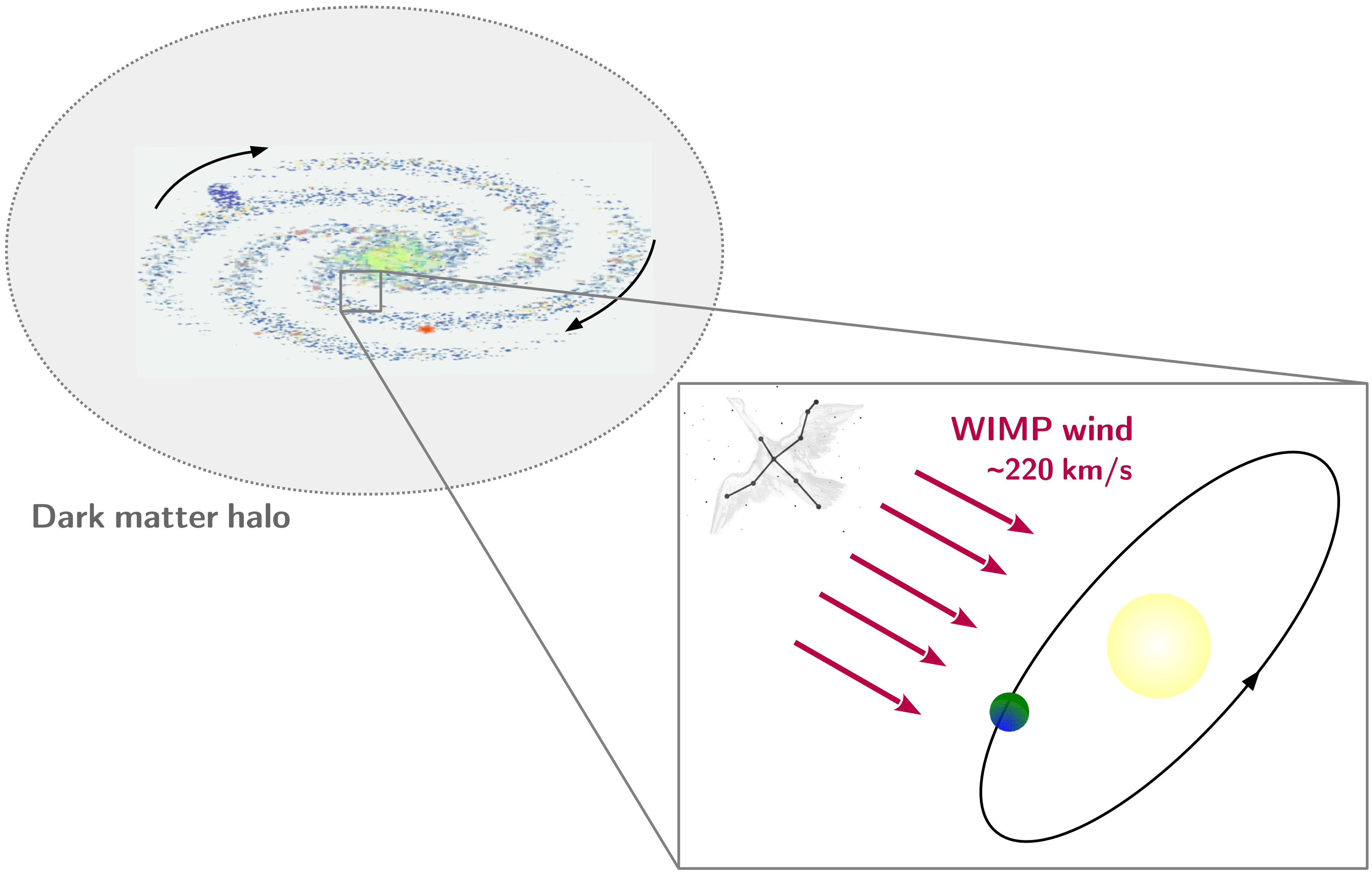
→ Uncertainty in experimental limits
→ Neutrino floor higher
→ Degeneracy with particle physics parameters
→ Possible presence of substructure

## Solution: go and measure the local Milky Way halo directly

**Bonus: find out about the formation history of the Milky Way...**

# Directional detection

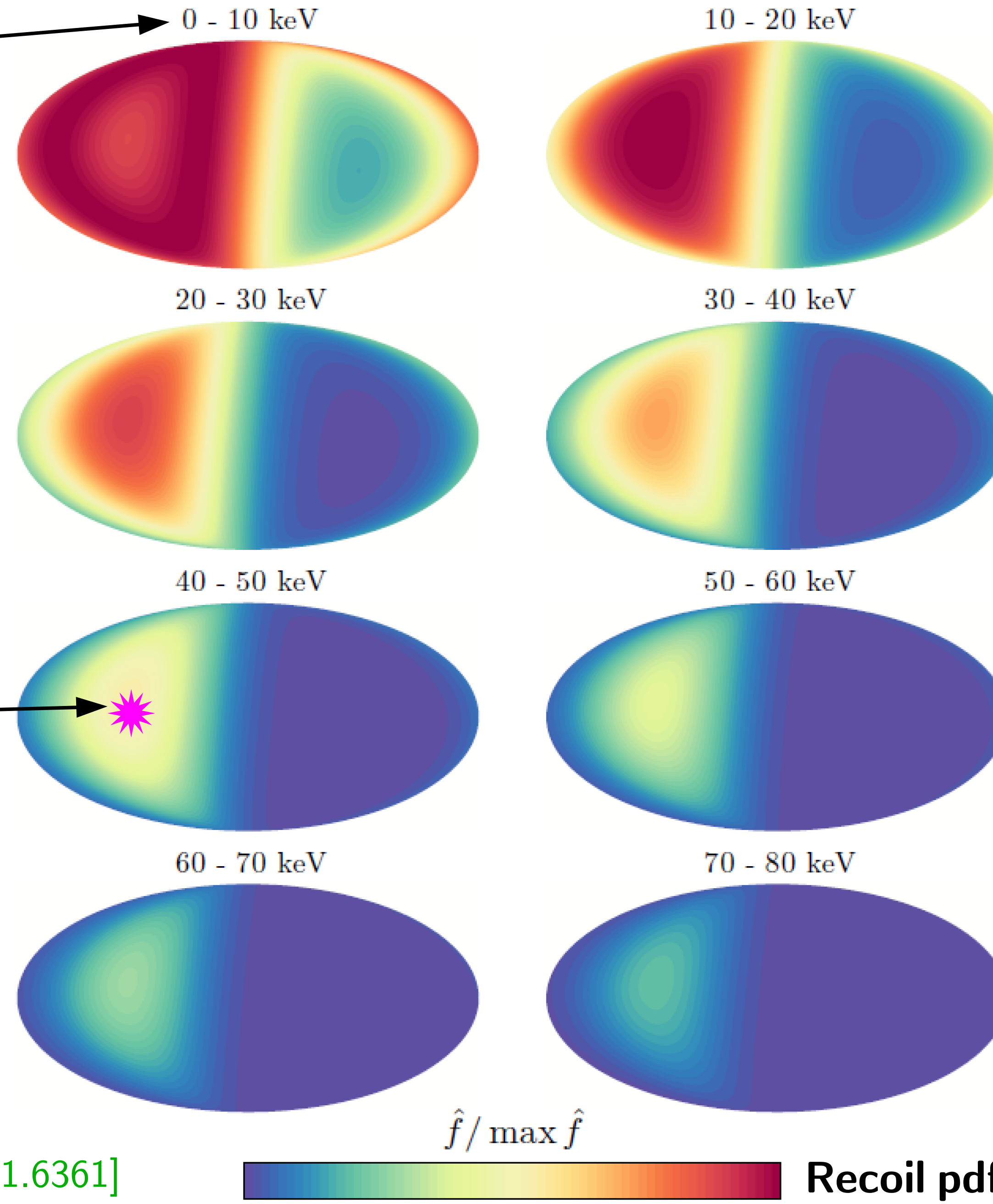
# Directional detection



# Energy+Direction dependence

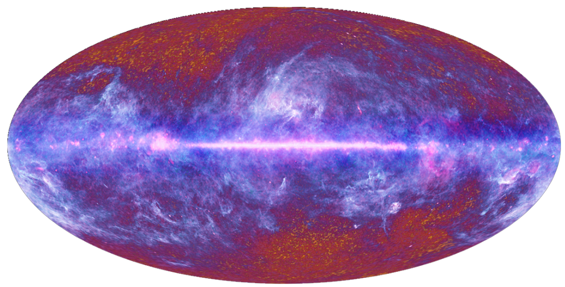
100 GeV WIMP

$^{19}$F recoil energy range




**Recoil pdf**

Mollweide projection of recoil skymap c.f.



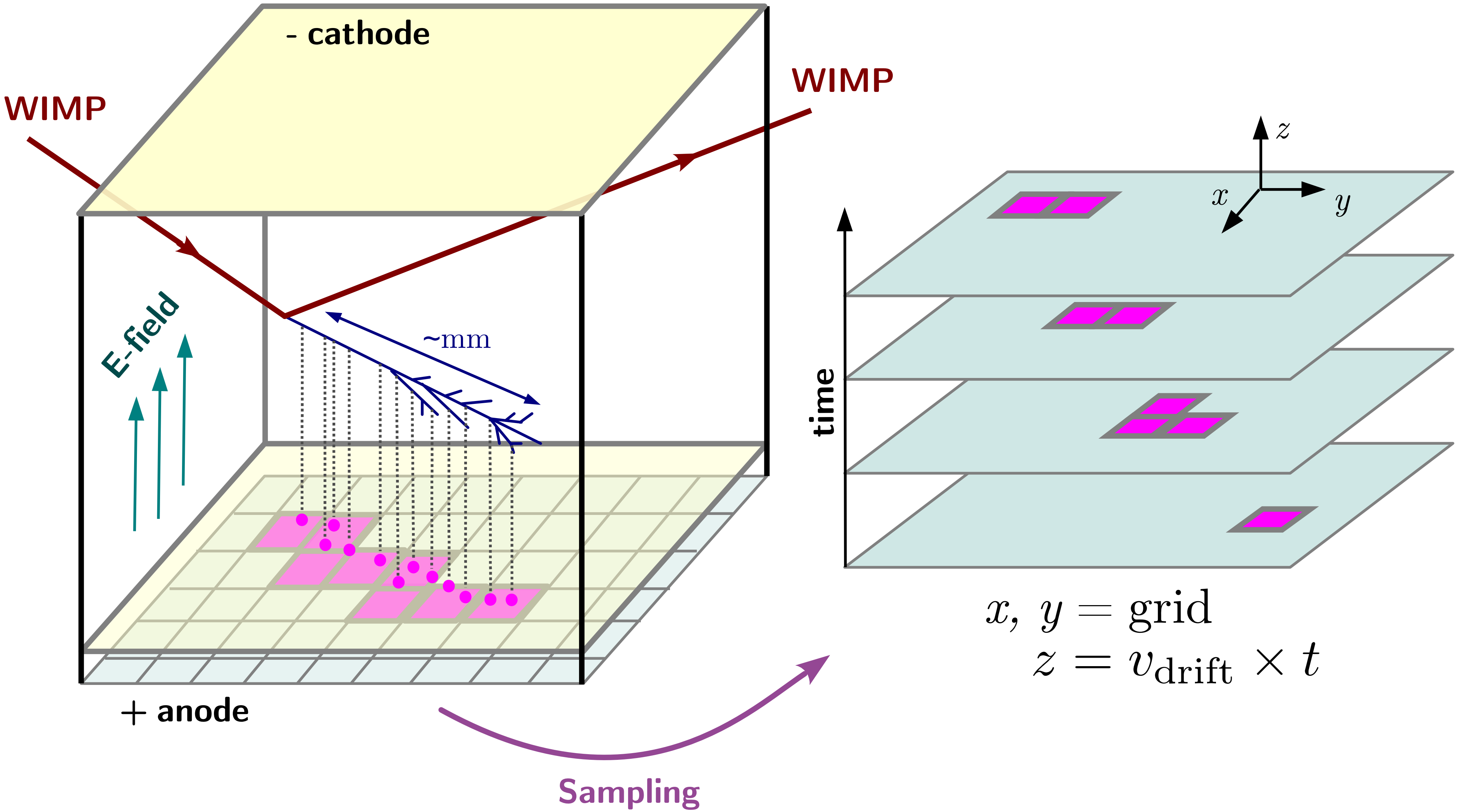
Peak direction toward $-\mathbf{v}_{\rm lab}$

## Secondary features

- Ring at low energies Bozorgnia [1111.6361]
- Aberration over time Bozorgnia [1205.2333]

# Directional detection

- Low pressure gas time projection chamber (TPC):



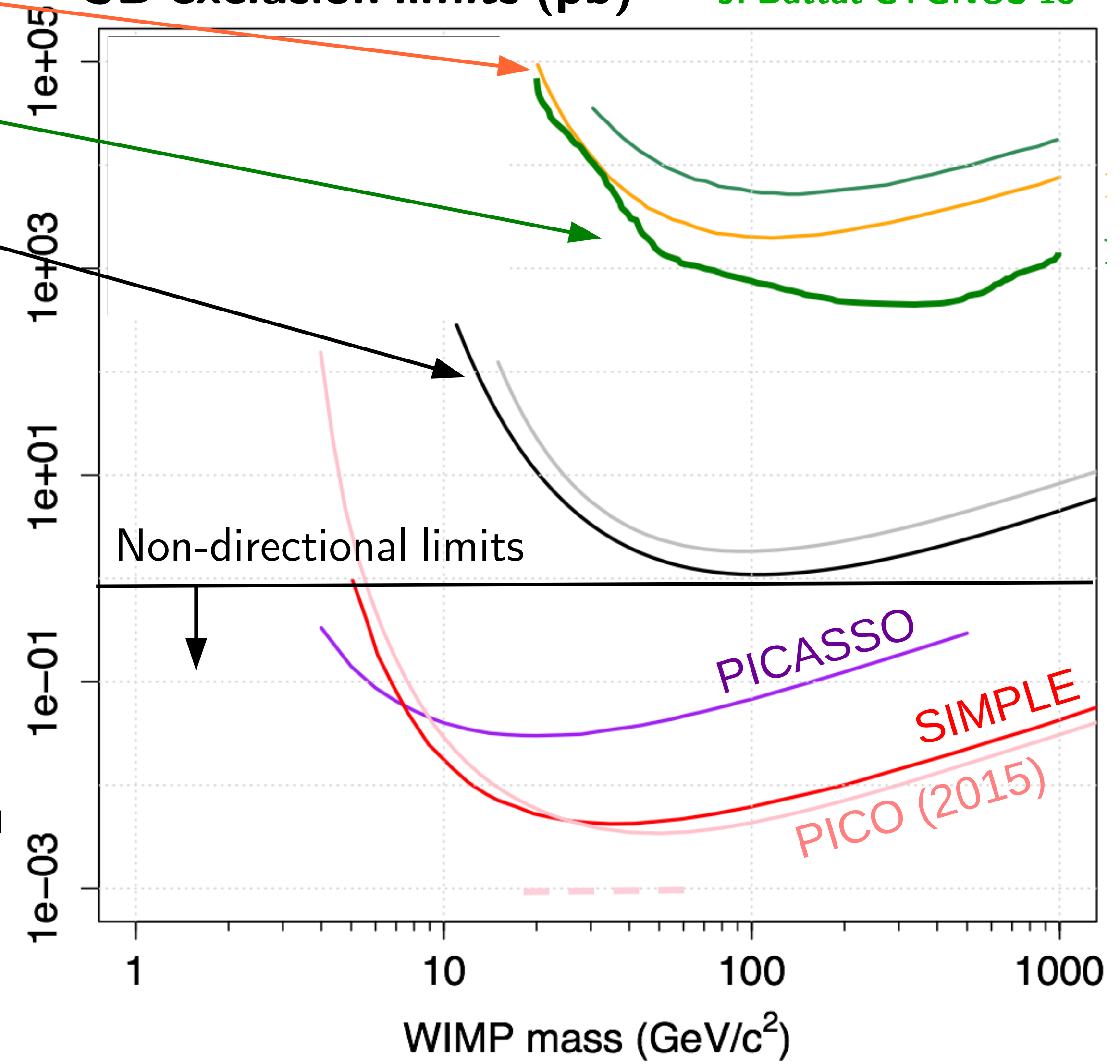

$$x,\ y = \text{grid}$$
$$z = v_{\text{drift}} \times t$$

# Directional detectors

**Best at the moment: low pressure gas TPCs**

- DM-TPC (USA)
- NEWAGE (Japan)
- DRIFT (UK)
- MIMAC (France)

**SD exclusion limits (pb)** J. Battat CYGNUS 15



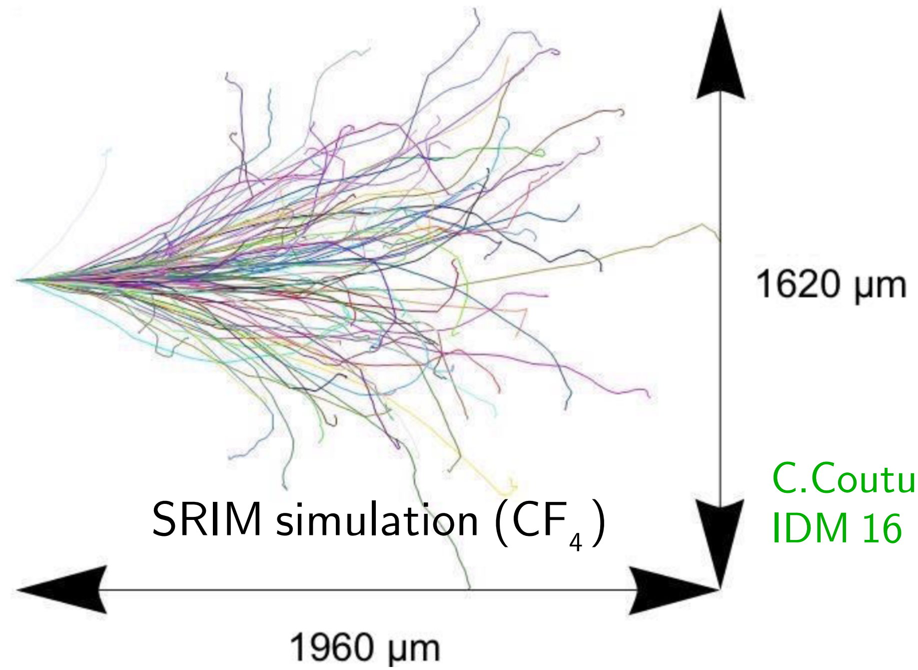

**Many other ideas*…**

- Emulsion plates
- Crystal scintillators
- LXe/Ar Columnar recombination
- DNA (perhaps…)

# Directional detection

**Disadvantages (TPCs):**

- Inherently low mass $O(0.1\text{ kg})$
- Angular resolution $O(10)$ deg.
- Sense recognition (+**q** or -**q**)
- 1-d/2-d/3-d readout



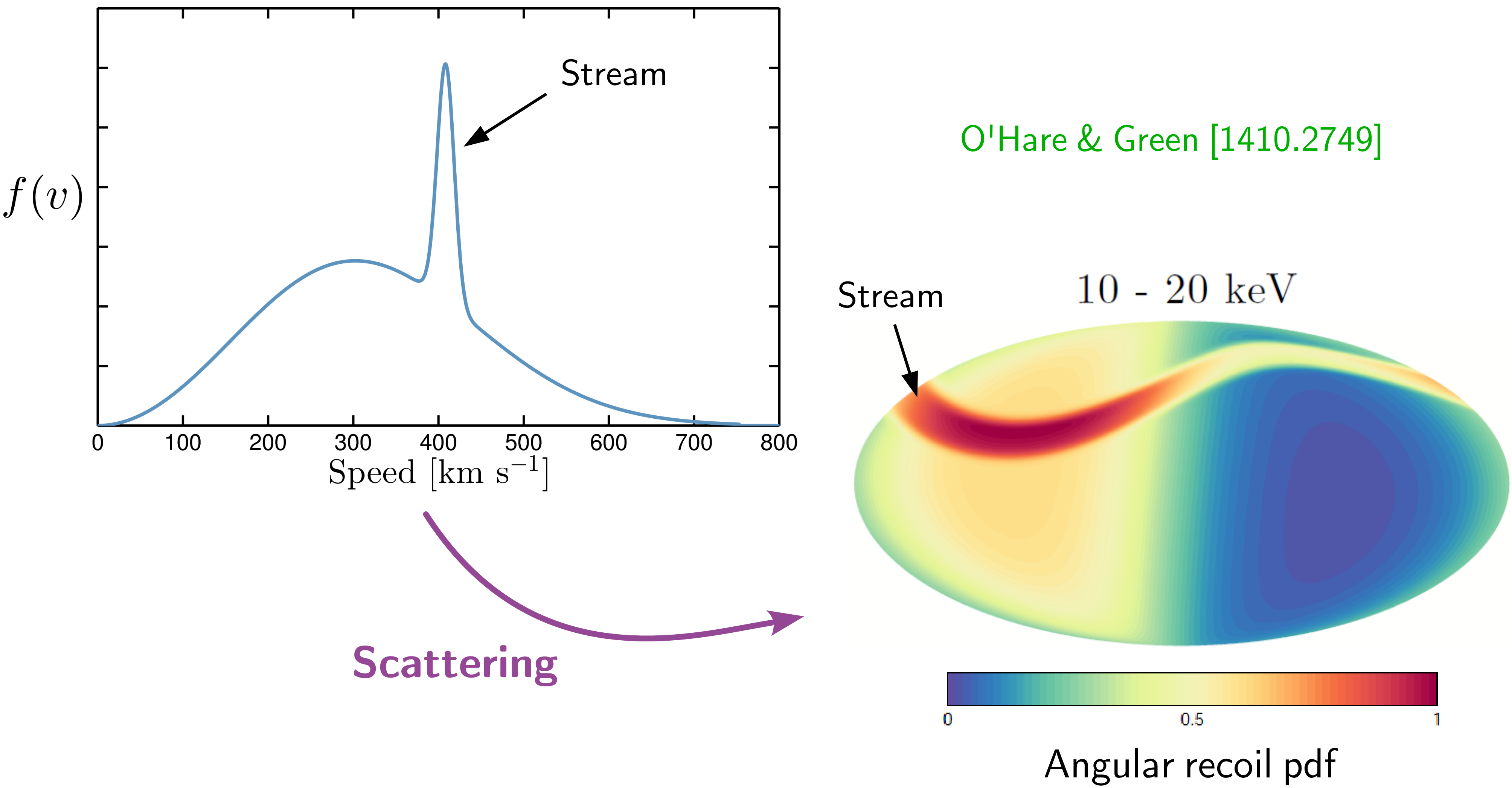

C.Couturier IDM 16

**Advantages:**

- Excellent electron-nuclear recoil discrimination Billard *et al* [1205.0973]
- Reject isotropy with $O(10)$ events Morgan *et al* [astro-ph/0408047]
- *Discover* DM with $O(30)$ events Green & Morgan[1002.2717]
- No neutrino floor Grothaus *et al* [1406.5047]
- Access *velocity* distribution Kavanagh & O'Hare [1609.08630]
- Probe DM substructure O'Hare & Green [1410.2749]

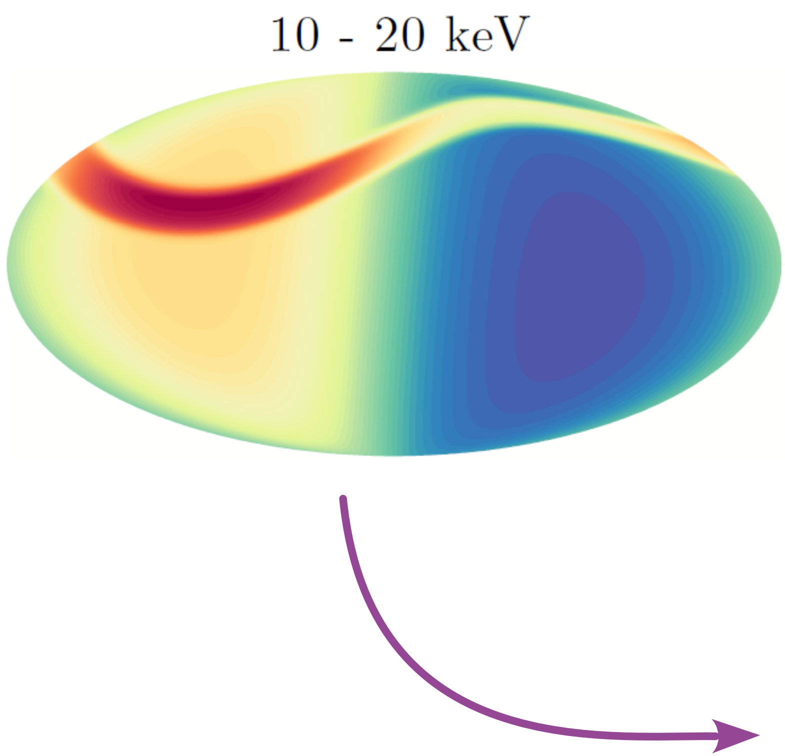
# Detecting streams

- Tidal streams produce striking directional recoil patterns:

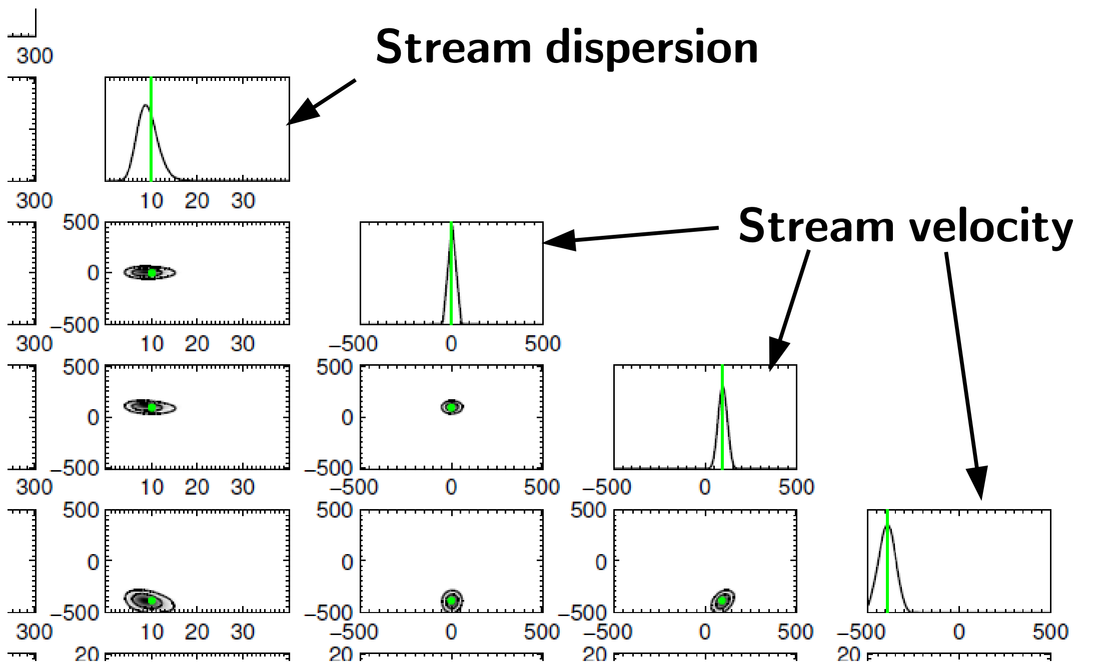


# Detecting streams

- Could detect Sagittarius stream with 20 kg-year directional detector
  - Non-parametrically (test for median direction/rotational symmetry)
  - Parametrically (model stream → likelihood fit)




O'Hare & Green [1410.2749]



# We want something more general...

**There are ways to deal with the unknown speed distribution in standard *non-directional* detection e.g.,**

- Halo independent methods
  e.g. Fox [1011.1915], Frandsen [1111.0292], Kahlhoefer [1607.04418], and many more...

  → Measure $g(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} \frac{1}{v} f(v) {\rm d}v$ from data

- General parameterisations e.g. Peter [1103.5145], Kavanagh & Green [1303.6868]

  → use something like $f(v) = \exp\left(-\sum_{k=0}^{N-1} a_k v^k\right)$ and fit for $a_k$

- Add uncertainties on parameters into fit e.g. Strigari & Trotta [0906.5361]

  → pick a model and estimate astrophysical parameters
  (with priors from measurements of MW)

- Add more parameters to deal with non-Maxwellian structure
  e.g. Lee, & Peter [1202.5035], O'Hare & Green [1410.2749]

**...But what about the <u>velocity</u> distribution?**

# Empirical velocity distribution

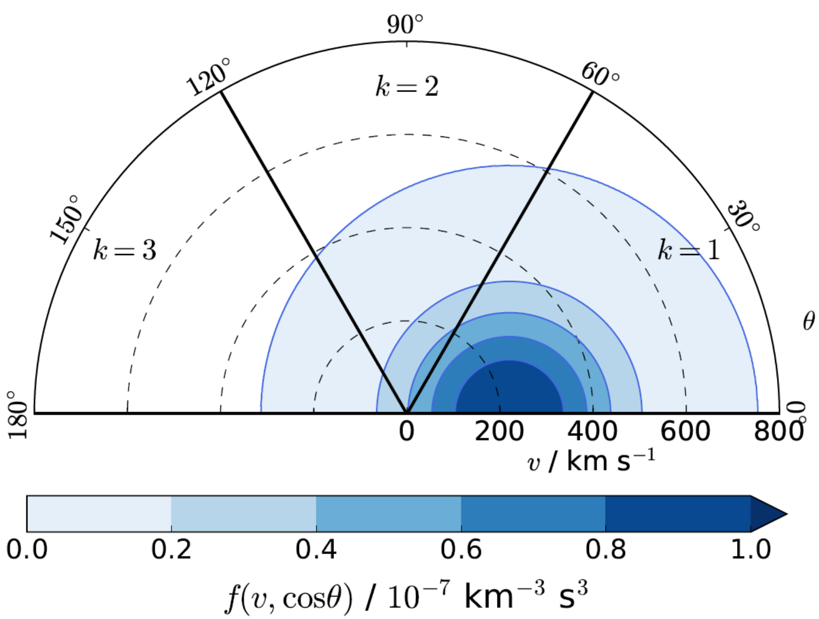
B. J. Kavanagh & C. A. J. O'Hare [1609.08630]

- Can we extract the velocity distribution from directional experiments in a model independent way?

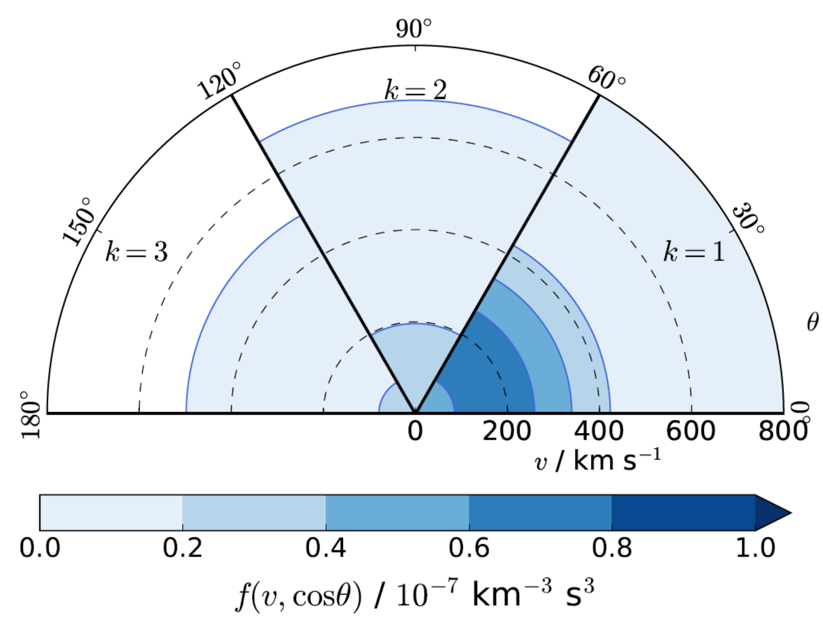
$$f(\mathbf{v}) = f(v, \cos\theta, \phi) = \begin{cases} f^1(v) & \text{for } \theta \in [0°, 60°] \\ f^2(v) & \text{for } \theta \in [60°, 120°] \\ f^3(v) & \text{for } \theta \in [120°, 180°] \end{cases}$$

**Empirical polynomial fit in each bin**
Kavanagh [1502.04224]

**True distribution**




**Angular discretisation**



# Reconstructing the velocity distribution

- For a given benchmark model generate mock data for two future directional detectors

| | Target | Threshold | Exposure |
|---|---|---|---|
| **Experiment 1:** | Xe | 5 keV | 1 ton-year |
| + | | | |
| **Experiment 2:** | F | 20 keV | 10 kg-year |

- Compare three methods of reconstruction

**Method A:**
**Best case**

We know the underlying velocity distribution and its parameters

***Fit: mass, cross-section***

**Method B:**
**Reasonable case**

We know the form of the velocity distribution but not the parameters

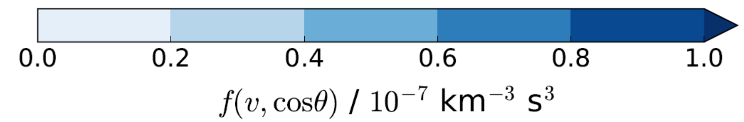
***Fit: mass, cross section + astrophysical params.***

**Method C:**
**Worst case**

We know nothing at all about the velocity distribution

***Fit: mass, cross section + empirical parameters***

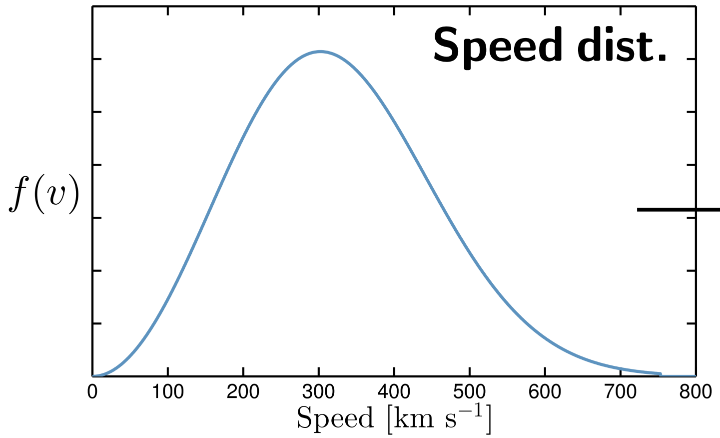
# Benchmarks

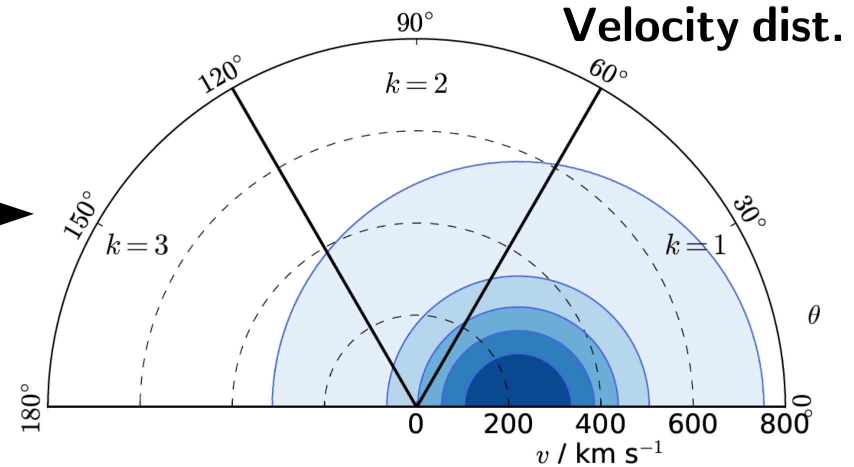



**SHM:**

$v_0 = 220$ km/s

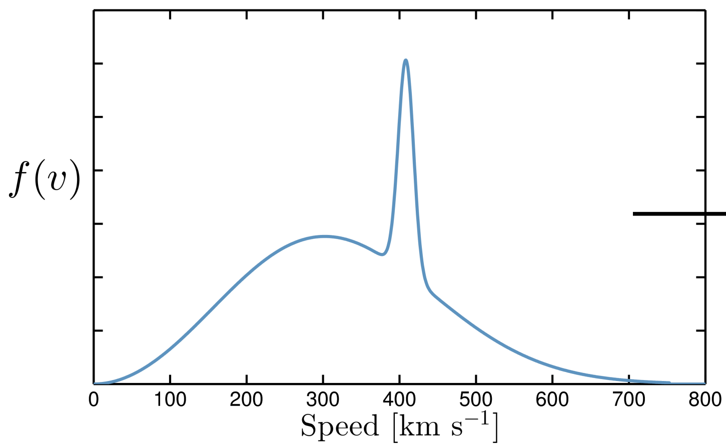
$v_{esc} = 533$ km/s

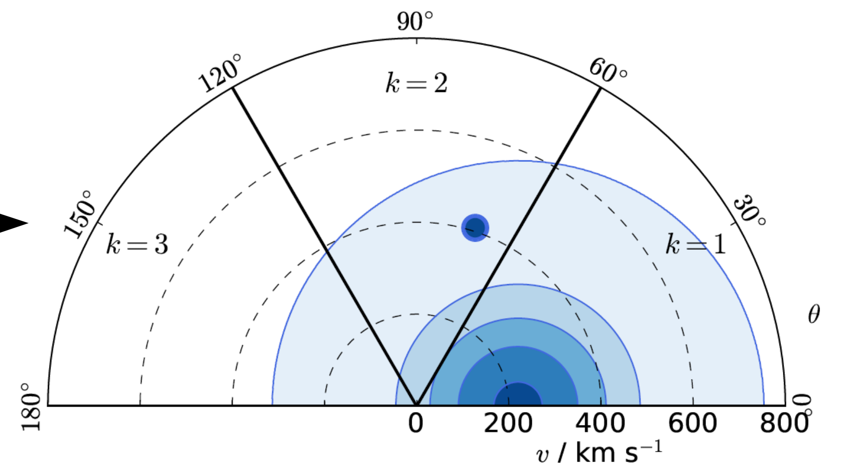



**SHM+Stream:**

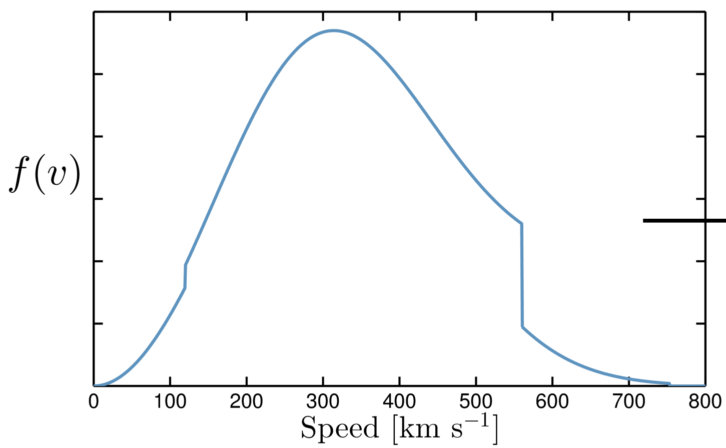
Purcell [1203.6617]

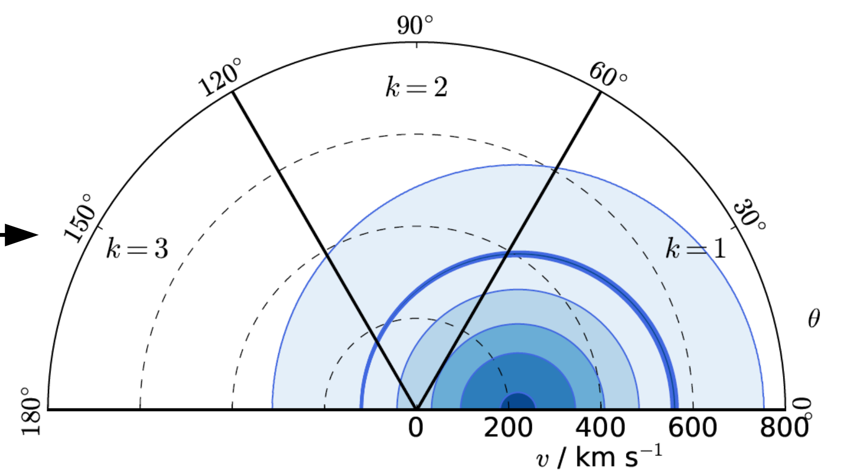


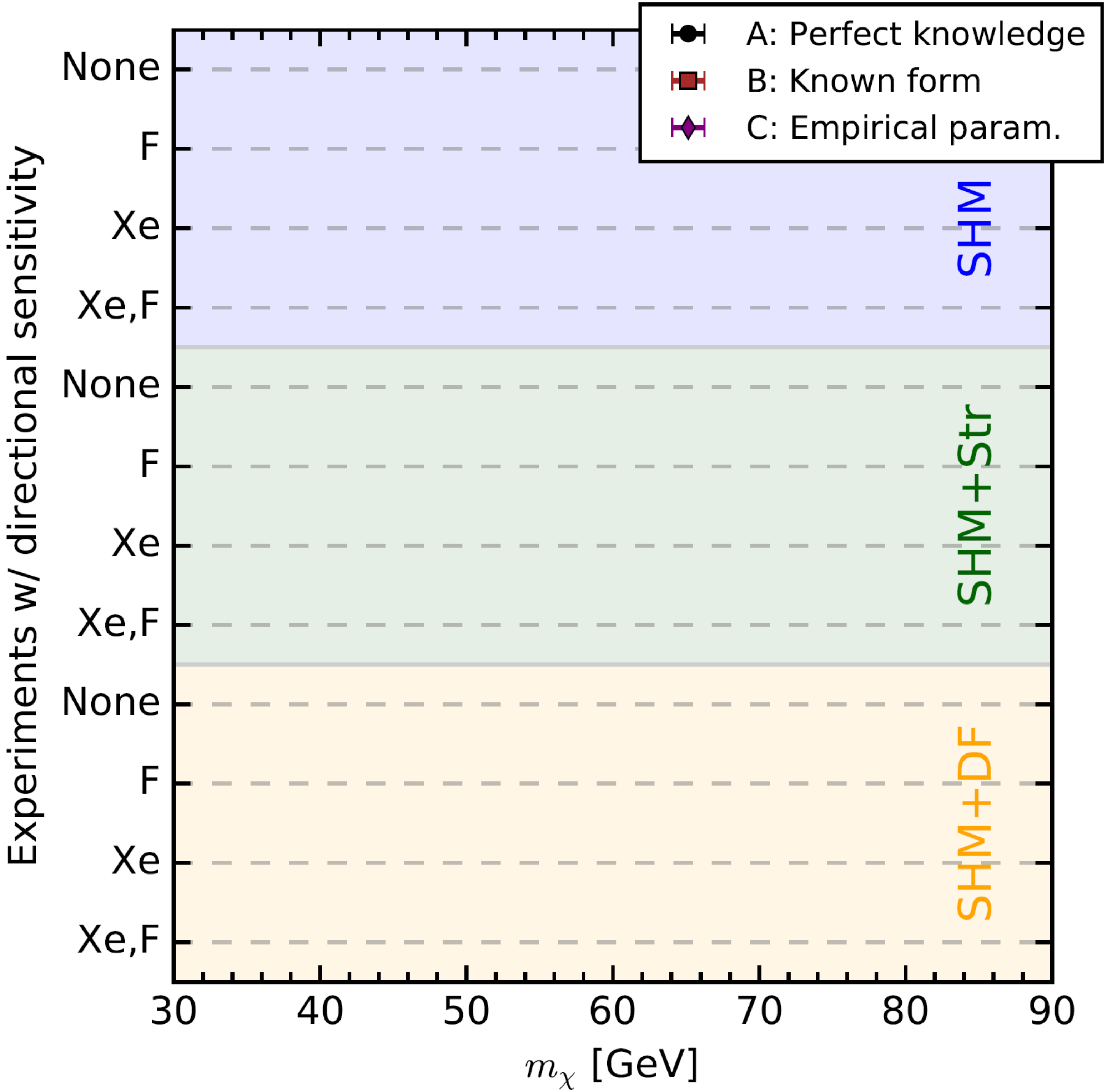



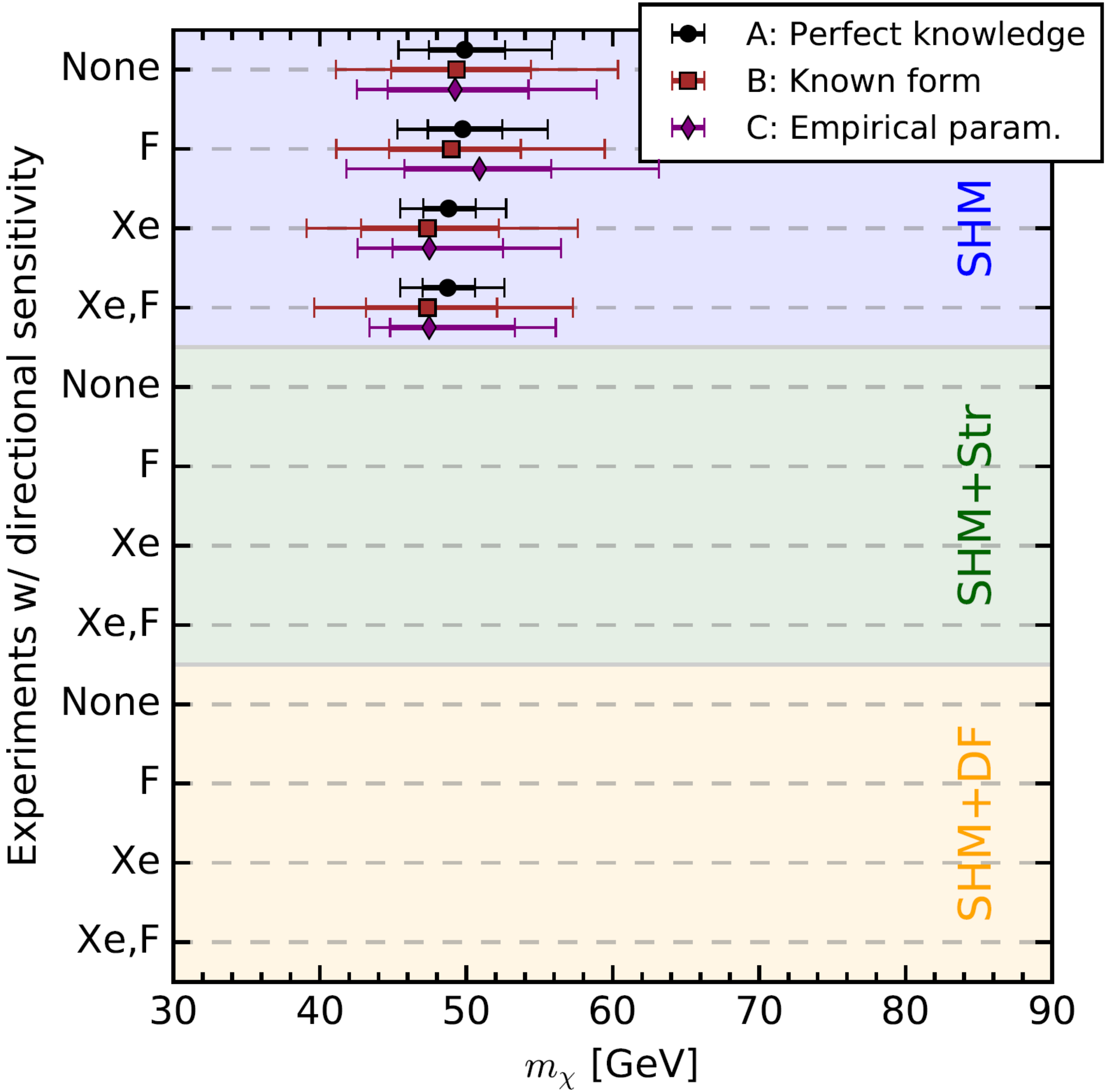

**SHM+Debris flow:**

Kuhlen [1202.0007]




A: Perfect knowledge
B: Known form
C: Empirical param.
SHM
SHM+Str
SHM+DF
None
F
Xe
Xe,F
Experiments w/ directional sensitivity
30
40
50
60
70
80
90
$m_\chi$ [GeV]



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Xe,F
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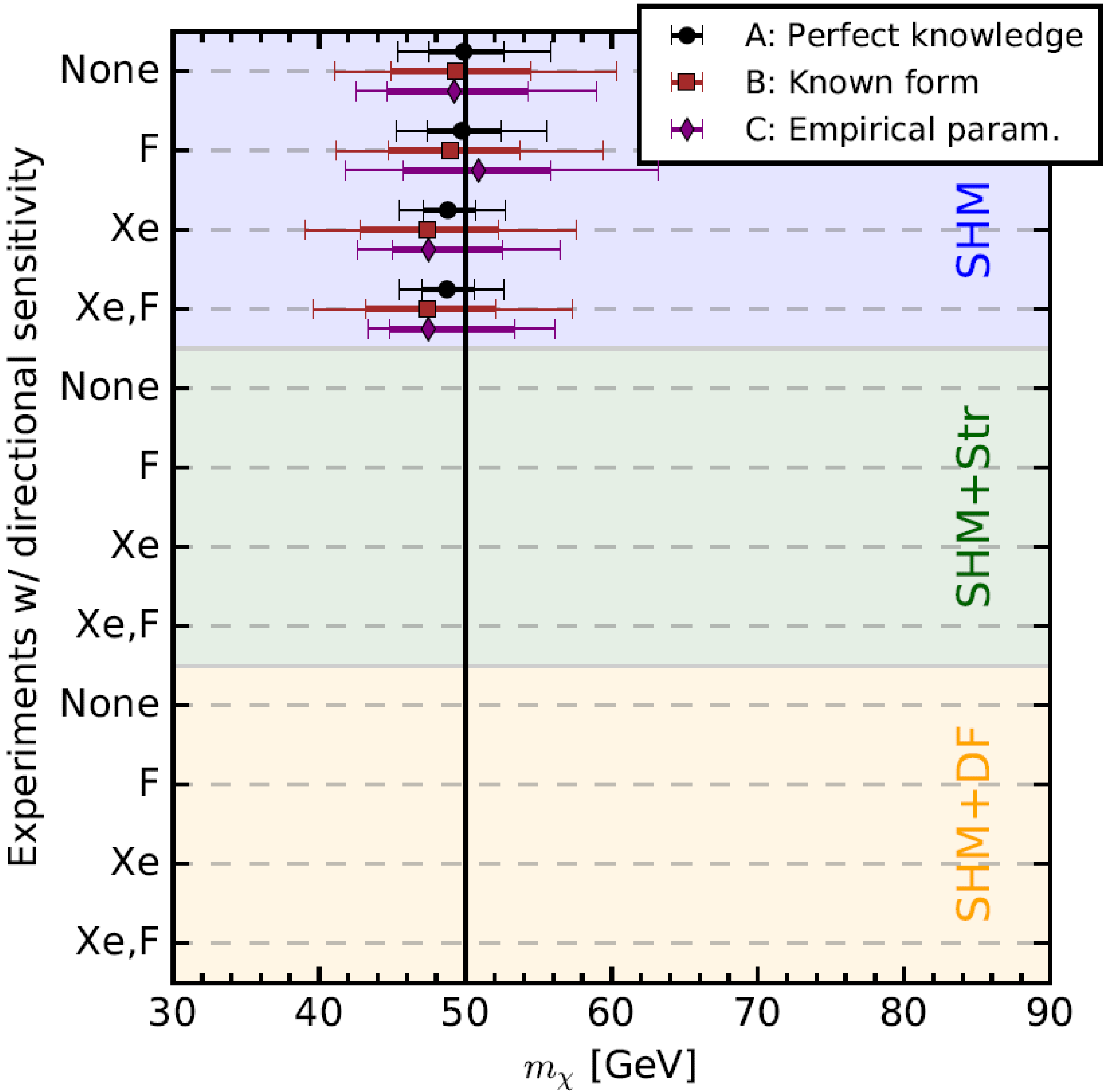

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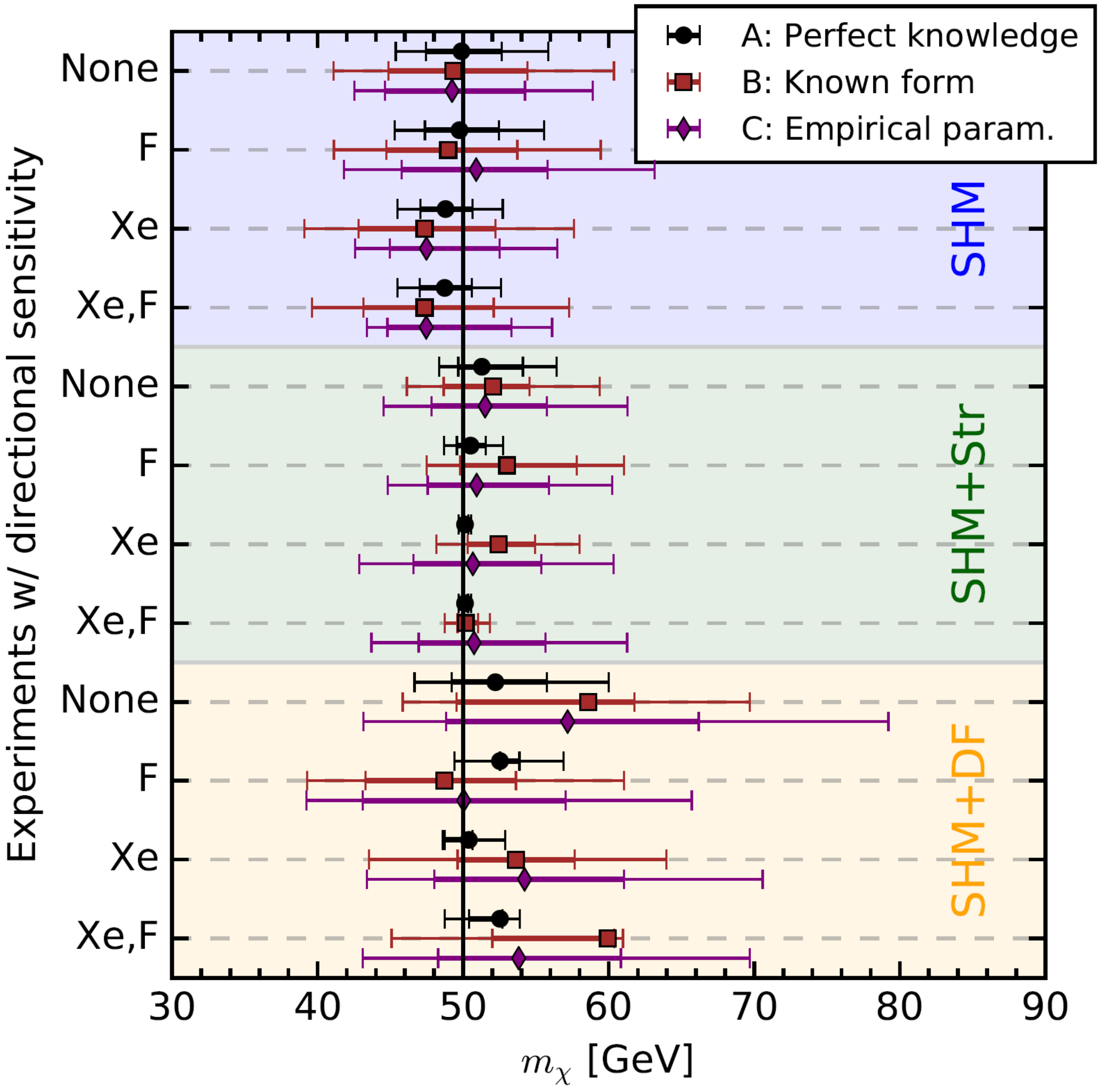

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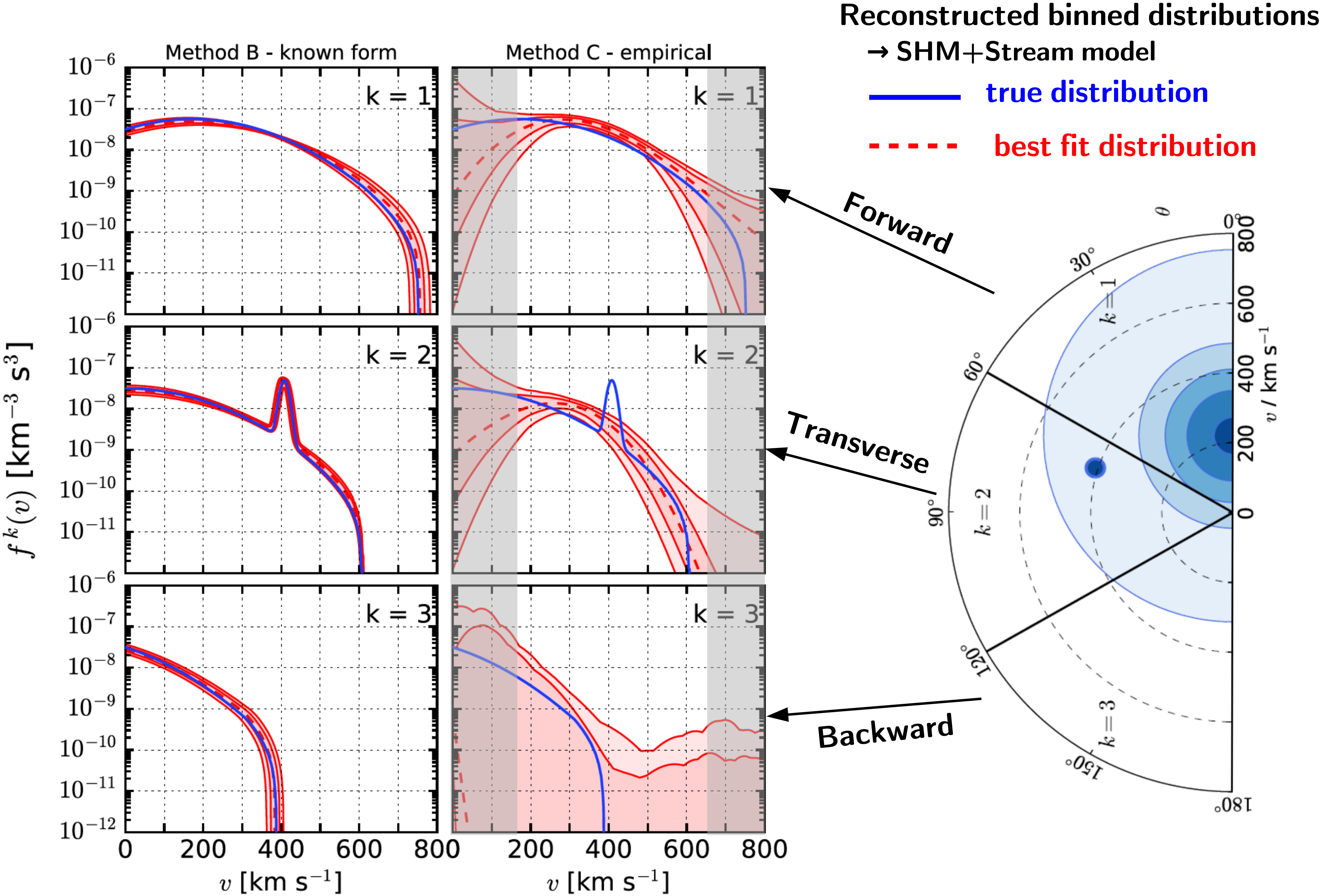
$m_\chi$ [GeV]

# Shape of velocity distribution

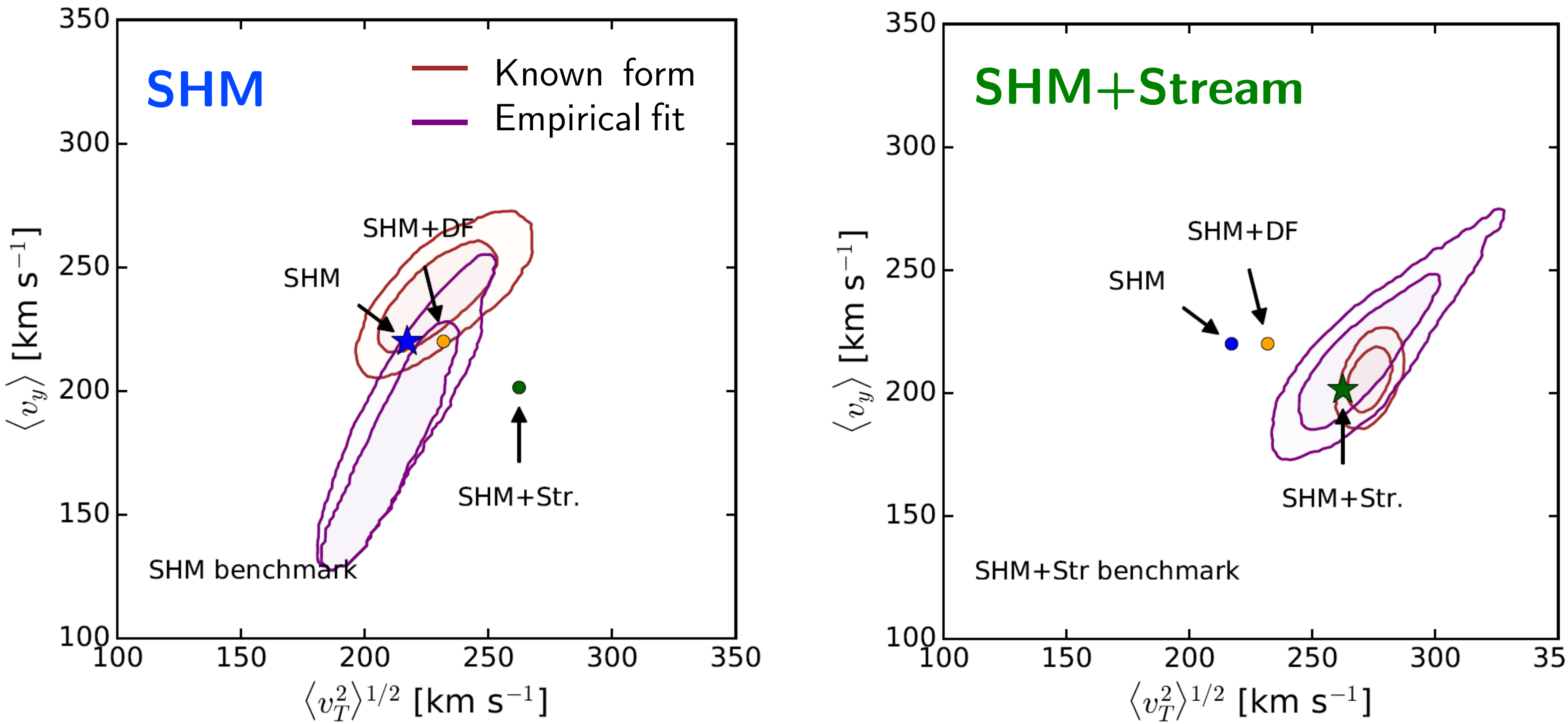


# Comparing reconstructions

- Ideally we extract something physical to hint towards substructure e.g. directionally averaged speeds:

Average *parallel* to Earth's motion: $\langle v_y \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v\cos\theta) \, v^2 f(\mathbf{v})$

Average *transverse* to Earth's motion: $\langle v_T^2 \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v^2 \sin^2\theta) \, v^2 f(\mathbf{v})$



# How could we use this method?

1. Detect dark matter (in a directional detector)

   ...

2. Measure WIMP parameters

   → use an empirical method to avoid bias

3. Derive velocity parameters

   → Do they hint towards substructure?

4. If so, fit with particular model

   → substructure detected?

# Axions

# Strong CP problem

QCD permits a CP violating term,

**Gluon fields** **Quarks** **CP-violating term**

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \bar{q}(i\gamma_\mu D^\mu - \mathcal{M}_q) q + \frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

**But neutron EDM measurements constrain phase** →

$$\bar{\theta} = \theta + \arg\det \mathcal{M}_q < 10^{-10}$$

Baker *et al* [hep-ex/0602020]

**Strong CP problem: why is the CP-violating phase so unnaturally small?**

# Peccei-Quinn mechanism

- Solution to strong-CP problem: promote phase to dynamical field

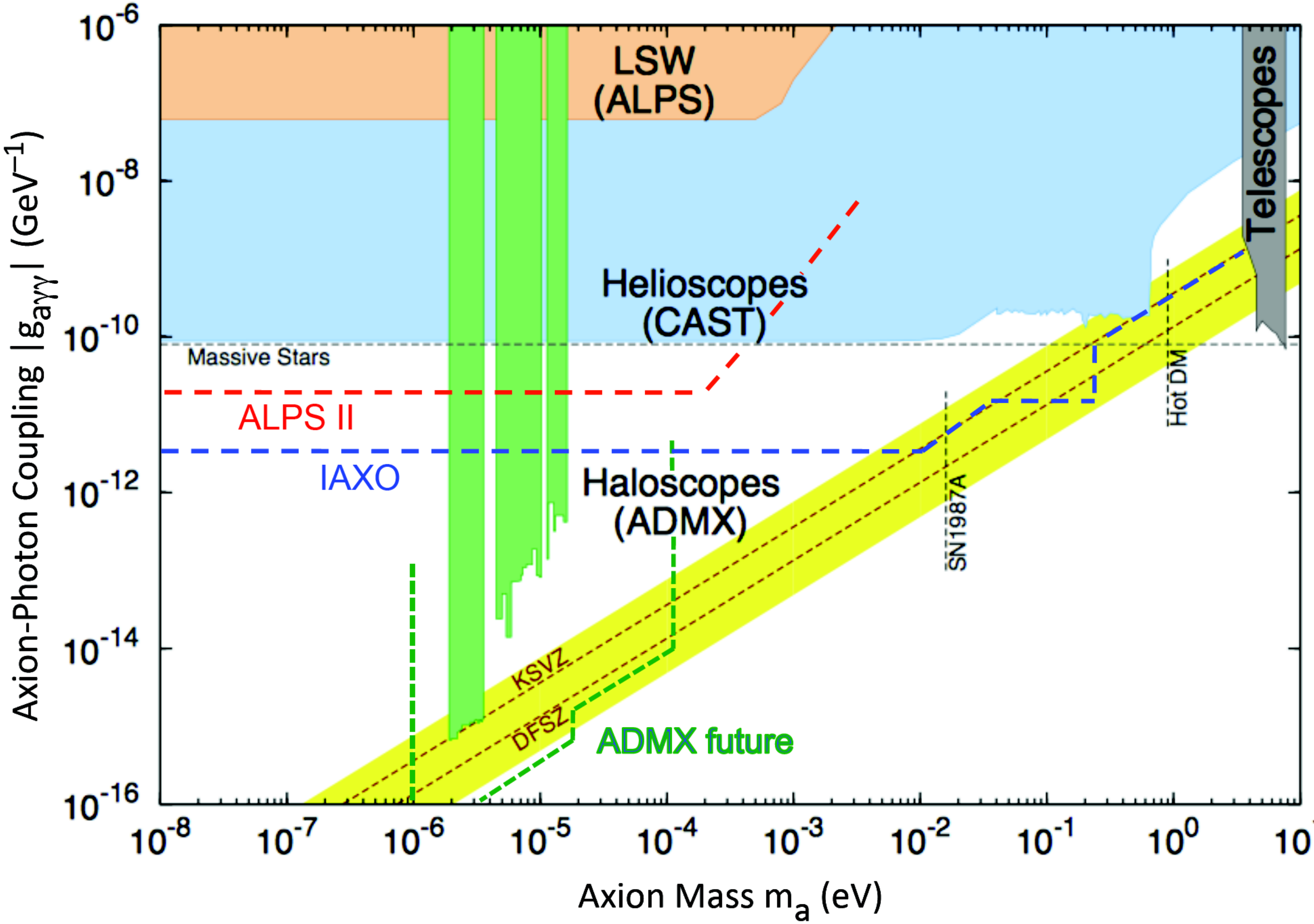
$$\mathcal{L}_{\mathrm{QCD+axion}} = \ldots + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Field vev nulls the CP violation
- Predicts a new particle, **the axion**
- Small mass given by QCD instanton effects (pion mixing)

$$m_a \sim 6\,\mathrm{eV}\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)$$

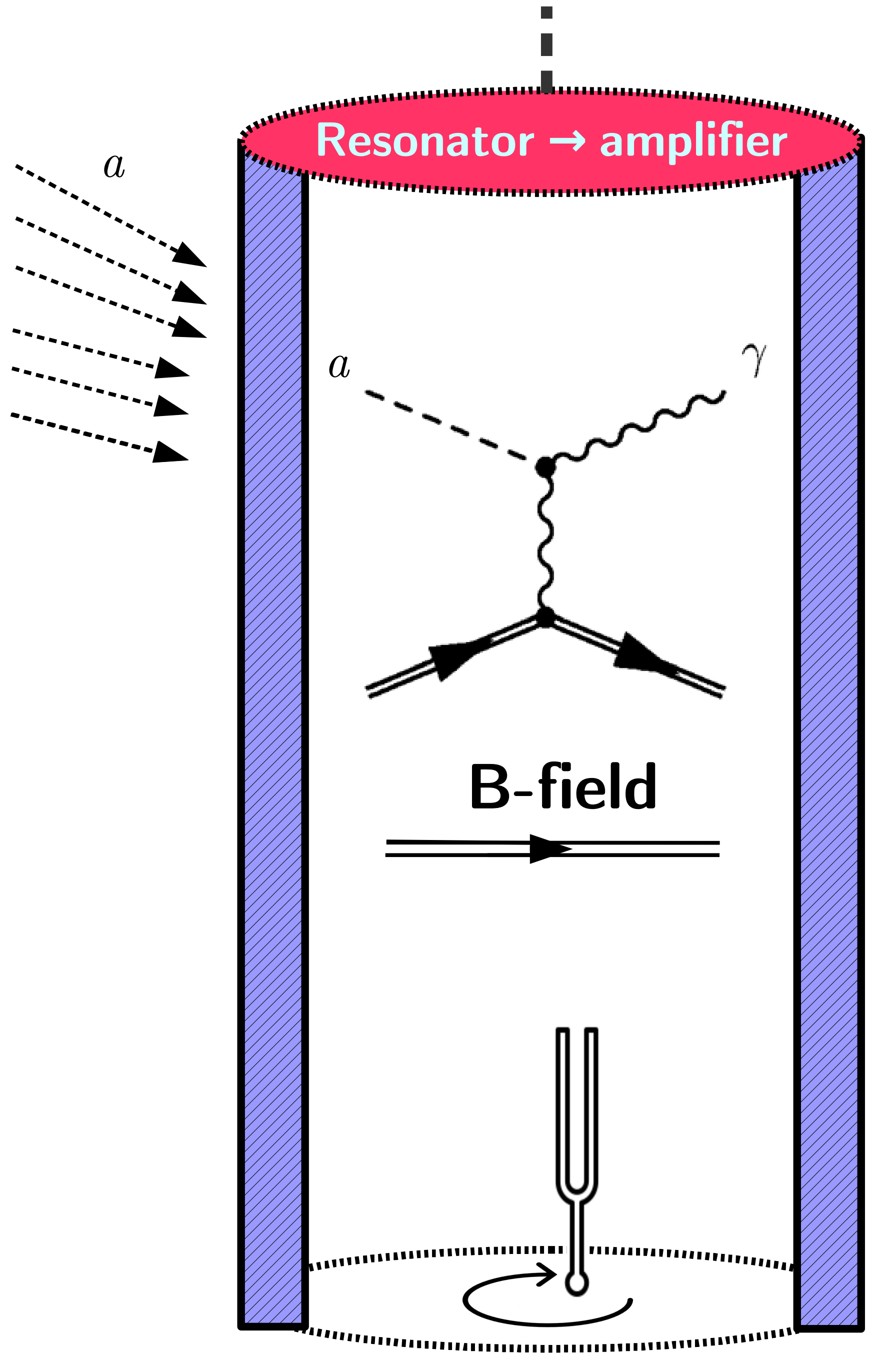
# Axion/ALP constraints

- Generalise to light particles outside of the PQ solution,
  → **axion-like particles (ALPs)**
- Measure conversion to photons inside magnetic fields:



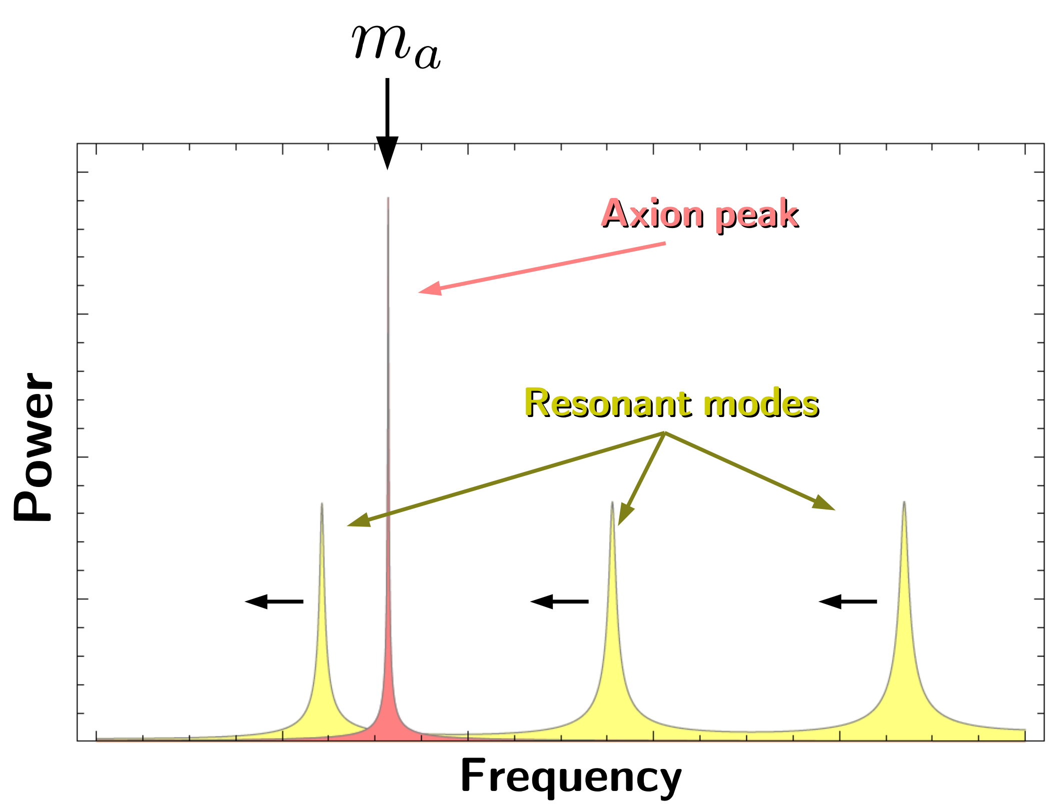

P.W. Graham *et al* [1602.00039]

# Axion Haloscope




- **Signal enhancement:**
  → resonant frequency = axion mass
  $$h\nu = m_a c^2$$

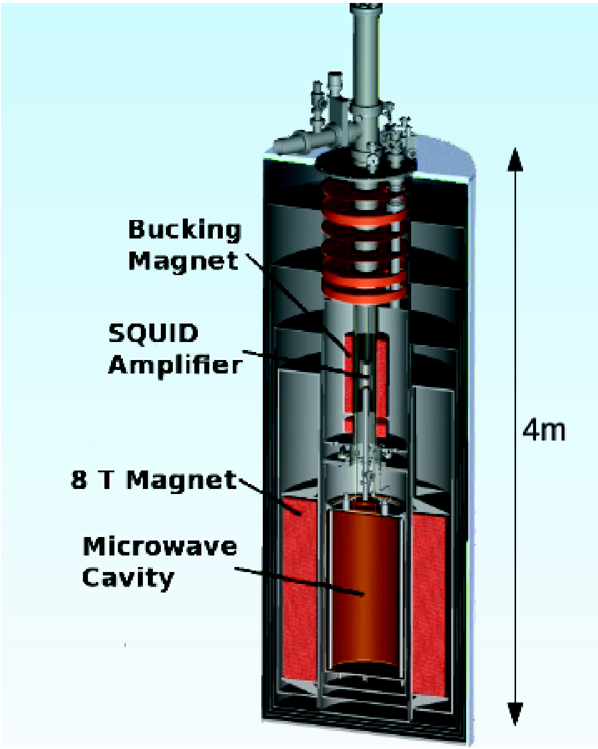
- **But we don't know axion mass...**
  → Must scan over a range of frequencies

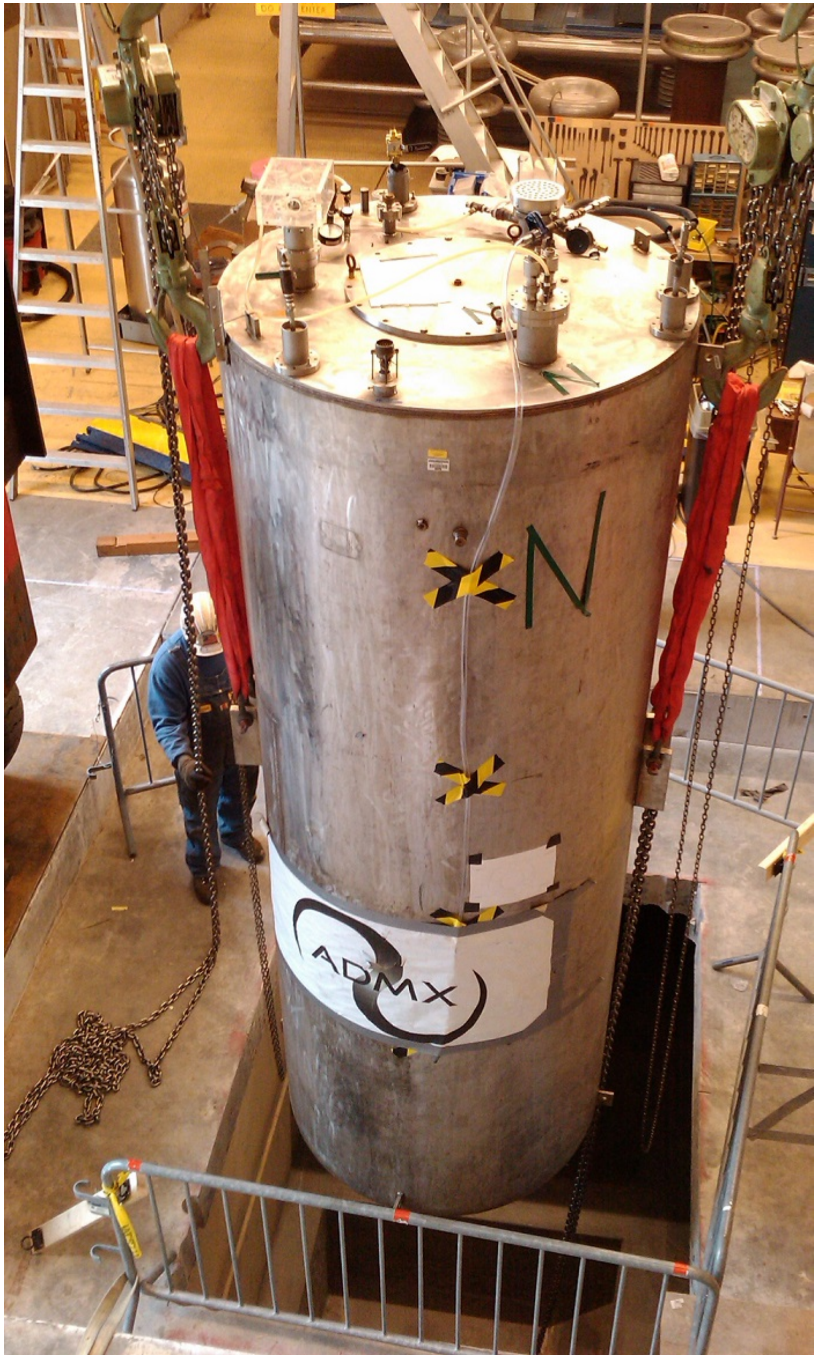


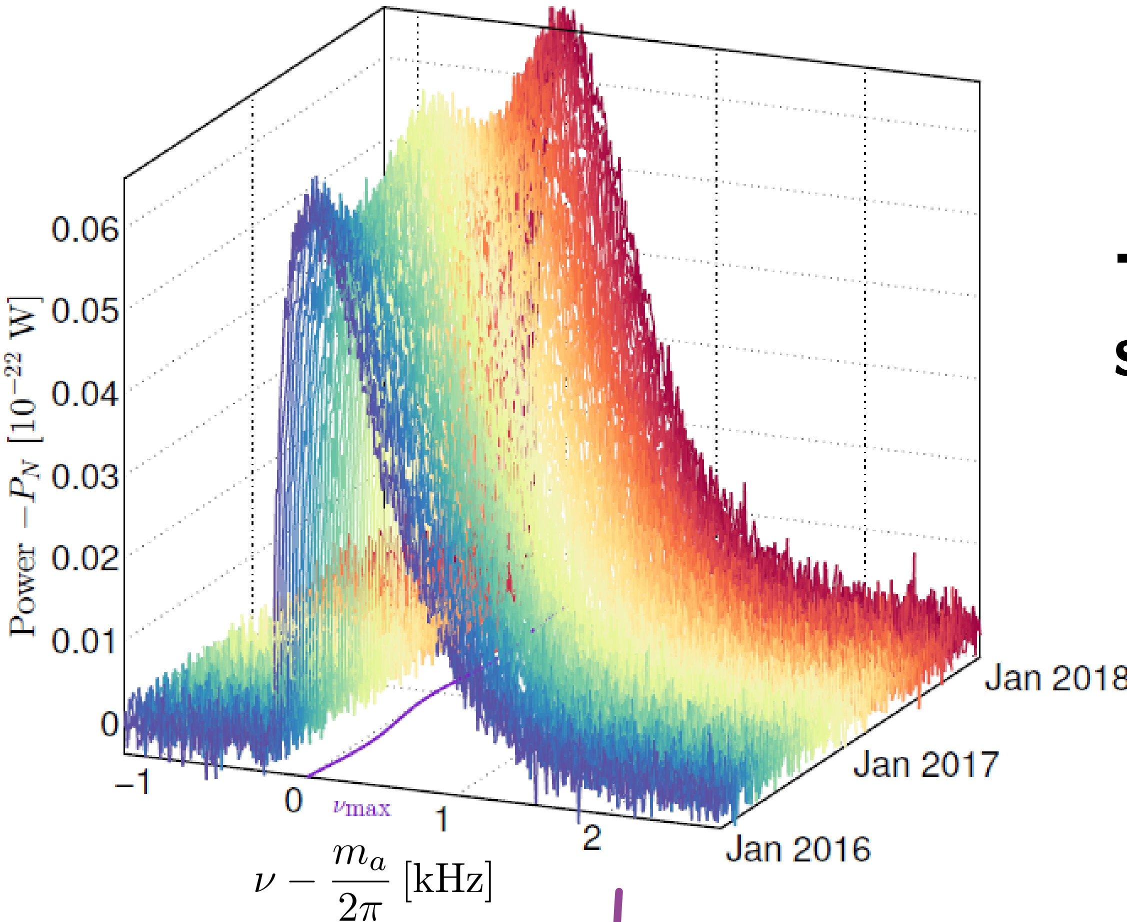
# Axion Dark Matter Experiment (ADMX)

ADMX Asztalos et al [0910.5914]

- Resonate at microwave freqs.
- 8T B-field
- 4 K noise temperature
- 200 litre volume
- Measure power < $10^{-22}$ W

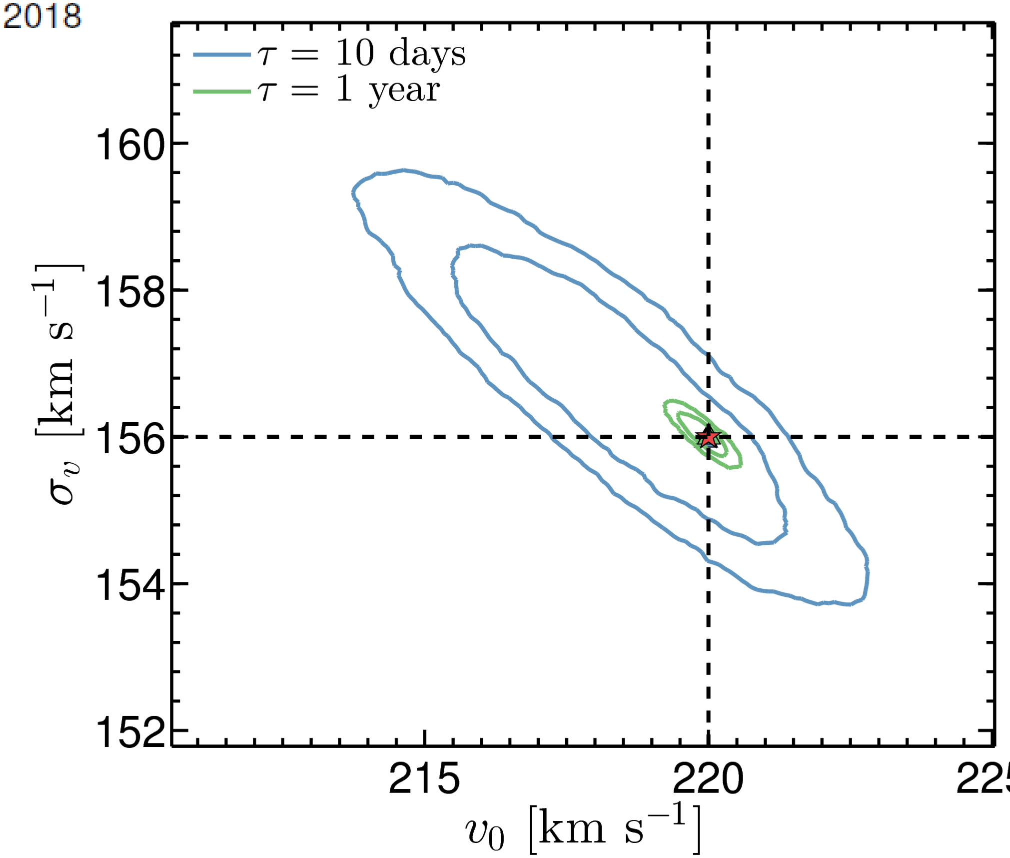




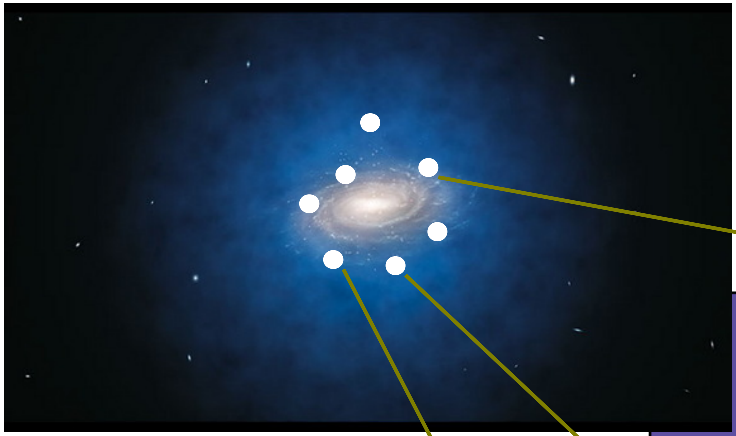

→ ***Measure*** **axion power spectrum**

O'Hare & Green [*in prep.*]



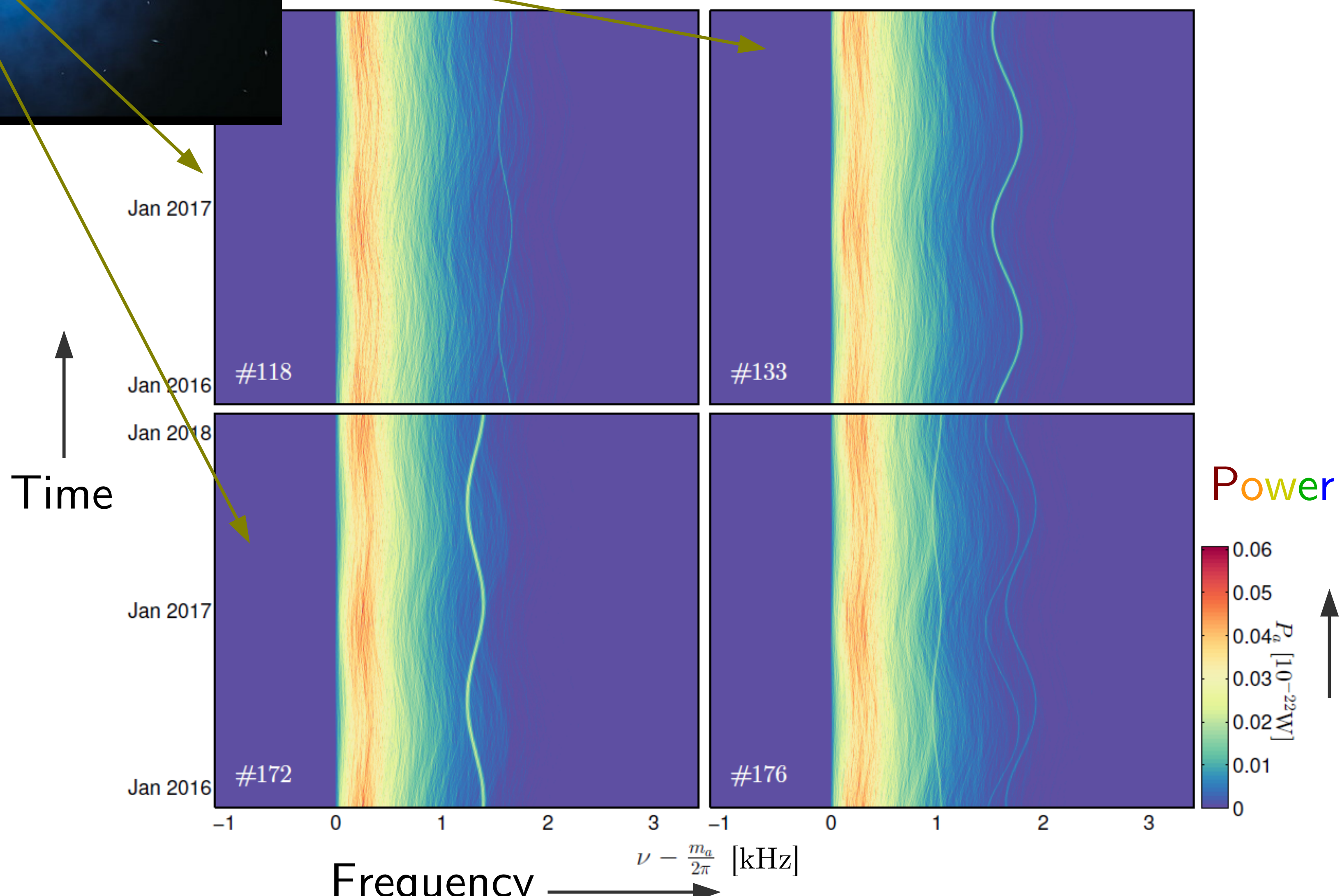

**Extract astrophysical parameters**

# Example power spectra from distributions in VL2 simulation



- **Samples from 1 kpc bubbles @ 8 kpc Gal. radius**

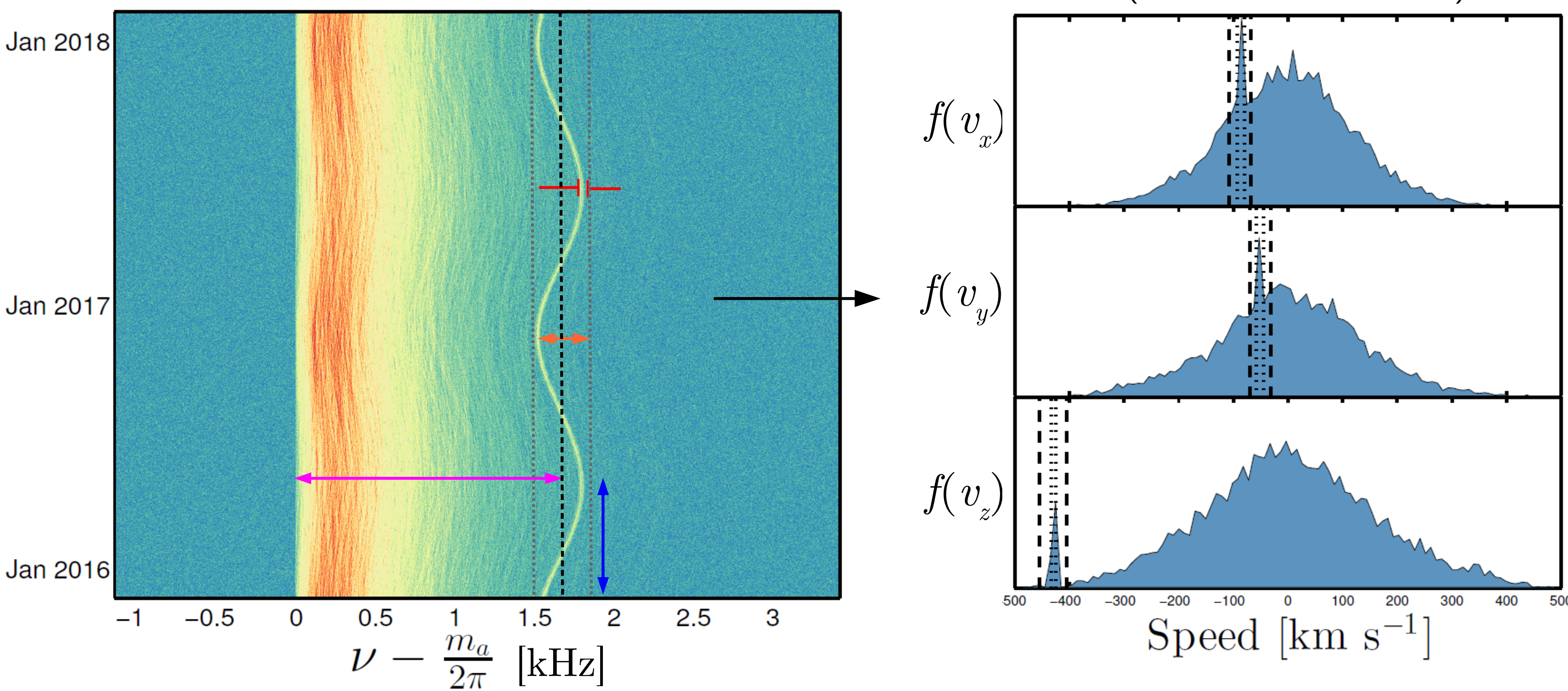
O'Hare & Green [*in prep.*]



# Measuring axion streams

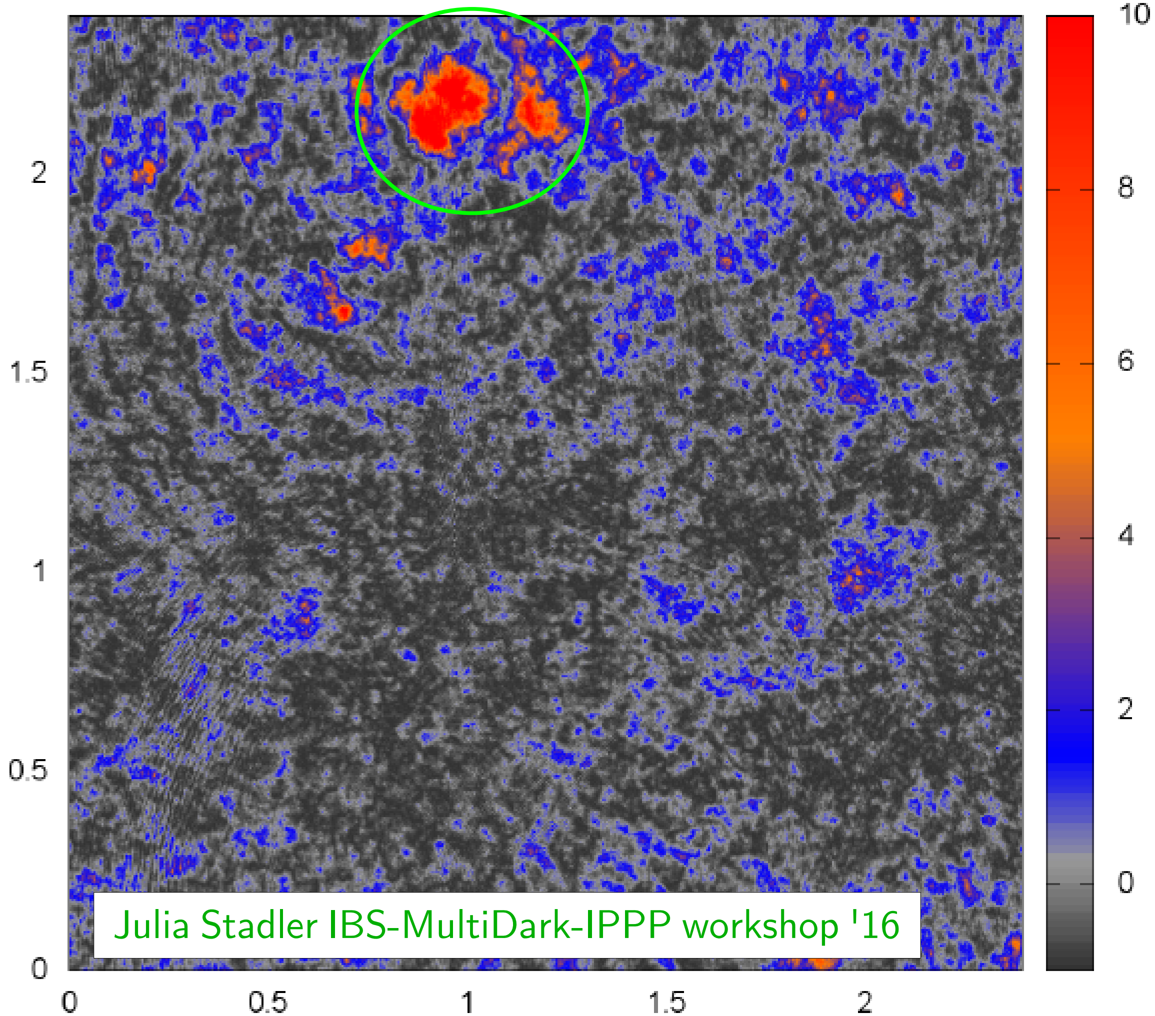
- **Can extract all five properties of a stream from sinusoid**
  - Stream density ← Power relative to bulk
  - Stream dispersion ← Width of sinusoid
  - Galactic velocity ← Amplitude, phase and mean of sinusoid

O'Hare & Green [*in prep.*]



# Axion miniclusters

- Collapsing density perturbations in the early Universe can form small clusters of axions




Density contrast: $\Phi = \frac{\delta\rho}{\rho} \sim 1$

Mass: $M \sim 10^{-12}\, M_\odot$

Radius: $R \sim 10^7\,\mathrm{km}$

Density: $\rho \sim 10^6\,\mathrm{GeV\,cm^{-3}}$

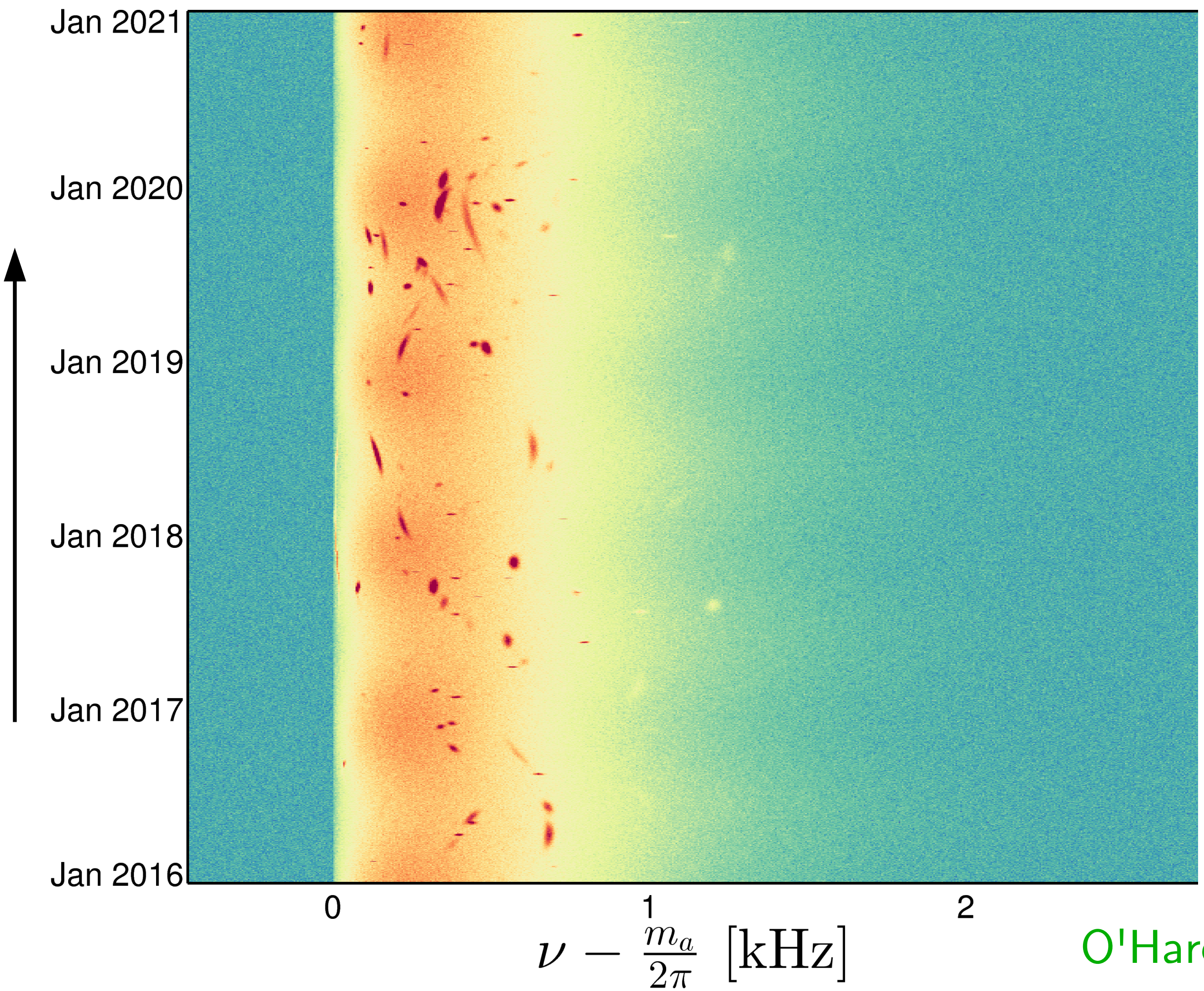
- Could comprise non-negligible fraction of DM halo
- Up to $10^{10}$ $\mathrm{pc}^{-3}$ in the local stellar neighbourhood?

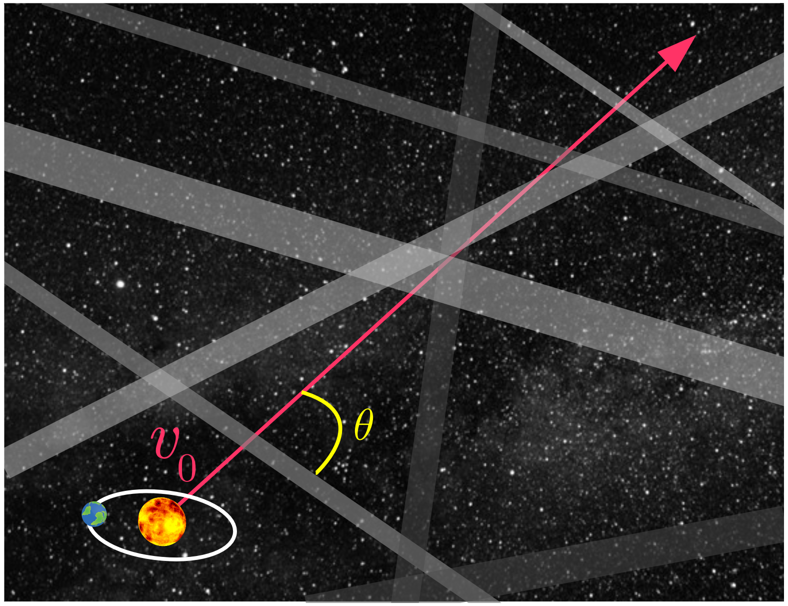
Tinyakov [1512.02884]

# Axion miniclusters

- Tidally disrupted by interactions with stars
  - → network of minicluster streams wrapping Milky Way
  - → stream crossing time O(1-100) days Tinyakov [1512.02884]

$$R_{\rm str} \simeq \frac{3.4\times 10^7\,{\rm km}}{\Phi(1+\Phi)^{1/3}}\left(\frac{M_{\rm mc}}{10^{-12}M_\odot}\right)^{1/3} \longrightarrow \tau_{\text{str-x}} = \frac{2R_{\rm str}}{v_0\sqrt{1-\frac{\mathbf{v}_{\rm str}\cdot\mathbf{v}_{\rm lab}}{v_0 v_{\rm str}}}}$$




**Would need to be separated from environmental noise peaks with use of time/daily modulation**

O'Hare & Green [*in prep.*]

# Summary

**We must understand local MW halo to do dark matter detection** ⟷ **Dark matter detectors can help us understand the local MW halo**

- Uncertainty in exclusion limits
- Biased particle measurements
- Neutrino floor closer to existing limits

- Directional detectors/ haloscopes well suited to study the local halo
- Observe non-Maxwellian structure
- Learn about formation history of MW

# Dark matter halo

**Event rate dependent on** $\rho_0 \int f_{\rm lab}(\mathbf{v},t)\delta(\mathbf{v}\cdot\mathbf{q} - \hat{v}_{\rm min})\mathrm{d}^3\mathbf{v}$

- local density $\rho_0$
- velocity distribution $f_{\rm lab}(\mathbf{v},t) = f_{\rm gal}(\mathbf{v} + \mathbf{v}_{\rm lab}(t))$

→ lab velocity: $\mathbf{v}_{\rm lab}(t) = \mathbf{v}_{\rm LSR} + \mathbf{v}_{\rm pec} + \mathbf{v}_{\rm rev}(t) + \mathbf{v}_{\rm rot}(t)$

~220 km/s ~18 km/s ~30 km/s ~0.5 km/s