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WIMP/axion astronomy in dark matter experiments

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The problem:

Predicting direct detection signals requires knowledge of the *unknown* dark matter velocity distribution

The solution:

Pre-detection

- Make an assumption
- Account for our ignorance
- Figure out what it might be (simulations)

→

Post-detection:

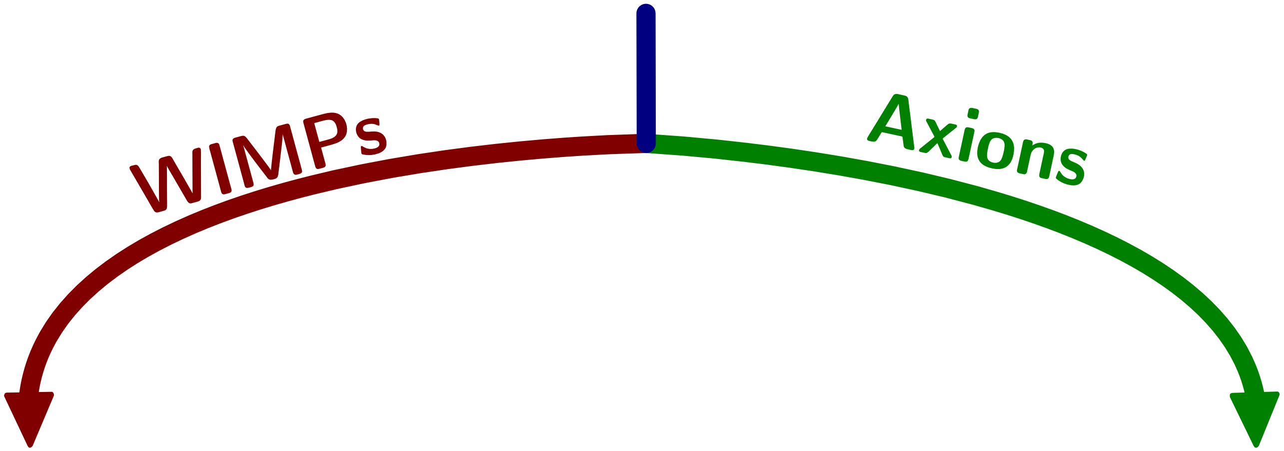
- Measure it (this talk)

Outline

Astrophysical uncertainties in dark matter detection

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

Measuring the dark matter velocity distribution



Directional detectors

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

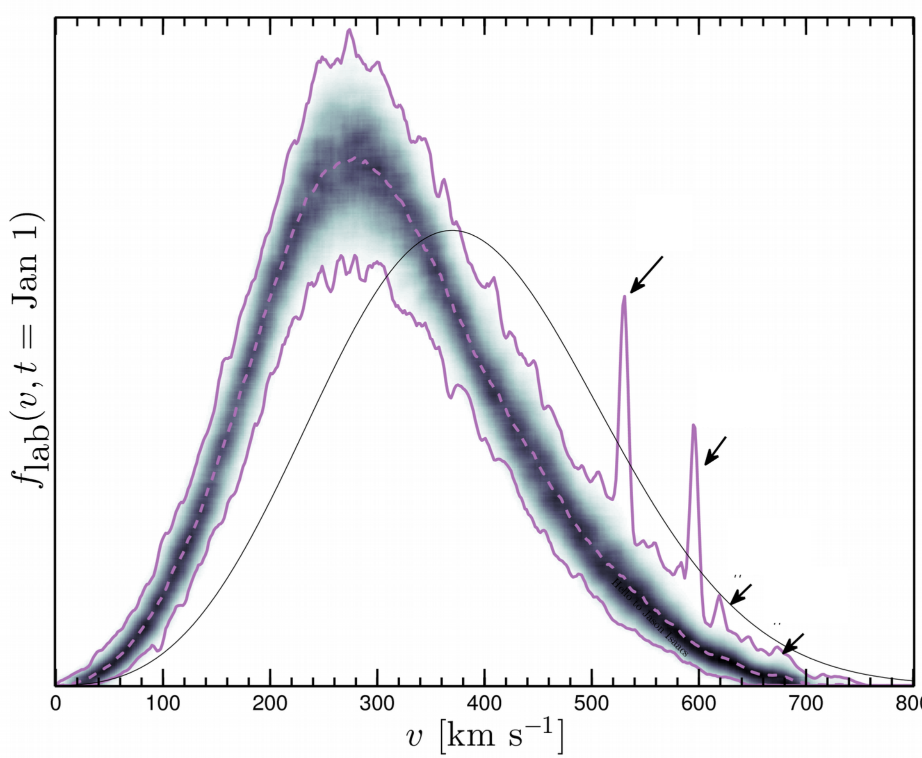
Haloscopes

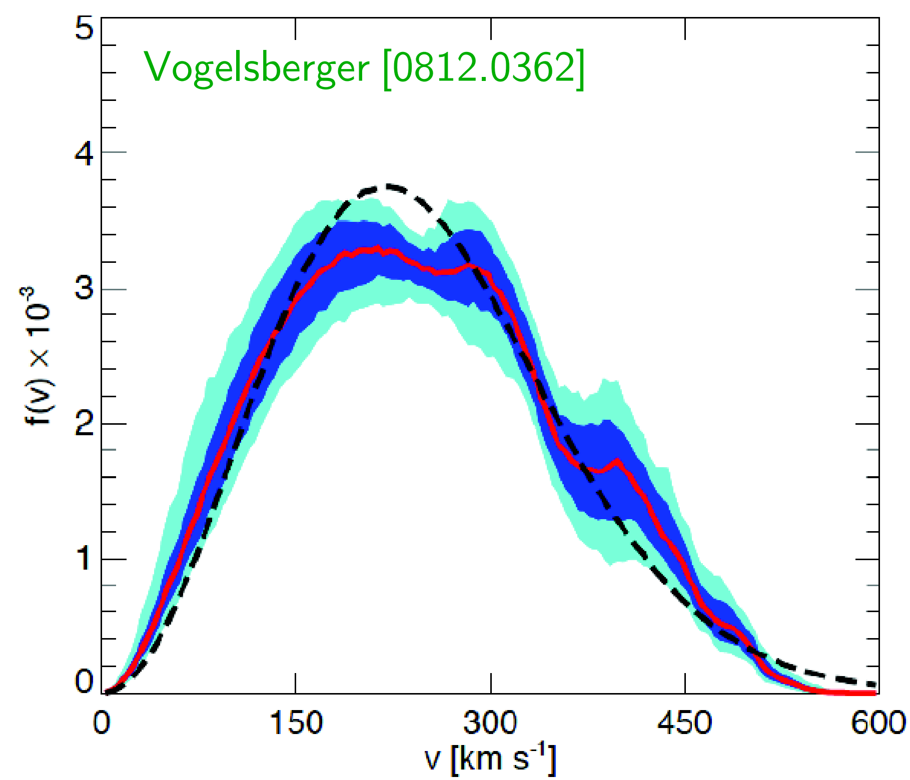
- C. A. J. O'Hare & A. M. Green [1701.03118]

The Milky Way velocity distribution

- Usually assume Maxwellian $f(v)$
- Simulations persistently exhibit non-Maxwellian features and can include substructure components,

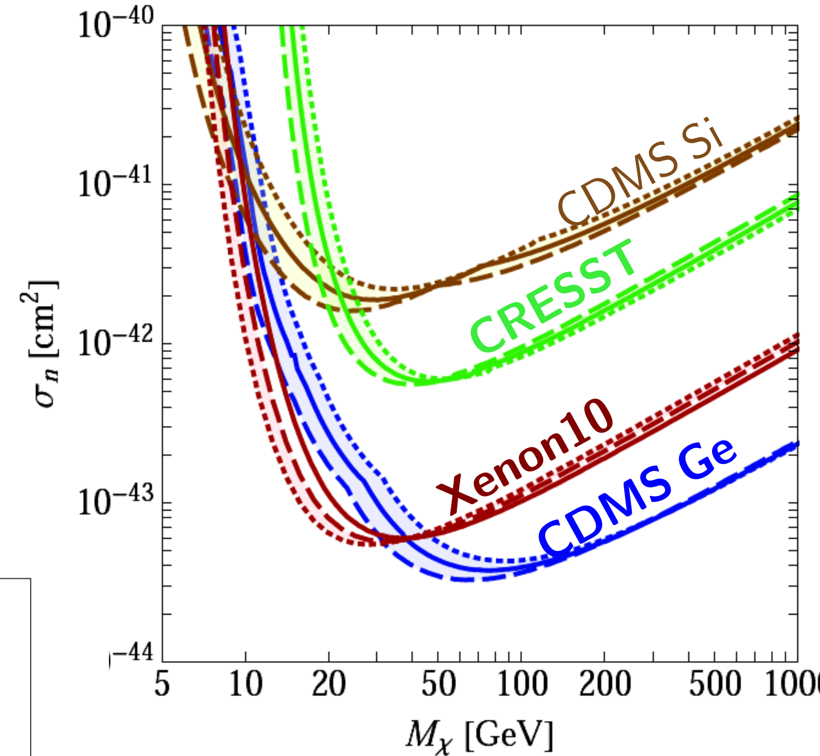
  e.g. → streams Purcell et al. [1203.6617]
  → dark disk Schaller et al. [1605.02770]
  → debris flows Kuhlen et al. [1202.0007]
  → axion miniclusters Kolb & Tkachev [hep-ph/9303313]

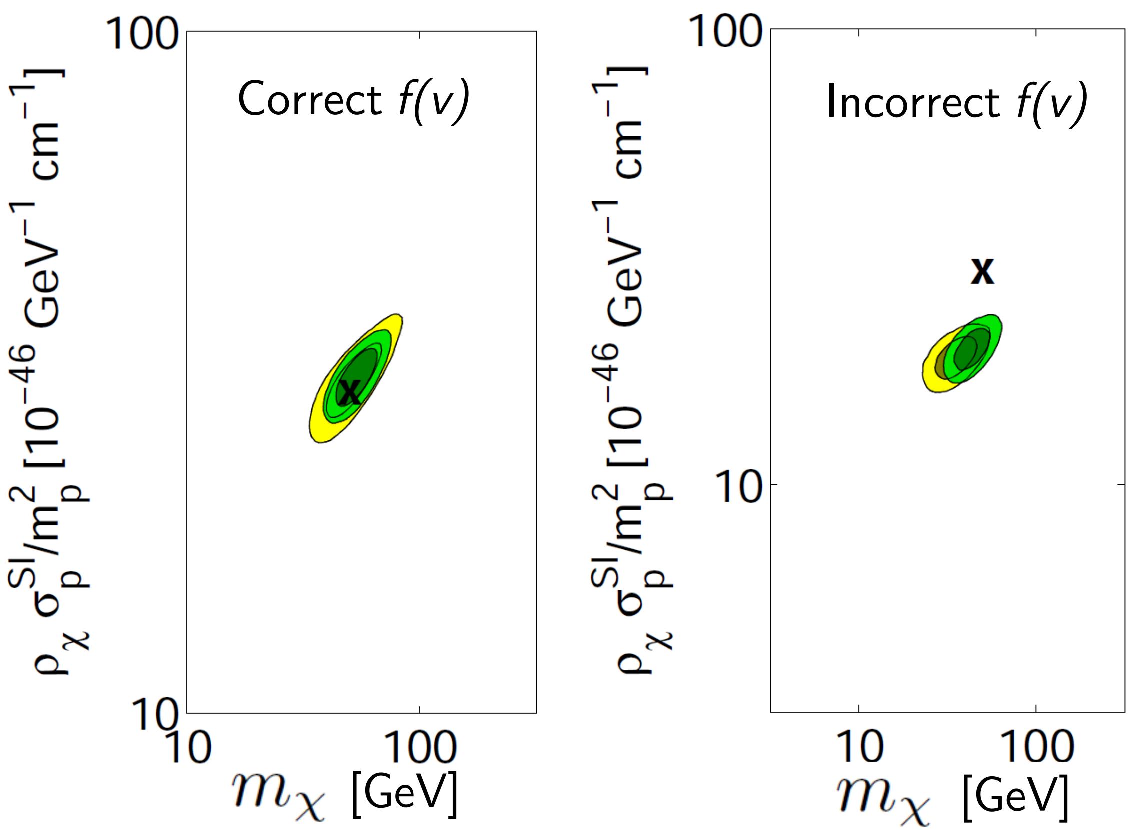




Effect of astrophysical uncertainties

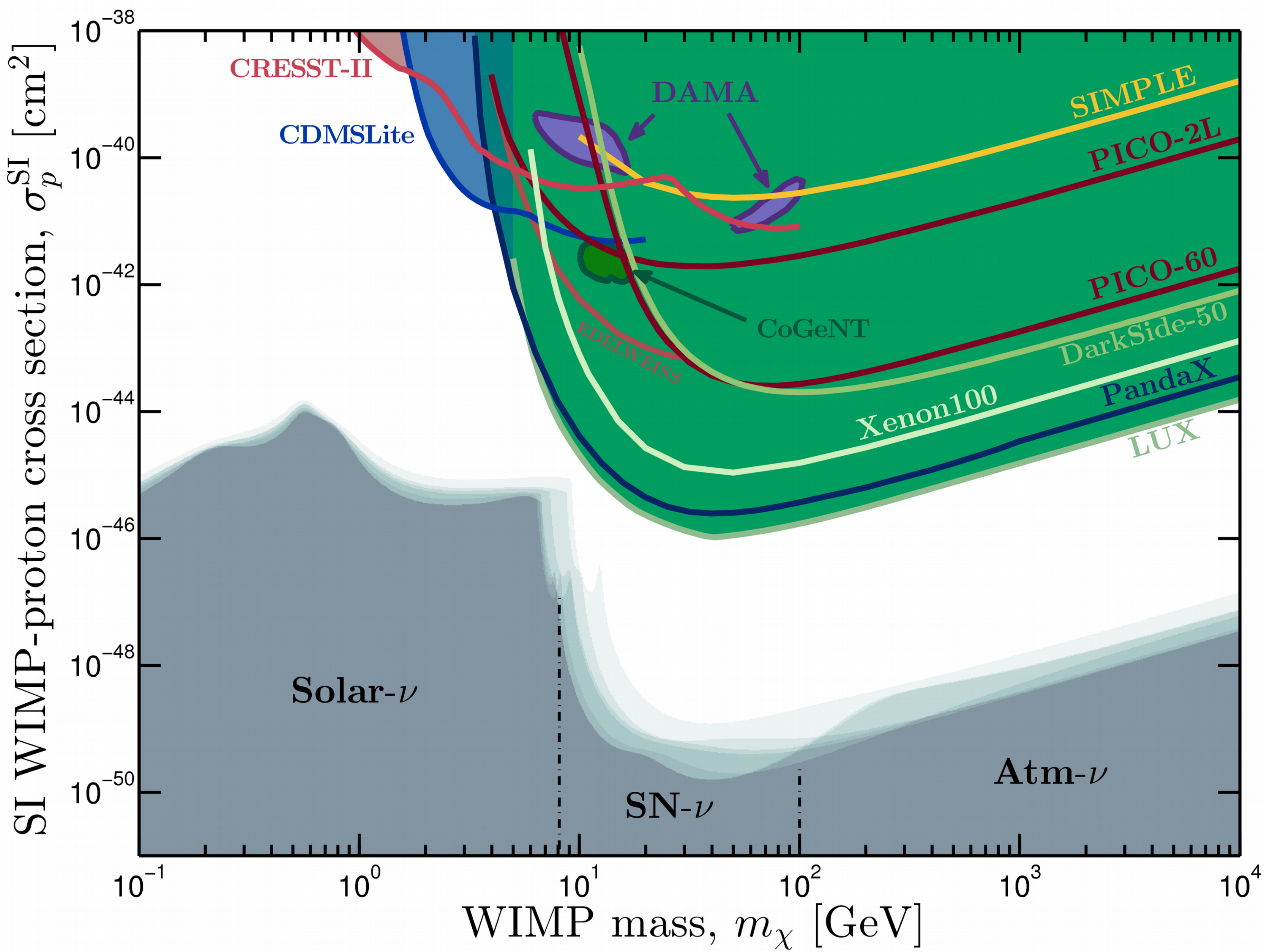
Uncertainty in exclusion limits →
e.g. McCabe [1005.0579]
"What have I ruled out?"



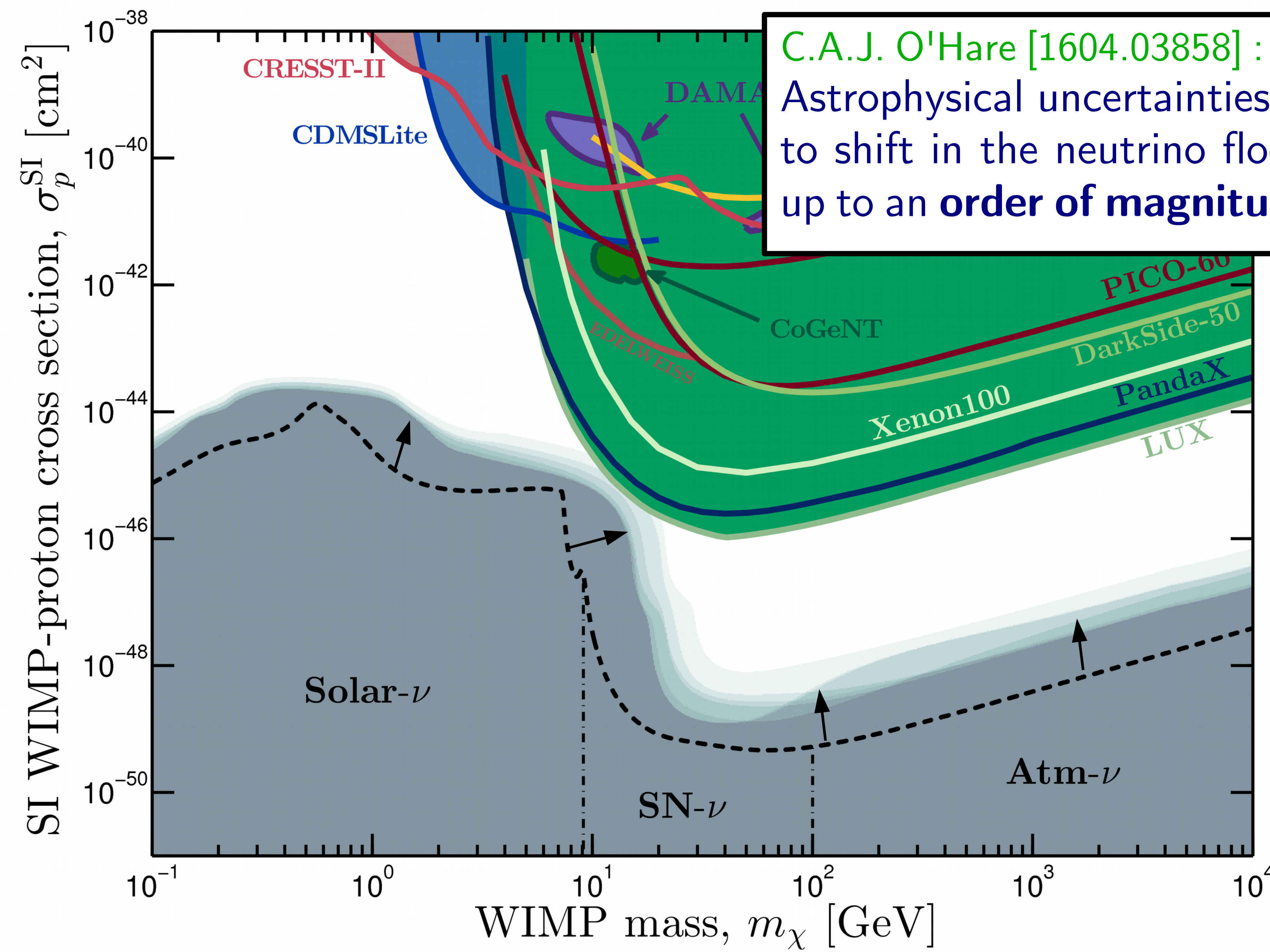


← Biased parameter estimation
e.g. Peter [1103.5145]
"What have I measured?"

The neutrino floor



The neutrino floor



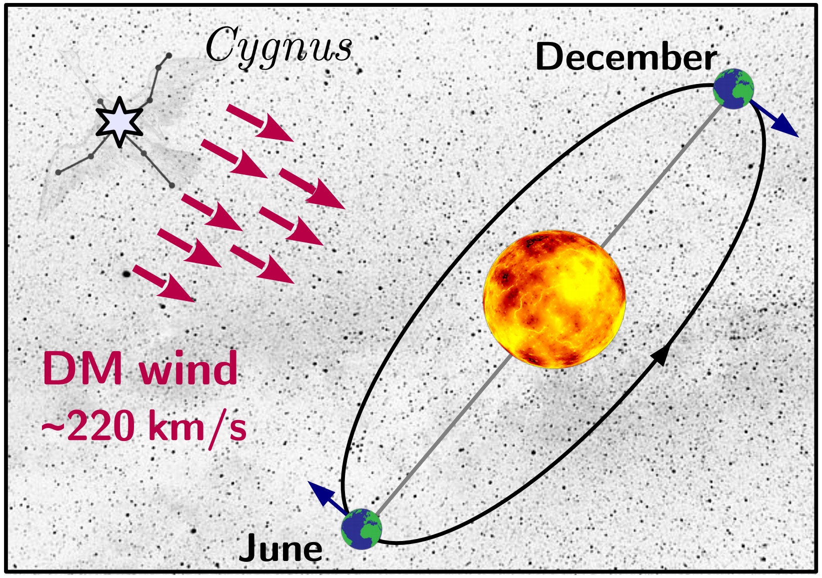
C.A.J. O'Hare [1604.03858] :
Astrophysical uncertainties lead to shift in the neutrino floor of up to an **order of magnitude**

Astrophysical uncertainties cause problems for direct detection

Solution: go and measure the local Milky Way halo directly

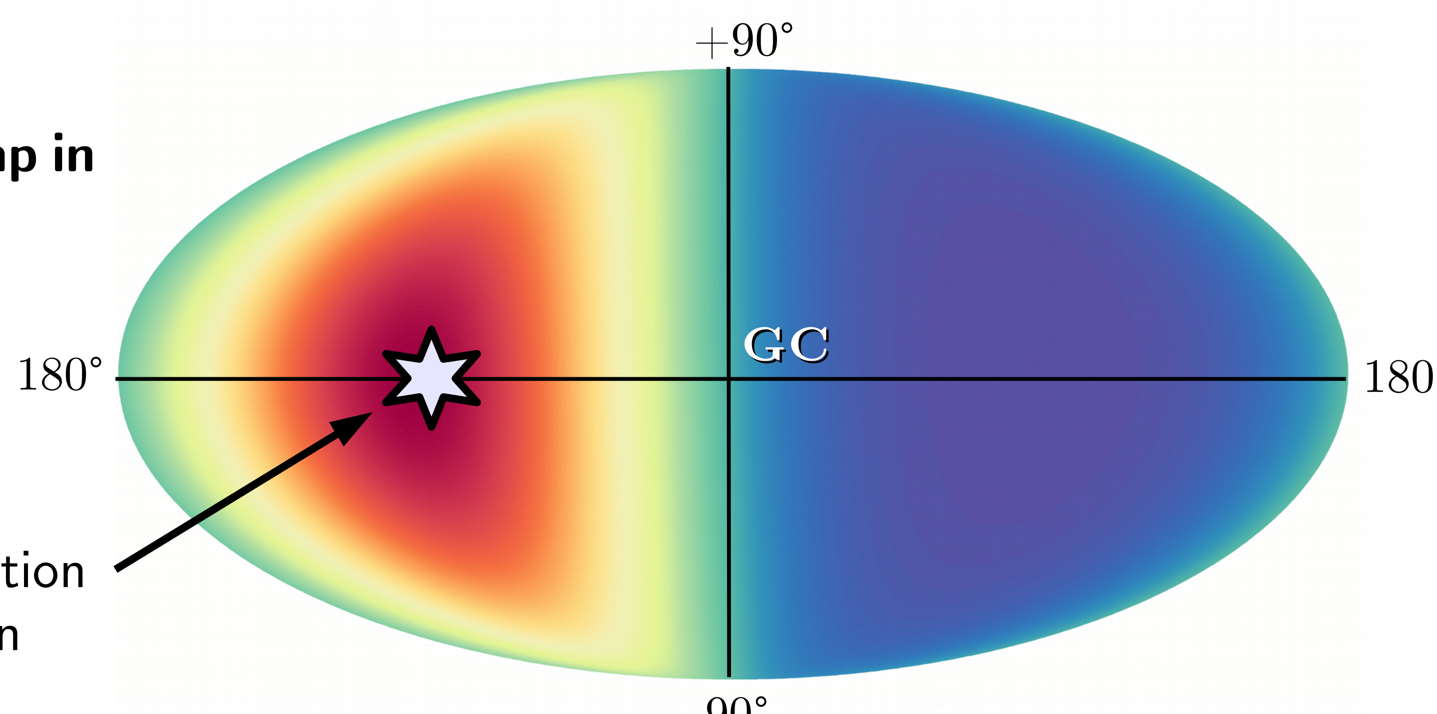
Bonus: find out about the formation history of the Milky Way...

Directional detection



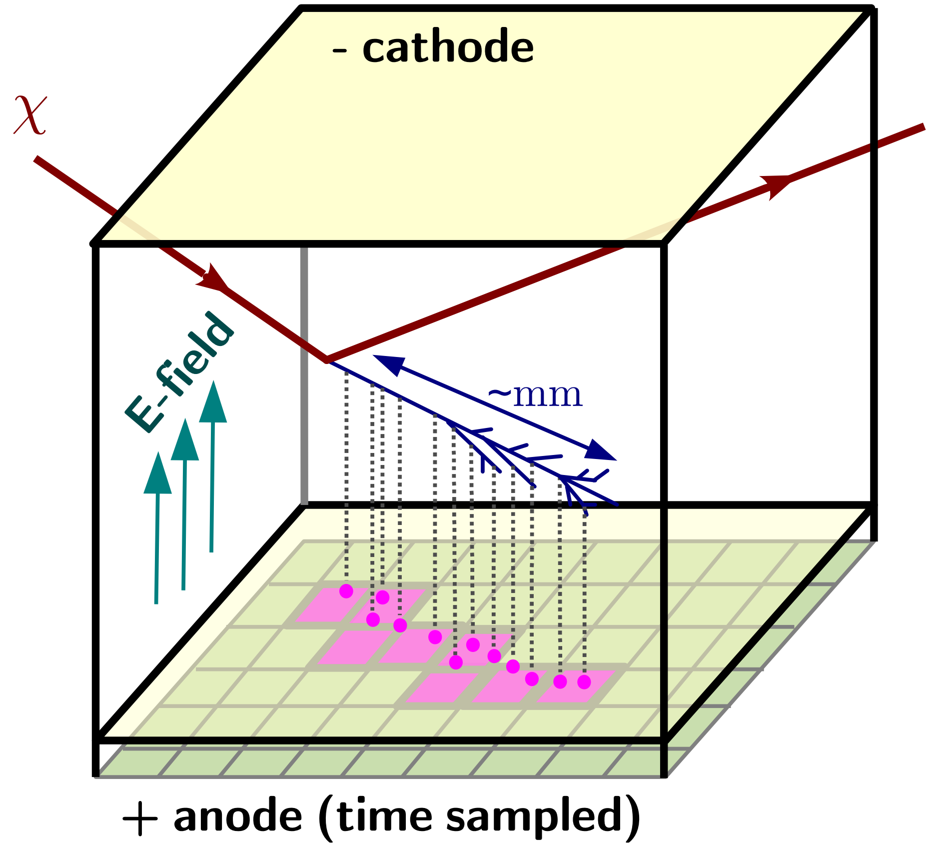
- Probing the velocity distribution is hard with recoil energy information alone
  Lee & Peter [1202.5035]
- But recoil energies **and directions...**

Recoil direction skymap in Galactic coordinates:



Peak towards direction of Galactic rotation

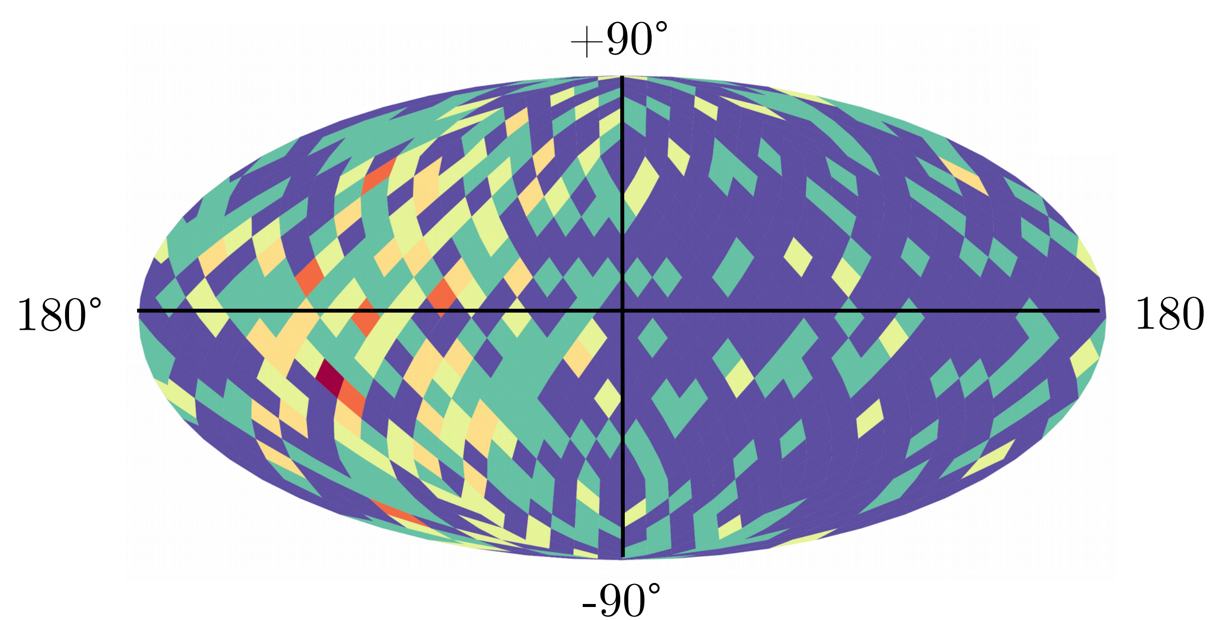
Directional detectors



How to measure directionality:

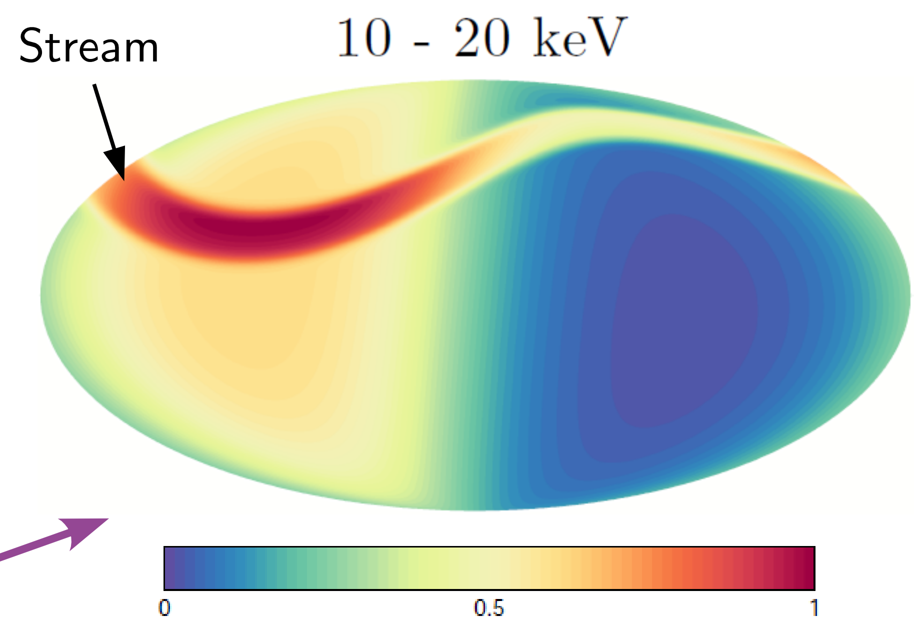
- **Low pressure gas TPC**
  e.g. DRIFT, DMTPC, MIMAC, NEWAGE
- Nuclear emulsions [1604.04199]
- LXe/LAr Columnar recomb. [1704.03741]
- $ZnWO_4$ scintillators [Cappella et al 17]

Experimentally challenging, but can discover DM with O(30) recoil directions



Detecting streams

- Tidal streams produce striking directional recoil patterns:



Scattering signal

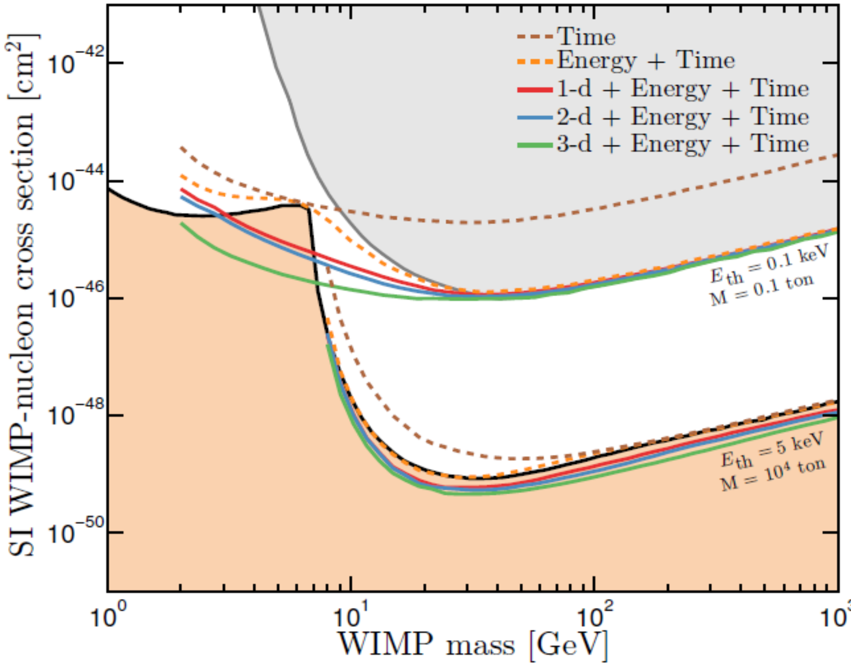
Angular recoil pdf

- Detection requires $O(1000)$ events in conventional detector
  → $O(100)$ events in directional detector O'Hare & Green [1410.2749]

More stuff with directional detectors...

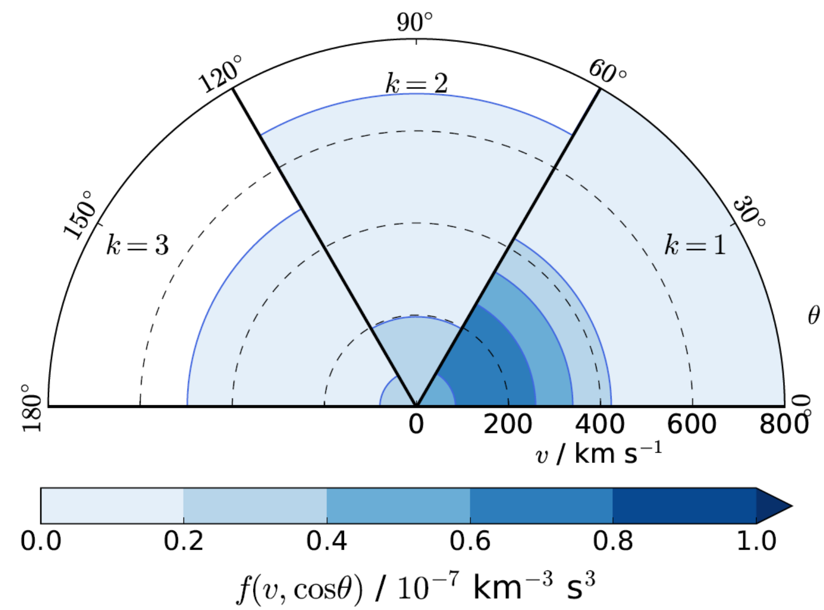
The neutrino floor
→ Directional information can be used to subtract the otherwise irreducible neutrino background

O'Hare et al [1505.08061]



Discretised velocity distribution:
→ How to measure the velocity distribution with **no** prior assumptions

Kavanagh & O'Hare [1609.08630]

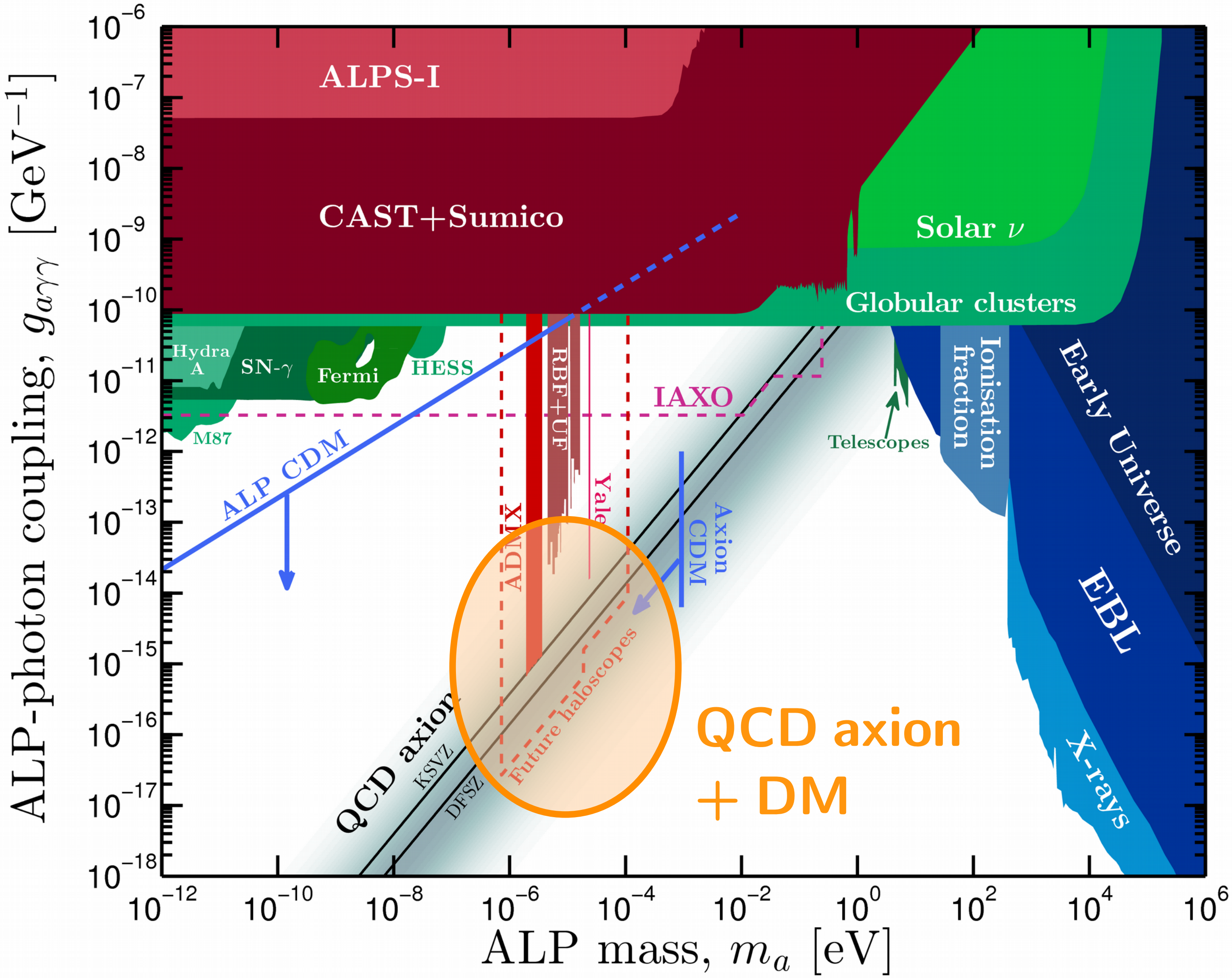


Axions

Axion/ALPs

- Search for pseudoscalar $a(x)$, with a coupling to EM:

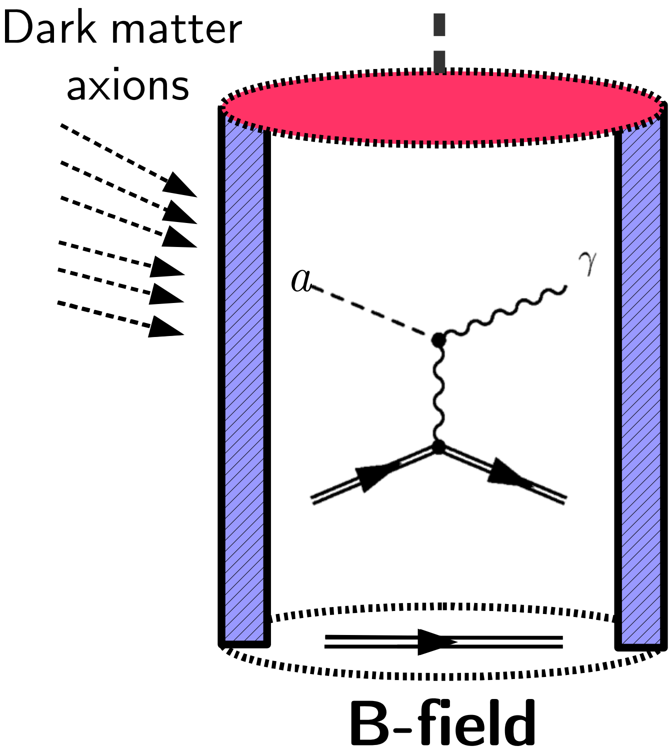
$$\mathcal{L} = -\frac{1}{4}\, g_{a\gamma\gamma}\, a(x)\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



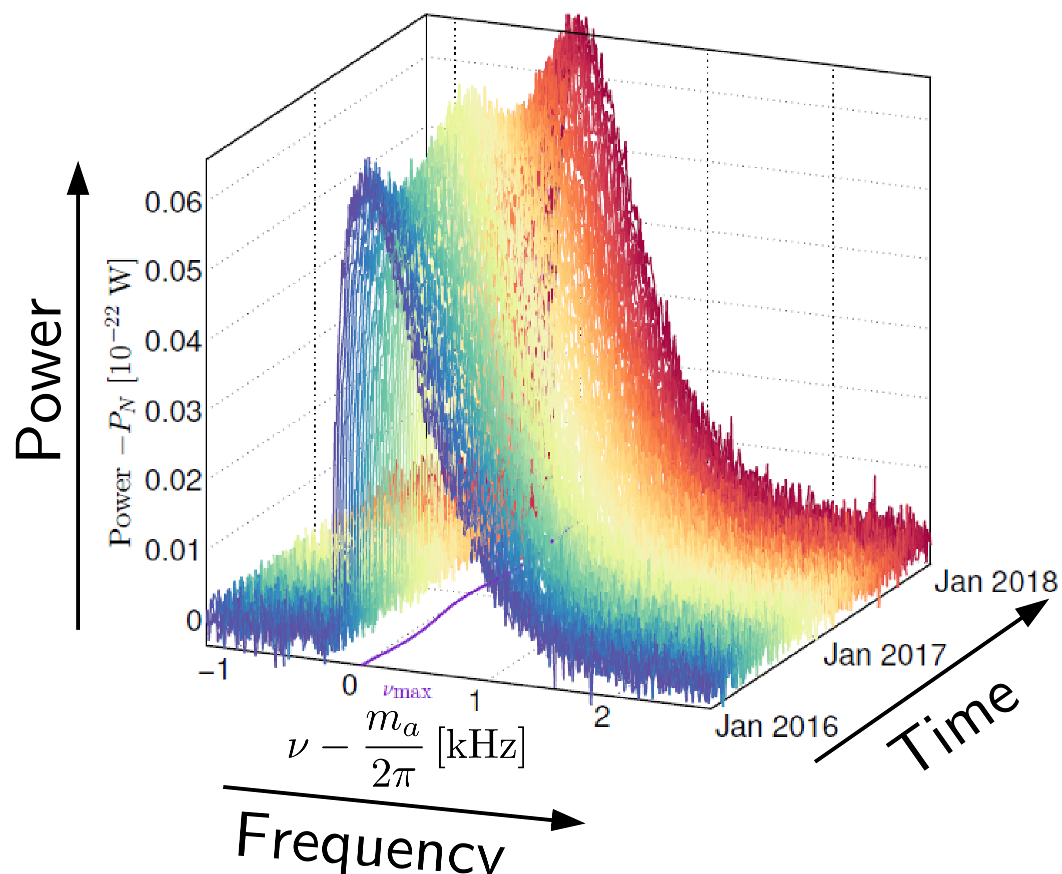
Constraints from:

- Experiments
- Astrophysics
- Cosmology

Axion Haloscope



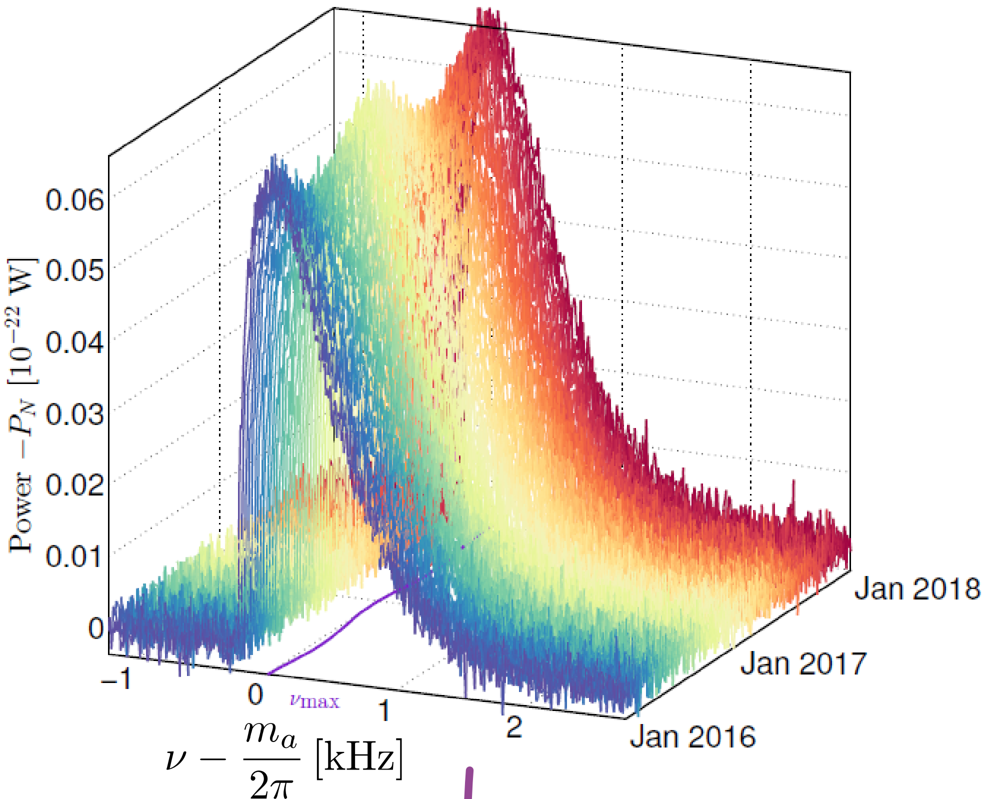
Resonant cavity experiment
→ To detect axion: resonance = axion mass



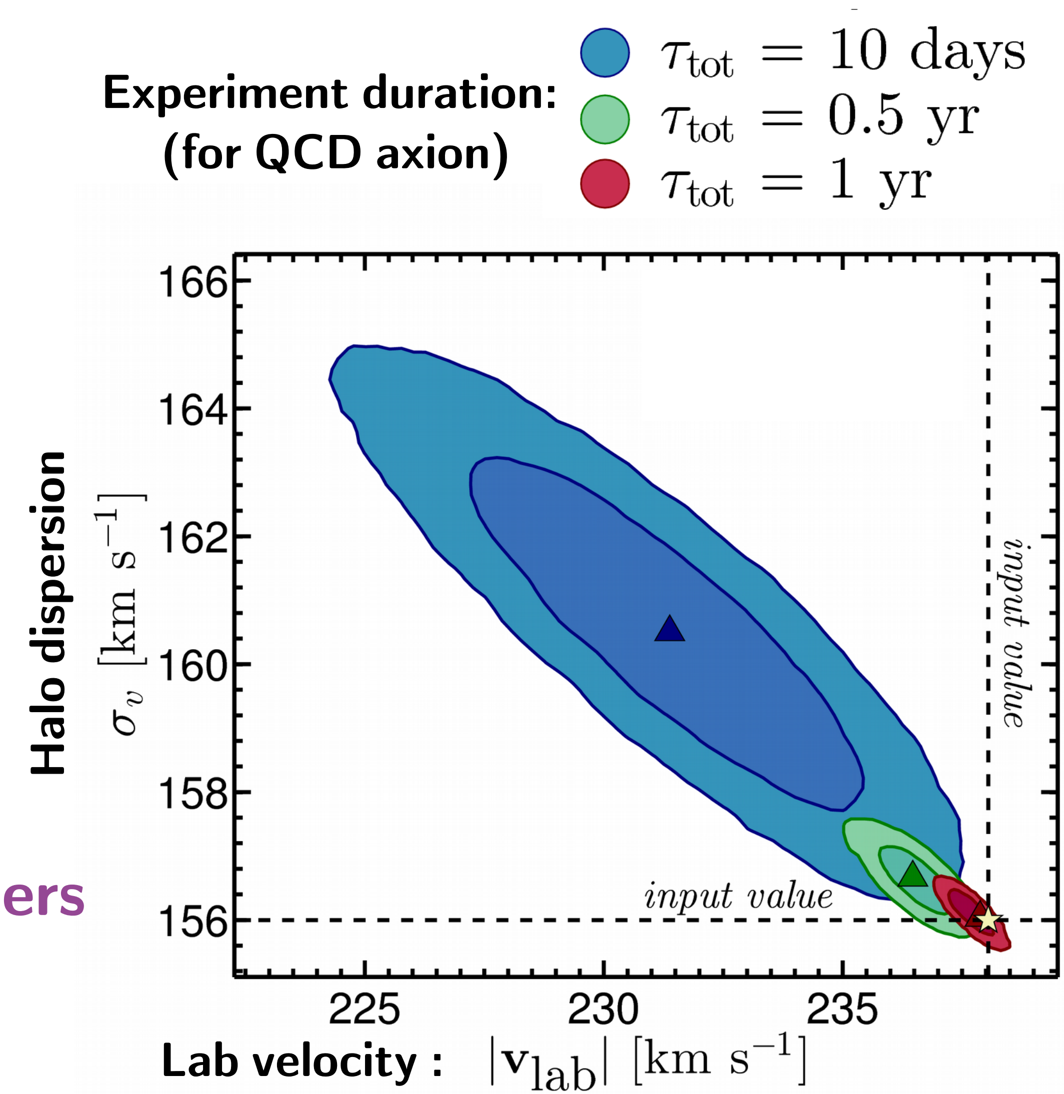
Once axion is detected:

- Measure power spectrum
- Measure annual modulation
- Probe substructure

→ ***axion astronomy***



O'Hare & Green [1701.03118]

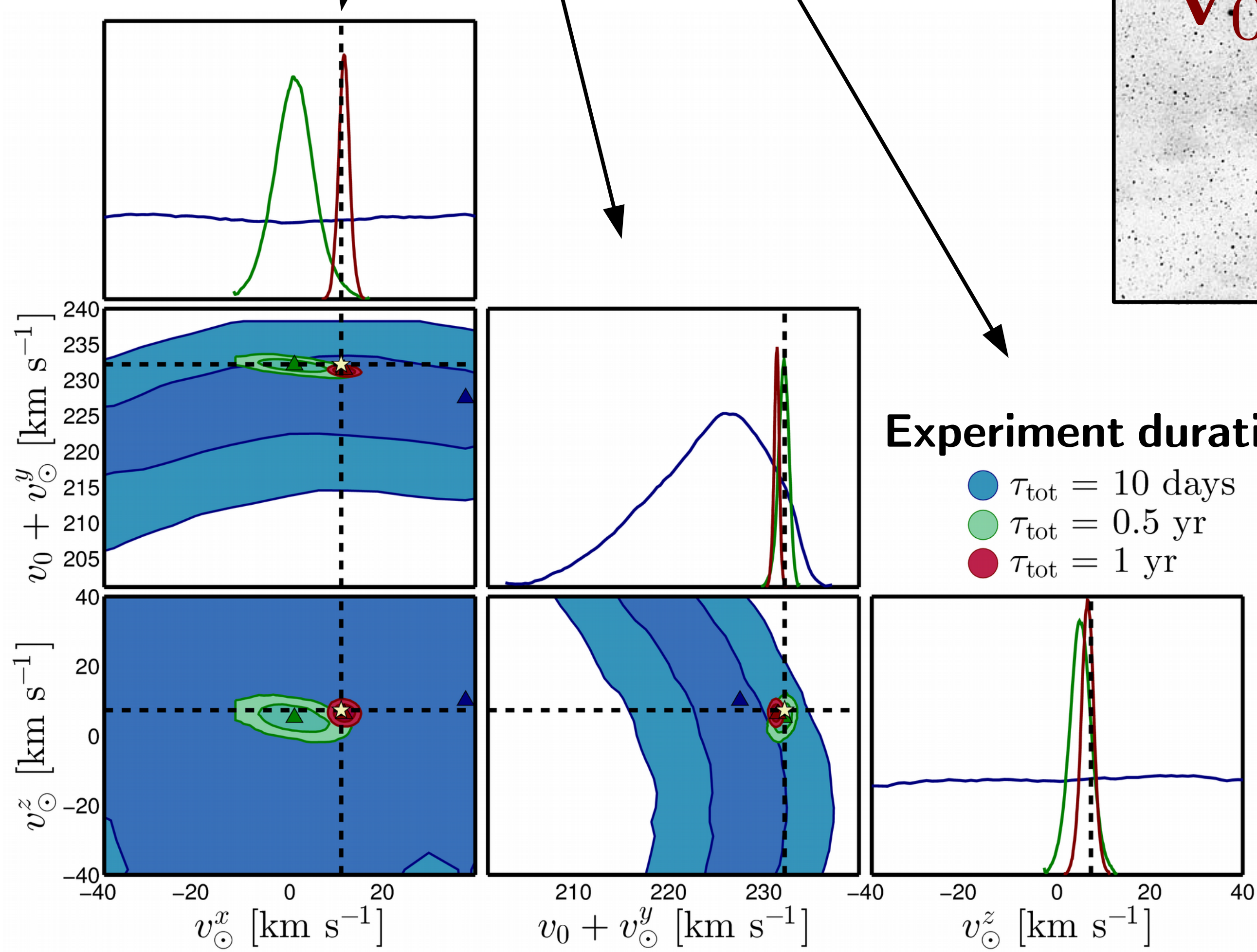


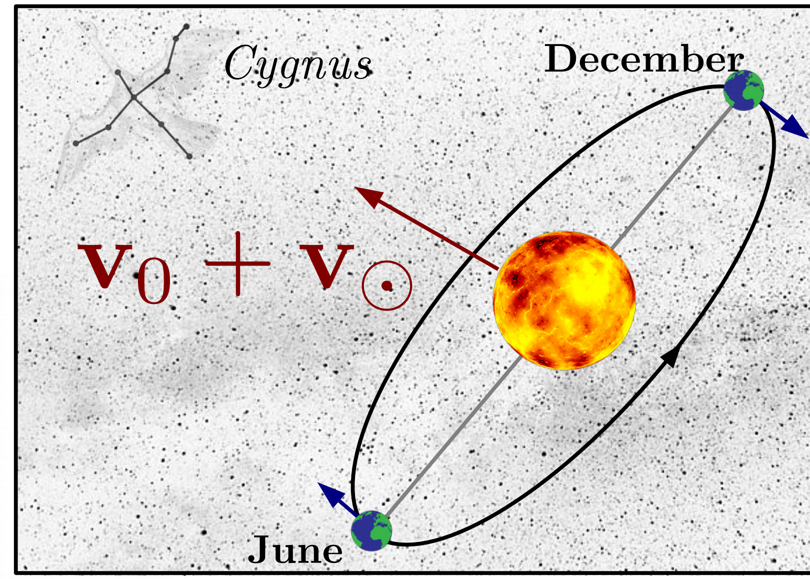
Max likelihood fit:
→ Extract astrophysical parameters

Measuring Solar velocity: $\mathbf{v}_0 + \mathbf{v}_\odot$

Components in Galactic coords:

$$= (v_\odot^x,\ v_0 + v_\odot^y,\ v_\odot^z)$$



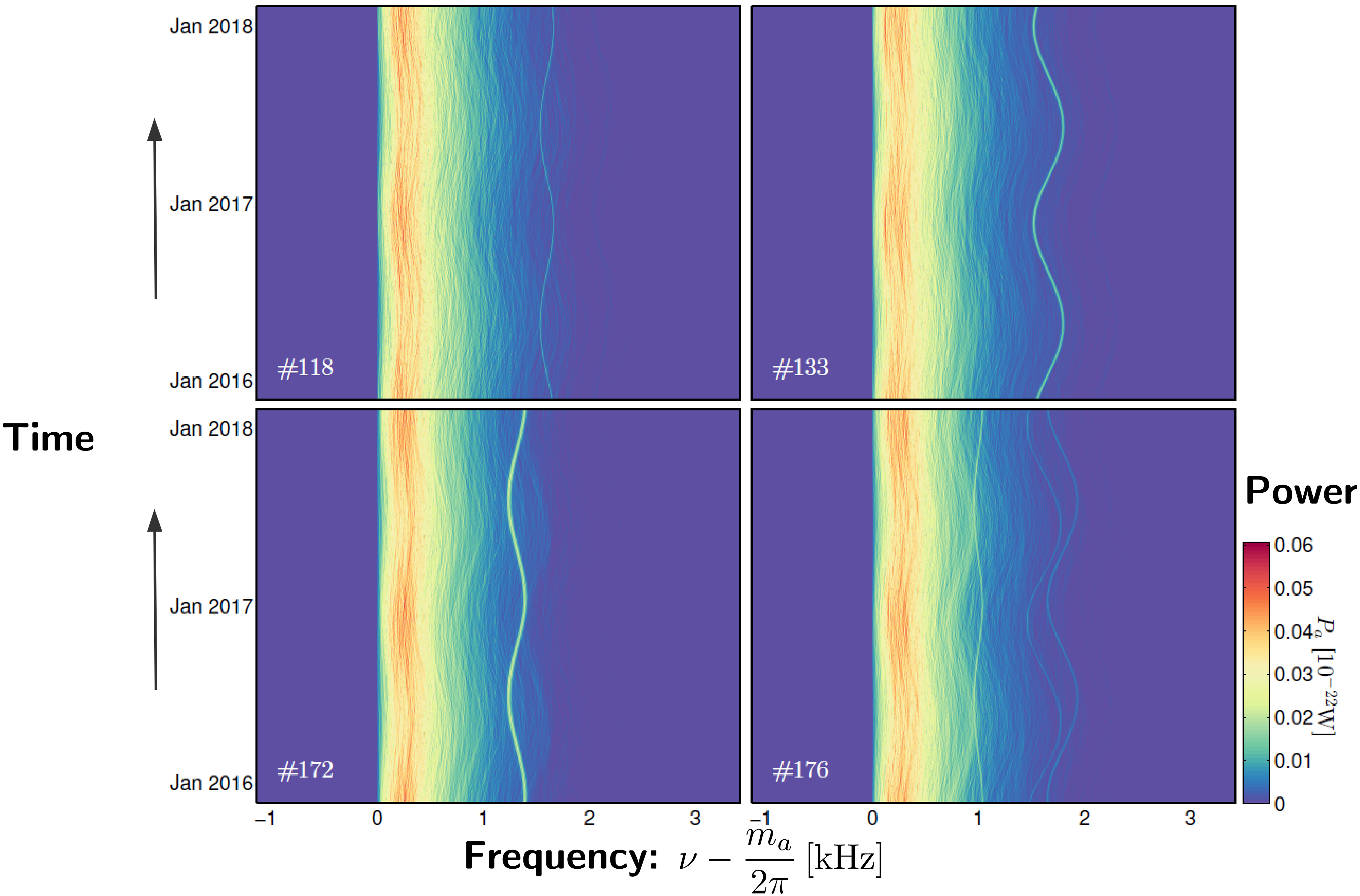


accuracy <1 km/s
→ Better than astronomical determinations

C. A. J. O'Hare & A. M. Green [1701.03118]

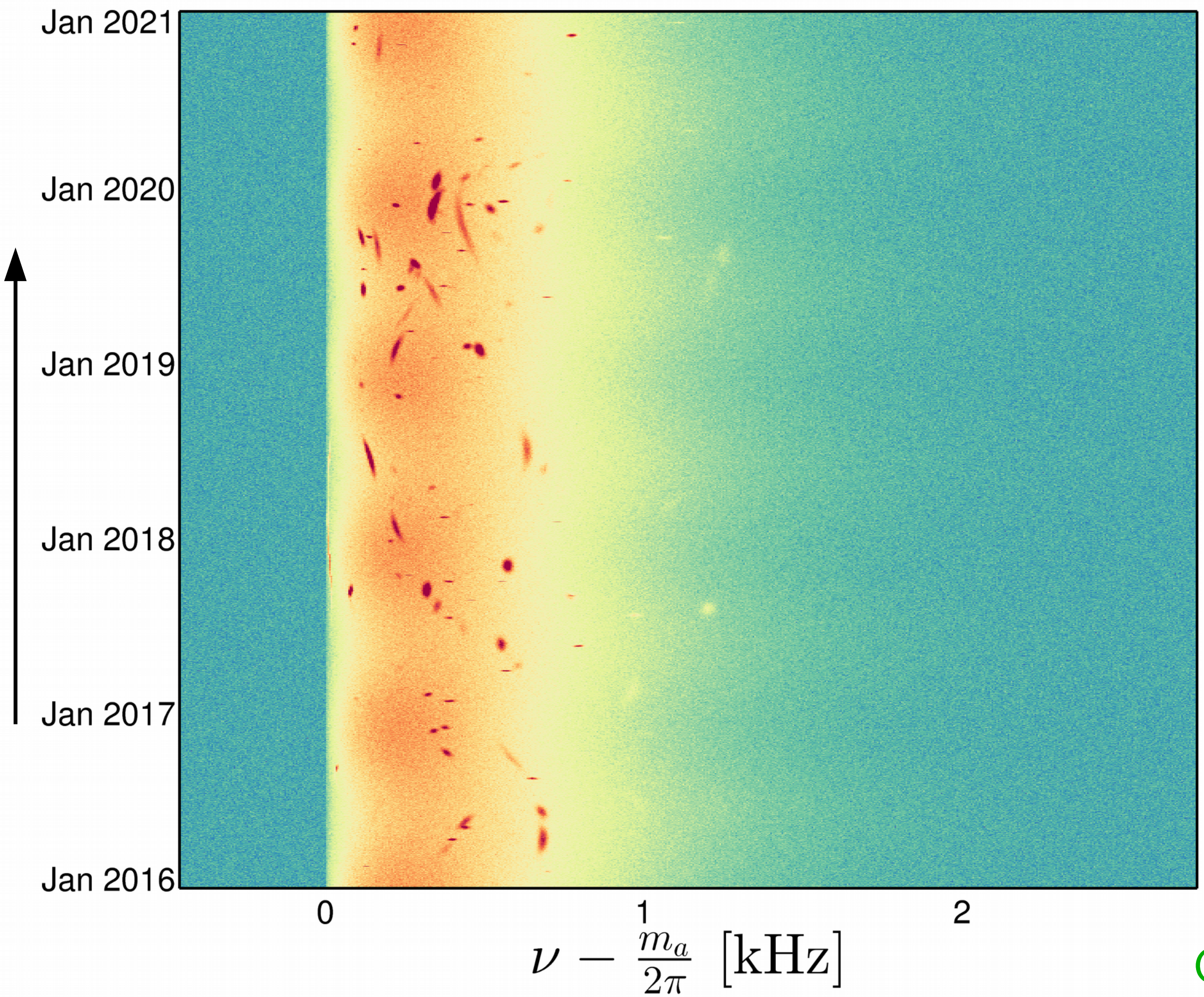
Example power spectra from an N-body simulation

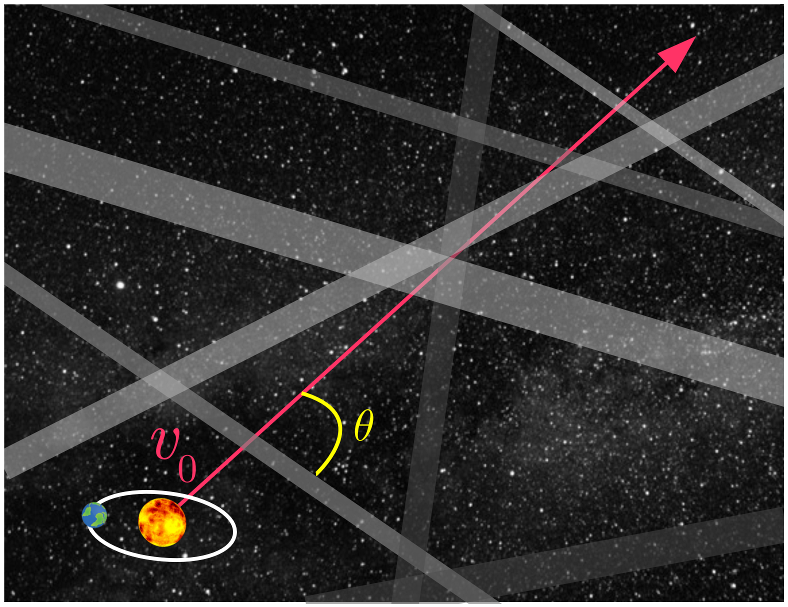
- Particles inside 1 kpc sized bubbles at $r = 8$ kpc Galactic radius



Axion miniclusters

- Collapsing perturbations in early Universe can form small clumps of axions
- Tidally disrupted by interactions with stars
  - → network of minicluster streams wrapping Milky Way Tinyakov [1512.02884]
  - → stream crossing time O(1-100) days





May need to be distinguished from environmental noise peaks with use of time/daily modulation

C. A. J. O'Hare & A. M. Green [1701.03118]

Take home:

Must understand local MW halo to do dark matter detection	⟷	Dark matter detection can help us understand the local MW halo

If a WIMP or axion has been detected...

Can you do WIMP astronomy?
Sort of, but you probably need a big detector and ideally a directional one

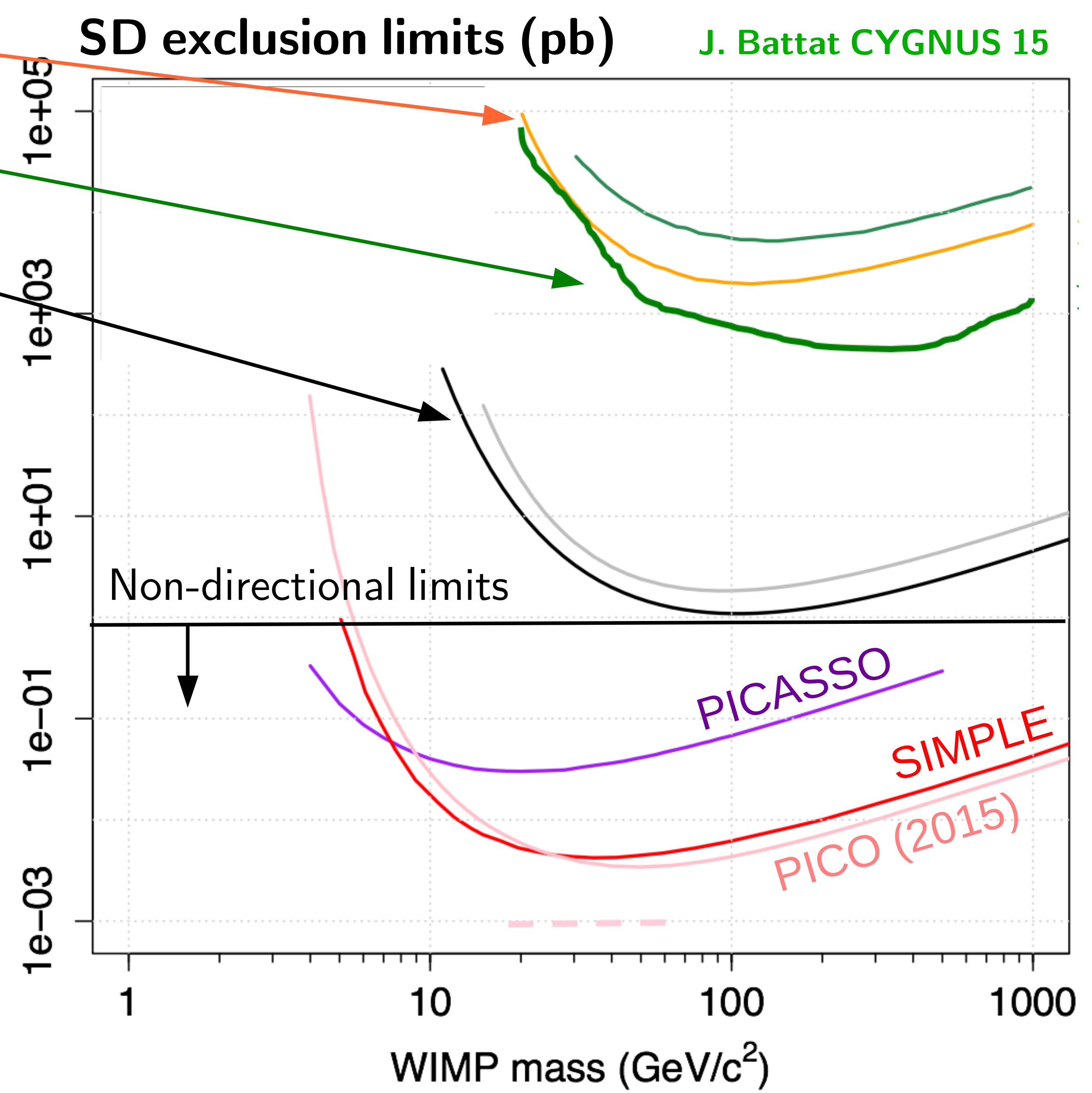
Can you do axion astronomy?
Yes! A haloscope could measure the local halo more accurately than an astronomer

Bonus

Directional detectors

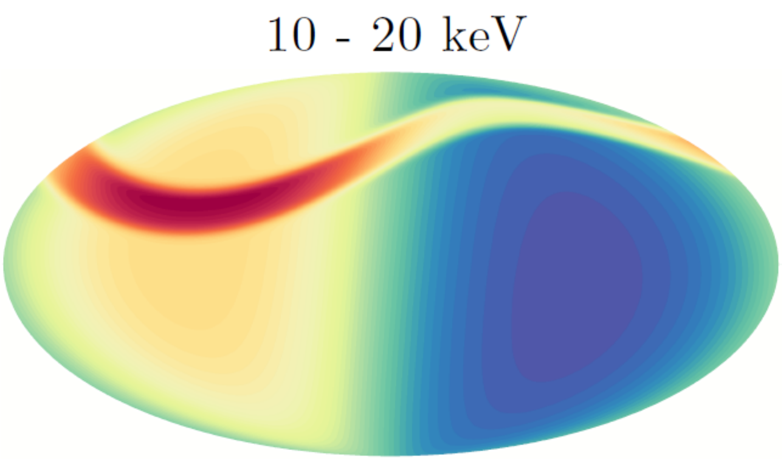
Best at the moment: low pressure gas TPCs

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



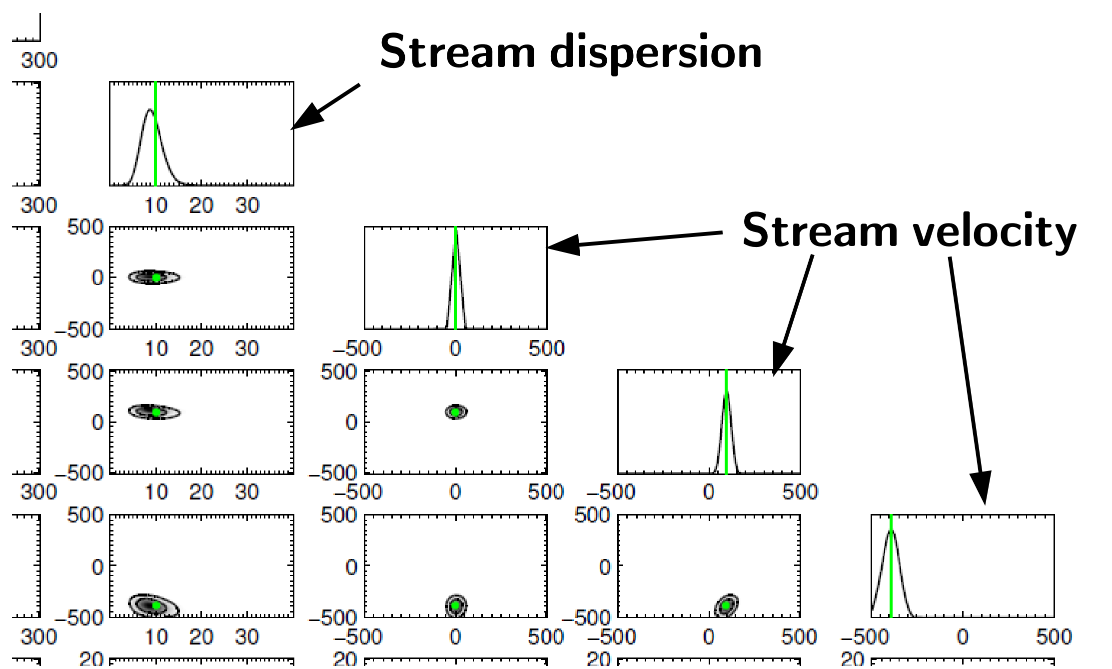
Detecting streams

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



Likelihood fit

O'Hare & Green [1410.2749]



Empirical velocity distribution

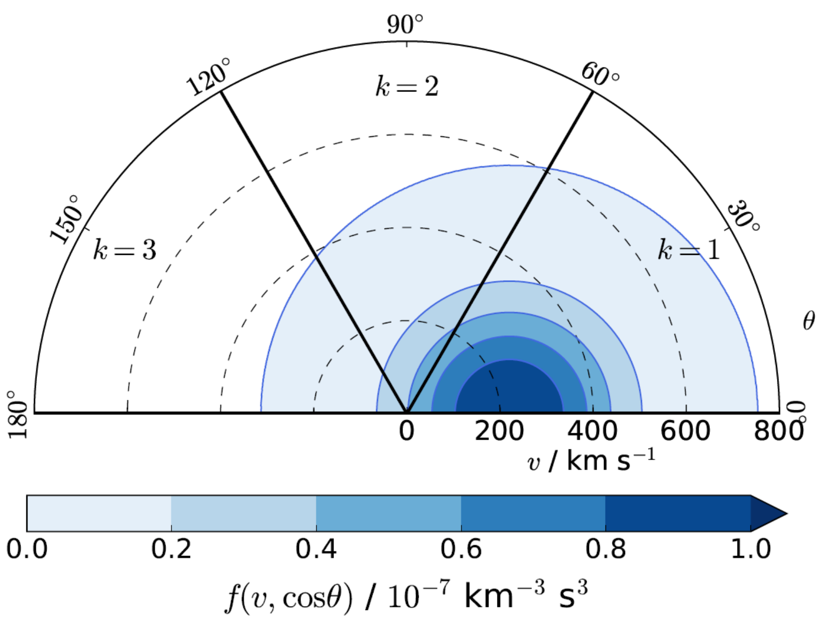
B. J. Kavanagh & C. A. J. O'Hare [1609.08630]

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

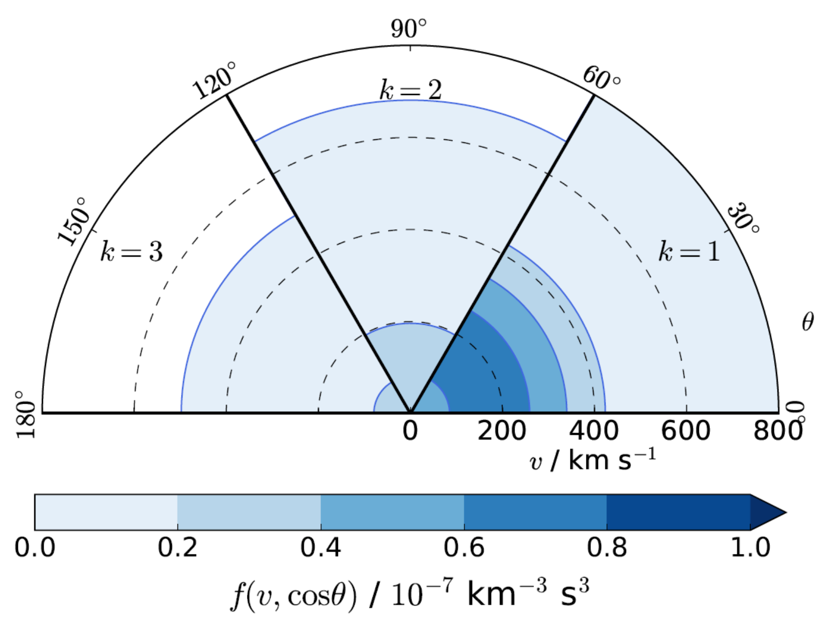
$$f(\mathbf{v}) = f(v, \cos\theta, \phi) = \begin{cases} f^1(v) & \text{for } \theta \in [0°, 60°] \\ f^2(v) & \text{for } \theta \in [60°, 120°] \\ f^3(v) & \text{for } \theta \in [120°, 180°] \end{cases}$$

Empirical polynomial fit in each bin

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 models:

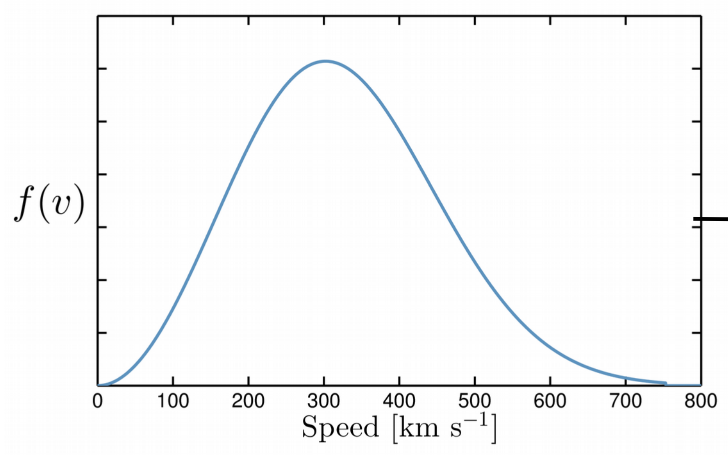
Speed distributions

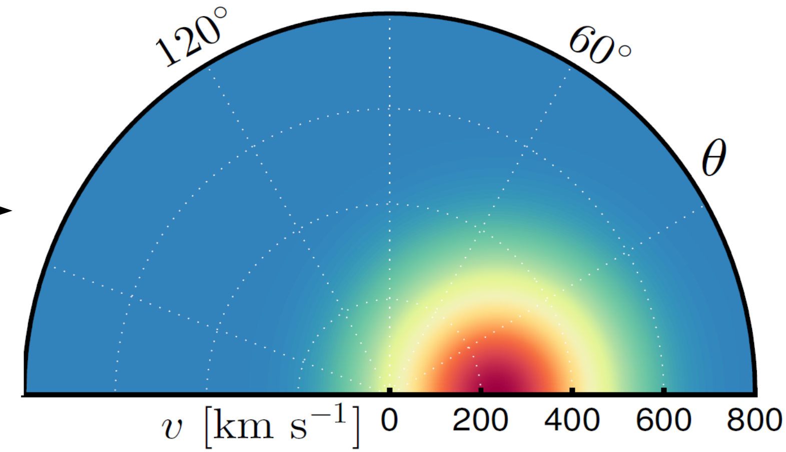
Velocity distributions

SHM:

$v_0 = 220$ km/s

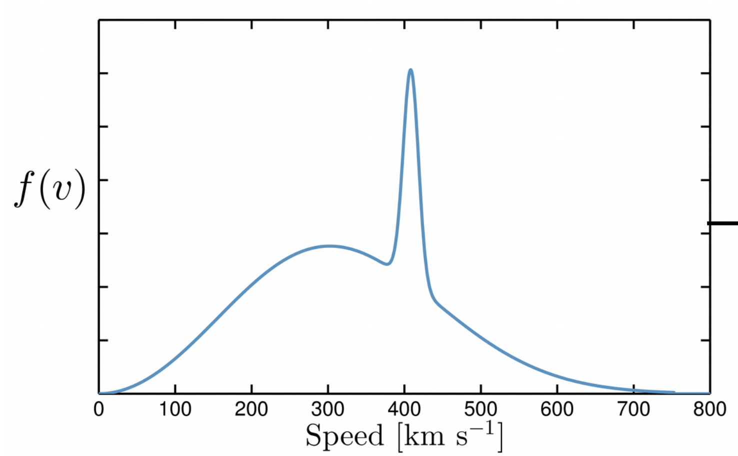
$v_{esc} = 533$ km/s

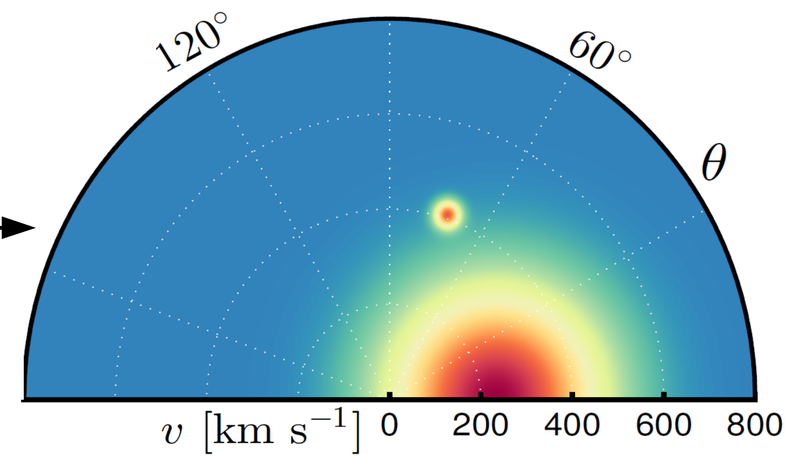




SHM+Stream:

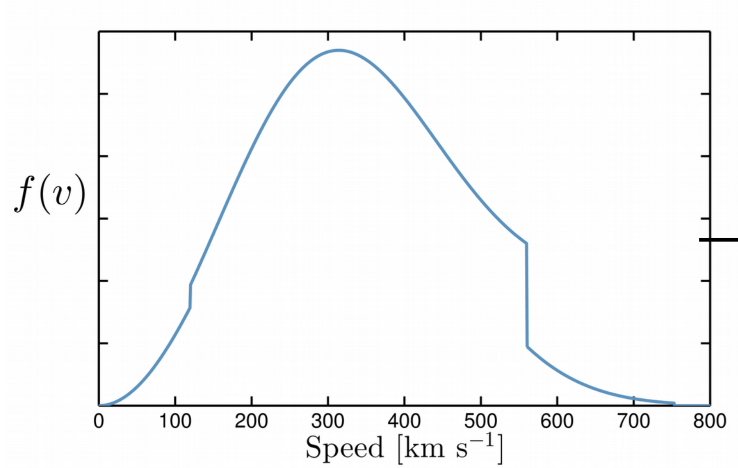
Purcell [1203.6617]

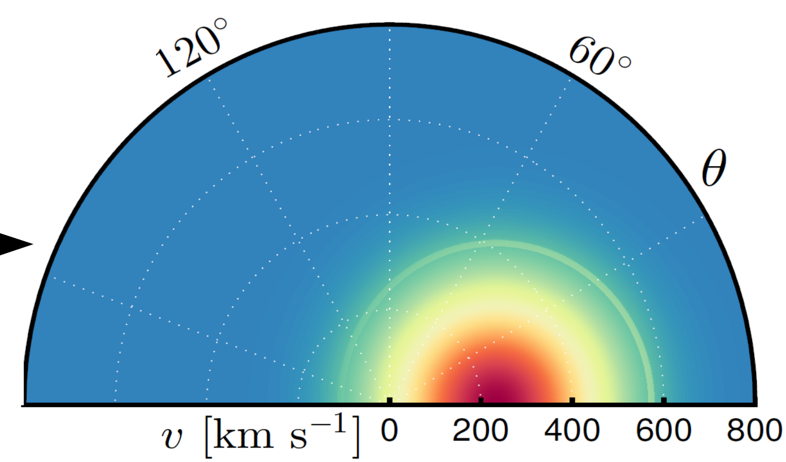


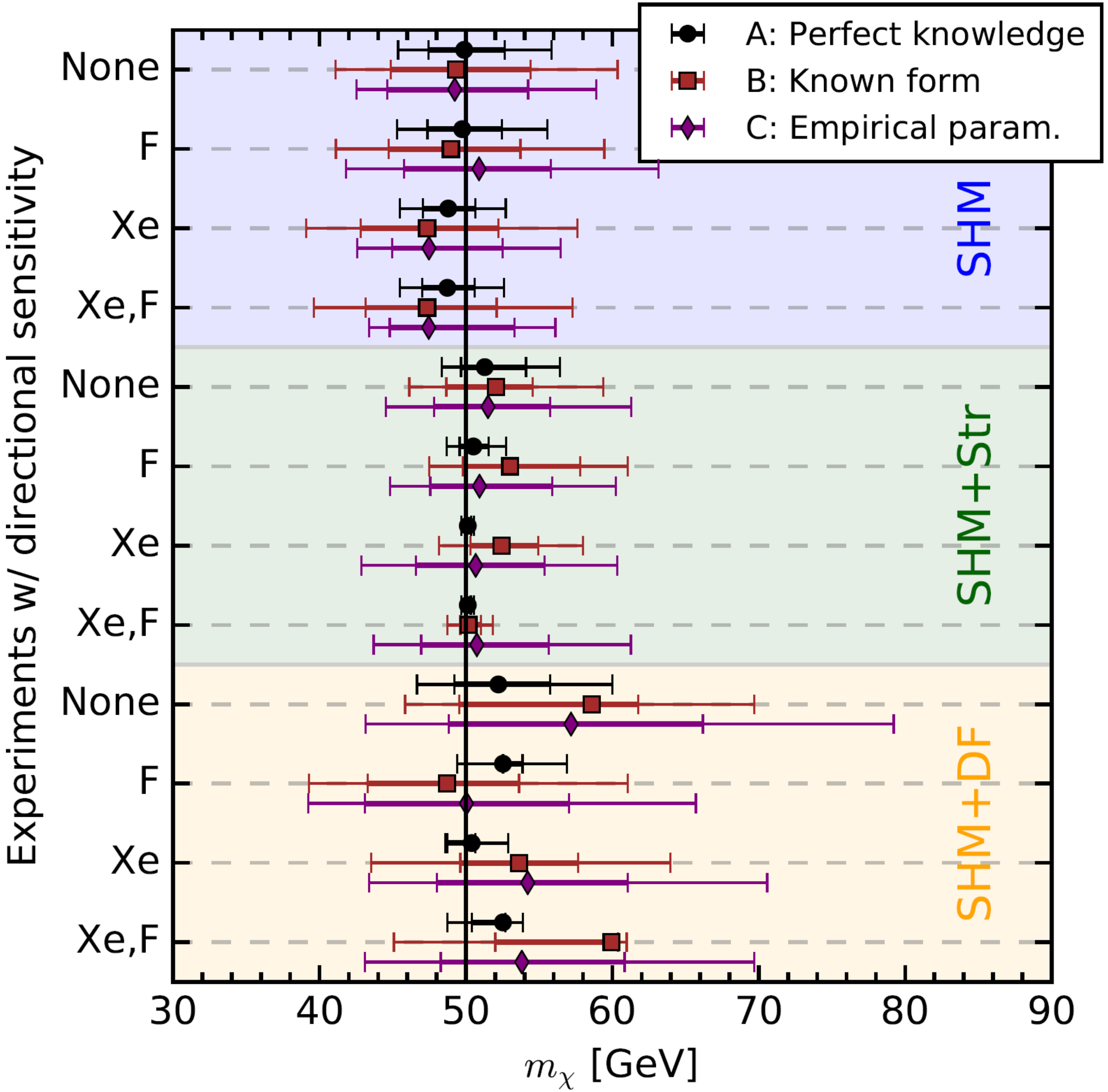


SHM+Debris flow:

Kuhlen [1202.0007]







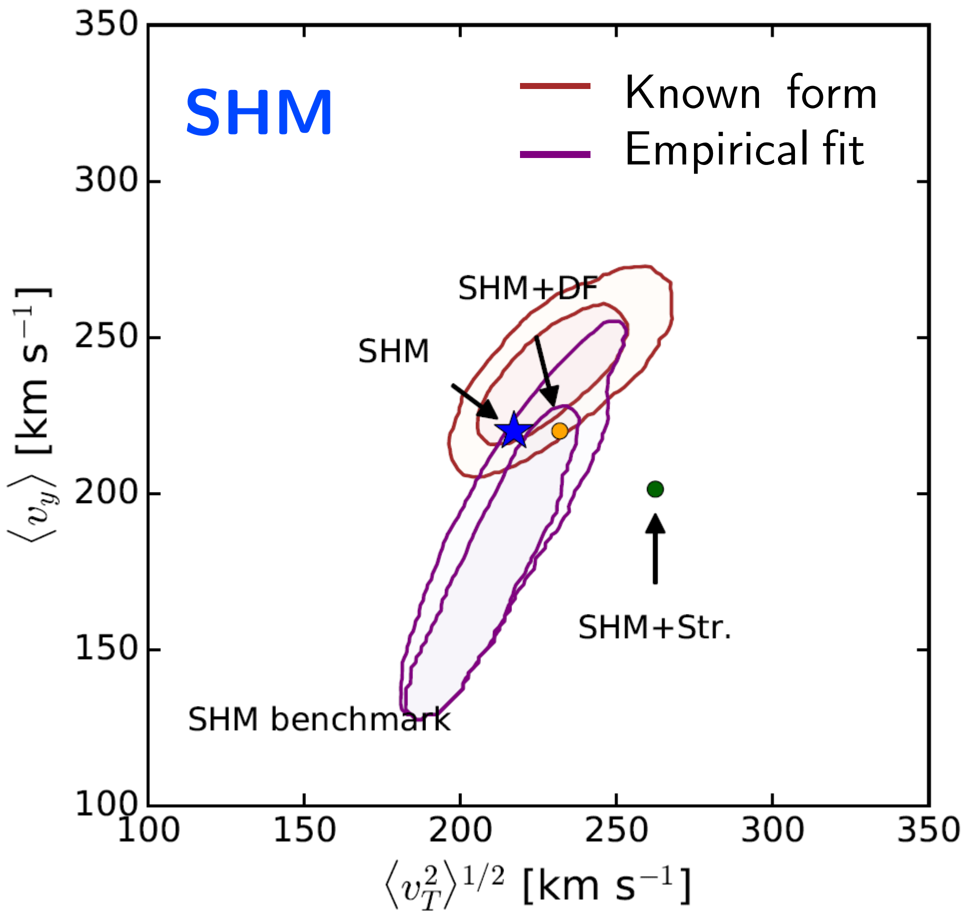
A: Perfect knowledge
B: Known form
C: Empirical param.
None
F
Xe
Xe,F
SHM
SHM+Str
SHM+DF
Experiments w/ directional sensitivity
30
40
50
60
70
80
90
m_χ [GeV]

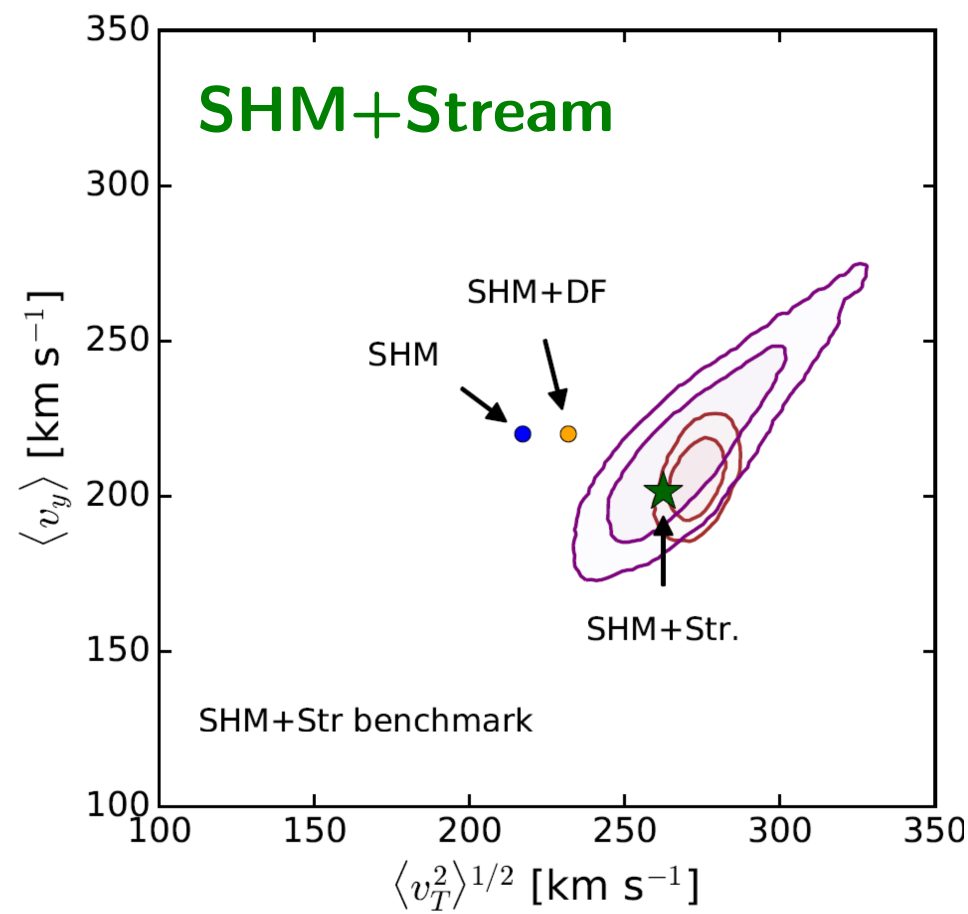
Comparing reconstructions

- Ideally we extract something physical to hint towards substructure

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: $\langle v_T^2 \rangle = \int \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \, (v^2 \sin^2\theta) \, v^2 f(\mathbf{v})$





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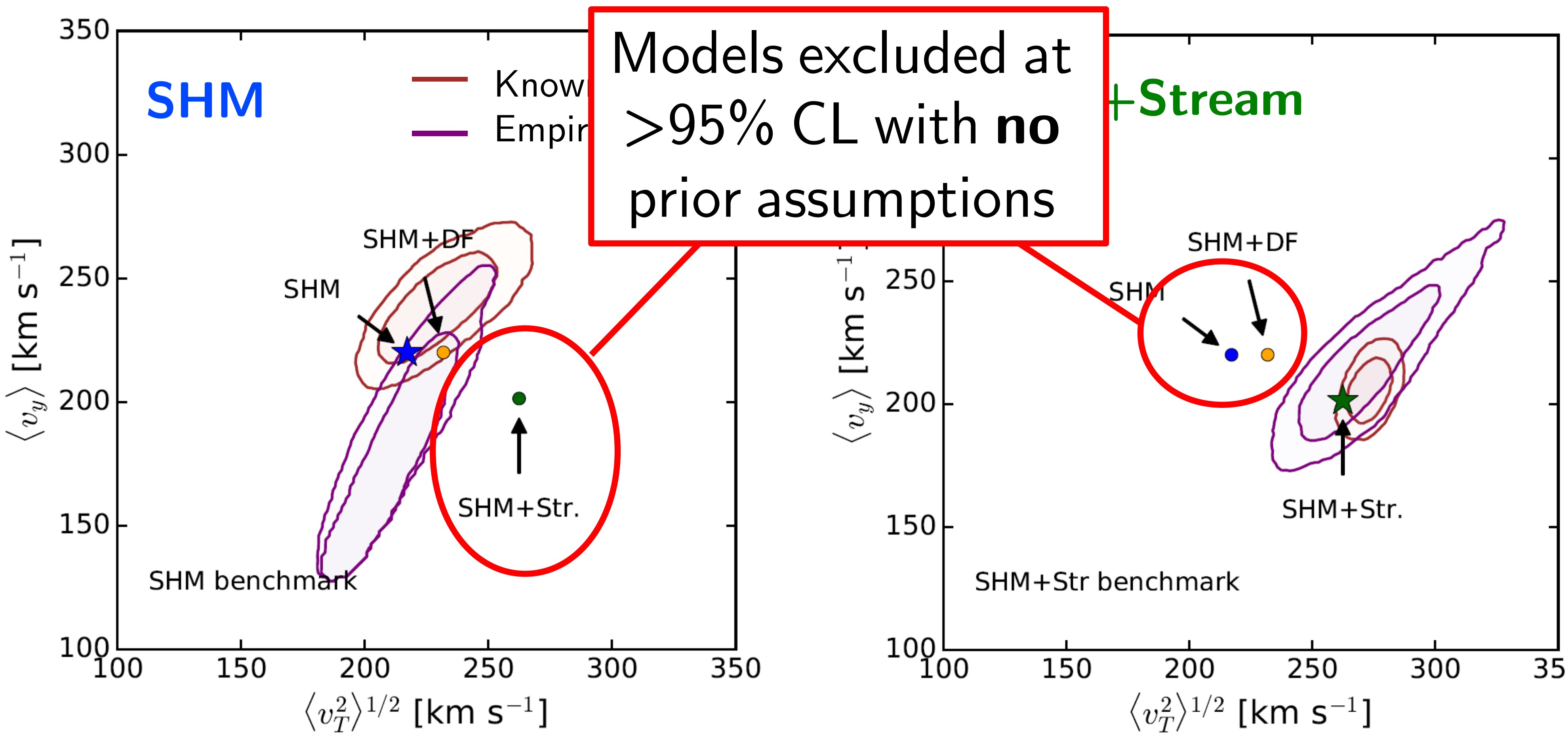
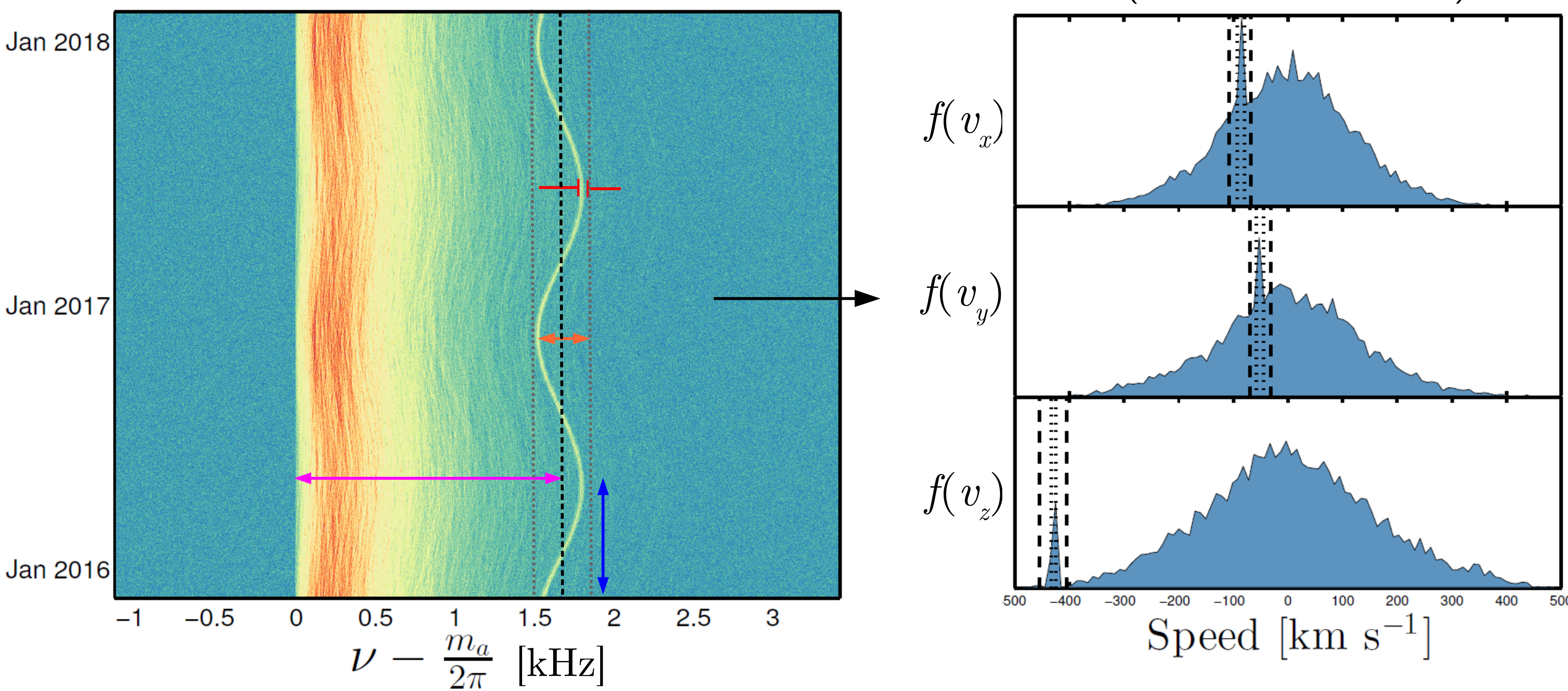


Measuring tidal streams

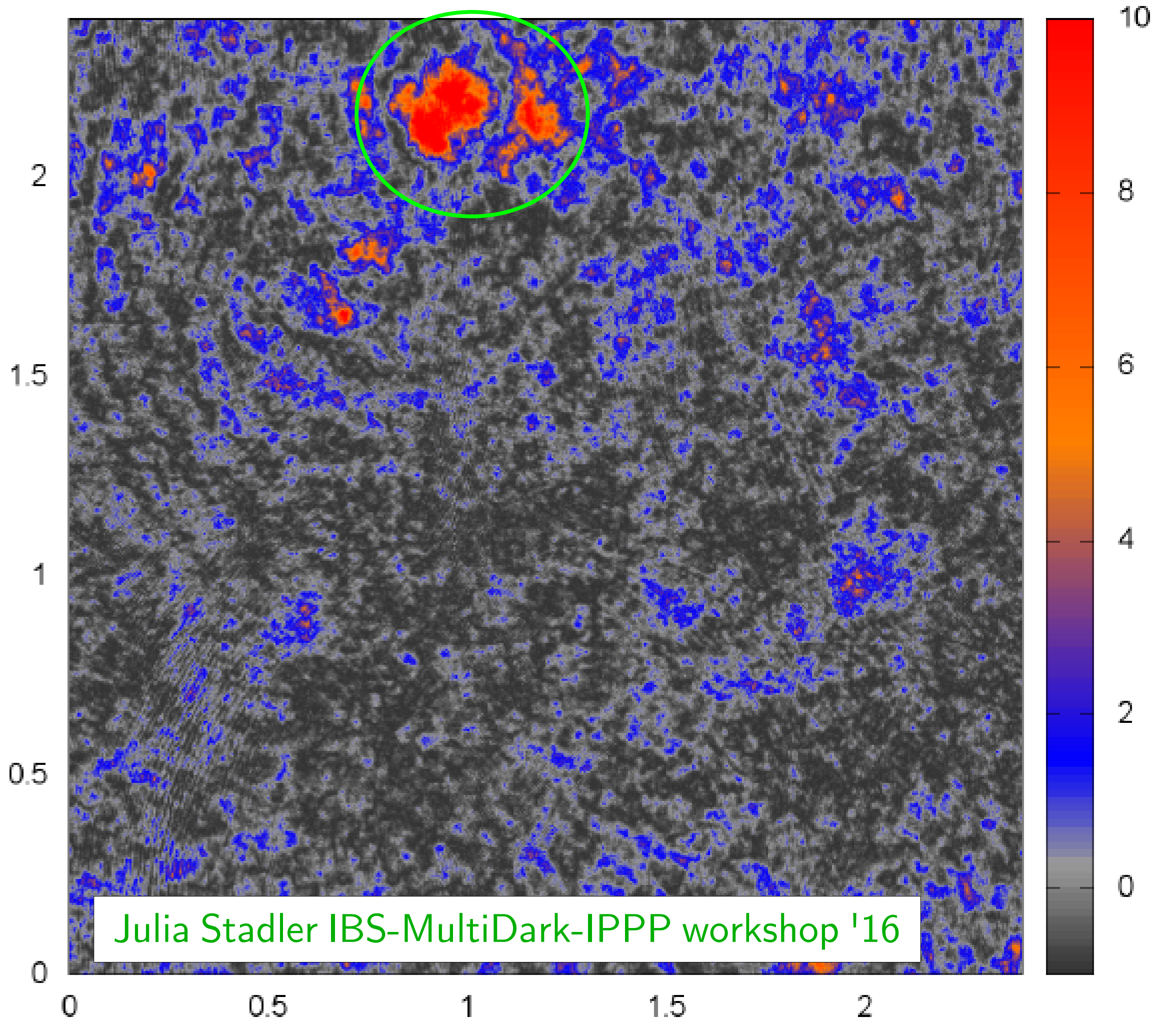
- **Can extract all five properties of a stream from sinusoid**
  - Stream density ← Power relative to bulk
  - Stream dispersion ← Width of sinusoid
  - Galactic velocity ← Amplitude, phase and mean of sinusoid

(Galactic co-ordinates)



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]