Universidad Zaragoza 1542

“Axiostronomy”

How to build an axion observatory

Ciaran O’Hare
Universidad de Zaragoza, España

+A. Green, S. Knirck, A. Millar, F. Steffen, X. Redondo MPP Munich Seminar 15th Feb.

Outline

- Terrestrial dark matter "astronomy"
- Example 1: WIMP directional detectors
- Example 2: Axion haloscopes
  - → Non-directional axiostronomy
  - → Directional axiostronomy

Local dark matter distribution

1. Dark matter density (r = 8 kpc)

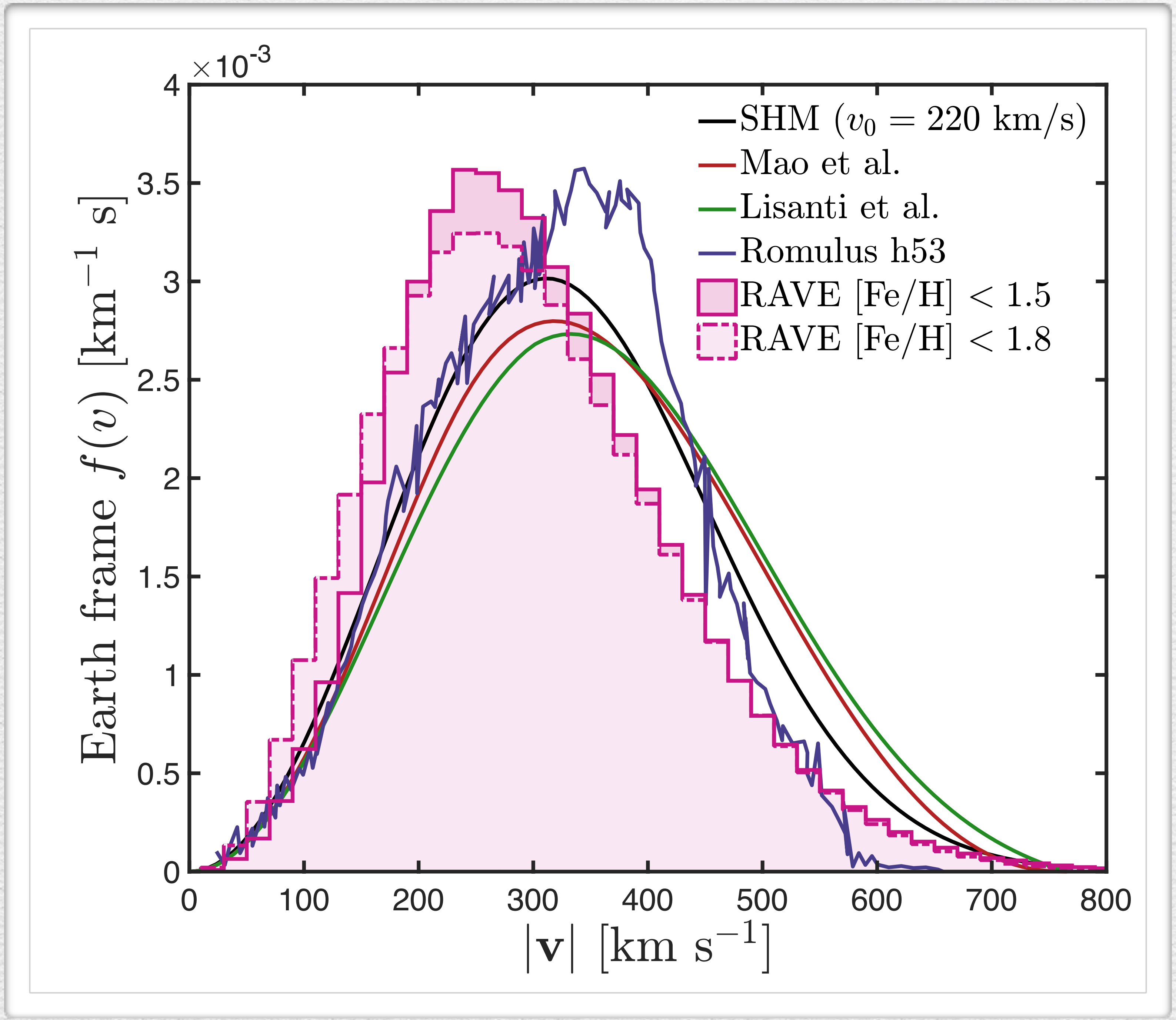
$$\rho_0 = \sum_{\text{DM species}} \rho_i \approx 0.4\,\text{GeV}\,\text{cm}^{-3}$$

See J. I. Read [1404.1938]

2. Dark matter velocity distribution

$$\mathrm{d}n = \mathrm{d}^3v \sum_{\text{DM species}} \frac{\rho_i}{m_i} f_i(\mathbf{v}) \approx ?$$

Determining $f(v)$



- Using models:

Standard halo model (SHM)
Mao+ [1210.2721] (fitting function)
Lisanti+ [1010.4300] (fitting function)
Kavanagh+ [1609.08630] (general polynomial)

- From simulations:

Bozorgnia [1705.05853] (WIMP-motivated)
Lentz+ [1703.06937] (axion-motivated)

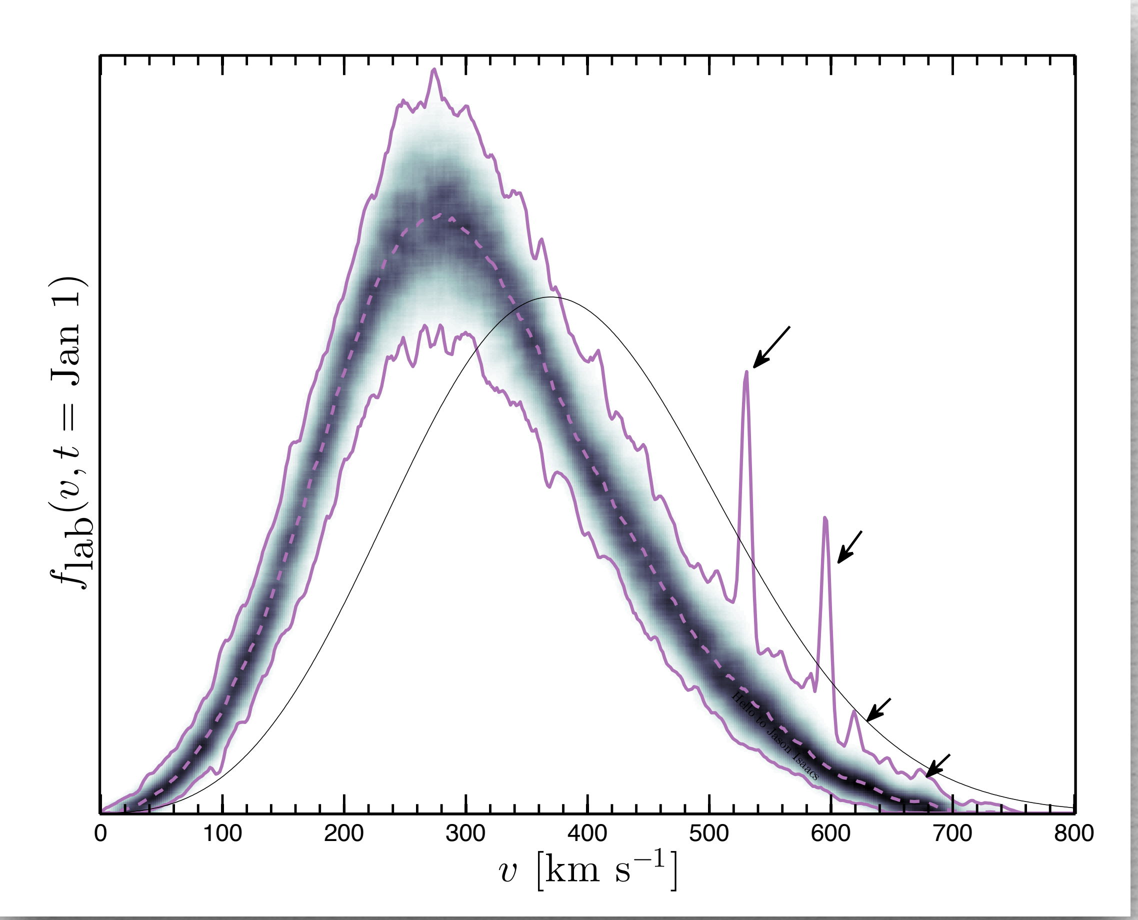
- Observationally:

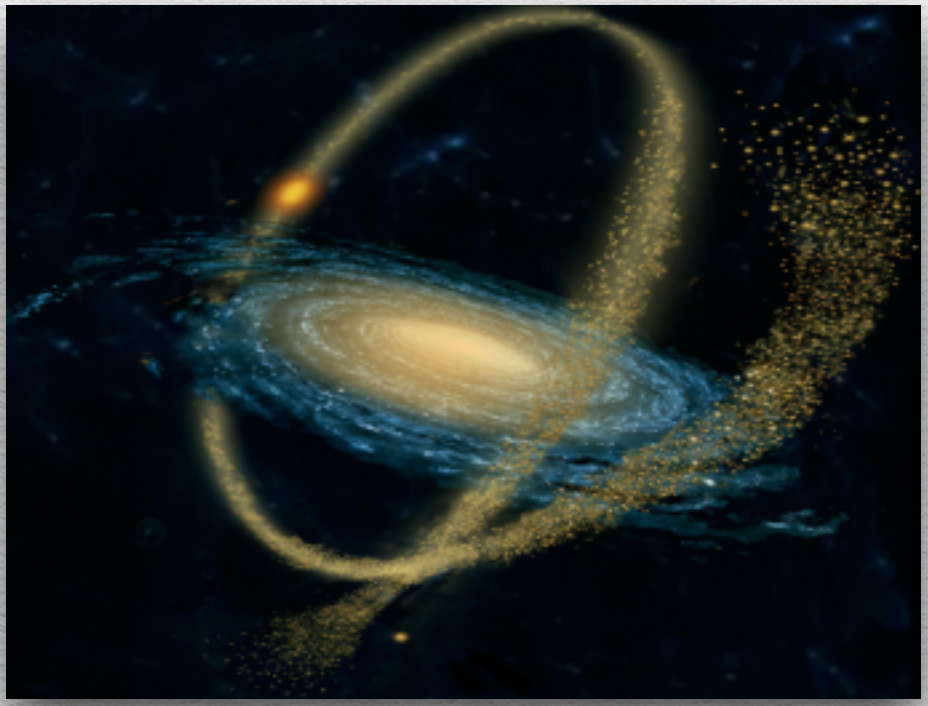
Herzog-Arbeitman+[1708.03635] (stellar kinematics)

Substructure

Hierarchical galaxy formation by merger and accretion ***will*** (and has) lead to substructure in the MW. The questions are:

- Is there any nearby?
- Do we expect more/less substructure due to DM particle interactions?





Some possibilities:

- **Streams** (from dwarf galaxies) Purcell+ [1203.6617]
- **Debris flows** Kuhlen+ [1202.0007]
- **Shadow bar** Petersen+ [1602.04826]
- **Dark disk** Schaller+ [1605.02770]
- **Miniclusters** Kolb & Tkachev+ [hep-ph/9303313]
- **Ministreams** (from miniclusters) Dokuchaev+ [1710.09586]

Dark matter "astronomy"

Terrestrial measurement of $f(\mathbf{v})$ with a dark matter experiment

<u>**Why?**</u>

→ *Only* way to resolve astro. uncertainties on DM signal
→ *Only* way to probe local halo on Solar System scale
→ Galacto-archaeology of MW
→ Information about cosmological production of DM

Example 1: WIMPs

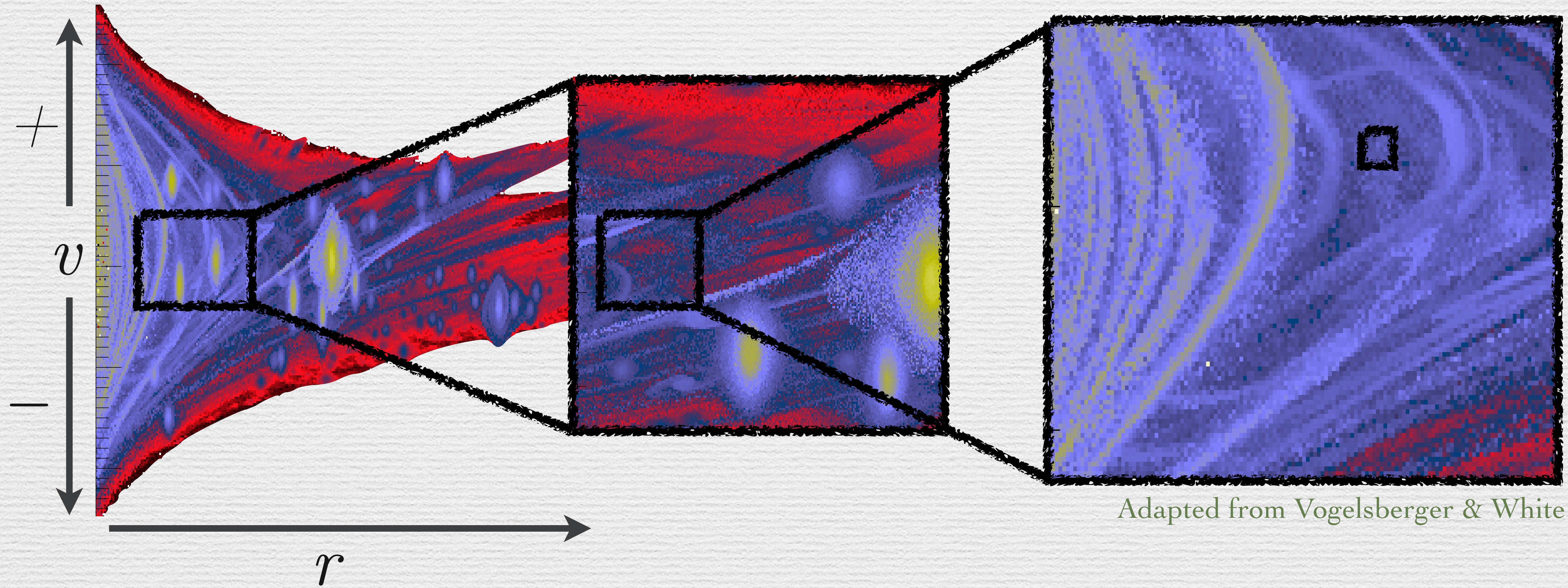
WIMPs are vanilla thermally produced CDM

→ Subhalos down to ~ Earth mass Green+ [astro-ph/0503387]

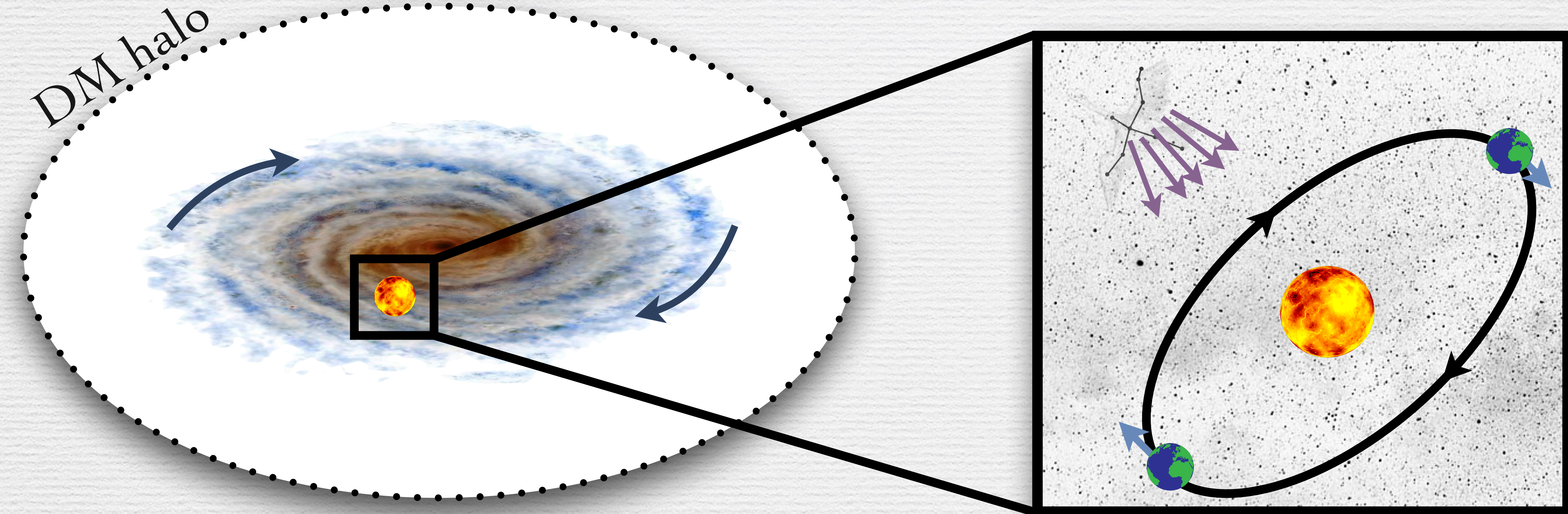
→ No ultralocal structure (< milli pc) Vogelsberger+ [1002.3162]

→ Possible tidal stream (Sgt. stream) Purcell+ [1203.6617]

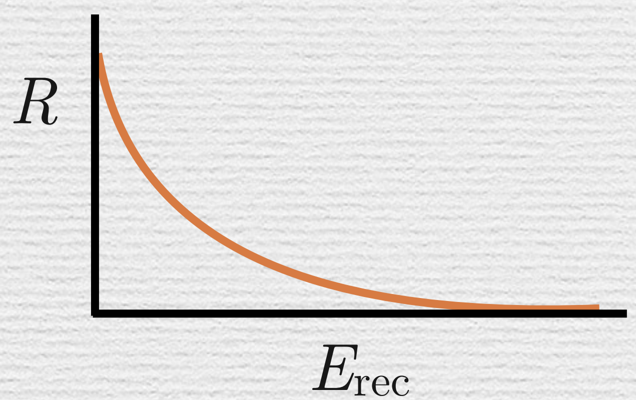
→ Unlikely dark disk Schutz+ [1711.03103]



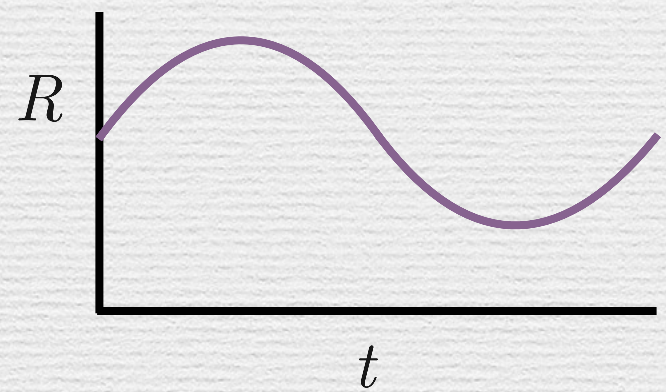
WIMP signals



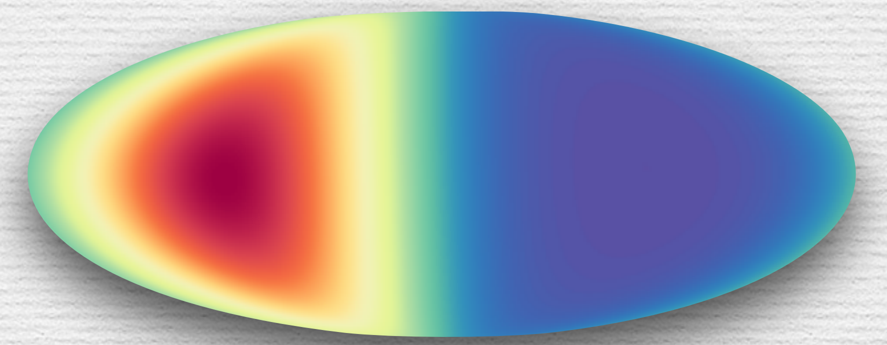
1. ~keV nuclear recoils
(rate/energy)



2. Annual modulation
(rate/energy-time)



3. Lab frame anisotropy
(rate/energy-time-direction)

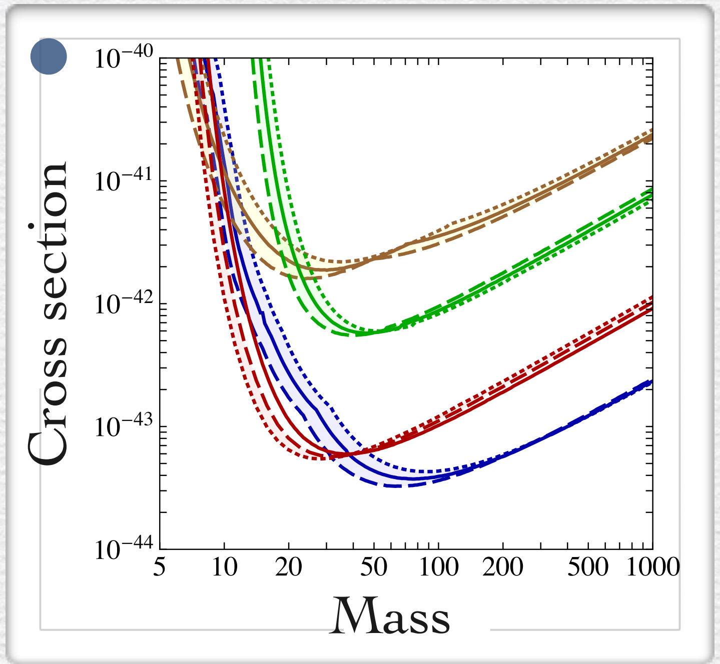


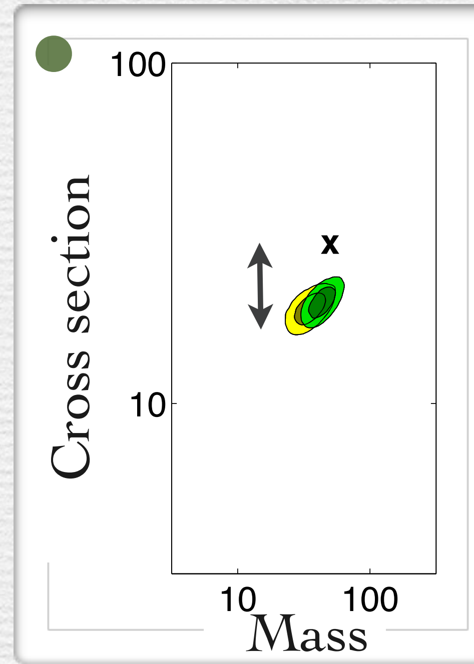
WIMPs: astrophysical uncertainties

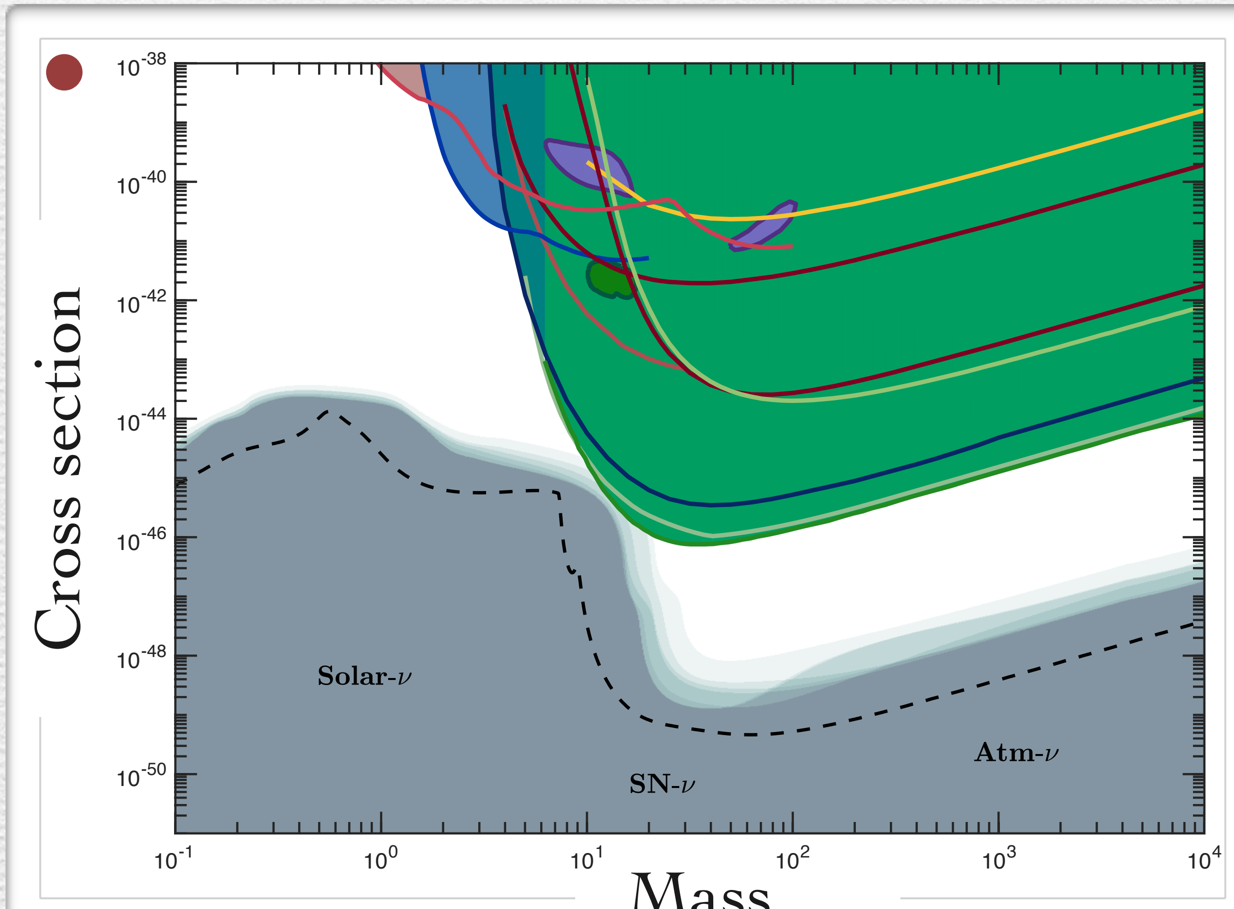
- **Uncertainty in exclusion limits**
  e.g. McCabe [1005.0579]
  "What have I ruled out?"

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

- **Neutrino floor**
  e.g. O'Hare [1505.08061]
  "Does my background mimic a signal?"

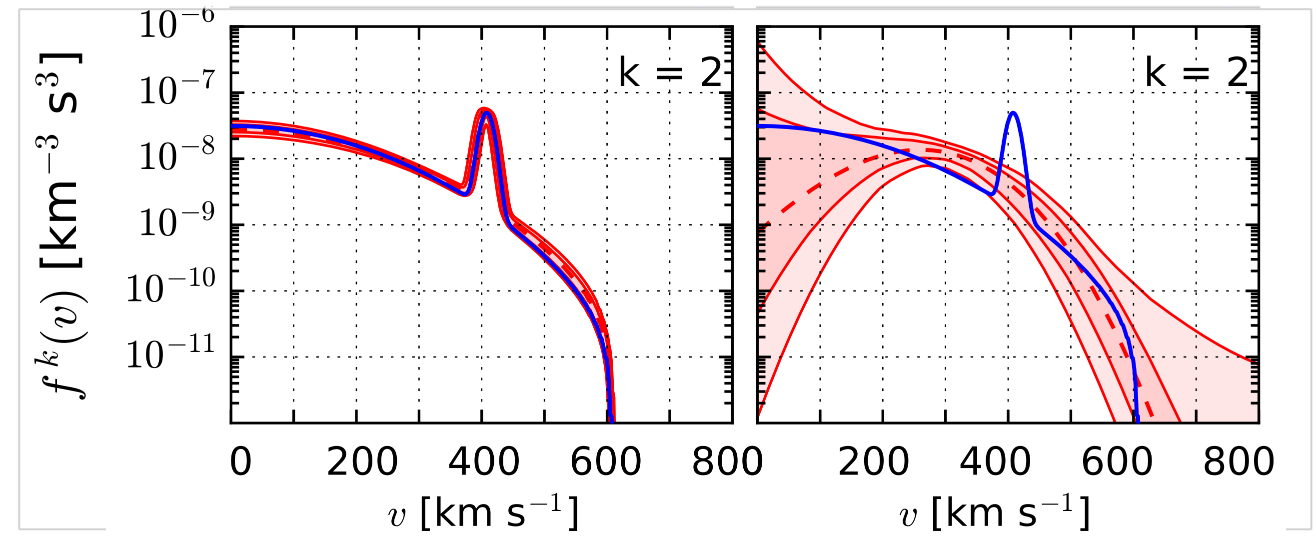




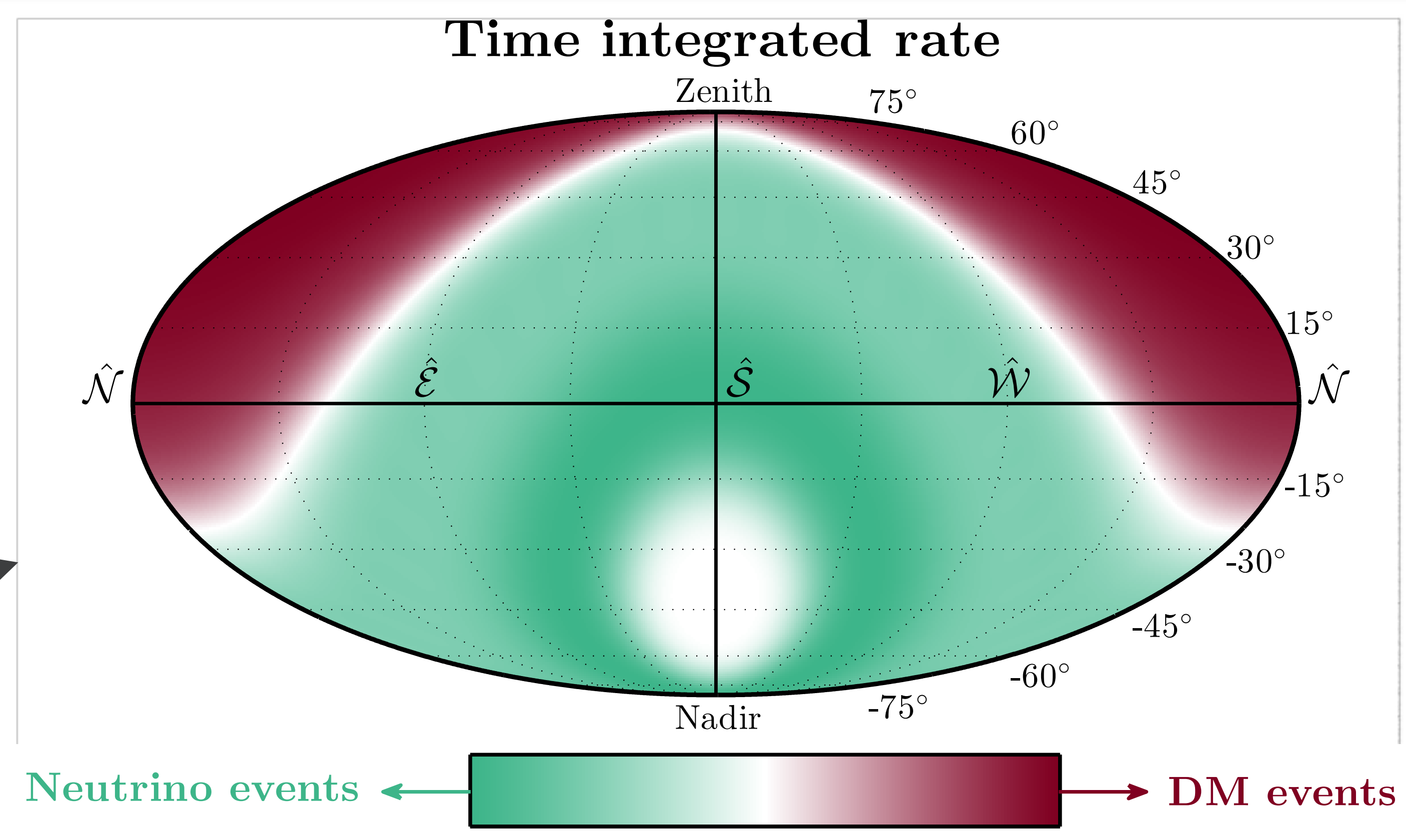


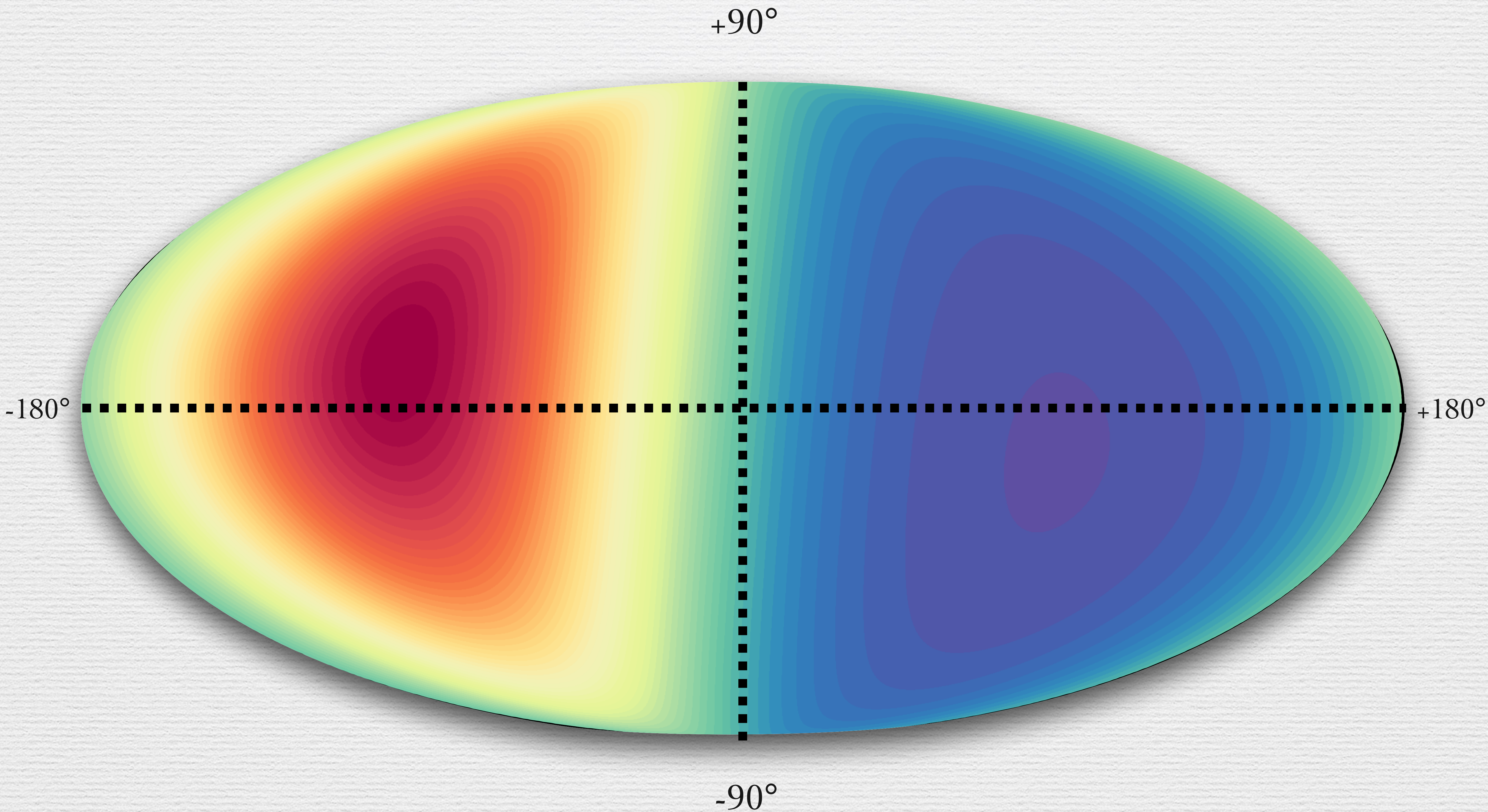
Directional detection

- Reconstruct full 3-d velocity distribution
  Kavanagh & O'Hare [1609.08630]



- Subtraction of neutrino background
  O'Hare+ [1505.08061]
  O'Hare+ [1708.02959]

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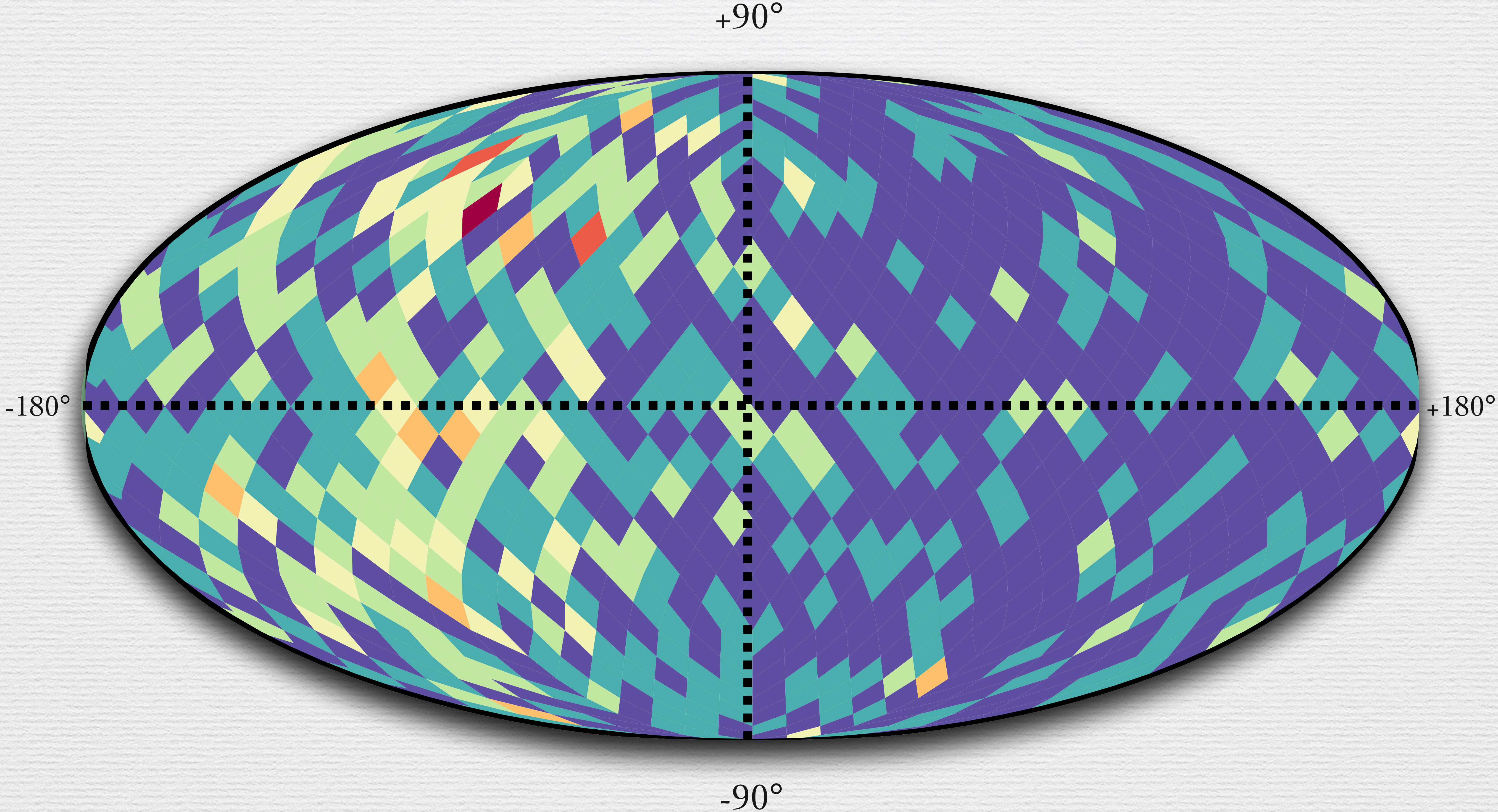
-180°
+180°
-90°


+90°
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-90°

Directional detectors

Disadvantages (gas TPCs):

- ✗ Hard to reconstruct complete recoil directions
- ✗ Need to balance large target mass vs. accurate tracks
- ✗ Signals often disappear at low energies

Advantages:

- ✓ Confirmation of *Galactic* DM discovery
- ✓ Enhanced signal discrimination
- ✓ Exploration of DM **velocity** distribution

Axion astronomy

The local axion field

- Axion dark matter behaves as a classical field oscillating in $(\mathbf{x},t)$, with modes $(\mathbf{p} = m_a\mathbf{v})$ that "explore" the astrophysical distribution:

$$a(\mathbf{x},t) = \frac{\sqrt{2\rho_a}}{m_a}\int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3}|\mathcal{A}(\mathbf{p})|\cos\left(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha_{\mathbf{p}}\right)$$

Axion power spectrum

- Define a "coherence" length and time, within which all modes of the field are in phase,

$$a(\mathbf{x},t) \approx \frac{\sqrt{2\rho_a}}{m_a}\cos\left(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha\right)$$

Axion dark matter

- If we measure the field over time/length scales larger than those that dephase the tail of the axion oscillations we effectively measure the distribution of modes

$>$ **coherence time:**

$$\tau_a = \frac{2\pi}{m_a \langle v \rangle^2} \simeq 40\,\mu\text{s}\left(\frac{100\mu\text{eV}}{m_a}\right)$$

1. Frequency of photons
$\rightarrow$ Axion speeds

$$|\mathcal{A}(\omega)|^2 \propto f(v)$$

$>$ **coherence length**

$$\lambda_a = \frac{2\pi}{m_a \langle v \rangle} \simeq 12.4\,\text{m}\left(\frac{100\mu\text{eV}}{m_a}\right)$$

2. Coherence loss across experiment
$\rightarrow$ Axion directions (weighted by geometry)

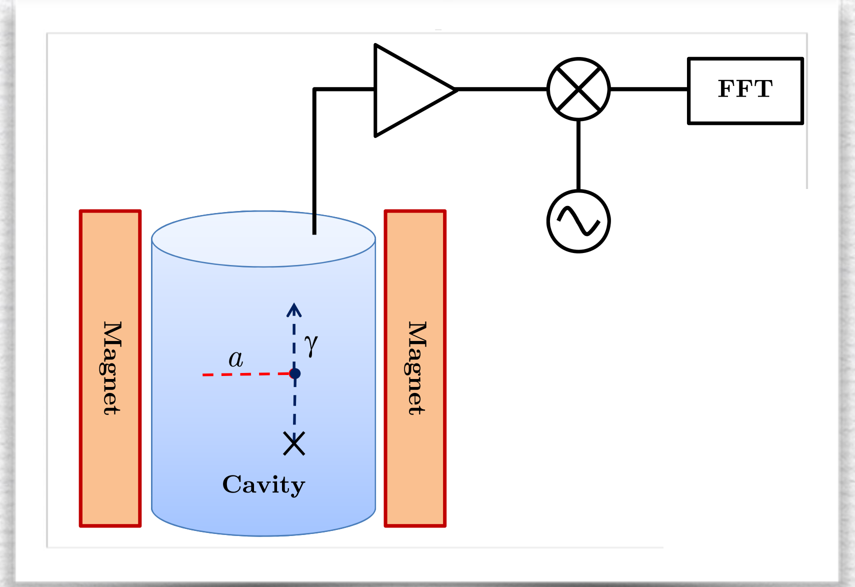
$$\int_{\text{expt.}} |\mathcal{A}(\mathbf{p})|^2 \rightarrow \int \text{d}\Omega_v\, \mathcal{G}(\mathbf{v}) f(\mathbf{v})$$

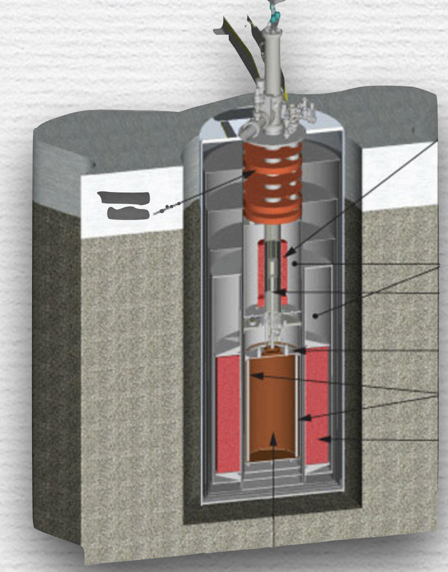
Ideally we measure both effects

(1) couple axion oscillation to the resonant mode of a cavity

ADMX [0910.5914]

HAYSTAC [1611.07123]

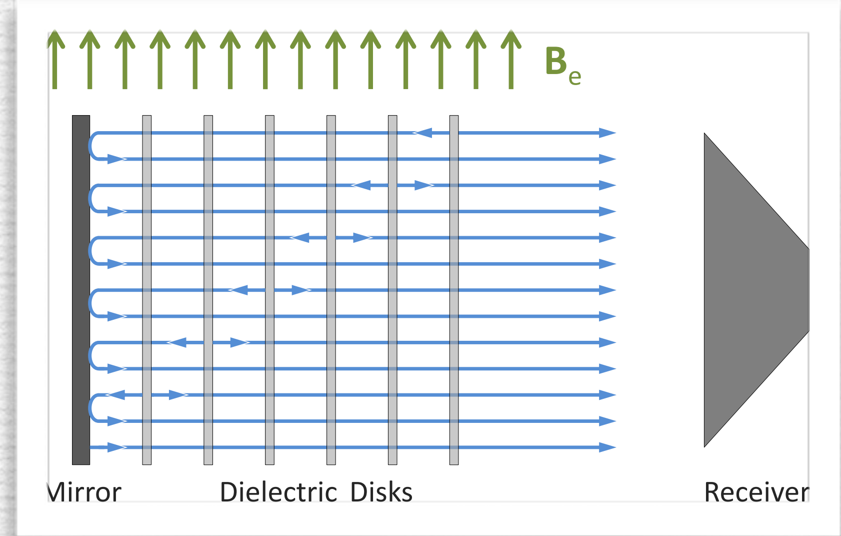


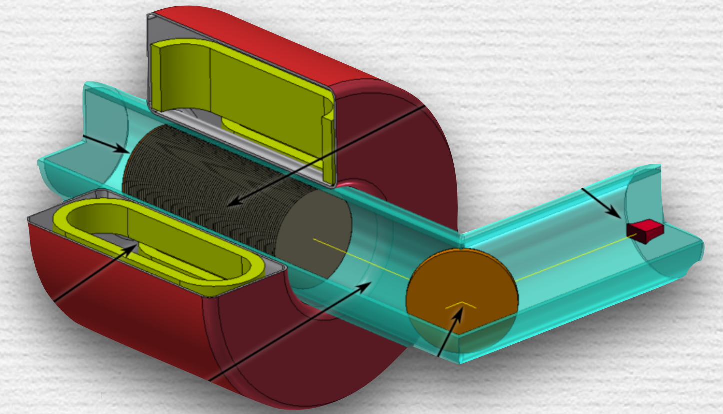


(2) generation of EM waves at magnetised boundaries

MADMAX [1611.05865]

BRASS [citation needed!]

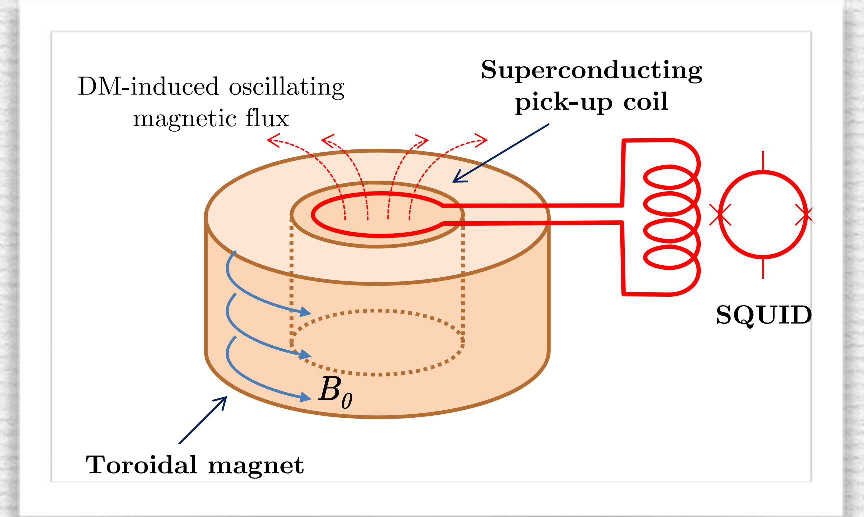


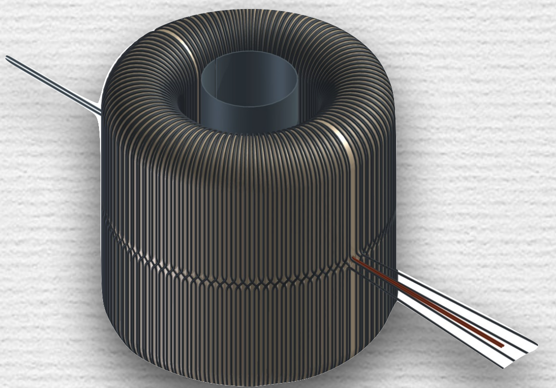


(3) Axion-induced electric currents

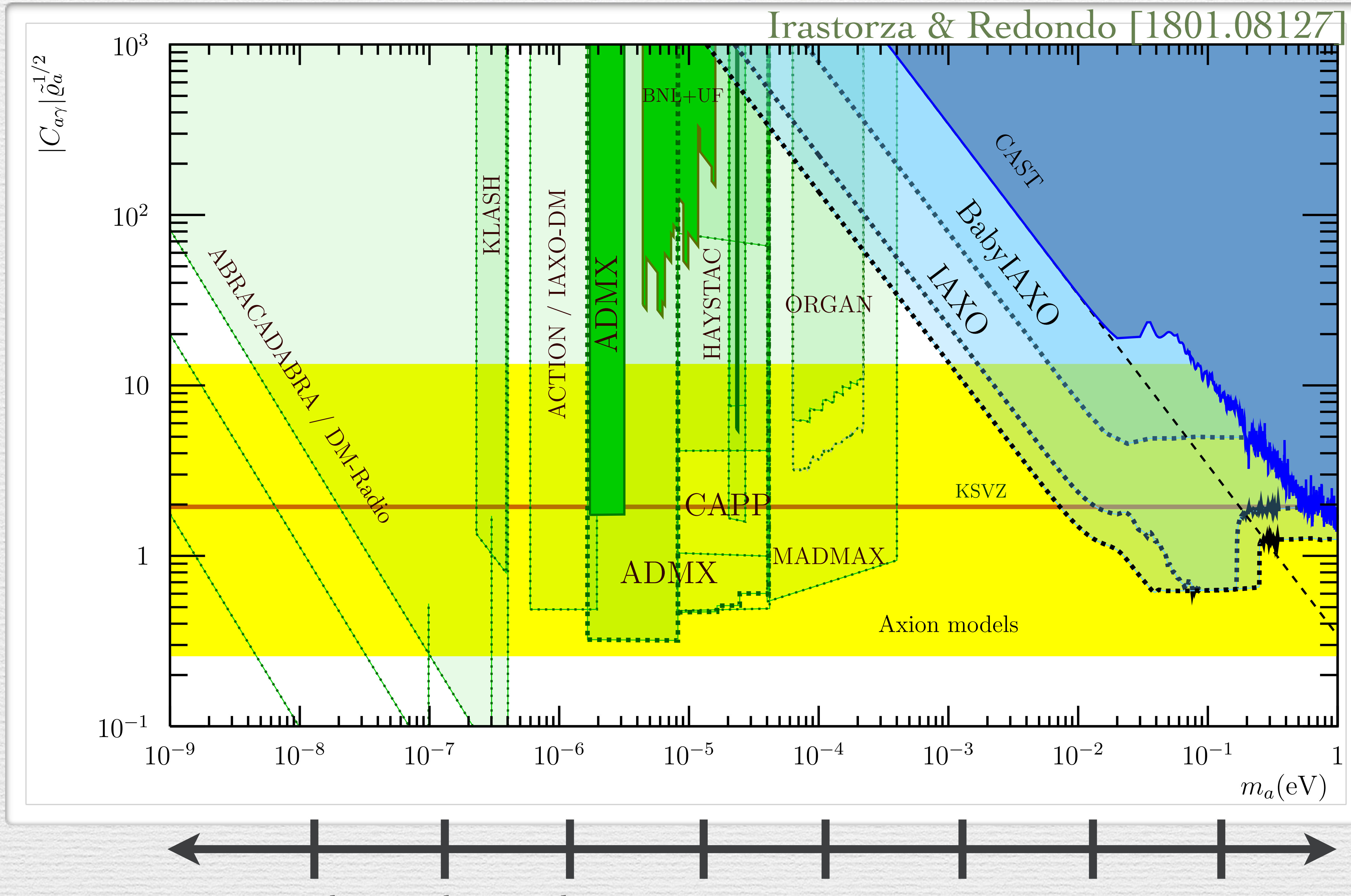
DM-Radio [1610.09344]

ABRACADABRA [1711.10489]





Haloscopes

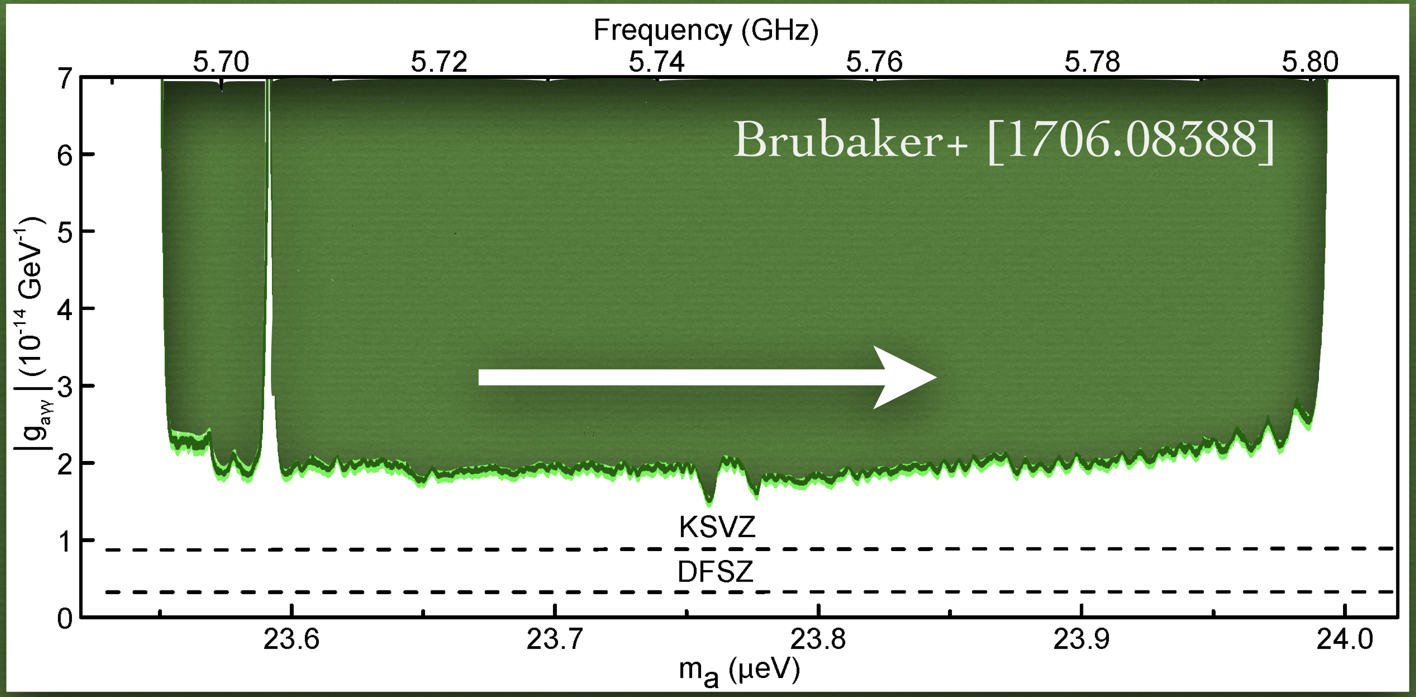


$$\left(C_{a\gamma} = \frac{2\pi f_a\, g_{a\gamma}}{\alpha}\right)$$

Axion search storyboard

Step 1: Axion search

for a given resonant freq. measure power extracted from cavity over bandwidth. Then move the resonant frequency and try again



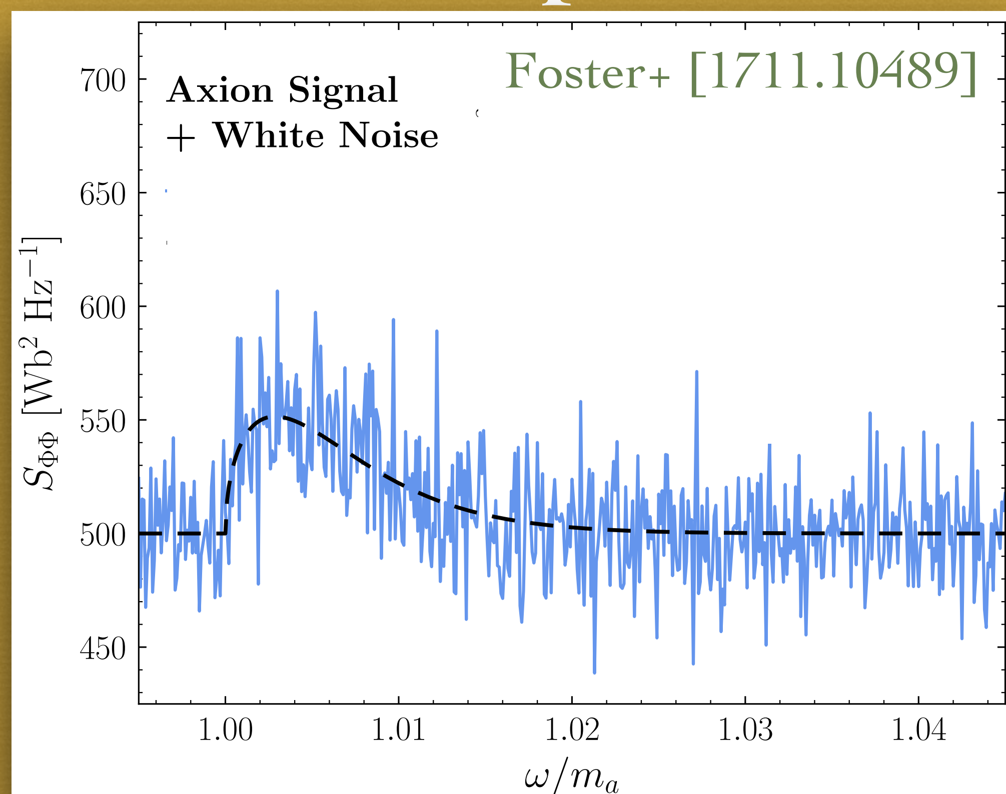
Axion search storyboard

Step 1: Axion search

for
pov
bar
res

Step 2: Axion signal

Once resonance is found, Fourier transform signal timestream to measure axion spectrum



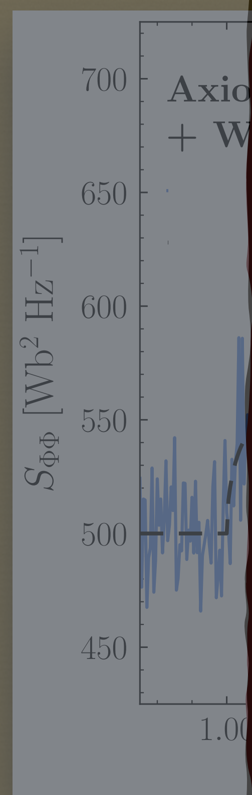
Axion search storyboard

Step 1: Axion search

for
pov
bar
res

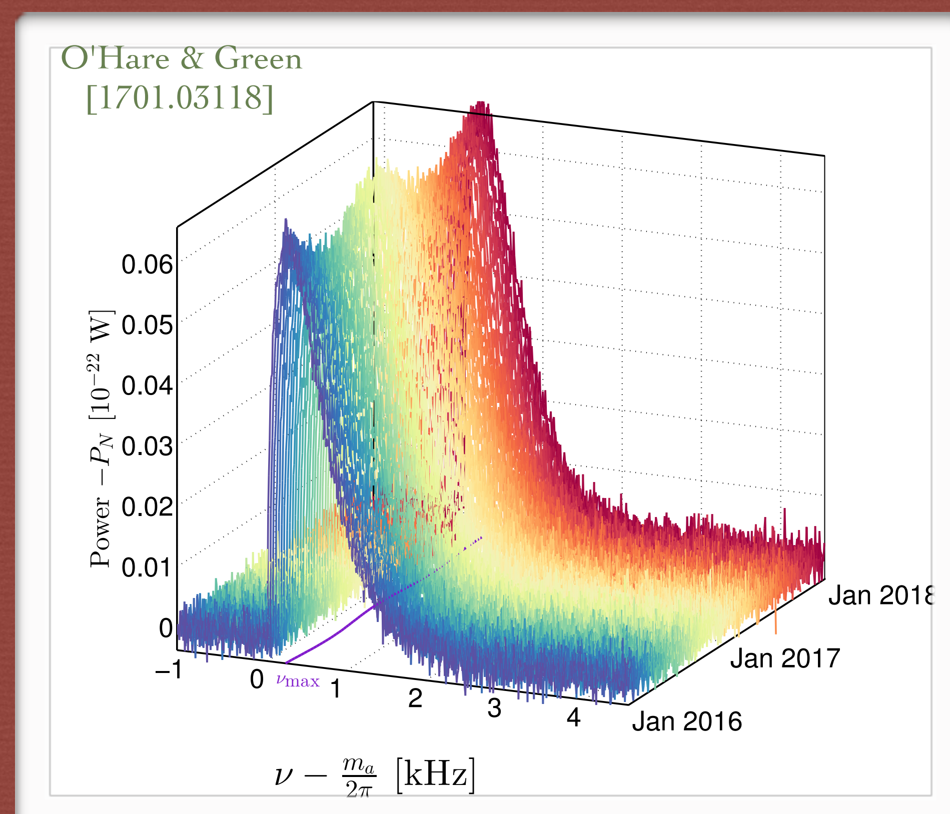
Step 2: Axion signal

Once res
transforr
measure



Step 3: Modulation

Repeat experiment to measure phase of annual modulation
→ confirmation of DM signal



Axion search storyboard

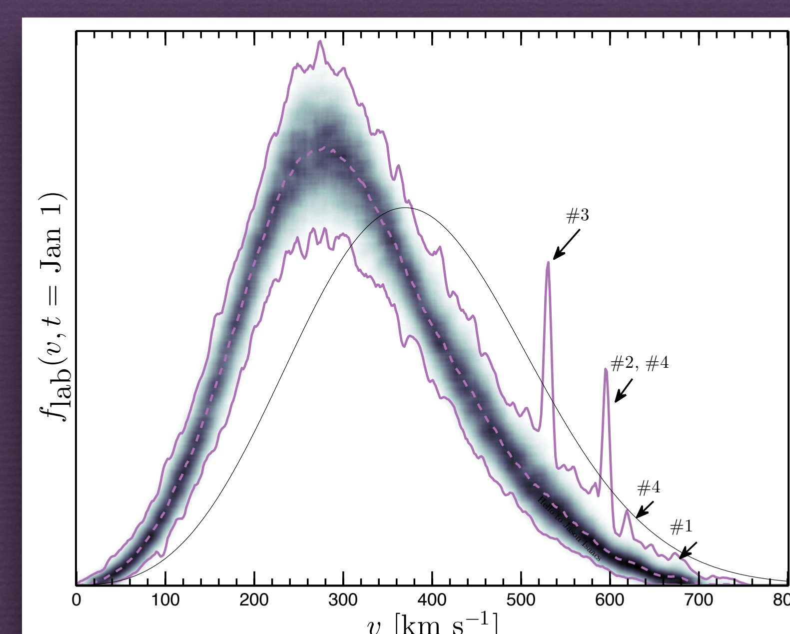
Step 1: Axion search

Step 2: Axion signal

Step 3: Modulation

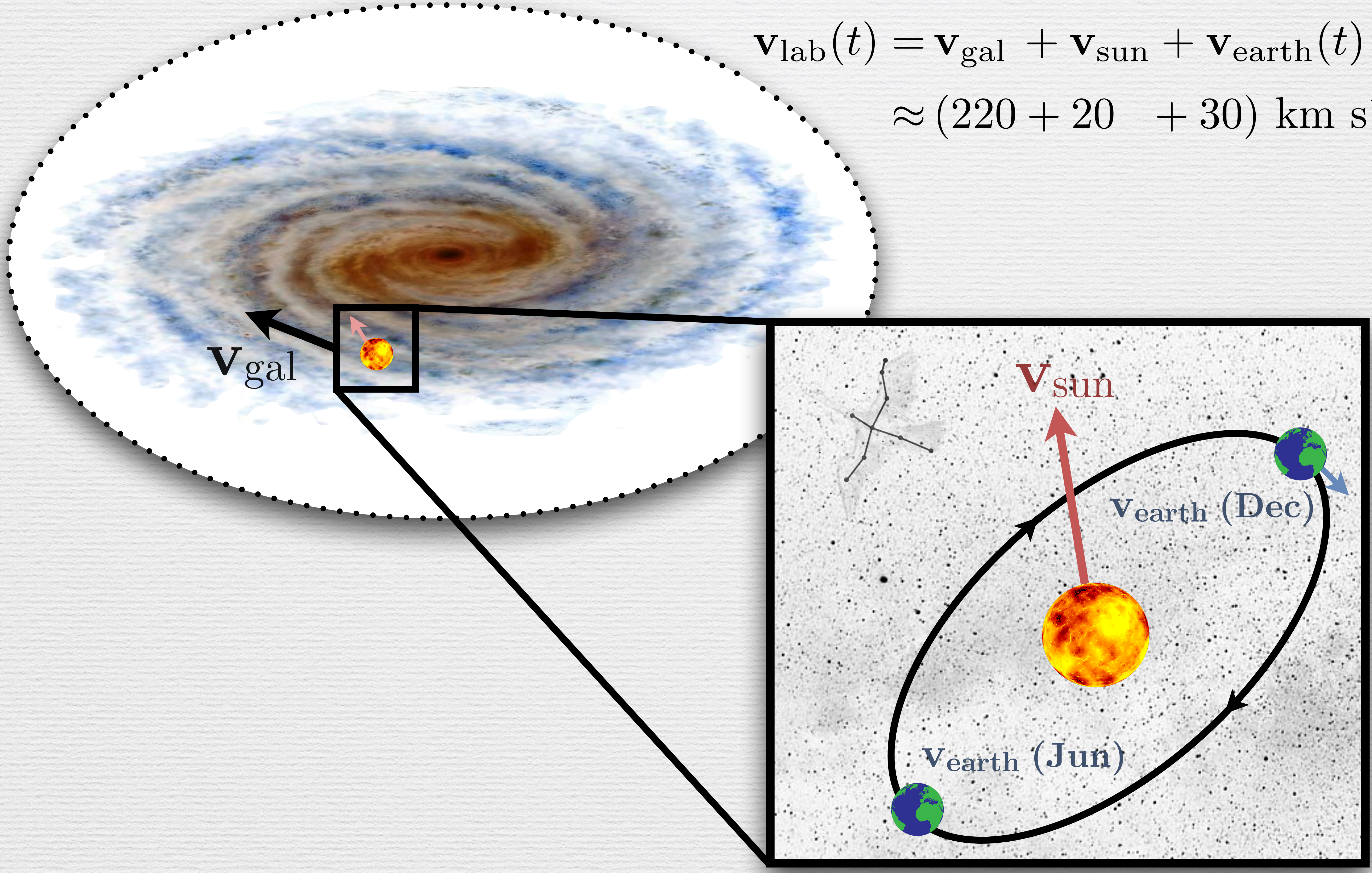
Step 4: Astronomy

Build specialised detectors, exploit directional dependence, measure features in distribution…



Axion astronomy: Measuring the lab velocity

$$\mathbf{v}_{\rm lab}(t) = \mathbf{v}_{\rm gal} + \mathbf{v}_{\rm sun} + \mathbf{v}_{\rm earth}(t)$$
$$\approx (220 + 20 \quad + 30)\ {\rm km\ s}^{-1}$$



Axion astronomy

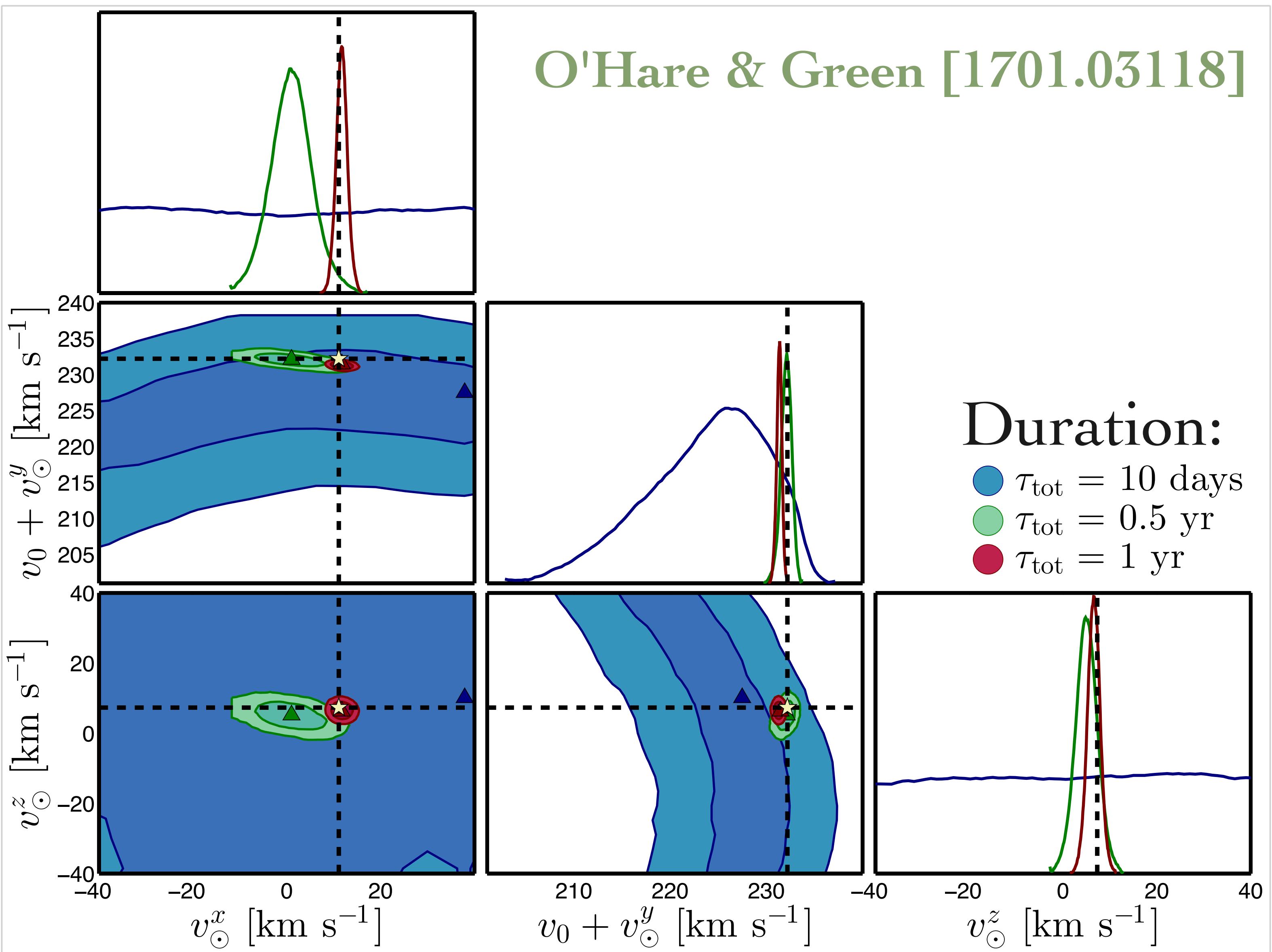
- Likelihood fit spectrum to astrophysical parameters

$$\mathbf{v}_{\rm sun+gal} = (v_\odot^x, \quad v_0 + v_\odot^y, \quad v_\odot^z)$$

Galactic centre

Galactic rotation

Galactic North

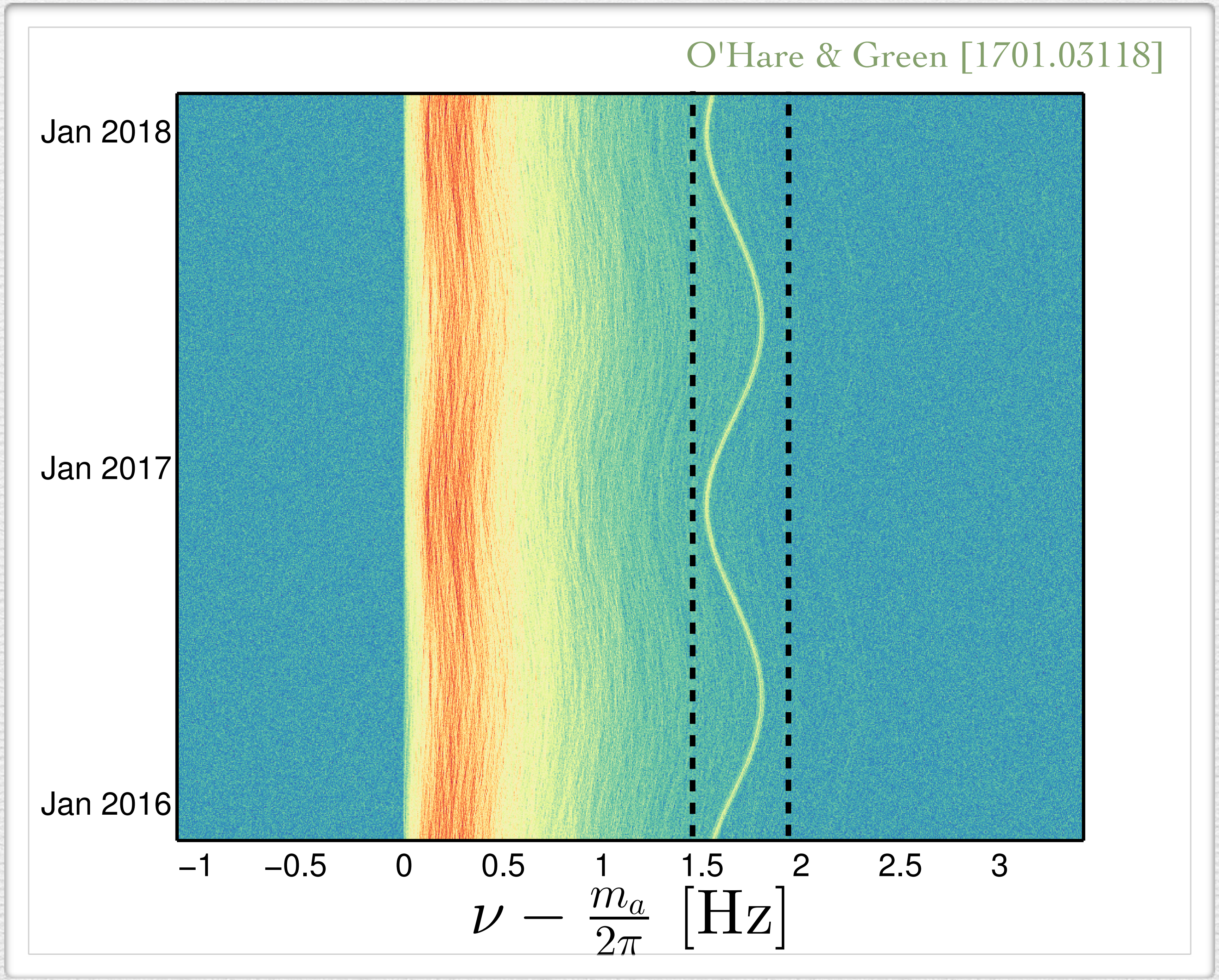


Astrometric uncertainty: ~ 1 km/s
Schoenrich+ [0912.3693]

Detecting Streams

- Modulations can be used to identify localised features by their unique phase, amplitude and frequency offset

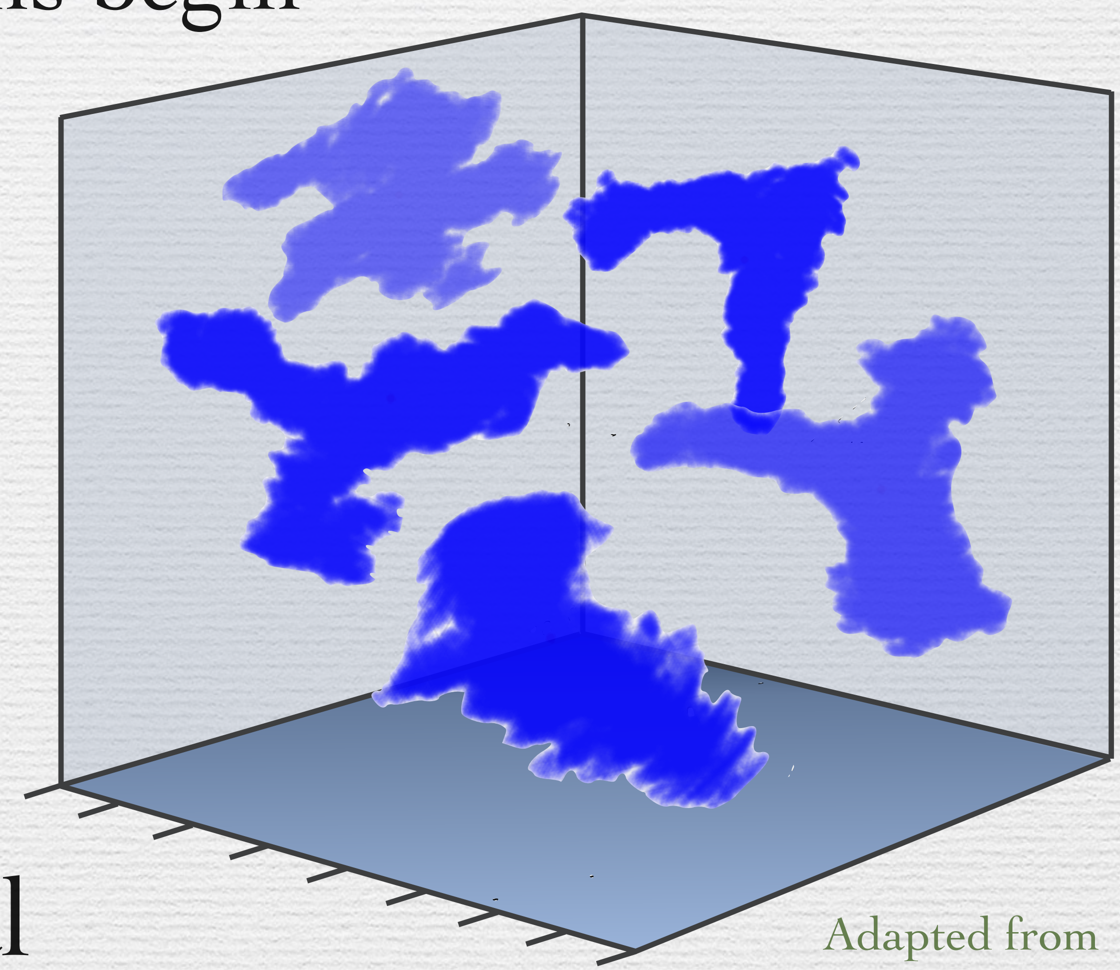
Power spectrum vs. time from N-body simulation



Miniclusters

Substructure for post-inflation scenario axionic DM
→ Collapsed overdensities of the axion field, formed from mass inside horizon when axion oscillations begin

$$\rho_{\rm mc} \sim 10^{6}\,{\rm GeV\,cm^{-3}}$$
$$R_{\rm mc} \sim 10^{7}\,{\rm km} \sim 0.2\,{\rm AU}$$
$$M_{\rm mc} \sim 10^{-12} M_{\odot}$$



Adapted from Stadler & Redondo

High density/low dispersion
→ sharp enhancement in signal
(but our encounter rate < 1 per 100,000 years)

"Ministreams"

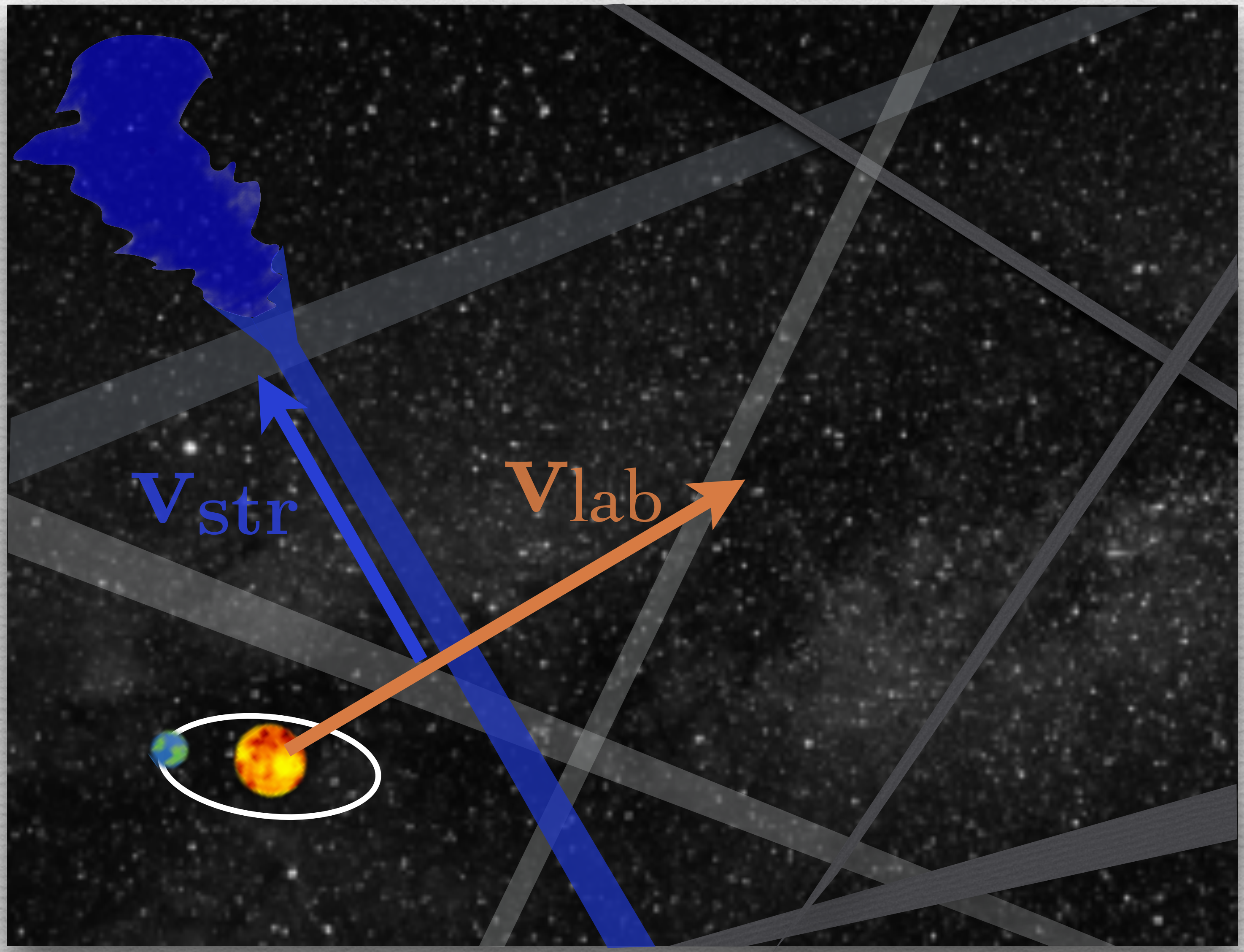
- Network of streams from mini clusters tidally disrupted by stars

$$R_{\rm mstr} \simeq \frac{0.23\,{\rm AU}}{\delta(1+\delta)^{1/3}} \left(\frac{M_{\rm mc}}{10^{-12}\,M_\odot}\right)^{1/3}$$

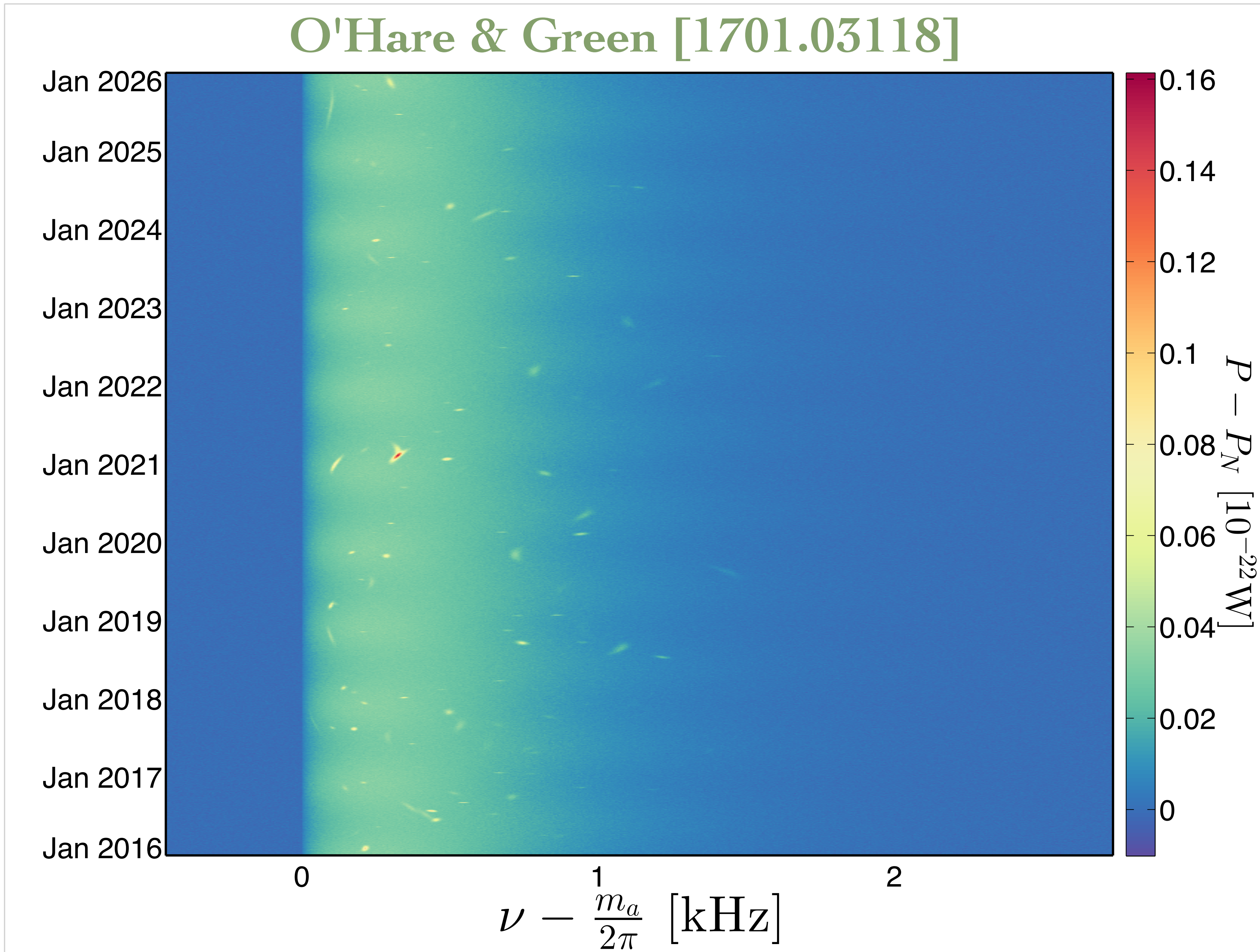
- Could be more regular, giving temporary enhancements in signal

$$\tau_{\rm str-x} = \frac{2R_{\rm mstr}}{v_{\rm lab}\sqrt{1-\frac{\mathbf{v}_{\rm str}\cdot\mathbf{v}_{\rm lab}}{v_{\rm str}v_{\rm lab}}}}$$

$$\sim \mathcal{O}(\text{hours} - \text{days})$$



"Ministreams"



A directional axion experiment?

A directional axion experiment?

- From "Maxiowell's equations" one can derive

$$\ddot{\mathbf{E}} - \nabla^2 \mathbf{E} = -g_{a\gamma} \mathbf{B}_{\rm ext} \ddot{a}$$

- Which has solutions (for electric field mode i : $\mathbf{E} = \sum E_i(t) \mathbf{e}_i(\mathbf{x})$)

$$\ddot{E}_i + \omega_i^2 E_i + \Gamma \dot{E}_i = -g_{a\gamma} \frac{1}{V} \int {\rm d}V \, (\mathbf{e}_i \cdot \mathbf{B}_{\rm ext}) \ddot{a}$$

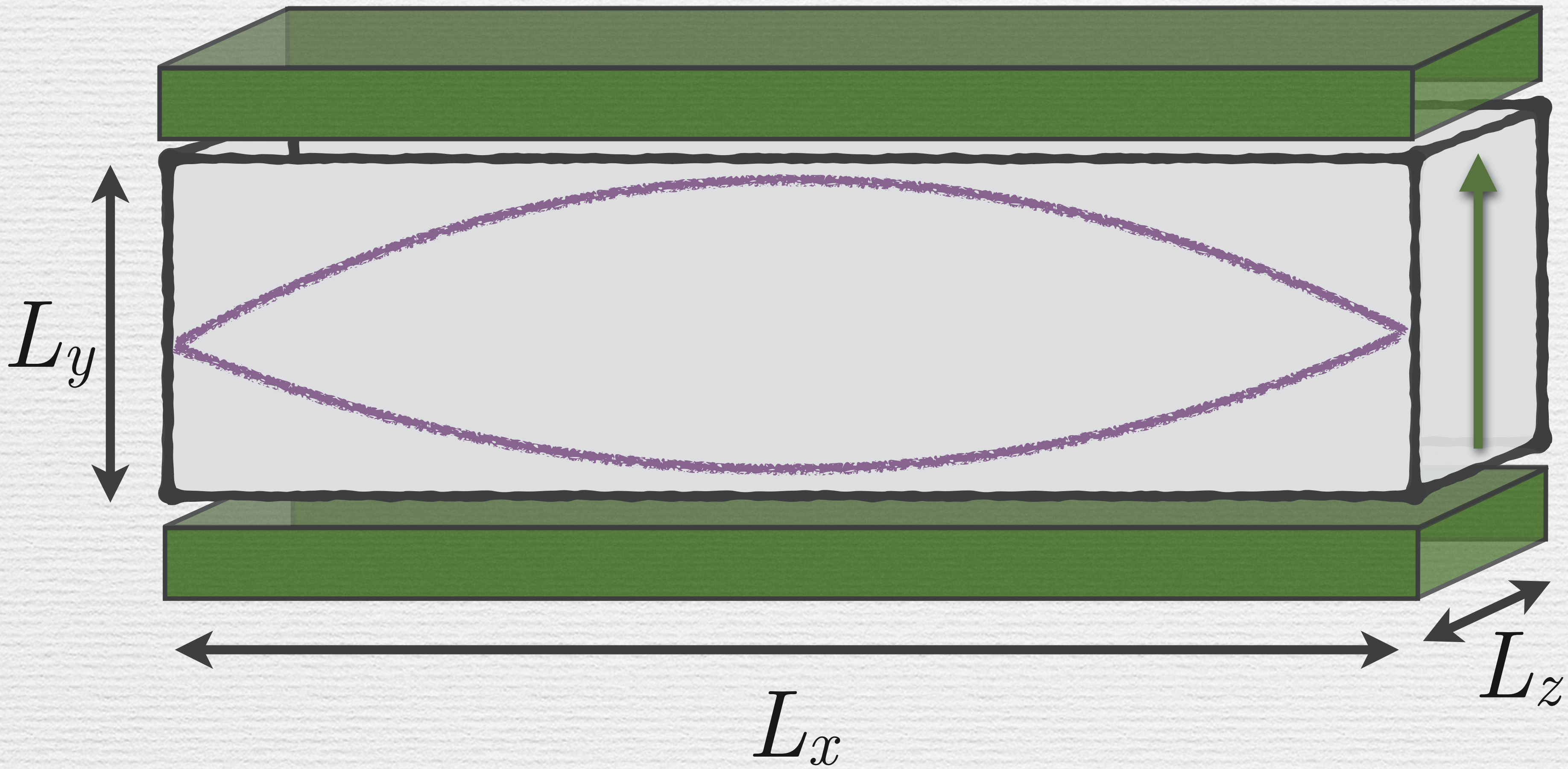
First put in one axion wave: $a(\mathbf{x}, t) \sim a_0 e^{-i(\omega t + \mathbf{p}\cdot\mathbf{x})}$

$$= -g_{a\gamma} B_{\rm ext} C_i \omega^2 a_0 e^{i\omega t}$$

C_i = Cavity form factor
(integrates axion spatial distribution over the EM geometry of the expt)

Simple example: rectangular cavity

Lowest resonant mode: $\mathbf{e}_{101} = \left(0, 2\sin\left(\frac{\pi x}{L_x}\right)\sin\left(\frac{\pi z}{L_z}\right), 0\right)$



$\mathbf{B}_{\rm ext} = (0,\ B_{\rm ext}\ ,\ 0)$

Form factor for axion wave of momentum $\mathbf{p} = m_a \mathbf{v}$

$$\rightarrow \qquad C = \frac{1}{V B_{\rm ext}} \int {\rm d}V \mathbf{e}_i \cdot \mathbf{B}_{\rm ext}\, e^{i\mathbf{p}\cdot\mathbf{x}}$$

Rectangular cavity

In the zero velocity limit we have the usual form factor

$$|C|^2 = \left|\frac{1}{VB_{\rm ext}}\int_V {\rm d}V\,\mathbf{e}_{101}\cdot\mathbf{B}_{\rm ext}\right|^2 = \frac{64}{\pi^2} \equiv C_0$$

Now including the axion velocity,

$$|C|^2 = \frac{64}{\pi^4}\left[1 + m_a^2(g_x v_x^2 + g_y v_y^2 + g_z v_z^2)\right]$$

$$= C_0(1+\mathcal{G}(\omega,\mathbf{v}))$$

"Geometry factor"

$$|C|^2 = 0.66 - 0.033\left(\frac{m_a}{100\,\mu\text{eV}}\right)^2\left(\frac{L}{10\,\text{m}}\right)^2\left(\frac{v}{300\,\text{km}\,\text{s}^{-1}}\right)^2$$

Signal from axion distribution

Axion field $a(\mathbf{x},t)$ oscillates with modes distribution $f(\mathbf{v};t)$

→ Integrate over velocities to get signal power vs. freq.:

$$\frac{\mathrm{d}P}{\mathrm{d}\omega}(t) = P_0 \mathcal{T}(\omega) \frac{\mathrm{d}v}{\mathrm{d}\omega} \left(f(v;t) + \int \mathrm{d}\Omega_v \, v^2 \mathcal{G}(\omega, \hat{\mathbf{v}}) \, f(\omega, \hat{\mathbf{v}};t) \right)$$

Total power on-resonance

Mode lineshape

Non-directional speed effect due to $\omega = m_a \left(1 + \frac{v^2}{2} + \ldots\right)$

Directional velocity effect due to geometry

→ **orientation-dependent**

→ **time-dependent**

Full velocity sensitivity

- General formalism would look something like:

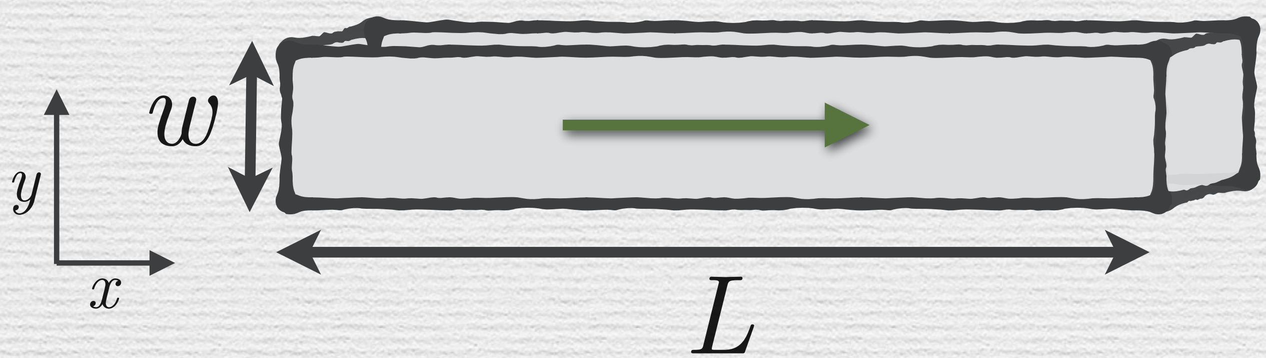
"**a**-type"
Linear velocity dependence

$$\mathcal{G}_a(\mathbf{v}) = \sum_{i=x,y,z} a_i v_i$$

"**b**-type"
Quadratic velocity dependence

$$\mathcal{G}_b(\mathbf{v}) = \sum_{i=x,y,z} b_i v_i^2$$

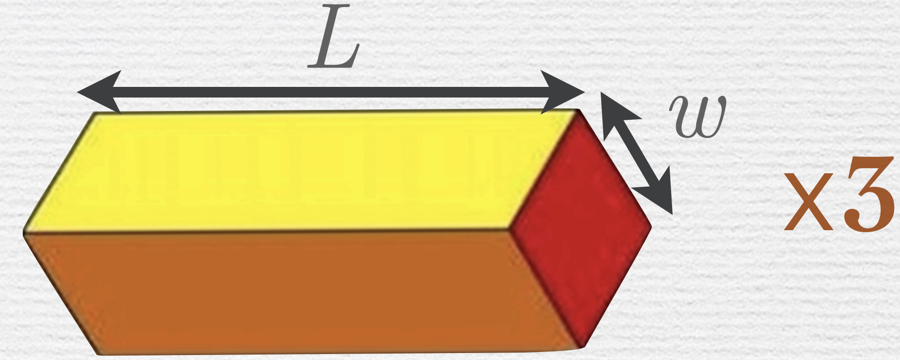
- For long aspect ratio experiments, expect one a_i/b_i component to dominate, e.g. rectangular cavity:



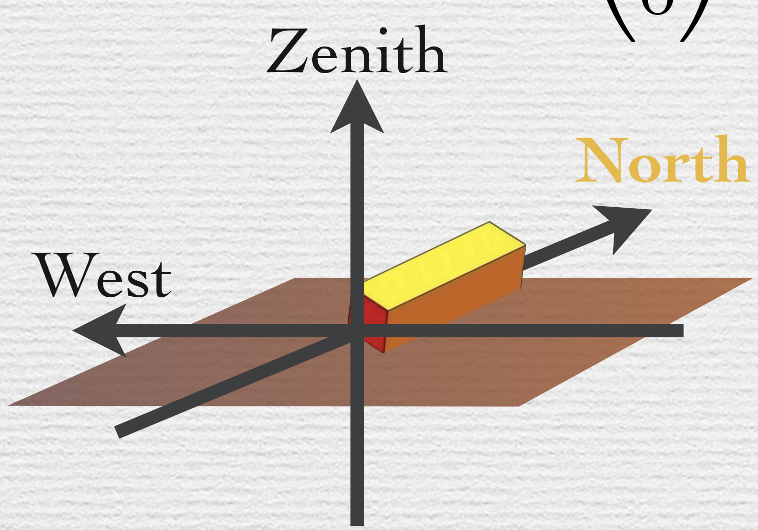
$$\mathbf{b}^2 = -m_a^2 \begin{pmatrix} L^2/12 \\ w^2(1/4 - 2/\pi^2) \\ w^2(1/4 - 2/\pi^2) \end{pmatrix}$$

Combining cavities

Set up multiple (e.g. three) cavities, and compare signals

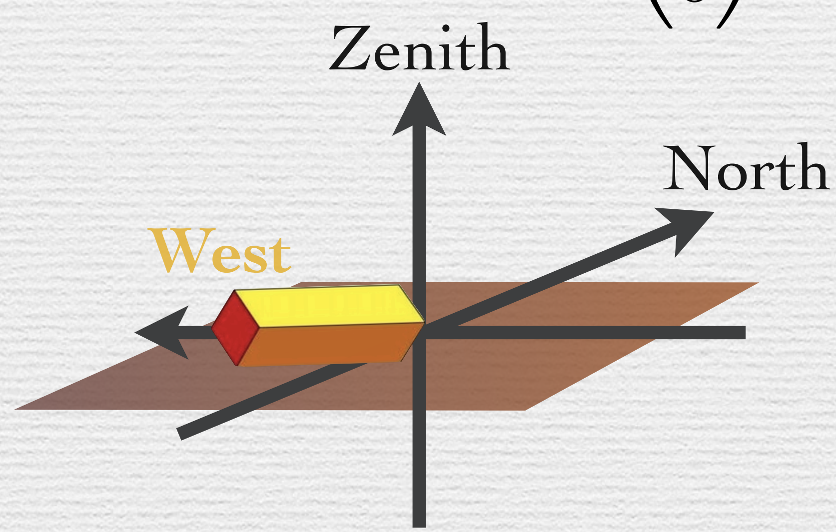


$$\mathbf{b}_N \approx -\frac{L^2 m_a^2}{12}\begin{pmatrix}1\\0\\0\end{pmatrix}$$



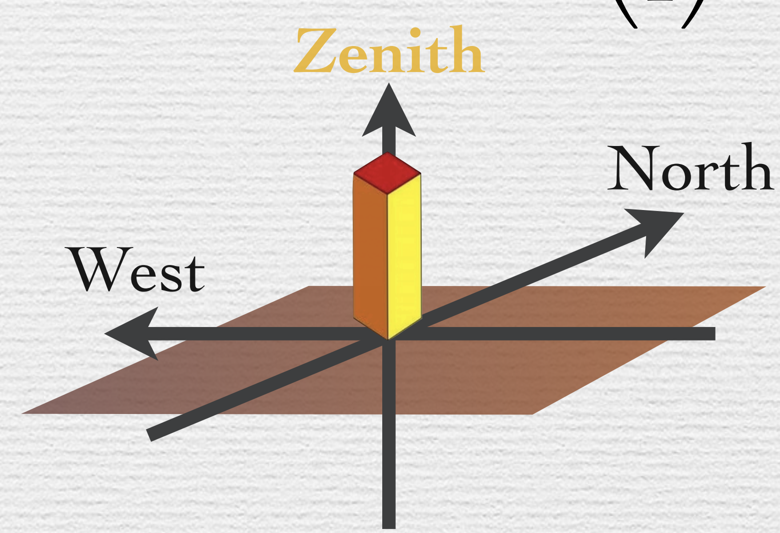
$\rightarrow\ v^2{}_N$

$$\mathbf{b}_W \approx -\frac{L^2 m_a^2}{12}\begin{pmatrix}0\\1\\0\end{pmatrix}$$



$\rightarrow\ v^2{}_W$

$$\mathbf{b}_Z \approx -\frac{L^2 m_a^2}{12}\begin{pmatrix}0\\0\\1\end{pmatrix}$$

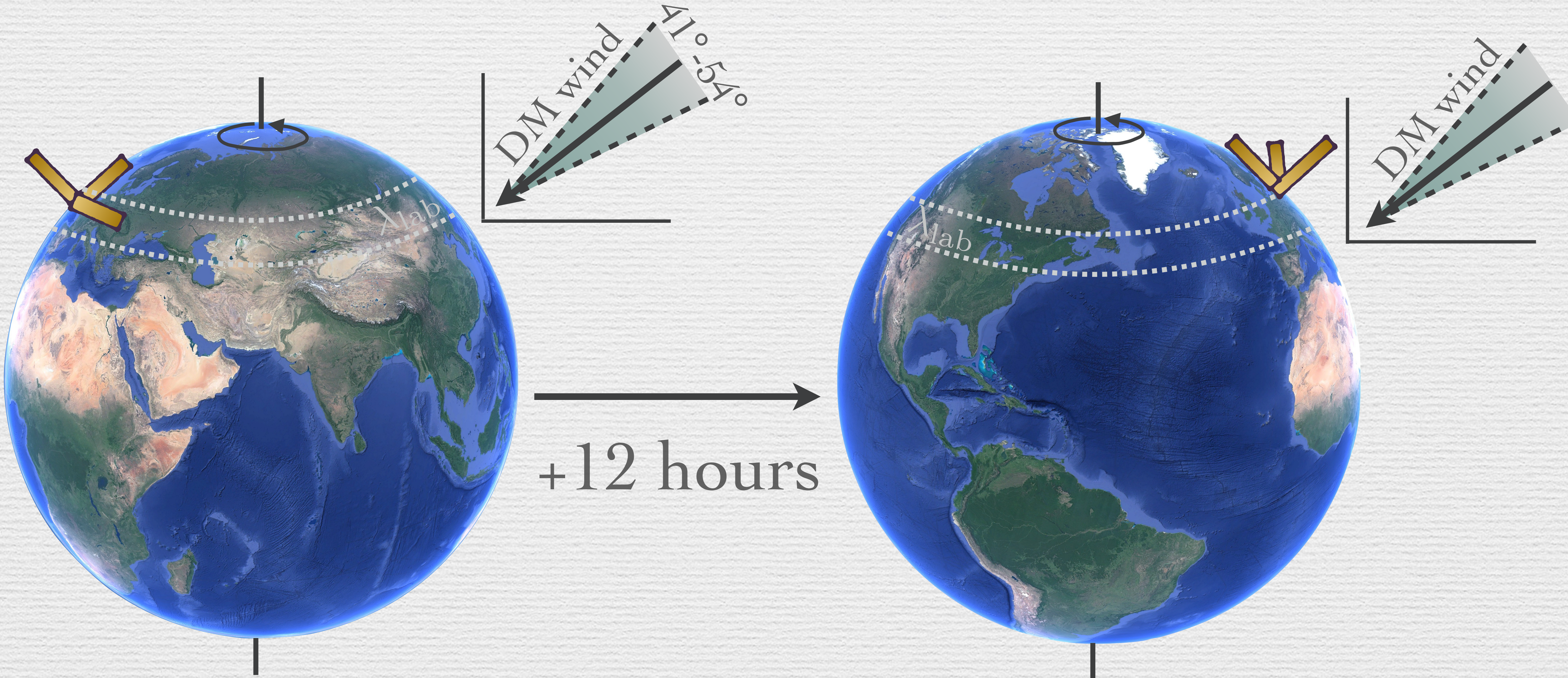


$\rightarrow\ v^2{}_Z$

Building an axion observatory

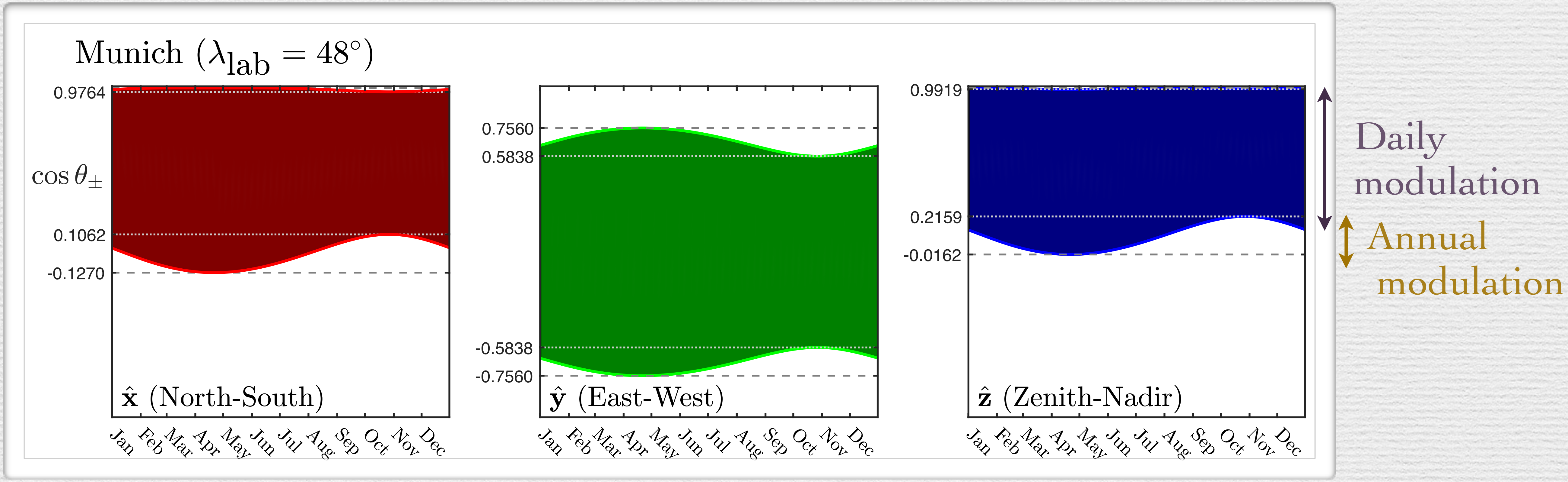
- Explore $f(\mathbf{v};\ t)$ by examining ratios of signals between cavities pointing in different directions
- But **b**-type experiment has no sensitivity to $\pm v_i$

  $\rightarrow$ But, the Earth is rotating and revolving



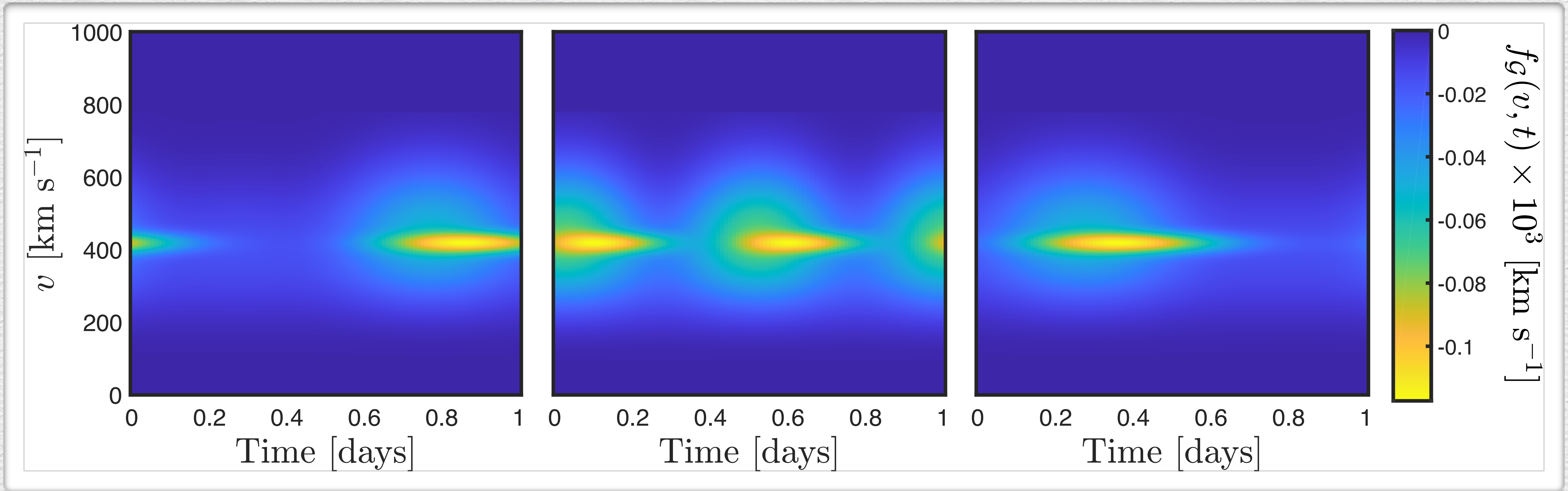
Daily modulation

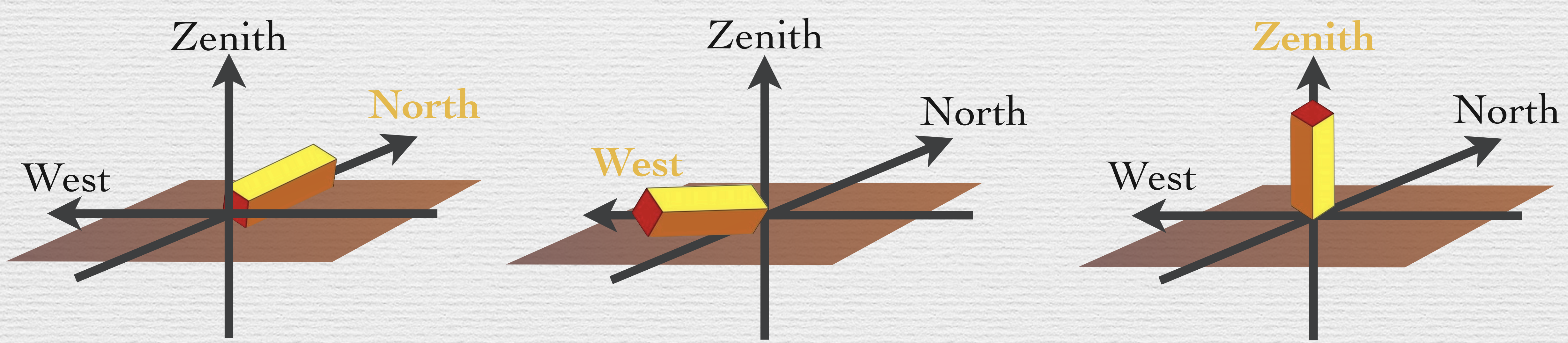
- For long cavity: daily modulation > annual
- Define $\cos\boldsymbol{\theta}_\pm(t)$ = range of angles between the axion wind and cavity directions: (North/West/Zenith)



Distribution with stream

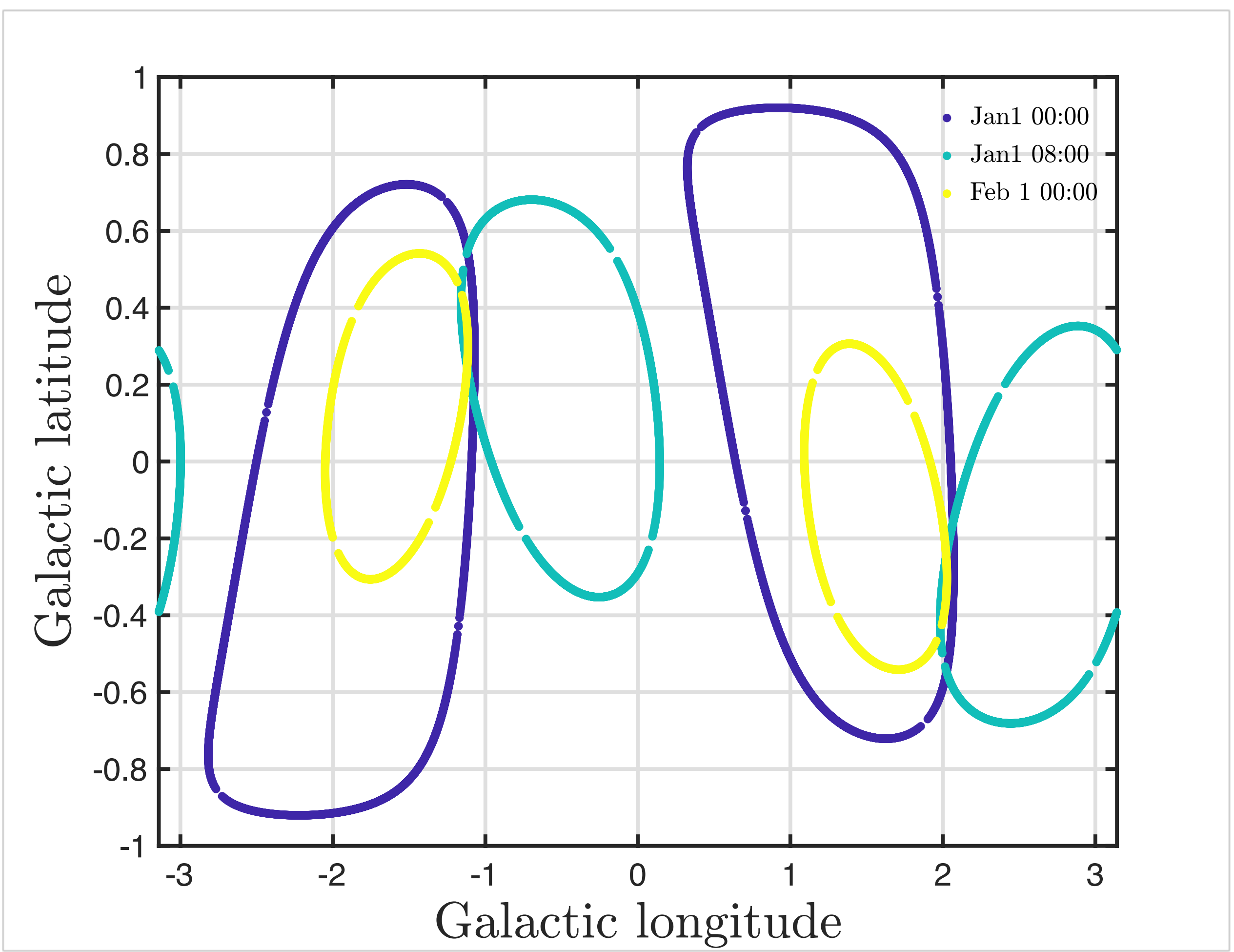
Daily modulation





Detecting a stream

- Detecting three velocity components of a stream:
  - $|v|$ $\rightarrow$ **No**-directionality: ~ O(1 year) of power spectra
  - $v^2{}_{x,y,z}$ $\rightarrow$ **b**-type directionality: ~O(1 month) of power spectra
  - $v_{x,y,z}$ $\rightarrow$ **a**-type directionality: ~ Single power spectrum



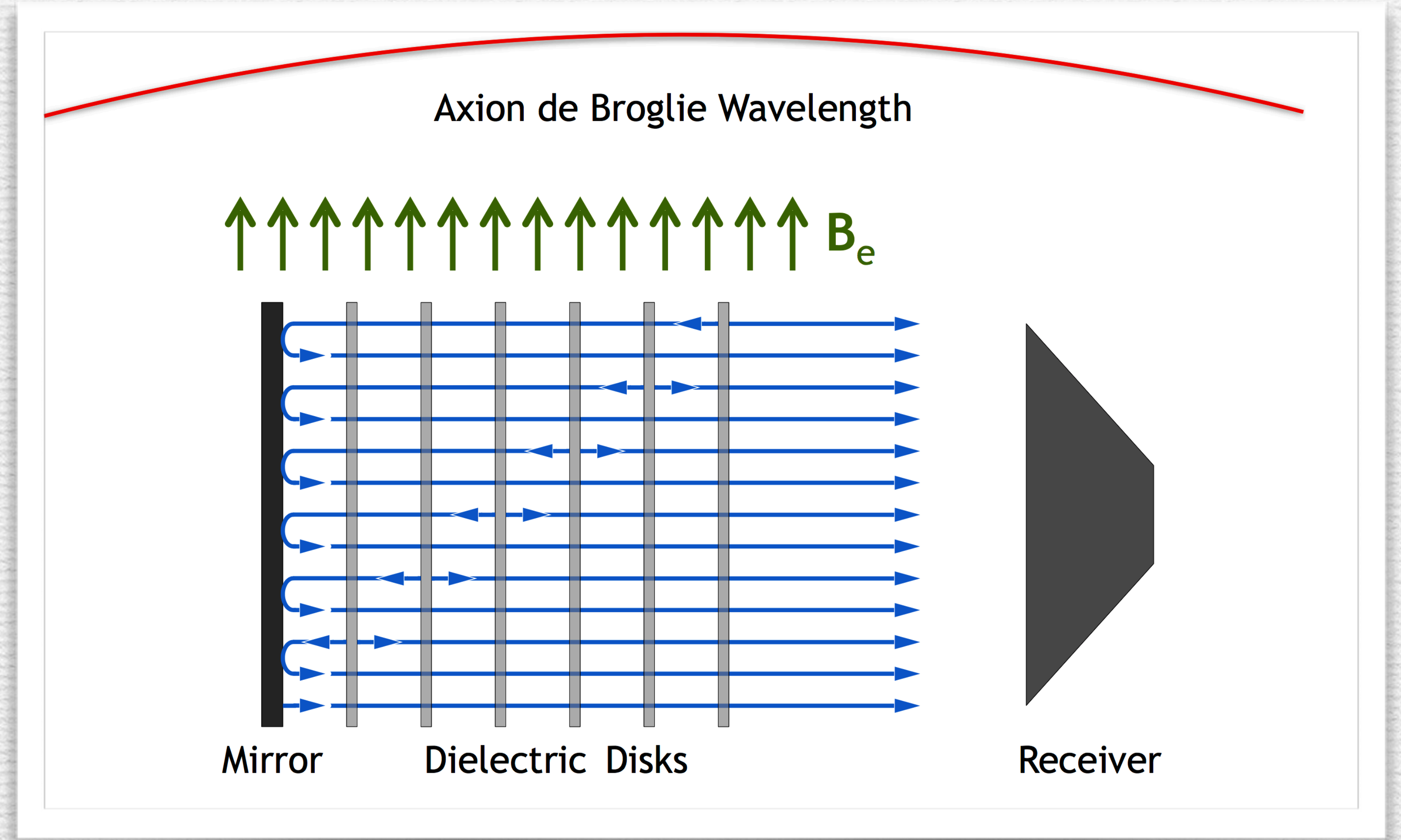
Purely from geometric arguments

(i.e. best case scenario with *no* noise)

Clearly an **a**-type experiment is desirable e.g. detection of ministreams

Dielectric disk haloscope

- Axion field crossing a magnetised boundary generates photons
- Line up multiple dielectric disks, spaced correctly to coherently enhance the reflected and transmitted EM waves



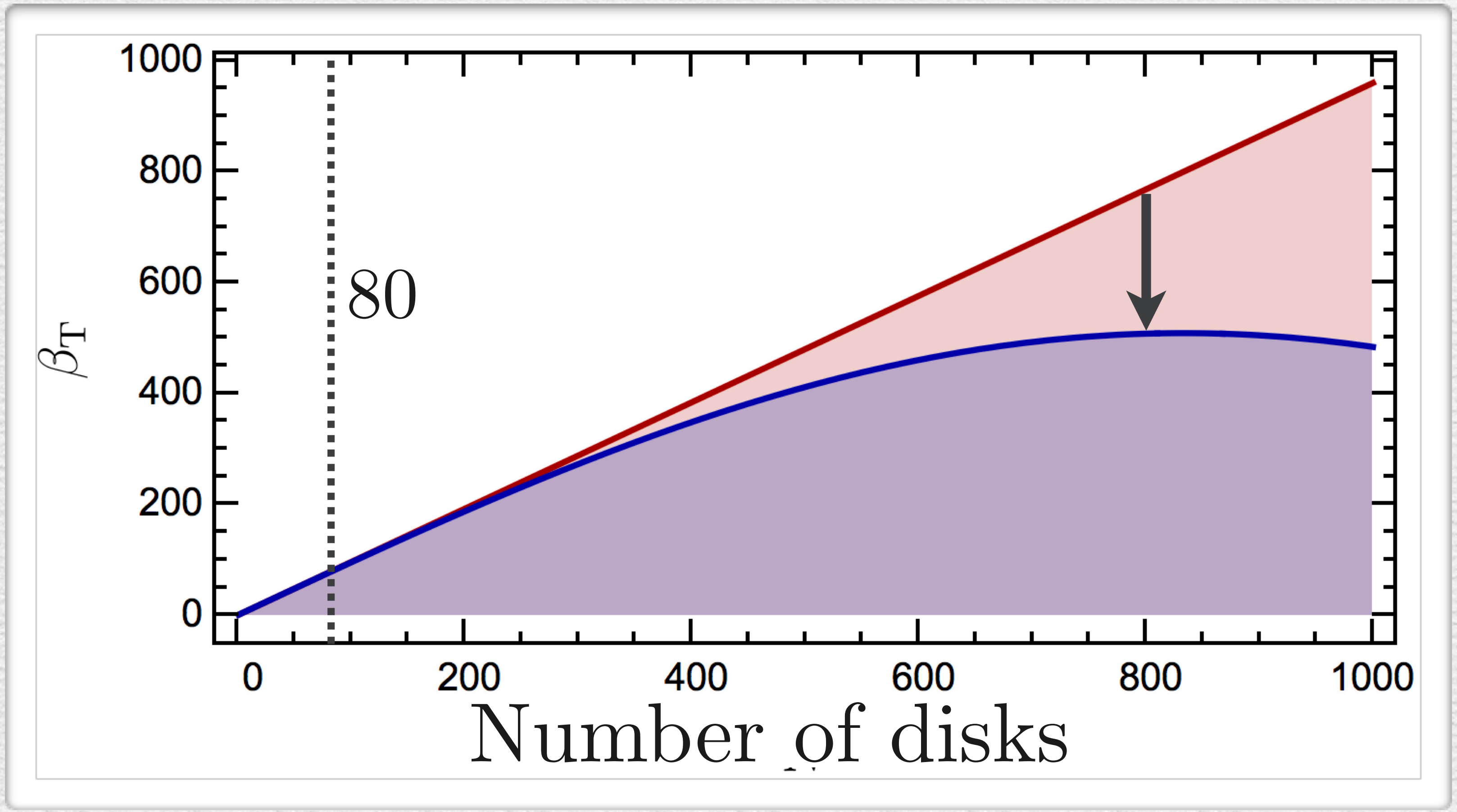
Millar+ [1707.04266]

$$\beta^2 \equiv \frac{P_{\rm dh}}{P_{\rm mirror}}$$

Dielectric disk haloscope

- Non-zero axion velocity causes phase difference across experiment
- Velocity dependent boost factor Millar+ [1707.04266]

Signal/area: $\frac{1}{A}\frac{\mathrm{d}P_{\mathrm{dh}}}{\mathrm{d}\omega} \propto \frac{\mathrm{d}v}{\mathrm{d}\omega}\int \mathrm{d}\Omega_v\, \beta^2(\mathbf{v}) f(\mathbf{v})$



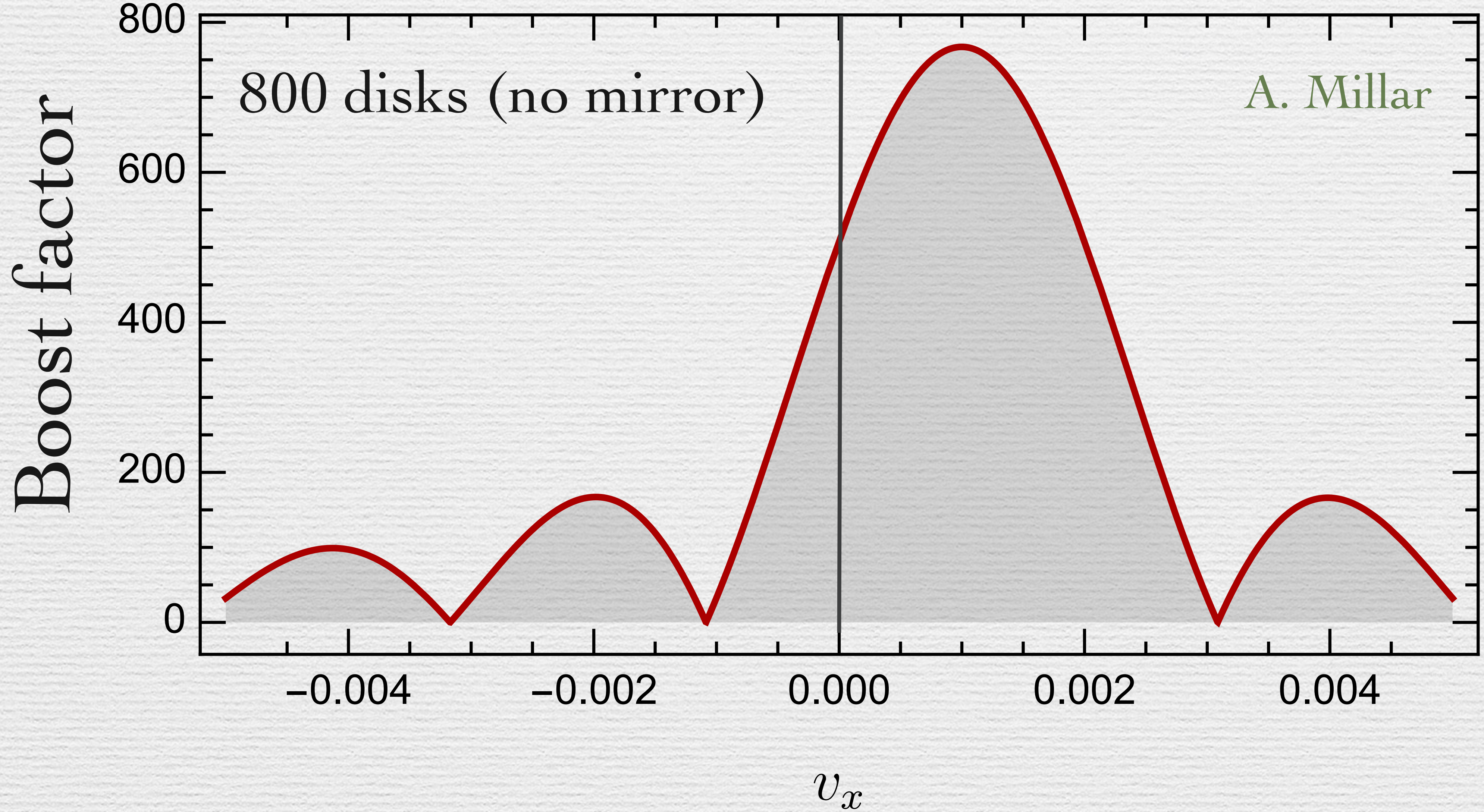
$v = 0$

$v = 300$ km s^{-1}

Example for transparent disks

Velocity effects in MADMAX

- Unimportant for standard 80 disk setup (this is a good thing!) but could be exploited in an extended experiment (>O(100) disks)



Sensitive to $\pm v_x \rightarrow$ b-type

Summary

- Uncertainty in the local DM distribution both a problem and a *motivation* for direct detection experiments
- Take some inspiration from WIMP dark matter, but directional detection in this context difficult to achieve experimentally
- Directional axion astronomy more straightforward, just scale up existing technology e.g.
  → Long aspect ratio cavities (e.g. ADM-XL)
  → Long dielectric disk experiments (e.g. BIGMAX)

Bonus

WIMPs: dealing with astrophysical uncertainties

- Halo independent $g(v_{\rm min})$ methods (integrate out uncertainty)
  e.g. Fox+ [1011.1915], Frandsen+ [1111.0292], Kahlhoefer+ [1607.04418], Catena+ [1801.08466], + many many more…

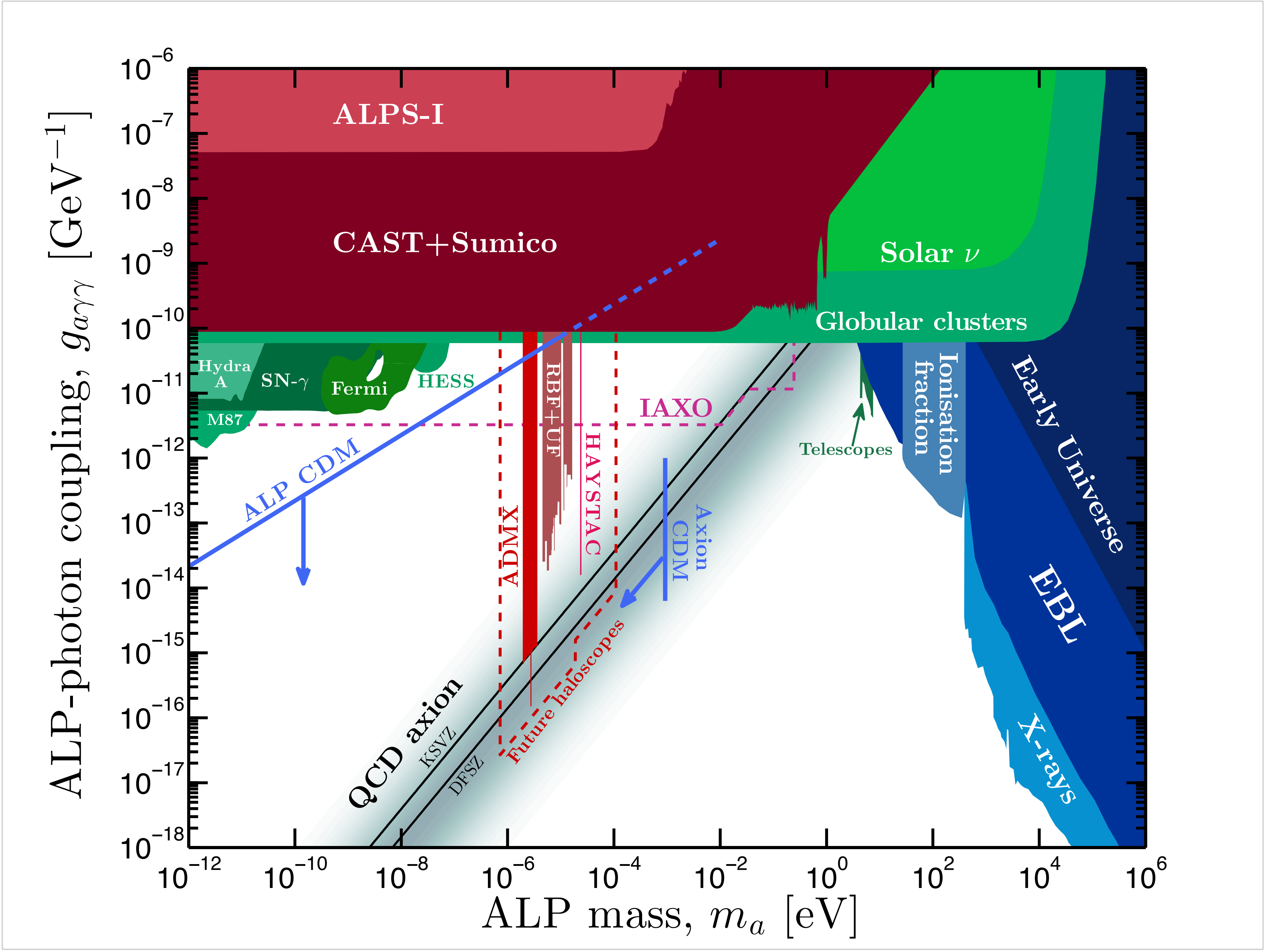
- General parameterisations (fit distribution, but remain agnostic)
  e.g. Peter [1103.5145], Kavanagh & Green [1303.6868], Kavanagh [1502.04224]

- Bayesian methods (with some astrophysically informed prior)
  e.g. Strigari & Trotta [0906.5361], Fowlie [1708.00181]

- Dealing with non-Maxwellian structure
  e.g. Lee, & Peter [1202.5035], O'Hare & Green [1410.2749]

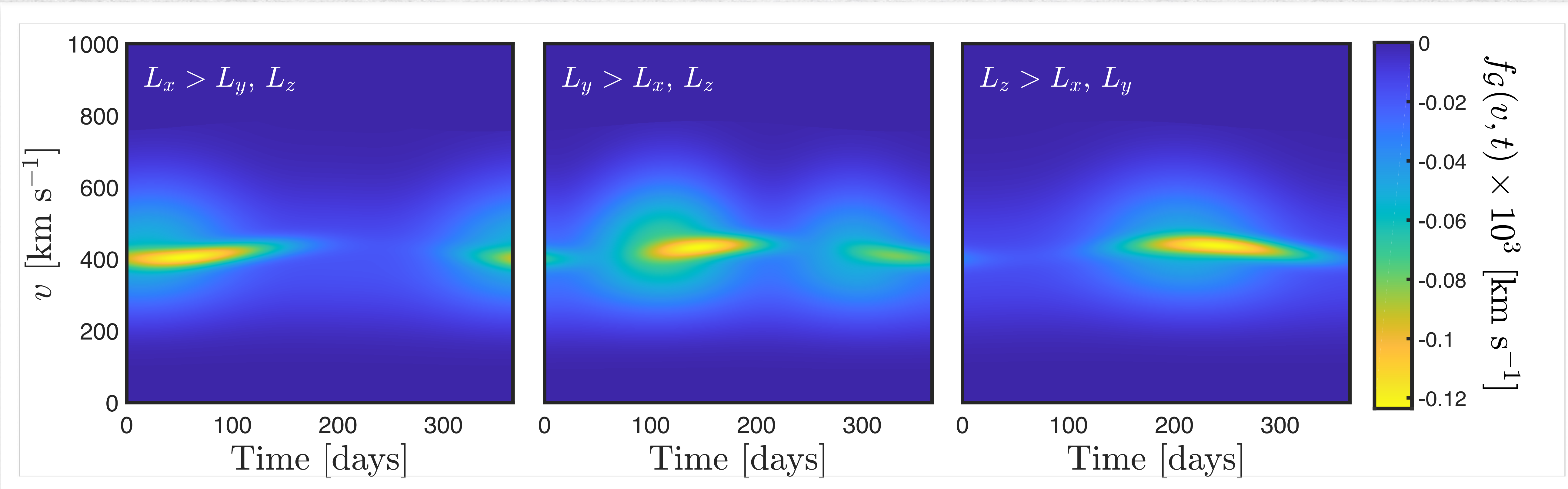
Detecting axion dark matter

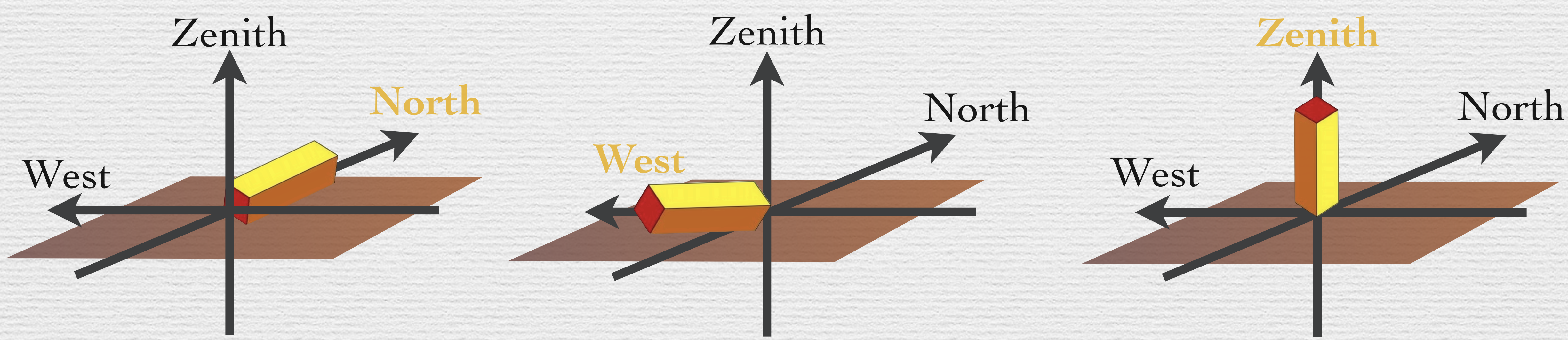
$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x},t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Distribution with stream

Annual modulation





Problems to consider

- Ideal detection scheme would have sensitivity to $\pm v_i$ components
  → Is Earth rotation enough? (cf. minicluster streams)
  → Is mirror-less MADMAX sensitive enough?

- Trade-off between strong velocity effect and high S/N

- Velocity effects for low mass axions (<10 μeV → $\lambda_a > 100$ m)
  → Phase tracked network of separated cavities?
  → Multiple NMR experiments exploiting axion-wind effect?
  (CASPEr-wind)

- Find the axion