Universidad Zaragoza
1542

Directional axion detection

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Based on arxiv:[1806.05927]
with S. Knirck, A. Millar, J. Redondo, F. Steffen

Patras Workshop (DESY) 17 - 22 June

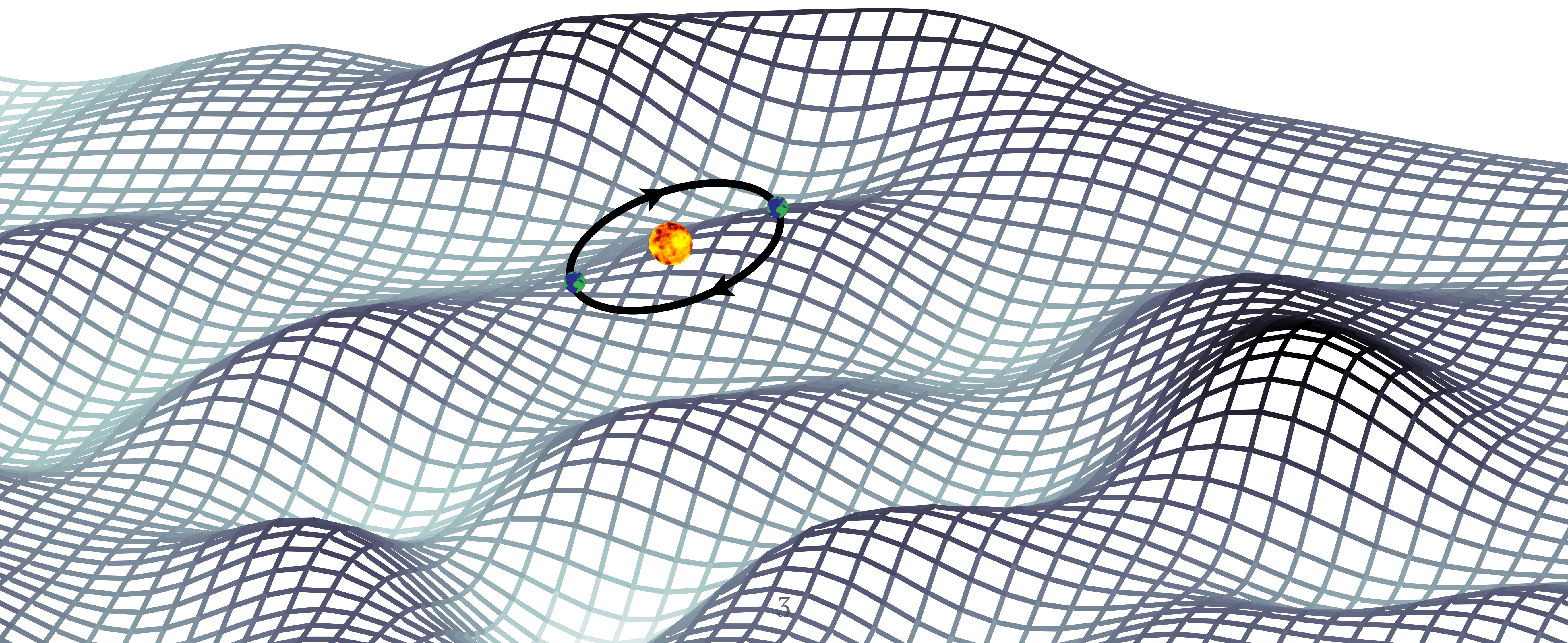
A directional axion experiment?

- What?
- Is it possible?
- Is it worth it?

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

Oscillations in time: $\omega = m_a\left(1 + \frac{v^2}{2}\right)$

Oscillations in space: $\mathbf{p} = m_a \mathbf{v}$



The axion field will actually be made of some distribution of modes

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

Related to $f(\mathbf{v})$, width ~ σ_v

~Time scale for oscillation to dephase

$$\tau_a = \frac{2\pi}{m_a\sigma_v^2} \simeq 40\,\mu\mathrm{s}\left(\frac{100\,\mu\mathrm{eV}}{m_a}\right)$$

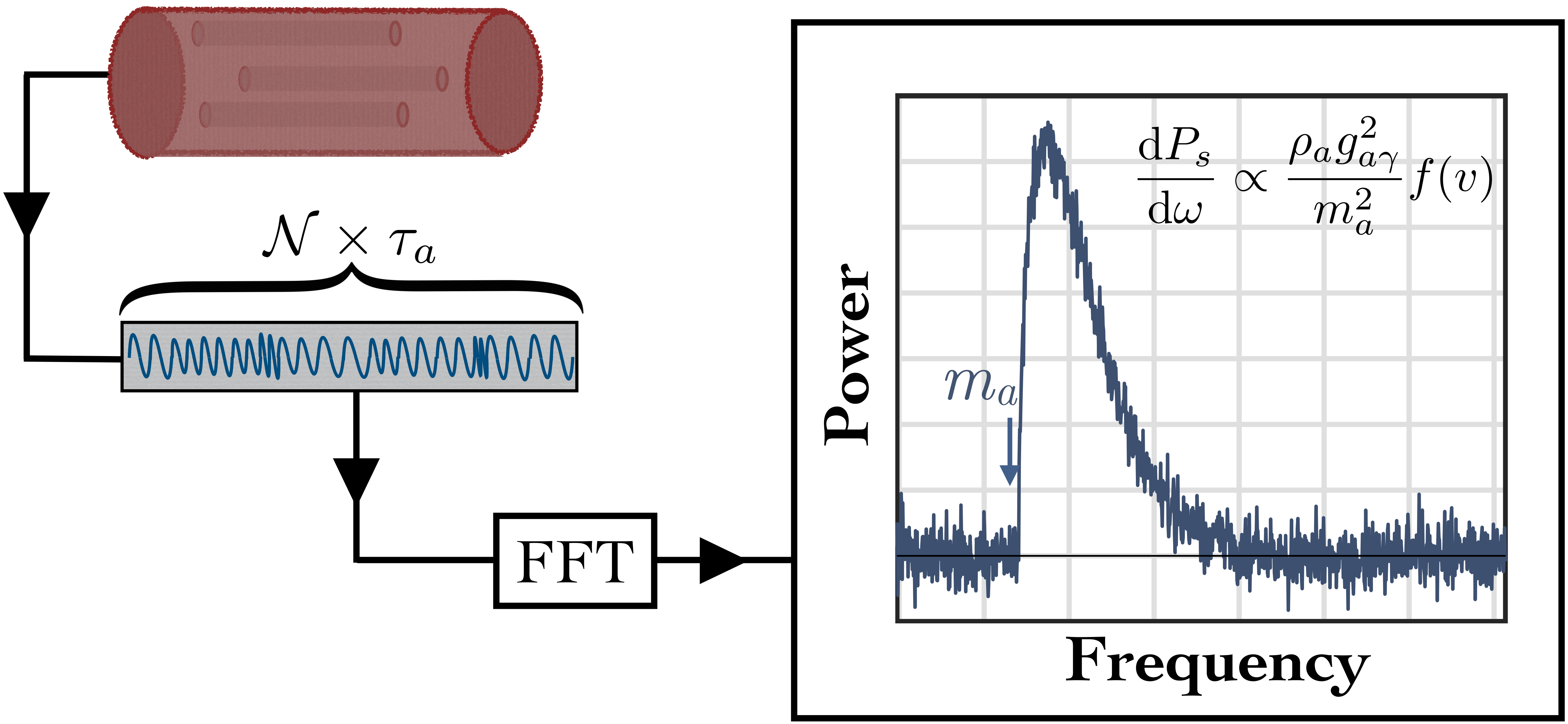
~Length scale for oscillation to dephase

$$\lambda_a = \frac{2\pi}{m_a\sigma_v} \simeq 12.4\,\mathrm{m}\left(\frac{100\,\mu\mathrm{eV}}{m_a}\right)$$

Measuring the axion distribution

Sampling axion field over many coherence times:

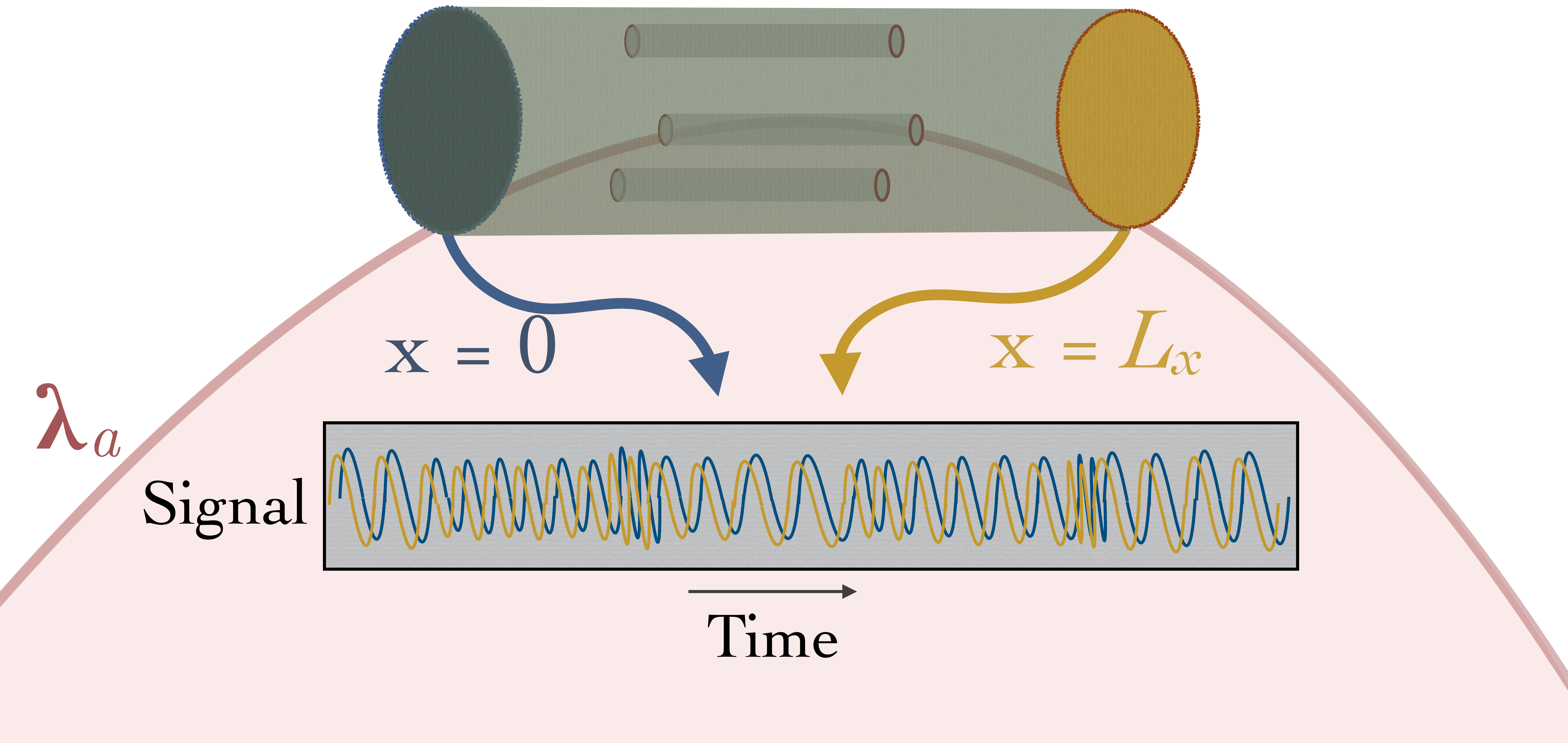
→ Power spectrum ~ $f(v)$



If axion wavelength ~ experiment size

→ Phase difference across experiment

$$a = a_0 e^{i(\omega t - m_a \mathbf{v}\cdot\mathbf{x})}$$



A general formalism

- Parameterise with velocity dependent **form factor:**

$$P \propto C(\mathbf{v}) = C_0\left(1 - \mathcal{G}(\mathbf{v})\right)$$

- At lowest order in v, an experiment will be linearly or quadratically directional

Linear directionality (l-type)	$C(\mathbf{v}) = C_0(1 - \sum_{i=x,y,z} g_\ell^i v_i)$	Directional correction positive **or** negative
Quadratic directionality (q-type)	$C(\mathbf{v}) = C_0(1 - \sum_{i=x,y,z} g_q^i v_i^2)$	Directional correction **always** negative

Signal from distribution of velocities

→ Power spectrum now includes integral over **directions.**

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

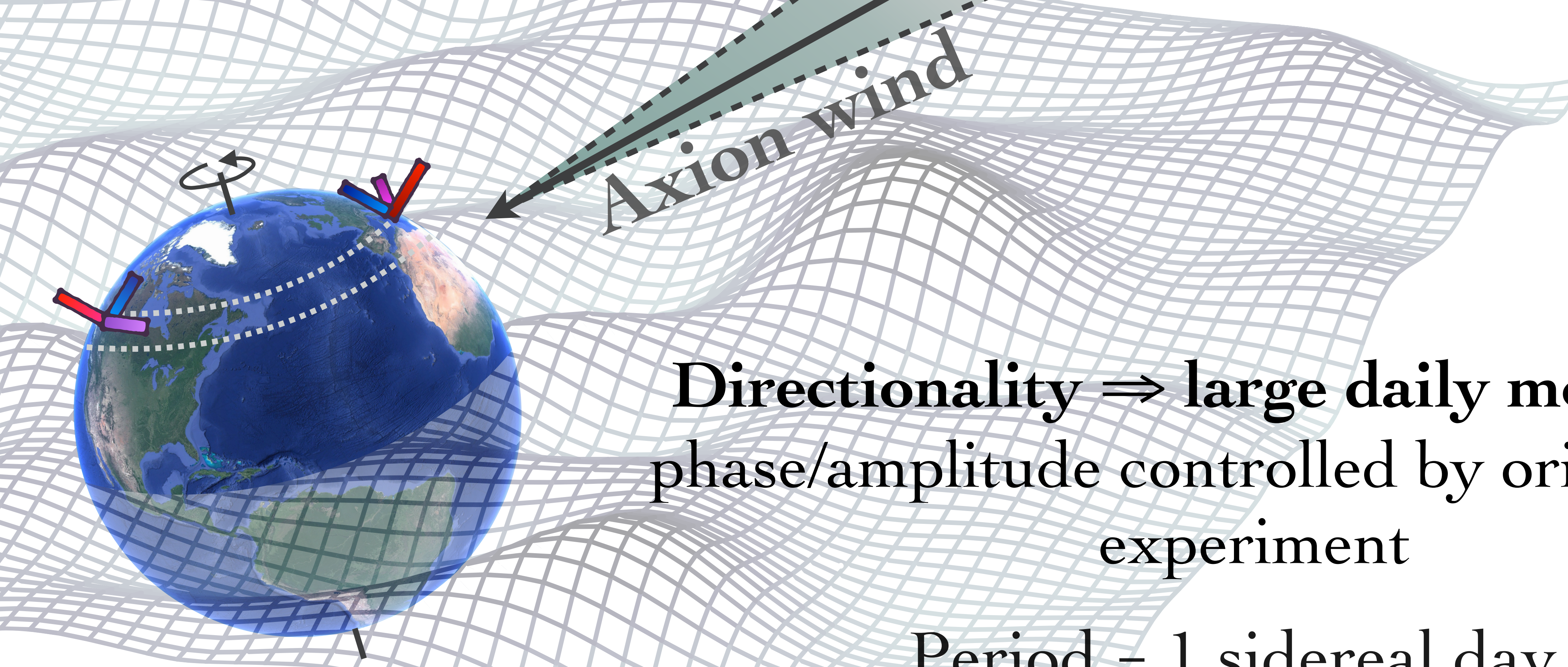
Total power

Mode/Boost factor

Non-directional *speed* effect

$$\omega = m_a \left(1 + \frac{v^2}{2} + \ldots \right)$$

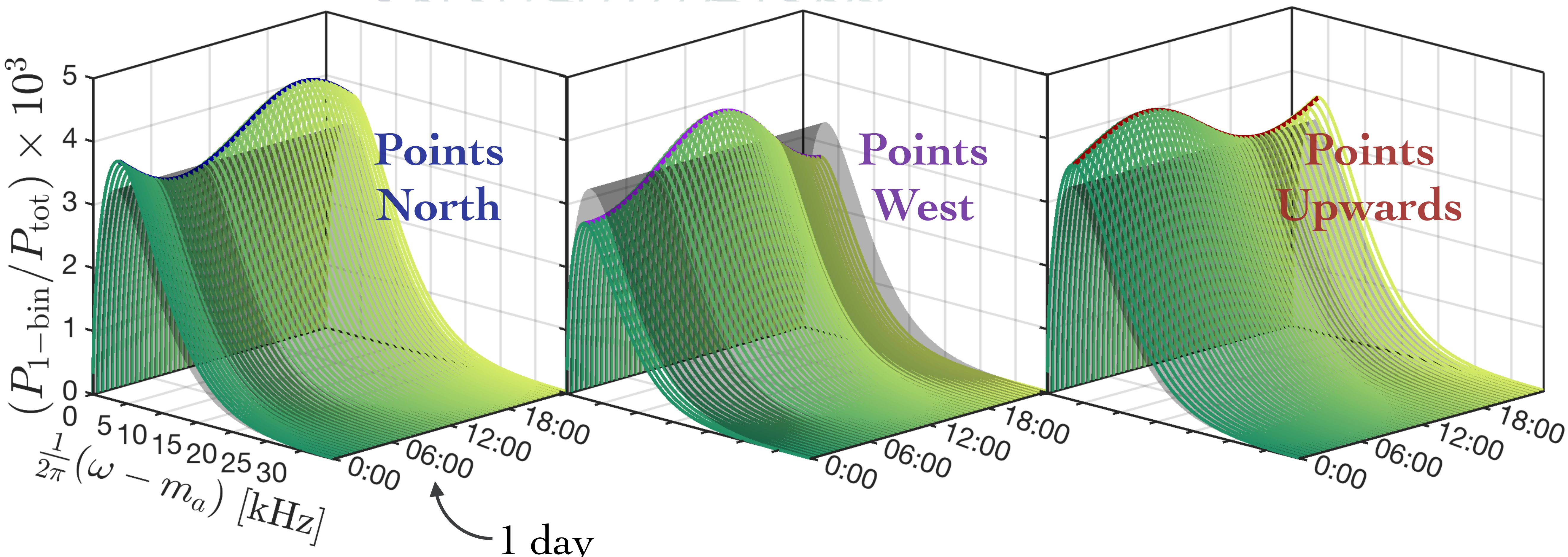
Directional *velocity* effect
→ Orientation dependent



Directionality ⇒ large daily modulation

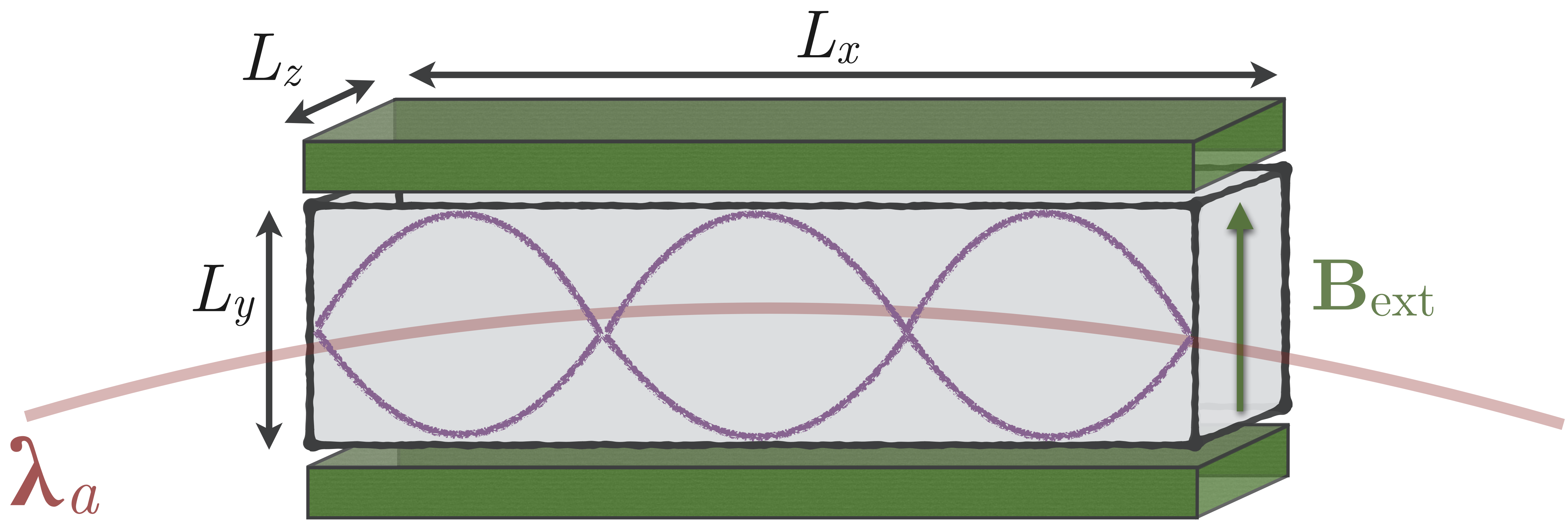
phase/amplitude controlled by orientation of experiment

Period = 1 <u>sidereal</u> day



Is it possible in practice?

Simple example: rectangular cavity



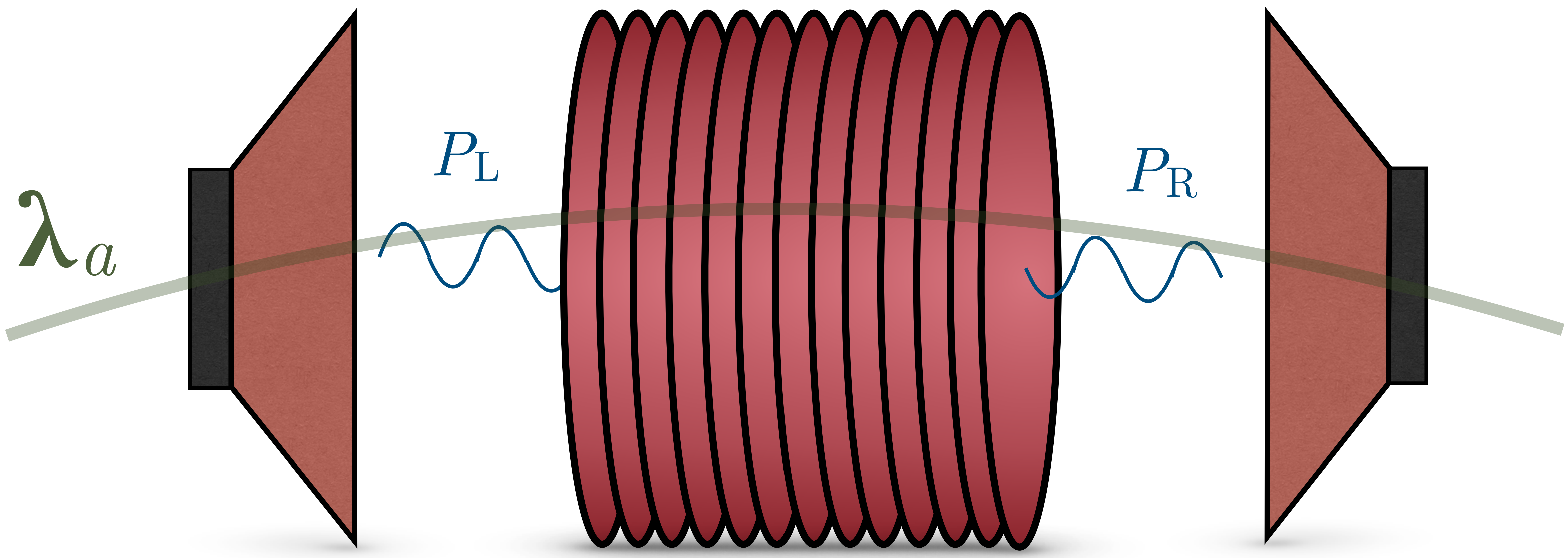
TE_{l0n} form factor modified for axion with non-zero $\mathbf{v}$

$\rightarrow$ quadratically dependent on v_x

$$C(\mathbf{v}) = \frac{1}{VB_{\rm ext}} \int \mathrm{d}V \, \mathbf{e}_{l0n} \cdot \mathbf{B}_{\rm ext} \, e^{i m_a \mathbf{v}\cdot\mathbf{x}} \simeq \frac{64}{l^2 n^2 \pi^4} \left[1 - \left(\frac{m_a v_x L_x}{2} \right)^2 \right]$$

More complex example: MADMAX-XL

- Scaled-up MADMAX with many disks spaced just out of phase from perfect constructive interference in the **v**=0 limit



Combining signals from L/R
→ can be made **linearly or quadratically** sensitive to v

More complex example: MADMAX-XL

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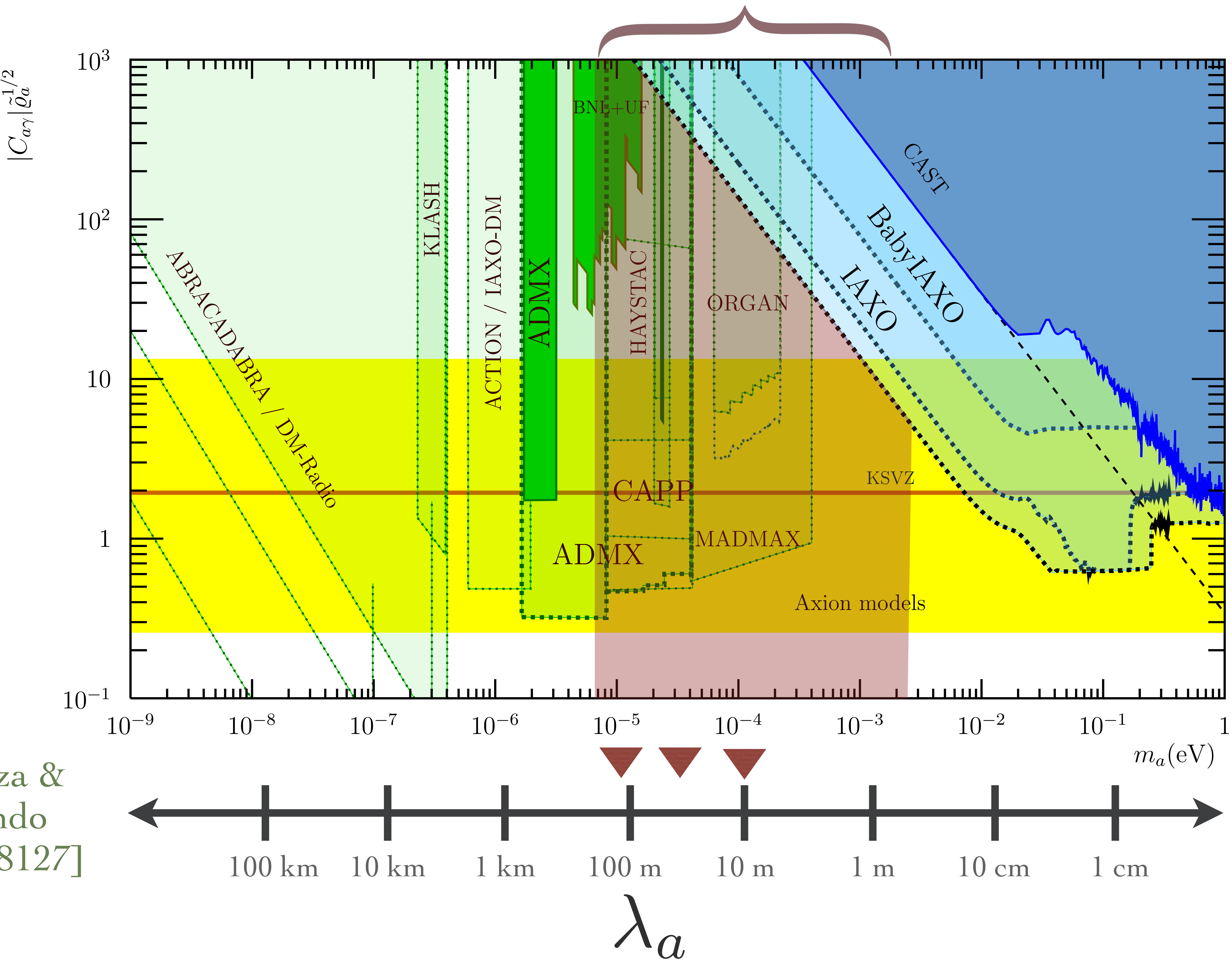
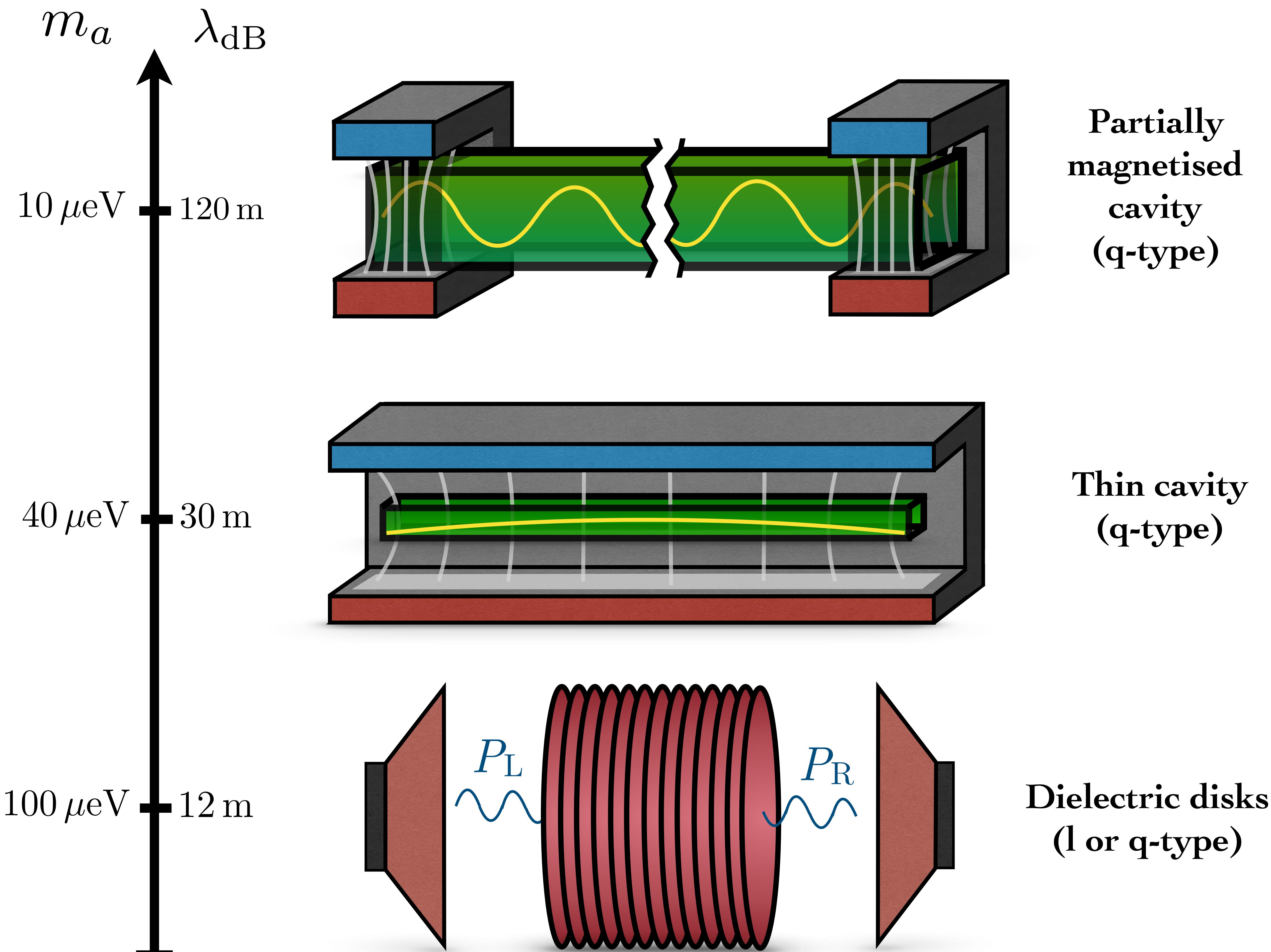
Axion wavelength needs to be a "reasonable" size



Irastorza & Redondo [1801.08127]


m_a
$\lambda_{\rm dB}$
10 μeV
120 m
40 μeV
30 m
100 μeV
12 m
Partially magnetised cavity (q-type)
Thin cavity (q-type)
$P_{\rm L}$
$P_{\rm R}$
Dielectric disks (l or q-type)

What can you do with it?

What I won't talk about

"Non-directional" signals (from freq. dependence)
→ 5% annual modulation
→ 0.2% daily modulation
→ 2% gravitational focusing by Sun Foster+[1711.10489]

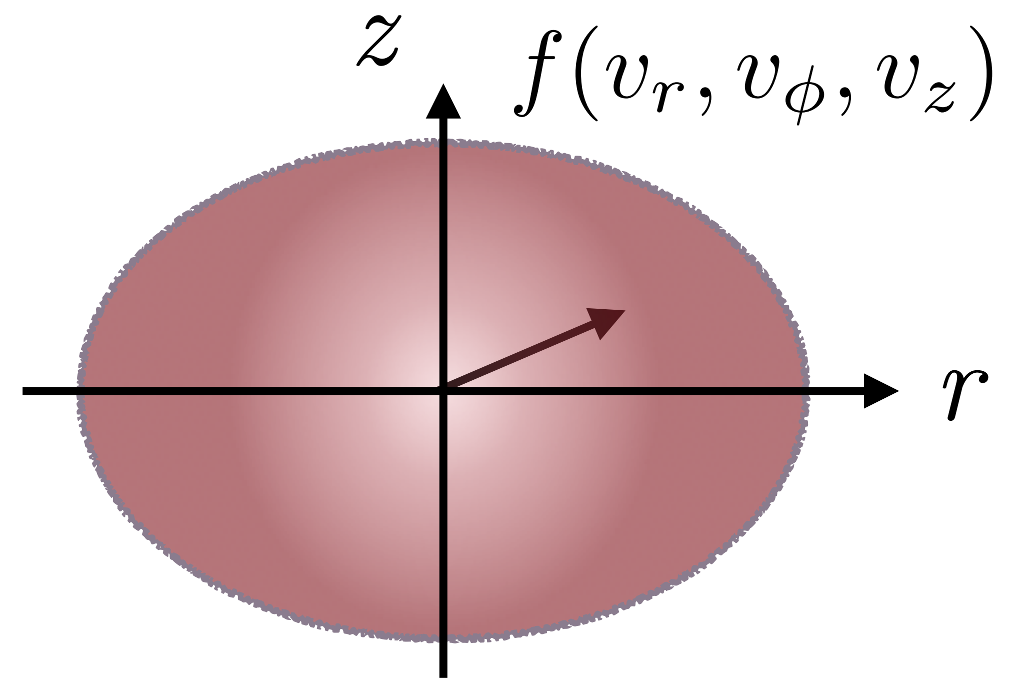
Axion astronomy

- Measurement of Solar velocity O'Hare+[1701.03118]
  → ADMX can reach astrometric accuracy ~1 year after detecting axion
  → +directional detector can do it in 4 days. [see paper 1806.05927]
- Measurement of a dark disk Foster+[1711.10489]
- Measuring streams from miniclusters [see extra slides]

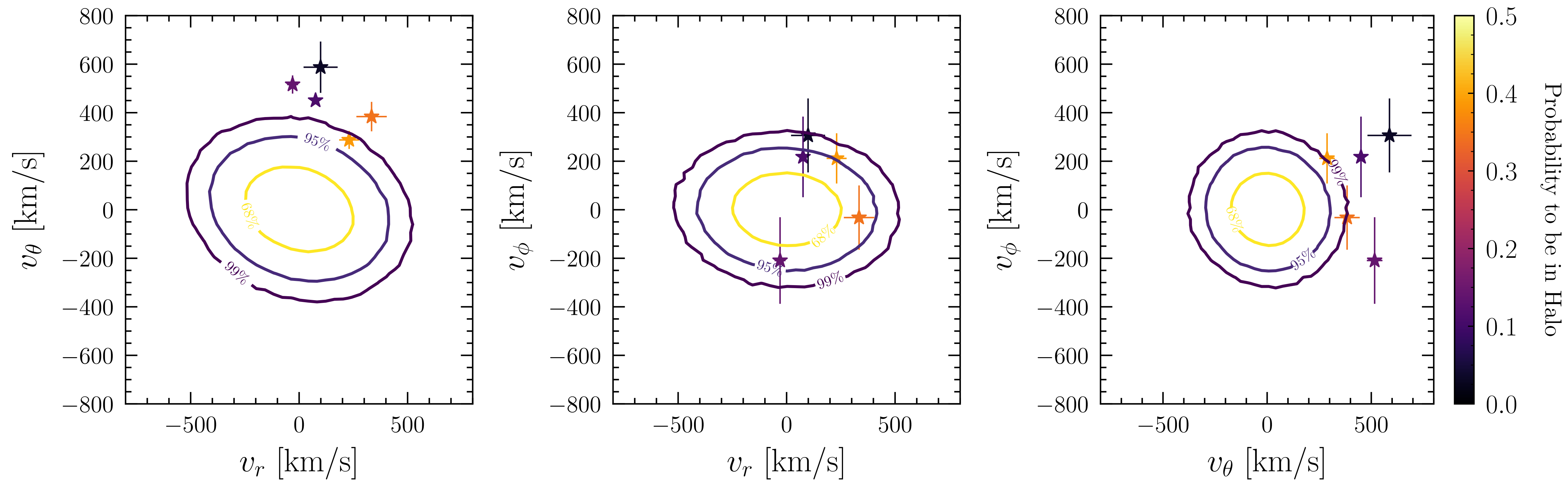
Anisotropy of velocity ellipsoid

- Halos cannot be perfectly isotropic
- Radial infall → typically leads to $f(\mathbf{v})$ hotter in radial direction

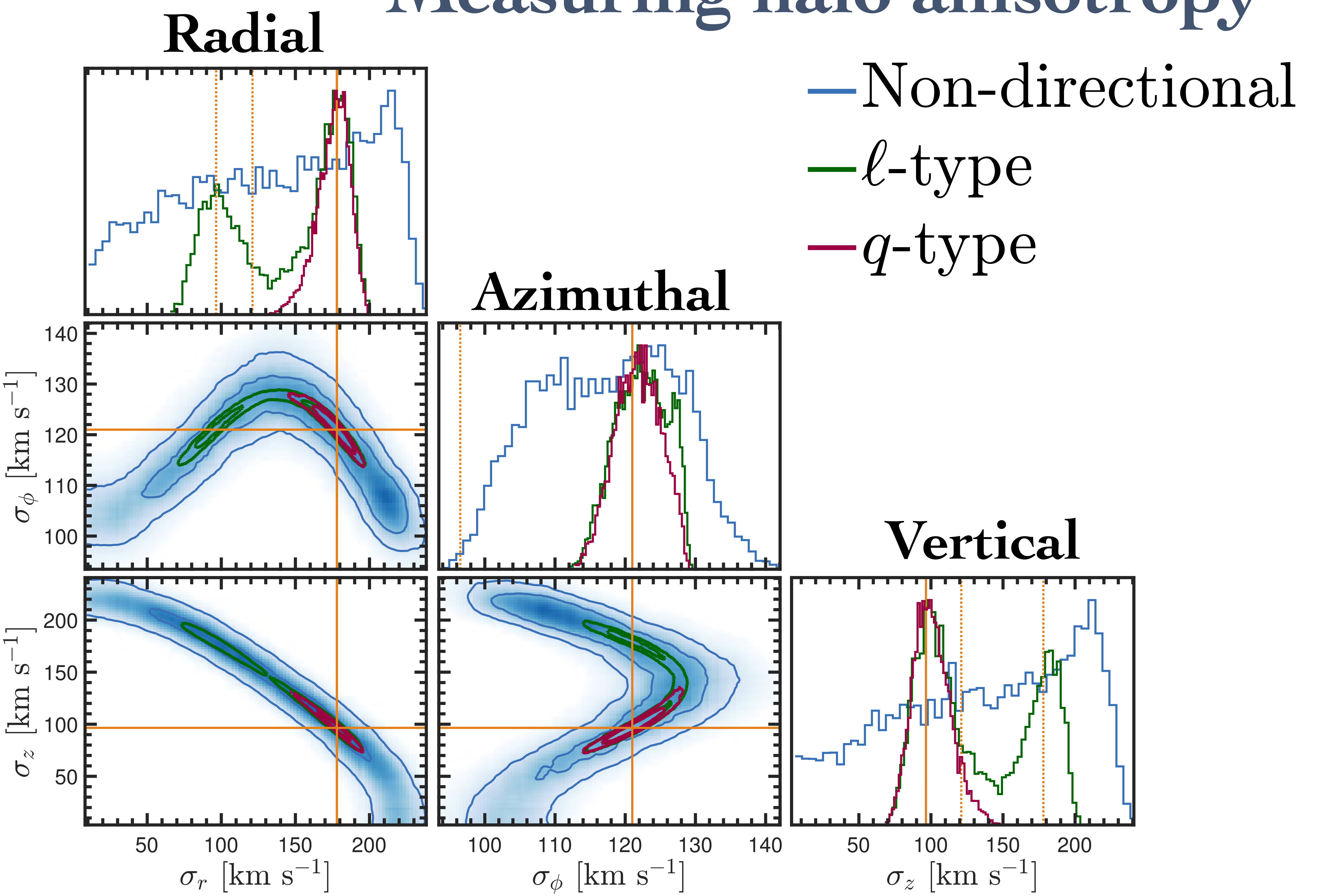
$$\sigma_r > \sigma_{z,\phi}$$



Herzog-Arbeitman [1708.03635]



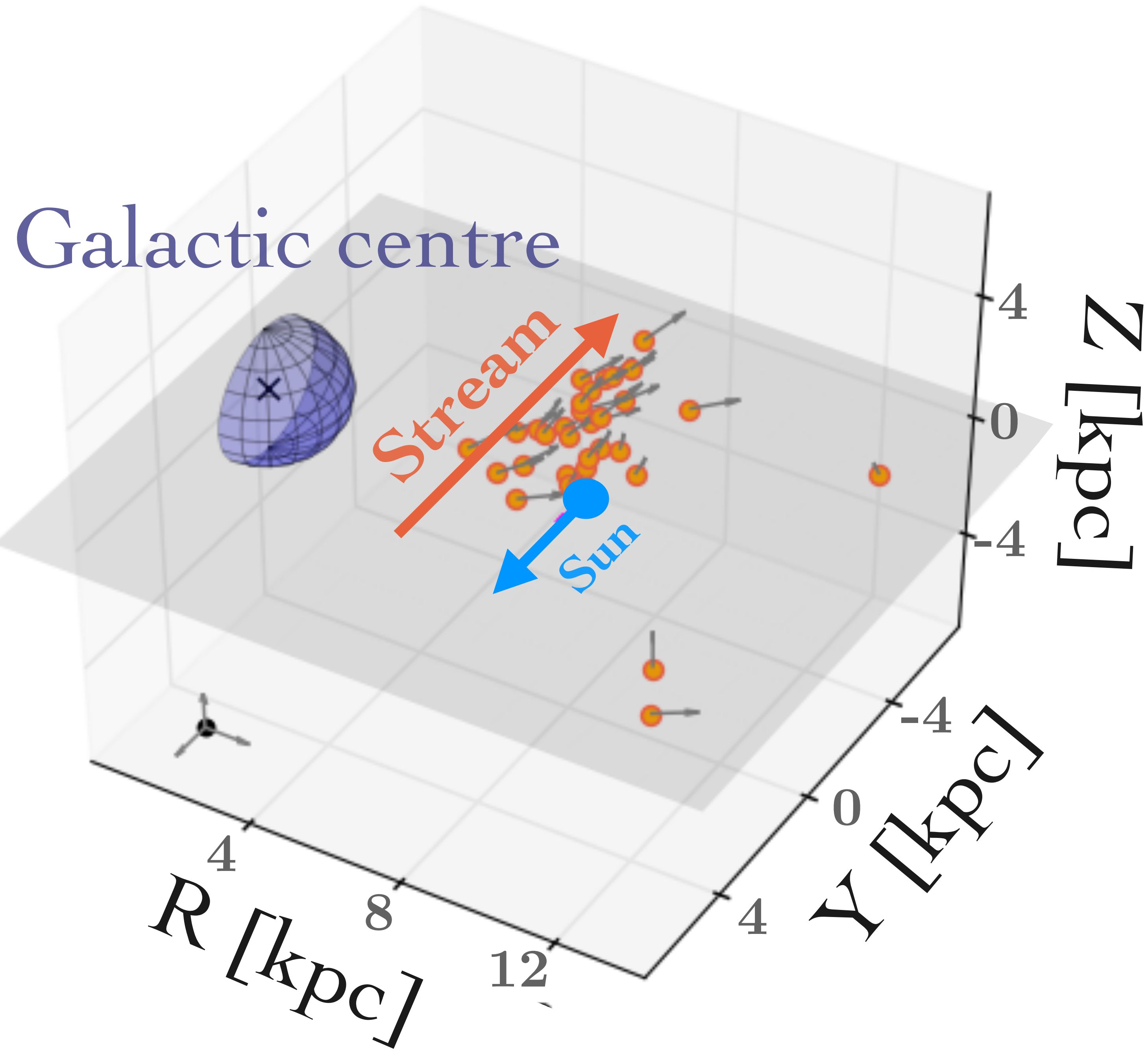
Measuring halo anisotropy

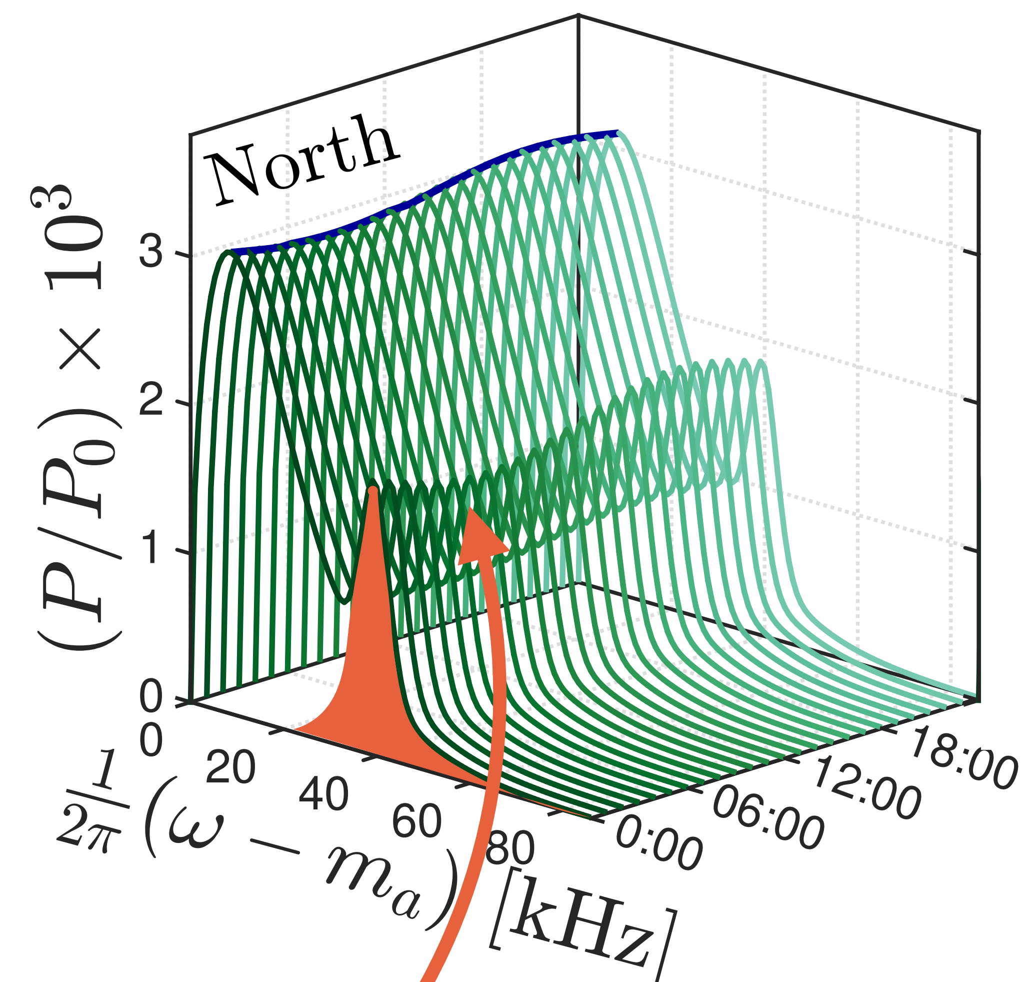


The "S1 stream"

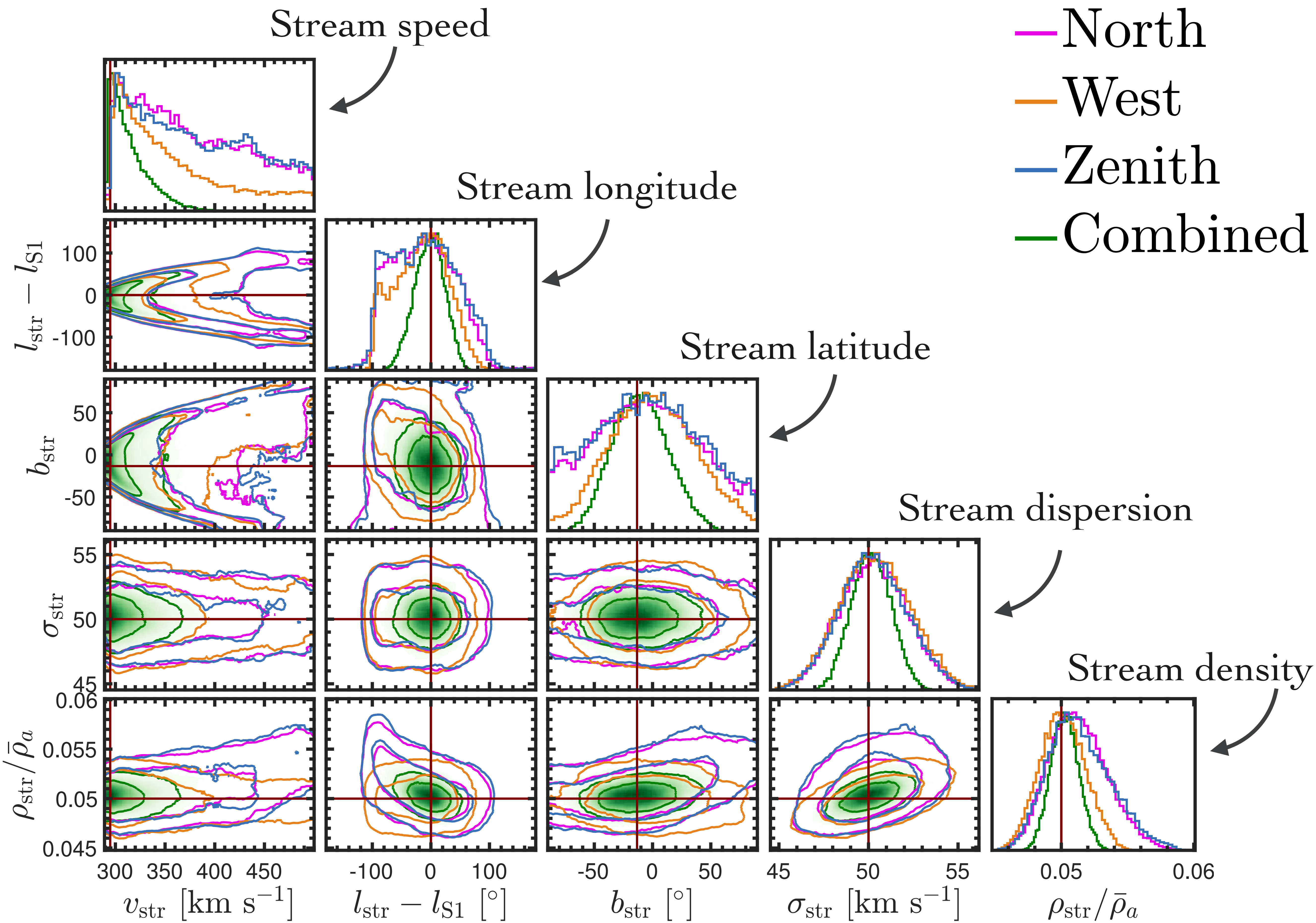
Stellar stream discovered in *Gaia* intersecting our Galactic position

Myeong+[1712.04071], Myeong+[1804.07050], Evans, McCabe, O'Hare [in prep]



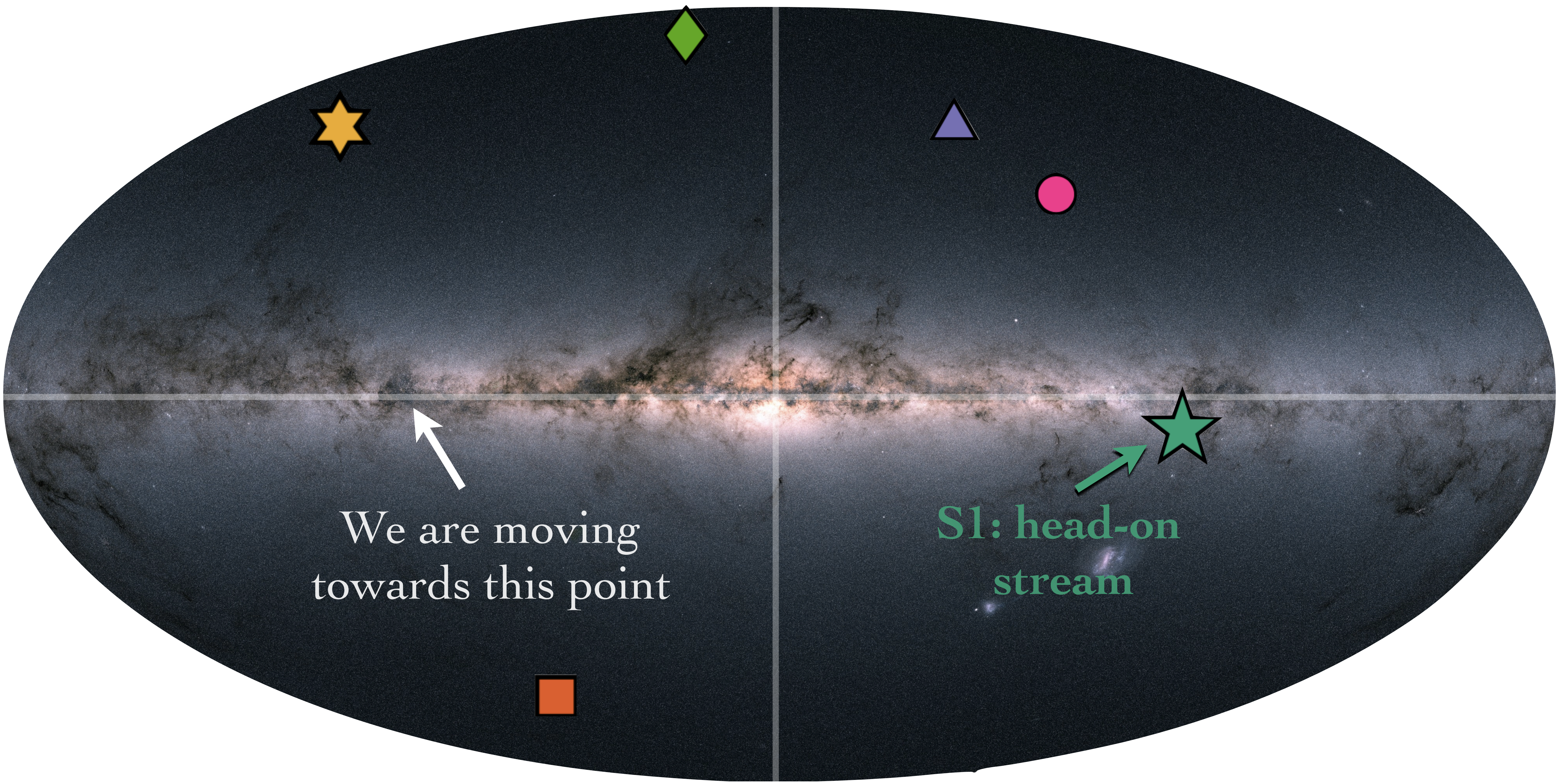


Signal with 5% S1 stream



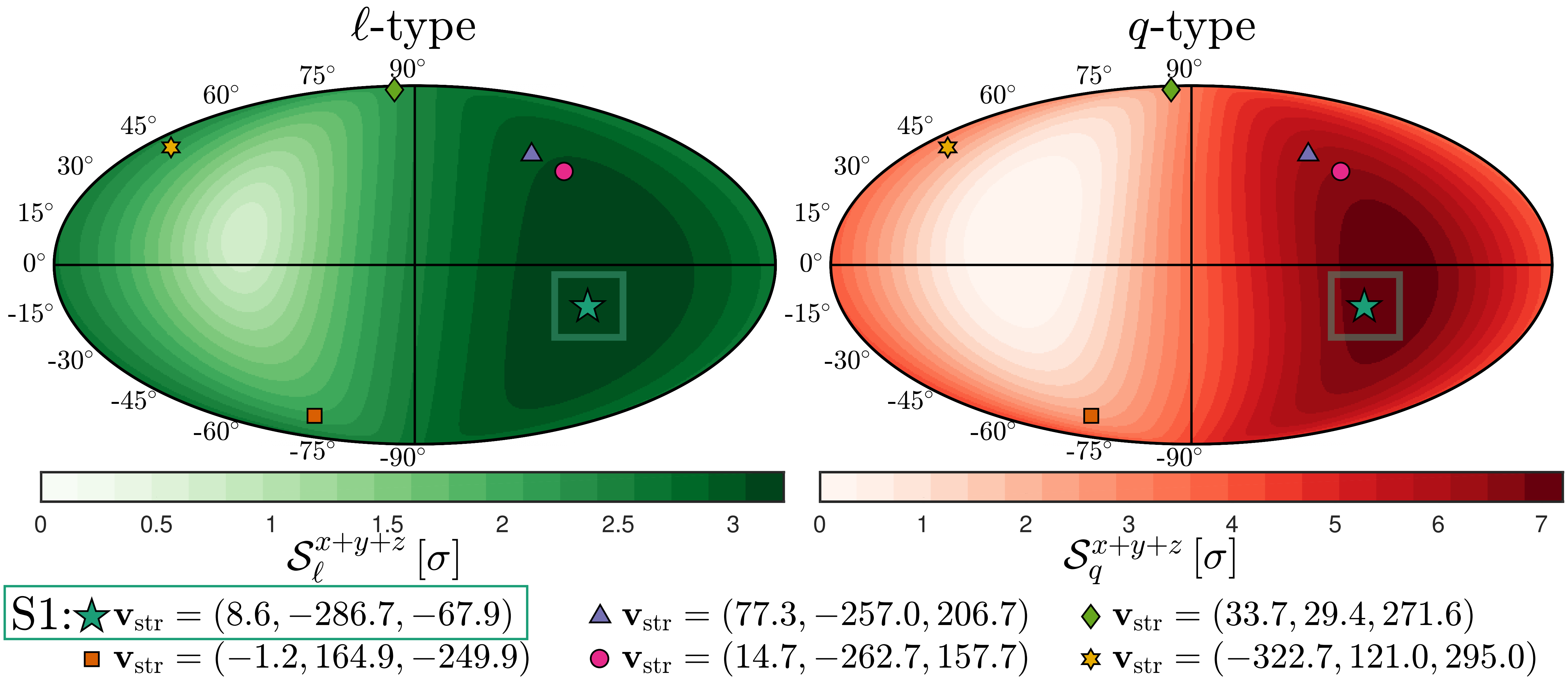
Stream speed
Stream longitude
Stream latitude
Stream dispersion
Stream density
North
West
Zenith
Combined
$l_{str} - l_{S1}$
b_{str}
σ_{str}
$\rho_{str}/\bar{\rho}_a$
v_{str} [km s^{-1}]
$l_{str} - l_{S1}$ [°]
b_{str} [°]
σ_{str} [km s^{-1}]
$\rho_{str}/\bar{\rho}_a$

Stream candidates



Sky map from *Gaia*

Measuring general streams



Linear experiments - Streams measured consistently well across sky

Quadratic experiments - Can only detect head-on streams but with greater significance

A directional axion experiment?

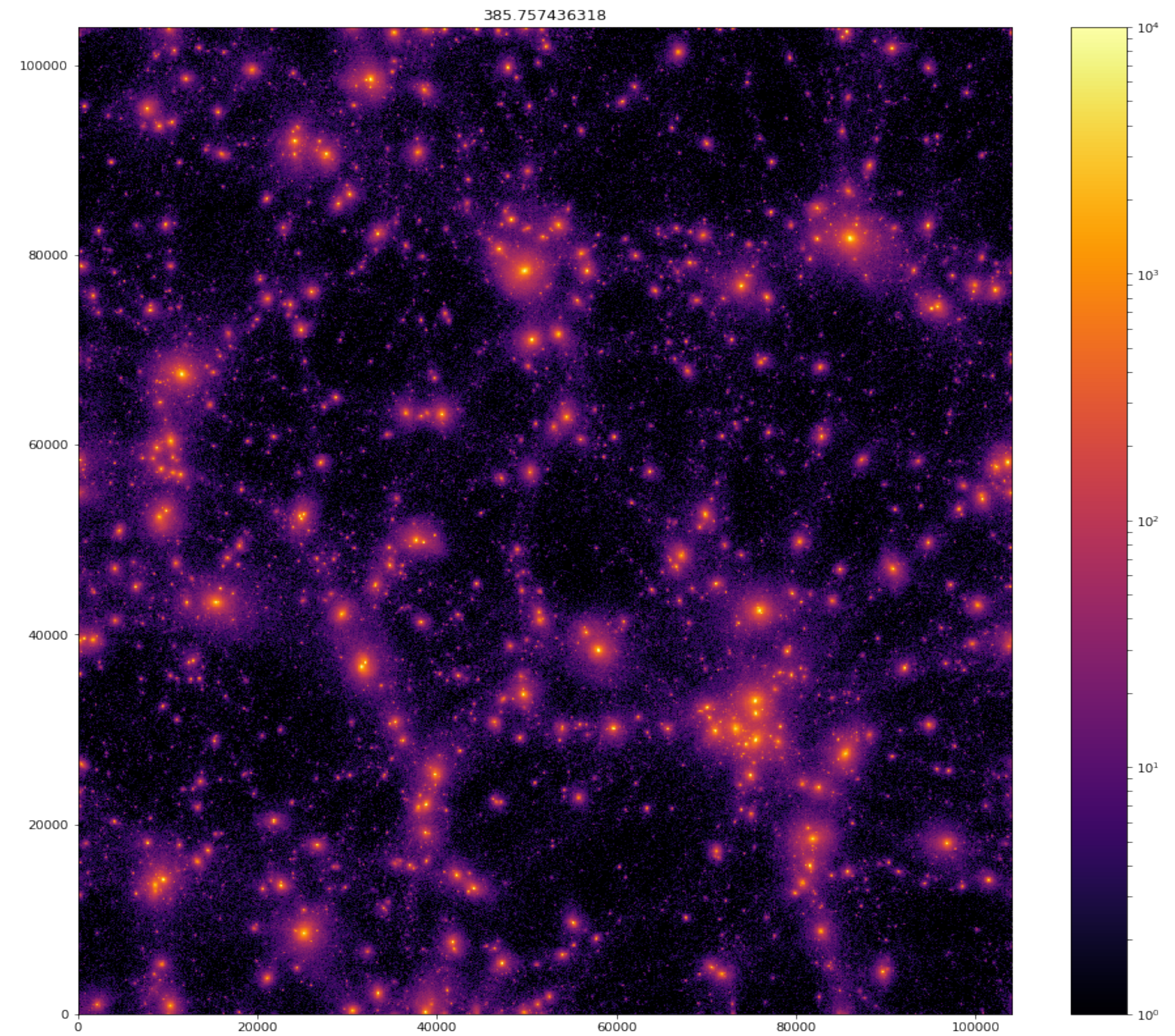
- **Is it possible in theory?**
  - **Yes**: Axion phase differences across large experiments + the rotation of the Earth gives you an O(1) directional effect
- **Is it possible in practice?**
  - **Well, it's not *im*possible** using a long cavity or dielectric disks
- **Is it worth it?**
  - ***Maybe* in the future… But,** this **is** how you maximise sensitivity to $f(\mathbf{v})$ in 3d. You can measure the Solar velocity, anisotropy of the halo, nearby streams, or minicluster debris +potentially more…

Miniclusters

Post-inflation scenario axion:
→ Collapsed over densities in axion field that decouple from Hubble flow around after QCD

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

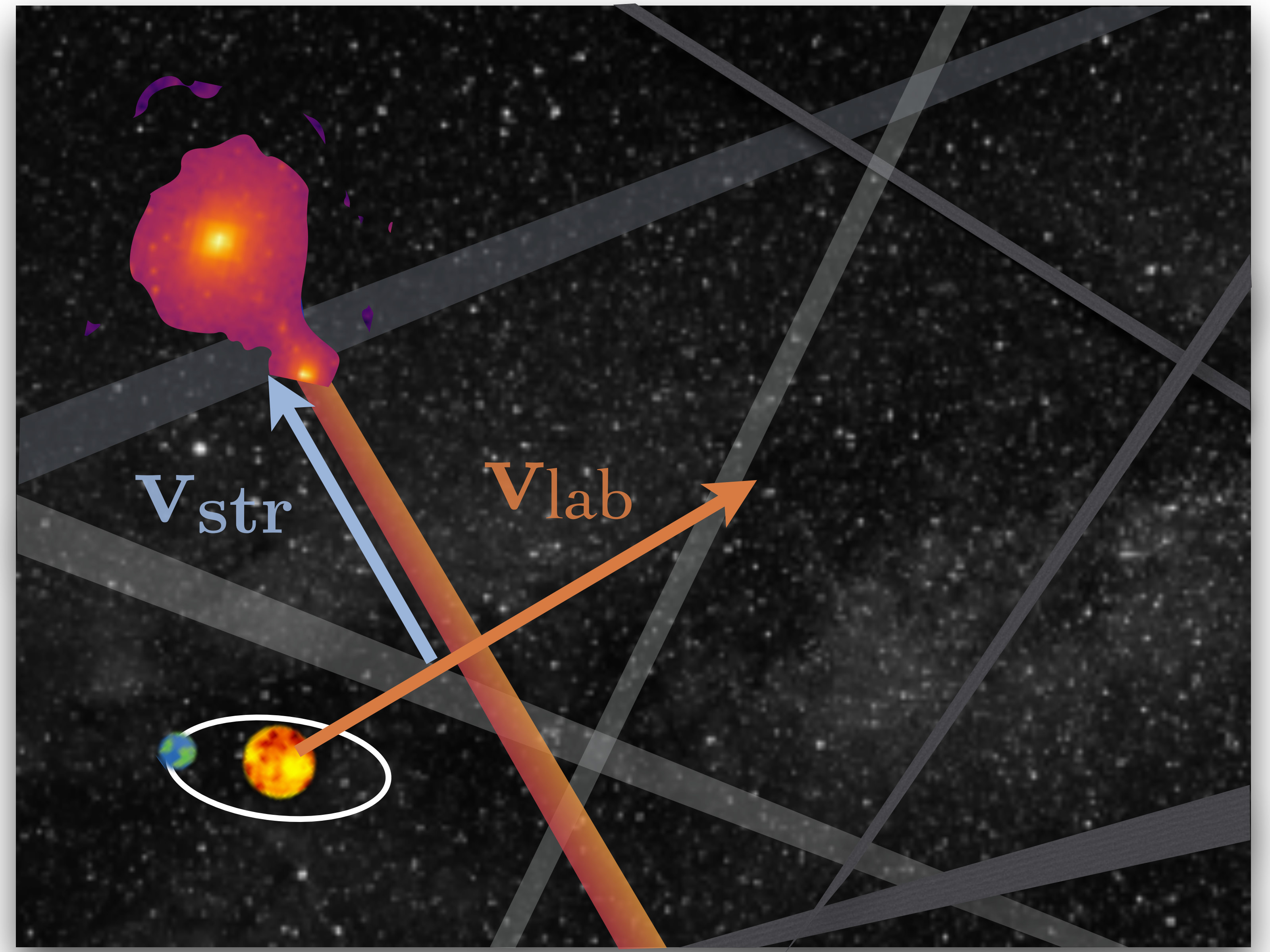
Javier Redondo



“Ministreams”

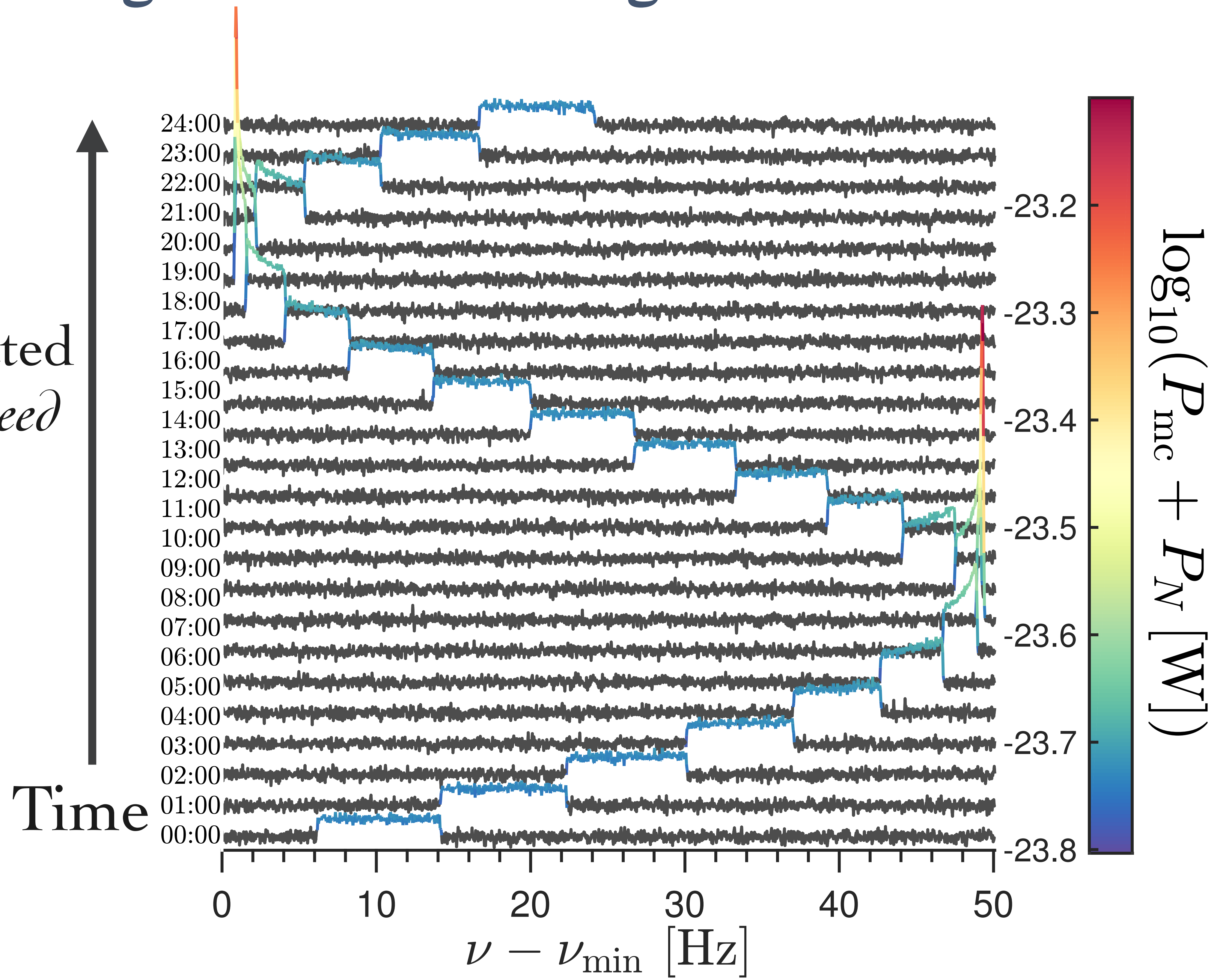
- Miniclusters tidally disrupted by stars
- Temporary enhancements in signal:

$$\tau = \frac{2R_{\rm mc}}{v_{\rm lab}\sin\vartheta_{\rm str}} \sim \mathcal{O}(\text{hours} - \text{days})$$



Simulated signal from crossing of a ministream

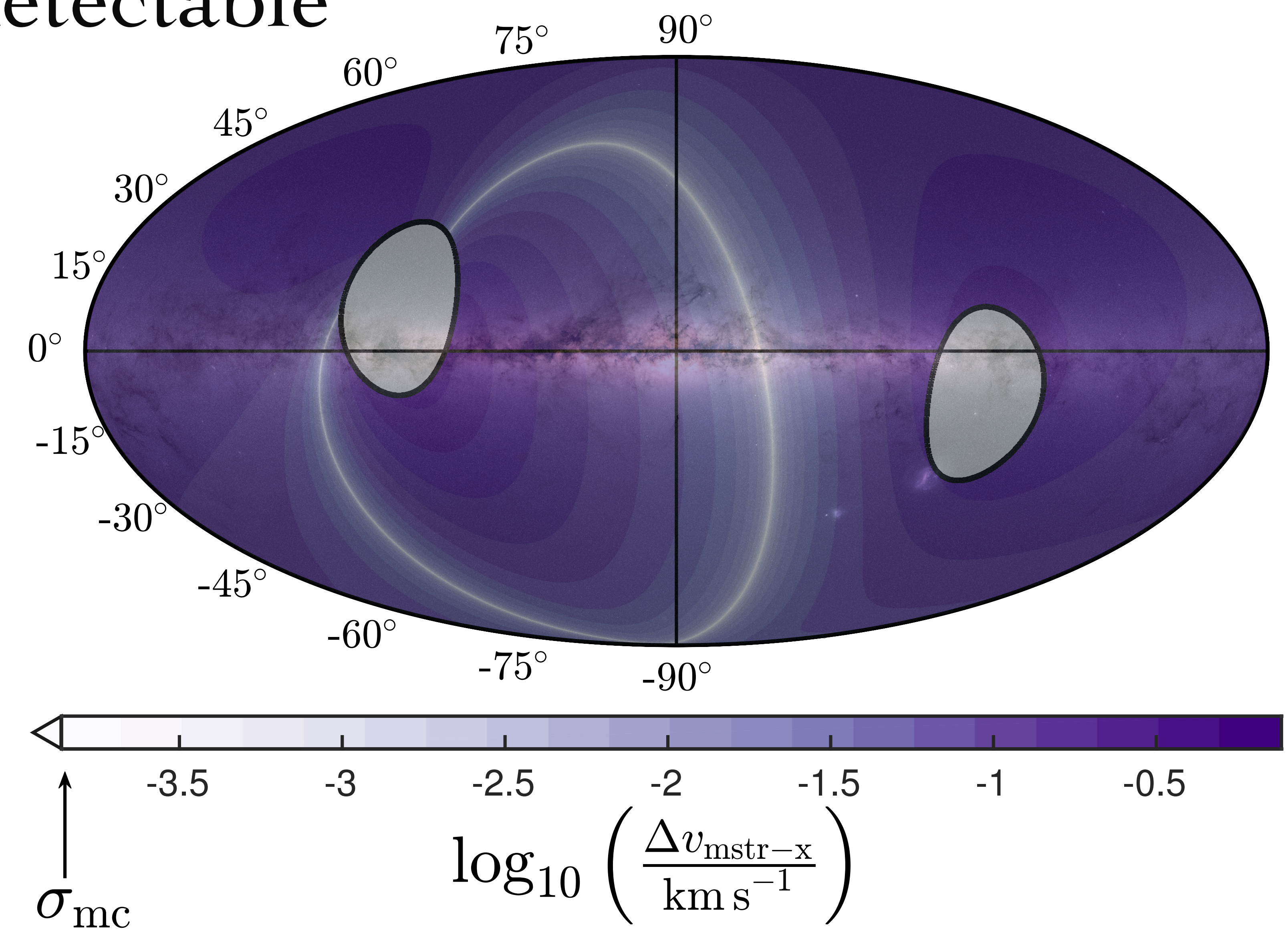
Signal modulated by rotation *speed* of earth



Minicluster streams

- Ministreams with directions in the light band would not give a sufficient daily modulation without directionality to be detectable

*Band potentially wider if miniclusters are significantly heated during tidal disruption



Phase of daily modulation from a stream