Directional axion detection

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S. Knirck et al arXiv:1806:05927

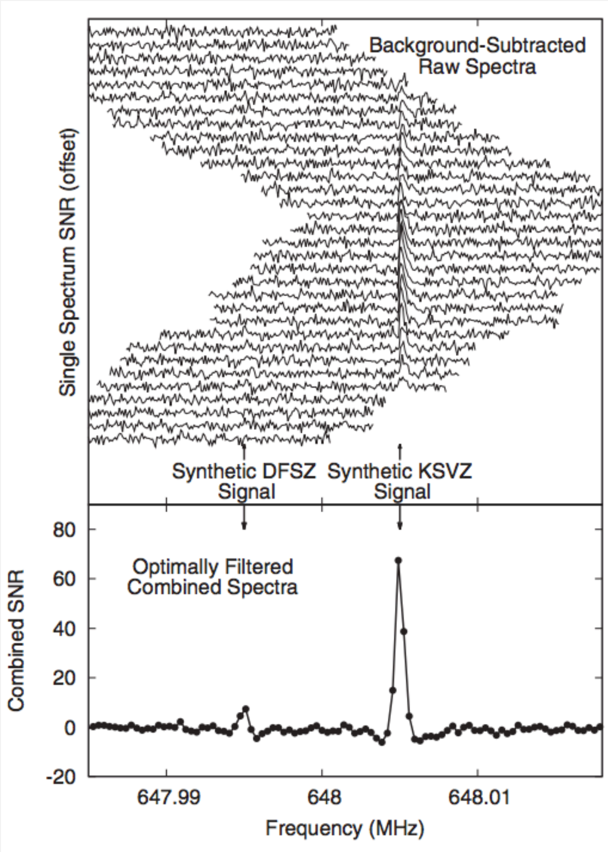
Oskar Klein centre

Outline

- Introduction
- The structure of the axion field
- Axion experiments
- How to make an experiment directional
- Axion astronomy

An optimistic view of the future

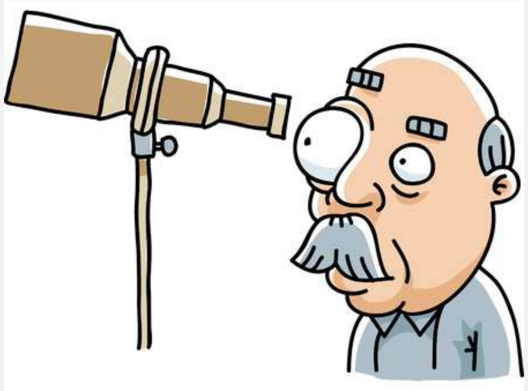
- Huge number of new ways to look for axions
- Many new experimental collaborations forming
- Old collaborations taking data
- What do we do if we succeed?

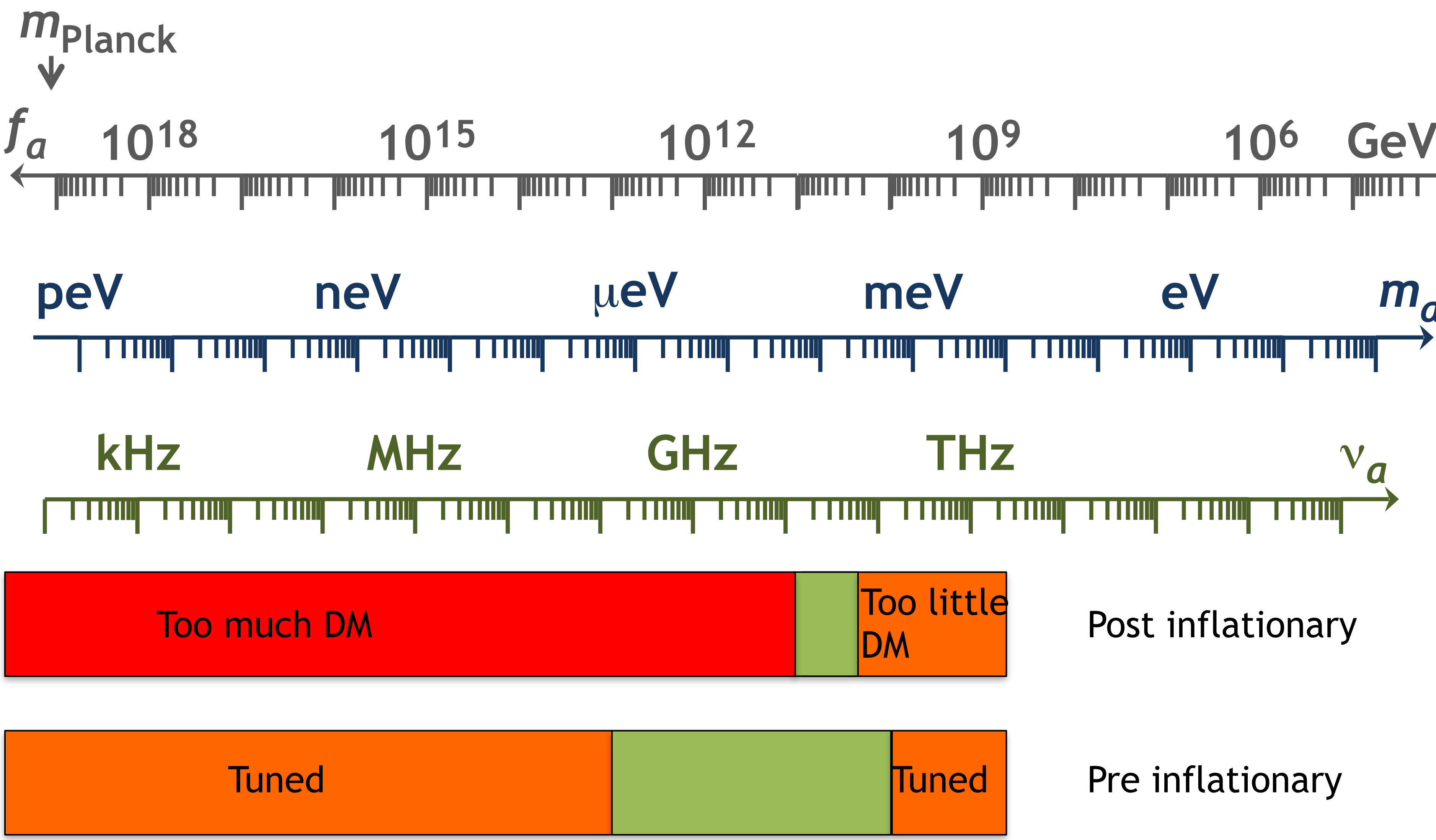


arXiv:1804.05750

The goal

- If we discover the axion, how do we extract as much information as possible?
- What would the ultimate "axion telescope" look like?





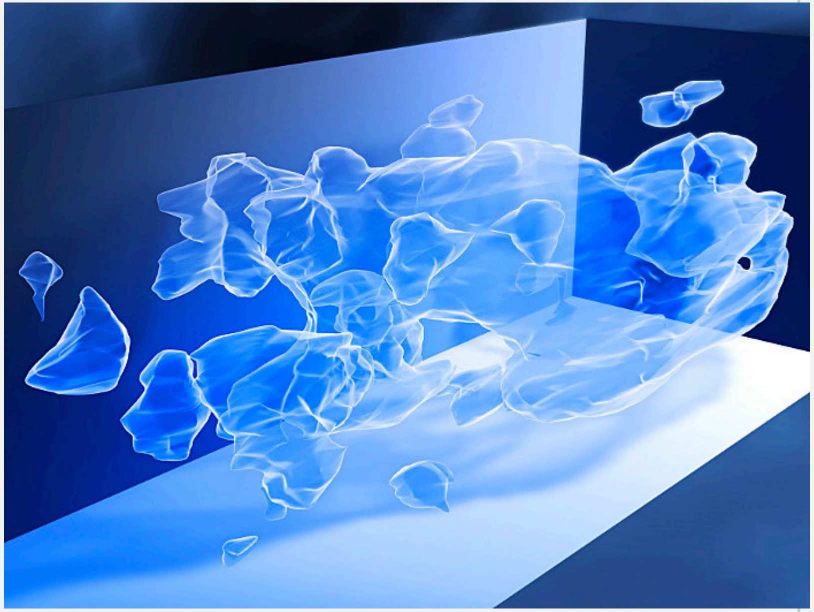
m_{Planck}
f_a
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
GeV
peV
neV
μeV
meV
eV
m_a
kHz
MHz
GHz
THz
ν_a
Too much DM
Too little DM
Post inflationary
Tuned
Tuned
Pre inflationary

Axion DM is a classical field

- Two classical limits of QFT: point particles and classical fields
- Wimps are an example of the first: heavy (~100 GeV) and low in number – direct detection looks for scatterings
- Axions are light (~10^{15} times lighter) and highly degenerate
- Totally different phenomenology

Field structure of the axion

- Usually just given as $a(t,\mathbf{x}) = a_0 e^{i(\mathbf{p}\cdot\mathbf{x}-\omega t)}$
- Good: simple
- Bad: ignores all the DM structure
- Solution: write down the Fourier decomposition



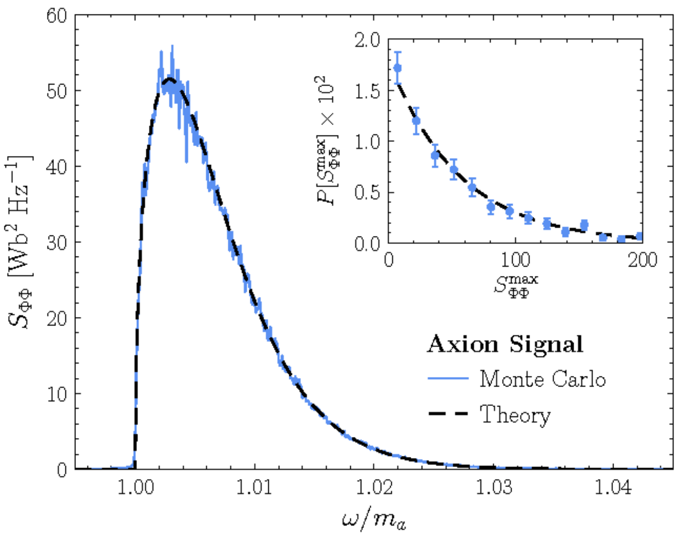
$$a(\mathbf{x},t) = \sqrt{V_\odot}\int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3}\frac{1}{2}\left[a(\mathbf{p})e^{i(\mathbf{p}\cdot\mathbf{x}-\omega_\mathbf{p}t)} + a^*(\mathbf{p})e^{-i(\mathbf{p}\cdot\mathbf{x}-\omega_\mathbf{p}t)}\right]$$

Velocity distribution

- Summarise all the information into the "velocity distribution"

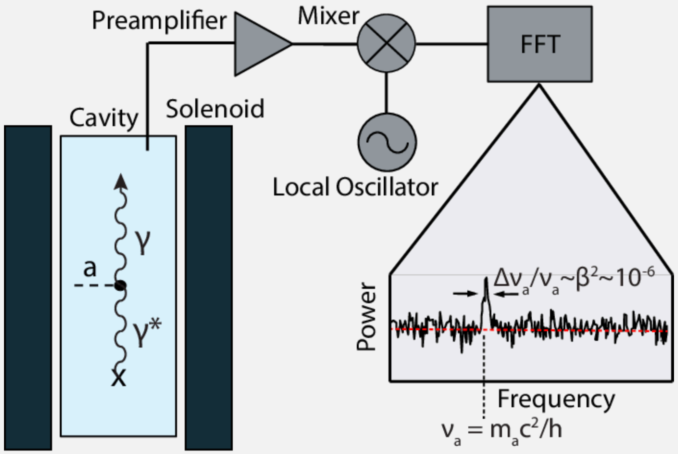
$$f(\mathbf{v}) \simeq \frac{1}{\bar{\rho}_a} \frac{m_a^3}{(2\pi)^3} \frac{1}{2} m_a^2 |a(\mathbf{p})|^2$$

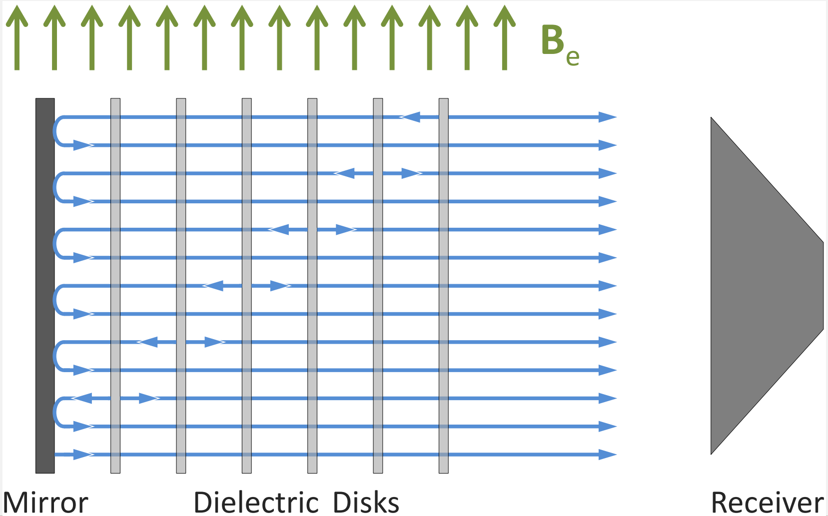
- Most experiments are just sensitive to the speed distribution



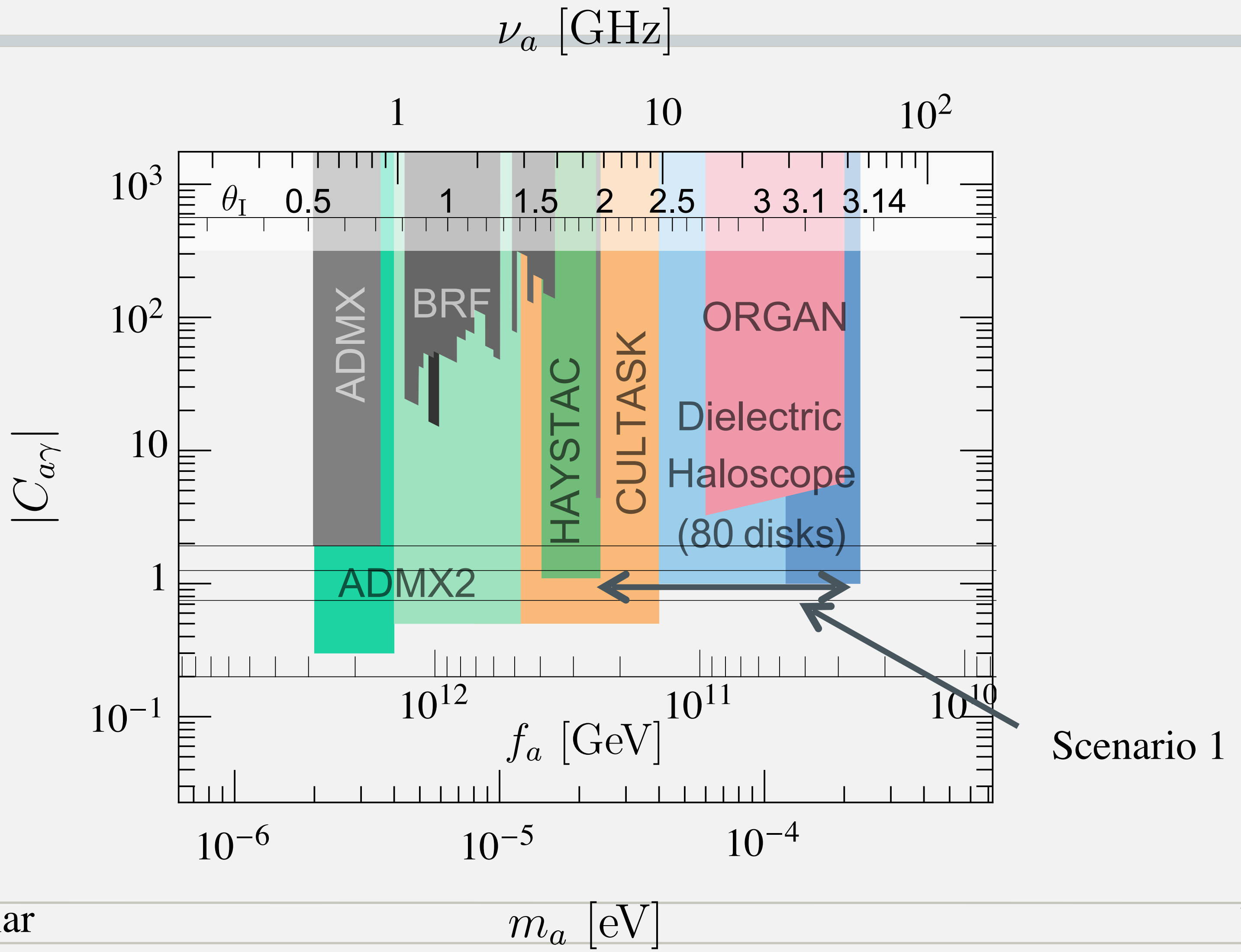
The scenario

- Huge number of possible detection methods exist
- Focus on cavity and dielectric haloscopes
- Complimentary, well motivated parameter space
- Can be handled with the same formalism



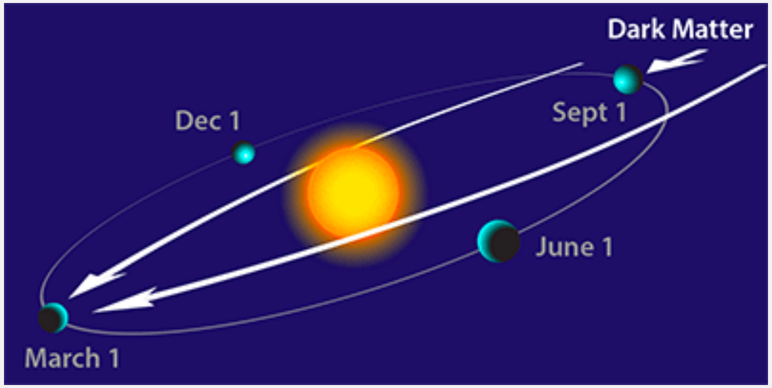


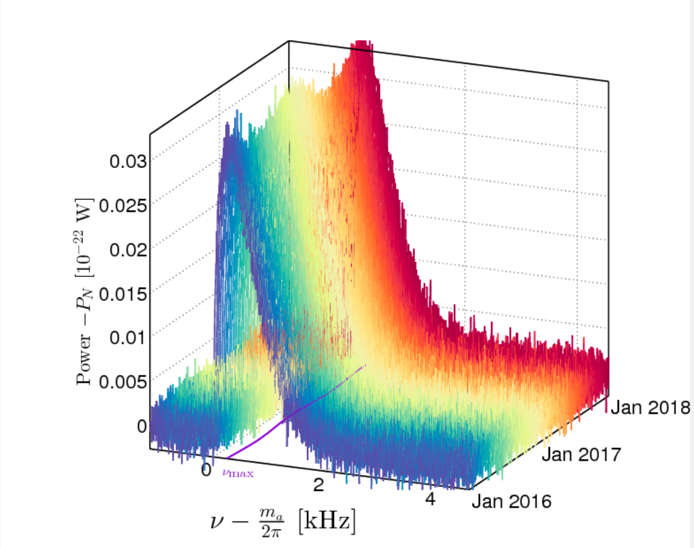
Discovery potential



What if we see it?

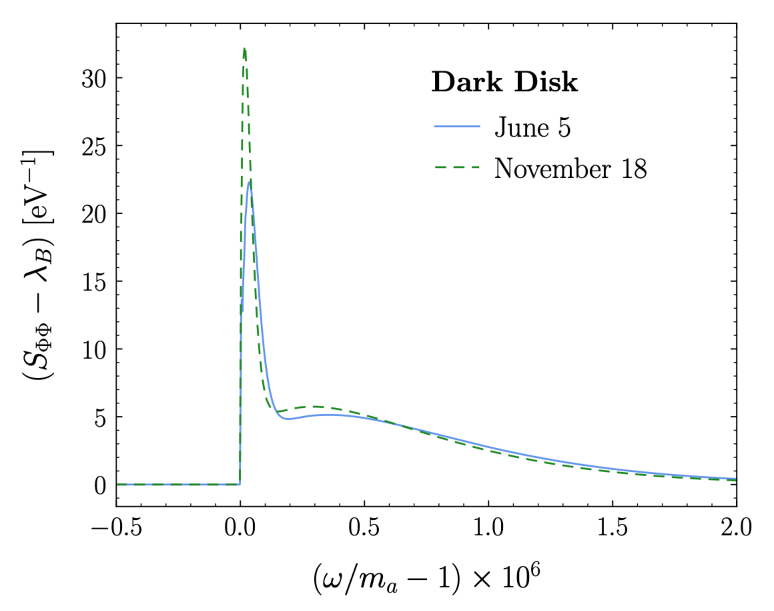
- Just sit and wait
- $\omega = m_a (1+v^2/2) \rightarrow$ good frequency resolution gives us speed distribution
- Quite sensitive to annual modulation (5%)
- Can detect frequency substructure
- Confirms DM nature of signal
- See more: arXiv:1701.03118, 1711.10489



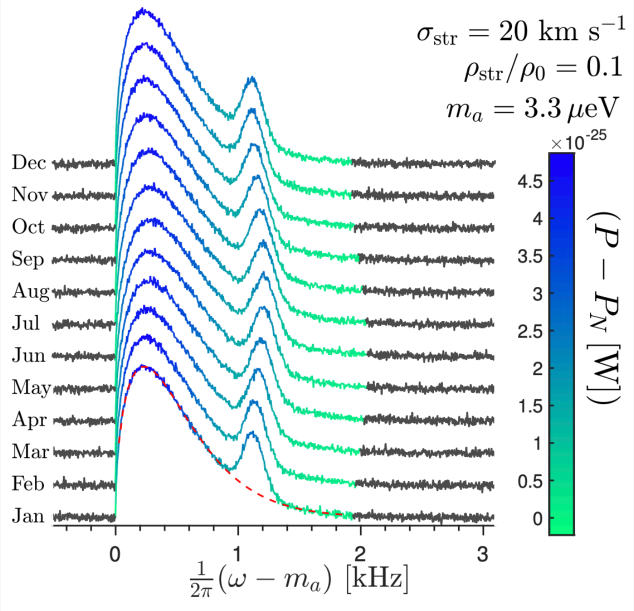


Substructure

- Miniclusters
- Tidal MC streams



- DM streams
- Dark Disks



Can we do better?

- Only sensitive to changes to overall speed: daily modulation difficult (0.2%)
- Cannot easily tell the relative direction of substructure
- Insensitive to the anisotropy of the DM halo
- Measure the velocity directly!

A unified framework

- How do experiments depend on the velocity?
- Simple case only done for cavities (arXiv:1207.6129)
- Understood for dielectric haloscopes, but with transfer matrices (arXiv:1707.04266) (very relevant to LAMPOST)
- Can we handle both with the same basic formalism?

Overlap integral formalism

- Resonant cavities use Sikivie's overlap integral formalism… Can we generalise?

$$P_{\rm cav} = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_{\rm e}^2, \;\; \mathcal{G} = \frac{\left(\int dV \, \mathbf{E}_{\rm cav} \cdot \mathbf{B}_{\rm e}\right)^2}{V B_{\rm e}^2 \int dV \, \mathbf{E}_{\rm cav}^2}$$

- Yes! Actually most axion experiments can be handled with overlap integrals…

- The overlap integral can be (most easily) proved by a QFT calculation

Quantum calculation

- Need to calculate the probability of a single axion converting to a photon
- Lowest order QFT→Fermi's golden rule

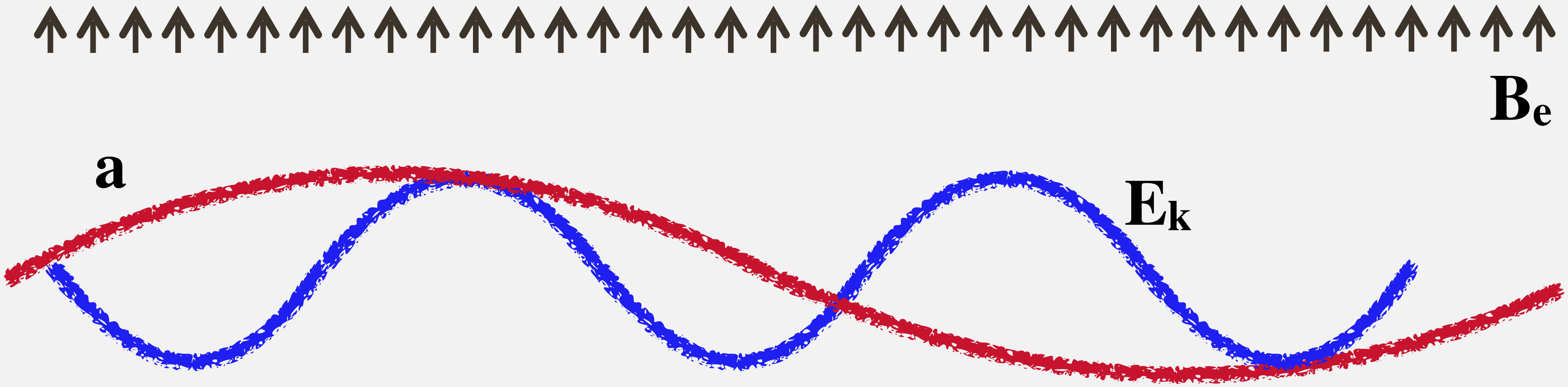
$$\Gamma_{a\to\gamma} = 2\pi \sum_{\mathbf{k}} |\mathcal{M}|^2 \, \delta(\omega_a - \omega_{\mathbf{k}}) \, .$$

- Matrix element is given by the overlap of the axion and photon wave functions

$$\mathcal{M} = \frac{g_{a\gamma}}{2\omega V} \int d^3\mathbf{r} \, e^{i\mathbf{p}\cdot\mathbf{r}} \, \mathbf{B}_{\rm e}(\mathbf{r}) \cdot \mathbf{E}^*_{\mathbf{k}}(\mathbf{r})$$

Axion-photon conversion

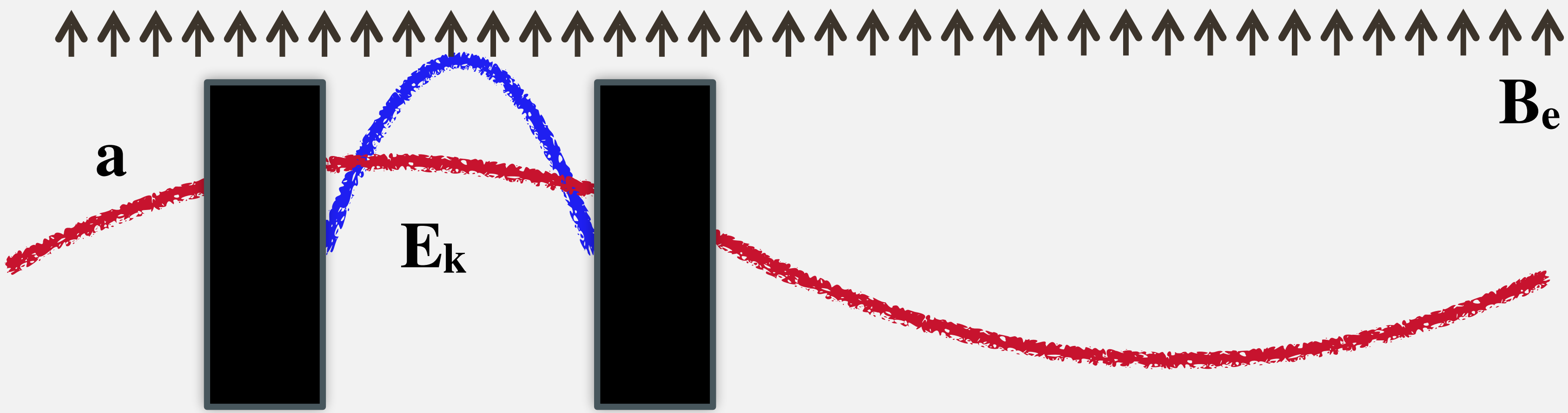
- In vacuum and constant B_e this oscillatory integral vanishes



- Modify the free photon wave function!

Cavity haloscopes

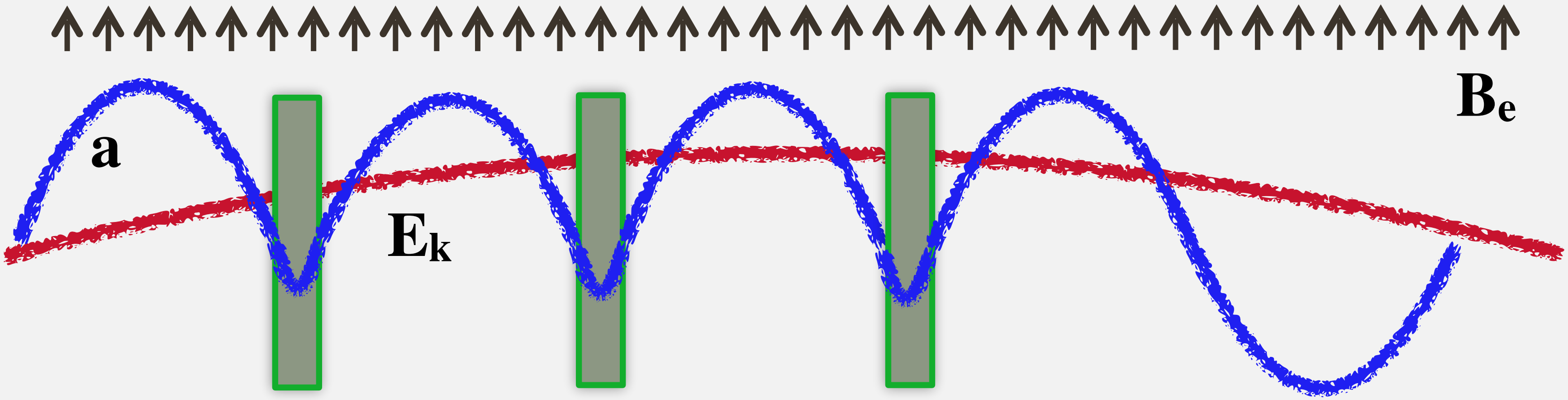
- Inside a cavity E_k becomes the cavity modes



- Normalisation is given by the "quality factor" of the cavity

Dielectric haloscopes

- Introduce a series of dielectric layers



- Dielectric layers distort the free photon wave function, giving a non-zero overlap

Generalised overlap integral

- We can write down one equation for both experiments

$$P = \kappa g_{a\gamma}^2 B_{\rm e}^2 V \frac{\bar{\rho}_a}{m_a} Q_{\rm eff} \int \mathrm{d}^3\mathbf{v}\, f(\mathbf{v}) C(\mathbf{v})$$

- Shows explicitly where the velocity dependence enters

$$C(\mathbf{v}) \propto \left| \int \mathrm{d}^3\mathbf{x}\, \mathbf{E}_{\mathbf{k}}(\mathbf{x}) \cdot \mathbf{B}_{\rm e} \left(1 + i\mathbf{p}\cdot\mathbf{x} - \frac{(\mathbf{p}\cdot\mathbf{x})^2}{2} + \ldots \right) \right|^2$$

- At lowest order we either have linear or quadratic dependence on v (only quadratic for cavities)

General formalism

Frequency dependence

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

Base power

Speed effect

Directional effect

$$C(\mathbf{v}) = C_0\left(1 - \mathcal{G}_{\ell,\,q}(\mathbf{v})\right)$$

$$\mathcal{G}_\ell(\mathbf{v}) = \sum_{i=1}^{3} g_\ell^i v_i$$

Linear

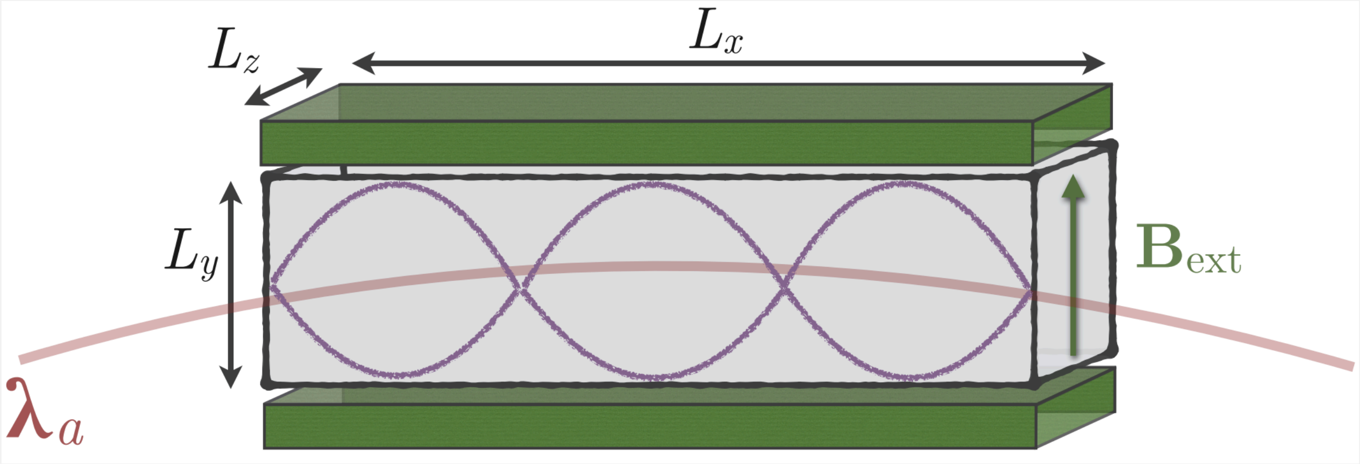
$$\mathcal{G}_q(\mathbf{v}) = \sum_{i=1}^{3}\sum_{j=1}^{3} g_q^{ij} v_i v_j$$

Quadratic (usually negative)

Cavity haloscopes

- Simple case: rectangular cavity
- Elongate one side to gain sensitivity in that direction

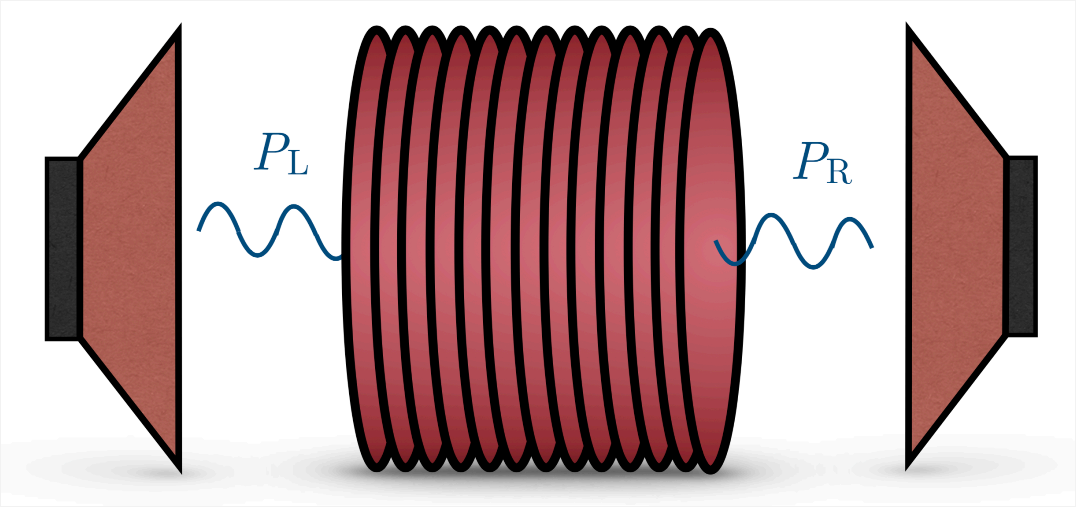
$$C(\mathbf{v}) = \frac{1}{VB_{\rm ext}} \int {\rm d}V\, \mathbf{e}_{l0n} \cdot \mathbf{B}_{\rm ext}\, e^{im_a \mathbf{v}\cdot\mathbf{x}} \simeq \frac{64}{l^2 n^2 \pi^4} \left[1 - \left(\frac{m_a v_x L_x}{2}\right)^2\right]$$



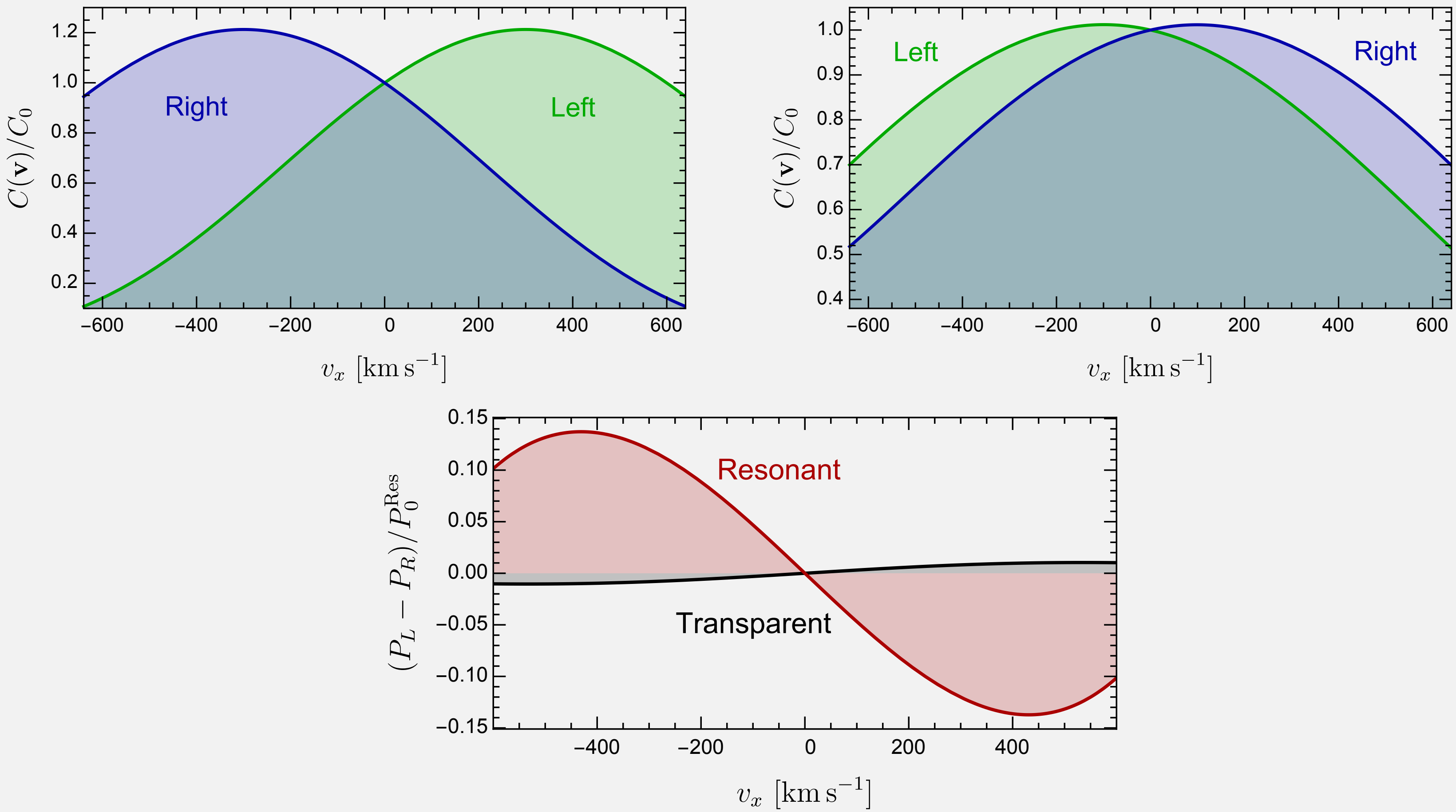
Dielectric haloscopes

- Combing the power from left and right can give linear and quadratic behaviour

- Optimum… measure both



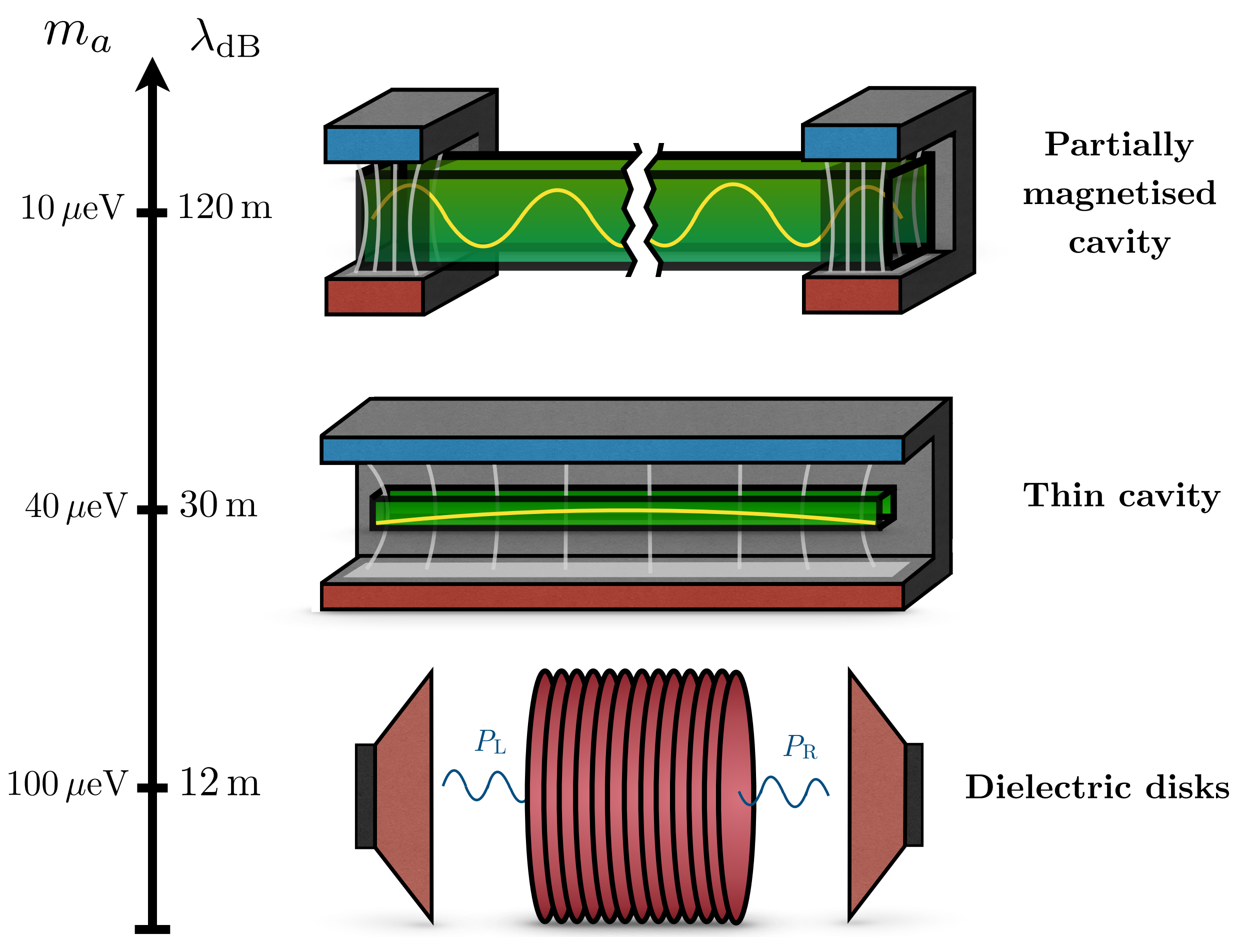
Dielectric haloscopes



Benchmarks

- Don’t need to tune
- Assume future technology realised (lots of R&D ongoing)
- Don’t need to scan: just need to design for a single frequency
- Well funded (finding DM is a big deal)
- Need length ~20% of the axion de Broglie wavelength

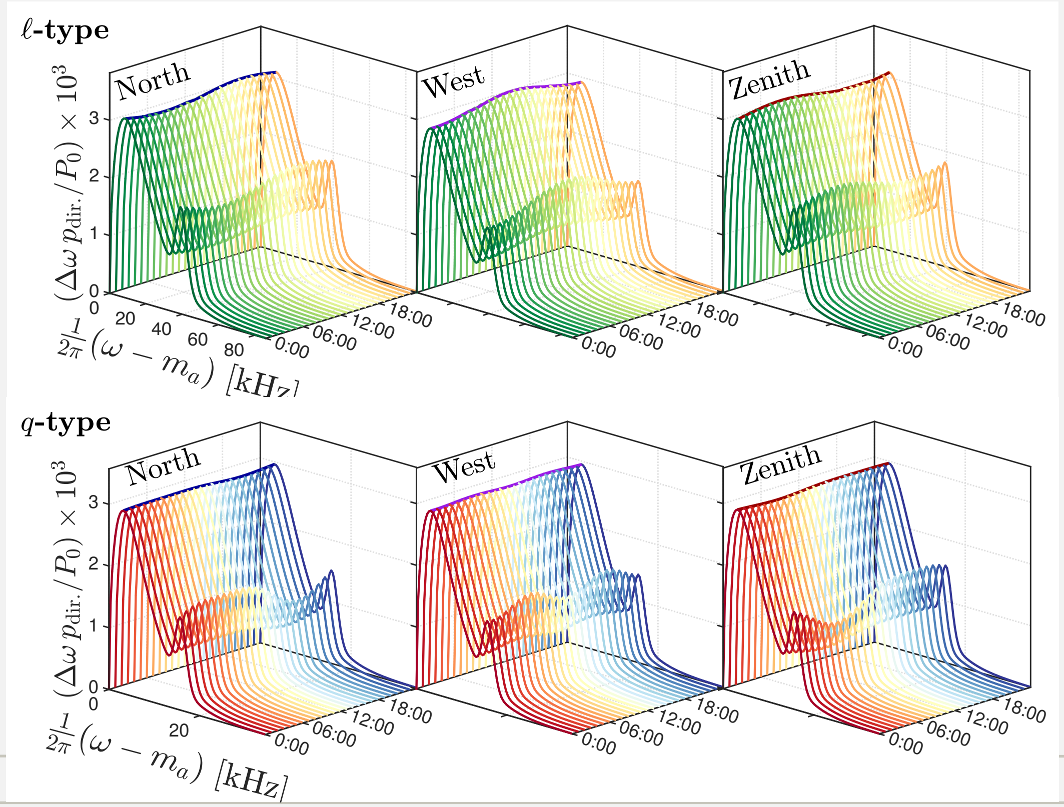
Benchmarks



m_a
$\lambda_{\rm dB}$
10 μeV
120 m
40 μeV
30 m
100 μeV
12 m
Partially magnetised cavity
Thin cavity
$P_{\rm L}$
$P_{\rm R}$
Dielectric disks

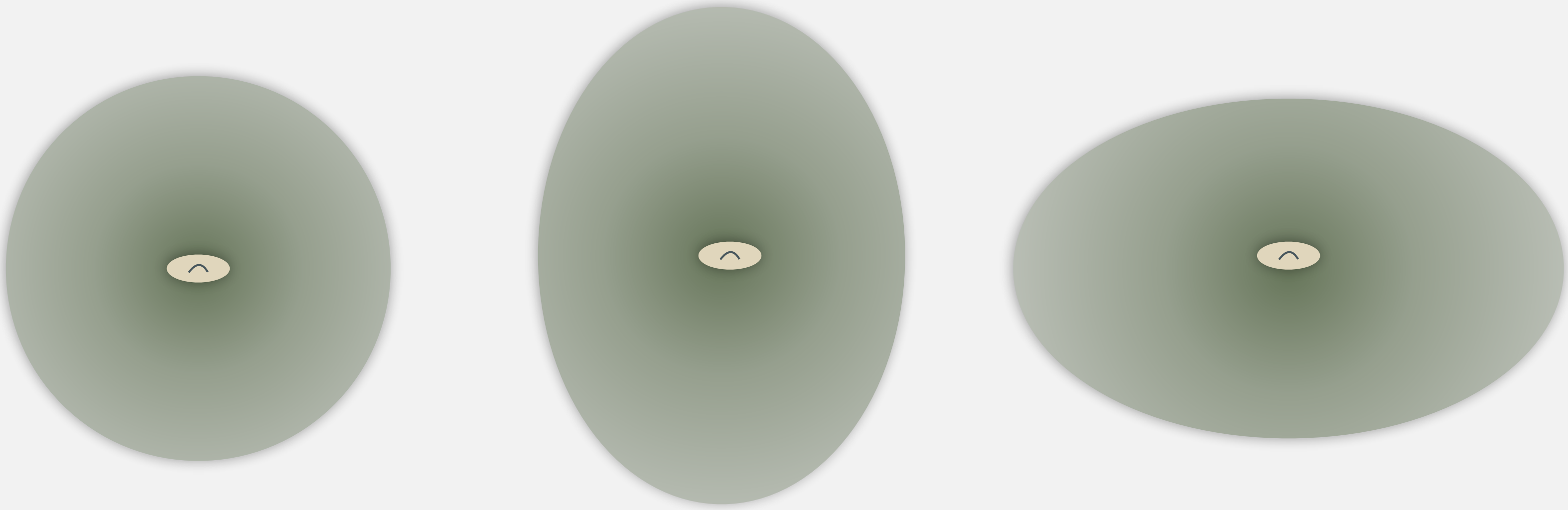
Daily Modulation

- Directionally insensitive devices need ~ a year
- Directionally sensitive… 4 days

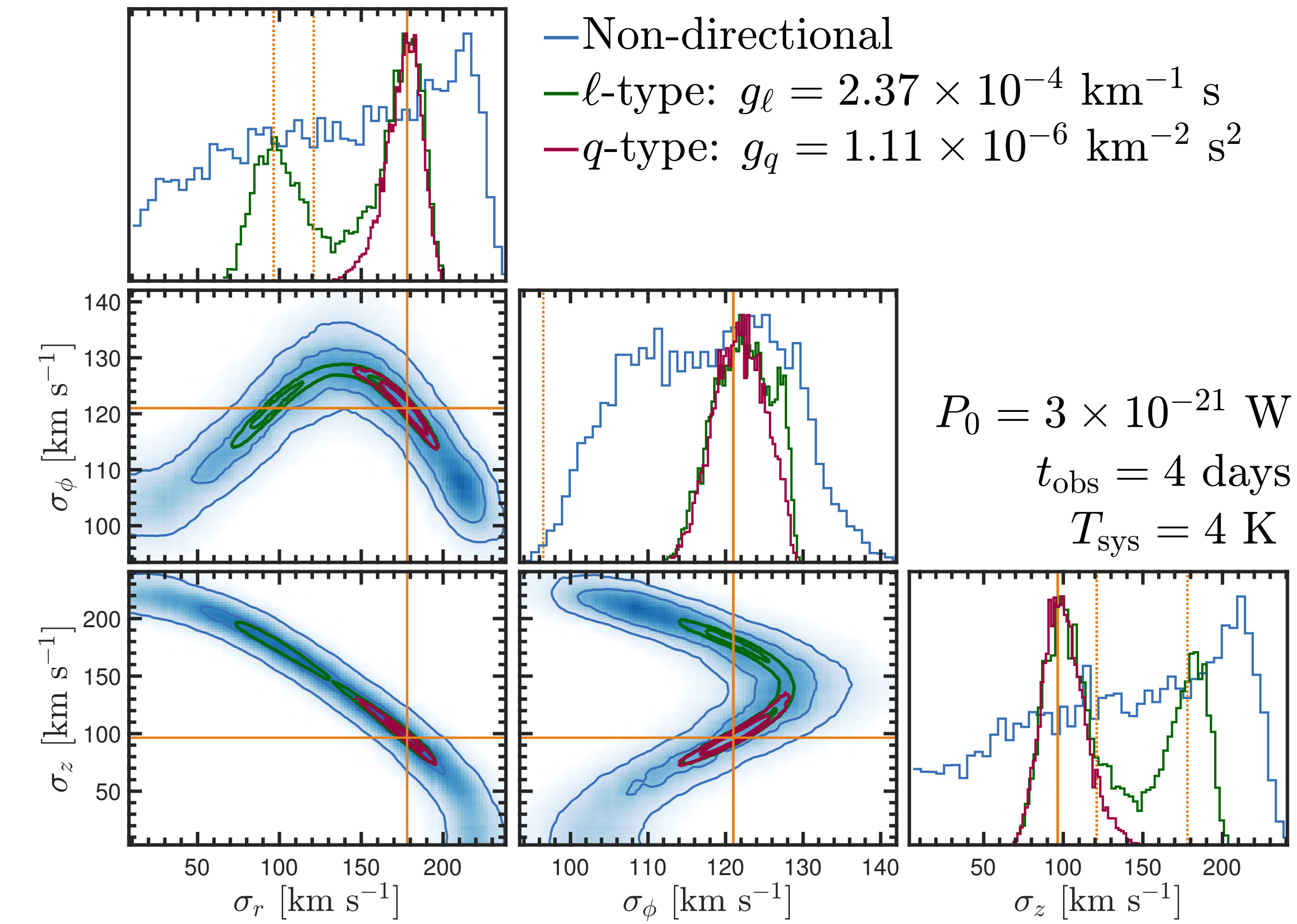


Anisotropy of DM halo

- The DM halo is not generally a perfect sphere
- Different velocity distributions in different directions… hard to detect without directional sensitivity

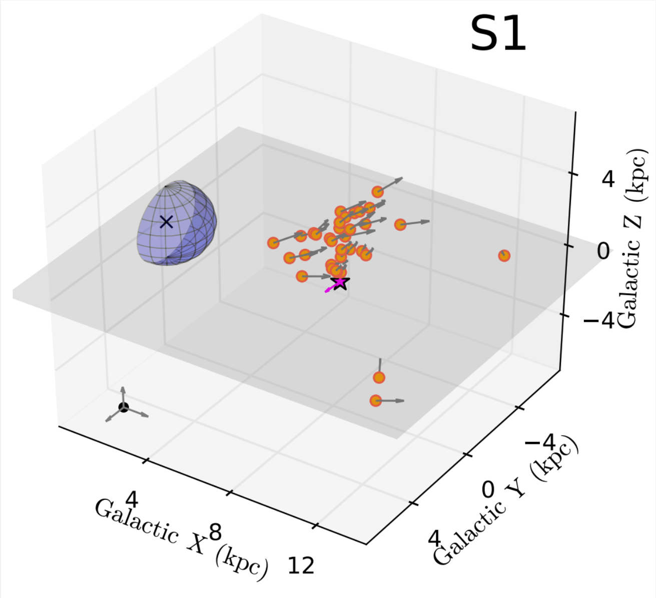


Anisotropy of DM halo



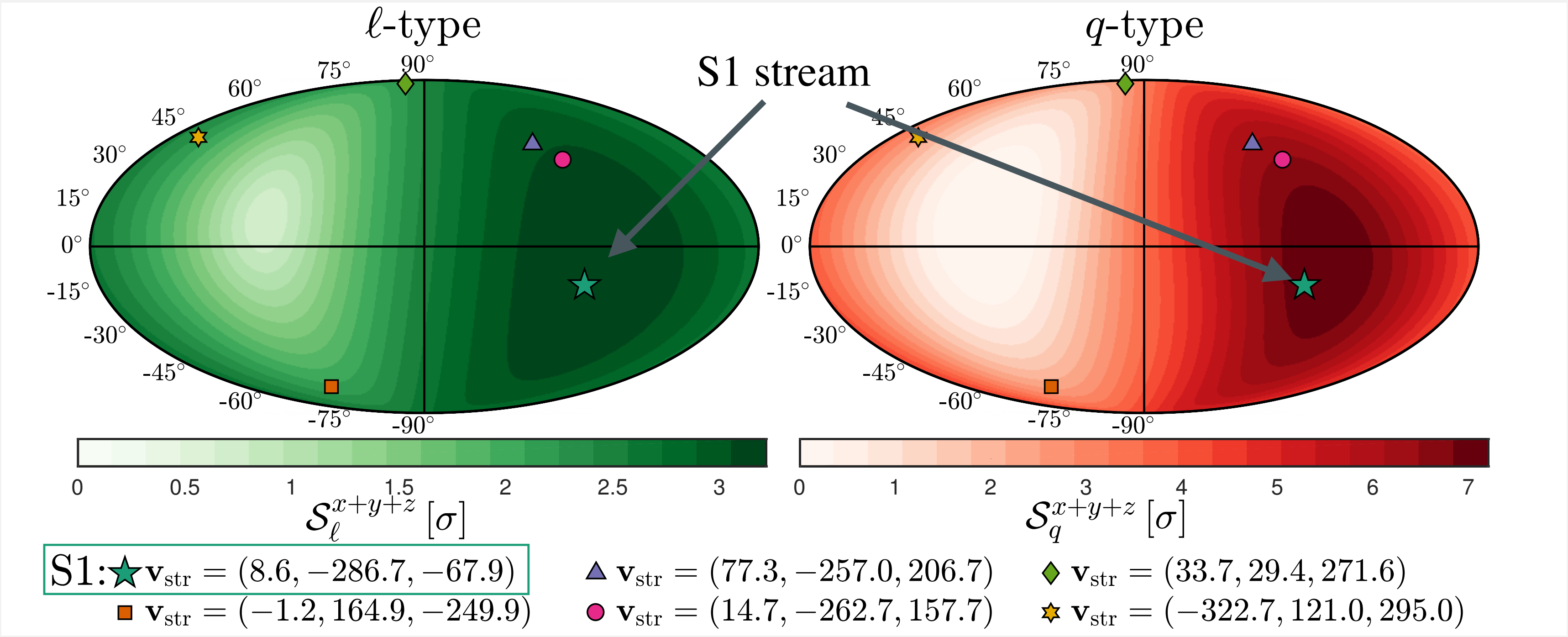
Streams

- Subhalos can be accreted and disrupted in the galaxy
- Leave very, very long "streams" of stars and DM
- Stellar component of "S1" stream seen by GAIA



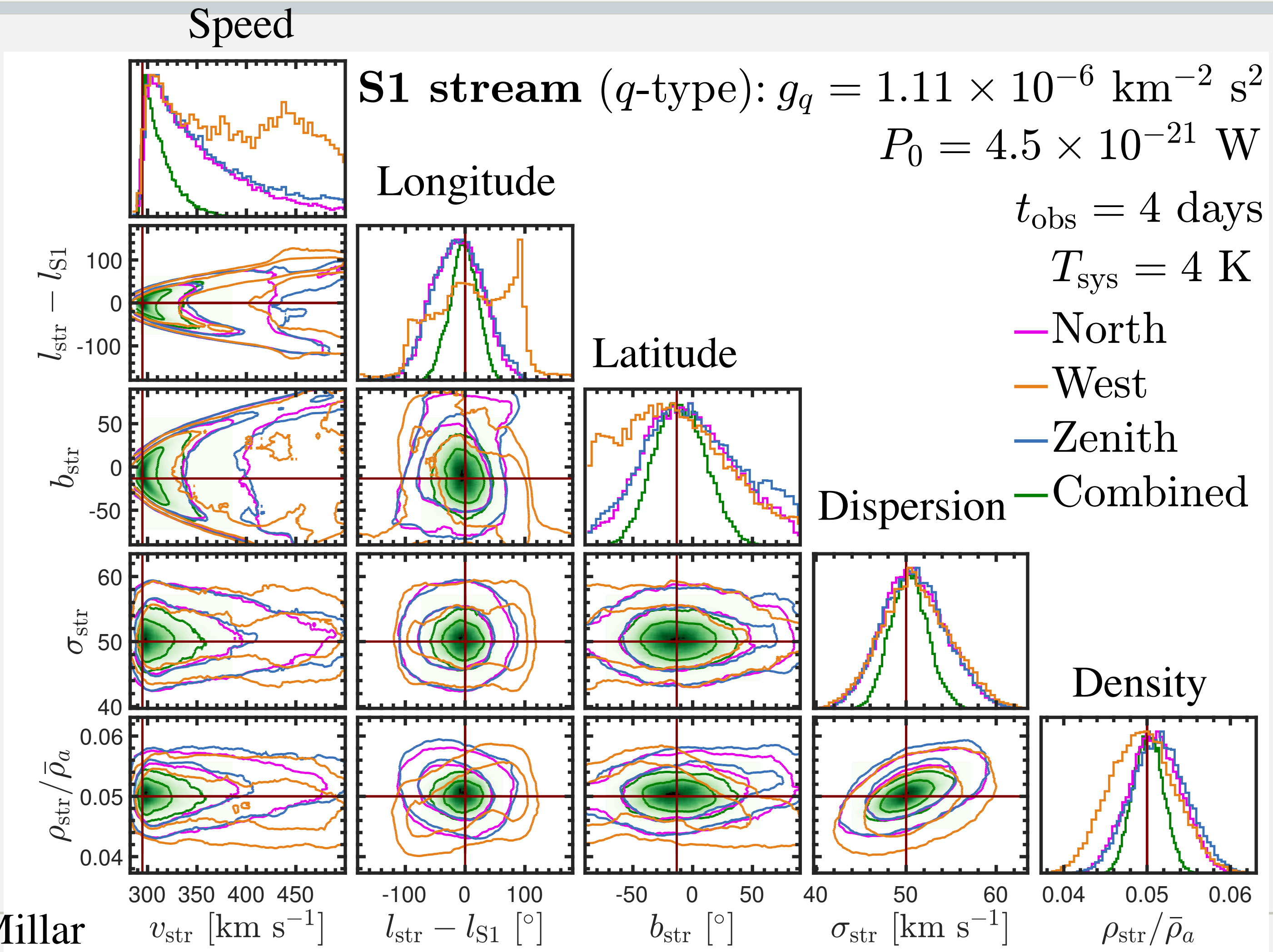
arXiv:1807.09004

Streams



Significance for daily modulation after 4 days

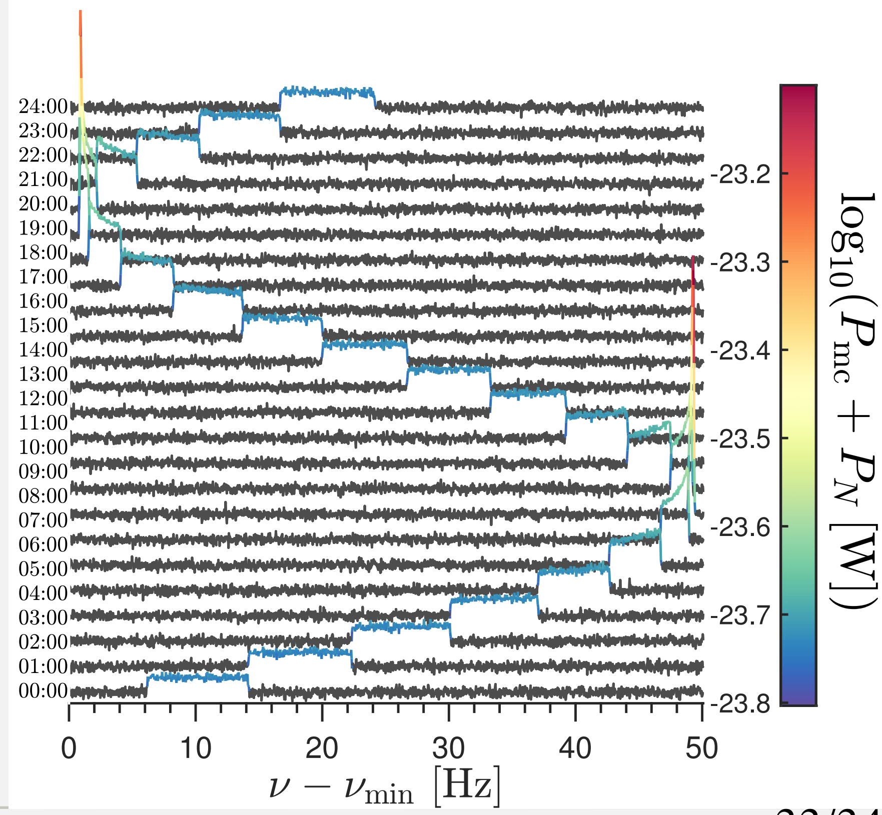
Streams



Speed
Longitude
Latitude
Dispersion
Density
S1 stream (q-type): $g_q = 1.11 \times 10^{-6}$ km^{-2} s^2
$P_0 = 4.5 \times 10^{-21}$ W
$t_{\rm obs} = 4$ days
$T_{\rm sys} = 4$ K
North
West
Zenith
Combined
$l_{\rm str} - l_{\rm S1}$
$b_{\rm str}$
$\sigma_{\rm str}$
$\rho_{\rm str}/\bar{\rho}_a$
$v_{\rm str}$ [km s^{-1}]
$l_{\rm str} - l_{\rm S1}$ [°]
$b_{\rm str}$ [°]
$\sigma_{\rm str}$ [km s^{-1}]
$\rho_{\rm str}/\bar{\rho}_a$

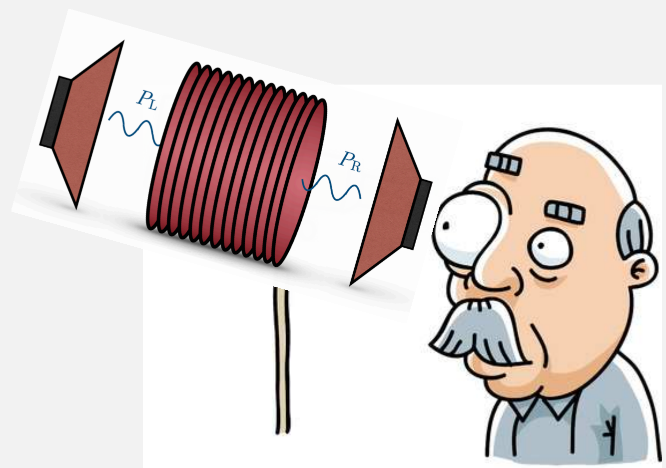
Ministreams

- Tails from tidally disrupted miniclusters
- Very, very cold… rotation of the Earth is actually a larger effect
- Very distinct signal

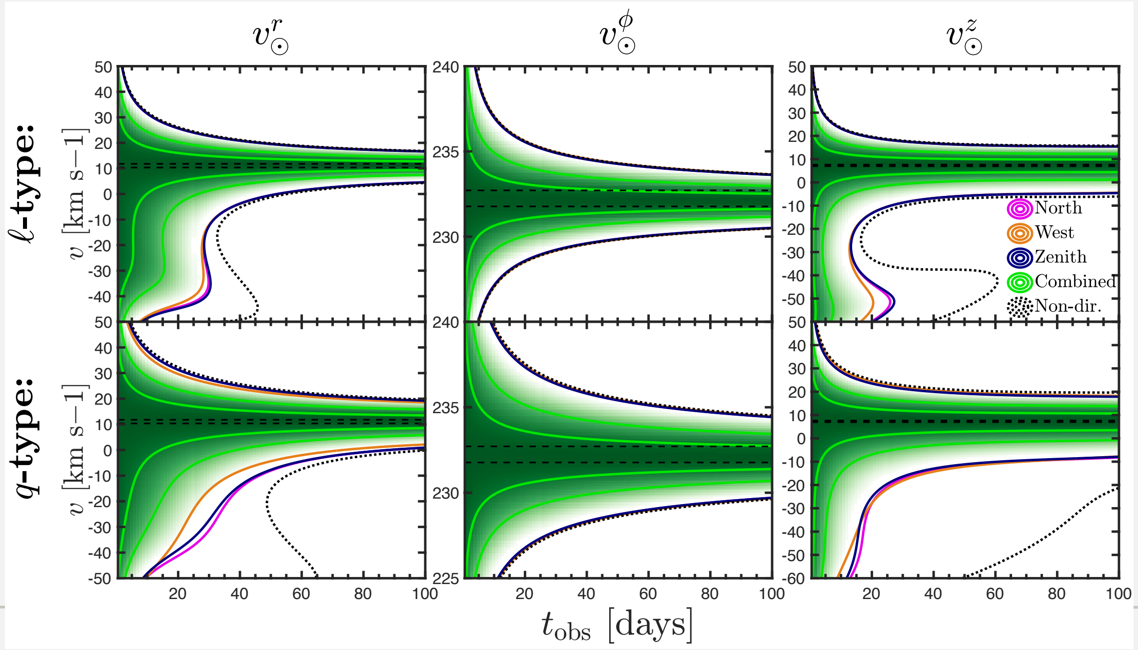


Conclusions

- Discovering the axion is the start, not the end
- Axion astronomy has huge potential for mapping DM
- Directional detection ambitious, but unparalleled

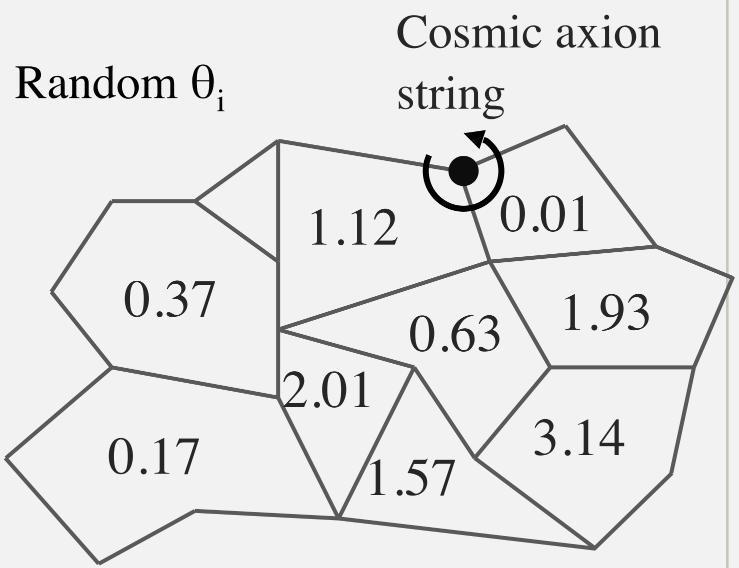


Solar Velocity



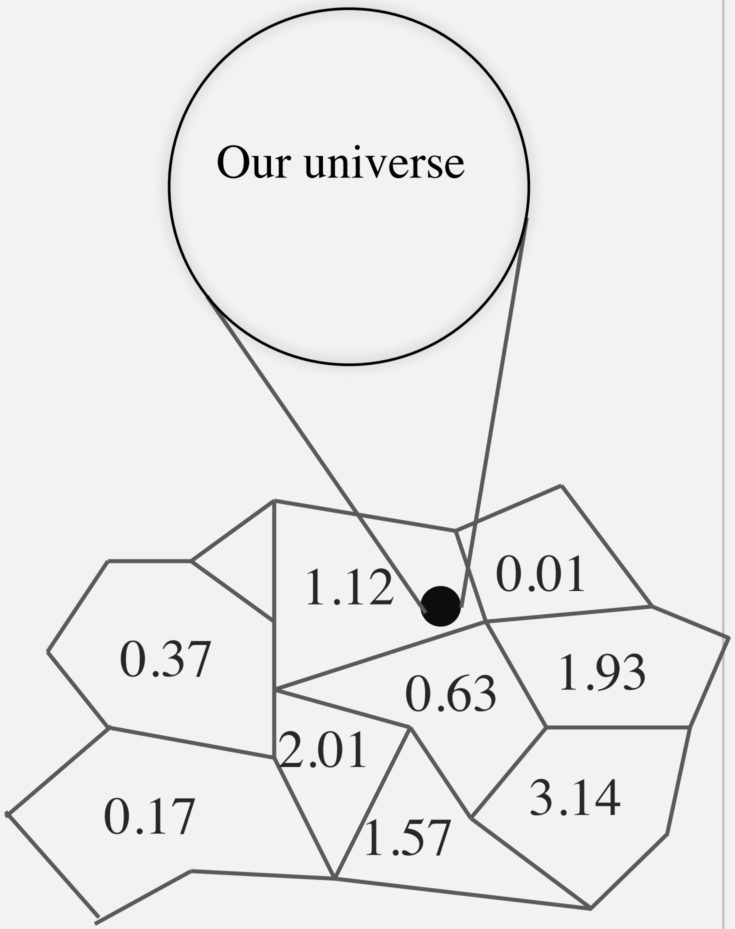
Axion DM: scenario 1

- Scenario 1: PQ broken after inflation
- θ_i has random values in every casual region, with the dark matter density determined by the average
- Topological defects such as strings and domain walls exist in the early universe



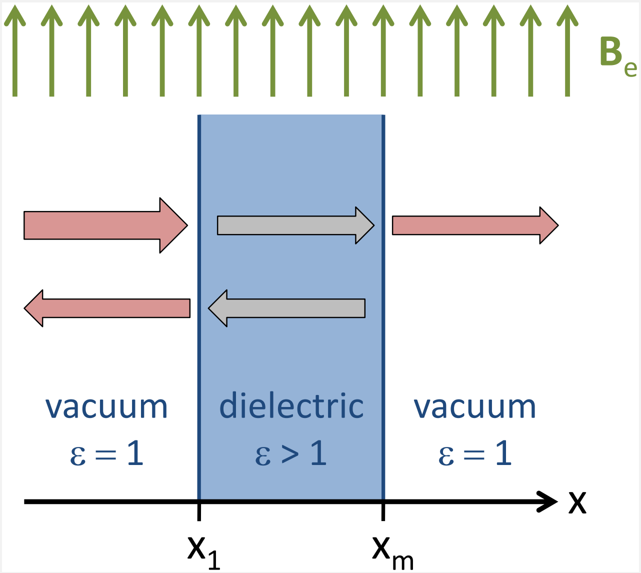
Axion DM: scenario 2

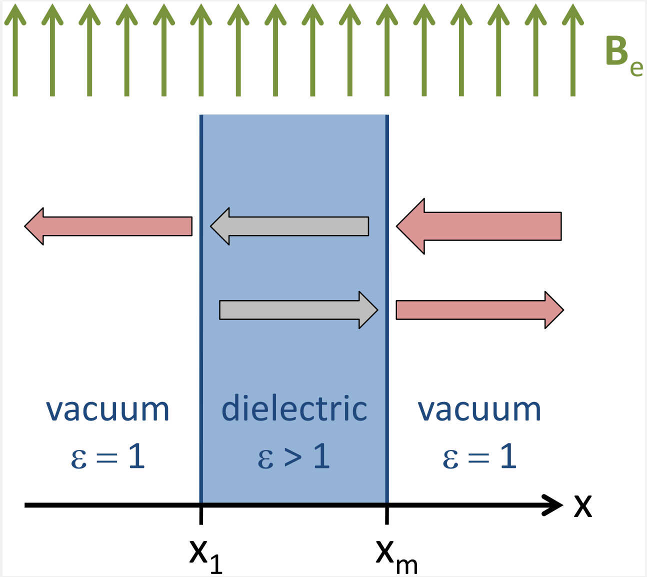
- Scenario 2: PQ broken before inflation
- θ_i has a single random value which determines the dark matter density
- No topological defects



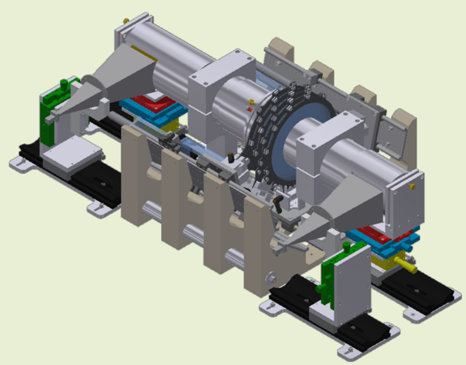
Overlap integral formalism

- The main trick is choosing the right free-photon wave functions: Garibian wave functions,





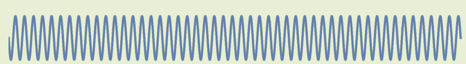
Length Scales



Apparatus in B-field
$\sim$ **1 meter**

m_a **= 100 μeV**

ν_a **= 25 GHz**

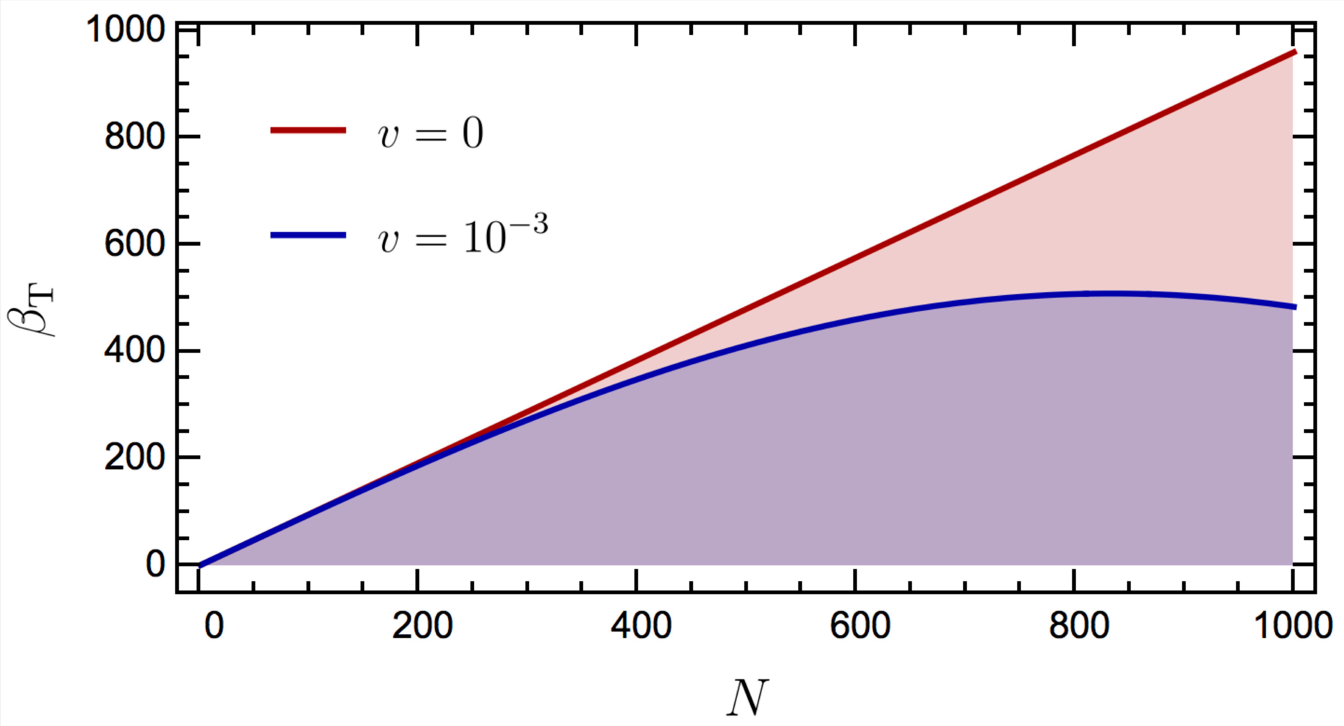


Photon wave length
$\lambda_\gamma \sim 1.24$ **cm**

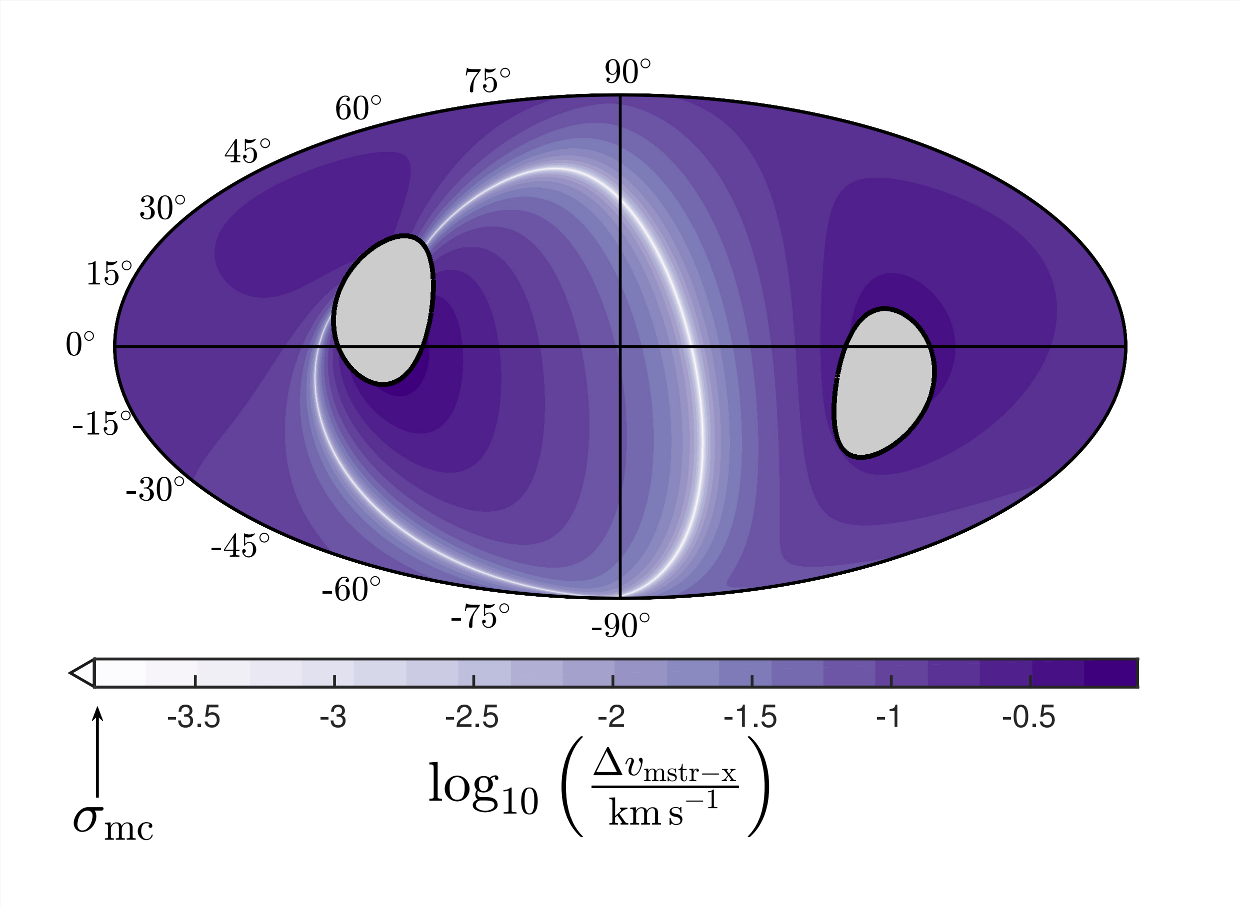
Benchmarks

Partially magnetised cavity $m_a = 10\,\mu\text{eV}$ $g_{a\gamma} = 3.84 \times 10^{-15}\ \text{GeV}^{-1}$	Magnetic field	B_e	15 T
	Quality factor	Q	10^6
	Widths	$L_{y,z}$	8.7 cm
	Length	L_x	12.5 m
	Mode number	l	142
	Form factor	C_0	$256/(142\pi^2)^2$
	Total power	P_0	1.6×10^{-23} W
	Geometry factor	g_q	$1.1 \times 10^{-6}\ \text{km}^{-2}\,\text{s}^2$
Thin cavity $m_a = 40\,\mu\text{eV}$ $g_{a\gamma} = 1.54 \times 10^{-14}\ \text{GeV}^{-1}$	Magnetic field	B_e	15 T
	Quality factor	Q	10^6
	Widths	$L_{y,z}$	2.20 cm
	Length	L	7.16 m
	Mode number	l	1
	Form factor	C_0	$64/\pi^4$
	Total power	P_0	1.2×10^{-20} W
	Geometry factor	g_q	$1.1 \times 10^{-6}\ \text{km}^{-2}\,\text{s}^2$
Dielectric disks $m_a = 100\,\mu\text{eV}$ $g_{a\gamma} = 3.84 \times 10^{-14}\ \text{GeV}^{-1}$	Magnetic field	B_e	15 T
	Number of disks	N	400
	Disk area	A	1 m^2
	Refractive index	n	5
	Phase separation	δ_s	3.138
	Phase thickness	δ_t	3.163
	Total power	P_0	2.6×10^{-19} W
	Geometry factors	g_ℓ	$2.4 \times 10^{-4}\ \text{km}^{-1}\,\text{s}$
		g_q	$1.1 \times 10^{-6}\ \text{km}^{-2}\,\text{s}^2$

Effect as a number of disks



Minicluster streams



Beyond linear/quadratic