Dielectric haloscopes: a new way to search for axion DM

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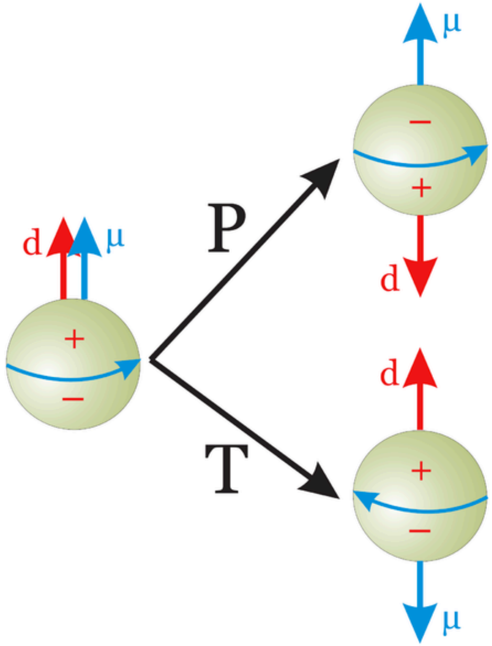
Strong CP problem

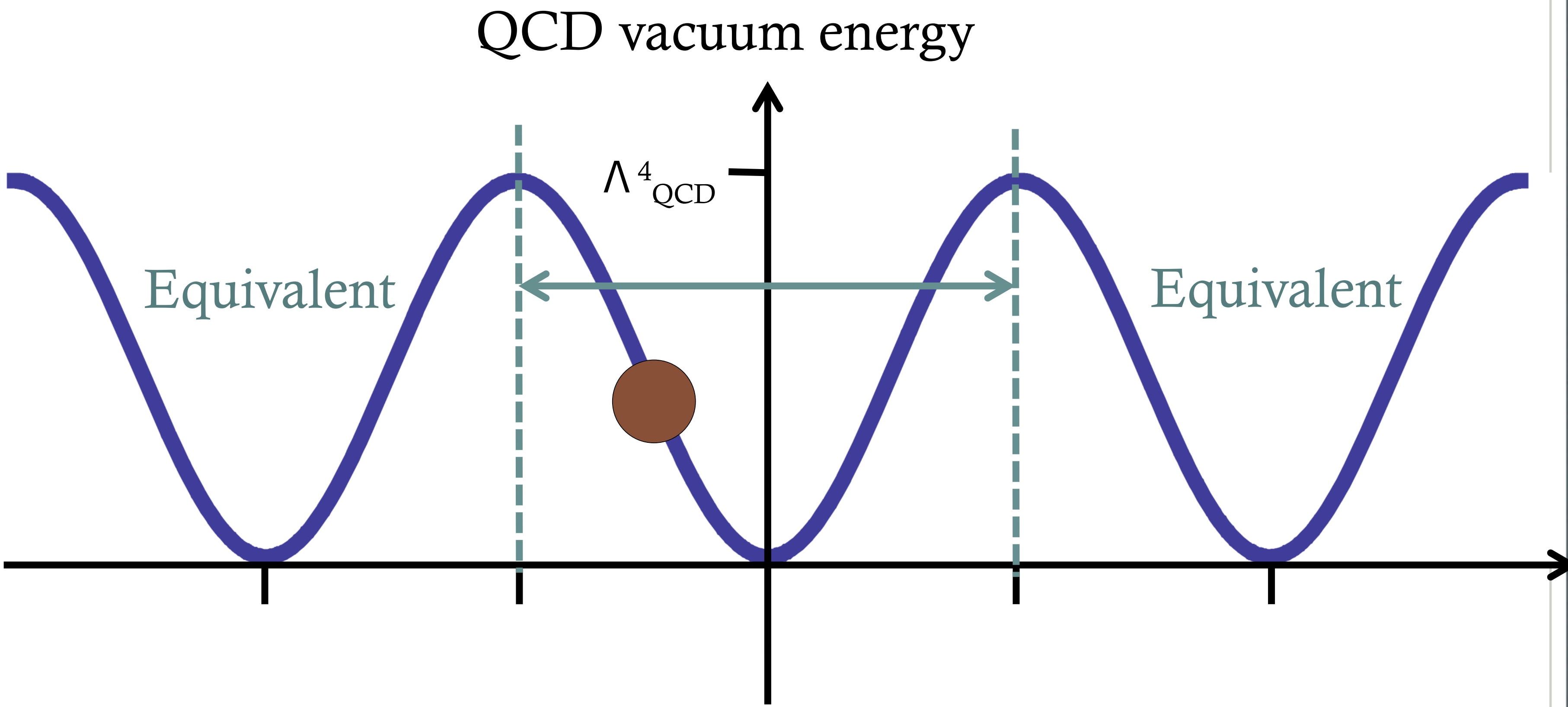
- QCD potentially has a CP violating term

$$\theta \frac{g^2}{32\pi^2} G\widetilde{G}$$

- Measurement of neutron EDM (which requires T violation) gives $\theta < 10^{-10}$
- No reason for θ to be so ridiculously small (even anthropics can't explain it)



Strong CP problem



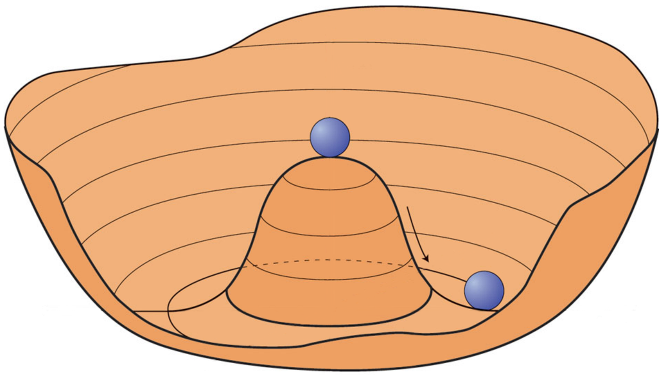
- θ =0 minimizes the vacuum energy, but θ is not a dynamical term

Axions

- Solve the strong CP problem by providing a dynamical explanation.

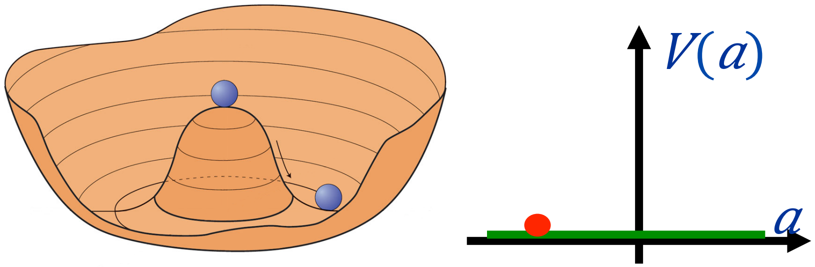
$$\mathcal{L}_{\text{stand mod + axion}} = \ldots + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Need a new anomalous U(1) chiral symmetry (Peccei-Quinn), which is broken at high temperature $\sim f_a$ (around 10^{12} GeV)

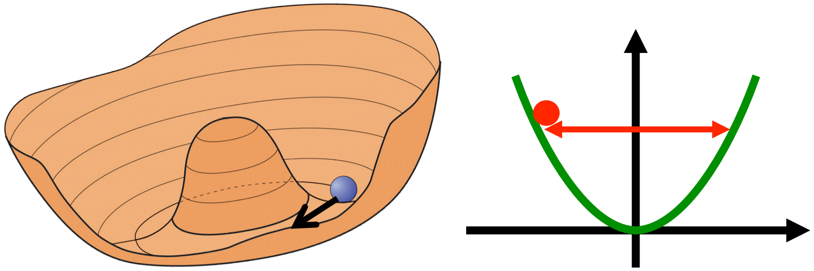


Axions

- The axion is the angular degree of freedom which is unbroken at intermediate temperatures

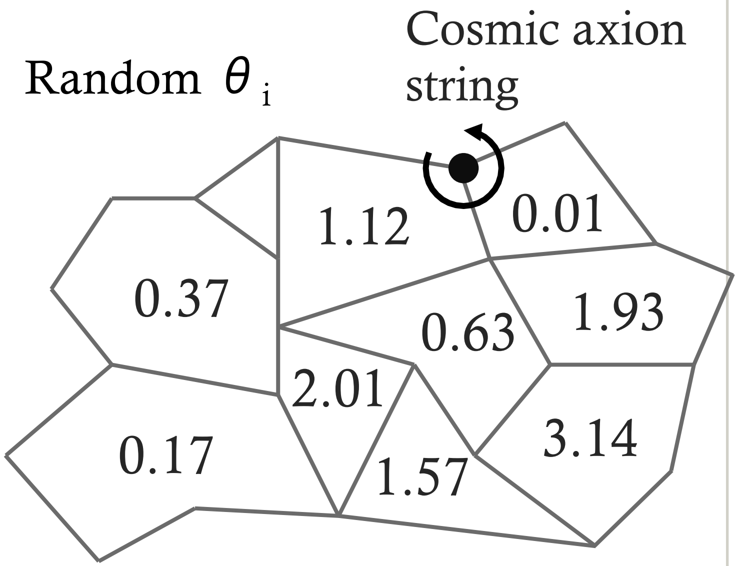


- At the QCD scale the potential tilts as the axion acquires a mass – axion rolls down to a CP conserving minimum



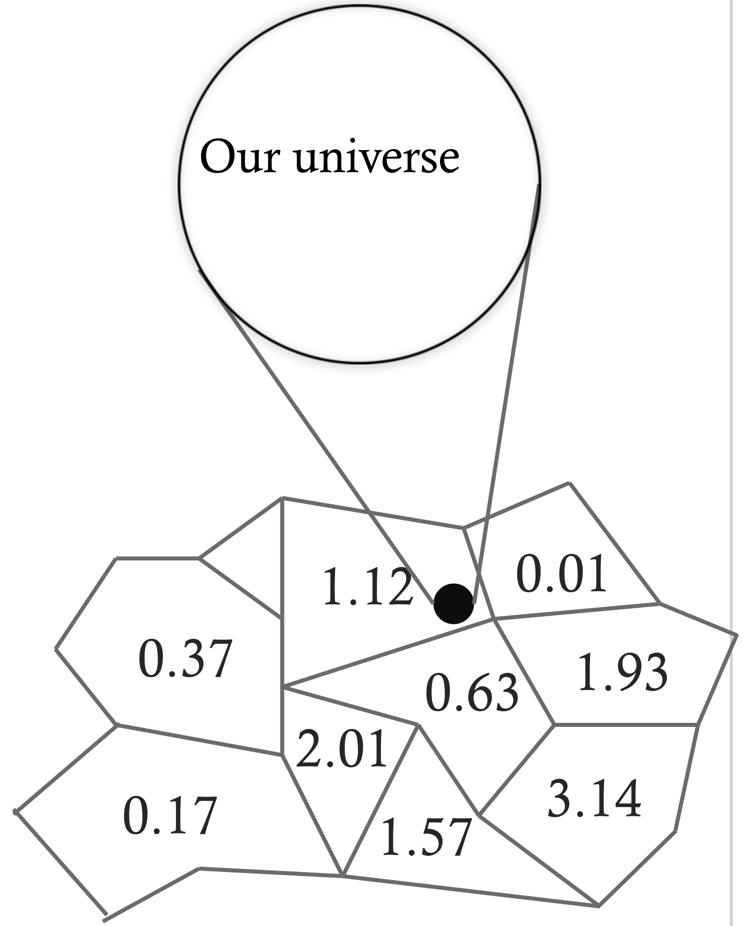
Axion DM: scenario 1

- 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



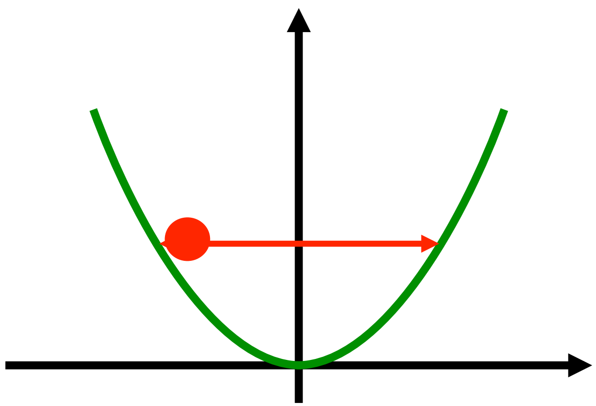
Axion DM: scenario 2

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

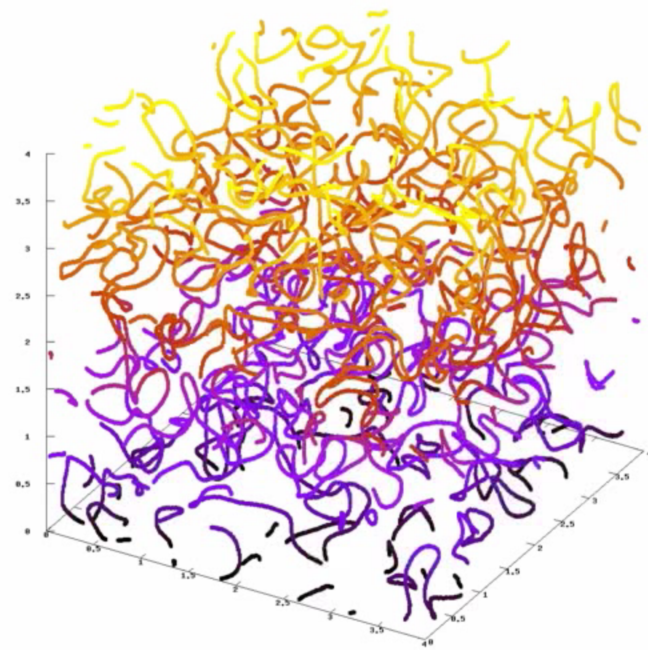


Axion production mechanisms

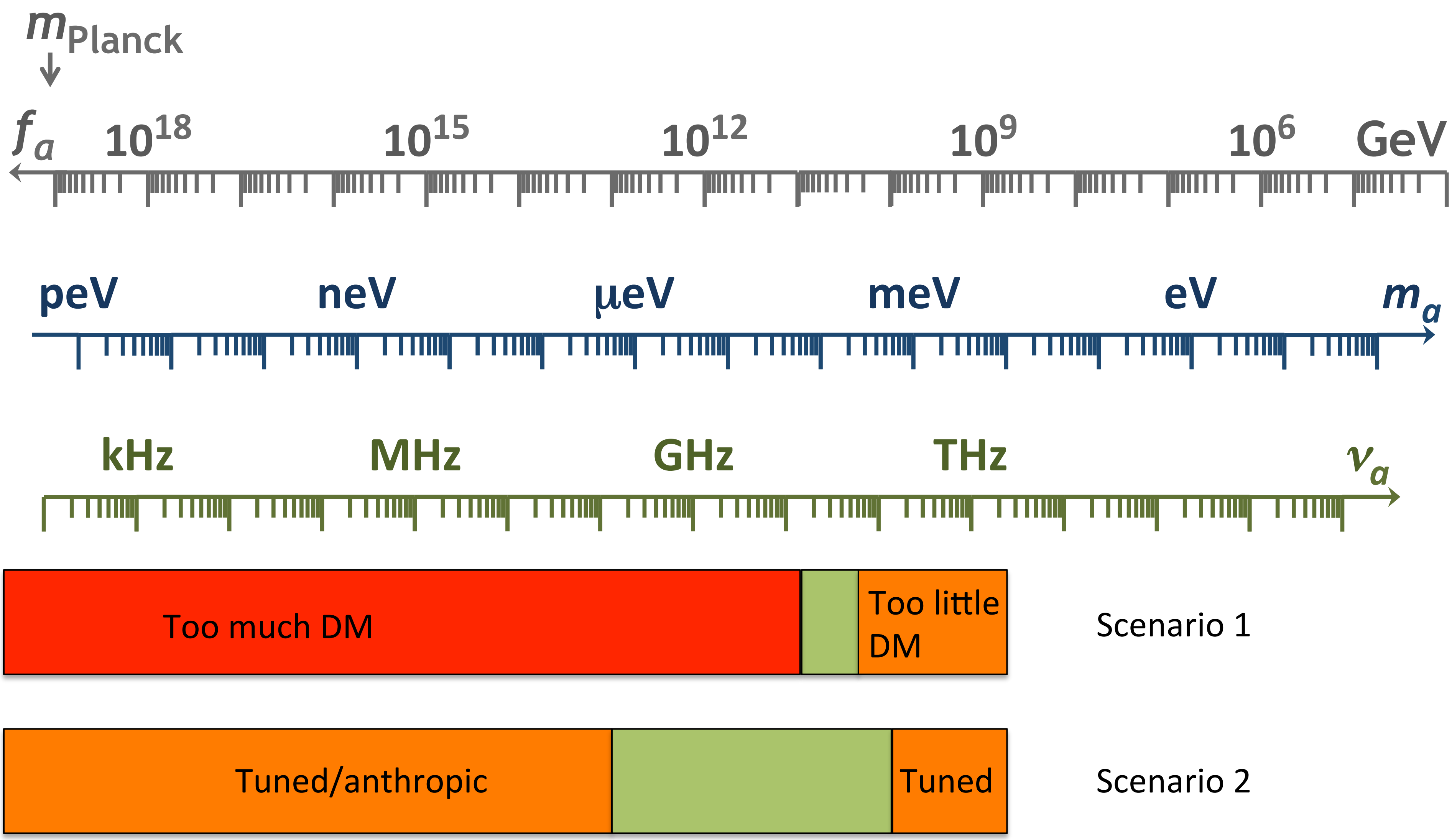
Vacuum Misalignment



Decay of topological defects



Animation credit: Javier Redondo



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
Scenario 1
Tuned/anthropic
Tuned
Scenario 2

Axions are classical fields

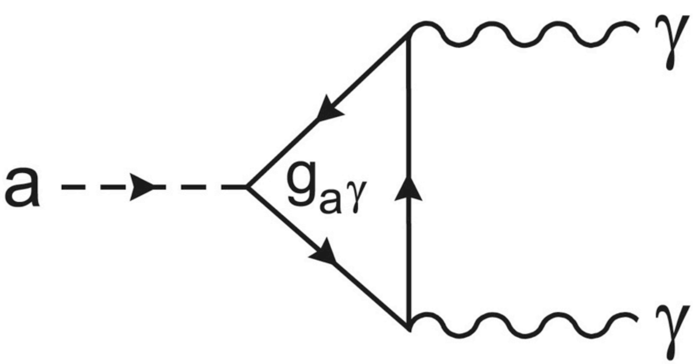
- Two classical limits of QFT: point particles and classical fields
- Wimps are an example of the first: heavy (~100 GeV) and low in number – direct detection looks for scatterings
- Axions are light (~10^{15} times lighter) and highly degenerate ($n_a \sim 10^{25}$)
- Totally different phenomenology

Axion-electrodynamics

- Axions and ALPs interact with photons through an anomaly term

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2 a^2 - \boxed{\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,}$$

- This coupling is tiny, but still important



$$m_a = 5.70(7)\,\mu\text{eV}\,\frac{10^{12}\text{GeV}}{f_a}\,,$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}C_{a\gamma} = 2.04(3)\times 10^{-16}\ \text{GeV}^{-1}\,\frac{m_a}{\mu\text{eV}}\,C_{a\gamma}\,,$$

$$C_{a\gamma} = \frac{E}{N} - 1.92(4)\,,$$

Axion induced E-field

- Maxwell's inhomogenous equations get new terms: axion acts as a current

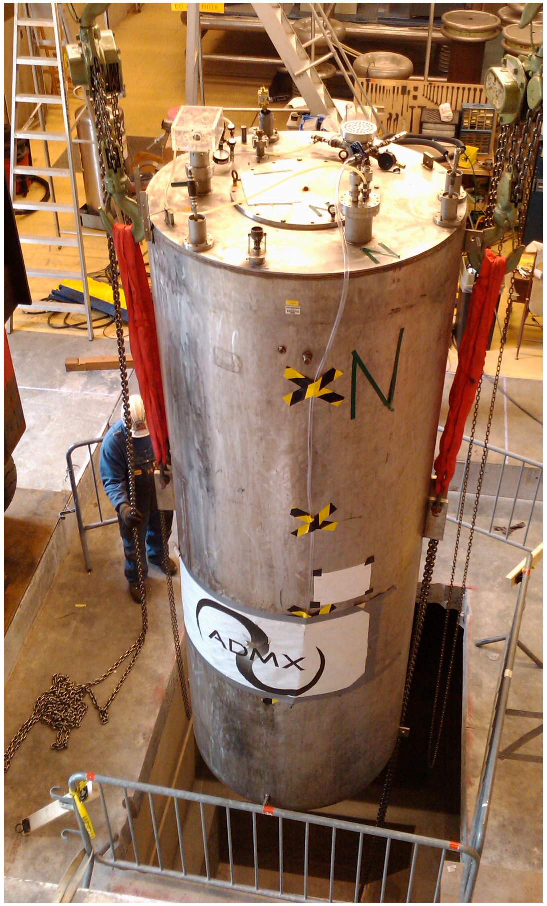
$$\begin{aligned} \epsilon \boldsymbol{\nabla} \cdot \mathbf{E} &= \rho - g_{a\gamma} \mathbf{B}_{\mathrm{e}} \cdot \boldsymbol{\nabla} a \,, \\ \boldsymbol{\nabla} \times \mathbf{H} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma} \mathbf{B}_{\mathrm{e}} \dot{a} \,, \\ \ddot{a} - \boldsymbol{\nabla}^2 a + m_a^2 a &= g_{a\gamma} \mathbf{E} \cdot \mathbf{B}_{\mathrm{e}} \,, \end{aligned}$$

- The upshot is that in an external B-field the axion sources an E-field

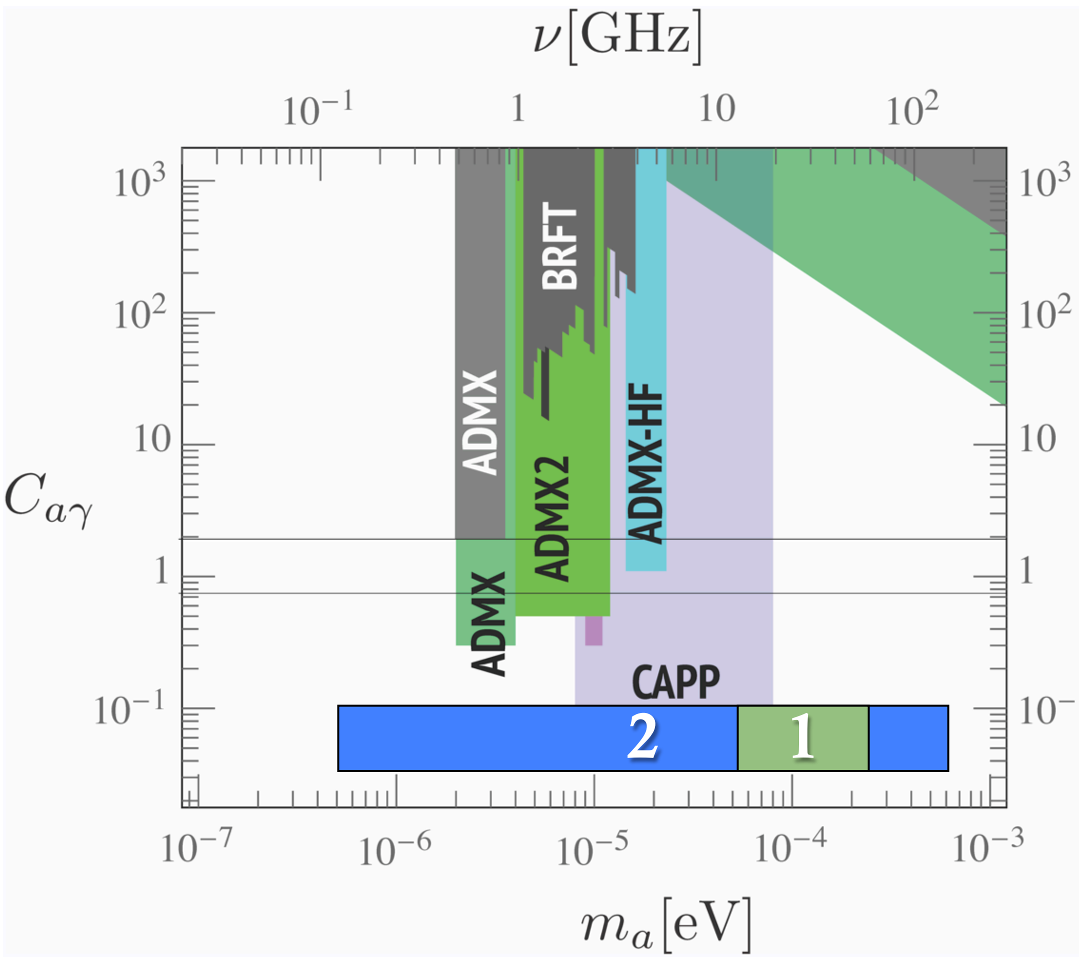
$$\mathbf{E}_a = -\frac{g_{a\gamma} \mathbf{B}_e a_0}{\epsilon} e^{-i m_a t} = 1.3 \times 10^{-12}\ \mathrm{V/m}\ \frac{B_{\mathrm{e}}}{10\ \mathrm{T}}\ \frac{C_{a\gamma} f_{\mathrm{DM}}^{1/2}}{\epsilon} \,.$$

Cavity Haloscopes

- Build a cavity at the same scale as the axion's Compton wavelength – resonant enhancement
- Hugely increases signal, but only in a very narrow range
- Power and bandwidth inversely related
- Requires large volume – hard to do for large axions masses (small wavelengths)



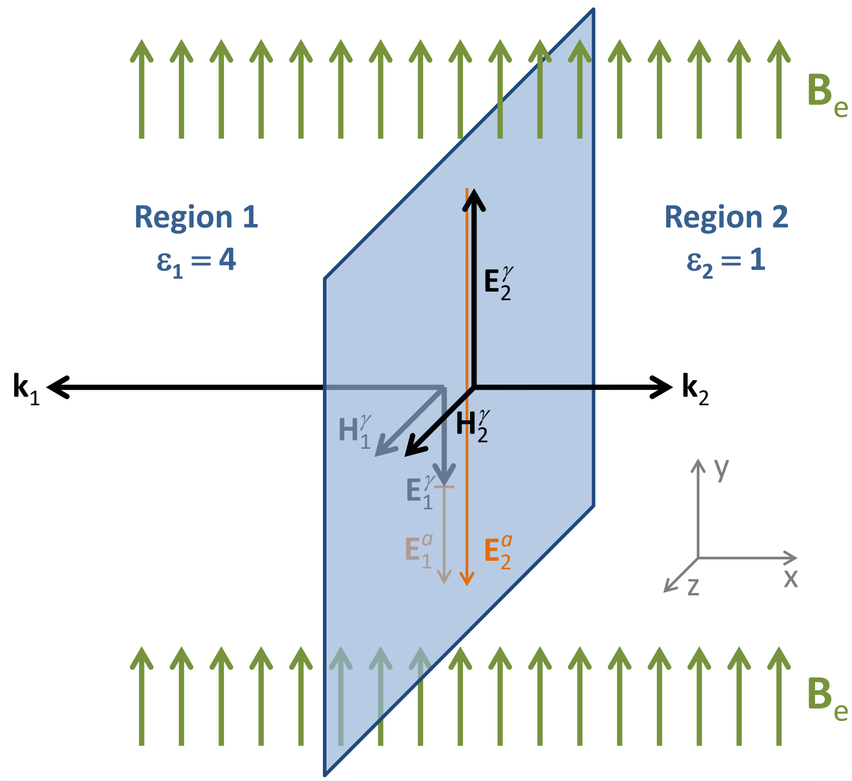
Cavity Haloscopes



Single interface
(fun with boundary conditions)

- E_a depends on the medium, so changing media causes a discontinuity.
- EM won't tolerate discontinuities in the parallel E and H fields
- Regular EM waves are emitted to compensate

$$\mathbf{E}_a(t) = -\frac{g_{a\gamma}\mathbf{B}_\mathrm{e}}{\epsilon}\, a(t)$$



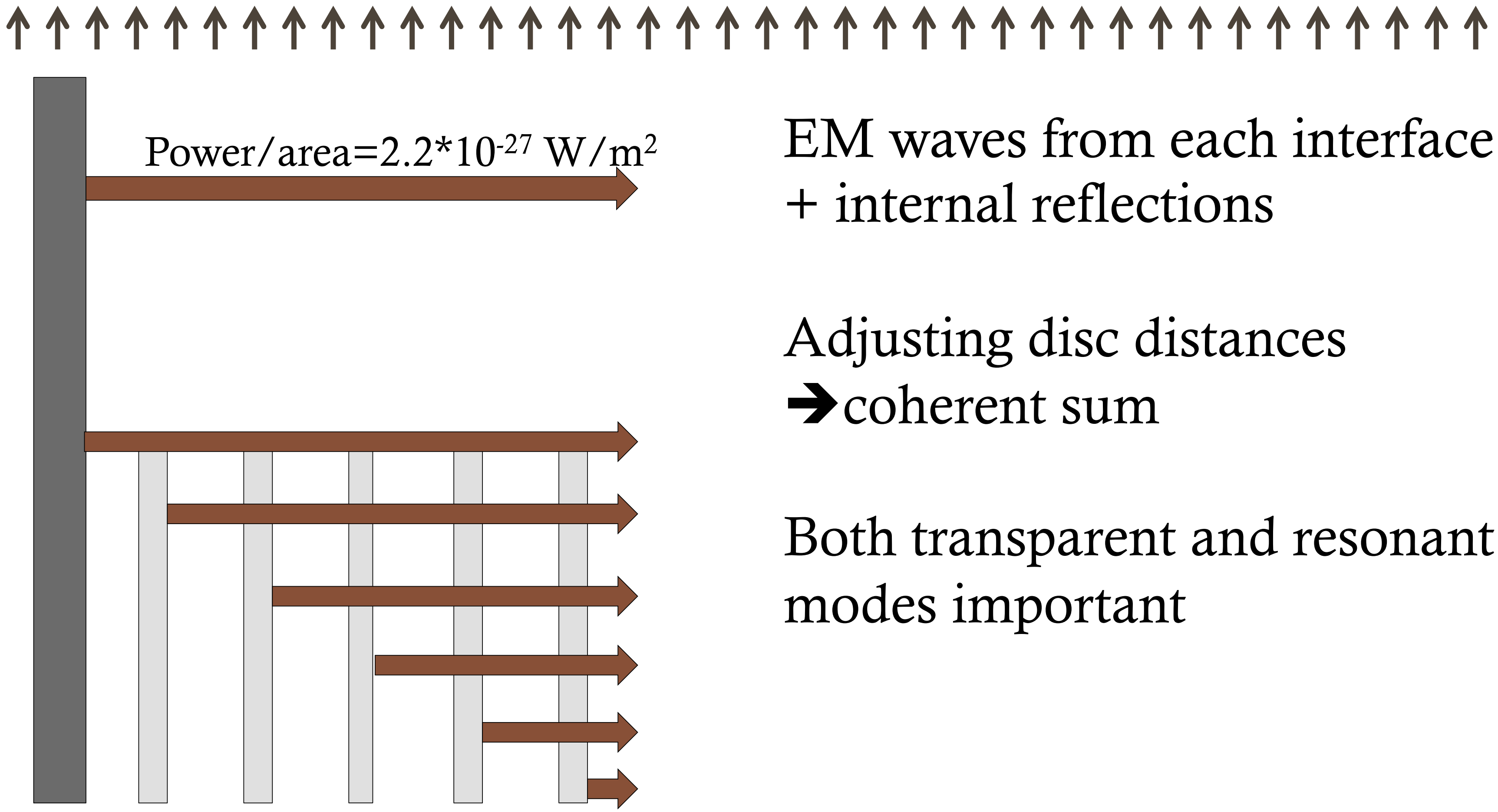
Single interface
(fun with boundary conditions)

- The ideal single interface is a mirror (dish antenna), which provides

$$\frac{P^\gamma}{A} = (\mathbf{E}_2^\gamma \times \mathbf{H}_2^\gamma)_x = \frac{E_0^2}{2} = 2.2 \times 10^{-27} \frac{W}{\mathrm{m}^2} \left(\frac{|\mathbf{B}_e|}{10\,\mathrm{T}} \right)^2 C_{a\gamma}^2 f_{\mathrm{DM}},$$

- 4-5 orders of magnitude too small for the QCD axion to be detected with modern technology
- Need more power!

Multiple layers: dielectric haloscope

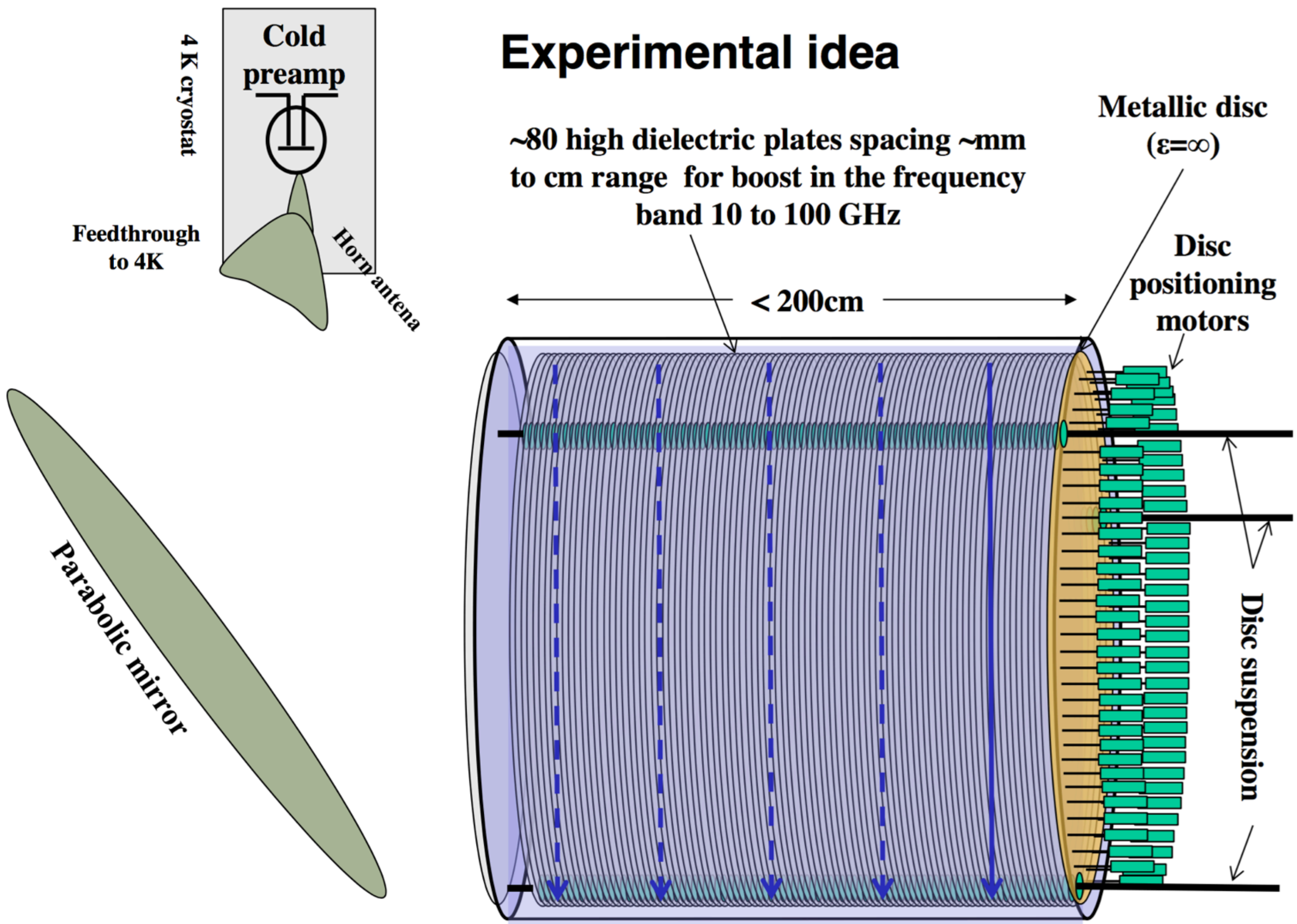


EM waves from each interface + internal reflections

Adjusting disc distances ➔coherent sum

Both transparent and resonant modes important

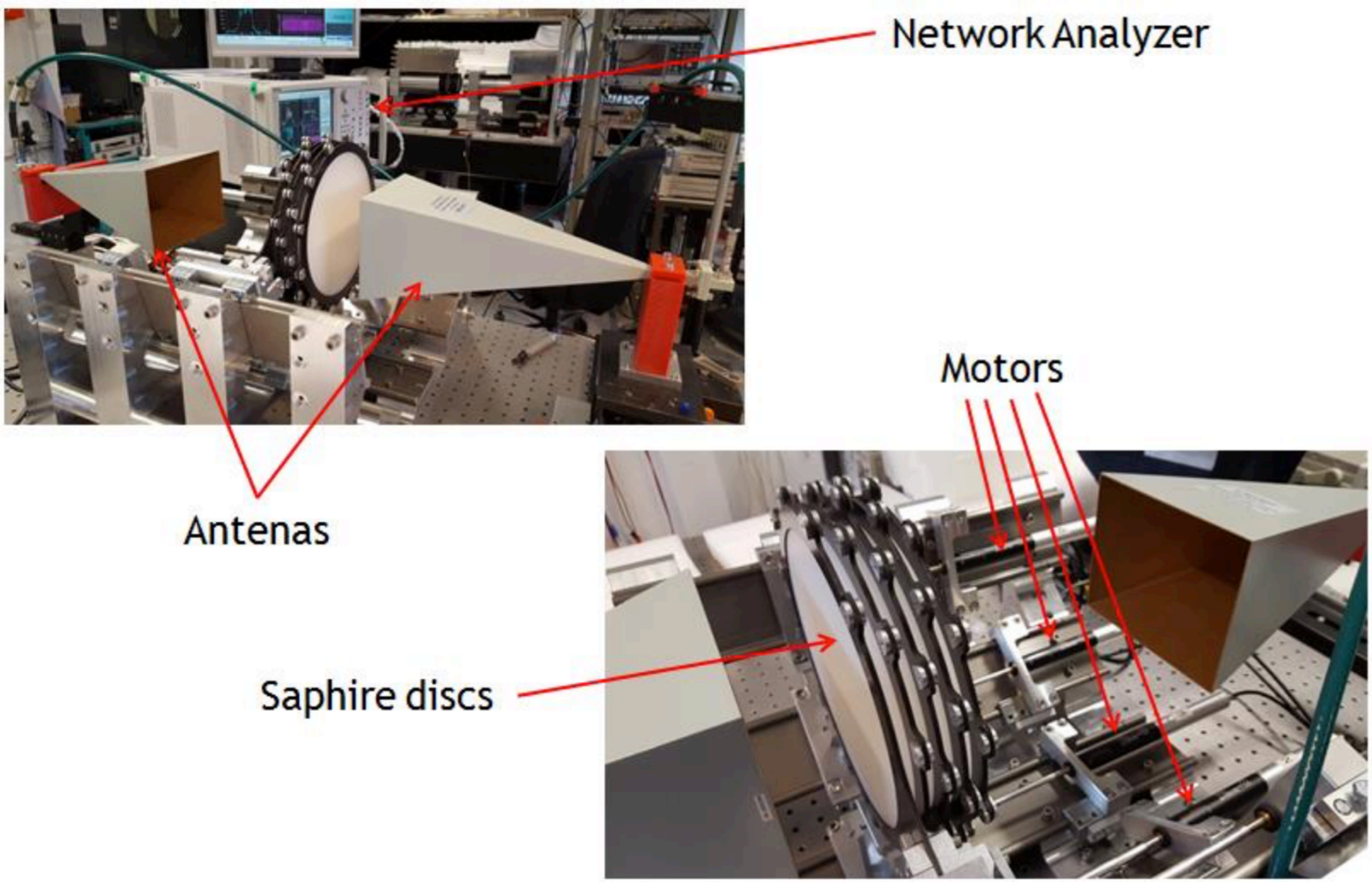
Towards an experiment: MADMAX



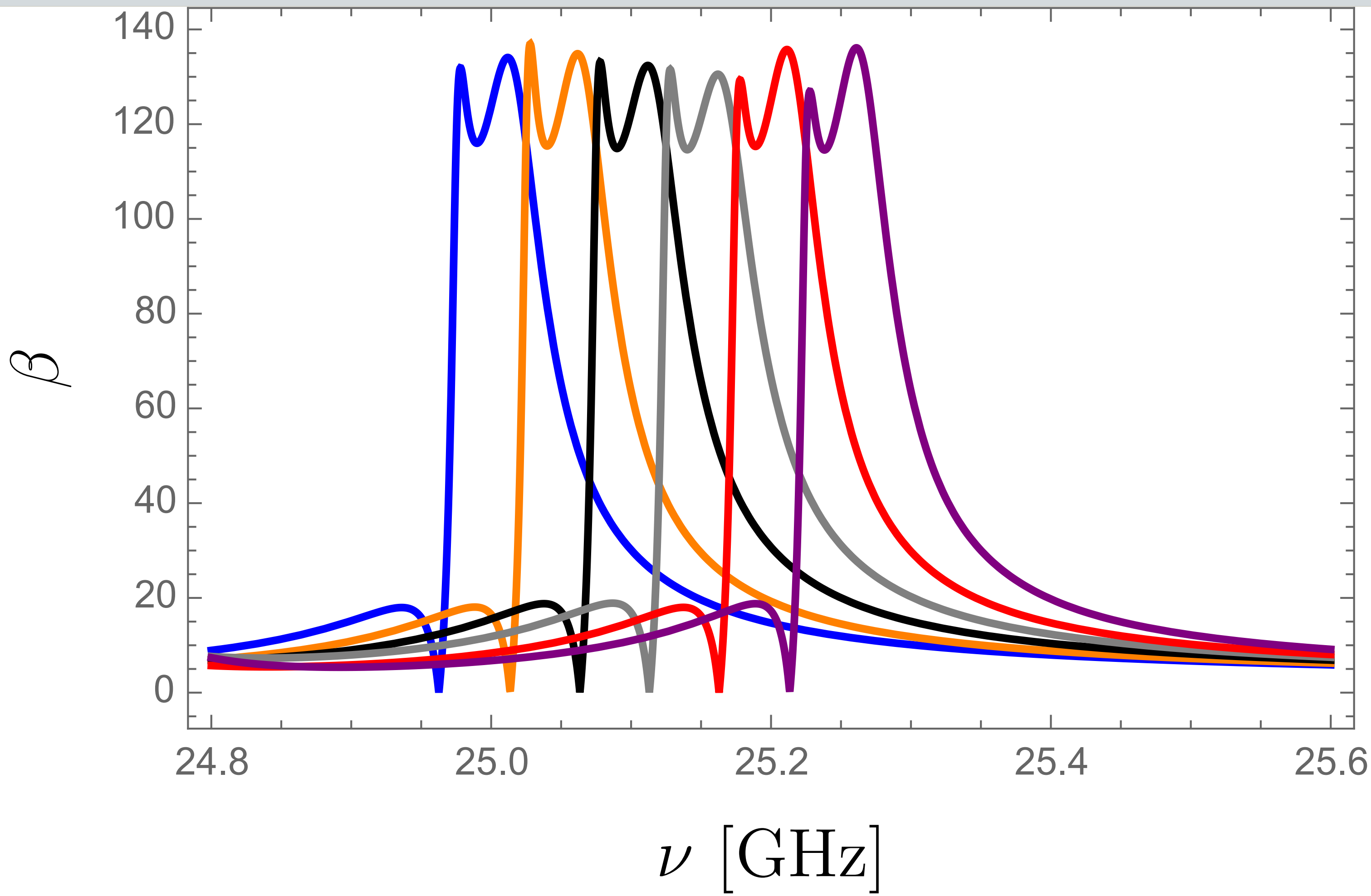
Conclusions

- Axions are a highly well motivated dark matter candidate with a unique phenomenology
- Dielectric haloscopes are an exciting new method for searching for axion dark matter
- They have the potential to detect axions produced in the predictive and currently unexplored post inflationary scenario for the first time

Prototype setup



Example 20 disk solutions

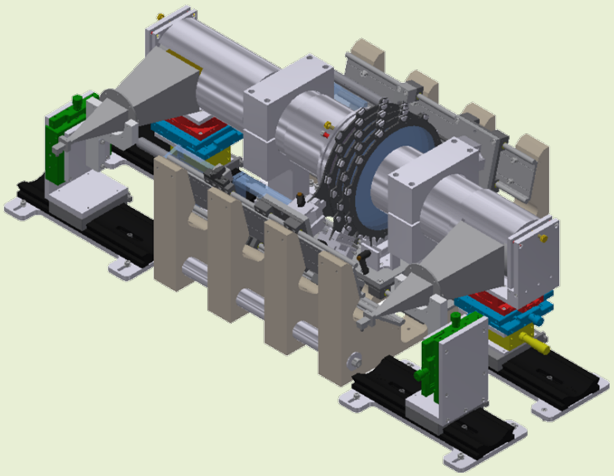


Length scales

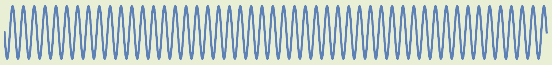
$m_a = 100\ \mu\text{eV}$

$\nu_a = 25\ \text{GHz}$

Axion de Broglie wave length



Apparatus in B-field



Photon wave length