Dielectric haloscopes: a new way to search for axion DM

Alex Millar on behalf of the new MADMAX Collaboration

SFB 1258 Neutrinos Dark Matter Messengers

A. Caldwell et al arXiv:1611.05865
A. Millar et al arXiv:1612.07057
A. Ioannisian et al arXiv:1707.00701
A. Millar et al arXiv:1707.04266

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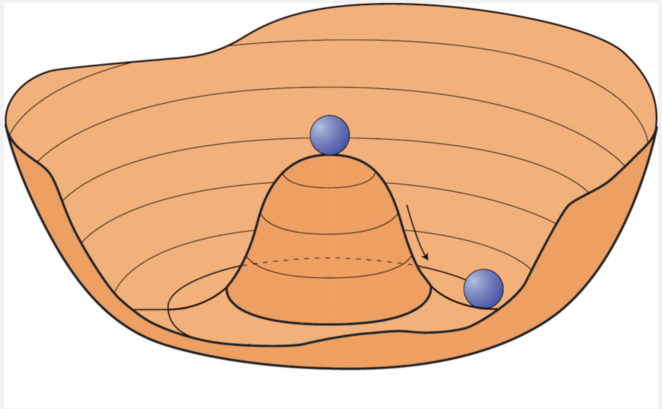
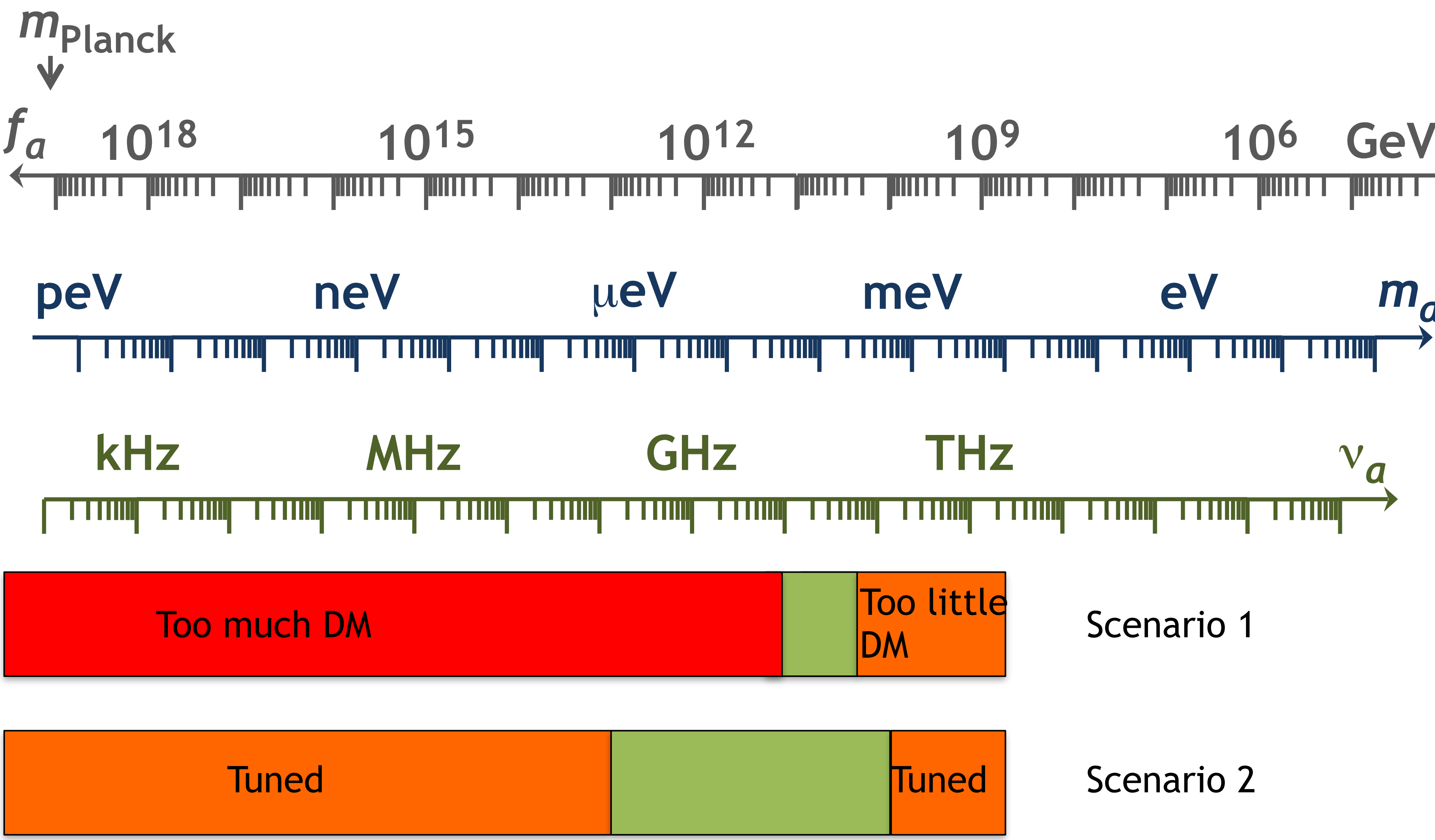
Axion dark matter

- Solution to the Strong CP problem: turn the CP violating phase into a dynamical field
- Need a new anomalous U(1) chiral symmetry (Peccei-Quinn), which is broken at high temperature ~f_a (around 10^{12} GeV)
- Coherent production mechanisms for CDM

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




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
Tuned
Scenario 2

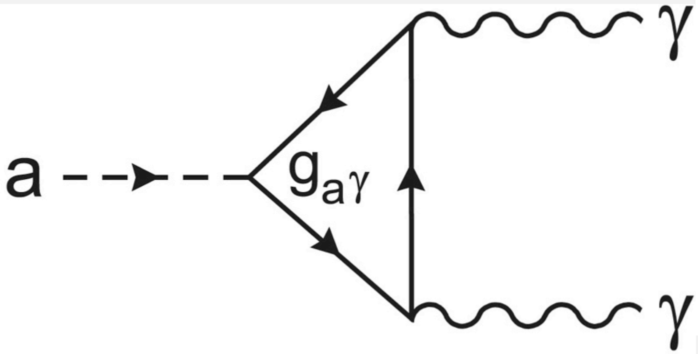
Alex Millar

Axion-electrodynamics

- Axions and ALPs interact with photons through an anomaly term

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

- 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

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

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

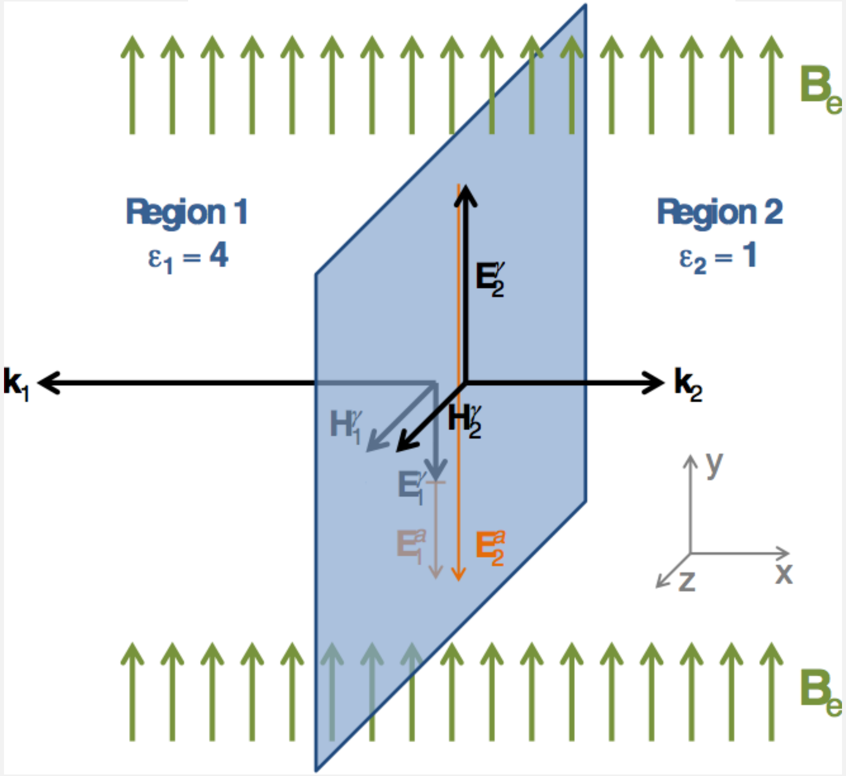
$$\mathbf{E}_a = -\frac{g_{a\gamma} \mathbf{B}_e a_0}{\epsilon} e^{-i m_a t} = 1.3 \times 10^{-12}\ \mathrm{V/m}\ \frac{B_{\rm e}}{10\ \mathrm{T}}\ \frac{C_{a\gamma} f_{\rm DM}^{1/2}}{\epsilon} \,.$$

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

$$\mathbf{E}_a(t) = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a(t)$$



Single interface

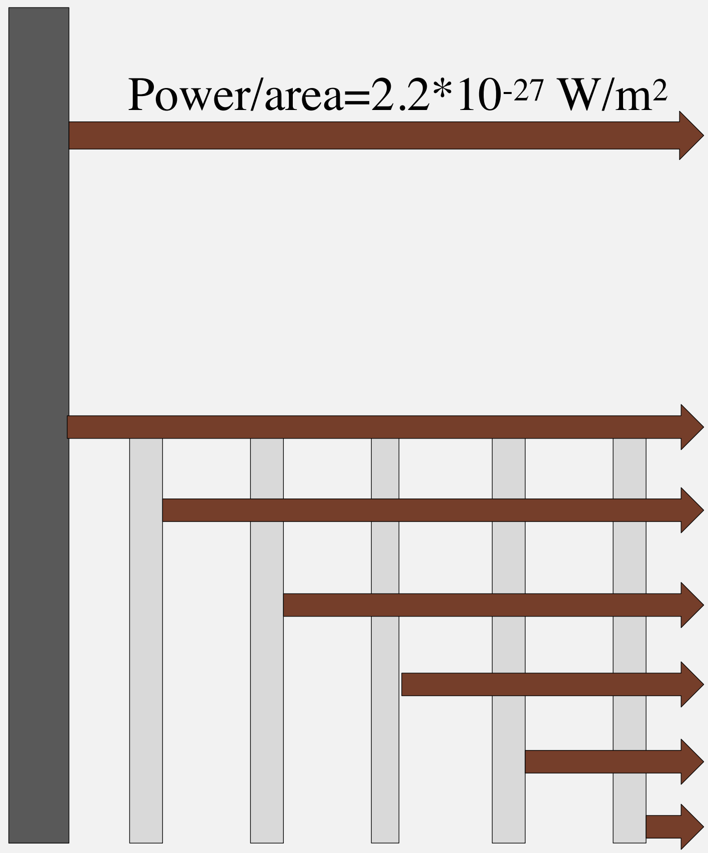
(fun with boundary conditions)

- The ideal single interface is a mirror, 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

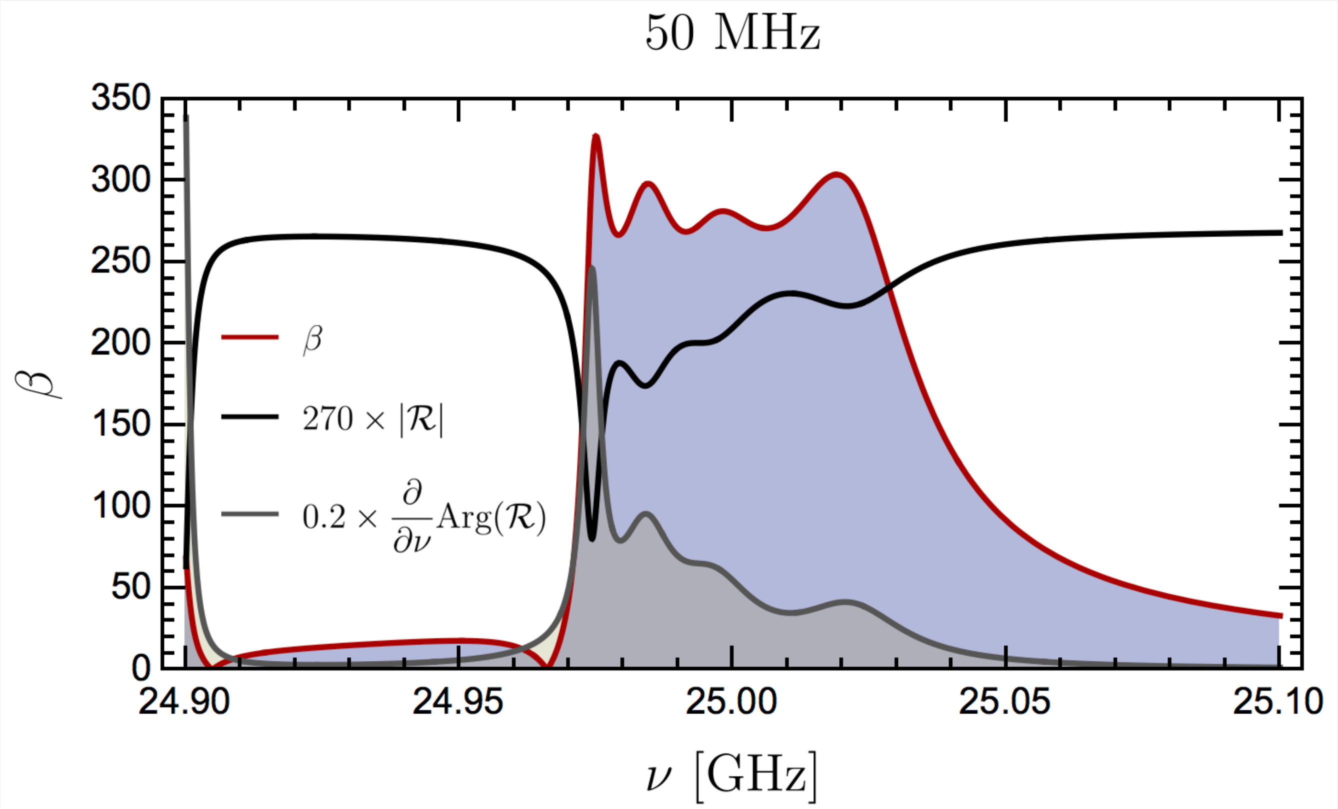
Both transparent and resonant modes important

Define boost factor β, gain in E-field over that of a mirror

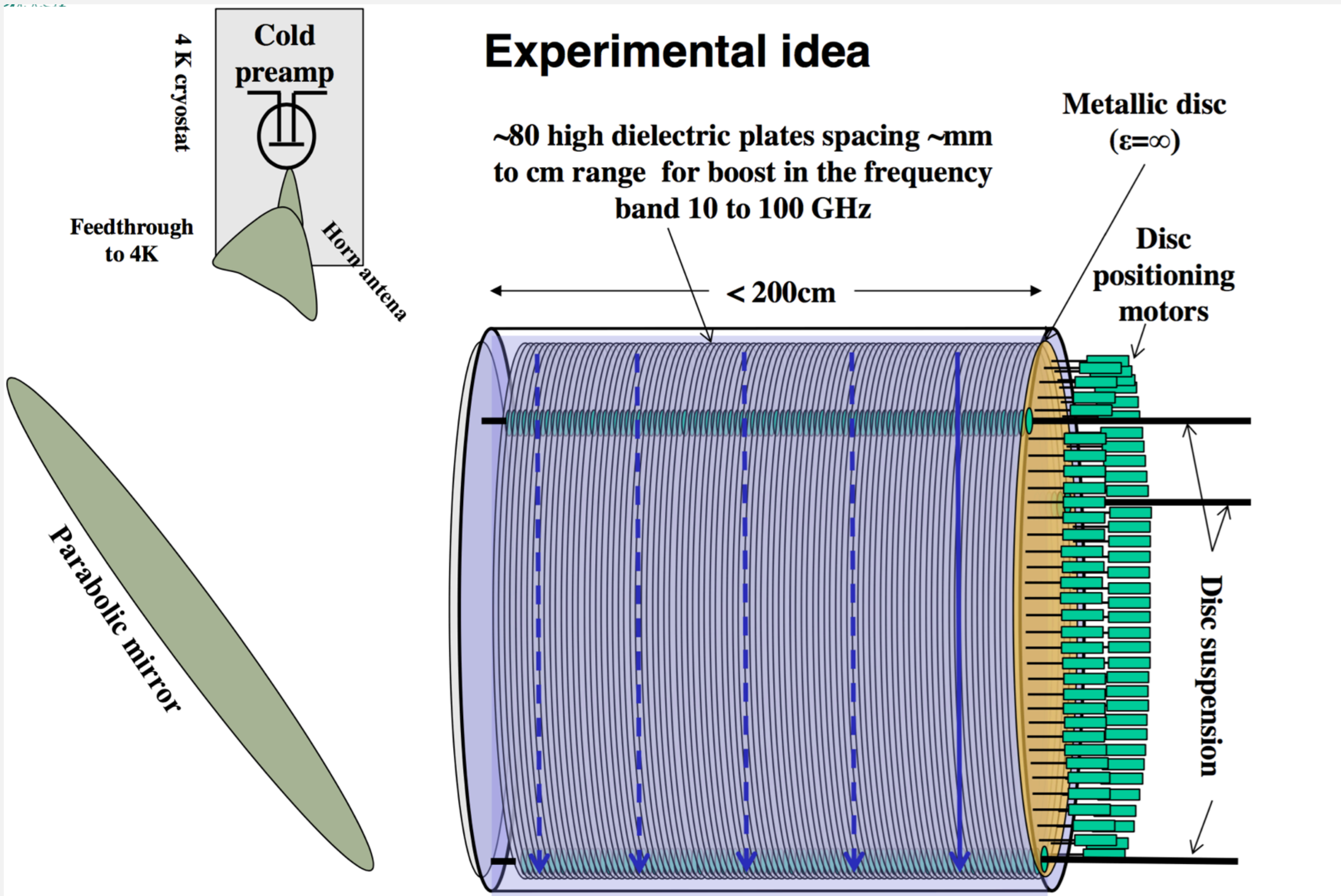
Theoretical formalisms

- **Transfer matrices (classical calculation)**
- All the action is at the interfaces
- Combination of axion and photon field satisfies axion-Maxwell equations: axion-photon wave function
- Solving for the classical E-field everywhere
- **Overlap integral (quantum field calculation)**
- All space is involved
- Axion and photons wave functions treated separately: photon wave function satisfies regular Maxwell equations
- Calculating transition probability

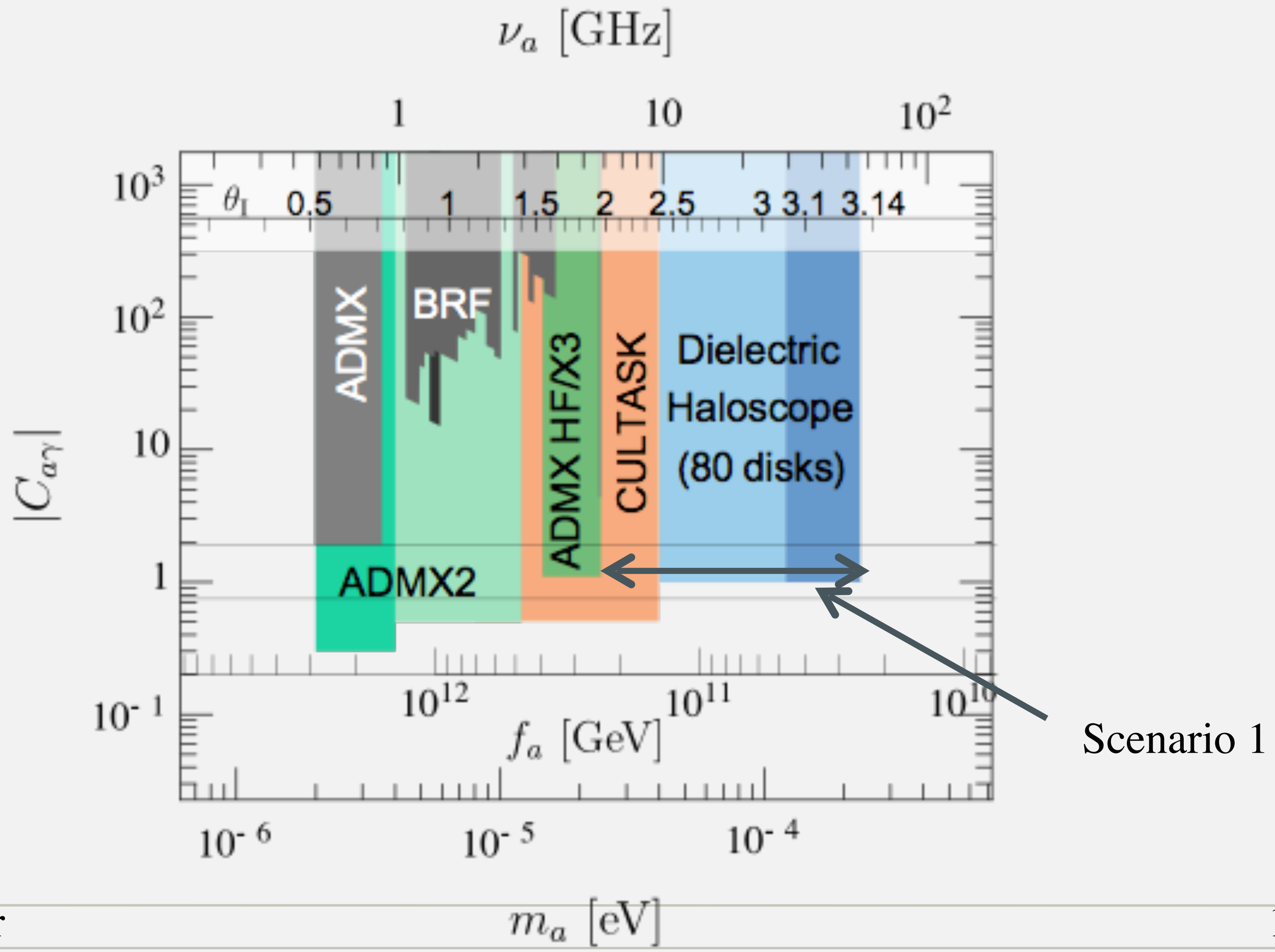
Example solution: 80 disks



Towards an experiment: MADMAX

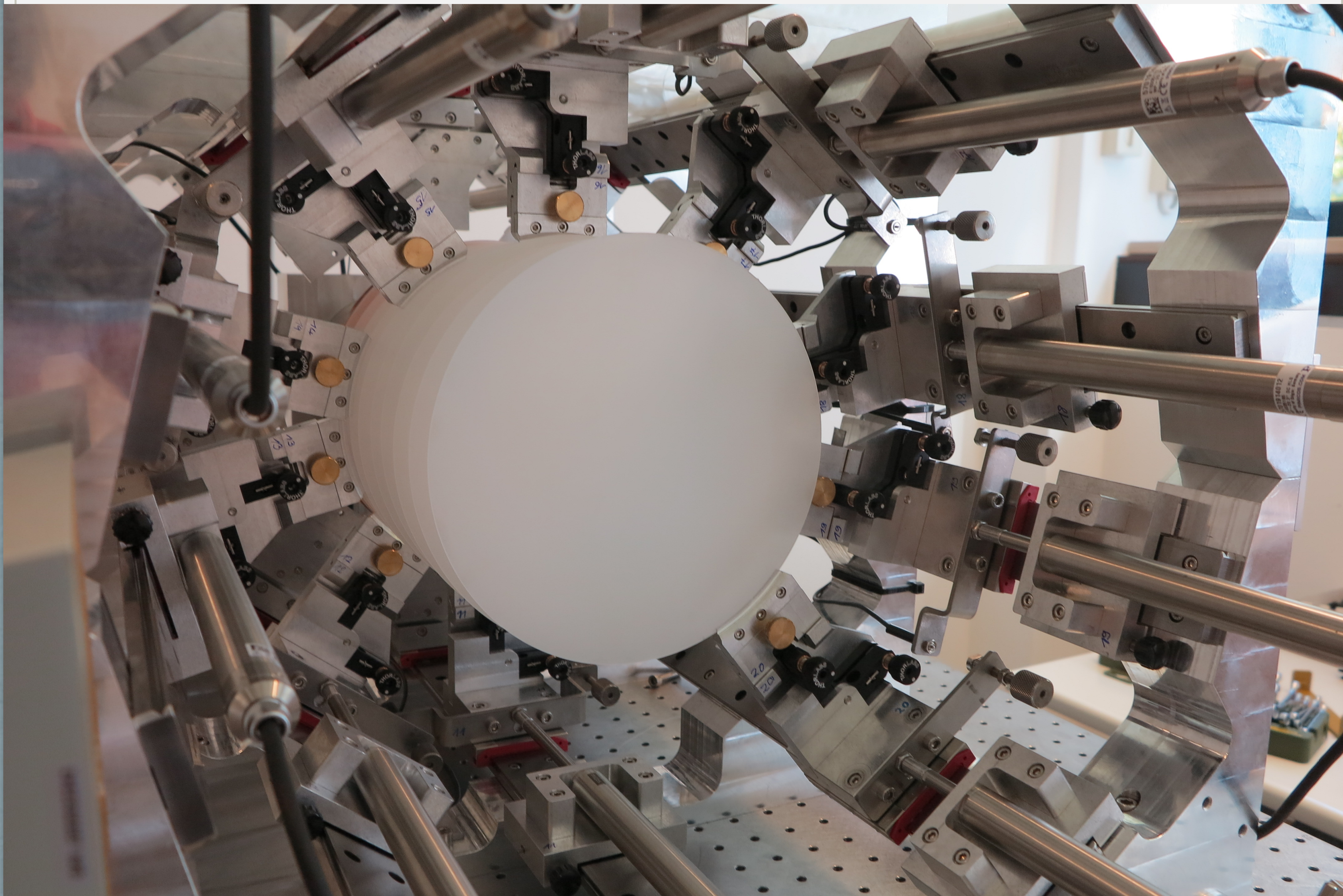


Discovery potential



MADMAX Collaboration

20 Disk Prototype

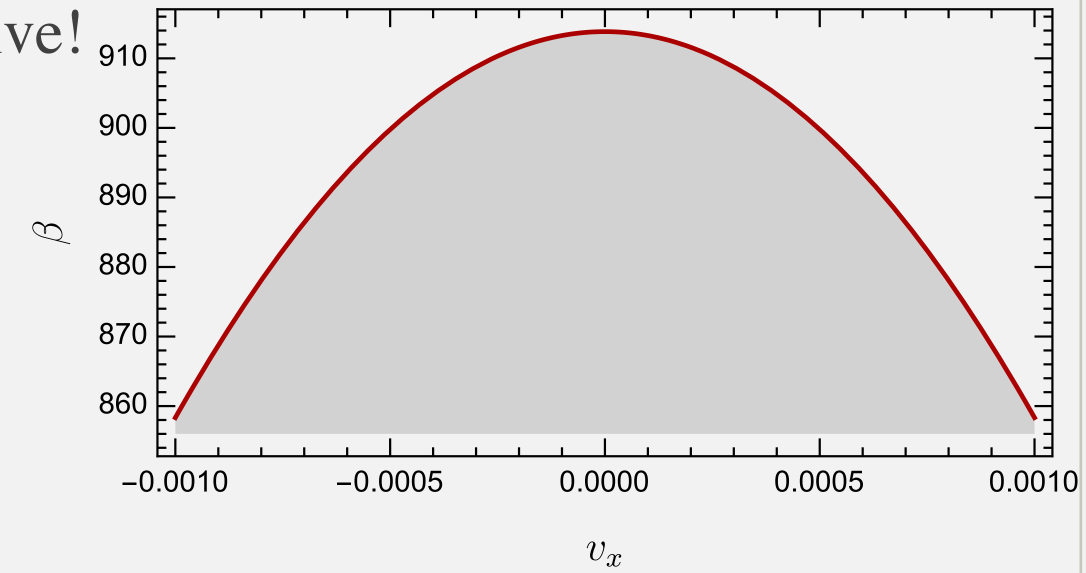


Conclusions

- Axions are a highly well motivated dark matter candidate with a unique phenomenology
- Dielectric haloscopes are an exciting new method for searching for high mass axion dark matter
- The new MADMAX collaboration is pushing forward to gain a full understanding of the experimental requirements
- Didn’t have time for: dielectric haloscopes have excellent potential for directional sensitivity

Directional sensitivity

- If the device is larger than ~20% of the axion de Broglie wavelength, the change of the axion's phase becomes important
- Directionally sensitive!



Transfer matrix formalism

- Encode every interface and distance as a matrix
- Add in a new source term at each interface to account for the axions

$$\begin{pmatrix} R \\ L \end{pmatrix}_m = \mathsf{T} \begin{pmatrix} R \\ L \end{pmatrix}_0 + E_0 \mathsf{M} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\mathsf{G}_r = \frac{1}{2n_{r+1}} \begin{pmatrix} n_{r+1}+n_r & n_{r+1}-n_r \\ n_{r+1}-n_r & n_{r+1}+n_r \end{pmatrix}$$

$$\mathsf{P}_r = \begin{pmatrix} e^{+i\delta_r} & 0 \\ 0 & e^{-i\delta_r} \end{pmatrix},$$

$$\mathsf{S}_r = \frac{A_{r+1} - A_r}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

$$\mathsf{M} = \sum_{s=1}^{m} \mathsf{T}_s^m \mathsf{S}_{s-1}.$$

$$\mathsf{T}_b^a = \mathsf{G}_{a-1}\mathsf{P}_{a-1}\mathsf{G}_{a-2}\mathsf{P}_{a-2} \ldots \mathsf{G}_{b+1}\mathsf{P}_{b+1}\mathsf{G}_b\mathsf{P}_b$$

Quantum calculation

- Need to calculate the probability of a single axion converting to a photon
- Lowest order QFT

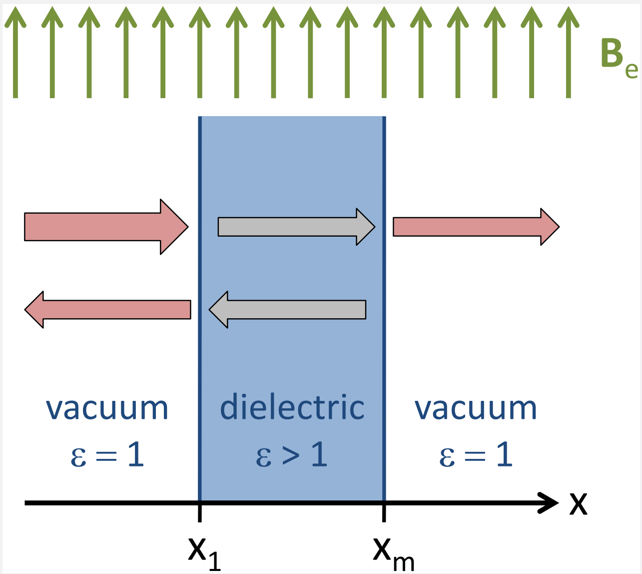
$$\Gamma_{a\to\gamma} = 2\pi \sum_{\mathbf{k}} |\mathcal{M}|^2 \, \delta(\omega_a - \omega_{\mathbf{k}}) \, .$$

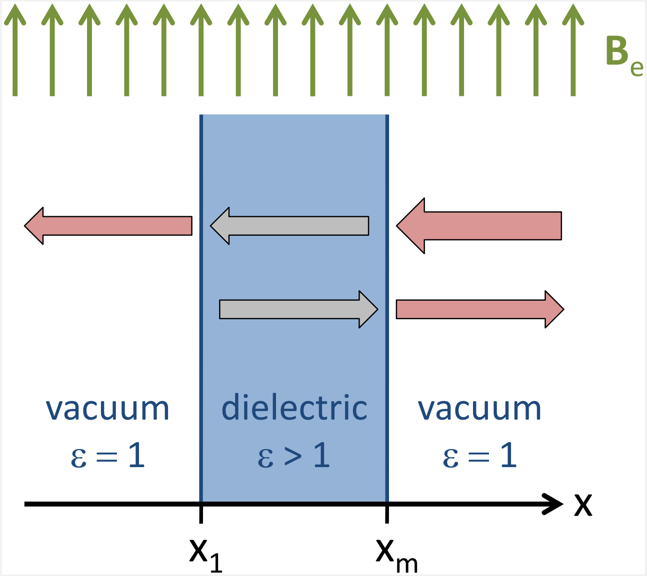
- Matrix element is given by the overlap of the axion and photon wave functions

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

Overlap integral formalism

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





Overlap integral formalism

- The E-field only encodes boundary conditions: in general it isn't excited