Axions: pushing towards the high mass range

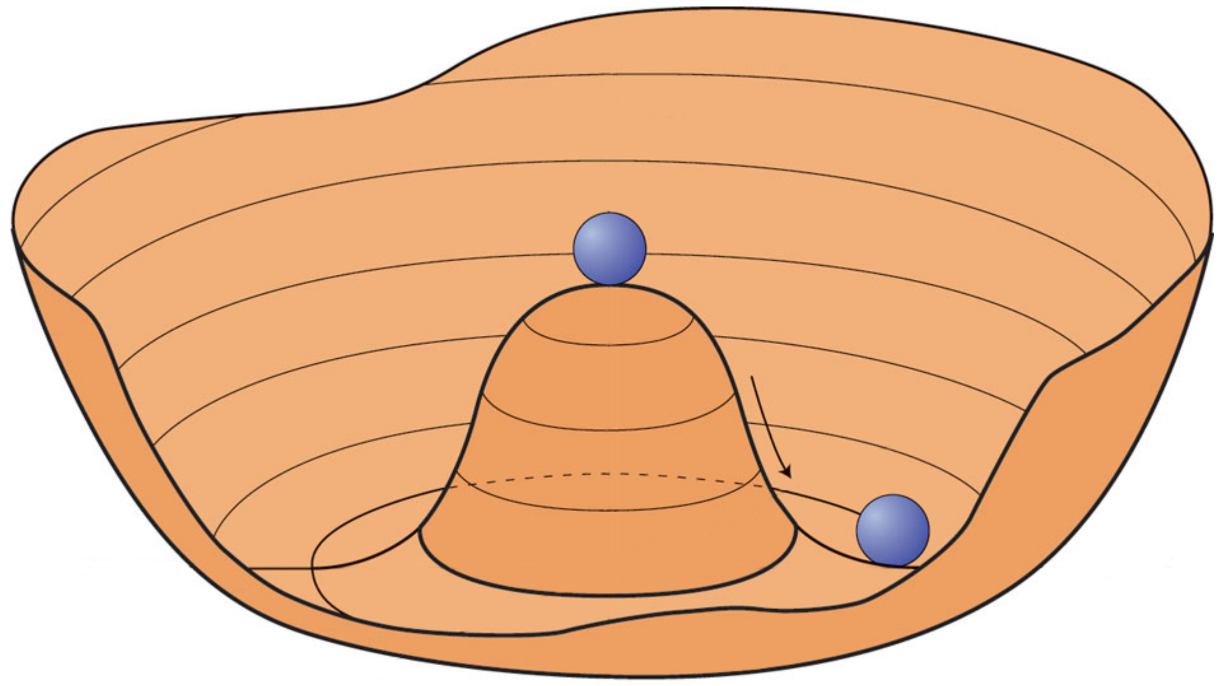
Fermilab

Alex Millar

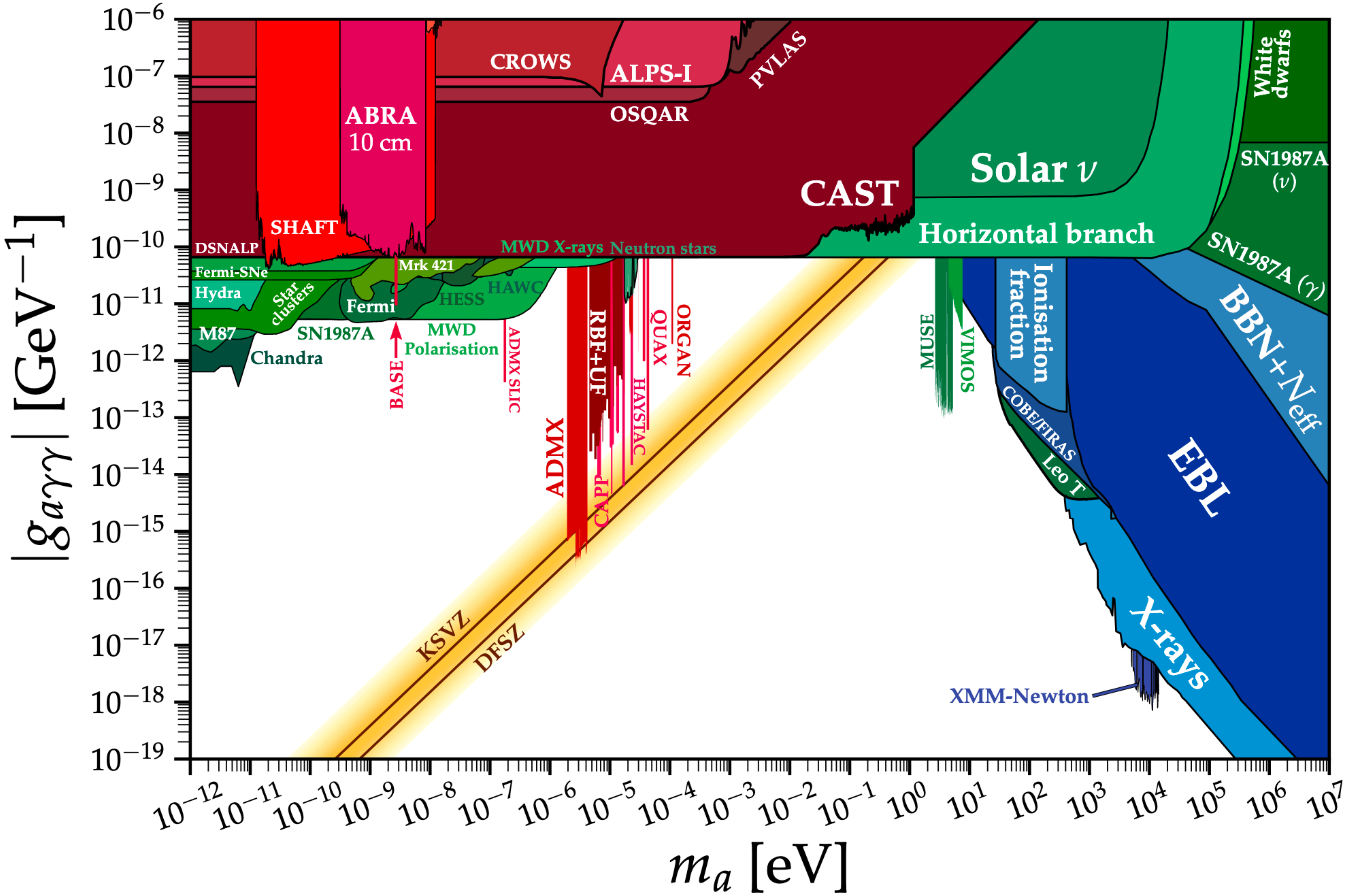
Axions

- Introduced to solve the Strong CP problem
- New light pseudoscalar
- Can be non-thermally produced as a good dark matter candidate
- Prototypical light dark matter example (also hidden photons, ALPs etc...)

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



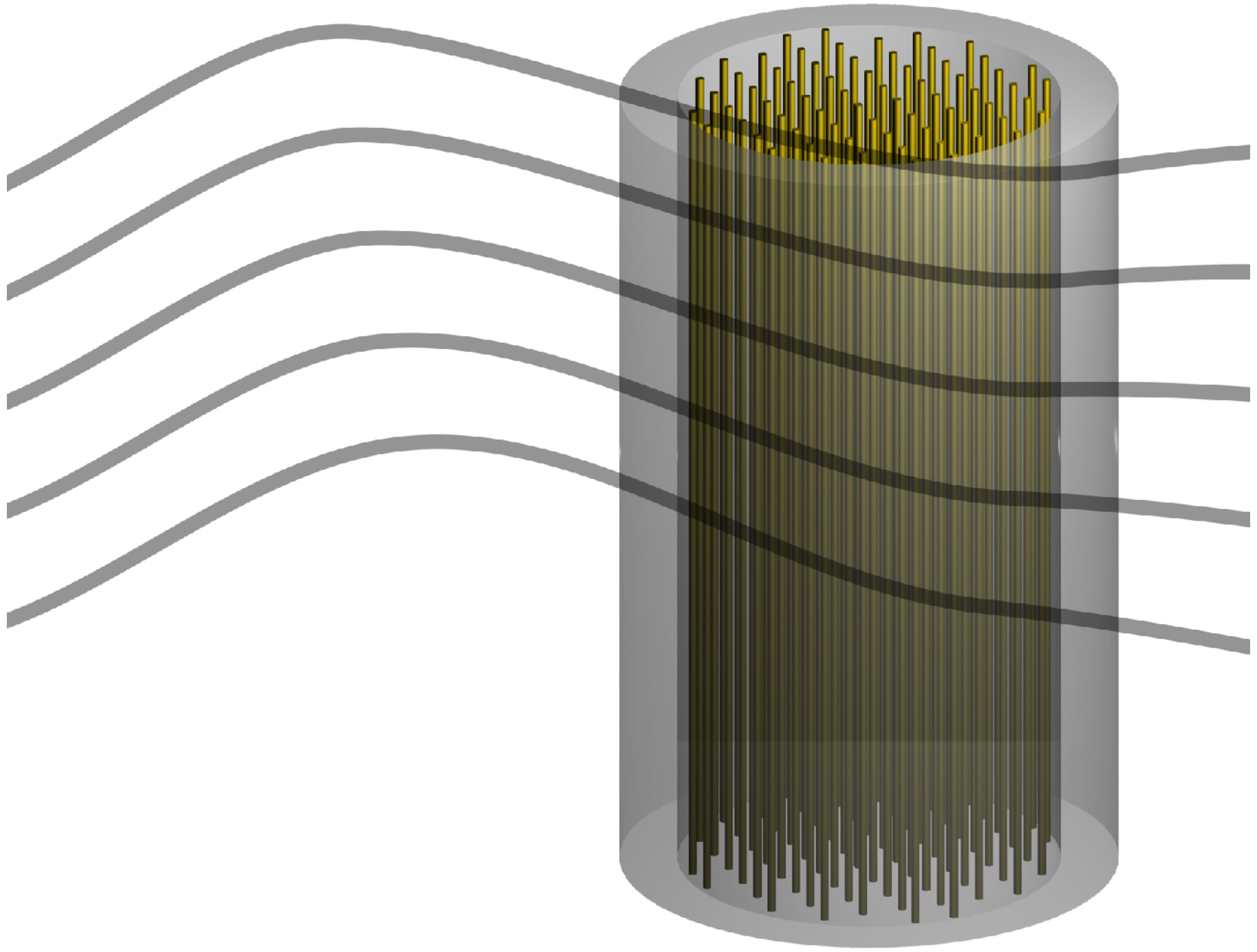
Parameter Space



https://github.com/cajohare

How do you find a wave?

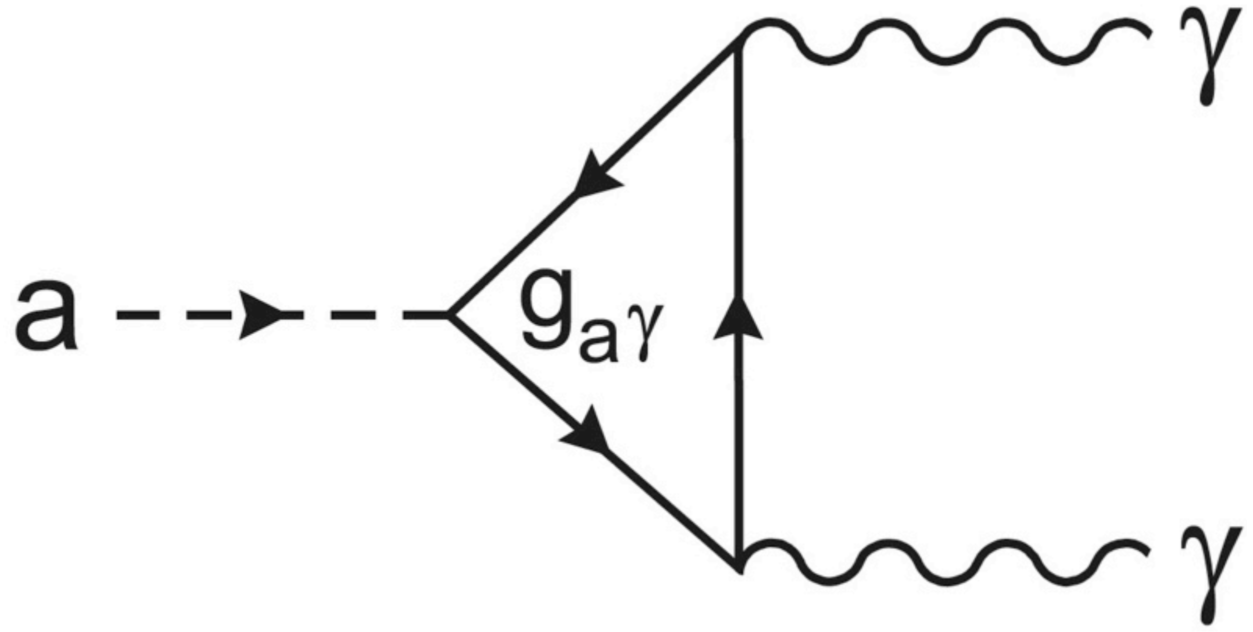
- Can’t just look for scatterings
- Exploit the coherence of the field to increase the signal
- Analogue: finding the right radio station
- Currently in an experimental boom: lots of new ideas and experiments



Axion Electrodynamics

- Axions and ALPs interact with photons through an anomaly term
- This coupling is tiny, but still important
- Mixes with the photon in an external magnetic field

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



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

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

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

Axion-Photon Conversion

- Inhomogeneous Maxwell equations get a new "current"-like term

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

- Strong external B-field creates a small E-field

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

Axion-Photon Conversion

- Lowest order QFT gives Fermi's Golden Rule

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

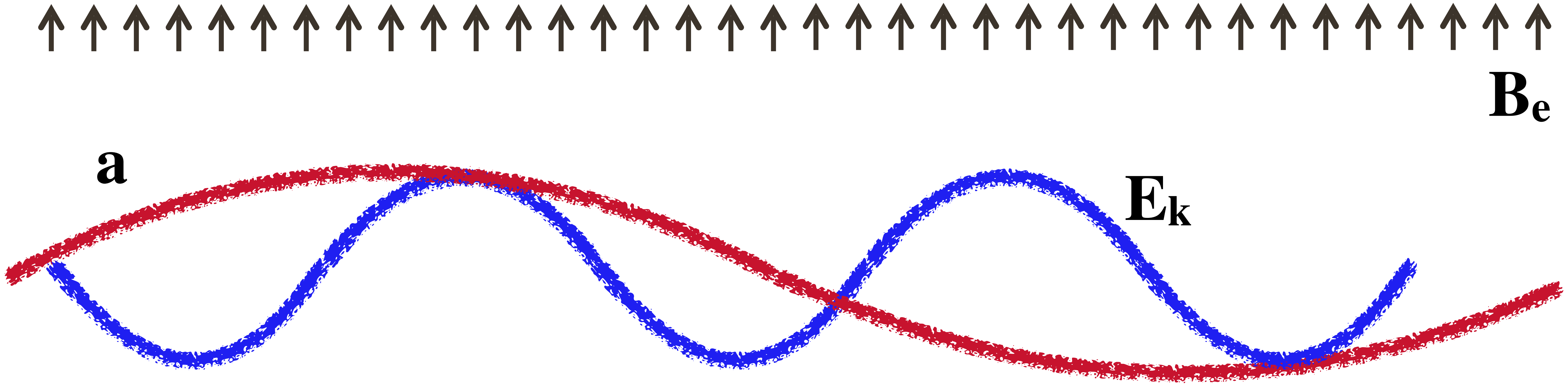
- Matrix element given by the overlap of the wave functions (arXiv:1707.00701)

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

- Experimental goal: how do we make this non-zero?

Axion-Photon Conversion

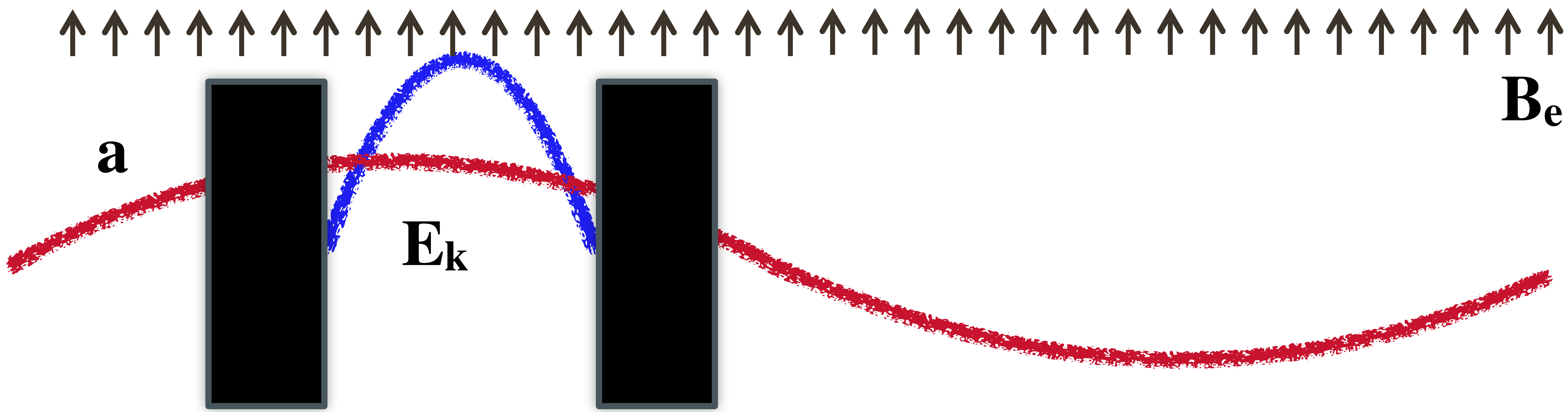
- In vacuum and constant B-field this vanishes



- Modify the free-photon wave function!

Cavity Haloscopes

- Inside a cavity the photon wavefunction matches the cavity modes



- Normalisation given by the quality factor

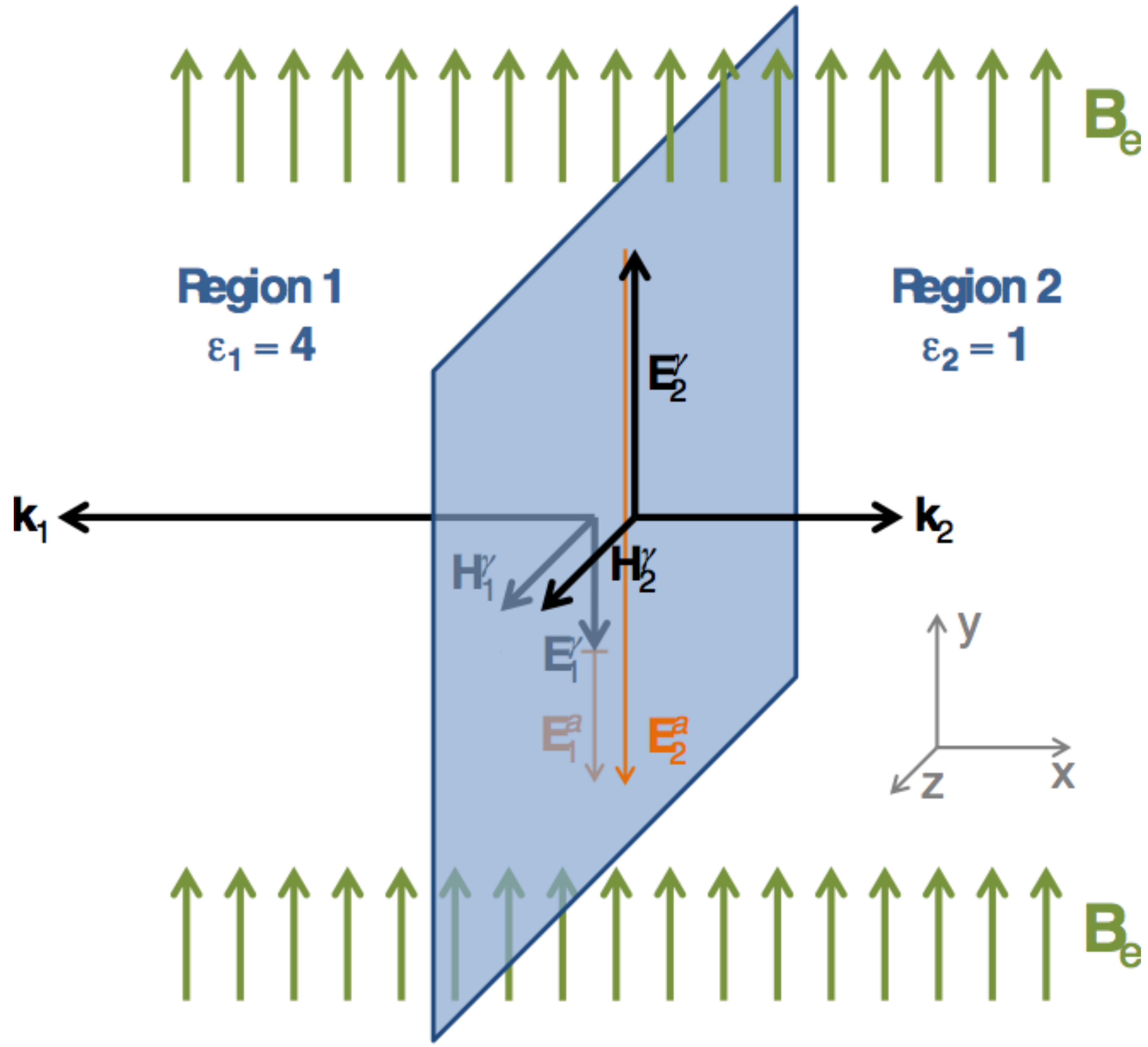
Beyond Cavities

- Dish Antennas (BREAD, BRASS)
- Dielectric haloscopes (MADMAX, MuDHI, LAMPOST)
- Plasma haloscopes (ALPHA)
- Resonators with LC circuits (ABRACADABRA, DM Radio, SHAFT, WISPLC)
- NMR (CASPER)
- 5th force (ARIADNE, QUAX)
- Atomic transitions (AXIOMA)
- Topological insulators (TOORAD)
- …

Dish Antenna

- E-field depends on medium!
- Breaks translation invariance with a mirror (arXiv:1212.2970)
- No resonance!
- Completely broadband response

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

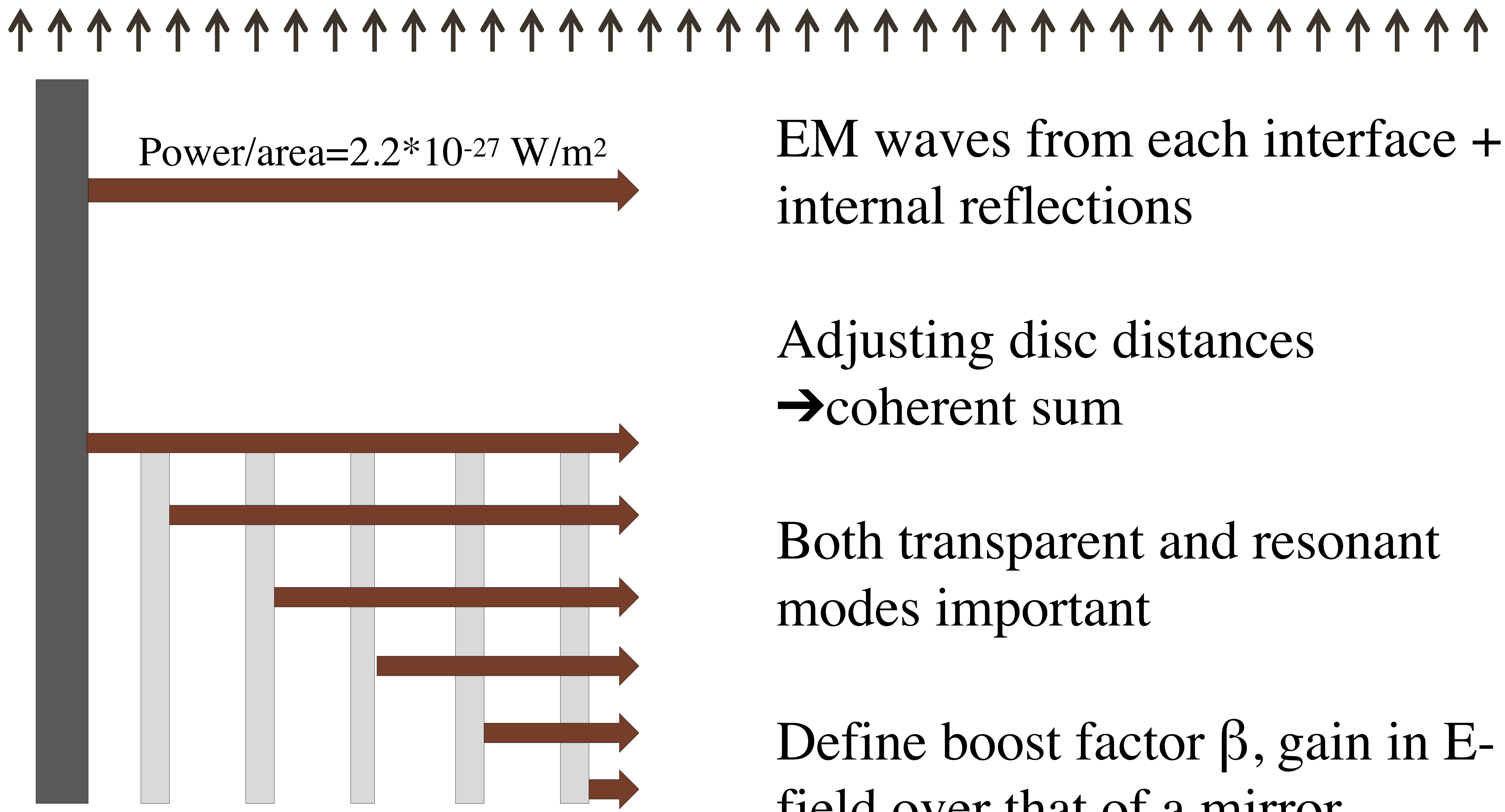


Dish Antenna

- Focus a large area onto a detector to increase S/N
- Experiments like FUNK, Tokyo, SHUKET, BREAD, BRASS...
- Tends to be best for HP

arXiv:2003.13144

Multiple Layers: Dielectric Haloscope



EM waves from each interface + internal reflections

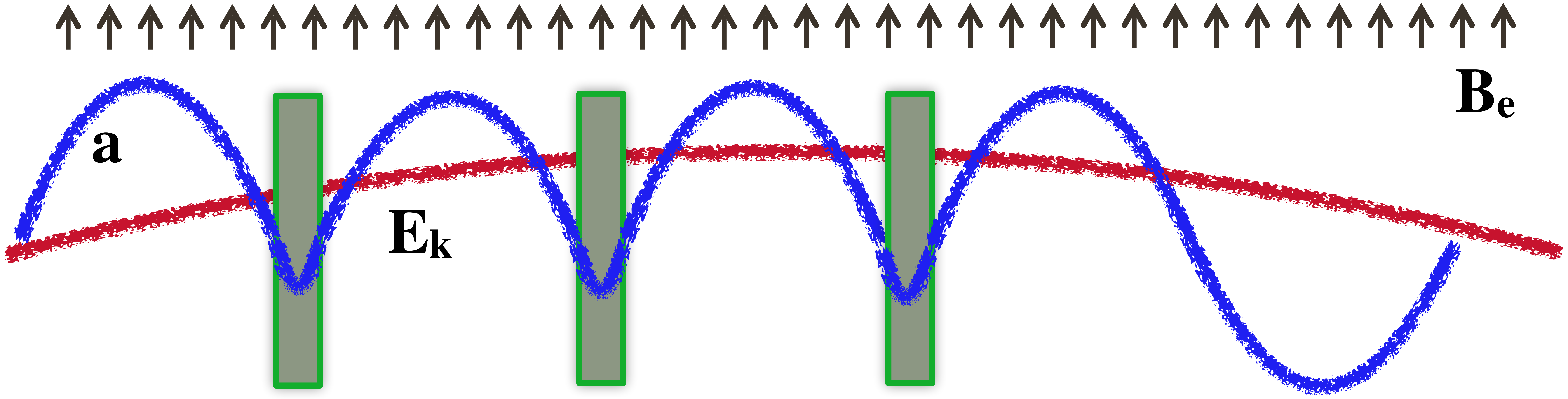
Adjusting disc distances ➔coherent sum

Both transparent and resonant modes important

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

Dielectric Haloscopes

- Two different pictures: interfaces and volumes

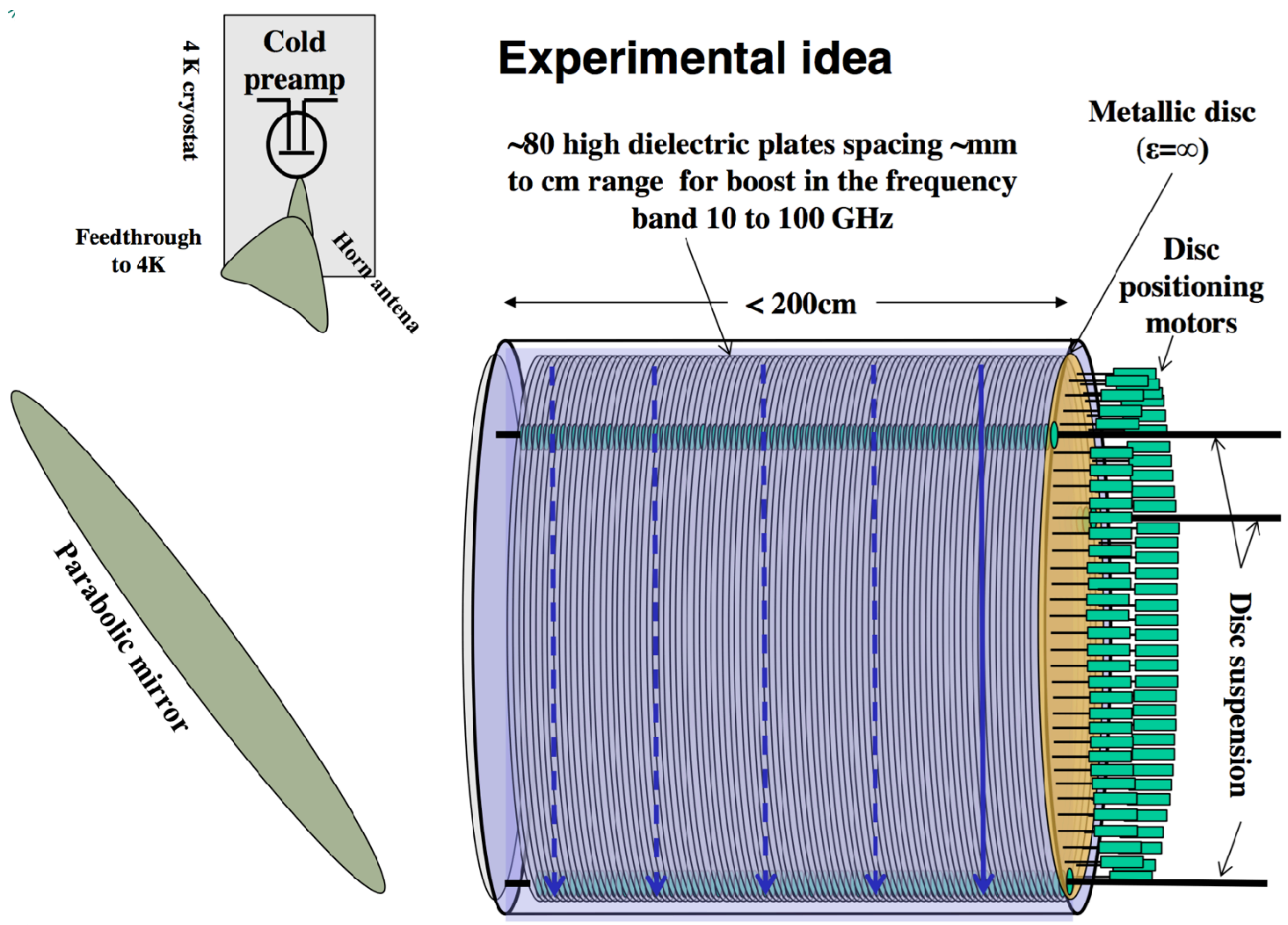


- Shape the wavefunction to get a non-zero overlap (arXiv:1612.07057, arXiv:1707.00701)

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

Dielectric Haloscopes

- Dish antenna on steroids (arXiv:1611.05865)
- Tune frequencies by controlling disk spacings
- Lots of freedom over frequency response!
- Very large volumes
- Being pursued by MADMAX, MuDHI and LAMPOST

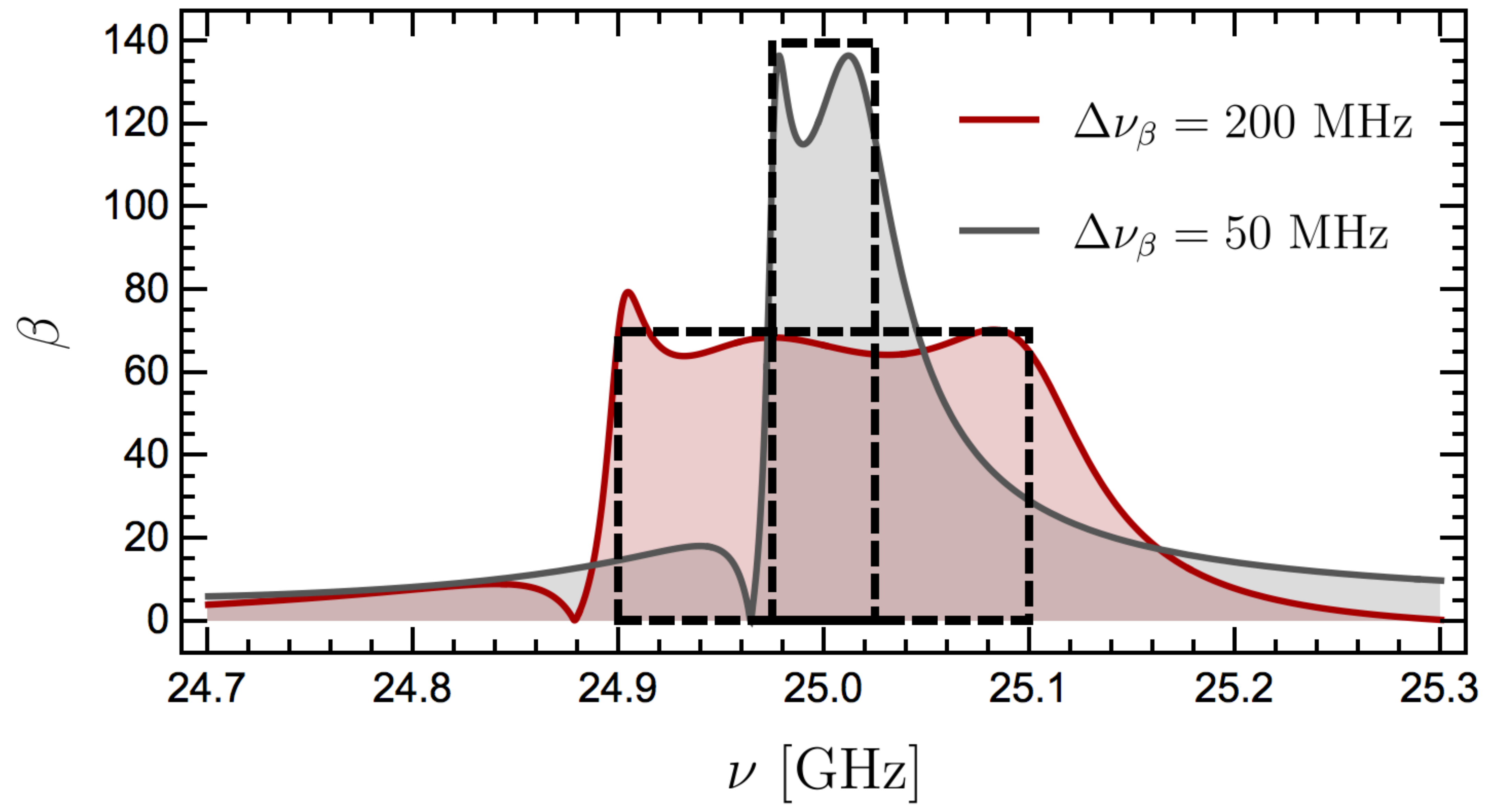


Area Law

- How much control do you have?

$$\int \beta^2 d\nu \propto N$$

- Turns out to be a limited case of a general feature of haloscopes (arXiv:1912.11467)



Area Law

Proof of the "area law"

We consider a haloscope consisting of N identical dielectric disks which are arranged with vacuum gaps of arbitrary width d_j with $j = 1, \ldots, N-1$. The thickness of the disk is d_ϵ. The haloscope is described by an N-dimensional vector of phase depths $\boldsymbol{\delta} = (\delta_1, \ldots, \delta_N)$, where $\delta_j = d_j\omega_0$ for $j = 1, \ldots, N-1$ and $\delta_N = nd_\epsilon\omega_0$, i.e., we use the dielectric disk properties as the Nth variable. Here, n is the refractive index of the disks and ω_0 some baseline frequency.

The boost amplitude $\mathcal{B}$ is constructed from polynomials and powers of all $e^{\pm i\delta_j}$. Moreover, $\mathcal{B}$ involves dividing two such expressions. Overall, $\mathcal{B}$ is 2π periodic in any of the δ_j, so we may write it as an infinite Fourier series

$$\mathcal{B} = \sum_{\boldsymbol{k}} a_{\boldsymbol{k}}\, e^{i\boldsymbol{k}\cdot\boldsymbol{\delta}}\,, \tag{0.1}$$

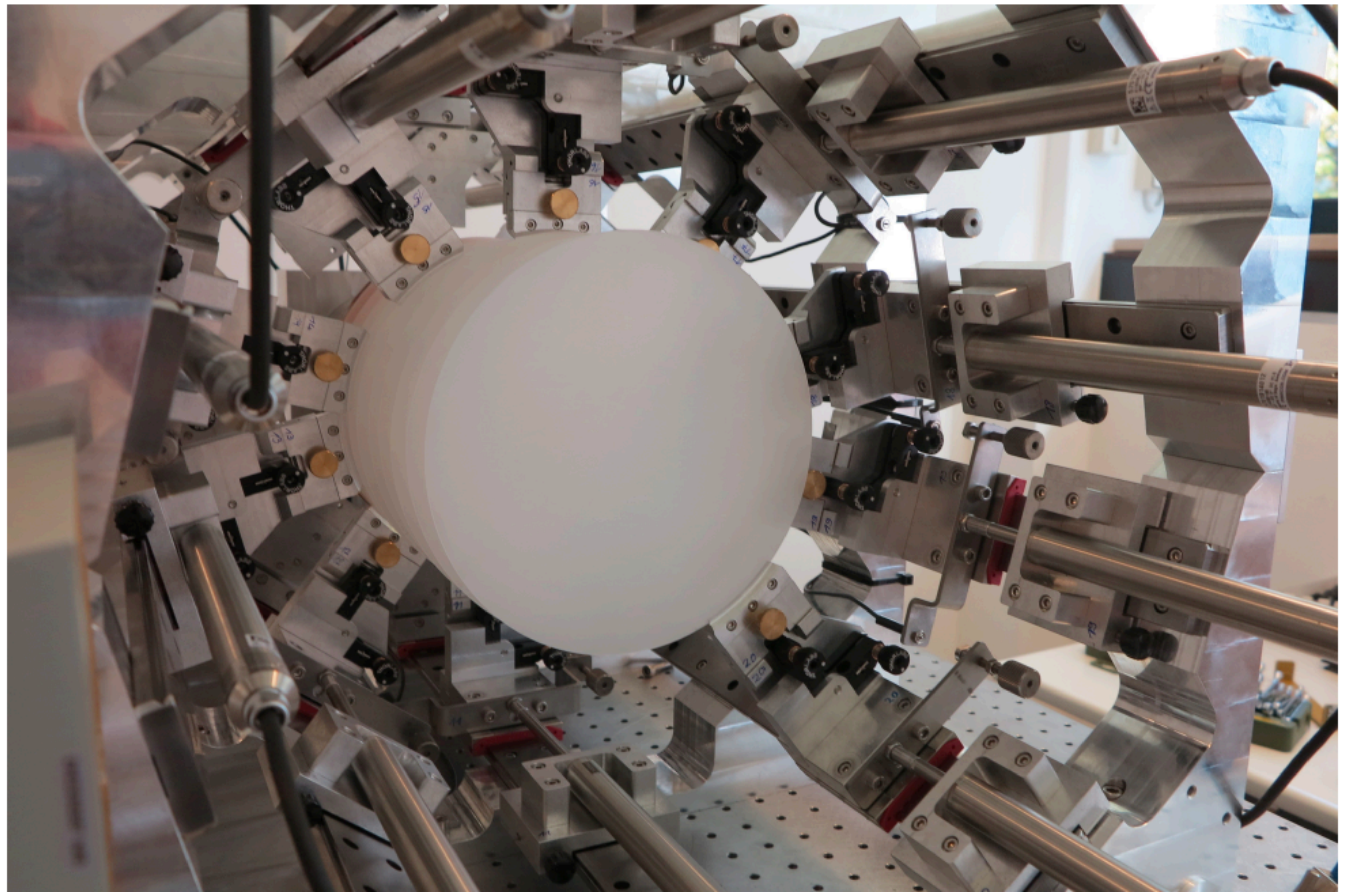
...

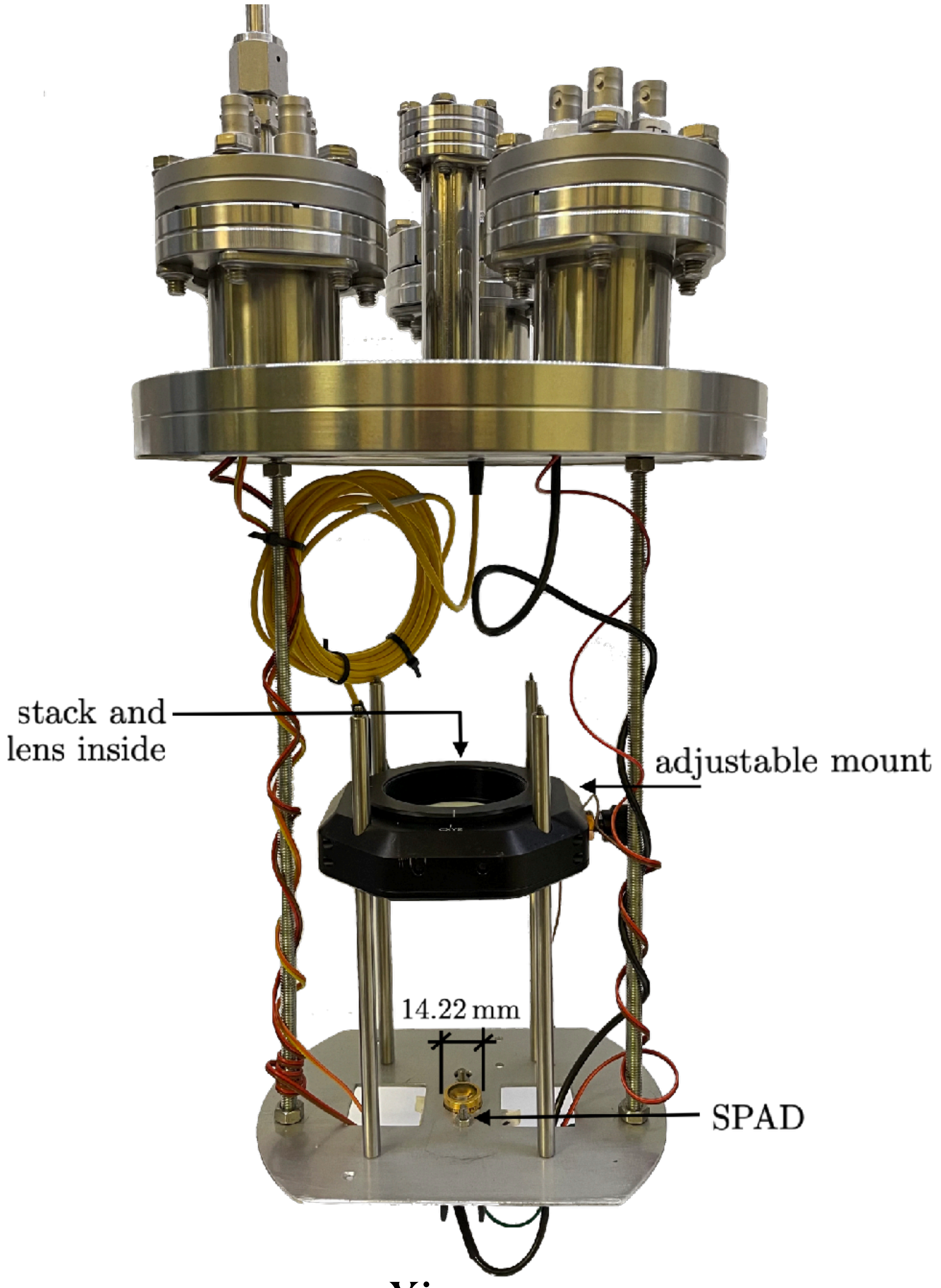
The second integral over phases vanishes if the integration range is large enough. Alternatively, if the different δ_j are commensurate, i.e., rational fractions of each other, then there exists some finite s interval which is some integer multiple of 2π over which $\mathcal{B}$ is periodic. In this case, we integrate over this period. In this sense, the average over the base volume in the N-dim space of all phase depths is the same as the 1D average over all frequencies, for any arrangement of phase depths.

Simple examples are the transparent mode where all δ_j are the same. Another example is the resonant mode, where all vacuum gaps are the same, $\delta_v = \delta_1 = \ldots = \delta_{N-1}$ whereas the phase depth of the disk is half as much, $\delta_N = \delta_\epsilon = \delta_v/2$. So in particular the transparent and resonant modes emit the same power, averaged over all frequencies.

Dielectric Haloscopes

- Two versions being pursued: movable disks, GHz version (MADMAX, DALI)
- Thin film optical version (MuDHI, LAMPOST)

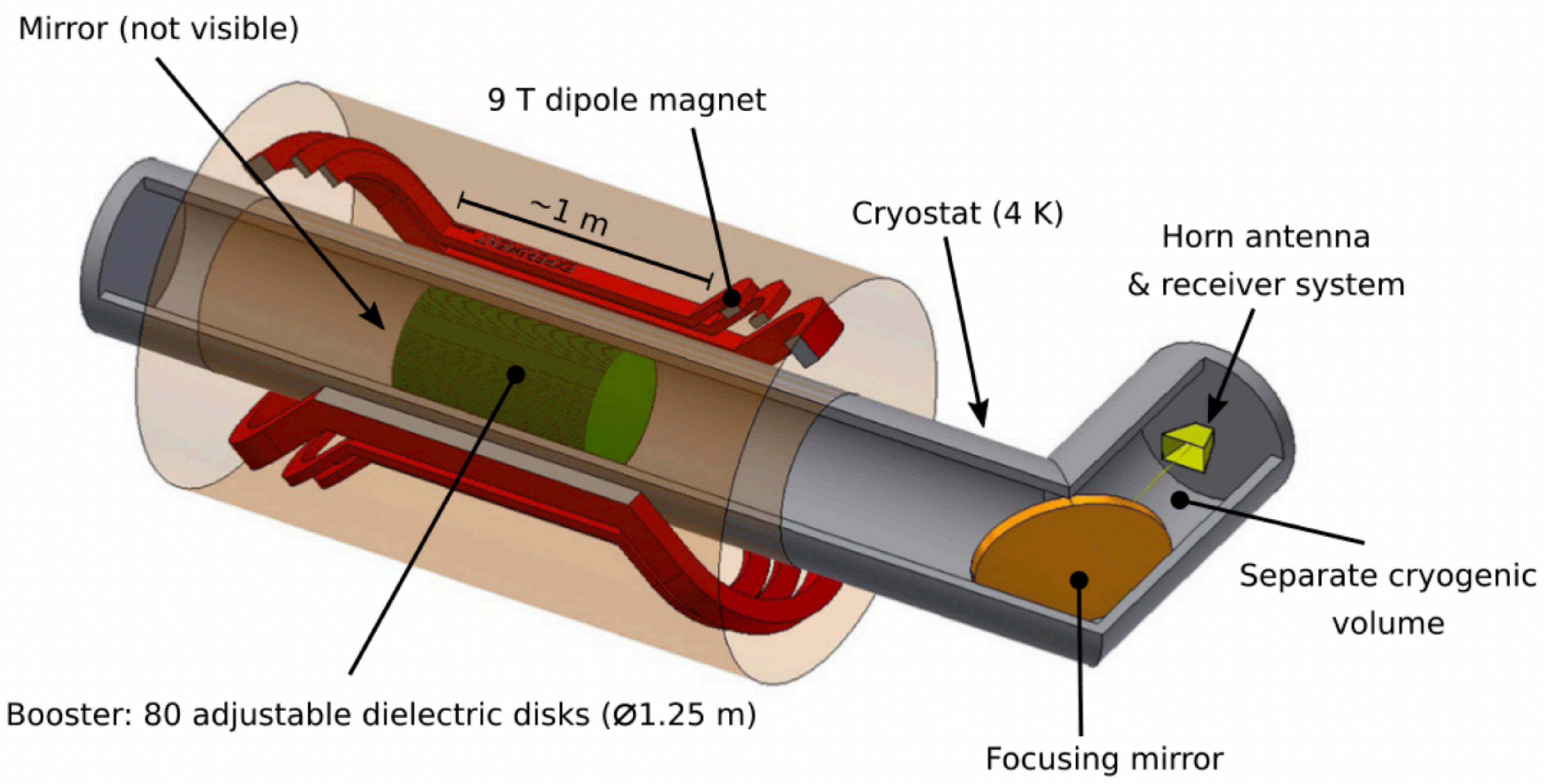




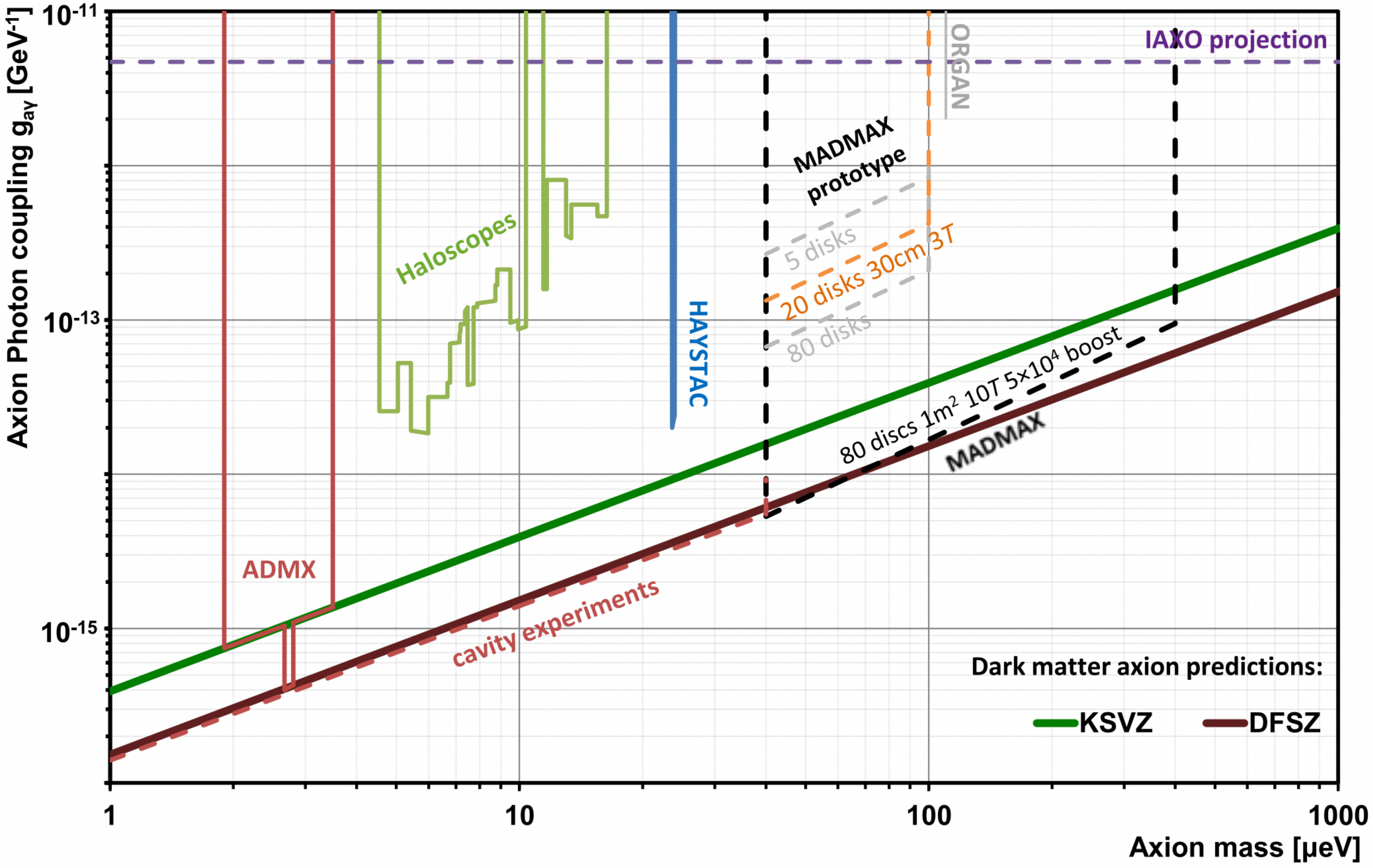
arXiv:2110.10497

MADMAX

- Started at the Max Planck Institute
- Planned to be hosted at DESY
- Prototyping underway with a magnet from CERN
- Full scale magnet being designed

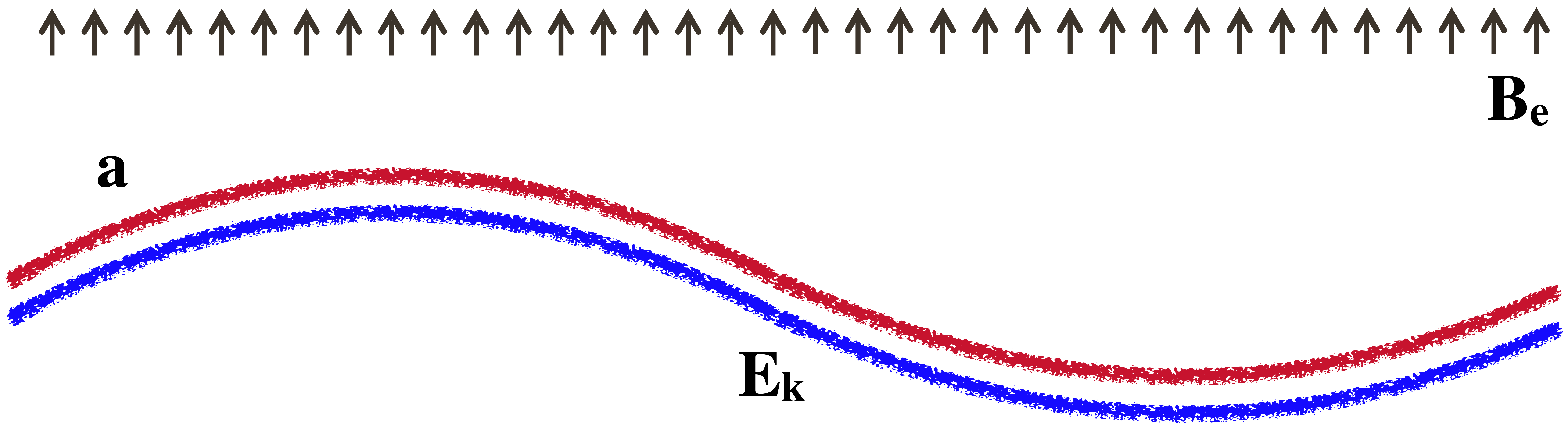


Projected Reach



Plasma Haloscopes

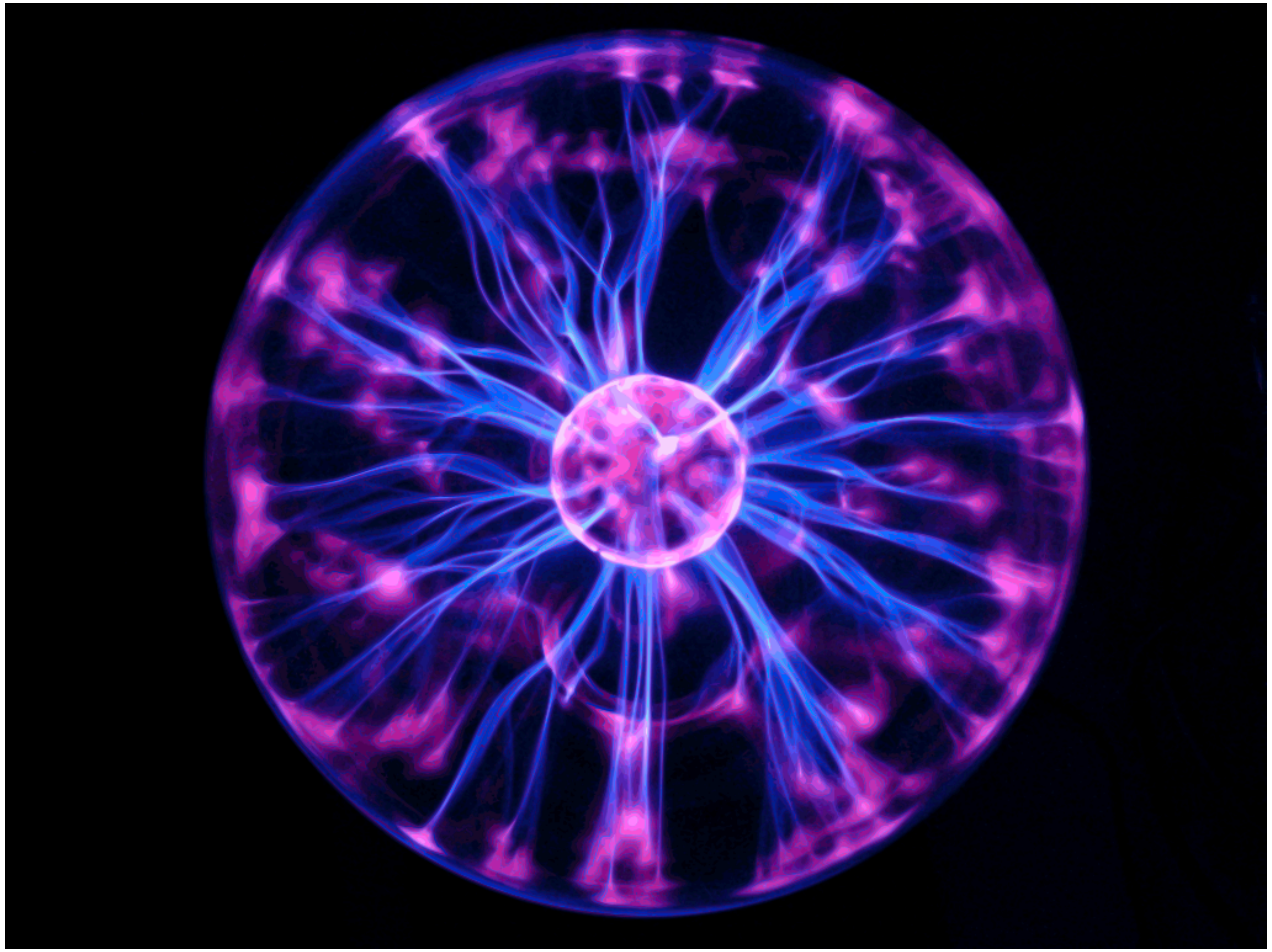
- What if you could match energy and momentum at the same time?



Idea

$$\mathbf{E} = -\frac{g_{a\gamma}\mathbf{B}_{\mathrm{e}}a}{\epsilon} = -g_{a\gamma}\mathbf{B}_{\mathrm{e}}a\left(1 - \frac{\omega_p^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

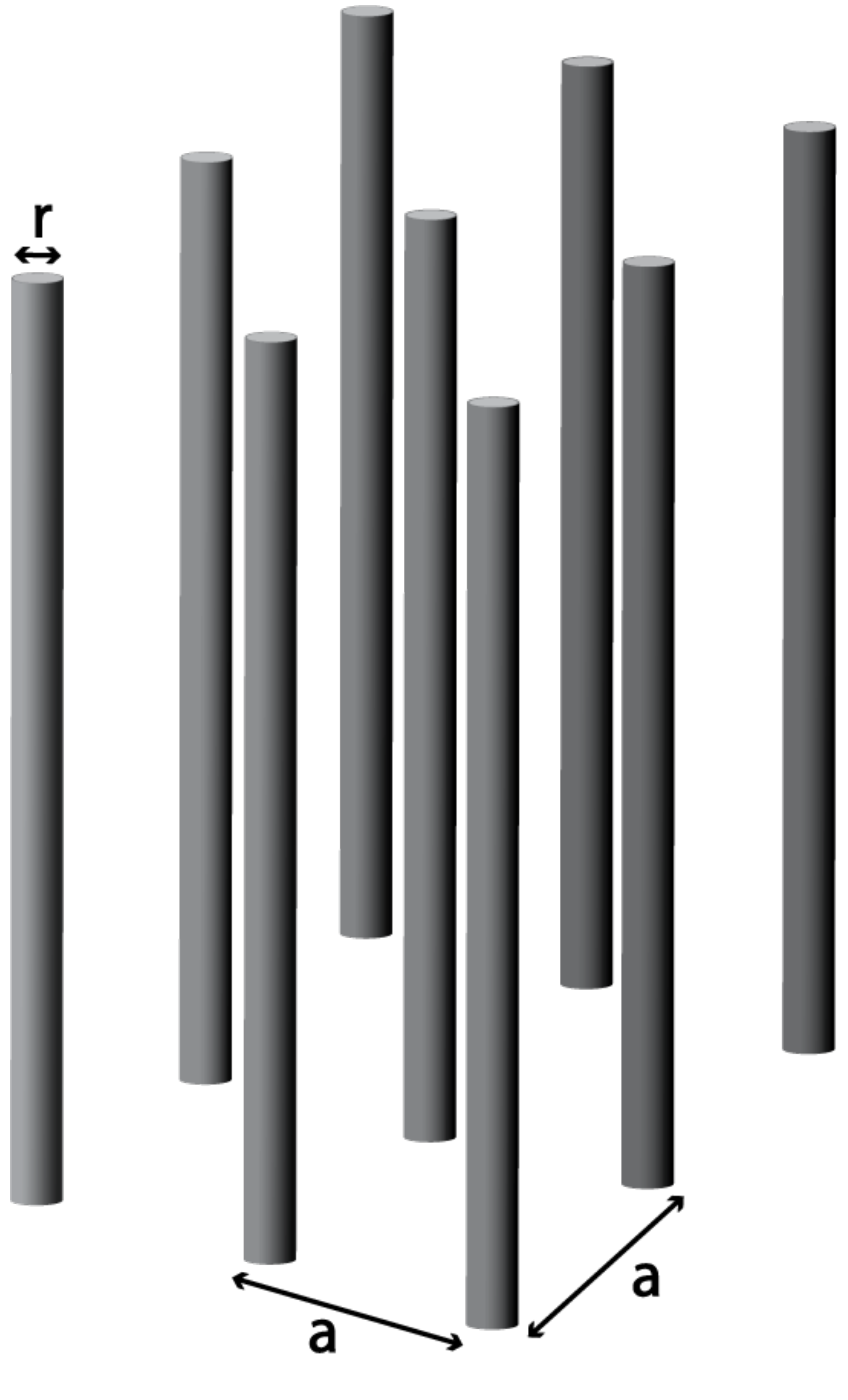
- Resonance doesn't care about the size!
- Could we use it to make a much larger device?
- What properties does it need?



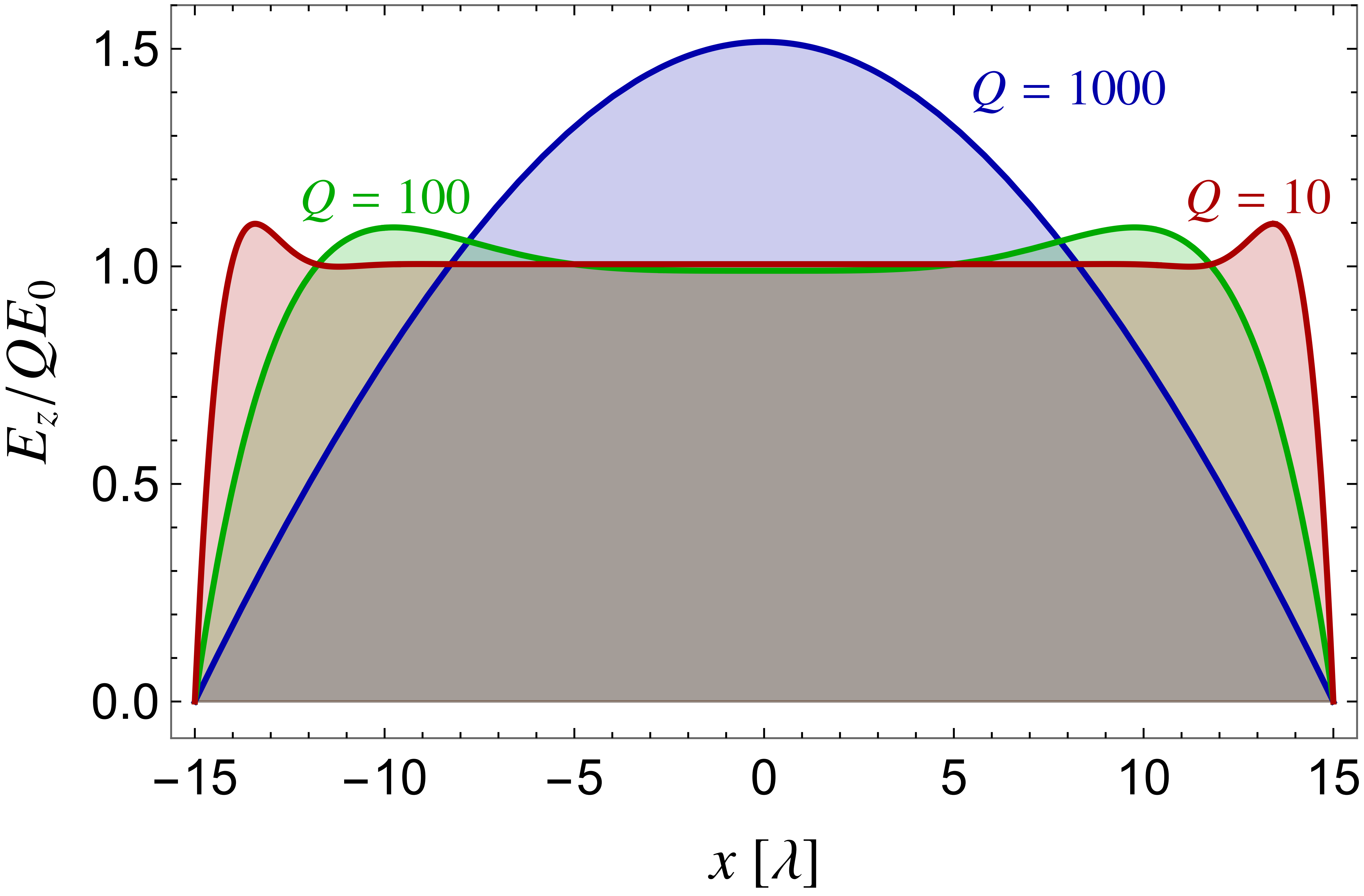
Wire Metamaterials

- Wire metamaterials!
- One of the first metamaterials
- Plasma frequency determined by two factors: effective electron number density and mass
- Wire spacing gives plasma frequency

$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{a^2 \log(a/r)} \ .$$

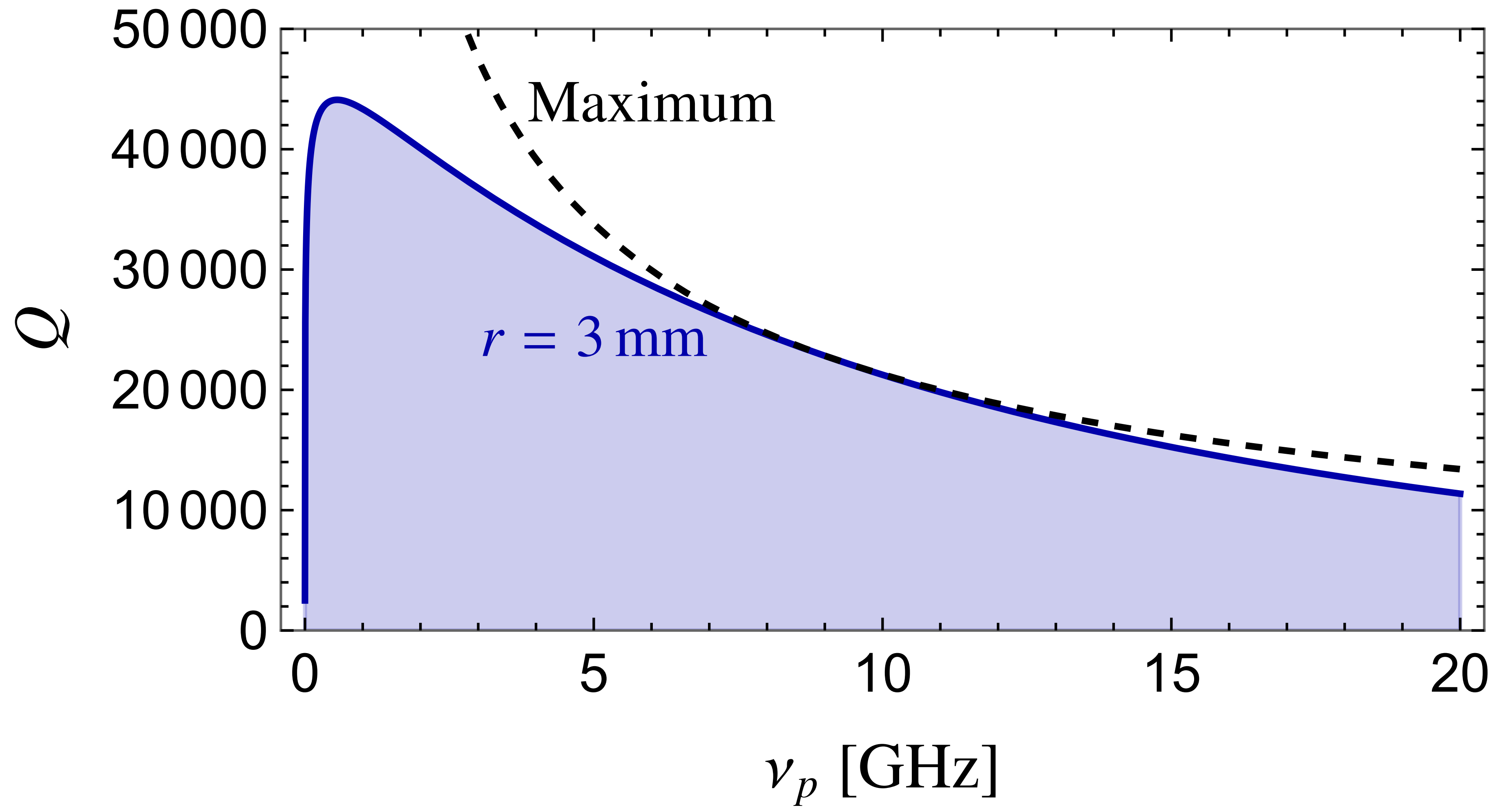


Finite Media

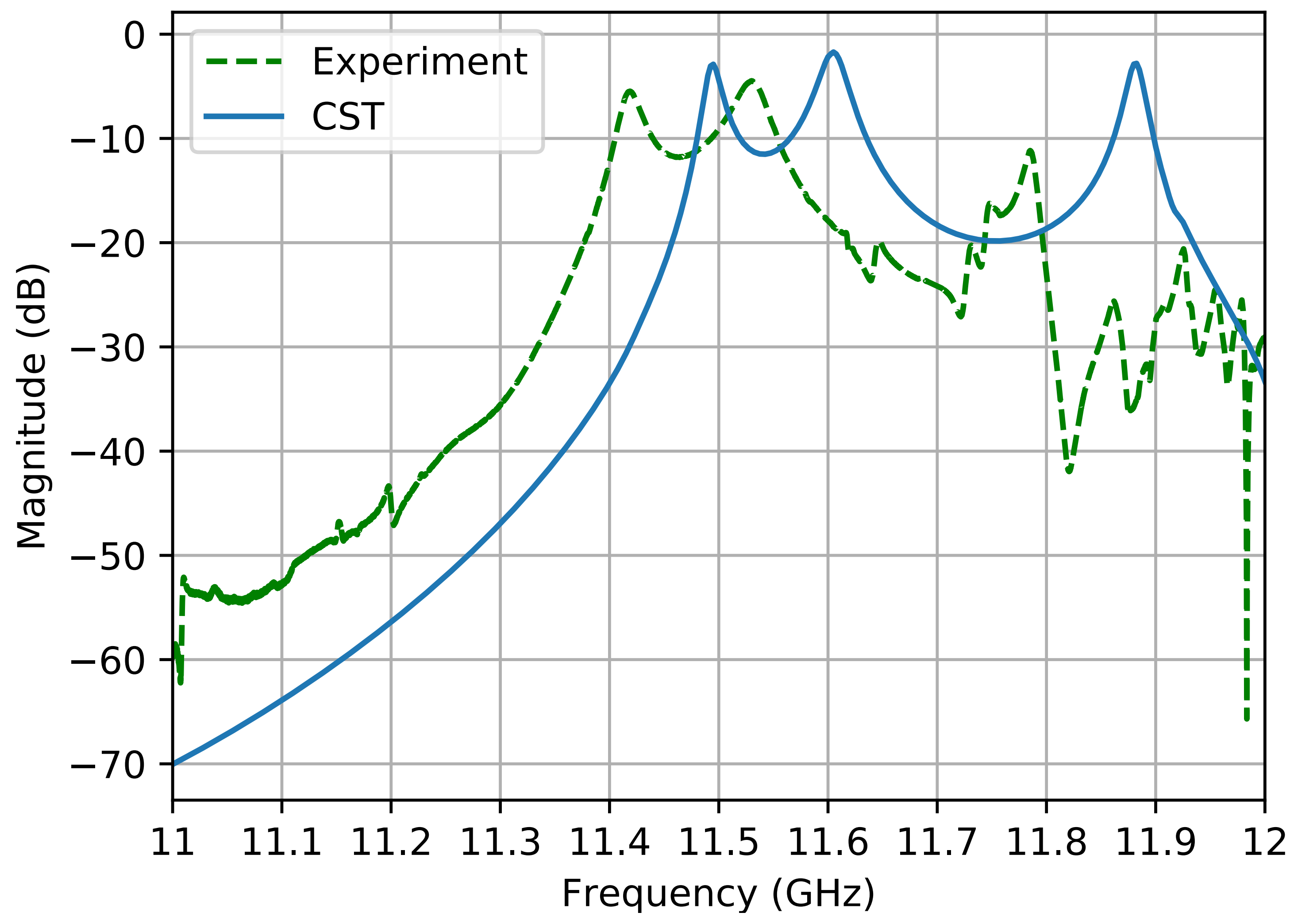


Quality factor

- In free space, radiative losses or resistance losses dominate depending on the size of the device
- In a cavity, wire losses are most significant
- Can expect Q in the 10's of thousands at cryogenic temperature with thick wires



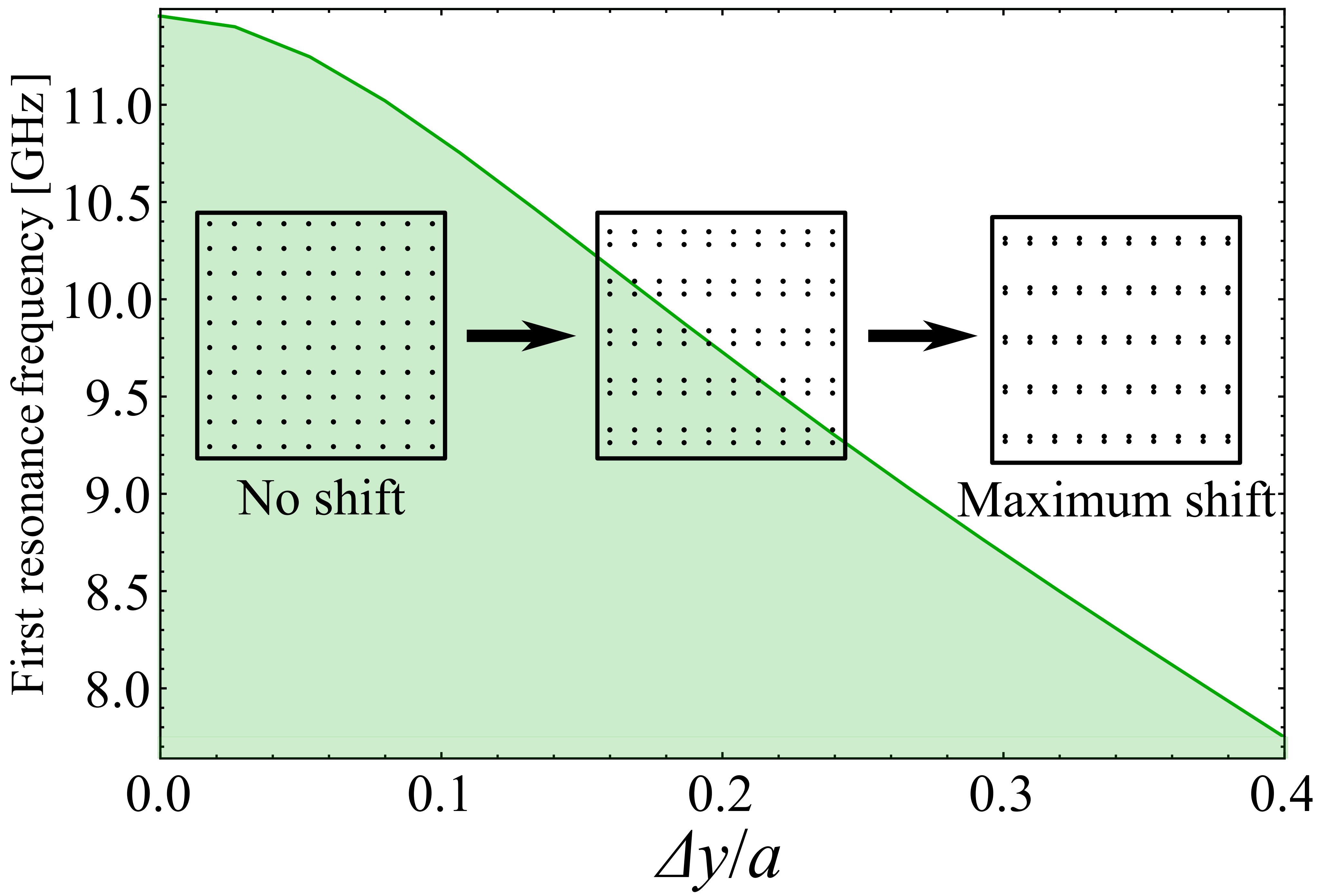
arXiv:2210.00017



arXiv:2203.10083

Tuning

- Only mutual inductance matters!
- Can tune by changing the wire geometry



arXiv:2210.00017

ALPHA

- Budding consortium with collaborators in SU, MIT, Berkeley, ITMO...
- Building better analytical and numerical tools (understanding of quality factors, mode structure)
- Early prototypes built, moving towards tuneable and larger prototypes (arXiv:2203.10083, arXiv:2203.13945)
- Likely to use a 13 T magnet at Oakridge
- ALPHA recently received ~$2.5M from the KAW
- More info in arXiv:2210.00017

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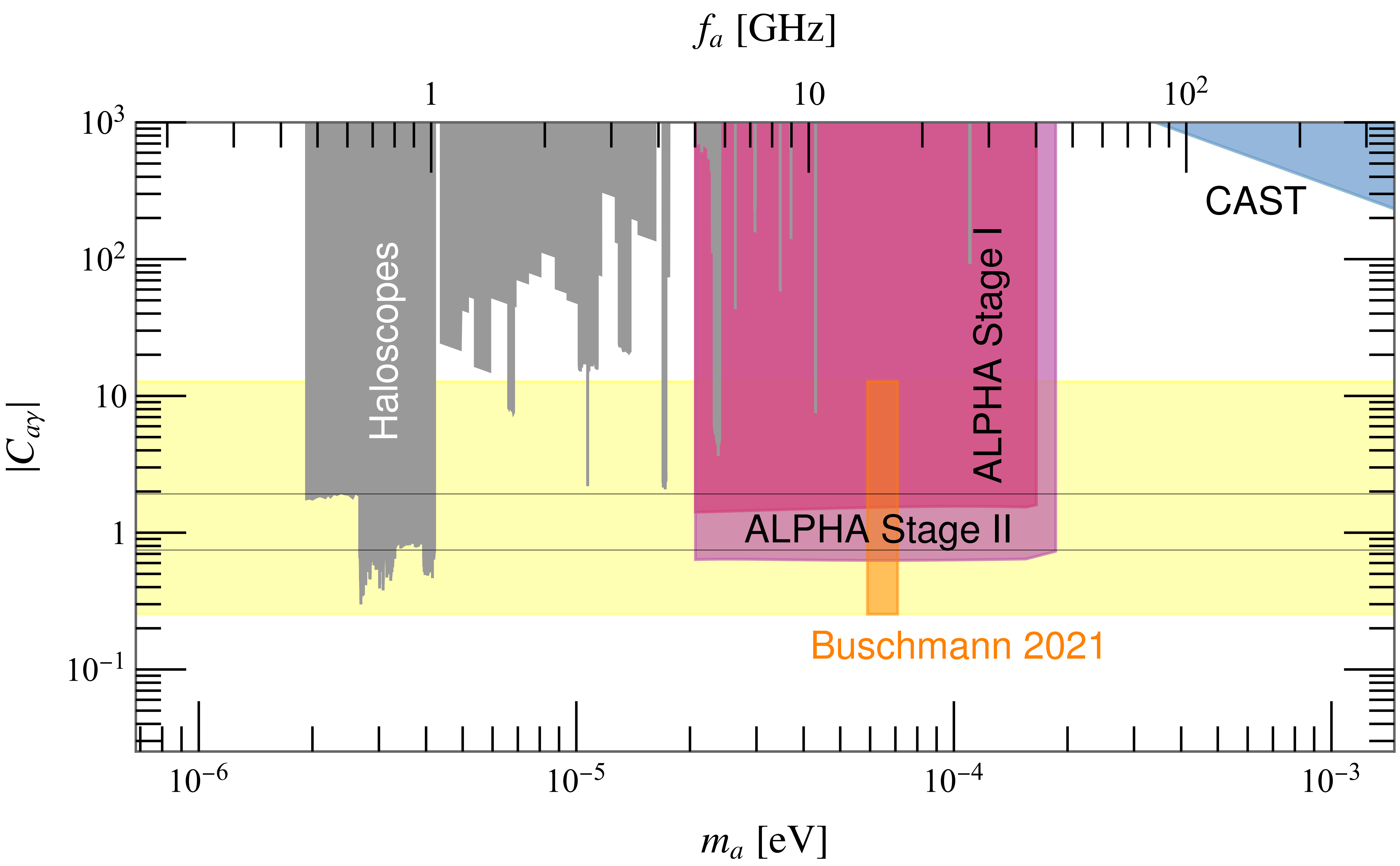
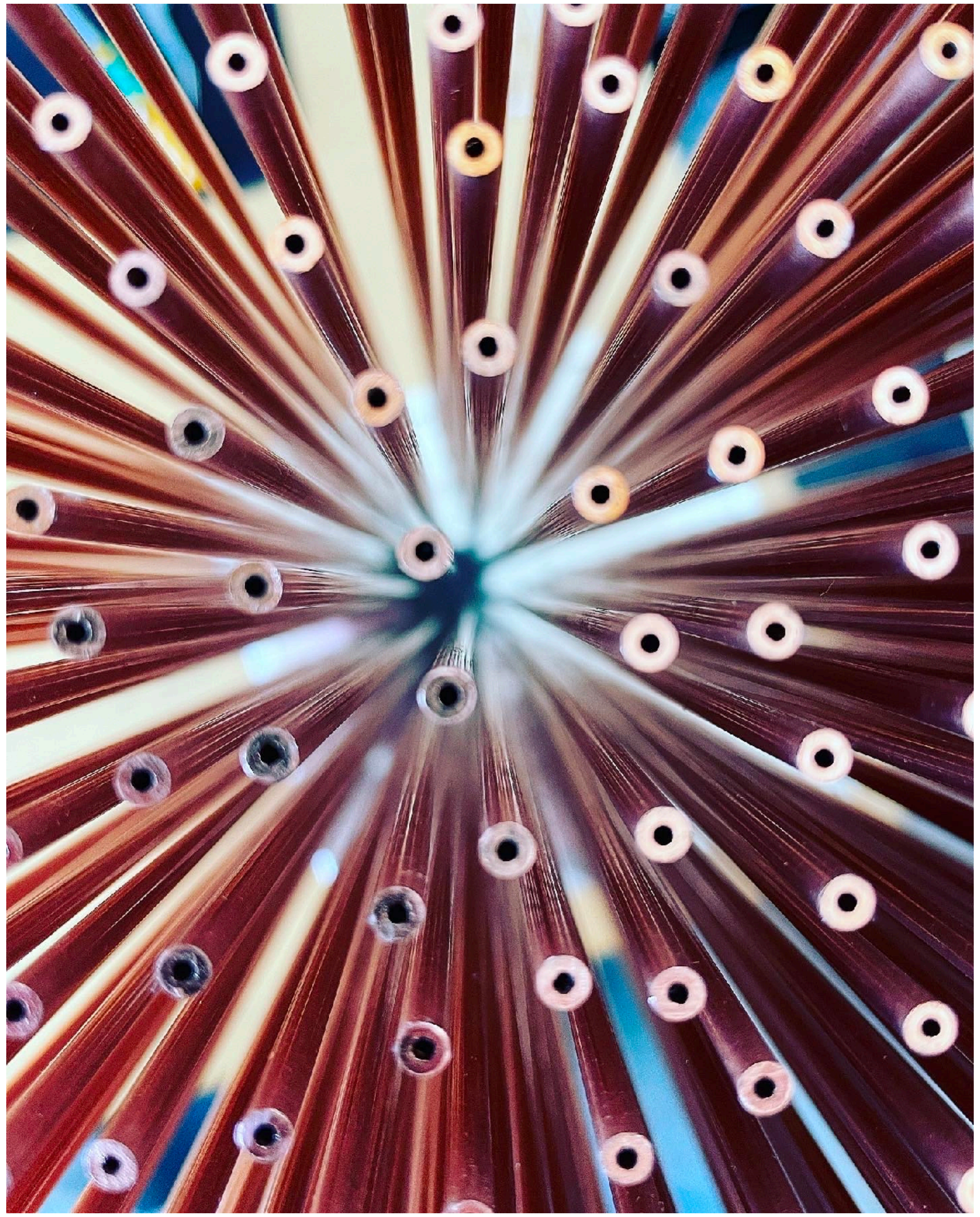
Discovery Potential



Conclusions

- Axions are an exception dark matter candidate
- The high mass regime is extremely promising
- New techniques such as dielectric and plasma haloscopes required to search for them
- Georg's work helped build the theoretical foundations to push into high mass axions



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