# Searching for Wavelike Dark Matter: The Experiments

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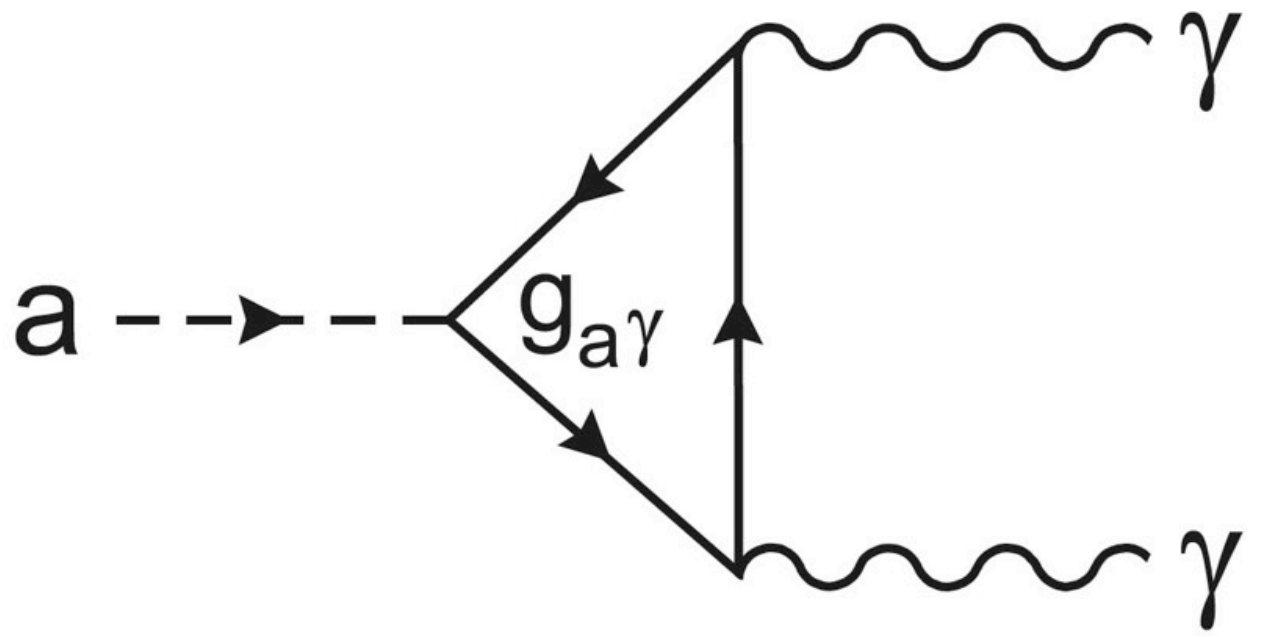
# Axion Electrodynamics

- 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

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

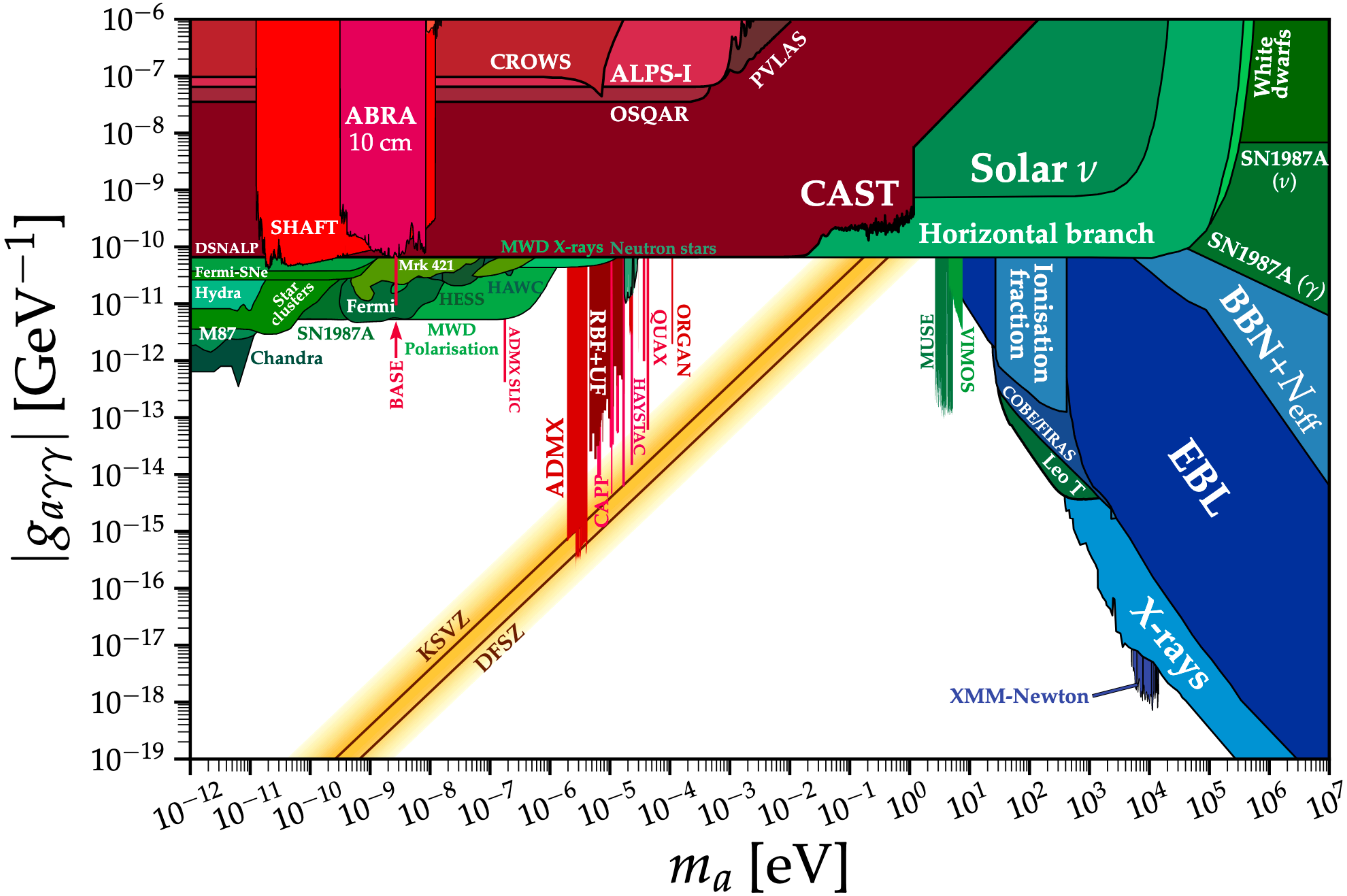



$$m_a = 5.70(7)\,\mu\text{eV}\,\frac{10^{12}\text{GeV}}{f_a},$$

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

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

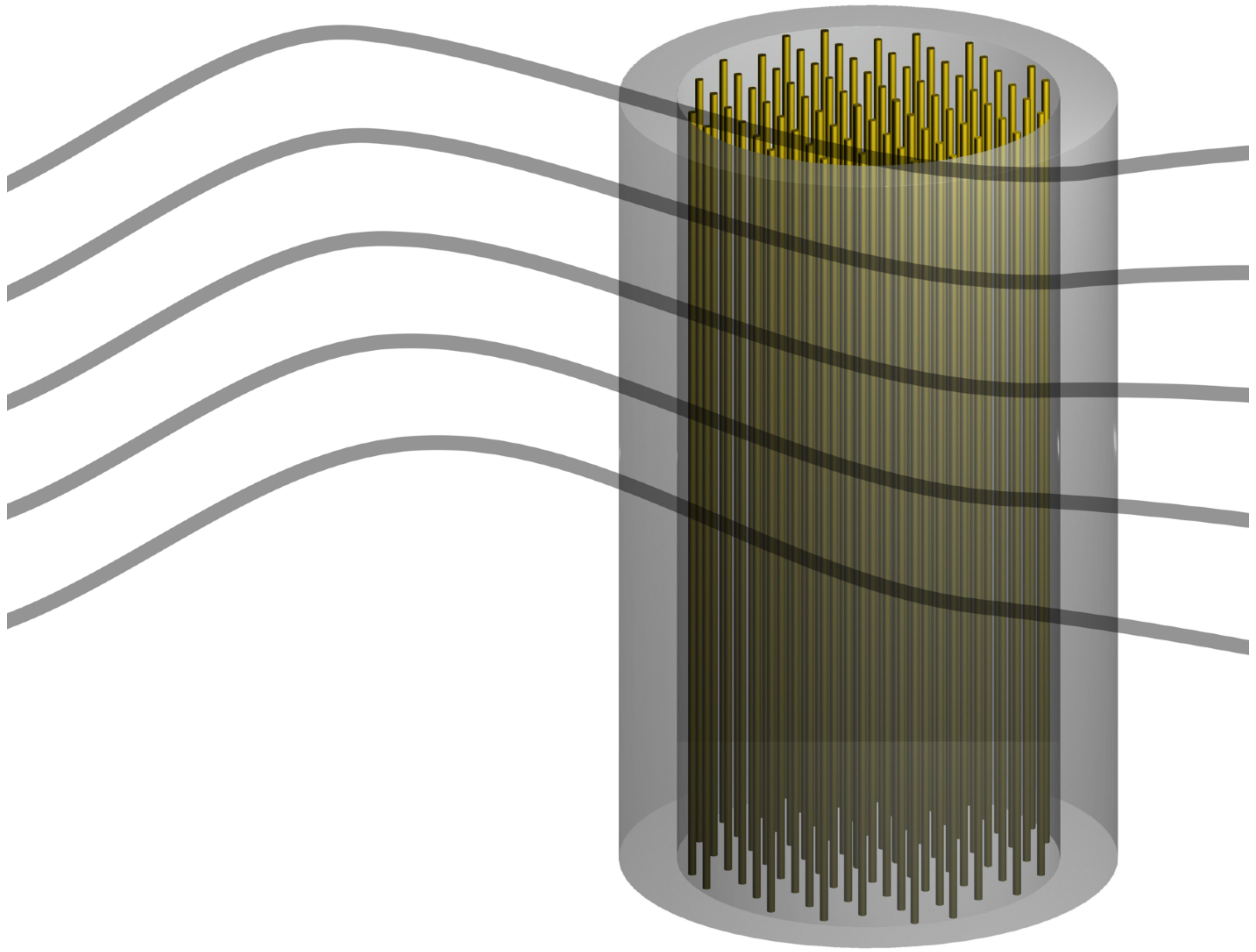
# Parameter Space




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 Photon Conversion

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

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

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

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

# Axion-Photon Conversion

- Lowest order QFT gives Fermi's Golden Rule

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

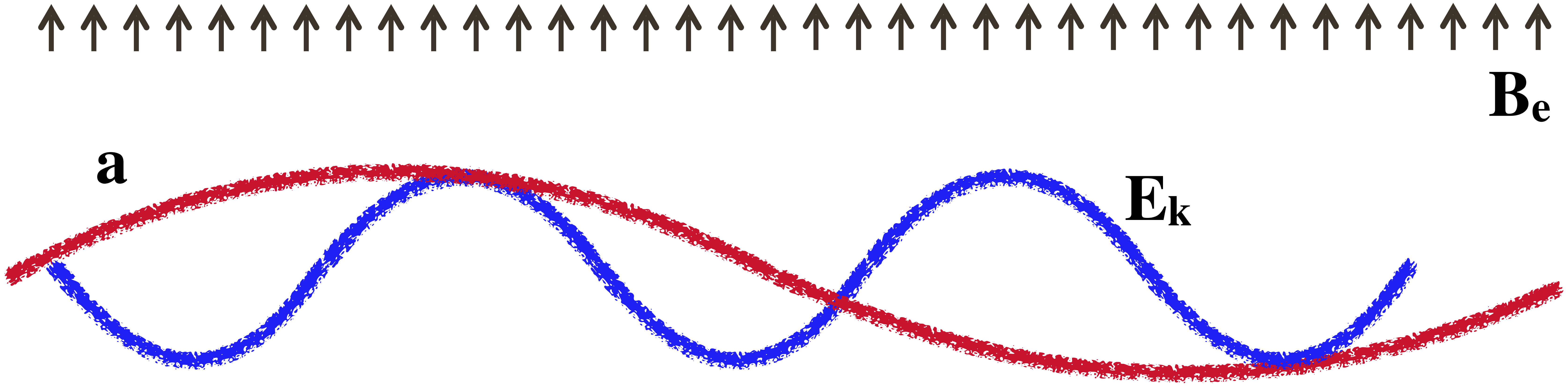
- Matrix element given by the overlap of the wave functions

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

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

# Axion-Photon Conversion

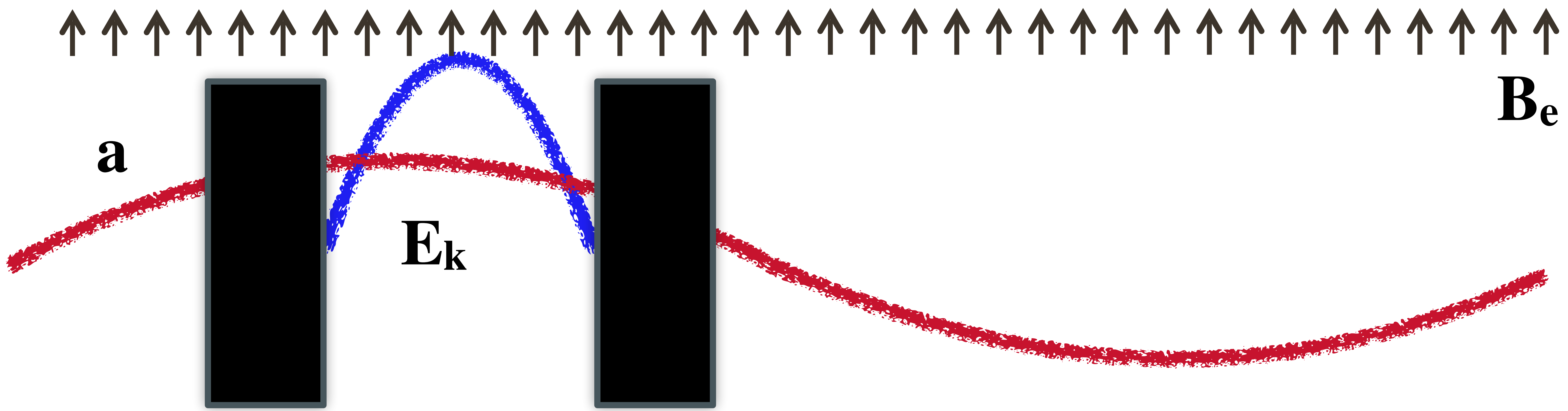
- In vacuum and constant B-field this vanishes




- Modify the free-photon wave function!

# Cavity Haloscopes

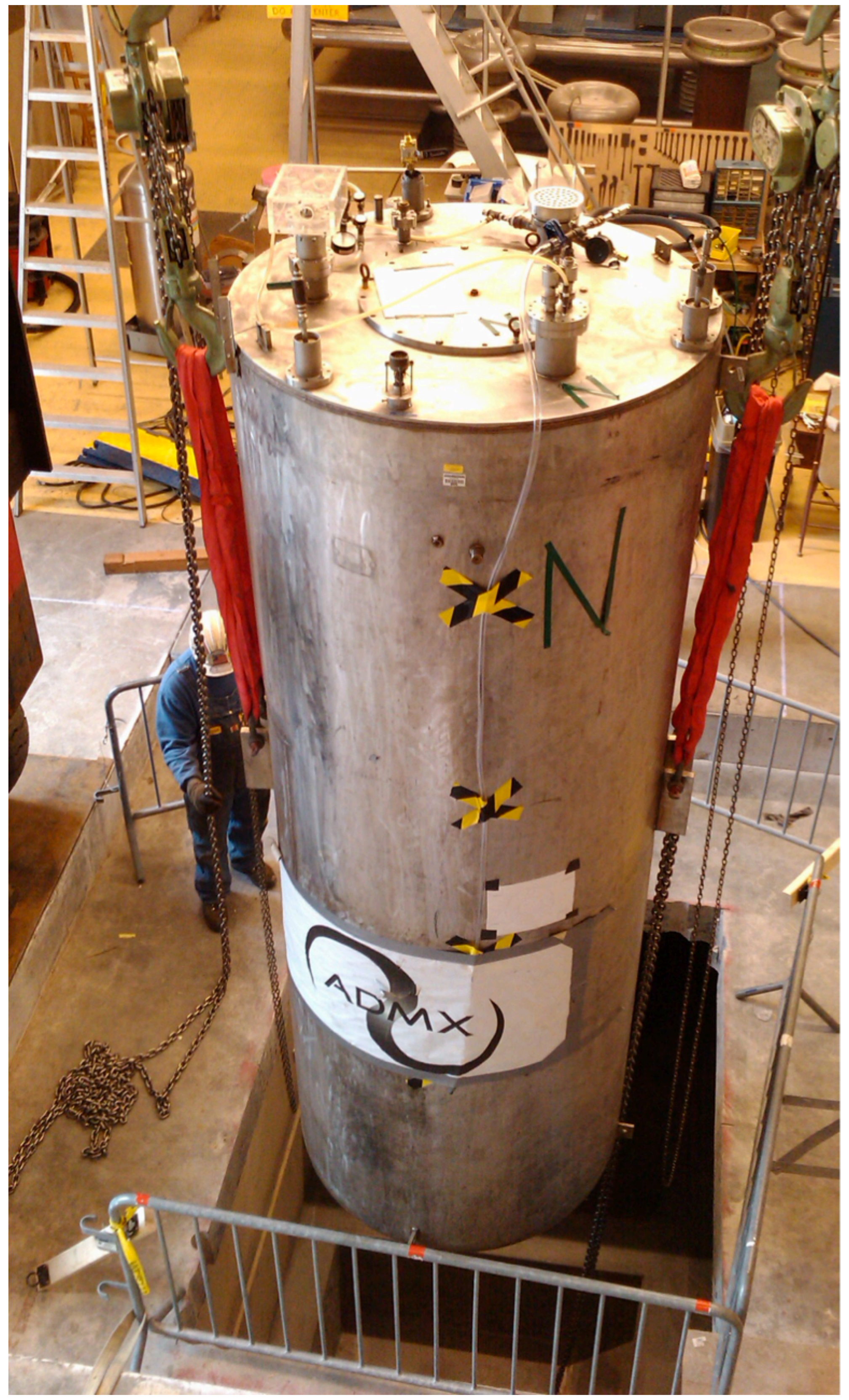
- Inside a cavity the photon wavefunction matches the cavity modes




- Normalisation given by the quality factor

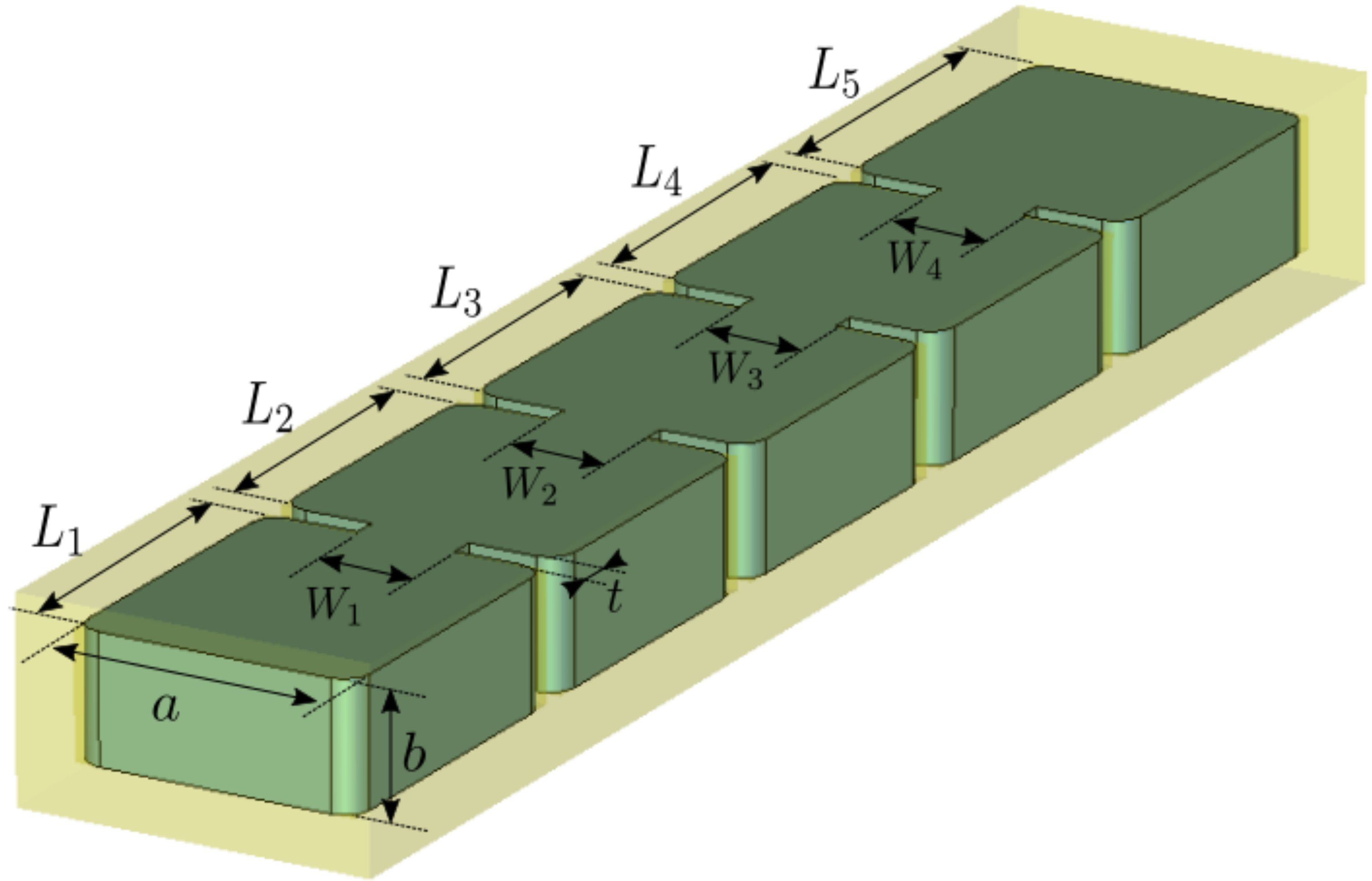
# Cavity Haloscopes

- Originally introduced to search for the axion
- Oldest and most established method (proposed by Sikivie)
- Build a cavity matching the Compton wavelength of DM to resonantly break translation invariance
- Requires large volume – hard to do for large axions masses (small wavelengths)
- Examples include ADMX, HAYSTAC, CULTASK, RADES...



# Cavity Extensions

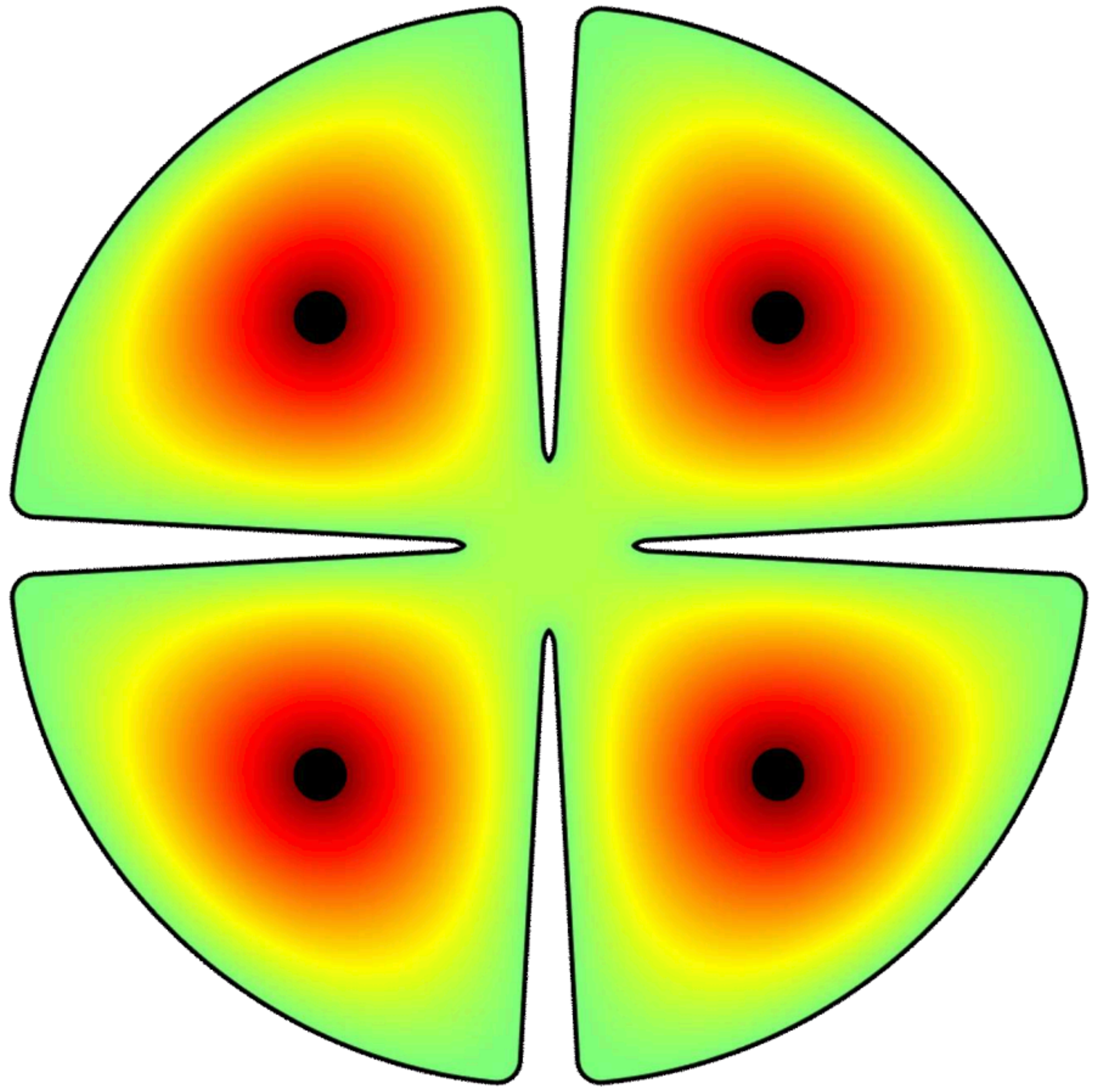
- Multiple cavities (ADMX, CULTASK)
- Coupled cavities (RADES, CULTASK, ORGAN)
- Non-traditional cavities (ADMX, HAYSTAC, CULTASK)
- Bigger Magnets
- Better detectors (Beyond the SQL)



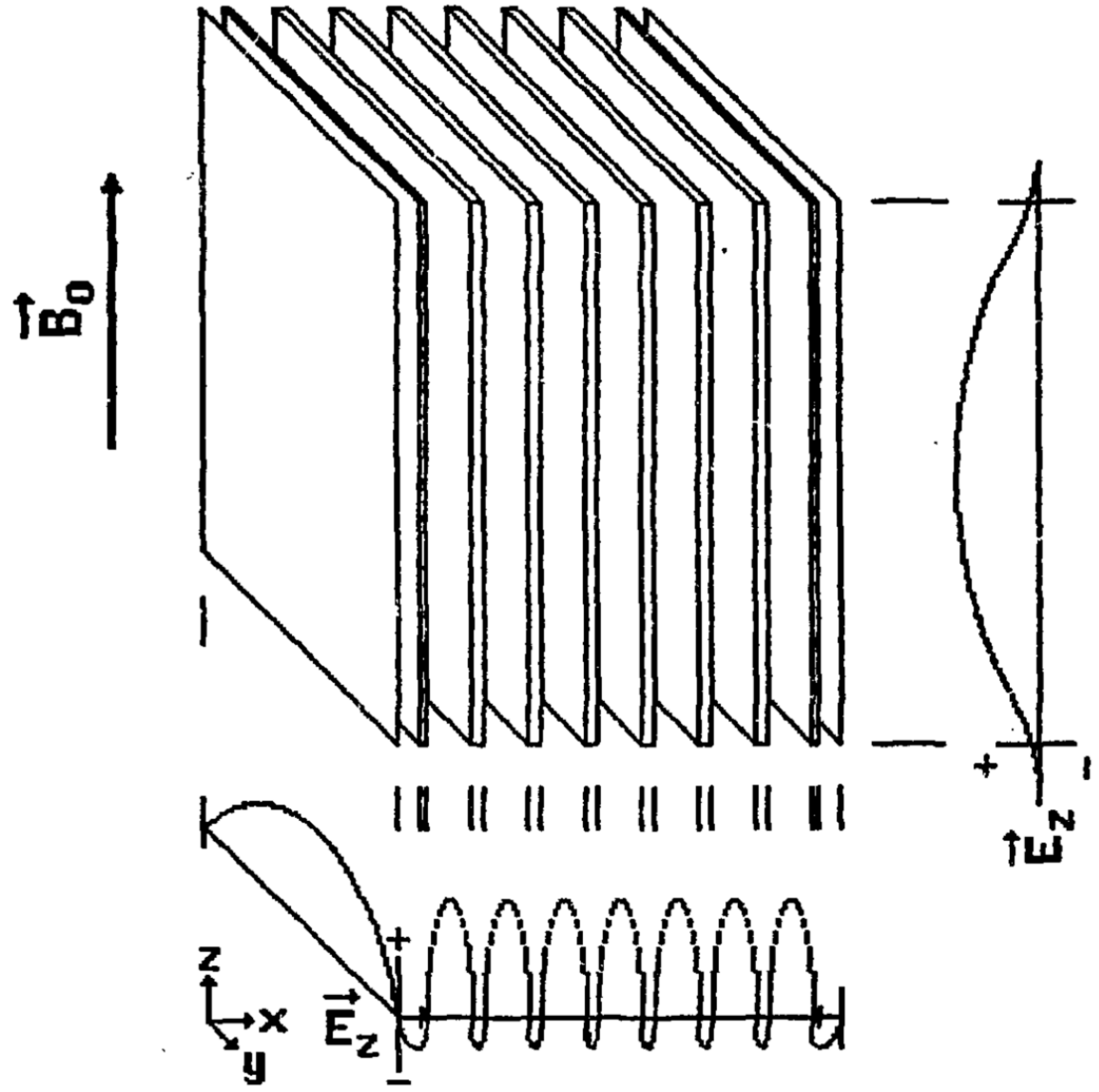

RADES (arXiv:1803.01243)

# Cavity Extensions

- General theme: increase the volume using multiple cavities/cavity sections
- Not strictly new, but much revitalised



arXiv:1710.06969





Morris 1984

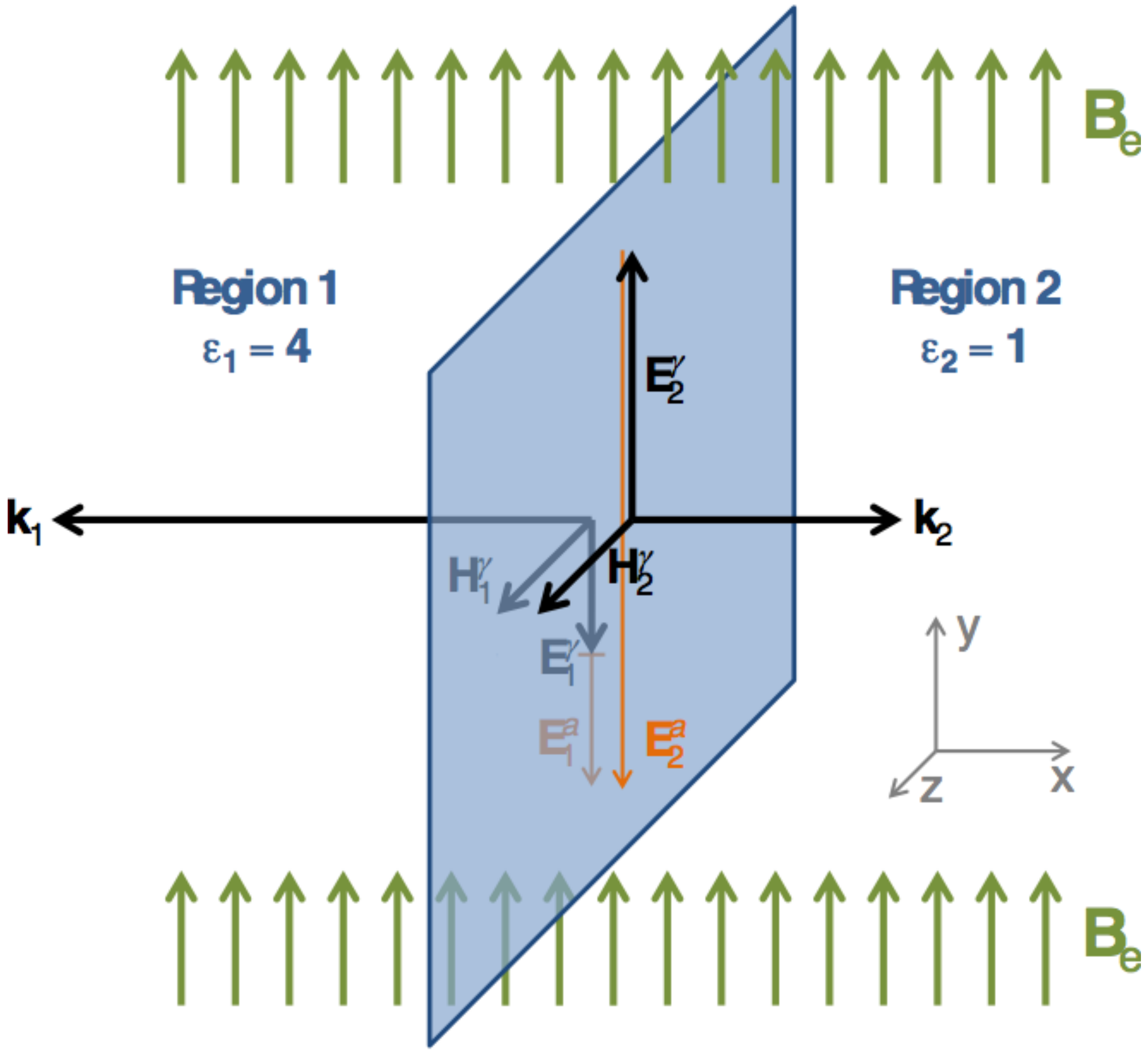
# Beyond Cavities

- Dish Antennas (BREAD, BRASS)
- Dielectric haloscopes (MADMAX, MuDHI LAMPOST)
- Plasma haloscopes (ALPHA)
- Resonators with LC circuits (ABRACADABRA, DM Radio, SHAFT)
- 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

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

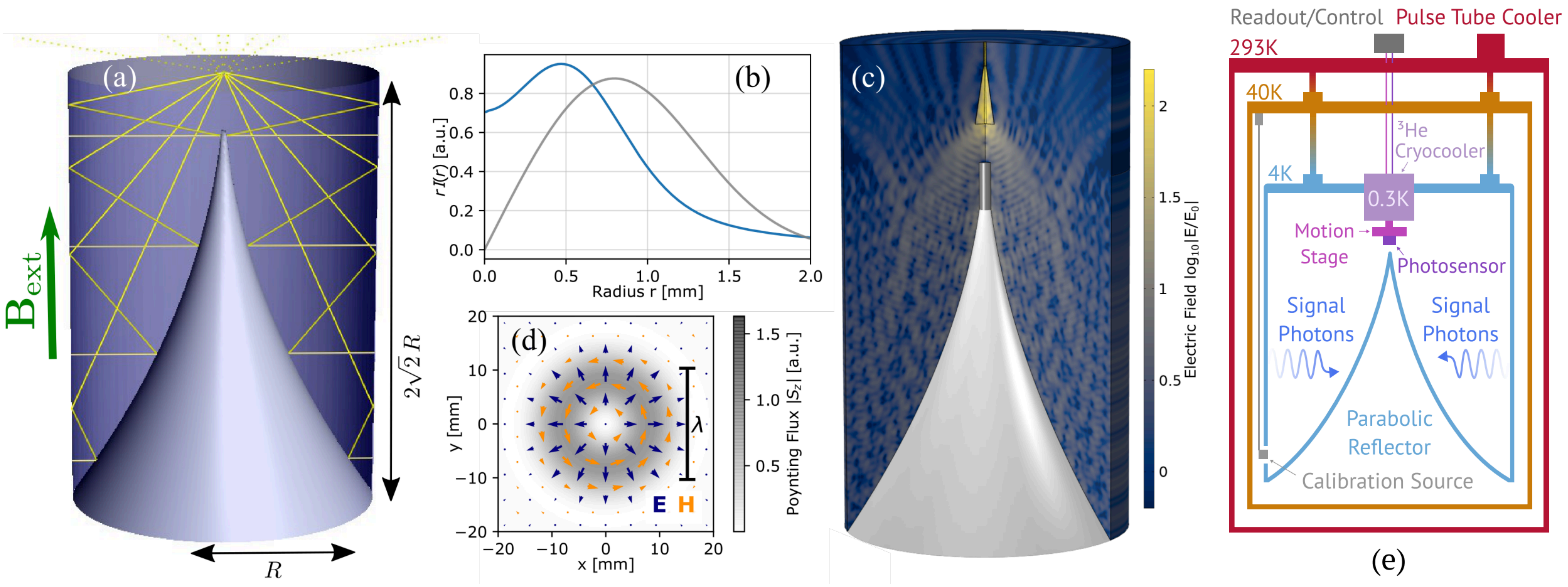


# Dish Antenna

- 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

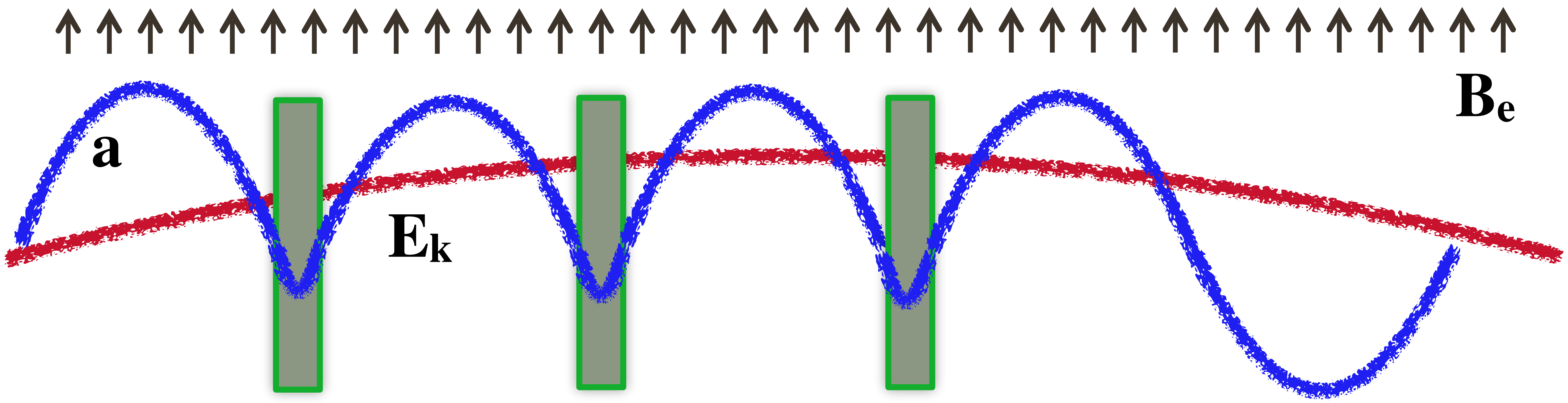
# BREAD



(a)
$\mathbf{B}_{\text{ext}}$
$2\sqrt{2}\,R$
$R$
(b)
$rI(r)$ [a.u.]
Radius r [mm]
(d)
y [mm]
x [mm]
$\lambda$
E H
Poynting Flux $|S_z|$ [a.u.]
(c)
Electric Field $\log_{10}|E/E_0|$
Readout/Control
Pulse Tube Cooler
293K
40K
4K
$^3$He Cryocooler
0.3K
Motion Stage
Photosensor
Signal Photons
Signal Photons
Parabolic Reflector
Calibration Source
(e)

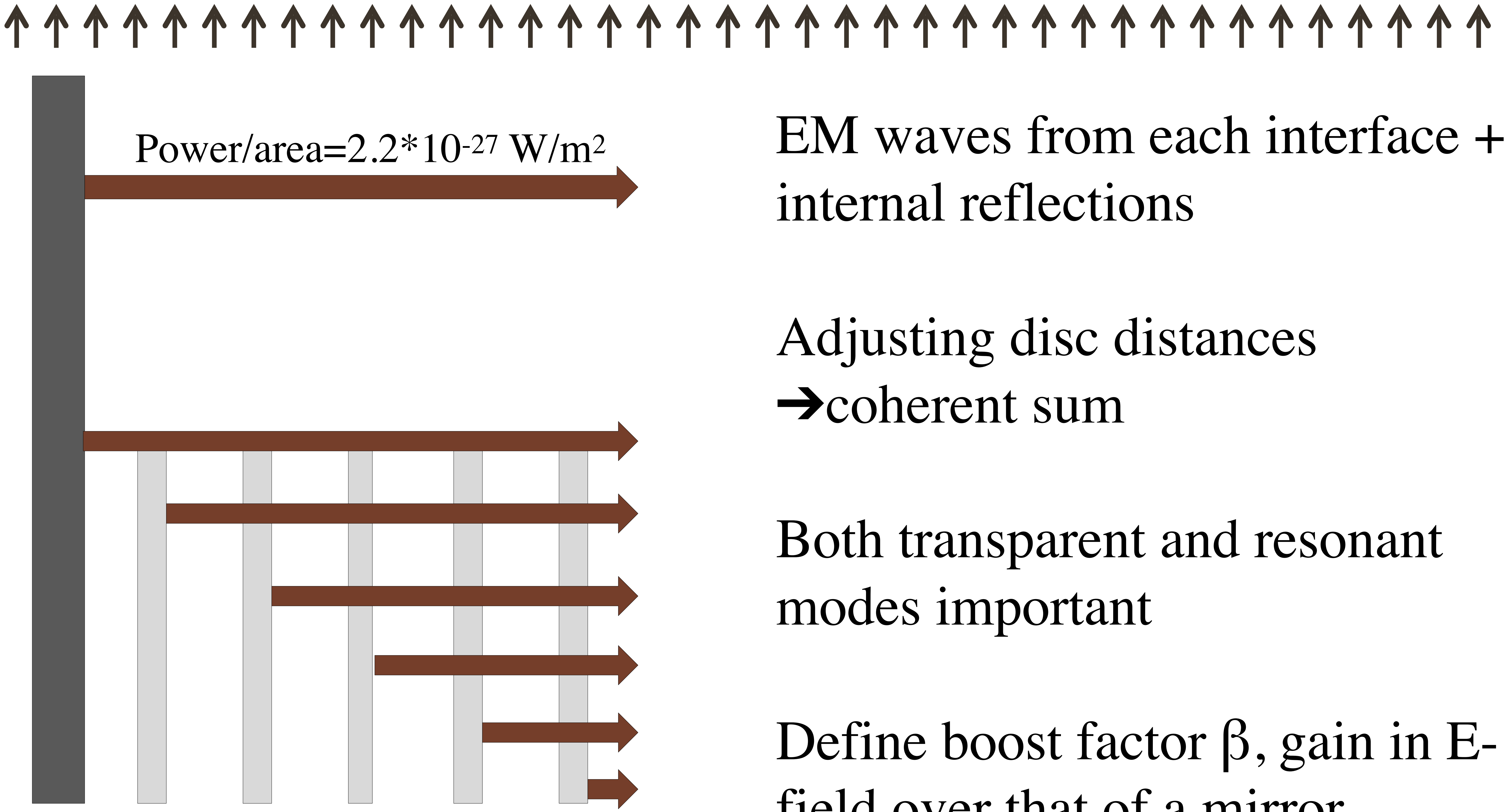
# Dielectric Haloscopes

- Introduce a series of dielectric layers




- Shape the wavefunction to get a non-zero overlap

# Multiple layers: dielectric haloscope




EM waves from each interface + internal reflections

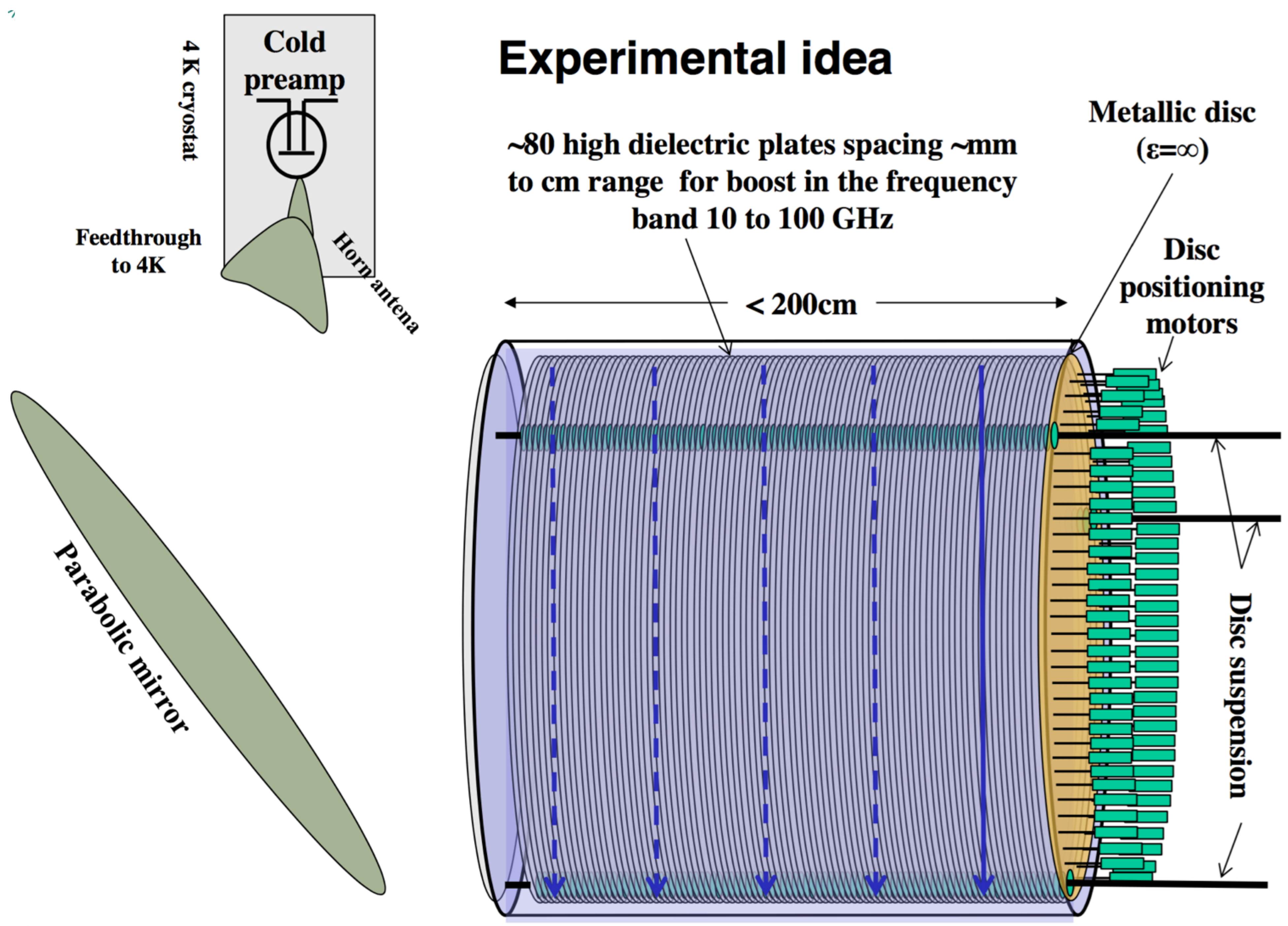
Adjusting disc distances
➔coherent sum

Both transparent and resonant modes important

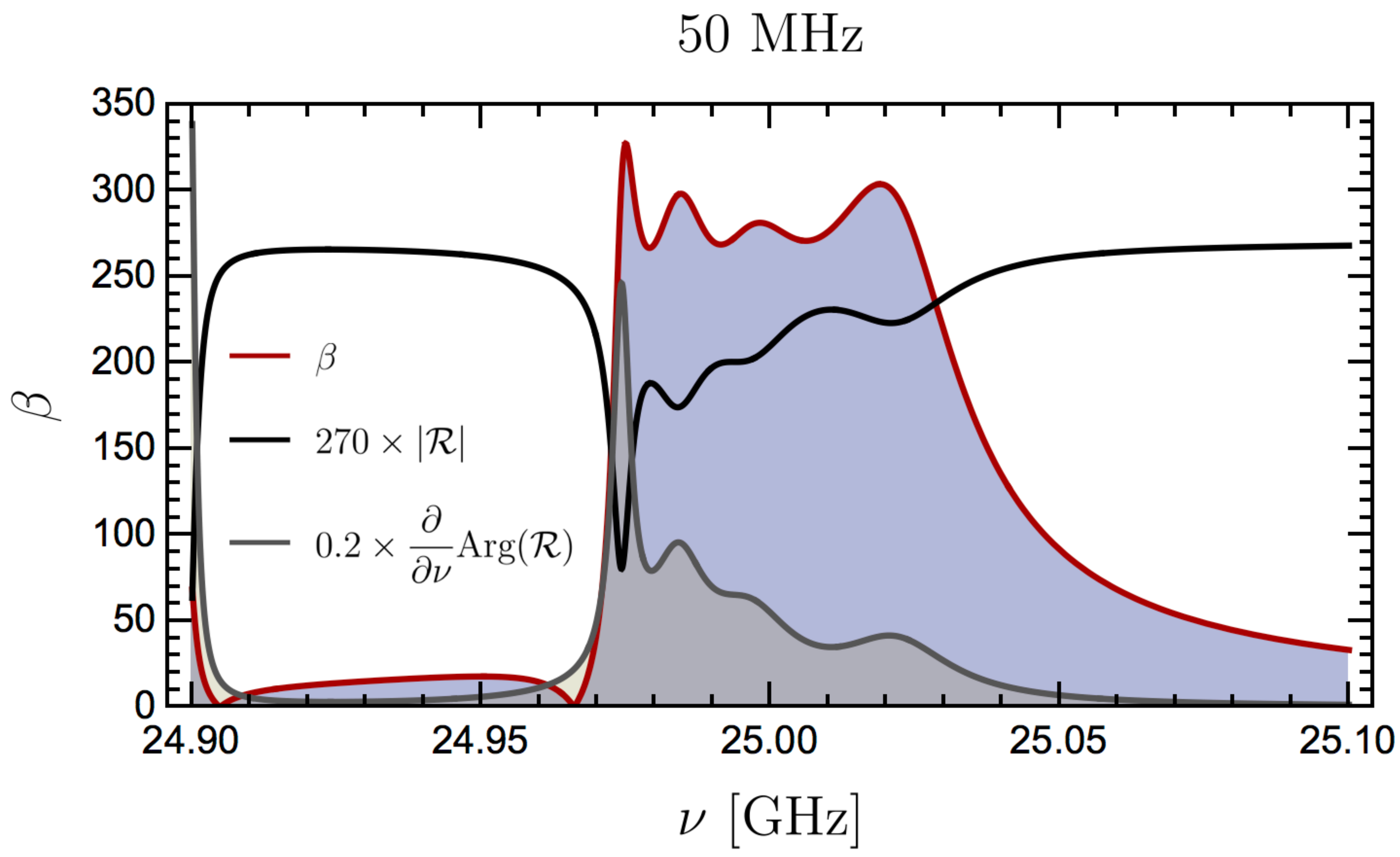
Define boost factor β, gain in E-field over that of a mirror

# Dielectric Haloscopes

- 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

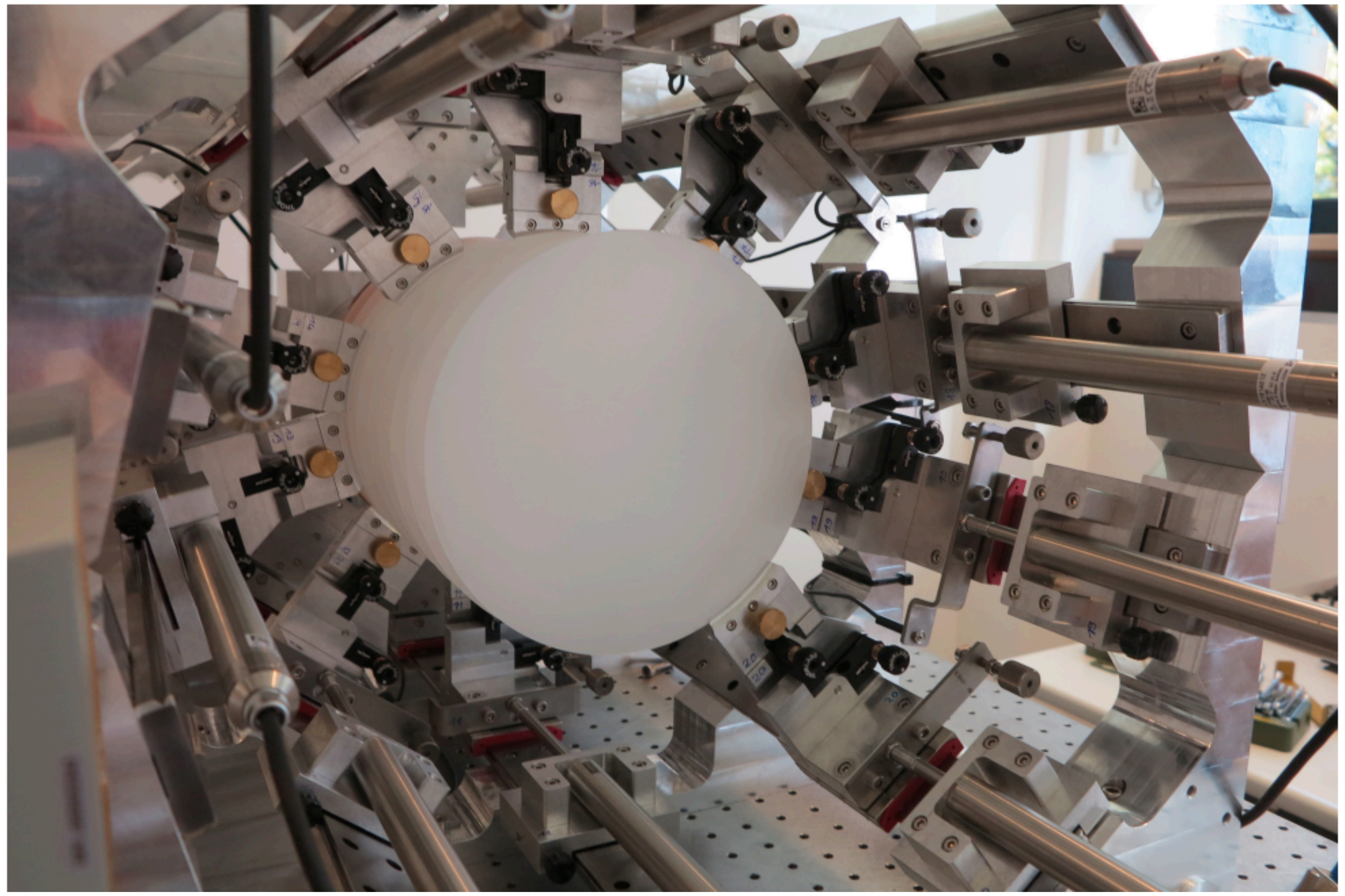


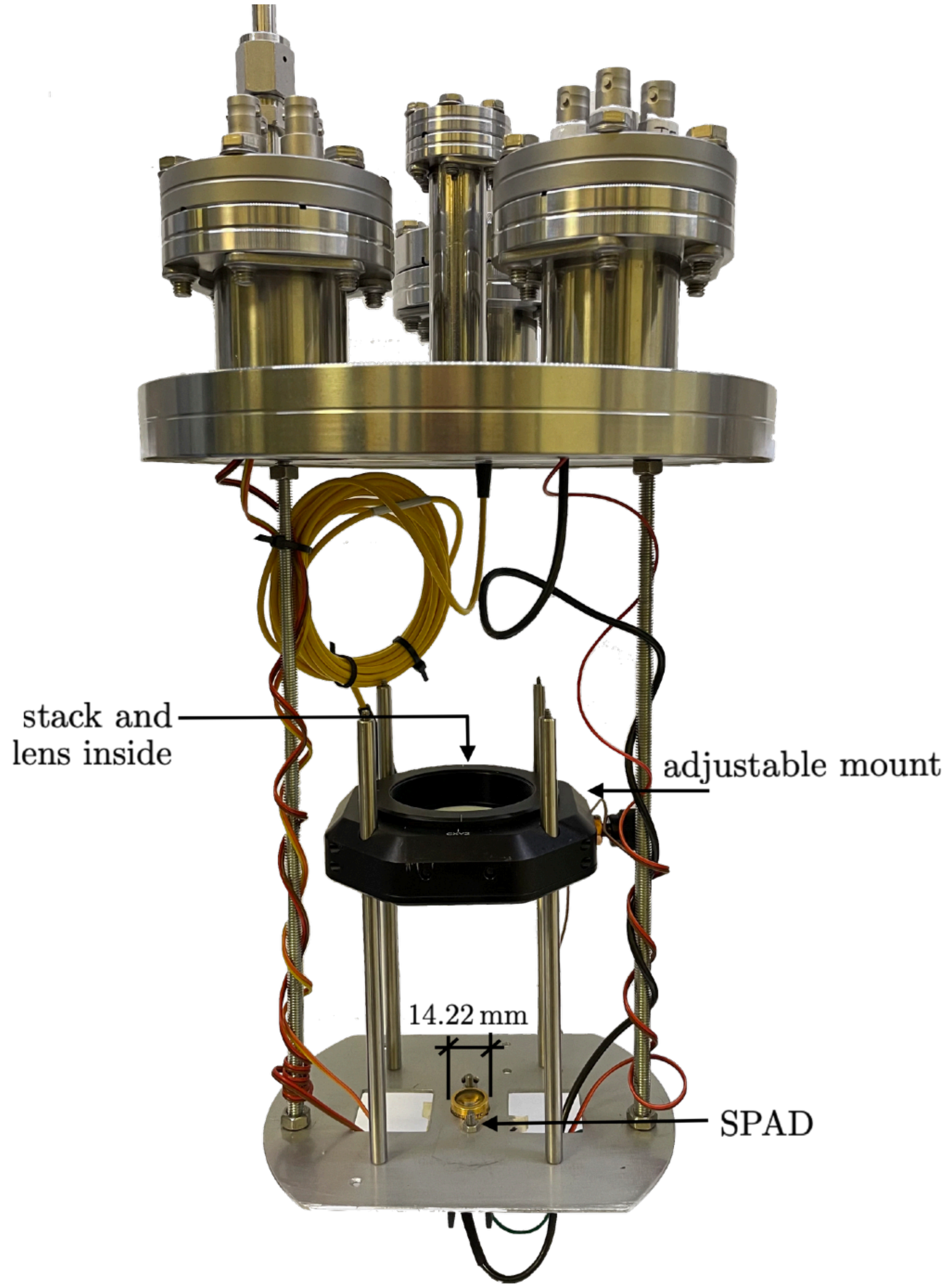
# Example Solution: 80 disks



# Dielectric Haloscopes

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

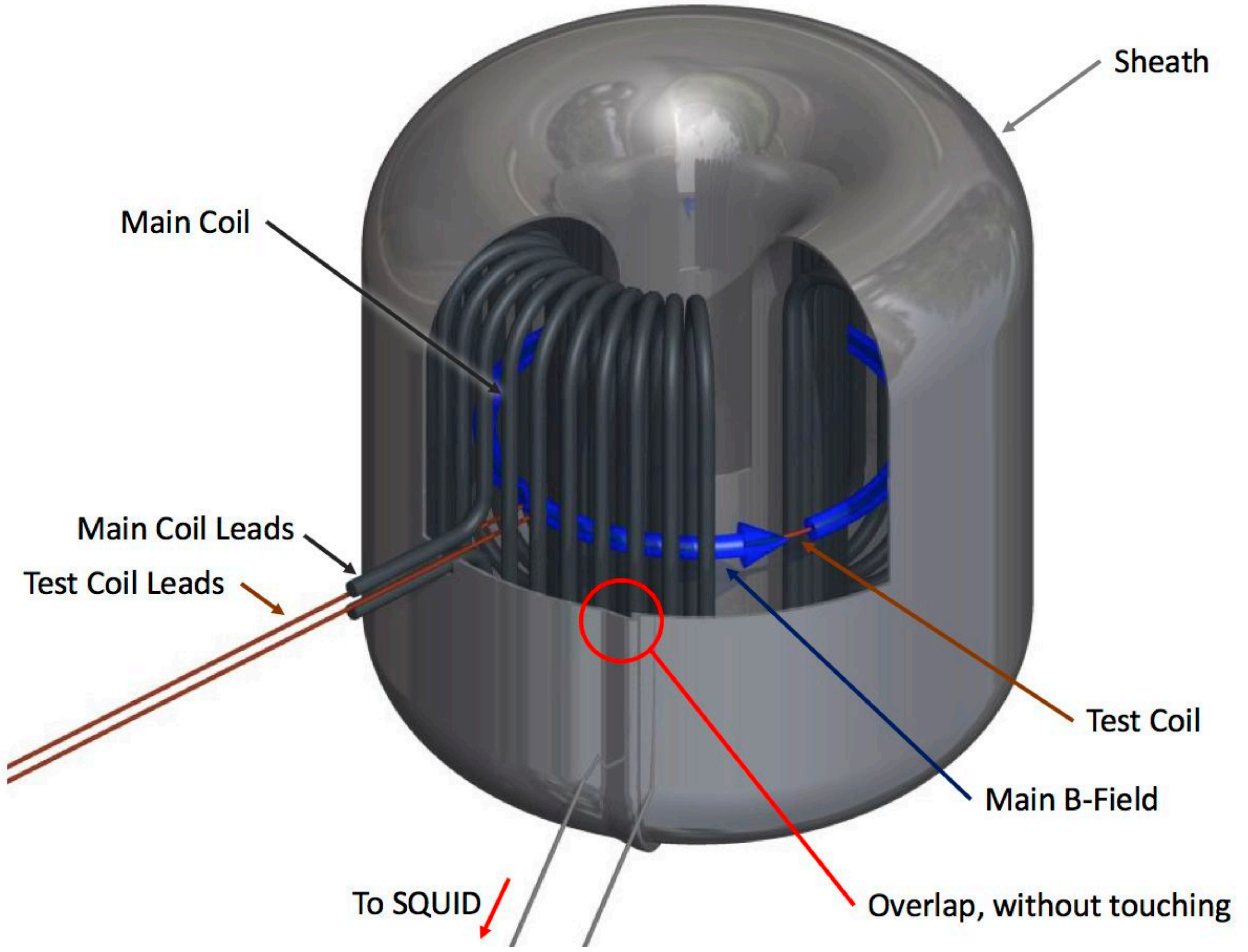





arXiv:2110.10497

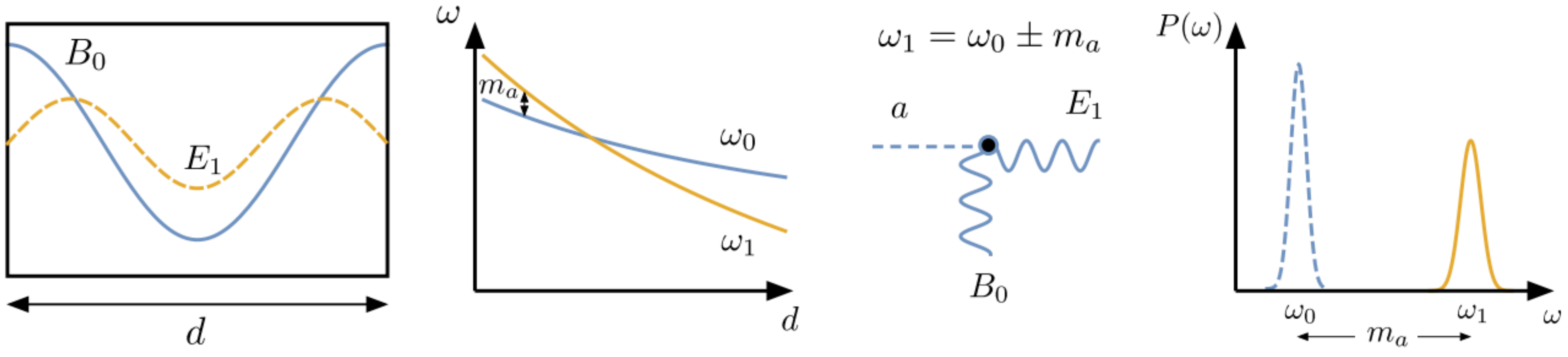
# LC Circuits

- Rather than measure E, create a circuit that measures B (1310.8545, 1602.01086)
- Can create geometries that generate B (but not E) in the presence of DM
- Can be made broadband or resonant
- Works sub-wavelength: good for low frequencies!
- ABRACADABRA and DM Radio are typical examples (recently they have combined forces)



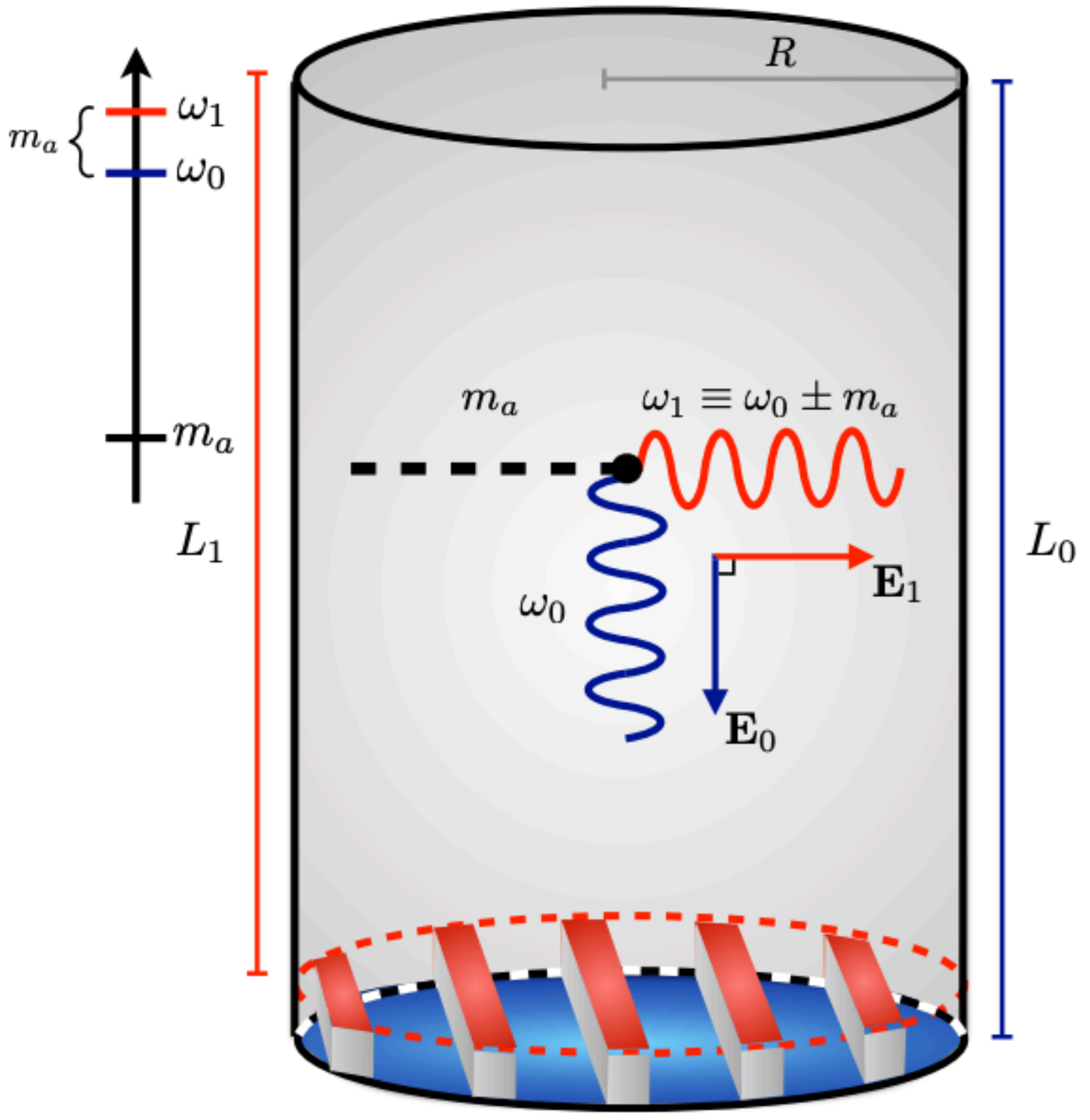
# Superconducting Cavities For Low Mass Axions

- Superconductive cavities have very high Q
- Tend to break in strong B-fields
- Pump in one cavity mode, read out an overlapping mode
- If the two modes are close, works for low axion masses
- Old idea recently revitalised: arXiv:1009.0762,1806.07141, 1902.01418, 1912.11056, 1912.11048, 2007.15656




Cavity modes Mode frequencies Interaction Signal

arXiv:1912.11056




(a) Cartoon of cavity setup.

arXiv:1912.11048

# Haloscopes for HP DM

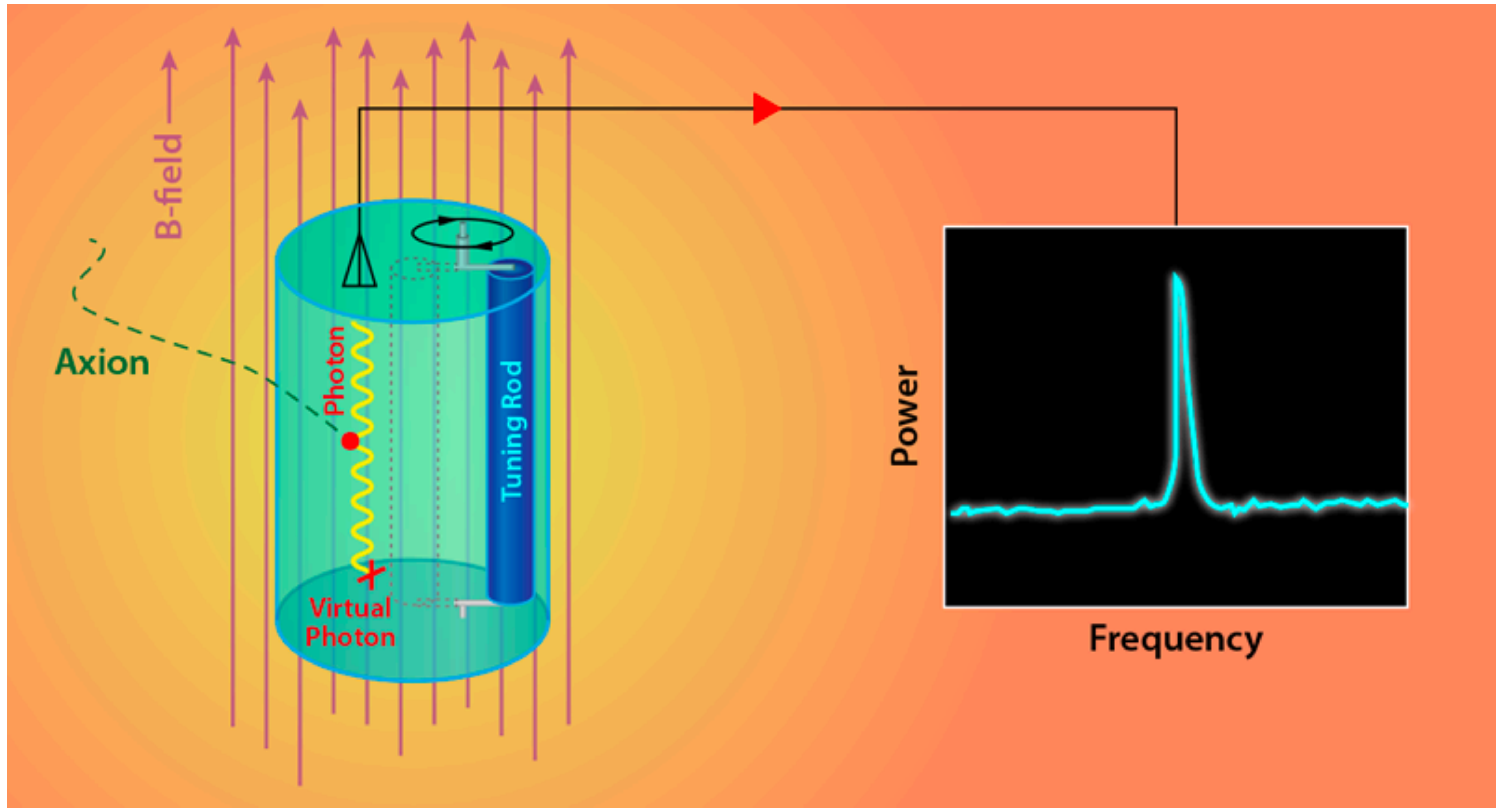
- In principle, most axion haloscopes using axion-photon mixing are sensitive to HPs
- For an example, take a cavity haloscope

$$P_{\rm cav}^{\rm DP} = \kappa \mathcal{G}^{\rm DP} V Q \rho_{\rm DM} \chi^2 m_X \,, \qquad \text{dark photon}$$

$$P_{\rm cav}^{\rm axion} = \kappa \mathcal{G}^{\rm axion} V \frac{Q}{m_a} \rho_{\rm DM} g_{a\gamma}^2 B^2 \,, \qquad \text{axion}$$

$$\mathcal{G}^{\rm DP} = \frac{\left(\int dV\, \mathbf{E}_\alpha \cdot \hat{\mathbf{X}}\right)^2}{V \frac{1}{2} \int dV\, \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2} \,,$$

$$\mathcal{G}^{\rm axion} = \frac{\left(\int dV\, \mathbf{E}_\alpha \cdot \mathbf{B}\right)^2}{V B^2 \frac{1}{2} \int dV\, \epsilon(\mathbf{x}) \mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2} \,.$$

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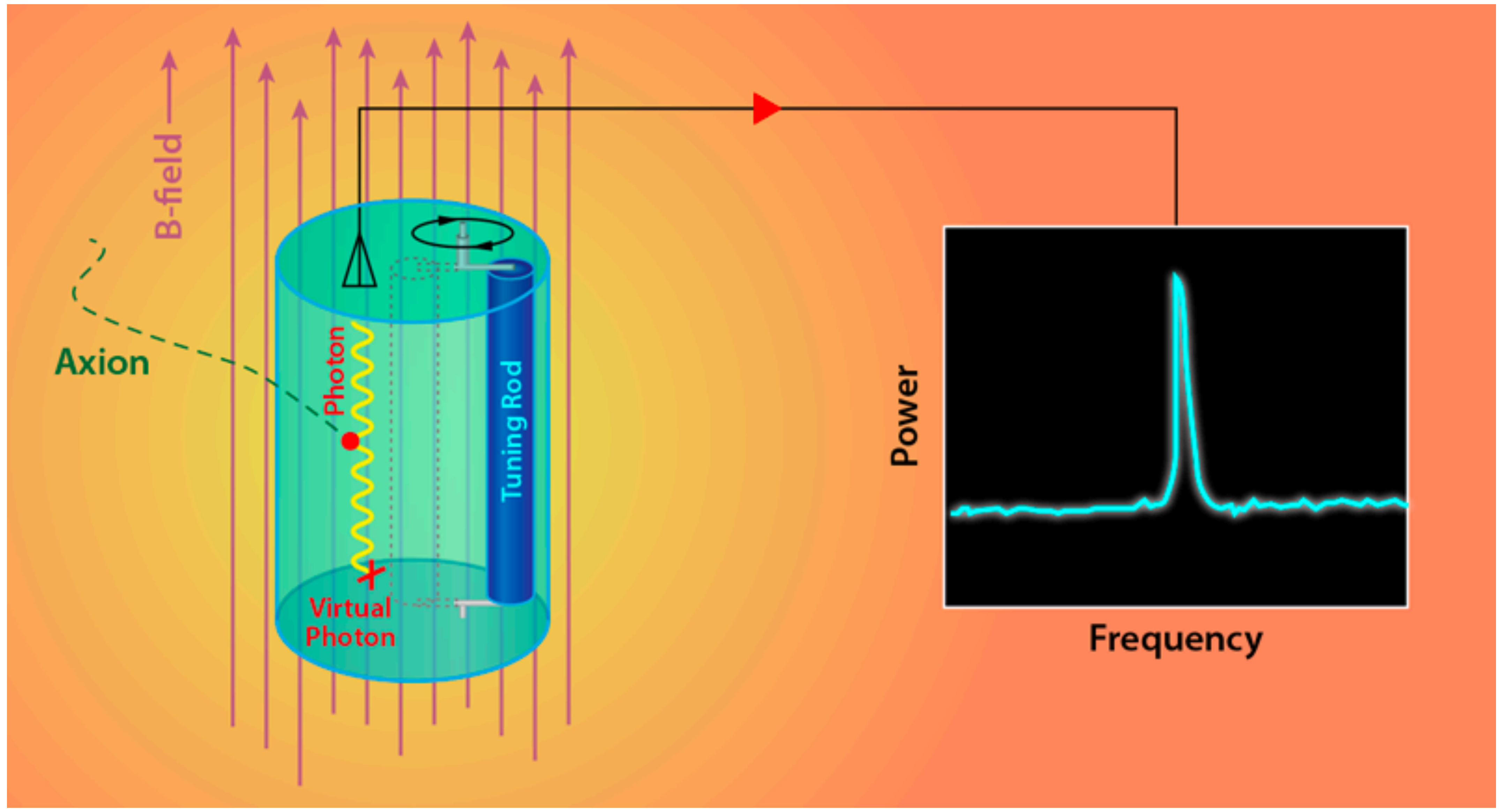
# Haloscopes for HP DM

- Two key differences
- HP does not need a B-field
- The polarisation direction of the HP matters
- (Usually) easy to convert between the two sensitivities

$$\chi = g_{a\gamma} \frac{B}{m_X |\cos\theta|}, \qquad \cos\theta = \hat{\mathbf{X}} \cdot \hat{\mathbf{B}}.$$

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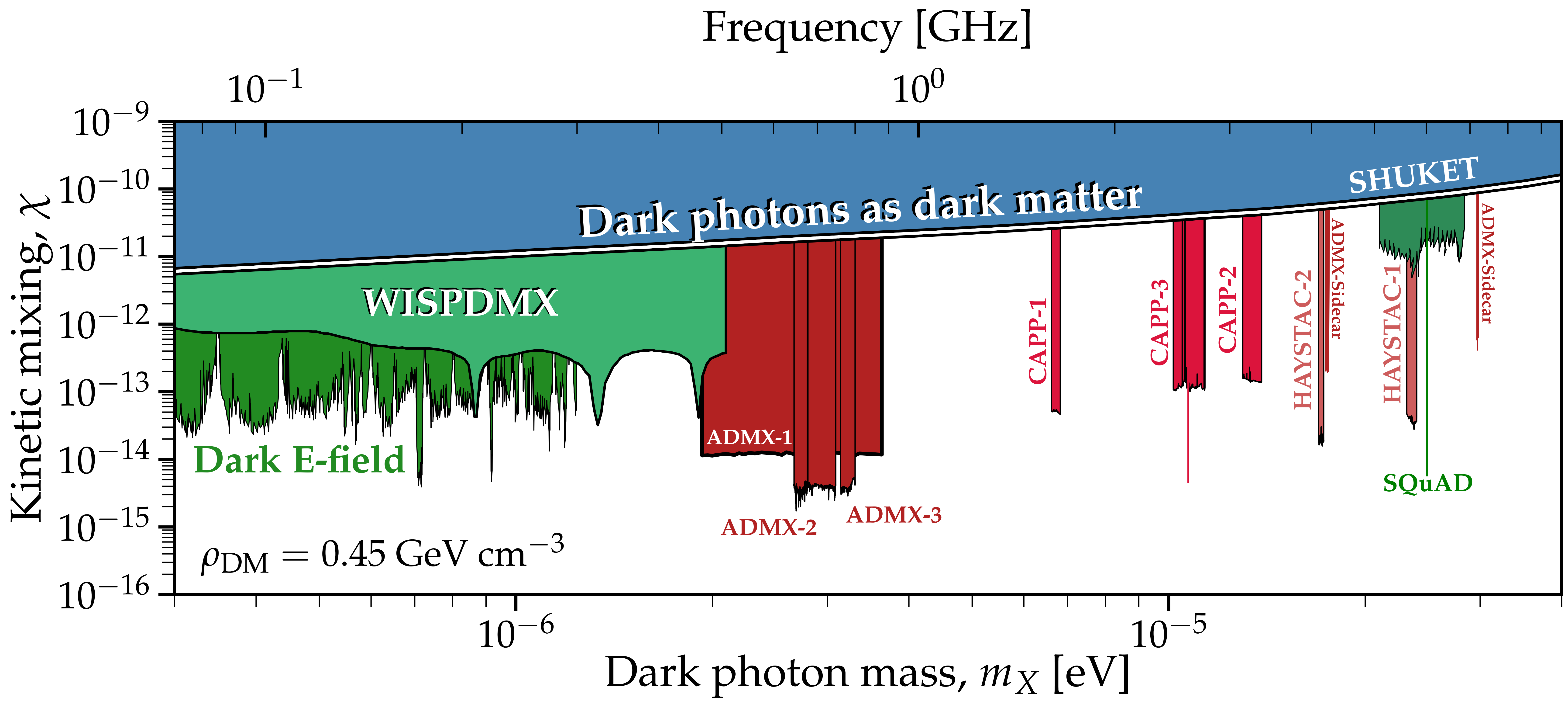
# Reinterpreting axion experiments

- Actually need to be very careful: many experiments use B-field vetos (arXiv:2006.06836)
- Polarisations can give a highly non-trivial time varying signal
- Timing and directional data rarely given
- Discovery potential can be improved by up to an order of magnitude with better search strategies (arXiv:2105.04565)

| | Experiment | | Magnetic field [T] | Latitude [°] | Measurement time, $T$ | Directionality | $\langle\cos^2\theta\rangle_T^{\text{excl.}}$ |
|---|---|---|---|---|---|---|---|
| Cavities | ADMX-1 | [107] | 7.6 | 47.66 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | ADMX-2 | [108] | 6.8 | 47.66 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | ADMX-3 | [110] | 7.6 | 47.66 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | ADMX Sidecar | [109] | 3.11[a] | 47.66 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | HAYSTAC-1 | [111] | 9 | 41.32 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | HAYSTAC-2 | [112] | 9 | 41.32 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | CAPP-1 | [113] | 7.3 | 36.35 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | CAPP-2 | [154] | 7.8 | 36.35 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | CAPP-3 | [155] | 7.2 and 7.9 | 36.35 | 90 s | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | CAPP-3 [KSVZ] | [155] | 7.2 | 36.35 | 15 hr | $\hat{\mathcal{Z}}$-pointing | 0.26 |
| | QUAX-$\alpha\gamma$ | [114] | 8.1 | 45.35 | 4203 s | $\hat{\mathcal{Z}}$-pointing | 0.03 |
| | †KLASH | [156] | 0.6 | 41.80 | $\mathcal{O}$(min) | $\hat{\mathcal{Z}}$-pointing | ∼0.025 |
| | RBF | [115] | Magnetic field veto | | | | |
| | UF | [116] | Magnetic field veto | | | | |
| | ORGAN | [117] | Magnetic field veto | | | | |
| | RADES | [157] | Magnetic field veto | | | | |
| LC-circuits | ADMX SLIC-1 | [158] | 4.5 | 29.64 | $\mathcal{O}$(min) | $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing | ∼0.37 |
| | ADMX SLIC-2 | [158] | 5 | 29.64 | $\mathcal{O}$(min) | $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing | ∼0.37 |
| | ADMX SLIC-3 | [158] | 7 | 29.64 | $\mathcal{O}$(min) | $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing | ∼0.37 |
| | ABRACADABRA | [118] | Magnetic field veto | | | | |
| | SHAFT | [119] | Magnetic field veto | | | | |
| Plasmas | †ALPHA | [159] | 10 | Unknown | $\mathcal{O}$(week) | $\hat{\mathcal{Z}}$-pointing | 0.28–0.33 |
| Dielectrics | †MADMAX | [160] | 10 | 53.57 | $\mathcal{O}$(week) | $\hat{\mathcal{Z}}$-pointing or $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing | 0.26 or 0.62–0.66[b] |
| | †LAMPOST | [36] | 10 | Unknown | $\mathcal{O}$(week) | Any-facing | 0.61–0.66 |
| | †DALI | [161] | 9 | 28.49 | $\mathcal{O}$(month) | Any-facing[c] | 0.61–0.66 |
| Dish antenna | †BRASS | [110] | 1 | 53.57 | $\mathcal{O}$(100 days) | Any-facing | 0.61–0.66 |
| Topological insulators | †TOORAD | [162] | 10[d] | Unknown | $\mathcal{O}$(day) | Any-pointing | 0.18–0.33 |

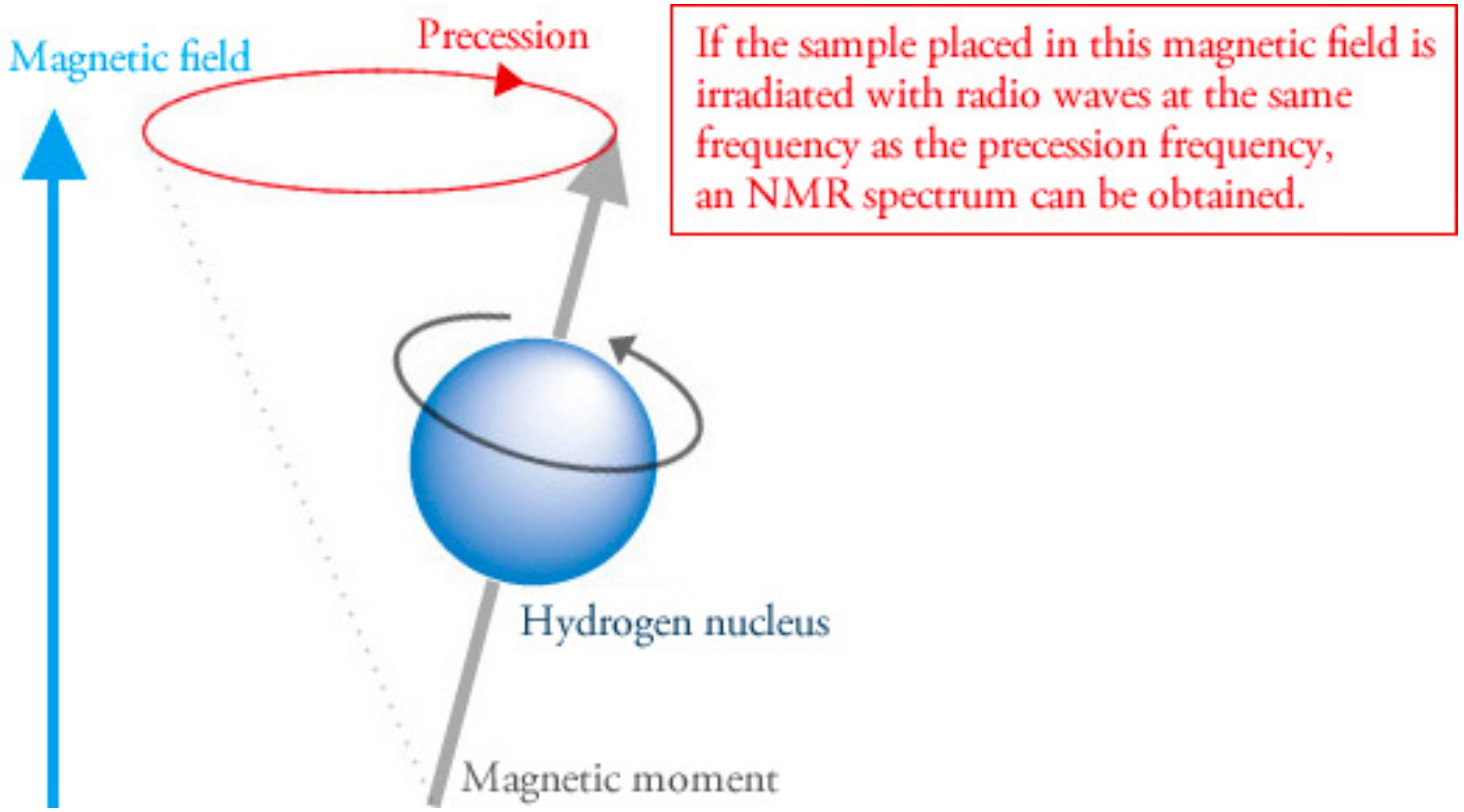
# Current HP Limits

- Rescaled for fixed polarisation (conservative case)



# Nuclear Magnetic Resonance

- Many other couplings to probe!
- NMR techniques have exquisite sensitivity
- Prepare atoms into a specific spin state and look for precession
- Resonance with the Larmor frequency



# Example: Axion Wind

- Axions also couple to fermions

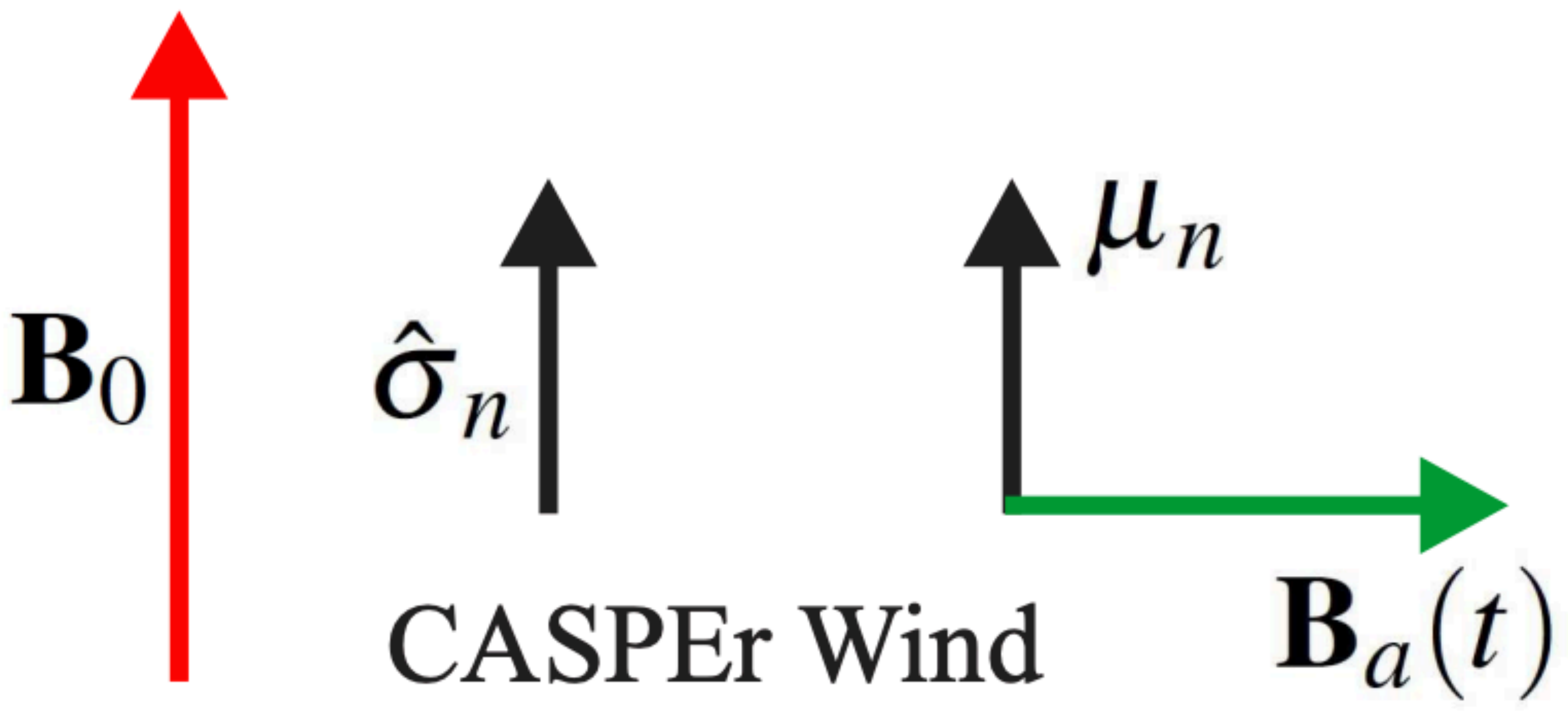
$$\mathscr{L} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m_e)\psi - a g_{ae} i\bar{\psi}\gamma^5\psi + \mathscr{L}_{\rm kin}$$

- Electrons are heavy, axions are slow…

$$H_{\rm int} = \frac{g_{ae}^2 a^2}{2m_e} - \frac{i g_{ae}}{2m_e} a\mathbf{p}_e \cdot \sigma + \boxed{\frac{g_{ae}}{2m_e}\nabla a \cdot \sigma}$$

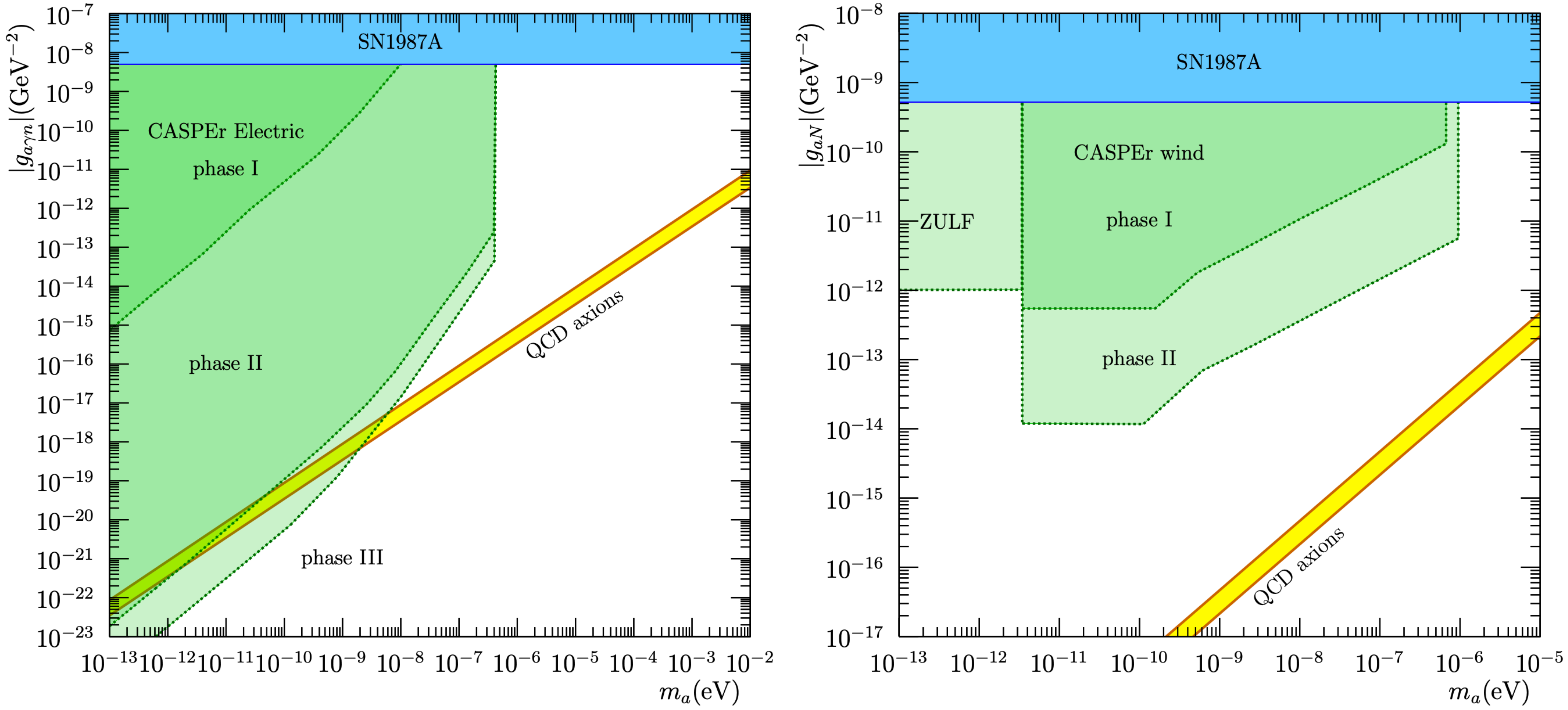
# CASPEr-wind

- Polarise a lot of spins in the same direction (like Xenon)
- Apply some magnetic field to give a Larmor frequency $\Omega = \gamma_N B_0$
- Axion wind causes precession if $m_a = \Omega$
- Measure for spins not aligned with B
- Great for low frequencies!




arXiv:1711.08999

# CASPEr

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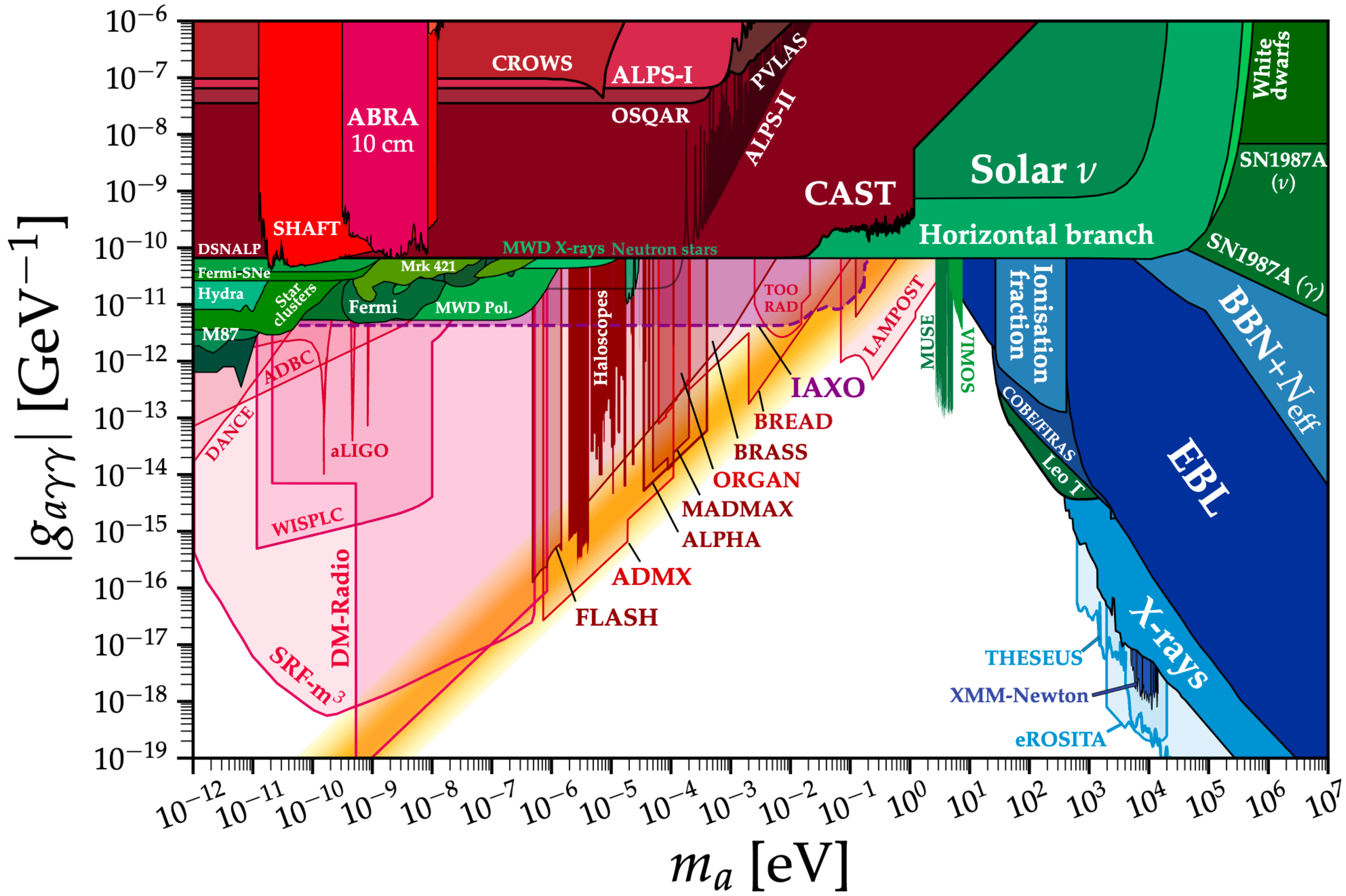
arXiv:1711.08999

# Conclusions

- Many new ideas that will be capable of searching a large fraction of the well motivated parameter space
- Still early days! Need to be shown practical
- Needs some standardisation about assumptions
- Axion experiments should do dedicated DP analysis, not just leave them for people to try to reinterpret them




https://github.com/cajohare

# Teaser for next time

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