New Ideas in Wavelike Dark Matter Detection

Alex Millar

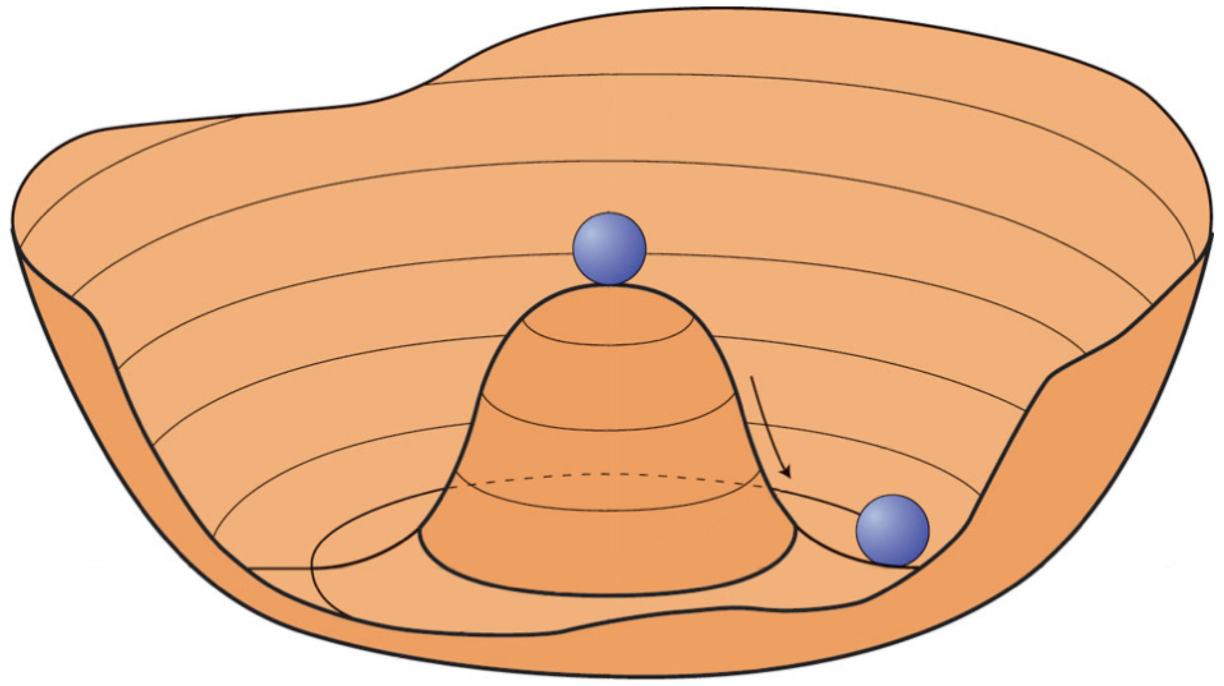
Wavelike Dark Matter

- 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
- What about light dark matter, say below eV?
- Much higher occupation numbers (can be more than 10^{25}): usually treated as a classical field
- Totally different phenomenology

Axions and ALPs

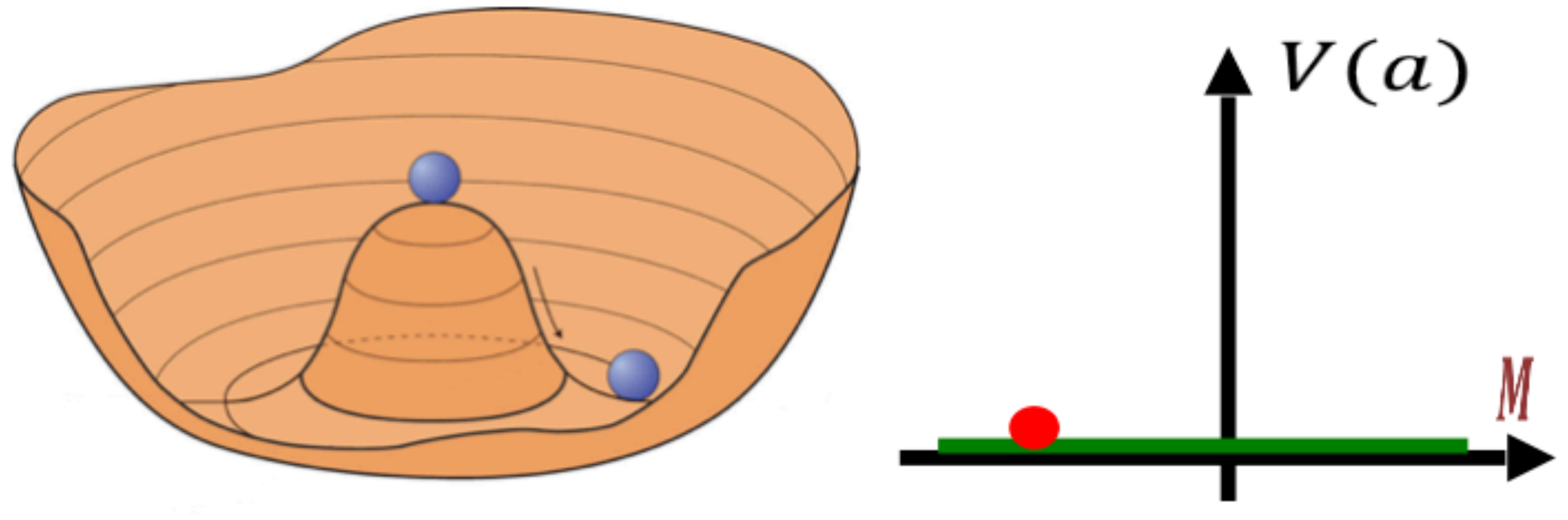
- Introduced to resolve the strong CP problem
- Introduce a new anomalous U(1) chiral symmetry
- New pseudoscalar degree of freedom

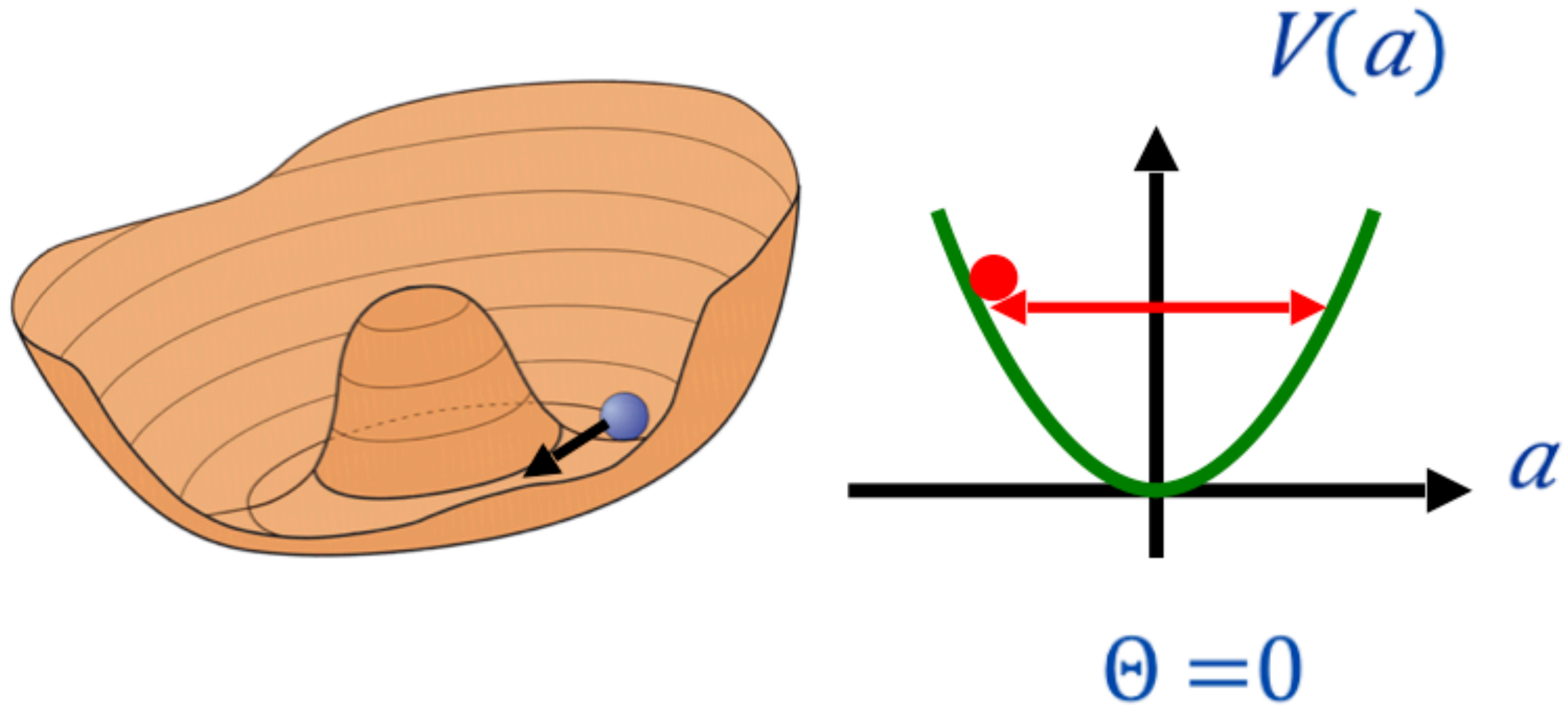
$$\begin{aligned}\mathcal{L}_{\text{stand mod + axion}} &= \dots + \frac{1}{2}\partial_\mu a \partial^\mu a \\ &+ \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\end{aligned}$$



Axions and Alps

- 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
- Can be produced by misalignment or topological defects

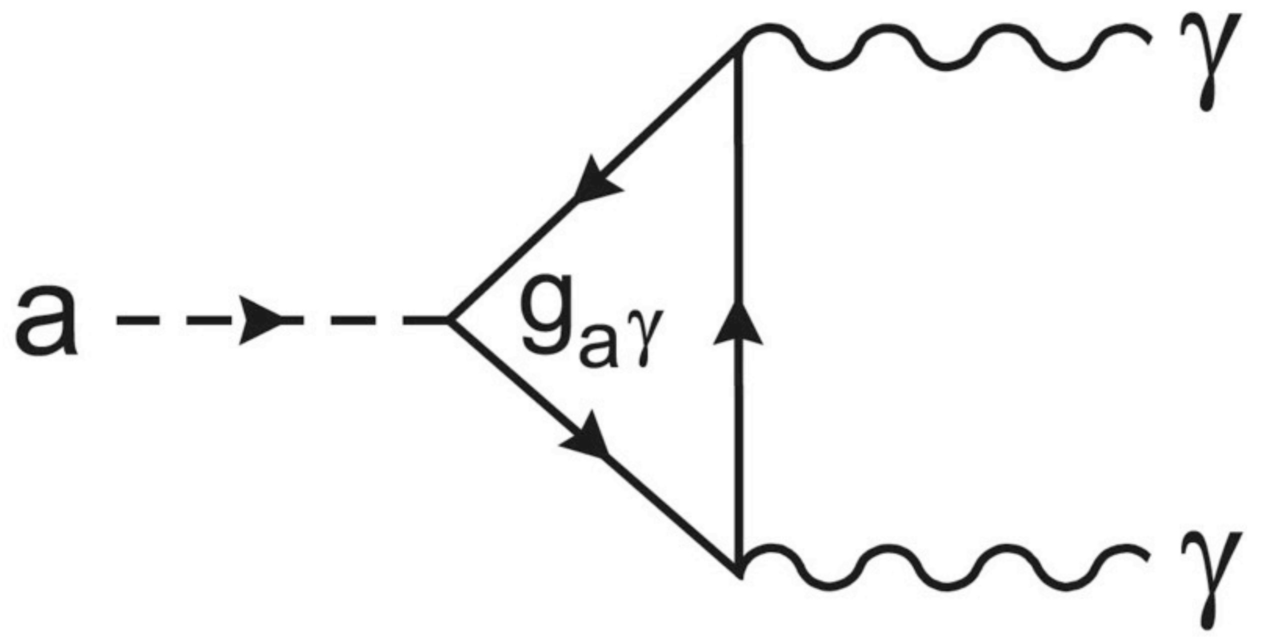




Axion Electrodynamics

- 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

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



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

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

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

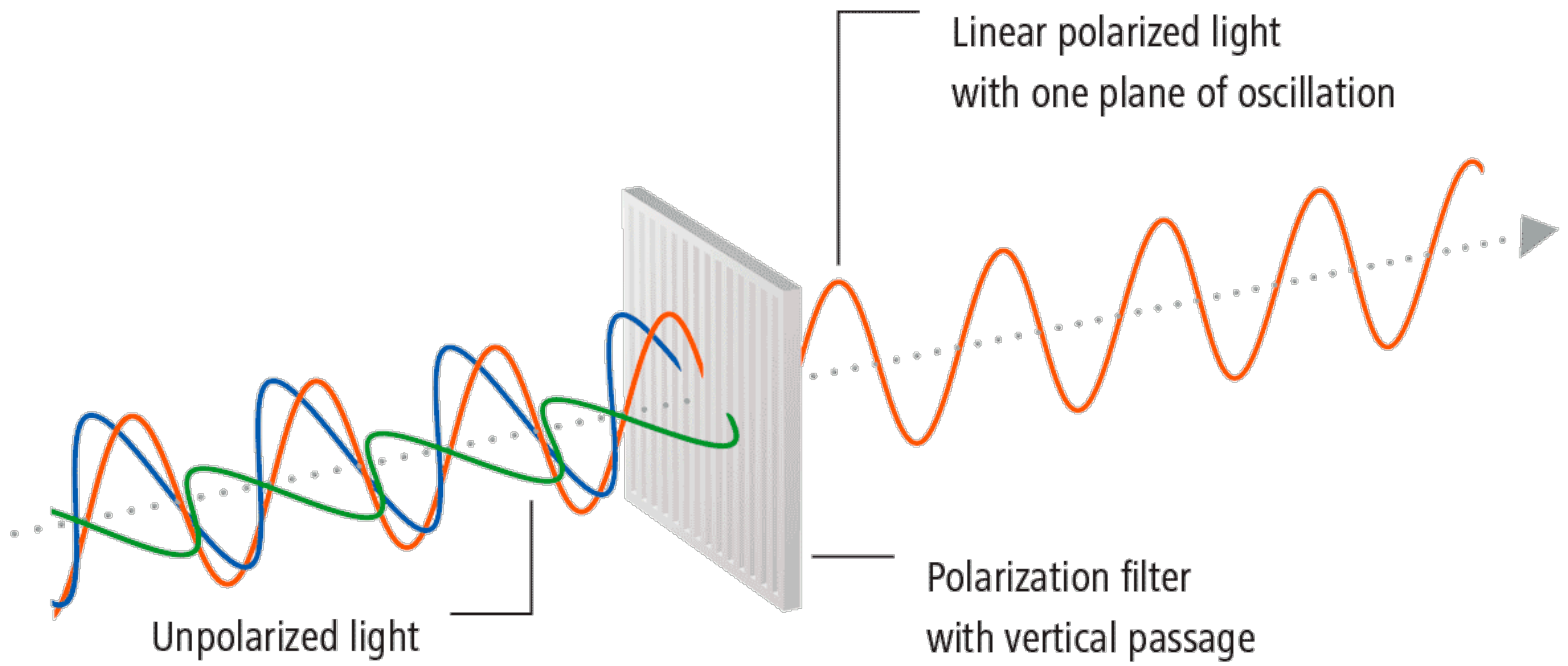
Hidden/Dark photons

- New U(1) gauge boson with tiny kinetic mixing with the visible photon
- Can be non-thermally produced as a good dark matter candidate

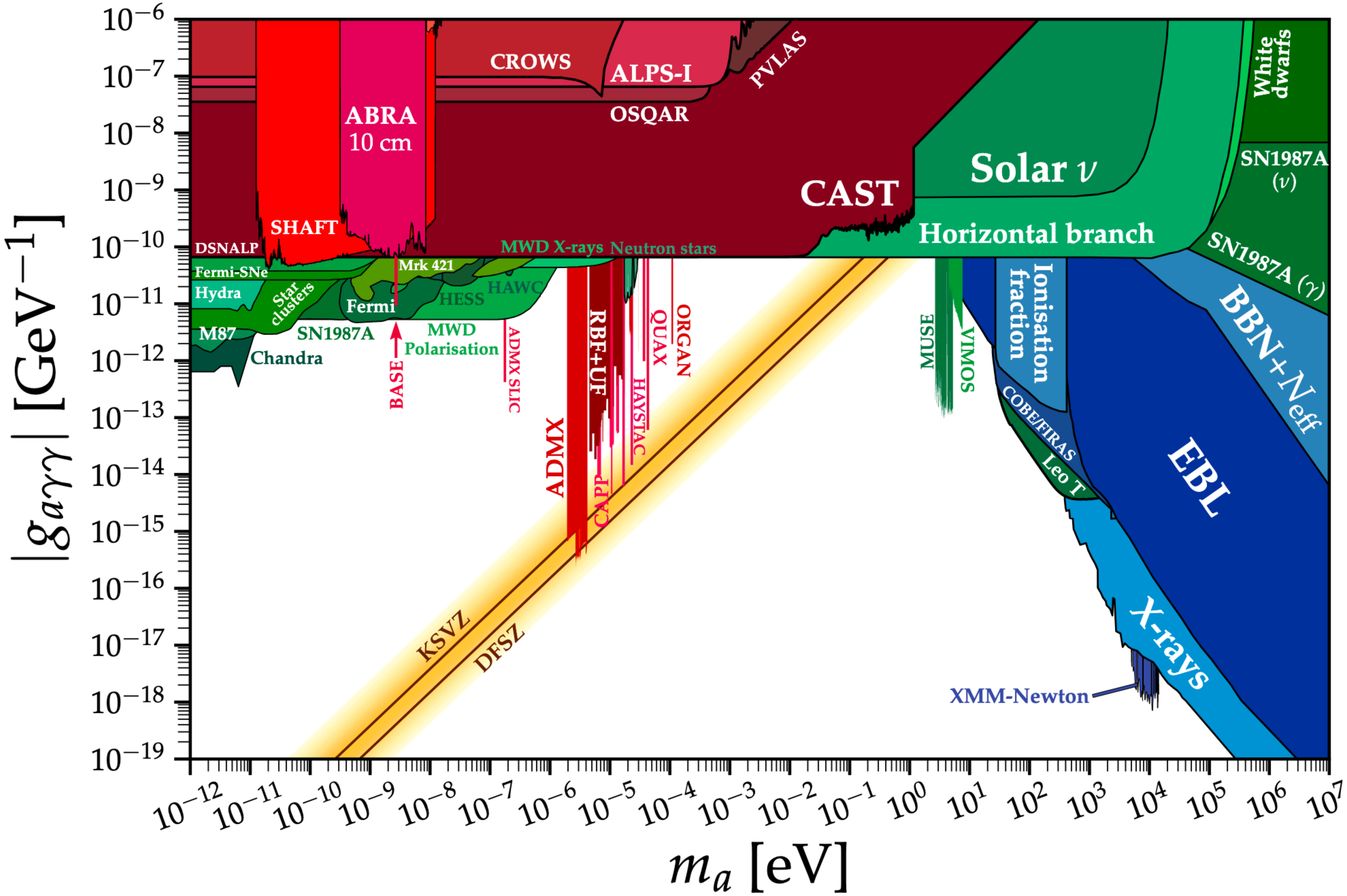
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + eJ^{\mu}_{\mathrm{EM}}A_{\mu} + \frac{m_X^2}{2}\left(X^{\mu}X_{\mu} + \boxed{2\chi X_{\mu}A^{\mu}}\right) ,$$

Hidden Photons vs ALPs

- Key difference: HP doesn't need B-field!
- Key difference: HP has a polarisation!
- May be randomised or fixed depending on the production mechanism (or somewhere in-between)
- Structure formation may change this, but no detailed studies



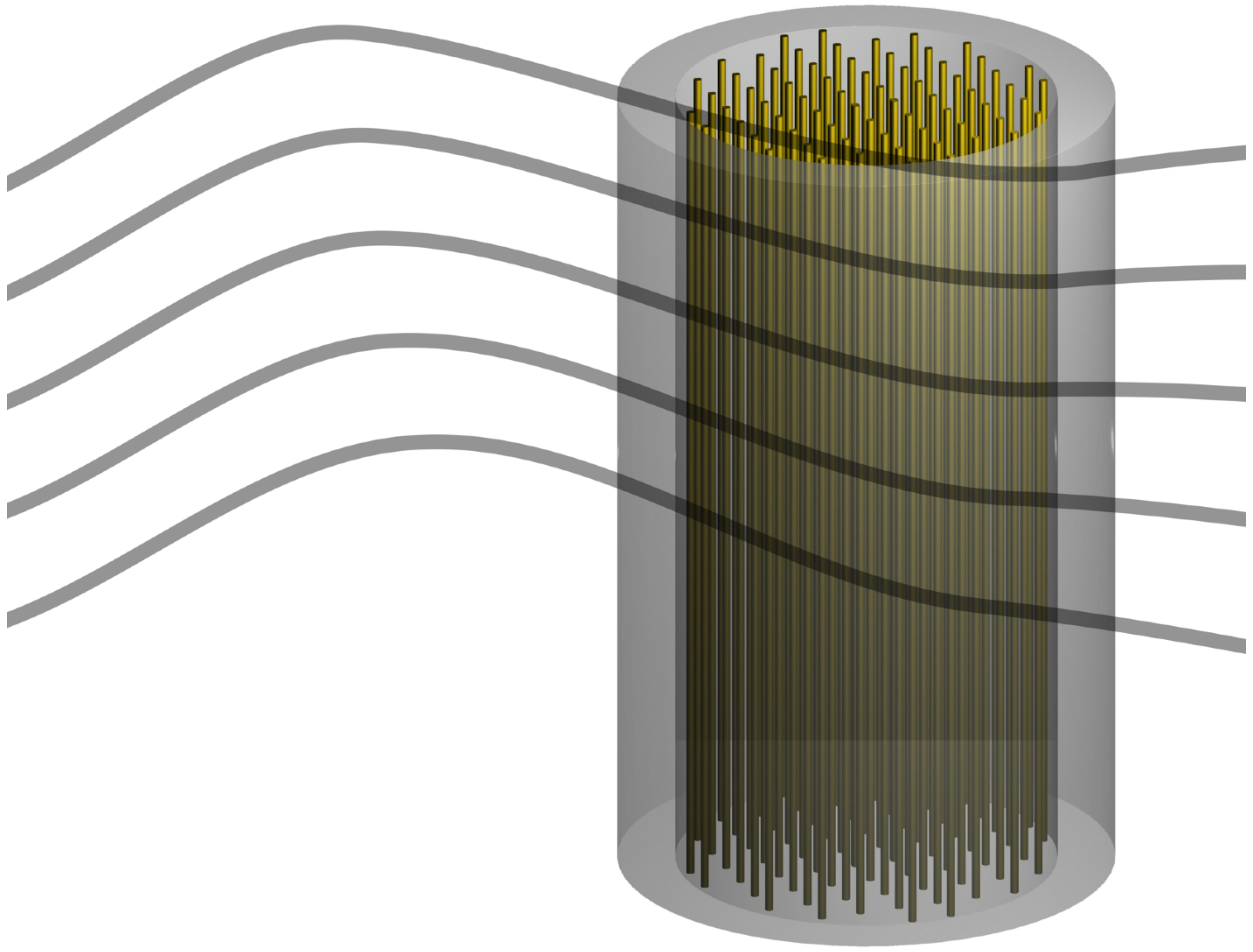
Parameter Space



https://github.com/cajohare

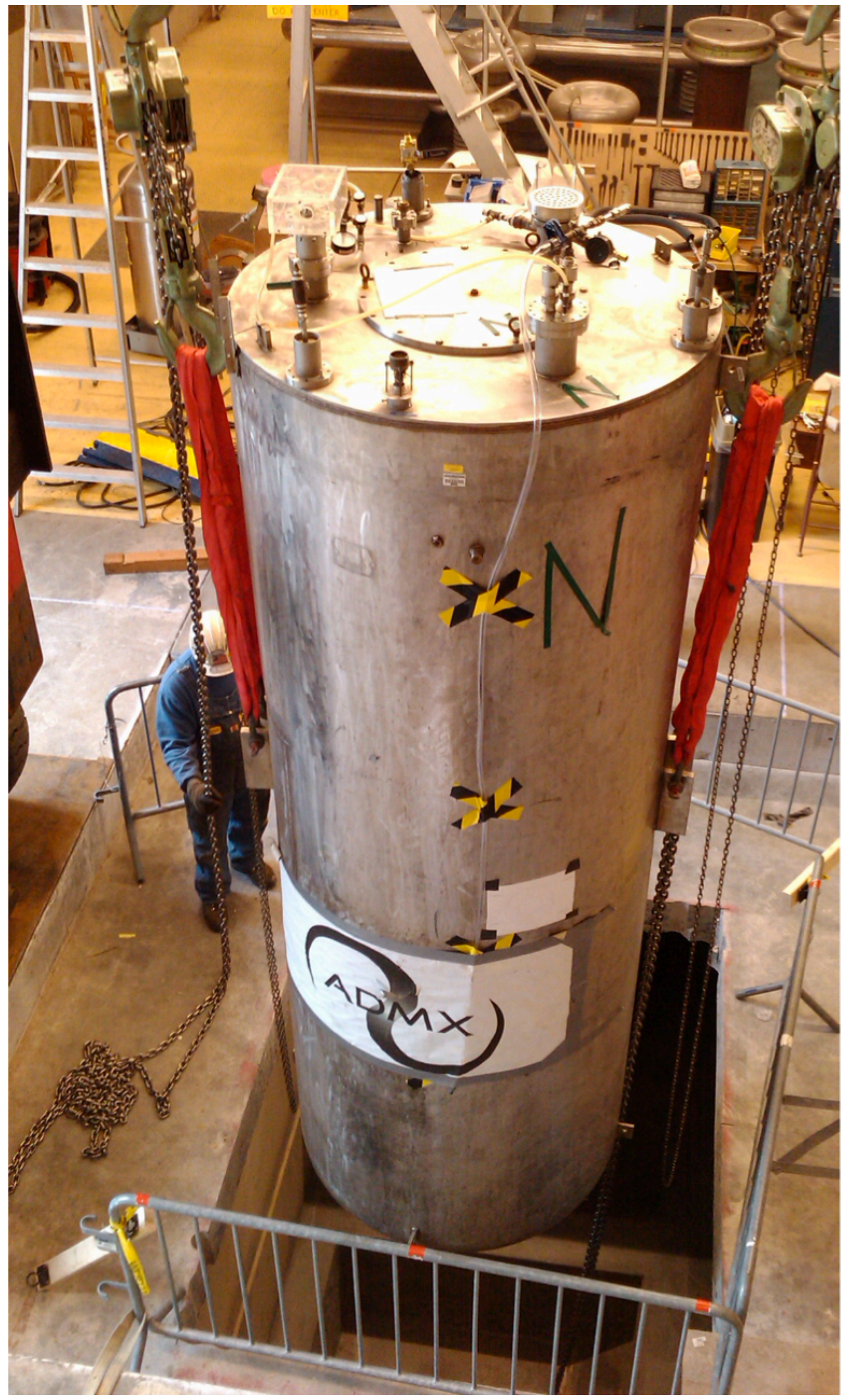
How do you find a wave?

- 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



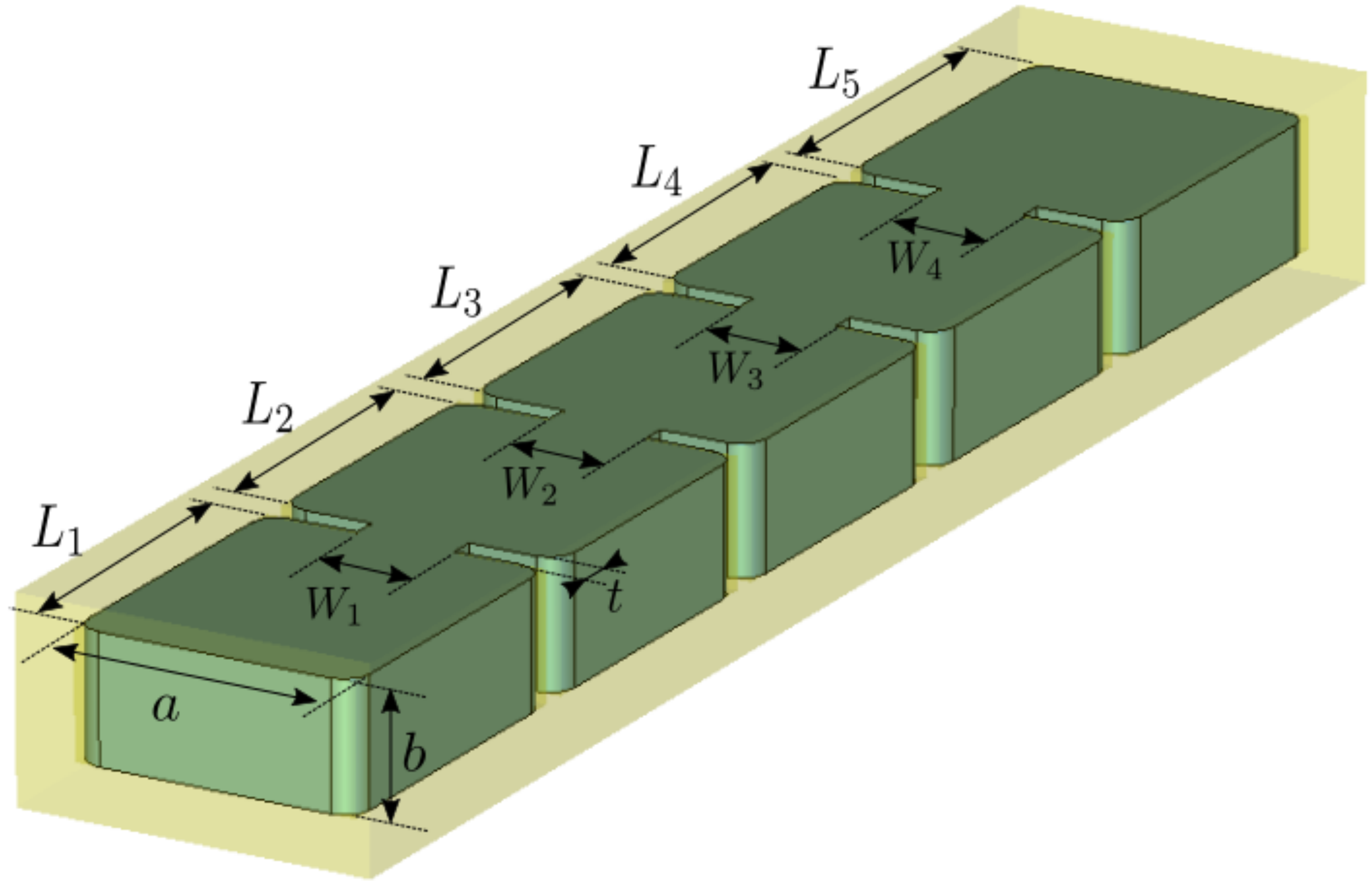
Cavity Haloscopes

- 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

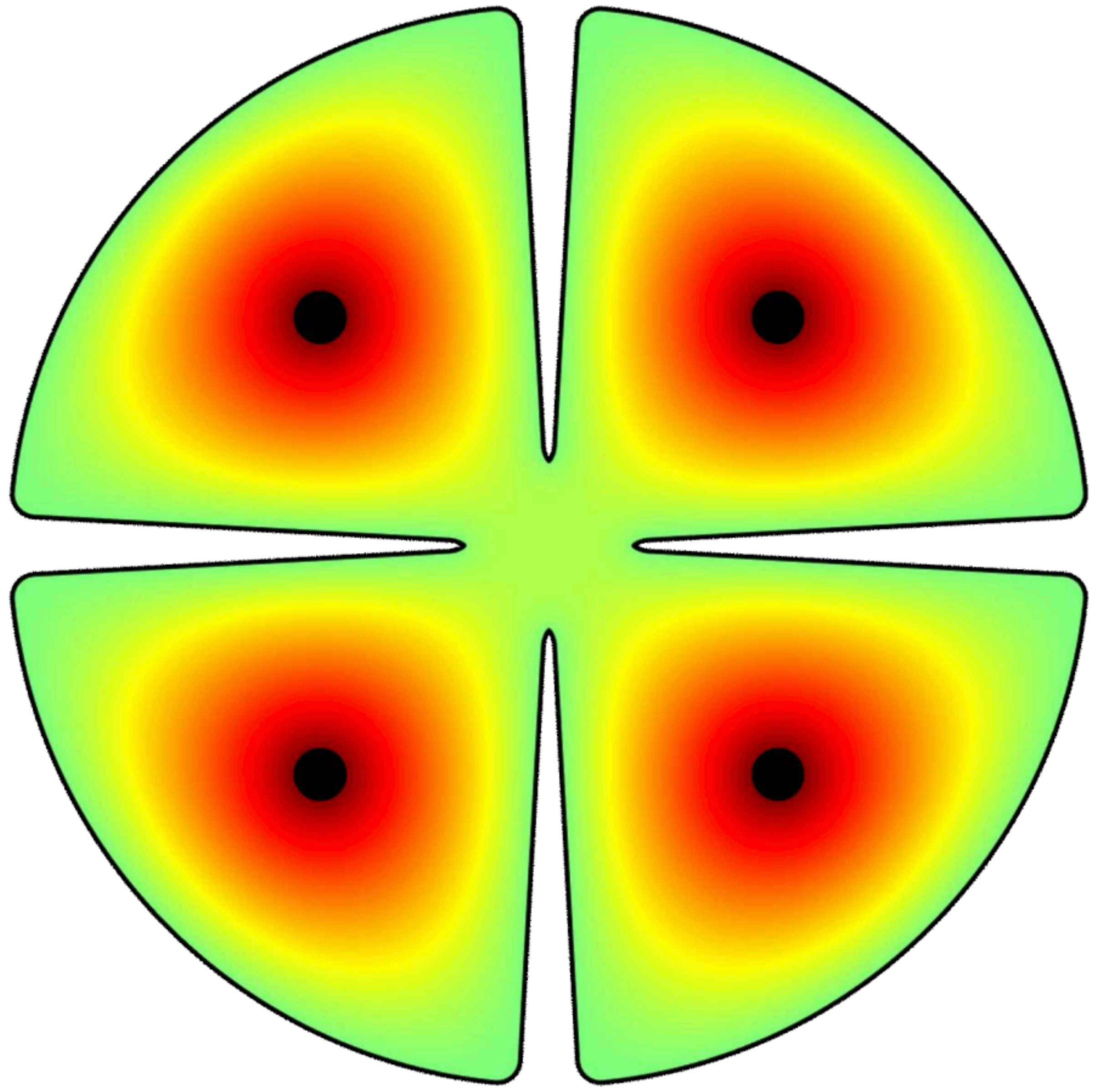
- Multiple cavities (ADMX, CULTASK)
- Coupled cavities (RADES, CULTASK, ORGAN)
- Non-traditional cavities (ADMX, HAYSTAC, CULTASK)
- Bigger Magnets
- Better detectors (Beyond the SQL)



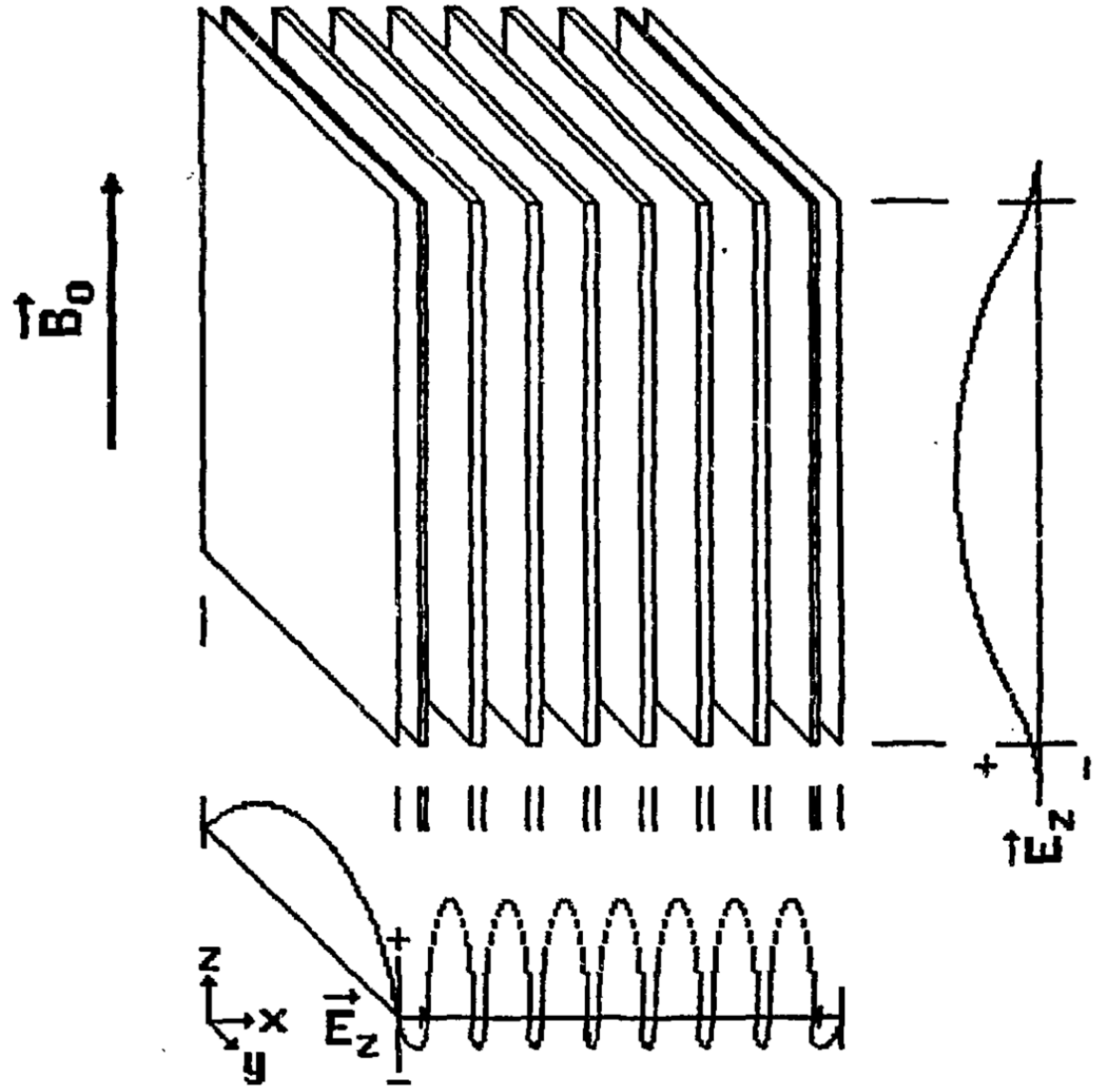
RADES (arXiv:1803.01243)

Cavity Extensions

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



arXiv:1710.06969



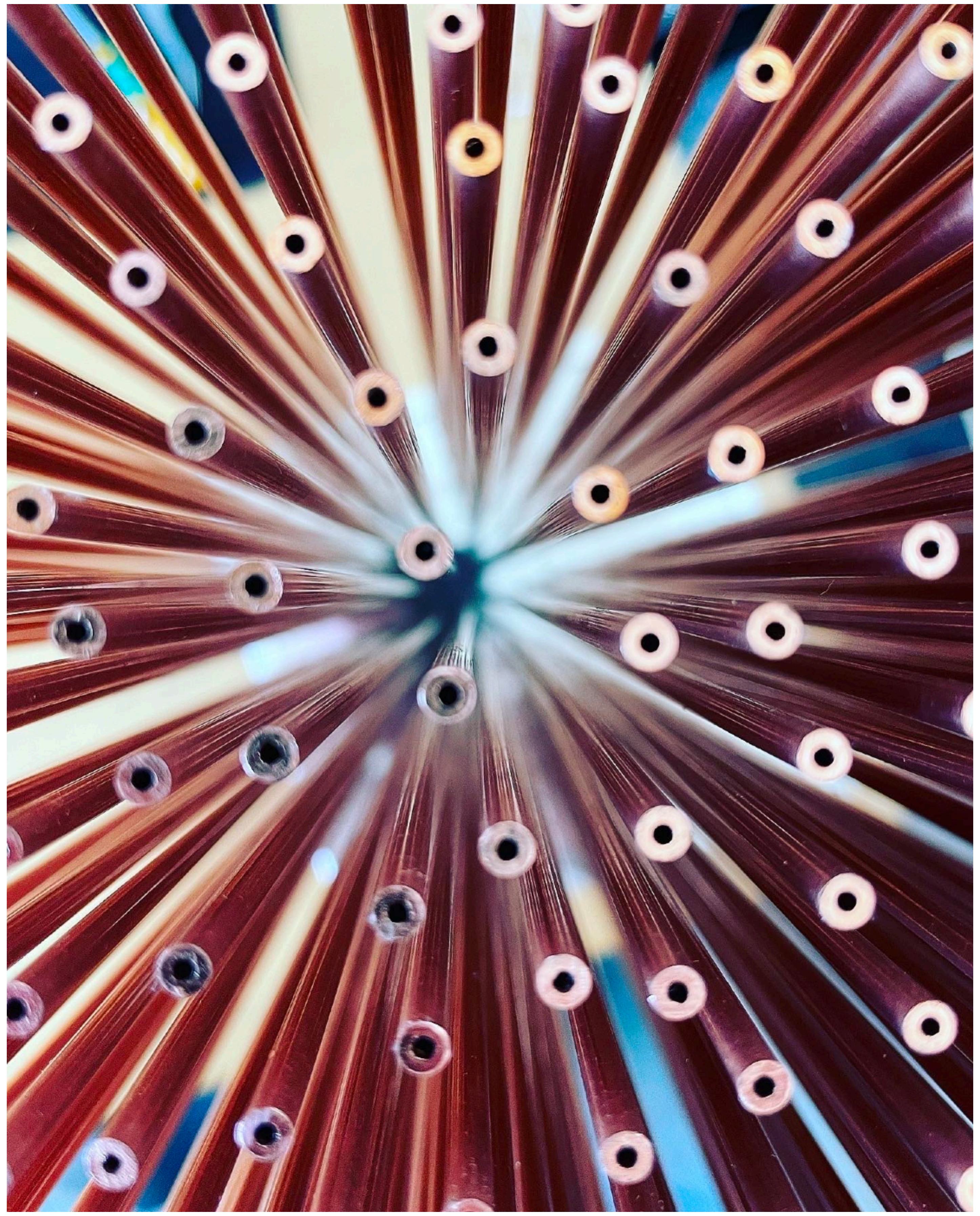
Morris 1984

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)
- Black hole super radiance
- Neutron star radio signals…

Plasma Haloscopes

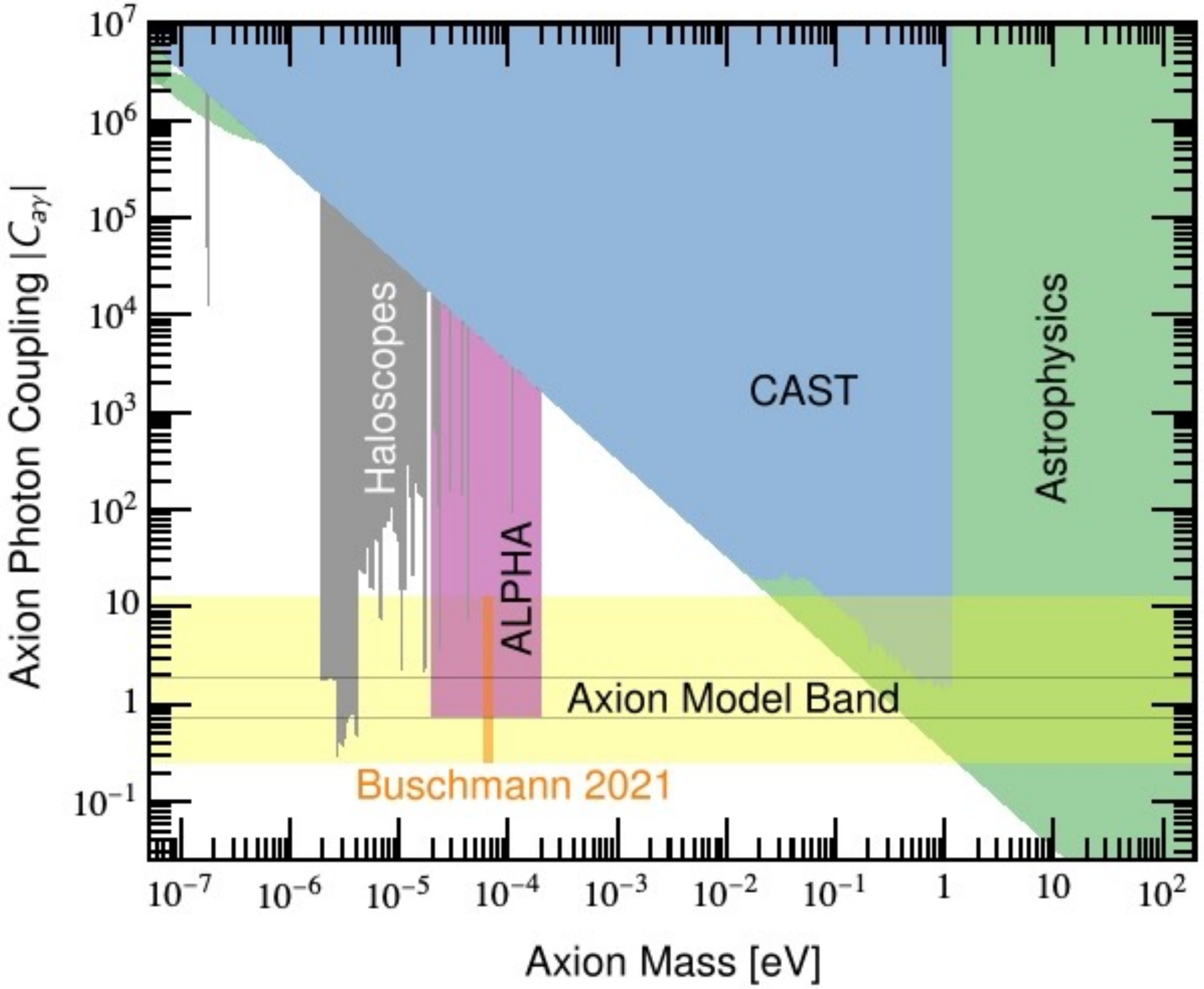
- Why break translation invariance?
- Just match the photon and DM masses: plasma!
- Strong possibilities using wire metamaterials (arXiv:1904.11872, arXiv:2006.06836)
- Not limited by the Compton wavelength!
- Allows for higher masses to be searched
- Being pursued by ALPHA
- Similar idea with dielectric rods instead of metal wires being pursued at CAPP (arXiv:2205.08885)



Jón Gudmundsson

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



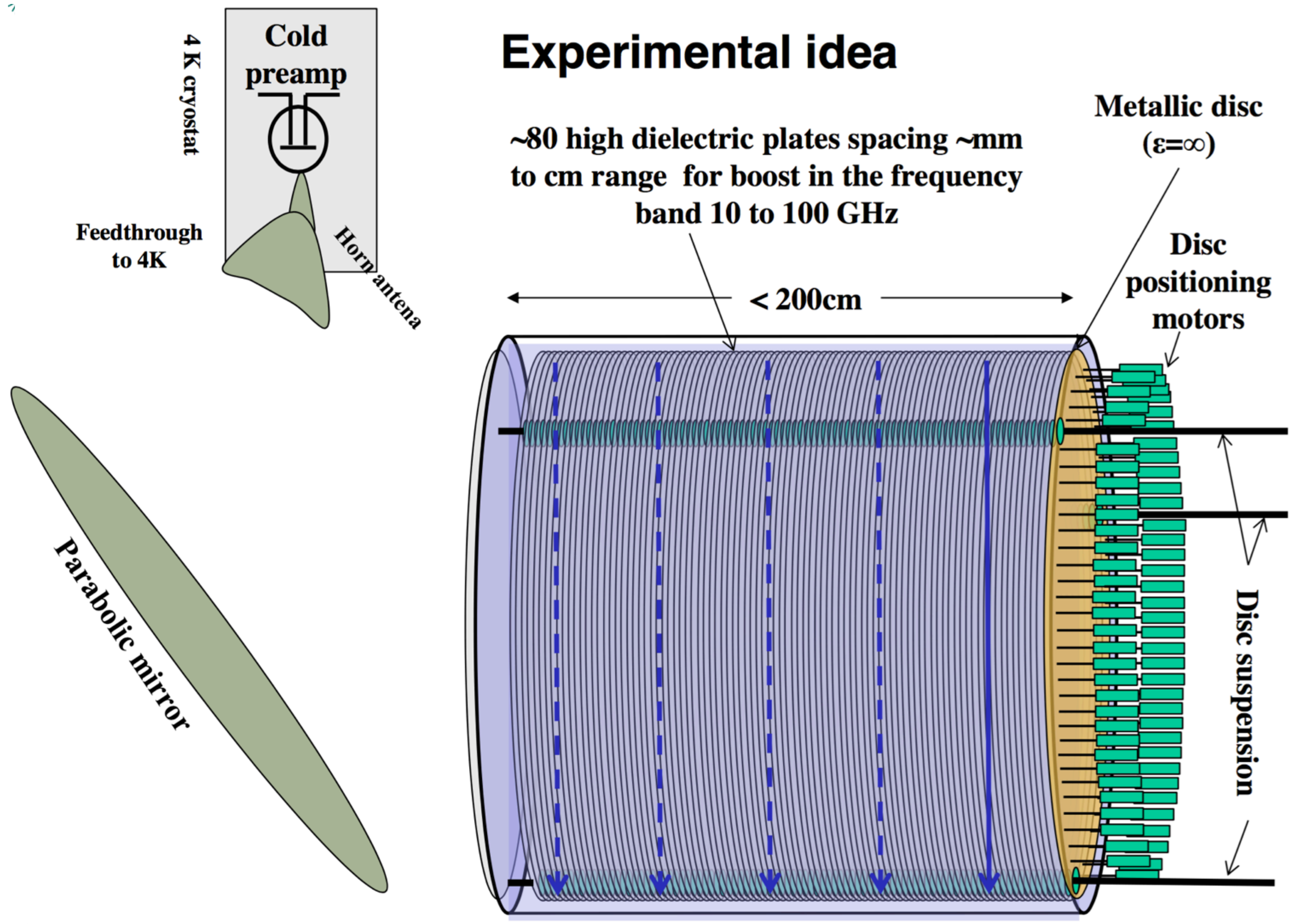
Dish Antenna

- Breaks translation invariance with a mirror (arXiv:1212.2970)
- No resonance!
- Completely broadband response
- Focus a large area onto a detector to increase S/N
- Experiments like FUNK, Tokyo, SHUKET, BREAD, BRASS…

arXiv:2003.13144

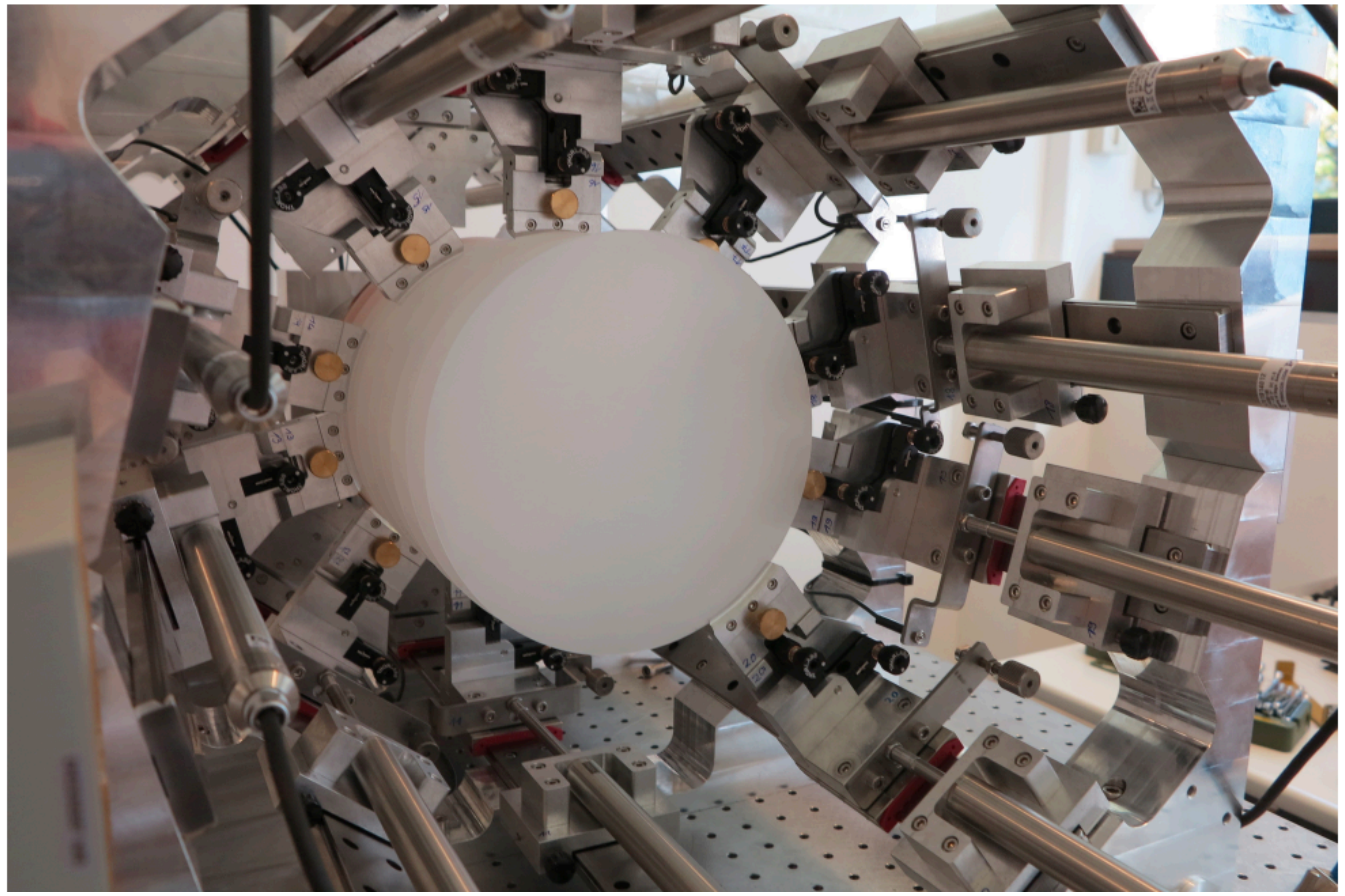
Dielectric Haloscopes

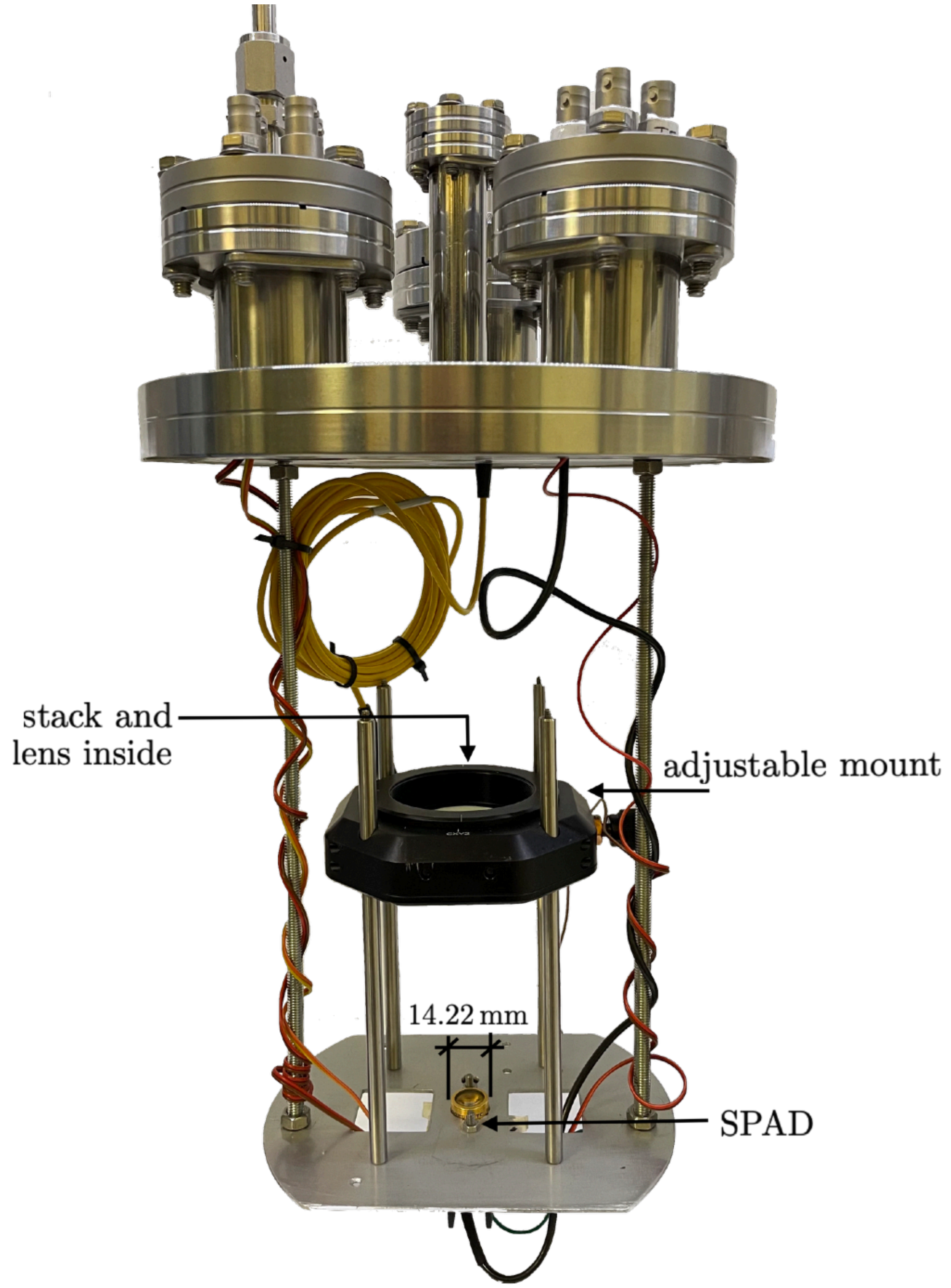
- Dish antenna on steroids (arXiv:1611.05865)
- Use many dielectric layers, each creating waves which constructively interfere
- Tune frequencies by controlling disk spacings
- Lots of freedom over frequency response!
- Very large volumes
- Being pursued by MADMAX, MuDHI and LAMPOST



Dielectric Haloscopes

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

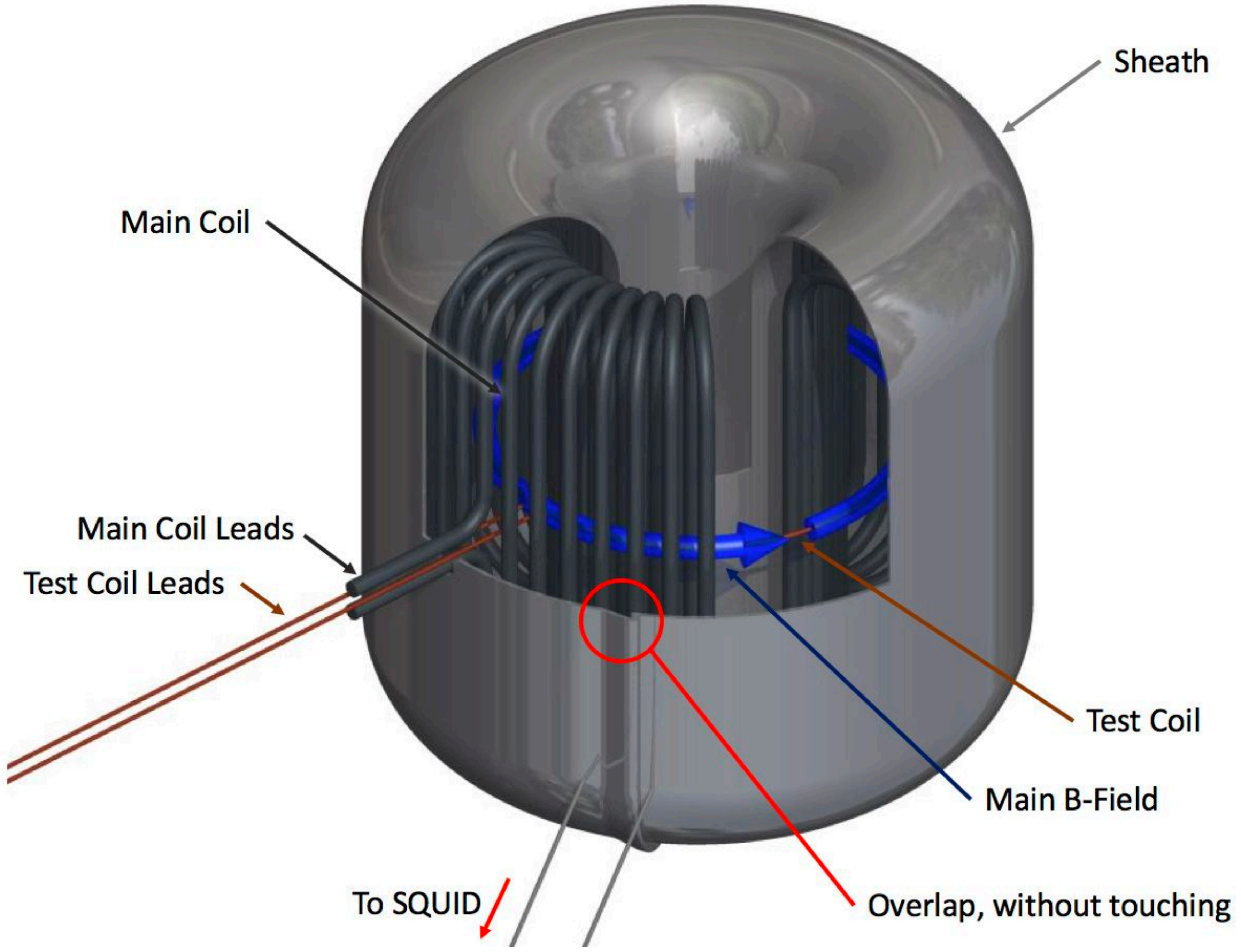




arXiv:2110.10497

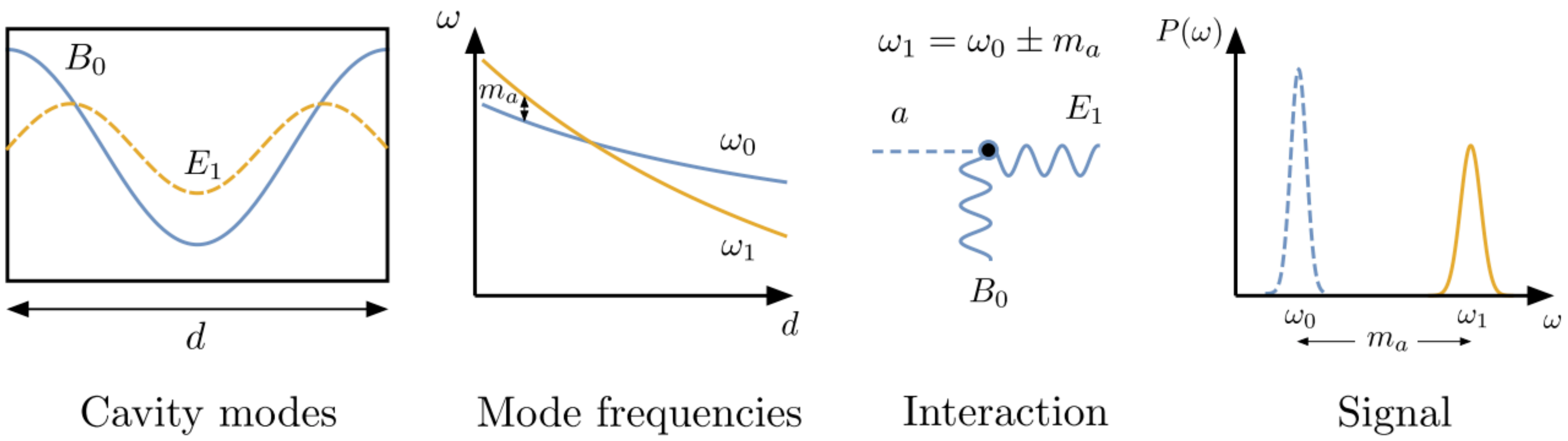
LC Circuits

- 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)

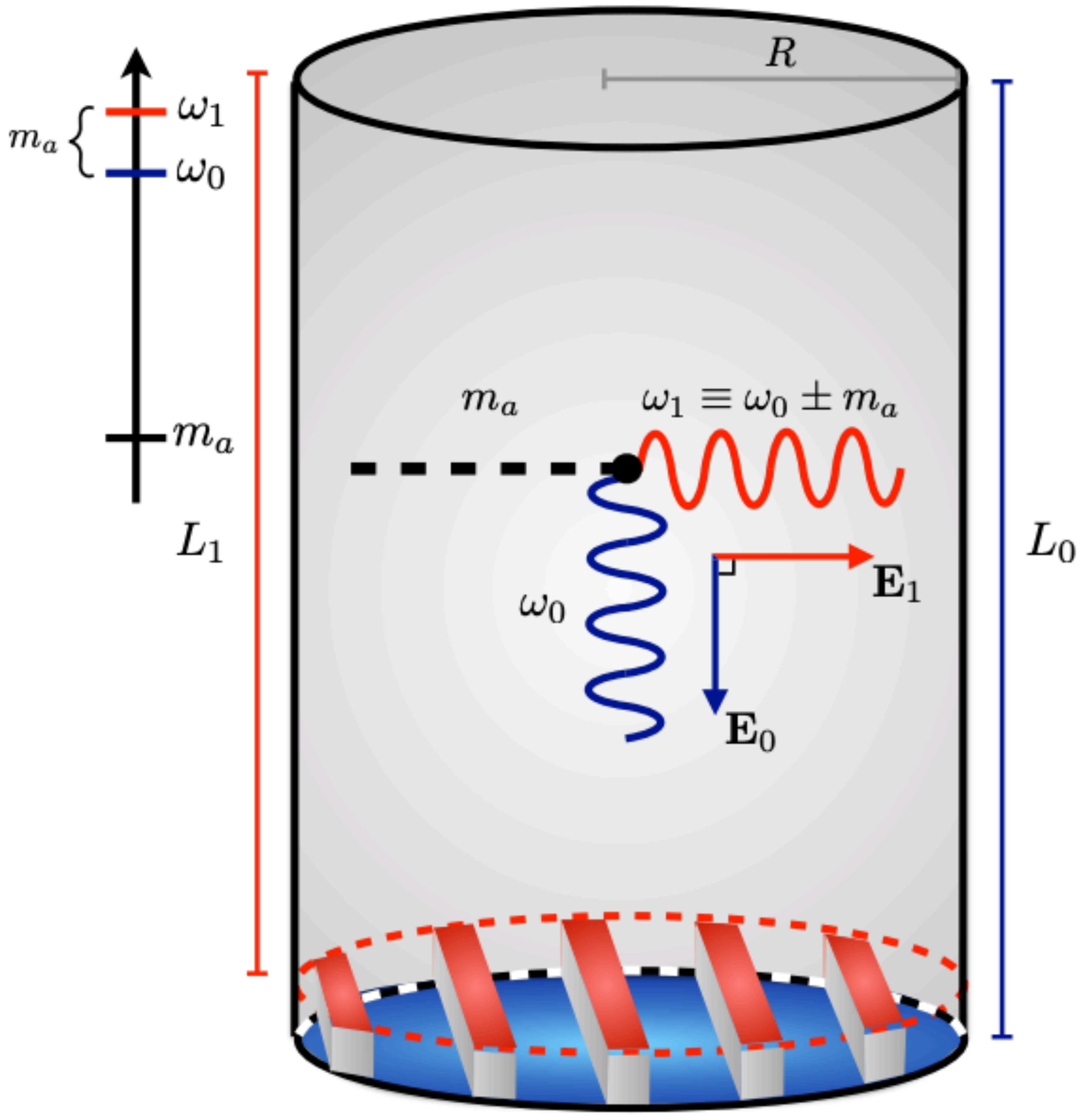


Superconducting Cavities For Low Mass Axions

- 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



arXiv:1912.11056



(a) Cartoon of cavity setup.

arXiv:1912.11048

Haloscopes for HP DM

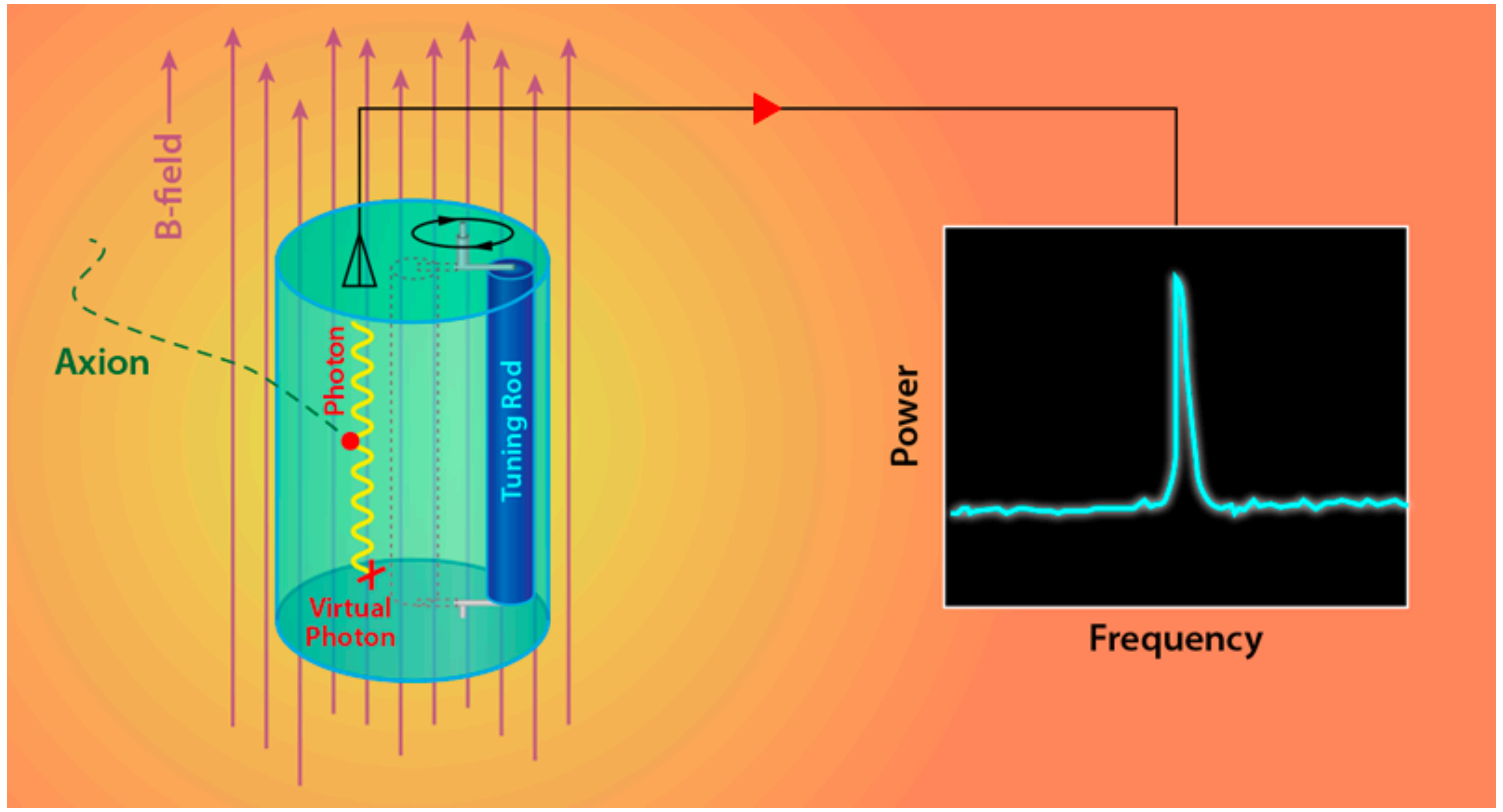
- In principle, most axion haloscopes using axion-photon mixing are sensitive to HPs
- For an example, take a cavity haloscope

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

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

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

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



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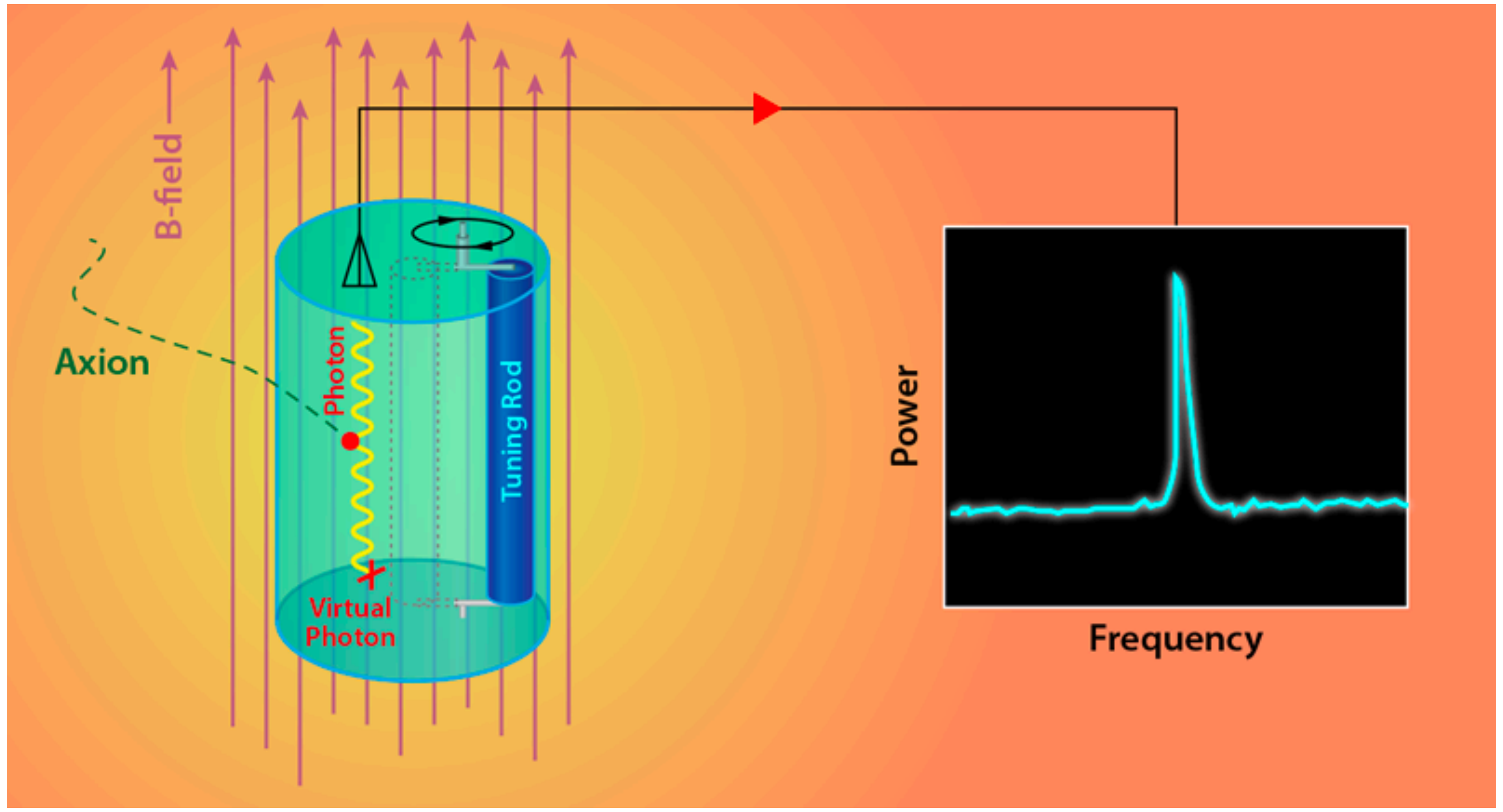
Haloscopes for HP DM

- 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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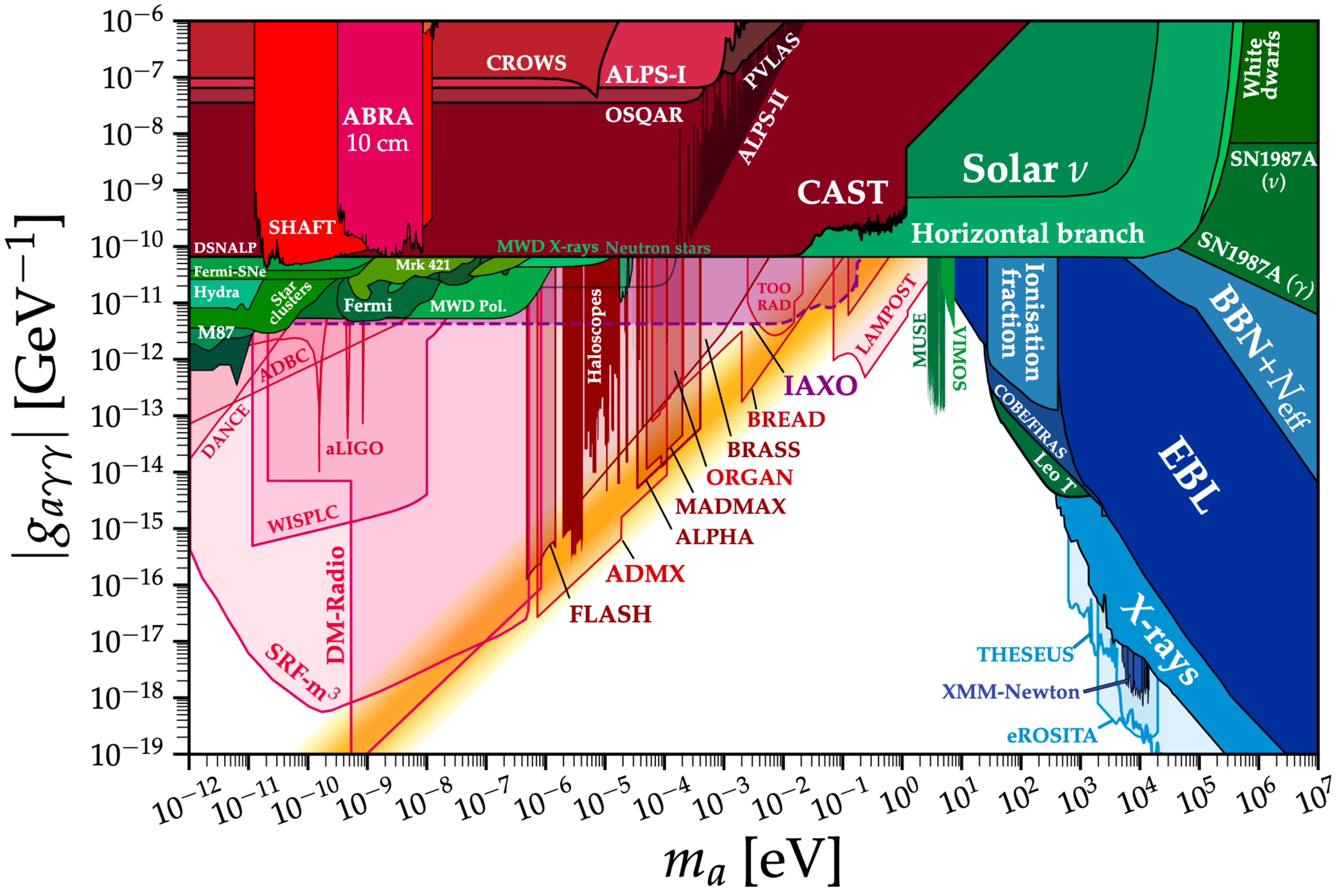
Reinterpreting axion experiments

- 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	$\langle\cos^2\theta\rangle_T^{\rm excl.}$
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

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



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Current HP Limits

- Rescaled for fixed polarisation (conservative case)