Spinning Light: Searching for Axion Dark Matter with Magnetic Haloscopes

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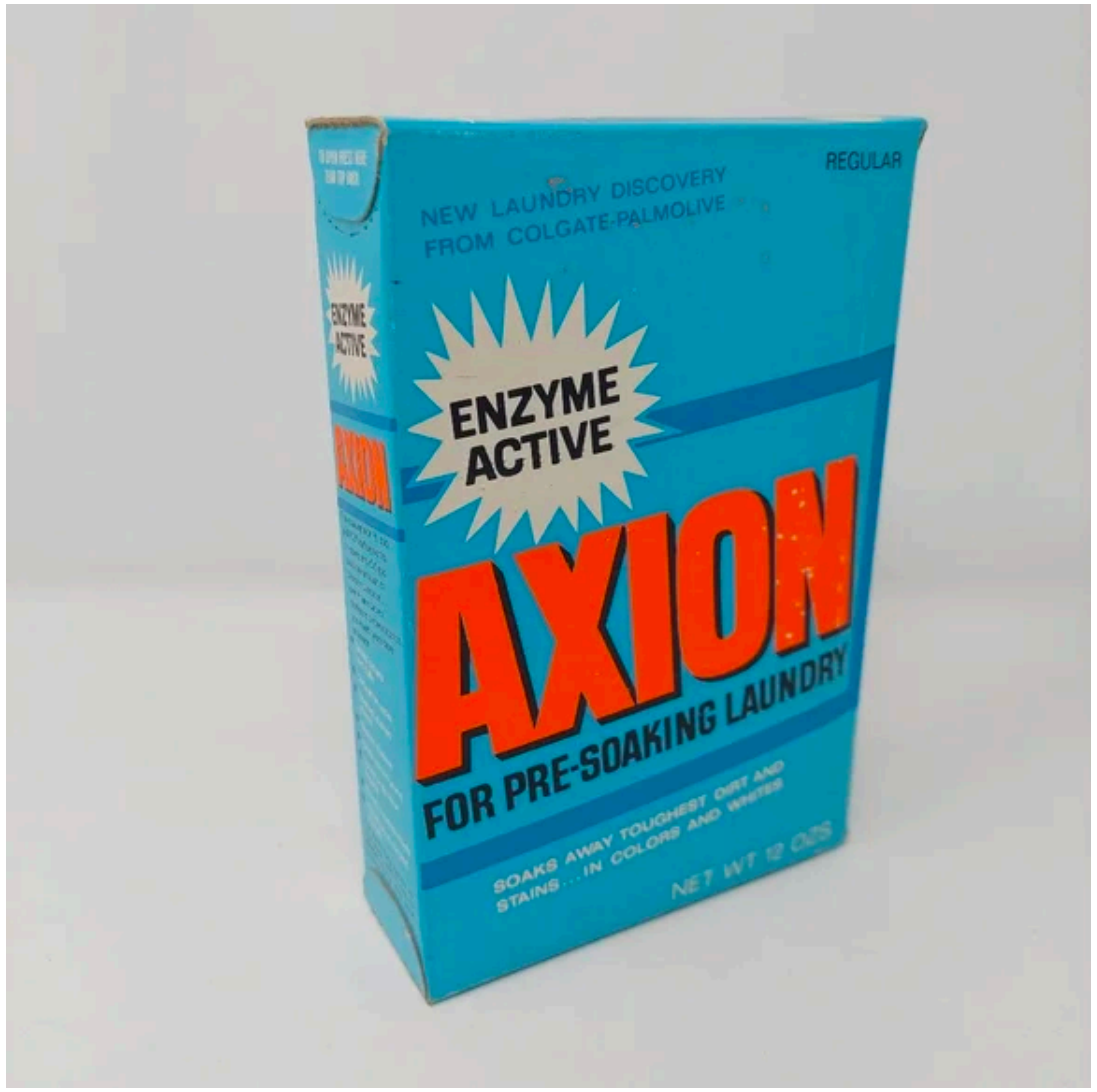
arXiv:2312.11601

Axions

- Introduced to resolve the strong CP problem
- New pseudoscalar degree of freedom!
- Can be produced early in the universe as coherent waves
- Axion like particles are also interesting: don't solve CP problem but do provide DM



Axion Interactions

- Lots of details depend on the model but we will only focus on two interactions

Coupling to matter (mostly spin)

$$L_{\text{int}} \supset g_{a\gamma} a \mathbf{E} \cdot \mathbf{B} + g_{af} \left(\partial_\mu a\right) \bar{\Psi} \gamma^\mu \gamma^5 \Psi \ ,$$

Coupling to electromagnetism

Non-relativistic Hamiltonian

- Need to be very careful and self consistent, depending on which Lagrangian one starts with there can be non-trivial operator redefinitions
- Lowest order terms

$$H \supset -g_{af}\,(\nabla a)\cdot\boldsymbol{\sigma} - \frac{g_{af}}{m_f}\,\dot{a}\,\boldsymbol{\sigma}\cdot\boldsymbol{\pi}\ ,$$

Wind

Axio-electric

$$\boldsymbol{\pi} \equiv \mathbf{p} - q_f\mathbf{A}$$

Axion-Induced Torques

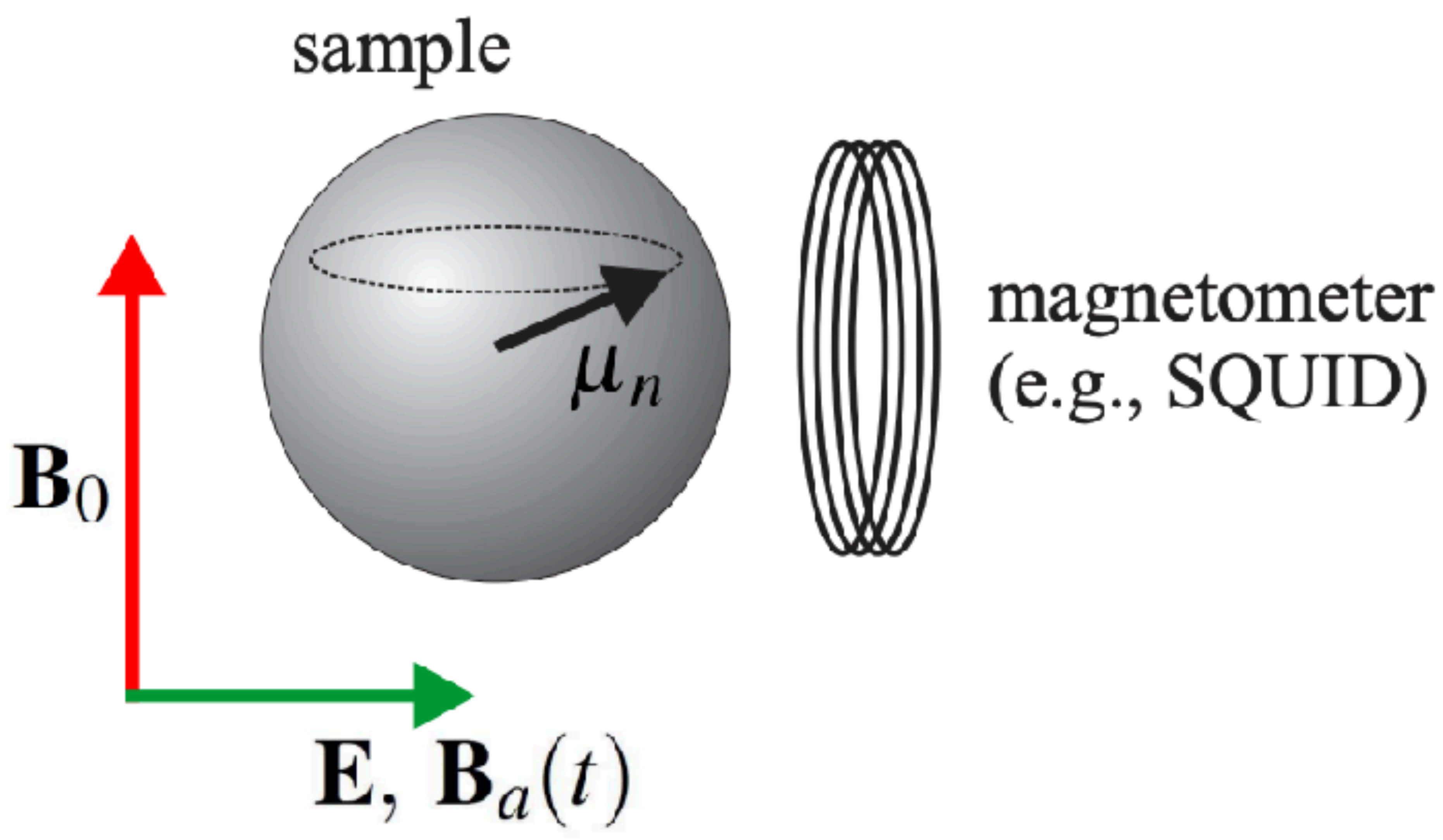
- Most well known effect of axion-fermion couplings
- Acts on spins similarly to a B-field

$$\frac{d}{dt}\langle \mathbf{S} \rangle = \langle\, 2\,\mu_f\, \mathbf{S} \times \mathbf{B} + 2 g_{af}\, \mathbf{S} \times (\nabla a + \dot{a}\,\mathbf{v})\,\rangle \;,$$

$$\mathbf{B}_{\rm eff} = (g_{af}/\mu_f)\,(\nabla a + \dot{a}\,\langle \mathbf{v} \rangle)$$

Axion-Induced Torques

- Most exploited fermion coupling!
- Usually used for NMR type experiments like CASPER WIND and ferromagnet haloscopes like QUAX
- Tends to be most important for low axion masses



arXiv:1711.08999

Axion-Induced Forces

- How does the axio-electric term act on the electron?
- Need to generalize the Lorentz force law

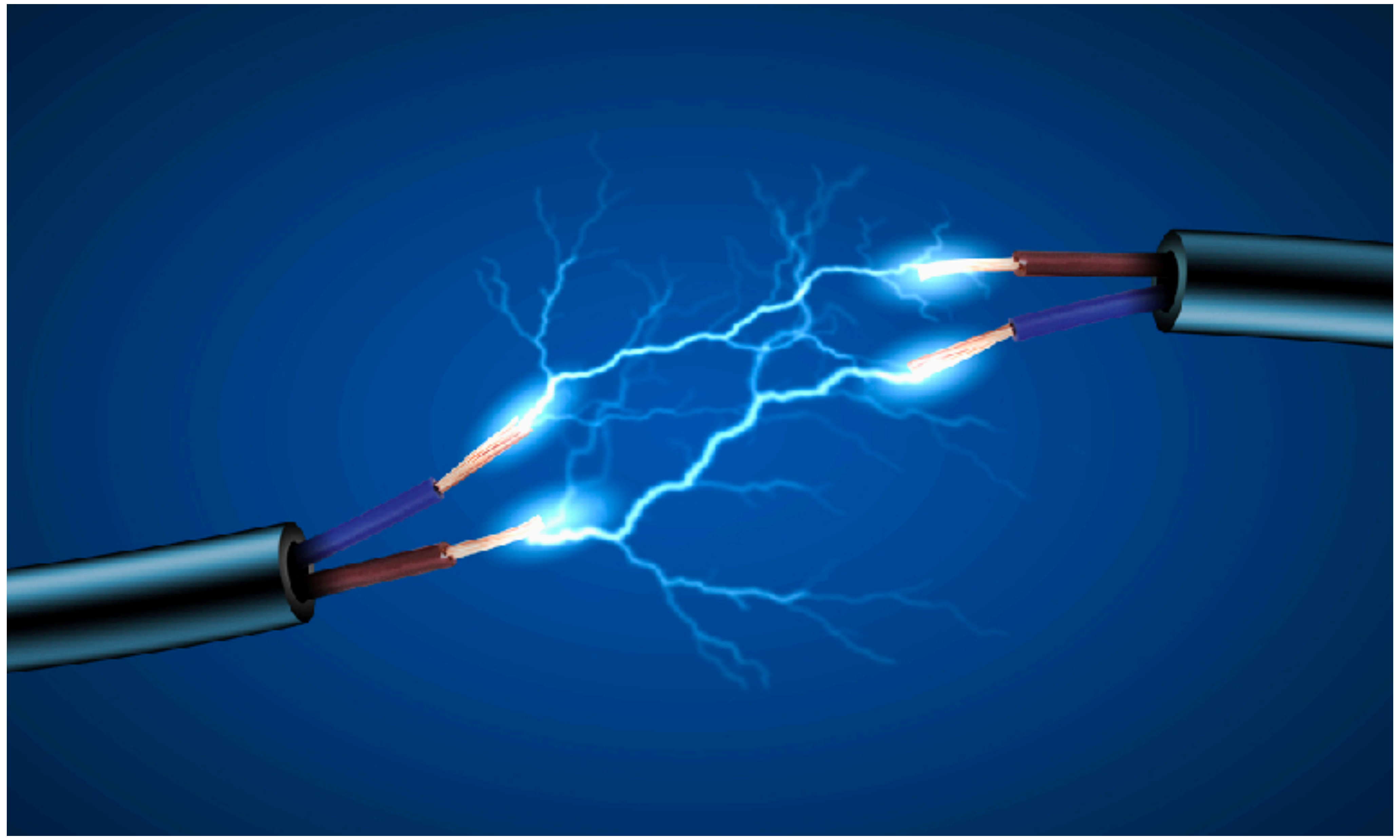
$$\mathbf{F} \equiv m_f \frac{d}{dt}\langle \mathbf{v}\rangle \simeq \left\langle q\,\mathbf{E} + \frac{q}{2}(\mathbf{v}\times\mathbf{B} - \mathbf{B}\times\mathbf{v}) + \mu_f \nabla(\boldsymbol{\sigma}\cdot\mathbf{B})\right\rangle$$

$$\boxed{- g_{af}\frac{d}{dt}\langle \dot{a}\,\boldsymbol{\sigma}\rangle} + g_{af}\left\langle (\nabla^2 a)\,\boldsymbol{\sigma} + (\nabla\dot{a})\,(\boldsymbol{\sigma}\cdot\mathbf{v}) - \frac{1}{2}(\mathbf{v}\cdot\nabla\dot{a} + \nabla\dot{a}\cdot\mathbf{v})\,\boldsymbol{\sigma}\right\rangle$$

$$\mathbf{E}_{\text{eff}} \simeq -(g_{af}/q)\,\frac{d}{dt}\left(\dot{a}\,\langle\boldsymbol{\sigma}\rangle\right)$$

Axion-Induced Forces

- This looks like an E-field, but it couples to spin rather than to charge
- Spin polarized case not well studied in the literature!
- How can we exploit an effective electric field?
- Turn it into a real electric field!



Axion Induced Currents

- New currents to source Maxwell equations

$$\mathbf{J}_a = \mathbf{J}_a^P + \mathbf{J}_a^M = (\varepsilon_{\sigma e} - 1)\,\partial_t \mathbf{E}_{\rm eff} + \nabla \times \left((1-\mu^{-1})\,\mathbf{B}_{\rm eff}\right)$$

- $\varepsilon_{\sigma e}$ is spin version of dielectric constant
- Generates a inhomogeneous wave equation

$$\nabla \times \nabla \times \mathbf{E} + n^2\,\partial_t^2 \mathbf{E} = -\mu\,\partial_t \mathbf{J}_a \ ,$$

Axion-Electrodynamics

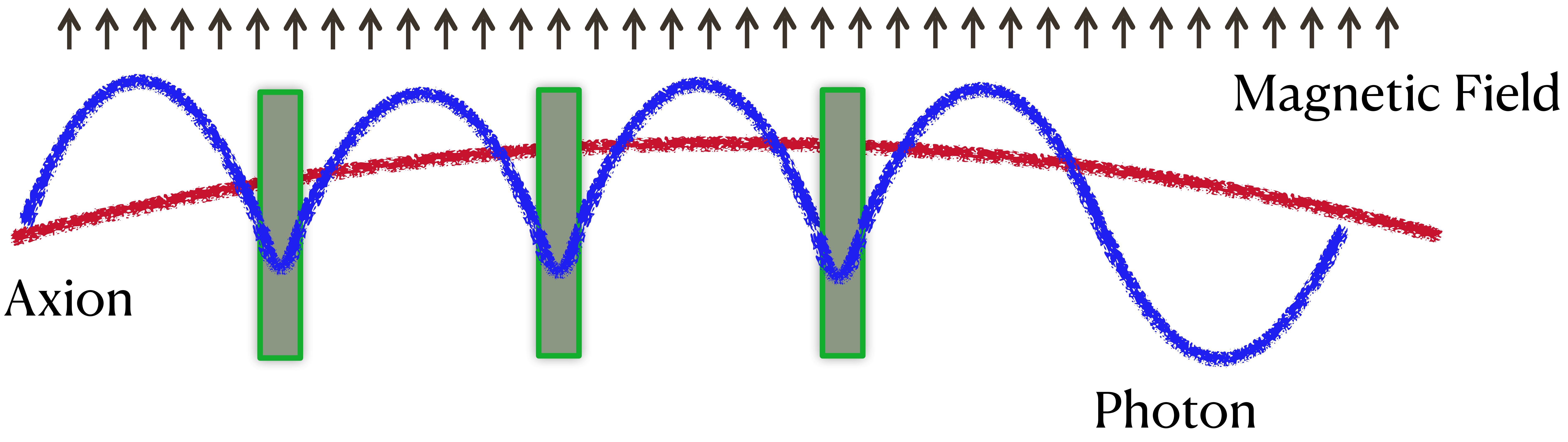
- Easiest to just think of the axion as modifying Maxwell equations
- External B-field $\mathbf{B}_e$ induces small effective current
- Use the coherence to resonantly excite E-fields
- Induced E-fields depend on the medium

$$
\begin{aligned}
\nabla \cdot (\epsilon \mathbf{E}) &\simeq \rho_f \,, \\
\nabla \times (\mathbf{B}/\mu) - \epsilon \dot{\mathbf{E}} &\simeq \mathbf{J}_f + \boxed{g_{a\gamma} \mathbf{B}_e \, \dot{a} \,,} \\
\nabla \cdot \mathbf{B} &= 0 \,, \\
\nabla \times \mathbf{E} + \dot{\mathbf{B}} &= 0 \,,
\end{aligned}
$$

Looks like a current!

Dielectric Haloscopes

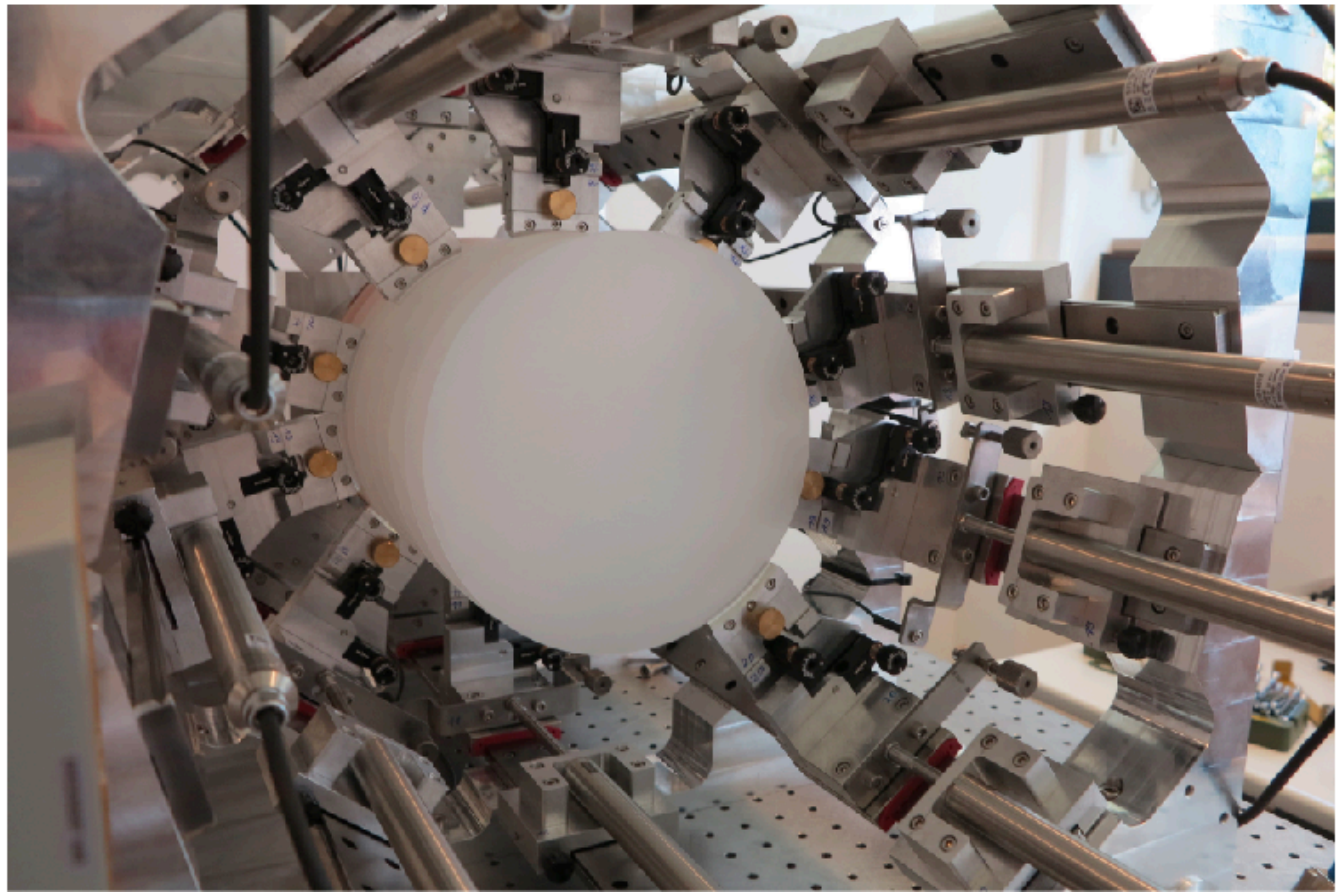
- Introduce a series of dielectric layers (arXiv:1611.05865)

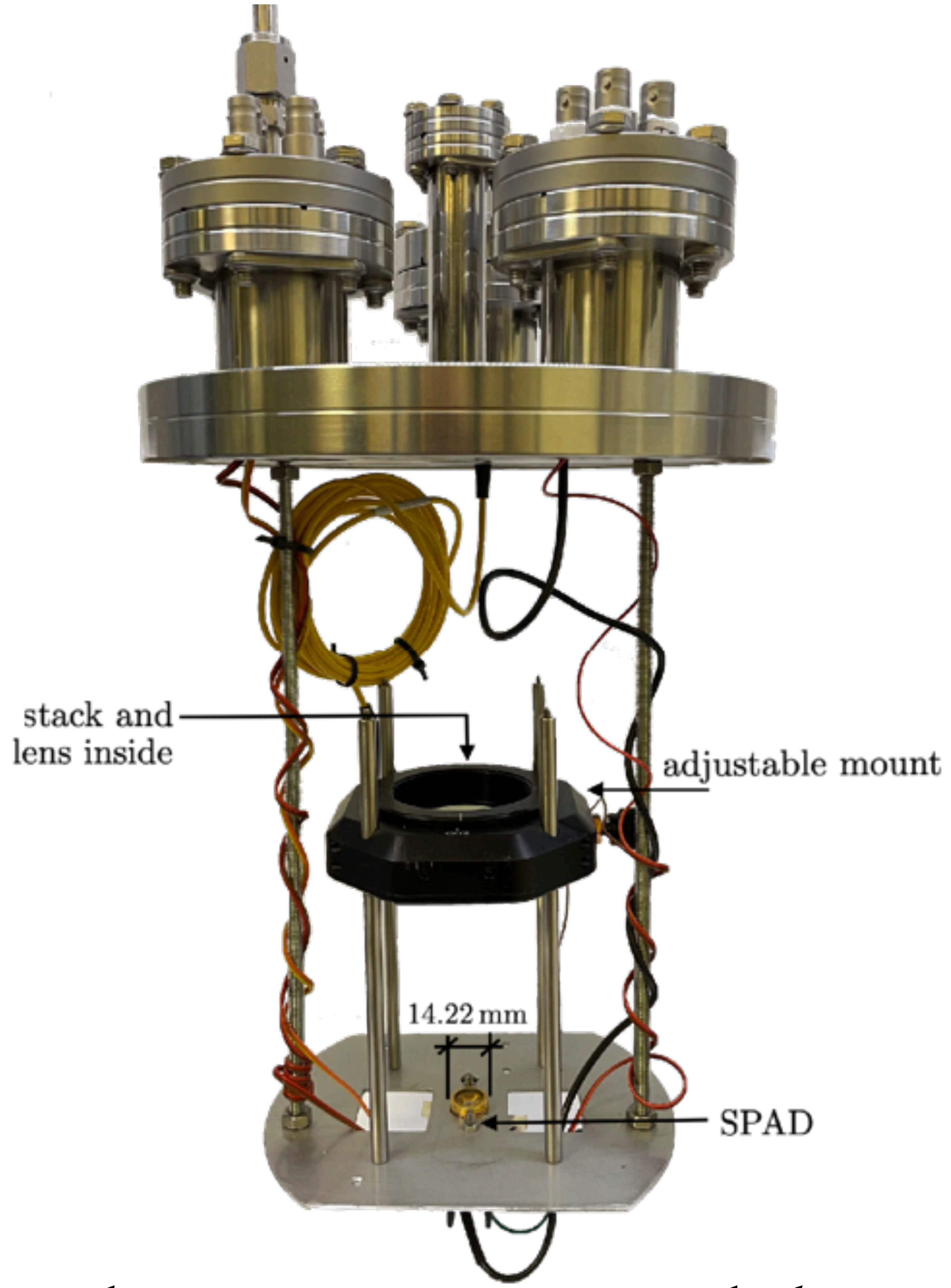


- Boundary radiation emitted from each slab

Dielectric Haloscopes

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



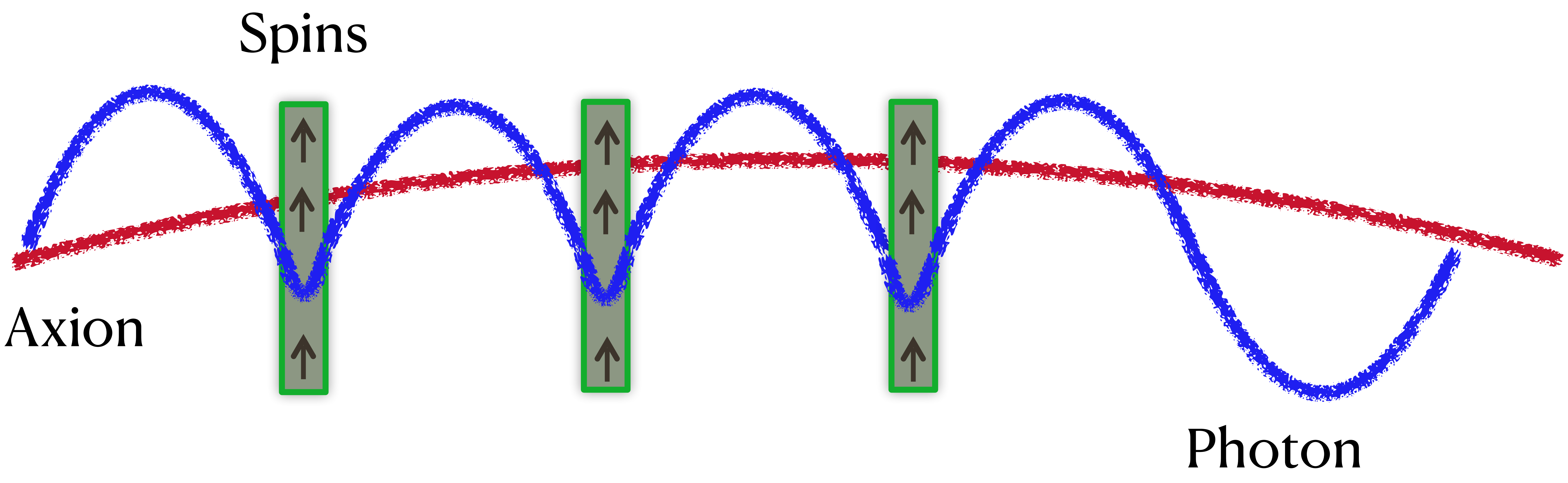


Stefan Knirck

Manenti, Mishra, Bruno, Giovanni, AM et al, *Phys. Rev. D* 105 (2022)

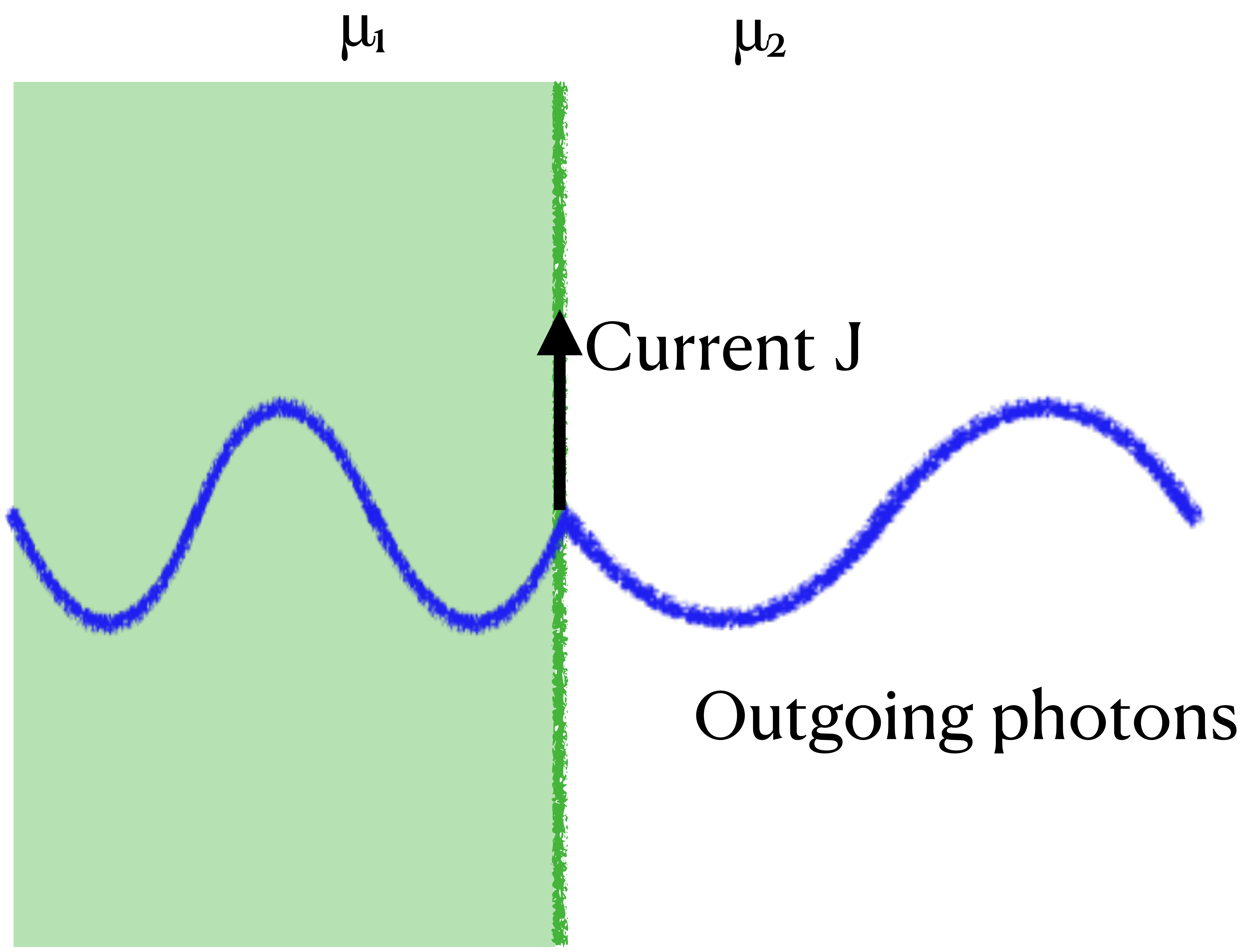
Case One: Axio-Electric

- Spin polarized slab emits propagating radiation
- Can directly map from the photon case $g_{ae} \leftrightarrow g_{a\gamma\gamma}\,(e\,B_0/m_a^2)$
- Tends to be best for optical frequencies



Case Two: Wind

- No bulk currents!
  $\nabla \times \mathbf{B}_{\mathrm{eff}} \propto \nabla \times (\nabla a/\mu)$
- Discontinuity in μ leads to boundary currents
- Doesn't directly map onto the photon coupling
- Better at lower frequencies

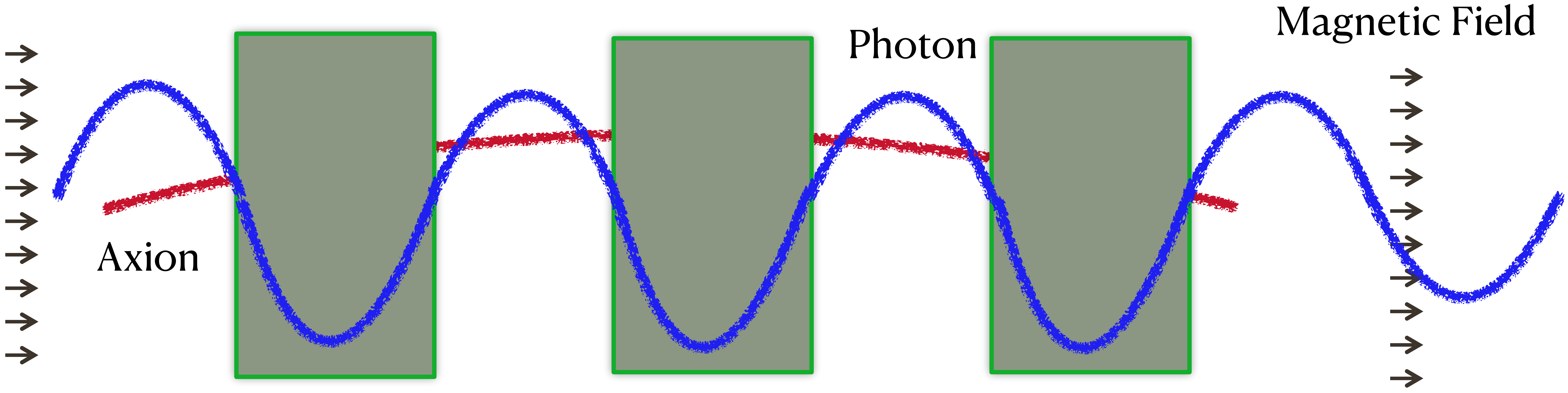


Case Two: Wind

- High frequency μ needs an applied B-field
- Can use larger size, lower Q materials than NMR
- Ferrites ideal!
- Magnon resonance tunable with B-field!
- Uses a solenoidal magnet
- Doesn't need large and high field at the same time

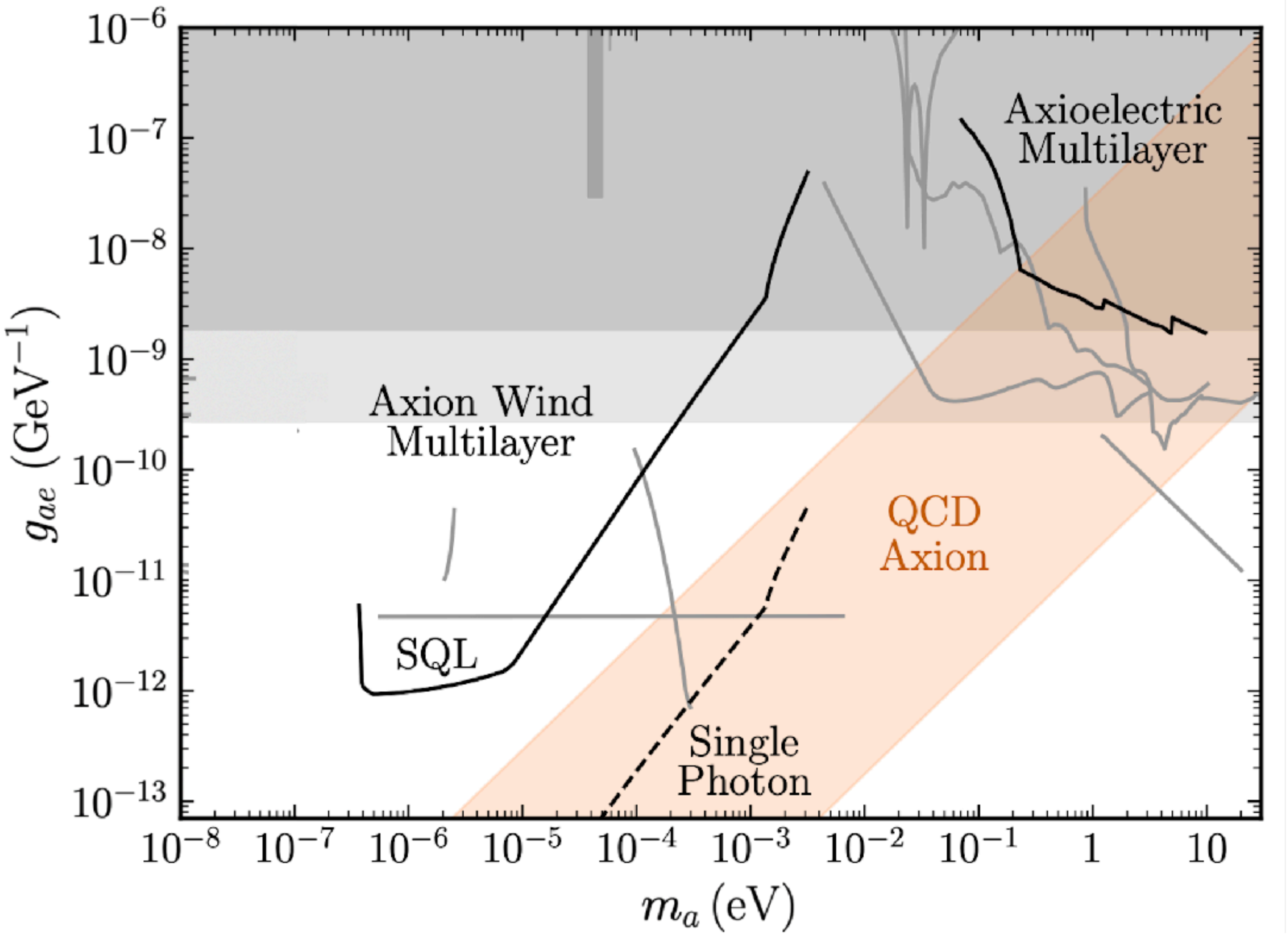
Magnetic Haloscope

- Introduce a series of magnetic layers



- Boundary radiation emitted from each slab

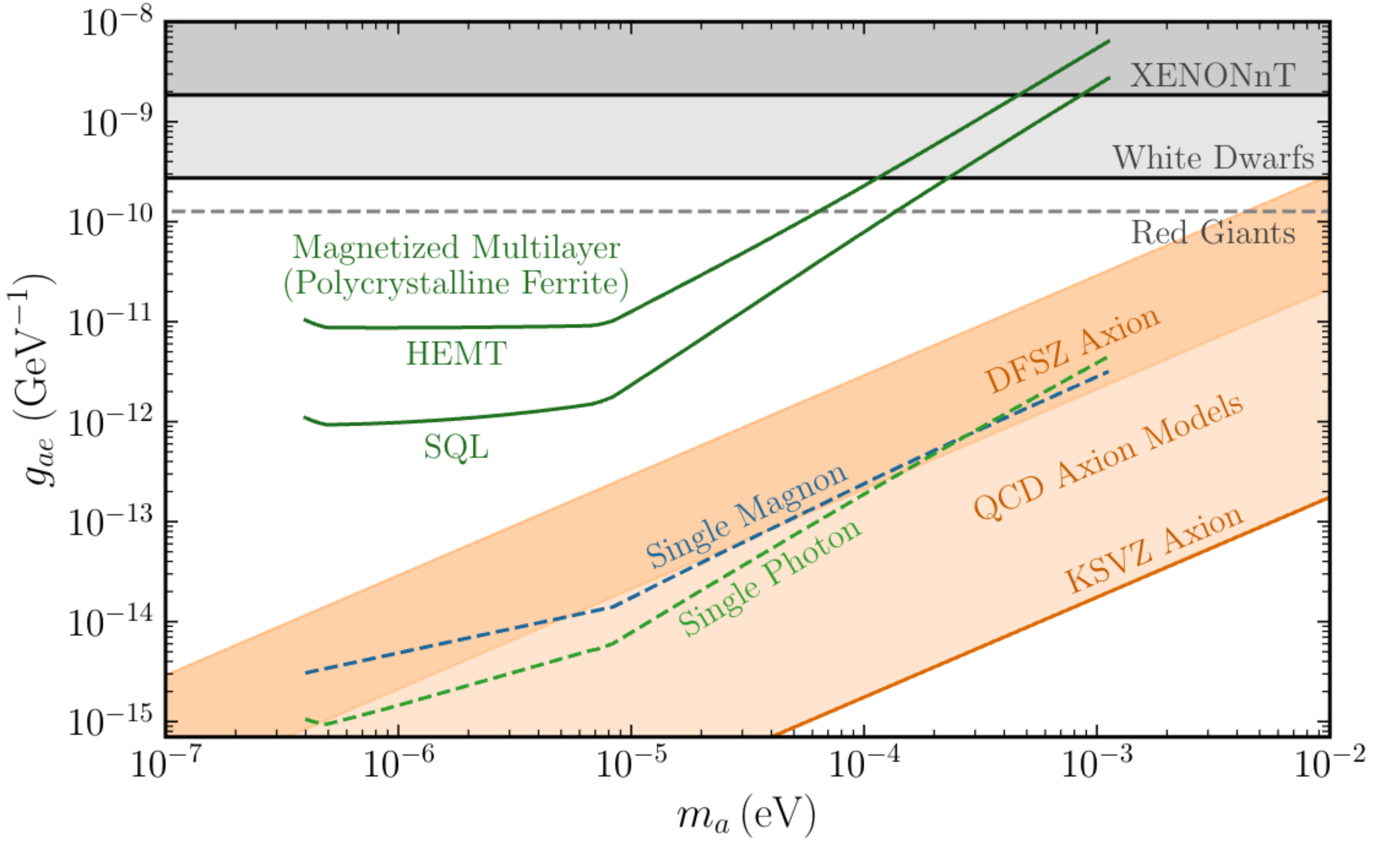
Sensitivity



Conclusions

- Axion-fermion couplings still have lots to explore
- Neglected boundary radiation can lead to powerful new experiments based on dielectric haloscopes
- High volume devices allow for cheaper, easier to manufacture materials
- Absorption via resonances in ϵ and μ also give useful probes

Sensitivity: Wind



Absorption

- More generally one can consider the absorption of an axion
- What if the system is polarized or magnetic?
- Can solve for the total losses of the axion field from the EOM
- Imaginary part of ω gives the energy lost by the axion
- Only comes from medium losses

$$(\partial^2 + m_a^2)\, a = -g_{ae}\left(\partial_t j_\sigma + \nabla \cdot \mathbf{n}_\sigma\right)$$

$$e\, j_\sigma = (\varepsilon - 1)\, \partial_t E_{\text{eff}} + (\varepsilon_{\sigma e} - 1)\, \partial_t \langle \mathbf{E} \cdot \hat{\mathbf{s}} \rangle$$

Axio-electric Wind

Absorption: Axio-Electric

$$R \simeq \frac{g_{ae}^2 m_a^2}{e^2} \frac{\rho_{\rm DM}}{\rho_{\rm det}} \times \begin{cases} 3\,\mathrm{Im}\left[\,\varepsilon(m_a)\right] & \text{(unpolarized target)} \\ \mathrm{Im}\left[\dfrac{-1}{\varepsilon(m_a)}\right] & \text{(polarized target)}\ , \end{cases}$$

- Polarized targets haven't been considered before!
- Two advantages
- Can spin polarize a system to remove background
- Absorption higher on resonances

Absorption: Wind

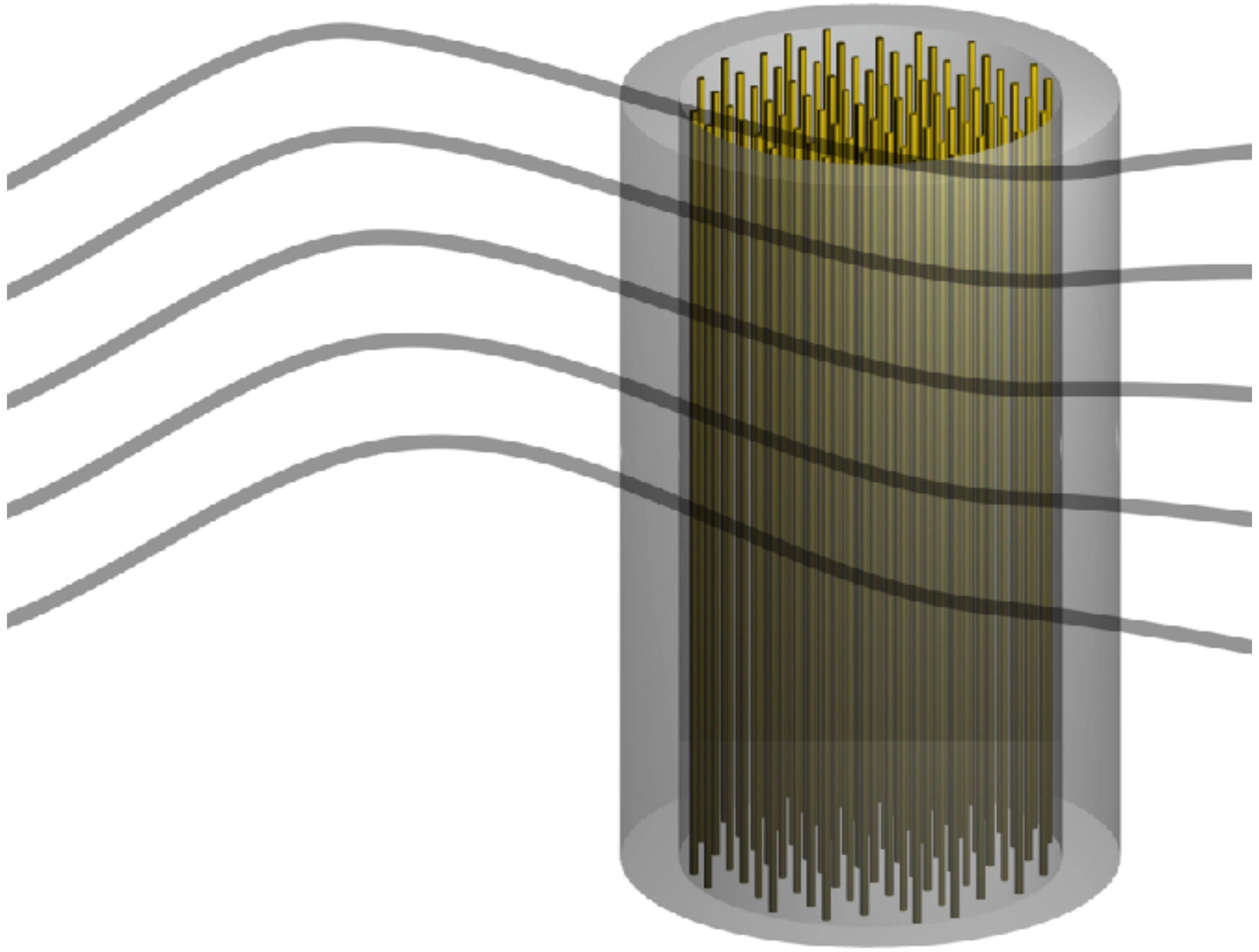
- Axion absorption onto magnons is not new (arXiv:2005.10256)
- Only been done from first principles calculations
- More generally one can just consider an arbitrary magnetized medium
- Magnetic equivalent of the "energy loss function"

$$R \simeq \left(\frac{g_{ae}\, v_{\rm DM}}{\mu_B}\right)^2 \frac{\rho_{\rm DM}}{\rho_{\rm det}}\, {\rm Im}\left[\frac{-1}{\mu}\right] \,,$$

- Anything with μ close to zero may be an interesting detector!

Quasiparticle Haloscopes

- Resonances in epsilon have been exploited in the photon coupling for EM readout
- Plasma haloscopes, TOORAD, phonon-polaritons…
- $\text{Im}[-1/\varepsilon]$ and $\text{Im}[-1/\mu]$ dependence should allow for similar devices
- Spin polarized plasma haloscopes, mu-near zero metamaterials…



Spurious EDMs

- It has been claimed (see, e.g., arXiv:2302.01142) that the axion induces a constant electronic EDM.
- You can do a field redefinition to get

$$\mathscr{L} \supset -2\, m_f\, g_{af}\, a\, \overline{\Psi} i \gamma^5 \Psi .$$

Looks like EDM

- With non-relativistic Hamiltonian

$$H_{\rm alt} \simeq \frac{\boldsymbol{\pi}^2}{2m_f} + q_f\,\phi - \frac{q_f}{2m_f}\mathbf{B}\cdot\boldsymbol{\sigma} - g_{af}\,(\nabla a)\cdot\boldsymbol{\sigma} - \frac{g_{af}}{4m_f}\{\dot{a}, \boldsymbol{\pi}\cdot\boldsymbol{\sigma}\} + \boxed{\frac{q_f\, g_{af}}{2m_f}\, a\, \mathbf{E}\cdot\boldsymbol{\sigma}}$$

Spurius EDMs

- But axion is derivatively coupled: can't have a constant EDM
- Actually the field redefinitions to get the non-relativistic Hamiltonian also redefine the position operator shifting the COM

$$\mathbf{x}_q = \mathbf{x}, \qquad \mathbf{x}'_q = \mathbf{x} + (d/q)\,\boldsymbol{\sigma}$$

- Doesn't reappear at higher order (unlike Schiff's theorem)
- Need to be very careful with non-relativistic derivations
- Actual EDMs are suppressed by $(m_a/m_e)^2$, see arXiv:1312.6667